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**Relativistic-Klystron Two-Beam Accelerator
Based Power Source for a
1 TeV Center-of-Mass Next Linear Collider
Preliminary Design Report**

**S. Yu, F. Deadrick, N. Goffeney, E. Henestroza, T. Houck, H. Li,
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February 22, 1995

Lawrence
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Based Power Source for a
1 TeV Center-of-Mass Next Linear Collider
Preliminary Design Report*

Prepared by

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February 1995

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Preliminary Design Report of a Relativistic-Klystron Two-Beam-Accelerator Based Power Source for a 1 TeV Center-of-Mass Next Linear Collider

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L. Reginato,¹ A. Sessler,¹ D. Vanecek,¹ and G. Westenskow²

Abstract

A preliminary point design for an 11.4 GHz power source for a 1 TeV center-of-mass Next Linear Collider (NLC) based on the Relativistic-Klystron Two-Beam-Accelerator (RK-TBA) concept is presented. The present report is the result of a joint LBL-LLNL systems study consisting of three major thrust areas: physics, engineering, and costing. The new RK-TBA point design, together with our findings in each of these areas, are reported.

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1. Introduction

1.1 Overview (S. Yu)

1.1.1 TBA Issues

As a power source candidate for linear colliders, two-beam-accelerators^{1,2} (TBA) have the inherent advantage of very high efficiency for power conversion from drive beam to rf. In addition, induction-linac-based TBA's have favorable scalings with high frequencies (≥ 11.4 GHz) and high accelerating gradients (≥ 100 MV/m). Conversion of high-current electron beam power to rf power has been demonstrated at the gigawatt level at 34 GHz in free electron laser experiments³, and at several hundred megawatt levels at 11.4 GHz in relativistic klystron experiments⁴. Recent reacceleration experiments⁵ have successfully demonstrated bunched beam transport through 2 reacceleration induction cells and 3 traveling-wave extraction cavities for a total rf output of over 200 MW. The phase and amplitude were shown to be stable over a significant portion of the beam pulse.

The technical challenges for making TBA's into realizable power sources lie in the dynamics of the drive-beam which must propagate over long distances. In particular, the beam-break-up instability through a long multi-cavity relativistic-klystron version (RK-TBA) is known to be severe. While BBU suppression techniques have been successfully demonstrated for a few cavities^{6,7}, a scenario with acceptable BBU control over many traveling-wave cavities must be constructed. Similarly, the longitudinal stability of the rf bunches over a multi-cavity TBA must be demonstrated. For rf phase and amplitude stability, the induction machine must produce and maintain a beam with constant current and energy over the duration of the pulse. In addition to technical feasibility, a case for economic attractiveness is no less essential for the viability of the TBA. Cost and overall system efficiency are essential elements of an acceptable linear collider power source.

With these general considerations in mind, we propose a new version of the RK-TBA which has acceptable longitudinal and transverse beam stability, as well as low cost and high efficiency. A systems study, including physics and engineering designs, as well as 'bottom-up' costing, has been conducted for a point design example with the RK-TBA as a power source for a 1 TeV center-of-mass Next Linear Collider (NLC).⁸

1.1.2 The Key Ideas

To address the critical TBA issues quantitatively is the subject matter of this report. A few key ideas underlie the whole design and are summarized below:

1. 'Betatron node scheme' for high frequency BBU control -- The most severe BBU instability is associated with the dipole mode (HEM₁₁ mode) in the rf cavities. Strong suppression of this mode is achieved by introducing a 'betatron node scheme'^{9,10} in which adjacent rf extraction cavities are placed exactly one betatron period apart. This scheme minimizes beam centroid displacement which excites the dipole mode, and alters the nature of the instability from exponential to a slow secular growth.

2. Landau damping for low frequency BBU suppression -- Quite apart from the high frequency dipole mode associated with the rf cavities, there is a low frequency (a few GHz) dipole

mode associated with the induction reacceleration gaps. This BBU instability is ameliorated by Landau damping due to a large energy spread inherent in the rf buckets of the bunched drive beam. Combining this feature with dipole mode suppression measures in the induction gap design, the calculated low frequency BBU growth is minimal.

3. Inductively detuned cavities for longitudinal beam stability -- To maintain tight rf bunches over long distances with multiple extraction cavities, the rf output structures are inductively detuned. While the concept of inductive detuning is not new, the theoretical framework has to be developed and implemented in simulation codes for traveling wave output structures. Cavity parameters required for stable beam propagation through multi structures were determined.

4. Small low-cost induction cells -- The induction cells in the present design are about 1 foot in diameter, much smaller than most of the known induction machines. This design was possible because of three key features: (a) use of Metglas for the induction cores. This is a low-cost magnetic material that can accommodate a large flux swing. (b) use of low-field permanent magnet quadrupoles. The relatively high drive beam energy of 10 MeV (compared to klystron beams) is a natural match to a strong focusing transport system with low-cost ferrites. An additional advantage of permanent magnets is, of course, the elimination of power supplies. (c) narrow beam pipes -- the design pipe diameter of 5 cm is much smaller than other existing high current machines. This is possible because of the relatively low current (by induction machine standards) of 600 amps, and the low frequency BBU suppression features described earlier. Large beam pipes in usual induction machines are dictated by BBU considerations.

5. Low-voltage pulse power system for efficiency and cost -- The induction cell design matches naturally a 20 kV system with pulse forming networks triggered by ceramic thyratrons and powered by DC power supplies and command resonant charging systems. This system requires no step-up transformers, and eliminates losses associated with going to a high voltage system.

1.1.3 Systems Study Approach

The objective of the present study is to assess the technical feasibility as well as the cost and efficiency of a TBA-based system. To achieve this goal, we felt that it was essential to be reasonably concrete. For this reason, we have chosen for our study a TBA power source for the NLC Upgrade⁸ considered by SLAC. The present thinking about the Next Linear Collider is a 15 km machine with a center-of-mass energy of 500 GeV powered by X-band klystrons and rf pulse compression systems. This machine should be upgradeable to 1 TeV center-of-mass. Our study considers the TBA as a power source candidate for the 1 TeV version of the NLC.

The engineering and costing efforts in the present study draw heavily from recent work in Heavy Ion Fusion¹¹ (HIF). The U.S. effort in HIF is focused on the induction accelerator approach. Research activities in the past few years have centered around the Induction Linac Scaled Experiments¹² (ILSE). Substantial engineering activities were committed to the ILSE CDR, and a 2 MV heavy ion injector at full driver scale was constructed and successfully operated in 1993. In addition, an engineering and costing study was performed recently for a recirculator version of the induction fusion driver. The present TBA study leverages against past HIF experience with many design features as well as engineering and costing expertise from the ILSE, heavy ion injector, and recirculator studies.

A first engineering and costing exercise for the full TBA system has been performed. The electrical design includes all components starting from the AC power distribution system, to the DC power supplies, the command resonant charging system, the pulse forming networks, and the induction cores. Racks and installation, as well as instrumentation and control, were included in this exercise. The mechanical design and costing includes details of the induction cells, rf structures, vacuum, alignment, and utilities. Costs were estimated with a 'bottom-up' approach, assuming mass production procedures for fabrication and assembly.

The physics study utilizes a number of simulation codes developed in the past few years in connection with the TBA experimental program at LLNL. The 1-D and 2-D longitudinal beam dynamics codes RKS¹³ have been used for the design of TBA experiments as well as the modeling of a number of other klystron experiments at SLAC and VLEPP, and code results were generally consistent with the measurements. The BBU code OMICE¹⁴ includes regenerative as well as cumulative effects, and code results agree with BBU observed in the TBA experiments. RKS and OMICE were used extensively for the physics design. For cavity design, we use URMEL and MAFIA, as well as the induction cell design code AMOS¹⁵ developed at LLNL.

1.1.4 The Key Results

We have constructed a point design of a power source for a 1 TeV NLC that consists of 50 independent RK-TBA units, each 300 m long. End-to-end modeling with the RKS code demonstrates stable rf output over the entire RK-TBA unit. BBU simulations with OMICE show acceptable high frequency as well as low frequency BBU growth over the whole 300 m. Sensitivity of these results to beam and cavity parameters were studied. The cavity parameters for the beam dynamics simulations were calculated with URMEL, MAFIA, and AMOS.

Conceptual engineering designs were performed for all electrical and mechanical components from wall plug to rf input to the high gradient accelerating structures. Our preliminary cost estimate for the TBA-based power source for a 1 TeV c.m. NLC is about \$1 billion. This estimate includes the fabrication and assembly of all components, as well as Engineering, Design, and Integration. Conventional facilities and institutional overhead are considered as part of the main NLC project, and are not separately costed in this power source engineering and costing exercise. The overall efficiency of the system (wall plug to rf) is estimated to be 36%.

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1.2 Point Design Example (S. Yu)

1.2.1 Power Source Requirements

The objective of the present study is to construct a conceptual design of the power source for the 1 TeV NLC. Our philosophy is to stay within the design constraints of the NLC and to have a power source system that matches the high gradient structures being considered for the NLC. However, since the parameters of the 1 TeV NLC have not been finalized, we need to make some choices for "power source requirements" in order to make design and costing studies concrete. The design goals for the present study are as follows:

rf frequency	11.424 GHz
repetition rate	120 Hz
peak power/cavity	360 MW
distance between extraction cavities	2 m
pulse length (flat-top)	200 ns
pulse rise time	125 ns

The peak power of 360 MW at 4 X SLAC frequency corresponds to an unloaded gradient of 100 MV/m in high gradient structures presently tested at SLAC. This power is generated from an extraction cavity in the TBA every 2 m, to match the 1.8 m accelerator sections, and to provide adequate spacing in between the HGS's for input and output couplers, focusing etc. In this study, we will be costing the power source for a total of 15 km of this high gradient structure, 7.5 km for each arm of the linear collider. There is a total of 7500 of these extraction cavities, with a total peak power of 2.7 TW. The unloaded energy gain from each arm of the linear collider is 675 GeV. Assuming a loaded gradient that is 75% of the unloaded, the final energies of the electron and positron bunches are 506 GeV each.

The pulse length is determined by the fill time of the structure plus the length of the multi-bunch particle train. In order to maintain constant particle energy from bunch to bunch, the required electric-field should grow linearly in the first 100 ns, and remain constant over the remainder of the beam-on time. The flat-top is specified as 200 ns, which allows us to accelerate pulse trains with twice the number of bunches in the 1 TeV NLC than the present SLAC parameter list (~ 100 ns flat-top), leading to a four-fold increase in luminosity. This is possible for our TBA design at only modest cost increase, and is a natural extension of the NLC parameter set to take advantage of the RK-TBA structure. Because of the intrinsically high efficiency of the RK-TBA, the average power required stays at about 200 MW.

The required electric field at the front of the 100 ns rise is roughly 25% of the asymptotic value. Hence, we specify our input pulse to rise linearly (in field) from zero to its full value in 125 ns. The power increases quadratically over the rise time. This pulse shape can be generated in an RK-TBA by a corresponding linear rise in the current waveform of the drive beam, and a linear rise in the reacceleration voltage as well. Further refinement of the pulse shape to match dispersion in the high-gradient structure and to further improve energy flatness can be achieved by appropriate shaping of the drive beam current and voltage, but are not considered in the present study.

1.2.2 RK-TBA Architecture

To power a 15 km long NLC, the present design consists of 50 independent TBA units. Each RK-TBA unit is about 300 m long, and has 150 extraction cavities (See Figure 1.2.1). To replenish the 360 MW generated from the extraction cavity every 2m, the 10 MeV drive beam with average current of 600 A is reaccelerated at 300 kV/m. The design current could be raised slightly to compensate for rf losses in the induction cells (e.g. 625 A for 4% loss). The main body of the TBA consists of identical 2-m modules each of which has six 100 kV induction cells and one extraction cavity. Both the drive beam current and the reacceleration voltage have a rise time of 125 ns and a 200 ns flat-top, with a fall time that is comparable to the rise time.

The front end of each TBA unit consists of an injector in which a 1.5 kA beam of electrons is generated and accelerated to 2.5 MeV. A 5.7 GHz choppertron is placed at this point to generate a bunched beam at 11.4 GHz. Chopping reduces the DC current from 1.5 kA to 600 A. This bunched beam at 2.5 MeV is then accelerated to 10 MeV in an 'adiabatic capture section'. Bunching cavities in this section further reduce the length of the bunches, and prepare the beam with the right phase space for injection into the main TBA. At the end of the TBA, there is an 'afterburner' section, in which rf extraction continues, but reacceleration is absent. The afterburner allows us to further extract rf power out of the bunched beam, and thus enhances the overall efficiency of the TBA. At the end of the afterburner, the spent beam (at 2 to 3 MeV) is collected at a beam dump. In the present design, the adiabatic capture section is 25 m long, while the main TBA has 138 extraction cavities over 276 m. The afterburner consists of 12 rf cavities over 12 m, making a total of 150 extraction cavities.

The overall length of the TBA unit is determined by a balance of two opposing considerations. The longer the TBA unit, the higher the overall efficiency, as the overhead losses from the front and the back ends become a smaller fraction of the total power. On the other hand, the control of beam instabilities and beam degradation effects become increasingly more difficult as the overall length is increased. The longitudinal and transverse beam dynamics simulations to date indicate that the bunched beam can be maintained stably over the 300 m long TBA unit.

The efficiency for conversion of power in the drive beam to rf power is easily evaluated for the proposed RF-TBA structure. Allowing for some rf loss in the induction cavities, the overall efficiency is estimated to be 90%. The 10% loss is shared among the beam loss on the chopper (3.7%), beam dump (2.8%) and rf into induction cavities (3.6%). From Section 3.1, the efficiency for wall plug to drive beam is 40%. Hence the total efficiency from wall plug to rf is 36%.

The rf power requirement of 360 MW per 2 meters determines the product of the accelerating gradient and beam current in the drive beam. Our particular choice of 300 kV/m and 600 A is again based on a balance of two considerations. With higher current and lower gradient, the volume of magnetic material required is reduced and the efficiency is increased. However, beam transport becomes more difficult with increasing current.

The linear rise in the drive beam current assures that the extracted rf field has the right waveform for beam loading in the HGS, while the linear rise in the voltage of the reacceleration cells assures that the entire drive beam stays at 10 MeV from head-to-tail. This is of course important for both beam transport as well as for rf phase stability. Hence, the rising portion of the

current and voltage generate "useful" rf power. But the fall portion is wasted. The corresponding loss in efficiency due to finite fall time is included in Section 3.1 when we consider the efficiency of the pulse power system.

1.2.3 Main TBA

The main TBA consists of identical 2-m modules. The key elements of the module are the permanent quadrupole magnets for focusing of the drive beam, the induction cells for reacceleration, and one rf extraction cavity. Design considerations for each of these major components will be discussed. The key issues in the design are of course related to the physics of rf extraction, reacceleration, and transport. However, much attention was paid to making the module compact and efficient. The resulting unit has a diameter of 35 cm. In comparison to other existing induction accelerators, the present design is quite small. A schematic of the 2-m module is shown in Figure 1.2.2.

1.2.3.1 Pipe size

In the design of induction accelerators, the size of the beam tube is usually determined by BBU considerations, since the transverse impedance from the acceleration gap is inversely proportional to the square of the pipe radius. In our TBA design, the low frequency BBU arising from the induction gaps is ameliorated by the low beam current of 600 A, and the Landau damping associated with the large energy spread inherent in the rf buckets. Hence, with proper attention to the gap geometry, we are able to design a narrow tube with a radius of 2.5 cm, and predict acceptable low frequency BBU growth. (See Sections 2.2 and 2.4)

1.2.3.2 Permanent magnet focusing

The small pipe radius allows us to take full advantage of permanent magnets, which have significant cost advantages when the focusing systems are small. Another major reason for the use of permanent magnets is the associated efficiency, as they eliminate the need for power supplies.

Several basic considerations govern the design of the FODO lattice: The foremost requirement is associated with a "trick" concocted to minimize the high frequency BBU growth arising from the HEM_{11} mode in the rf extraction cavities. To suppress the instability growth, we demand that the betatron period be equal to the distance between adjacent extraction cavities, i.e. 2 meters. In addition, the phase advance per lattice period must be less than 90 degrees to ensure beam stability. Finally, the focusing strength must be sufficient to keep the beam envelope small to stay within the beam tube.

The zeroth order design equation is given by the thin lens approximation

$$\sigma_0 = \frac{\eta B L^2}{R [B\rho]} \quad (1.2.1)$$

where σ_0 is the phase advance per lattice period, B the quadrupole field strength at pole tip with radial position R. L is the half lattice period, and η the occupancy factor for the quadrupole. The rigidity of the electron beam is given by

$$[B\rho] = \frac{\beta\gamma mc}{e} \quad (1.2.2)$$

where $\beta\gamma mc$ is the momentum of the relativistic beam. $[B\rho]$ has the value of 0.035 T-m for 10 MeV electrons.

A first order correction for deviations from the thin lens approximation is obtained by replacing the phase advance and occupancy factor with scaled variables given by¹

$$\hat{\sigma}_0 = \sqrt{2(1 - \cos\sigma_0)} \quad (1.2.3)$$

and

$$\hat{\eta} = \eta \sqrt{2\left(1 - \frac{2\eta}{3}\right)} \quad (1.2.4)$$

In our design, we use σ_0 of 60 degrees. There are 12 half-lattice-periods in 2 meters. The physical occupancy factor is 0.48. The modified thin lens formula then gives a B-field at pole tip of 800 Gauss. This estimate is within a few % of the actual B field required to give a 2-m betatron period, when we include realistic spatial profile of the magnetic field, as well as the energy variations of the drive beam as it is accelerated over the 2-m module.

A preliminary quad design was constructed by Klaus Halbach.^{2,3} It consists of 4 rectangular blocks of ferrites with residual field B_r of 3.2 kG. The dimensions of the blocks are 1.1 cm x 3.22 cm x 8 cm. This design has as the first non-zero harmonic $n=10$, with 8.6% strength of quad field at aperture radius. Finite differential permeability effects have not been included in this preliminary design.

A basic requirement of the transport channel is that the focusing strength must be sufficiently strong to keep the beam from hitting the beam tube. The beam envelope in the focusing channel can be estimated from the equilibrium formula

$$\frac{\epsilon^2}{a^2} = \sigma_0^2 \left(\frac{a}{L}\right)^2 \quad (1.2.5)$$

where $\epsilon = \epsilon_n/\beta\gamma$ and a are respectively the unnormalized edge emittance and the edge radius of the beam envelope. With a normalized edge emittance of 600 mm-mr, (which is achievable with a good gun design), we obtain an edge radius of about 2 mm for the beam.

1.2.3.3 Steering and focusing corrections

Steering and focusing corrections are achieved in the present design by means of low-field (~10 Gauss) DC coils located in the region immediately outside of the permanent magnets, at radial positions of about 4 cm from axis. These correction coils can be manufactured inexpensively on printed circuit boards.

Since the beam apertures are small, particularly around the extraction cavities, beam centroid displacements must be kept to a minimum. Quad misalignments, when combined with energy variations from head to tail, can lead to beam offsets that change over the length of the

pulse, i.e. the "corkscrew" phenomenon. Our strategy for minimizing beam displacements and associated corkscrew is to impose misalignment tolerances that are not excessively tight, design for energy flatness of $\leq 1\%$, and to correct alignment errors with closely spaced dipole steering coils. Detailed steering algorithms have not been worked out yet, but for the purpose of costing, we provide 3 sets of steering coils and two beam position monitors per betatron period.

A key ingredient for the suppression of high frequency BBU is that the betatron period be equal to the distance between adjacent cavities. To ensure that this requirement is obeyed, a feedback system with 2 correction quadrupoles per betatron period is incorporated into the design. A possible monitor for the betatron motion is to use the rf output from the extraction cavities at the dipole frequency. Whether the signal sensitivity is adequate for this purpose needs to be further explored.

1.2.3.4 Induction Cores

The design of induction cells for reacceleration is based on the relation

$$V \cdot (\Delta t) = A \cdot (\Delta B) \quad (1.2.6)$$

where the core size (with magnetic flux over area A) is determined by the required voltage V and pulse length Δt . The allowed flux swing ΔB is different for different magnetic material. Our present design uses Metglas with ΔB of ~ 1.3 T. Flux swings for Metglas are several times larger than, for example, ferrites, which are commonly used in short pulse induction machines such as ATA and ETA. The cores are correspondingly more compact. Furthermore, Metglas is quite inexpensive, particularly when bought in large quantities.

To determine the transverse dimensions of the core, (with outer radius R_o , and inner radius R_i), we recast Eq. (1.2.6) in terms of the accelerating gradient G and core occupancy factor η_c (fraction of the axial length occupied by induction cores) as follows:

$$R_o - R_i = G \Delta t / (B \eta_c [PF]) \quad (1.2.7)$$

where PF is the packing factor, or the fraction of the total core that is occupied by magnetic material, and has a value of 0.65 to 0.75 for typical Metglas cores. Since the accelerating gradient and pulse length are fixed by overall system requirements, our design philosophy is to maximize axial core occupancy. The present design has η_c of 0.75 and a core thickness $R_o - R_i$ of about 10 cm.

Compact cores reduce cost as well as energy loss. Empirical measurements of core losses, as described in Section 3.1, can be parametrized to give the following phenomenological formula for the core current (in Amps)¹:

$$I_c = 437 (R_o + R_i) \cdot (\Delta B / \Delta t)^{0.67} \quad (1.2.8)$$

where the radial dimensions are in meters, ΔB in tesla, and Δt in microseconds. The fraction of energy lost in the core (I_c / I_{total}) is proportional to the size of the core. Our design parameters give a core current of about 400 A. With a 600 A beam, the core efficiency is 60%.

The magnetic material in a 2 m module is packaged into 6 independent 100 kV induction cells. Each cell in turn consists of five 20 kV cores. Packaging into small induction cores provides a natural match to the low-voltage pulse power system.

1.2.3.5 Pulse Power

The desired voltage pulse from each core has a 125 ns linear rise, followed by a 200 ns flat-top at 20 kV, followed by a fast fall. This voltage waveform is generated with pulse-forming-networks (PFN's) with tapered impedance to match the induction core. Power input to the PFN's consists of a DC power supply and a Command Resonant Charging unit. The entire pulse power train is at low voltage, and no step-up transformers are needed. Hence, high efficiency and low cost is possible.

1.2.3.6 Acceleration Gap

Each 100 kV induction cell has an induction gap, which is one of the more critical components of the design. The ongoing design efforts are reported in Section 2.4, but they evolve around the following key issues :

1. Reduction of high voltage breakdown risks-- To have an induction gap that is safe from breakdown, we need to have sufficiently low gradient across the insulator (< 30 kV/cm), sufficiently low fields on the metal surfaces (< 100 kV/cm), proper shielding of the insulators from secondary electrons and X-rays generated by the beam, and proper design of the triple-point (the interface between insulator, metal, and vacuum).

2. Suppression of low frequency BBU -- Dipole modes associated with the cavity (at a few GHz) can lead to severe beam-break-up problems if not carefully damped. The required transverse impedance was achieved with heavy de-Q-ing by placing microwave absorbing material at critical locations around the cavity.

3. Reduction of transverse and longitudinal impedances at high frequencies -- While the high frequency BBU (HEM₁₁ mode at ~14 GHz) is generated primarily in the rf extraction cavities, and the major BBU suppression activities center around them, one must be careful to ensure that the transverse impedance contribution from the induction cavities are indeed negligible. In the present designs, the transverse impedance around 14 GHz can be made to be lower than half an ohm, and its effect on the high frequency BBU is insignificant. The longitudinal impedance at 11.424 GHz must be low to minimize the microwave power loss. Our design goal is to maintain the induction gap loss to less than 4%, which requires that the longitudinal impedance be less than 4 ohms. Present designs are approaching the required impedance.

1.2.3.7 RF Extraction cavities

Design of the rf extraction is a major ongoing activity in theory and simulations. Present designs evolve around traveling-wave-structures with 3 cells of 8-mm inner radius. The rf output is extracted through 2 separate ports in the 3rd cell, with 180 MW each transported through separate waveguides, and fed directly into the two input couplers of the high gradient structure. Detail design of the cavities center around five key issues:

1. Required output power -- The extraction cavity must have the right effective impedance of about 540 ohms in order to extract 360 MW from a highly bunched beam (70 degrees microbunch length) whose first harmonic current at 11.424 GHz is about 1.15 kA.

2. Minimal breakdown risks -- Our present designs use traveling-wave-structures with 3 cells in order to reduce the surface fields. Surface field gradients of less than 70 MV/m appear possible.

3. Inductive detuning -- In addition to generating the right amounts of power, the rf cavities provide continuous longitudinal bunching for the drive beam. This is accomplished by inductively detuned traveling-wave-structures.

4. Dipole de-Q-ing -- The rf cavities must have low transverse impedances for the suppression of BBU. Fortunately, there is a natural de-Q-ing mechanism, as the required extraction cavities have inner radii of around 8 mm, and the dipole modes in the cavity couple to the TE_{11} mode in the pipe. Simulations to-date suggest that the resulting impedances are sufficiently low for BBU suppression provided that the betatron-node scheme is used.

5. Transverse focusing -- rf cavities have transverse fields associated with the fundamental mode. They can degrade the beam envelope if they are sufficiently strong and/or not properly corrected. Evaluation of these transverse forces from theory and simulations is ongoing.

1.2.4 Front End and Back End

Each main TBA unit has a front end that consists of a 'pre-chopper', a chopper, and an 'adiabatic capture' section. At the end of each TBA unit, there is an 'afterburner', followed by a final beam-dump. These five elements will be briefly described.

1.2.4.1 Pre-chopper

The 'pre-chopper' is basically a short induction accelerator to generate an unbunched 300-ns electron beam at 2.5 MeV. This section may consist of an injector (at 1 to 1.5 MeV), followed by a short induction accelerator section that takes the beam to 2.5 MeV. The required current from the injector is 1 to 1.5 kA, depending on the efficiency of the chopper, which is required to produce at its exit a bunched beam with a DC current of 600 Amps.

The current waveform required consists of a linear rise over 100 ns, followed by 200 ns of flat-top. The beam energy should be constant over the entire 300 ns, including the front portion with the rising current. To generate the linearly rising current, the voltage pulse in the 1 MeV injector will also, by the Child-Langmuir Law, have a (nonlinear) 100 ns rise time. The pulse-forming-network in the subsequent short accelerator section must be arranged to produce a higher voltage at the beam front, thereby compensating for the low energy at injector exit.

Since the electron beam will be transported over 300 m of narrow pipes, caution must be taken to minimize head-to-tail energy variations, as well as transverse beam offsets and beam temperature. The injector design should produce a bright beam with a normalized edge emittance of 600 mm-mr or less., and transverse displacement of 200 microns or less.

1.2.4.2 Chopper

The purpose of the chopper is to generate cleanly separated microbunches at 11.4 GHz. The basic scheme follows the design of Haimson Research Corporation which has been deployed at LLNL. A subharmonic dipole deflecting cavity at 5.7 GHz causes the electron beam to oscillate about a limiting aperture, leading to 'chopped' bunches at twice the oscillating frequency. A similar device can serve as the TBA front end chopper, except that much more effective heat dissipation is required for the 120 Hz operation of the NLC upgrade.

Since a substantial amount of energy is lost on the chopper, there is incentive to make it efficient. One idea is to precede the subharmonic deflecting cavity with conventional bunching cavities at 11.4 GHz. The role of the chopper then is primarily to 'clean up' the particles with the wrong phase. This requires straight-forward phasing of the 5.7 GHz input power to the deflecting cavity relative to the incoming pre-bunched beam.

1.2.4.3 'Adiabatic Capture'

The exiting beam from the chopper has microbunch lengths equivalent to 180° or greater in longitudinal phase space. In the 'adiabatic capture' region, the microbunch lengths are further reduced to 70° which is the needed bunch length for long-distance propagation in the main TBA. This is accomplished by a number of idler cavities that are more inductive than the rf extraction cavities in the main TBA.

In addition to microbunch sharpening, this section also serves to provide the energy transition from 2.5 MeV to 10 MeV. The induction core structures are very similar to the main TBA. However, the voltage waveform should be flat over the 300 ns of beam-on time, so that the head-to-tail energy flatness required for phase stability could be maintained at 10 MeV.

The quadrupole magnets are weaker at the lower energies, and continues to increase with increasing energy, so that the betatron wavelength is kept fixed at 2 m. Structurally, the 'adiabatic capture' section looks very similar to the main TBA, except that no power is extracted from the idler rf cavities.

1.2.4.4 'Afterburner'

At the end of the TBA is an 'afterburner' section, the primary purpose of which is to increase overall system efficiency by extracting more power out of the nicely bunched beam at the end of the main TBA. This section has a number of rf extraction cavities, permanent magnets for focusing, but no reacceleration cells. The spacing of the rf cavities is changed as the average energy of the beam continues to decrease. The impedance of the cavities is also modified to compensate for changes in the rf bucket. The present design has 12 cavities in the 'afterburner' section, each generating 360 MW, and together covering a total of 12 meters.

1.2.4.5 Beam-dump

As the spent electron beam reaches the final beamdump, its average energy is less than 3 MeV. The design of this component is straightforward.

Figure 1.2.1 A 300 m RK-TBA unit with 150 rf extraction cavities.

Figure 1.2.2 The main RK-TBA consists of repeated 2 m modules.

References

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2. RK-TBA Physics Studies

2.1. Longitudinal Beam Dynamics (H. Li)

2.1.1 Introduction

2.1.1.1. The main issue and the concept of inductive detuning

Longitudinal stability of the drive beam is among the important issues for the demonstration of technical feasibility of the relativistic klystron two-beam accelerator (RK-TBA) concept. In the present scheme, the drive beam is required to stay bunched longitudinally over 150 extraction cavities. Space charge effects cause initially tight bunches to expand. The debunching process is further aggravated by the energy spreads along the beam bunches as they interact with rf fields. In usual traveling extraction cavities, rf waves are in synchronism with the drive beam and debunching becomes very severe after a few cavities. Beam debunching, if uncompensated, will result in reduced power extraction in subsequent cavities, as is shown in Figure 2.1.1. To overcome this problem, we employ a scheme in which the drive beam is off synchronism with the operating

Figure 2.1.1. Simulation result of power extraction versus cavity number for 3-cell traveling wave structures in which the field ($2\pi/3$ mode) is in synchronism with the drive beam (operating frequency 11.424 GHz, cavity group velocity 0.28 c, beam energy 10 MeV and average beam current 600 A.)

wave mode; more specifically, the phase velocity of the rf field is larger than the speed of light, c , so that the beam bunches always lag behind the wave, as is illustrated in Figure 2.1.2. This is what we call the "inductive detuning" scheme and it can effectively bunch the beam. In fact, the concept of the inductive detuning is well known for standing wave structures (SWS's), e.g., the "penultimate" cavity in a klystron, in which the frequency of the cavity is detuned away from the resonant frequency¹. For the traveling wave structures (TWS's) of RK-TBA, the approach we take is to keep the frequency ω of the operating mode unchanged, but reduce its wave number k , such that wave field advances faster than the beam. In this case particles at the front of the beam bunch lose more energy and slow down, while particles at the tail of the bunch lose less energy, and will therefore, "catch up". This mechanism causes a continuous "sharpening" of the beam bunch, thus counteracting the debunching forces. The resulting longitudinal phase space continues to rotate in a stable "beam bucket" with a relatively stable bunch length. In this way, the stable power extraction and beam bunching can be achieved simultaneously over many cavities.

Figure 2.1.2. Schematic of the "inductive detuning" concept

As mentioned above, the extraction cavities used in the RK-TBA are TWS's. They are favored over the SWS's because of their reduced electrical surface field stress. A typical TWS consists of multiple cells with the last cell, normally, being the output cell. An analytic theory and a numerical code named "RKS" have, previously, been developed by Ryne and Yu for theoretical investigation of using TWS's^{2,3}. This theory, however, applies only to the synchronism case when the beam and the field are in phase, while we are mostly interested in the non-synchronism cases. To use the RKS code to study the inductive detuning cases, a more general theoretical framework is needed and is derived in this work.

2.1.1.2. Summary of results

This study concerns itself with the longitudinal dynamics of a 300-m long RK-TBA unit. We carried out extensive investigations on how to employ the inductive detuning scheme on RK TWS's to achieve power extraction and beam bunching at the same time, and we also examined several other related issues. In Section 2.1.2, we first develop an analytical theory on using inductively detuned TWS for power extraction. We obtain the matching condition under which a TWS propagates and amplifies only a forward traveling wave and we derive an analytic formula for predicting the power output from a TWS. In Section 2.1.3, we present our simulation results on the inductive detuning scheme and demonstrate that with appropriate detuning angle(s) the output power can be maintained stably for 150 extraction cavities across one RK-TBA unit. In Sections 2.1.4 and 2.1.5, we present, respectively, our simulation studies on the "adiabatic capture" scheme and the chopper operation and show that an initial DC beam of 2.5 to 5 MeV and of 1.5 kA out of the injector can be manipulated into a bunched beam of 10 MeV and 600 A average current with the required microbunch length for stable propagation in the main RK-TBA. In Section 2.1.6, we examine the "after-burner" scheme and show that the electron beam that comes out of the main TBA can continue to drive at least another 12 cavities, and therefore, can further enhance the beam to rf efficiency and make the disposal of the beam easier. In Section 2.1.7, we present our ongoing study on the transverse focusing problem.

2.1.2 Theory of Inductively Detuned Traveling Wave Structures for Power Extraction

We adopt the analytical approach employed by Ryne and Yu in Reference 2. Consider a TW structure consisting of N cells. Let the electric field in the n^{th} cell of the structure be given by

$$\vec{E}_n(\vec{r}, t) = a_n(t) \cdot \vec{e}_n(\vec{r}) \cdot e^{-i\omega t} \quad (2.1.1)$$

where $\vec{\epsilon}_n$ denotes the eigenmode of the n^{th} cell with eigenfrequency ω_n , and where we have assumed that $\omega_n \approx \omega$, with ω being the frequency of the RF field. It can be shown that, in the steady state, the excitation amplitudes a_n are governed by the following difference equations:

$$(\omega_n^2 - \omega^2 - i\frac{\omega\omega_n}{Q_n})a_n - (K_n^{n-1}a_{n-1} + K_n^{n+1}a_{n+1}) = \frac{i\omega}{\epsilon_0} \int (d^3r)_n \vec{\epsilon}_n^* \cdot \vec{J}_1 \quad (2.1.2)$$

where $n = 1, \dots, N$ and $a_0 \equiv a_{N+1} \equiv 0$. In the above equations, K_n^{n-1} and K_n^{n+1} describe the coupling of cell n to cell $n-1$ and cell $n+1$, respectively. The quantity Q_n denotes the quality factor of the n^{th} cell. $\vec{J}_1$ denotes the first harmonic of the RF current associated with the bunched beam. For the purpose of our analytic study, we assume that

$$K_n^{n-1} = K_n^{n+1} \equiv K. \quad (2.1.3)$$

Then the difference Eq. (2.1.2) can be rewritten as

$$(\omega_n^2 - \omega^2 - i\frac{\omega\omega_n}{Q_n})a_n - K(a_{n-1} + a_{n+1}) = S_n \quad (2.1.4)$$

where $S_n = \frac{i\omega}{\epsilon_0} \int (d^3r)_n \vec{\epsilon}_n^* \cdot \vec{J}_1$ is the drive term.

Most of the previous theoretical works on the TWS's assume an infinitely periodic structure, the treatment of which is straightforward. In this study, we too start by deriving the dispersion equation for an infinitely periodic structure. We then proceed to focus on the case of a structure with finite number of cells and develop a theory to show that if ω_N and Q_N for the last cell (the output cell) satisfy certain "matching conditions", then the structure behaves just like a structure with infinite number of cells and there exists only a forward propagating wave. The properties of an infinitely periodic structure then applies also to this finite structure. The derivations are valid whether the wave is in synchronism with the particles or not.

2.1.2.1. Dispersion equation for an unloaded TWS with infinite number of cells

We will first review briefly the case with no source ($I_n = 0$) and no loss ($Q_n \rightarrow \infty$). We may assume a plane wave solution $a_n \sim e^{in\phi_p}$ and obtain from (2.1.4)

$$\omega_n - \omega \approx \frac{K}{\omega} \cos(\phi_p), \quad (2.1.5)$$

where $\phi_p = kL_p$ is the phase advance of the wave across a single cell, k is the wave number and L_p is the longitudinal dimension of the cell. In obtaining (2.1.5) $\omega_n + \omega \approx 2\omega$ is used. The coupling constant K can be expressed in terms of the group velocity, V_g . Taking the derivative on both sides of Eq. (2.1.5) with respect to k , it is found that

$$K = \frac{\omega V_g}{L_p \sin(\phi_p)}. \quad (2.1.6)$$

Substituting (2.1.6) into (2.1.5) we find that for an unloaded TWS with infinite number of cells (i.e., $N \rightarrow \infty$) the operating frequency ω and the eigenfrequency of cell n , ω_n , are related by the following dispersion equation

$$\omega_n = \omega + \frac{V_g}{L_p} \text{ctg}(kL_p). \quad (2.1.7)$$

2.1.2.2. Matching conditions for a TWS with finite number of cells

In reality, a TWS has only finite number of cells. We consider the case where, except for the first and last cells which may serve, respectively, as the input and the output cavities, the cells in between are identical, i.e.

$$\begin{aligned} Q_n &= Q_v & (n = 2, \dots, N-1), \\ \omega_n &= \omega_v & (n = 2, \dots, N-1). \end{aligned} \quad (2.1.8)$$

We will show that ω_1 , Q_1 , ω_N and Q_N can be determined in such a way that (i) for the other $N-2$ cells the TWS behaves just like an infinitely periodic structure, and (ii) there is no reflected wave in the structure but only a forward propagating wave. (i) is essentially the boundary condition(s), while (ii) is the so-called "matching condition(s)" in its original sense.

The matching conditions can be obtained in the following way (detailed algebra is given in Appendix 2.1.A): First, we solve difference equations (2.1.4) analytically. The general solution is

$$a_n = e^{i\alpha n} \left[\frac{-i}{2\sin(\alpha)} \sum_{r=1}^n f_r \cdot e^{-i\alpha r} + C_1 \right] + e^{-i\alpha n} \left[\frac{i}{2\sin(\alpha)} \sum_{r=1}^n f_r \cdot e^{i\alpha r} + C_2 \right], \quad (2.1.9)$$

where the phase advance of the field from cell to cell, α , and the drive terms, f_n , are defined, respectively, as follows

$$\cos \alpha = \frac{1}{2K} (\omega_v^2 - \omega^2 - i \frac{\omega \omega_v}{Q_v}) \quad (2.1.10)$$

and

$$f_n = -S_n/K. \quad (2.1.11)$$

Also C_1 and C_2 are constants that need to be determined by the boundary condition and the matching condition. In obtaining (2.1.9), it is assumed that α is not equal to an integral multiple of π and also $\sum_{r=1}^0 f_r \cdot e^{\pm i\alpha r} = 0$.

Before proceeding further we assume a stiff beam, i.e., the drive terms f_n have constant amplitudes but the phases of f_n increase from cell to cell by α' , and therefore $f_n = f e^{i\alpha' n}$. The synchronism case occurs when $\alpha = \alpha'$, i.e. the field and the beam travel in phase. The non-synchronism case occurs when $\alpha \neq \alpha'$, i.e. the field and the beam are out of phase. We are most interested in the inductive detuning case where $\alpha < \alpha'$. We then specify that the 1st cavity be the same as the $N-2$ cells that are behind it and only the last cell ($n=N$) is different from the rest. We also assume that $\cos(N\alpha') = 1$ and $\sin(N\alpha') = 0$ (e.g., in our present RK-TBA design, $\alpha' = 2\pi/3$

and $N = 3$), Eq. (2.1.9) could be viewed as a sum of two traveling waves, one forwards and the other backwards. With appropriate choice of C_1 and C_2 , the backward component can be eliminated (see Appendix 2.1.A). This so-called matching condition can be recast in the following form

$$\begin{aligned}\omega_N &= \omega_v - \frac{V_g}{2L_p \sin(\alpha)} \left[\frac{\sin(N+1)\Delta^-/2}{\sin(N\Delta^-/2)} \cos \Delta^+/2 \right] \\ (Q_N)^{-1} &= \frac{V_g}{\omega_N L_p \sin(\alpha)} \left[\frac{\sin(N+1)\Delta^-/2}{\sin(N\Delta^-/2)} \sin \Delta^+/2 \right]\end{aligned}\quad (2.1.12)$$

where $\Delta^\pm = \alpha' \pm \alpha$ with Δ^- being defined as the so called detuning angle. $\Delta^- = 0$ corresponds to the synchronism case, and $\Delta^- \neq 0$ corresponds to the non-synchronism case. In deriving (2.1.12) relation (2.1.6) is used and $Q_v \gg 1$ is assumed.

Now, we have obtained the formula for the condition which once satisfied will guarantee a TWS to propagate a single forward traveling wave. The formula applies to the nonsynchronism cases as well as the synchronism case, and therefore, once implemented in the RKS code it will allow the code to simulate the physical processes of beam-rf interactions in the detuned TWS's. The numerical results are presented in Section 2.1.3.

2.1.2.3. Power balance equation

The principal motivation of this study is to investigate how to achieve sustained output power level for many TWS's with the inductive detuning scheme. Before carrying out numerical simulations it is helpful to obtain the power balance relation for a detuned TWS to quantify the generation and the transmission of *EM* energy inside the TWS so that we can have a better understanding of the process.

We start with Eq. (2.1.2) and after some algebra (see Appendix 2.1.B) we find that the power extracted from the last cell of the TWS may be expressed as

$$P_{out} = \sum_{n=1}^N \frac{1}{2} \text{Re} \left[\left(- \int d^3 r_n \vec{\epsilon}_n^* \cdot \vec{J}_1 \right) \cdot a_n^* \right] \quad (2.1.13)$$

where $|a_n|$ ($n = 1, 2, \dots, N$) is the amplitude of the field at cell n and where $\int (d^3 r_n) |\vec{\epsilon}_n|^2 = 1$. We

then introduce $I_n^{id} \cdot e^{i\phi_n} = (L_p)^{1/2} \int (d^3 r_n) (\vec{\epsilon}_n^* \cdot \vec{J}_1)$ as the induced current and $V_n \cdot e^{i\psi_n} = (L_p)^{-1/2} \cdot a_n$ as the voltage across the cell n , and rewrite the power balance equation (2.1.13) in the following form

$$P_{out} = \frac{1}{2} \sum_{n=1}^N (-I_n^{id} \cdot V_n) \cdot \cos(\phi_n - \psi_n) \quad (2.1.14)$$

It is seen from (2.1.14) that the output power from a TWS is equal to an accumulation of the *EM* energy generated in each cell which is proportional to the induced current, I_n^{id} and the voltage

across each cell, V_n . It is also seen that the maximum output power is achieved for the synchronism case when the beam and the rf field have the same phase advance across each cell (i.e., $\phi_n - \psi_n = 0$). For the non-synchronism cases the output power declines as the detuning angle increases.

2.1.2.4. Power extraction formula

For a stiff beam it is possible to derive an analytic expression for P_{out} in terms of the induced current and the cavity related parameters, i.e. the shunt impedance R/Q , the group velocity V_g , longitudinal dimension L_p and the cell number N . This formula is useful for zeroth order cavity design.

First, we treat the synchronism case when $\Delta^- = 0$. In this case, the matching condition (2.1.12) reduces to

$$\begin{aligned}\omega_N &= \omega_V - \frac{V_g}{2L_p \sin(\alpha)} \left(\frac{N+1}{N} \right) \cos(\alpha), \\ (Q_N)^{-1} &= \frac{V_g}{\omega_N L_p \sin(\alpha)} \left(\frac{N+1}{N} \right)\end{aligned}\quad (2.1.15)$$

and the power balance equation (2.1.14) becomes

$$\begin{aligned}P(0) &\equiv P_{out}(\Delta^- = 0) \\ &= \frac{1}{2} \sum_{n=1}^N (-I_n^{id} \cdot V_n) .\end{aligned}\quad (2.1.16)$$

Then, starting from Eq. (2.1.9) and after some mathematical manipulations (for detail algebra, refer to Appendix 2.1.C) we can rewrite (2.1.13) in the following form

$$P(0) = \frac{(I_{ind})^2}{4} \left(\frac{\omega L_p}{V_g} \right) \left[\left(\frac{R}{Q} \right) / 2 \right] \cdot N(N+1). \quad (2.1.17)$$

where it is defined that the induced current

$$I_{ind} \equiv \int dS (J_1 \cdot e^{ikz}) \quad (2.1.18)$$

and the shunt impedance

$$\frac{R}{Q} \equiv \frac{\left| \int dz (\epsilon e^{ikz}) \right|^2}{\omega \epsilon_0}. \quad (2.1.19)$$

Note that in (2.1.17), $P(0)$ is proportional to $N(N+1)$.

Next, for the detuning cases when $\Delta^- \neq 0$, the extracted power may be expressed as

$$P(\Delta^-) = \Gamma(\Delta^-) \cdot P(0), \quad (2.1.20)$$

where the coefficient $\Gamma(\Delta^-)$ is a function of the detuning angle Δ^- . It is seen from Eq. (2.1.14) that $\Gamma(\Delta^-) = 1$ if $\Delta^- = 0$ and $\Gamma(\Delta^-) < 1$ if $\Delta^- \neq 0$. For any given Δ^- , Γ may be determined from the numerical simulation using the RKS code as will be seen in Section 2.1.3.

Eqs. (2.1.17) and (2.1.20) relate the output power requirement $P(\Delta^-)$ to the induced current and detuning angle Δ^- . The specific cavity structure that meets the requirements can be designed with the *URMEL* and the *MAFIA* codes. The study has been carried out and the results are presented in Section 2.1.3 of this report. For our present design parameters, a 30° inductively detuned 3-cell TWS with inner, outer aperture radii and longitudinal dimension per cell (L_p) being, respectively, 8 mm, 12.5 mm and 8.754 mm, has a R/Q of 13.5 Ω and V_g of 0.28 c. In our case I_{ind} is about 1.15 kA, and the calculated output power is around 360 MW.

2.1.2.5. Field amplitudes and phases

In our present conceptual RK-TBA design, each TWS has 3 cells. In the following we present two sets of analytic formulas to quantify the amplitudes and the phases of the rf field in a detuned 3-cell TWS:

(i) Between two adjacent cells in the TWS (with detuning angle Δ^-)

$$\begin{aligned}\frac{a_2}{a_1} &= e^{i(\alpha' - \Delta^-/2)} \cdot [2\cos(\Delta^-/2)], \\ \frac{a_3}{a_2} &= e^{i(\alpha' - \Delta^-/2)} \cdot \left[\frac{\sin(3\Delta^-/2)}{\sin(\Delta^-)} \right].\end{aligned}\tag{2.1.21}$$

(2.1.21) describes how the field evolves across the TWS.

(ii) Between the cells in the detuned TWS (a_i) and the corresponding cells in the corresponding non-detuned TWS ($a_i(0)$) which is used as the base case

$$\begin{aligned}\frac{a_1}{a_1(0)} &= e^{-i(\Delta^-/2)} \cdot \left[\frac{\sin(\alpha')}{\sin(\Delta^+/2)} \right], \\ \frac{a_2}{a_2(0)} &= e^{-i(\Delta^-)} \cdot \left[\frac{\sin(\alpha')}{\sin(\Delta^+/2)} \cdot \frac{\sin(\Delta^-)}{2\sin(\Delta^-/2)} \right], \\ \frac{a_3}{a_3(0)} &= e^{-i(3\Delta^-/2)} \cdot \left[\frac{\sin(\alpha')}{\sin(\Delta^+/2)} \cdot \frac{\sin(3\Delta^-/2)}{3\sin(\Delta^-/2)} \right].\end{aligned}\tag{2.1.22}$$

(2.1.22) quantifies the effects of the cavity detuning on the amplitude and the phase of the rf field in each cell of the TWS.

The above relations have been used to check the RKS code. The results are presented in Tables 2.1.1.1 and 2.1.1.2 of section 2.1.3.1.

2.1.3 Numerical Simulations of the Main RK-TBA

2.1.3.1. RKS Code

We carried out numerical simulations using the RKS code. RKS was developed by Ryne and Yu to study the power extraction from a RK due to the interaction of a charged particle beam with an electromagnetic wave in a TWS or a SWS³. The code solves self-consistently the single particle equations of motion for the beam and the coupled circuit equations that govern the cavity excitation, and it includes the calculation of the space charge effect. It assumes a single dominant mode and cylindrical symmetry of its fields inside the cavity. RKS code simulations have been checked against the relativistic klystron experiments conducted by the Microwave Source Facility group at LLNL³ and has also been employed to assist in the design of the reacceleration experiment⁴. These studies show that results from the code are consistent with experiment^{3,5}.

However, in all the previous RKS simulations on TWS's the beam bunches and the operating fields were in synchronism^{3,5}, while we are mainly interested in the nonsynchronism case. Therefore, in the following, we use relation (2.1.22) to verify that the RKS code can also be used for the inductive detuning cases. The ratio of the rf field (amplitude and phase) in each of the 3 cells of the detuned TWS to the corresponding one in the non-detuned TWS is evaluated both analytically (with (2.1.22)) and numerically (with RKS) for four different detuning cases. The results are tabulated in Table 2.1.1.1 and Table 2.1.1.2, respectively.

Table 2.1.1.1 Analytical Results

$\alpha' - \alpha$	0°	10°	20°	30°	40°
$ a_1/a_1(0) $	1.	0.956	0.922	0.896	0.879
$ a_2/a_2(0) $	1.	0.952	0.908	0.865	0.826
$ a_3/a_3(0) $	1.	0.946	0.884	0.816	0.742
$\psi_1 - \psi_1(0)$	0°	-5.0°	-10.0°	-15.0°	-20.0°
$\psi_2 - \psi_2(0)$	0°	-10.0°	-20.0°	-30.0°	-40.0°
$\psi_3 - \psi_3(0)$	0°	-15.0°	-30.0°	-45.0°	-60.0°

Table 2.1.1.2 Numerical Results (from RKS code)

$\alpha' - \alpha$	0°	10°	20°	30°	40°
$ a_1/a_1(0) $	1.	1.04	1.07	1.07	1.02
$ a_2/a_2(0) $	1.	1.02	1.03	1.00	0.94
$ a_3/a_3(0) $	1.	1.02	1.01	0.948	0.84
$\psi_1 - \psi_1(0)$	0°	-3.1°	-8.3°	-13.0°	-18.2°
$\psi_2 - \psi_2(0)$	0°	-9.0°	-18.5°	-28.4°	-38.3°
$\psi_3 - \psi_3(0)$	0°	-14.2°	-29.0°	-44.0°	-59.0°

It is seen that, in general, the agreement is fairly good for the phase although there is a 1-2° systematic discrepancy for almost all the cases. The agreement for the amplitude is not as good as that of the phase. However, for any given detuning angle, the ratio of the amplitudes does decrease as predicted by the analytical calculations. In the following, we present the results of our RKS simulation studies.

2.1.3.2. RK-TBA with inductively detuned TWS's

Figure 2.1.3 presents the output power from each of 150 TWS's in the main TBA section for both a successful inductive detuning case and its corresponding synchronism case. The parameters for the inductive detuning case are given in Table 2.1.2. It is seen that for the synchronism case, the level of the extracted power P_{out} declines sharply due to the space charge debunching effect as the drive beam traverses the RK-TBA. In contrast, when the TWS's are properly detuned, the rf bucket can be maintained stably and output power can be sustained at the desired level (~360 MW) for all the 150 extraction cavities. The physical mechanism of the inductive detuning effect can be explained as follows: In a TWS that is inductively detuned, the field advances faster than the beam, therefore, particles at the front of the beam bunch lose more energy and slow down, while particles at the tail of the bunch lose less energy, and will "catch up". This causes a continuous "sharpening" of the beam bunch, thus counteracting the debunching forces from the space charge. The resulting longitudinal phase space continues to rotate in a stable "beam bucket" with a relatively stable bunch length (the small fluctuation on the power level is due to this "synchrotron motion" of a rotating "beam bucket"). In this way, the stable power extraction and beam bunching can be achieved simultaneously over many cavities.

Figure 2.1.3. Power extraction from 150-cavities in one unit of RK-TBA: (a) with inductive detuning ($\Delta^- = 30^\circ$, phase velocity 1.33c); (b) no inductive detuning ($\Delta^- = 0^\circ$, phase velocity 1.0c).

Figures 2.1.4(a) and (b) are the longitudinal phase distribution of a beam bucket for the inductive detuning case in Figure 2.1.3 just before the 1st TWS and after the 110th TWS,

respectively. It is seen that after 110 extraction cavities, the beam bucket maintains the initial bunch length of about 70° (the wave length is measured as 360°). It is also noted that the bucket has a large energy spread, $10 \sim 15\%$. This energy spread provides strong Landau damping and drastically reduces the beam break-up (BBU) instability in the induction machine. This issue is discussed by Houck, et al., in Section 2.2.

Figure 2.1.4. Phase distribution of a beam bucket for the inductive detuning case in Figure 2.1.3: (a) Just before the 1st TWS; (b) after the 110th TWS and 2 m reacceleration.

A key feature for RK-TBA design is the cavity filling time, i.e., the time it takes for the rf field in a cavity to reach equilibrium state. In Figure 2.1.5 we present the time dependencies of output power at the 50th, 100th and 150th extraction cavities for the inductive detuning case in Figure 2.1.3. It shows that after about 15 ns the fields in all the cavities reach their equilibrium states. This indicates that the erosion on the beam head due to cavity filling process is not serious. The short fill time is a result of low Q and high V_g .

Figure 2.1.5. Time evolutions of output power at 50th, 100th and 150th TWS's for the non-synchronism case in Figure 2.1.3.

Further RKS simulation studies were conducted to examine the sensitivities of the inductive detuning scheme to two important parameters: the bunch length and the detuning angle;

(i) With respect to the bunch length

Figures 2.1.6(a) and (b) show power extraction from 150 cavities that are 30° detuned with a bunch length of 50° and 90° , respectively. It is seen that for the 30° detuning angle the effective bunch length can be fairly flexible, although when the bunch length is beyond 90° the results start to deteriorate.

Figure 2.1.6. Power extraction from 150 cavities that are 30° detuned: (a) 50° bunch length; (b) 90° bunch length.

(ii) With respect to the inductive detuning angle

Figures 2.1.7(a) and (b) show power extraction from 150 cavities that are, respectively, 35° and 25° detuned and driven by a beam of 70° bunch length. It is seen that when the detuning angle is above 30° the result is similar to that of the 30° detuning case. But when the detuning angle is somewhat below 30° , e.g. at 25° the TWS's are unable to sustain the level of output power up to 150 TWS's.

Figure 2.1.7. Power extraction from 150 cavities driven by a beam of 70° bunch length: (a) 35° cavity detuning angle; (b) 25° cavity detuning angle.

2.1.3.3 Cavity parameters for RK-TBA simulations

The synchronism case in Figure 2.1.3 consists of conventional 3-cell TWS's operating at the $2\pi/3$ mode. In the inductively detuned case the operating detuning angle is 30° . The cavity is therefore operating in a " $\pi/2$ " mode (i.e., phase advance of the field across one cell is 90°). The longitudinal dimension of each cell is the same in the two cases while the transverse dimensions are varied. *URMEL* and *MAFIA* codes were used for detailed cavity design (Section 2.3 of this report). Cavity parameters from this detailed design are listed in Table 2.1.2.

Table 2.1.2. Parameters related to the inductive detuning case

Drive frequency	11.424 GHz
Forward Traveling Mode	TM ₀₁
Number of cavities	3
Phase shift per cavity	90°
Wave length	2.626 cm
Phase velocity	1.33 c
Group velocity	0.28 c
Shunt impedance per cell (R/Q)*	27.0 (Ω)
Eigenfrequency for the first 2 cells	11.424 GHz
Eigenfrequency for the 3 rd cell	11.666 GHz
Wall-dissipation quality factor	7000
External quality factor for the 3 rd cell	6.5
Aperture inner radius	8 mm
Aperture outer radius	12.5 mm
Iris thickness	2.5 mm
Longitudinal dimension of each cell	8.754 mm
Beam energy	10 MeV
Beam current (average)	600 A
Bunch length	0.51 cm
Beam radius (rms)	2.5 mm

* Note: Traveling-wave shunt reactance is twice the standing-wave shunt reactance.

2.1.4 "Adiabatic Capture"

As shown in Section 2.1.3.2, the desired bunch length for the drive beam of the main TBA section is about $1/5$ of the operating wave length. Such a train of beam bunches could, of course, be generated in a straightforward way by chopping a continuous beam with a chopper as will be discussed in Section 2.1.5. However, this method is undesirable from efficiency consideration because as much as $4/5$ of the beam will be lost. For the same reason, we also prefer that the beam has relatively low energy before it goes through the chopper. As the efficiency of the modulator improves, the gap between generated beam parameters (bunch length and energy) and those required for the main TBA section widens. To bridge this gap, we have a section called "adiabatic capture". This section consists of several "idler" cavities (cavities with large detuning angles) that are properly spaced and induction cells along the drift tubes between the cavities. A schematic of the "adiabatic capture" section is given in Figure 2.1.9. In this section, a beam of low energy and long bunches is bunched by the "idler" cavities and accelerated by the induction cells to evolve

eventually into a beam of bunches with desired energy and bunch length for stable propagation in the main RK-TBA.

Figure 2.1.9. Schematic of the "adiabatic capture" scheme

2.1.4.1. 5 MeV and 180° bunch length

Figure 2.1.10 presents the evolutions of bunch length and energy of a beam through the "adiabatic capture" section shown in Figure 2.1.9. The beam has an initial kinetic energy of 5 MeV and initial uniform bunch of length 180°. Figures 2.1.11(a) and (b) are, respectively, phase distribution of the bunch before and after the adiabatic capture. It is seen that the bunched beam has about 10% energy spread which is consistent with the equilibrium rf bucket in the main TBA section (see Figure 2.1.4(b)). The main parameters associated with this process are given in Table 2.1.3.1. In Table 2.1.3.1, L denotes the distance from the 1st cavity, $\Delta\Phi$ denotes the bunch length in degrees (360° corresponds to one full wave length, 2.63 cm) and E_k denotes the kinetic energy of the beam. All the "idler cavities" used are 60° detuned TWS's.

Figure 2.1.10. Evolutions of length and energy of a beam bunch during the "adiabatic capture" process illustrated in Figure 2.1.9

Figure 2.1.11. Phase space distribution of the beam bunch in Figure 10: (a) before the "adiabatic capture" process; (b) after the "adiabatic capture" process.

Table 2.1.3.1. Some Parameters for "Adiabatic Capture" (5 MeV)

TWS #	V_g (c)	L (m)	$\Delta\Phi$ (°)	E_k (MeV)
1	0.20	5.5	140.7	6.22
2	0.20	11.0	104.5	7.51
3	0.20	16.0	85.2	8.47
4	0.20	20.0	70.4	10.02

2.1.4.2. 2.5 MeV and 240° bunch length

The efficiency of the RK-TBA could be further increased by starting from a lower energy and less chopped beam (compared to the 180° bunch length). In Figure 2.1.12 we present the simulation results of evolutions of bunch length and energy of a beam from an initial 2.5 MeV kinetic energy and 240° bunch length (uniform) to the final 10 MeV and 70° bunch length. All the "idler cavities" used are 70° detuned TWS's. The main parameters associated with this process are given in Table 2.1.3.2.

2.1.5 The Chopper

As has been mentioned in Section 2.1.4, in our RK-TBA design, the drive beam needs to go through a chopper to generate a train of beam bunches before entering the "adiabatic capture" section to acquire further bunching and acceleration. A layout of the original Choppertron made by Haimson Research Corporation⁶ and used by the LLNL Microwave Source Facility group⁷ is shown in Figure 2.1.13. The modulator of the Choppertron is a 5.7 GHz chopping system designed to produce a train of beam bunches with a period corresponding to 11.4 GHz from an initial uniform beam.

Fig. 2.1.12. Evolution of length and energy of a beam bunch during the "adiabatic capture" process.

Table 2.1.3.2 Some Parameters for "Adiabatic Capture" (2.5 MeV)

TWS #	V_g (c)	L (m)	$\Delta\Phi$ (°)	E_k (MeV)
1	0.20	2.0	226.0	3.12
2	0.20	4.0	187.0	3.63
3	0.20	6.0	140.9	4.14
4	0.18	8.0	106.8	4.70
5	0.18	10.5	97.7	5.26
6	0.16	12.5	89.8	5.77
7	0.16	15.0	78.1	6.49
8	0.15	19.0	65.7	8.43
9	0.14	22.5	66.3	8.94
10	0.14	26.0	70.0	10.00

Figure 2.1.13. Layout of the original Choppertron used at LLNL.

The chopper operation is simulated with the 2-1/2 D RKS code. The phase distribution of a beam bunch that is produced by the chopper simulation is given in Figure 2.1.14. In this case, the initial electron beam is a DC beam of 5 MeV energy, 1.5 kA current and no energy spread. With 0.2 MW rf drive power for the dipole field (TM₁₁₀) in the deflection cavity, we obtained a bunched beam of 600 A (average current) coming out of the chopper with each bunch spanning a length about 180° for the 11.4 GHz wave (some "cleaning" on the head and tail of the bunch may be needed). As we can see from Figure 2.1.16, the phase space at the chopper exit has a small but finite energy spread. The distribution does have some non-uniformity, although it is still fairly flat overall. We used this more realistic distribution of the beam bunch as the initial condition for RKS simulations to re-examine the "adiabatic capture" process and the main TBA transport. Figure 2.1.15 presents the rf power from each TWS across the "adiabatic capture" section and the main TBA section. The output power is sustained at 360 MW throughout the entire main TBA section with fluctuations of less than 8.5% between the outputs. The parameters of the cavities used in the "adiabatic capture" section and the main TBA section are the same as those given, respectively, in Section 2.1.3.2 and Section 2.1.4.1.

2.1.6 After-burner

The electron beam that comes out of the main RK-TBA is still a beam of about 9.4 MeV kinetic energy and 600 A average current. To make the most use of this amount of energy, and to further enhance the beam to rf efficiency, we have another section called the "after-burner", which consists of a dozen or so TWS's that are just like or similar to those used in the main TBA. A schematic of this section is given in Figure 2.1.16. In the "after-burner" section the cavities are designed and arranged in such a way that each of them extracts about 360 MW of power from the beam. In the "after-burner" section, compared to the main TBA section: (1) there is no reacceleration, and (2) the distance between two adjacent cavities is adjustable so that the cavities can be placed at positions where the rf current (I_{ind} in Eq. (2.1.17)) of the drive beam is relatively stable (about the same as it is in the main TBA section). In addition to efficiency enhancement, another benefit of the "after-burner" scheme is that it lowers the beam energy considerably, which makes the disposal of the beam much easier.

Figure 2.1.14. Phase space distribution of a bunched beam that comes from a chopper chopped initially uniform beam.

Figure 2.1.15. Evolution of output power from the adiabatic capture section to the main TBA section with the beam bucket shown in Figure 2.1.14 as the initial bunched beam.

Figure 2.1.16 Schematic of "after-burner" section

We have carried out RKS simulations on the "after-burner" section in which 12 TWS's with 30° detuning are properly arranged (Figure 2.1.16). The results and some related parameters are presented in Table 2.1.4. As we can see in Table 2.1.4, with the proper choices of the group velocities (V_g) and the spacings (L_s), each of the cavities is able to extract about 360 MW from the beam and the final energy of the beam is around 2.2 MeV. This means a 77% beam to rf efficiency, $\eta_{b \rightarrow rf}$, for this section. The efficiency, $\eta_{b \rightarrow rf}$, of the whole system increases from 84% to 91%, or from 87% to 94%, depending on whether the beam bunches at the exit of the chopper is 5 MeV and 180° (Section 2.1.4.1) or 2.5 MeV and 240° (Section 2.1.4.2). Figures 2.1.17 show corresponding phase distributions of a beam bunch in the "after-burner" section: (a) before the 1st cavity; (b) after the last cavity. The beam bunch is still well preserved in the phase space at the end of the "after-burner" section, as we can see from Figure 2.1.17(b).

Table 2.1.4. Some Parameters for "After-Burner"

TWS #	V_g (c)	L_s (m)*	P_{out} (MW)	E_k (MeV)
1	0.28		363.	8.80
2	0.28	1.50	365.	8.19
3	0.28	1.40	365.	7.58
4	0.28	1.30	362.	6.98
5	0.27	1.30	366.	6.37
6	0.27	0.80	357.	5.77
7	0.26	0.60	362.	5.17
8	0.26	0.50	355.	4.58
9	0.25	0.60	361.	3.98
10	0.24	0.70	361.	3.37
11	0.22	0.65	369.	2.76
12	0.22	0.45	358.	2.16

* Distance from the last cavity.

(Initial energy spread $\Delta\gamma/\gamma = 15\%$)

Figure 2.1.17. Phase distribution of a beam bunch in the "after-burner" section: (a) before the 1st cavity; (b) after the 12th cavity

2.1.7 Transverse Focusing Issue

In addition to the issue of axial stability of the beam bunch there is potentially another issue concerning stability in the radial direction. The latter is due to the defocusing force of the radial component of RF electric field, E_r , that acts on the beam. There exists, simultaneously, another RF

radial force, $V_z B_t$, acting in the opposite direction of E_r on the beam, which provides a focusing force. However, analytic calculation indicates that compensation occurs only for the synchronism case for a cavity with cylindrical symmetric shape (Appendix 2.1.D). It has been realized that for the inductive detuning case, E_r is the dominant component and, if uncompensated, may result in transverse defocusing of the beam. For example, if we simply take the eigenfields that correspond to our current TWS configuration and run a 2-1/2 D RKS simulation for parameters that are appropriate to the 1 TeV RK-TBA design (but with solenoidal focusing), the beam envelope starts scraping the wall and losing current before it drives more than 10 extraction cavities. The radial defocusing effect noted in the simulation is due to the introduction of our inductive detuning scheme for longitudinal stability and, possibly, limitations of the RKS code to model this effect. Alternative cavity designs are possible for inductively detuning the traveling wave structures. These designs need to be explored to find schemes that achieve both longitudinal and radial stability. In addition, further analytical work is required to quantify the radial defocusing effect and check the accuracy of the computer modeling. Studies are being pursued using the *MAFIA* and RKS codes.

2.1.8 Appendices

Appendix 2.1.A. Derivation of the Matching Conditions for a TWS With Finite Number of Cells

Consider Eq. (2.1.4). Since $a_0 = a_{N+1} = 0$ the equations for the 1st ($n=1$) and the last ($n=N$) cells are different in forms from those for the rest of the cells ($n = 2, \dots, N-1$). By choosing appropriate ω_1 , Q_1 , ω_N and Q_N , the equations for the first and the last cells may be written in the same form as those for the rest of the cells. Introducing parameters μ and η we define

$$\begin{aligned}\hat{a}_0 &= \mu a_1, \\ \hat{a}_{N+1} &= \eta a_N, \quad (n = 1, \dots, N) \\ \hat{a}_n &= a_n,\end{aligned}\tag{2.1.A-1}$$

where

$$\begin{aligned}\mu &= \frac{1}{K}[(\omega_v^2 - i\frac{\omega\omega_v}{Q_v}) - (\omega_1^2 - i\frac{\omega\omega_1}{Q_1})] \\ \eta &= \frac{1}{K}[(\omega_v^2 - i\frac{\omega\omega_v}{Q_v}) - (\omega_N^2 - i\frac{\omega\omega_N}{Q_N})]\end{aligned}, \quad (v = 2, \dots, N-1).\tag{2.1.A-2}$$

In above, the first two equations of (2.1.A-1) combined with equations (2.1.A-2) form the so-called boundary conditions. In this way the system acts like a structure with infinite number of cells (for $n = 2, \dots, N-1$), where ω_v can be determined by formula (2.1.7) ($Q_v \gg 1$ is normally assumed). We may now rewrite Eq. (2.1.4) in the following form (with "hats" removed for simplicity of notation):

$$a_{n+1} - 2a_n \cos(\alpha) + a_{n-1} = f_n \quad n = 1, \dots, N,\tag{2.1.A-3}$$

where

$$\cos \alpha = \frac{1}{2K}(\omega_v^2 - \omega^2 - i\frac{\omega\omega_v}{Q_v}),\tag{2.1.A-4}$$

$$f_n = -S_n/K.\tag{2.1.A-5}$$

The difference equations (2.1.A-3) with constant coefficients can be solved analytically. The general solution is given by

$$a_n = e^{i\alpha n} \left(\frac{-i}{2\sin(\alpha)} \sum_{r=1}^n f_r e^{-i\alpha r} + C_1 \right) + e^{-i\alpha n} \left(\frac{i}{2\sin(\alpha)} \sum_{r=1}^n f_r e^{i\alpha r} + C_2 \right),\tag{2.1.A-6}$$

where C_1 and C_2 are constants that need to be determined by the boundary conditions and the matching condition. In obtaining (2.1.A-6), it is assumed that

$$\sum_{r=1}^0 f_r e^{\pm i\alpha r} = 0\tag{2.1.A-7}$$

and also that α is not equal to an integral multiple of π .

We now apply the above results to a TW output structure. Suppose the drive terms, f_n , have constant amplitude, but that the phase of f_n increases from cell to cell by α' (to be distinguished

from the corresponding phase advance of field, α). The synchronism case refers to $\alpha = \alpha'$ where the field and the beam travel in phase ($\omega/k = c$ for a relativistic beam). The non-synchronism case refers to $\alpha \neq \alpha'$ where the field and the beam are out of phase. The particular case where $\alpha < \alpha'$ is called inductive detuning. The latter case is of major interest in this study. Writing

$$f_n = f e^{i\alpha' n} \quad (2.1.A-8)$$

and substituting (2.1.A-8) into (2.1.A-6) we have

$$a_n = e^{i\alpha n} \left[\left(\frac{-i}{2\sin \alpha} \right) f \sum_{r=1}^n e^{ir\Delta^-} + \left(\frac{-i}{2\sin \alpha} \right) f \cdot \frac{e^{i\Delta^+}}{1-e^{i\Delta^+}} e^{ir\Delta^-} + C_1 \right] + e^{-i\alpha n} \left[\left(\frac{i}{2\sin \alpha} \right) f \cdot \frac{e^{i\Delta^+}}{1-e^{i\Delta^+}} + C_2 \right], \quad (2.1.A-9)$$

where $\Delta^\pm = \alpha' \pm \alpha$ with Δ^- being defined as the so called detuning angle. Then, $\Delta^- = 0$ corresponds to the synchronism case, and $\Delta^- \neq 0$ corresponds to the non-synchronism case(s). Since we have assumed that the fields vary as $e^{-i\omega t}$, the first term ($e^{i\alpha n}$) in (2.1.A-9) represents a wave traveling in the forward direction (from $n = 1$ to $n = N$), and the second term ($e^{-i\alpha n}$) represents a wave traveling in the backward direction.

Now we must apply the boundary conditions given by (2.1.A-1) and (2.1.A-2). Substituting a_0 and a_I into (2.1.A-6), respectively and using (2.1.A-7) and (2.1.A-1) for a_0 , we find that the condition relating a_0 and a_I can be expressed as

$$\mu = \frac{C_1 + C_2}{C_1 e^{i\alpha} + C_2 e^{-i\alpha}}. \quad (2.1.A-10)$$

To simplify the algebra and also to be more specific, in the following we only consider our special case in which there is no input cavity. This means that the first cell can be treated the same as the $N-2$ cells that are behind it and only the last cell is likely to be different from the rest. Then, from (2.1.A-2) we immediately find that

$$\mu = 0. \quad (2.1.A-11)$$

(2.1.A-11) leads to $C_1 = -C_2$ (2.1.A-10).

Our next task is to choose ω_N and Q_N such that the resulting solution would consist of just a forward traveling wave. Referring to (2.1.A-9), the backward traveling wave will vanish when

$$C_2 = -\frac{if}{2\sin \alpha} \frac{e^{i\Delta^+}}{1 - e^{i\Delta^+}}. \quad (2.1.A-12)$$

Substituting a_N and a_{N+1} , respectively, into (2.1.A-6), using (2.1.A-1) for a_{N+1} , assuming that

$$\begin{aligned} \cos(N\alpha') &= 1 \\ \sin(N\alpha') &= 0 \end{aligned} \quad (2.1.A-13)$$

(e.g., in our present RK-TBA design, $\alpha' = 2\pi/3$ and $N=3$), and then some mathematical manipulations, we find that

$$a_N = f \frac{e^{i\alpha} (1 - e^{iN\alpha})}{(e^{i\Delta^-} - 1)(e^{i\Delta^+} - 1)}, \quad (2.1.A-14)$$

$$a_{N+1} = f \frac{e^{i\alpha} (e^{i\alpha} - e^{i(N+1)\alpha})}{(e^{i\Delta^-} - 1)(e^{i\Delta^+} - 1)}.$$

In obtaining (2.1.A-14), $C_1 = -C_2$ and (2.1.A-12) are used. Plugging (2.1.A-14) in (2.1.A-1) for η , we get

$$\eta = \frac{a_{N+1}}{a_N} = e^{i\Delta^+ N} \frac{\sin(N+1)\Delta^-/2}{\sin(N\Delta^-/2)}. \quad (2.1.A-15)$$

The "matching conditions" for the eigenfrequency and the external quality factor of the output cell of a detuned N-cell TWS can now be obtained by equating (2.1.A-15) to (2.1.A-2), and they are given as follows:

$$\omega_N = \omega_v - \frac{V_g}{2L_p \sin(\alpha)} \left[\frac{\sin(N+1)\Delta^-/2}{\sin(N\Delta^-/2)} \cos(\Delta^+/2) \right], \quad (2.1.A-16)$$

$$(Q_N)^{-1} = \frac{V_g}{\omega_N L_p \sin(\alpha)} \left[\frac{\sin(N+1)\Delta^-/2}{\sin(N\Delta^-/2)} \sin(\Delta^+/2) \right]$$

In deriving (2.1.A-16) relation (2.1.6) is used and $Q_v \gg 1$ is assumed.

Appendix 2.1.B. Derivation of Power Balance Equation

Applying Eq. (2.1.2) to the last cell of a N-cell TWS, and taking the real portion of the equation after multiplying both sides of the equation by $i(a_N^*)$, we have

$$\frac{\omega \omega_N}{Q_N} |a_N|^2 = \text{Re} \left[\left(-\frac{\omega}{\epsilon_0} \right) \int (d^3 r)_{N\epsilon_N} \vec{J}_1 \cdot a_N^* \right] + \text{Re}(iK a_{N-1} a_N^*). \quad (2.1.B-1)$$

Rewriting $\text{Re}(iK a_{N-1} a_N^*)$ as $\text{Re}(-iK a_{N-1}^* a_N)$ and then repeating the above procedure sequentially from the $(N-1)^{\text{th}}$ cell to the 1st cell, we come to the following relation

$$\frac{\omega \omega_N}{Q_N} |a_N|^2 = \sum_{n=1}^N \text{Re} \left[\left(-\frac{\omega}{\epsilon_0} \right) \int d^3 r_n \vec{\epsilon}_n \cdot \vec{J}_1 \cdot a_n^* \right], \quad (2.1.B-2)$$

where $Q_n \gg 1$ with $n = 1, 2, \dots, N-1$ are assumed. We also know that the power extracted from the last cell of a N-cell TWS can be quantified by the following expression

$$P_{out} \equiv \frac{\omega_N U_N}{Q_N}$$

$$= \frac{\omega_N [\epsilon_0]}{Q_N} \int (d^3 r)_N |E_N|^2 \quad (2.1.B-3)$$

$$= \frac{\omega_N [\epsilon_0]}{Q_N} |a_N|^2 \int (d^3 r)_N |\vec{\epsilon}_N(r)|^2,$$

where $U_N \equiv \frac{\epsilon_0}{2} \int |E_N|^2 (d^3r)_N$ is the stored energy in cell N . Then, choosing the normalization convention $\int (d^3r)_n |\vec{\epsilon}_n|^2 = 1$ and substituting (2.1.B-2) into (2.1.B-3) we find the following power balance relation

$$P_{out} = \sum_{n=1}^N \frac{1}{2} \text{Re} \left[\left(- \int d^3r_n \vec{\epsilon}_n^* \cdot \vec{J}_1 \right) \cdot a_n^* \right]. \quad (2.1.B-4)$$

Appendix 2.1.C. Derivation of Power Extraction Formula

For the synchronism case, we have $\Delta^- = \alpha' - \alpha = 0$, so the matching condition (2.1.A-15) reduces to

$$\eta = e^{i\alpha} \left(\frac{N+1}{N} \right), \quad (2.1.C-1)$$

which recovers (25) of Ref. [14]. Correspondingly, another form of the matching condition, (2.1.A-16) reduces to

$$\begin{aligned} \omega_N &= \omega_V - \frac{V_g}{2L_p \sin(\alpha)} \left(\frac{N+1}{N} \right) \cos(\alpha) \\ (Q_N)^{-1} &= \frac{V_g}{\omega_N L_p \sin(\alpha)} \left(\frac{N+1}{N} \right) \end{aligned} \quad (2.1.C-2)$$

The power balance equation (2.1.B-4) becomes

$$P(0) \equiv P_{out}(\Delta^- = 0) = \frac{1}{2} \sum_{n=1}^N (-I_n^{id} \cdot V_n) \quad (2.1.C-3)$$

and the field evolution (2.1.A-9) reduces to

$$a_n = e^{i\alpha n} \left[\left(\frac{-i}{2\sin(\alpha)} \right) \cdot n f \right]. \quad (2.1.C-4)$$

Also from the definition of S_n ((2.1.4)), and equations (2.1.11) and (2.1.A-8), we know that

$$\int (d^3r)_n \cdot (\vec{\epsilon}_n)^* \cdot \vec{J}_1 = \left(\frac{K\epsilon_0}{i\omega} \right) f e^{i\alpha n}. \quad (2.1.C-5)$$

Substituting (2.1.C-4) and (2.1.C-5) into (2.1.B-4), we then have

$$P(0) = \left[\frac{K\epsilon_0}{4\omega \sin(\alpha)} f^2 \right] \cdot \left[\frac{N(N+1)}{2} \right]. \quad (2.1.C-6)$$

Introducing, respectively, the axial voltage across one cell

$$V_{axis} \equiv \int dz (E_n \cdot e^{ikz}) = a_n \cdot \int dz (\epsilon_n \cdot e^{ikz}), \quad (2.1.C-7)$$

and the induced current

$$I_{ind} \equiv \int dS (J_1 \cdot e^{ikz}), \quad (2.1.C-8)$$

we find that the corresponding shunt impedance may be expressed as

$$\frac{R}{Q} \equiv \frac{|V_{axis}|^2}{2\omega U_s} = \frac{\left| \int dz (\epsilon e^{ikz}) \right|^2}{\omega \epsilon_0} \quad (2.1.C-9)$$

with $U_s \equiv \frac{1}{2} \epsilon_0 |a_n|^2$ being the stored energy in the cell (as defined in Appendix 2.1.B). We also find that (2.1.C-5) may be rewritten as

$$f \cdot e^{i\omega t} = - \frac{i\omega}{K\epsilon_0} I_{ind} \left[\int dz (\epsilon_n \cdot e^{ikz}) \right]^* \quad (2.1.C-10)$$

From (2.1.C-9) and (2.1.C-10) we have

$$\begin{aligned} f^2 &= |f \cdot e^{i\omega t}|^2 \\ &= \frac{\omega^3}{K^2 \epsilon_0} (I_{ind})^2 \left(\frac{R}{Q} \right). \end{aligned} \quad (2.1.C-11)$$

Substituting (2.1.C-11) into (2.1.C-6) and then a few steps of algebra, we obtain a formula that relates the extracted power from the TWS to the induced current (I_{ind}) of the beam, the frequency (ω) of the operating wave and several key cavity parameters — the shunt impedance R/Q , the group velocity V_g , the longitudinal dimension L_p and the cell number N :

$$P(0) = \frac{(I_{ind})^2}{4} \left(\frac{\omega L_p}{V_g} \right) \cdot \left[\left(\frac{R}{Q} \right) / 2 \right] \cdot N(N+1). \quad (2.1.C-12)$$

Appendix 2.1.D. Calculation of Transverse Focusing Force

The combined effect of E_r and $V_z B_t$ on the beam can be quantified as follows:

From the Maxwell equations we have

$$\nabla \cdot \vec{E} = 0, \quad \text{and} \quad \nabla \times \frac{\vec{B}}{\mu_0} = \frac{\partial}{\partial t} (\epsilon_0 \vec{E}_z). \quad (2.1.D-1)$$

For a cylindrical symmetric cavity (2.1.D-1) reduces to

$$\frac{1}{r} \frac{\partial}{\partial r} (r E_r) + \frac{\partial}{\partial z} (E_z) = 0, \quad \text{and} \quad \frac{1}{r} \frac{\partial}{\partial r} (r B_\theta) = (\mu_0 \epsilon_0) \cdot \frac{\partial}{\partial t} (E_z). \quad (2.1.D-2)$$

Also, for a *TM* mode: $B_z = 0$ and $\frac{\partial}{\partial \theta} = 0$. Therefore

$$E_r = \frac{r}{2} \left(\frac{d}{dz} E_z \right), \quad \text{and} \quad B_\theta = \frac{r}{2} \frac{1}{c^2} \left(\frac{d}{dt} E_z \right). \quad (2.1.D-3)$$

Since in general, it may be written that $E_z = \sum_{n=-\infty}^{+\infty} a_n J_0(k_{cn}r) \cdot e^{i(\alpha - \beta_n z)}$ and thus for the $\bar{TM}_{01}$ mode we have $E_z = E_0 J_0(k_c r) \cdot e^{i(\alpha - k_z z)}$. The total transverse moment acquired by an electron in the above field while crossing the structure can be calculated as follows:

$$\begin{aligned} p_\perp &= \int_0^L (-e) dz [E_r - V_z B_\theta] \\ &= \frac{-e}{V_z} \int_0^L dz \left[-\frac{r}{2} \left(\frac{d}{dz} E_z \right) - \frac{V_z}{c^2} \left(\frac{d}{dt} E_z \right) \right] \\ &= \frac{er}{2V_z} \int_0^L dz \left[(-ik_z E_z) + \frac{V_z}{c^2} (i\omega E_z) \right] \\ &= \frac{er}{2V_z} \int_0^L dz \left[(-ik_z E_z) + \frac{V_z}{c^2} (i\omega E_z) \right] \\ &= \frac{erk_z}{2iV_z} \int_0^L dz \left[\left(1 - \frac{V_z V_p}{c^2} \right) E_z \right] \end{aligned} \quad (2.1.D-4)$$

As we can see from (2.1.D-4), for the synchronism case when $V_p \approx V_z$, we have

$$p_\perp = \frac{erk_z}{2ic} \int_0^L dz \left(\frac{1}{\gamma^2} \right) E_z \quad (2.1.D-5)$$

which shows that the compensation of $V_z B_t$ to E_r is up to the order of $1/\gamma^2$, while for the inductive detuning case when $V_p > V_z$, the compensation disappears.

Appendix 2.1.E. Determination of Total Q -factor For a 3-cell TWS

In our RKS simulations, a specific value of the Q -factor, Q_i , is assigned to each cell of the traveling wave (TW) output structure with the Q for the output cell, Q_{out} , normally being the only one that is treated as a finite quantity. On the other hand when using *MAFIA* code to do cavity design, the Q -factor we encounter is often the one for the entire structure, Q_{total} . Therefore, it is desired to quantify the relation between Q_{out} and Q_{total} so that a concrete cavity design can be carried out to yield cavities that have the desired rf properties for the RK-TBA.

The approach we take here is to apply the circuit equation (2.1.4), which contains information of individual cells, to each cell of the TWS, and then solve the resulted set of equations and obtain the eigenfrequencies (complex values) of the whole structure. Using the definition for Q -factor, we

can express the Q_{total} in terms of the quantities for the individual cells, ω_i and Q_i . In the following, we apply this approach to the case of our 3-cell TW output structures for the RK-TBA. We start by first writing down the circuit equation (2.1.4) for each of the 3 cells in the TWS

$$\begin{aligned}(\omega_1^2 - \omega^2 - 0) \cdot a_1 - K \cdot (0 + a_2) &= 0, \\(\omega_1^2 - \omega^2 - 0) \cdot a_2 - K \cdot (a_1 + a_3) &= 0, \\(\omega_3^2 - \omega^2 - i\frac{\omega\omega_3}{Q_3}) \cdot a_3 - K \cdot (a_2 + 0) &= 0.\end{aligned}\tag{2.1.E-1}$$

In (2.1.E-1), we have dropped the drive term in each of circuit equations. We also have assumed that $Q_i \gg 1$ for the first two cells and $\omega_1 = \omega_2$. The boundary conditions are $a_1 = a_4 = 0$. We then set the determinant of (2.1.E-1) to be 0, which yields

$$(\omega_1^2 - \omega^2)^2 \cdot (\omega_3^2 - \omega^2 - i\frac{\omega\omega_3}{Q_3}) - K^2 \cdot [(\omega_3^2 - \omega^2 - i\frac{\omega\omega_3}{Q_3}) + (\omega_1^2 - \omega^2)] = 0.\tag{2.1.E-2}$$

The eigenfrequencies of this 3-cell TWS can be obtained by solving the above equation. First, we neglect the effect of the output cell and treat the third cell the same as the first two cells, i.e., $Q_3 \gg 1$ and $\omega_3 = \omega_1$. Eq. (2.1.E-2) is then reduced to

$$(\omega_1^2 - \omega^2)^2 \cdot (\omega_1^2 - \omega^2) - 2K^2 \cdot (\omega_1^2 - \omega^2) = 0.\tag{2.1.E-3}$$

One of the three solutions of Eq. (2.1.E-3) is that $\omega^{(0)} = \omega_1$. In the following, we will focus on this eigenfrequency value, since the drive frequency of the system, ω^{pp} , happens to be also equal to ω_1 for our current RK-TBA design. Our next step is to take into account the effect of a finite Q_3 and solve the complex equation (2.1.E-2). In (2.1.E-2), we write $\omega = \omega_r + i\omega_i$ ($\omega_i < 0$ for power loss) with $\omega_r \equiv \omega^{(0)} + \Delta\omega_r$ and assume that both $\Delta\omega_r$ and ω_i are $\ll \omega_1$. It is noted that in (2.1.E-2) ω_1 and K can be calculated from (2.1.7) and (2.1.6), respectively, while ω_3 and Q_3 can be determined by the matching conditions (2.1.12). For the parameters that are appropriate to the current RK-TBA design (see Table 2.1.2), we have $\omega_1 = \omega^{pp} = 11.424$ GHz, $\omega_3 = 11.666$ GHz, $K = 0.134\omega^{pp}$ and $Q_3 = 6.5$. From the above figures it is calculated that $|(\omega_3 - \omega_1)/\omega_1| \approx 0.02$. If we assume that $|\Delta\omega_r/\omega_1| \leq 0.02$, then it is estimated that the effect of $\Delta\omega_r$ on ω_i is negligible. Now we are ready to solve Eq. (2.1.E-2) for ω_i . Substituting $\omega = \omega_r + i\omega_i$ into (2.1.E-2), using the approximation that $\omega_1 \approx \omega_r$ and keeping only the lowest order terms, we have

$$\begin{aligned}&-4\omega_r^2\omega_i^2 \cdot \{(\omega_3^2 - \omega_r^2) - i[\omega_r(\omega_3 + \omega_r) + \frac{\omega_r\omega_3}{Q_3}] + \frac{\omega_i\omega_3}{Q_3}\} \\&= K^2 \cdot \{[(\omega_3^2 - \omega_r^2) + i\omega_i(-2\omega_r) + \omega_i^2] - i(\frac{\omega_r\omega_3}{Q_3} + 2\omega_i\omega_r)\}.\end{aligned}\tag{2.1.E-4}$$

Taking the imaginary part of (2.1.E-4) we get

$$4\omega_r^2\omega_i^2 \cdot [\omega_i(\omega_3 + \omega_r) + \frac{\omega_r\omega_3}{Q_3}] = -K^2 \cdot (4\omega_i\omega_r + \frac{\omega_r\omega_3}{Q_3}).\tag{2.1.E-5}$$

Using the approximation $\omega_3 \approx \omega_r$ and then normalizing the above equation with ω_r^6 , (2.1.E-5) may be recast as

$$(2\omega_i/\omega_r)^3 + \frac{1}{Q_3}(2\omega_i/\omega_r)^2 + \frac{2K^2}{\omega_r^4}(2\omega_i/\omega_r) + \frac{K^2}{\omega_r^4} \frac{1}{Q_3} = 0. \quad (2.1.E-6)$$

For the parameters given in Table 2.1.2, it can be calculated that $1/Q_3 = 0.1538$, $2K^2/\omega_r^4 = 0.0357$ and $(K^2/\omega_r^4)/Q_3 = 2.75e-3$. Solving the above cubic equation we find that

$$\begin{aligned} Q_{total} &\equiv \omega_r/(2\omega_i) \\ &\approx 11. \end{aligned} \quad (2.1.E-7)$$

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2.2 Transverse Beam Dynamics (T. Houck, N. Goffeney)

The excitation of transverse beam instabilities due to higher order modes has been identified as a major issue in the design of a long multi-cavity RK-TBA. The narrow aperture and high average current of the TBA accentuates the problem. There are two separate structural components that contribute to the transverse instability. The induction module with an aperture of 5.0 cm has a trapped dipole mode around 2 to 5 GHz and the output structure with a 1.6 cm aperture has a transverse mode near 14 GHz. Both modes interact strongly with the beam. The effect of these structures on the transverse stability of the beam can be studied independently because of the large separation in resonant frequencies.

2.2.1 Theory

Beam breakup (BBU) instabilities^{1,2,3} are classified generally into two major types, the cumulative BBU, where the resonant cavities are assumed to be electromagnetically isolated, and the regenerative BBU, where the cavities are coupled. The low frequency, induction cavity generated BBU in the RK-TBA is cumulative. The high frequency BBU is a combination of the cumulative and regenerative, since the individual cells in a traveling-wave extraction structure are coupled (regenerative) while successive extraction cavities, spaced every 2 m in our design, are electromagnetically decoupled (cumulative). The numerical code developed to study BBU in RK-TBA's incorporates both effects in one unified treatment, and the mathematical framework will be briefly described. We will then review the theory of cumulative BBU with Landau damping and the concept of the 'betatron node scheme' before embarking on the numerical studies reported in 2.2.2 and 2.2.3.

2.2.1.1 Mathematical framework

The OMICE (One Mode Instability Circuit Equation) Code⁴ was developed at LLNL to numerically study the transverse instability in microwave structures comprised of electromagnetically coupled cavities. The OMICE Code assumes that a single dipole cavity mode is dominant and the magnetic field in the n^{th} cavity can be expressed as

$$\vec{B}_n(\vec{r}, t) = b_n(t) \vec{\xi}_n(\vec{r}) e^{i\omega t}, \quad (2.2.1)$$

where $\vec{\xi}_n$ denotes an eigenmode with eigenfrequency ω_n . Here ω denotes a characteristic frequency of the generator assumed near the transverse instability resonance. It is possible to show that the excitation amplitudes b_n are governed by the following circuit equations:

$$\begin{aligned} \frac{\partial^2 b_n}{\partial t^2} + \left(\frac{\omega_n}{Q_n} - 2i\omega \right) \frac{\partial b_n}{\partial t} + \left(\omega_n^2 - \omega^2 - \frac{i\omega\omega_n}{Q_n} \right) b_n = \\ K_n^{n-1} b_{n-1} + K_n^{n+1} b_{n+1} + \frac{i\omega\omega_n^3}{\epsilon c^2} \left(\frac{Z_{\perp}}{Q} \right) I x e^{i(\omega t + \phi_n)}, \end{aligned} \quad (2.2.2)$$

where Q_n is the quality factor of the n^{th} cavity, $K_n^{n\pm 1}$ denotes the coupling of the n and $n\pm 1$ cavities, I is the current, x is the transverse displacement of the beam centroid in the x direction from the center line, ϕ is a phase advance, and $Z_{\perp}$ is the transverse impedance. A similar equation gives the excitation in the y -direction. Propagation of the beam centroid (x and y) are given by single

particle equations of motion in quadrupole focusing channels. Several features of the OMICE Code are essential for modeling the RK-TBA:

- 1) Transient effects are modeled,
- 2) RF structures are treated as separate entities with specific rf properties,
- 3) Adjacent rf structures/cavities can be electromagnetically coupled,
- 4) Variable current and energy profiles can be used, and
- 5) Actual external electromagnetic focusing fields can be included.

The electromagnetic coupling of cavities allows the effect of regenerative BBU to be included in the analysis while cumulative BBU corresponds to the special case of $K_n^{n+1} = 0$.

A limitation is that the beam is treated as a series of rigid disks. Thus, beam parameters such as current and energy can only be varied longitudinally. To simulate an instantaneous transverse energy spread for study of Landau damping effects, the energy is varied longitudinally on a length scale much smaller than the wavelength of the instability. Figure 2.2.1 illustrates the method for simulating a transverse energy spread. The energy starts at a desired minimum value and increases per slice to a maximum and then returns to the minimum value to repeat the cycle. Since there is a finite number of slices to a cycle, there will be a finite number of betatron frequencies. If the beam performs a sufficient number of betatron oscillations, the paths of the slices will tend to vary in phase with respect to the average energy betatron oscillation, but periodically the paths will come into phase. For a physical beam with several billion electrons per bunch the energy spread is essentially continuous and requires an infinite number of oscillations to bring the orbits back into phase. This continuous spread of energy is modeled by randomly varying the energy of each beam slice about its nominal energy by an amount not to overlap the possible energy range of neighboring slices or exceed the extreme of the beam's energy variation.

Figure 2.2.1. Technique for simulating a transverse energy spread.

2.2.1.2 Cumulative Beam Breakup

There has been extensive analytical work accomplished for the case where the resonant structures are not coupled.¹ The multi-cavity model² for cumulative beam breakup treats the structures as a continuous distribution along the beamline and assumes the dominance of a single

dipole resonant mode with frequency ω_0 . Within this frame work, the asymptotic behavior of the transverse instability can be studied using the following equations:³

$$\left(\frac{\partial^2}{\partial t^2} + \frac{\omega_0}{Q} \frac{\partial}{\partial t} + \omega_0^2 \right) \Delta = \omega_0^2 G \xi / \gamma \quad (2.2.3)$$

$$\frac{\partial}{\partial z} \left[\gamma \frac{\partial \xi}{\partial z} \right] + \gamma k_\beta^2 \xi = \gamma \Delta, \quad (2.2.4)$$

where ξ is the transverse displacement of the beam centroid from the axis. $\Delta \equiv \Delta p_\perp / (L_g p_z)$ is the normalized z-averaged transverse angular change of the beam centroid per unit length, L_g is the cavity spacing, $\Delta p_\perp$ is the change in transverse momentum, and p_z is the longitudinal momentum. The strength of the coupling between the beam and the dipole field is represented by the term $G \equiv 4\pi \epsilon \omega_0 (Z_\perp / Q) I / (L_g I_0)$, where I is the current and $I_0 = 17$ kA. $Z_\perp$ and Q are the transverse impedance and quality factor of the cavity, and k_β is the wave number for the betatron motion of the beam. In the RK-TBA concept the average energy of the drive beam remains constant over an extraction-reacceleration cycle. For the following analysis γ is treated as a constant.

Equations (2.2.3) and (2.2.4) can be solved by Fourier transforming from t to ω and using the WKB method. The transform inversion to recover ξ can only be done analytically in a few special cases of initial/boundary conditions. However, general information on the growth of the transverse instability can be obtained if two simplifying assumptions are made:

$$k_\beta^2 \gg \frac{\omega_0^2 G}{\gamma(\omega_0^2 - \omega^2 - i \omega_0 \omega / Q)},$$

and the instability growth is sharply peaked near the resonance, $\omega = \omega_0$. The solution can then be approximated as:

$$\xi \approx \frac{A(\omega_0) \omega_0}{2\pi Q} \exp \left(-i\omega_0 t + i \int_0^z k_\beta - \frac{i G Q}{2\gamma k_\beta} dz \right) \sim \exp \left[\frac{G Q z}{2\gamma k_\beta} \right] = e^{\Gamma z}, \quad (2.2.5)$$

where $A(\omega_0)$ is determine by boundary conditions and Γ is the growth factor. Equation (2.2.5) exhibits the exponential growth with distance that is characteristic of this instability.

The impedance term, $Z_\perp$, used in the definition of G is the "normalized" impedance as calculated by URMEL for the $m=1$ mode, i.e. $Z_\perp = (c/\omega_0 b)^2 R$ where $R = V^2/2P_{\text{dis}}$, P_{dis} is the power dissipated, $V = \left[\int E_z e^{i\omega z/c} dz \right]_{r=b}$, and b is the radial distance at which V is calculated.

This impedance definition is related to the impedances, Z_{11} and Z_{L1} , calculated with the electromagnetic codes TBCI, ABCI, and AMOS for the $m=1$ mode by:

$$Z_\perp = \left(\frac{c}{\omega_0} \right) Z_{11} = \left(\frac{c}{\omega_0} \right)^2 Z_{L1}. \quad (2.2.6)$$

$$\text{The growth factor can be expressed as: } \Gamma = \frac{2\pi \epsilon c}{\gamma k_\beta L_g I_0} Z_{11}. \quad (2.2.7)$$

Phase mixed damping due to a spread in energy across the beam can be included in the analysis by using the techniques of hose instability theory.⁵ The beam is divided into "beamlets" with different energies, oscillation amplitudes, and betatron wavelengths such that $k_\eta^2 = \eta k_\beta^2$, where k_β is the maximum wave number, $0 \leq \eta \leq 1$, and ξ_η are the associated oscillation amplitudes. The model equations are

$$\left(\frac{\partial^2}{\partial t^2} + \frac{\omega_o}{Q} \frac{\partial}{\partial t} + \omega_o^2 \right) \Delta = \omega_o^2 G \langle \xi \rangle / \gamma, \text{ and} \quad (2.2.8)$$

$$\frac{\partial^2 \xi_\eta}{\partial z^2} + k_\eta^2 \xi_\eta = \Delta, \text{ where} \quad (2.2.9)$$

$$\langle \xi \rangle = \int_0^1 g(\eta) \xi_\eta d\eta, \gamma = \int_0^1 g(\eta) \gamma_\eta d\eta, \text{ and } \int_0^1 g(\eta) d\eta = 1.$$

For this analysis, let the distribution function be:

$$g(\eta) = \begin{cases} 0 & \text{for } 0 \leq \eta < 1 - \delta \\ 1/\delta & \text{for } 1 - \delta < \eta \leq 1 \end{cases} \quad (2.2.10)$$

A dispersion relationship can be obtained from equations (2.2.8) and (2.2.9) by Fourier transforming ω to t , z to k and using the distribution in equation (2.2.10):

$$1 = \frac{\omega_o^2 G}{\gamma(\omega_o^2 - \omega^2 - i \omega_o \omega / Q) \delta k_\beta^2} \ln \left[\frac{k_\beta^2 - k^2}{k_\beta^2(1 - \epsilon) - k^2} \right] \quad (2.2.11)$$

Again assuming that the greatest growth in the instability occurs when $\omega = \omega_o$, equation (2.2.11) can be used to determine k :

$$k^2 = k_\beta^2 \left(1 + \frac{\delta e^{i\phi}}{1 - e^{i\phi}} \right) = k_\beta^2 \left(1 - \frac{\delta}{2} + i \frac{\delta}{2} \cot \left(\frac{\phi}{2} \right) \right), \text{ where} \quad (2.2.12)$$

$$\phi = \delta \gamma k_\beta^2 / (G Q). \quad (2.2.13)$$

If $\phi = \pi$, k will be a purely real number and ξ will not exhibit exponential growth.

2.2.1.3 Betatron Node Scheme

The Betatron Node Scheme⁶ takes advantage of the electron orbit oscillations in the transport system to reduce the growth in higher order mode (HOM) induced transverse instabilities. Figure 2.2.2 illustrates the motion of an electron as it passes through a series of resonant cavities. The cavities are spaced at an interval equal to the betatron wavelength of the electron's oscillation in the focusing field. This configuration leads to minimal transverse displacement at the location of the extraction cavities which in turn results in minimal excitation of the higher order mode.

Figure 2.2.2. Particle motion for the "Betatron Node Scheme."

The growth in the particle's transverse motion is easily analyzed for the case where the resonant cavities are exactly a betatron wavelength apart. The transverse position, ξ , and velocity, $v_{\perp}$, of the particle at the entrance of the n^{th} cavity can be related to the position and velocity at the exit of the $n-1$ cavity through a matrix transformation:

$$\begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(n)}^{(-)} = \begin{bmatrix} \cos(\theta) & \frac{1}{\omega_{\beta}} \sin(\theta) \\ -\omega_{\beta} \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(n-1)}^{(+)} = M_f \begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(n-1)}^{(+)} \quad (2.2.14)$$

where θ is the phase advance, ω_{β} is the betatron frequency, and M_f is the transformation matrix. If the gap is sufficiently narrow, the transverse position of the beam centroid can be assumed to remain constant while crossing the gap, but the momentum will change. Equation (2.2.3) can be used to determine the increase in $v_{\perp}$. For this discussion, let the change in momentum be expressed as

$$\Delta v_{\perp} = R\xi \quad (2.2.15)$$

When $\theta=2\pi$, as we will soon see, ξ is the same at every cavity (n), although it may vary from head to tail (t). It follows that R may also vary with t , but is independent of n in this special case. Thus, ξ and $v_{\perp}$ at the exit of the gap can be expressed as

$$\begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(n-1)}^{(+)} = \begin{bmatrix} 1 & 0 \\ R & 1 \end{bmatrix} \begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(n-1)}^{(-)} = M_g \begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(n-1)}^{(-)} \quad (2.2.16)$$

Equations (2.2.14) and (2.2.16) can be combined to find the relationship between ξ and $v_{\perp}$ at the n^{th} cavity in terms of the initial conditions at the first cavity:

$$\begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(n)} = [M_f M_g]^n \begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(0)} \equiv M^n \begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(0)} \quad (2.2.17)$$

Equation (2.2.17) has been solved for arbitrary phase advance by Neil et al.,⁷ and shows that ξ increases exponentially with n when $\sin(\theta) \neq 0$. In the "Betatron Node Scheme" $\theta = 2\pi$, and equation (2.2.17) becomes simply:

$$\begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(n)} = \begin{bmatrix} 1 & 0 \\ R & 1 \end{bmatrix}^n \begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(0)} \equiv \begin{bmatrix} 1 & 0 \\ nR & 1 \end{bmatrix} \begin{pmatrix} \xi \\ v_{\perp} \end{pmatrix}_{(0)} \quad (2.2.18)$$

The transverse position of the beam centroid at the n^{th} cavity does not change and the transverse velocity increases linearly with n . Since the maximum centroid displacement ξ_{max} , occurring at a position of one quarter betatron wavelength from the cavity, is proportional to $v_{\perp}$, ξ_{max} increases linearly with the number of cavities. The change from exponential to linear dependence on n substantially reduces the instability growth.

2.2.2 Low-Frequency Instability (Induction Modules)

2.2.2.1 Problem Description

There are three induction modules per meter through the RK-TBA. Refer to Sections 2.4 and 3.2 for detailed descriptions of the induction module. Although considerable damping can be accomplished by the insertion of absorbing material, design constraints imposed by maximum surface electrical fields and vacuum requirements preclude complete damping of higher order modes. Modeling the module as a cylindrical resonator with an impedance boundary condition on the outer wall⁸ and assuming an optimum design, the transverse impedance, $Z_{\perp 1}$, will be on the order of 4,000 Ω/m . Experience with the Advanced Test Accelerator (ATA)⁹ and the Experimental Test Accelerator II (ETA II)¹⁰ indicate a growth of 4 to 5 e-folds is tolerable in the transverse instability. Thus the growth factor Γ should be no more than 4.6 over 300 m. For a 10 MeV e-beam, using $k_{\beta} = \pi/\text{m}$, $I = 600\text{A}$, and $L_g = \text{m}/3$, equation (2.2.7) can be used to estimate the maximum tolerable transverse impedance of the module: $Z_{\perp 1} = 573 \Omega/\text{m}$. Thus, additional measures are needed to suppress the transverse instability.

2.2.2.2 Suppression Techniques

There are several methods commonly used for suppressing the transverse instability. The addition of absorbing material or ports to extract energy from the higher order modes lowers the Q of the cavity and results in a lower effective impedance. This effect was assumed when the transverse impedance was calculated based on the optimum design of the cylindrical resonator model. Staggered tuning or varying the geometry of individual cavities to shift their higher order mode frequencies can be very effective for high Q structures. However, when the Q of the induction modules is very low (<10), staggered tuning is not viable. A more novel suppression scheme (see Section 2.2.1.3) involving the spacing of the rf extraction cavities at integer multiples of the focusing field betatron wavelength is not applicable for the induction gaps.

The most promising technique for suppressing the transverse instability is Landau damping. To maintain longitudinal equilibrium, inductively detuned structures were deployed (see Section 2.1). The resulting rf buckets have an intrinsic spread in beam energy over the microbunch of the order of $\pm 7.5\%$. Using equation (2.2.13) with $\phi = \pi$, this amount of energy spread, together with a transverse impedance, $Z_{\perp 1}$, of less than 5,178 Ω/m will lead to total suppression of low frequency BBU growth.

2.2.2.3 Results of Numerical Analysis

The OMICE Code was used to model the growth of the transverse instability. In practice, the technique for simulating a transverse energy variation on the beam was found to have limitations. In Figure 2.2.2 relative growth in the displacement of the beam's centroid from axis as a function of distance along the axis is shown for several different energy spreads and for the spreads based on a 5 slice and 9 slice variation. The random dithering of energy was insufficient to avoid some rephasing at larger energy spreads, i.e. the effect of Landau damping appears to saturate. The general conclusion is for a 5 (9) slice variation the relative growth is overestimated for energy spreads greater than $\pm 1.5\%$ ($\pm 2.5\%$). The number of slices in the energy variation could have been further increased to simulate more accurately the full effect of Landau damping. However, the runs presented, using either 5 or 9 slice variations as indicated, provide a conservative upper bound. Table 2.2.1 lists additional input parameters used in the OMICE Code. The "seed" perturbation for exciting the instability was a sinusoidal oscillation of the centroid's transverse displacement at the instability frequency.

In Figure 2.2.3, the growth rate for the case of no energy spread is about two thirds of the value predicted by equation (2.2.7); Γ is 0.107 m^{-1} from equation (2.2.7) and is 0.066 m^{-1} from Figure 2.2.3. From Figure 2.2.3 the growth rates are about 0.066 , 0.040 , and 0.018 m^{-1} for $\delta\gamma/\gamma = 0$, $\pm 0.6\%$, and 1.2% respectively. For $\delta\gamma/\gamma = \pm 2.5\%$ the BBU growth appears to be adequately suppressed by Landau damping. The three growth rates before saturation decrease linearly with a slope proportional to $\delta\gamma/\gamma$. This is a result predicted by Caporaso for a Lorentzian energy distribution.¹¹ There are several possible reasons for the discrepancy between analytical and numerical results. The analytical derivation assumed that the spacing of the resonant gaps is small compared to the betatron wavelength of the focusing system. The induction cell gaps are spaced one sixth of a betatron wavelength apart. The results appear to be dependent on the details of the energy distribution. Also, the perturbation "seed" used in the numerical work is suppressed by phase mixing when there is an energy variation.

Figure 2.2.3. Effect of energy spread and simulation technique on instability.

Table 2.2.1 Input Parameters for Simulated Induction Cell Gaps	
BBU Frequency	3.0 GHz
Z_{11} (Ω/m)	5,400
Z_{11}/Q (Ω)	42.972
Cell Q	2
Gap Width	2.5 cm
Average Beam Energy	10 MeV
$\Delta\gamma$ ($\gamma_{\text{max}} - \gamma_{\text{min}}$)	3
Current (dc component)	0 - 600 Amps in 100 ns 600 Amps "flat top" for 200 ns
Focusing System	Quadrupole - 2m period
Time Step	1/600 ns

Figure 2.2.4 indicates the relative growth in transverse displacement of the beam's centroid from axis as a function of distance along the axis. Three different cases are shown for Z_{11} equals 3,800 Ω/m , 5,400 Ω/m , and 7,000 Ω/m to verify that the growth factor is proportional to Z_{11} . Additional simulations were performed for different Q's and cavity resonances, also to verify scaling, and no significant differences from analytic predictions were noted. A sample of these results are shown in Figure 2.2.5.

Figure 2.2.4. Effect of varying Z_{11} .

Figure 2.2.5. Effect of changing Q and ω .

The conclusion from the numerical modeling is that the instability growth will be acceptable for Z_{11} less than or equal to 5,400 Ω/m and energy spreads of $\pm 2.5\%$ or greater.

2.2.3 High-Frequency Instability (RF Extraction Cavities)

2.2.3.1 Problem Description

There is one 3-cell, traveling-wave, output structure (TWS) every two meters through the RK-TBA. Refer to Sections 2.3 for a detailed description of the output structure. In the context of our current design, we limit the growth of transverse beam displacement to 4 to 5 e-folds over the 300 meter system, or 150 TWS's. In order to keep BBU to this level, we need to minimize or suppress excitation of the higher order (transverse) modes in the TWS's.

The contribution of the output structures to the transverse instability of the beam is greater than that of the induction cell gaps for several reasons. The output structure has a smaller aperture to obtain the desired longitudinal shunt impedance. Damping of the higher order modes must not affect the fundamental mode used for power extraction. Also, the three cells comprising the TWS are electromagnetically coupled. Within a TWS, the regenerative BBU mechanism will increase the interaction of the higher order modes with the beam.

2.2.3.2 Suppression Techniques

The basic design of the output structure has a transverse shunt impedance ($Z_{\perp}/Q$) of about 3 ohms per cell. This is significantly lower than for the induction cell gaps. However, the Q_{wall} of the cells is high, on the order of several 1,000. The third cell has two output ports that removes energy from the higher order modes. This produces an effective Q_{ext} of about 15. In addition, fields in the 1st and 3rd cell couple strongly to the TE_{11} mode of the connecting pipe, thus leading to a drastic reduction of Q_{ext} in both the first and last cavities. The growth in the transverse instability is also reduced by Landau damping due to the energy spread on the beam. However, even with these instability reduction features, the high frequency BBU growth is still too high.

The "Betatron Node Scheme" is used to limit the growth in the transverse instability to an acceptable level. This technique is described in detail in Section 2.2.1.3. In this scheme, the betatron wavelength of the focusing system is set to correspond to the spacing of the TWS's. Deflections of the beam passing through a TWS will not result in further increase of transverse displacement of the beam at the following TWS. The excitation of the higher modes of the TWS is proportional to the transverse displacement of the beam in the TWS. Thus the "Betatron Node Scheme" minimizes the excitation of the higher order modes and therefore the growth of the transverse instability. Figure 2.2.6 shows the large difference in BBU growth as we go from the on-node to the off-node scenario.

The Betatron Node Scheme works well in principle; the key issue is the robustness of the scheme to deviations in the betatron wavelength resulting from errors in focusing field and/or beam energy, as well as sensitivities to cavity parameters. The main goal of our numerical studies is to delineate the parameter space for acceptable high frequency BBU growth.

2.2.3.3 Results of Numerical Analysis

The OMICE Code was used to model the growth of the transverse instability. For our analysis, we chose a set of base parameters that are consistent with the cavity design calculations with URMEL and MAFIA as presented in Section 2.3. A list of the pertinent variables, and their base values, is given in Table 2.2.2. We then used the code to model the time-dependent

transverse behavior of one 300 ns pulse over the 300 m length of the RK-TBA beam line. An initial constant offset of the beam centroid was used as the "seed" perturbation for exciting the instability. The base parameters were varied individually to characterize the system's sensitivity to different design parameters such as effective impedance, Q values of the cells, quadrupole focusing field strengths, and variation in average beam energy.

Table 2.2.2 Base Parameters for Simulated Traveling Wave Structures	
Transverse Mode	HEM ₁₁
Frequency of Mode ω_0	14.1 GHz
Number of Cells/TWS	3
Electrical Length of Each Cell L_c	8.754 mm
Phase Advance/Cell ϕ	120°
Group Velocity v_g	0.25c
Q_{wall} (1 st and 2 nd cells)	3,500
Typical Q_{damped}	15
Z_L/Q for each cell	3
Current (dc component)	0 - 600 Amps in 100 ns 600 Amps "flattop"
Pulse Length	300 ns
Average Beam Energy	10 MeV
Quadrupole Field	0.0812 T

Figure 2.2.6. Relative Beam Centroid Displacement vs. the distance the beam has traversed. (a) By matching the betatron wave-length to the TWS spacing, BBU growth is strongly suppressed. (b) By over-focusing with a quadrupole field 11% stronger, the suppression effect is lost.

Figure 2.2.7. Relative Growth after 150 TWS's vs. the quadrupole focusing field, normalized to B_0 , the optimum field for suppression. Below the 'tolerable growth' line is the region of operational stability for the system.

The sensitivity of the "Betatron Node Scheme" to systematic errors in the focusing field, or equivalently beam energy, was studied. Figure 2.2.7 shows the relative growth of the displacement of the beam centroid after passing through the 150 output structures. As can be seen, deviation from the correct quadrupole B-field strength in either direction will result in increased BBU. As shown in Figure 2.2.7, use of the betatron node scheme results in near total suppression of the transverse instability; however, a systematic deviation of the focusing field, or beam energy, of less than 0.5% will result in excessive growth.

By varying the cross-sectional energy of the beam by a small amount ($\pm 2.5\%$ to $\pm 7.5\%$) around the 10 MeV level, the nature of the transverse stability is changed. When such an energy spread is introduced, there is also a spread in betatron wavelengths about the optimum value of 2 meters; most of the beam will thus be slightly over- or under-focused at all times. The effect of Landau damping on the betatron node scheme is not immediately obvious. Here we have to rely on numerical studies to provide the answer.

Figure 2.2.8 illustrates the effect of an energy spread about the average beam energy on the "Betatron Node Scheme." For Figure 2.2.8, a five slice energy variation ($\pm 7.5\%$) was used. Two curves are shown representing a case of a constant average beam energy and a separate case with a high-frequency, ($\pm 1.5\%$) random variation imposed on the average beam energy. From Figure 2.2.8, it can be seen that Landau damping significantly reduced growth in the transverse instability for values of the focusing field off optimum, but the energy spread resulted in higher growth near the optimum.

Figure 2.2.8. Relative growth after 150 TWS's as a function of the variation in the quadrupole focusing field strength with $\pm 7.5\%$ energy spread introduced on the beam. The effect of a high-frequency, $\pm 1.5\%$ random variation in the average beam energy is also shown. It can be seen that the tolerance to systematic errors in the focusing field is increased, but this gain in tolerance also results in an increase in the growth at optimum focusing.

It is clear from Figures 2.2.6 and 2.2.7 that the "Betatron Node Scheme" allows us to approach our goal of suppressing BBU to 4-5 e-fold, and Landau damping blunts the extreme sensitivity of the node scheme to fluctuations in the B field. However, additional measures are needed to increase the error tolerance for a viable design. The most straight forward method is to reduce the effective impedance of the TWS's, thereby lowering the overall growth of the BBU.

The parameters most easily controlled in the design are the Q values of the individual cells, and, with somewhat more difficulty, the Z_1/Q of the output structure. The Q of an RF cell can be reduced by increasing the aperture to permit propagation of electromagnetic energy from the cell, adding absorbing material to the cell, and making external ports in the cell walls to couple out energy. The last option has the least interference with the fundamental mode and has been used successfully in the experimental program at LLNL.^{12,13}

The possibility of regenerative BBU within each TWS limits the applicability of the well-understood cumulative BBU theory outlined in Section 2.2.1. However, by varying the Q and Z/Q of the output structure cells in our simulations, we demonstrated the exponential dependence of the asymptotic BBU growth rate with respect to these parameters. (See Figure 2.2.9).

We have performed further tests of the sensitivity of the BBU growth to different sets of Q values for the 3 cells of the output structure. In Table 2.2.3, we list the relative growth at optimum focusing for 4 realistic sets of Q values. The first entry in Table 2.2.3 reflects the 'baseline parameters' used to obtain our stability graph in Figure 2.2.8. We see that reducing the Q value of

Figure 2.2.9. Asymptotic Growth Rate vs. Z/Q and Q . The growth in the transverse displacement of the beam centroid is proportional to $e^{\Gamma z}$, where Γ is the growth rate.

Table 2.2.3			
Relative Growth after 150 TWS for Different de-Q-ing Schemes			
Q(cell 1)	Q(cell 2)	Q(cell 3)	Relative Growth
3,500	3,500	15	32.7
3,500	3,500	12	16.3
15	3,500	15	9.1
12	3,500	12	4.4

the third cell even slightly will reduce the relative growth significantly. When both the first and third cell are de-Qed, the growth rates are further reduced. It is important to note, that for our cavity design with an inner aperture of 8 mm, the first and third cavity are naturally de-Qed, as the HEM₁₁ modes are strongly coupled to the TE₁₁ mode in the connecting pipe. Low Q's for the first and third cavity are quite consistent with our dipole wake calculations (see Section 2.3).

When low Q values for both the first and third cavities are used, the sensitivity to B-field errors is dramatically reduced. The results of these simulations are shown in Figure 2.2.10. If these Q values are attained, the tolerance in the focusing fields for stability will be very loose indeed.

The next issue studied involved the variation of average beam energy over the 300 ns pulse. The "flatness" of the pulsed power system will be determined by the complexity of the pulse forming network. (Refer to Section 3.1). Two different forms of energy variations were studied as illustrated in Figure 2.2.11. In the first case, the average energy is initially less than 10 MeV, increases to a maximum value greater than 10 MeV, and then returns to the initial value describing a half period of a sinusoidal curve. The second case starts at 10 MeV and follows a sinusoidal path before returning to 10 MeV. The actual voltage waveform will be a sum of several sinusoidal components to approximate a rectangular pulse with the first few having the largest components.

Figure 2.2.10. Relative growth after 150 TWS's vs. variation from the optimum focusing field. Comparison of an aggressively lowered Q to a high Q for the first cell.

The results of the simulations with the average energy variations are shown in Figure 2.2.12. In these simulations the Q values of the first and third cavity were 10 and the focusing field was optimum. Variations of $\pm 0.5\%$ in the average energy results in small increases to the relative growth. Even variations of $\pm 1.5\%$ are within the stability criteria. Additional studies using actual voltage waveforms should be performed, but this initial work is encouraging.

Figure 2.2.11. Average energy variations modeled.

Figure 2.2.12. Effect of variation in average beam energy on the relative growth of the transverse displacement of the beam centroid.

2.2.4 Conclusions on Transverse Instability

The primary contributor to transverse instability is the output structure. The "Betatron Node Scheme" is a promising means for controlling the high frequency instability caused by these structures. Requirements on energy flatness and field accuracy are quite acceptable provided that the output structures are indeed strongly de-Qed. The lower frequency instability of the induction cell gaps is adequately suppressed by Landau damping resulting from the anticipated energy spread on the beam.

Several questions remain to be studied. The rf parameters used in the computer simulations are assumed to be achievable, but actual components need to be constructed and tested. Measured rf parameters can then be used in the modeling. Additional studies are required to determine the effect of different perturbation "seeds" on the initial growth of the instability. Finally, the sensitivity of the "Betatron Node Scheme" to head-to-tail energy variation over the beam pulse needs to be studied in more detail. Feedback schemes may further relax the requirements on field and energy accuracies. Finally, the higher order modes (beyond the lowest dipole mode) should be examined.

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2.3 RF Extraction Cavity Design (E. Henestroza)

This section is concerned with the design of the rf extraction cavities. The most basic requirement for the cavity design, of course, is that it would generate 360 MW of rf power for a drive beam current of 600 A DC and about 1-1.5 kA rf. Secondly, the cavities must be inductively detuned in order to maintain longitudinal beam stability over long distances. Thirdly, the surface fields of the structure must be sufficiently low to avoid breakdown. Finally, the cavity must have low transverse shunt impedance in order to minimize the high frequency BBU. The required cavity parameters have already been discussed in Sections 2.1 and 2.2. In this section, we present electromagnetic calculations to determine the structure of the extraction cavities. We have chosen in this design effort one specific path to meet the general requirements. The procedure adopted is by no means unique, and we anticipate further optimizations and more detailed calculations in the future.

The tools we have used are URMEL and SUPERFISH for 2-D frequency domain calculations, ABCI and TBCI for 2-D time-domain calculations, and MAFIA for 3-D frequency as well as time-domain calculations.

The design procedure is carried out in several steps, starting with the simplest approximations, and adding more realistic features with each successive iteration. The successive approximations are briefly summarized as follows:

1. First, we want to determine roughly the geometry of the overall structure. As a starter, we construct a 3-cell disk-loaded traveling-wave structure that is synchronous ($v_p=c$), using Eq. (2.1.17). The rf structure should give 360 MW with a tightly bunched drive beam with an rf current of 1-1.5 kV. We choose initially a conventional $2\pi/3$ structure with cell length (p) of 8.75 mm. The power extraction formula gives a requirement of $(R/Q)/v_g$.

URMEL is exercised for an infinitely periodic structure, varying the inner radius a and outer radius b of a disk-loaded structure, and the set of solutions with $v_p=c$ is obtained, following the procedure of Thompson, et al.¹ For each value of the aperture radius satisfying $v_p=c$, the cavity parameters R/Q and v_g are determined.

2. The inductively detuned structure is next constructed by a variation of step 1. What we want is a structure whose resonant frequency remains unchanged, but the wavelength is increased by 1.33 of the results from step 1. This will result in a phase velocity of 1.33 c , which is the desired detuning angle, according to the numerical studies of Section 2.1. To achieve this, we choose to fix the cell length $p=8.75$ mm as in step 1, and reduce the outer radius b for each value of a , until the $2\pi/3$ field configuration of step 1 becomes a $\pi/2$ configuration at the same frequency of 11.424 GHz. Each wavelength now extends over 4 cells, instead of the 3 cells in step 1. The R/Q and v_g for this new configuration are determined with URMEL. The required geometry is determined by ensuring that the corresponding R/Q and v_g provides the right power extraction. The solution is $a=8$ mm, $b=12.5$ mm, $R/Q=13.5 \Omega$ and v_g is 0.28 c . Slight-refinements from this geometry are obtained by numerically iterating on the power extraction formula to account for the reduction in power due to inductive detuning, as indicated in Section 2.1.2.4.
3. The finite cell structure is included by modeling a 3-cell structure with finite beam pipes. The effect of the modified geometry on the field configuration and cavity parameters are then studied.

4. Finally, the 3-D aspects of the output ports are studied using MAFIA. Recalling that the matching condition derived in Section 2.1 demands that the frequency and Q-value of the last cell be uniquely determined to absorb the reflected waves from the 3-cell structure. MAFIA is exercised by variation of the geometry of the output until the right value of Q and ω for proper matching are obtained.

As we go through each of the above 4 steps, we also evaluate the relevant dipole cavity parameters for BBU considerations, as well as the field enhancement factor to determine the surface field for assessing breakdown risks.

2.3.1 Infinitely Periodic Structure

As a first step, assume that the cavity is a part of an infinitely periodic structure. Figure 2.3.1 shows a schematic cross section of the structure, where the cavity parameters are defined. Neither beam pipes nor output structures are considered at this time.

Figure 2.3.1. Schematic Cross Section of cells

The structure is a disk loaded waveguide driven at $f_{rf}=11.424$ GHz. If the phase advance per cell is chosen to be $\phi=2\pi/3$ then in order for the accelerating mode to be synchronous with the beam the cell length is $p=8.747$ mm.

Using the computer code URMEL, a study of the behavior of the RF parameters of the structure while varying the iris aperture (a) and the cavity aperture (b) was performed. The first case that we studied is one in which the beam was synchronous with the accelerating wave ($2\pi/3$ mode). The second case corresponds to an inductively detuned cavity in which the beam was lagging by 30 degrees ($\pi/2$ mode).

Figure 2.3.2. Field configuration for the $2\pi/3$ mode.

2.3.1.1 Synchronous structure

Figure 2.3.2 shows the field configuration for the $2\pi/3$ mode for an rf structure whose wave speed is synchronous with the relativistic beam.

Figure 2.3.3 shows the cavity aperture radius (b) for a given iris radius (a) such that the structure is synchronous, using the procedure of Thompson, et al.

Figures 2.3.4-6 show the quality factor and field enhancement factor; R/Q (per cavity) and group velocity; and dipole mode synchronous frequency and shunt impedance (per cavity), as functions of the cell iris radius (a).

Figure 2.3.3. Cavity Radius vs. Iris Radius for $f_{rf}=11.424$ GHz and $\phi=2\pi/3$.

Figure 2.3.4. Quality Factor and Enhancement Factor for $f_{rf}=11.424$ GHz and $\phi=2\pi/3$.

Figure 2.3.5. Shunt Impedance (per cavity) and Group Velocity for $f_{rf}=11.424$ GHz and $\phi=2\pi/3$.

Figure 2.3.6. Dipole Mode Synchronous Frequency and Shunt Impedance for $f_{rf}=11.424$ GHz and $\phi=2\pi/3$.

A sensitivity analysis of the enhancement factor versus the iris thickness (t) is shown in Figure 2.3.7. An iris thickness of 2.5 mm appears to be required for minimum field enhancement.

Figure 2.3.7. Field Enhancement Factor as function of iris thickness for $f_{rf}=11.424$ GHz and $\phi=2\pi/3$.

2.3.1.2 Inductively detuned structure (30° lag)

Figure 2.3.8 shows a $\pi/2$ mode field at resonant frequency = 11.424 GHz.

Figure 2.3.8. Field configuration for the $\pi/2$ mode.

Figure 2.3.9 shows the outer cavity radius b required for obtaining a $\pi/2$ mode at 11.4 GHz for various iris radii a .

Figures 2.3.10-12 show the quality factor and field enhancement factor; shunt impedance (per cavity) and group velocity; dipole mode synchronous frequency and shunt impedance (per cavity), as functions of the cell iris radius (a). Figure 2.3.13 shows the dipole mode group velocity at synchronous frequency.

Figure 2.3.9. Cavity Radius vs. Iris Radius for $f_{rf}=11.424$ GHz and $\phi=\pi/2$.

Figure 2.3.10. Quality Factor and Enhancement Factor for $f_{rf}=11.424$ GHz and $\phi=\pi/2$.

Figure 2.3.11. Shunt Impedance (per cavity) and Group Velocity for $f_{rf}=11.424$ GHz and $\phi=\pi/2$.

Figure 2.3.12. Dipole Mode Synchronous Frequency and Shunt Impedance for $f_{rf}=11.424$ GHz and $\phi=\pi/2$.

Figure 2.3.13. Dipole Mode Group Velocity at Synchronous Frequency for $f_{rf}=11.424$ GHz and $\phi=\pi/2$.

There is a subtlety about the field enhancement factor. What we have calculated in Figures 2.3.4, 7 and 10 are the enhancement factors from URMEL and SUPERFISH, defined as the ratio of the maximum amplitude of the electric field in the whole structure to the average electric field along the axis (including the transit time factor). This calculation is performed with URMEL and SUPERFISH for standing-wave cavities. Since we are interested in traveling-wave structures there is need to convert the standing wave result to traveling wave following a procedure described in a paper by Loew et al.² In essence the traveling-wave solution is obtained from the standing-wave solution by shifting the fields in the axial direction and adding the original and the shifted solutions with appropriate phases. The enhancement factor that we are interested in is defined for traveling-wave structures as the ratio of the maximum amplitude of the electric field in the whole structure to the average amplitude of the electric field on axis without including the transit time factor. By following this procedure we obtained for the case of $a=8$ mm an enhancement factor of 1.5 as compared to the value of about 4.0 calculated using the definition for standing-wave structures.

2.3.2 2-D Finite Structure

The next step was to consider a three cell inductive ($\pi/2$ mode) cavity with beam pipes as shown in Figure 2.3.14.

Figure 2.3.14. Three cell cavity with beam pipes.

2.3.2.1 Frequency Domain Calculations.

The computer code URMEL was used to find the length of the beam pipe that confines the fields inside the structure. Figure 2.3.15 shows the axial electric field on axis for three beam pipe lengths. From these calculations, we determine that a length of 3 cm on each side of the structure will adequately contain the fringe fields. The cavity fields still retain their $\pi/2$ structure (See 2.3.3).

Figure 2.3.15. Axial field on axis for three beam pipe lengths.

2.3.2.2 Time Domain Calculations

A wakefield calculation using TBCI was performed to find the resonant frequencies and impedances of the structure and to compare the results with the frequency domain calculations to check for consistency. Figures 2.3.16-19 show the wakefields and impedances for the monopole and dipole modes. The resonant frequencies as well as the relative impedance behavior agree with those calculated in frequency domain.

Figure 2.3.16. Longitudinal wake field of a three cell structure with beam pipes.

Figure 2.3.17. Longitudinal impedance of a three cell structure with beam pipes.

A very important point to note is that the dipole wake of Figure 2.3.18 is heavily damped. This is due to the strong coupling of the cavity field to the TE_{11} mode in the beam pipe. This results in a very low Q . To translate the wake calculation to the Q of individual cells in a coupled cavity formulation is somewhat subtle, and has not been fully understood yet. But initial estimates suggest that the dipole Q for the first and last cavity of our 3-cell structure could be as low as 10. (See Appendix, Section 2.1)

Figure 2.3.18. Transverse (dipole) wake field of a three cell structure with beam pipes.

Figure 2.319. Transverse (dipole) impedance of a three cell structure with beam pipes.

2.3.3 3-D Cavity with Output Structure

From the 2-Dimensional analysis of the cylindrically symmetric cavity without output structures the parameters were set to: $p=8.747$ mm, $t=2.5$ mm, $a=8.0$ mm, $b=12.4334$, and a beam pipe length of 3.0 cm, for a $\pi/2$ mode. The 3-Dimensional electromagnetic code MAFIA has been used to calculate the Q_{ext} of the cavity including output structures. Figure 2.3.20 shows a schematic x-cut of the complete structure. Figure 2.3.21 shows a schematic of a z-cut at the waveguide, showing the coupling iris aperture.

Figure 2.3.20. Schematic Cross Section of 3-D cavity with output structure (x-cut).

Figure 2.3.21. Schematic Cross Section of 3-D cavity with output structure (z-cut).

2.3.3.1 The Output Structure

The output structure consists of two WR90 RWG waveguides attached to the last cell of the cavity. The shorter (0.4" long) side is oriented along the z-axis. The last cell is required to have a $Q_{\text{ext}} < 10$ in order to have only a forward traveling wave in the cavity.

The determination of the external Q of the 3-D cavity with output structure is based on the Kroll-Yu method³. For a given waveguide iris aperture several calculations (at least four) are performed varying the length of the output waveguide. The phase change along the waveguide, ψ , is defined as $2\pi D/\lambda_g$, where λ_g is the waveguide wavelength and D is the waveguide length. The mode of interest (in our case the $\pi/2$ mode) is identified and the frequency recorded. From the phase change versus frequency relationship the external Q is approximately given by $-(1/2)f(d\psi/df)$.

Taking into account the whole structure we calculated $Q_{\text{ext}} \approx 80$ for various waveguide iris apertures. To relate the Q of the entire 3-cell structure calculated with MAFIA to the Q of the individual cells in a coupled-cavity formulation, we use the results from the Appendix of Section 2.1. The equivalent Q for the 3rd cavity is shown to be less than 10. Figure 2.3.22 shows a field configuration for the $\pi/2$ mode of the 3-D cavity with output structure. Figure 2.3.23 shows a typical D vs. f curve.

Figure 2.3.22. Field configuration for the $\pi/2$ mode of the 3-D cavity with output structure.

Figure 2.3.23. D vs. f curve.

The calculation of the Q_{ext} of the last cell for a $\pi/2$ mode configuration is facilitated from the fact that such configuration is obtained naturally by applying neuman and dirichlet boundary conditions at the left and right boundaries of the structure shown in Figure 2.3.24. The left and right labels are arbitrary since the system is symmetric. Using the Kroll-Yu method we calculated a $Q_{\text{ext}} \approx 5$ for a waveguide iris aperture of 1.24 cm, a value that is within that required to meet the matching condition.

Figure 2.3.24. Schematic cross section of single cell with output structure (y- and x-cut).

Figure 2.3.25 shows the field configuration for the $\pi/2$ mode of the single cell with output structure. Figure 2.3.26 shows the phase versus frequency curve.

Figure 2.3.25. Field configuration for the $\pi/2$ mode of the single cell with output structure (y- and x-cut).

Figure 2.3.26. Phase versus frequency curve for the $\pi/2$ mode of the single cell with output structure.

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2.4 Induction Cavity Design (T. Houck)

The interaction of the induction cell gap with the beam is a critical issue for the RK-TBA. Numerical modeling of the characteristic impedances of proposed gap designs for the induction cells is presented below. Additional details concerning the overall induction cell design can be found in Sections 3.1 and 3.2.

2.4.1 Design Criteria

There are three major criteria that the cell gap must meet: hold-off of the applied 100 kV voltage, low transverse impedance for BBU minimization, and low longitudinal impedance at the beam modulation frequency and harmonics to minimize power loss.

In Section 2.2.2 numerical modeling determined that low frequency BBU could be well controlled if Z_{11} is less than 5,400 Ω/m . The transverse impedance scales as $Z_{11} \sim W/b^2$ where W is the width of the gap and b is the radius of the beam pipe.¹ The gap should be as narrow as possible consistent with the maximum surface electrical fields. Larger apertures reduce the transverse impedances, but increase the volume of the cell core. An aperture of 5 cm was chosen as a base design. This allows sufficient room for the focusing magnets while meeting the desired core volume.

Microwave absorbing materials can be used to damp resonant modes. These materials have a complex permittivity and/or permeability. Table 2.4.1 lists nominal values of the permittivities and permeabilities for the absorbing materials used in the numerical modeling. The permittivity and permeability are expressed as $\epsilon = \epsilon_0(\epsilon' + i\epsilon'')$ and $\mu = \mu_0(\mu' + i\mu'')$, respectively. Here ϵ_0 and μ_0 are the free space permittivity and permeability.

The most difficult design problem is achieving a low longitudinal impedance. Our design goal is to have a power loss to the induction cells of less than 4% of 360 MW per two meter module. This requires a gap impedance, Z_{L0} , of less than 2.4 Ω at the modulation frequency of 11.424 GHz. Impedance decreases rapidly above the cutoff frequency. Table 2.4.2 lists cutoff frequencies for several modes in a cylindrical pipe of radius 2.5 cm. We have considered 3 different gap designs, and the lowest Z_{L0} achieved thus far is about 10 Ω at 11.4 GHz.

Table 2.4.1. Electrical properties of simulated microwave absorbers.

Material	ϵ'	ϵ''	μ'	μ''
Ferrite* ¹	13.0	0.0	1.0	9.4
TDK* ²	25	3.3	1.9	2.1
carbon loaded ceramic* ³	5.9	1.07	1.0	0.0

*¹ Ferrite is modeled after the ferrite used in the ATA induction cells.² Measured at 1 GHz. *² TDK Electronics Co., LTD., Absorber IR-B006. Measured at 2.5 GHz. *³ University of Maryland ceramic.³ Carbon concentration 0.34% (by weight). Measured at 9.9 GHz.

Table 2.4.2. Cutoff Frequencies for a 2.5 cm Radius Cylindrical Pipe.

Resonant Mode	Cutoff Frequency	Resonant Mode	Cutoff Frequency
TE ₁₁	3.52 GHz	TM ₂₁	9.81 GHz
TM ₀₁	4.59 GHz	TE ₁₂	10.18 GHz
TE ₂₁	5.83 GHz	TM ₀₂	10.54 GHz
TE ₀₁ /TM ₁₁	7.32 GHz	TM ₃₁	12.18 GHz
TE ₃₁	8.02 GHz	TE ₂₂	12.81 GHz

2.4.2 Possible Induction Cell Gap Designs

Three designs were considered for the gap. Poisson was used to study the geometry required for acceptable surface electrical fields. An electromagnetic field solver, AMOS,⁴ was used to determine the rf characteristics of the gap. AMOS simulations include power loss to absorbing material.

2.4.2.1 Conventional Design

A “conventional” design similar to the ETA II induction cell gap was studied first. Figure 2.4.1 displays a full scale schematic of this design. Several changes to the basic design were made to study the effect on the impedance. The simulated material properties of the absorbers and insulator were varied over a nominal range. The location and size of the absorbers were also varied.

Figure 2.4.1. Schematic of a “conventional” design induction cell gap.

The advantages to the “conventional” design is that it has been well tested on several induction accelerators at LLNL, the ceramic insulator is hidden from the electron beam, lowering the susceptibility for arcing, and surface electrical fields can be kept relatively low. The disadvantages are a large inner radius for the Metglas core and a low gap capacitance. A low gap

capacitance is desired for fast rise times, but is not needed for this RK-TBA design. In addition, a low gap capacitance also tends to be related to a high longitudinal impedance which is undesirable.

Figure 2.4.2 and 2.4.3 show graphs for the lowest impedances found for this design. In Figure 2.4.2, the third resonant peak is at a frequency approximately equal to the TE_{11} mode cutoff frequency for the beam pipe. This resonance is most likely an artifact of the AMOS code. Refer to the discussion in Section 2.4.2.2 below. The first two resonant peaks are caused by trapped modes. The transverse impedance is sufficiently low to meet the stability criteria. The longitudinal impedance shows a trapped mode resonance around 2 GHz and a second response near the cutoff for the TE_{11} mode. The principal issue with the longitudinal impedance is that it remains above 20 Ω near the 11.424 GHz. This is about an order of magnitude greater than the desired value. Some further design modifications are therefore necessary to lower Z_{LO} .

Figure 2.4.2. Transverse impedance for the "conventional" design gap.

Poisson was used to determine the electric fields associated with the "conventional" design gap. The equipotential lines are shown in Figure 2.4.4. The field across the surface of the ceramic insulator is about 25 MV/m. The highest fields are located on the small radius nose pieces and are approximately 100 MV/m.

2.4.2.2 Compact Design

A more compact design that had a higher gap capacitance was studied. Figure 2.4.5 displays a full scale schematic of this design. Advantages of the "compact" design are the decreased inner radius of the Metglas core and a lower longitudinal impedance. The disadvantages are that the ceramic insulator is exposed to the beam and surface electrical fields tend to be high at the triple points (interface between vacuum, metal and insulator).

Figure 2.4.6 shows a graph for the lowest transverse impedance found for this design. The first impedance peak in Figure 2.4.6 is a trapped mode. The second peak is associated with the cutoff

frequency of the TE_{11} mode and is considered an artifact of the AMOS code. Variations in the boundary conditions at the ends of the beam tube have significant effects on the height of the transverse impedances. Figure 2.4.7 illustrates the sensitivity of this peak to variations in the length of the beam pipe used in the simulations. A radiative boundary condition at the termination of the pipe end was used in the simulation in an attempt to avoid nonphysical reflections. The third peak is above cutoff for the TE_{11} mode, but near the cutoff for the TM_{01} and TE_{21} modes. While the finer details of this peak are affected by the boundary conditions, the general structure is not appreciably affected. Figure 2.4.8 shows changes in the third peak as the beam pipe is

Figure 2.4.3. Longitudinal impedance for the "conventional" design gap.

Figure 2.4.4. Equipotential lines for the "conventional" gap design.

lengthened in the simulations. The third peak may represent a partially trapped resonant mode that does not couple well to the TE_{11} pipe mode.

Figure 2.4.5. Schematic of the "compact" gap design.

Figure 2.4.6. Transverse impedance for the "compact" gap design.

The longitudinal impedance is shown in Figure 2.4.9. Although there is a high peak value near 4 GHz, the impedance is much lower at high frequency than for the "conventional" design. Figure 2.4.10 shows additional details of the longitudinal impedance over the frequency range of 8 to 13 GHz. The impedance "valley" between about 9 and 10 GHz can be shifted to the range of 7.5 to 9 GHz with minor variations to the gap geometry and ceramic permittivity. However, the peak at 10.5 GHz is persistent and requires a change in aperture to shift. The effect of different

simulated pipe lengths is minor for the region of interest as indicated in Figure 2.4.10. The impedance of the "valley" is reduced by half if metal instead of carbon loaded ceramic nose pieces are used. The detailed structure of the higher "valley" from about 11 to 12 GHz is affected by boundary conditions on the pipe ends, but has an average value of about $10\ \Omega$. Figure 2.4.11 shows the equipotential lines for the "compact" gap design. The "triple point", intersection of vacuum, ceramic, and metal, has excessively high electric fields as shown in the figure. Adjustments to the gap geometry will be required to lower these fields, but are considered possible.

Figure 2.4.7. Details of the second peak.

Figure 2.4.8. Details of the third peak.

Figure 2.4.9. Longitudinal impedance for the "compact" gap design.

The "compact" design is promising, although longitudinal impedance and surface fields are still above acceptable levels. The small outer radius permits flexibility with geometry variations which may lead to the required impedance and field values.

Figure 2.4.10. Longitudinal impedance of "compact" gap design near 11.4 GHz.

Figure 2.4.11. Equipotential lines for the "compact" gap design.

2.4.2.3 Shielded Gap

A shielded gap design that had a higher gap capacitance was studied. Figure 2.4.12 displays a full scale schematic of this design. Advantages of this design are a small inner radius for the Metglas core, lower surface electrical fields, and lower longitudinal impedance. The disadvantages are a complex design which will be more expensive to fabricate than the other designs, and the longitudinal impedance is still higher than desired.

Figure 2.4.13 shows a graph for the lowest transverse impedance found for this design. The first impedance peak in the figure is a trapped mode. The second peak is associated with the cutoff frequency of the TE_{21} mode. Figure 2.4.14 is a graph for the longitudinal impedance associated with Figure 2.4.13. The intermediate electrodes across the gap both shield the ceramic from the beam and interrupts the path of electrons across the ceramic surface. The primary distraction to this design is the complexity involved with manufacturing and installing the ceramic with electrodes.

Figure 2.4.12. Schematic of the "shielded" gap design.

Figure 2.4.13. Transverse impedance for the "shielded" gap design.

2.4.3 Conclusions

All the designs listed above meet the requirement for $Z_{\perp 1} \leq 5,400 \Omega/\text{m}$. This was accomplished by using absorbing material to damp all resonances. It is critical that no undamped resonances are permitted. Figure 2.4.15 illustrates the effect of not damping a trapped mode. The two impedances are for the "conventional" design gap shown in Figure 2.4.1. The difference is that the carbon loaded ceramic in Figure 2.4.1 was replaced with a metal surface. The high Q resonance could not be totally resolved with the AMOS code, but its magnitude is probably well above 15 k Ω/m . The horizontal line below 6 k Ω/m indicates the maximum tolerable $Z_{\perp 1}$. The "compact" gap

design appears to be the most promising design to achieve the required longitudinal impedance. Further design work needs to be completed that will demonstrate lower surface electrical fields, but this aspect of the design should not be a severe constraint.

The analytical and numerical determination of impedances well above cutoff is difficult. Additional work is needed to determine impedances well above the frequency cut off for the pipe aperture. Theoretical studies have been performed,⁵ but, for our case where we need to know the

Figure 2.4.14. Longitudinal impedance for the "shielded" gap design.

Figure 2.4.16. Comparison of damped versus undamped "conventional" gaps.

longitudinal impedance precisely at 11.424 GHz, it is not clear whether analytical results can produce sufficiently accurate results. Numerically, the parameters of the test charge used, fineness of the grid, and the boundary conditions have significant impact on the results. A "cold test" model needs to be fabricated and tested in the laboratory for a definitive answer.

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3. RK-TBA Engineering

3.1 Electrical Systems (L. Reginato)

3.1.1 Induction Accelerator Module

The linear induction accelerator can simply be described as multiple transmission line transformers driven in parallel by a pulse modulator which add energy to the electron beam in series as it passes through them. In order for the acceleration process to be efficient, the transformer or induction losses should be small compared to the energy imparted to the beam. Simply put, the transmission line current should be small compared to the beam current; therefore, the effective impedance of the transmission line, Z_{eff} , should be greater than the beam impedance $Z_b = V_{drive}/I_{beam}$. In all previously constructed induction accelerators, the high impedance is achieved by loading the transmission line with a ferri-or-ferro-magnetic material which is appropriate for the pulse duration. This material increases the impedance by $\sqrt{\mu/\epsilon}$ and the electrical length by $\sqrt{\mu\epsilon}$. Typically, induction accelerators with pulse duration shorter than 100 ns have used ferrites while those with longer duration have used ferromagnetic materials such as Nickel-Iron or Metglas. The optimization process in selecting the type of material and quantity is based on pulse duration, impedance, magnetizing losses and economics. For the TBA accelerator the parameters are as follows:

$$I_{beam} = 600 \text{ A} \quad V = 300 \text{ kV/m} \quad T = 300 \text{ ns}$$

To satisfy the requirement where the effective impedance, Z_{eff} , is greater than the beam impedance, $Z_{beam} \approx 500 \text{ ohm}$, we can use the equation for a coaxial transmission line where $Z = \sqrt{\mu/\epsilon} 60 \ln r_o/r_i$. For ferrites, $200 < Z_{eff} < 1000$, and for ferromagnetic materials $1000 < Z_{eff} < 5000$ depending on the type of material used and the magnetization rate. To satisfy the pulse duration requirements in practice the transmission line length is set about equal to a single transit time. Since transit time is proportional to $\sqrt{\mu\epsilon}$, for ferrites and for ferromagnetic materials $T_{eff} \approx 100 T_{vac}$. The design of the transmission line (induction cell) must also insure that no portion of the line is driven into saturation. This requirement dictates the outer radius of the line once the inner radius is determined by beam transport physics. Since ferromagnetic materials have three to four times the saturation flux of the ferrites we can see that the outer radius of the ferrite loaded line would be considerably larger. By following the basic operating principles in the design of an induction accelerator cell we can conclude that the preferred material for our parameter range is one of the ferromagnetic varieties.

One of the most important considerations in the selection of a magnetic material for an induction cell is the actual losses during the magnetization pulse. In applying the basic operating principles the losses and the cost of the material were not considered in choosing ferromagnetic materials over ferrites. Figure 3.1.1 shows the losses in Joules/m³ for ferri and ferro-magnetic materials and for different saturation times. Although the induction cell is well below saturation, this graph shows the comparative losses between ferrites, Metglas 2605 SC and nickel-iron at different thicknesses. If we compare the two at the 0.3 μ s saturation time we see that the losses for Metglas are about five times those of the ferrites. Recalling from the flux swing (ΔB) argument that a much larger radius was required for ferrites, or a volume nearly one order of magnitude larger, it appears that at the pulse duration of 0.3 μ s for the TBA, Metglas, or an equivalent other ferromagnetic material such as nickel-iron, is the right choice.

Ferromagnetic materials such as nickel-iron have been available in thin ribbon cores since the late 50's when the first induction accelerator, the Astron, was constructed at Livermore by N.C. Christofilos. These iron based alloys are manufactured to this day and are very competitive in magnetic properties to the amorphous materials manufactured by Allied Signal referred to as Metglas.* The time-dependent losses in ferromagnetic ribbons are typically explained in terms of a saturation wave which encircles the tape and proceeds toward the center at a rate proportional to the applied voltage. The magnetic intensity required to change the state of magnetization is

$$H_a = H_c + (d^2/4\rho)(\Delta B/2B_s)(\Delta B \Delta t), \quad (3.1.1)$$

where H_c is the DC anisotropy coercive field, d is the ribbon thickness and ρ is the resistivity. The energy density deposited in the tape during saturation is given by

$$E_L = H_c \Delta B + (d^2/4\rho)(\Delta B^2/2B_s)(\Delta B \Delta t). \quad (3.1.2)$$

One can see that the losses are proportional to the thickness of ribbon squared and inversely proportional to the resistivity. Since the ΔB of the iron alloys is similar to that of Metglas but the resistivity of Metglas is three times that of the iron alloys, the ribbon thickness must be thinner in order for the losses to be comparable to the Metglas. The Ni-Fe alloys are manufactured by a rolling technique which yields more uniform cross-section while the Metglas alloys are manufactured by rapidly quenching a mixture of silicon and iron which remains amorphous. The quenching process leaves the ribbon surface rough compared to the rolled ribbon hence it is more difficult to insulate and it can yield uneven cross-section in the core winding process. Currently the unannealed Metglas is wound into cores with 2.5 μ m mylar between layers yielding a packing factor of .65 to .75 for a finished core. The iron alloys can be rolled into thinner ribbon than the Metglas and have produced lower overall losses. However, the manufacturing and winding process for Metglas has resulted in a less expensive core. The losses per unit volume at different saturation times is documented on Figure 3.1.1.

There are many options in arranging the series transformers to obtain 300 kV/m of acceleration. Three high voltage cells at 100 kV or many lower voltage cells at tens of kilovolts will generate the desired voltage. Before selection is made of the cell voltage, one must decide on the type of drive modulator which is the most cost effective at achieving the desired parameters. A brief discussion is in order prior to the cell design. The magnetic pulse compression modulator is unchallenged in terms of longevity and reliability when short pulses are required at repetition rates exceeding 1 kHz. The TBA requirements are not so stringent since the repetition rate is only 120 Hz and the pulse duration is 300 ns. In this parameter range thyatron driven modulators may offer acceptable reliability at lower cost. After a brief design study of a magnetic modulator driven system, it was concluded that the TBA induction cell drive based on a line modulator using thyatrons would be more cost effective. A detail design will be described in a later section and it suffices at this time to say that the induction cell will be driven directly by the modulator without step-up transformers. To obtain 300 kV, about 15 induction cells will be required. Of the one meter allotted to the acceleration module, about 15-20 cm will be required for the RF coupler and vacuum port while the remaining space will be used by the 15 induction cells. Since a standard width for the Metglas is two inches, we will base the cell design on this width. The optimum Metglas alloy for this application is 2605 SC. The minimum amount of material would be required if the flux swing approached saturation. Minimizing the amount of magnetic material, however, does not lead to a cost effective design. A flux swing approaching saturation requires a very

* Metglas is a trade name of Allied Signal.

nonlinear drive current. This leads to a pulse forming network (PFN) which is difficult to design in order to achieve a flat voltage pulse. Furthermore, since the losses per unit volume are nearly proportional to ΔB^2 a better design is achieved by allowing a flux swing of less than one half of the saturation value. In this case a ΔB of 1.3 T results in a dB/dt of 4.3 T/ μ s and from Figure 3.1.2(b) the losses per unit volume will be 900 J/m³. The inner radius of the induction cell is dictated by beam transport physics and the outer radius can be calculated from the equation

$$V = A \Delta B / \Delta t (PF), \quad (3.1.3)$$

where, for our purposes, $\Delta B = 1.3$ T, $\Delta t = 300$ ns, $V = 20$ kV, and $r_1 = 4.5$ cm. The PF is defined as the packing factor or the ratio of the actual magnetic material area to the total area which includes the interlaminar insulation. An average packing factor for some of the previously wound cores is about 0.75. We can now find the outer radius of the core by substitution. From

$$V = (r_2 - r_1) (\Delta Z) (\Delta B / \Delta t) (PF) \quad (3.1.4)$$

and by substituting the above parameters, we find that $r_2 = .146$ m. The volume of material is

$$V_d = \pi (r_2^2 - r_1^2) (\Delta Z) (PF) = 2.4 \cdot 10^{-3} \text{ m}^3. \quad (3.1.5)$$

From Figure 3.1.2 (b), the losses in joules are $E_L = (900 \text{ J/m}^3) (2.4 \cdot 10^{-3} \text{ m}^3)$ or 2.2 Joules per cell. The drive voltage for this induction cell is 20 kV and the average current can be obtained from the total losses, $E_L = (V \cdot I) (\Delta t)$. For a 300 ns pulse the average magnetizing current or drive current $I_c = E_L / (V) (\Delta t) = 366$ A. The magnetizing current will actually have a nonlinear component which reflects the characteristics of the B-H loop. A simplified equivalent circuit is shown on Figure 3.1.3. The total drive current (I_T) from the PFN is the sum of the beam current (I_B) the core current (I_C) and compensation network current (I_N) $I_T = I_B + I_C + I_N = 1,000$ A.

3.1.2 Line Modulator

A cost effective modulator to drive the induction cells must now be designed. The critical component of any modulator is the switch which delivers the PFN energy to the cell. The larger the number of cells that can be driven in parallel, the lower the overall cost. To satisfy the voltage and di/dt drive requirements of a single cell (20 kV, 1 kA) it would require a large array of series-parallel solid state devices. The cost of these devices would be nearly one order of magnitude greater than the cost of a thyatron switch. The choice is therefore quite clear: find the most cost effective thyatron to deliver as large a current as possible at 40 kV PFN charge voltage. After a preliminary search, the English Electric Valve (EEV) CX1525A seems like one of the best choices. It is a two gap deuterium filled thyatron with a voltage hold-off of 50 kV and capable of delivering 15 kA at 120 Hz repetition rate. Such a device would allow us to drive 15 cells for a total of 300 kV. A simplified schematic is shown in Figure 3.1.4. The PFN can now be designed to supply the proper current to the induction module consisting of 15 cells of 20 kV each. The PFN impedance $Z_0 = V/I = 20 \text{ kV} / 15 \text{ kA} = 1.33$ ohms. The total energy storage in the PFN is $E_T = V \cdot I_T \Delta t$, or $E_T = 80$ Joules. The PFN charge voltage will be twice the output voltage or 40 kV. For a five stage PFN, the individual capacitors and inductors will be chosen to have the same temporal impedance as the induction cell. Recalling the fact that the drive current will increase during the pulse, the PFN impedance will likewise be time dependent, that is, the stages which deliver the initial part of the pulse will be higher impedance than the latter stages. An accurate design will be made where the impedance of the load and the PFN are matched in time using computer codes such as P-Spice or Microcap.

3.1.3 Command Resonant Charging and Core Reset

During the energy delivery cycle to the beam, the magnetic core requires a large magnetic intensity to swing 1.3 T in 300 ns as shown by path 1-2 in Figure 3.1.5. After the pulse is over, the magnetic intensity is reduced to zero but the flux density has a remnant field, B_r , at point 3. In order for the core to be useful on the next forward or energy delivery cycle, a reversed magnetic intensity or reset must be applied to the core (path 3-4). The reverse magnetic intensity, however, is much smaller than the forward one since the rate of demagnetization can be much lower or $\Delta I_{\text{reset}} \ll \Delta I_{\text{forward}}$. By applying the reset current, the flux density is returned to $-B_r$ and the core is ready for the next forward or acceleration pulse. The pulse forming network (PFN) must be recharged after each forward cycle. The charging process occurs when the command resonant charging (CRC) switch is closed and delivers a half sine current pulse from the large energy storage capacitor, C_E , to the PFN capacitors. The waveforms are shown on Figure 3.1.6 and it can be seen that the charging current flows through the induction cells in the proper direction to reset them. By arranging the impedance and charge time, the proper reset current can be delivered to the cores at the same time that the PFN is being recharged. The reverse magnetic intensity required for reset is about 25 A/m. This is equivalent to about 24 A per core or 360 A for a complete induction module. Since one CRC charges six line modulators, a total of 2.2 kA are required. At the charging voltage of 4 kV, the reset/recharge impedance is $40 \text{ kV} / 2.2 \text{ kA} = 18.2 \text{ ohms}$. The total capacitance (C_T) of six line modulators is $0.66 \mu\text{F}$. The resonant impedance, $Z_R = \sqrt{Z_T / C_T}$, requires a charging inductor $L_T = 225 \mu\text{H}$. Hence, the reset/recharge period $T_R = \pi \sqrt{Z_T / C_T} = 38 \mu\text{s}$.

3.1.4 Injector for the Low Energy Accelerator

Each RK-TBA will require a high current injector. At the entrance to the chopper, the current will be 1.5 kA at an energy of 2.5 MeV. The injector will use induction cores of a larger diameter than the standard 2 m acceleration module in order to house the hot cathode and the anode with solenoidal focusing (Figure 3.1.7). There will be a total of 25 cores on the cathode side and 25 on the anode side with vacuum pumping in between. Each cell is split radially in two equal sections for more uniform magnetizing current. One modulator will drive five cells each with two parallel 50 ohm cables. The total injector energy will be 1.0 MeV. Since the injection into the chopper requires 2.5 MeV, there will be five additional 300 kV modules for a total of 2.5 MeV prior to injection into the adiabatic capture section. These modules will likewise have a slightly larger diameter than the standard module as required by beam transport physics.

When the beam emerges from the injector the rising portion of the current will have an energy variation from zero to 1 MeV. It is important that prior to the adiabatic capture section that the beam be as monoenergetic as possible. The energy variation will be made up mostly by shaping the PFN pulse with an overshoot during the rise time. Each induction module in the 1.5 MeV post-injector acceleration will have a 50% overshoot. Figure 3.1.8 shows the correction waveform for the 1.5 MeV section. The beam will now emerge from the injector section with an energy variation from 2.25 MeV to 2.5 MeV. The remaining energy correction will be made in the adiabatic section.

3.1.5 Focusing and Steering of Low Energy Beam

Periodic focusing and steering correction coils will be required in the low energy accelerator. The standard dipole and quadrupole magnets will be used. These magnets have been

previously employed with kiloampere electron beams where less than ten gauss are required. These magnets have been described elsewhere but basically they consist of the quadrupole or dipole winding geometry on flexible printed circuit board which is wrapped over the beam pipe where there is no axial electric field. These magnets require about ten amperes at 5 volts. The arrangement in a two meter section is shown on Figure 3.1.9. These power supplies will provide current regulation to less than 0.1% and will be controllable from the central computer.

3.1.6 DC Power Supply for Induction Module

The traditional method of power conversion from 60 Hz AC to DC has been to use phase controlled solid state devices. This method of AC to DC conversion can produce efficiencies above 90% with power factor of over 0.9. The disadvantages of the conventional power rectification methods are the relative large size of the transformers, line harmonics, and less than unity power factor. In the last decade, in low to medium power applications, the engineers have developed high frequency power supplies to overcome the disadvantages mentioned above. Modern high frequency power supplies have incorporated active input power factor correction. These power supplies have been constructed in the few kilowatt range but not in the tens to hundreds of kilowatts. The near unity power factor is achieved using expensive switching devices and complex synchronization logic. The cost per kilowatt for the switching type of power supply is more than twice that of the conventional 60 Hz units. It is expected that the high frequency power supplies will be developed for higher power (100 kW) and that their cost will be more competitive with the conventional ones. For this design, the conventional 60 Hz unit was chosen.

3.1.7 Primary AC Power System

The power distribution system described in this section provides the AC power to all electrical and mechanical systems. By far the largest fraction (over 90%) of the AC power provided is for the low energy (induction) accelerator. It is assumed that the 120 kV power from the utilities is nearby and is capable of providing 200 MVA. The block diagram of Figure 3.1.10 shows the total megawatts required by the modulators. It is expected that the power factor for the power supplies will be about 0.9 or greater. Hence this will require the AC power grid to supply 11% greater MVA than the total calculated megawatts. The power system will utilize a minimum of two main transformers. This provides redundancy in case of failure and still allows the accelerator to operate at full energy but at half the repetition rate or half power. Figure 3.1.11 is a conceptual one-line diagram of the power distribution system. Two transformers each capable of 100 MVA are shown for feeding the main power supplies including thyatron filament transformers and miscellaneous bias power supplies. Each power supply will require 80 kVA at the 480 V level. Two separate transformers of 5 MVA each will provide power for all auxiliary equipment such as vacuum pumps, lighting, instrumentation, controls and general multiple outlet boxes. This accelerator is a conceptual design and there is not sufficient information for a detail design and costing of the power distribution system. The overall requirements, however, for the low energy (induction) accelerator are known fairly accurately and some well accepted costing rules used by industrial contractors can be applied. These cost estimating guidelines were generated by industrial contractors of large installations and assume that the power grid is nearby and is capable of delivering 200 MVA. If this is not the case, then additional costs may be incurred in the power distribution to the TBA.

3.1.8 Efficiency of Induction Accelerator Components

The power conditioning system for the low energy accelerator will have energy losses associated with each major component from the utilities feeding the DC power supply to the induction cell coupling to the electron beam. Each one will be investigated in reverse order beginning with the induction cell to beam coupling as shown on Figure 3.1.12.

The acceleration voltage pulse is shown on Figure 3.1.3. It shows a rise time and a fall time of 100 ns with 200 ns flat-top. There is no useful energy generated during the fall time, hence, this is considered energy lost. The energy during the rise and fall of the pulse is $E_r = \int_0^{t_1} V \cdot I \, dt$ where $V = V_0 (10^7 t)$ and $I = I_0 (10^7 t)$. By taking the integral we find that $E_r = 10^{14} V_0 I_0 (t^3/3)$. By substitution we find that $E_r = 0.4 \text{ J}$ while the total energy during the pulse is $E_t = 3.2 \text{ J}$. The induction cell to beam efficiency $\epsilon_b = 2.8/3.2 = 87.5\%$.

The magnetic materials losses have been discussed in a previous section. The magnetization current for each induction cell was calculated to be 366 A. Another 34 A of current was added for compensation network at the cell. The total current drive was 1 kA, hence, the efficiency of the induction accelerator cell $\epsilon_c = 600/1000 = 60\%$.

As previously discussed, the modulator consists of an impedance tapered pulse forming network (PFN) matched to the drive required by the magnetic material, Metglas 2605 SC. The efficiency is calculated by including the thyatron dissipation, filament, grid bias, keep-alive and the pulse shaping resistors losses. The modulator losses add up to nearly one kilowatt. At 120 Hertz operation the total power input has been calculated at 10.6 kW which yields an efficiency $\epsilon_m = 90.5$.

The line modulator is charged by a solid state command resonant charging (CRC) system. The CRC generates a $1 - \cos \omega t$ voltage waveform which charges the PFN. The current in the CRC is a half sinusoid which flows through the induction cells in the resetting direction while the PFN is being charged. The losses for the CRC include the inductor mode-damping resistors, the solid state switch losses, the trigger generator and de-Q-ing or regulation system if the DC power supply has insufficient regulation. The overall efficiency of the CRC is calculated to be $\epsilon_{ch} = 92\%$.

The 20 kV DC power supply will be a conventional 60 Hz 3 phase full wave rectifier with filter. The power supply design is discussed elsewhere, but it is projected that the power factor will be 0.9 and the efficiency $\epsilon_{ps} = 92\%$.

The overall efficiency of the low energy or induction accelerator from the utilities to the electron beam which drives the RK is the product of the individual component efficiencies or $\epsilon_o = 40\%$.

Figure 3.1.1. Losses of ferri and ferro-magnetic materials at different saturation times.

Figure 3.1.2. a) Magnetic intensity required to drive the Metglas 2605 SC at different saturation rates. (b) Losses for different Metglas alloys at different rates of magnetization.

Figure 3.1.3. Simplified schematic of modulator PFN driving the induction cell with beam and compensation network.

Figure 3.1.4. Simplified schematic of line modulator. The PFN will have the same temporal impedance as the nonlinear magnetic core of the induction cells.

Figure 3.1.5. B-H loop of 2605 SC Metglas in the forward or acceleration cycle (1 to 2) and the reset cycle (3 to 4).

Figure 3.1.6. The command resonant charging (CRC) system charges six modulators and also resets the induction accelerator cores.

Figure 3.1.7. 10 MeV, 1.5 kA injector for each RK-TBA.

Figure 3.1.8. Post Injector energy correction acceleration voltage wave form.

Figure 3.1.9. Focusing and Steering Power Supplies for a 2 m section.

Figure 3.1.10. Simplified block diagram of low energy accelerator power distribution system.

Figure 3.1.11. Three phase AC power distribution system to all the modulators.

Figure 3.1.12. Two meter section of the low energy induction accelerator with all power conditioning system.

3.2 Mechanical Systems (C. Peters, D. Vanecek)

3.2.1 Module Design and Fabrication

The Two beam Accelerator consists of essentially 50 identical linear induction accelerators stacked end to end to form the 15 kilometer overall length. Each of the 300 meter long LINAC contain 150 identical extraction and re acceleration sections. These 2 meter long sections are referred to as cell blocks. A top and side view of a typical cell block is shown in Figure 3.2.1.

Assembly and alignment of the cell blocks will be described later. A cell block consists of 6 identical induction modules and one extraction cavity. A cross sectional view of the cell block is shown in Figure 3.2.2. A single module is shown in Figure 3.2.3. Each 300 meter section contains 900 modules and the TBA will contain 45,000 identical modules.

In the design of the module a large effort was made to keep the geometry of individual parts simple and amenable to mass production. This basically boils down to designing so a minimum amount of material has to be removed during part fabrication. Drilling, tapping, and machining of small slots are kept to a minimum as these operations are relatively slow operations. All metal parts are made of 304 stainless steel alloy. Advances in modern stainless steel alloys enable significantly greater cutting speeds than a few years ago. Metal stamping and molding of plastic parts are used to further reduce part costs.

The module assembly relies on brazing and welding. The beam pipe assembly uses 6 brazed joints as shown in Figure 3.2.4. Use of simple fixtures to align the stacked parts and brazing in large batches keeps the time and cost per assembly very low as compared to other methods of assemblies. The final housing assembly is done with an inner and outer weld at each end plate. Automatic welding machines make this a quick and reliable operation.

3.2.2 Core Winding

An individual core winding is made by winding approximately 4700 turns of Metglas™ ribbon onto a winding mandrel. The ribbon is 20µm thick and 51 mm wide. A thin layer of insulation will be dipped or sprayed onto the Metglas™ during the winding process in order to provide adequate resistance to eddy currents between turns. The average voltage between turns is 5 volts. This insulation will replace the thin mylar ribbon presently used to provide core interturn insulation. The mylar ribbon overhangs the core edges and presents a serious problem to edge cooling the cores. A technique being developed at LBL uses a thin layer of epoxy, dipped or sprayed on, and then dusted with alumina grit to form a tough interlayer insulation. The epoxy additionally binds the Metglas™ layers together to form a rigid self supporting core.

3.2.3 The Quadrupole Magnets

The quadrupole magnets consist of 4 bars of strontium ferrite and iron oxide mixed into a ceramic base. This is commonly referred to as ceramic grade 8 material. This type of material is up to a factor of 10 times cheaper than the higher strength rare earth type magnets.

These blocks are bonded into a precise holder. The arrangement is shown in Figure 3.2.5. The dimensional tolerances on the blocks are moderate, but, due to the hardness of the material, will require that the blocks be ground to final size.

The magnetic gradient required at the center of the beam line is 320 gauss per cm. This is achieved by using ceramic grade 8 blocks of the dimensions shown. The normal residual induction of this material is 3850 gauss. The blocks will be lowered to 3550 gauss after pressing in order to achieve field uniformity and stability over time. The field strength in ceramic type blocks normally varies by ± 3 to $\pm 5\%$. This will require that the strength and direction of the field in each block be measured. The blocks will be sorted and blocks of similar strength (about $\pm 0.5\%$) will be used in each quadrupole. The long term field stability of the blocks is good; all blocks will decrease in strength by 1% over a long period (~10 years). The blocks are thermally stable and will not be subject to any heating. They will essentially be held at a constant temperature by the oil which will cool the cores.

3.2.4 Correction Coils

Dipole and quadrupole correction coils are placed between the quadrupoles and the core. Each coil is a simple printed circuit etched on a flexible substrate and is wrapped around the outside of the quadrupole housing, and held down in a simple fashion. The two leads from each coil are brought to a feedthrough at the nearby housing end.

3.2.5 The Gap Insulator

The gap insulator, shown in Figures 3.2.3 and 3.2.4, is very similar to commercially available high voltage insulators. The insulating portion is high purity alumina brazed to a single stainless steel convolution at each end. The two brazed magnet holder subassemblies are brazed to the gap insulator using an internal mandrel to align the parts during brazing. The braze temperature is lower than that for the separate assemblies to assure the original braze joints are not disturbed. The convolutions permit small relative motions to occur between the magnet holder subassemblies when the beam pipe assembly is eventually welded to the module end plates.

The shape of the insulator and the metal surfaces surrounding the gap are important for several reasons. Beam breakup is a serious concern. Breakdown across the ceramic surface is another problem and is often triggered by electrons hitting the surface of the insulator. This can be minimized by shaping the gap geometry to minimize the line of sight from the beam to the insulator surface. "Pointing" the gap in the down stream direction reduces the likelihood of electrons hitting the surface. Additionally, the triple points, the joints between ceramic and stainless steel at the insulator ends, are shielded from high field gradients in order to reduce stray electrons from being accelerated along the surface and producing breakdown. Work done to this point is only preliminary and considerable further study is required.

Slightly conductive coatings can be applied to the ceramic insulator to reduce insulator surface breakdown by reducing charge buildup on the insulator. RF diode sputtering using nichrome wire produce coating resistivities of between 10 ohms and 200 ohms per square centimeter. Up to 1000 ohms per square centimeter can be achieved with fired on thick films of

glaze. In moderate quantities the cycle time to apply these coatings is around 30 minutes per unit. This is based on recent experience at the ALS. In large quantities the time per unit should be substantially less.

3.2.6 Electrical

The number of electrical components within the modules is minimal. Two high voltage leads connect to the mandrel of each core. This is schematically shown in Figure 3.2.6. One lead is grounded to the housing at the outside diameter of the core. The other lead is the power lead and enters the housing through a feedthrough in the housing. Two feedthroughs are required per core and ten per module. Each feedthrough contains a resistor, capacitor, and a sealed connector. The connector has low pressure oil on the inside and air on the outside. The oil is used for cooling and insulation of the core windings and is discussed further in section below. The arrangement of the feedthroughs for each module is shown in Figure 3.2.7.

3.2.7 Core Cooling

Heat generation within the cores will be about 300 watts per core. Cooling of the core windings is accomplished by circulating oil through the module housing. This is shown schematically in Figure 3.2.8. Oil flows in at one end of the module housing and flows out at the other end on the opposite side. This causes the oil to flow transversely in the gaps between the cores. Spacers around the outside diameter of the cores prevent oil from flowing around the outside of the cores. Only moderate oil flow rates are required and as a result there is low pressure drop between supply and return manifolds. For a flow rate of 27°C oil at 1.25 gpm through the module, the maximum temperature for all the cores is about 60° C on the down stream side. Quadrupling of the oil flow rate will drop the core temperature by about 13°C. Core temperatures in this range are acceptable; magnetic properties are not affected, thermal stresses are minimal since the core remains at a nearly uniform temperature, and temperature limits on the plastic materials within the module are not approached.

Development of an interlayer insulation to replace the presently used mylar tape is critical for the cooling of the cores. Presently used mylar tape overhangs the edges and largely blocks the transfer of heat from the Metglas™ to the oil. As described in the Core Winding Section, alternative interlayer insulations are being developed.

3.2.8 Vacuum System

The accelerator will be pumped in two places in each 2 meter cell block. Pumping will occur at the start of each module on each side of the extraction cavity as shown in Figure 3.2.9. There is a 2 cm gap between modules at these points which permits good pumping conductance to a standard mounting flange. The two ports are manifolded together to a single ion vacuum pump. The total gas load per cell block is about 8×10^{-7} torr-liter per second. For this geometry the pressure between the pump and the cavity entrance is calculated for several pumping speeds and results are shown in Figure 3.2.10. In this Figure, Cell 1 refers to the entrance to the extraction cavity, while cells 5 and 2 are various points between the pump and the cavity. If a 20 liter per second pump is chosen, the pressure at the cavity entrance will be about 5×10^{-7} torr.

An inline gate valve between every fourth cell block will enable isolation of small sections of the accelerator. In each of these 4 cell block sections a right angle gate valve will be used to enable initial pump down with a portable turbomolecular pumping station.

Moderate pressure levels within the LINAC will enable some of the more costly cleaning methods used on ultrahigh vacuum systems to be avoided. This will be an unbaked system with a base pressure in the 10^{-7} torr range. Systems of this type are generally cleaned by chemical or glow discharge cleaning techniques and perhaps a bake at low temperatures.

3.2.9 Assembly and Alignment

Alignment requirements for the TBA can be achieved using standard fabrication, assembly, and alignment techniques. Each module will be aligned to within 0.1 mm in X and Y with respect to its nearby neighbors. A gradual accumulation of position errors between successive modules will occur and will result in the accelerator not being straight. This is acceptable as long as these bends are not extreme and occur gradually over many half lattice periods.

Six modules will be supported and aligned accurately with respect to one another on one strongback support beam. As shown in Figure 3.2.3, the magnet blocks are bonded into holders which are held by magnet extensions which are, in turn, held by the module end plates. Relatively few part tolerances are involved in insuring that the magnet blocks are well centered with respect to the outside diameter of the housing end plates. The inherent and readily achievable precision in the parts involved ensure this.

The support mounts for all the modules on each strongback beam will be positioned and aligned accurately during fabrication of the beam. Mounts for the modules will be welded, machined, and then ground to the required precision. As a result, within each 2-meter section, the 12 magnetic quadrupoles will be aligned to the required precision when the modules are assembled onto the beam. There will be no provision made for adjusting the position of modules within a 2-meter section with respect to each other on the beam.

There will be an X and Y set of fiducials at each end of the beam. After the installation of the modules onto the beam, a precise measuring fixture will be used to adjust the position of each fiducial accurately with respect to the center of the last quadrupole at each end of the beam. It is desirable to make the fiducials reflect the position of the end quadrupoles rather than some average position for each 2 meter section. This will enable the last quadrupole on one beam to be aligned well to the first quadrupole on the next beam.

As successive 2 meter sections are installed, they will be aligned using the fiducials to a straight line reference system. Each section is supported and articulated using a 6-strut system. This arrangement is shown in Figure 3.2.11. This enables the section to be moved easily and with precision in all six degrees of motion. The straight line reference system will be able to accurately detect the position of each fiducial. The 2 meter section is then articulated in order to bring the fiducials into a straight line.

A stretched wire can be used with optical sensors to detect the position of the wire. A laser based system can be used although a pipe under vacuum is necessary for the light. A series of overlapping straight reference lines will be needed in order to form the entire 300 meter length.

3.2.10 RF System

The RF output system consists of output cavity, rectangular and circular wave guides, windows, flower-petal converters, and vacuum pumping manifolds. These components will be patterned after those components developed for NLC. The arrangement of components is shown in Figure 3.2.12 The output cavities consist of diamond turned and brazed together copper disks, shown in Figure 3.2.13. Water cooling tubes are brazed to the outside of the cavity. Short rectangular guides diametrically opposed on the cavity connect to flower-petal mode converters. Vacuum pumping manifolds provide good vacuum to the ceramic windows located on each leg. Circular wave guides extend through the floor to connect to the high gradient structure below, shown in Figure 3.2.14.

Figure 3.2.1 Top and side view of a 2 m cell block.

(Infor/varecek/TBA/4-METER-ASM.Y-VG...25-Apr-94)

Figure 3.2.2 Cross sectional view of a cell block.

Figure 3.2.3 A single induction module.

Figure 3.2.4 Beam pipe assembly with 6 brazed joints

Figure 3.2.5 Permanent quadrupole magnet in block holder.

Figure 3.2.6 A high voltage feedthrough to an induction core.

Figure 3.2.7 Feedthrough arrangement in a module.

Figure 3.2.8 Core cooling with circulating oil.

Figure 3.2.9 Pumping arrangement.

Figure 3.2.10 Gas pressure distribution within module.

(Rifar/Vanecek/TBA/HOOUE SUPPORT_MTH/HOOUE--2-Jun-94)

Figure 3.2.11 A six-strut system for support and alignment of a 2 m cell block.

Figure 3.2.12 Rf output system with extraction cavity, rectangular and circular waveguides, rf windows, flower-petal converter, and vacuum pumping manifolds.

Figure 3.2.13 Output cavity with copper disks.

Figure 3.2.14. Elevation view of the RK-TBA.

3.3 Control and Diagnostics (F. Deadrick)

The accelerator control and diagnostics system for the RK-TBA will play a significant part in the overall operation of the linear collider. Each of the fifty RK-TBA sub-accelerators will be individually controlled, monitored, and optimally tuned to provide the required RF drive for the accelerated beam. Overall, the control and diagnostic tasks are of a complex magnitude which will likely exceed the human capabilities of any one machine operator, and perhaps even a team of operators, without the aid and assistance of an automated beam control and tuning system. A reliance must be placed upon the use of autonomous closed-loop computer control to achieve optimal beam performance.

Two functionally separate, but closely linked, control subsystems will be utilized in the overall system design. A supervisory control system will be responsible for the direct operational control and monitoring of all RK-TBA hardware, while a second beam analysis system will be used to analyze relevant beam diagnostic measurements, and then optimally command the hardware to be set for best beam performance. Recent developments in the fields of Expert Systems and Artificial Intelligence applied to the problem of automated beam tuning and control^{1,2} clearly demonstrate the feasibility of following this approach.

Significant advances have also taken place in the area of control system architecture and software tools, where today it is no longer necessary to devote large manpower efforts to completely design the software needed to build a new control system from scratch. A notable example of a successful control system software package is EPICS (Experimental Physics and Industrial Control System)³. EPICS was initially developed by the Los Alamos National Laboratory, and the Argon National Laboratory. EPICS use is now widespread among US national laboratories, and developments continue through a joint consortium of scientific laboratories including LANL, ANL, CEBAF, DESY, and LBL. Current EPICS implementations range in scale from single instrumentation crate/single workstation sites with a few hundred channels, up to 100 crates/30 workstations sites with about 30,000 channels. (The SSCL had planned to extend EPICS to the scale of 2000 crates with 100 workstations and 1 million channels.) The EPICS model will be used to form the baseline design for the overall RK-TBA control and diagnostic system.

3.3.1 EPICS Supervisory Controls for the RK-TBA

Architecturally, EPICS embodies the "standard model" of a fully distributed control system design. EPICS requires no central device or software entity at any layer. This feature achieves the goals of easy salability, of robustness (no single point of failure), and allows incremental operation and upgrade. Thus it is natural for parts of a total EPICS system to be in operation, while other parts are in development, and yet other parts are shut-down. This will greatly aid in bringing the various elements of the overall RK-TBA system on-line.

Given the physical extent of the Linear Collider plus the high degree of duplication in each of the RK-TBA sub-systems, it is logical to distribute the control of the overall system. Such a system design is illustrated in Figure 3.3.1, where there exists an overall supervisory control system which communicates with many distributed sub control systems which, in turn, are tasked with the local control of each subsystem.

By way of background, EPICS comprises three physical layers of hardware and five software layers. The physical front-end, which will interface with the RK-TBA hardware, is built around the internationally standardized VME/VXI modular instrumentation crates. These crates can contain CPU boards, I/O boards, transient digitizers, etc., and are distributed as needed throughout the facility. These modules are used to drive the accelerator hardware directly through a variety of standard buses such as IEEE-488 (GPIB), Bitbus, RS-232, and Allen-Bradley 1771 Programmable Logic Controllers. The CPU boards, which are also located in the VME/VXI crates, run a real-time kernel called VxWorks, and handle the bulk of the low-end hardware control and processing. The physical back-end layer which an operator observes, can be implemented on a wide choice of popular workstations from suppliers such as Sun Microsystems, Hewlett Packard, Digital Equipment Corporation, and others running Unix. These hardware layers are interconnected by a network layer, which can be any combination of media such as Ethernet or FDDI which support TCP/IP Internet protocol, and some form of broadcast or multicast.

The software layers start with the client-server paradigm. The client layer runs in the workstation physical layer, and represents the top software layer. Typical clients are operator control screens, alarm panels, and data archive/retrieval tools. EPICS clients can be serviced at a very high level of performance. For example, operator screens with 1000 objects are brought up in less than one second, and can be updated dynamically at about 5000 objects/second on Sparc station IPC class workstations.

The second software layer is called "channel access", and is the layer which connects all clients with all servers. Channel access uses a technique called "reporting by exception" or callback. Once a client has expressed an interest in certain data to a server, the server notifies the client only when the data changes. This not only minimizes traffic, but signals both the health of the server and the freshness of the data. Performance on the order of 10,000 "gets" for "puts" per second can be achieved even under heavy load. Channel access routines will be the mechanism in which the supervisory control system will communicate with the beam control system.

The third software layer is the server layer. The fundamental server is the channel access server that runs on the CPU's embedded in each of the VME/VXI crates. The server layer cooperates with all channel access clients to implement the callback and synchronization of data.

The heart of EPICS is the fourth layer, or database layer. The database is described in terms of records, and presently about 50 record types exist for performing such chores as analog input and output, binary input and output, storing waveforms, moving motors, performing calculations, and implementing PID control loops. A fundamental entity in the EPICS database is the "channel". A channel is a path to a record in the database, and besides its name, a record has a value, and perhaps other attributes such as units, maximum/minimum, and so forth. The record name and the attribute is the only way that channel access connects a client to a server. Record activity can be initiated in several ways: from VME hardware interrupts, from software "events" generated by clients such as the Sequencer, when fields are changed from a "put", or using a variety of periodic scan rates. Data can flow from the hardware level up, or from the software level down.

At the bottom is the fifth layer, which is the hardware device driver. There currently exist a wide variety of device drivers already written, and new drivers are being written by members of the cooperative consortium.

EPICS provides the software tool kit to implement the supervisory controls for the RK-TBA. Cost and time savings will be realized through the use of such a widely standardized control system framework. The supervisory controls task will be largely hardware dominated, while the beam control system will be predominantly a software task.

3.3.2 RK-TBA Pulse Power Supervisory Controls

A significant portion of the hardware control tasks will be directed toward the operation of the induction linac pulse power system for the TBA. However supervisory control and diagnostics for the injector and the RK sections of the accelerators will be equally important. In defining the overall control system architecture, a standard philosophy and rule-of-thumb for control systems is that any parameter or quantity which can be controlled should be monitored. Additionally, any parameter which can change state, i.e. an over-temperature switch, or a vacuum level, should also be monitored and be made available to any process which might be affected by the quantity.

Each RK-TBA can be broken down into 150 identical 2 meter long modules containing six 100 kV induction cells. Figure 3.3.2 illustrates a block diagram of this fundamental 2m building block module along with the pulse power hardware which drives it. Also shown on this figure is a listing of the necessary control and monitor functions associated with the pulse power system.

Basically, three classes of controllables/measureables are encountered. The lowest level class of input and output is the binary (B) state which is used to control and monitor simple on/off functions such as whether or not an over-temperature switch has been activated, or whether a power supply has been turned on or not. Control systems typically have very large numbers of binary control and monitor functions, and often many of these quantities serve as the I/O devices for programmable logic controllers, which contain "rules" used to establish the proper sequence of operating conditions.

Analog states (A) represent the next higher class of data complexity. Typically these are quantities which represent a scalar quantity such as the voltage reference set point used as a power supply control, or as a voltage or current monitor. Judicious use of analog monitors will be used throughout the RK-TBA to assess the state of accelerator performance. Through the use of devices such as peak detectors, boxcar averagers, sample and hold devices, etc., signals with time varying waveforms will be quantified by relevant scalar analog quantities.

In those cases where the temporal form of a signal is important, the signals will be monitored as waveform (W) data. Transient waveform recorders are typically two orders of magnitude more expensive than analog I/O, and as such, a limited number will be shared as needed instead of being permanently assigned to a particular signal channel.

EPICS Input/Output -- As described earlier in section 3.3.1, the physical front-end of EPICS is built around the modular VME/VXI crate. Each VME/VXI crate can contain an assortment of

binary, analog, waveform, and interface modules which interface to the accelerator hardware as shown in Figure 3.3.2. Each crate also contains one or more CPUs to handle the real-time processing tasks associated with signal acquisition and device control. Naturally, there is a practical limit to the number of signals which may be interfaced to a single crate. There is also a limit to the length of cable runs between the crate and the accelerator hardware devices. So it is desirable to divide up the overall control system tasks. One of the principal features of EPICS is that it is a true distributed system—the hardware can be distributed physically as needed, and at some point it is more practical to install an additional crate, than run long cable runs to one centralized control location. Most crates contain 12-20 hardware module slots, and at least one of the slots is dedicated to the CPU module, so a wide variety of signal types can be easily handled. In order to make an estimate of the total number of crates required, a count of the number of pulse power control and monitor signals per 2 m accelerator section is listed in Table 3.3.1. When these numbers of channels are totaled for 300 meters of a RK-TBA, we can get an estimate of the total number of pulse power control and monitor channels as well as determine the number of VME crates which will be required for operation. These estimates are shown in Table 3.3.2.

	Binary	Analog	Waveforms
Controls	7/3	1/3	--
Monitors	17/3	8/3	2

Table 3.3.1. Number of pulse power control and monitor signals for a representative 2 m RK-TBA section.

	Binary	Analog	Waveforms
Controls	350	50	--
Monitors	850	400	300

Table 3.3.2. Total number of pulse power control and monitor signals for 300 m of RK-TBA.

If one considers the type makeup of these controls and monitors, approximately 75% of the binary I/O signals will be directly associated with hardware control and safety interlocks tasks, and as such will probably be handled through dedicated programmable logic controllers (PLCs) and not interface directly with crate modules. These controls and monitors will remain functional regardless of the operational status of the supervisory control system, and the PLCs in turn will be interfaced to the to the EPICS control system through the VME crates.

A majority of the analog signals and waveforms, however, will be directly interfaced to the VME crate, and typical analog I/O modules can handle between 16-32 individual signals. Binary I/O modules are available which can handle up to 64 bits, and the selection of the number of crates needed to support the 300 meters of RK-TBA will be a compromise between the cost and capacity of the crates, and the desire to keep the length of cabling to a minimum. A reasonable choice is to install a VME crate every 30 meters of the accelerator, and this will provide adequate signal handling capacity, while minimizing cable runs to lengths on the order of less than 15 to 20 meters. (Note that additional data channels are required for beam diagnostic measurement and control, and these will be discussed in a later section.) PLC I/O devices will also be installed every 30 meters to handle interlock conditions.

Waveform Acquisition -- Not discussed above is the acquisition of the transient waveforms associated with the induction accelerator drive pulses. During test and tuning periods, it is sometimes necessary to monitor the drive pulse waveforms out of the pulse forming networks to ensure that the pulse power system is functioning properly. The drive pulse is approximately 300 ns long, with a rise time of less than 100 ns, and to faithfully record this waveform requires a digitizer with a sample rate of at least 500 M Samples/sec. Such digitizer units are today becoming available in VXI format, however today the cost per channel remains relatively high at \$1500 to \$2000. It is expected that the cost per channel will, however, continue to drop in the next few years as the high speed technology improves. The approach followed here is to install two dedicated transient acquisition channels per VME crate (30 meter section), and signal switch (multiplex) between channels to observe all the necessary pulse power transient waveforms. This assumes that the waveforms are repeatable, and that it is not necessary to observe all waveforms simultaneously on a given accelerator pulse. This technique has worked out well in earlier systems, and represents a necessary cost savings considering the number of channels possible to observe.

3.3.3 Accelerator Beam Diagnostics Acquisition and Beam Control

In addition to the supervisory controls associated with the pulse power system, an equally important control system task involves the acquisition of the electron beam diagnostic data used for handling beam focus and steering controls, and RF data to monitor the performance of the relativistic klystron. The beam analysis system will utilize the beam diagnostics data to optimally steer and focus the beam through the accelerator. As shown in Figure 3.3.3, each 2 meter section of the induction linac contains two beam position monitors (beam bugs), three sets of X-Y beam steering coils, and two sets of adjustable focus coils.

Each of the beam position monitors (BPM) has three pulse waveform outputs: X-position, Y-position, and current amplitude. These pulses must be viewed as waveform data, and acquired through transient digitizer modules capable of showing detailed beam position information as a function of time. It is frequently necessary to observe two successive BPM's on a single pulse, so six transient digitizer modules may be required for a single 2 m accelerator module. However, like the waveform monitors for pulse power system, it is feasible to signal multiplex the inputs from several 2 m modules to a given set of digitizers, and again if the acquisition VME crates are installed every 30 meters, this would mean 15 sets of BPM data would be acquired on a set of six digitizers located in a VME crate.

Based upon the BPM measurements, the operator and/or Beam Analysis Control will determine the proper settings for low voltage DC power supplies used to drive current through beam steering trim coils, and focus coils. These DC supplies will be controlled through the supervisory control system based in part upon input from the beam analysis system. Figure 3.3.3 lists the number of diagnostic control and monitor channels for each 2 meter section.

3.3.4 RF Diagnostics Acquisition

Diagnostic data will also be required to monitor the RF output from the RK. Two primary diagnostic measurements are presently used. These are the RF power output levels, and phase measurements. RF power output is measured with a relatively simple diode detector, and the data

is acquired as a waveform. However, the diode detector is a non-linear device, and it is necessary to have selectable attenuators as part of the measurement circuit. (The detector non-linearities can be corrected in the analysis programs.) Each RK module will have two RF output structures, and it is necessary to measure both forward and reflected RF power, so four power measurements are needed for each 2 meter section.

The RF phase measurements are made by mixing the output power pulse of the RK structure with the frequency doubled modulator drive pulse in a double-balanced four-diode ring mixer. The phase information will also be acquired as waveform data. However, it is sufficient to only measure phase information once in every 30 meter section. Figure 3.3.4 shows the RK diagnostics used, and the signals which would be acquired through the VME hardware interfaces.

3.3.5 Accelerator Timing System

Timing is everything, and the timing system for the RK-TBA is no exception. In order to time coordinate the RF power from each of the 50 RK-TBA individual accelerators, it will be necessary to have a master timing system which distributes delayed master trigger pulses with timing jitters of less than ± 2 ns to each the 50 accelerators. Additionally, each RK-TBA will require it's own dedicated timing system to trigger the switched PFN drivers at the proper time sequence in order to match the propagation of the relativistic electron beam through each accelerator cell. Figure 3.3.5 shows a block diagram of a proposed timing system. It should be noted that the critical timing is mainly for the PFN triggers. The CRC timing is not critical since the CRC flat top lasts for several microseconds, and essentially the same trigger pulse can be used for all CRC circuits within a given RK-TBA. As shown in Figure 3.1.6 each CRC drives six PFNs. The trigger delay between successive PFN's is fixed at approximately 3.3 ns. To save costs, these short fixed delays will be handled through the use of fixed hard-wired cable delays. This means that approximately 50 precision digital delay units will be required for each RK-TBA installation, and 50 separate delay generators will be used to properly distribute the master trigger to each of the 50 RK-TBA's. Thus the total number of delay channels will be 2550.

3.3.6 Accelerator Operator Control

EPICS provides all the tools and mechanisms needed to develop interfaces for full operator control through workstation display consoles. Any quantity which can be controlled or monitored can be made available for information display, and parameters can be changed via an operator's consoles. Keyboards, mice, and knobs will be the primary input devices used by operators. Data can be displayed in a number of formats including numeric, and graphic. EPICS tools are available to develop console displays similar to the example shown in Figure 3.3.6. The number of operator consoles required to operate each of the 50 RK-TBA units is estimated to be less than 10 per RK-TBA.

Current design plans call for the Beam Analysis Control System (BACS) to aid the operator in making many of the decisions associated with accelerator tuning tasks. Under ideal conditions, the machine operators will only be required to monitor operations to ensure that each of the 50 accelerators are operating as required. However, it would be naive to think that the operator will be completely replaced.

3.3.7 Beam Analysis and Optimal Control

The problem of accelerator tuning to achieve optimal operation has been in existence for some time. Recent experiments with MAESTRO at the ETA-II induction linac^{4,5}, and at other facilities⁶ have demonstrated the utility of expert systems to aid in tuning. The approach taken at ETA-II was to minimize beam corkscrew by optimally steering the beam through the accelerator. The beam at each beam position monitor was observed as the up-stream steering magnets were swept through their operating range. This process resulted in what was termed tuning V's, which plotted beam corkscrew as a function of steering magnet setting, and the optimal performance was achieved at the minimum of each of the V's.

A similar approach can be adapted to the tuning of the RK-TBA. Here we are ultimately interested in maximizing the RF output power, and to achieve this it is important to minimize parasitic terms such as BBU (beam break up) instabilities. The controls which one can adjust to optimize performance are the settings of the steering and quadrupole focus coils described earlier in section 3.3.3.

The job of the Beam Analysis and Optimal Control system will be largely a software task designed to read diagnostic data and interact back with the accelerator hardware. For the purposes of this design plan it will be handled by a computer system with sufficient computational power. It should be particularly noted that EPICS provides all the "hooks" needed to allow external processes to gain both read and write access (channel access) to it's data base.

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3. Dalesio, L., et al., "The Experimental Physics and Industrial Control System Architecture", ICALEPCS, (Berlin Germany, October 1993).
4. D. L. Lager, H. R. Brand, W. J. Mauer, F. Coffield, and F. Chambers, "MAESTRO -- A Model and Expert System Tuning Resource for Operators", *Nuclear Instruments and Methods in Physics Research*, vol. A293, pp 480-485, 1990.
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6. Dobrott, D., et al., "Control System User Interface for Accelerator Commissioning and Operation", Proc 1991 Part. Accl Conf. (San Francisco, 1991) p1305.

Figure 3.3.1 EPICS Control System Structure

Figure 3.3.2. Pulse Power Control and Monitor points for each 2 meter module driver.

Figure 3.3.3 Beam position, steering and quad focus elements are present in each 2m accelerator module.

Figure 3.3.4. Each 2 m module has an RF output structure with two waveguides. Both forward and reflected klystron output power is measured for each output. Every 30 m RF is sampled for phase measurement.

Figure 3.3.5. Precision timing system.

Figure 3.3.6 Sample of an EPICS operator interface window.

4. RK-TBA Costing

4.0 RK-TBA Cost Summary

RK-TBA costing is performed separately for the electrical systems (section 4.1) and the mechanical systems (section 4.2). The total of cost of the entire RK-TBA project is summarized below. Details of each subsystem are described in subsequent sections.

	k\$
4.1 Electrical Systems	486,025
4.2 Mechanical Systems	338,090
4.1.9 Controls and Diagnostics	80,000
4.1.6 Primary AC Power	50,000
GRAND TOTAL	954,115

4.1 Electrical Systems (L. Reginato)

4.1.1 Electrical Systems Cost Summary

A breakdown of the cost of the electrical systems is as follows:

4.1.2	Line Modulators	219,300
4.1.3	Command Resonant Charging	50,125
4.1.4	Focusing and Steering	4,600
4.1.5	DC Power Supplies	110,000
4.1.7	Installation and Cabling	50,000
4.1.8	Engineering Design and Inspection (12%)	52,000
	Total Cost of Electrical Systems	486,025 k\$

4.1.2 Line Modulator

The line modulator consists of a pulse forming network (PFN) and a ceramic thyratron switch. A simplified schematic is shown on Figure 3.1.4. The PFN will have a tapered impedance to match the induction core. The inductors are coupled to each other and the inductance is tunable. The total capacitance will be made up of 80 individual strontium titanate capacitors each 1.25 nF. These capacitors and inductors will be mounted on two large PC boards.

Parts

CX 1725 Thyratron (present unit cost \$7000)	4000.00
Filament and Bias Supplies	350.00
Strontium Titanate Capacitors (80 ea @ \$20)	1600.00
Inductors (6 ea @ \$45)	270.00
Cooling	250.00
HV output connectors (30 ea @ \$20)	600.00
Cable and Connectors to Induction Cores (30 ea @ \$50)	1800.00
Voltage divider	250.00
Trigger Amplifier (1.5 kV, 1 μ s)	450.00
Chassis Hardware	250.00
	<u>\$ 9,820.00</u>

Labor

160 hrs. EE Tech @ 30	<u>4,800.00</u>
	\$ 14,620.00
Total required is 15,000	
Total Cost	219.3 M\$

4.1.3 Command Resonant Charging

The command resonant charging (CRC) system charges the pulse forming network (PFN) and resets the induction cores simultaneously. One CRC charges six PFN's hence a total of 2500 are needed. A simplified schematic is shown on Figure 3.1.6 and a detailed parts list was made from complete drawings of previously constructed CRC's.

Parts

Capacitor Bank (10 μ F 25 kV)	3150.00
Crowbar and Grounding	500.00
SCR's and Hardware (40 ea @ \$180)	7200.00
Isolation and Trigger Transf. (40 ea @ \$20)	800.00
Trigger Chassis (PS + low level 1 ea)	550.00
Charging Inductor (air core 5 kA 50 μ H)	850.00
Clamp Diodes and Resistors	1200.00
High Voltages Dividers	500.00
Current Transformer	250.00
Chassis and Misc. Hardware	250.00
	<u>\$ 15,250.00</u>

Labor

1 EE Tech 160 hrs. @ 30 hr	4,800.00
Cost of one CRC	<u>\$ 20,050.00</u>

Total cost of 2500 CRC's 50,125 k\$

4.1.4 Focusing and Steering

As described in Section 3.1.5, the focusing and steering correction system consists of standard magnetic quadrupole and dipole magnets. The magnets are driven by low current, low voltage DC power supplies readily available from many industrial manufacturers. The total quantity is estimated at 46,000 units and the cost was obtained from vendors with quantity discounts applied. These power supplies average 100 watts each and cost about \$1/watt. So for the quantity required the cost will be 4.6 M\$.

4.1.5 DC Power Supplies for Induction Modules

As described in section (3.1.6), these power supplies will be of the conventional 60 Hz type and not of the high frequency switchers. The cost to achieve a 0.1% regulation will be about 0.5\$/watt for units in the 75-100 kW range.

	k\$
Cost of 75 kW	36.00
Cabling and Trays	2.00
Installation 150 hrs @ \$40	<u>6.00</u>
	44.00
Total number required is 2500	
Total cost 2500 x 44 k\$	110.00 M\$

4.1.6 Primary AC Power

The AC power distribution system is described in section (3.1.7). This a standard system which takes power from the 120 kV lines and steps it down as required by the power supplies and conventional facility.

A well accepted figure for a primary power distribution substation is 200 \$/kVA. This power distribution includes all interrupters, circuit breakers, fuse disconnects, cabling and step down transformers to the 12 kV distribution. A separate estimate was made to distribute and step down the voltage to each 75 kW power supply and to multiple outlet boxes in the low energy accelerator building. This additional cost was estimated at 50 \$/kVA. The total cost of power distribution to each power supply and to all other utilities is 250 \$/kVA or 50 M\$ for a total of 200 MVA.

4.1.7 Power Conditioning and Control System Racks, Installation and Cabling

Each individual modulator, command resonant charging, power supply, and controls will be housed in standard size 7' high rack. These racks will form two rows with sufficient isle space in front and behind for installation and servicing (Figure 3.2.14). The occupancy factor in the long direction will be 50% which allows for tunnel stairs and access for the low energy accelerator modules. The dual racks will feed the dual induction accelerator cells through the floor with symmetric 50 ohm cables. The racks will house all the power distribution, cross connects, venting manifolds and cabling for the control system. Previous accelerator racks have cost 1 to 2 k\$ per foot depending on complexity. Because of the large quantity and duplicity, all these racks will be pre-wired at the factory at an estimated price of 1,000 \$/foot. For 15 km and dual racks, the cost will be 2,000 per liner foot. The total cost for the accelerator will be:

$$(2,000) (0.5) (50,000) = 50.00 \text{ M\$}$$

4.1.8 Engineering Design and Inspection

This work consists of detail design, inspection, and testing of all electrical components associated with the low energy induction accelerators. In previous high energy accelerators the cost of ED&I has been in the range of 20-30% of the total cost of all electrical components exclusive of the cost of utilities. Because of the large duplicity of components, the ED&I for the TBA low energy accelerator is taken at 12% of the total cost of the electrical systems or 52 M\$.

4.1.9 Control and Diagnostics

The cost estimates are based upon the costs for an individual accelerator. However we consider the high degree of replication in each of the accelerators, and include this factor in the manpower calculations. The estimates are also based upon current and near-term estimates of costs per channel of the data channels discussed earlier in section 3.3.

The following table summarizes the hardware costs for the pulse power system controls and monitors, plus the timing system, the beam diagnostics, the focus and steering controls, and the beam analysis system.

Function	Cost \$k
Pulse Power Supervisory Controls	\$393
Timing System	\$67
Beam Diagnostics Acquisition	\$698
Beam Focus and Steering	\$153
Beam Analysis and Control	\$25
Manpower (Pro rated per RK-TBA)	\$253
Total	\$1,590

The costs for the beam diagnostics acquisition is a significant part of the overall control system costs. This is due in part to the large numbers of diagnostics installed on the accelerator, as well as the high cost for high performance waveform acquisition. It should also be noted that the costs for beam focus and steering is quite high, and again it is a result of having 1500 channels of focus and steering functions. Design efforts should be directed to develop low-cost control and monitor hardware for the many low voltage power supplies needed for beam control.

Manpower costs are included in the above estimates to do the hardware installation, as well as engineering, design and integration (ED&I). For these engineering design tasks, it is estimated that 25 man-years of engineering professionals (engineers/programmers), plus 25 man-years of engineering associates, and 50 man-years of engineering technician support will be adequate to design and develop the control system for the entire project (all 50 RK-TBA's).

The total of \$1.6M for each RK-TBA will undoubtedly increase as the need for additional features becomes necessary. A good rule of thumb for control systems is that they will cost between 10% and 12% of a project's budget. Since each of these accelerators is essentially identical, the engineering costs can be amortized over the total project costs, and overall manpower cost savings should be realized. The total project cost is approximately \$80 M for controls and diagnostics.

4.2 Mechanical (C. Peters, D. Vanecek)

4.2.1 Overview of Cost Estimates

Table 4.2.1, TBA Cost Rollup, is a summary of mechanical costs by section, such as Injector or Main Section, or by subsystem, such as RF or vacuum. Subsystem costs listed in this table are all costs from all sections relating to that particular subsystem. For instance, vacuum subsystem costs on this table, includes all costs in table 4.2.6 for the Main Section Vacuum System plus the vacuum portions of the Injector, Chopper, and Afterburner Sections, tables 4.2.9, 4.2.10, and 4.2.11, respectively.

Costs for the main accelerator section are given in these tables;

Table 4.2.2	Main Accelerator Section Module: Component Fabrication
Table 4.2.3	Main Accelerator Section Module: Assembly
Table 4.2.4	Main Accelerator Section 2-Meter Section: Fabrication & Assembly
Table 4.2.5	Main Accelerator Section RF Output Subsystem
Table 4.2.6	Main Accelerator Section Vacuum Subsystem
Table 4.2.7	Main Accelerator Section Alignment Subsystem
Table 4.2.8	Main Accelerator Section Mechanical Subsystem & Special Utilities.

The last 4 tables above contain costs only for the subsystems within the main accelerator section.

Costs for the other accelerator sections are given in the following tables;

Table 4.2.9	Injector Section
Table 4.2.10	Chopper Section
Table 4.2.11	Afterburner Section.

These tables for Injector, Chopper, and Afterburner Sections are broken down into components such as cores and housings, solenoids, stands and supports, etc. Installation, alignment, vacuum system, and special utilities for these sections are also contained within these tables..

Each accelerator section and subsystem cost includes cost (between 15% and 25%) for coordination and support for the activities that are listed. This would take care of such things as supervision of labor, inventory and control of supplies and material, and documentation and record keeping associated with construction.

4.2.2 Module Fabrication & Assembly

Forty-seven percent of the mechanical costs for the TBA is for the fabrication and installation of the 45,000 acceleration modules. The fabrication costs alone for these modules constitutes 40% of the total TBA mechanical costs. A detail list of module fabrication costs are given in table 4.2.2. The cost estimating of these components was done very thoroughly since they

form such a large fraction of the total TBA cost. Detail drawings were produced for almost all the components. Where possible vendor quotations were obtained based on these drawings. Sixty-three percent of the module component costs are substantiated by vendor quotations.

In the design of the module, a large effort was made to keep part geometry's simple and amenable to mass production. This basically boils down to designing so a minimum amount of material has to be removed during part fabrication. Drilling, tapping, and machining of small slots are kept to a minimum as these operations are relatively slow operations. All metal parts are made of 304 stainless steel alloy. Advances in modern stainless steel alloys enable significantly greater cutting speeds than a few years ago. Metal stamping and molding of plastic parts are used to further reduce part costs.

A detail list of module assembly steps and costs are given in table 4.2.3. Manpower effort estimates for each operation are given in minutes. These efforts are engineering estimates based on experience with similar types of operations and processes required for accelerator construction. A cost of \$40 per hour is used for these estimates. This is a typical unoverheaded cost for technical support at the Lawrence Berkeley Laboratory in 1994.

During the assembly process for the modules, a production line approach will be used. Brazing of assemblies will be done in large batches of 100 units or more. Costs for cleaning and brazing operations will then become dominated by time required to load and unload trays of parts. Some processes will be automated in order to increase throughput rate. Programmed automatic welders will enable one technician to simultaneously weld several assemblies.

TBA will require about 250,000 cores. Winding a single core is a relatively slow process. Feed rates are approximately 3 feet per second which will require about 1 hour to wind a single core. The setup process between each successive core may take 5 minutes which means one operator will be able to start 12 cores per hour. With a machine that can simultaneously wind 12 cores, or with 12 small machines, one operator will be able to complete 12 cores per hour at an average time of 5 minutes each. Note that the cost of cores is dependent mostly on the turn around time to stop and start winding process and not the core winding rate. A slower winding rate just means more machines. At a rate of 12 cores per hour one operator will require 10.4 years to produce the total number of cores. Obviously, 4 or 5 production lines will be needed to produce the cores. Metglas™ cost per core will be about \$110 so the winding cost will be 5% to 10% of the material cost.

4.2.3 Main Section 2-Meter Girders

Cost for the 2-meter girder weldment, support stands and brackets, and adjustment links are given in table 4.2.4. A straight forward "low-tech" set of hardware is required for support and adjustment of the girder position. Simple welding and machining operations are involved and costs are estimated based on similar hardware used on other accelerators.

4.2.4 Main Section RF Output Subsystem

Costs for the Main Section RF output hardware are given in table 4.2.5 and are based upon cost experience for similar hardware at SLC and upon engineering estimates for the particular configurations required for TBA. Output cavities, wave guides, flower pedal converters, windows,

and vacuum pumping manifolds are required and are very similar to those used in the SLC accelerator. Recent estimates from SLC place the cost of this hardware at about \$5000 per output channel. TBA costs are conservatively estimated to be about 75% of this. High production quantities should reduce this cost significantly.

4.2.5 Main Section Vacuum Subsystem

Costs for the Main Section vacuum subsystem are given in table 4.2.6. All hardware costs were based on vendor quotations except the distribution manifold which will be built to print. Cost for five turbopump startup stations is included. Installation cost for the system is included. No cost for centralized monitoring and control of the vacuum system is included.

4.2.6 Main Section Alignment Subsystem

Costs for the Main Section alignment Subsystem are given in table 4.2.7. Costs for fiducialization, installation, and alignment of the 2-meter sections as well as the cost of the fiducialization and measurement facility, monuments, and survey equipment are included. Since Each 300 meter section will be aligned independently the alignment task becomes far easier than would be the case with a longer machine. Capital costs for survey equipment and the fiducialization facility are amortized over fifty 300 meter sections and as a result are a minor fraction of alignment costs. Alignment costs are 3% of the total mechanical costs for TBA and are quite in line with cost experience on other accelerators.

4.2.7 Main Section Special Utilities

Special utilities for the TBA include water and oil distribution and control systems. Simple manifolds are used for distribution. Precise control of temperatures and flow rates is not necessary. Monitoring for safety will be required. Each 300 meter section will require one or several cooling stations for both systems. The costs are given in table 4.2.8.

4.2.8 Injector, Chopper, and Afterburner Sections

Costs for the Injector, Chopper, and Afterburner Sections are given in tables 4.2.9, 4.2.10, and 4.2.11, respectively. The cores for the Injector Section are similar to those used in the main accelerator section and cost is based on the same cost per unit weight. Solenoids, quadrupoles, vacuum system, beam pipes, and support stands costs are engineering estimates based on historical costs for similar types of hardware. Special utilities for these sections is 7%, the same fraction as for the main accelerator section.

4.2.9 ED&I

The mechanical ED&I estimate of 12% of the mechanical portion of the special research facility is lower than the fraction normally used for accelerators. This will provide about 360 man years or a team of 45 people working over an 8 year period to provide engineering, design, and inspection support for the design and construction of the accelerator. This lower than normal fraction is justified due to the highly repetitive nature of the hardware. After design and construction of the first 300 meter section, the tasks required for completing the remaining 49 identical sections become largely QA, coordination, and book keeping tasks.

TBA Cost Rollup by Section & Subsystem

<u>Section/Subsystem</u>	<u>(K\$)</u>
Injector	\$27,005
Chopper	\$6,497
Main Accelerator	\$161,660
Afterburner	\$1,978
Vacuum	\$29,335
Alignment	\$7,984
FF	\$52,452
Utilities	\$14,955
ED&I (12%)	\$36,224
Grand Total	\$338,090

Table 4.2.1 TBA Cost Rollup by Section & Subsystem

**Main Accelerator Section
Module: Component Fabrication**

	Unit Cost	Quantity	Total Cost
1 magnet extensions	\$6	2	\$13
2 magnet holder	\$18	2	\$37
3 magnets	\$6	8	\$48
4 ferrite dampers	\$5	4	\$20
5 insulator	\$84	1	\$84
6 insulator shielding rings	\$13	2	\$26
7 Metglas (kg)	\$5	100	\$500
8 core mandrels	\$7	5	\$35
9 core spacers	\$0	50	\$5
10 core grounding disc	\$2	5	\$10
11 HV feedthru assembly	\$50	10	\$500
12 end plates	\$55	2	\$110
13 module housing	\$126	1	\$126
14 dipole steering coils	\$125	2	\$250
15 steerer feedthru	\$15	2	\$30
16 steering coil leads	\$2	2	\$4
17 beam monitor	\$500	0.33	\$167
18 oil connections	\$5	2	\$10
19 Inspection (15%)			\$296
20 Coordination & support (15%)			\$340

Single Module Parts Total \$2,610

X 45,000 Modules \$117,440,777

Table 4.2.2 Main Accelerator Section Module: Component Fabrication

Main Accelerator Section

Module: Assembly

	Minutes	Unit Cost	Quantity	Total Cost
1 braze magnet holder assemblies	18	\$12	2	\$24
2 braze bore tube assembly	12	\$8	1	\$8
3 glue magnet blocks	3	\$2	8	\$16
4 mount steering coils	15	\$10	2	\$20
5 mount absorbers	3	\$2	4	\$8
6 wind cores	8	\$5	5	\$27
7 weld 1 st end plate	8	\$5	1	\$5
8 weld outer housing	15	\$10	1	\$10
9 install cores & leads	15	\$10	5	\$50
10 install steering coil leads	8	\$5	2	\$11
11 install feedthru assemblies	30	\$20	10	\$200
12 weld 2 nd end plate	20	\$13	1	\$13
Test & Inspection (15%)				\$59
Coordination & support (15%)				\$68
Single Module Parts Total				\$518
X 45,000 Modules				\$23,305,571

Table 4.2.3 Main Accelerator Section Module: Assembly

Main Accelerator Section

2-Meter Section: Fabrication & Assembly

	Minutes	Unit Cost	Quantity	Total Cost
1 2-meter girder weldment		\$1,080	1	\$1,080
2 Floor stands		\$120	3	\$360
3 Girder support brackets		\$40	6	\$240
4 Adjustment links		\$40	6	\$240
5 Mount modules on girder	90	\$60	6	\$360
6 Mount vacuum components	90	\$60	1	\$60
7 Test & Inspection (15%)				\$351
8 Coordination & support (15%)				\$404

Per 2-meter Section \$3,094

Total all sections \$23,205,709

Table 4.2.4 Main Accelerator Section 2-Meter Section: Fabrication & Assembly

Main Accelerator Section

RF Output Subsystem

	Minutes	Unit Cost	Quantity	Total Cost
1 RF cavities		\$520	7500	\$3,900,000
2 Rectangular waveguide		\$100	15000	\$1,500,000
3 Flower pedal		\$520	15000	\$7,800,000
4 Pumping sections		\$300	30000	\$9,000,000
5 Vacuum manifolding		\$480	7500	\$3,600,000
6 Window assembly		\$600	15000	\$9,000,000
7 Circular waveguide		\$200	15000	\$3,000,000
8 Vacuum installation per 2-meter	270	\$180	7500	\$1,348,650
9 Coordination & support (25%)				\$15,252,201

Per 2-meter Section \$7,253

Total all sections \$54,400,851

Table 4.2.5 Main Accelerator Section RF Output Subsystem

Main Accelerator Section Vacuum Subsystem

	Minutes	Unit Cost	Quantity	Total Cost
1 Ion pumps		\$688	7500	\$5,156,250
2 Manifold		\$480	7500	\$3,600,000
3 Controller		\$495	1875	\$928,125
4 HV Cables		\$145	9375	\$1,359,375
5 HV splitter		\$300	1875	\$562,500
6 Roughing gate valve		\$500	1875	\$937,500
7 Beamline gate valve		\$1,500	1875	\$2,812,500
8 Beamline bellows		\$100	7500	\$750,000
9 Turbopump station*		\$6,545	5	\$32,725
10 Ion gage w/cable*		\$1,500	10	\$15,000
11 Startup Controller*		\$1,000	5	\$5,000
12 Vacuum system installation per 2 m	270	\$180	7500	\$1,350,675
13 Coordination & support (25%)				\$4,377,413
* equipment for startup				
Per 2-meter Section				\$2,918
Total All Sections				\$21,887,063

Table 4.2.6 Main Accelerator Section Vacuum Subsystem

Main Accelerator Section Alignment Subsystem

	Minutes	Unit Cost	Quantity	Total Cost
1 Measurement facility		\$500,000	1	\$500,000
2 Fiducialize 2-meter section	90	\$60	7500	\$449,550
3 Install 2-meter section	270	\$180	7500	\$1,348,650
4 Align 2-meter section	270	\$180	7500	\$1,348,650
5 Alignment monuments per 300 m		\$50,000	50	\$2,500,000
6 Survey equipment		\$1,000,000	1	\$1,000,000
7 Coordination & support (25%)				\$674,325
Per 2-meter Section				\$1,043
Total All Sections				\$7,821,175

Table 4.2.7 Main Accelerator Section Alignment Subsystem

Main Accelerator Section

Mechanical Subsystems & Special Utilities

	Unit Cost	Quantity	Total Cost
1 Oil distribution & control	\$100,000	50	\$5,000,000
2 Water distribution & control	\$100,000	50	\$5,000,000
3 Coordination & support (25%)			\$2,500,000

Total All Sections \$12,500,000

Table 4.2.8 Main Accelerator Section Mechanical Subsystems & Special Utilities

Injector Section

	Unit Cost	Quantity	Total Cost
1 Cores & housings	\$7,730	40	\$309,200
2 12 cm cathode	\$50,000	1	\$50,000
3 Solenoids	\$3,000	30	\$90,000
4 Vacuum system	\$3,000	6	\$18,000
5 Stands & supports	\$2,000	6	\$12,000
6 Installation & alignment	\$500	6	\$3,000
7 Utilities (7%)			\$33,754
8 Coordination & support (15%)			\$77,393

Single Injector \$593,347
Total All Injectors \$29,667,355

Table 4.2.9 Injector Section

Chopper Section

	Unit Cost	Quantity	Total Cost
1 Klystron	\$100,000	1	\$100,000
2 Beam pipe	\$2,000	1	\$2,000
3 solenoid	\$5,000	1	\$5,000
4 Beam aperture	\$2,000	1	\$2,000
5 Vacuum system	\$5,000	1	\$5,000
6 Stands & supports	\$2,000	1	\$2,000
7 Installation & alignment	\$500	1	\$500
8 Utilities (7%)			\$8,155
9 Coordination & support (15%)			\$18,698

Single Chopper \$143,353

Total All Choppers \$7,167,663

Table 4.2.10 Chopper Section

Afterburner Section

	Unit Cost	Quantity	Total Cost
1 Beam enclosure	\$1,000	12	\$12,000
2 Quadrupoles & holders	\$300	12	\$3,600
3 RF outputs, wave guides, etc.	\$5,000	12	\$60,000
4 Vacuum system	\$1,500	12	\$18,000
5 Stands & supports	\$500	12	\$6,000
6 Installation & alignment	\$250	12	\$3,000
7 Utilities (7%)			\$7,182
8 Coordination & support (15%)			\$16,467

Single Afterburner \$126,249

Total all Afterburner \$6,312,465

Table 4.2.11 Afterburner Section

5. CONCLUSIONS

5.1 Summary of key results and issues (S. Yu)

In this report, we have presented a preliminary design of an RK-TBA based power source for a 1 TeV center-of-mass NLC. The overall architecture of our point design was presented in Chapter 1. The three major areas of focus for the present study are: 1) RK-TBA physics (Chapter-2), 2) RK-TBA engineering (Chapter 3) and 3) RK-TBA costing (Chapter 4). The key results in each of these areas, as well as the issues presently under study, are briefly summarized here.

Longitudinal beam dynamics (Section 2.1) is our first key area of study. Our point design requires that the bunched drive beam delivers 360 MW of rf power at 11.4 GHz in each of the 150 rf extraction cavities in a 300-m long RK-TBA unit. To achieve this goal, and to maintain longitudinal beam stability over these long distances, the extraction cavities must be inductively detuned. To maintain low surface fields to avoid breakdown, we consider traveling-wave structures. Our first major task in this section was to derive an analytic theory of inductively detuned traveling wave cavities. This theory allows us to determine the cavity parameters (R/Q and v_g) required for the extraction of 360 MW with an rf current of 1.15 kA (600 A DC). In order for a 3-cell disk loaded structure to behave like a traveling wave structure with no reflected waves, the output ports must be properly matched. The resonant frequency and Q of the output cell required for proper matching are also derived. The 1-D code RKS was then exercised to simulate longitudinal beam dynamics and rf power extraction over the entire 300-m long RK-TBA unit. Sensitivity studies show that optimal operation is obtained when the 3-cell extraction cavities have a phase velocity of 1.33 c. The simulation studies were then extended to the front-end (chopper and "adiabatic capture" sections) and the back-end (the after-burner). At the front-end, we show that a chopper at 2.5 to 5 MeV, followed by an adiabatic capture section of about 20 m of acceleration combined with up to 10 bunching cavities, is able to take the drive beam to the full operating energy of 10 MeV with the right length of the microbunch ($\sim 70^\circ$) for longitudinal stability of the rf buckets. At the back-end, the simulations indicate that good quality rf power (360 MW each) can be extracted from 12 successive cavities after the reacceleration units are terminated. These simulations indicate that the conversion efficiency of drive beam power to rf could be higher than 90% (not including power losses in the induction gaps, which are separately discussed in Section 2.4).

A key issue that is yet unresolved has to do with the transverse defocusing experienced by the beam during its traversal through the rf structures. When the phase velocity of the structure is not equal to the speed of light, the cancellation of the transverse magnetic and electric forces is no longer valid. Our 2-D calculations to-date indicate that these forces, if uncorrected, could lead to deleterious envelope oscillations. We are studying possible modifications of the cavity geometry (for which there is still large degrees of freedom for design modifications within the overall constraints) and various schemes to compensate the cavity induced defocusing. This is an area of active research at the present.

The beam break-up instability has been considered a major difficulty for RK-TBA's and is studied in detail in Section 2.2. There are 2 rather distinct instabilities that are easily identifiable. The first is a low frequency BBU (~ 2 to 5 GHz) associated with the induction gaps, and the second

is a high frequency BBU (~ 14 GHz) associated with the HEM_{11} mode of the rf extraction cavities. An important mechanism of the damping of the low frequency BBU is inherent in the beam dynamics of inductively detuned structures. The rf buckets have large energy spreads ($\sim \pm 7.5\%$) which provide Landau damping for the BBU mode. With reasonable care in the design of the induction gaps to de-Q the dominant dipole modes, the low frequency BBU is shown to be totally suppressed. Control of the high frequency dipole mode requires a rather different strategy. The "betatron node scheme" is deployed with the betatron period set exactly equal to the spacing of adjacent cavities. This scheme can be shown theoretically to reduce the usual exponential BBU growth to a slow secular increase. Our key concern here is the robustness of the scheme and extensive sensitivity checks were performed to ascertain the accuracy requirements on the focusing fields, beam energies, particle energy spread, and extraction cavity parameters. With sufficiently strong damping of the dipole mode, (which as we see later, comes almost "for free") the simulations indicate that errors in field and energy of 1 to 2% could be tolerated. This kind of accuracy is quite achievable.

Of course the longitudinal and BBU dynamics results depend strongly on the cavity parameters. A closely related effort in the design of rf cavities is reported in Section 2.3. The calculations here are purely electromagnetic, with no beam dynamics involved. Both 2-D as well as 3-D calculations, in both the frequency and time domain, were reported. The geometries of the disk loaded structures, the effects of a finite number of cells, as well as the output ports were modeled. Inductively detuned extraction cavities with the required impedance and group velocity were constructed, and the field enhancement effects evaluated.

The dipole impedances were also evaluated. The natural damping eluded to earlier arises from the fact that the beam pipes are above cutoff for the HEM_{11} mode, and the cavity mode couples strongly to the TE_{11} mode within the beam pipe.

3-D calculations of the output ports were conducted with MAFIA. The calculated Q's are close to the values required to satisfy the matching condition of Section 2.1.

We do not consider the cavity geometries obtained in Section 2.3 to be final in any sense. There are still large degrees of freedom for design modifications, and further refinements will be conducted to reduce transverse focusing fields and to ensure minimal surface fields over the entire 3-D structure.

Finally in Section 2.4, we present calculations of the induction gap with AMOS and Poisson. With adequate damping, the required transverse impedance for BBU stability is easily achieved. Our present designs still show a longitudinal impedance that is too high. Further work is continuing to reduce the longitudinal power loss in induction cavities to an acceptable level. There is also more optimization work to do to ensure safety against high voltage breakdown.

Engineering design of the RK-TBA is covered in Chapter 3. The electrical system (Section 3.1) consists of an efficient low-voltage network. The design covers all components from induction core to wall-plug, including the induction module, the pulse forming network, the command resonant charging and core reset, the DC power supplies, as well as the primary AC power system. The system invokes no novel elements, and all components are well-known. Our efficiency estimates are based on what has been achieved (with good electrical engineering practice), and

does not assume future innovations. The efficiency estimate arrived at is 40% from wall plug to drive beam. In addition to the overall pulse power, we have also discussed 2 special components of the RK-TBA, namely, the injectors, and the steering and correction system.

The electrical system design we believe to be quite conservative. One question which may require some further investigation is the life-time of the ceramic thyratrons. This is an issue that we share with the modulators of the conventional high power x-band klystrons. In addition, we need to do further design work to specify the details of the pulse-forming-network to ensure the required energy flatness. This is an exercise that we have carried out in the past for other applications (e.g. Heavy Ion Fusion), both numerically, as well as experimentally. A detailed design of the PFN for the RK-TBA has yet to be performed.

On the side of the mechanical design (3.2), we have also tried to be comprehensive, including all components for the entire RK-TBA up to the rf input into the high gradient structures. The design of the basic induction modules was conducted in some detail, with particular attention to incorporate features amenable to mass production. Conceptual engineering drawings exist for all parts of the module. Cooling, vacuum, alignment, and assembly were also studied and incorporated into the design. The rf system, on the other hand, was borrowed heavily from the recent work at SLAC. The assumption is that our extraction cavities would be similar in nature to the output cavities of the x-band klystrons. Hence, the mechanical design of the cavity structures, windows, waveguides and flower petals, were all adaptations of the SLAC systems. The difference of course is that rf combining has been eliminated, and the power is fed directly from extraction cavities to the high gradient structures through short waveguides.

The area with the largest remaining uncertainty is the design of the induction gap. The detailed geometry, the optimal strategy for shielding of the ceramics, the incorporation of microwave absorbing material, the possible use of slightly conducting material on the insulator surfaces, are all areas requiring further physics as well as engineering development. The details of this component are expected to have little effect on the overall cost, but are quite essential for the physics.

Control and diagnostic is an important component of the engineering design. In this exercise, we have attempted to work out the overall architecture of the control system. Our design of the control system is based on the EPIC system which is relatively well used in the accelerator community. The fact that we have 50 identical but, by and large, independent RK-TBA units is a natural match to the distribution system described in Section 3.3.

The costing is presented in Chapter 4. Since the engineering design is based entirely on conventional components, and the level of engineering has been performed to sufficient details for making actual count of individual parts and components, the costing we believe to be reliable. The main new feature is to incorporate mass production and assembly cost reductions. The costs we have arrived are based either on actual quotes from vendors for large quantities, or from our own estimates, based on step-by-step construction of the fabrication and assembly procedure. Where we have been able to do both, our own estimates are quite consistent with vendor quotes when averaged over many items.

We have included in the costing the fabrication and assembly of individual components, as well as the construction and assembly of the full accelerator. Costs for Engineering, Design and Inspection are also included in the present estimate. It is roughly 12% of the total cost, which is a low number compared to usual ED&I costs of 20 to 30% for large projects. Our estimate is based on the fact that we are building 50 identical units, and there is a large amount of repetition.

Costs of building and conventional facilities as well as institutional overheads on the entire project have not been included, as these items are considered an integral part of the overall linear collider project. A separate accounting for the power source portion would not make sense.

The grand total for the entire project is \$954 million U.S. (1994 dollars). Detail breakdown of the cost are listed in Chapter 4.

5.2 TBA perspective (S. Yu)

The issue of rf power source is central to the development of future linear colliders. While induction-linac based TBA is known to have the potential for very high efficiency, research support received to-date has been somewhat limited. The general concerns about TBA as a realizable power source evolve around 3 issues:

1. The induction linac technology is not as mature as existing rf-klystron technology.
2. The TBA beam dynamics, particularly BBU, is difficult.
3. Induction linacs are perceived to be very expensive.

The objective and the approach undertaken in the present study were motivated by these concerns.

In regards to the cost issue, past cost estimates were based on induction linacs built for other applications (short pulse, high repetition rate, high current). Our belief has been that the induction linac design ought to be optimized for the specific mission. Hence, we have attempted in this study to design an induction linac specifically for the RK-TBA.

Since cost is, and will be, a key issue for future colliders, we feel that it is essential to have a believable cost estimate. It seemed to us that the only way to have a believable cost is to carry the engineering study to sufficient details to make a 'bottom-up' estimate possible. We have tried to estimate cost for fabrication and assembly on the basis of engineering drawings and proposed mass production procedures. For the induction modules, a major component of the machine we have sent out for external bids for various parts, to cross check our own estimates. Our estimate, for approximately ten different items, agreed with external quotes to a few percent on the total. All components are based on known technology, with relatively well-known costs. Hence for the engineering design proposed, we believe that our cost estimate is realistic.

Similarly, the efficiency estimate for our pulse power design is based on well-known numbers with today's technology. We have not made any extrapolations for possible future innovations. We might note here that in comparison to the 40% number quoted in our design study for the efficiency of the pulse power system, some recent tests in the Heavy ion Fusion group at

LBL have demonstrated 50% efficiency for a somewhat different system but with very similar performance goals in terms of current, voltage, and repetition rate.

It is certainly true that as we learn more about the technology, we may introduce new design changes which may alter the cost and efficiency estimates. Yet, on the basis of the work that has been performed thus far, we can safely argue that the cost of the new TBA is competitive.

In regards to the beam dynamics issues, we have offered in this design conceptual solutions for longitudinal beam stability as well as BBU control for both the low frequency component, associated with induction gaps, and the high frequency component, associated with rf extraction cavities. These concepts are supported by detailed simulations. We hope to have demonstrated by these studies that the solutions offered have a reasonable chance of success.

Of course, these studies are only the beginning. Further theoretical and computation studies need to be conducted. Cavity design work needs to continue, in particular in relation to the issue of how to minimize the transverse defocusing on the beam envelope. The induction cavity design need to be optimized to make sure that both the longitudinal as well as transverse impedances are adequately small. Feedback systems should be studied to relax the constraints on energy flatness and quadrupole field errors.

Finally, we need hardware development and experimental tests. The purpose of this conceptual design study is not to argue that we are ready to build an RK-TBA based power source for a linear collider today, but rather, that the concept is viable and merits further support in technology development. A technology that is not developed cannot be expected to mature.