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HIGH AVERAGE POWER
INDUCTION ACCELERATORS

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(Editor)

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HIGH AVERAGE POWER INDUCTION ACCELERATORS

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1. THE INDUCTION ACCELERATOR CONCEPT

Historical Development of the Induction Accelerator

The concept of accelerating charged particles by the induction method received its first extensive investigation at Livermore in the 1950's. Nicholas Christofilos proposed to use intense circulating electron beams of several hundred amperes at 5 MeV electron energies to confine plasmas in the Astron magnetic fusion concept. Since such an electron beam source did not exist, the program proceeded to develop an accelerator based on the induction principle. The successful completion and operation of the Astron accelerator [1] also provided a new tool to test particle beam weapon propagation ideas under the auspices of ARPA. This program, named SEESAW, was centered at LLNL from 1958 to 1972.

During the early 1970's, the Lawrence Berkeley Laboratory (LBL) developed the induction accelerator further in the testing of a new concept for accelerating protons. The machine that was built, called the Electron Ring Accelerator (ERA), used high voltage accelerator modules that became the basis for the next generation of induction accelerators at Livermore. Significant technological development has also occurred in the Soviet Union since the early 1960's in the induction accelerator field [2]. These developments are part of an extensive program in high current particle beams within the USSR. The induction accelerator and free electron laser work at the Tomsk Polytechnic Institute is particularly noteworthy [3].

The Beam Research Program at Livermore was dormant from 1972 to

1974 when it was revived by the Navy under the name CHAIR HERITAGE. Under Navy sponsorship, LLNL built the Experimental Test Accelerator (ETA) which produced peak currents an order of magnitude higher than had been previously achieved. The Naval Research Laboratory also assembled a strong induction accelerator program during this period. The ETA served as a test-bed and was the forerunner of the Advanced Test Accelerator (ATA), a 50 MeV/10kA machine with burst mode capability to 1 kHz. Beginning with the construction of the AIA, the project was placed under the auspices of the Defense Advanced Research Projects Agency (DARPA), which provided funding for the particle beam weapons research from 1978 to the present. The ATA has provided the necessary beam currents and energies to continue exploring beam propagation physics and will be the test-bed for validation of the physics of single pass free electron laser extraction as part of the Paladin experiment which is scheduled to begin in FY86.

The Livermore program has traditionally focused on solid core induction modules. Other induction schemes include air core, radial pulse line, and cyclical concepts [4].

The Magnetic Induction Principle

Although power levels and materials may differ, all linear induction accelerators impart energy gain to the particles in the same manner. The drive voltage is applied to an axially symmetric gap that encloses a toroidal ferromagnetic material, as shown in Fig. 1. The change in flux density in the magnetic core induces an axial electric field that provides acceleration according to the following relation.

The magnetic induction module

Figure 1

$$\oint \vec{E} \cdot d\vec{l} = - \int_S \frac{d\vec{B}}{dt} \cdot d\vec{S}$$

$$\oint \vec{E} \cdot d\vec{\ell} = - \int_S \frac{d\vec{B}}{dt} \cdot d\vec{S} \quad (1)$$

In this equation, $\vec{E}$ is the electric field, $\vec{\ell}$ defines an integration path enclosing the induction core and the accelerating gap. The core experiences a rate of change of magnetic flux density, $d\vec{B}/dt$, over the cross-sectional area S . The line integral of the electric field gives the accelerating potential at the gap. The energy added to the particle beam by each accelerator module thus scales with the rate of change of the magnetic flux density in the ferromagnetic material and the cross-sectional area of the material. The permeability of ferromagnetic materials is a function of the applied magnetic field, producing saturation of the flux-carrying capability of the material at threshold values of the magnetic field in either direction. The total flux density excursion in the core is dependent on the material. A typical hysteresis curve of magnetic field H vs. flux density B is shown in Fig. 2. The implication for scaling of induction accelerators is that longer e-beam pulse lengths require proportional increases in the cross-sectional area of the accelerator cores. The cores can become longer (core volume scales linearly) or larger in diameter (core volume scaling as the square of the diameter). From a practical point of view, in order to stretch the pulse length, the designer may have to reduce the overall accelerator gradient (MeV/m) or accept large module size and high costs for the core material.

Induced flux in ferromagnetic materials

- High permeability in region 1 – 2
- Flux density saturation
- Hysteresis during reset of magnetic field

Figure 2

Components of the High Average Power Induction Accelerator

A schematic diagram of the two principal versions of the high average power induction accelerators needed for free electron laser applications is shown in Fig. 3. These two versions differ in the way that sufficient focusing is applied to the electron beam to overcome the electrostatic forces trying to make it expand. Focusing can be imposed by externally applied magnetic fields or by guiding the electron beam in a diffuse plasma channel produced by a pulse of short wavelength laser light propagating through a low density gas (e.g. benzene). The choice between these two schemes must be based on two considerations relating to the performance of an FEL extraction device coupled to such an accelerator.

- The accelerator must develop high peak current in order for the FEL to have high extraction efficiency in a single pass, yet it must avoid beam break-up (BBU) instabilities.
- The emittance of the electron beam must be preserved, not only within the accelerating section but also during the transition into the FEL device. Emittance is a measure of the spot-size and divergence of the e-beam pulse. FELs prefer small, high intensity beams with low transverse energy.

Point designs investigated at Livermore tend to indicate that accelerators operating in the current regime near 3 kA can be operated without BBU using external focusing techniques. These designs tend to be longer than equivalent laser-guided versions. The major technical issues affecting

Component technologies for a high power master oscillator power amplifier FEL

Figure 3

selection of laser guiding include the availability of high repetition rate drive lasers and the uncertainty about getting the e-beam off the laser channel and into a wiggler without spoiling its emittance.

The major features of the system components are discussed below.

The e-beam injector. The sins that the designer can commit which result in increased emittance usually occur in the injector. The selection of cathode material and the shaping of all the surfaces in the critical region near where the e-beam is born represent key design issues. Even in laser-guided versions, the injector is a region of moderately high vacuum. Plasma effects can be particularly difficult to overcome in this region of the accelerator if the goal is to achieve low emittance. At Livermore, Dan Birx has begun a series of tests on the High Brightness Test Stand to evaluate the capabilities of dispenser cathodes operating at elevated temperature for high repetition rate applications. These cathodes can be poisoned if pressures in the injector exceed 10^{-6} to 10^{-7} torr. Therefore, in the injector region, even for laser-guided accelerators, focusing must be achieved with solenoidal external fields. Differential pumping is employed to permit operation at higher pressures when the e-beam is on the laser channel (after the initial stages of acceleration).

The guide laser. Benzene at pressures near 10^{-3} torr has been used on the Advanced Test Accelerator in conjunction with pulses from a commercial KrF laser to produce a plasma channel in which the e-beam can propagate stably at high current. The laser energy in a single

pulse is a few hundred millijoules. The leading edge of the electron pulse repels electrons from the diffuse plasma formed by the passage of the laser pulse, producing a net positive channel in which the e-beam can propagate. The strong focusing effect of this channel is sufficient to balance the electrostatic forces tending to expand the electron beam. For high average power applications, excimer lasers (or other sources) must be developed which can match the repetition rate capability of the accelerator.

The high energy accelerator. Most of the accelerator length is occupied by blocks of accelerator modules operating on the magnetic induction principles described above. The ATA partitions the accelerator into 10 cell blocks. Solenoidal focusing is provided throughout unless laser-guiding is being used. The space between blocks is used to provide access for vacuum pumping, injection of gas, and beam diagnostics.

The pulse power system. The magnetic flux induced in the accelerator cores is produced by application of a fast voltage pulse across the accelerator gap. This voltage pulse (on ATA, 250 kV/50 ns) is developed by a series of pulse compression steps, beginning with the resonant charging of intermediate energy storage components by the prime power source, continuing on through a step-up transformer which drives a fast pulse forming device [5]. In the case of ATA, a Blumlein pulse forming line stores energy during charging until a triggered, gas blown spark gap discharges the line into the load. The pulse length is governed by the length of the Blumlein.

High average power accelerators will require the use of the magnetic modulator technology developed on the High Brightness Test Stand.

Pulse compression is achieved in two stages on these devices based on concepts developed during the early days of radar [6,7].

The beam transport system. After beam acceleration is complete, the electron pulse must be transported to the FEL extraction device. The beam envelope must be carefully matched into the wiggler. In order to permit injection of the laser pulse at the entrance to the wiggler, the e-beam may need to be transported through a jog, which must maintain the emittance of the e-beam. The beam transport section may also contain a component which scrapes off unwanted components of the beam which will spoil the FEL extraction process. This so-called emittance selector is designed to precisely define the phase space of location and transverse momentum in which electrons must exist before being permitted to enter the wiggler [8]. For laser-guided accelerators, it is in this region of beam transport and matching that the e-beam must be taken off the laser channel.

The e-beam dump. The electron pulse emerges from the wiggler with a significant fraction of the particles left relatively unaffected by the wiggler. A significant fraction also has been robbed of energy by the FEL, producing a beam with a broad energy spread. This high power electron beam must be captured in an e-beam dump, where the radioactivity and heat produced by its capture can be effectively handled. The dump must take on many of the characteristics of a moderately large nuclear reactor designed for burst-mode operation. The transport of the e-beam to this dump can be identified as a significant design challenge.

2. BEAM TRANSPORT AT HIGH INTENSITY

Propagation of High Intensity E-beams

The generation and transport of high current relativistic electron beams requires a detailed understanding of the physical processes that shape the beam and which drive the transverse motions of individual particles as they travel through the complex structures of the accelerator and on to the regions where they deposit their energy. The charged particle beam weapons program and the advent of laser guiding have served to expand the transport problem beyond just that of e-beam propagation in vacuum. The major physical processes affecting the propagation of these beams in FEL applications are discussed below.

Propagation in Vacuum

For induction accelerator FELs, the propagation medium for the electron beam varies depending on the particular concept being employed. Accelerators using external magnetic fields allow propagation in vacuum all the way through the device. Some significant background pressure may be inevitable near the e-beam dump for high average power systems. The laser guided accelerators require transport through a diffuse background gas in the high energy accelerator section.

Consider the geometry shown in Fig. 4 where a cylindrical e-beam is assumed to travel through an evacuated region. The beam has a charge density ρ that is constant in the radial direction r . Thus, the current density J_z is given by [8]

$$J_z = \rho v_z = \frac{I_b}{\pi a^2} \quad (2)$$

Forces on a cylindrical e-beam in vacuum

Solenoidal magnet

Charge density

Figure 4

where v_z is the axial particle velocity, I_b is the total current, and a is the radius of the beam. For $r < a$, the azimuthal magnetic field B_θ generated by the current is

$$B_\theta = \frac{2I_b r}{a^2 c} = \frac{2\pi \rho v_z r}{c} \quad (3)$$

where c is the speed of light. The charge density also generates a radial electric field E_r which is directed outward and given by

$$E_r = \frac{2I_b r}{v_z a^2} = 2\pi \rho r \quad (4)$$

These fields are large at the edge of the beam. For example, for $I_b = 10$ kA and $a = 1$ cm,

$$E_{r, \text{edge}} = \frac{20 I_b (\text{amps})}{a (\text{cm})} = 600 \text{ kV/cm} \quad (5)$$

and

$$B_{\theta, \text{edge}} (\text{gauss}) = \frac{I_b (\text{amps})}{5a (\text{cm})} = 2 \text{ kG} \quad (6)$$

These fields exert nearly equal and opposite forces on the particles, i.e.

$$\begin{aligned} F_r &= q(E_r - \frac{v_z}{c} B_\theta) \\ &= 2\pi q \rho r (1 - \frac{v_z^2}{c^2}) \end{aligned} \quad (7)$$

In these expressions, q is the electron charge. Introducing the usual relativistic notation $\gamma = (1 - v^2/c^2)^{-1/2}$ as a measure of the particle energy in units of its rest mass, it is seen that the magnitude of the radial force decreases as $1/\gamma^2$. Nonetheless, the net force is always defocusing -- radially outward.

To hold the beam together in vacuum, an external longitudinal magnetic field B_z must be applied. Assuming that B_z is constant in the radial direction, the equation of motion for a particle in the beam is given by

$$\gamma m_e \left(\frac{d^2 r}{dt^2} - \frac{v_\theta^2}{r} \right) = q (E_r - \frac{v_z}{c} B_\theta) + q \frac{v_\theta}{c} B_z \quad (8)$$

where m_e is the electron mass. The equation describes the radial forces on a particle due to the fields generated by the beam and the external field. By introducing the relativistic cyclotron frequency ω_c , where

$$\omega_c = \frac{q B_z}{\gamma m_e c} \quad (9)$$

and applying the condition that the beam undergo uniform rotation such that $v_\theta = \omega_c r$, it can be shown that the external field B_z required to constrain the beam size to uniform radius scales as

$$B_z \propto \frac{1}{\sqrt{\gamma}} \quad (10)$$

A more complete derivation of the beam envelope equation and the conditions for stable propagation are given in reference [9].

Laser Guiding

In 1983, a new technique was demonstrated that permitted stable propagation of high current e-beams in the accelerator without the need for external fields. A commercial injection-locked KrF laser (Lambda Physik EMG 150 ES, 500 mJ, 27 ns, 0.2 mrad) was used to guide the e-beam of the Experimental Test Accelerator (8 kA, 4.5 MeV, 25 ns, 1 Hz). A diffuse atmosphere of benzene (10^{-4} to 10^{-3} torr) was used in the region beyond the injector to provide an ionization channel in which the e-beam could propagate [10].

The Livermore group had been motivated to explore alternatives to external fields as a result of severe instabilities that had been identified in the induction accelerators operating at high current. The externally applied fields could not be conveniently produced with sufficient strength to control the effects of offset beams. Small displacements of the beam from the accelerator axis were observed to couple to electromagnetic fields being driven in the accelerator gaps in such a way that the beam displacement increased rapidly down the length of the accelerator. There was concern at the time that the performance goals for the ATA (10 kA, 50 MeV, 50 ns) could not be met using the conventional approach. For several years (11,12), people had been toying with ways to make use of the strong focusing effects of diffuse plasmas interacting with

the head of the high current electron beam to provide an ionization channel that would tend to keep the beam on axis. It was believed that if these techniques could be made to work, the solenoidal magnets in the region outside the injector could be turned off altogether. Early ideas focused on the direct interaction of the e-beam with low pressure gases or wires. By 1980, it had become clear [13] that multiphoton ionization of polyatomic gases could provide a way to generate an absolutely straight ionization channel for the beam, as illustrated in Fig. 5. In the ETA experiments, the KrF laser produced only a few percent fractional ionization of the benzene and, since the recombination times were long, the timing of the delivery of the laser pulse was observed to be uncritical.

Three conditions were identified as being necessary for effective laser guiding in the ion focused regime, where the e-beam itself produces the net positive channel by expelling plasma electrons produced by the laser.

1. The channel radius should be smaller than the beam radius in order that the radial focusing force be anharmonic and lead to phase-mix damping of transverse beam motion.
2. The electron beam charge density should be greater than the channel ionization density to assure complete plasma electron expulsion and to prevent a two-stream instability.
3. The betatron wavelength should be short compared to the channel length to assure reaching equilibrium in the channel.

The theoretical treatment of the response of the e-beam to the laser channel is complicated by the need to treat the transverse "thermal"

Principles of laser guiding

$$\text{Net force on beam electrons } F = E_R^{\text{ion}} + \underbrace{(E_R^e - v_z B_\theta)}_{\sim 0 (1/\gamma^2)}$$

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energy of the electrons. The electrons are mapped on to a phase space along any axis normal to the direction of propagation, consisting of two dimensions denoting a particle's position and transverse momentum. The area that the beam occupies in this phase space is called the emittance. Beams with large size and transverse momentum have high emittance, a characteristic that is particularly detrimental to FEL extraction.

If the linear charge density of the laser channel is given by λ and the channel is a uniform cylindrical volume of radius a , the radial electric field due to the ions in the laser channel is given by

$$\begin{aligned} E_r &= \frac{2\lambda r}{a^2} \quad \text{for } r \leq a \\ &= \frac{2\lambda}{r} \quad \text{for } r > a \end{aligned} \tag{11}$$

Assuming that the e-beam can be regarded as an isothermal fluid in motion with a characteristic temperature defined by a Maxwellian distribution of transverse velocities, the electrostatic problem can be solved, yielding the equilibrium beam envelope defined by radius R .

$$\frac{\epsilon^2}{R^2} = \frac{2q\langle\lambda\rangle}{\lambda m_e c^2} \tag{12}$$

In this equation, $\langle\lambda\rangle$ is the channel's linear charge density averaged over the beam profile and ϵ is the unnormalized emittance of the beam.

The laser approach has been successfully employed on the ATA and was a key factor in the achievement of the design goals for that machine. In the following section the design issues governing the decision to use laser guiding for high average power induction accelerators are discussed in light of the suppression of BBU and the uncertainties about the extraction of the e-beam from the channel without emittance growth.

3. SCALING THE INDUCTION ACCELERATOR MODULE

The Induction Accelerator Module

The heart of the induction accelerator is the module containing the accelerator gap, the induction core, and the evacuated tube in which the e-beam is transported. There are several fundamental limits on the capability of these modules that translate directly into accelerator size, output characteristics, and cost.

Limits imposed by coherent (or collective) forces on the electron beam. These forces describe the interaction of the beam with itself. In an earlier era when electrostatic forces played the dominant role, these forces were referred to as "space charge" effects. In general, the high degree of cancellation of the forces generated by the radial electric self-field and the azimuthal magnetic self-field reduces the effect of the collective forces on the incoherent motion of the beam, i.e., the motion of individual particles with respect to each other. Incoherent effects are important in the low energy portion of the accelerator, where the beam envelope equation must be modified to include collective effects.

Limits imposed on peak current due to virtual cathode formation.

Due to the existence of a conducting wall serving as the beam pipe and as a return current path, the particles in the beam have potential energy in the field set up between the beam and the wall. Particles in the beam have a higher potential energy (and therefore a lower kinetic energy) than they would if no other particles were present. If the radius of the beam is r_b and the radius of the pipe is r_p , then the limiting current is

given by [14]

$$I_L = \frac{mc^3}{e} \frac{(\gamma^{2/3} - 1)^{3/2}}{(1 + 2\ln(r_p/r_b))}, \quad \begin{aligned} r_b &\leq r_p/2 \\ \frac{mc^3}{e} &= 17 \text{ kA} \end{aligned} \quad (13)$$

$e = \text{electron charge}$

In this equation, γ corresponds to the energy that the particle would have in the absence of collective effects.

This current limit was a real consideration in the design of the ETA and ATA systems. At 10 kA, the potential difference from the center to the edge of the beam can be several hundred kilovolts, which translates into an equivalent amount of energy spread in the beam.

The effect of the surroundings on the coherent motion of the beam. The spatial average of the incoherent motion of the beam gives the net motion of the beam as a whole. This motion is called the coherent motion and is the effect that is most often sensed or measured in the laboratory. A beam of particles moving along the axis of a conducting pipe gives rise to an azimuthally symmetric surface charge and current distribution on the surface of the pipe [15]. If the beam is displaced transversely from the axis of the pipe, these distributions become asymmetric. The asymmetric surface charge attracts the beam toward the wall while the surface current repels the beam. In a continuous pipe with smooth walls, these two forces cancel to within a factor γ^{-2} .

At a discontinuity in the pipe, such as an accelerating gap, the electric self-field will decrease exponentially with r in the region $r > r_b$ if the gap width is less than the pipe radius. On the other hand, the magnetic self-field will extend much further into this region, decreasing in magnitude as r^{-2} . Thus, the surface charge and current distributions are displaced from each other, and the cancellation of electric and magnetic forces is lost in the gap region. The potential beam instability that can arise due to this effect must be reduced to acceptable levels in the design of the accelerator, but in general its importance is diminished compared to the beam breakup instability discussed below. Continuous focusing of the beam is required within the accelerator to reduce the growth rate of the "image displacement" or "resistive wall" instability [16] and to correct for the residual expansion of the beam due to its own self-fields. The magnetic focusing field B and the beam radius r_b are related as follows.

$$B(\text{kG}) \cdot r_b(\text{cm}) = 1.36 \left[\frac{I(\text{kA})}{\gamma} \right]^{1/2} \quad (14)$$

The value of B must be chosen small enough so that r_b is large enough to avoid the limiting current imposed by collective effects. Another constraint on B results from the need to damp the resistive wall instability. If the width of the accelerator gap is w and the distance between gaps is L , then for pipe radius r_p the focusing field is given by

$$B(\text{kG}) \cdot r_p(\text{cm}) = \left[1.36 I(\text{KA}) \frac{\gamma_w}{L} \right]^{1/2} \quad (15)$$

This criterion results in stabilization of the coherent transverse motion due to the low frequency displacements induced by the image displacement effect.

Limits imposed by the beam breakup instability. The coupling of the pulse power systems to the electron beam in an induction accelerator does not involve resonant cavity structures. Nevertheless, there is the possibility of resonant interaction of the coherent transverse beam motion with the characteristic rf modes of the accelerator cavities. Studies on the ETA identified the TM_{1n0} modes [17] as being the most troublesome. The sinusoidal dependence in azimuth associated with these modes produces an unstable transverse coherent motion in the beam. The TM_{130} mode near 800 MHz was the most intense on ETA. The transverse oscillation of the beam will grow exponentially down the length of the accelerator. The displacement x as a function of the initial beam offset x_0 is given by

$$x = x_0 e^{\Gamma} \quad (16)$$

where the exponent scales as

$$\Gamma = \left(\frac{I_b}{I_0} \right) \left(\frac{\omega_{0z}}{K_{0s}} \right) \left(\frac{mc^2}{\Delta E_g} \right) (\gamma_f - \gamma_0) \quad (17)$$

In this equation, ω_0 is the angular frequency of the rf mode, Z is

the coupling impedance, I_b is the peak current, I_0 is 17 kA, ΔE_g is the energy increase per gap, and γ_f/γ_0 are the final and initial Lorentz factors of the beam. The factor $k_{os} = eB/mc^2$, where B is a solenoidal magnetic field. For ATA operating at 10 kA, the exponent is about 11 with the solenoids operating at their maximum capacity. The measured noise level X_0 is roughly 10^{-4} cm.

For an accelerator that uses laser guiding, the appropriate expression for BBU growth is

$$X = X_0 \left(\frac{\gamma_0}{\gamma_f} \right)^{1/4} \exp \left[\left(\frac{I_b}{I_0} \right) \left(\frac{\omega_0 Z}{K_0} \right) \left(\frac{mc^2}{\Delta E_g} \right) (\sqrt{\gamma_f} - \sqrt{\gamma_0}) \right] \quad (18)$$

In this expression, the exponent is proportional to the square root of the final energy in contrast with the solenoidal focusing case.

Several issues are associated with the use of laser guiding in a high brightness, high repetition rate accelerator. At present, the effects of laser guiding on the brightness of the electron beam are not precisely known. It is known that focusing of the ion channel is time dependent due to the coherent radial motion of the channel ions in the electric field of the beam. Some indirect evidence suggests that the emittance of the beam increases somewhat from head to tail. A second issue is that of channel lifetime and formation at high repetition rates. It is not known with what frequency a sufficiently strong laser channel can be formed. A third issue is technological in nature. The laser

that would be required for the high repetition rate accelerator does not exist at present and would have to be developed.

The laser guiding technique does have several important benefits. First, it has unquestionably been demonstrated that the technique can control BBU. Secondly, the channel does provide an anharmonic focusing force which acts to phase mix damp any instability or unwanted beam motion. The use of the technique on ATA has properly been called a technological breakthrough.

Many of the benefits of laser guiding may be achieved by using quadrupoles. If these elements are properly spaced (namely let the spacing be proportional to $\gamma^{1/2}$) then the appropriate BBU growth formula is again Eq. (3.6). Some degree of anharmonicity may be introduced into the transport by including some higher order multipole moments in the quadrupole fields. Other quadrupole designs have taken the approach of increasing the magnetic field with γ , resulting in growth of BBU as a power law expression instead of an exponential.

Recent design studies at Livermore have begun to define the requirements for an accelerator with the characteristics 300 MeV / 3 kA. The reduced current compared to ATA provides some relief from the BBU instability, but the increased energy makes the design task difficult once again. In the conceptual design, solenoidal focusing was used up to $\gamma = 25$, giving way to quadrupole focusing through the rest of the accelerator. The injector delivers the beam at $\gamma = 5$.

The results of all of these studies indicate that external focusing and laser guiding both remain as options for the control of BBU in

the accelerator. The externally focused systems are larger than for laser guiding but are perhaps better understood. Laser guiding represents potentially a high leverage solution to the problem if concerns about control of emittance can be resolved.

4. THE PULSE POWER SYSTEM

Pulse Power Technology for the High Average Power Accelerator

The electrical drive for the induction accelerator modules has received a significant level of effort at Livermore over the years. The four orders of magnitude compression of the electrical pulse in the ETA/ATA technology required the use of a resonant charging system driving a pulse forming line which was discharged by triggering a spark gap [5]. It was realized when this choice was made that high average power versions of the induction accelerator would require a more rugged component than the gas blown spark gap for switching the energy in intermediate storage into the load. Spark gaps suffer from electrode erosion and finite recovery times that limit their utility for continuous operation above a kilohertz.

A parallel effort was initiated to apply the technique of pulse compression by means of saturable reactors to generate fast pulses. This technique was first described by Melville in 1951 [6] and has been used for many years to generate low power pulses for radar. Since 1980, a number of magnetic pulse compressors have been constructed taking full advantage of the advances made in amorphous alloys of very thin cross-section, high resistivity and large magnetic flux swing [18].

The basic circuit for magnetic pulse compression is essentially the same as originally conceived in the 1950s. The fundamental principle involved is to use the large changes in permeability exhibited by saturating ferri-(ferro-)magnetic materials to produce large changes in im-

pedance. Figure 4.1 illustrates the standard technique for capitalizing on this behavior. First, a repetitive power source generates the initial pulse. As this pulse propagates through the network, it goes through several stages of compression until it achieves the desired shape. By using multiple stages as shown, it is possible to achieve a much larger effective change in impedance than can be obtained from a single stage. In fact, the effective change in impedance is limited only by the physical layout and materials properties.

The operation of the circuit in Fig. 6 can be described as follows. Capacitor C_1 charges through inductance L_0 until inductance L_1 saturates, becoming much less than L_0 . Once this happens, C_2 will begin to charge from C_1 through L_{1sat} , but since L_{1sat} is much less than L_0 , C_2 charges more rapidly than C_1 did. This process continues through the successive stages until C_n discharges into the load through L_{nsat} . To make this process efficient, each successive stage is designed so that saturation occurs at the peak of the voltage waveform. The core is then reset to its original state in preparation for the next pulse. Aside from creating the ability to operate at increased repetition rates, the installation of magnetic pulse compressors in future induction accelerators appears warranted based on increased reliability and lower maintenance. A cross-sectional view of the most recent magnetic compressor design is shown in Fig. 7. It consists of an input step-up transformer, one stage of compression to charge the transmission line, a second stage of compression, and the output coupling

Simplified schematic of a magnetic pulse compressor

Figure 6

**Magnetic modules designed for ATA upgrade
have been tested for $>10^8$ pulses**

transformer. The output transformer can be housed as part of the magnetic pulse generator or as part of the load for best impedance matching.

Adding coupling transformers at both the input and the output of the magnetic pulse compressor improves the system's versatility by permitting it to achieve the desired output pulse while allowing the compression stages and the input switching device to operate at their most efficient values of voltage and current. At this point in the evolution of the pulse-shaping hardware, we can design the transformer turns and the interstage capacitors as integral parts of the system. A cross-sectional view of the accelerator cell connection is shown in Fig. 8, where the ferrite shock line sharpeners and the CuSO_4 compensation loads can be seen.

At the input end of the magnetic pulse compressor, there are special requirements imposed on the charging system in order to ensure the reproducibility of pulses coming from a device operating on highly time-dependent electrical properties [19]. Charging of the system is accomplished using a command resonant charging circuit, diagrammed in Fig. 9. Energy storage capacitor C_1 begins inductively charging capacitor C_2 when switch S_I closes at time T_I . At time T_{II} , switch S_{II} closes to halt the charging process. Finally, after allowing time for switch S_I to recover, the open switch S_{III} can be closed and the energy stored in C_2 is transferred to the load. The act of closing switch S_{II} is called de-Queing and is used to achieve a constant final voltage on C_2 even though the voltage on capacitor C_1 droops during

Figure 8

Simplified schematic of the command resonant charge system

Figure 9

-35-

C_1 – Main capacitor bank

C_2 – Intermediate storage capacitor, $C_2 \ll C_1$

the burst. An active compensation circuit is employed to correct for the finite delay between measurement of the desired voltage on the intermediate storage capacitor and the firing of the de-Queing tube. Changes in the magnetic flux density excursion in the saturable inductors are also important. Control of the temperature of the insulating medium and the timing of the core reset pulse is required.

The pulse repetition rate of the magnetic switch is constrained by the need to reset the saturable inductors between pulses. In the switches currently operating on ETA, a capacitor is charged to a reverse polarity between pulses, causing reset of the inductors in a cascaded process. The finite propagation times of the reset pulse through the circuit, along with certain considerations pertaining to the efficiency of the circuit serve to limit the repetition rate of the switch to approximately 10 kHz. Other magnetic switch circuits have been proposed by Birx et al. [20] that involve connecting the pulse compressors in parallel in such a way that the discharge of one stage of a compressor begins the resetting of its neighbor in parallel. This kind of circuit permits the generation of bursts of pulses at very high repetition rate (~ 10 MHz). While such a waveform for an FEL has not found a clear application, the apparent flexibility of the pulse power equipment used to drive the induction accelerator could provide interesting design options.

5. THE INJECTOR

The E-beam Injector

The free electron laser operates most efficiently when the e-beam entering the wiggler has a minimum energy spread and is particularly low in transverse momentum. These two conditions simplify the problem of establishing the resonance conditions between the optical wave and the oscillating ensemble of electrons within the wiggler. Excessive transverse momentum on the electrons going into the wiggler results in betatron motions of increased spatial extent that can lead to significant detrapping of the electrons and reduced extraction efficiency [21].

Most of the conditions leading to significant transverse energy in the beam are present in the low energy portion of the accelerator, particularly in the region near the cathode (the so-called e-beam injector sub-system). A key parameter correlating to the magnitude of the optical gain in the FEL wiggler is the "brightness" of the electron beam. The brightness is defined as the ratio of the current density to the solid angle into which the electrons are projected.

$$\mathcal{B} = \text{const.} \times \frac{J}{\theta^2} \quad (19)$$

In this equation, J is the current density (amps/cm²) and θ is the characteristic divergence angle of the electron beam (radians). So the units of brightness are amps/rad²-cm². The achievement of high extraction efficiency on the induction accelerator FEL requires that the e-beam brightness scales upward as the laser wavelength decreases.

<u>Wavelength Regime</u>	<u>E-beam Brightness Required</u>
	<u>amps/rad²-cm²</u>
Microwaves	of order 10 ⁴
Mid-infrared	of order 10 ⁵
Near infrared, visible	of order 10 ⁶

Of course, real e-beams are not completely isotropic. The divergence and size of the beam can vary depending on the axis of interest. The brightness is often defined in terms of the peak current and the emittance of the beam.

$$\mathcal{B} = \frac{2I}{\epsilon} \quad (20)$$

In this expression, I is the peak current (amps) and ϵ is the so-called edge emittance of the beam. The electrons located along any transverse axis of the beam can be mapped on to a two dimensional space describing their displacement from the origin and transverse momentum as shown in Fig. 10. The area occupied by the ensemble of electrons is a measure of the beam's edge emittance along that axis. A similar map can be obtained along an axis orthogonal to the first, thus describing a four dimensional volume in phase space that describes the instantaneous state of the beam in a particular plane. The brightness can then be defined in terms of this volume δV_4 in transverse phase space as follows.

The electron beam in phase space

Edge emittance

$$\epsilon = ab$$

Normalized emittance

$$\epsilon_n = \gamma\beta\epsilon \text{ (invariant with energy)}$$

Diverging
beam

Beam
at a waist

Converging
beam

Figure 10

$$\mathcal{B} = \frac{\sigma^2(\delta I)}{B^2 \gamma^2 (\delta V_4)} \quad (21)$$

δI is the current enclosed by the four-volume δV_4 . The relativistic parameters B and γ appear in the expression as normalization factors, so that the brightness becomes invariant with electron energy. Hence, the normalized brightness of the beam emerging from the injector is identical to the brightness of the beam leaving the accelerator unless something happens to destroy the beam quality along the way. In any accelerator, especially when self-forces are important, the forces on the electron are not linear. The normalized emittance will tend to increase down the accelerator due to these effects. However, most of the sins that the designer can commit that lead to reduced brightness occur in the injector.

The brightness of an injector is set by a variety of practical design choices such as peak voltage, cathode type, electrode geometry, and focusing field topology. At Livermore, the High Brightness Test Stand has been used to gain understanding of this design space while at the same time providing an opportunity to gain experience with the magnetic modulator technology needed for high average power applications [22]. The major components of the HBTS injector are shown in Fig. 11.

Several fundamental physical effects contribute to the emittance in an injector [23]. These effects include 1) source temperature, 2) source uniformity, 3) normal magnetic field on the cathode, 4) beam filamentation

Schematic of the high brightness test stand

by a grid (if present), 5) non-linear forces, and 6) non-linear space charge forces.

1) Source Temperature (T) - The beam brightness is inversely proportional to the source temperature, a measure of the transverse energy in the beam. Injector brightness has not been significantly affected up to now by this effect, however as we push brightness above 10^6 A/rad²-cm², maintaining effective source temperature below 1 eV will be critical for cathode types with emissivity less than 10 A/cm².

2) Source Uniformity - To the extent that emission is non-uniform, the beam transport through regions dominated by non-linear radial forces will entrain regions of "phase space vacuum" via phase mixing. As this dilution can become irreversible after one quarter of a betatron wavelength, an estimate of this effect is obtained by using the volume of the smallest ellipse enclosing all significant current regions as a measure of the emittance.

3) Normal Magnetic Field - In the presence of a normal magnetic field at the cathode surface, electrons are emitted with a finite canonical angular momentum. When the electrons leave the region of axial field, they acquire a kinetic momentum sufficient to keep their canonical angular momentum constant. This motion gives the beam an equivalent emittance in both transverse planes.

$$c = \frac{eBR^2}{2\gamma Bmc} \quad (22)$$

In this equation, B is the mean normal field and R is the cathode radius. Reducing the cathode radius reduces this contribution in two ways: 1) the emittance scales as R^2 and 2) the average value of B can be kept more nearly constant over a smaller area.

4) Filamentation by a Grid - In the event that grid structures are used in the injector, each hole in the grid can act as a focusing or defocusing lens. This effect has been studied on the ETA where it is exceeded by the effects of non-linear forces as described below. In the design of extremely bright, high current injectors, grid filamentation may be a limiting factor unless the grid material is extremely fine and the grid highly transparent. Unfortunately, such a grid is unlikely to be consistent with thermionic or dispenser cathodes which have a low effective electron temperature. Moreover, this incompatibility rules out grid designs in high current injectors in which high repetition rate is sought.

5) Non-linear Applied Forces - The radial forces from the applied electric and magnetic fields have significant anharmonic components that increase with r^3 . In general, these effects can be made to compensate for each other by careful design using simulation codes [24]. In such simulations, the anharmonicity introduced by the non-linear self-fields of the beam itself must be included.

6) Non-linear Space Charge Effects - The strong space charge forces of an intense, low energy beam will distort the free space equipotentials to result in a defocusing spherical aberration in the beam

transport. Proper shaping of the potentials by a graded accelerating column with shaped electrodes (Pierce correction) can eliminate this effect for a specific operating voltage and current. Self-forces can also lead to increase in emittance whenever the beam cannot be matched into the transport system leading to the main accelerator. At high current, beam loading of the drive circuits will lead to an energy variation correlated with the rise of the beam current. Since the initial transport is space charge dominated, not all segments of the beam can be matched into the low energy portion of the main accelerator. Phase mix damping of the mismatch oscillations will lead to an increase in beam emittance.

An important tool for evaluating the relative contribution of the several sources of beam emittance is a computational model of relativistic electron beam dynamics, which can accommodate the wide range of realistic electrode geometries available to the designer. For this purpose, LLNL developed the EBQ steady state simulation code, which was used for the design of the 10 kA ATA injector. More recently, the DPC particle simulation code was developed to support the work on the High Brightness Test Stand, allowing investigation of the transient effects in high field stress geometries.

Current electrode designs are generated through a combined use of EBQ, DPC, and EGUN (a more familiar code developed by Bill Hermannsfeldt at SLAC). The electron optics are determined by the shape and position of the cathode and the anode, along with intermediate electrodes that grade the potential. The specific choice of intermediate electrode

voltage and position is set by requiring the spherical aberrations of the applied forces to cancel the non-linear space charge forces produced by the beam. For a planar cathode surface, this requirement can be met if the potential gradient is chosen so that the radial force on any electron is always zero. Our experience with implementing this approach using the relativistic Pierce column reveals the sensitivity to the initial conditions, particularly the beam current and its spatial distribution. An alternative approach, often used in the design of high brightness electron guns for high average power klystrons, is to shape the cathode so that the initial electron trajectory is inward (focusing). Space charge forces and gradient shaping then deliver a parallel beam into the anode.

The design of a high brightness gun is further complicated by the fact that once the beam enters the anode stem it must be focused by magnetic fields that match the beam into the main accelerator transport. These fields generally extend into the anode-cathode gap, providing the designer with an additional degree of freedom in the choice of field topology in the gun.

In recent design studies at Livermore, a conceptual design was identified for a high average power injector. A tungsten dispenser cathode is employed in the design, consisting of a porous matrix uniformly loaded with a barium oxide formula. An 8.9 cm diameter convex cathode is currently undergoing testing on HBTS. The cathode is commercially available and is used on the 50 MW SLAC klystrons. It operates at

1250°C and produces an average current density of 30 A/cm² from the surface. At these operating conditions the cathode lifetime is about 100 hours. The vacuum required is 10⁻⁷ to 10⁻⁸ torr. In the near future, the gun configuration will be redesigned to accommodate a 12.4 cm cathode of the same type in an effort to obtain 2 - 3 kA of current. Oxide coated cathodes of the type used in the SLAC RK-5 will be tested if the required peak currents cannot be achieved with the dispenser types. Published test results for the oxide cathodes indicate that 10 to 100 A/cm² can be obtained, making them a potential candidate for this high peak current, low duty factor application.

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