BNL-52292
CAP-125-95P

SELECTED TOPICS IN PARTICLE ACCELERATORS

PROCEEDINGS OF THE CAP MEETINGS

VOLUME V

**Edited / Compiled
by
Zohreh Parsa**

CENTER FOR ACCELERATOR PHYSICS

**BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.**

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UNITED STATES DEPARTMENT OF ENERGY

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MASTER

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FORWARD

This Report includes copies of transparencies and notes from the presentations made at the Center for Accelerator Physics at Brookhaven National Laboratory. Editing and changes to the authors contributions were made only to fulfill the publication requirements.

We would like to take this opportunity and thank the speakers for their informative presentations and for providing copies of their transparencies and notes for inclusion in this Report. We regret the delay in the processing of this report, due to lack of secretarial assistance.

We also would like to thank L. Allen and J. Hanson for their assistance with the meeting announcements and processing of this Report.

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TABLE OF CONTENTS
VOLUME V

<u>TOPIC</u>	<u>AUTHOR(S)</u>	<u>SECTION</u>
FORWARD	Z. PARSA	
THE ENERGY EXCHANGE AND EFFICIENCY CONSIDERATION IN KLYSTRONS	Y. ZHAO	I
SOME PROPERTIES OF MICRO- WAVE RF SOURCES FOR FUTURE COLLIDERS + OVERVIEW	G. NUSINOVICH	II
FIELD QUALITY IMPROVEMENTS IN SUPERCONDUCTING MAGNETS FOR RHIC	R. GUPTA	III
HADRONIC B-PHYSICS	M. ATIYA	IV
SPIKING PULSES FROM FREE ELECTRON LASERS: OBSERVATIONS AND COMPUTATIONAL MODELS	T. C. MARSHALL	V
CRYSTALLINE BEAMS IN CIRCULAR ACCELERATORS	J. WEI	VI
ACCUMULATOR RING FOR AGS & RECENT AGS PERFORMANCE	T. ROSER	VII
RHIC PROJECT MACHINE STATUS	M. HARRISON	VIII
GAMMA-GAMMA COLLIDERS	A. SESSLER	IX
APPENDIX		

**THE ENERGY EXCHANGE AND
EFFICIENCY CONSIDERATION
IN KLYSTRONS**

Y. ZHAO
BNL

I

THE ENERGY EXCHANGE AND
EFFICIENCY CONSIDERATION
IN KLYSTRONS

Yongxiang Zhao
Braookhaven National Laboratory
May 1994

The Comparison Between Accelerator and Klystron

The Energy Exchange in a Klystron Cavity

--- 4 factors affecting the efficiency

Bunching Theories and the Design of the Drift Tube Length

--- Space Charge Wave Theory and Plasma Wavelength

The Factors Affecting the Uniformity of the Beam

The Coupling between Beam and Cavity

Design of the Cavity Parameters

--- How to optimize the cavity voltage

The Summary of the Parameters of Current Cluster Klystron

--- A Discuss of the Parameters

THE COMPARISON BETWEEN ACCELERATOR AND KLYSTRON

	Accelerator	Klystron
Bunch located at	Positive field	Negative field
Energy direction	Field --> Beam (Acceleration)	Beam --> Field (Deceleration)
Bunch size	Compacted	Widely spread
Space charge effect	Rather weak	Strong
Beam energy	$\gg$ Gap voltage (no reflection)	$\approx$ Gap voltage (necessitate to prevent reflection)
Energy spread	Relative small	Large

THE PHASE RELATION BETWEEN VOLTAGE AND CURRENT IN DIFFERENT FACILITIES

BUNCH LOCATION IN DIFFERENT DEVICES

THE ENERGY EXCHANGE IN A KLYSTRON

(4 Factors affecting the efficiency)

1. Beam Bunching

Bunching current
$$I_1 = \frac{1}{\pi} \int_0^{2\pi} i e^{-j\omega t} dt$$

Bunching efficiency:
$$\eta_{bun} = \frac{1}{2} \cdot \frac{I_1}{I_0}$$

Ideal: δ -function $i = I_0 \delta(t)$

In fact: Bunching efficiency is limited, due to space charge
 $\eta_{bun} = 0.7 \sim 0.8$ will be excellent

2. Uniformity of Beam Velocity

Ideal: All electrons with same velocity

In fact: Nonuniform due to many factors

3. Cavity Voltage

Ideal: $V = \frac{V_0}{M}$ Total beam energy transfer to cavity

If: $V < \frac{V_0}{M}$ Part of energy go to damper (collector)

$V > \frac{V_0}{M}$ Part of electrons will be reflected.

4. Uniformity of Cavity Field

Ideal: Gap field is uniform,
so electrons are exerted same voltage.

In fact: The field near edge is stronger,
near axis the field is weaker.

Another concern

Circuit efficiency:
$$\eta = 1 - \frac{Q_{ext}}{Q_0}$$

It is sometimes of concern, especially for very low perveance.

BUNCHING THEORIES
AND THE DESIGN OF THE DRIFT TUBE LENGTH
--- Space Charge Wave Theory and Plasma Wavelength

Bunching Theories

- Kinetic Theory (ballistic theory) --- Applegate Chart
- Space Charge Wave Theory --- Solving Field Equation.
- Digital Method --- Making use of computer program

What is Space Charge Wave ?

- A wave exists in a beam of charge, which can be dealt with as an anisotropic dielectric. In klystron usually characterized by plasma wavelength.
- A plasma is like an elastic dielectric, but positive ion is not necessary, so an electron beam behaves similarly.

The Significance of Space Charge Wave

- The affection of the space charge is of major concern with the efficiency.
The more space charge, the more difficult to bunch the beam.
- Plasma wavelength is a measure of the affection of the space charge.
The more the space charge, the shorter the plasma wavelength.
- The bunching process can be described as a beat of two space-charge waves.

Comparison Between Space Charge Wave and Waveguide Wave

<u>Waveguide without beam</u>	<u>Drift tube with beam</u>
1. Wave equation $\nabla_t^2 E_z + k_c^2 E_z = 0$	$\nabla_t^2 E_z + T^2 E_z = 0$
2. Eigen Value: (critical wave number)	
$k_c^2 = k^2 - \beta^2$	$T^2 = (k^2 - \beta^2) \cdot \left(1 - \frac{\omega_p^2 / \omega^2}{(1 - \beta / \beta_e)^2}\right)$
3. Each eigen value corresponds to 2 field waves (except degeneration) a forward wave and a backward wave:	corresponds to 4 waves 2 field wave (which are similar as waveguide), and 2 space charge wave:
$\beta_{1,2} = \pm \sqrt{k^2 - k_c^2}$	$\beta_{3,4} = \beta_e \cdot (1 \pm \alpha)$
	$\alpha = \frac{\omega_p}{\omega} \cdot \left[1 + \frac{T^2}{\beta_e^2 - k^2}\right]^{-1/2}$
4. Phase velocity is higher than light velocity	Wave velocity is close to beam velocity
5. Exists cut-off frequency	No cut-off frequency

Plasma Wavelength and Drift Tube Length

How to design the drift tube length?

- Efficiency mainly depends on the last two sections, while gain depends on the proceeding sections.
- Too short a length can not get enough bunching, while too long increases the total length.
- Normally calculate the plasma wavelength as first step and then choose the physical length according to (but not uniquely):

	Length measured by plasma wavelength λ_q
Gain sections	≤ 90 degree ($\leq 1/4 \lambda_q$)
Last section	25~ 40 degree
Before last	40 ~ 60 degree

How to figure out the plasma wavelength?

$$\omega_p \text{ (plasma angular frequency)} \quad \omega_p^2 = \frac{e\rho}{m\epsilon}$$

$$\text{or:} \quad \omega_p = 1.83 \times 10^{10} \cdot \frac{j^{1/2}}{V^{1/4}}$$

k_p (relativistic correction factor)

$$k_p = \frac{1}{\gamma} \cdot \left(\frac{2}{\gamma+1} \right)^{1/4}, \text{ where}$$

$$\gamma \text{ (relativistic factor)} \quad \gamma = 1 + \frac{V}{511kV}$$

$\omega'_p (= k_p \omega_p, \text{correcting } \omega_p)$

$\omega_q = F \omega'_p$ (modified plasma frequency),

F (plasma modification coefficient)

(Refer to: G. M. Branch, T. G. Mihran, IRE trans. PGED-2, No.2, p.3, Apr. 1955)

λ_q (modified plasma wavelength) $\lambda_q = 2\pi v / \omega_q$

CALCULATION EXAMPLES

Present designing parameters

Drift tube between cavities		1-2	2-3	3-4
L (Length)	cm	3.7	2.8	1.5
For 100 kV				
L / λ_q (relative to plasma wavelength)		0.215	0.163	0.087
	degree	77	59	31
For 370 kV				
L / λ_q (relative to plasma wavelength)		0.0342	0.0259	0.0139
	degree	12.3	9.3	5.0

SLAC X-band 100MW Klystron:

Drift tube between cavities		1-2	2-3	3-4	4-5
L (Length)	cm	8.0	8.0	8.3	3.0
L / λ_q (relative to plasma wavelength)		0.183	0.183	0.190	0.069
	degree	66	66	68	25

THE FACTOR AFFECTING THE UNIFORMITY OF THE BEAM

This is probably the most difficult problem to deal with.

- Phase difference
- Nonuniformity of field
- Repulsion between space charge
it may improve uniformity also.
- Transverse velocity
- Thermal velocity (ignorable in most practice)

The energy spread:

$$V = V_0 \pm MV_1 \pm MV_2 \pm MV_3 - V_{\text{transverse}} \pm \delta_{\text{collision}} \\ \approx V_0 \pm MV_3$$

Usually V_3 can be of the order of 0.3 ~ 0.4 V_0 , this is remarkable. However, in practice this can be somewhat improved due to the repulsion of space charge.

THE COUPLING BETWEEN BEAM AND CAVITY

Coupling parameters

- It is the ratio of the force exerted on the electrons and the potential across the gap.
- It is always less than one.
- It is nonuniform along radius. The electron near edge has better coupling, while at the center has poorer coupling.
- The smaller the diameter of the drift tube, the stronger the coupling, while it enhance the space charge, because the diameter of the beam should be reduced too. So compromise must be made between the coupling and the space charge.

Formulae

$$M(r) \text{ (coupling coef.)} \quad M(r) = \frac{\int_{-\infty}^{\infty} f(z, r) e^{j\beta_e z} dz}{\int_{-\infty}^{\infty} f(z, r) dz}$$

or

$$M(r) = M_z \cdot M_r(r)$$

$$M_z \text{ (longitudinal coupling coef.)} \quad M_z = \left(\sin \frac{\theta_d}{2} \right) / \frac{\theta_d}{2}$$

or termed “time factor”

where θ_d is transit angle

$$\theta_d = \beta_e \cdot d$$

$$M_r(r) \text{ (transverse coupling coef.)} \quad M_r(r) = \frac{I_0(\gamma_e r)}{I_0(\gamma_e a)}$$

where I_0 is zero order modified Bessel function.

and

$$\gamma_e = \sqrt{\beta_e^2 - k^2}$$

$$\overline{M}_r \text{ (transverse average coupling)} \quad \overline{M}_r = \frac{1}{I_0(\gamma_e a)} \cdot \frac{2\pi}{A} \cdot \int_{b_2}^{b_1} I_0(\gamma_e r) r dr$$

$$\overline{M} \text{ (average coupling coefficient)} \quad \overline{M} = M_z \cdot \overline{M}_r$$

Curves

EXAMPLE OF COUPLING CALCULATION

Gap and coupling parameters

(For different beam voltage:)		100 kV		370 kV	
Cavity number		1, 2,3	4	1,2,3	4
d (gap of cavity0	cm	0.2	0.33	0.2	0.33
a (radius of drift tube)	cm	0.5	0.55	0.5	0.55
$\theta_d = \beta_e d$ (transit angle)	radian	0.872	1.44	0.587	0.969
	degree	50.0	82.4	33.64	55.5
$\beta_e a$ (normalized radius)		2.18	2.398	1.46	1.615
$A = \gamma_e a$		1.82	2.01	0.853	0.938
$B_1 = \gamma_e b_1$		1.532	1.532	0.717	0.717
$B_2 = \gamma_e b_2$		0.767	0.767	0.368	0.368

Coupling coefficient

M_z (longitudinal coupling coef.)	0.969	0.915	0.986	0.961
$M_r(b_1)$ (transverse coupling at b_1)	0.83	0.731	0.951	0.920
$M_r(b_2)$ (transverse coupling at b_2)	0.572	0.502	0.868	0.839
$\overline{M}_r$ (average)	0.697	0.612	0.908	0.877
$M(b_1)$ (coupling coef. outer electron)	0.804	0.669	0.938	0.884
$M(b_2)$ (coupling coef. inner electron)	0.554	0.459	0.856	0.806
$\overline{M}$ (average)	0.675	0.560	0.895	0.843

SLAC X-band 100MW Klystron:

a (radius of drift tube)	cm	0.476				
Cavity number		1	2	3	4	5
d (gap of cavity0	cm	0.28	0.38	0.48	0.55	0.55
$\theta_d = \beta_e d$ (transit angle)	radian	0.795	1.079	1.363	1.562	1.562
	degree	45.6	61.8	78.1	89.5	89.5
Cavity number		1	2	3	4	5
$\overline{M}$ (average)		0.902	0.882	0.856	0.835	0.835

DESIGN OF THE CAVITY PARAMETERS

How to optimize the cavity voltage

Design Steps:

1. Inner diameter of the drift tube --- a

Choosing the parameter is a compromise.

increase a --> favorable to: space charge (weakened)
focus magnetic field (lower)
unfavorable to: coupling (weakened)
 R/Q (lower)

2. Gap distance ---- d

increase d --> favorable to: breakdown (strengthen)
 R/Q (higher)
unfavorable to: coupling (weakened)

3. Cavity shape

After a and d are chosen, making use of computer program to get the highest R/Q , in consideration of the mechanical realizability.

4. External Q

After R/Q is defined, external Q s are important for gain and efficiency.
(see below for detail)

5. Realization of external Q

- Making use of a 3-dimensional code to calculate the size of coupling iris.
- Experiment by cut-and-try.

DESIGN OF THE EXTERNAL Q

Q_{ext} of input cavity

- Decided by a best match between the source and the load. The “load” is mainly beam loading, which can be estimate, but not precise.
- Experiential beam loading (admittance) is usually larger than calculated one. Experiential data:

$$G_e = 0.1 \sim 0.15 G_b, \quad \text{where } G_b = I_b/V_b$$

- Input cavity: $Q_{ext} = \frac{1}{G_e \cdot (R/Q)}$

Q_{ext} of output cavity

- Decided by optimization of gap voltage. Once bunching current, I_1 , is known, the gap voltage should be:

$$V_{gap} = M I_1 \cdot Q_{ext} \cdot (R/Q)$$

- The V_{gap} is chosen so that the electrons will meet maximum retarding potential in a condition of no reflection.

$$V_{gap} = \frac{V_b}{M}$$

- Once the R/Q is defined and the bunching efficiency, $\eta_i = I_1/2I_0$, is known, then:

$$Q_{ext} = \frac{1}{\eta_i M^2} \cdot \frac{1}{(R/Q)} \cdot \frac{V_b}{2I_b}$$

Estimate of external Q of output cavity:

V_b (beam voltage)	kV	100	370
M		0.669	0.884
V_{cav} (cavity voltage required)	kV	150	419
I_b (beam current)	A	100	100
R/Q		95	95

Estimated external Q of input cavity:

V_b (beam voltage)	kV	100	370
I_b (beam current)	A	100	100
$Q_{in.ext}$		105	390

V =100 kV,						
$\eta_i = I_1/2I_0$		0.4	0.5	0.6	0.7	0.75
R	k Ω	2.80	2.24	1.87	1.60	1.49
Q_{ext}		29	24	20	17	16

V =370 kV,						
$\eta_i = I_1/2I_0$		0.4	0.5	0.6	0.7	0.75
R	k Ω		4.74	3.95	3.39	3.16
Q_{ext}			50	42	36	33

THE ENERGY EXCHANGE IN THE KLYSTRON CAVITY

Ideal condition

1. Beam fully bunched

$$I_1 = \frac{1}{\pi} \int_0^{2\pi} i e^{-j\omega t} dt$$

$$\eta_{bun} = \frac{1}{2} \cdot \frac{I_1}{I_0}$$

For ideal condition $i = \delta$ -function:

Then

$$I_1 = 2I_0 \text{ and } \eta_{bun} = 1$$

Real situation

Bunching efficiency is limited

In practice:

$$\eta_{bun} = 0.7 \sim 0.8$$

will be excellent

2. Beam with uniform velocity

The velocity is not uniform due to:

- a. phase difference;
- b. nonuniformity of field;
- c. repulsion between space charge (may improve uniformity also);
- d. transverse velocity;
- e. thermal velocity(omittable).

3. Cavity voltage optimized

$$V = \frac{V_0}{M}$$

It can be realized by adjusting Q_{ext}

M -- Coupling coefficient

(or time factor), $M < 1$

RF voltage V should be slightly larger than beam voltage V_0 .

4. Electrical field be uniform in cavity

$$M = M(r) = \frac{1}{d} \int_{-\infty}^{\infty} f(z, r) e^{(j\omega z)/v_0} dz \quad \text{M is nonuniform at different radius.}$$

In principle, simulation can take into account all above factors, while it is difficult.

**SOME PROPERTIES OF
MICROWAVE RF SOURCES FOR
FUTURE COLLIDERS +**

***G. NUSINOVICH
UNIVERSITY OF MARYLAND***

II

Some Perspectives of Microwave (RF)
Sources for Future Linear Colliders. +
Overview of Microwave Generation
Activity at the University of Md.

Gregory Nusinovich

Institute for Plasma Research,
University of Maryland,
College Park, MD

Reminiscence: ~ 25 years ago

Lasers

Active medium: coupled electrons
in excited atoms and/or molecules.

Energetic spectrum is very
non-equidistant.

$\hbar\omega_1 \neq \hbar\omega_2$ - single-photon
radiation

(A few photons can contribute
into one laser resonator mode
if

$$|\omega_s - \omega_s| \leq \frac{\omega}{Q}$$

When we go from optical to infrared
waves ω decreases. Correspondingly,
an energy of one photon decreases
and the power of single photon sources
drops

Note: Lines of radiation and absorption
correspond to different frequencies:

Microwave Tubes

Conventional microwave tubes are based on transition and Cherenkov (Smith-Purcell) radiation.

Transition radiation:

Klystron:

To localize the RF field inside $d < \lambda$ the transverse size of the beam tunnel must also be $< \lambda$.

Wavelength shortening $\Rightarrow$ miniaturization.

Since RF field is restricted by a breakdown (pulse) or by Ohmic losses (cw),

the maximum RF power drops.

Cherenkov radiation

$$v_{ph} = \frac{c}{n} \approx v_e$$

Smith-Purcell radiation

Floquet's theorem

$$E = \sum_n E_n e^{in \frac{2\pi}{d} z}$$

Spatial harmonics with $k_{z,n} = k_{z0} + n \frac{2\pi}{d}$.

Typically for $n=1$ $v_{ph} = \frac{\omega}{k_{z1}} = \frac{\omega}{k_{z0} + \frac{2\pi}{d}} \approx v_e$.

In other words, $\omega \approx k_z v_z$.

Since $v_{ph} \approx v_e < c$, $k_{\perp 1}^2 = \left(\frac{\omega}{c}\right)^2 - \left(\frac{\omega}{v_{ph}}\right)^2 < 0$.

The field of the synchronous spatial harm. is localized near the structure wall. So, to be coupled with this field the electrons must also propagate there.

So, all sizes (axial $\sim d$ and transverse) scale with $\lambda \Rightarrow$ miniaturization $\Rightarrow P \downarrow$.

Present Status

Single Pulse Operation

From "Applications of High-Power Microwaves", ed. A.V. Gaponov, V.L. Granatstein (Artech House, 94)

Gyrotrons (cyclotron resonance masers)

are based on Bremsstrahlung of free electrons in a constant magnetic field.

Landau levels are almost equidistant but non-equidistant.

Since they are almost equidistant, one electron may radiate a huge number of photons with close frequencies. Also the absorption line is close to the radiation line.

Example: To extract a significant amount of energy from 0.5-1 MeV electrons for radiation at 30 GHz ($\lambda = 1 \text{ cm}$) a number of photons must be $\geq 10^9$.

Therefore, it is reasonable to describe this radiation in terms of a classical physics.

In terms of classical physics this non-equidistance follows from the relativistic dependence of electron cyclotron frequency on its energy: $\Omega = \frac{eH_0}{m_0 c \gamma}$, γ is electron energy normalized to $m_0 c^2$.

$$\frac{d\Omega}{d\gamma} \neq 0$$

This $\rightarrow$ fact causes orbital bunching of electrons after initial modulation of their energies by the RF field.

This orbital bunching is similar to the axial ballistic bunching of electrons in klystrons.

Cyclotron resonance condition:

$$\omega - k_z v_z \approx s \Omega$$

harmonic number

$$k_z = \frac{\omega}{v_{ph}} \rightarrow \omega \approx \frac{s \Omega}{1 - v_z / v_{ph}}$$

Electrons can interact with fast waves.

No need in slow-wave structures.

Interaction volume can be $\gg \lambda^3$.

Electron bunching at the fundamental cyclotron resonance

Transverse structure of the synchronous field

$s=1 \rightarrow$ Dipole $s=2$ -Quadrupole . . .

Similarity between linear beam devices and gyrodevices.

O-TYPE DEVICE
	MONOTRON	KLYSTRON	TWT	BWO	TWYSTRON
TYPE OF GYROTRON
	GYRO-MONOTRON	GYRO-KLYSTRON	GYRO TWT	GYRO BWO	GYRO-TWYSTRON

Note: In the limiting case of $k_z \rightarrow \frac{\omega}{c}$ the gyro-TWT is called CARM (cyclotron autoresonance maser).

Autoresonance: $k_z = \frac{\omega}{c}$, in $\omega \approx \Omega + k_z v_z$ shifts in $\Omega(\gamma)$ and $k_z v_z(\gamma)$ completely compensate each other.

Another family of microwave sources based on coherent Bremsstrahlung radiation are free electron lasers, FELs.

In FELs electrons oscillate in periodic magnetic (or electric) fields produced by wigglers.

The resonance condition is the same as for gyrodevices:

$$\omega - k_z v_z \approx s \Omega,$$

where $\Omega = \frac{2\pi v_z}{d}$ $d \leftarrow$ wiggler period

However, there is no autoresonance effect. Therefore, to realize a highly efficient operation it is necessary to taper the wiggler period, d .

Doppler Frequency Up-Shift

Bremsstrahlung: $\omega \approx \frac{s \Omega}{1 - v_z / v_{ph}}$

For fast wave interaction with relativistic electrons (when $v_z \rightarrow c$ and $v_{ph} \rightarrow c$)

$$\omega \sim \gamma_0^2 s \Omega$$

$v_{ph} \gg c$

Cherenkov Devices at High Voltages

$$v_{ph} \approx v_e$$

As γ grows, $v_e \rightarrow c$, so $v_{ph} \rightarrow c$.

$$\frac{\Delta v_z}{v_z} = \frac{1}{(\gamma_0^2 - 1)} \frac{\Delta \gamma}{\gamma}$$

large $\Delta \gamma$ correspond to
small $\Delta v_z \Rightarrow$ decelerated
electrons stay in synchro-
nism with the wave.

2) $v_{ph} \rightarrow c \Rightarrow$ no need to slow down the wave
phase velocity significantly.

From here:

a) smoothly corrugated structures
with a small height
of ripples
(breakdown $\downarrow$)

b) as $k_z \rightarrow \frac{\omega}{c}$ $k_{\perp}^2 = \left(\frac{\omega}{c}\right)^2 (1 - \beta_z^{-2})$

$$\downarrow$$

$$L_{\perp} \sim \gamma_0 \lambda$$

As γ grows, the tolerance becomes better

Combined Devices

Relativistic klystrons with the traveling wave output section $\equiv$ twystron

Since $P_{out} \sim \frac{\omega}{Q} E^2 V$ (V is the interacting space volume),
a traveling-wave output section provides
for a given P_{out} a lower value of
the E -field inside the structure
than that of a high- Q cavity
of a klystron resonator.

So, at high P_{out} $E < E_{break}$.

Note:

$$Q \approx Q_{dif} = \frac{\omega L}{v_{gr}(1 - |R_{in}| \cdot |R_{out}|)}$$

RF Sources (Amplifiers) for Particle Accelerators

GYROKLYSTRON EXPERIMENTS AT THE UNIVERSITY OF MARYLAND ($V \lesssim 500$ kV, $\tau \approx 1.5\mu\text{s}$)

I. Initial Experimental Results :

Output Power P_0	Effi- ciency η	$\alpha =$ $v_{\perp}/v_{\parallel}$	f	Harmonic No. s
27 MW	32%	1.2	9.87 GHz	1
32 MW	29%	1.2	19.7 GHz	2

The value of P_0/λ^2 may be the largest realized in any amplifier with $\tau \gtrsim 1\mu\text{s}$.

II. Experiment Under Construction (Diode e-gun, co-axial ckt)

P_0	η	$v_{\perp}/v_{\parallel}$	f	s
100 MW	35%	1.5	17.1 GHz	2

Extension to 4th harmonic operation at 34.2 GHz is being considered.

UM Gyroklystron Experiment Performance Summary (as of 10/93)

2nd Harmonic Gyroklatron Tube #4

coaxial GKL

Magnetron Injection Gun

A possible scheme of a coaxial gyrotron without beam intersection

with the support of the coax insert

b) If a built-in quasioptical mode converter is used after the resonator, then the insert can also be supported from the collector side.

EFFICIENCY ENHANCEMENT IN GYROTRONS

I. Since primarily transverse energy is converted to microwaves in output cavity, increase value of
 $\alpha = v_{\perp}/v_{\parallel}$.

(α being increased from 1.2 to 1.5 in current work.
Further increase to $\alpha > 2$ may be possible.)

II. Develop traveling-wave output ckt which can tap energy in $v_{\parallel}$ as well as in $v_{\perp}$.

(gyro-twyston)

III. Depressed collector

Numerical simulations have been carried out on designs of depressed collectors for gyrotrons

(e.g. a single-electrode depressed collector can increase efficiency from 36% to 56%).

Microwave Generation Programs

at the IPR, Univ. of Md.

- Gyroamplifiers for Future Linear Colliders
(sponsored by DoE),
- Gyrotron Oscillators for Plasma Fusion:
Electron Cyclotron Heating and Current Drive
(in collaboration with MIT and Varian)
(sponsored by DoE),
- Low Voltage Harmonic Gyroamplifiers
for Radar Application.
(sponsored by AFOSR),
- HPM Sources Driven by Relativ. e-Beams
(sponsored by ARL),
- Plasma-Filled HPM Sources
(sponsored by AFOSR),
- Microwave Processing of Materials
(sponsored by DoE).

UNIVERSITY OF MARYLAND AT COLLEGE PARK

INSTITUTE FOR PLASMA RESEARCH

ENEE 608D

ELECTROPHYSICS SEMINAR

Professor M. Reiser
Institute for Plasma Research
University of Maryland

**"CHARGED PARTICLE BEAMS FOR ADVANCED
ACCELERATOR APPLICATIONS"**

Abstract

Some of the advanced accelerator concepts being developed at various laboratories around the world for applications in energy, science, and technology have high beam current and beam quality requirements that exceed the current state of the art. Examples are heavy-ion inertial fusion, transmutation of radionuclear waste, materials testing for fusion reactors, high-energy physics colliders, spallation neutron sources, and high-power free electron lasers. The charged particle beams for these applications are dominated by space-charge effects which may cause unacceptable beam quality deterioration and particle losses. The physics of such beams, in particular the mechanism responsible for emittance growth and halo formation, will be reviewed. Results of related experimental theoretical and computer simulation work at the University of Maryland will be presented. Design strategies for obtaining high-quality beams in advanced accelerator applications will be discussed.

Friday, October 28, 1994
4:00 p.m.

Energy Research Building
Large Conference Room
Room 1207

COLLABORATORS

Associate Research Scientists:

S. Guharay

J.G. Wang

Graduate Research Assistants:

C. Allen

H. Suk

S. Bernal

*D. Kehne**

N. Brown

*D.X. Wang**

C.H. Chen

* Now at CEBAF

Outside Collaborators (Simulation):

I. Haber (NRL)

H. Rudd

Experimental and Theoretical Studies on the Physics of Space-Charge Dominated Beams

"Numerical and Experimental Studies of Halo Formation due to Mismatch in a Space-Charge Dominated Electron Beam", D. Kehne and M. Reiser, Conference Record of the IEEE 1993 Particle Accelerator Conference, 93CH3279-7, pp. 65-67.

"Experimental Verification of a Longitudinal Beam-Envelope Model for a Space-Charge Dominated Parabolic Bunch", D. X. Wang, J. G. Wang, D. Kehne, and M. Reiser, Appl. Phys. Lett., 62(25), pp. 3232-3234, 21 June 1993.

"Longitudinal Instability of Space Charge Dominated Beams in Transport Channels with Complex Wall Impedances", J. G. Wang and M. Reiser, Physics Fluids B, 5(7), pp. 2286-2294, July 1993.

"Generation of Space-Charge Waves due to Localized Perturbations in a Space-Charge Dominated Beam", J. G. Wang, D. X. Wang, and M. Reiser, Phys. Rev. Lett., 71(12), pp. 1836-1839, September 20, 1993.

"Determination of the Geometry Factor for Longitudinal Perturbations in Space-Charge Dominated Coasting Beams", J. G. Wang, H. Suk, D. X. Wang, and M. Reiser, Phys. Rev. Lett., 72(13), pp. 2029-2032, March 28, 1994.

"Restoration of Rectangular Pulse Shape after Edge Erosion for a Space-Charge Dominated Electron Bunch", D. X. Wang, J. G. Wang, and M. Reiser, Phys. Rev. Lett., 73(1), pp. 66-69, July 4, 1994.

"Reflection and Transmission of Space-Charge Waves at the Ends of a Space-Charge Dominated Electron Bunch", J. G. Wang, D. X. Wang, H. Suk, and M. Reiser, submitted for publication to Phys. Rev. Lett..

Theoretical Work on Beam Equilibrium and Image Effects

"Thermal Distribution of Relativistic Particle Beams with Space Charge", Martin Reiser and Nathan Brown, *Physical Review Letters* **71**, 18, p2911 (1993).

"Solution to the Stationary Longitudinal Envelope Equation", Nathan Brown and Martin Reiser, *Particle Accelerators* **43**, p231 (1994).

"Image Effects for Bunched Beams in Axisymmetric Systems", Christopher K. Allen, Nathan Brown and Martin Reiser, *Particle Accelerators* **45**, p149 (1994).

"Zero-Temperature Equilibrium for Bunched Beams in Axisymmetric Systems", Christopher K. Allen and Martin Reiser, accepted for publication in *Particle Accelerators*.

"Proposed High-Current rf Linear Accelerators with Beams in Thermal Equilibrium", Martin Reiser and Nathan Brown, submitted to *Physical Review Letters* (September 1994).

"Thermal Equilibrium of Bunched Charged Particle Beams", Nathan Brown and Martin Reiser, submitted to *Physics of Plasmas* (October 1994).

Book

Theory and Design of Charged Particle Beams, Martin Reiser, Wiley Series in Beam Physics and Accelerator Technology (September 1994).

Kind of Illumination That Burns Brightly, but Not C

THE SULFUR LAMP

Last week, the Department of Energy and a company called Fusion Lighting Inc. announced the development of a new device called the Sulfur Lamp. It produces bright white light by exposing a sealed quartz bulb containing argon gas and a small amount of sulfur to microwave radiation. In test installations at the DOE's Forrestal Building headquarters and the National Air and Space Museum, the bulb is coupled with 10-inch diameter "light pipes" that carry the rays over long distances.

Comparing lamp efficiency

■ Different kinds of lamps can be compared by measuring the number of lumens (a standard unit of light flow) they emit per watt of energy use. Some approximate averages for various designs are listed at right.

■ For many applications, engineers want illumination that closely resembles sunlight. The chart above shows the output of the Sulfur Lamp compared to that of sunlight in those frequencies (marked by the white curve) in which the human eye is most sensitive. Ultraviolet range lies beyond the chart on the left; infrared to the right.

Lacking Electr

One of the bulb's ally, DOE's Andert- trode will break it and multipart tub-

versions have elimi- required two fans Michael Lry, left) says Fusion Lighting do "in about 3 sec- quartz from mecha- tions per minute has to be rotated at "The sulfur bulb is decrease on the sur- tion of all colors gen- while sunlight, which wave lengths, very c "The result is a spec- commonly wide va- large quantity of the found, they expect- plates, the fusion- ions drop back to As the molecules forms into two-stom- and vaporizes the oven puts out, the what the average is 2.4 billion cycles pe- ated with electroneg- safety match. When p- proximately the amou- leath atmosphere pi- golf ball is filled wit- Building, a bulb abo-

Energy is

albs, fluo- metal halide

giving re- sive, will

s devices compared by measuring the number

intensely flow) they emit per watt of energy use. Some approximate averages for

high-tech- lets need

not in micro-

isms, but

act of that prototype lighting of DOE.

re contain- with ordi- waves, the bright and

allations of not Air and- JOE head- out Energy called it "a

**FIELD QUALITY IMPROVEMENTS
IN SUPERCONDUCTING MAGNETS
FOR RHIC**

R. GUPTA
BNL

III

**Field Quality Improvements
in
Superconducting Magnets for RHIC**

**R. Gupta, M. Anerella, J. Cozzolino, A. Ghosh,
A. Greene, A. Jain, S. Kahn, E. Kelly, G. Morgan,
W. Sampson, P. Thompson, P. Wanderer, E. Willen**

Result of over a decade of combined work of physicists, engineers and technicians.

RHIC Magnet Production Status				
All Actuals as of 10/31/94				
	Built By	Required	Built	% Complete
8cm Dipole	NGC	373	34	9.12
8cm Quadrupole	NGC	432	24	5.56
13cm Quadrupole	BNL	78	46	58.97
Sextupole	EEC	300	300	100.00

RHIC Arc Dipoles

Northrop Grumman 8cm Dipole

RHC Arc Quadrupoles

Northrop Grumman 8cm Quadrupole

RMS / File Name: * 3D Charts Chart 2

11/1/84 5:55 PM

Most Important Magnets in RHIC

1. Low β QUADS : (our top-of-the line magnets)

Determines the luminosity performance of RHIC due to a large beam size.

2. Arc Dipole Magnets :

Covers the maximum space in the RING.

Typical Field Quality Requirements

$$\frac{\Delta B}{B} = 10^{-4} \quad \text{at } \frac{2}{3} \text{ coil radius.}$$

RHIC Arc Dipoles and Quadrupoles

Coil Aperture : 80 mm

Circumference : 251 mm

Mechanical tolerances for 10^{-4} field quality :

$$251 \text{ mm} \times 10^{-4} = 0.0251 \text{ mm (1 mil)}$$

General argument; in detail, it depends on the location of error.

If these tolerances and other sources of errors can not be controlled, the magnet aperture must be increased (example SSC and LHC).

In RHIC magnets, we have developed techniques by which all specified tolerances (wish lists) are being honored and in fact, in critical magnets, we are aiming for 10^{-5} in field quality by some new features.

Error Analysis : HARMONIC COEFFICIENTS

$\frac{\Delta B}{B}$ errors are analysed in terms of harmonic coefficients.

“cos (θ)” terms are called the normal coefficients (b_n)

“sin (θ)” terms are called the skew coefficients (a_n)

In both cases the n^{th} order harmonic produces a field error which increases as r^n . However, the angular dependence of error goes as $\cos(n\theta)$ for normal harmonics (b_n) and $\sin(n\theta)$ for skew harmonics (a_n).

Formal Definition

The field harmonics are defined in the following relation:

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} [b'_n + ia'_n] [\cos(n\theta) + i \sin(n\theta)] \left(\frac{r}{R_0}\right)^n,$$

where B_0 is the field at the center, B_x and B_y the components at (r, θ) , R_0 the normalization radius. a'_n are the skew harmonics and b'_n are the normal. In RHIC arc dipoles R_0 is 25 mm.

BASIC SYMMETRY & Allowed harmonics

Dipole Symmetry : 4-fold

Suppose Vendor delivers Wedge #3 which is systematically larger by 1 mil (within spec)

This will create a field error, BUT basic 4-fold symmetry is still maintained.

Harmonics, thus created, are called allowed harmonics

$b_2, b_4, b_6, \dots$ (in dipole)

All others are non-allowed harmonics : $b_1, b_3, b_5, \dots$ $a_1, a_2, a_3, \dots$

Generally average (mean) value of allowed harmonics is much larger than non-allowed.

BUT ONE CAN ITERATE DESIGN TO REDUCE THEM!

SOURCES OF FIELD HARMONICS

...and how we reduce them

Field errors come from several sources and all must be controlled (or corrected) to obtain good field quality in the entire range of operation.

1. Persistent Currents

Reduced by Improvements in Superconductors.

2. Iron Saturation (Non-linear B-H curve)

Reduced by Improvements in Techniques.

3. Magnet Geometry

Reduced by Iterations and Post Construction Corrections.

HARMONICS INDUCED BY IRON SATURATION

Iron is good because:

1. It provides a good shielding
2. Iron gets magnetized and gives additional field

$$B_{\text{Total}} = B_{\text{coil}} + B_{\text{iron}}$$

RHIC Dipole } at Design } 3.45 T ~ 2.3 T ~ 1.15 T

and iron is cheap

— x —

Iron Contribution in all RHIC Cosine(θ) magnets
30% - 40%

In other Cosine(θ) magnets around the world.

only ~ 20% [WHY?] ^{BECAUSE IT IS FAR AWAY}

PROBLEM (with close-in iron).

Iron is highly non-linear at ~~high field~~ and may distort the uniformity at the center of the magnet.

BUT At BNL we have used several methods to minimize this effect despite a larger contribution

Non-linear Magnetization of Iron

$$B = \mu(H) H$$

In CGS $\mu=1$ for Air

$$\frac{B}{\mu_0} = H + M$$

Applied Field

PT/SK

$|B|$ in Iron at the design field (3.45T),
if the yoke was circular with no holes, etc.

Note: Variation in $|B|$ near the yoke aperture
(Iron is non-linear at these fields)

Saturation induced harmonics in the prototype (developmental) magnets and in the final design

Field Quality Improvements through Yoke Design

88

Order of magnitude improvements over time
 → 10 years!

Saturation induced $b_4 = (b_{4up} + b_{4dn})/2$

Again, order of magnitude Improvement!

Contribution to field by IRON

For a constant μ

$$B_{\text{TOTAL}} = B_{\text{coil}} \left[1 + \frac{\mu-1}{\mu+1} \left(\frac{R_{\text{coil}}}{R_{\text{iron}}} \right)^{2(n+1)} \right]$$

$n=0$, for dipole; $n=1$ for quadrupoles, ...

[Note: μ must be constant every where in the iron]

If not, the field shape will get changed.

HOW TO MINIMIZE THE CHANGE?

Minimize $\frac{\mu-1}{\mu+1}$ as a function of field
particularly near the yoke aperture as
a function of azimuthal angle!

But this is a guide; in reality change in
harmonics as a function of current
is minimized!

$\frac{\mu-1}{\mu+1}$ in Yoke with no structure (at 8 kA)

See a large change in $\frac{\mu-1}{\mu+1}$ near the yoke aperture.

0.43 $\rightarrow$ $\sim$ 0.8 (about a factor of 2)

This means that iron contribution is now a function of angle
and field shape gets deformed.

A more uniform $\frac{\mu-1}{\mu+1}$ is forced by a number of holes & cutouts

A lengthy and elaborate investigation made possible by improvements in computer software, hardware and some human thinking

Reduction in Saturation Induced Allowed Harmonics

Used in
8cm RHIC
Dipoles

- Varying the yoke inner radius
- Varying the yoke outer radius
- Varying the location of the helium bypass hole in the
yoke
- Additional Saturation suppressor holes in the iron yoke . .
- Yoke-yoke alignment keys
- Tooth at the midplane of the yoke aperture

Investigated
on RHIC Dipoles

- Cutout or Bump in the iron aperture
- Elliptical iron aperture (6M).
- Yoke aperture described by two radii

Used in RHIC
Interaction Region Quadrupoles

Saturation a_1

(a_1 : Skew Quadrupole Harmonic)

Principle Cause

Top-bottom asymmetry between the cryostat and the COLD MASS.
~~yoke.~~

Field lines can not be contained in the yoke at high fields, and CRYOSTAT provides extra iron for the flux return path.

Harmonic Generated
by this asymmetry:
Skew Quadrupole (a_1)
value ≈ -2 unit
2 part in 10,000.

PROPOSED FIX :
(To be implemented soon)

Yoke is made of laminated iron,
and there is a slight variation in the weight of laminations.

Make lower half a little heavier ($50\frac{1}{4}\%$, upper $49\frac{3}{4}\%$.)

This extra iron would compensate for the iron of the
cryostat at the top.

Geometric Multipoles

Due to errors in Magnet Geometry

1. Design Imperfections
2. Component errors (systematic)
3. Construction errors

FIXES

- CROSS - SECTION ITERATION
and some psuedo - iterations $\Rightarrow$ fast & cost-eff
- POST CONSTRUCTION CORRECTION

Harmonics in the BNL magnets during R&D Phase

b_2 (Sextupole) and b_4 (decapole) at 2kA

Geometric b_2 - b_4 in Prototype RHIC Dipoles

[GUPTA.MEASURE.RHIC]TEMP2KA_NH.DAT:1

09:28:05, 14-NOV-94 GPlot

DRG Dipoles -- Integ. b2 (5000A)

No Change in Coil X-section;
 Only the insulation (Kapton caps)
 between top & bottom coil
 is changed
 11/14/94

DRG Dipoles -- Body b4 (660A)

DRGTRND.XLS

11/14/94

Table 1: A comparison between the RMS errors in the magnets built for various accelerators at the maximum design field. Note that b_2 , b_4 and b_6 should further get reduced.

Harmonic ↓	Tevatron (4kA) 788 magnets	HERA (5kA) 433 magnets	RHIC (5kA) 23 magnets
b_1	0.52	0.61	0.19
b_2	3.5	2.68	1.58
b_3	0.84	0.25	0.08
b_4	1.51	0.81	0.44
b_5	0.34	0.10	0.04
b_6	1.07	0.53	0.27
a_1	0.57 ¹	1.81 ²	1.46
a_2	1.29	0.41	0.19
a_3	1.59	0.95	0.42
a_4	0.5	0.19	0.05
a_5	0.62	0.23	0.12
a_6	0.39	0.10	0.03

Generally a factor of 2 improvement.

R. Gupta, 11/15/94

A significant improvement in random errors implies a significant control over the manufacturing process and parts used in building magnets.

A few crucial parts are :

1. Control in cable dimensions
2. Control and choice of kapton insulation on the cable
3. Control in coil dimensions
4. Wedge dimensions

Table 1: A comparison between the mean of harmonics in the magnets built for various accelerators at the maximum design field. Note that b_2 and b_4 in RHIC are further reduced by the iteration already applied.

Harmonic ↓	Tevatron (4kA) 788 magnets	HERA (5kA) 433 magnets	RHIC (5kA) 23 magnets
b_1	0.08	-0.03	0.01
b_2	0.9	0.16	0.98
b_3	-0.3	0.12	0.01
b_4	-0.7	1.1	-0.35
a_1	0.2	-0.27	-1.51
a_2	0.3	-0.25	-1.11
a_3	-0.1	0.27	-0.39
a_4	-0.07	0.05	0.20

R. Gupta, 11/15/94

Note : Large systematic values of a_n 's are caused by the particular geometry chosen to optimize the construction.

Field Quality in Large Aperture Quadrupoles

Determines the ultimate luminosity performance of RHIC.

Field Quality in Superconducting Magnets:

- Depends on the accuracy of the parts used in building magnets.
- Depends on the accuracy in the manufacturing process in making magnets from the given parts.

Both of these errors are of the order of $25\text{-}50\ \mu\text{m}$ (1-2 mil).

Field errors caused by them is more than what is desired.

To overcome these limitations we have developed the *SHIMMING* technique for post-construction correction based on magnetic measurements.

NOTE: Field errors should get reduced to 10^{-5} level rather than 10^{-4} level.

Interaction Region Quadrupoles

Location of large aperture quadrupoles (in triplet)

Beam Sizes in arc and in triplet for $\beta^* = 1$

Beam Size changes rapidly in these quads which limits the effectiveness of external correctors!

Ratio of Beam Size Triplet/Arc ≈ 7 ($\beta^* = 1$)

Ratio of Aperture Size Triplet/Arc ≈ 1.6

Reduction in b_5 (dodecapole) Saturation in Quads

First allowed harmonic in quadrupoles : b_5
(like b_2 in dipoles)

DRAMATIC IMPROVEMENT

TUNING SHIM MATERIAL WORKSHEET A

RHIC 13cm QUADRUPOLE

MAGNET SERIAL NUMBER _____

Tuning shim are made of partly magnetic material.

$T = 0, .005, .010, .015, \dots, .240$

PRINCIPLE

- If magnetic material is introduced it will create field distortion and hence field harmonics.
- Introduce correct amount to compensate the errors already present
- 8 Tuning Shims can correct 8 harmonics

sk/s00501ml

REV 0 OF 3

PHIC-WUG-B-1035

PROCEDURE FOR SHIMMING

Steps to adopt tuning shim correction :

1. Warm Magnetic Measurements:

Obtain values of harmonics in the magnet.

2. Compute Shim Thickness:

Compute the thickness of 8 shims to reduce following 8 harmonics

a_2, a_3, a_4, a_5 and b_2, b_3, b_4, b_5 .

Note : Higher order harmonics will be created in the process; e.g., if b_3 is changed b_7 will change too!

3. Insert SHIMS:

The shims will be inserted “without opening” the magnet.

It (not opening the magnet) is important because:

(a) When the magnet is opened and assembled again, the harmonic may change.

(b) Makes it much faster and cost effective to implement.

Advantage of shimming

Will achieve field quality significantly better than what is expected from the superconducting magnets.

- Easy to implement.
- Corrects the error where "it is" and therefore more efficient than the global and lumped correctors – important since the beam size is changing rapidly within the triplet.

Since the maximum luminosity is desired at the top energy, the magnets are designed to have the best field quality at the maximum operating gradient.

Another paper in this conference,
"Magnetic Multipole Compensation for the RHIC Triplet",
J. Wei, R. Gupta and S. Peggs.

Comparison between Calculations & Measurements (WARM)

Eight tuning shims of varying amount of (IRON) thickness are inserted, one by one

Measurements: Symbols
Calculations: Lines

Shims in QSR120 (Warm)

A VERY GOOD AGREEMENT

Shims in QRI120 (Warm)

Shims in QRI120 (Warm)

Shims in QRI120 (Warm)

Conclusion on Tuning Shims

- 1. This is a very effective technique in improving field quality in superconducting magnets by a large amount.**
- 2. The early experimental results indicate that it should deliver what is advertised.**
- 3. This technique would be crucial in all future accelerators in maximizing the luminosity performance of the machine.**
- 4. As compared to the "smart bolts" in Tevatron magnets and "coil shims" in HERA magnets which were design to correct only one harmonic, this scheme correct several harmonics.**
- 5. This is an alternate technique to increasing magnet aperture to improve field quality in ring magnets. However, it is much more efficient and cost effective.**
- 6. WE LOVE IT!**

Conclusions

- 1. Field Quality in RHIC Superconducting Magnets has been significantly improved over time.**
- 2. RHIC is setting new standards for field quality in superconducting magnets.**

HADRONIC B-PHYSICS

M. ATIYA

BNL

IV

Hadronic B-Physics

Where do we stand?

October 11 1994

- Physics Objectives
 1. CP-violation studies: CKM angles and direct decays.
 2. $B_s^0 - \bar{B}_s^0$
 3. Rare decays.
 4. Lepton number violation in the third generation.
- Current & near-term experiments
 1. CDF & D0 current and Run II upgrades.
 2. HERA-B
- Future prospects
 1. Dedicated FNAL effort.
 2. Dedicated RHIC effort.
 3. LHC: dedicated and general purpose.

What are the parameters of an experiment at RHIC to study the large number of B's produced during HEP running, assuming the following:

Parameter	Value
$\sqrt{S}$	500 GeV
L_{peak}	$5 \times 10^{32} cm^{-2} sec^{-1}$
β^*	1 m
$\epsilon_{95\%}$	$15\pi \times 10^{-6} m$
Number of bunches	114
Bunch separation	110 nsec
Luminous region (Initial)	$\sigma_z = 9 cm$ $\sigma_{x,y} = 65 \mu m$
Free space between splitting dipoles	20 m

Define 10^{10} as 1 RHIC Run

Comparison of current and future facilities

	RHIC	Tevatron Post MI	SLAC ABF(4S)	LEP (Z^0 pole)	HERA-B 820 Gev
L	5×10^{32}	5×10^{31}	10^{34}	2×10^{31}	3×10^{33}
$\sigma (\mu b)$	10	50	10^{-3}	3×10^{-2}	6×10^{-3}
Sec/y	2×10^6	10^7	10^7	10^7	10^7
B-pair	10^{10}	2.5×10^{10}	10^8	10^6	2×10^8
$B_{u,d}$	5×10^9	1.2×10^{10}	10^8	5×10^5	10^8
B_s	1.5×10^9	4×10^9	0	2×10^5	3×10^7
B_c	10^7	2.5×10^7	0		2×10^5
Λ_b	10^9	2.5×10^9	0		10^7

What do we know about the CKM angles and what is allowed?

The allowed region is roughly an ellipse in the ρ - η plane.

The corners yield the following extremes

$\sin 2\alpha$	$\sin 2\beta$	$\sin 2\gamma$	x_s
0	0.7	0.99	16
1	0.55	-0.84	25
0.8	0.25	-0.9	16
0.55	0.15	-0.64	15
-0.6	0.3	0.8	12

Principle of measurement

$$A_{asy} = \frac{N - \bar{N}}{N + \bar{N}} = \frac{x}{1 + x^2} \sin 2\phi$$

assuming perfect tagging. Tagging imprefections are introduced as a result of B mixing and detector misidentification.

The *error* on $\sin(2\phi)$ is then

$$\delta \sin 2\phi = \left[\frac{1}{\frac{x}{1+x^2}} \right] \left[\frac{1}{1 - BR_{lepton}} \right] \left[\frac{1}{D} \right] \left[\frac{1}{\sqrt{N_{event} \frac{S}{S+N}}} \right]$$

See

* Ali CERN-TH-7123/93

* A. Sowi BNL 60828

Comparison of anticipated reach in CKM angles, circa 2003

	RHIC-B	CDF	HERA-B	BaBar
Integrated Luminosity	1.6 fb^{-1}	1.5 fb^{-1}	90 fb^{-1}	100 fb^{-1}
$\delta \sin 2\beta$ ($B_d^0 \rightarrow J/\psi K_S$)	0.12	0.18	0.1	.08
$\delta \sin 2\alpha$ ($B_d^0 \rightarrow \pi^+ \pi^-$)	0.1	N/A	N/A	0.14
$\delta \sin 2\gamma$ ($B_d^+ \rightarrow D^0 K^+$) ($B_d^+ \rightarrow \bar{D}^0 K^+$) ($B_d^+ \rightarrow D_{CP}^0 K^+$)	possible	possible	N/A	N/A

$B_s^0 - \bar{B}_s^0$ mixing

The mixing parameter between $B_s^0 - \bar{B}_s^0$ is a relatively clean means of determining $|V_{ts}/V_{td}|$ through the following

$$\frac{x_s}{x_d} = \frac{m_{B_s} \tau_{B_s} \eta_{B_s} f_{B_s}^2}{m_{B_d} \tau_{B_d} \eta_{B_d} f_{B_d}^2} \left| \frac{V_{ts}}{V_{td}} \right|^2$$

Critical parameters are

- Number of events.
- Proper time resolution (need time-evolved study since $x_s > 5$).
- Dilution factor.

Assuming proper time resolution of 4%, and dilution factor $\simeq 0.3$ then one needs (preliminary estimates)

x_s limit	Number of events Fully tagged
10	500
20	1500
30	5000

What can we get

Factor	Number
Produced/1 RHIC Run	2×10^9
Observable BR	5×10^{-4}
Geometrical Acceptance	.05-.1
Reconstruction	.3

To measure asymmetry with x_s as high as 25 one needs

- Aim for both lepton (0.1) and kaon (> 0.3) tag.
- Proper-time cuts must have $> 10-20\%$ efficiency.
- Keep tag acceptance efficiency + misc. to around 20%.

Comparison of the x_s reach of various experiments.

	RHIC-B	HERA-B	SLD
Integrated L	1.6 fb^{-1}	90 fb^{-1}	10^6 Z^0
x_s limit	25	17	15
σ_{x_s}	0.1	0.1	0.1
Decay Mode	$B_s^0 \rightarrow D_s^{*-} \pi^+ \pi^+ \pi^-$	$B_s^0 \rightarrow D_s l X$	N/A

Rare decays and B spectroscopy

- $B_s^0 \rightarrow K^* l^+ l^-$ and $B_s^0 \rightarrow \phi l^+ l^-$. Emphasize particle ID and rejection of backgrounds.
- Large sample ($> 10^4$) of baryons will be observed.
- B_c decays observable with $\sim \text{few} \times 10^3$ events.
- Push the limits on $B_s^0 \rightarrow K^* \mu^+ \mu^-$.
- Search for asymmetry in various decays ($K^0 \pi^-$, $D^- D^0$, $K^* K^*$). Generally BR.Asymmetry $\sim 10^{-8}$.
- Lepton number violation in the third generation ($B_s^0 \rightarrow K^* \mu^+ e^-$).
- Non-standard CP violation effects ($B_s^0 \rightarrow J/\psi \phi$)
- Many more.....

What two years of running will buy....

Decay	$f \cdot \sigma_{b\bar{b}}$	BR	Yield
$B_s^0 \rightarrow \rho K_s$	1.5×10^{-1}	4×10^{-5}	≈ 1000
$B_s^0 \rightarrow K^* l^+ l^-$	1.5×10^{-1}	4×10^{-7}	≈ 20
$B_s^0 \rightarrow \phi l^+ l^-$	1.5×10^{-1}	6×10^{-6}	≈ 200
$B_s^0 \rightarrow K^* \mu^+ e^-$	1.5×10^{-1}	0	limit $\leq 5 \times 10^{-8}$
$B_c^+ \rightarrow \psi/J \pi^+$	10^{-3}	2×10^{-3}	≈ 1000
$B_c^+ \rightarrow \psi/J l \nu$	10^{-3}	2×10^{-2}	≈ 5000
$\Lambda_b \rightarrow \Lambda J/\psi$	5×10^{-2}	2×10^{-2}	$\approx 10^5$
$\Omega_b \rightarrow \Omega J/\psi$	2×10^{-5}	2×10^{-2}	≈ 100

So where are we?

- HERA-B is on target for 1998-99 startup followed by a 2-4 year run.
- FNAL dedicated detector is delayed till at least 2004.
- RHIC-B EOI is submitted.

HeraB
160894

Among those 10^7 interactions per second, the trigger system has to identify the few 100 events with the most promising candidates for B decays; archiving much higher event rates over years of continued running seems unrealistic. Fortunately, the most promising decay mode $B^0 \rightarrow J/\psi K_S^0$ provides a very clean signature, if one restricts oneself to the leptonic decay modes of the J/ψ : a dilepton in the J/ψ mass range originating from a secondary vertex. The proposed trigger exploits this feature, but nevertheless both the trigger and the DAQ systems require a technological tour-de-force.

1.3.1 Halo Target

An intrinsic part of the experiment, and integrated into the detector, is the internal target positioned in the halo of the HERA proton beam. The target scrapes the beam halo and effectively acts like a collimator. Outward diffusion of beam particles, driven by nonlinearities, e.g. due to beam-beam forces, continuously replenishes the halo (at a rate of about $6 \cdot 10^7$ particles per second for 100 h current lifetime and design currents). The presently favored configuration consists of two sets of 4 metal ribbons of about $50 \mu\text{m}$ transverse width and $500 \mu\text{m}$ thickness (in the beam direction), separated along the beam by about 5 cm (see Fig. 13). Such a target

Figure 13: Schematic view of the halo target, consisting of 8 wires on independently movable forks.

- provides a well-localized source of B hadrons; for the measurement of the B decay lengths, the error is almost exclusively determined by the reconstruction of the decay vertex; in the transverse direction the (rms) size of the wire and the experimental resolution are comparable

- allows spreading multiple interaction vertices in a single bunch crossing over up to 8 wires, resulting in an usually unambiguous assignment of particles to vertices
- does not interfere with the cp operation of the machine and does not significantly influence the luminosity lifetime of the machine, which is governed by the emittance growth of the proton beam, rather than by the much longer current lifetime
- is robust and relatively simple to operate; servo mechanisms can be used to maintain a constant total rate and an equal rate sharing among wires throughout a fill.

A halo target is always in competition with other sources of particle losses, such as the collimators or other aperture limitations. In addition, the target wire itself may cause multiple scattering of halo particles into the collimators. A series of tests has however clearly shown that the rate at which particles interact in the wire corresponds to more than 50% of all current loss in the machine (see Chapter 3 for details). More general, the interaction rate R can be written as

$$R \approx 60 \text{ MHz } \epsilon_T \frac{I}{I_{\text{Design}}} \frac{100 \text{ h}}{\tau} \quad (39)$$

where ϵ_T is to probability for a halo proton to interact, I is the current in the machine and τ is the current lifetime. With the large values $\epsilon_T > 0.5$ and the relatively frequent fills of the proton beam, governed by the luminosity lifetime, the experiment does not necessarily require the full design current.

1.3.2 Spectrometer

At first glance, the HERA- B spectrometer (Fig. 14) is a relatively conventional fixed-target multi particle spectrometer. Its complexity arises mainly from the high granularity required to cope with the extreme particle densities. The main detector components are summarized in Table 9. The basic design choices were:

- A solid angle coverage from 10 mrad polar angle to about 200 mrad, corresponding to about 90% coverage in the center of mass system; a larger solid angle would significantly increase the length and width of the spectrometer with a very limited gain in acceptance.
- Use of a single dipole magnet for momentum analysis, again determined by the limited available length for the detector. The location of the magnet, 4.5 m downstream of the target, is a compromise between

**SPIKING PULSES FROM FREE
ELECTRON LASERS:
OBSERVATIONS AND
COMPUTATIONAL MODELS**

***T. C. MARSHAL
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V

Spiking Pulses from Free Electron Lasers: Observations and Computational Models

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with the collaboration of

T. B. Zhang and L-Y Lin

References:

L-Y Lin and TC Marshall

Phys. Rev. Lett. 70, 2403 [1993] ; NIM A341 265 [1994]

“High Power Self-Similar Radiation Pulse in a Free Electron Laser”
to appear in NIM, 1995 [FEL International Conference, Stanford, 1995]

Research supported by the ONR

OUTLINE

I. Summary of Experimental Findings and Possible Cause of Spikes

II. The fiber-optics model of spiking (Ginzburg-Landau equation);

--- Comparison with data

--- Startup from noise

III. Slippage pulse model

--- Generation of TW Gaussian Pulses

FEL

Wiggler $\rightarrow$ helical or sinusoidal electron beam trajectory ($v_{\perp}, v_{\parallel}$)

In presence of EM wave (ω_s, k_s)

$\underline{v}_{\perp}(\text{wiggler}) \times \underline{B}_{\perp s} \rightarrow$ Axial PM force
 $\rightarrow$ beam bunching.

periodicity of bunching is $k_w + k_s$

phase velocity " is $\frac{\omega_s}{k_s + k_w} < \frac{\omega_s}{k_s} = c$

$\therefore$ match $\frac{\omega_s}{k_s + k_w} = v_{\parallel}$ (resonant wave/particle interaction)

$\Rightarrow \lambda_s \approx \lambda_w / 2\gamma^2$ ("resonance relation")

to extract energy, $\underline{j}_{\perp} \cdot \underline{E}_{\perp s}$ must be maintained!

$\Rightarrow$ As e^- passes over one undulator period λ_w , the optical wave slips ahead one wavelength.

(leads to same λ_s as above)

Synchronism

- phasing of synchronous interaction permits exchange of energy between e^- beam and photons.

Sideband Instability

Slippage allows "mixing" to occur between optical wave and synchr. oscillation.

- PWA propagates at $v_p \approx v_{||} = \frac{\omega}{k_w + k_s} < c = \frac{\omega}{k_s}$

Simple model: $z = v_{||} t$, from above, get

$$0 = (k_w + k_s) z - \omega t$$

if $k_{\text{sideb.}} = k_s \pm \Delta k$ then:

$$k_{\text{syn}} z = [k_w + (k_s \pm \Delta k)] z - (\omega \pm \Delta \omega_{\text{syn}}) t$$

define $v_g = d\omega/dk \approx \Delta \omega_{\text{syn}} / \Delta k_{\text{syn}}$

$$\rightarrow \Delta \omega_{\text{syn}} \approx \frac{k_{\text{syn}} v_{||}}{1 - v_{||}/v_g}$$

since $k_{\text{syn}} \approx k_w \frac{N_{\text{syn}}}{N_w}$

$$\approx \frac{\Delta \omega_{\text{syn}}}{\omega_s} = \frac{N_{\text{syn}}}{N_w} \left[\frac{1 - v_{||}/c}{1 - v_g/c} \right] \approx \frac{1}{N_w}$$

Sideband Control

↑ carrier ↑ sideband

$$L_0 = 1.45 \text{ cm}$$

$$\frac{\delta\omega}{\omega} = 6\%$$

$$\frac{v_u}{v_g} = .93$$

↑ carrier ↑ sideband

$$\frac{\delta\omega}{\omega} = 30\%$$

$$\frac{v_u}{v_g} = .98$$

$$L_0 = 1.85 \text{ cm}$$

SPIKING RADIATION

* High power operation of the FEL produces spiking

--synchrotron oscillations of electrons in bunches occurs and couples to a "decay instability", causing sidebands.

-- the AM of the sidebands corresponds to temporal spikes

-- spike widths are likely to be under 1psec in IR and visible

[REDACTED]

* Two possibilities:

1) Sidebands are "bad", causing a deteriorated spectrum, so eliminate them!

2) Sidebands are "good" because narrow high intensity pulses of radiation are desirable for some applications; but they must be "tamed"!

* We first show elimination of sidebands does not cure spiking. Spiking is an inherent capability of the FEL system.

* We "design" a travelling-wave FEL amplifier to grow a very intense nearly Gaussian pulse of radiation in the IR: a different undulator tapering algorithm is used.

SPIKES OBSERVED ON A 0.5GHZ ANALOG SCOPE

Experimental Setup

Operating Parameters

Undulator period (<u>helical</u>)	<u>4 cm</u>	
Undulator length	80 cm	
Electron pulse length	150 nsec	
Electron beam diameter	6 mm	
Beam current density	$\sim 2 \text{ kA} / \text{cm}^2$	
Drift tube (waveguide) diameter	<u>24 mm</u>	<u>17 mm</u>
Electron beam energy	620 keV	720 keV
Slippage time	$\sim 300 \text{ psec}$	$0 \sim 60 \text{ psec}$
Wiggler parameter	$\sim 0.5 = \gamma(\frac{v_u}{c})$	
FEL wavelength	$\sim 12.5 \text{ mm} (24.6 \text{ THz})$	

Examples of Spiking
(High Power, $\sim$ saturation, $\sim 10 \text{ MW/cm}^2$)

SPECTRA

∴ Try an optical fiber mode of a
radiation pulse in an FEL :

- Although Spiking may be caused by sideband instability, we still find spiking for zero slippage.
- Other cause: there are current pulsations

HOW DOES A SIGNAL DEVELOP AS IT PROPAGATES ALONG AN AMPLIFYING, DISPERSIVE ELECTRON BEAM FILAMENT IN THE FEL?

"FIBER - OPTICS" MODEL (Buckley + Co.)

$$A(z, t) = A(z, t) e^{i(k_0 z - \omega_0 t)}$$

where $\omega_0 = \text{freq. of max. linear gain}$, $k_0 = \omega_0/c$; $A(z, t)$ varies slowly and includes a spectrum.

• At $z = z_0$, Fourier transform $A(z, t)$:

$$\tilde{A}(z_0, \Delta\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} A(z_0, t') e^{i(k_0 z_0 + i\omega t')} dt'$$

where $\Delta\omega = \omega - \omega_0$. Now advance Δz along beam:

$$\tilde{A}(z_0 + \Delta z, \Delta\omega) = \tilde{A}(z_0, \Delta\omega) e^{i(\omega/c + \gamma(\omega))\Delta z}$$

• Inverse-transform to $A(z_0 + \Delta z, t)$ and $\Delta z \rightarrow dz$:

$$\frac{\partial A(z, t)}{\partial z} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d(\Delta\omega) \int_{-\infty}^{\infty} dt' A(z, t') e^{i\Delta\omega(t-t')} \left[\frac{\omega}{c} + \gamma(\omega) \right]$$

• Since FEL gain-bandwidth is usually narrow, expand $\gamma(\omega)$ in a Taylor series around ω_0 :

$$\frac{\omega}{c} + \gamma(\omega) \approx \gamma_0(\omega_0) + \beta |A|^2 + \frac{1}{2} (\alpha_1 + i\alpha_2) \Delta\omega^2 + \dots$$

$$\left\{ \begin{array}{l} v_g = \text{group velocity} = c / (1 + c^2 \lambda / \omega) \\ (\alpha_1 + i\alpha_2) = \left. \partial^2 \gamma_0 / \partial \omega^2 \right|_{\omega=\omega_0} \text{ (gain \& grp. velocity dispersion)} \\ z' - t = z/v_g \\ z = z_0 \end{array} \right.$$

⇒ Ginzburg-Landau Equation Model (Nonlinear Schrödinger Eqn. with Complex Coefficients)

$$i \frac{\partial A}{\partial z} - \frac{\alpha_1 + i\alpha_2}{2} \frac{\partial^2 A}{\partial t^2} + \underbrace{\lambda_0(\omega_0)A + \beta|A|^2 A}_{\Rightarrow \text{steady saturated level for } A} = 0$$

A is the amplitude of the normalized radiation field vector potential,

$\lambda_0(\omega_0)$ is the opt. eigenvalue for signal growth at frequency ω_0 ,

$\alpha_1 + i\alpha_2 = \partial^2 \lambda_0 / \partial \omega|_{\omega=\omega_0}$ α_1 is group velocity dispersion

α_2 is gain dispersion,

β is a complex coefficient which determines the signal saturation.

Coefficients: $\lambda_0(\omega_0)$, α_1 , α_2 , and β

-----to be obtained by WKB analysis of the reduced equations.

Advantages of the GLE model

- * Comes from a fiber optics model & includes multiple frequencies
- * Coefficients can be derived via FEL equations
- * GLE has one variable A (easy to solve)

GLE has **solitary wave** analytic solution:

$$A(z', t') = \frac{q \exp(-i\Omega z')}{[\exp(Kt') + \exp(-Kt')]^{1+i\sigma}}$$

$$*1. \quad |A|^2 = \frac{|q|^2}{4 \cosh^2(K_1 t')}, \quad \text{single peak, FWHM} = 1.76 / K_1$$

$$2. \quad |A|^2 = \frac{|q|^2}{4 \cos^2(K_2 t')}, \quad \text{periodic, finite-time singularities}$$

Numerical Simulation of a Solitary Wave Propagating in a Dispersive Medium

Reduced Equations (Single-frequency)

Basic FEL equation: (*no slippage, eikonal*)

$$\frac{d\gamma_j}{dz} = -\frac{k_s a_s a_w}{\gamma_j} \sin \Psi_j + \frac{2\omega_p^2}{k_s c^2} [\langle \cos \Psi \rangle \sin \Psi_j - \langle \sin \Psi \rangle \cos \Psi_j]$$

$$\frac{d\Psi_j}{dz} = k_w \left(1 - \frac{\gamma_r^2}{\gamma_j^2} \right) + \frac{k_s a_s a_w}{\gamma_j^2} \cos \Psi_j$$

$$\left(\nabla_{\perp}^2 + 2ik_s \frac{\partial}{\partial z} \right) u(r, z) = -\frac{\omega_p^2 a_w}{c^2} \left\langle \frac{e^{-i(\Psi - \phi)}}{\gamma} \right\rangle$$

$u(r, z)$ consists only of the TE_{11} mode of the circular WG

$$\frac{du}{dz} = i(p - k_s)u + i \frac{\omega_p^2 a_w k_s}{2c^2} \frac{J_0(qr) r_b^2 F}{p^2 (R^2 - 1/\kappa^2) J_1^2(\kappa R)} \left\langle \frac{e^{i(\Psi - \phi)}}{\gamma} \right\rangle$$

"Collective variables:"
$$\begin{cases} x \equiv \langle e^{-i(\Psi_j - \Psi_r - \phi)} \rangle \\ y \equiv \left\langle \frac{\gamma_j - \gamma_0}{\gamma_0} e^{-i(\Psi_j - \Psi_r - \phi)} \right\rangle \\ A \equiv u e^{i\Psi_r} \end{cases}$$

Reduced set of equations:

$$\frac{dA}{dz} = i(\delta + \underbrace{p - k_s}_{\uparrow \text{"}\kappa_s\text{"}})A + i\bar{g}x$$

$$\frac{dx}{dz} = -i\bar{h}y$$

$$\frac{dy}{dz} = i\bar{f}A - 2i\bar{h}y_0(y - xy_0) + 2i\delta xy_0 - 2i\bar{f}(x^*A + A^*x)x - \underbrace{iBx}_{\uparrow \sim \omega_p^2}$$

WKB analysis (Bhattacharjee & Cai)

$$\ddot{A} - (i\Delta - 2i\epsilon h y_0) \ddot{A} + [2\epsilon h y_0(\Delta - \epsilon h y_0 - \delta) + Bh] \dot{A} - i h (fg + B\Delta + 2\epsilon y_0 \delta \Delta) A + \frac{2\epsilon f h}{ig} [2\Delta |A|^2 + (\dot{A} A^* - \dot{A}^* A)] (\dot{A} - i\Delta A) = 0$$

$$\xi \sim y_0 \text{ (small)}$$

New eigenvalue equation:

$$\lambda_0^3 - \Delta \lambda_0^2 - Bh \lambda_0 + h(fg + B\Delta) = 0, \text{ to } O(\epsilon^0),$$

where $\lambda_0 = \xi - i\chi$, χ is gain; $\lambda = \lambda_0 + \beta |A|^2$.

$$\beta = -\frac{fh}{g} \frac{(\lambda_0 - \Delta)[2\lambda_0 + 4\text{Re}\lambda_0 + 4i\Delta] + 2\delta(\lambda_0 + \Delta)}{2\text{Im}\lambda_0[2\text{Im}\lambda_0 - i(3\lambda_0 - \Delta)] - 3\lambda_0^2 + 2\Delta\lambda_0 + Bh}$$

$$\alpha_1 + i\alpha_2 = \partial^2 \lambda_0 / \partial \omega^2|_{\omega=\omega_0}; \text{ non linear index } n = 1 + \lambda/k$$

$z=45\text{cm}$

IR FEL spike pulse TWA

Fig. 1 Schematic of radiation spike propagating in an electron beam pulse.

Note: Optical pulse sweeps over "fresh" electrons!

3. FEL equations and computational model

- 1D time-dependent FEL equations:

$$\left(\frac{\partial}{\partial z} + \frac{1}{v_{//}} \frac{\partial}{\partial t} \right) \gamma_j(z, t) = - \frac{a_w a_s k_s \sin \psi_j}{\gamma_j \beta_{j//}} \quad (3)$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{v_{//}} \frac{\partial}{\partial t} \right) \theta_j(z, t) = k_w + k_s \left(1 - \frac{1}{\beta_{j//}} \right) \quad (4)$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{c} \frac{\partial}{\partial t} \right) u(z, t) = i \frac{a_w \omega_p^2}{2k_s c^2} \left\langle \frac{e^{-i\theta}}{\gamma} \right\rangle \quad (5)$$

where,

$$\beta_{j//} = \left[1 - \frac{\mu^2 - 2a_w a_s \cos \psi_j}{\gamma_j^2} \right]^{\frac{1}{2}}, \quad \mu^2 = 1 + a_w^2 + a_s^2 \quad (6)$$

- computational model:

Variables transformation from z and t into new independent variables x and y :

$$x = (ct - z)/l_c, \quad y = (z - v_{//}t)/l_c \beta_{j//} \quad (7)$$

$l_c = \lambda_s/4\pi\rho$ is defined as the cooperation length.

↑ "Pierce Parameter"

$$\frac{\partial \gamma_j(x, y)}{\partial x} = - \frac{2\rho \gamma_r^2 A_s \sin \psi_j}{\gamma_j \beta_{j//}} \quad (8)$$

electron phase
 $\downarrow$
 $(\theta_j = \psi_j - \phi)$
 $\uparrow$
 optical phase

$$\frac{\partial \theta_j(x, y)}{\partial x} = \frac{1}{2\rho} \left[1 - \frac{k_s (1 - \beta_{j//})}{k_w \beta_{j//}} \right] \quad (9)$$

$$\frac{\partial A(x, y)}{\partial y} = i\gamma_r \left\langle \frac{e^{-i\theta}}{\gamma} \right\rangle \quad (10)$$

where,

$$A(x, y) = A_s e^{i\phi}, \quad A_s = \frac{1}{\sqrt{\gamma_r \rho}} \frac{\omega_s}{\omega_p} a_s \quad (11)$$

(1000 e.m. e's / radiation λ_s)

- integration scheme for x and y:

Table I. Simulation parameters for short wavelength pulse

Beam parameters

Electron beam energy	$\gamma = 89.5$	
Electron beam current	$I_b = 150$	(A)
Electron beam radius	$r_b = 0.02$	(cm)
Beam pulse length	$L_b = 300 \lambda_s$	(2.4mm)

Undulator parameters

Undulator period	$l_w = 2.5 - 1.5$	(cm); linear ramp
Undulator parameter	$a_w = 2.0$	(constant)
Undulator length	$N_w = 150$	

Radiation pulse

Radiation wavelength	$\lambda_s = 8.0$	(μm)
Spike length(FWHM, intensity)	$L_r = 12\lambda_s$	
Pulse amplitude range	$a_s = 10^{-4} - 0.021$	(200 MW-9TW/cm ²)

Fig.1. The initial radiation pulse with a Gaussian profile and its Fourier-transformed spectrum.

Fig. 1

Constant Period undulator

Radiation spike profile

Fourier-transformed spectrum

Fig. 2

Beam energy profile

tapered undulator period

Radiation spike profile

Fourier-transformed spectrum

Fig. 3

Beam energy profile

Tapered Undulator
 $\lambda_s = 1.5 \text{ mm}$, $\delta = 2.5$
 Initial FWHM $= 10\lambda_s$

... starting with diff pulse width
 converges to an asymptotic width
 (approx given by G-L eqn)

Particle noise included ($\lambda_s = 8\mu$)
 ("High Gain" [45dB] amplifier problem)

taper: $a_w = 2.0$
 to 1.5

(smaller taper)

3075.d3

$a_w = 2.0 - 1.0$

(larger taper)

3075.d4

f075.d3

f075.d4

band. prob. width
 $\Delta = (\eta/N_2)^{1/2}$

where: $\begin{cases} n = \# \text{ sim. e's in one } \lambda_s \\ N_2 = \# \text{ real e's " " " } \end{cases}$

**CRYSTALLINE BEAMS IN
CIRCULAR ACCELERATORS**

J. WEI

BNL

VI

Crystalline Beams in Circular Accelerators

I. Introduction

II. Theoretical approaches

beam frame equations of motion

molecular dynamics calculation

III. Conditions for crystallization

strong focusing vs. weak focusing

below transition energy vs. above

IV. Conditions for melting

V. Conclusion

Jie Wei

Xiao-ping Li

Andrew M. Sessler

1/95

* Introduction

crystalline beam : ultimate "cold" beam

focusing force v.s. Coulomb force
⇒ crystalline structure

"Coulomb lattice"

"one-component plasma"

History :

1980 Novosibirsk group (Dementiev, et.al.)
see anomaly in cooled proton beam.

1986 Schiffer and Rahman.

theoretical study use MD method

:

Habs, Hasse, Avilov, Hoffmann, Hangst.

1988 Gilbert, Bollinger, Wineland

observe layered structure of ions

in penning trap

1993 Wei, Li, Sessler

study actual storage ring, rest frame EOM

:

conditions for crystallization & melting

current Experiments (laser cooling). Aarhus, Heidelberg

Italian proposal for a dedicated ring.

Okamoto, Sessler, Möhl, 3-D laser cooling

Novosibirsk experiment

NAP - M proton beam, electron cooling

65 MeV, ($E_t = 110$ MeV)

can not be explained by
intrabeam scattering theory

E. Dementiev, et. al.

Sov. Phys. Tech. Phys. 25 1001 (1980).

"Anomalous Schottky Signals from a Laser - Cooled Ion beam"

J. S. Hangst, et al. (Aarhus, Denmark)

Phys. Rev. Lett. 74 86 (1994)

FIG. 1. Measured Schottky signal for the uncooled beam. The solid line is a fit to the theoretical model from Ref. [3]. The inset shows the Gaussian velocity distribution measured by laser fluorescence. The characteristic velocities $\pm v_e$ for charge density waves are indicated.

J. S. Hangst et al.

PRL 74 86 (1995)

FIG. 3. (a) Schottky spectra measured at various detunings (shown between figures) during laser cooling. Dashed lines indicate the noise floor of the measurement; each vertical tick mark is one decade in relative power. The asymmetry in peak heights is probably due to a slight difference in laser powers, leading to larger diffusion past one laser. The nonzero resistivity of the vacuum chamber may also play a role. (b) The corresponding velocity distributions, measured by LIF. Each spectrum contains about 10^5 fluorescence counts.

Figure 5-3 ASTRID diagnostic systems

Figure 5-10 ASTRID laser systems

Table 5-1
ASTRID Design Parameters

Circumference	40 m
Length of Straight Sections	7.83 m
Vacuum Chamber Diameter	100 mm
Maximum Magnetic Rigidity	1.87 T-m
Betatron Tunes: Vertical	2.73
Horizontal	2.29
Transition γ	4.58
Chromaticities: Vertical	-7.5
Horizontal	-3.4
Betatron Acceptances: Vertical	60π mm-mrad
Horizontal	320π mm-mrad

Figure 5-2 ASTRID lattice functions for one superperiod (one-fourth of the ring) ; solid line $-\beta_x$, dot-dashed line $-\beta_y$, dotted line $-\eta_x$

" Three dimensional Laser cooling of Stored
and Circulating Ion Beams by Means of a
Coupling Cavity "

H. Okamoto , A.M. Sessler , D. Möhl

Phys. Rev. Lett. 72 3977 (1994)

" Low-energy states of Circulating Stored Ion Beams:
crystalline Beams "

J. Wei, X-P. Li, A.M. Sessler

Phys. Rev. Lett. 73 3089 (1994)

Fig. 1. Layout of the CRYRING facility.

FIG. 2 Colour coded images of crystalline structures of laser-cooled $^{24}\text{Mg}^+$ ions. The intensity increases from violet to blue yellow and red. Individual ions could be resolved in these images. The ions arrange themselves in minimum energy configurations: *a*, For low ion density ($\lambda = 0.29$) the ions form a string along the field axis; *b*, increasing the ion density changes the configuration to a zig-zag ($\lambda = 0.92$). At still higher ion densities the ions form ordered helical structures on the surface of a cylinder: *c*, two interwoven helices at $\lambda = 1.9$; *d*, three interwoven helices at $\lambda = 2.6$. Experimental images are displayed above, visualizations below.

FIG. 3 Images and intensity profiles of (a) string, (b) one shell ($\rho/a=1.05$, total ion number in the ring $N=5 \times 10^4$), (c) one shell plus string ($\rho/a=1.8$, $N=1 \times 10^5$), (d) two shells ($\rho/a=2.7$, $N=2 \times 10^5$), (e) two shells plus string ($\rho/a=3.4$, $N=3 \times 10^5$) and (f) four shells ($\rho/a=6.2$, $N=8 \times 10^5$). The ions are not individually resolved. The structures can be identified with the help of the radial intensity profiles (right). The images are colour-coded as in Fig. 2. Integration times are longer than 3 min each.

leads to a harmonic confining potential¹⁴ of the form $\psi = \psi_0 r^2 / r_0^2$ with the potential depth $\psi_0 = q^2 U_{RF}^2 / 4m\Omega^2 r_0^2$, where q is the ion charge, m the ion mass, r the distance from the field axis and r_0 half the distance between opposite electrodes. The oscillation frequency in this harmonic potential, $\omega_{ecc} = (2\psi_0 / mr_0^2)^{1/2}$;

FIG. 1 Quadrupole storage ring, with the atomic beam oven and electron gun. The storage ring consists of four circular electrodes, and the diameter of the toroidal storage volume is $2R = 115$ mm. The insert shows an enlarged cross-section with opposite electrodes having a separation of $2r_0 = 5$ mm. The laser beam enters the storage volume tangentially. Resonance fluorescence is detected with a photomultiplier tube or an imaging photon detector system.

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Multiple-shell structures of laser-cooled $^{24}\text{Mg}^+$ ions in a quadrupole storage ring

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THE possibility of creating ordered ion beams in high-energy storage rings^{1,2} by means of electron and laser cooling has opened up a new era in accelerator physics. The enhanced luminosity and suppressed momentum spread in such systems create the highest possible phase-space density. The first experimental results were obtained by cooling $^7\text{Li}^+$ beams to temperatures of a few kelvin or even to sub-kelvin temperatures^{3,4}, and the ordered structures have been studied theoretically⁵⁻⁷ by methods of molecular dynamics. Predicted configurations for the lowest ion densities have been observed in low-energy quadrupole storage rings⁸ and linear traps⁹. Recently we showed that at slightly higher ion densities helical structures are obtained¹⁰. Here we present a series of new experimental results on ordered ion structures in a quadrupole storage ring. In order of increasing ion number, a linear chain of ions, a zig-zag structure, helical structures and finally multiple concentric shells could be observed. The experimental results agree with molecular dynamics calculations.

When ordered structures in storage rings are simulated⁵⁻⁷, a cylindrically symmetric, static harmonic potential is usually assumed to describe the confining field. The pseudopotential of a low-energy quadrupole storage ring is closer to the theoretical model than the confining field of a high-energy storage ring, where the ions are subjected to periodic squeezing and pulling in the focusing sections, Coulomb explosion in the drift sections and shear forces in the bending sections. The principle and first realizations of quadrupole storage rings are described in refs 11-13. In the ring the ions can move freely along the axis of the quadrupole field and are radially confined by applying a

crystalline structure

1-D

2-D

increasing
↓
density

breathing

3-D

breathing

$$\mu_x^2 - \gamma^2$$

$$\mu_y^2$$

3-D

breathing

multi-layer

Motivation :

Condensed Matter Physics

1. Systematic (relatively easy to control) study of transition from 1D to 2D to 3D in the ground state; i.e., a careful study of the change in symmetries associated with change of density and with (easily changed) focusing.
2. Study of transport properties in the crystal.
3. Study of the stochasticity temperature. Special to beams vs. particles in traps. Stochasticity for a many-body system vs. usual 1 particle stochasticity studies.
4. Study of a suspended phase; interaction of a solid with a "gas" phase (A special aspect is that the gas phase (especially) absorbs heat at a steady rate from the lattice).
5. Study of phase transitions (sharp or not?) in this system (which could, well, be different than the situation in traps).
6. A new state of matter.

Accelerator Physics

1. In the course of getting crystals have learned many things that are useful more generally:
 1. How to do laser cooling, with two lasers, induction units, RF cavities, etc
 2. How to cool in three dimensions.
 3. How to measure velocity distributions using fluorescence.
 4. New methods of laser cooling (like adiabatic fast passage) are being considered.
2. Very fine beams should be useful for a variety of things such as, (after extraction) for very fine fabrication of semiconductors (ion implant), to study nuclear levels that are close together (but can't use thick targets because of Landau straggling), for atomic physics (marginal, channeling is a possibility).
3. Development of diagnostic techniques for crystalline beams (Schottky scans, etc.) will be generally useful.
4. Study of intra-beam scattering and various instabilities in a controlled environment.
5. Useful for high luminosity colliders?

Questions :

- * Does the crystalline structure exist ?
- * What are the effects of shearing ,
AG focusing , straight / bending section ?
- * What are the ground-state structures ?
- * What machine is most suitable ?
- * How long can a crystal last ?
- * What is the "melting temperature" ?
- * What cooling method can be used ?

II. Theoretical approaches

- * derive equations of motion in beam rest frame
- * use molecular dynamics method for simulation

Equations of motion in beam rest frame

- * non-relativistic motion in the rest frame
- * straightforward to adopt MD method
- * crystallization : $\dot{x} = \dot{y} = \dot{z} = 0$

Derivation:

- * use general relativity formalism, EOM in tensor form
- * find the transformation
- * EOM in lab frame $\Rightarrow$ EOM in rest frame

* Hamiltonian

$$H(x, P_x, y, P_y, z, P_z, t) = \frac{1}{2}(P_x^2 + P_y^2 + P_z^2) - \gamma \times P_z + \frac{1}{2}[(1-n)x^2 + ny^2] + V_c$$

$$V_c = \frac{1}{\beta^2 r^2} \sum_j \frac{1}{r_j}$$

$$r_j^2 = (x_j - x)^2 + (y_j - y)^2 + (z_j - z)^2$$

$$\begin{cases} \dot{x} = P_x \\ \dot{y} = P_y \\ \dot{z} = P_z - \gamma \times \end{cases}$$

$$\dot{P}_x = \gamma P_z - (1-n)x - \frac{\partial V_c}{\partial x}$$

$$\dot{P}_y = -ny - \frac{\partial V_c}{\partial y}$$

$$\dot{P}_z = -\frac{\partial V_c}{\partial z}$$

* Relation to the lab. frame

$$(P_x, P_y, P_z) = \frac{R}{\xi} (x', y', \frac{\Delta p}{p})$$

rest frame

lab frame

$$\xi = \left(\frac{r_0 R^2}{\beta^2 \gamma^2} \right)^{1/3}$$

$$r_0 = z^2 e^2 / A m_0 c^2$$

For straight section:

(Non-bending, but focusing)

$$\dot{x} = P_x$$

$$\dot{y} = P_y$$

$$\dot{P}_x \approx -\frac{\partial V_c}{\partial x} + nx$$

$$\dot{P}_y \approx -ny - \frac{\partial V_c}{\partial y}$$

* Molecular dynamics and numerical results

* long-range force. Ewald-type summation

Coulomb potential includes image charges

assume perfectly conducting long pipe

$$\phi(x_i, x_j) = \frac{1}{r_{ij}} + \frac{4}{L} \int_0^\infty \frac{\cosh(2z_{ij}k/L) J_0(2\rho_{ij}k/L) - 1}{\exp(2k) - 1} dk + \frac{2}{L} [\log(\pi b/L) + C].$$

* 1-D periodic condition in azimuthal direction

* integrate the equations of motion

4th order Runge-Kutta algorithm

potential by 15th order Gauss-Laguerre

* start with random distribution, impose

periodic requirement and drift correction

to reach ground state

storage ring model:

$$\begin{cases} B_x = B_1 y \\ B_y = B_0 + B_1 x \\ B_z = 0 \end{cases}$$

⇒ reference orbit

$$ZeB_0 R = m_0 c^2 \beta \gamma$$

* equations of motion (in reduced units)

$$\begin{cases} \ddot{x} - \gamma \dot{z} + (-\gamma^2 + 1 - n) x = - \frac{\partial V_c}{\partial x} \\ \ddot{y} + n y = - \frac{\partial V_c}{\partial y} \\ \ddot{z} + \gamma \dot{x} = - \frac{\partial V_c}{\partial z} \end{cases}$$

$$n = - \frac{B_1 R}{B_0} \quad \text{focusing strength}$$

$$\begin{cases} \text{time } t \text{ in unit of } \frac{R}{\beta \gamma c} \\ \text{spacial coordinates in } \xi \equiv \left(\frac{r_0 R^2}{\beta^2 \gamma^2} \right)^{1/3} \\ \text{energy in } \frac{\beta^2 \gamma^2 Z^2 e^2}{\xi} \end{cases} \quad r_0 = \frac{Z^2 e^2}{m_0 c^2}$$

III. Conditions for crystallization

1. ... Weak - focusing machine

Constant focusing strength

$$0 < n < 1$$

without Coulomb force

$$\begin{cases} \ddot{x} + (1-n)x = 0 \\ \ddot{y} + n y = 0 \\ \dot{z} + \gamma x = \text{const.} \end{cases}$$

magnetic quadrupole $\Rightarrow$ horizontal defocusing
vertical focusing

centrifugal force $\Rightarrow$ horizontal focusing

with Coulomb force & crystallization

$$\begin{cases} \ddot{x} + (-\gamma^2 + 1 - n)x = -\frac{\partial V_c}{\partial x} \\ \ddot{y} + n y = -\frac{\partial V_c}{\partial y} \\ \dot{z} \equiv 0, \end{cases}$$

centrifugal force $\Rightarrow$ horizontal defocusing

- * 3-D crystalline structure can not exist in weak-focusing machine for lack of stability
- * 1-D and 2-D structure can not exist either.

Example: 2-D structure can not exist
in weak-focusing machine

consider a perturbation on a particle at $z_0 = 0$

$$\begin{cases} \dot{x} = p_x \\ \dot{p}_x = \gamma p_z - (1 - n - C_x) x \\ \dot{z} = p_z - \gamma x \\ \dot{p}_z = -C_z z \end{cases}$$

$$C_x = \sum_j \frac{1}{r_j^3} > 0, \quad C_z = \sum_j \frac{1}{r_j^3} \left(\frac{3z_j^2}{r_j^3} - 1 \right)$$

eigenvalue problem

stability:

$$\begin{cases} \gamma^2 - 1 \leq -n - C_x & (H) \\ 0 \leq n & (V) \end{cases}$$

not possible! $\gamma > 1$

2. AG focusing machine

stability conditions

$$\begin{cases} \nu_x^2 - \gamma^2 \overset{\text{kinematic}}{>} \sum_j \left(\frac{1}{r_j^3} - \frac{3(x_i - x_j)^2}{r_j^5} \right) \\ \nu_y^2 > \sum_j \left(\frac{1}{r_j^3} - \frac{3(y_i - y_j)^2}{r_j^5} \right) \end{cases}$$

(for γ near γ_T)

* crystalline structure can exist

only when the beam is below transition energy, $\gamma < \gamma_T$

$$\gamma < \gamma_T$$

$$\ddot{x} + (\nu_x^2 - \gamma^2)x + F_c = 0$$

* effect of AG focusing

the crystal "breathes" with the lattice

* effect of shear (bending - straight)

the crystal "stretches" with the lattice

*Constant
Bending*

Fig. 2

Figure 1: A single-shell structure with particle positions projected (a) into the $x-y$ plane and (b) into the $\phi-z$ plane, where ϕ is the polar angle. The machine consists of 10 FODO (focusing, open or drift, defocusing, open or drift) cells with constant bending with $\nu_x=2.7$ and $\nu_y=2.3$, and the particle energy is $\gamma=1.4$. The number of particles (N) per MD super-cell is 40 and the MD super-cell length (L) is 10ξ . The particles move periodically in time, with the solid lines showing their trajectories and the circles indicating their positions at the start and end of each lattice period.

effect of AG focusing

Constant Bending
 $N=60, L=10$

Figure 2: A multi-shell structure with particle positions projected into the $x-y$ plane. The machine consists of 10 FODO cells with 25% bending with $\nu_x=2.8$, $\nu_y=2.1$, and the particle energy is $\gamma=1.4$. The calculation is done with $N=1000$ and $L=40\xi$.

Figure 3: The effect of shear. In this study $N=40$, $L=40\xi$. Motion occurs both in the x direction (breathing) and in the z direction (shear) for a particle (with largest horizontal displacement and no vertical displacement) through a lattice cell. Lattice components are displayed on the figure, B is a bending section, F is a focusing section, D is a defocusing section. The machine parameters are the same as that used in Fig. 2, with $\gamma=1.4$, $\nu_x=2.8$ and $\nu_y=2.1$.

beam energy $\gamma = 1.4$

$V_x = 2.8$, $V_y = 2.1$, $V_z = 2.6$

superperiod = 10

circumference 25.1 m. bending radius 1 m.

Lattice example:

particle trajectory in one FODO period

With Shear

* Crystalline structure in TSR lattice

TSR lattice, superperiodicity = 2.

$$U_x = 2.3, \quad \gamma = 1.001 \quad (?)$$

modeled with 376 steps per revolution

low density structures has been formed.

1-D string

.

2-D zig-zag, rotating transversely

twice per revolution

.

.

high density structures hard to achieve

too much heating ?

too much shear ?

Figure 4: A zig-zag structure formed with the Heidelberg TSR machine lattice with (a) the polar angle ϕ and (b) displacements in x , y , and z of the particle changing with time during one lattice period. Lattice components are displayed on the figure, and the lattice periodicity is 2.

Condition for $1D \rightarrow 2D$ transition

dispersion relation (smooth approximation)

$$\left\{ \begin{aligned} \omega_{1,3}^2(k) &= \frac{1}{2} \left\{ \nu_x^2 + \Omega_k^2 \pm \left[(\nu_x^2 + \Omega_k^2)^2 - 8\Omega_k^2(\nu_x^2 - \gamma^2 - \Omega_k^2) \right]^{\frac{1}{2}} \right\} \\ \omega_2^2(k) &= \nu_y^2 - \Omega_k^2 \end{aligned} \right.$$

$$\Omega_k^2 = 2 \sum_{n=1}^{\infty} \frac{1 - \cos(kn\Delta)}{n^3 \Delta^3}, \quad \Delta = \frac{d_z}{\langle \xi \rangle} \cdot \gamma$$

when

$$\nu_x^2 - \gamma^2 < \frac{4.2}{\Delta^3}$$

or

$$\nu_y^2 < \frac{4.2}{\Delta^3}$$

transverse
focusing

Coulomb
repulsion

$1D \rightarrow 2D$

Dispersion relation

* High density limit

$$\nu_x^2 - \gamma^2 = \Omega_k^2$$

$\hookrightarrow \Delta Q^2$, incoherent
tune shift

$$\Omega_k^2 = \Delta Q^2 = \rho \cdot \frac{2 r_0 R^2}{\beta^2 \gamma^3}$$

$$\rho \leq \frac{\beta^2 \gamma^3 (\nu_x^2 - \gamma^2)}{2 r_0 R^2} \leftarrow \nu_x^2$$

With ASTRID ring, $^{28}\text{Mg}^+$, $\beta = 3 \times 10^{-3}$

$$\rho \leq 2.4 \times 10^{12} \left(\frac{1}{\text{m}^3} \right)$$

$$d = \left(\frac{1}{\rho} \right)^{1/3} \geq 75 \mu\text{m}$$

i.e.
$$\rho_{\text{max}} \approx \frac{\gamma \nu_x \sqrt{\nu_x^2 - \gamma^2}}{2 \beta^3}$$

IV. Conditions for melting

beam frame

* Lattice vibration emits phonons into crystal

⇒ heat up , melt

* resonance condition (energy conservation)

$$\omega_{\text{lattice}} = \omega(k_1) + \omega(k_2) + \dots$$

↑
phonons

- * define "temperature" under time-dependent environment

$$T_x = \langle \Delta P_x^2 \rangle, \quad T_y = \langle \Delta P_y^2 \rangle, \quad T_z = \langle \Delta P_z^2 \rangle$$

deviation from the ground state value
 $\uparrow$
 periodic

- * relation to emittances and momentum $\frac{\Delta p}{p}$

$$\left(\Delta \xi_x, \Delta \xi_y, \frac{\Delta p}{p} \right) = \left(\frac{\xi^2}{R^2} \bar{\beta}_x T_x, \frac{\xi^2}{R^2} \bar{\beta}_y T_y, \frac{\xi}{R} \gamma \sqrt{1 - \beta^2} \right)$$

- * determine critical T_x, T_y, T_z by calculating the correlation function under certain temperature

Survival plot

Figure 6: Vibrational density of states (a) under smooth approximation and (b) for the exact Hamiltonian from molecular dynamics (with $N=100$ and $L=180\xi$) for a 1-D chain. The machine consists of 8 lattice periods, each containing a FODO cell and an insertion (containing drift spaces and two quadrupole magnets), with $\nu_x = 2.07$, $\nu_y = 1.38$, and $\gamma = 1.1$.

* Condition for melting :

$$f_{\text{lattice}} > 2 \cdot \max(v_x, v_y)$$

for the crystal to last a meaningful time.

Figure 9: Two-body correlation function $G_2(z)$ at various temperatures. The machine and beam parameters are the same as that used in Fig. 7.

* scaling rules of break-up temperature

longitudinal

$$\langle P_z^2 \rangle \approx \frac{0.6}{\Delta_z}$$

kinetic energy $\sim$ potential energy diff.

$$\omega_z^2(k) = \frac{4}{\Delta_z^3} \sum_m \frac{1}{m^3} - \frac{4}{\Delta_z^3} \sum_m \frac{\cos(mk\Delta_z)}{m^3}$$

transverse

$$\langle P_{x,y}^2 \rangle \sim \Delta_z^2$$

$$dx \sim \Delta_z$$

$$\omega_x^2(k) = (\mu_x^2 - \gamma^2) - \frac{2}{\Delta_z^3} \sum_m \frac{1}{m^3} + \frac{2}{\Delta_z^3} \sum_m \frac{\cos(mk\Delta_z)}{m^3}$$

Figure 5: Break-up temperatures in the (a) azimuthal and (b) transverse direction as functions of the inverse of the beam density. The machine parameters are the same as that in Fig. 1. The result has been verified by comparing cases with different L and N ($N=10, 20, 50, 100$, and 200) while keeping the line density $\Delta_z^{-1} = N/L$ constant ($\Delta_z = 2$).

Figure 8: The heating rate as a function of the temperature T . The machine and beam parameters are the same as that used in Fig. 7. The break-up temperature is about $T \approx 0.3$.

* storage ring model

10 identical FODO cells, $N = \pm 50$
circumference = 24 meter

$$\nu_x = 2.7, \quad \nu_y = 2.3, \quad \nu_z = 2.5$$

chosen $\gamma = 1.4$

$$\bar{\beta}_x = 9 \text{ m}, \quad \bar{\beta}_y = 10.5 \text{ m}$$

$$\xi = \begin{cases} 1.8 \times 10^{-6} & (\text{proton}) \\ 2.2 \times 10^{-5} & (\text{electron}) \end{cases}$$

* condition for ordered state

$$\left(\Delta \mathcal{E}_x, \Delta \mathcal{E}_y, \frac{\Delta p}{p} \right) < \begin{cases} (0.8 \times 10^{-11} T_x, 0.9 \times 10^{-11} T_y, 1.3 \times 10^{-6} \sqrt{T_z}) \\ (1.2 \times 10^{-9} T_x, 1.3 \times 10^{-9} T_y, 2.1 \times 10^{-5} \sqrt{T_z}) \end{cases}$$

$\uparrow$
 $x \rightarrow z$

$\uparrow$
 $y \rightarrow z$

$\uparrow$
 ordering
in z

heat transfer

no crystallization possible if $\gamma > \gamma_T$

V. Conclusion

- * crystalline beam can form in AG machine when beam energy is below transition energy.
- * crystals can last long if lattice periodicity is higher than twice betatron tunes.
- * require careful ring design and effective cooling to achieve it.

**ACCUMULATOR RING FOR AGS
AND
RECENT AGS PERFORMANCE**

T. ROSER

BNL

VII

Accumulator Ring for AGS

A Mini Kaon Factory

- Recent AGS Performance*
- AGS with an Accumulator*
- Time Domain Stacking with a Barrier Bucket Cavity*
- Summary of Upgrade Parameters*

*Thomas Roser
Feb. 28, 1995*

Recent AGS Performance (as of February 24, 1995)

	<u>1994</u>	<u>1995</u>
Proton Beams:		
Beam Energy	24 GeV	24 GeV
Peak Beam Intensity	40×10^{12} ppp	50.7×10^{12} ppp
Typical Beam Intensity	35×10^{12} ppp	45×10^{12} ppp
Spill Length / Cycle Length	1.0 sec / 3.8 sec	1.2 sec / 3.2 sec
Duty Cycle	26 %	38 %
Spill Structure Modulation [(peak-ave.)/ave.]	50 %	20 %
Average Beam Current	1.7 μA	2.5 μA
Availability	~ 83 %	~ 92 %
Heavy Ion (Gold) Beams:		
Beam Energy	11 GeV / nucleon	11 GeV / nucleon
Peak Beam Intensity	2×10^8 ions/pulse	2×10^8 ions/pulse
Spill Length / Cycle Length	1 sec / 3.8 sec	1 sec / 3.8 sec
Availability	~ 85 %	~ 90 %

AGS Peak Intensity

'SLOW LOSS'
→ STOP BANDS

TRANSITION
ENERGY

AGS
CURRENT
TRANSFORMER

AGS PROTON INTENSITIES

ACCELERATOR IMPROVEMENT PROJECTS

TRANSVERSE DAMPING SYSTEM

AGS RF

GAMMA TRANSITION JUMP

LONGITUDINAL DAMPING SYSTEM

HIGH INTENSITY PROTON OPERATION

JUNE 1994: 3.7×10^{13} PROTONS PER PULSE

- BOOSTER: 1.7×10^{13} PROT./CYCLE
- NEW AGS RF PA'S
- γ_T JUMP SYSTEM

← BUNCH DILUTION
WITH VHF CAVITY
ON AGS INJ. PORCH

W/O γ_T JUMP

WITH γ_T JUMP

→ AHRENS ET AL.; WEP04F AND J.M. BRENNAN ET AL.; MOPI4F

BUNCH STRETCHING USING A VHF CAVITY

→ REDUCED SPACE CHARGE

Front Panel

AGS WITH ACCUMULATOR RING

SLOW EXTRACTED BEAM:

FAST EXTRACTED BEAM:

Accumulator vs. Stretcher:

	<u>AGS only</u>	<u>AGS+Stretcher</u>	<u>AGS+Accumulator</u>
Rigidity:		80 Tm	8 Tm
SEB:			
Duty Cycle (1s spill):	33%	100%	50%
Average Intensity:			
4 Booster Cycles/AGS Cycle	20 TP/s, 3.2 μ A	30 TP/s, 4.8 μ A	30 TP/s, 4.8 μ A
8 Booster Cycles/AGS Cycle	34 TP/s, 5.4 μ A	60 TP/s, 9.6 μ A	60 TP/s, 9.6 μ A
FEB:			
Rep. Rate:	1.7 s		1.0 s
Average Intensity:			
4 Booster Cycles/AGS Cycle	35 TP/s, 5.6 μ A		60 TP/s, 9.6 μ A
8 Booster Cycles/AGS Cycle	54 TP/s, 8.6 μ A		120 TP/s, 19.2 μ A
Heavy Ion:			
4 Booster Cycles/AGS Cycle	2.3x10 ⁹ /s		4.0x10 ⁹ /s
8 Booster Cycles/AGS Cycle	3.6x10 ⁹ /s		8.0x10 ⁹ /s

(15 TP [1x10⁹ Gold]/Booster Cycle, 7.5 Hz Max. Booster Rate, 1 Hz Max. AGS Rate)

Accumulator Parameters: (First Pass!)

Max. Kinetic Beam Energy	1.8 GeV
Rigidity	8 Tm
Circumference	819.07 m
Number of Superperiods	20
Number of FODO Cells	60
Number of Dipoles / Quadrupoles	20 / 120
Dipoles Length / Field	2 m / 1.25 T
Quadrupoles Length / Field	0.5 m / 2.5 T/m
Length of FODO Cell	13.65 m
Length of straight sections	6.325
Phase Advance per FODO Cell	82 degrees
Magnetic Bending Radius	6.4 m
Vacuum Chamber x / y	150 mm / 75 mm
Acceptance Geometric x / y	234 / 58 π mm mrad
Acceptance Normalized @ 1.5 GeV x / y	560 / 140 π mm mrad
Space Charge Limit : (100 π mm mrad, $\Delta v=0.5$, 1.5 GeV, debunched)	4.1 x 10¹⁴ ppp
Betatron Tunes x / y	8.65 / 8.78
Chromaticities x / y	-1.00 / -1.08
Beta Max. x / y	24.2 m / 24.3 m
Beta Min. x / y	9.2 m / 8.8 m
Dispersion Max.	3.4 m
Transition Gamma	12.42

AGS Accumulator Lattice

AGS Accumulator

X in m.

S in m.

02/28/95
11:58:25

BOOSTER

0 10 20
FEET

0 10 20
SCALE IN FEET

BARRIER BUCKET CAVITY

SUPPRESSED
BUCKETS

$$\gamma > \gamma_T$$

FENILAB $\bar{p}$
DEBUNCHER RING:
KEEPS GAP FOR
KICKER RISE TIME

$$\gamma < \gamma_T$$

TWO BARRIER VOLTAGE

TIME DOMAIN STACKING WITH TWO BARRIERS

M. BLASKIEWICZ, TN 409

$\frac{T_H}{T_c}$
↑

Possible AGS Intensity Upgrades:

Barrier Bucket Cavity in AGS or Accumulator for Stacking of

8 Booster Cycles in AGS [Cost: ~ 1 M\$]

1.5 GeV Accumulator in AGS Tunnel [Cost: ~ 60 M\$ in 1998\$]

30 GeV Stretcher [Cost: ~ 100 M\$ in 1998\$]

	<u>AGS only</u>	<u>AGS +Accumul.</u>	<u>AGS +Accumul.+ Stretcher</u>
<u>Slow Extracted Beam:</u>			
Duty Cycle (1s spill):	33% / 28%	50%	100%
Average Intensity:			
4 Booster Cycl/AGS Cycle	20 TP/s, 3.2 μA	30 TP/s, 4.8 μA	60 TP/s, 9.6 μA
8 Booster Cycl/AGS Cycle	34 TP/s, 5.4 μA	60 TP/s, 9.6 μA	120 TP/s, 19.2 μA
<u>Fast Extracted Beam:</u>			
Rep. Rate:	1.7 s / 2.2 s	1.0 s	
Average Intensity:			
4 Booster Cycl/AGS Cycle	35 TP/s, 5.6 μA	60 TP/s, 9.6 μA	
8 Booster Cycl/AGS Cycle	54 TP/s, 8.6 μA	120 TP/s, 19.2 μA	
<u>Heavy Ion:</u>			
4 Booster Cycles/AGS Cycle	2.3×10^9/s	4.0×10^9/s	
8 Booster Cycles/AGS Cycle	3.6×10^9/s	8.0×10^9/s	

(15 TP [1×10^9 Gold]/Booster Cycle, 7.5 Hz Max. Booster Rate, 1 Hz Max. AGS Rate)

Recent AGS Performance

(as of May 10, 1995)

	<u>1994</u>	<u>1995</u>
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Typical Beam Intensity	35×10^{12} ppp	55×10^{12} ppp
Spill Length / Cycle Length	1.0 sec / 3.8 sec	1.6 sec / 3.6 sec
Duty Cycle	26 %	44 %
Spill Structure Modulation [(peak-ave.)/ave.]	50 %	20 %
Average Extr. Beam Current	1.7 μA	2.7 μA
Average Beam Current w/o Spill	2.3 μA	4.8 μA
Average Availability / Best Week	~ 83 %	~ 83 % / 93 %
Heavy Ion (Gold) Beams:		
Beam Energy	11 GeV / nucleon	11 GeV / nucleon
Peak Beam Intensity	2×10^8 ions/pulse	2×10^8 ions/pulse
Spill Length / Cycle Length	1 sec / 3.8 sec	1 sec / 3.8 sec
Availability	~ 85 %	~ 90 %

AGS Peak Intensity

AGS CURRENT TRANSFORMER:
'SLOW LOSSES' TRANSITION

INTENSITY LIMITS:

- 'SLOW LOSSES' AT AGS INJECTION
- STOP BANDS?
- TRANSVERSE INSTABILITIES
- TRANSITION LOSSES

⋮

GOAL: HIGH INTENSITY OPERATION ($> 6 \times 10^{13}$ ppp)

WITH HIGH RELIABILITY AND LOW LOSSES.

AGS BUNCH MANIPULATIONS

← BUNCH DILUTION
WITH VHF CAVITY
ON AGS INJECTION
PORCH

TRANSITION ENERGY JUMP:

WITHOUT JUMP:

$\lesssim 20 \times 10^{12}$ PROTONS

WITH JUMP:

@ 50×10^{12} : $\sim 5\%$ LOSS

TRANSITION ENERGY JUMP UPGRADE

CURRENT JUMP:

- GLOBAL DISTORTION,
2ND ORDER EFFECT (QUADR)
- LARGE LATTICE DIST.
- LIMITED MOMENTUM
APERTURE
- INTENSITY LIMIT,
LARGE LOSSES

UPGRADE:

- LOCAL DISTORTION,
1ST ORDER EFFECT (LINEAR)
- MUCH SMALLER DIST.
- HIGHER INTENSITY,
LOWER LOSSES
- PLANNED FOR
RHIC γ_T JUMP

TRANSVERSE COUPLED BUNCH INSTABILITY

Time Domain Stacking with Barrier Bucket Cavity

AGS WITH ACCUMULATOR RING

SLOW EXTRACTED BEAM:

FAST EXTRACTED BEAM:

Possible AGS Intensity Upgrades:

**Barrier Bucket Cavity in AGS or Accumulator for Stacking of
8 Booster Cycles in AGS**

1.5 GeV Accumulator in AGS Tunnel

	<u>AGS only</u>	<u>AGS +Accumul.</u>
<u>Slow Extracted Beam:</u>		
Duty Cycle (1s spill):	33% / 28%	50%
Average Intensity:		
4 Booster Cycl/AGS Cycle	20 TP/s, 3.2 μA	30 TP/s, 4.8 μA
8 Booster Cycl/AGS Cycle	34 TP/s, 5.4 μA	60 TP/s, 9.6 μA
<u>Fast Extracted Beam:</u>		
Rep. Rate:	1.7 s / 2.2 s	1.0 s
Average Intensity:		
4 Booster Cycl/AGS Cycle	35 TP/s, 5.6 μA	60 TP/s, 9.6 μA
8 Booster Cycl/AGS Cycle	54 TP/s, 8.6 μA	120 TP/s, 19.2 μA
<u>Heavy Ion:</u>		
4 Booster Cycles/AGS Cycle	2.3x10⁹/s	4.0x10⁹/s
8 Booster Cycles/AGS Cycle	3.6x10⁹/s	8.0x10⁹/s

(15 TP [1x10⁹ Gold]/Booster Cycle, 7.5 Hz Max. Booster Rate, 1 Hz Max. AGS Rate)

AGS Accumulator Lattice

AGS Accumulator

X in m.

S in m.

02/28/95
11:58:25

Accumulator Parameters: (First Pass!)

Max. Kinetic Beam Energy	1.8 GeV
Rigidity	8 Tm
Circumference	819.07 m
Number of Superperiods	20
Number of FODO Cells	60
Number of Dipoles / Quadrupoles	20 / 120
Dipoles Length / Field	2 m / 1.25 T
Quadrupoles Length / Field	0.5 m / 2.5 T/m
Length of FODO Cell	13.65 m
Length of straight sections	6.325
Phase Advance per FODO Cell	82 degrees
Magnetic Bending Radius	6.4 m
Vacuum Chamber x / y	150 mm / 75 mm
Acceptance Geometric x / y	234 / 58 π mm mrad
Acceptance Normalized @ 1.5 GeV x / y	560 / 140 π mm mrad
Space Charge Limit :	
(100 π mm mrad, $\Delta v=0.5$, 1.5 GeV, debunched)	4.1 x 10¹⁴ ppp
Betatron Tunes x / y	8.66 / 8.78
Chromaticities x / y	-1.00 / -1.08
Beta Max. x / y	24.2 m / 24.3 m
Beta Min. x / y	9.2 m / 8.8 m
Dispersion Max.	3.4 m
Transition Gamma	12.42

AGS ACCUMULATOR WITH PERMANENT MAGNETS

Figure. 1. Cross section of a dipole magnet. Temperature compensating strips are placed symmetrically between blocks of ferrite material.

FE-NI ALLOY COMPENSATION

100 DIPOLES : $\int B dl \approx 0.5 Tm$, $B_0 \approx 0.25 T$
COMBINED FUNCTION !

ELEMENT SEQUENCE		I		HORIZONTAL								VERTICAL					
POS. NO.	ELEMENT NAME	SEQ. NO.	DIST I [M]	BETAX [M]	ALFAX [T]	MUX [2PI]	X(CO) [MM]	PX(CO) [.001]	DX [M]	DPX [T]	BETAY [M]	ALFAY [T]	MUY [2PI]	Y(CO) [MM]	PY(CO) [.001]	DY [M]	DPY [T]
BEGIN	ACCUM	1	0.000	24.676	-1.991	0.000	0.000	0.000	1.778	0.114	7.481	0.719	0.000	0.000	0.000	0.000	0.000
BEGIN	SUPER	1	0.000	24.676	-1.991	0.000	0.000	0.000	1.778	0.114	7.481	0.719	0.000	0.000	0.000	0.000	0.000
	1 BF	1	2.000	24.676	1.991	0.012	0.000	0.000	1.778	-0.114	7.481	-0.719	0.045	0.000	0.000	0.000	0.000
	2 LDDEFF	1	8.224	7.683	0.739	0.087	0.000	0.000	1.089	-0.114	24.295	-1.982	0.122	0.000	0.000	0.000	0.000
	3 BD	1	10.224	7.683	-0.739	0.131	0.000	0.000	1.089	0.114	24.295	1.982	0.134	0.000	0.000	0.000	0.000
	4 LDDEFF	2	18.448	24.676	-1.991	0.208	0.000	0.000	1.778	0.114	7.481	0.719	0.211	0.000	0.000	0.000	0.000
END	SUPER	1	18.448	24.676	-1.991	0.208	0.000	0.000	1.778	0.114	7.481	0.719	0.211	0.000	0.000	0.000	0.000
END	ACCUM	1	822.400	24.676	-1.991	10.287	0.000	0.000	1.778	0.114	7.481	0.719	10.532	0.000	0.000	0.000	0.000
TOTAL LENGTH =			822.400000	QX =		10.287348		QY =		10.532447							
DELTA(S) =			0.000000 mm	QX' =		-11.699115		QY' =		-12.717829							
ALFA =			0.108781E-01	BETAX(MAX) =		24.676133		BETAY(MAX) =		24.295253							
GAMMA(TR) =			9.587895	DX(MAX) =		1.777748		DY(MAX) =		0.000000							
				XCO(MAX) =		0.000000		YCO(MAX) =		0.000000							
				XCO(R.M.S.) =		0.000000		YCO(R.M.S.) =		0.000000							

AGS COMPLEX AS $\mu^+\mu^-$ COLLIDER SOURCE:

- LINAC, BOOSTER: 10 Hz @ $\sim 2.5 \times 10^{13}$ ppp, 1.5 GeV
- AGS + ACCUMULATOR: 1 Hz @ $\sim 10 \times 10^{13}$ ppp, 24 GeV

OR: 2.5 Hz @ $\sim 10 \times 10^{13}$ ppp, 7 GeV
($\gamma < \gamma_T$)

$$\langle I \rangle = 10 \mu A$$

- EXTRACT WITH γ CLOSE TO $\gamma_T \rightarrow$ SHORT BUNCHES:
- $\rightarrow$ CERN PS '81: $\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_T^2} = 5 \times 10^{-4}$!
- $\rightarrow$ ADJUST α , WITH CHROMATICITY SEXTUPOLES!

**RHIC PROJECT
MACHINE STATUS**

M. HARRISON

BNL

VIII

RHIC PROJECT MACHINE STATUS

MAGNETS

DESIGN ISSUES

STATUS

MEDIUM TERM GOALS

RELATIVISTIC HEAVY ION COLLIDER

BASIC PARAMETERS

ION SPECIES	Au (79/197)	->	p(1/1)
ENERGY RANGE	30 GeV/u	->	100 GeV/u (Au) 250 GeV (p)
BUNCH INTENSITIES	10^9 (Au)	->	10^{11} (p)
# OF BUNCHES	57	->	114
BUNCH SPACING	220ns	->	110ns
AVERAGE LUMINOSITY	2×10^{26} (Au),		$\sim 10^{31}$ (p) at top energy
UP TO 6 IR's, IP LENGTH	18 cm rms		
STORE LENGTH	~ 10 hr's		

LAYOUT TWO COUNTER-ROTATING SUPERCONDUCTING
RINGS + EXISTING ACCELERATOR COMPLEX AS INJECTOR

Fig. 11-1. Layout of the collider and in parenthesis of the tunnel.
The ring circumference is 3833.845 m.

Fig. 11-2. Layout of inner(outer) arc half cell.

MAGNET PROGRAM

INDUSTRIAL PRODUCTION:-

DIPOLES (GRUMMAN)	121 OUT OF 373
QUAD COLD MASSES (GRUMMAN)	130 OUT OF 432
SEXTUPOLES (EVERSON)	300 OUT OF 300
TRIM QUADS (EVERSON)	54 OUT OF 78

BNL PRODUCTION

CORRECTOR COLD MASSES	200 OUT OF 502
COMBINED ELEMENT UNITS	30 OUT OF 432
TRIPLET QUAD COLD MASSES	52 OUT OF 78
IR SPLITTING DIPOLE	MAGNETIC DESIGN
IR TRIPLET DIPOLE	MECHANICAL DESIGN

**QUENCH PERFORMANCE SHOWS ~ 25% OPERATING MARGIN
PRESENTLY TESTING ~10% COLD**

FIELD QUALITY:	DIPOLES - INJECTION
	TRIPLET QUADS - STORAGE

ARC DIPOLE TEST STATISTICS

Total production run: 298 (9.7 m only)

Delivered to BNL, measured warm: ~ 115

Rate: 1/day (maximum)

Cold tested: 40

All magnets tested so far have been accepted (...two spares)

(Also needed: 75 8 cm dipoles with $L < 9.7$ m)

CURRENT PRODUCTION TESTING

100%: 2 warm axial scans (mole), at Grumman

100%: warm integral measurement at BNL (non-rotating coil)

50%: 1 warm axial scan at BNL

10%: cold test (quench, field quality - 2 days)

③

Industry Magnet Production Status

All data as of
Mar 31, 1995

Grumman Dipole Magnets

PLAN	8	14	13	16	19	20	20	22	22	18	20	21
ACTUALS	4	7	14	13	19	22						
CUM PLAN	38	52	65	81	100	120	140	162	184	202	222	243
CUM ACT	33	40	54	67	86	108						
DELTA	-5	-12	-11	-14	-14	-12						

Grumman Quadrupole Cold Mass Assemblies

PLAN	40	40	38	40	40	40	40	40	26	26	0	0
ACTUALS	10	16	16	12	22	37						
CUM PLAN	102	142	180	220	260	300	340	380	406	432	432	432
CUM ACT	24	42	58	70	92	127						
DELTA	-78	-100	-122	-150	-168	-173						

Everson Electric

ARC Sextupole/trim quadrupole pma's

PLAN	0	0	0	0	0	0						
ACTUALS	5	0	0	0	18	35						
CUM PLAN	378	378	378	378	378	378						
CUM ACT	300	300	300	300	318	355						
DELTA	-78	-78	-78	-78	-60	-23						

Sextupole Production Complete

BNL Magnet Production Status

All data as of
Mar 31, 1995

8 cm corrector cold mass assemblies

PLAN	20	24	24	24	24	24	24	24	24	24	24	24
ACTUALS	23	25	21	20	30	39						
CUM PLAN	121	145	169	193	217	241	265	289	313	337	361	385
CUM ACT	114	139	160	180	210	249						
CUM DELTA	-7	-6	-9	-13	-7	8						

13 cm quadrupole storage units

PLAN	4	4	4	4	4	0	0	0	2	4	4	4
ACTUALS	9	4	2	0	0	0						
CUM PLAN	36	40	44	48	52	52	52	52	54	58	62	66
CUM ACT	46	50	52	52	52	52						
CUM DELTA	10	10	8	4	0	0						

CQS assemblies

PLAN	7	9	12	16	16	16	16	16	16	16	16	16
ACTUALS	3	4	8	3	5	6						
CUM PLAN	23	32	44	60	76	92	108	124	140	156	172	188
CUM ACT	4	8	16	19	24	30						
CUM DELTA	-19	-24	-28	-41	-52	-62

DRG DIPOLE MAGNET FIELD PROFILE

M DRG113 01 27	N DRG114 01 24	O DRG115 01 23	P DRG116 01 19	Q DRG117 01 19	R DRG118 01 19
S DRG119 01 19	T DRG120 01 27	U DRG121 01 23	V DRG122 01 27	W DRG123 01 23	X DRG124 01 23
Y DRG125 01 18	Z DRG126 01 15	1 DRG127 01 15	2 DRG128 01 21	3 DRG129 01 20	4 DRG130 01 22
5 DRG503 01 22	6 DRG505 01 22				

Warm-Cold Correlation in DRG dipoles, body
Warm - Grumman; Cold=1450A

2/1/95 4:38 PM

DRG Dipoles -- Integ. T.F. (Mole) (Warm)

DRGTRND.XLS

4/10/95

DRG Dipoles -- S.S. T.F. (Warm)

(5)

DRG Dipoles -- Integ. Fid. Ang. (Warm)

116 Magnets: Mean = -0.406 STD Dev. = 0.744

DRGTRND.XLS

4/10/95

DRG Dipoles -- Fid. Ang. STD (Warm)

116 Magnets: Mean = 0.763 STD Dev. = 0.408

DRG Magnet Sequence Number

7

Arc dipole integral b_2 (warm)

Arc dipole integral a_1 (warm)

(11)

QRI999 QUENCH TEST

MAGNETS HAVE VOLTAGE
TAPS, SPOT HEATERS &
ARE TESTED WITH A

QRI998 QUENCH TEST

QUENCH
ANTENNA

NOTE: The test temperature was 4.35K (nom).
The ramp rate for quenches was 16A/s.

J. Muratore

35

DESIGN ISSUES

**DESIGN ESSENTIALLY STABLE - WORK IN PROGRESS TO
ASCERTAIN AND IMPROVE OPERATING PARAMETERS**

**MAGNETIC FIELD QUALITY
DIPOLE SORTING ON EFFECTIVE LENGTH**

**COMBINED ELEMENT FIDUCIALISATION
MEASURING AND UNDERSTANDING CONSTRUCTION**

**MINOR LATTICE MODIFICATIONS
SHORT DIPOLE LENGTHS
SIBERIAN SNAKES & SPIN ROTATORS**

**DECOUPLING
TRIPLETS - SKEW QUAD CONFIGURATION
OFF MOMENTUM DECOUPLING**

**TRACKING
SPACE CHARGE
BEAM-BEAM
COLLIMATORS - BEAM CLEANING**

**BEAM STABILITY & IMPEDANCES
INJECTION KICKERS
BEAM ABORT SYSTEM**

CQS

Fig. 1-5. Corrector, quadrupole, sextupole (CQS) assembly. Lamination length is shown.

Will test first 30 cold
17 cold-tested so far

→ all ok:

quench

vacuum

trim leads

trim/corrector polarity
(checked twice) ←

(36)

"WARM" PULSED QUAD (0.8 sec, 300A)

CQS Mdagnet Assembly Optical Measurement Alternate Setup

Relative difference between measured BPM electrical center and surveyed position of antenna

data for a given BPM is grouped on the horizontal axis

Polarized Proton Collisions at Brookhaven

(3/11/95)

Multipoles:
d8 34 dipoles
q8 quads
Tables_e

(4/02/95)

Multipoles:
 d8 34 dipoles
 q8 36 quads,
 other: Tables_e

charge/bunch = -1.0×10^9

POLARISED PROTONS

DEVELOPING TECHNIQUES TO EVALUATE "SNAKES"

RHIC -> MACHINE PERFORMANCE

**LARGE AMPLITUDE ORBITS IN COMPLEX E-M
FIELDS**

PROponents -> SPIN

RHIC / AGS MACHINE STUDIES

RHIC INTENSITY PROTON BUNCH PARAMETERS

GAMMA-T JUMP DYNAMICS

SPACE CHARGE EFFECTS AT TRANSITION

ATTEMPTED IBS EMITTANCE GROWTH MEASUREMENT

GOLD BEAM BUNCH PARAMETERS

III. NewFEB Extraction Scheme

A. Fast Kicker

- at ssG10
- C-type open magnet
 - » multi-pulsing
 - » limited aperture
 - » -2.0 mrad kick

B. Ejector Magnet

- at ssH10
- thick septum magnet
 - » 10mm thick septum
 - » multi-pulsing
 - » 22 mrad kick

C. Orbit Bumps

- for FKG10 and SMH10
- backleg windings
- two 1λ bumps
 - » BLWG09 + BLWH11
 - » with trim BLWs
 - » multi-pulsing

D. Assoc. Instrument

- local loss monitors
- injection bump at G10

BNL/AGS/AD

AGS CLOSED ORBIT FOR RHIC
EXTRACTION

beam loss vs. ramp rate

MACHINE STATUS

**DESIGN PHASE ESSENTIALLY COMPLETE
ENGINEERING PROTOTYPES - PRODUCTION UNITS UNDERWAY**

**INJECTION LINE MECHANICAL INSTALLATION 95% COMPLETE
LINE UNDER VACUUM
CABLES & BUSS WORK STILL IN PROGRESS
POWER SUPPLY CHECKOUT & CONTROL SYSTEM INTERFACING**

**CRYOGENIC DISTRIBUTION SYSTEM STARTED (JUST) - FRIDGE
TO RING PIPING & VALVE BOXES
COMPRESSOR TESTS IN JUNE 95 (LAST RUN 1984)**

**TUNNEL INSTALLATION HAS STARTED WITH INFRASTRUCTURE IN
PLACE (STANDS, CABLE TRAY, LIGHTS, POWER ETC...)
SURVEY GRID COMPLETE
~ 105 DIPOLES IN THE TUNNEL
~14 COMBINED ELEMENT UNITS IN THE TUNNEL
INITIAL INTERFACING IN PROGRESS**

**FIRST MAGNET CONTROLLED & RAMPED THROUGH RHIC
CONTROL SYSTEM**

**PROTOTYPE INSTRUMENTATION TESTED:
LOSS MONITORS (AGS)
BEAM PROFILE FLAGS (AGS)
BEAM POSITION MONITOR (FERMILAB)**

RHIC INJECTION LINE SCHEMATIC

INVENTORY

143 MAGNETS
39 BPM'S
54 BLM'S
12 PROFILE MONITORS
28 ION PUMPS
3 COLLIMATORS

SEC 1-2265 VI.1 (M) 00179001-1 2000

27100143

RE : 02700

51020222 - 476010

MOULTON, J. L. - 1010

Students learn: full

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**SERVICE BUILDINGS AND INTERACTION REGION CONVENTIONAL
CONSTRUCTION COMPLETE - EXPERIMENTAL HALLS IN
PROGRESS**

**SUPERCONDUCTING BUSS CABLE - IN-HOUSE
5KA MAIN POWER SUPPLIES - IN HOUSE
CONTROL LOOPS CLOSED
OUTPUT FILTER - PARTS ON ORDER
QUENCH BY-PASS SWITCHES - PARTS ON ORDER
ENERGY DUMP RESISTORS - COMPLETE & TESTED
QUENCH DETECTION & 50A CORRECTOR SUPPLIES IN
PRELIMINARY DESIGN**

**VACUUM: WARM BORE ANALYSIS COMPLETE
CQS VACUUM COMPONENTS - DELIVERY IN PROGRESS
TURBO PUMPS - DELIVERY IN PROGRESS
ION PUMPS AND GAUGES - ORDER PLACED
PARTIAL PRESSURE ANALYZERS - NEXT**

**FIRST PRODUCTION 26 MHz RF CAVITY UNDERWAY
10 196 MHz CAVITIES ACQUIRED FROM CERN**

MEDIUM TERM GOALS :- INTEGRATED SYSTEMS TESTS

INJECTION TESTS - SEPT 95 -> DEC 95

BEAM TO THE INJECTION LINE INTERNAL DUMP

**AGS EXTRACTION
INJECTION LINE HARDWARE
INJECTION LINE OPTICS & BEAM PARAMETERS**

**WARM VACUUM
POWER SUPPLIES
SAFETY SYSTEM
INSTRUMENTATION
CONTROLS**

SEXTANT TEST - OCT 96 -> DEC 96

**BEAM THROUGH 1 SEXTANT OF COUNTERCLOCKWISE
RING**

**INJECTION SYSTEM
RING HARDWARE
RING OPTICS**

**COLD VACUUM
CRYOGENICS
QUENCH PROTECTION**

**SAFETY SYSTEM
INSTRUMENTATION
CONTROLS
POWER SUPPLIES**

GAMMA-GMMA COLLIDERS

A. SESSLER

***LAWRENCE BERKELEY
LABORATORY***

IX

Gamma-Gamma Colliders

I. Introduction

II. General Considerations

- a. Generation of gamma rays
- b. Spectrum of the gamma rays
- c. Configuration of a collider
- d. Luminosity estimates

III. Particle Physics

- a. Theory
- b. Detector considerations

IV. Solid State Lasers

- a. Characteristics
- b. Experiment E 144

V. Free-Electron Lasers

- a. Ten amplifiers, induction driven
- b. Oscillator-amplifier
- c. Oscillator, RF driven
- d. Induction linac driver

VI. An Experiment at the SLC

VII. Conclusions

References

1. I.F. Ginsburg, et al, Nucl. Instr. and Meth. in Phys. Res. **205**, 47 (1983); I.F. Ginsburg, et al, ibid **219**, 5 (1984).
2. V.I. Telnov, Nucl. Instr. and Meth. in Phys. Res. **A294**, 72 (1990).
3. S. Chattopadhyay and A.M. Sessler, ed. Proceedings of the Gamma-Gamma Workshop, Berkeley, March 1994, Nucl. Instr. and Meth. in Phys. Res. **355** (1995).

I. Introduction

History of $\gamma\gamma$ -physics

equivalent photons, E. Fermi 1926,
Weizsacker 1934, Williams, Dan 1935

$$ZZ \rightarrow ZZ e^+ e^-$$

Landau, Lifshits, 1936

$$\gamma\gamma \rightarrow e^+ e^-$$

Breit, Wheeler, 1936

$$\gamma\gamma \rightarrow \gamma\gamma$$

Euler 1936

$$\begin{aligned} \omega \ll mc^2 &\Rightarrow \sigma \sim \omega^6 \\ \omega = 2\text{eV} &\Rightarrow \sigma_{\gamma\gamma \rightarrow \gamma\gamma} = 5 \cdot 10^{-64} \text{cm}^2 \\ \omega \sim mc^2 &\Rightarrow \sigma_{\text{max}} \sim 10^{-30} \text{cm}^2 \end{aligned}$$

$$e^+ e^- \rightarrow e^+ e^- \pi^0$$

F. Low 1960

$$\sigma \sim \Gamma_\pi \quad \text{C-even resonance}$$

$$e^+ e^- \rightarrow e^+ e^- \pi^+ \pi^-$$

Calogero, Zemach, 1960

Experiment:

$$e^+ e^- \rightarrow e^+ e^- + e^+ e^- \quad 1969, 1970 \text{ VEPP-2 Novosibirsk}$$

$$e^+ e^- \rightarrow e^+ e^- + \mu^+ \mu^- \quad 1974 \text{ Frascati}$$

$$e^+ e^- \rightarrow e^+ e^- + \eta^1 \quad 1979 \text{ Mark-2, SPEAR}$$

$$(\sum \mathbf{p}_i)_\perp \leq 100 \text{ MeV}, \text{ without detection of scattered } e^+ e^-$$

Virtual Photons at Storage Rings

$$q^2 \sim 0$$

$$dn_\gamma \sim \frac{\alpha}{\pi} \frac{dy}{y} \left[\left(1 - y + \frac{y^2}{2} \right) \ln \frac{(1-y)y m^2}{m^2 y^2} \right]; y = \frac{\omega}{E}$$

$$dn_\gamma \sim 0.035 \frac{d\omega}{\omega}; \quad \omega \ll E$$

$$L_{\gamma\gamma} \sim n_\gamma^2 L_{e^+e^-} \sim 10^{-2} L_{ee} \quad \text{at } \frac{W_{\gamma\gamma}}{2E_0} > 0.1$$

$$\sim 10^{-4} L_{ee} \quad \text{at } -\frac{W_{\gamma\gamma}}{2E_0} > 0.5$$

1. soft spectrum
2. $L_{\gamma^*\gamma^*} \ll L_{e^+e^-}$

Nevertheless, in $\gamma^*\gamma^*$ collisions a lot of interesting results

Fig. 15. Comparison of cross sections for charged pair production in e^+e^- and $\gamma\gamma$ collisions. The cross section $\sigma = (\pi\alpha^2/M^2)f_p(x)$; $p = S$ (scalars), F (fermions), W (W-bosons). M is particle mass; $x = W_{p\bar{p}}^2/4M^2$, $f_p(x)$ are shown.

Linear Colliders with γ - γ Collisions

- Physics with $e^+ - e^-$ collider is special and complementary to that with a hadron supercollider.
- A linear collider should have $e^+ - e^-$, $e^- - \gamma$ and $\gamma - \gamma$ collisions; $e^- - \gamma$ and $\gamma - \gamma$ will provide unique access to some areas of fundamental physics as well as some desirable redundancy with $e^+ - e^-$ measurements.
- The technology is sufficiently advanced to seriously consider a $\gamma - \gamma$ collider.

Proposed Linear Collider Configuration (Based on the JLC)

γ - γ Collisions of High Monochromaticity & Luminosity can be achieved

II. General Considerations

Methods of $e \rightarrow \gamma$ conversion

1. Bremsstrahlung $dn_\gamma \approx \frac{x}{x_0} \frac{d\omega}{\omega}$
 $x/x_0 \sim 0.3 \Rightarrow dn_\gamma \sim 0.3 \frac{d\omega}{\omega} \sim 10 dn_{\gamma^*}$
 $L_{\gamma\gamma} \sim 10^2 L_{\gamma^*\gamma^*}$ (in e^+e^- collision)

2. Coherent bremsstrahlung in crystals
 (rad. length is shorter $\sim$ factor 10 in W)

- a) soft spectrum
 b) background from photonuclear reactions ($\sim 10^6 - 10^7$ /collision)
 c) heat destruction

1 and 2 disadvantages:

3. Beamstrahlung in e^+e^- collisions (synchrotron radiation)
 $n_\gamma \sim 1 - 5 n_e \Rightarrow L_{\gamma\gamma} \geq L_{ee}$

- [Disadvantage:] a) wide spectrum ($dn \sim 1/\omega^{2/3}$)
 b) background, beam-beam collision effects
 c) background reaction ($\gamma e \dots$)
 d) no polarization (at $\omega \ll E_0$)
 e) large disruption angles

continued...

Methods of $e \rightarrow \gamma$ conversion

4. Undulator

$$\lambda_0 \text{ min} \sim 10^{-2} \text{ cm} \Rightarrow E_\gamma \sim 100 E_0^2 (\text{TeV}), \text{Gev}$$

very strong field $E_\gamma = 6 \text{ GeV}$ at $E_0 = 250 \text{ GeV}$

too low

5. Backward Compton Scattering

0.25 TeV laser ($\omega_0 \sim 1 \text{ eV}$) γ $[E_\gamma \sim 0.2 \text{ TeV}] \theta \sim 1/\gamma$

1. Clean γ beam
2. $\Delta E / E_\gamma \sim 10\%$ is possible
3. $L_{\gamma\gamma} > L_{e^+e^-}$ is possible due to absence of main collision effects

Resumé:

Compton scattering - best method of $e \rightarrow \gamma$ conversion.

BACKWARD COMPTON SCATTERING (#1)

In the conversion region, a photon with energy ω_0 is scattered on an electron with energy E_0 at a small collision angle α_0 . The energy of the scattered photon ω depends on its angle θ relative to the motion of the incident electron as follows:

$$\omega = \frac{\omega_m}{1 + \left(\frac{\theta}{\theta_0}\right)^2}, \quad x = \frac{4E_0\omega_0}{m^2c^4} \quad y = \frac{\omega}{E_0} \leq y_m = \frac{x}{x+1}$$

where

$$\omega_m = \frac{x}{x+1} E_0 \quad \theta_0 = \frac{m}{E_0} \sqrt{x+1}$$

ω_m is the maximum photon energy

BACKWARD COMPTON SCATTERING (#2)

The scattered photon differential cross section is:

$$\frac{1}{\sigma_c} \frac{d\sigma_c}{dy} \equiv f(x, y) = \frac{2\sigma_0}{x\sigma_c} \left[\frac{1}{1-y} + 1 - y - 4r(1-r) + 2\lambda P_c r x (1-2r)(2-y) \right]$$

$$\sigma_0 = \pi \left(\frac{e^2}{mc^2} \right)^2 = 2.5 \times 10^{-25} \text{ cm}^2$$

where:

λ = electron helicity

P_c = photon circular polarization

$$r = \frac{y}{x(1-y)}$$

$$\frac{1}{\sigma_c} \frac{d\sigma_c}{dy}$$

BACKWARD COMPTON SCATTERING (#3)

The total Compton cross section is:

$$\sigma_c = \sigma_c^{np} + 2\lambda P_c \sigma_1,$$

$$\sigma_c^{np} = \frac{2\sigma_0}{x} \left[\left(1 - \frac{4}{x} - \frac{8}{x^2} \right) \ell n(x+1) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(x+1)^2} \right]$$

$$\sigma_1 = \frac{2\sigma_0}{x} \left[\left(1 - \frac{2}{x} \right) \ell n(x+1) - \frac{5}{2} + \frac{1}{x-1} - \frac{1}{2(x+1)^2} \right].$$

σ_c is hardly effected by $2\lambda P_c = 1$ or $2\lambda P_c = 0$, but the spectrum very much depends upon $2\lambda P_c$.

HARDENING OF THE GAMMA SPECTRUM

The geometry of conversion and collision produces a significant hardening of the spectrum.

Luminosity spectrum strongly depends on beam parameters.

Monochromaticity depends on: $\rho^2 = \left(\frac{\ell / \gamma}{a_e} \right)^2$ a_e is radius of electron beam

$$\text{Luminosity } L_{ee} \cong \frac{N^2 f}{2\pi a_e^2}$$

SPECTRAL LUMINOSITIES (round beams)

$$Z = \frac{W_{\gamma e}}{2E_0}$$

$$Z = \frac{W_{\gamma}}{2E_0}$$

Far from a Compton Spectrum!

$\gamma - \sim 10\%(\text{FWHM})$

CHOICE OF LASER WAVELENGTH

Incident photons, ω_0 , can't be too energetic.

If

$$2\gamma\omega + \frac{\omega_0}{2\gamma} > 2mc^2$$

(double Doppler effect into center of mass) then pairs are produced.

Thus if

$$\omega\omega_0 > (mc^2)^2$$

That is

$$x \equiv \frac{4E_0\omega_0}{m^2c^4} > 2(1+\sqrt{2}) \approx 4.8$$

Best for x close to 4.8 or

$$\lambda \approx 4.2E_0(\text{TeV})\mu\text{m}$$

REQUIREMENT ON LASER POWER #1

$$N_\gamma = \left(\frac{N_{ph}}{\pi w^2} \right) \sigma_c N_e$$

w=laser waist

If require $N_\gamma = N_e$ then

$$N_{ph} = \frac{\pi w^2}{\sigma_c}$$

Energy in laser pulse $W = N_{ph} \cdot \hbar \omega_0$

But Rayleigh Length should be the length of the electron bunch: $\ell_e = \frac{\pi w^2}{\lambda}$

Combining

$$N_{ph} = \frac{\lambda \ell_e}{\sigma_c}$$

Independent of electron bunch radial size (provided $a_e < w$)
(More careful treatment put the π upstairs)

$$W = \frac{\hbar c \ell_e}{\sigma_c}$$

REQUIREMENT ON LASER POWER #2

Find: $W \sim 251_e(\text{cm})$ J

For various projects $W \sim 1$ to 4 J

$$\tau \equiv (l_e / c) \sim 1 \text{ to } 5 \text{ psec.}$$

	Direct operation	Modified FFS	Reduced emittance	Emittance reduction	
	L gg	L gg	Lgg		
Machine				x	y
TESLA	2.59E+32	9.20E+32	1.84E+33	1.00	4.00
SBLC	2.23E+32	4.12E+32	1.43E+33	3.00	4.00
JLC	5.47E+32	9.48E+32	1.90E+33	2.00	2.00
NLC	5.32E+32	1.11E+33	1.93E+33	2.00	1.50
CLIC	1.89E+32	4.33E+32	1.06E+33	2.00	3.00
VLEPP	4.93E+32	1.97E+33	1.97E+33	1.00	1.00

III. Particle Physics

Physics goals for a gamma-gamma collider

The structure functions of the photon, probed by deep inelastic scattering from a photon target, is a fundamental and largely unresolved area of investigation in quantum chromo-dynamics. Clearly the electron-photon collision option would provide the paramount facility for these studies. In another important area of QCD, photon-photon collisions would allow studies of the top quark threshold region that would complement studies performed in electron-positron collisions. Here some unique measurements are possible using polarized photon beams: large circular polarization will allow direct observation of p-wave toponium, not possible in electron-positron collisions, while with linear polarization it may also be possible to make very sensitive measurements of the strong coupling constant.

"Physics goals.." continued

Study of W boson pair production in photon-photon collisions provides the most sensitive tests for quartic anomalous interactions of the electroweak gauge bosons. The photon-photon option also provides some unique advantages for Higgs boson studies. The two photon width of a Higgs boson is most directly measured here; it is a fundamental probe both of the electroweak theory and for electrically charged ultraheavy quanta which would affect the two photon rate if their mass is generated by the Higgs boson. The search for supersymmetric Higgs bosons is also enhanced by the photon-photon option.

The heavy scalar and pseudoscalar of the minimal supersymmetric model must be produced together in the same event in electron-positron collisions, requiring energy greater than the sum of their masses, but in photon-photon collisions they can be produced and observed individually. The circular polarization of the photon beams is an important asset in these studies, both enhancing the signal and suppressing the background. Linear photon polarization may also be useful, since it would allow direct measurement of the parities of the Higgs bosons, which might not be directly measured in any other way.

1. The simplest reactions are the direct $\gamma\gamma$ couplings to pairs of leptons, W 's, and quarks. Any energetically accessible particle which carries the electromagnetic charge, including supersymmetric and technicolor particles, can be produced in pairs. In each case, the charged line can then radiate its respective gauge partners: e.g., photons, gluons, Z 's as well as Higgs bosons.

2. As shown in Figure 1b, one can produce pairs of charge-less fundamental particles in $\gamma\gamma$ collisions through quantum loop diagrams, as in the traditional light-by-light scattering box graph. For example, two photons can annihilate and produce two outgoing photons or a pair of co-planar Z 's through virtual W and quark loops. A pair of gluon jets can be produced through a quark box diagram. A single Higgs boson or an excited Z' can be produced through triangle graphs.

3. At high energies, one or both of the incident photons can "resolve" itself as a pair of fundamental charged particles which can then interact via scattering subprocesses. Thus, as illustrated in Fig. 1c, a photon can develop into a Fock state of $q\bar{q}$ or W^+W^- or leptonic pairs, which then interact by $2 \rightarrow 2$ processes; e.g., quark-quark scattering through gluon exchange or top-quark scattering through Higgs exchange. In addition, one can have interactions of a directly coupled photon with the resolved constituent of the other photon.

CROSS-SECTIONS

	Standard Model	Monitoring	SUSY
300 nb	σ_{ToT}		
100 nb			
100 pb	$\gamma\gamma \rightarrow W^+W^-$ $\gamma e \rightarrow W\nu$	$\gamma\gamma \rightarrow e^+e^-$ $\gamma e \rightarrow \gamma e$	
10 pb	$\gamma e \rightarrow eZ$		$\gamma\gamma \rightarrow x^+x^-$
1 pb	$\gamma\gamma \rightarrow b\bar{b}$ SM Higgs		
100 fb	$\gamma\gamma \rightarrow Z_T Z_T$		$\gamma e \rightarrow \tilde{e}\tilde{Z}$
10 fb	$\gamma\gamma \rightarrow \gamma\gamma$		$\gamma\gamma \rightarrow H, A$

Fig. 14. A schematic layout of the interaction region in a photon collider.

SWEEPERS

3 mm 15 mm $\times$ IP

Fig. 7. Two possible setups proposed to generate the strong transverse magnetic field needed to sweep the used electrons in a PLC. On top, one has two superconducting Helmholtz coils outside the vacuum tube. An alternate scheme uses two superconducting coils parallel to the beam and located inside the vacuum tube. A transverse cross section of this layout is shown below, indicating the size of the bars and the corresponding dead zone for the vertex detector.

2. Slight misalignments cause the beams to deflect each other (Telnov) (c.f. Balakin's "HeadUp" bunches, but for normal bunches).

with some
beamsstrahlung!

so perhaps we don't need a
sweeper!

3. Plasms lenses look best of all

May bring conversion point to $\sim 5\text{mm}$ $\rightarrow$ bigger L
(at the expense of wider spectrum)

Mirror Placement within Detector

Laser = $f/10$ (100 mrad). Mask = $f/6.7$ (150 mrad).

Fig. 8. A schematic layout of the IP in a photon collider.

Fig. 9. A conventional detector scheme using drift chambers and with the electromagnetic calorimeter inside the coil.

Fig. 10. A compact detector scheme using MSGC chambers and with the electromagnetic calorimeter outside the coil.

IV. Solid State Lasers

LASER POSSIBILITIES

1. Solid State Lasers
2. Free-Electron Lasers
 - 10 FELs each driven by 3-4 kA, 150 MeV, induction accelerated e-beam.
 - MOPA with amplifier driven by 1 GeV, 2.5 kA, induction accelerated e-beam.
 - Photon compression of a ~100 nsec induction accelerated e-beam of 100 MeV and 1 kA.
 - Oscillator, with RF accelerated e-beam & with high-power output switching.

SOLID STATE LASERS

Laser Requirements: Wavelength for electron energy of E_0 (TeV)

$$\lambda = 4.2 E_0 \text{ } \mu\text{m}$$

Laser power

$$P > 1\text{TW}$$

Pulse length

$$\tau = 1 \text{ psec}$$

Enhancement of γ -spectrum peak at maximum energy
Helically polarized laser

Pulse structure

90 pulses with rep rate of 120 Hz

Examples:

Mourou et al.	TIS/GLASS (1053nm)	
	640mJ/400fs $\rightarrow$ 0.5TW	0.03Hz
Kmetec et al.	TIS/TIS (807nm)	
	60mJ/125fs $\rightarrow$ 0.5TW	10Hz
Continuum	TIS/TIS (800nm)	
	200mJ/200fs $\rightarrow$ 1.0TW	10Hz

A chirped pulse amplifier and compression laser system produces 1-J, 1-ps laser pulses at 1- μm wavelength

Z847

Layout of the 1 Hz, 2 TW laser system for E-144

A number of parameters determine the suitability of different laser materials for high average power system

- **Saturation fluence (J/cm^2):**

The cross-section of material required is determined by the saturation fluence.

Goal: reduce the cross section

- **Nonlinear index**

This determines the maximum peak power which can be amplified.

Goal: maximize the peak power

- **Storage lifetime**

The longer the storage lifetime, the lower the peak power of the pump. This helps determine the suitability for laser pumping.

Goal: maximize the storage lifetime

Comparison of laser parameters for different media

UR
LLE

<u>Material</u>	<u>Nd:Glass</u>	<u>Ti:Sapphire</u>	<u>LiCAF</u>	<u>LiSAF</u>
<u>Wavelength (nm)</u>	1053	800	800	825
<u>Saturation Fluence (J/cm²)</u>	5	0.8	10	5
<u>Nonlinear Index</u>	1	1	0.4	0.5
<u>Storage Lifetime(μs)</u>	350	3	170	70

- **KrF₂**

saturation fluence of ~25 mJ/cm²

the important nonlinearities are in the windows of the discharge cells

The primary limitation to the repetition rate of solid state lasers is thermal effects in the material

- **Flashlamp pumped solid state laser systems suffer from severe thermal effects due to the low pumping efficiency**
 - depolarization due to thermal gradients**
 - mechanical stress**
- **High repetition rate, high average power, systems will have to be laser pumped.**
 - The high efficiency reduces the temperature**
- **Optimized pumping geometries also minimized thermal effects.**
- **Discharge lasers must recycle their gas and reduce the thermal effects on the windows.**

Multiplying Pulses

Passive approach...

Active approach...

Areas in need of research and development

- High average power
 $\swarrow$ lasing media
 $\rightarrow$ diode pumps
 $\searrow$ optical components
- Does phase conjugation work @ 1 ns pulses with broadband?
- Phase stabilization of laser/electrons to < 1 psec.
- Measurements of damage thresholds for "multi-bunch" pulse
- Composition and impact of halo around spent e^+/e^- beam
 — strategies for protecting optics
- Study characteristics of long-wavelength (>2 μm) solid-state lasers
- Effectiveness of crab crossing for photon beams (can we move out of harm's way?)
- De-polarization of laser light at grazing angles

coating might
fix this problem

- Angular-multiplexing at final focus

E-144

QED at Critical Field Strengths

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Nonlinear QED will be studied in two experimental configurations

Phase 1

Phase 2

E-144 will study QED at Critical Field Strengths on FFTB

- Recent advances in laser technology, such as Chirped Pulse Amplification, allow the generation of focused laser intensities up to 10^{19} W/cm² with relatively compact laser systems.
- At these intensities, laser-electron collisions can reach the QED critical field strength at electron energies of 50 GeV
- A 1Hz, 1 μ m, 2 TW, laser system is being installed.
- We have begun tests of the detectors and diagnostics required for the experiment.

V. Free-Electron Lasers

Concept of FEL System

of 10 FEL amplifiers (Single pass FEL's)

Each FEL driven by a 150 MeV S-band linac
($f=11.44\text{GHz}$, micro-bunch peak current $\cong 4\text{kA}$)
produces 100 GW radiation at $4\mu\text{m}$.

Two-stage FEL Scheme for a Photon Collider

A choice of the FEL configuration is a two-stage FEL system consisting of a tunable FEL oscillator (output power $\sim 1 - 10$ MW) with subsequent amplification of the master signal in a FEL amplifier up to the power ~ 300 GW (MOPA configuration).

FEL Parameters for a Gamma-Gamma Collider

FEL amplifier

Electron energy, $\mathcal{E}_0$	1 GeV
Beam current, I	2.5 kA
Radiation wavelength, λ	10 μm
Undulator period, λ_w	18 cm
Undulator field, H_w	12.26 kG
FEL amplifier efficiency, η	12 %

FEL master oscillator

Electron beam

Energy, $\mathcal{E}_0$	35 MeV
Peak current, I	50 A
Energy spread, $\Delta\mathcal{E}/\mathcal{E}$	0.5%
Normalized emittance, ϵ_n	100 π mm·mrad
Micropulse duration	15 ps
Macropulse duration	10 μs
Repetition rate	150 Hz

Undulator

Undulator period, λ_w	4 cm
Undulator field, H_w	3 kG
Number of undulator periods, N_w	40

Optical resonator

Radiation wavelength, λ	10 μm
Resonator length	6 m
Curvature radius of mirrors	3.2 m
Radiation power losses	6 %

Table 2: FEL amplifier parameters for the PLC

	2×0.25 TeV	2×0.5 TeV	2×1 TeV
<u>Electron beam</u>			
Electron energy $\mathcal{E}_0$, GeV	2	2	2
Beam current I , kA	2.5	2.5	2.5
Energy spread σ_E/E , %	0.3	0.3	0.3
Normalized emittance ϵ_n , cm-rad	1.3×10^{-2}	2.6×10^{-2}	5×10^{-2}
<u>Undulator</u>			
Undulator period λ_w , cm (entr./exit)	15 / 12.9	20 / 17.2	20 / 17.1
Undulator field H_w , kG (entr./exit)	10.2 / 11.9	9.34 / 10.9	13.2 / 15.44
Length of untapered section, m	11.7	15.6	14.0
Total undulator length, m	37.5	46.9	43.7
<u>Radiation</u>			
Radiation wavelength λ , μm	1	2	4
Input power W , MW	10	10	10
Output power W , TW	0.3	0.3	0.3
Efficiency η , %	6	6	6
<u>Reduced parameters</u>			
Diffraction parameter B	0.3	0.25	0.18
Energy spread parameter $\hat{\Lambda}_T^2$	0.1	0.1	0.1
Space charge parameter $\hat{\Lambda}_p^2$	0.08	0.1	0.14
Gain parameter Γ , cm^{-1}	5.1×10^{-3}	3.84×10^{-3}	3.84×10^{-3}
Saturation parameter $\beta = \lambda_w \Gamma / 4\pi$	0.006	0.006	0.006

Oscillation

Oscillator for NLC

Length of train $\leq$ Round Trip Time of Optical Resonator.

Whole Pulse Train in Cavity

	$f_b =$	250 MHz	
	$E_b =$	100 MeV	200 MeV
	$q =$	4 nC	2 nC
	$\eta =$	8%	
	# passes $\geq$	50	
	e^- bunch length	18 ps	Pulse compress γ 18 ps $\rightarrow$ 1ps Injection Chirpped Signal
	W_γ	1.6 J	
Current	I	222 A	
Macro	I	1 A	
Long term	I	2.7 mA	
macro pulse	$L_{rf} >$	$50 \times 120 \text{ ns} \geq 6 \mu\text{s}$	
	Linac Duty Factor	$\sim 2 \times 10^{-3}$	
	Macro Power	100 MW	
	Average Power	200 kW	

Summary of Oscillator FELs

	NLC	TESLA	SLC
λ_γ	1 μm	1 μm	0.25 μm — 20 μm
N_{train}	30	800	10
$\Delta\tau_{\text{sep}}$	4 ns	1 μs	25 ns
L_{train}	120 ns	.80 ms	250 ns
W/pulse	1 J	1 J	1 J
τ_γ	1 ps	1 ps	1 ps
Rep	180 Hz	10 Hz	180 Hz
<u>Optical</u>			
<u>Power Peak:</u>	1 TW	1 TW	1 TW
Macro			
Average:	250 MW	1 MW	40 MW
Long-Term			
Average:	5.4 kw	8 kw	1.8 kw

A PULSE STRETCHING, FEL AMPLIFYING, PULSE COMPRESSION SCHEME (PS/FEL/PC)

PULSE COMPRESSION

$$E_f(t) = \frac{1}{\sqrt{2\pi}} \int G(t-t') E_i(t') dt'$$

$$G(t) = \frac{1}{\sqrt{2\pi b i}} \exp \frac{i t^2 \tilde{\mu}}{2} \exp^{-i \omega_0 t}$$

$$\frac{1}{\tilde{\mu}} = \frac{4\pi^2 c b}{\omega_0^3 d^2 \left\{ 1 - \left[\frac{2\pi c}{\omega_0 d} - \sin \gamma \right]^2 \right\}}$$

(Time delay/freq. interval)

$$E_i(t) = \exp \left[-i \left[\omega_0 t + \frac{\mu}{2} t^2 \right] - \frac{t^2}{4T^2} \right]$$

(T: rms pulse length - μ : freq. chirping)

Then the width of $E_f(t)$ (it is also a Gaussian) is, instead of T ,

$$\tau = \sqrt{\frac{1}{4T^2\bar{\mu}^2} + T^2\left(\frac{\mu}{\bar{\mu}} - 1\right)^2}$$

thus if the grating is designed properly $\bar{\mu} = \mu$ and then $\tau = \frac{1}{2T\bar{\mu}}$

If $T \approx 1\text{ns}$ and desire $\tau \approx 1\text{ps}$

then require

$$\bar{\mu} = \frac{10^{21}}{2} \text{sec}^{-2}$$

Since

$$\omega = \omega_0 + \frac{\mu}{2}t$$

$$\frac{d\omega}{dt} = \mu$$

So over the uncompressed pulse

$$\Delta\omega \approx \bar{\mu}T \approx \frac{1}{2} \times 10^{12} \text{sec}^{-1}$$

or, for, $1\mu\text{m}$ radiation $\frac{\Delta\omega}{\omega} \approx \frac{1}{4 \times 10^3} \approx 2 \cdot 10^{-4}$

Sensitivity to jitter in μ is given by

$$T^2 \left(\frac{\mu}{\tilde{\mu}} - 1 \right)^2 \ll \frac{1}{4T^2 \tilde{\mu}^2}$$

$$\mu - \tilde{\mu} \ll \frac{1}{2T^2}$$

Or

$$\left| \frac{\Delta\omega}{\omega} \right| \ll \frac{1}{2T\omega} \approx \frac{10^{-6}}{4} \approx 2 \cdot 10^{-7}$$

error over pulse

FEL Frequency Error

Consider the exponential growth regime (easy to do analytically).

Phase

$$\varphi \sim \frac{2\pi\rho}{\lambda_w} z$$

$$\Delta\varphi \sim \frac{2\pi z}{\lambda_w} (\Delta\rho)$$

$$\rho \sim I^{1/3} / \gamma$$

$$\frac{\Delta\rho}{\rho} \sim \frac{1}{3} \frac{\Delta I}{I} - \frac{\Delta\gamma}{\gamma}$$

$$\frac{\Delta\omega}{\omega} = -\left(\frac{\lambda}{T_c}\right) \frac{\Delta\varphi}{2\pi}$$

At end of wiggler, L_w length,

$$\frac{\Delta\omega}{\omega} = -\left(\frac{\lambda}{T_c}\right)\left(\frac{L_w}{\lambda_w}\right)\phi\rho\left[\frac{1}{3}\frac{\Delta I}{I}-\frac{\Delta\gamma}{\gamma}\right]$$

So

So, at end of wiggler, taking

$$\begin{aligned} L_w &= 20\text{m} \\ \lambda_w &= 4\text{cm} \\ \lambda &= 1\mu\text{m} \\ \rho &= 2.10^{-3} \end{aligned}$$

$$\frac{\Delta\omega}{\omega} \sim 10^{-5} \left[\frac{1}{3} \frac{\Delta I}{I} - \frac{\Delta\gamma}{\gamma} \right]$$

If $\frac{\Delta I}{I}, \frac{\Delta\gamma}{\gamma}$ are of the order of 1%, then the compression requirement is satisfied.

PARAMETERS FOR THE PS/FEL/PC SCHEME

No Taper

$$I = 2 \text{ kA}$$

$$E = 100 \text{ MeV}$$

$$\Delta E/E = 10^{-3}$$

$$\varepsilon_N = 60 \times 10^{-6} \text{ } \pi\text{m-r}$$

$$\lambda_\beta = 6 \text{ m}$$

sc wiggler

$$\lambda_w = 1.5 \text{ cm}$$

$$K = 2.0$$

$$a = 6 \text{ mm}$$

$$L_W = 3 \text{ m}$$

$$P_{\text{in}} = 100 \text{ W}$$

$$P_{\text{out}} = 1/2 \text{ GW}$$

$$E_{\text{out}} (1.4 \text{ nsec}) = 0.7 \text{ J}$$

Taper

$$I = 1 \text{ kA}$$

$$E = 100 \text{ MeV}$$

$$\Delta E/E = 10^{-3}$$

$$\varepsilon_N = 50 \times 10^{-6} \text{ } \pi\text{m-r}$$

$$\lambda_\beta = 11.3 \text{ m}$$

Conventional planar wiggler

$$\lambda_w = 4.0 \text{ cm}$$

$$K = 1.4$$

$$L_{\text{sat}} = 16 \text{ m}$$

$$L_W = 25 \text{ m}$$

$$P_{\text{in}} = 100 \text{ W}$$

$$P_{\text{out}} = 1.6 \text{ GW}$$

$$E_{\text{out}} (1.4 \text{ ns}) = 2.24 \text{ J}$$

Many Challenging Issues

- parameter optimization
W, Spotsizes, IP-conversion distance, crossing angles,.....
- Detectors and masking.
- High power lasers including FELs.
- Special final focus components.
- Bright sources of polarized electrons.
- High power, low-loss optical components.

An R and D Program

1. Parameter Studies

INP
LBL
KEK

2. Numerical Simulations

INP
SLAC
Hiroshimna

3. Solid State Laser Development

LLNL
Osaka (?)
Rochester (?)

4. Compton Experiments

SLAC/Rochester/Princeton
Hiroshima

5. FEL

Dubna/Samara
LBL
INP (?)

6. Optics

LLNL
Osaka

7. Separators

INP (magnetic)

UCLA/SLAC/LBL (Plasma Lens)

8. Detectors and Masking

VII. Conclusions

Question to the HEP community:

**How seriously do you take the $\gamma\text{-}\gamma$,
 $\gamma\text{-}e$, and $e\text{-}e$ capability ?**

Possible answers and consequences:

1. "Not at all". Then you don't need to build and instrument a second interaction region.
2. "As an add-on". Then the Luminosity $L_{\gamma\text{-}\gamma} = (1/10) L_{e^+e^-}$ (and is probably not very interesting). If you change the final focus, then $L_{\gamma\text{-}\gamma} = (1/4 \text{ to } 1/5) L_{e^+e^-}$.
3. "Very seriously". Then one designs rather different damping rings, initiates an R and D program now, and can achieve $L_{\gamma\text{-}\gamma} = (1/2) L_{e^+e^-}$.

1. Someday, a high-energy linear collider should be built.

Why ? Because the particle physics it can do is special, and complementary, to that of a hadron collider.

2. When a linear collider is built it will, from the start, have the capability of e^+e^- , e^-e^- , $e^-\gamma$, and $\gamma\gamma$.

Why ?

- a) Because the physics capability of these different modes are often different and unique.
 - b) Because these different types of colliders are within our technical grasp.
 - c) Because the four different colliders are the same, except in the final focus region, and therefore the increment in cost is very small.
3. The various forms of linear colliders all require R and D. However, that required for $e^-\gamma$, and $\gamma\gamma$ is no more difficult than that required for a $e^+ - e^-$ collider.

Such R and D, perhaps at a modest level, should be initiated now. It is important to integrate this effort into the R and D programs for e^+e^- colliders, the more general nature of the collider, for it is likely to influence the present programs.

The R and D has both immediate aspects (such as designing detectors with masks and laser light ports, studying mirror damage in particle backgrounds, designing final focus magnets for gamma conversion, etc.) and long-term aspects (such as developing low-loss out-switching from optical cavities, plasma sweeping lenses, etc) .

4. The SLC could provide a test bed for a higher energy $\gamma\text{--}\gamma$ collider and, furthermore, would provide interesting new particle physics.

(Many of the problems faced by detectors, final focus geometry, and the development of laser, etc. are almost the same as in a higher energy collider.)

R and D towards implementing such a collider should be initiated immediately. It consists of the development of conventional lasers and free-electron lasers, experiments in the FFTF,

a development of a low-rep rate collider at the SLC, and, finally, the development of a high-rep rate (high-luminosity) $\gamma\text{-}\gamma$ collider at the SLC.

5. Efforts should be made, first to inform, and then to convince, the high energy physics community and the accelerator community of these beliefs. This means presentations at Rochester Conferences, Photon-Photon Conferences, Lepton Conferences, Physics of Colliders Conferences, EPAC, PAC, AACC, LC-xx, etc.
6. Further meetings devoted to the special problems of $e\text{-}\gamma$, and $\gamma\text{-}\gamma$ colliders are required.

APPENDIX

LIST OF THE SCHEDULED PRESENTATIONS

List of the scheduled (dates, topics and speakers)
Center For Accelerator Physics Seminars:

10/ 2/89 R. Palmer (SLAC/BNL), An Immersed Field Cluster
Klystron, (Part I).

10/16/89 Z. Parsa (BNL), Beam Dynamics, Emittance and
Moments in Accelerators and Beamlines (Part I)

10/30/89 Z. Parsa (BNL), Application - Emittance Analysis
For ATF Transport Beamline (II).

11/ 6/89 Z. Parsa and Participants, Round Table Discussion
of Future Control System for Accelerators; plus
E. Bozoki, a report on the Vancouver meeting.

11/20/89 T. Rao, T. Tsang (BNL), on Photocathod

12/ 4/89 R. Palmer (SLAC), An Immersed Field Klystron (II)

1/ 9/90 A. Fisher, on ATF YAG Laser

2/ 9/90 Z. Parsa, Re - evaluation of ATF - Photocathod RF Gun
and Transport Beamline to LINAC (PART I)

2/13/90 Z. Parsa, Re-evaluation of ATF - Injection System (II)

2/27/90 P. Wandrer, Results for SSC Superconducting Magnets

2/13/90 Z. Parsa, Discussions on use of the code PARMELA

2/27/90 Z. Parsa, K. Batchelor, Informal Discussions on ATF
and PARMELA results.

5/22/90 L. Wielopolski (Univ. Hospital, Stony Brook), Electron
Acceleration in Radiotherapy.

5/29/90 D. Goodman (MIT), KLystron Expts. at MIT / Science
Research Lab.

9/18/90 E. Forest (LBL), Why a Map Approach to Accelerator
Theory.

10/ 9/90 H. Riege (CERN), Electron Emissions from Ferroelectrics

10/30/90 K. Batchelor (BNL), Accelerator Test Facility - Progrss
Report and a report on LINAC 90 Conf., Albuquerque, NM.

11/ 6/90 Z. Parsa (BNL), On Beam Emittance Applicatin to ATF.

11/20/90 I. Ben-Zvie (BNL), On Development of Superconducting
RFQ at SUNY.

12/ 4/90 S. Krinsky (BNL), Theory of High Gain Free-Electron Laser.

12/18/90 L. Yu (BNL), On Ultra Violet FEL at BNL.

1/08/91 M. Petrossyan (Yerevan Phys. Institute), Development of
New Methods for Charged PArticle Acceleration at Yerevan.

1/10/91 R. Palmer (SSC/SLAC), High Luminosity at SSC.

1/22/91 A. Chao (SSC), Nonlinear Dynamics of SSC.

2/ 5/91 S. Ozaki (BNL), Update on Status of Relativistic Heavy Ion Collider (RHIC).

2/12/91 H. Padamsee (Cornell Univ.), RF Superconductivity for Particle Accelerators.

3/12/91 B. Claire (ANL), Overview of Argonne's Applied ACC. Progs.

3/26/91 J. Wurtele (MIT), High Gradient Acceleration Research at MIT.

4/16/91 Z. Parsa (BNL), Preliminary Emittance Measurements and Calculations of the Laser Excited Beam from the BNL- ATF Radio Frequency Electron Gun.

4/30/91 M. Tigner (Cornell Univ.), Cornell B-Factory.

5/21/91 H. Wiedemann (Stanford Univ.), Radio Frequency (RF) Gun Development at Stanford.

6/ 4/91 R. Gluckstern (Univ. of Maryland), Single Bunch Beam Breakup and BNS Damping.

6/18/91 S. Ozaki (BNL), Update on Status of Relativistic Heavy Ion Collider (RHIC).

9/17/91 M. Reiser (Univ. of MARYland), Physics of High Brightness Beams.

9/17/91 L. Yu (BNL). Radio Frequency Beam Conditioner For Fast-Wave Free-Electron Generators of Coherent Radiation.

9/17/91 Z. Parsa (BNL), Wake-Field and Space Charge Effects on High-Brightness Beams. Calculations and Measured results for BNL-ATF.

9/17/91 A. Dragt (Univ. of Maryland), Non-Linear Orbit Theory and Accelerator Design.

9/17/91 A. Luccio (BNL), Problems of Modeling for Accelerators

9/17/91 J. Deford (LLNL), Development and Application of Dispersive Soft Ferrite Models for Time Domain Simulation.

9/17/91 K. Bane (SLAC), Bunch Lengthening in the SLC Damping Ring.

1/ 7/92 P. Thieberger (BNL), The Proposed Booster Application Facility at BNL.

1/21/92 R. Palmer (BNL/SLAC), Cluster Klystrons Project at BNL.

2/ 4/92 W. Kimura (SPI Optronics), Inverse-Cerenkov Proj. at BNL

2/25/92 D. Carey (FNAL), 3rd Order TRANSPORT wit MAD input.

3/10/92 D. Kirkpatrick (SAIC), High - Brightness Field-Emission Cathodes.

3/24/92 Z. Parsa, On 3rd order Transport - Application to ATF Transport Beamline, and Possible Quadrupole schemes to improve the Beam Emittance.

4/ 7/92 Z. Parsa, K. Batchelor, Informal discussions on the results obtained with PARMELA, and TRANSPORT Codes.

4/29/92 A. Kennedy (SCRI, Florida State Univ.), The Proposed QCD / Teraflop Project at BNL

5/ 5/92 P. Wanderer (BNL), Update on SSC Magnets

5/19/92 R. Palmer (BNL/SLAC), Production of Positron by an Electron Beam in the Focus of an Intense Laser

6/ 2/92 W. Barletta (UCLA), Luminosity Limitations in Supercolliders at 10-100 TeV.

6/16/92 Z. Parsa, J. Fisher (BNL), On Cathode studies - and ATF Laser driven Photoelectron Gun.

12/22/92 J. Walsh (Dartmouth), Smith Purcell Radiation from Relativistic Electron Beams: Recent Results.

1/26/93 Z. Parsa (BNL), Discussions on the use and results of Beam Dynamic calculations with Program PARMELA.

2/ 9/93 E. Platner (BNL), STAR Experiment at RHIC

2/23/93 G. Danby (BNL), Magnetic Levitation: Update

3/ 9/93 M. Harrison (BNL), Update on Status of Relativistic Heavy Ion Collider (RHIC).

3/30/93 S. Aronson (BNL), Status of PHENIX Project at RHIC.

4/27/93 D. Neuffer (CEBAF), Mu+ Mu- Colliders.

5/25/93 Z. Parsa (BNL) and S. K. Ko (U. of Ulsan, Korea), Optimization of the Photocathode-Linac separation for the new ATF Straight-ahead-Injection System with PARMELA

6/22/93 Z. Parsa (BNL) and S. K. Ko (U. of Ulsan, Korea), effects of the variation in Solenoid Field for ATF injection system.

9/28/93 R. Palmer (BNL), Unconventional Colliders

9/28/93 S. Krinsky (BNL), Prospects for UVFEL (Free Electron Laser)

9/28/93 G. Bauer (PSI, Seitzerland), Accelerators as Intense Spallation Sources.

9/28/93 K. McDonald (Princeton Univ.), B Physics at Hadron

Accelerators.

- 11/18/93 J. Xie (IHEP, China), First Lasing of an IR-FEL at IHEP, Beijing.
- 11/30/93 R. Palmer, Update on Muon Collider
- 12/7/93 G. Van Tuyle (BNL), Applications of Accelerator Driven Spallation Targets - Including Tritium Production of Nuclear Waste Transmutation.
- 12/21/93 Y. Zhao (BNL), Practical Problems in Klystron Design.
- 1/11/94 L. Blumberg (BNL), Pulsed Spallation Neutron Project
- 1/25/94 K. Halbach, Designing and Understanding of Magnets with the help of Conformal Mapping.
- 2/ 8/94 P. Hahne (Germany), Application of Maxwell's equation with Finite Integration Algorithm code in Acc. Physics
- 2/22/94 S. Peggs (BNL), Update on RHIC Accelerator Physics
- 3/ 8/94 A. Luccio (BNL), Laser - Electron Beam Scattering - Coherent X-Ray Sources.
- 3/22/94 Z. Parsa (BNL), Optimization of ATF Alternate Injection System with Program PARMELA.
- 3/24/94 L. Evans (CERN), Large Hadron Collider (LHC) at CERN
- 4/12/94 Z. Parsa, H. Pang (BNL), Particle Simulations, Theory and Computer Modeling at Center for Accelerator Physics.
- 4/26/94 S. Sutton (Univ. of Chicago), The Impact of Advanced Accelerators in the Earth Sciences: From Wheat Take-all Disease to the Evolution of our Solar System.
- 5/10/94 A. Luccio (BNL), Measurement of Spin Polarization Using Synchrotron Radiation.
- 5/24/94 Y. Zhao (BNL), The Energy and Efficiency Consideration of a Klystron.
- 6/ 7/94 L. Meringa (CEBAF), Commissioning of Continuous Electron Beam Accelerator Facility - First Result.
- 6/21/94 Z. Parsa (BNL), Space Charge and Emittance Growth Compensation for the Brookhaven Accelerator Test Facility With the Solenoid-Gun-Solenoid Injection Scheme.
- 10/11/94 M. Atiya (BNL), Update on Status of Hadronic B Exps.
- 10/25/94 G. Nusinovich (U. of Maryland), Some Prospectives of Microwave RF Sources for Future Colliders + Overview of RF and Accelerator Physics activity at U. Maryland.
- 11/15/94 R. Gupta (BNL), Field Quality Improvemnets in Superconducting Magnets for RHIC.

11/29/94 R. Palmer (BNL), Review of Power Sources for NExt Linear Collider (summary of the Workshop).

12/ 6/94 D. Cline (UCLA), Overview of Mu+ Mu- Collider (summary of Phys. Potential and Development of Mu+Mu- Colliders Workshop, Sausalito, California, Nov. 17-19, 1994).

12/20/94 Z. Parsa (BNL), On Physics Possibilities at Muon Collider -- at BN?

1/10/95 T. Marshall (Columbia Univ.), Spiking Pulses from Free Electron Lasers: Observation and Computational Models.

1/24/95 J. Wei (BNL), Crystalline Beams in Circular Accelerators

2/6-8/95 Muon Collaboration Meeting, Berkner Hall, BNL

2/28/95 T. Roser (BNL), Accumulator Ring for AGS - A Mini Kaon Factory.

3/7/95 V. Barger (U. of Wisconsin), "Physics Goals of a Muon Collider". (Summary of the Physics Working Group at the Physics Potential and Development of Mu+Mu- Colliders Workshop, Sausalito, California, Nov. 17-19, 1994).

4/12/95 A. Sessler (LBL), Gama - Gama Collider

4/25/95 M. Harrison (BNL), Update on Status of Relativistic Heavy Ion Collider (RHIC).

5/ 9/95 K. Bongardt (Juelich), European Spallation Source Update.

6/ 13/95 Arch Thiessen (LANLL), A High-Intensity Proton Source for Muon-Muon Collider.