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PROCEEDINGS OF THE CAP MEETINGS (11/1990 - 2/1991)

Volume I

**Edited by
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MASTER

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"FORWARD"

This Report include copies of transparencies and notes from the presentations made at the Center for Accelerator Physics bi-monthly meetings.

The attendance and participation by members of various Departments has been overwhelming. In that, I would like to thank the speakers for their informative presentations, their participation in our meetings, and for providing copies of their transparencies and notes for inclusion in this proceedings. I also would like to thank Peter Bond for providing the space, Bill Willis for his full support of the program, and others for their interest and participation. We also would like to acknowledge K. Tuohy and R. Scarola's assistance with meeting notices and refreshments.

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ON BEAM EMITTANCE - APPLICATION TO ATF

ZOHREH PARSA

**ADVANCED ACCELERATOR GROUP
BROOKHAVEN NATIONAL LABORATORY**

ON BEAM EMITTANCE

- APPLICATIONS TO ATF BEAMLINE*

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Abstract

Formulations of moments Invariants and emittance (including the correlations between degrees of freedom) is discussed and are used as useful tools for analyzing the beam behavior. Some of the results of our analysis for the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF) beamline are also included.

Beam Emittance ++

~ Emittance is some measure of the volume in phase space occupied by some significant fraction of the particles in a transport line, accelerator or in an electron or ion source.

To clarify, consider a single particle with coordinates q, p in 6 - Dim. Phase space and let

$$\mathcal{P}(\vec{q}, \vec{p}) = \{\vec{q}, \vec{p}\}$$

(see sec. I),

and let $f(\mathcal{P})$ be the distribution of particles in phase space at any instant (see sec. II).

Beam Dynamics:

Let $\xi(\vec{q}, \vec{p}) = (q_1, q_2, q_3, p_1, p_2, p_3)$ be the coordinates of a particle in a magnetic field, described by a Hamiltonian $H(\vec{q}, \vec{p}, t)$ e.g., in Cartesian coordinate system (x, y, z) :

$$H(x, y, z, p_x, p_y, p_z; t) =$$

$$\left\{ m_0^2 c^4 + c^2 [(p_x - qA_x)^2 + (p_y - qA_y)^2 + (p_z - qA_z)^2] \right\}^{1/2} + q\phi \quad (1)$$

where A and ϕ are vector and scalar potentials, m_0 and q are rest mass and charge of particles. It is of interest to know when a particle will reach a particular location, and what its transverse displacement and momentum will be there. Thus changing the independent coordinate $t \rightarrow z$, and making canonical transformation, with K the new Hamiltonian

$$H(x, y, z, p_x, p_y, p_t; t) \rightarrow K(x, y, p_x, p_y, p_t; z). \quad (2)$$

with

$$x' = \partial K / \partial p_x, \quad p'_x = -\partial K / \partial x,$$

$$y' = \partial K / \partial p_y, \quad p'_y = -\partial K / \partial y$$

$$t' = \partial K / \partial p_t, \quad p'_t = -\partial K / \partial t$$

where prime $\equiv d/dz$ and $p_t = -E$ (Negative of Total Energy). The Hamiltonian eq. can be described by: $d\vec{\xi}/dt = -[H, \vec{\xi}]$. (3) with $(\vec{\xi}^0, t^0)$ and $(\vec{\xi}^f, t^f)$ as the initial and final phase space coordinates of particle respectively. The trajectory of particle between these two points may be described by an invertible map M such that,

$$\vec{\xi}^f = M \vec{\xi}^0 \quad (4)$$

In our application, the transfer maps could correspond to various beamline elements (relating the coordinates and momenta at exit face of an element to those at entrance face). We can express M in terms of symplectic transfer maps for each element using Lie operators (e.g. a map for collection of elements can be) expressed as:

$$M = \exp(:f_2:) \exp(:f_3:) \exp(:f_4:) \dots \quad (5)$$

where each f_n is a homogeneous polynomial of degree n in phase space variable $\vec{\xi}^0$

Noting that, if f and g are functions of phase space variables ($\vec{\xi}^0$) then there exist a Lie operator $:f:$ such that $:f: g \equiv [f, g]$ (poisson brackets); $:f:^0 g = g$, $:f:^1 g = [f, g]$, $:f:^2 g = :f: :f: g = [f, [f, g]]$ etc., (defined as power of Lie operators); and

$$\exp (:f:) \equiv \sum_{m=0}^{\infty} :f:^m / m!$$

(exponential of Lie operators), such that

$$\exp(:f:) \xi_j = \xi_j + [f, \xi_j] + [f, [f, \xi_j]] / 2! + \dots$$

(for more details see e.g. [2,3]).

Moments, Kinematic Invariants and Emittance:

Let $\rho(\xi)$ be the distribution of particles in phase space at any instant e.g.

$$d^6N = \rho(\xi) d^6\xi$$

where d^6N and $d^6\xi$ are the No. of particles, and small volume in a 6-Dimensional phase space $\xi = [\vec{q}, \vec{p}]$, $q_i, p_i = 1, 2, 3$, respectively.

Let $\rho(M^{-1}\xi)$ be the final distribution at the end of the system such that a set of initial moments are (j = index), defined as $k_j^0 \equiv \int \rho(\xi) F_j(\xi) d^6\xi$. Where the final moments become:

$$k_j^f = \int \rho(\xi') F_j(M\xi') d^6\xi' \quad (6)$$

with

$$F_j(M\xi) = \sum D_{jk}(M) F_k(\xi) ,$$

(D_{jk} is a matrix and $F_j(\xi)$ are a complete set of homogeneous polynomials.) Thus, the moment transport can be expressed in a simple form as:

$$k_j^f = \sum_k F(M)_{jk} k_k^0 .$$

E.g. 1st moment, denoted by

$$\langle \xi_a \rangle = \int d^6\xi \xi_a f(\xi)$$

and 2nd moment

$$\langle \xi_a \xi_b \rangle = \int d^6\xi \xi_a \xi_b f(\xi)$$

etc. (similarly for higher moments).

To see this, e.g. assume M is a linear map in two Dim. Phase space, thus

$$(*) \quad \langle q^2 \rangle^f = \int d^2\xi \xi^0 f(\xi) (M q)^2 , \quad \text{etc.}$$

with the linear map M :

$$M q = M_{11} q + M_{12} p \quad (\text{inserted in eq. } (*)) \text{ one obtains,}$$

E.g. in 2-Dimensional phase space (with a linear map M),

$$(a) \quad \langle q^2 \rangle^f = (M_{11})^2 \langle q^2 \rangle^0 + 2 M_{11} M_{12} \langle qp \rangle^0 + (M_{12})^2 \langle p^2 \rangle^0,$$

$$(b) \quad \langle qp \rangle^f = M_{11} M_{12} \langle q^2 \rangle^0 + (M_{11} M_{22} + M_{12} M_{21}) \langle qp \rangle^0 \\ + M_{12} M_{22} \langle p^2 \rangle^0, \quad [eqs. (6a), (6b), (6c)]$$

and

$$(c) \quad \langle p^2 \rangle^f = (M_{21})^2 \langle q^2 \rangle^0 + 2 M_{21} M_{22} \langle qp \rangle^0 + (M_{22})^2 \langle p^2 \rangle^0.$$

Thus $D(M)$ are quadratic functions of matrix elements M_{ij}

(when restricted to quadratic moments).

For a Gaussian distribution

$$\langle q^2 \rangle = \beta \sigma^2; \quad \langle qp \rangle = -\alpha \sigma^2; \quad \langle p^2 \rangle = \gamma \sigma^2,$$

$$\beta \gamma - \alpha^2 = 1, \quad (\alpha, \beta, \gamma \text{ are Twiss parameters});$$

and
$$\epsilon^2 \equiv [\langle q^2 \rangle \langle p^2 \rangle - (\langle qp \rangle)^2]. \quad (7)$$

ϵ^2 is a kinematic invariant in 2-Dim, i.e., if M is a linear map, then

$$(\epsilon^2)^f = (\epsilon^2)^0;$$

to see this, define $(\tilde{\epsilon}^2)^0 = \langle q^2 \rangle^0 \langle p^2 \rangle^0 - (\langle qp \rangle^0)^2$ and substitute eqs. 6 (a, b and c) into these and simplify ==> $(\tilde{\epsilon}^2)^f = (\det M)^2 (\tilde{\epsilon}^2)^0$ where $\det M = 1$. (Symplectic condition), thus $(\tilde{\epsilon}^2)^f = (\tilde{\epsilon}^2)^0$ as stated above

ϵ^2

is referred to as mean square emittance. Where the emittance is defined as "some measure of the volume in Phase space "occupied" by some significant Portions of the Particles".

In 6-Dim phase space, there are 3 functionally independent kinematic invariants made up of quadratic moments, e.g. $\varepsilon_x^2, \varepsilon_y^2, \varepsilon_z^2$, such that:

$$I_2(k) = \varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2$$

$$I_4(k) = \varepsilon_x^4 + \varepsilon_y^4 + \varepsilon_z^4$$

$$I_6(k) = \varepsilon_x^6 + \varepsilon_y^6 + \varepsilon_z^6$$

or in general
$$I_n(k) = \frac{1}{2} (-1)^{n/2} \text{tr}(\xi J)^2 \quad (8)$$

where $\xi = 6 \times 6$ matrix, whose entries are moments, $\xi_{jk} = \langle \xi_j \xi_k \rangle$, with $I = 3 \times 3$ identity matrix and $J = -\begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix}$.

E.g.,
$$I_2(k) = \langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2 + \langle y^2 \rangle \langle p_y^2 \rangle - \langle y p_y \rangle^2 + \langle z^2 \rangle \langle p_z^2 \rangle - \langle z p_z \rangle^2$$

$$+ 2 \langle xy \rangle \langle p_x p_y \rangle - 2 \langle x p_y \rangle \langle y p_x \rangle + 2 \langle xz \rangle \langle p_x p_z \rangle - 2 \langle x p_z \rangle \langle z p_x \rangle + 2 \langle yz \rangle \langle p_y p_z \rangle - 2 \langle y p_z \rangle \langle z p_y \rangle$$

Note that $I_2, I_4, I_6 \dots$ are invariants even if there is a linear coupling between x, y, z degrees of freedom.

This is a generalization of 2-Dim mean square emittance (e.g. See Refs. [2,3]). Higher order Kinematic invariants (e.g. cubic and quartic moments); and correlations between various degrees of freedom may be constructed, and used as a tool, in beam studies. E.g., for a beam transport system with misalignment one may use an invariant: $I \equiv \langle x^2 \rangle \langle p_x^2 \rangle - \langle p_x^2 \rangle \langle x^2 \rangle - 2 \langle x p_x \rangle \langle x \rangle \langle p_x \rangle$ (Constructed from a linear and quadratic moments).

Note the set of quadratic moments transforms the 21 dimensional representation of $SP(6)$.

For

$$I_2 = \sum_{i,j} U^{ij} k_i k_j$$

U^{ij} act as Clebsch - Gordan coefficients (C.G.C.) for the $SP(6)$ group, that pick up the identity (representation), "1" + (higher representations) in the direct product

$$2 \otimes 21 = "1" + \dots$$

Similarly for

$$I_4 = \sum_{i,j,k,l} T^{ijkl} k_i k_j k_k k_l$$

where C. G. Coeffts. T^{ijkl} pick "1" in direct product

$$21 \otimes 21 \otimes 21 \otimes 21 = "1" + \dots$$

etc.

Eg. cubic and higher order moments also transform according to certain representation of $SP(6)$, (see following Figures).

a) Second Moment Invariants :

 $I_2 =$

 $I_4 =$

 $I_6 =$

2 line vertex corresponds to the quadratic moment $\langle \xi_i \xi_j \rangle$

b) Mixed Second and Third Moment Invariants :

c) Third Moment Invariants :

3 line vertex corresponds to the 3rd order moment $\langle \xi_i \xi_j \xi_k \rangle$

d) Fourth Moment Invariants :

(All the quantities shown are invariant properties of a Particle distribution that remain unchanged under transport in the linear approximation.)

Diagrams describing the construction of kinematic invariants from 2nd, 3rd, and higher order moments.

Notations:

In the next section, for convenience, we change the phase space variables from (x, p_x, y, p_y, t, p_t) to a set of dimensionless quantities $(X, P_x, Y, P_y, \tau, P_\tau)$, by scaling transformation. Such that, $X = x/\ell$, $P_x = p_x/p_0$, $Y = y/\ell$, $P_y = p_y/p_0$, $\tau = t/(\ell/c)$, $P_\tau = p_t/(p_0 c)$. Where (ℓ) , (ℓ/c) , (p_0) and $(p_0 c)$ are used as the length, time, momentum and p_t (negative of the particle energy) scales respectively. E.g. we use $\ell = 1$ m (scale), thus units of $x = X$ in [m], $y = Y$ in [m], $t = \tau/c$ in [sec], where c is the speed of light in [m/sec], etc. These scales and units should be noted in interpreting the calculated results, e.g. parameters used in Figures 2 and 3.

Applications – ATF-Beamline

Brookhaven Accelerator Test Facility (ATF) consists of a high brightness rf-gun, and a 50 MeV/c electrons LINAC, both operating at 2.856 GHz, [4,5]. Figure 1, shows a schematic layout of the beamline, designed to transport an intense, low emittance electron beam, from the rf-gun to the LINAC entrance, while preserving the beam emittance.

As an application of the Lie algebraic formulation discussed, we present some results of the analysis for the beam along the ATF transport line. With an initial distribution of 3,353 particles ((from the 5000 particles generated in Gaussian distribution), that corresponds to a proposed beam of 4.5 MeV/c momentum at the gun exit), and using the configuration shown in Figure 1, and e.g. Ref. [5]. Figures 2 and 3 show the beam profiles at the proposed location of the momentum monitors (X-slit), and at the LINAC entrance. These parameters were calculated including third order aberrations, and were used to calculate the beam emittance, illustrated.

Fig. 1. ATF injection system

Figure 3 a-d, shows (transverse and longitudinal) beam profile
at the LINAC entrance.

Fig. 4

Summary

An analytical perturbation method for computing particle trajectories (using Lie algebra and Lie groups), and an application to beamline elements for Brookhaven Accelerator Test Facility is discussed. This includes formulation of the familiar mean square emittance (a kinematic invariant) in 2-Dim (with a Gaussian distribution), invariants in 6-Dim phase space, and generalization of kinematic invariants (e.g., cubic, quartic moments). The correlations between various degrees of freedom should be noted and may become detrimental in the beam emittance calculations. As an application we calculated the beam parameters including the emittance for the ATF transport line shown in Figure 1. Where the initial quadrupole triplet is used to bring the diverging beam to a double waist at the momentum slit and the second set of quadrupole triplets is to provide a matching of the beam at the LINAC entrance. Our calculations include nonlinear effects including 3rd order aberrations in the beam (e.g., due to magnet fringing fields), a reason for the differences in the results (e.g., see beam profile at momentum slit, or at LINAC entrance), as compared to those obtained with 1st and/or 2nd order calculations with TRANSPORT (used at ATF as a standard design program)*. The beam emittance growth is illustrated in Table I, and may be improved by: e.g., a better fitting of quadrupoles (including the fringing effects); use of slits (to reduce beam size); use of smaller initial (laser spot) beam size; improvement of the photocathode gun performance [5]; and placing of the gun directly into the LINAC entrance (see Refs. [5,6]). These and other possibilities are being investigated to assure the production of a high brightness, low emittance electron beam, required for the new methods of acceleration such as used for FEL and IFEL experiments.

For mapping formulations of the particles through beamline elements and/or additional beam parameters along the ATF beamline, see e.g., Refs. [3] and [6]. (* E.g., see Fig. 4, (after fitting, plotted

ices

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A REVIEW OF BROOKHAVEN ACCELERTOR TEST FACILITY (ATF)

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The Brookhaven Accelerator Test Facility

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THE BROOKHAVEN NATIONAL LABORATORY ACCELERATOR TEST FACILITY

1. BRIEF OVERVIEW SHOWING CURRENT STATUS
2. DESIGN CONSIDERATIONS AND PROPOSED TESTS.
3. BEAM SIMULATIONS.
4. BEAM STABILIZATION AND SYNCHRONIZATION
5. BEAM TESTS WITH EXCIMER LASER
6. FUTURE IMPROVEMENTS.
7. EXPERIMENTS.

The Brookhaven Accelerator Test Facility

Features

- (1) 50 Mev/c Electron Linac
- (2) Source is RF Gun with Photo-cathode
 - high brightness
 - short pulses (6 psec)
- (3) 100 G-Watt CO₂ Laser (6 psec)
- (4) Synchronization of electron pulses and CO₂ Laser

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ELECTRON BEAM PARAMETERS

Low Current Mode

Energy at experiment [MeV]	50
Electrons per bunch	2×10^5
Energy at the gun output [MeV]	4.65
Energy spread at the gun output	5×10^{-3}
Normalized emittance ε_n [π m-rad]	3×10^{-8}
τ_e [psec]	6
Repetition rate [Hz]	6

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att

ELECTRON BEAM PARAMETERS

High Current Mode

Energy at experiment [MeV]	50
Electrons per micro-bunch	6×10^9
Energy at the gun output [MeV]	4.65
Energy spread at the gun output	8×10^{-3}
Normalized emittance ε_n [π m-rad]	14×10^{-6}
τ_e [psec]	6
Repetition rate [Hz]	6

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FIGURE 7
ARRANGEMENT OF HIGH ENERGY BEAM TRANSPORT SYSTEM

Design Considerations

- The electron bunch length is determined by the laser pulse width which may be small compared to the radio frequency wavelength thus eliminating the need for a buncher and permitting small energy spreads.
- The electron bunch is synchronized with the laser pulse to picosecond accuracy.
- Very low emittance beams can be produced by suitably shaping the laser pulse.
- The rf cavity can support gradients at the cathode of the order of 100 MV/m thus minimizing emittance growth due to space charge forces.
- A multicavity gun can deliver a beam of several MeV.
- The gun can operate at the same frequency as the linac.
- Optimum design of the gun cavity can minimize the emittance growth due to nonlinear components of the transverse electric and magnetic fields.

Photocathode Design

The photocathode requirements are as follows:

- It should have fractional picosecond response time in order to precisely follow the laser pulse form.
- It should have good quantum efficiency for operation with the laser well below damage thresholds.
- The cathode material should be robust, have good mechanical and chemical stability, and long lifetime.
- The work function should be close to and less than the photon energy of the laser.

EXPERIMENTS

USE COPPER WITH WORK FUNCTION $\sim 4.3 \text{ eV}$
 AND YTTRIUM " $\sim 3.1 \text{ eV}$
 TO TEST EFFECT OF INITIAL ENERGY OF
 ELECTRONS ON TRANSVERSE EMITTANCE.
 ALSO USE DIFFERENT PREPARATION METHODS
 TO TEST SURFACE EFFECTS.

FREQUENCY QUADRUPLD Nd:YAG
 GIVES 4.65 eV PHOTONS.

INPUT BEAM PARAMETERS

LASER SPOT RADIUS = 3 mm, LASER PULSE WIDTH = 0.6 mm
 BUNCH CHARGE = 1 nC, ϵ_x at cathode = 3.5 mm-mrad.

Figure 4. The transverse phase space at the exit of the rf gun for a bunch as given in the table. $\sigma_z = 4.2$ mm, $\sigma_{z'} = 28$ mrad, and $\epsilon_z = 7.3$ mm-mrad.

Figure 5. The longitudinal phase space at the exit of the gun. $\sigma_z = 0.6$ mm, and $\sigma_E = 17$ keV.

$$\epsilon_x = \frac{1}{mc} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2} = \sqrt{\langle x^2 \rangle \langle \gamma^2 \beta_x^2 \rangle - \langle x \gamma \beta_x \rangle^2}$$

SO CALLED R.M.S. EMITTANCE

Figure 8. The transverse emittance (solid curves) as a function of the peak rf field on the cathode, and the optimum phase (dashed curve) for the laser pulse to strike the cathode. Other parameters are as in the table.

Figure 9. The transverse emittance ϵ_x as a function of the charge of the electron bunch, with other parameters as in the table.

The Injection System

Features

- (1) Convenient Laser Access to Photocathode**
- (2) Magnetic Pulse Compression**
- (3) Allows for Momentum Selection**

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Sources of Emittance Growth in the Transport Line

- mismatch caused by linear space charge forces and nonlinear space charge effects

OPERATE FIRST TRIPLET IN NON SYMMETRIC DFD' HORIZONTAL MODE.

- chromatic effects

- nonlinear magnetic fields

- spherical aberrations

USE LARGE APERTURE QUADRUPOLES WITH GOOD FIELD QUALITY.

USE APERTURES TO CUT OFF UNWANTED ELECTRONS.

SLIT CAN BE SET TO ELIMINATE ELECTRONS OF MOMENTUM SPREAD $> 0.1\%$

BEAM PIPE CUTS OFF ELECTRONS AT $> 2\sigma$ RADIAL DIMENSION

75% OF ELECTRONS FROM THE GUN SURVIVE FOR A MOMENTUM CUT OF 0.4%

HORIZONTAL EMITTANCE GROWS BY A FACTOR OF 2.5 WHILE VERTICAL EMITTANCE IS UNCHANGED.

Factors Effecting the Output Energy and Phase Spread of the Electron Beam

- a. microscopic effects within a single bunch such as:
- RF field and phase changes during the bunch
 - longitudinal wake fields **MAJOR CONTRIBUTION**
 - space charge effects

SOLUTION - USE RF FIELD GRADIENT COMPENSATION IN THE ACCELERATING SECTIONS.

- b. macroscopic effects during a 100 bunch train of pulses such as:
- rf field and phase changes during the macropulse due to the modulator etc.
 - input beam microbunch to microbunch energy and phase variations **BEAM LOADING.**
 - amplitude and phase variations due to different filling times of the gun and accelerating sections
 - beam loading effects

$$\frac{G_{UN}}{V_{OUT}} \propto \sqrt{P_{IN}}$$

SOLUTION - FEED FORWARD SYSTEM.

- c. macropulse to macropulse effects due to:
- modulator pulse jitter in amplitude and time
 - temperature effects
 - laser amplitude and phase jitter

SOLUTION - LASER AMPLITUDE CONTROL AND TIMING STABILIZATION.

BLOCK DIAGRAM OF THE MODULATOR FEED
FORWARD CONTROL SYSTEM

COMPARISON BETWEEN CORRECTED AND UNCORRECTED PHASE AND AMPLITUDE SIGNALS OUT OF THE KLYSTRON

LIGHTWAVE ELECTRONICS SYSTEM
TIMING JITTER OF 20pSec REDUCED TO < 0.3pSec r.m.s.

Laser Timing Stabilizer

ATF-YAG BEAM TRANSPORT

Brookhaven Accelerator Test Facility RF Gun Results

- 5.6 MW input RF power
- 600 μ J laser power at 248 nm
- Photo-ejected electrons accelerated to 4.2 MeV
- Measured Shunt Impedance = 50 M Ω /m
- $dp/p = \pm 0.5 \%$
- $I_{avg} = 8$ mAmps
- $I_{peak} = 0.6$ Amps
- Initial quantum efficiency is 1.4×10^{-4}

USED EXCIMER LASER AT $\lambda = 248$ nm
20 nsec PULSE WIDTH SO EQUIVALENT TO
CW DURING 3.5 μ sec GUN RF PULSE.

MEASURED EMITTANCE RMS (σ) < 10 π mm.mrad.

USED "DARK CURRENT" TO MEASURE
ELECTRON MOMENTUM.

MOMENTUM DISTRIBUTION OF DARK CURRENT

Fig.1 Experimental dark current momentum spectrum

Future Improvements

- the effect of solenoidal focussing on the output beam divergence and emittance
- the effect of multicell gun cavities on the emittance and beam divergence
- the effect of cathode shaping and of laser pulse distributions.
- the effect of different cathode materials on the emittance from the gun
- connecting the electron gun directly to the linac and exciting the photocathode at an angle

The Brookhaven Accelerator Test Facility

Proposed Experiments

- (1) **Laser Grating** OPEN STRUCTURES - LASER EXCITED, $\lambda \sim 10 \mu\text{m}$
3 mm INTERACTION REGION $\rightarrow$ 3 MeV ENERGY GAIN.
(BNL, LANL)
- (2) **Inverse FEL** USE ELECTROMAGNET, TAPERED WIGGLER OF 125T
EXCITED BY THE CO₂ LASER AT $10 \mu\text{m}$.
(BNL, Columbia, LANL, Yale)
- (3) **Picosecond X-ray Source**
(BNL, Princeton)
- (4) **Inverse Cerenkov Acceleration** USE RADIALY POLARIZED RADIATION
FROM CO₂ LASER ONTO THE AXIS AT THE CERENKOV ANGLE TO ACCELERATE THE
ELECTRONS (Spectra Technology, UC Santa Barbara) USES H₂ GAS CELL
- (5) **Non-linear Electrodynamics** USE CO₂ LASER BEAM TO STRIKE
ELECTRON BEAM HEAD-ON - LOOK FOR HIGHER HARMONICS IN COMPTON SCATTERED
PHOTONS. (BNL, LANL, Princeton)
- (6) **FEL** USE SUPERCONDUCTING MICROWIGGLER, 60 cm LONG, 8.8 mm PERIOD
WITH PEAK FIELD OF 0.47T. SHOULD GIVE PEAK POWER $\sim$ 11 MW, AT 500 nm.
(BNL, MIT, Rockwell International, Stony Brook)
- (7) **Switched-Power Acceleration**
(BNL, CERN, Rochester)

bnl
bnl

LINAC APPLICATIONS

[ELECTRON, POSITRON, PROTON, HEAVY ION, NEUTRAL BEAM]
(CONFERENCES ORIGINALLY DOMINATED BY PROTON MACHINES)

NUCLEAR & HIGH ENERGY FIXED TARGET RESEARCH (BATES CEBAF ...)

INJECTORS (MANY)

COMPONENTS IN RECIRCULATING MACHINES (CEBAF--LEP)

LINEAR COLLIDERS (SLC CLIC VLEPP JLC DESY)

TRITIUM PRODUCTION (NEUTRON SOURCE)

FISSION REACTORS (NEUTRON SOURCE)

MEDICAL APPLICATIONS (ELECTRON/PROTON/NEUTRON/PION/HEAVY ION)

INDUSTRIAL MANUFACTURING AND TESTING (X-RAYS, GLUES, STERILIZING)

SDI APPLICATIONS (BEAR ACCELERATOR)

FEL DRIVERS

ADVANCES IN TECHNOLOGY

CRYOGENICS

VACUUM AND HIGH VOLTAGE CAPABILITY

RADIO FREQUENCY QUADRUPOLES

RADIO FREQUENCY POWER SOURCES

FEED FORWARD SCHEMES FOR ENERGY CONTROL

BEAM EXPERIMENT ABOARD ROCKET

NEW FACILITIES

RF ELECTRON GUNS

LINEAR COLLIDERS

CEBAF RECIRCULATING LINAC

SSC INJECTOR LINAC (600MEV H-)

CW PROTON LINAC DESIGNS

JAPANESE HADRON PROJECT

A LINEAR ACCELERATOR IN SPACE—THE BEAM EXPERIMENT ABOARD ROCKET*

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ABSTRACT

On July 13, 1989, the Beam Experiment Aboard Rocket (BEAR) linear accelerator was successfully launched and operated in space. The flight demonstrated that a neutral hydrogen beam could be successfully propagated in an exoatmospheric environment. The accelerator, which was the result of an extensive collaboration between Los Alamos National Laboratory and industrial partners, was designed to produce a 10-mA (equivalent), 1-MeV neutral hydrogen beam in 50- μ s pulses at 5 Hz. The major components were a 30-kV H^- injector, a 1-MeV radio-frequency quadrupole, two 425 MHz radio-frequency (RF) amplifiers, a gas cell neutralizer, beam optics, vacuum system, and controls. The design was strongly constrained by the need for a light-weight rugged system that would survive the rigors of launch and that would operate autonomously. Following the flight, the accelerator was recovered and continues to operate in the laboratory. A description of the accelerator design and operation will be given.

*Work supported and funded by the US Department of Defense, Army Strategic Defense Command, under the auspices of the US Department of Energy.

REPORTS AT CONFERENCE

Table 4

LABORATORY	STATUS	BEGINNING OF DESIGN	BEGINNING OF TESTS	PURPOSE
THERMIONIC RF GUNS				
EEPL — DFELL	TESTED	1983	1/85	FEL
HEP	TESTED	5/86	1/88	R FEL
MITSUBISHI	TESTED	?	?	?
IPT	TESTED	?	?	?
AET/VARIAN/SSRL	UNDER TESTS	1988 ?	1989	STO. RING INJ.
KEK	DES./CONST.	1989	1989	FEL/OTHER
NCCU	DES./CONST.	?	1991	MICROWAVE GEN.
LASER-DRIVEN RF GUNS				
LANL	TESTED	1984 ?	1985	RF GUN
LANL (HIBAF)	OPERATING	9/88	5/89	R FEL
SPRL — DFELL	TESTED	1987 ?	9/88	FEL
CEA	UNDER TESTS	3/86	1989	R FEL
BNL	UNDER TESTS	1987 ?	1989	NEW ACC. METE.
CERN	CONSTRUCTION	1989	1990	COLLIDER
ANL	CONSTRUCTION	1988	?	WAKEFIELD ACC.
WUPPERTAL	CONSTRUCTION	1987 ?	?	BRIGHT INJ.
TWENTE	CONSTRUCTION	?	?	FEL
BOEING	DES./CONST.	?	?	FEL
LANL (AFEL)	DESIGN	1988 ?	?	R FEL
INFN MILAN	DESIGN	1988 ?	?	FEL
LAL	DESIGN	9/89	1991	RF GUN
INFN FRASCATI	DESIGN	?	?	4-FACT./FEL
LLNL/SLAC/LBL	STOPPED	1987	-	HIGH GRAD. ACC.
FIELD EMISSION RF GUNS				
HEP	PREL. STUD.	1988 ?	?	FEL
LAL	STOPPED	1988	1/89	RF GUN

Table 5: Thermionic RF guns parameters

	DFELL ⁽¹⁾	IHEP ⁽¹⁾	IPT ⁽¹⁾	SSRL ⁽²⁾	KEK ⁽²⁾
CATHODE	LaB ₆	LaB ₆	Ba-Ni	DISP.	LaB ₆
CATHODE AREA (cm ²)	7. 10 ⁻²	7. 10 ⁻²		0.28	7. 10 ⁻²
NUMBER OF CAVITIES	1	1	1	2	1
FREQUENCY (MHz)	2857	2856	2797	2856	2856
MAX. ON AXIS FIELD (MV/m)	55	50		60 - 80 ⁽³⁾	40
MAX. SURFACE FIELD (MV/m)	95	85		160	
FIELD AT CATHODE (MV/m)	40	30	60	15 - 20	40
MACROPULSE LENGTH (μs)	9	2	1.4	2	4
MACROPULSE FREQ. (Hz)	30	12.5		10	25
KINETIC ENERGY (MeV)	~ 1	0.7 - 0.9	0.5 - 0.9	1.7 - 2.5	
CHARGE (nC)	0.078	0.08 - 0.1		0.075	
RMS MICROPULSE LENGTH (ps)	2 - 3	4 - 5	3 - 5	2.5 - 3.5 2.5 - 4.0	
MICROPULSE FREQ. (MHz)	2857	2856	2797	2856	2856
PEAK CURRENT (A)	20 - 40	10 - 20		1.5 ⁽⁴⁾	
NORM. EMIT. (π mm mrad)	10 (4) ⁽⁵⁾	30 (10) ⁽⁶⁾	≤ 20	44 ⁽⁴⁾	
NORM. BRIGHT. (10 ¹⁰ A/m ² rad ²)	20.3	1.35		> 1.0	
RMS ENERGY SPREAD (KeV)	220	200		~ 300	

(1) EXPERIMENTAL RESULTS (GUN + α MAGNET)

(2) DESIGN PARAMETERS

(3) IN THE FIRST CELL: 20-30 MV/m

(4) NO α MAGNET

(5) HORIZONTAL (VERTICAL) EMITTANCE DEFINED AS FWHM: $\epsilon = 2 \ln(2) \beta \gamma \sigma \sigma'$ (6) HORIZONTAL (VERTICAL) EMITTANCE DEFINED AS: $\epsilon = \beta \gamma \pi \sigma \sigma'$

Table 6: Laser-driven RF guns parameters

	LANL				DFELL
	PHASE I ⁽¹⁾	PHASE II ⁽¹⁾	HIBAF ⁽¹⁾	AFEL ⁽²⁾	(1)
LASER TYPE	Nd:YAG	Nd:YAG	Nd:YLF	Nd:YLF	Nd:YAG
LASER WAVELENGTH (nm)	532	532	527	527	355
LASER MICROPULSE LENGTH (ps)	70	16	5 - 30	10	100
LASER MICROPULSE ENERGY (μ J)			4.6		40
CATHODE	Cs ₃ Sb	CsK ₂ Sb	CsK ₂ Sb	CsK ₂ Sb	LaB ₆
CATHODE AREA (cm ²)	1	1	0.5	0.5	
NUMBER OF CAVITIES	1	2	5 1/2		1
FREQUENCY (MHz)	1300	1300	1300	1300	2857
MAX. ON AXIS FIELD (MV/m)			25		55
MAX. SURFACE FIELD (MV/m)	58.9	58.9	59.8	60	95
FIELD AT CATHODE (MV/m)			26		40
MAGNETIC FOCUSING	YES	YES	YES	YES	
MACROPULSE LENGTH (μ s)	20	10	10 - 100	10	3
MACROPULSE FREQ. (Hz)	1	10	1		10
KINETIC ENERGY (MeV)	1.1	2.7	6	15	~ 1
CHARGE (nC)	11	13.2	4	5	0.17
MICROPULSE LENGTH (ps)	70	22	15	16	2 - 3 ⁽³⁾⁽⁴⁾
MICROPULSE FREQ. (MHz)	108.33	108.33	21.67	21.67	95.2
PEAK CURRENT (A)	200	600	270	350	60 - 80 ⁽³⁾
NORM. EMIT. (π mm mrad)	40		35 ⁽⁵⁾	10	8 (4) ⁽³⁾⁽⁶⁾
RMS ENERGY SPREAD (KeV)	66	380	50		300
NORM. BRIGHTNESS (10^{10} A/m ² rad ²)	2.53		4.47	70.9	50.7

(1) EXPERIMENTAL RESULTS

(2) DESIGN PARAMETERS

(3) WITH α MAGNET(4) RMS VALUE (1 σ)

(5) MEASURED AT 17 MeV

(6) HORIZONTAL (VERTICAL) EMITTANCE DEFINED AS FWHM: $\epsilon = 2 \ln(2) \beta \gamma \pi \sigma \sigma'$

Table 7: Laser-driven RF guns parameters

	CEA	BNL	CERN	ANL	BUGW
LASER TYPE	Nd:YAG	Nd:YAG	Nd:YLF		Nd:YAG
LASER WAVELENGTH (nm)	532	266	351/527	248 - 266	527
LASER PULSE LENGTH (ps)	30 - 100	6	6 - 50	1	70
LASER PULSE ENERGY (μ J)	10 - 20	100	500/2000	5000	0.01
CATHODE	CsK ₂ Sb	YTTRIUM	(1)	YTTRIUM	CsK ₂ Sb
CATHODE AREA (cm ²)	1 - 2	0.28	~ 1	~ 3	1.13
NUMBER OF CAVITIES	1	1 1/2	1 1/2	1	1 ⁽²⁾
FREQUENCY (MHz)	144.4	2856	3000	1300	500
MAX. ON AXIS FIELD (MV/m)	20	100 ⁽³⁾	100		25
MAX. SURFACE FIELD (MV/m)	23.2	118	134	120	30
FIELD AT CATHODE (MV/m)	20	100	100	92	25
MAGNETIC FOCUSING	YES	NO	NO	YES	
MACROPULSE LENGTH (μ s)	400	3.5	≤ 4.5	8	CW
MACROPULSE FREQ. (Hz)	10 - 30	6	10	30 - 60	-
KINETIC ENERGY (MeV)	1.3 - 1.5	4.17	3.9	2	1.87
CHARGE (nC)	1 - 20	1	9	100	2.5
MICROPULSE LENGTH (ps)	~ 100	8	30	8	70
MICROPULSE FREQ. (MHz)	14.4 - 72.2	80	1 PULSE	1 PULSE	125
PEAK CURRENT (A)	150 - 200	125	400 - 500	10 ⁴	35
NORM. EMIT. (π mm mrad)	90 ⁽⁴⁾	46	≤ 150	1360	
RMS ENERGY SPREAD (KeV)		17	80	400	
NORM. BRIGHT. (10 ¹⁰ A/m ² rad ²)	0.25	1.2	≥ 0.45	0.11	

(1) METALLIC OR MULTI-ALKALINE

(2) SUPERCONDUCTING CAVITY

(3) EXPERIMENTAL DATA: 90 MV/m

(4) EXPERIMENTAL DATA FOR 10 nC

Table 8: Laser-driven RF guns parameters

	TWENTE	BOEING	MILAN	LAL	FRASCATI	LBL
LASER TYPE	Nd:YLF		Nd:YLF		Nd:YLF	Nd:YAG
LASER WAVELENGTH (nm)			526			532 ..
LASER PULSE LENGTH (ps)			150 - 200	30	20/40	15
LASER PULSE ENERGY (μ J)			20		0.17/17	0.5
CATHODE	CsK_2Sb		CsK_2Sb	DISP.	Cs_3Sb	Cs_3Sb
CATHODE AREA (cm^2)	1	0.63	7	0.28		0.28
NUMBER OF CAVITIES	5 1/2	2	1 1/2	2	3 ⁽¹⁾	2 1/2
FREQUENCY (MHz)	1300	433.3	352	2998.5	499.5	1269
MAX. ON AXIS FIELD (MV/m)		38.6	15	70		60
MAX. SURFACE FIELD (MV/m)			22.5	112		67.2
FIELD AT CATHODE (MV/m)	25			52.5	30 - 40	60
MAGNETIC FOCUSING	YES	YES	YES	NO		NO
MACROPULSE LENGTH (μs)	10			2 - 5	CW	0.02
MACROPULSE FREQ. (Hz)	10		> 50	10	-	1 - 5
KINETIC ENERGY (MeV)	6	1.92	3.6	2.9	3.8/6.8	10
CHARGE (nC)	7	10	80	2	0.5/20	1
MICROPULSE LENGTH (ps)	20	60	200	17	21/42	4 - 12
MICROPULSE FREQ. (MHz)	81.25		352		$10^{-3}/3 \cdot 10^{-5}$	423
PEAK CURRENT (A)	350	167	400	118	18.5/350 ⁽²⁾	118 - 212
NORM. EMIT. (π mm mrad)	17	90	640	34	22/424	30 - 50
RMS ENERGY SPREAD (KeV)	50	80	60	< 30	34/195	20 - 30
NORM. BRIGHT. (10^{10} A/m ² rad ²)	24.5	0.42	0.02	2.07	0.77/0.04	1.7 - 2.7

(1) SUPERCONDUCTING CAVITIES

(2) BEFORE MAGNETIC BUNCHING

briefly describe the different elements of the accelerator. The new technology of the photoinjector has been applied to this design to extract the 80 nC beam and a superconducting accelerator is used to accelerate the electrons up to 10 MeV. The second part of the paper will be dedicated to the most important aspects of the beam dynamics and to the solutions found for optimizing the emittance and the energy spread of the beam. Recent theoretical calculations have proved that the combined action of space charge forces and of focussing forces can reduce the transverse emittance [ref 1].

1 MeV respectively. Two units, the first between the accelerators and the second between the last accelerator and the wiggler, allow the installation of the diagnostic instruments, the injection of the photocathode laser beam, and the 3 mm radiation into the wiggler. Enough space remains for the cryostat. A focussing system on the injector reduces the effects of the space charge force and four quadrupoles, in the last drift, match the beam into the wiggler (fig 1).

The design of the injector and all the cavities parameters are chosen to minimize the emittance growth caused by the space charge and by the non linear

Fig.1. Schematic view of the accelerator.

*Work supported and funded by INFN, Italian Institute of Nuclear Physics, through a collaboration with Los Alamos National Laboratory under the auspices of the US Department of Energy.

ELFA

A 2-MeV MICROWAVE THERMIONIC GUN[†]E. Tanabe,[‡] M. Borland,^{*} M. C. Green,[§] R. H. Miller,^{*} L. V. Nelson,[§] J. N. Weaver,^{*} and H. Wiedemann^{*}[†] AET Associates, Cupertino, CA 95014, USA^{*} Stanford Synchrotron Radiation Laboratory, Stanford University, Stanford, CA 94309, USA[§] Varian Associates, Palo Alto, CA 94303, USA^{*} Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

SSRL

ABSTRACT

A high gradient, S-band microwave gun with a thermionic cathode is being developed in a collaborative effort by AET, Varian, and SSRL. A prototype design using an upgraded Varian dispenser cathode mounted with thermal isolation directly in the first half-cell of a 1-1/2 cell, side-coupled, standing-wave cavity has been fabricated and is being tested. Optimization of the cavity shape and beam formation was done using SUPERFISH, MASK, and PARMELA. An overview of design details, as well as the status of in-progress beam tests, will be presented.

INTRODUCTION

In a collaborative effort, AET Associates, Varian Associates (VA) and the Stanford Synchrotron Radiation Laboratory (SSRL) are developing a 2 MeV S-band microwave electron gun. In one application it would be an integral part of a VA medical or radiographic accelerator. In another application it would be part of a SSRL pre-injector for SPEAR as a synchrotron light source. In the first case simplicity and compactness are the design criteria. The goal is to be able to mount a cathode directly in the first half cell of a standard VA side-coupled, standing-wave accelerator section. Thus, the normally-used 20 kV gun insulator and pulse-transformer winding would be eliminated, but cathode thermal isolation and back-bombardment heating problems might be substituted. In the second case, a 1-1/2 cell (plus one side-coupling cell) microwave gun will generate a train of bunches that will be compressed in time by an alpha magnet and narrowed in energy spread by slits built into the alpha magnet. A fast, FET-switched chopper-collimator at the entrance to a 150 MeV linac will allow selection of three bunches out of the train of bunches that are produced over a range of energies

Fig. 1: Cross-sectional view of the 1-1/2 on-axis cells.

particles that do not reach the second cavity return to hit the cathode, but with about half the average kinetic energy of the particles that exit the first cell. For $60 \text{ MV/m} < E_{p1} < 80 \text{ MV/m}$, 85–90% of the particles in the second cell exit by the desired route. The remaining particles are accelerated back into the first cell or hit the cavity walls.

The transverse distribution is affected by many factors, including the rate of acceleration in the first cell, the focusing nose near the cathode, the size of the cathode, the current density, the radial electric fields produced by the noses in the second cell, and the thermal energy of electrons (this latter effect is negligible). Of these, the focusing nose near the cathode, the size of the cathode, and the current density are most readily varied and controlled. The rate of acceleration in the first cell is limited by the desire to keep back-bombardment low. For simplicity in construction and design, the noses in the second cell were unaltered from a standard Varian design. However, due to the RF nature of the focusing from these noses, they affect the beam emittance, and modifying their shape may be worthwhile in future designs.

To the authors' knowledge, there is no prescription for optimum radial fields near the cathode for an RF gun that emits a long pulse, for which the time dependence of the RF focusing dominates the emittance, though such a criterion does exist for a short pulse.^{2,3} From simulations with MASK, it was found that the emittance is a weak function of the shape and position of the focusing noses, provided that the beam is not focused to a waist in the first cell. Hence, the focusing was made only weakly convergent; i.e., only sufficient to keep the beam from hitting the "anode" nose and the drift-tube walls between the first and second cells. In order to further reduce transverse space-charge effects and maximize the lifetime of the cathode, the cathode current density was kept low by using a 6-mm-diameter cathode. A beam tube diameter of 7.5 mm was chosen to maintain a high shunt impedance with minimum beam interception. No claim is made that the optimum possible combination has been found.

Figure 3 shows the comparison of numerical results from SUPERFISH and experimental results from a beam-drop

Fig. 3: The longitudinal electric field profile along the beam centerline through the gun (solid = computed; dashed = measured).

measurement of the axial electric field of the cavity of Fig. 1. Figures 4(a), (b) and (c) shows that the beam size increases as the current density is increased for a fixed accelerating field. A comparison of Figs. 4(a) and (d) shows that the beam size—and, in fact, the emittance—decreases with decreased accelerating field; for the lower accelerating field, this smaller emittance may be a result of less charge entering the second cell. Figure 5 gives the energy spectra versus bunched-beam charge, Q , for various RF accelerating field levels. Figure 6 shows the dependence of emittance and accelerated charge on the peak cathode current.

ACKNOWLEDGMENTS

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Fig. 4: Transverse phase-space distribution at the gun exit with $\alpha = 3$ in all cases: (a) $E_{p2} = 75 \text{ MV/m}$ and $J = 10 \text{ A/cm}^2$, (b) $E_{p2} = 75 \text{ MV/m}$ and $J = 40 \text{ A/cm}^2$, (c) $E_{p2} = 75 \text{ MV/m}$ and $J = 80 \text{ A/cm}^2$, and (d) $E_{p2} = 60 \text{ MV/m}$ and $J = 10 \text{ A/cm}^2$.

BOEING

Table I. Electron Beam and Thunder Wiggler Parameters.

Electron Beam:

Electron Beam Energy	110 Mev
Repetition Rate	2 Hertz
Macropulse Length	110 microseconds
Micropulse Spacing	443 nanoseconds
Emittance (4 rms)	100-120 π mm mR
Macropulse Energy Jitter	.5% to .75% FWHM
Micropulse Energy Spread	.5% FWHM
Micropulse Width	12 picoseconds FWHM
Micropulse Charge	3 nanocoulombs

Thunder Wiggler:

Length	5 m in 10, 50 cm sections
Wiggler Period	2.18 cm
Number of Periods	220 periods
Peak Magnetic Field	10.2 KGauss
Wiggler Parameter	1.8 (peak)
Wiggler Parameter	1.31 (rms)
Betatron Period	5.6 m

LASL

PLANNED CONFIGURATION

The planned configuration for the HIBAF facility is shown in Fig. 1. The second wiggler is to be employed in a master oscillator, power amplifier (MOPA) configuration. The 150° bend can be tuned as a buncher.

40 MeV

PHOTOINJECTOR/ACCELERATOR CONFIGURATION

The photoinjector/accelerator (Fig. 3) operates in a $\pi/2$ mode with on-axis coupling cells. The Molybdenum cathode plug is retracted into the cathode preparation chamber to prepare a new cathode by vapor deposition of the elemental components. The first accelerating cell, operating at fields of 26 MeV/m, is designed for minimum emittance growth of the electron beam. For maximum lifetime of the photocathode, the tank is designed to be bakable and operates at a pressure of $<10^{-9}$ Torr.

AT-1

PHOTOINJECTOR LINAC PERFORMANCE SUMMARY

April 1990

	<u>Design</u>	<u>Performance</u>
Beam Energy (MeV)	17	14-17
Micropulse Energy Spread (%)	0.3	0.3
Macropulse Length (μ s)	10-100	10-40
Macropulse Rep.Rate (Hz)	1	1
Micropulse Length (ps)	15	15
Micropulse Rep Rate (MHz)	21.7	21.7
Emittance (π mm-mrad at 5nc)	25-50	35-50
Micropulse charge (nC)	0-5	0-10
Peak Current (A)	300	>300
Cathode Quantum Efficiency (%)	>1	7

Work is underway to upgrade the linac to 40 Mev for FEL experiments

MEASURED EMITTANCES

Figure 8 shows some of the measured emittance values together with the micropulse charge. The emittances are based on single micropulse, two screen, full width half max beam profile measurements, with with an assumption that the profiles are Gaussian. The calculated emittance from beam profiles and PARMELA simulations is under study.

EFFECT OF CATHODE MAGNETIC FIELDS ON EMITTANCE

Measured beam emittance is a strong function of cathode magnetic field. From Busch's theorem:

$$\epsilon_m = [\epsilon_i^2 + (2eR_c^2 B_c / mc)^2]^{0.5}$$

Where

ϵ_m = Measured emittance

ϵ_i = intrinsic emittance

R_c = cathode radius

B_c = Magnetic field on cathode

Figure 7 illustrates the variation in emittance caused by varying the field on the cathode. The emittance values are based on two-screen, full width beam profile measurements.

THE STANFORD LINEAR COLLIDER*

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The Stanford Linear Collider (SLC) has been in operation for several years. The initial round of particle and accelerator physics experiments has been completed. A synopsis of these results will be given. The second round of experiments is now under preparation. A new physics detector will be installed. An increase in the peak luminosity of about a factor of 80 by late 1991 is under development. Collisions at high intensity and with polarized electrons are planned. The beam dynamics and technological advances needed for these improvements will be covered in detail.

* Work supported by Department of Energy contract DE-AC03-76SF00515.

NEW WORK SLAC/LBL/LLNL
RELATIVISTIC KLYSTRON FOR 1TeV LINEAR COLLIDER
TESTED ~ 200MW, 11.4GHz, ~ 100nsec.
1.2MV, 1KA ELECTRON BEAM IN KLYSTRON
6 CELL TW OUTPUT CAVITY.
POWERED ACCELERATING SECTION AT
140 MV/m.

MO1-2

STATUS OF CERN LINEAR COLLIDER STUDIES

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ABSTRACT

A description is given of the topics which have been the subject of studies and developments, and the status of the work on a CERN linear collider (CLIC) is summarized. Progress was made on the test facility, for investigating the critical question of generating the short and intense bunches required for the driving beam. In the drive linac, the wake fields associated with the transfer structure and the consequent stability issue are severe. Therefore, studies and calculations are carried on overmoded pipes, cylindrical with either symmetrical corrugations or combs asymmetrically placed on one side. In the main linac, the question was addressed of minimizing the energy spread by shifting the phase of the accelerating voltage, leading to requirements conflicting with those for beam stability. A prototype of high-gradient accelerating cells has been built and measured. In parallel with the design studies of the final focus system, a model of a small-aperture, high-gradient quadrupole, that could be part of the scheme, has been realized and measured.

1 TeV COLLIDER, 296 Hz, DISC LOADED STRUCTURE
WITH SLOTS IN SOME CELLS TO SUPPRESS TRANSVERSE MODES
5000 SECTIONS, 24.8 CM LONG.
TWO BEAM ACCELERATOR, STUDIES ON DRIVE BEAM.

THE JAPAN LINEAR COLLIDER

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ABSTRACT

Various R&D activities are held on at KEK for the basic technology for the Japan Linear Collider, JLC, a TeV class electron/positron linear collider in Japan. The main linac for each beam will be 5 km long with the RF frequency being 11.4 GHz and average gradient 100 MV/m. As the RF source X-band klystrons of the output power 30 to 100 MW are under development. The high gradient studies are going on for an S-band 60 cm long structure and a gradient of 85 MV/m has been stably attained. Since the emittance blow up should be minimized in the long linac, careful studies of the wakefields including the method for damping them have been the most important issue in the structure design.

VLEPP LINEAR COLLIDER PROJECT IN THE SOVIET UNION

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Abstract

In the USSR we have developed a project for a linear collider with polarized electron-positron beams at an energy of 2×250 GeV for the first step and 2×1000 GeV for the final step. I will describe a new approach to designing the rf-power source, a new scheme of power compression, and also requirements for acceleration of very intense single bunches without instability and dilution of emittance.

Design Study of a 500 GeV Linear Collider

T. Weiland for the DESY/THD Linear Collider Study Group*

Future accelerator schemes for linear colliders, such as high-gradient, very high-frequency rf linacs, two-beam and wakefield accelerators, are not likely to lead to a realizable high energy e^+e^- collider in the near future. Thus we propose to consider a 500 GeV c.m. linear collider based almost entirely on conventional technology. The basic components are S-band travelling wave, constant-gradient accelerating structures, 130MW klystrons, damping rings at 3 GeV, and a final focus lattice. We present a status report of the investigations that have recently been started. Already at this early stage of our studies, it seems very likely that such a conventional collider could indeed be built in this decade.

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CEBAF PROGRESS REPORT

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At the Continuous Electron Beam Accelerator Facility (CEBAF), under construction in Newport News, Virginia, a pair of 400-MeV superconducting linacs interconnected for five-pass recirculation will provide 4-GeV, 200- μ A, cw electron beams to simultaneous nuclear physics experiments in three end stations. As of June 1990, the first production-version cryomodule has been successfully tested; the injector's initial superconducting quarter-cryomodule has accelerated beam to the required 5 MeV; and the first industrially produced accelerating cavities, klystrons, and cryomodule components have been received and successfully tested. Concrete work on the 1400m cast-in-place, racetrack-shaped tunnel was completed in June, and the first section was occupied in January 1990; occupancy is to proceed in stages through late 1990. Installation has begun on the 4800-W central helium refrigerator and on the helium transfer lines, accelerator control, and DC power systems. Installation of the 45-MeV injector is to begin in fall 1990, with systems tests to follow. Initial nuclear physics experiments have been defined, the conceptual design report for experimental equipment is complete, and end station construction has begun. Project completion is scheduled for 1993, with first physics in 1994. Construction cost is \$265M.

CAVITY POWER ~ 10 W
 BEAM POWER ~ 1 KW

AMPLITUDE STABILITY $\pm 2 \times 10^{-5}$
 SHORT TERM, 10^{-3} LONG
 PHASE $\pm 0.2^\circ$ SHORT TERM
 1.0° LONG TERM

MO2-2

THE SSC LINAC

Jerry M. Watson
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2550 Beckleymeade Avenue
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The preliminary design of the 600 MeV H^- linac for the Superconducting Super Collider injector will be described. The linac must provide a 25 mA beam during 7–35 μ sec macropulses at 10 Hz within injection bursts. Normalized transverse emittances of less than 0.5π mm-mrad (rms) are required for injection into the Low Energy Booster synchrotron. Cost, ease of commissioning, and operational reliability are important considerations. The linac will consist of an H^- source with electrostatic LEBT, 2.5 MeV radiofrequency quadrupole accelerator, a 70 MeV drift-tube linac, and 530 MeV of side-coupled linac. The RFQ and DTL operate at 428 MHz and the side-coupled linac operates at 1284 MHz. Several design tradeoffs between cost, beam dynamics, and reliability will be discussed. A modest total length of 150 m results from the tradeoff between cost optimization and reliability. The expected performance from beam dynamics simulations and the status of the design will be described.

*Supported by Universities Research Association, Inc. under contract with the United States Department of Energy.

MO3-1

LINEAR ACCELERATOR FOR BURNER-REACTOR

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ABSTRACT

A concept of powerful proton linear accelerator to operate in continuous regime with the power of several hundred megawatts is presented. The burner-reactor is proposed on the basis of the linac. Design principles, scheme, accelerator parameters are considered. Economy, reliability and radiation purity problems are analysed. Special attention is given to a new HF device, which generates superpower by use of REB with distributed power output. High efficiency enables to generate power up to ten megawatts. Strong axial magnetic field focusing in the initial part of the accelerator provides limiting current of the order of several amps.

1 TO 1.5 GeV, PROTON LINAC, 300 mA, Cu.
ELECTROSTATIC INJECTOR AT 311 kV
3 TO 5 MeV RFQ
5 TO 200 MeV, H-STRUCTURE OR ALVAREZ WITH
PERMANENT MAGNET QUADRUPOLES
200 MeV UP EITHER SIDE COUPLED OR
DISC AND WASHLET

TH3-3

Fig.1. Block-diagram of the 1A deuteron linac.

W_{output} (MeV)	3.5	150	1500
f (MHz)	75	150	900
I_{beam} (mA)	2x150	300	300
P_{RF} (MW)	2x0.66	14	58
P_{beam} (MW)	2x0.525	44	405
P_{Z} (MW)	2.5	60	500
V_{z} (cm mrad)	5.5-3	5.5-9.4	12.3-23
I_{fil} (A)	0.93	4.4	42
l (cm)	8	69	330

Fig.2. Block-diagram of high-energy linac.

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Mitsubishi Heavy Industries, Ltd. (MHI)

Nagoya Aerospace Systems Works

E.TAKASAKI, T.KATO, F.NAITO and Y.YAMAZAKI

KEK-National Laboratory for High Energy Physics

ABSTRACT

A model of the drift tube provided with permanent magnets has been fabricated in joint collaboration by KEK AND MHI.

Some particulars on

- 1) Fabrication of drift tube by cold shrinking method,
 - 2) Precise method of fitting permanent magnets to the drift tube shell,
 - 3) Method of fitting drift tubes inside tank, and easy alignment device,
- are described.

MO4-31

FABRICATION TECHNIQUE OF ACS CAVITY FOR THE JHP

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Mitsubishi Heavy Industries, Ltd. Mihara Works

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KEK-National Laboratory for High Energy Physics

ABSTRACT

A high-power model of the ACS (Annular Coupled Structure) cavity has been fabricated and tuned to an operating frequency of 1296 MHz for the JHP (Japanese Hadron Project). The nose cone region is cooled by water flowing through channels in the septum in order to match the high-duty operation. Some details are described for machining high-Q, ultra-precision cavity segments including coupling slots. Detailed tuning procedures and heating testing are

BEAM DIAGNOSTICS FOR HIGH-BRIGHTNESS BEAMS

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ABSTRACT

Special techniques are required for beam diagnostics on high-brightness beams. Examples of high-brightness beams include low-emittance high-duty-cycle proton linacs, electron linacs suitable for free-electron-laser applications, and future linear colliders. Noninterceptive and minimally-interceptive techniques for measuring beam position, beam profile, bunch length, and transverse and longitudinal emittance will be reviewed. Included will be stripline, wire scanner, laser neutralization, beam-beam scattering, interceptive microgratings, spontaneous emission, optical transition radiation, and other techniques.

*Work supported by the US Department of Energy, Office of High Energy and Nuclear Physics

THE 433 MHZ PROTON LINAC

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ABSTRACT

RF power test of a 433 MHz proton linac is going on at Institute for Chemical Research, Kyoto University. The linac consists of a multi-cusp type ion source, 4-vane RFQ linac (50 keV to 2 MeV) and Alvarez DTL linac (2 MeV to 7 MeV). The design value of output current is 50 mA peak. The repetition rate is up to 180 Hz and the duty is 1%. The RFQ is made of CrCu and has length of 2.2 m and inner diameter of 170.4 mm. The average bore radius is 2.99 mm. The vanes are machined with two dimensional process using a concave cutter. The vane top curvature is constant, and the machining process is very easy compared to a three dimensional process. The field distribution is controlled by 24 side turners. The Alvarez cavity has 30 drift tubes of 5.5 cm diameter and length of 1.9 m. The bore radius of the drift tube is 5.5 mm. Each drift tube has eight segmented permanent magnetic Q lens made of Nd-Fe-B. The magnetic field gradient is 17.5 kG/m. Two 1.25 MW Klystron (Litton L-5773) are used to feed the RF power to each cavity. For the RF coupling, a coupling loop is used in RFQ cavity, and a coupling slot is used in Alvarez cavity.

THE FERMILAB LINAC UPGRADE

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The Fermilab Linac Upgrade is planned to increase the energy of the H⁻ linac from 200 to 400 MeV. This is intended to reduce the incoherent space-charge tuneshift at injection into the Booster which can limit either the brightness or the total intensity of the beam. The Linac Upgrade will be achieved by replacing the last four 201 MHz drift-tube tanks which accelerate the beam from 116 to 200 MeV, with seven 805 MHz side-coupled cavity modules operating at an average axial field of about 8 MV/m. This will allow acceleration to 400 MeV in the existing Linac enclosure. Each accelerator module will be driven with a klystron-based rf power supply. A prototype 24 MW rf modulator has been built and tested at Fermilab and a prototype 12 MW klystron is being fabricated at Litton Industries. Fabrication of production accelerator modules is in progress.

*Operated by the Universities Research Association under contract with the U.S. Department of Energy.

THE BNL ACCELERATOR TEST FACILITY

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The design of the Brookhaven National Laboratory Accelerator Test Facility is presented including the design goals and computational results. The heart of the system is a radiofrequency electron gun utilizing a photo-excited metal cathode followed by a conventional electron linac. The NdYAG laser used to drive the cathode with 5 psec long pulses can be synchronized to a high peak power CO₂ laser in order to study laser acceleration of electrons. Current operational status of the project will be presented along with early beam tests.

MULTIPOLES IN RFQs WITH LARGE MODULATION

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ABSTRACT

A study of the multipole content of an RFQ with large modulation is presented. We consider a practical electrode shape which is machined using a tool having a constant radius of curvature and following a curve generated by a two-term potential function. The coefficients of a truncated Fourier-Bessel series are found by fitting the potential at a number of points on the three dimensional electrode surface. An expansion containing 8 to 10 terms is found to be sufficient to reproduce the three dimensional electrode profile. This multi-term electrical potential function is used to evaluate the ratio between the accelerating and peak electric fields, and its dependence on the RFQ parameters, such as the modulation factor, and the radius of the cutting tool.

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FABRICATION TECHNIQUE OF ACS CAVITY FOR THE JHP

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Abstract

A high-power model of the ACS (Annular Coupled Structure) cavity has been fabricated and tuned to an operating frequency of 1296 MHz for the JHP (Japanese Hadron Project). The nose cone region is cooled by water flowing through channels in the septum in order to match the high-duty operation. Some details are described for machining high-Q, ultra-precision cavity segments including coupling slots. Detailed tuning procedures and brazing techniques are also presented.

SOME NEW METHODS OF RF CONTROL*

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ABSTRACT

This presentation will focus on several recent developments at Los Alamos in the area of RF control for accelerators. Included in the discussion will be in-phase/quadrature (I/Q) field control, the application of six-port reflectometers for cavity instrumentation and resonance control, a technique for phase stabilization of critical RF cables, an application of state-variable feedback for field control, and the direct integration of RF and computer-interface hardware using the VXIbus standard.

*Work supported and funded by the US Department of Defense, Army Strategic Defense Command, under the auspices of the US Department of Energy.

**A LINEAR ACCELERATOR IN SPACE—THE BEAM EXPERIMENT ABOARD
ROCKET***

Wake Field Accelerators*

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The need for new and better acceleration methods has resulted in a spectrum of proposed schemes. Among these is the wake field method, which promises significant advances in performance over conventional means while maintaining credible feasibility. Experimental programs at Argonne and elsewhere have produced a maturing of wake field concepts, and research is underway to further explore important questions regarding practical limits of the method. A survey of new accelerating methods is presented. Wake field acceleration is then discussed in light of past, present, and future R&D.

Work supported and funded by US Department of Energy, Division of High Energy Physics

**ON DEVELOPMENT OF A SUPERCONDUCTING RFQ
AT STONY BROOK UNIVERSITY**

**I. BEN-ZVI
SUNY / BNL ATF**

Nov. 20, 92

Superconducting RFC @ SUNY Stony Brook

I. Ben-Zvi

A. Jain (Bombay)

A. Lombardi (Legnaro)

P. Paul

H. Wang (Beijing)

Why RFC?

Why superconducting?

PI

Hi current

Radioactive beams

ACCELERATING SLOW IONS -

One must work the hardest and achieve the least...

Low β structures are characterized by

- * Inadequate focussing
- * Limited apertures
- * Poor transit time factors
- * Complication

Slow beams are

- * Poorly bunched
- * Have large divergence
- * Susceptible to emittance growth

... need low β end in linacs...
motivation - heavier ions.

Motivation

Research for an efficient
c.w. accelerator for very
slow ions.

- * Nuclear Physics of heavy ions.
- * Atomic / molecular Physics.
- * Ion implantation.
- * Surface treatment
- * Explosive detectors

Coincidence $\Rightarrow$ duty factor

Precision experiments $\Rightarrow$ phase space

PI = ECR ion source $\Rightarrow$ very low β

Radioactive beams $\Rightarrow$ cw

High current $\Rightarrow$ low dissipation

The Radio Frequency
Quadrupole (RFQ)
is a new type of
linear accelerator
that is especially
suited to the acceleration
of low velocity ion
beams.

THE RFQ

History:

1945 Alvarez Drift Tube Linac
(Transverse-grid focussing)

1952 Blewett suggests magnetic
quadrupole focussing.

(Velocity dependent) $\rightarrow$ HV inject.

1969 Kapchinskij & Teplyaev
Spatially continuous focussing
(Electric Radio Freq. Quad, velocity
independent)

1978 Los Alamos

Today about 50 RFQs are
in operation or under construct.

What is the RFQ?

An electric quadrupole with
a.c. voltage.

The electrodes are
continuous.

Time periodicity $\Rightarrow$
 $\Rightarrow$ Space periodicity.

How does it work?

Strong focussing principle:

The beam cross section is varying.

The acceleration
is a
"perturbation"

Longitudinal variation results in E_z .

THE SUPERCONDUCTING RFQ

Why make a superconducting RFQ?

⊛ CW operation in RFQs - difficult
For heavy ions - impossible.

★ Low cost in construction
and operation

★ Good match to S.C. linacs

★ High fields!

S.C. linacs - today's almost
standard solution for heavy
ions.

ANL SUSB WEIZMANN

Seattle FSU Saclay

KSU Daresbury Jaeli

Legnaro ANU Tata

Superconducting
Accelerating
Structures
Are
Different !

Difficulties (s.c. H.I. RFQ)

★ Beam dynamics

- Very wide range of β 1%-5%
- Low product $\frac{qV}{M}$ low B
- $Ea \propto \frac{1}{\beta}$

★ Construction (+plating) of very large, high precision units welding, cooling...

★ Mechanical stability / Electromechanical coupling Historically most difficult

★ Electron multipactoring

★ ?? (Joining two new technologies)

RFQ equations

The potential function $U(z, r, \psi, t) =$
 $= \frac{V}{2} \left[\chi \left(\frac{r}{a} \right)^2 \cos 2\psi + A I_0(kr) \cos kz \right] \sin(\omega t + \phi)$

(Result of two lowest order terms in a Fourier-Bessel series. Can choose geometry to make this accurate)

"Acceleration" constant:

$$A = \frac{m^2 - 1}{m^2 I_0(ka) + I_0(mka)}$$

"Focussing parameter":

$$\chi = 1 - A I_0(ka)$$

$$k = \frac{2\pi}{\beta \lambda}, \quad \lambda = \text{wavelength}$$

$$E_r = \frac{\chi V}{a^2} r \cos 2\psi - \frac{KAV}{2} I_1(kr) \cos kz$$

$$E_\psi = \frac{\chi V}{a^2} r \sin 2\psi$$

$$E_z = \frac{KAV}{2} I_0(kr) \sin kz$$

Average accelerating field on axis:

$$E_a = \frac{KAV}{4} = \frac{\pi AV}{2\beta\lambda} \quad T = \frac{\pi}{4}$$

$$E_p = \alpha \sqrt{x} \frac{V}{a} \quad \alpha = 1.35 - 1.45$$

$$\frac{E_a}{E_p} = \frac{kaA}{5.8\sqrt{x}} \quad (\text{function of } T)$$

ka and m only)

All the parameters are well known.

Transverse stability

Mathieu equation:

$$\frac{d^2x}{d\tau^2} + [\Delta - B \cos 2\pi\tau]x = 0$$

$$\tau = \frac{1}{2\pi}(\omega t + \phi)$$

$$B = \frac{qV}{mc^2} \frac{\lambda^2}{a^2} \chi \quad \Delta = \frac{\pi^2}{2} \frac{qV}{mc^2} \frac{A}{\beta^2} \Sigma \phi_s$$

$\Delta < 0$ for longitudinal stability

Design considerations

I. Ben-Zvi, Particle Acc. 23 (1988)

• Transverse stability: $B^2 > -8\pi^2 \Delta$
 $\Rightarrow -\sin \phi_s < \frac{1}{\pi^2} \frac{qV \chi^{1/2}}{mc^2 a} \frac{\chi^{3/2}}{(ka)^2 A} \frac{\lambda^2}{a}$

• Transverse acceptance:

Aperture limit - $\epsilon_n \sim \frac{a^2}{\beta_+ \lambda}$ (large)

Trans. x Long. coupling limit -

$$\epsilon_n \sim \frac{1}{\pi^3} \frac{\beta^2 \lambda}{\beta_+} \phi_s \sin \phi_s$$

• Longitudinal acceptance:

$$\frac{\delta W_s}{W_s} \leq 4.8 \times 10^{-7} \left(\frac{qV}{mc^2} \right)^3 \frac{\chi^5}{A^2} \beta^4 \left(\frac{\lambda}{a} \right)^{10}$$

(injection max. energy spread)

6. Transverse acceptance
"aperture limit"

$$\epsilon = \frac{\pi a^2}{\beta + \beta\lambda}$$

$$\epsilon_n = \frac{\pi a^2}{\beta + \lambda} \quad (\gamma \approx 1)$$

But $\frac{dW}{dz} = \frac{\pi q A V \cos \phi_s}{2\beta\lambda} I_0(kr)$

$$I_0(kr) \approx 1 + \left(\frac{kr}{2}\right)^2$$

Equate the energy gain of the $\left(\frac{kr}{2}\right)^2$ term over half a longitudinal period,

$$\left(- \frac{2\pi\beta^3 M c^2 \lambda}{k q A V \sin \phi_s} \right)^{1/2}$$

to $\delta W_{\max}$.

Result:

Result: Normalized
transverse acceptance

$$\epsilon_n = \frac{1}{\pi^2} \frac{\beta^2}{\beta_+} \phi_s \sin \phi_s$$

$$\Rightarrow \epsilon_n = 0.4 \text{ mm mRad.}$$

$\epsilon_n(\text{ECR}) < 0.1 \text{ mm mRad}$
(even better for heavier ions)

$$P(F/2 \text{ D } F/2) = \begin{pmatrix} \cos \Omega & \beta_+ \sin \Omega \\ -\frac{1}{\beta_+} \sin \Omega & \cos \Omega \end{pmatrix}$$

$$\cos \Omega = \cosh \Theta_- \cos \Theta_+ + \frac{l_+}{2l_-} \sinh \Theta_- \sin \Theta_+ \left(1 - \left(\frac{l_-}{l_+}\right)^2\right)$$

$$\beta_+ = \frac{l_+}{\sin \Omega} \left[\cosh \Theta_- \sin \Theta_+ + \sinh \Theta_- \left(\frac{l_-}{l_+} \cos^2 \frac{\Theta_+}{2} + \frac{l_+}{l_-} \sin^2 \frac{\Theta_+}{2} \right) \right]$$

$$\Theta_{\pm}^2 = \frac{1}{4} \left(\frac{\beta}{\sqrt{2}} \pm \Delta \right); \quad l_{\pm}^2 = \frac{1}{\frac{\beta}{\sqrt{2}} \pm \Delta}$$

I. Ben-Zvi, A. Lombardi, P. Paul, Particle Accel.
(in press)

New developments in Stony Brook project:

• "Four rod" resonator

• Small RFQ units

(small = $\sim 2\beta\lambda$)

Not done before - space
charge, economy of rf amp.

Advantages:

- * Ramp V
- * Reduce U/E_a^2
- * Broaden T(p)
- * Construction
- * Plating
- * Tolerances
- * maintenance
- * Variable E
- * Control of field and
phase in individual
resonators - a new
degree of freedom!

● Optimized structure

We want to maximize the acceleration at a given peak surface electric field

$$\frac{E_a}{E_s} = \frac{ka A}{5.8 \lambda^{1/2}}$$

There is a unique solution if $ka = \frac{2\pi}{\beta\lambda} a$ can be held constant.

With small RFG resonators ka can be held constant.

REQ Universal Curve

Consequences:

- $\kappa a = \frac{2\pi}{\beta \lambda} a = \text{constant} \Rightarrow a \propto \beta$
 - $E_s = 1.45 \frac{V}{a} \chi^{1/2} \Rightarrow \underline{V \propto \beta}$
 $(\chi = \chi(\kappa a) = \text{constant})$ Voltage tapering
- Thus $E_a = \text{constant}$

and the acceleration is improved considerably.

$$\bullet \quad B = \frac{q V \chi^{1/2}}{m c^2 a} \frac{\chi^{1/2} \lambda^2}{a} \Rightarrow B \propto \frac{1}{\beta}$$

But $\Delta \propto \frac{1}{\beta^2}$ so motion
is stable ($B^2 \propto \Delta$)

• Modulated Phase Focussing

Conventional RFQ: $\begin{array}{c} \cdot \text{O} \cdot \cdot \cdot \text{O} \cdot \cdot \text{Bunching} \\ \cdot \text{OXX} \cdot \text{OXX} \cdot \cdot \text{Focussing} \\ \hline \beta\lambda \quad \beta\lambda \end{array}$

MPF: $\begin{array}{c} \cdot \text{O} \cdot \cdot \cdot \cdot \cdot \cdot \text{Bunching} \\ \cdot \text{OXX} \cdot \cdot \text{OXX} \cdot \cdot \text{Focussing} \\ \hline n\beta\lambda \quad n\beta\lambda \end{array}$

A "super period" results in more transverse focussing. This, in turn, may be traded for higher rate of acceleration or optimize both longitudinal and transverse motions.

Modulated Phase Focussing

$$U = \frac{1}{2} C V^2$$

$$\operatorname{tg} k l_2 = \frac{1}{2 \omega c}$$

$$k = \frac{\omega}{c}$$

$$l_2 = \frac{\omega c V}{\pi d}$$

$$\Gamma = \frac{\pi d}{2 \omega C l_2}$$

$$Z = \frac{\eta}{\pi} \left[2p \frac{1-q^2}{1+q^2} - (1-4q^2) \frac{1+4p^2}{16p^2} \right]$$

$$\eta = 377 \Omega$$

$$p = S/d$$

$$q = S/D$$

The capacitance of RFQ vanes

$$\frac{C}{L} = \frac{39.37}{\cosh^{-1}\left(\frac{r_0/p+1}{\sqrt{2}}\right)} + \frac{31.05}{r_0/p - \sqrt{2} + 1} + 25.28 \ln\left(1 + \frac{h}{a+p}\right)$$

BEN-ZVI 3.1 8/90 WC

(PF/m)

Set up for bead pull
measurement of asymmetry

Neutral axis offset due to voltage asymmetry

$$\text{rf quad field} \begin{cases} x'' + k^2 x = 0 \\ k^2 = \frac{qV}{MU_0^2 r_0^2} \end{cases}$$

$$\text{dipole field component} \begin{cases} x'' = \frac{q}{MU_0^2} E_d \\ E_d = \frac{\Delta V}{a} \frac{2 \cos(kz + \phi_s)}{m+1 - (m-1) \sin^2 \phi_s} \end{cases}$$

$$\overline{E_d} = \frac{\Delta V}{a} \frac{1}{\sqrt{m}} \frac{\sqrt{m}-1}{\sqrt{m}+1} \sin \phi_s$$

X_0 = neutral axis offset:

$$X_0 = r_0 \frac{\Delta V}{V} \frac{m+1}{2\sqrt{m}} \frac{\sqrt{m}-1}{\sqrt{m}+1} \sin \phi_s$$

$$\beta^* = \frac{1}{k}$$

$$\frac{X_0}{\overline{G}_x} = \frac{\Delta V}{V} \left(\frac{qV}{Mc^2} \right)^{1/4} \left(\frac{r_0}{\overline{E}_n} \right)^{1/2} \frac{m+1}{2\sqrt{m}} \frac{\sqrt{m}-1}{\sqrt{m}+1} \sin \phi_s$$

$$\delta = \frac{L_1 - L_2}{L_1 + L_2}$$

$$\epsilon = \frac{C}{C}$$

$$\ell = \frac{1}{2}(L_1 + L_2)$$

$$\alpha = \frac{\ell}{2(L + \ell)}$$

$$\omega_0 = \frac{1}{2\sqrt{(L + \ell)C}}$$

$$\omega_1 = \frac{\omega_0}{\sqrt{2}}$$

$$\frac{\Delta V}{V} = \frac{\alpha}{1-\alpha} (2\delta - \epsilon)$$

Bead pull test on a RFQ prototype at a few radially offset positions

Frequency deviation

Multipole Analysis

The potential function of the RFQ can be expanded in a Fourier Bessel series :

$$U(r, \theta, z) = \sum_n A_{0n} r^{2n} \cos 2n\theta + \sum_n \sum_m A_{mn} I_{2n}(mkr) \cos 2n\theta \cos mkz$$

The indices n and m have to satisfy the condition:
 $n + m = 2p + 1$ for any integer p .

The two lowest order coefficients describe the focusing strength and the longitudinal acceleration. Assuming a two terms potential function, these coefficients for the model structure should be:

$$A_{01} = 0.0882; A_{10} = 0.85$$

The measured coefficients in the first cell are:

$A_{01} = 0.0725$	$A_{03} = -0.0033$	$A_{05} = -0.0002$
$A_{10} = 0.73$	$A_{12} = 390.$	$A_{14} = 0.000$
$A_{21} = 0.24$	$A_{23} = 770.$	$A_{25} = 0.000$
$A_{30} = -0.007$	$A_{32} = -2.9$	$A_{34} = 1790.$

single cell - expansion

Frequency deviation

single cell - measured

Short Superconducting RFQ, 50 MHz

	Un-modulated			Modulated	
	MAFIA	Meas	Approx	MAFIA	Approx
f (MHz)	51.9	53.5	54.8	54.7	60.8
Q (Cu)	14300	—	13300	10000	9000
C_{tot} (pF)	48.2	42.2	34.2 [*]	45.4	24.7 ⁺
$E_{s/V}$ (m ⁻¹)	53.6	—	65.3	62.0 ⁺	38.5
B/V (G/mV)	1220	1190	1320	1360	1270
E_a/E_s	—	—	—	0.114 ⁺	0.161
$\Delta V/V$ (%)	3.8	2.5	7.0	2.6	15

*) Contribution of supports not included

+) Sharp corners in MAFIA simulation

Simulation with PARMTEC

$$\beta_{in} = 0.01 \quad P_b^{(35+)} 208 \quad 50 \text{ MHz}$$

$$\epsilon_n = 0.1 \pi \text{ mm mRad}$$

$$\Delta t = 1.1 \text{ ns} \quad (20^\circ) \quad \frac{\Delta W}{W} = 10^{-4}$$

$$\underline{E_s = 16 \text{ MV/m}}$$

	$\frac{\epsilon_{out}^x}{\epsilon_{in}^x}$	$\frac{\epsilon_{out}^y}{\epsilon_{in}^y}$	$X_{out}(\text{mm})$	$Y_{out}(\text{mm})$
MMF $0^\circ \rightarrow -25^\circ$	1.16	1.26	3.2	3.8
$\phi_s = -12.5^\circ$	1.26	1.24	4.6	4.2
$\phi_s = -21.7^\circ$	1.40	1.56	12.7	6.2

Reduce V_u by 40%

Increase V_z, V_s by 20%

No change in ϵ_n

Slight increase in longitudinal ϵ .

E_s change from 256 MeV to 252 MeV

Resonator	1	2	3	4	5	6
Length (m)	.37	.42	.40	.46	.52	.58
Calls	12	8	4	4	4	4
β_{in}	.01	.021	.0303	.0358	.0408	.0463
β_{out}	.021	.0303	.0358	.0408	.0463	.0514
V (mV)	.135	.285	.419	.464	.535	.607
A_{in} (cm)	.067	1.1	1.57	1.68	1.94	2.2
A_{out} (cm)	5.7	1.316	"	"	"	"
m	3.5	3.5	4	4	4	4
A_{in}	.662	.733	.758	.781	.778	.778
A_{out}	.802	.768	.794	.804	.801	.798
B_{in}	4.9	3.2	2.6	1.83	1.59	1.41
B_{out}	3.1	2.0	1.8	1.68	1.47	1.32
E_a (MV/m)	1.8	2.2	2.6	2.5	2.5	2.6
ϕ_s (deg)	-15	-15	0	-25	0	-25
E_{out} (MeV)	42.7	88.7	124.6	161.5	208.0	256.0

Phase space at injection

phase space at end

Summary

- A superconducting RFQ is being developed.
- A new approach to RFQ design has been formulated
 - Small (few gap) RFQs
 - Optimized acceleration
- Modulated phase focussing
- ~~RFQ~~ At model constructed and bead testing ^{done} ~~in progress~~
 Lead plated prototype being ~~designed~~
 constructed

**DEVELOPMENT OF NEW METHODS FOR CHARGED PARTICLE
ACCELERATION AT YEREVAN PHYSICS INSTITUTE**

M. PETROSSYAN

YEREVAN PHYSICS INSTITUTE, USSR

Development of New Methods for Charged
Particle Acceleration at Yerevan Physics
Institute

E. M. Laziev and M. L. Petrossyan
Yerevan Physics Institute

Development of new acceleration methods at the Yerevan Physics Institute

Authors of the Review:

A.Ts. Armatuni, S.S. Elbakyan, E.M. Losiev,
G.A. Nagorsky, M.L. Petrossyan, E.V. Sechpassyan

Items:

1. Surface waves arising at the
total internal reflection.
2. Inverse Vavilov-Cerenkov Eff.
3. IFEL
4. Wake Fields in passive struct.
5. Nonlinear Eff. in PWFA.

ЭЧАЯ, 1989, том. 20, вып. 5

XIV Int. Conf. HEPA, Tokyo, KEK, 1988

Part. Acc. 32, part V, p 221-222
1989

1. Acceleration by surface waves arising at total internal reflection

Lohman (IBM report, 1962)
WORKS done at Yer Ph I:

1. Kheifetz S.A. (1972)
2. Nagorsky G.A., Amatuni A.Ts., Harutunian W.M. (1972)
3. Kazar'yan N.A., Nagorsky G.A., Ogadjanyan A.A. F.O.D.O. (1987)
4. Mail'yan M.R., Kazar'yan N.A. polarization (1977)
5. Harutunyan S.G., Savvick N.G. materials (1986)
6. Arakelyan G., Begloyan E., Lohman E. surface-waves (1987)

in SWS — $E_{acc}^{y'} = (n_{eff} - 1)^{1/2} h_3$

- h_3 — phase equilibrium, acceleration
- h_2 — vertical equilibrium
- phase jumps for sign changeable h_2

Example (not competly optimized):

Laser — $10^3 J$, 1 nsec pulse duration
 900 cm² aperture (TIR-I)

Dielectric — KCl

Magnetic field — $h_3 = 1 T$

Acc. gradient $\approx 100 \text{ MeV/m}$

K 4p 3

fig 1. Sketch of
 crystal layout in
 experimental installation
 for demonstration of principle
 experiment for surface wave
 acceleration.

2. Inverse Vavilov-Cerenkov Effect

First idea - Shimoda K. (1962)

$$\cos \theta = 1/n(\omega) \beta$$

Cerenkov phase cond.

Work done by Yerevan group:

Harutunyan V.M., Avetisyan H.K. (1972)

Nagorsky G.A., Orlov Yu.F. (1973)

Nagorsky G.A., Petrosyan M.L. (1976)

Nagorsky G.A. (1976, 1978, 1979, 1983, 1986, 1987)

- ① Problem of stability of resonance cond.
- magnetic field of laser destabilized the resonance cond. →

Cure: → 1. applic. of constant magnetic field along the direction of laser wave magnetic field
→ 2. three Cerenkov waves appl. simultaneously.

- ② Multiple scattering → short pulses (ps) and large electric field ($\sim 10^{14}$ V/cm²) will be suitable for stable acc.

3. Double inversion of Čerenkov Eff.
 a) first using inverse Čerenkov Eff. to modulate the electron bunches from traditional acc. b) then produce intense Čerenkov Radiation in a specially chosen medium c) to accelerate charged particles by the inverse Čerenkov Eff. Achievable acc. gradient could be $\sim 10 \text{ GeV/m}$
 (1), (2) Vavilov-Čerenkov Klystron

3. Inverse Free Electron Laser (IFEL)

First idea - A.A. Kolomensky,
A.N. Lebedev (1962), Davidovsky V.Ya. (1962)

Experimental proof of principle
at YERPHI:

Petrosyan M.L., Petrossyan B.V.,
Amatuni A.Ts., Hovsepian A.S., et al
(1984, 1987, 1988)

fig 1 - installation

fig 2 - results

10^{13} W/cm^2

The new installation:

- 12 MeV microtron 50 MeV
- 5 GW (10^{13} W) CO₂-laser (Start) $\gamma \sim 1 \text{ keV}$
- 20 cm undulator; $H \sim 1 \text{ T}$

Expected:

$$\Delta E = 6 \text{ MeV}, \quad eE \sim 30 \frac{\text{MeV}}{\text{m}}$$

Collaboration YERPHI - Kirchatov

Data taking stage now.

K 9P 6

fig 1. Installation of experimental equipment for IFEL experiment

K chap 6

fig 2 Result of IFEL exper.

Comparison between measured and theoretical
 exper. points at compression very small

4. Acc. by Wake Fields

in ^{passive} structures
B. Kozanskij, A. Kiselev, A. Lebedev, (1971)
G. A. Voss, Th. Weiland (1982)

Problems with optimization -

- higher gradients, higher
transformation ratio $R = \frac{\Delta V}{V}$

YerPhi group - Losiev E.M.

Tsarenkov V.M.

1. Resonators of different shape -
e.g. elliptic cross sec;

2. Various periodic structures;

3. Sequences of shaped bunches
with the increasing charges;

Results: $e \approx 100$ MeV/m

$$R \approx 10$$

4. Construction of the exper.
facility, based on linac
(under installation):

$$E = 30(50) \text{ MeV} \rightarrow 120 \text{ MeV}, \Delta E/E \sim 10^{-3}$$

$$I_{av} = 1000(1500) \mu\text{A} \quad \tau_{pulse} = 8 \cdot 10^{-6} \text{ sec}$$

$$n_{bunch} = 3,3(2,2) \cdot 10^9 \text{ cm}^{-3} \quad \tau_{bunch} = 3,6 \cdot 10^{-8} \text{ sec}$$

"Electrophysics", "Kosintern" corps, L-1

fig 5

Значения коэффициента трансформации
R от мощности нагрузки. в теории
и при разных формах ~~керна~~.
Значения илотности ~~керна~~
в теории

5. Nonlinear Effects in Plasma Wake Field Acc. (PWFA).

The possibility of the acceleration by longitudinal electric wake fields, generated by moving electrons in plasma were outlined by

Bolotovskiy B.M. (1955, 1964)

Fainberg Ya.B. (1956, 1959)

Nonlinear waves in free (without mov. charge) relativistic plasma were studied (exact solution) by

Akhiezer A.I., Polovin R.B. (1955, 1956)

Combination of the both ideas by YerPhI group - Armutani A.G., Elbakyan S.S.

Mogomedov M.R., Serdpassyan E.V.

(1977, 1979, 1985, 1986, 1987, 1987, 1988, 1989).

and also by

Ruth R.D., Chao A.W., Morton P.L., Wilson P. (1985).

Rosenzweig J.B., (1987, 1987, 1988).

Kotzouleas Th., Mori W.B. (1988).

Keinings T., Jonce M. (1987).

Some results of the YerPhI group

1. Wake f. and transf. ratio

perturbed
plasma:

$$\begin{aligned} n_i &= n_0, \\ n_e(z) &< n_0, \\ \tilde{z} &= z - v_p t, \\ v_e(z), \\ E_w(z), \end{aligned}$$

unperturbed
plasma:

$$\begin{aligned} v_e &= 0, \\ E &= 0, \\ n_e &= n_0 = n_i, \\ \omega_p &= \frac{4\pi e^2 n_0}{m}; \end{aligned}$$

$$E_i(z) \leq \frac{nc\omega_p}{e};$$

Boundary conditions:

$$\begin{aligned} \tilde{z} = d \quad v_e(d) &= 0, \quad n_e(d) = n_0, \\ E_i(d) &= 0; \end{aligned}$$

$$\begin{aligned} \tilde{z} = 0 \quad v_e^w(0) &= v^i(0), \quad n_e^w(0) = n_e^i(0) \\ E_w(0) &= E_i(0); \end{aligned}$$

Eqs. system

$$\left(\beta - \frac{\rho_z}{\sqrt{1+\rho_z^2}}\right) \frac{d\rho_z}{d\tilde{z}} = \frac{eE_z}{mc^2}, \quad \beta = \frac{v_z}{c}$$

$$\frac{d}{d\tilde{z}} [n_e(v_z - v_0)] = 0$$

$$\frac{dE}{d\tilde{z}} = 4\pi e(n_0 - n_e - n_b)$$

Exact solution (at l_0) exists

which depends on $\frac{n_b}{n_0}, \omega_p, \gamma_b, d$

Some limits

Case A

$$E_{\text{max}} \approx \sqrt{2} \frac{mc^2}{2} \gamma_b^{1/2}, \quad R = \gamma_b^{1/2}$$

when

$$\frac{n_b}{n_0} \leq \frac{1}{2}, \quad d = \frac{v_b}{\omega_p} \gamma_b,$$

$$(A): \quad 1 \ll \gamma_b \ll \frac{n_b}{n_0} \left(1 - \frac{2n_b}{n_0}\right)^{-1}$$

Case B

$$E_{w \max} = \sqrt{2} \frac{m c \omega_p}{e} \left(\frac{n_{e0}}{n_0} \right)^{1/2} \left(1 - \frac{2n_{e0}}{n_0} \right)^{-1/4}$$

$$R = \left(\frac{n_{e0}}{n_0} \right)^{1/2} \left(1 - \frac{2n_{e0}}{n_0} \right)^{-1/4}$$

$$\frac{n_{e0}}{n_0} \leq \frac{1}{2}, \quad d = \frac{2^{1/2}}{\omega_p} \left(\frac{n_{e0}}{n_0} \right) \left(1 - \frac{2n_{e0}}{n_0} \right)^{-3/2}$$

$$1 \ll \frac{n_{e0}^2}{n_0^2} \left(1 - \frac{2n_{e0}}{n_0} \right)^{-3/2} \ll \gamma_0^2; \quad (B)$$

Case C

$$E_{w \max} \approx 2 \frac{m c \omega_p}{e} \gamma_0, \quad R \sim \gamma_0$$

when conditions are the same as in Case A, but

$$d \approx \frac{8^{1/2}}{\omega_p} \gamma_0^2 \text{ is too long, so}$$

This Case may have application in acceleration of cosmic Rays in the astrophysical objects.

Numerical Examples Case A

a) $n_0 = 2 \cdot 10^{11} \text{ cm}^{-3}$, $\omega_p = 2,4 \cdot 10^{10}$, $n_b = \frac{n_0}{2} = 10^{11}$

$\gamma_b = 60$ (30 MeV - Yer Ph I Test Facility)

$eE_{\text{max}} = 0,5 \frac{\text{GeV}}{\text{m}}$, $d = 1,5 \text{ m}$

$L = d + 2z_b = 2,5 \text{ m}$

b) $n_0 = 10^{13} \text{ cm}^{-3}$, $\omega_p = 1,1 \cdot 10^{11} \text{ sec}^{-1}$, $n_b = \frac{1}{2} n_0$

$\gamma_b = 10^3$ (50 MeV - LLNL)

$eE_{\text{max}} = 4,1 \frac{\text{GeV}}{\text{m}}$, $d = 0,35 \text{ m}$

$L = 0,54 \text{ m}$

2. Selfacceleration of the Bunch Electron

Nonfixed bunch - nonlinear influence of excited wave fields on the bunch Hamiltonian -

$$H_0 = \sqrt{1 + p_z^2} - \beta p_z - \frac{e\varphi}{mc^2} = \text{const} =$$

$$= \sqrt{1 + p_{z0}^2} - \beta p_{z0}, \quad \beta = \frac{v_{ph}}{c}$$

- $\varphi > 0$ and increase when $z \rightarrow 0$;
 motion less non-linear at the end of the bunch. So
 $p_z(z)$ also increased inside the bunch

Case A: $p_z(0) \approx p_z(d) + 2\gamma_0^3$;

$$\gamma_0 \approx \gamma_{ph} \gg 1;$$

Case B: $p_z(0) \approx p_z(d) + 2\gamma_0^2 \left(1 - \frac{2n_0}{n_0}\right)^{-1/2}$;

Case D: $p_z(0) \approx p_z(d) + 2 \frac{n_0}{n_0} \gamma_0^2$;

$$n_0 \approx 1, \quad v_0 \gg 1, \quad d = \frac{\pi v_0}{\omega}$$

Example, Case D:

$$\frac{n_b}{n_0} = 10^{-3}, \quad n_0 = 10^{13} \text{ cm}^{-3}, \quad \gamma_b = 10^4 (5 \text{ GeV}),$$

$$d = 2.7 \text{ mm} \quad \Delta d \sim 0.1 d$$

$$E_b(0) = 100 \text{ GeV},$$

$$N_b \approx 3 \cdot 10^3 \quad (s = 1 \text{ cm}^2)$$

3. Some recent development (some cond.-s of applicability)

1. Ions motion ion M, ze

a). $n_b/n_0 \ll 1$: no influence

b). $\frac{n_b}{n_0} \approx \frac{1}{2}$: ① $\gamma < \left(\frac{M}{64zm} \right)^{1/4}$
when $1 \ll \gamma^2 \leq \frac{n_b^2/n_0^2}{1 - 2n_b/n_0}$

② $\gamma > \left(\frac{M}{64zm} \right)^{1/4}$

$$\bar{E}_{\max} = \sqrt{2} \frac{mc\omega p}{e} \left(\frac{M}{4zm} \right)^{1/4}$$

instead of

$$\bar{E}_{\max} = \frac{2mc\omega p}{e} \gamma$$

in case ①

Details in

A.G. Ananyuk, Z.B. Serenya,
C.C. Zhukovskiy, UZB AKA "Dzokk"
25, 18-23, (1990).

2. Finite transverse dimensions
of the bunch - radius "a".
Results obtained in $a \rightarrow \infty$
case are valid in general
when
$$\gamma \frac{\lambda_p^2}{a^2} \ll 1; \quad \frac{a^2}{\lambda_p^2} \ll 1.$$

In case of the short bunches
 $d \ll \lambda_p$ the conditions of
applicability are
$$\frac{n_b}{n_0} \frac{d^2}{\lambda_p^2} \ll 1, \quad \frac{\sigma^2 d^2}{6 a^2} \left(\frac{n_b d^2}{n_0 \lambda_p^2} \right) \ll 1$$

$$\frac{a^2}{\lambda_p^2} \frac{n_b}{n_0} \ll 1.$$

Details in

A.G. Amiryuk, F.B. Ceruscu

C.C. Enixgu Uzh. ANPA. Figure
1990 (in press).

3. Influence of thermal motion of the plasma electron, ($T_e \neq 0$).

Previous results.

T. Ketzor, R.B. Nori

Phys. Rev. Lett. 61, 90, (1988)

J.B. Rosenzweig Phys. Rev. A. 38, 3634
(1988)

- essential influence

Some times effects
are proportional to $\left(\frac{kT}{mc^2}\right)^{-1/4}$

Correct results are obtained
using the derived generalized
Euler eq. for charged

Relativistic fluid:

$$u^\mu \frac{\partial u_\mu}{\partial x^\nu} = \frac{\partial p}{\partial x^\nu} - u_\mu u^\mu \frac{\partial p}{\partial x^\nu} + \frac{1}{c} F_{\mu\nu} j^\mu$$

$w = e + p$ - e, p - energy and pressure of unit volume of fluid in local rest frame

u_i - 4-velocity, $u^i(\gamma, \gamma \vec{v}/c)$

$F_{\mu\nu}$ - el. mag. field tensor

j^μ - 4-current

Scalar product on u^μ gives zero in both sides of eq.

Model of ideal relativistic

$$p = n k T / \gamma$$

$$w = \frac{n m c^2}{\gamma} \left[\frac{K_3 (m c^2 / k T)}{K_2 (m c^2 / k T)} \right] =$$

$$= \frac{n m c^2}{\gamma} \left(1 + \frac{5}{2} \frac{k T}{m c^2} + \dots \right).$$

main difference:

$$m_{\text{eff}} = m \left(1 + \frac{5}{2} \frac{kT}{mc^2} + \dots \right)$$

$$F_{1\text{max}} = \frac{m_{\text{eff}} c \omega_{\text{eff}} \left(1 - \frac{kT}{2m_{\text{eff}} c^2} \right)^{1/4}}{e \left(1 - \frac{2nq}{n_0} \right)^{1/4}}$$

$$\gamma_{\phi}^2 = \gamma_0^2 \Rightarrow \frac{n_0^2/n_0^2}{1 - 2nq/n_0} \Rightarrow 1$$

$$\gamma_0 = \left(1 - \frac{v_0^2}{c^2} \right)^{-1/2}, \quad v_0 \approx c.$$

So the thermal effects are
very small. at lab. cond.

4. Non stationary treatment

$$v_{\phi} = v_0 \quad \tilde{z} = z - v_{\phi} t$$

Lagrange approach and
coordinates: τ

$$\tilde{z} = \tilde{z} + \int v(\tilde{z}, \tau') d\tau'$$

non relativistic case - (13)
exact solution. Result

$$v_{\phi}^{\text{eff}} = \frac{1}{t} \int_0^t [v_0 - v(\tilde{z}, \tau)] d\tau$$

$$v_0 \leq v_{\text{eff}, \phi}(t) \leq v_0(1+2q)$$

$$0 \leq q \equiv \frac{n_8/n_0}{1 - n_8/n_0} \leq 1, \quad \frac{n_8}{n_0} \leq \frac{1}{2}$$

in case $n_8/n_0 \ll 1 - q \ll 1$

linear case and

$$\boxed{v_{\phi}^{\text{eff}} \approx v_0} -$$

stationary treatment is

correct.

in $n_8/n_0 \sim \frac{1}{2}$, $\gamma \gg 1$

cases more work is
necessary.

Part II

Experimental program

1. Photo- and Electroproduction of hadrons in intermediate energy range 2-6 GeV

Spin correlation exp.:

pol: - γ , target, recoil products

Transition region from
proton-neutron picture to

quark-gluon picture

(Scaling starts at $E > 26$ GeV)

2. Nuclear physics -

relativistic nuclear physics or
cumulative effects

3. Applied physics:

- Radiation defects in solids
- SR
- FEL. channelus radiation

quasi-Čerenkov, TR, TRD

- medical apparatus and sterilization
- microtrons, linear ecc. vacuum pumps and oth. for industrial and medical purposes.

Program for modernization

1. New injector
 $E = 120 \text{ MeV}$ (240 MeV)
 $I_p = 1.0 - 1.5 \text{ A}$ (0.5 A)
 $\tau = 8 \cdot 10^{-9} \text{ sec.}$
 $\nu = 50 - 100 \text{ Hz}$
 $P_{av} = 120 - 150 \text{ kW}$

2. Duty factor

D.W.C. - 10% $\rightarrow$ 50-70%
 flat top system
 stretcher ring

3. New RF system

$\nu = 137 \text{ MHz} \rightarrow 466 \text{ MHz}$

$P_p = 1 \text{ MW}$

$P_{av} = 0.3 \text{ MW}$

FERVON Electron Synchrotron
in operation since 1967

$$E = 1,5 \div 6,1 \text{ GeV}$$

$$I_{\text{pulse max}} = 20 \text{ mA}$$

$$E_{\text{inj}} = 75 \text{ MeV}$$

$$I_{\text{inj}} = 170 \text{ mA}$$

$$\tau = 1,0 \text{ } \mu\text{sec}$$

$$\left(\frac{\Delta E}{E}\right)_{\text{inj}} = 1,5\%, \quad \left(\frac{\Delta E}{E}\right)_{\text{exte}} = 0,1\%$$

$$\left. \begin{array}{l} \gamma \text{ channel} - 3; \\ e \text{ channel} - 1; \end{array} \right\} \begin{array}{l} D = 5-10\% \\ \tau = 1,0 \div 3,5 \text{ msec} \end{array}$$

$$\text{SR channel} - 3$$

$$\frac{\Delta \lambda}{\lambda} = 10^{-3} \quad E_e = 4,5 \text{ GeV}$$

$$\lambda = 0,6 \text{ } \text{\AA}$$

$$N_\lambda = 4 \cdot 10^{10}$$

$$\frac{\tau}{T} = D$$

" ... безонности народом
 человека - учить других, как сделать:
 все то хорошее, чего он сам не
 сумел совершить из-за злобности,
 времени и обстоятельств. Когда
 окажется много людей, способных
 к добру, некоторые из них -
 те, что будут - более всех любить
 добру - смогут крепко удержать это
 добро в жизни "

" Рассуждения о первой
 книге Тит. Ливия "

кн 2., Вступительное

Никколо

Максимально

Conclusions

Further theoretical and especially experimental investigations of the new methods of acceleration of the charged particles are urgent and seems promising not only for high energy physics but also for application in industry and medicine.

$$Y^0 = \frac{\sigma L_s}{Y^A (1 + Y_s^0)}$$

$$Y = \frac{\sigma \mu c_s}{\sigma \mu c_s + Y^A}$$

$$L = \frac{\mu}{\mu c_s}$$

$$Y^0 = \frac{\mu}{\mu c_s}$$

a)

b)

c)

Elliptical wake transformer (a) with two separated single beams and a multi beam star transformer (b and c)

Resonance Work Field

transformer -
-DESY.

init. ring bunches 50-100nC, 50-100
16 GeV $\times 61 \rightarrow$
 $\rightarrow 1796$

движущийся в плазме
столкновения электронов
 $v \sim c$ (РЭП)
1. момент влета в плазму

2. стадия образования продольных волн.
 $v_{ph} \approx v \approx c$

$$n_p \ll n_0$$

волны плотности
заряда, кинетическая
волна, порождающая
продольные электрические
поля

$E_{max} \sim \frac{m c v_p}{e}$

рис 1

$$\omega_p^2 = \frac{4\pi e^2 n_e}{m_e}$$

DEVELOPMENT OF NEW METHODS OF ACCELERATION AT YPI

1

DEVELOPMENT OF NEW METHODS FOR CHARGED PARTICLE
ACCELERATION AT YEREVAN PHYSICS INSTITUTE

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Abstract Theoretical and experimental works done at YPI are reviewed: the acceleration of charged particles by surface waves arising at total internal reflection, by inversion of the Vavilov-Cherenkov effect, by inversion of the free electron laser and by wake fields generated in passive and active (plasma) structures by intense relativistic electron beams. For the plasma case special attention was made on nonlinear effects, when the acceleration rate and the transformation ratio are high. The possible self-acceleration of electrons in a relativistic bunch passing through a plasma column is also considered.

ACCELERATION BY SURFACE WAVES ARISING AT TOTAL INTERNAL REFLECTION

The main property of the surface waves (their propagation in vacuum with a smaller than light velocity) makes them appropriate for acceleration of charged particles. This idea was first stated probably by Lohman in 1962. Later on, this phenomenon was independently discussed at YPI in 1972. A more complete analysis providing a sufficiently high acceleration rate and at the same time the fulfillment of vertical and phase equilibrium conditions was carried out in reference¹. High acceleration rate and phase equilibrium conditions are achieved by an additional vertical magnetic field. Vertical equilibrium is provided by a sign-changing magnetic field parallel to the surface and perpendicular to the particle trajectory. In this case, as it follows from the equations of motion, jumps in radiation phase are needed. The full system of equations was studied and optimal conditions for the type of the focusing system, angle of reflection and polarisation of the laser beam were derived. Finally, the breakdown properties of the dielectrics, which could be used in future experimental equipment were analysed. Acceleration gradients of the order of 100 MeV/m are expected.

Part Acc. 32, v,
p 221-227, (1991)

EXIV Int. Conf. on
HEAC Tech. Rep
1990

INVERSE VAVILOV-CHERENKOV EFFECT

In 1962 K.Shimoda suggested in his pioneering work to use the inverse Vavilov-Cherenkov effect for particle acceleration. Starting from 1972 the detailed theory of this effect was developed in the works of the Yerevan group. Special attention was made on the problem of the stability of motion. In particular, the role of the laser wave magnetic field, whose strength in the medium is higher than that of the electric field, was considered. It was shown that at relativistic velocities, the effect of the magnetic field disturbs the phase equilibrium. To ensure the stability it was suggested to introduce a constant magnetic field directed along the wave magnetic field. A system of three Cherenkov waves was proposed and analysed, where stable mode of particle acceleration with a large phase volume of the beam is also feasible². For both of these versions a method has been developed to take into account the multiple scattering effect on acceleration stability and it was shown, that the latter is possible only for sufficiently high strengths (flux $\sim 10^{14}$ W/cm²) of the wave electric field and short (picosecond) pulses².

In a series of works (see review²) an interesting feasibility to create high accelerating gradients using the double inversion of the Vavilov-Cherenkov effect was proposed. First a particle beam, accelerated in an ordinary machine, is modulated by the inverse Cherenkov effect. Then it passes into another specially chosen medium and produces Cherenkov radiation with higher field strength which is used again for acceleration of another particle beam by an inverse Cherenkov effect. Acceleration gradients of the order of 10 GeV/m may be expected.

ACCELERATION BY WAKE FIELDS

The first proposal on wake field acceleration in passive structures belongs to G.A.Voss and Th.Weiland. The experimental studies of the effect were carried out at DESY with a device called by authors the wake field transformer. Later on, the method was also studied experimentally at ANL.

From 1985 theoretical studies were carried out at YPI in search of ways to enhance the acceleration rate and the transformation ratio in various decelerating passive structures. In particular, calculations were made for cylindrical waveguides with elliptical cross section, when the

DEVELOPMENT OF NEW METHODS OF ACCELERATION AT YPI 3

driving beam passes through one of the focuses and generates the wake fields along the axis going through the other focus; the problem of increasing the transformation ratio and the acceleration rate by using specially shaped sequences of the driving beam bunches, with various distributions of charge in each bunch, was also studied in detail^{2,4,5}. Acceleration rate $\approx 100\text{MeV/m}$ and transformation ratio ≈ 10 may be obtained.

The ideas of using longitudinal wake fields excited by electrons or electron bunches in a plasma to accelerate charged particles were initiated by B.M.Bolotovskiy and Ya.B.Fainberg in early fifties. At nearly the same time A.I.Akhiezer and R.V.Poiovin formulated and exactly solved the equations for free nonlinear longitudinal waves in an infinite relativistic plasma. Since the end of seventies and up to now in works of the Yerevan group both of these ideas were used in consideration of the generation of longitudinal nonlinear waves in plasma by extended bunches of relativistic electrons. Some of the results of these investigations (see ref.^{6,7,9} and review⁸) are as follows. The essential parameters in question for the case of a fixed bunch are the ratio n_b/n_0 , where n_b - is the density(fixed) of the electron bunch, n_0 - is the electron density of a neutral cold plasma in equilibrium, γ_b - the Lorentz factor of the bunch, d - longitudinal length of the bunch and ω_p - the plasma frequency. It was shown that when

$$\frac{n_b^2}{n_0^2} \left(1 - 2 \frac{n_b}{n_0} \right)^{-1} > \gamma_b^2 > 1, \quad \frac{n_b}{n_0} \leq \frac{1}{2}, \quad d = \frac{\gamma_b}{\omega_p} \gamma_b, \quad (1)$$

the maximum of the electric field behind the bunch in the nonlinear longitudinal wake field is

$$E_{\text{max}} = \sqrt{2} \frac{mc\omega_p}{\gamma_b} \gamma_b^{1/2}$$

For the case when

$$\gamma_b > \frac{n_b^2}{n_0^2} \left(1 - 2 \frac{n_b}{n_0} \right)^{-1} > 1, \quad \frac{n_b}{n_0} \leq \frac{1}{2}, \quad d = 2 \frac{\gamma_b n_b}{\omega_p n_0} \left(1 - 2 \frac{n_b}{n_0} \right)^{-1/2} \quad (2)$$

the maximum of the field is

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$$E_{\max} = \sqrt{2} \frac{mc\omega_p}{e} \left(\frac{n_b}{n_0} \right)^{1/2} \left(1 - 2 \frac{n_b}{n_0} \right)^{-1/2}$$

In both cases (1,2) the decelerating electric field inside the bunch is of the order of $mc\omega_p/e$, and therefore the transformation ratio could be sufficiently high along with a high value of the acceleration rate.

The above mentioned results follow from the exact solution of the equations of magnetic hydrodynamics for bunches which are infinite in transverse directions. The results for cylindrical bunches with a finite radius a show, that the conditions for the fulfillment of the above mentioned results are the following:

$$\frac{n_b}{n_0} \frac{d^2}{\lambda_p^2} < 1, \quad \lambda = \frac{2\pi v_b}{\omega_p} \cdot \frac{\lambda_p^2 \gamma_b^2}{a^2} \frac{n_b}{n_0} < 1,$$

$$\frac{n_b}{n_0} \frac{r^2}{a^2} < 1, \quad 0 \leq r \leq a;$$

For $n_b/n_0 < 1$ the influence of ion motion is not essential, but for $n_b/n_0 \leq 1/2$ a restriction, namely $\gamma_b < 1/2(M_i/Zm_e)^{1/2}$ exists where M_i is the ion mass.

The Yerevan group has taken into account in a selfconsistent way the inverse action of the beam and plasma electron fields on the longitudinal density and momentum distributions in the electron bunch. It is assumed that some quasistationary state of the plasma-beam system arises for a while after the injection of the electron bunch into the plasma, when the energy exchange between the bunch and plasma electrons is practically negligible¹⁰. In this situation the velocity of the bunch front (at $z = d$) is assumed to be fixed and exceeds the phase velocity of the excited quasistationary longitudinal wave. Then in the extreme relativistic case the longitudinal distribution of the bunch electrons is practically not changed, but in the momentum distribution at the end of the bunch (at $z = 0$) one finds accelerated electrons. For case (1) we have for the dimensionless momentum

$$p_b(0) \equiv P_z(0)/mc = p_b(d) - \frac{3}{2} \gamma_b, \quad p_b(d) \equiv P_z(d)/mc$$

and for case 2)

$$\rho_b(0) \approx \rho_b(d) - 2\tau_b^2 \left(1 - 2\frac{n_b}{n_0}\right)^{-1}; \quad \tau_b \approx \tau_{ph} > 1;$$

For the case which is nearest to existing laboratory conditions

$$\frac{n_b}{n_0} \ll 1, \tau_b > 1, d \approx \frac{\pi v_b}{2\omega_p}, \rho_b(0) \approx \rho_b(d) - 2\frac{n_b}{n_0} \tau_b^2;$$

The relations, which define the phase velocity and wave vector of the wake through τ_b , n_b/n_0 , d and ω_p are derived (dispersion relation).

The increase of the momentum of bunch electron inside the plasma follows from conservation of the Hamiltonian and the decrease of the potential energy of electrons at the rear part of the bunch. This decrease is due to the motionless ion excess at the end of the bunch. Consideration of ion motion, gives the same restrictions as for the previous case. Results obtained show the possible longitudinal contraction of the beam.

For example if $n_b/n_0 = 10^{-3}$, $n_0 = 10^{13} \text{ cm}^{-3}$, $\tau_b = 10^4$, $d = 3 \text{ mm}$ the maximal energy at the end of the bunch approaches the value $\sim 100 \text{ GeV}$, and the number of accelerated particles is $\sim 3 \cdot 10^3$ when the cross section of the bunch is 1 cm^2 . When $\tau_b = 10$ in this example the distance needed for noticeable contraction of the bunch is a few meters long.

For the experimental investigation of various schemes of wake field generation in passive and active structures and demonstration of the effects of self-acceleration of the electron beams in plasma a linac is under construction at VPI with the following parameters: energy $\sim 30 \text{ MeV}/50 \text{ MeV}$ at half the current, pulse current $\sim 1.0 - 1.5 \text{ A}$, pulse duration $\sim 3 \cdot 10^{-9} \text{ sec}$, bunch duration $\sim 3.6 \cdot 10^{-11} \text{ sec}$, repetition rate $\sim 50 - 100 \text{ Hz}$, particle density in a bunch $\sim (2.2 - 3.3) \cdot 10^9 \text{ cm}^{-3}$, bunch length $\sim 0.5 - 1.0 \text{ cm}$, bunch diameter $\sim 0.5 - 0.7 \text{ cm}$, average power $\sim 30 - 45 \text{ KW}$. The new linac will have also a beam monochromatization system.

INVERSE FREE ELECTRON LASER (IFEL)

The accelerators based on IFEL may become in the future a promising source of intense electron beams with energies up to hundreds of GeV

Having in mind this final goal, experiments were carried out at YPI to observe laser acceleration in undulators and for elaboration of experience for future developments. The first experimental results were delivered at the previous conference¹¹. A 8MeV microtron 10MW CO₂ laser, undulator with period 5.25mm, 20cm length and magnetic field up to 1KOe were used. Later on the energy of the microtron was increased up to 12MeV and the laser power was doubled. The results¹² with the new arrangement are presented in Fig. 1, where the maximum change of electron energy is given as a function of the undulator magnetic field H. The curve shows the standard interaction function F(H) of electrons and the laser wave.

Fig. 1

At present the collaboration YPI - Troitsk branch of Kurchatov Institute has assembled a new experimental setup at Yerevan where a 5GW CO₂ laser, developed at the Kurchatov Institute is used. Now the measurements are underway, and an acceleration rate up to ~ 30 MeV/m is expected.

At the next stage it is planned to construct the prototype of the FEL-accelerator with electron energy up to 1GeV, and current up to 1kA. To this end, as the estimates show, ~ 10¹²W laser power will be needed.

A more detailed description of the ideas and results presented in this talk are given in a recent review³.

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THEORY OF HIGH GAIN FREE ELECTRON LASER

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THEORY OF HIGH GAIN FEL

RESONANCE CONDITION

EXPONENTIAL GROWTH

GAIN REDUCTION DUE TO ELECTRON BEAM

ENERGY SPREAD + EMITTANCE

GAIN REDUCTION DUE TO WIGGLER ERRORS

with L.H. Yu + R.L. Gluckstern

Spontaneous Radiation

Wiggler Vector Potential

$$\frac{e}{mc} \vec{A}_w = -a_w (\hat{x} \cos k_w z + \hat{y} \sin k_w z)$$

Electron Trajectory

$$\frac{\vec{v}_\perp}{c} = - \frac{e \vec{A}_w}{mc \gamma} = \frac{a_w}{\gamma} (\hat{x} \cos k_w z + \hat{y} \sin k_w z)$$

$$\frac{v_{||}}{c} = 1 - \frac{1 + a_w^2}{2 \gamma^2} \quad a_w \approx 0.93 B_w(T) \lambda_w(\text{cm})$$

Fundamental Radiation Wavelength

$$(c - v_{||}) \frac{\lambda_w}{v_{||}} = \lambda$$

$$\boxed{\frac{1 + a_w^2}{2 \gamma^2} \lambda_w = \lambda}$$

Length of pulse radiated by one e^-

$$N \lambda_s \quad (N = \# \text{ wiggler periods})$$

FEL Amplifier

Consider e^- passing through wiggler
interacting with external EM-wave

$$\frac{\vec{E}}{mc} = \omega_s a_s \left[\hat{x} \sin(k_s z - \omega_s t + \phi) + \hat{y} \cos(k_s z - \omega_s t + \phi) \right]$$

$$\frac{v_{\perp}}{c} = \frac{a_w}{\gamma} \left[\hat{x} \cos k_w z + \hat{y} \sin k_w z \right]$$

Energy Transfer

$$\frac{d\gamma}{dz} = - \frac{e}{mc^2} \vec{v}_{\perp} \cdot \vec{E}_s = - \frac{\omega_s a_s a_w}{\gamma c} \sin \psi$$

$$\psi \equiv (k_w + k_s)z - \omega_s t + \phi$$

Resonance: Electron longitudinal velocity
equals phase velocity of ponderomotive
wave

$$v_{\parallel} = \frac{\omega_s}{k_s + k_w}$$

Electron sees constant ψ

$$\frac{v_{\parallel}}{c} = 1 - \frac{1 + a_w^2}{2\gamma^2}$$

Resonance Condition

$$\frac{d\psi}{dz} = k_w - \frac{k_s}{v_{||}} (c - v_{||}) = 0$$

$$(c - v_{||}) \frac{\lambda_w}{v_{||}} = \lambda_s$$

$$\frac{1 + a_w^2}{2\gamma^2} \lambda_w = \lambda_s$$

At resonance, while traversing one period of wiggler field, e^- falls one radiation wavelength behind EM-wave.

Pendulum Equations

$$\frac{d\psi}{dz} = k_w - k_s \frac{1+a_w^2}{2\gamma^2}$$

Resonant Energy $\gamma = \gamma_r$

$$0 = k_w - k_s \frac{1+a_w^2}{2\gamma_r^2}$$

Consider $\left| \frac{\gamma - \gamma_r}{\gamma_r} \right| \ll 1$

$$\frac{d\psi}{dz} = 2k_w \frac{\gamma - \gamma_r}{\gamma_r}$$

$$\frac{d\gamma}{dz} = - \frac{\omega_s a_s a_w}{\gamma_r c} \sin \psi$$

When a_w, k_w and a_s constant

$$\psi'' + \Omega^2 \sin \psi = 0, \quad \Omega^2 = \frac{2k_w \omega_s a_s a_w}{\gamma_r^2 c}$$

$$\psi'' = - \frac{\partial U}{\partial \psi}$$

$$\frac{1}{2}(\psi')^2 + U = H \text{ invariant}$$

$$\psi'' = - \frac{\partial U}{\partial \psi}$$

"synchrotron oscillations"

Electromagnetic Field Variation

Exponential FEL Amplifier

Electron Beam Power: $P_e (\text{GW}) = E_{\text{GeV}} I_{\text{Amp}}$

$E = 0.25 \text{ GeV}$, $I = 100 \text{ Amp}$, $P_e = 25 \text{ GW}$

Saturated Output Power: $P_s = \eta P_e$

$\eta \approx 10^{-4}$

$P_s = 2 \text{ MW}$

Constraint on Electron Beam Energy Spread

V-10

$$\frac{1+a_w^2}{2\gamma_r^2} \lambda_w = \lambda_s \quad (\text{Resonance})$$

$$\gamma = \gamma_r + \Delta\gamma$$

$$\frac{1+a_w^2}{2\gamma^2} \lambda_w = \lambda_s + \delta\lambda$$

For high gain, require

$$|\delta\lambda| < \frac{\lambda}{4N_G}$$

hence

$$\left| \frac{\Delta\gamma}{\gamma_r} \right| < \frac{1}{8N_G}$$

$$N_G \approx 100, \quad \frac{\Delta\gamma}{\gamma_r} < 10^{-3}$$

$N_G = \#$ of wiggler periods in one e-folding length

Betatron Oscillations (matched beam)

$$\sigma = \sqrt{\beta \epsilon} \quad \text{rms transverse size}$$

$$\sigma' = \sqrt{\epsilon / \beta} \quad \text{rms angular spread}$$

$$\text{Beta function} \quad \beta = \lambda_\beta / 2\pi$$

Emittance $\epsilon = \sigma \sigma'$ conserved by
linear optics

In LINAC, emittance inversely proportional
to energy $\epsilon = \epsilon_n / \gamma$

$\epsilon_n \equiv$ normalized emittance

Constraint on Electron Beam Emittance

$$\frac{1+a_w^2}{2\gamma_r^2} \lambda_w = \lambda_s \quad (\text{Resonance})$$

$$\left(\frac{1+a_w^2}{2\gamma_r^2} - \frac{\theta^2}{2} \right) \lambda_w = \lambda_s + \delta l$$

Require: $|\delta l| < \frac{\lambda}{4N_G}$

$$\theta < \sqrt{\frac{\lambda}{2L_G}}$$

Electron Emittance: $\epsilon = \sigma_x \sigma_x' = \sigma_y \sigma_y'$

$$\sigma_x = \sigma_y = \sqrt{\beta \epsilon}, \quad \sigma_x' = \sigma_y' = \sqrt{\epsilon/\beta}$$

$$\frac{\sigma_x'^2 + \sigma_y'^2}{2} \lambda_w < \frac{\lambda}{4N_G}$$

$$\boxed{\epsilon < \frac{\lambda}{4} \frac{\beta}{L_G}}$$

L. H. Yu, S. Kruisky, R. L. Gluckstern: Phys. Rev. Lett. 64, 3011 (1990)

3-D Vlasov - Maxwell Eqs. $\Rightarrow$ Dispersion Relation For FEL Gain

Include: Electron: Energy Spread σ (Gaussian)
 Entrance E (Water-bug)
 Focusing k_F

Radiation: Diffraction & Guiding

Derive: Scaling Law For Gain Length L_G

$$\frac{1}{k_w L_G} = D G(k_r E, \frac{\sigma}{D}, \frac{k_F}{k_w D}, \frac{\omega - \omega_r}{\omega_r D})$$

$$D = \left[\frac{4eZ_0}{\pi m c^2} \frac{K^2}{1+K^2} \frac{I_0}{\gamma_0} \right]^{1/2} [JJ]$$

$$k_r = \frac{\omega_r}{c} = \frac{2\gamma_0^2 k_w}{1+K^2} \quad (\text{resonant freq.})$$

Maximum Gain Near Detuning

$$\frac{\omega - \omega_r}{\omega_r D} = -3 \left[\frac{k_F}{k_w D} \right] k_r E$$

Use Variational Principle to Calculate Scaling Function G

FIG. 1. Scaling function vs scaled emittance for several values of $k_d/k_w D$, corresponding to scaled energy spreads (a) $\alpha/D=0$, (b) $\alpha/D=0.1$, and (c) $\alpha/D=0.2$, with the detuning as given in Eq. (13).

write the electric field of the fundamental guided laser mode of frequency ω in the form

$$E(r, \omega) e^{-i k_z z} e^{-i(\omega t - z/c)} \hat{e} + c.c., \quad (3)$$

where $\hat{e}$ is either the helical-polarization vector $(\hat{x} + i\hat{y})/\sqrt{2}$ or the linear-polarization vector $\hat{x}$. The function $E(r, \omega)$ describes the transverse-mode profile in terms of the dimensionless coordinates¹³ $r = \sqrt{2k_r k_w} R$. The factor $\exp(-i\mu k_w z)$ describes the deviation from free-space propagation and $2\chi \text{Im}\mu$ is the growth rate per wiggler period. The e-folding length L of the electric field of the amplified mode is given by

$$1/L = k_w \text{Im}\mu. \quad (4)$$

Assuming $\gamma_0 \gg 1$, so that space-charge effects are negligible, Vlasov-Maxwell equations have been used to derive a dispersion relation¹ determining μ and $E(r)$:

$$(\nabla_\perp^2 + \mu)E(r) = \frac{1}{2}(2\rho\gamma_0)^3 \int \frac{d\gamma}{\gamma^2} h'(\gamma) \int d^2p \int_{-\infty}^{\infty} ds e^{-i\omega s} u(p^2 + \kappa^2 r^2) E \left[r \cos(\kappa r) + \frac{p}{\kappa} \sin(\kappa r) \right], \quad (5)$$

where $\kappa = k_p/k_w$ characterizes the focusing strength and the Laplacian $\nabla_\perp^2$ corresponds to the dimensionless coordinates r . In addition, we have defined

$$\alpha = \mu + (\omega - \omega_r)/\omega_r - 2(\gamma - \gamma_0)/\gamma_0 + (p^2 + \kappa^2 r^2)/4,$$

$$u(p^2 + \kappa^2 r^2) = (1/\pi \kappa^2 a^2) \theta(\kappa^2 a^2 - p^2 - \kappa^2 r^2),$$

$$(2\rho\gamma_0)^3 = e^2 Z_0 \omega_0 K^2 [J]^2 / 2m c k_w^2,$$

with $[J] = 1$ for a helical wiggler, and

$$[J] = J_0(K^2/2(1+K^2)) - J_1(K^2/2(1+K^2))$$

for a flat wiggler. The radius corresponding to the edge of the electron beam expressed in dimensionless coordinates is

Table 1. Gain Lengths Calculated by Simulation and Solving Dispersion Relation

	<u>FELEX (J. Goldstein)</u>	<u>Dispersion Relation</u>
Case 1	105 cm	108 cm
Case 2 ($a_0 \times 2$)	268 cm	271 cm
Case 3 ($a \times 2$)	166 cm	164 cm
Case 4 ($\lambda_p/2$)	107 cm	104 cm
Case 5 ($\lambda_p/3$)	115 cm	108 cm

Wiggler Errors (1-D Calculation)

L.H. Yu, S. Krinsky, R.L. Gluckstern

Consider magnetic field amplitude errors giving rise to longitudinal phase error.

Ignore transverse trajectory wander (assume corrected by external steering)

$$\frac{e}{mc} \vec{A}_w = \frac{K}{\sqrt{2}} (\hat{e}_- a(z) e^{ik_w z} + \hat{e}_+ a^*(z) e^{-ik_w z})$$

Ideal wiggler $a(z) \equiv 1$

$$\vec{v}_\perp = - \frac{e \vec{A}_w}{m \gamma}$$

$$\underline{v_{||} \approx v \left(1 - \frac{v_\perp^2}{2v^2} \right) = c \left(1 - \frac{1 + K^2 |a(z)|^2}{2\gamma^2} \right)}$$

Radiated Electric Field

$$\vec{E} = \frac{1}{\sqrt{2}} E e^{ik_w z - i\omega_w t} \hat{e}_+ + \frac{1}{\sqrt{2}} E^* e^{-ik_w z + i\omega_w t} \hat{e}_-$$

Pendulum Equations: zero detuning

$$\dot{\xi}_j = (k_r + k_w) \xi - \omega \cdot t_j, \quad \tau = k_w \xi$$

$$\frac{d\xi_j}{d\tau} = 2 \left(\frac{\xi_j - \xi_0}{\xi_0} \right) + \frac{d\delta(\tau)}{d\tau}$$

$$\frac{d\xi_j}{d\tau} = -\frac{D_2}{\xi_0} (E a e^{-\xi_j} + E^* a^* e^{-\xi_j^*})$$

$$\frac{dE}{d\tau} = \frac{D_1 a^*}{\xi_0} \langle e^{-\xi_j} \rangle$$

$$\begin{aligned} \delta(\tau) &\equiv \int_0^\tau \frac{k^2}{1+k^2} (1 - |a(\tau')|^2) d\tau' \\ &= k_r \int_0^\tau \frac{d\xi}{\xi_0} (\nu_n(\tau, \xi) - \nu_0) \end{aligned}$$

This is the longitudinal phase error employed by Halbach and others.

$$\nu_n(\xi_0, \xi) = c \left(1 - \frac{1 + K^2 |a(\xi)|^2}{2\xi_0^2} \right)$$

$$\nu_0 = c \left(1 - \frac{1 + K^2}{2\xi_0^2} \right)$$

$$\frac{k_r}{\xi_0} = \frac{k_w}{c - \nu_0} \quad \text{resonance condition}$$

$$b(\tau) \equiv a(\tau) e^{i\delta(\tau)}, \quad E(\tau) \equiv b^*(\tau) y(\tau)$$

$$\frac{d^3 y}{d\tau^3} + \frac{d^2}{d\tau^2} (i\Delta(\tau) y) = i(2\rho)^3 y$$

$$i\Delta(\tau) \equiv \frac{1}{b^*} \frac{db^*}{d\tau} = \frac{1}{a^*} \frac{da^*}{d\tau} - i \frac{d\delta(\tau)}{d\tau}$$

Assume correlation of wiggler errors short compared to gain length

Consider $\Delta(\tau)$ stochastic variable

$$\langle \Delta(\tau) \rangle = 0$$

$$\langle \Delta(\tau) \Delta(\tau') \rangle = A e^{-\alpha(\tau - \tau')^2}$$

Then to second-order in $\Delta(\tau)$

$$y = y_0 \exp \left\{ -i e^{-i\tau/\lambda} 2\rho \tau - \frac{i}{3} \int_0^\tau \Delta(\tau') d\tau' - \frac{1}{9} \left[\int_0^\tau \Delta(\tau') d\tau' \right]^2 \right\}$$

$$y = y_0 \exp \left\{ -\alpha e^{-2\pi/\lambda} 2\rho\tau - \frac{1}{3} \int_0^\tau \Delta(\tau') d\tau' - \frac{1}{9} \left(\int_0^\tau \Delta(\tau') d\tau' \right)^2 \right\}$$

For wiggler errors to have small effect on gain

$$\left\langle \left(\int_0^\tau \Delta(\tau') d\tau' \right)^2 \right\rangle < 2\rho\tau$$

$$\langle \Delta(\tau) \Delta(\tau') \rangle = A^2 e^{-\alpha^2(\tau - \tau')}$$

$$\sqrt{\frac{\pi}{\alpha^2}} A^2 \tau < 2\rho\tau$$

$$A \approx \frac{\kappa^2}{1+\kappa^2} 2 \left(\frac{\Delta B}{B} \right)_{rms}$$

$$\alpha \approx 2\pi$$

$$\boxed{\frac{\kappa^2}{1+\kappa^2} \left(\frac{\Delta B}{B} \right)_{rms} < \sqrt{\rho}}$$

ON ULTRA VIOLET FREE ELECTRON LASER AT BNL

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Time structures and different FEL configurations

wiggler

Oscillator

single pass

Scheme 1

Scheme 2

(L. Bonifacio, H. White, S. Kim, L. H. Yu)

free wiggler scheme (R. Bonifacio)

e-beam parameters

energy 250 Mev ($\gamma = 500$)

current 100 A

emittance (norm) 6 mm-mrad

 $(\epsilon_n = \epsilon \gamma)$

$$\left(\frac{6 \times 10^{-6} \text{ m}}{500} = 120 \text{ \AA} \sim \frac{\lambda}{2\pi} \right)$$

 σ_t 3 ps

energy spread 0.5%

local energy spread 0.1%

Rocketdyne/Stanford 125 A 40 MeV
(accomplished)

ATF (BNL) 160 A 50 MeV
(design)

PHOTOINJECTOR LINAC PERFORMANCE SUMMARY

April 1990

	Design	Performance
Beam Energy (MeV)	17	14-17
Micropulse Energy Spread (%)	0.3	0.3
Macropulse Length (μ s)	10-100	10-40
Macropulse Rep Rate (Hz)	1	1
Micropulse Length (ps)	16	16
Micropulse Rep Rate (MHz)	21.7	21.7
Emittance (p mm mrad at bnc)	26-60	35-60
Micropulse charge (nC)	0-5	0-10
Peak Current (A)	300	>300
Cathode Quantum Efficiency (%)	>1	7

Work is underway to upgrade the linac to 40 MeV for FEL experiments

calculated
energy
distribution
from gun
output

$$\frac{\Delta \gamma}{\gamma}$$

$$\frac{20 \text{ kev}}{250 \text{ mev}} = 0.008$$

$$< 0.1\%$$

Exponential growth

Analytical tool is developed, include

diffraction — optical guiding

finite emittance — focusing

energy spread (L.H. Yu. S. Krinsky)

(A. Gluckstern)

Agree with simulation by other lab

(LANL, LLNL)

Gain function

$$\frac{\bar{I}_m(\mu)}{D} = G \left(\frac{\epsilon}{\lambda_s}, \frac{\sigma}{D}, \frac{k_p}{k_w D}, \frac{\omega - \omega_c}{\omega_c D} \right)$$

↓
growth
rate

emittance

energy
spread

detuning

focusing
strength

$$D \sim \sqrt{\frac{\bar{I}_0}{\gamma}}$$

scaling constant

design optimization

given:

$$I = 100 \text{ A}, \quad \epsilon_n = 6 \text{ mm-mrad}$$

$$\text{gap} = 4 \text{ mm}, \quad \sigma = 0.1\%$$

get

$$\gamma = 500 \quad (250 \text{ MeV})$$

$$\text{wiggler period } \lambda_w \quad 1.75 \text{ cm}$$

$$\text{field } B_w \quad 1.2 \text{ Tesla}$$

$$\text{e-beam radius } R_0 \quad 0.3 \text{ mm}$$

$$\text{wiggler parameter } K \quad 1.94$$

$$L_{\text{e-folding length}} = 1.1 \text{ m} \sim 1.4 \text{ m} \quad (\pm 0.12\% \text{ energy detuning})$$

seed $0.02 \mu\text{J}$ by H.G. of dye laser
FEL near but before saturation

$$G = \frac{8 \mu\text{J}}{0.02 \mu\text{J}} = 400 \cong e^6$$

6 L_G exponential growth
2 L_G start

wiggler length:

$$L = 8 L_G = 8 \times 1.4 \text{ m} = 11 \text{ m}$$

if seed is $0.004 \mu\text{J}$

$$L \cong 13 \text{ m}$$

Tapering:
capture into bucket

assume 50% capture

Estimate on tapered section

1-d calculation as an estimate
diffraction is neglected

— Rayleigh range comparable
to wiggler length
model gives:

$$P_{out}(w) \cong 6 \times 10^{-11} \left(\frac{f_b N_w \lambda P_e(w)}{R_0} \right)^2$$

$$P_e = 250 \text{ MV} \times 100 \text{ A} = 25 \text{ GW} \quad \text{e-beam pow}$$

$$R_0 = 0.3 \text{ mm} \quad \text{e-beam radi}$$

$$\lambda = 1000 \text{ \AA} \quad , f_b = 50\% \quad \text{capture efficiency}$$

take $N_w = 560$ wiggler periods, get

$$P_{out} = 0.32 \text{ GW}$$

$$0.32 \text{ GW} \times 3 \text{ ps} = 1 \text{ mJ}$$

$$L = N_w \lambda_w = 560 \times 1.75 \text{ cm} \cong 10 \text{ m}$$

total wiggler length

$$11 \text{ m} + 10 \text{ m} = 21 \text{ m}$$

We have obtained a simulation code
from J. Wurtele (MIT)

Simulation

code TDA (Wurtzle)

Equations of motion

$$\frac{dY}{dt} = - \frac{k_s \sin \theta_s \frac{1}{Y} \sin(\theta + \theta_s)}{Y}$$

$$\frac{d\theta}{dt} = k_w \left(1 - \frac{k_s}{k_w} \frac{1 + a_x^2 + p_x^2 + p_y^2}{2Y^2} \right) = k_w \left(1 - \frac{Y_p^{(n)} \cdot p_x p_y}{Y^2} \right)$$

$$\frac{dp_x}{dt} = - \frac{1}{2Y} \frac{\partial}{\partial x} a_w^2$$

$$\frac{dp_y}{dt} = - \frac{1}{2Y} \frac{\partial}{\partial y} a_w^2$$

$$\frac{dx}{dt} = \frac{p_x}{Y}$$

$$\frac{dy}{dt} = \frac{p_y}{Y}$$

Maxwell Equation

$$\left[\frac{\partial}{\partial t} + \frac{1}{2ik_s} \nabla^2 \right] a_s e^{i\phi_s} = i \frac{e E_0}{mc^2} \frac{f_s}{2k_s} \frac{1}{N} \sum_{j=1}^N \delta(x-x_j) \delta(y-y_j) a_w(x_j, y_j) e^{-i\theta_j}$$

$$\theta \equiv (k_s + k_w)z - \omega_s t$$

$$a_w = a_{w0} \left[1 - \frac{1}{2} k_w (x^2 + y^2) \right]$$

$$f_a = f_0 \left[\frac{a_w}{2(1+a_w)} \right] - f_1 \left[\frac{a_w}{2(1-a_w)} \right]$$

Table 1 FEL Parameters at 1000 Å

	UV	Harmonic	Harmonic	Harmonic
	seed	Generation	Generation	Generation
current (Amp.)	100	100	100	160
input wavelength (Å)	1000	3000	3000	3000
input power (MW)	0.0007	1.5	0.5	0.9
FWHM local energy spread (%)	0.1	0.1	0.05	0.1
normalized rms emittance (mm-mrad)	5	5	5	7
dispersion $d\psi/d\gamma$	-	1	5	2
length of untapered section (m)	11	8	6	3
length of tapered section (m)	10	12	14	12
tapering (%)	1.3	1.5	3	2.5
output power (MW)	160	100	220	300
output energy in a 6ps pulse (mJ)	1	0.6	1.3	1.3

FEL Parameters at 1000 Å

	UV	Harmonic	Harmonic
	seed	Generation	Generation
	(ATF gun)	(ATF gun)	(LANL gun)
current (Amp.)	100	100	300
input wavelength (Å)	1000	3000	3000
input power (MW)	0.0007	1.5	4.2
FWHM local energy spread (%)	0.1	0.1	0.1
energy stability requirement (FWHM in %)	0.18	0.17	0.25
normalized rms emittance (mm-mrad)	6	6	8
dispersion $d\psi/d\gamma$	-	1	5
length of untapered section (m)	11	3	7
length of tapered section (m)	10	12	4
tapering (%)	1.8	1.2	
output power (MW)	160	100	155
pulse length (ps)	6	6	15
output energy (mJ)	1	0.6	2.2

Scheme 1

Scheme 2

Modifying Variables cont'd

To include Harmonic Generation

- (1) Increase phase range

$$(-\pi, \pi) \rightarrow (-3\pi, 3\pi)$$

- (2) Introduce dispersion section

first wiggler, output.

$$x, p_x, y, p_y, \gamma, \theta, a_s, \phi_s$$

dispersion:

$$\theta \rightarrow \theta - \frac{d\theta}{d\gamma} (\gamma - \gamma_0)$$

second wiggler, input

$$x, p_x, y, p_y, \gamma, \theta$$

$$a_s(\theta) = 0$$

$\epsilon_{imp} 100.566$
 $K \in VREN = 100.4$
 $\epsilon_{psig} m = 1$
 $\rho_{KATV} = 1.5 \text{ MW}$
 $1.5 \cos f(1) = 4$
 $0.2649441 - 0.5072014$
 $0.2649441 - 0.5072014$

FIGURE 1. (continued) AT 1 - 0.0500

$$\chi \in U(RN - 100) \quad PRADO = 1.1 MW \quad DELTA = 0.3092 \text{ sig} \quad \exp(-y_{m-1})$$
[illegible]

Test against 1-D analysis

$$\text{density} \sim 1 + 2 \sum_{n=1}^{\infty} e^{-\frac{1}{2} n^2 \sigma_r^2 \left(\frac{d\theta}{dr} \right)^2} J_n \left(-n \Delta x_{\max} \frac{d\theta}{dr} \right) \cos n\theta$$

Fourier component:

n th harmonic

For 1-D and small energy spread

problem is solved analytically

to check simulation

scaled field

$$\alpha \equiv \frac{k_s}{k_w} a_w a_s \cdot \frac{1}{2} f_B$$

Result:

$$\alpha = \begin{cases} (\rho \gamma_0)^2 J_n(n s) & 4\rho \tau \\ (\rho \gamma_0)^2 J_n(n s) & \frac{2}{3} e^{\sqrt{3}\rho \tau} \end{cases}$$

super-radiance
linear growth
($\rho \tau \ll 1$)

($\rho \tau \gg 1$)
exponential
growth

$$n s = (\Delta \gamma)_{\max} \frac{d\theta}{d\gamma}$$

$$\tau \equiv \langle \omega \rangle$$

PHOTOINJECTOR LINAC PERFORMANCE SUMMARY

April 1990

	Design	Performance
Beam Energy (MeV)	17	14-17
Micropulse Energy Spread (%)	0.3	0.3
Macropulse Length (μ s)	10-100	10-40
Macropulse Rep Rate (Hz)	1	1
Micropulse Length (ps)	15	15
Micropulse Rep Rate (MHz)	21.7	21.7
Emittance (n mm mrad at 5ac)	25-50	35-60
Micropulse charge (nC)	0-5	0-10
Beam Current (A)	300	>300
Cathode Quantum Efficiency (%)	>1	7

Work is underway to upgrade the line to 40 MeV for FEL experiments

Niggler errors

$$\frac{\partial \gamma}{\partial \beta} = - \frac{\beta_1 \beta_2 \beta_3 \frac{1}{3} \sin(\theta - \theta_1)}{\beta^2}$$

$$\frac{\partial \theta}{\partial \beta} = \omega \left(1 - \frac{\beta_1}{\omega} \frac{1 - \frac{\beta_1^2 - \beta_2^2 - \beta_3^2}{\beta^2}}{\beta^2} \right) \equiv \omega \left(1 - \frac{\gamma_{\beta_1 \beta_2 \beta_3}}{\gamma^2} \right)$$

$$\frac{\partial \beta_1}{\partial \beta} = - \frac{1}{\beta^2} \frac{\beta}{\beta_1} \beta^2 - \frac{\beta_2 \beta_3}{\beta}$$

$$\frac{\partial \beta_2}{\partial \beta} = - \frac{1}{\beta^2} \frac{\beta}{\beta_2} \beta^2$$

$$\frac{\partial \beta_3}{\partial \beta} = \frac{\beta_3}{\beta}$$

$$\frac{\partial \gamma}{\partial \beta} = \frac{\beta_3}{\beta}$$

Niggler error causes:

(1) Transverse wandering

(2) Longitudinal phase drift

case of wiggler errors without steering error
for (1-2) problem is solved

(L.H. Yu, S. Krinsky, R. Gluckstern)

model of correlated half periods.

second order perturbation gives:

$$\left\langle \left| \frac{E}{E_0} \right|^2 \right\rangle = e^{\left(\sqrt{3} - \frac{2}{9} \pi \Delta p \right) \cdot 2_0 k v_z + \frac{\sqrt{3}}{27} \pi \Delta p^2} = \sqrt{\frac{\sqrt{3} \pi}{18} \Delta p}$$

NONLINEAR DYNAMICS STUDIES OF ACCELERATORS

ALEX CHAO

SSC LABORATORY, TEXAS

A ex Chap
1.22/3.

Nonlinear Dynamics Studies of Accelerators

Will discuss storage ring accelerators. Nonlinear dynamics is a crucial part of storage ring physics.

Particle motion in an accelerator is

- basically linear
i.e. accelerator $\approx$ 3-D simple harmonic potential well with three frequencies v_x , v_y and v_s
- but perturbed by nonlinear error fields

Can particles survive for ^{10⁹⁻¹⁰}~~10¹⁰~~ turns in such an environment ? ($\approx$ Earth lifetime)

Storage rings provide excellent & unique experimental device for nonlinear dynamics.

Observe the motion of a single particle in a storage ring. Collect the turn-by-turn data

$(q, p)_0, (q, p)_1, (q, p)_2.$

Ideally, motion is linear

$\Rightarrow$ the turn-by-turn data fall on a circle.

"tune" ν_0 = phase advance per turn $/2\pi$
 = same for all amplitudes A

Assume ν_0 = irrational!

Now add nonlinearities (error fields). Several things happen

First effect

$$v = v(A)$$

=> tune no longer stays irrational

=> phase space spontaneously
degenerates into an infinitely layered
sandwich

The system however remains "integrable" at this point. The difficulty of nonlinear dynamics is not due to $\Delta v(A)$.

Much nastier effect

those "dots" have finite sizes, i.e.,
"dots" are actually "islands"

=> islands break neighboring circles into
stochastic layers -- signature of
non-integrability.

(better to call them "lakes" than "islands" ...)

Not all irrational numbers are created equal

$$v_{\text{most irrational}} = \underline{(m+n\sqrt{5})/p}$$

Increasing A

=>

larger islands

=>

more circles are broken

But circles corresponding to $\sqrt{5}$ tunes persist.
They are only distorted, but not broken.

circles --> "invariant surfaces"

Particles inside the invariant surfaces are bounded. Deviation of the invariant surface from a circle is called "distortion function" or "smear".

As A increases more, islands are large enough to "overlap". Even $\sqrt{5}$ invariant surfaces are broken.

(Chirikov 1979)

The last invariant surface defines the "dynamic aperture", beyond which unbounded motion occurs.

Recap: nonlinear dynamics effects in accelerators (in increasing A)

circles

distortion & smear

$\Delta v(A)$

resonances & islands

stochastic layers

invariant surfaces

dynamic aperture

Where do nonlinearities come from.

E.g. SSC magnet cross-section.

ideal superconducting
current distribution

$$= \cos \theta$$

$\Rightarrow \vec{B}$ uniform inside

$\Rightarrow$ linear

real dist. $\neq \cos \theta$

$$\Rightarrow \frac{\Delta B}{B} = \sum_n b_n (n\text{-th mult})$$

$$\sim 10^{-4} @ 1 \text{ cm}$$

Field is "99.99%" linear.

But 10^{-4} nonlinearity can do damage for $< 10^{13}$ turns.
potentially

Recent Nonlinear Dynamics Studies for the SSC

A. Chao

- other people's work
- I am just a reporter

Nonlinearities in the SSC

$$\Delta B_y + i \Delta B_x = B_0 \sum_n (b_n + i a_n) (x + iy)^n$$

Random multipole errors (rms)

	<u>4 cm aperture</u>	<u>5 cm aperture</u>
b2	0.4	0.272
b3	0.3	0.18
b4	0.7	0.35
a2	0.6	0.41
a3	0.7	0.41
a4	0.2	0.1

Systematic multipole errors at injection at 2 TeV

	<u>4 cm aperture</u>	<u>5 cm aperture</u>
b2	-3.0	-1.9
b4	0.2	0.09
b6	-0.05	-0.017

- Every dipole is assigned a set of a_n, b_n
- 4000 dipoles in SSC
- track particles

*Ztrack**Van
Braunhoff
Schachinger*

Figure 12. X vs. Turns Run = 68.4 cm Magnet

Titson
Hearing
Jaworska
Kaufman

TRANSVERSE AMPLITUDE

Yan
Borisanoff

Figure 14. Mod 1 and 2 vs. Turns Run = 681 Chaos

Figure 15. Mod 1 and 2 Turns Run = 681 Chaos

NATLOG. NORM. AMPL.

HORIZONTAL

0 1 2 3 4 5 6

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55

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0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55

PARTICLE 4

turns 512

x y
q(nom) 1072850 1067819
alpha 00719 00054
beta 3002268 515705
min 00002 08104
max 60093 36350
sinear 07909 03228
pos 52030 03 20010 03
d/ds 14510 06 -10460 05

1 0 0 2853 0.000
0 1 0 2587 0.458
2 0 0 1038 1.649
2 0 0 4084 3.490
1 1 0 4450 3.117
1 1 0 0358 2.762
0 2 0 4800 3.904
1 0 1 2881 1.098
0 1 1 2915 1.552
0 1 1 2635 1.052
0 0 2 2559 1.790
0 0 2 0076 4.005
3 0 0 1141 3.688
2 1 0 1497 3.371
2 1 0 3309 3.504
1 2 0 1853 3.040
0 3 0 2241 2.480
2 0 1 2209 2.703
2 0 1 4058 4.454
2 0 1 4132 3.830

NATLOG. NORM. AMPL.

HORIZONTAL TUNE SPECTRUM

PARTICLE 3

turns 512

	x	y
Q(nom)	1072850	1062649
alpha	00719	00254
beta	3002268	515705
min	00177	08641
max	11631	15381
smear	04034	02374
pos	5341D 03	1317D 03
d/ds	1210D 05	5413D 05

1	0	0	2948	0.000
0	1	0	2612	0.850
0	0	1	0040	1.572
2	0	0	4108	5.584
1	1	0	4442	4.081
1	1	0	0334	2.028
0	2	0	4770	3.887
1	0	1	2986	1.776
1	0	1	2907	2.109
0	1	1	2651	1.258
0	1	1	2572	1.158
0	0	2	0079	3.897
3	0	0	1181	4.228
2	1	0	1498	4.204
2	1	0	3281	4.747
1	2	0	1830	4.381
-1	2	0	2277	2.800
0	3	0	2185	4.047
2	0	1	4088	5.487
2	0	1	4147	4.907
1	1	1	4402	6.185

inverse survival times from seq_5
range= $\pm 4.5 \times 10^{-4}$ times X_0

Bourianoff

Accelerator Modelling and Taylor Maps

The map concept is a familiar one

Linear map = Courant-Snyder matrix

Nonlinear map = Taylor map of order M

$$X_f = \sum C_k X_i^k$$

accurate if close enough to the closed orbit.

a theorist's accelerator
= model
= some form of map

*From pt. A to
pt. B:*
*Don't worry
about the
details.
Just give me
the map.....*
*What map are we
going to use
today for the SSC?*

A bad model for SSC:

each nonlinear element is modelled by
ray-tracing with infinitesimal step size

=> have to compromise without losing
physics

=> art of modeling

A better model for the SSC:

each magnet element modelled by a single thin-lens kick

=> element-by-element tracking

Two ways to improve:

1. concatenating elements

element-by-element $(\text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠})$
10 kicks / cell

concatenate $(\text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠} \text{⊠})$
4 kicks / cell

Ritso.

2. one-turn maps

element-by-element 4000 kicks / turn

one-turn map 1 map / turn

Consider an accelerator with a thin-lens sextupole

=> X_f for one turn = second order power series X_i

For SSC with 4000 dipoles, each containing a thin-lens sextupole

=> one-turn Taylor map = 2^{4000} -th order

SSC with a_n and b_n in the dipoles

=> Taylor map = n^{4000} -th order

Drastic truncation is needed, and actually works !

Sen
Yan

CRAY CPU times:

element-by-element tracking for 1
million turns = 200 hrs
11-th order Taylor map = 12 hrs
tracing using the 11-th order map for 10
million turns = 5 hrs
6-th order map = 1/2 hr

Advantages of maps :

faster
same map can be used for different
launching conditions
allow analytical studies

Weakness : must check against element-by-
element tracking to be sure.

Symplecticity

this is a big deal !

The M -th order Taylor map is symplectic only to $\mathcal{O}(\epsilon^M)$.

Why $\begin{cases} (11\text{-th order map}) \approx (\text{element-by-element}) \\ (10\text{th} \quad \dots \quad \dots) \neq (\quad \quad \quad) \end{cases} ?$

Is it because

$\begin{cases} 10\text{th order map is not symplectic enough,} \\ \text{or,} \\ \text{it misses some 11-th order "driving terms"} \end{cases} ?$

ans 10-th order map is not symplectic enough !

conclusion : A low order (6?) map is sufficient for the SSC provide it is symplectic

Diffusion phenomenology

Assume there is such a thing as $\tau(A)$

Start with $A(0)$

n turns later, amplitude = $A(n)$

$\Rightarrow$

$$\tau(A(0)) - \tau(A(n)) = n$$

Given $\left\{ \begin{array}{l} \tau(A) \\ A(0) \end{array} \right\}$ can calculate $A(n)$ as function of n .

Also, assume the mechanism is a diffusion.

Define a "diffusion coefficient"

$$D(A) \equiv \frac{dA^2}{dn}$$

$\tau(A)$ also gives an expression for $D(A)$

$$D(A) = - \frac{2A}{d\tau/dA}$$

Rapid loss at
the end
→ Consistent with
tracking observ.

Manipulation of maps offers a useful way to analyze the nonlinear dynamics effects:

- artificially removing the detuning terms
- artificially removing a specific resonance
- identify slow diffusion by observing the invariant as a function of time
- effect of tunes on dynamic aperture

Figure 1. Second order (Courant-Snyder) invariant for 400 turns at $x = y = 5.4$ mm.

Figure 2. Sixth order invariant for 400 turns at $x = y = 5.4$ mm.

Do you see
a diffusion?

Irwin
Yan

Conclusions / Recap

- Nonlinear dynamics is an important part of accelerator physics / SSC
- active / rich research area
lots of ideas around

How to model an accelerator

canonical integration techniques

symplecticity

maps

Lie maps

normal form

Taylor maps

kick maps

different perturbation variables

differential algebra

post-analysis of tracking results

⋮

chaos

diffusion

Modelling by Kick Maps

A special case of Taylor map is actually symplectic,
i.e. the Kicks :

$$\Delta \vec{x} = 0$$

$$\Delta \vec{x}' = f(\vec{x}) \neq f(\vec{x}')$$

Can a general one-turn map be represented
as several Kicks ?

↑
This model is
symplectic

HIGH LUMINOSITY AT SSC

R. PALMER

BNL/ SLAC/ SSC

SSC Luminosity1/14/91
Palmer

Ultimate Luminosity

Vacuum Problem

Synchrotron Heating

Quas Aperture

- 1) need for shield
- 2) dynamic aperture
- 3) Costs
- 4) Missing Magnets

SSC Ultimate Luminosity

John Gareyte, Simon
Brown, Palmer

Luminosity

$$L \propto \frac{N^2}{\epsilon_n s \beta^*}$$

N^2 (ps/bunch)
 ϵ_n (normalized emittance)
 s (bunch spacing)
 β^* (mm)

Head on Tune Shift

$$\Delta Q \propto \frac{N}{\epsilon_n} \leq 0.01 \quad \left(\frac{h}{4\pi I_{\text{int}}} \right)$$

Long Range Tune Spread

$$\Delta Q_{LR} \propto \frac{N \epsilon_n}{s \beta^*} \cdot \left(\frac{D}{s^2 \beta^* \phi^*} \right)$$

Combining the above

$$L \propto \Delta Q \quad \Delta Q_{LR} \quad \frac{\gamma}{E_n} \quad \left(\frac{\gamma^2 \beta^* \phi^4}{D} \right)$$

Approximate intersection scattering

$$\left. \begin{array}{lcl} \beta^* & \propto & \gamma^{1/2} \\ D & \propto & \gamma^{1/2} \\ \phi & \propto & 1/D \end{array} \right\} \left(\frac{\gamma^2 \beta^* \phi^4}{D} \right) \rightarrow \text{const}$$

So

$$L \propto \Delta Q \quad \Delta Q_{LR} \quad \frac{\gamma}{E_n}$$

$$\left[L \approx 4 \cdot 10^{25} \frac{\gamma}{E_n \text{ (m)}} \right]$$

		$\wedge$ LHC	$\wedge$ SSC	SSC ₀	SSC ₁
Ξ	TeV	7.7	—	20	—
$\mathcal{L}$	$10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$	33	85	.1	10
E_n	10^{-6} m rad	1	—	1	—
N	10^9	80	80	6	60
S	m	2	1	5	5
I	amps	2.5	5	.07	.7
U	GJ	1.7	23	.3	3
P_{Synch}	KW	60	1000	16	160
					$\uparrow$

Many other problems
but none obviously crazy

Maximum	(design) currents in some machines
ISR	> 40 amperes
AGS	942 ma
PS	1790 "
Hera	(163) (500?) "
SPS	230 (400) "
LHC	830 - 850 "
76 GeV (USSR)	545 "
KEK-PS	708
Fermi booster	355
SSC_0	(72)
SSC_1	700
SSC_{∞}	5000

Vacuum Problem

Synchrotron Rad

H₂ emits in large quantity

H₂ → walls (4.35°) & sticks - OK

But 2 problems:

- A) Continuous Synch Radiation knocks it off
- B) It builds up till vapour pressure rises

FIG. 4. Adsorption isosteres for H_2 on stainless-steel cryosurface partially exposed to radiation from 300 K. $\circ$ 0.2×10^{16} , $\bullet$ 0.4×10^{16} , $+$ 0.6×10^{16} , $\circ$ 0.8×10^{16} , ∇ 1.0×10^{16} , $\square$ 22×10^{16} , Δ 66×10^{16} molecules cm^{-2} .

When either limit is reached

Beam Gas $\rightarrow$ heating

heating $\rightarrow$ more gas

more gas $\rightarrow$ - - - - CLIFF.

Time before Cliff

$$I = I_0$$

$$I = 10 I_0$$

A) $\propto I^2$ 3 - 30 days .03 - .3 days

B) $\propto I$ 3 - 30 days .3 - 3 days

Note : large uncertainty $\pm$ factor 3

at

($\sim 20^\circ\text{K}$)

time to warm up pump $\approx$ 2 days

ie

- serious risk of $\sim 50\%$ DC. at $I = I_0$
- certain $\leq 50\%$ DC at $I = 10 I_0$

Solutions

(A) Any Shield at any Temp

(B) 1) Operate at 3.1°
2) ASS Charcoal getter

Note: neither solution absolutely requires separate cooling or shield
BUT if not cooled, it's a getter MUST be welded or soldered to pipe (HARD)

Synchrotron Heating Problem

$$I = I_0$$

2 Watts / magnet

$$= 16,000 \text{ W} + 36 \text{ kW} = 52 \text{ kW}$$

$$I = 10 I_0$$

20 Watts / magnet

$$= 160,000 \text{ W} (+ 36 \approx 200 \text{ kW})$$

Cost inc of $10 \times I_0 \approx 400 \text{ M\$}$ X

But present designs cannot cool 20 W/mag X

So Require cooled Shields

BORE TUBE AND
BEAM TUBE LINE

SCALE 12:1
BY U. GONZALEZ

Cost of Shields

COST

?

But beam tube ~ 5 M\$

SAVINGS

- No Plating of Cu 16 M\$
 - Less Gyr at 4° 13 M\$
-
- 30 M\$

Quad Aperture Needs

For cooled OR uncooled shield
we require ~ 5cm

Shield for Vac MUST be EVERYWHERE
∴ QUAD must be 5cm too

Some solutions considered included

But UGLY !

Quad Aperture Need

For cooled OR uncooled shields
we require $\sim 5\text{ cm}$

Shields for Vac MUST be EVERYWHERE
 $\therefore$ QUAD must be 5 cm too

Some solutions considered included

But UGLY !

Quas Aperture

Beam Dynamic Aperture for injection

Tracking Studies

Steinwig

Putson

Kaufman

Palmer

GEE WHIZ PLOT RUN=25

Assumptions

- Elements ± 1 mm to beam
- Chromaticity corrected to 5 units
- Tune $x \approx 0.425$ $y \approx 0.410$
- $Q_{th} = 1st$ harmonic of skew Quad corrected (12 knobs)
- 1 mm orbit drift after correction
- magnets NOT sorted
- NO Octupole or Decapole correction

4-0

Figure 2. Hypothetical simulation of SSC injection with 5 cm amplitude errors and 1 cm quadrupole errors.

Figure 4 Numerical simulation of SSC injection with 5 cm dipole errors and 5 cm quadrupole errors.

Quad Magnet Bore (cm)

Consequences of $4 \rightarrow 5$ cm Quad

Shapiro
Zbarak

- Quad gradient $\sim 8\%$ less
 $\therefore$ Quad length $\sim 8\%$ more (~ 40 cm)
 - Corrector lengths increase but remain inside present spool
 - Require minimum decrease in Dipole lengths of 0.5% (7.5 cm)
 - Thus minimum increase in Dipole Field of 0.5% (0.03 Tesla)
 - Quad Cost increase 25 M \$
 - Corrector Cost increase 18 M \$
-
- 43 M \$
 ($\sim 0.5\%$)

Option ANotual

- Remove 1 dipole / 6 cells (1.7%)
(approx 1 / km)

- Shorten all dipoles 20cm (1.3%)

 3%

- Operate $B = 6.7 \times 1.03 = 6.9$

- Operate $T = 4.35^\circ - .23^\circ = 4.12^\circ$

- Magnet Savings 28 M\$

- Cryo Cost inc. - 4 M\$

 24 M\$ (44)

Option B : next natural step

- Remove 1 dipole / 2 cells (5%)
1/300m
 - shorten all dipoles 7.5 cm (.5%)
(room for longer Quads)
-
- 5.5%
-
- Operate at $B = 6.7 \times 1.055 = 7.07 T$
 - Operate at $T = 4.35^\circ - .38^\circ = 3.97^\circ$
(for same margin)
-
• Magnet Cost Saving	53 M\$
• Cryo Cost increase	- 7 M\$
	46 M\$
	cf 43 M\$

Random
PulsarMissing Magnets

DSA207 50mm (1.8m) Current at Quench

Fig 1
Magnet Current Margin
VS operating Temp

T

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CAP

**CENTER FOR ACCELERATOR PHYSICS
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973**

FROM: ZOHREH PARSA, CAP,

**TO: PHYSICS, ADD, AGS, NSLS,
INS., and DISTRIBUTION LIST**

SUBJECT: SEMINAR SCHEDULE

November 6	Z. Parsa On Beam Emittance Application to ATF
November 20	I. Ben-Zvi On Development of a Superconducting RFQ at Stony Brook
December 4	S. Krinsky Theory of High Gain Free-Electron Laser (FEL)
December 18	L.-H. Yu On Ultra Violet FEL at BNL
January 8	
January 22	Alex Chao, SSC Nonlinear Dynamics of SSC
February 5	S. Ozaki Update on Status of Relativistic Heavy Ion Collider (RHIC)

****NOTE THE TIME CHANGE TO 1:30 - 3:00 PM, PHYSICS BUILDG. 510**

Coffee will be available prior to the seminars.

**BNL
GRI**

SPECIAL MEETING NOTICE

**CENTER FOR ACCELERATOR PHYSICS
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973**

**FROM: Z. PARSA, CAP, Build. 510
TO: PHYSICS, ADD, AGS, NSLS, INS.,
and DISTRIBUTION LIST
SUBJECT: SPECIAL CAP SEMINAR ****

HIGH LUMINOSITY AT SSC

BY

**R. B. PALMER
SSC and SLAC**

DATE: Thursday 1/10/91

Time: 1:30 P.M.

Place: Small Seminar Room, Physics Dept., Bldg. 510.

**Coffee will be available prior to the seminars.
** Please note the nonstandard date.**

**bnl
att**

MEETING NOTICE

CENTER FOR ACCELERATOR PHYSICS BROOKHAVEN NATIONAL LABORATORY UPTON, NEW YORK 11973

FROM: ZOHREH PARSA, CAP, BLDG. 510D
TO: PHYSICS, ADD, AGS, NSLS, INS.,
and DISTRIBUTION LIST
SUBJECT: 1991 CAP SEMINARS

Following are the dates for the 1991 CAP seminars. The talks will be held at 1:30 p.m., in the Small Seminar Room, Physics Department, Bldg. 510. Coffee will be available prior to the seminars.

- Feb. 12 *"RF Superconductivity for Particle Accelerators"
Hasan Padamsee, Cornell University,
- March 12 *"Overview of Argonne's Applied Acc. Programs",
Bart Claire, Argonne National Laboratory
- March 26 *"High Gradient Acceleration Research at M.I.T."
J. Wurle Massachusetts Institute of Technology
- April 16 "Preliminary Emittance measurements and calculations
of the Laser Excited Beam from the BNL Accelerator
Test Facility (ATF) Radio Frequency Electron Gun",
Zohreh Parsa, Brookhaven National Laboratory
- April 30 *"Cornell B - Factory",
Maury Tigner, Cornell University
- May 21 "Radio Frequency (RF) Gun Development at Stanford"
Helmut Wiedemann, Stanford University
- June 4 "Single Bunch Beam Breakup and BNS Damping"
R. L. Gluckstern, University of Maryland
- June 18 *"Update on Status of Relativistic Heavy Ion Collider
(RHIC)", Satoshi Ozaki, Brookhaven National Laboratory

* Please note the date and Room changes. For more infos. call 3845.

BNL
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