CAP

RECEIVED

OCT 16 1995

OSTI

BNL-52292-Vol. 4
CAP-124-95P

**SELECTED TOPICS IN PARTICLE
ACCELERATORS**

PROCEEDINGS OF THE CAP MEETINGS

VOLUME IV

**Edited / Compiled
by
Zohreh Parsa**

CENTER FOR ACCELERATOR PHYSICS

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

Under Contract No. DE-AC02-76CH00016 with the

UNITED STATES DEPARTMENT OF ENERGY

**bnl
at**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

BNL-52292 - Vol. 4
CAP-124-95P

SELECTED TOPICS IN PARTICLE ACCELERATORS

PROCEEDINGS OF THE CAP MEETINGS

VOLUME IV

**Edited / Compiled
by
Zohreh Parsa**

Center For Accelerator Physics

**Brookhaven National Laboratory
Associated Universities, INC.
Under contract No. DE-AC02-76CH00016
with the United States Department of Energy**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

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.

*Zohreh Parsa
Center for Accelerator Physics
Physics Department Building 901A
Brookhaven National Laboratory.*

TABLE OF CONTENTS

VOLUME IV

<u>TOPIC</u>	<u>AUTHOR(S)</u>	<u>SECTION</u>
FORWARD	Z. PARSA	
APPLICATION OF ACCELERATOR DRIVEN SPALLATION TARGETS- INCLUDING TRITIUM PRODUCTON & NUCLEAR WASTE TRANSMUTION	G. VAN TUYLE	I
BNL 5 MW PULSED SPALLATION NEUTRON SOURCE STUDY	L. BLUMBERG	II
DESIGNING AND UNDERSTAND- ING OF MAGNETS WITH THE HELP OF CONFORMAL MAPPING	K. HALBACH	III
THE LHC PROJECT	L. EVANS	V
OPTIMIZATION OF THE PHOTOCATHODE-LINAC SEPARATION FOR ATF	Z. PARSA & S. K. KO	VI
ON CEBAF COMMISSIONING	L. MERMINGA	VII
THE PROPOSED BOOSTER APPLICATION FACILITY AT BNL	P. THIEBERGER	VIII
APPENDIX	DISCLAIMER	

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**APPLICATION OF ACCELERATOR -
DRIVEN SPALLATION TARGETS -
INCLUDING TRITIUM PRODUCTION
AND NUCLEAR WASTE
TRANSMUTATION**

***GREGORY J. VAN TUYLE
BROOKHAVEN NATIONAL LAB***

I

Applications of Accelerator-Driven Spallation Targets -
Including Tritium Production and
Nuclear Waste Transmutation

Gregory J. Van Tuyle

Deputy Division Head
Applied Technologies Division

Department of Advanced Technology

Accelerator Driven Concepts: History

- 1949 Materials Test Accelerator (MTA) Project:
 - Produce Fissionable Material
- 1955 Intense Neutron Source (ING)
- 1977-1984 Accelerator Breeder Considered
- 1989 Accelerator Production of Tritium (APT) Proposed
ERAB Panel Assessment: *Too Much Electricity* (900 MWe)
- 1990-91 Accelerator Transmutation of Waste (ATW), LANL
also: PHOENIX, BNL
- 1992 APT Returns, with Lower Tritium Production Goals
and More Time to Develop the Technology

Accelerator Production of Tritium (APT)

- Non-Reactor Option for Producing Tritium
 - Neutrons from Spallation, Not Fission
 - Reduced Environmental, Safety, & Health Concerns
 - Fewer Political and Regulatory Difficulties
- For Large Goal Amounts, Operating Costs (Electricity) for Accelerator Too High Compared to Reactors
- For Smaller Goals, Accelerator Has Economic Advantage (Even Small Reactors Are Expensive)

APT

TEAM

Sandia National Laboratories

Los Alamos National Laboratory

Brookhaven National Laboratory

Industrial Participants

Reference Accelerator for 3/8-Goal Production 1000-MeV, 200-mA CW Proton Linac

Beam power	200 MW
Total RF power	275 MW
RF to beam efficiency	0.73
AC to RF efficiency	0.58
AC power requirement	500 MW
Average CCL gradient	1.25 MV/m
Transverse output emittance	0.04 π cm-mrad
CCL aperture/beam-size ratio	13-26

Demonstrated Linac Technology Base

HIGH ENERGY PROTON-INDUCED NUCLEAR SPALLATION REACTION

Number of neutrons produced per an incident proton energy

Heavy Elements Considered for SILC Target Lattice

#Protons per Atom	Element Name	High Cost	Rare+ Active	Transurnic Waste	Very Hazardous	Further Consideration
71	Lutetium	X				
72	Hafnium					X
73	Tantalum					X
74	Tungsten					X
75	Rhenium	X				
76	Osmium	X				
77	Iridium	X				
78	Platinum	X				
79	Gold	X				
80	Mercury				X	
81	Thallium				X	
82	Lead					X
83	Bismuth				X (Polonium)	
84	Polonium		X			
85	Astatine		X			
86	Radon				X	
87	Francium		X			
88	Radium				X	
89	Actinium		X			
90	Thorium			X		
91	Protactinm			X		
92	Uranium			X		
93	Neptunium			X		
94	Plutonium			X		
95	Americium			X		

Neutron Absorption Cross-Sections: Thermal and Resonance

APT: Accelerator Production of Tritium

Spallation Induced Lithium Conversion (SILC) Target:

APT: Accelerator Production of Tritium

Spallation Induced Lithium Conversion (SILC) Target:

*Conical Section
of SILC Blanket*

17

Beam Expansion Chamber
(Vacuum = 10^{-5} torr)

LINAC Protons
200 mA at 1 GeV

2-Dimensional
Beam Expander
Basis: BNL REF

SILC Blanket:

Aluminum Pressure Tubes

(Alternate is Alum or Zirc Tank)

LiAl w/ Aluminum Cladding Pins

(Alternate is LiAlO_2 G-B Targets)

H₂O Cooled and Moderated

APT DUAL TARGET BEAM TRANSPORT AND EXPANDER

Distribution Of Protons From BNL's Two-Dimensional Beam Expander

Notes: 1) Monte Carlo Calculations and Measurements Subject to Statistical Variations
2) Distribution Is Key Consideration, Alignment and Width Can Be Controlled

bnl
au

Comparison of Gaussian and Modified Gaussian Illuminating the Same Target

NEUTRON SOURCE ARRAY GENERAL ENVELOPE

SILC TARGET CHAMBER EXPLODED VIEW

SILC TARGET CHAMBER

02-3100899

Figure 3.12 Major Spallation Products in Neutron Source Array After One-Year of Operation

Objectives of Current Experiments

- Materials: How Will Materials Perform in Proton Beam?
 - Important for Determining Operating Costs and Safety Issues
 - Program is Focused on Old Accelerator Windows (Some Failed)
- 25 • Beam Experiments
 - N/P Measurement Around 1 GeV Reduces Electricity Uncertainties
 - Activation Measurement (Gammas) Important for "Source Term"
 - Decay Heat (Beta) Important for Safety Systems & Analyses

*Note: While APT Target Designs are Based Largely on Computations,
the Underlying Models Needs Further Validation via Experiments*

Neutron Yield Data

- Neutron Yield Data for Pb Sparse for Proton Energies >800 MeV
 - Mostly from 1964 Cosmotron Data for Small Diameter Targets
(Reduces Yield + More Sensitive to Beam Misalignment)
- 1964 Experiment Yields Below HETC/NMTC Predictions
 - Gold Foil Data ~18% Lower
(Includes Complicated Data Analysis and Large Error Bars)
 - Beta Current Data <10% Lower
 - Experimental Procedures & Calibration Not Documented
- APT Goal: Reduce Uncertainty in Yield to $\pm 5\%$

"WORD"

Momentum of Incident Particle

"SPILL" Number

Event Number

- TOF of Incident Particle (Momentum)
- Detection Time For Each Detected Neutron (MCS)
- Amplitude of Paddle Signal
- Division Between Inner and Outer Detector Rings
- Total Neutron Count
- Etc.

* Pb 10.2 cm D x 61 cm L
W 10.2 cm D x 40 cm L

Time-Of-Flight (TOF) Spectrum

Neut. Capt. by He^3 vs. Time, Pb Target
 $y = 12726 \exp(-0.0176991) + 848.40$

(n/p): Experimental vs Monte Carlo

Pb, 10.2 cm D x 61 cm L

----- exptl. LS
 ▲ BNL @ BNL (present Exp.)
 ■ AECL @ BNL
 — MC AECL, LANL, BNL
 --- MC extended
 AERE @ Birming.

BNL
 (111)

**phoenix - a unique mythical bird of great beauty
fabled to live 500 or 600 years, to burn itself to death,
and to rise from its ashes in the freshness of youth,
and live through another life cycle**

Impact of Partial Waste Processing

33,000 MWd/MTU & 10 Year Decay

Approximate Mass Flows from All U.S. LWRs in 1991 (Predicted, Not Measured)

Energy Produced By Fissioning Throughput of Key Actinides from All U.S. LWRs (~65% Capacity Factor)

Note: Assumes Non-Fissile Isotopes Fissioned in a Fast Spectrum or After Absorbing Neutrons and Becoming Fissile Isotopes

Transmuting Key Isotopes

- The Minor Actinides Can Be Fissioned, Creating Heat and Neutrons (~2.7/Fission)
 - Most Would Not Fission Well in LWRs (Probably On 3rd Neutron)
 - All Actinides Are Likely to Fission In *Fast* Spectrum (Probably On 1st Neutron)
 - Option: Fission in Very High Flux *Thermal* Spectrum (Hopefully On 2nd Neutron)

[First Neutron Absorbed Creates Short-Lived *Fissile* Isotope]

- Some Fission Products Will Absorb Neutrons (from Fission) and Become Stable
 - Long-Lived Iodine-129 and Technetium-99 Transmute to Stable Isotopes
 - For Cs and Sr, Multiple Isotopes Make Transmutation More Difficult
 - Over Near Term, Storage or Repackaging of Some Isotopes Best Option

Transmutation Chains for Iodine and Technetium

	<u>Initial Isotopes</u>	<u>Short-Lived</u>	<u>Stable Isotopes</u>
76%	I-129 + n →	I-130 $\xrightarrow{\beta-}$	Xe-130 + n → Xe-131 + n → Xe-132
24%	I-127 + n →	I-128 $\xrightarrow{\beta-}$	Xe-128 + n → Xe-129 + n → Xe-130
			<i>Xe is a Gas Above 166 K (-160 F)</i>
100%	Tc-99 + n →	Tc-100 $\xrightarrow{\beta-}$	Ru-100 + n → Ru-101 + n → Ru-102

Tc and Ru are Solids Below 2445 K (3942 F)

The PHOENIX Concept

39

Advantages In Driving Lattice Using Accelerator

- **Can Operate System at Low k , effective**

- Initially Almost None of Minor Actinides Will Fission Thermally
- In a Reactor Would Need to Add Plutonium to Attain Criticality

(Fissioning Pu Adds to the Heat Load, as well as FP & Actinide Inventories)

40

- Can Adjust Current to Compensate for Increasing k , effective ("burnup")

- Can Maintain Lattice Safely Subcritical,

- **Eliminating Reactivity Accidents As A Major Safety Concern**

- Can Compensate for Large Uncertainties in Neutron Cross-Sections
- Can Drive Additional Targets - Possibly Designed to Transmute Other Wastes (Cs,Sr)
- Can Passively Shut Down Lattice Using Fuses Connected to Accelerator

Conversion Ratio-Protons to Transmutations

Number of Transmutations = Number of Fissions + Number of Spallations (Proton Induced Fissions)

Number of Neutrons = Number of Source Neutrons $\times (1 + k + k \times k + k \times k \times k + \dots)$,

where: Number of Source Neutrons = Number from Spallation + Number from Evaporation

$k=k$, effective = Effective Neutron Multiplication Factor for the Lattice

Therefore: Number of Neutrons = Number of Source Neutrons $\times (1/(1-k))$ (Geometric Series)

Number of Fission Neutrons = Number of Neutrons - Number of Source Neutrons

= Number of Source Neutrons $\times (k/(1-k))$

Number of Fissions = Number of Fission Neutrons / ν ,

where: ν = Number of Neutrons Released per Fission

Therefore: Number of Fissions = Number of Source Neutrons $\times (k/(1-k)) / \nu$

Number of Transmutations = Number of Source Neutrons $\times (k/(1-k)) / \nu$ + Number of Spallations

Assuming: 5 Proton Induced Fissions, 50 Source Neutrons, 2.7 Neutrons per Fission:

$\Rightarrow$ If $k = 0.95$, Expect 357 Transmutations per Proton
If $k = 0.9$, Expect 172 Transmutations per Proton

Reactivity Increase & Mass of Principal Actinides During First 12 Years of Burn-Up in 3600 MWt PHOENIX Lattice *Assumes Plutonium Removed During Reprocessing*

Other Target Applications

- Spallation Neutron Source (Power Density Advantage)
- Isotope Production: Medical, Pu-238, etc
- Multi-Purpose Machines (Trimurti)

Summary

- Accelerator Production of Tritium (APT): Very Promising
for the Right Goal Quantity
- Waste Transmutation Viable But Politically Difficult
- Additional Missions Interesting & Viable - But When ??

BNL 5 MW PULSED SPALLATION NEUTRON SOURCE STUDY

L. N. BLumberg
Brookhaven National Laboratory

II

SPALLATION NEUTRON SOURCE INJECTION STRAIGHT DC + FAST BUMP

FOR FRACTIONAL MAGNETIC STRIPPING H^- LOSS = $10^{-4}/m$

$B = 5.366 \text{ kG}$ at $E_K(H^-) = 600 \text{ MeV}$

ADMITTANCE $A = 400 \pi \text{ mm-mrad}$

$L_{\text{straight}} \approx 444 \text{ cm}$

$\beta_s = 7.96 \text{ m}$

$\alpha_s = -1.36$

$\eta_{xs} \approx 2.21 \text{ m}$

$(\Delta p/p_0)_{inj} \approx 0.5\%$

FCS Quadrupole Magnet, $R_p = 120$ mm

ref: 7/13/93 SNS meeting. From AvS.

H⁻ MAGNETIC STRIPPING FRACTIONAL LOSS, FIELD vs. ENERGY

MOTIVATION FOR THE CALCULATION

For the 1-MW Japanese Hadron Facility (JHF), Yamane, et al.¹ have estimated coulomb and nuclear scattering injection losses for 1-GeV H^- on a $250 \mu\text{g}/\text{cm}^2$ C^{12} stripper foil as $5.3 \cdot 10^{-4}$. They (and others) regard fractional distributed losses of $\sim 10^{-3}$ as a maximum permissible loss. Our BNL design at 600-MeV injection energy will result in higher coulomb losses and comparable nuclear scattering and could therefore get into the 10^{-3} range, although our ring acceptance (now $A=320 \text{ mm-mr}$) is larger than the 120 mm-mr JHF value.

CONCLUSIONS FROM THE PRESENT CALCULATION

- (1) Distributed scattering losses out of the $A=400 \text{ mm-mr}$ acceptance of the preliminary BNL ring design² can, under optimal conditions, give fractional losses as small as $3 \cdot 10^{-5}$ for 300 turn injection through a $300 \mu\text{g}/\text{cm}^2$ 10 mm 10 mm "postage stamp" C^{12} stripper foil with the H^- beam tracking the $y' = -(x'/\beta)y$ ellipse axis, 50% filling of the acceptance area, and an exponentially collapsing injection "bunch".
- (2) If we go to 600 turns, the losses increase by only $\sim 50\%$. This may be more acceptable than increasing the Linac current to 100 mA from the originally² specified 50 mA to accommodate $\sim 50\%$ chopping for efficient longitudinal capture, although

¹ Yamane, Kitagawa, Someya and Yano, KEK report 88-8 (1988).

² A.G. Ruggiero and A. van Steenbergen, BNL report 49246 (1993)

CONCLUSIONS (continued)

- 600 turns may complicate longitudinal capture since the increased time required (.458 to .917 msec) will result in larger momentum change of ring during injection period.
3. Increasing the foil thickness from 300 to 600 $\mu\text{g}/\text{cm}^2$ will increase scattering losses by ~ 2 . This may be acceptable since we also improve $\text{H}^- \rightarrow \text{H}^+$ conversion efficiency from $\sim 10^{-3}$ losses to ~ 0 , which will be useful in terms of beam dumps needed to intercept the unconverted H^0 (and H^-).
 4. It would be useful to program the angle of incident H^- beam on the stripper foil so that it follows the acceptance ellipse axes $y' = -(\alpha/\beta)y$ rather than remain fixed on the horizontal and vertical phase ellipse axes $x' = z' = 0$. The penalty for not tracking ellipse axis is about a factor of 5 increase in losses. This can be accomplished by a pair of programmed horizontal and vertical deflecting magnets in the H^- transport line. Of course, the tracking problem would vanish if lattice had $\alpha = 0$ at stripper.
 5. It is important to use a "postage stamp" stripper foil (10mm x 10mm used here) similar to that developed by INS (U. Tokyo) and used successfully at the LANL PSR.³ The penalty for using large area conventional edge supported foil (20 x 160mm assumed here) is an additional factor of ~ 13.4 loss and smaller foil lifetime. The lifetime of a 16mm x 16mm 200 $\mu\text{g}/\text{cm}^2$ C^{12} foil is 10^{23} protons/ cm^2 ; if traversals/proton approach 300 as was the case at LANL (R. Maciek, private comm. the life time can be as small as 30 hours due to radiation damage.

³ Borden, Adamson, Johnson and Nicause, NIM A303 (1991) 63.

PROBLEMS REMAINING TO BE ADDRESSED

1. I have no independent means to check the calculation.
One possibility — starting with the Moliere scattering probability function rather than using the Moliere expansion — is ruled out because that function goes negative for some angle intervals within the present range of interest.
2. The Moliere series expansion in inverse powers of the parameter B does not allow solutions for $B \leq 1$ which corresponds, for our problem, to C^{12} foils $\leq 245 \mu\text{g}/\text{cm}^2$. How does one apply Moliere Theory to foils of $200 \mu\text{g}/\text{cm}^2$ used at LANL?
3. The optical model used here to calculate the nuclear elastic scattering cross-section used a radius about 10% higher than the value which would give a good fit to the 597-MeV LANL data. Consequently, the nuclear scattering probabilities and losses are about 20% too large in the present results.
4. The calculation uses a tune variation with amplitude corresponding to $(\Delta\nu)_{\text{max}} = .25$, a value consistent with a Gaussian space charge distribution of standard deviation about $1/3$ of the acceptance ellipse size $x_m = 56.4 \text{ mm}$ for $A = 400 \text{ mm-mr}$. Although the loss results are probably not sensitive to the assumed tune spread, the program's output can be used to obtain the space charge distribution which allows a consistency check on the assumed $\bar{V}(r)$ function. The present calculations have an $r = 2 \text{ mm}$ "hole" in the beam center to reduce the central space charge so the tune shift theory will have to be revised to accommodate a non-Gaussian space charge function.

MULTIPLE COULOMB SCATTERING THEORY

Moliere⁴ gives probability for scattering an incident particle of charge Ze , rest mass m , and momentum P (in energy units, i.e. $P=pc$) as (Eq. 5.5) into angle between θ and $\theta+d\theta$ as

$$(1) \quad P(\theta)d\theta = \frac{\theta d\theta}{\theta_1^2} \int_0^{\Omega_0^{1/2}} y dy J_0\left(\frac{\theta}{\theta_1} y\right) e^{\frac{y^2}{4}(\ln \frac{y^2}{4} - 6)} \quad (1)$$

$$\text{where } \theta_1^2 = 4\pi N_0 \rho t \frac{Z^2}{A} \frac{Z(Z+1)e^4}{P^2 \beta^2 A} \quad (2)$$

$$= 1.569149936 \cdot 10^{-13} Z(\mu g/cm^2) \frac{Z^2 Z(Z+1)}{A} / P^2 (GeV) \beta^2 A \quad (3)$$

where in Eq. (2), N_0 is Avogadro's number, ρ is the target foil density, A is the target atomic weight, and t the thickness, and Ze is the target nucleus charge. In Eq. (3), the areal density $\tau = \rho t$ is used. Eq. (2) is Bethe's⁵ Eq. 77a. In Eq. (1) Moliere approximates the upper limit of integration (his Eq. 1.7) as, using Bethe's notation (see BA Eq. 81f)

$$\Omega_0 \approx \left(\frac{\theta_1}{\theta_a}\right)^2 = 4\pi N_0 \tau \left(\frac{h}{m_e c}\right)^2 \frac{(Z+1)Z^{1/3}}{\beta^2 A} \left[\frac{.885^2}{1.13 + 3.76\alpha^2} \right] \quad (4)$$

$$\text{with } \alpha^2 = \frac{Z^2 Z^2 e^4}{h \beta c} = \frac{Z^2 Z^2}{\beta^2} \frac{r_0^2 (m_e c^2)^2}{(hc)^2} = 5.3251367 \cdot 10^{-5} \frac{Z^2 Z^2}{\beta^2} \quad (5)$$

In practical units

$$\left(\frac{\theta_1}{\theta_a}\right)^2 = \frac{8.838530658 \cdot 10^{-3} (Z+1) Z^{1/3} Z \tau (\mu g/cm^2)}{\beta^2 A (1.13 + 2.002251163 \cdot 10^{-4} Z^2 Z^2 / \beta^2)} \quad (6)$$

⁴ G. Moliere, Z. Naturforsch. 3a (1948) 78

⁵ H. Bethe and J. Ashkin, Exptl. Nucl. Phys. Vol. 1. Ed. E. Segre (J. Wiley, 1952) Part II, pp. 166-357. (referenced as BA here).

In Eqs 4-6, $\beta = vc$ is the relativistic factor

$$\beta^2 = 1 / [1 + (mc^2/p)^2] \quad (7)$$

and in Eq.(5) r_0 is the classical radius of the electron
 $r_0 = e^2/mc^2 = 2.81794092 \cdot 10^{-13} \text{ cm.}$

Moliere and BA give for the quantity b in Eq.(1)

$$b = \ln\left(\frac{\theta_1}{\theta_a}\right)^2 + 1 - 2C = \ln\left(\frac{\theta_1}{\theta_a}\right)^2 - .154431329803 \quad (8)$$

with $C =$ Euler's constant $C = 0.577215664901533...$

Eq.(1) is an extremely inconvenient expression for a Monte-Carlo problem since it is specific to all of the scattering parameters such as $\beta, A, T, P, z, Z, \dots$ etc. More serious, it is negative ^{for specific ranges of angles θ} for the parameters of the present problem, where (θ_1/θ_a) from Eq.(6) is about 1.98 at an incident proton kinetic energy $T_p = 600 \text{ MeV}$, $T = 300 \mu\text{g/cm}^2$, $Z = 6$. (Note that Bethe has incorrectly transcribed Eq.(1) from Moliere's paper, giving the upper limit of integration as ∞ for which the integral diverges due to the exponential in the integrand. I am unable to evaluate Eq.(1) for values of $\Omega_0^{1/2}$ larger than about 6. I have varied the upper limit for a range of values of $\Omega_0^{1/2}$ between 1 and 6 and find that Eq.(1) always gives negative values for various θ intervals)

Moliere provides a more convenient method for evaluating the scattering probability by expanding Eq.(1) in inverse powers of a parameter B :

$$P(s)ds = s ds \left[2e^{-s^2} + f_1(s)/B + f_2(s)/B^2 + \dots \right] \quad (9)$$

$$= s ds \left[2e^{-s^2} + \sum_{n=1}^{\infty} f_n(s)/B^n \right]$$

The functions $f_n(s)$ are universal functions of the normalized angle $s = \theta / (\theta_1 \sqrt{B})$ with

$$f_n(s) = \frac{1}{n!} \int_0^{\infty} y dy J_0(sy) e^{-y^2/4} \left(\frac{y^2}{4} \ln \frac{y^2}{4} \right)^n \quad (10)$$

In a previous work⁶ these integrals were evaluated over a limited range $0 \leq s \leq 7$ and only the first 3 terms were tabulated to 6 significant digits. In the present work I have evaluated Eq. (10) up to $n=10$ and extended the range to $0 \leq s \leq 1000$ in intervals as small as $\Delta s = .01$ for $s \leq 20$ and with 15 significant digits (REAL*8 arithmetic on the VAX 8600). For Monte-Carlo use, the integrated probability is required so a second numerical integration is performed to obtain the distribution function

$$F(s) = \int_0^s P(s) ds = 1 - e^{-s^2} + \sum_{n=1}^{NT} F_n(s)/B^n \quad (11)$$

$$\text{where } F_n(s) = \int_0^s s f_n(s) ds \quad (12)$$

The scattering parameters specific to the problem are contained in the quantity B which is the solution of

⁶ L.N. Blumberg and F. Krausz, BNL report 24901 (March 1971).

The transcendental equation

$$B - \ln B = b. \quad (13)$$

which is solved by Newton's iteration. Eq. (13) does not allow values of $B \leq 1$. For our 600-MeV H^- on C^{12} problem, $B = 1.7994$ for $300 \mu\text{g}/\text{cm}^2$ and $B = 3.0055$ for $600 \mu\text{g}/\text{cm}^2$. The ^{rms} multiple Coulomb scattering angle is given by Bethe as

$$\langle \theta^2 \rangle^{\frac{1}{2}} = \theta_{mc} = \theta_1 \sqrt{B} \quad (14)$$

and thus $\theta = \theta / \theta_{mc}$. For the present problem, $\theta_{mc} = 17.82 \mu\text{rad}$ at $300 \mu\text{g}/\text{cm}^2$ and $32.58 \mu\text{rad}$ at $600 \mu\text{g}/\text{cm}^2$. Note that the Particle Properties Book⁷ gives the approximation

$$\theta_{mc} \approx \frac{14.1}{p\beta} \sqrt{\frac{L}{L_R}} \left[1 + \frac{1}{9} \log_{10} \frac{L}{L_R} \right] \quad (15)$$

with p = projectile momentum in MeV/c, L the foil thickness, and L_R = radiation length. At our momentum of $p = 1219 \text{ MeV}/c$ and $\beta = .792$ and using their value $L_R = 42.7 \text{ g}/\text{cm}^2$ for C^{12} we obtain for an $L = 300 \cdot 10^{-6} \text{ g}/\text{cm}^2$ foil $\theta_{mc} = 16.55 \mu\text{rad}$ which is in reasonable agreement with Eq. (14).

⁷ Review of Particle Properties, Particle Data Group, Phys. Lett. 170B (10 April 1986), 1-350.

Wed Dec 8 16:10 1993

MOLIERE & BETHE θ_{ms} vs TARGET THICKNESS, P+C¹²

Wed Dec 8 16:34 1993

INTEGRATED PROBABILITY FUNCTION, MULTIPLE COULOMB SCATTERING

Mon Dec 20 12:50 1988

INTEGRATED PROBABILITY FUNCTION, MULTIPLE COULOMB SCATTERING

Mon Dec 20 13:19 1993

RANDOM ANGLES, MULTIPLE COULOMB SCATTERING DISTRIBUTION, $P+C^{12}$

Mon Dec 6 14:30 1993

RANDOM ANGLES, MULTIPLE COULOMB SCATTERING DISTRIBUTION, P+C¹²

Sat Dec 4 20:57 1993

RANDOM ANGLES, MULTIPLE COULOMB SCATTERING DISTRIBUTION, P+C¹²

Sat Dec 4 22:37 1983

Sat Dec 4 22:24 1993

RANDOM PROJECTED ANGLES, MULTIPLE COULOMB SCATTERING, P+C¹²

LOSSES FROM LARGE ANGLE SINGLE COULOMB SCATTERING^{*} (Blumberg and Krausz, BNL 47356 (1971))

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Ruth}} = \left(\frac{Ze^2}{2mc^2}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

Z = atomic number of target

$m = m_0 \gamma$ m_0 = proton rest mass $\gamma_{inj} = 1.63947$

Total coulomb cross section for particles scattered thru angle $\theta > \theta_{\min}$ (i.e. lost)

$$\sigma_c = 2\pi \int_{\theta_{\min}}^{\pi} \left(\frac{d\sigma}{d\Omega}\right)_{\text{Ruth}} \sin\theta d\theta = \frac{Z^2 \pi r_0^2}{2\gamma^2} \frac{(1 + \cos\theta_{\min})}{(1 - \cos\theta_{\min})}$$

Small angle approximation for $\cos\theta_{\min}$ gives

$$\sigma_c = 2Z^2 \pi r_0^2 / \gamma^2 \theta_{\min}^2$$

r_0 = classical radius of proton = $\frac{e^2}{mc^2} = 2.818 \times 5.446 \times 10^{-4}$ Fm

For $\theta_{\min}$ use maximum allowable amplitude a within ring admittance. $x = \theta \sqrt{\beta_s \beta_{\max}} \sin\psi$ $a \rightarrow \theta_{\min} \sqrt{\beta_s \beta_{\max}}$

For horizontal, $\beta_s = 7.9597$ m $\beta_{\max} = 16.43$ m
 $a = \sqrt{\epsilon \beta_{\max}} = 81.38$ mm for 40π mm-mrad ellipse, include 0.25% momentum spread $\Delta p/p_0$. $\theta_{\min} = 7.116$ mrad

$$\sigma_c = 39.144 \text{ mb}$$

Probability of event occurring in foil of thickness

$$\tau = \rho t$$

$$p = \frac{N_0}{A} \tau \sigma_c$$

$$N_0 = 6.022 \times 10^{23}$$

$$A = 12$$

For $\tau = 250 \mu\text{g}/\text{cm}^2$ C¹²

$$p = 4.91107 \times 10^{-7} \text{ per traversal}$$

for 40 traversals $p \rightarrow 1.96 \times 10^{-5}$

In good agreement with Yamane, et al, KEK 88-8 (1988)

1. See also Blumberg, BNL-47356 (1992).

FORMULATION OF NUCLEAR ELASTIC SCATTERING (OPTICAL MODEL)

ref. Fernbach, Serber and Taylor, Phys. Rev. 75 (1949) 1352.
(FST)

cm Scattering amplitude

$$f(\theta) = k \int_0^R [1 - e^{(-K+2ik_1)RS}] J_0(kp \sin \theta) p dp$$

with $KR = \frac{3A}{4\pi R^2} \sigma$ $\sigma = [Z\sigma_{pp} + (A-Z)\sigma_{pn}] / A \approx \sigma_{pp}$

$\sigma_{pp} \approx 37 \text{ mb at } T_p = 600 \text{ MeV.}$ $S = \sqrt{1 - (p/R)^2}$ $R = r_0 A^{1/3}$

$k = p/\hbar = p/\hbar c$ $k_1 = k \left[\left(1 + \frac{V}{T}\right)^2 - 1 \right]$ Set $y = p/R$
and $S = kR \sin \theta$. Then

$$\frac{d\sigma_d}{d\Omega} = (kR)^2 R^2 [I_1^2(S) + I_2^2(S)]$$

where $I_1(S) = \int_0^1 [1 - e^{-KRS} \cos(2k_1 RS)] J_0(yS) y dy$

$$I_2(S) = \int_0^1 e^{-KRS} \sin(2k_1 RS) J_0(yS) y dy$$

Also FST obtain

$$\sigma_d = \pi R^2 \left\{ 1 + \frac{1}{2(KR)^2} [1 - (1 + 2KR)e^{-2KR}] - \frac{1}{\left(\frac{1}{4}K^2 R^2 + k_1^2 R^2\right)^2} \times \right. \\ \left. \left[\left(\frac{1}{4}K^2 - k_1^2\right) R^2 + e^{-KR} \left(2k_1 R \left(\frac{1}{4}K^2 + k_1^2\right) + k_1 K\right) R^2 \sin 2k_1 R \right. \right. \\ \left. \left. - e^{-KR} \left(\frac{1}{4}K^2 - k_1^2 + \left(\frac{1}{4}K^2 + k_1^2\right) KR\right) R^2 \cos 2k_1 R \right] \right\}$$

Set $r_0 = 1.25 \text{ fm}$ [1]. Evaluate I_1, I_2 with program
DEFINITE1 with values of k, R, kR, KR & σ_d obtained
from program ELCROSS as

[6] Palovsky, Friedes, Sotter, Bennett, Igo, Simpson, Phillips, Corley, Wall, Stearns & Gottschalk, Phys. Rev. Lett. 18, 26 (1967) 1200 give $\sigma_{\text{tot}}(1000 \text{ MeV}) = 370 \pm 9$

NUCLEAR ELASTIC SCATTERING FORMULATION (cont'd)

$$k_i R = \frac{3.1426}{15.9778} \cdot 586017 \quad 62.59$$

$$kR = \frac{183.991}{15.9778} = 1/\theta_{ds} \quad \theta_{ds} = \frac{1}{183.991} \text{ mrad}$$

$$KR = 1.29426$$

The Monte-Carlo distribution function is then evaluated by program DEFINITE4 using I_1, I_2 tables

$$F(\theta_{\text{lab}}) = \int_0^{\theta_1} \frac{1}{J} \left(\frac{d\sigma}{d\Omega} \right)_{\text{cm}} \sin \theta_2 d\theta_2$$

where J is the lab to cm solid angle kinematic transformation $(d\sigma/d\Omega)_{\text{cm}} = (d\sigma/d\Omega)_{\text{lab}} \left(\frac{d\Omega_{\text{lab}}}{d\Omega_{\text{cm}}} \right) = J \left(\frac{d\sigma}{d\Omega} \right)_{\text{lab}}$

The relativistic kinematics are given in [2, 3]. 145.270

Total elastic cross-section from FST is $\sigma_e = 107 \text{ mb}$ confirmed by direct integration $\sigma_e = 2\pi \int_0^\pi \frac{1}{J} \left(\frac{d\sigma}{d\Omega} \right)_{\text{cm}} \sin \theta_2 d\theta_2$

Total non-elastic cross-section for 600 p+¹²C from DiGiacomo, et al. [4] is $\sigma_n = 233 \text{ mb}$ [5] Hence $\sigma_{\text{tot}} = 378 \text{ mb}$ [6] Interaction probability on foil of areal density τ is $p_{\text{int}} = N_A \tau \sigma_{\text{tot}} / A$, $N_A = \text{Avogadro's no.}$ For $\tau = 600 \mu\text{g/cm}^2$, $p_{\text{int}} = 1.14 \cdot 10^{-5}$ per traversal.

[1]. Blumberg, Gross, van der Woude, Zucker & Bassel. Phys. Rev. 147 (1966) 812.

[2] Blumberg and Krauss. BNL report 24901 (1971).

[3] Blumberg and Schlesinger, Los Alamos report LAMS-1718 (1955).

[4] DiGiacomo, DeVries, Peng, Phys. Rev. Lett. 45 (1980) 527.

[5] Renberg, Heasday, Pepin, Schwaller, Favier, Richard-Serte, Nucl. Phys. A183 (1972) 81. $\sigma_{\text{ne}}(552 \text{ MeV}) = 233 \pm 5 \text{ mb}$.

DiGiacomo, DeVries and Peng, Phys. Rev. Lett. 45(1980)527
 FIG. 2. The calculated proton-nucleus and neutron-nucleus total reaction cross section as a function of laboratory energy. Data shown were collected from Refs. 29(a)–29(r). The dotted curves are the results of calculations in which Eq. (3) was solved for a straight-line trajectory with no Fermi motion or Pauli blocking. The solid lines are the results of calculations in which the Coulomb (where applicable) and real nuclear potentials, Fermi motion, and Pauli blocking

ELASTIC DIFFERENTIAL CROSS SECTION(LAB), PROTONS ON C¹²

INTEGRATED TOTAL ELASTIC CROSS SECTION, PROTONS ON C¹²

64 000 25 0000 0000

ELASTIC DIFFERENTIAL CROSS SECTION(LAB), PROTONS + C¹²

REC'D DEC 13 1963

RANDOM ANGLES FROM ELASTIC SCATTERING DISTRIBUTION, P+C¹²

Mon Nov 29 12:00 1993

X AND Y PROFILES FOR H⁻ MULTITURN INJECTION INTO PSNS

Mon Nov 1 15:30 1992

Space-Charge Time Shift with Gaussian Distribution [1]

(FOLLOWING BRUCK, CHAPT. XXVII) [2]

Given charge density $\rho(r) = en(r)$ $n(r) = n_0 e^{-\alpha^2 r^2}$
 $(\alpha^2 = 1/2\sigma^2)$. Gauss' Law (MKSI) gives

$$\epsilon_0 \int_S E_r r d\theta dl = en_0 \int_V e^{-\alpha^2 r^2} r dr d\theta dl = 2\pi en_0 \int_0^r r e^{-\alpha^2 r^2} dr$$

The integral on right side is elementary and gives

$$\int_0^r r e^{-\alpha^2 r^2} dr = \sigma_r^2 [1 - e^{-\alpha^2 r^2}]$$

Then $E_r = \frac{en_0 \sigma_r^2 (1 - e^{-\alpha^2 r^2})}{\epsilon_0 r}$ after integral along unit length $\int dl$ of beam.

Note that for small r , $E_r \propto r$ and $\rightarrow 0$ as $r \rightarrow 0$, i.e. it is a radially defocusing quadrupole field.

The incremental electric force from space charge is eE_r and we must also put in factor of γ^2 in denominator to account for the magnetic force from beam on particle. Then force increment

$$\delta f_r = \frac{e^2 n_0 \sigma_r^2 (1 - e^{-\alpha^2 r^2})}{\epsilon_0 \gamma^2 r}$$

$$\text{but } \delta f_r = m \gamma \delta \left(\frac{d^2 r}{dt^2} \right) = m \gamma \beta^2 c^2 \delta \left(\frac{d^2 r}{ds^2} \right)$$

m = proton rest mass

$$\text{So } \delta \left(\frac{d^2 r}{ds^2} \right) = \frac{4\pi r_0 n_0 \sigma_r^2 (1 - e^{-\alpha^2 r^2})}{\beta^2 \gamma^3 r}$$

$$\text{where classical radius of proton is } r_0 = \frac{e^2}{4\pi \epsilon_0 m c^2} = 1.534698558 \times 10^{-18} \text{ m}$$

For the trajectory equation, Bruck writes

$$\frac{d^2 r}{ds^2} + \left(\frac{v}{R} \right)^2 r = 0 \quad \text{circumference } C = 2\pi R$$

$$\text{Thus } \delta \left(\frac{d^2 r}{ds^2} \right) = -2v r \delta v / R^2 = \frac{2v r \Delta v}{R^2} \quad \Delta v = -\delta v$$

11/11/77
LB

~ ~ ~

With $v = v_0 + \delta v = v_0 - \Delta v$ we get

$$\frac{n_0 r_0 \sigma_r^2 C^2}{2\pi \beta^2 r^3} \frac{(1 - e^{-\alpha^2 r^2})}{r^2} = v \Delta v$$

To get n_0 assume that azimuthal density is uniform except for bunching factor B . Also assume sharp cut-off in particle distribution at $r = r_m = \sqrt{E_A \beta}$. Then total number of particles in ring, N_0 , is

$$N_0 = 2\pi n_0 C B \int_0^{r_m} r e^{-\alpha^2 r^2} dr = 2\pi n_0 C B \sigma_r^2 (1 - e^{-\alpha^2 r_m^2})$$

Substituting n_0 gives expression for r dependence of time shift Δv

$$(\Delta v)^2 - v_0 (\Delta v) + \frac{r_0 C N_0}{(2\pi)^2 \beta^2 r^3 B (1 - e^{-\alpha^2 r_m^2})} \frac{(1 - e^{-\alpha^2 r^2})}{r^2} = 0$$

Define $K = \frac{r_0 C N_0}{(2\pi)^2 \beta^2 r^3 B}$

$$A(r) = \frac{K}{(1 - e^{-\alpha^2 r_m^2})} \frac{(1 - e^{-\alpha^2 r^2})}{r^2}$$

Then $(\Delta v) = \frac{1}{2} [v_0 - \sqrt{v_0^2 - 4A(r)}]$

$$v(r) = \frac{1}{2} [v_0 + \sqrt{v_0^2 - 4A(r)}]$$

Note that $A(r) \rightarrow 0$ as $r \rightarrow \infty$ so $v(\infty) = v_0$

Also note that $\Delta v = (\Delta v)_{\max}$ at $r = 0$, i.e. $A(r) \rightarrow \text{const}$

PROGRAM TESTTUNE has two options

- (1) If σ_r (actually σ_{rx} and σ_{rz}) are given, $(\Delta v)_{\max}$ computed and $v(r)$ tabulated
- (2) If $(\Delta v)_{\max}$ given, then σ_{rx} , σ_{rz} computed by iteration.

11/7/95

(5) of 2

(stimulated by 11/23 meeting with Ruggiero, van Steenkoven, Shen)

PROOF THAT GAUSSIAN $\rightarrow$ UNIFORM DISTRIBUTION TUNE
SHIFT OF LASLETT ^{BT} AND THAT UNIFORM DISTRIBUTION
GIVES SMALLEST POSSIBLE $(\Delta\nu)_m$

Ruggiero's AGS BOOSTER TN (1104) ^{BT} also derives $\Delta\nu$
for Gaussian $n(r)$. He (and us) can show that (1)
 $\Delta\nu \rightarrow$ Laslett (aka Bruck) expression when Gaussian $\rightarrow$ uniform

(1) since $(\Delta\nu)_m = \frac{1}{2} \left[\nu_0 - \sqrt{\nu_0^2 - 4A(0)} \right]$ i.e. $\Delta\nu$ is
largest at $r=0$
where $A(0) = \frac{K}{2\sigma_r^2 (1 - e^{-u^2 r_m^2})}$

To go to a uniform distribution, let $\sigma_r \rightarrow \infty$. Then

$$\lim_{\sigma_r \rightarrow \infty} A(0) = \frac{K}{r_m^2}$$

Then $(\Delta\nu)_m \rightarrow \frac{1}{2} \nu_0 \left[1 - \sqrt{1 - \frac{4K}{\nu_0^2 r_m^2}} \right]$ and, since

$$4K/r_m^2 \ll \nu_0^2, \text{ i.e. } \frac{4K}{\nu_0^2 r_m^2} \ll 1 \text{ since } \Delta\nu \text{ is } \ll \nu_0$$

we have $(\Delta\nu)_m \rightarrow K/\nu_0 r_m^2$. Substitute $S = \pi r_m^2$
for cross-sectional area of beam and we have ($C = 2\pi R$)

$$(\Delta\nu)_m = \frac{\nu_0 R N_0}{2 \nu_0 \beta^2 \gamma^3 S B}$$

which agrees with Bruck 27.12 for unbranched beam ($B=1$)

(2). We can also show that this value of $(\Delta\nu)_m$ is smallest
tune shift possible, i.e. it is minimum value of $A(0)$ since

$$\frac{K}{r_m^2} < \frac{K}{2\sigma_r^2 (1 - e^{-r_m^2/2\sigma_r^2})} \text{ because RHS goes}$$

$$\text{to } \frac{K}{2\sigma_r^2 \left[\frac{r_m^2}{2\sigma_r^2} - \frac{1}{2} \left(\frac{r_m^2}{2\sigma_r^2} \right)^2 + \dots \right]} = \frac{K}{r_m^2 (1 - \frac{1}{2} \frac{r_m^2}{2\sigma_r^2} + \dots)} > \frac{K}{r_m^2}$$

(OVER)

(3). Finally, I note that in limit of uniform distribution ($\sigma_r \rightarrow \infty$) the time dependence with r vanishes, i.e. $(\Delta V) \rightarrow \text{constant}$.

$$\lim_{\sigma_r \rightarrow \infty} A(r) = \frac{K}{r_m^2} = A(0).$$

So the minimum value of $(\Delta V)_{\text{max}}$ is also the time shift of all particles in the beam, independent of r .

Thus the entire beam shifts ^{down} by $\Delta V = \frac{V_0 C N_0}{(2\pi)^2 V_0 \beta^2 \gamma^3 \epsilon_k^2 B}$

and we have no space-charge-induced time spread - just a shift. This might be an undesirable consequence of uniform distribution since we want some time spread to suppress instabilities.

[1] suggested by A. Luccio (private communication, Oct. 26, 1993).

[2] H. Bruck, Circular Particle Accelerators, Inst. Nat. des Sciences et Techniques Nucléaire, Saclay France. ⁽¹⁹⁶⁶⁾ Translation: Los Alamos Nat. Lab. report LA-TR-72-10 Rev. (1972), Chapt. XXVII

[3] L.J. Laslett, On Intensity Limitations Imposed by Transverse Space Charge Effects in Circular Particle Accelerators, in Proc. 1963 Summer Study on Storage Rings, Accelerators and Exptm. at Super-High Energ BNL Report 7534 (1963). Ed. J. Bittner.

[4] A.G. Ruggiero, Review of Space Charge Calculations. AD Booster Tech. Note 104 (Jan. 1988).

LASLETT SPACE-CHARGE TUNE SHIFT vs RADIUS FOR GAUSSIAN DENSITY

LASLETT SPACE-CHARGE TUNE SHIFT vs RADIUS FOR GAUSSIAN DENSITY

LASLETT SPACE-CHARGE TUNE SHIFT vs RADIUS FOR GAUSSIAN DENSITY

Mon Nov 22 14:01 1983

PSNS X-XP PHASE SPACE, 600 TURNS, 600- $\mu\text{g}/\text{cm}^2$ C12

TRAVERSALS/TURN NUMBER FOR H⁻ MULTITURN INJECTION INTO PSNS

Mon Nov 1 17:33 1983

PSNS X-XP PHASE SPACE, 600 TURNS, 300- $\mu\text{g}/\text{cm}^2$ C12

X AND Z PROFILES FOR H⁻ MULTITURN INJECTION INTO PSNS

Tue Nov 23 11:01 1993

PROFILE FOR UNIFORM PHASE SPACE DENSITY, $AX=400\pi$ mm-mr

Wed Nov 24 11:37 1993

HORIZONTAL PHASE SPACE ELLIPSE AT PSNS STRIPPER FOIL

FILE 0101 12 11:13 1980

H^- to H^+ Conversion Efficiency

M. Joy, FNAL TM-699 (1976) gives for fraction of H^- beam converted to H^+

$$f_{H^+} = 1 - \frac{\sigma_{-1,0} e^{-\sigma_{0,1} X} - (\sigma_{0,1} - \sigma_{-1,1}) e^{-(\sigma_{-1,0} + \sigma_{-1,1}) X}}{\sigma_{-1,0} + \sigma_{-1,1} - \sigma_{0,1}}$$

where $\sigma_{-1,0}$ = cross section for reaction $H^- \rightarrow H^0 + e^-$

$\sigma_{0,1}$ = cross section for reaction $H^0 \rightarrow H^+ + e^-$

$\sigma_{-1,1}$ = cross section for reaction $H^- \rightarrow H^+ + 2e^-$

and $X = \frac{N_A \tau}{A}$

N_A = Avogadro's number

A = atomic weight of target

τ = areal density of target (g/cm^2)

Hojvat, Joy and Webber [HJW], IEEE Trans. Nucl. Sci.

NS-26 (1979) 4009 measured $\sigma_{-1,0}$ and $\sigma_{0,1}$ at

$T_{\text{proton}} = 200 \text{ MeV}$ on C^{12} , etc. They get for C^{12}

$$\sigma_{-1,0} = (-.174 + .2837) 10^{-18} \text{ cm}^2/\text{atom}$$

$$\sigma_{0,1} = (-.120 + .1017 + 4.32 \cdot 10^{-3} T^2) 10^{-18} \text{ cm}^2$$

Webber and Hojvat, IEEE Trans. Nucl. Sci. NS-26 (1979) 4012

state that $\sigma_{-1,1}$ is very small (consistent with zero)

and plot $\sigma_{-1,0}$ and $\sigma_{0,1}$ vs T_p . At 600 MeV on C^{12}

$$\sigma_{-1,0} \approx 1.2 \cdot 10^{-18} \text{ cm}^2 \quad \sigma_{0,1} \approx 0.5 \cdot 10^{-18} \text{ cm}^2$$

So, dropping $\sigma_{-1,1}$ in M. Joy's expressions we get at 600 MeV

$$f_{H^+}(200 \mu g/cm^2 C^{12}) = .9887$$

$$f_{H^+}(300 \mu g/cm^2 C^{12}) = .9991$$

$$f_{H^+}(600 \mu g/cm^2 C^{12}) \approx 1.0000$$

Fig. 4: Comparison of the results from this experiment with previous results and theoretical predictions.

REFERENCES

H-MINUS TO H-PLUS CONVERSION FRACTION, 600MeV PROTONS ON C¹²

TRAVERSALS/PROTON vs TURN NUMBER FOR H⁻ MULTITURN INJECTION

Mon Dec 6 16:05 1983

LOST PROTONS vs TURN NUMBER FOR H⁻ MULTITURN INJECTION

PROTON LOSSES & TRAVERSALS vs TURN NUMBER IN H⁻ INJECTION

Sun Jan 2 18:45 1994

PROTON LOSSES & TRAVERSALS vs TURN NUMBER IN H⁻ INJECTION

IS 2-MAGNET $\lambda/2$ BUMP BETTER THAN 4-DIPOLE BUMP?

for $\lambda/2$ bump starting at pt. i with kick k

Courant and Snyder [Ann. Phys. 3(1958)1] give matrix between two points $1 \rightarrow 2$ separated by betatron phase shift ψ

$$M_{12} = \begin{bmatrix} \sqrt{\frac{\beta_2}{\beta_1}} (\cos\psi + \alpha_1 \sin\psi) & \sqrt{\beta_1 \beta_2} \sin\psi \\ \frac{(\alpha_1 - \alpha_2) \cos\psi - (1 + \alpha_1 \alpha_2) \sin\psi}{\sqrt{\beta_1 \beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}} (\cos\psi - \alpha_2 \sin\psi) \end{bmatrix}$$

At peak of bump, pt. o with $\psi = \pi/2$, coordinates of bumped orbit are then

$$\begin{pmatrix} x_o \\ x'_o \end{pmatrix} = \begin{pmatrix} \alpha_1 \sqrt{\frac{\beta_o}{\beta_1}} & \sqrt{\beta_o \beta_1} \\ -\frac{(1 + \alpha_o \alpha_1)}{\sqrt{\beta_o \beta_1}} & -\alpha_o \sqrt{\frac{\beta_1}{\beta_o}} \end{pmatrix} \begin{pmatrix} 0 \\ k \end{pmatrix}$$

This gives $x_o = k \sqrt{\beta_o \beta_1}$

$$x'_o = -k \alpha_o \sqrt{\frac{\beta_1}{\beta_o}} = -\frac{\alpha_o}{\beta_o} x_o$$

Thus, central orbit of bumped beam at pt. o moves along line $x' = (-\alpha/p) x$ and, if we require H^- beam to track this line, we are no better off with $\lambda/2$ bump than with 4-magnet bump where H^- beam must also be displaced in x to track axis of acceptance ellipse.

LOSS COMPARISONS FOR 600-MeV H⁻ ON CARBON STRIPPER FOIL. CODE HMINUSINT

Σ X	N (10 ⁶)	T μg/cm ²	TURN	A _{x,z} mm-mv	EB mm-mv	FOIL mmxmm	NBC	LOST	INT	SCAT	LOSS FRACTION	$\bar{N}_t$	COMMENTS AND CONCLUSIONS
36	2	300	300	400	200	10x10	1	61	77	21	3.05 10 ⁻⁵	4.91	BEST CASE
38	2	300	600	400	200	10x10	1	76	109	36	3.48 10 ⁻⁵	7.35	increasing turns to 600 costs factor of ~1.25
38	2	300	600	400	200	10x10	1	76	109	36	3.8 10 ⁻⁵	7.35	
33	1	600	600	400	200	10x10	1	58	77	20	5.8 10 ⁻⁵	7.33	increasing foil thickness to 600 μg/cm ² costs ~1.5 NES ~ T but MCS not ~ T
38	2	300	600	400	200	10x10	1	76	109	36	3.8 10 ⁻⁵	7.35	
35	1	300	600	320	160	10x10	1	51	49	18	5.1 10 ⁻⁵	8.35	reduced acceptance to 320π mm-mv costs ~1.34
36	2	300	300	400	200	10x10	1	61	77	21	3.05 10 ⁻⁵	4.91	
39	1	300	300	400	200	10x10	0						H ⁻ beam fixed on X'=z'=0 axes costs
38	2	300	600	400	200	10x10	1	76	109	36	3.8 10 ⁻⁵	7.35	
37	3	300	600	400	400	10x10	1	116	89	38	3.87 10 ⁻⁵	4.03	filling entire 400π acceptance gives about 10% faster loss, smaller, i.e. bump is moving faster.
33	1	600	600	400	200	10x10	1	58	77	20	5.8 10 ⁻⁵	7.33	
34	.5	600	600	400	200	20x160	0	164	160	638	3.29 10 ⁻³	251	WORST CASE. increasing foil area to 20x160 and fixing H ⁻ beam on X'=z'=0 gives ~56.7 more loss
9	3	300	300	200	200	10x10	1	130	94	31	4.3 10 ⁻⁵		BEST CASE WITH 200π acceptance
18	3	300	600	200	200	10x10	1	216	139	45	7.2 10 ⁻⁵		increasing to 600 turns increases loss by ~1.7 because bump is slower and $\bar{N}_t$ should go up
28	3	300	600	200	200	10x10	1	216	139	45	7.2 10 ⁻⁵		
31	1.5	300	600	200	200	10x10	0	490	256	99	3.27 10 ⁻⁴		H ⁻ beam fixed on X'=z'=0 axes gives increase of ~4.5 compared to tracking y' = -(1/4) y
28	3	300	600	200	200	10x10	1	216	139	45	7.2 10 ⁻⁵		
30	3	300	600	200	200	20x160	1	2903	1110	404	9.68 10 ⁻⁴		increasing foil area to 20x160 mm increases losses by factor of ~13.4
ALL ABOVE RUNS WITH EXPONENTIAL BUMP $X_0 = A_x e^{-u^2}$, $z_0 = A_z [1 - e^{-(t+t/2)}]$													

H⁻ MULTITURN TRANSVERSE INJECTION LOSSES
from 600-MeV Multiple Coulomb and Nuclear
Elastic Scattering on Carbon Stripper Foils

BNL 5MW PULSED SPALLATION NEUTRON SOURCE STUDY

L. N. Blumberg
BNL Center for Accelerator Physics Seminar
January 11, 1994

With acknowledgements for contributions by :

K. Jones (LANL)
Y. Y. Lee
A. Luccio
R. Macek (LANL)
A. Ruggiero
A. van Steenbergen
J. B. Murphy

SPALLATION NEUTRON SOURCE BOOSTER RING

**DESIGNING AND UNDERSTANDING
OF MAGNETS WITH THE HELP OF
CONFORMAL MAPPING**

K. Halbach
LBL / ANL

III

Table of Content

1) Introduction

Momentum kick from magnet

Reminder: Theory of a fct. of a compl
variable

2) Applications

Decay of error fields in dipole

Shimming of dipole

Design of non-dipole in mapped geomet.

Sextupole

Combined function magnets

Septum quadrupole

High order multipoles / insertion device.

International Journal of Modern Physics B,
Vol. 4, p. 1201-1222, (1990)

Purpose of talk:

- 1) Show that conformal mapping is not only a powerful tool for quantitative analysis, but a unique tool for thinking about, and understanding, system with minimal or no computation.
- 2) Successful application of conformal mapping techniques does not require encyclopedic knowledge of maps because most of the time, the explicit form of the map can be obtained by appropriate formulation of the Physics.

1/25/94 D BNL

High energy e-storage ring with lifetime ≈ 10 h

need bend magnets

$$E_{\text{equ}} = C \cdot B; B = 1 \text{ T} \rightarrow E_{\text{equ}} = 3 \cdot 10^8 \text{ V m}^{-1}$$

Need focusing and optics correction magnet.

y

z

Beam $\approx \parallel$ z-axis

Transverse kick $\sim \int \text{field} \cdot dz$

$$\int \vec{\mathcal{H}}(x, y, z) dz / L = \vec{H}(x, y)$$

$$\frac{\partial \mathcal{H}_x}{\partial x} + \frac{\partial \mathcal{H}_y}{\partial y} + \frac{\partial \mathcal{H}_z}{\partial z} = 0 \rightarrow \frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y} = H_z / L \Big|_{z_2}^{z_1} = 0$$

$$\frac{\partial \mathcal{H}_y}{\partial x} - \frac{\partial \mathcal{H}_x}{\partial y} = 0 \rightarrow \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = 0$$

Same equations as
2D field equations

High energy e-storage ring with lifetime $\gtrsim 10$ h

need bend magnets

$$E_{\text{equ}} = C \cdot B; B = 1 \text{ T} \rightarrow E_{\text{equ}} = 3 \cdot 10^8 \text{ V m}^{-1}$$

Need focusing and optics correction magnet.

Beam $\approx$ || Z-axis

Transverse kick $\sim \int \text{field} \cdot dZ$

$$\int \vec{\mathcal{H}}(x, y, Z) dZ / L = \vec{H}(x, y)$$

$$\frac{\partial \mathcal{H}_x}{\partial x} + \frac{\partial \mathcal{H}_y}{\partial y} + \frac{\partial \mathcal{H}_z}{\partial Z} = 0 \rightarrow \frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y} = H_z / L \Big|_{z_2}^{z_1} = 0$$

$$\frac{\partial \mathcal{H}_y}{\partial x} - \frac{\partial \mathcal{H}_x}{\partial y} = 0 \rightarrow \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = 0$$

Same equations as
2D field equations

9

$$H_x(-y) = -H_x(y); H_y(-y) = H_y(y); \frac{\partial H_y}{\partial y} = -\frac{\partial H_x}{\partial x}$$

H_x, H_y = periodic with period $2h$

$$H_x - iH_y = \sum C_n e^{2\pi n i y / 2h} \rightarrow \sum C_n e^{n\pi z / h}$$

$$C_n = \text{imaginary}; C_n = 0 \text{ for } n > 0 \left(|e^{n\pi z / h}| = e^{n\pi x / h} \right)$$

$$H_x - iH_y = H^* = i \sum_{n=0}^{\infty} b_n e^{-n\pi z / h}$$

b_0 = field deep inside

Antisymm. fields

$$* H^* = \sum_{n=0}^{\infty} a_n e^{-(n+1/2)\pi z / h}$$

Analytical function $F(z) = A(x,y) + iV(x,y)$; $z = x + iy$

Only $+, -, \times, \div$ allowed in definition of $F(z)$.

$$\frac{\partial F}{\partial x} = \frac{dF}{dz} \cdot \frac{dz}{dx} = F' = \frac{\partial A}{\partial x} + i \frac{\partial V}{\partial x} = \frac{\partial V}{\partial y} - i \frac{\partial A}{\partial y} \quad \text{C-R}$$

$$\frac{\partial F}{\partial y} = \frac{dF}{dz} \cdot \frac{dz}{dy} = iF' = \frac{\partial A}{\partial y} + i \frac{\partial V}{\partial y}$$

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) F = 0 \rightarrow \nabla^2 A = 0; \nabla^2 V = 0$$

$W(z) \rightarrow dW = dz \cdot dW/dz = \text{conformal map}$

if $W' \neq 0$; $z' \neq 0$

Example: $F(z) = z^2 = \underbrace{x^2 - y^2}_A + i \underbrace{2xy}_V$; $\frac{\partial F}{\partial x} = 2x + i2y$; $\frac{\partial F}{\partial y} = -2y + i2x$

Math. I

Physics: Fields in vacuum: $B_x = -\partial V/\partial x = \partial A/\partial y$; $B_y = -\partial V/\partial y = -\partial A/\partial x$

$$\rightarrow B_x - iB_y = -\frac{\partial V}{\partial x} + i \frac{\partial A}{\partial x} = i \left(\frac{\partial A}{\partial x} + i \frac{\partial V}{\partial x} \right)$$

$$B^* = i dF/dz. \text{ Dipole: } iF' = B_0^* = \text{const.} \rightarrow F = -iB_0^* z$$

* H from current filament at $z=0$

$$H = H_x + iH_y = \frac{I}{2\pi r} e^{i\phi} i = -\frac{I}{2\pi i z^*}$$

$$H^* = \frac{I}{2\pi i z}$$

$$\text{filament at } z = z_0: H^* = \frac{I}{2\pi i (z - z_0)} = iF' \rightarrow F = -\frac{I}{2\pi} \ln(z - z_0)$$

$\rightarrow F(z) = z^2 = x^2 - y^2 + i2xy$; $xy = \pm V_0 = \text{iron poles} \rightarrow \text{hyperbola}$

(10)

Antisymmetric fields in dipole:

*

 $B_x = 0$ at $y = \pm h$; even fct. of y

↓

 $\partial B_y / \partial y = 0$ at $y = \pm h$; odd fct. of y
Both: periodic in y , period = $4h$

$$B_x - iB_y = \sum_{-\infty}^{\infty} g_n e^{n i y 2\pi / 4h}; \quad g_n = \text{real};$$

 $x \neq 0 \rightarrow i y = z$; no exponential increase for $x > 0$

$$B^x = \sum_1 g_n e^{-n z \pi / 2h}; \quad B_x = 0 \text{ at } y = \pm h \rightarrow n = \text{odd}$$

$$B^x = \sum_0 b_n e^{-(n+\frac{1}{2})\pi z / h} \quad n=1 \text{ term decays} \\ \rightarrow \underline{\text{3 times faster than}} \\ n=0 \text{ term!}$$

(12)

Design of non-dipole magnet in (conformally mapped) dipole geometry.

1) Can apply the understanding of, and the experience with, the simplest of all magnets, the dipole, to all 2D magnets by applying a conformal transformation to the geometry of the field shaping entities (i.e. $V = \text{const.}$ surfaces = poles; currents; $A = \text{const.}$ surfaces in some cases) such that the ideal non-dipole is mapped into an ideal dipole.

2) Applying the conformal coordinate transformation $z(w)$ to the geometry of the field shaping entities leads to the complex potential as a function of $w = u + iv$:

$$F(z(w)) = A(x(u, v), y(u, v)) + i V(x(u, v), y(u, v))$$

Knowing, on one hand, from the desired fields what $F(z)$ should be, and, on the other hand, that the complex potential in the w plane should be $= \text{const.} \cdot w$ (for ideal dipole)

No shimming: $\Delta H/H = \exp(-2.77(\frac{D}{A} + .9))$

MART-shimming: $\Delta H/H = \exp(-7.14(\frac{D}{A} + .25))$

No shimming: $D/A = -.36 \ln(\Delta H/H) - .9$

MART shimming: $D/A = -.14 \ln(\Delta H/H) - .25$

Numbers for $\Delta H/H = 10^{-3}$: $D/A = 1.59$; $.72 \mid 69^\circ \ 60^\circ$
 $\Delta H/H = 10^{-4}$: $D/A = 2.43$ $1.04 \mid 74^\circ \ 64^\circ$

Shimming can be important for one or more of the following reasons

- Weight • stored energy • saturation
- space

(13)

the desired mapping function is given by

$$F(z) = \text{const.} \cdot w$$

↑ Yes, it is that simple!!

Detailed design procedure for the case where the field distribution is controlled by iron poles:

- 1) From wanted field distribution, get mapping function (e.g. for sextupole, for $y=0$: $B_y = ax^2$; $B_x = 0 \rightarrow B^* = -ia z^2 = i F'_3 = i W'$
 $F = -a z^3/3 = W(z)$)
- 2) Map vacuum chamber from z - to w -plane
- 3) Map boundary of good field region from z - to w -plane
- 4) Design dipole-poles in w to give good dipole field quality in good field region in w -plane
- 5) Map that pole into the z -plane
- 6) Design rest of magnet in z -plane. If necessary, iterate between detailed design modifications in z - and w -plane.

(14)

Execution, specific case.

Optics requires in midplane:

Example

$$H_y = a_1 + 2a_2 x + 3a_3 x^2 ; H_x = 0$$

$$\hookrightarrow M^* = -i(a_1 + 2a_2 z + 3a_3 z^2) = iF'$$

$$F = -(a_1 z + a_2 z^2 + a_3 z^3) = \text{const.} \cdot W = \text{map.}$$

$$a_1 = a_2 = 0 : \text{sextupole} \quad \boxed{\text{diagonal lines}}$$

$$a_1, a_2, a_3 \neq 0 \quad \text{SLC are magnets.}$$

Most of the time, $w(z)$ is computationally easy; $z(w)$ seems more difficult, but is not really significantly more difficult, since it requires additionally only to solve a (complex) equation in one (complex) variable.

15

16

6a) Map of vacuum chamber and good field regions for sextupole

$$W' = 3^2$$

(17)

Poles of conventional sextapole.

(18)

Small circles on map of vacuum chamber are maps of equidistant points on vacuum chamber in "real", i.e. z_1 -geometry. They are a rough indication of W'

Small circles on poles in z -plane are maps of equidistant points on dipole-pole in W -geometry. These markers can be used to translate width-of-pole judgement from dipole (W) geometry to "real" (z_1) geometry. Also: $B \sim 1/\text{spacing between markers}$

(14)

Relationship between field errors
in z - and w - plane.

$$B_w^* = i \frac{dF}{dw} ; B_z^* = i \frac{dF}{dw} \frac{dw}{dz} = B_w^* \cdot w'$$

$$\Delta B_z^* = \Delta B_w^* \cdot w' ; \Delta B_z^* / B_z^* = \Delta B_w^* / B_w^*$$

$$\Delta B_z / B_z = \Delta B_w / B_w$$

Relative field errors are the same
in both planes

(26)

Comments:

- 1) If saturation of the iron is significant, its harmful effects can be reduced if one makes poles narrow.
- 2) POISSON can evaluate fields in conformally mapped geometry when $B(H)$ of the iron is non-linear if one "gives" POISSON the mapping function.

22

PROB. NAME • SAM30 : N° ,1ST CORRECTED FIN. N CYCLE • 2350

23

$$B_y(x,0) = b_1 + b_2 x + b_3 x^2; B_x(x,0) = 0$$

$$B^x(z) = -i(b_1 + b_2 z + b_3 z^2) = iF = iW'.const$$

$$W = b_1 z + b_2 z^2/2 + b_3 z^3/3$$

PROB. NAME = SIG L31 : N=1, OPT. POLE FROM SA CYCLE = 78
 POISSON in mapped geometry, with nonlinear iron

24

(25)

Retrospective comment on design in dipole geometry:

While it is clear from start that the ideal field shaping surfaces should be $V(x,y)=\text{const.}$ (or $A(x,y)=\text{const.}$) surfaces, the concept of designing in dipole geometry gives much, much more: it allows to make judgements on pole widths, how a pole should be shimmed, what a not quite ideal pole will do, the problems lack of symmetry will cause, e.t.c.

But probably even more important than this kind of help on practical details when actually executing a design is the perspective one gets about problems when one looks at them in mapped geometry.

Map of 1. quadrant of "septum quad"
with $W = z^2$. Lengths normalized with
aperture radius.

Dominant term for error fields from coil:

$$B_w^* = i \cdot C \cdot \exp(2\bar{N}(W - W_0))$$

$$B_z^* = i \cdot C \cdot 2z \cdot \exp(2\bar{N}(z + z_0)(z - z_0))$$

(Exponential decay away from perturbation source.)

$$\beta^* = i\beta_0(1 - 0.43 - 5.25 \cdot 10^{-4} z^2) \quad (z \text{ in cm})$$

$$W = z - 0.02 z^2 - 1.75 \cdot 10^{-4} z^3$$

27

8a) Electrodes for uniform field extraction

8b) Idealized electrodes for extraction with focusing

(28)

8c) Original electrode design

8d) Map of original electrodes

(29)

8e) Map of original electrodes with modification

8f) Improved electrode design

(31)

$$\Delta A_n = -\frac{V_0}{\pi} \ln \left(1 - \frac{\sin^2 \bar{\alpha}/N}{\sin^2 \alpha \bar{\alpha}/N} \right)$$

32

33

34

24

35

36

Summarizing comments to this theorem

- 1) Theorem very general
- 2) Most people find it very counter-intuitive
- 3) Proof did not require to write down a single formula
- 4) It is very hard (impossible?) to conceive of a method to prove this theorem without using conformal mapping techniques or the thinking + understanding that comes with it.

**LASER - ELECTRON BEAM
SCATTERING COHERENT
COMPTON X-RAY SOURCES**

A. Luccio
Brookhaven National Lab

IV

LASER-ELECTRON BEAM SCATTERING COHERENT COMPTON X-RAY SOURCES

(Center for Accelerator Physics Seminar)

Alfredo Luccio

AGS Dept., Brookhaven National Laboratory

149

Coherent X-rays can be produced by scattering of laser light by a beam of relativistic electrons, provided that

- the electron beam is density modulated, or
- the scattering is done at, or near 90° .

Since the coherent scattering is proportional to N^2 , where N is the number of electrons, and the incoherent scattering is proportional to N , also a modest degree of coherence can substantially increase the X-ray yield.

Acknowledgements

A great fraction of what follows stems from work done together (and papers written together) with Gianni Matone and Franco Giordano of the Frascati Laboratory, and with Lino Miceli of the Physics Department of Brookhaven.

Discussions with Janos Kirz of Stony Brook on X-Ray Microscopy topics were very useful

References

A.Luccio, G.Matone, L.Miceli and G.Giordano. "Coherent backscattering in the soft X-ray region". *Laser and Particle Beams* (1990), vol. 8, no. 3, pp. 383-398

¹⁵⁰ G.Giordano, A.Luccio, G.Matone and L.Miceli "Coherence in Compton Scattering at Large Angles". *Brookhaven Report BNL-49502, Sept. 1993, Submitted for Publication.*

Sources of X-Rays

Röntgen tubes

Conventional produced X-rays in the KeV range, with an energy spectrum characteristic of the anti cathode.

Synchrotron radiation, SR

The radiation spectrum from a bending dipole in synchrotrons is a continuum. Desired energies are obtained by slicing this continuum.

The spectrum from an undulator (array of magnetic dipoles with relatively weak alternate fields) has a line structure, with a photon energy of the order of 25 KeV and multiples thereof, for the highest energy machines in existence.

Super conducting wigglers produce a spectrum of intermediate shape. The X-rays are of several KeV.

(Compton) Scattering, CS

Scattering of laser light by a beam of relativistic electrons. In a collision between a laser photon and an electron, a fraction of the energy of the electron is given to the photon, whose energy is in turn up shifted from the visible to the X-rays.

The spectrum of X-ray energies is a continuum with a strong correlation between energy and angle, so a given X-ray energy can be selected by an appropriate collimator.

Coherence

X-ray Microscopy or X-ray Holography require spatially and time coherent radiation.

Radiation is defined as

spatially coherent if we can define in space a set of surfaces over which the phase assumes a constant value, and

time coherent if it is essentially monochromatic in a given location (the frequency spectrum is the Fourier transform of the time spectrum of the radiation field).

¹⁵² The coherence can be measured from the correlation between photon counts in two separated locations or in the same position at two distinct times.

The flux of incoherent SR or CS X-rays is proportional to the number N of the electrons contained in a volume of interaction,

The coherent flux of X-rays is proportional to the square of this number, N^2 .

Then, coherence can greatly enhance the yield of the process even for applications, like X-ray imaging, where the coherence *per se* is not interesting.

Coherence

For X-rays generated by an ensemble of free electrons, a photon count and a measure of the correlation as a function of the number of electrons allow an equivalent definition of coherence: coherent radiation is proportional to N^2 and incoherent radiation to N .

In SR from an arc source, it has been shown that the degree of coherence decreases in the continuum from the red to the uv, because the number of photons per unit arc length (or per wavelength) was decreasing

153 In a small cone the coherence is enhanced. For undulators SR, where the interference among successive periods squeezes the radiation in a narrower cone, the flux is reasonable. Undulator radiation is being used for X-ray Microscopy.

Ordinary CS only produce a marginal coherence: the scattered radiation doesn't preserve the coherence of the laser, unless the electron beam is

density modulated: the electron beam acts as a moving diffraction grid for the primary radiation, or

the scattering is performed at large angles: the interaction length is so short that the laser photons are all reflected in a small region.

X-rays by Compton scattering of a laser beam by a charged particle beam

In head-on collisions, the energy of the scattered and of the incoming photons are related by

$$\hbar\omega_s \cong \hbar\omega_L \frac{2(1+\beta)\gamma^2}{1+\gamma\xi+\gamma^2\theta_s^2} \quad \xi = 2(1+\beta)\frac{\hbar\omega_L}{mc^2}$$

θ_s the angle of the scattered photon with respect to the collision line.

¹⁵⁴ The frequency of the scattered radiation is up shifted by a factor $\approx 4\gamma^2$ with respect to the frequency of the primary photon.

A visible laser scattered by electrons of a few tens or hundreds of MeV produces X-rays in the KeV range.

The scattered photon energy has a maximum in the forward direction of the electron beam, decreases with the increasing scattering angle, and reaches 1/2 of its maximum for

$$\gamma\theta \approx 1$$

Kinematics of Compton Scattering

Derivation of the Compton Scattering Formulas.

Comparison of the kinematics of scattering in the LAB (un-primed quantities) and in the ERF (primed quantities).

$$\left[\begin{array}{cc} \text{photon} & \text{energy} & \text{momentum} \\ \varepsilon = \hbar\omega & \mathbf{k} = \frac{\hbar\omega}{c} \mathbf{n} \\ \text{particle} & E = \gamma mc^2 & \mathbf{p} = \gamma m\mathbf{v} \end{array} \right]$$

Conservation laws

$$\text{LAB:} \left\{ \begin{array}{l} \mathbf{p}_0 + \mathbf{k}_0 = \mathbf{p}_1 + \mathbf{k}_1 \\ E_0 + k_0 c = E_1 + k_1 c \end{array} \right. \quad \text{ERF:} \left\{ \begin{array}{l} E'_0 = mc^2 \\ \mathbf{k}'_0 = \mathbf{p}'_1 + \mathbf{k}'_1 \\ E'_0 + k'_0 c = E'_1 + k'_1 c \end{array} \right.$$

The Compton scattering formula is derived in the ERF
Use the relativistic transformations of angles from ERF to LAB

$$k'_1 = \frac{k'_0}{1 + \frac{c k'_0}{E'_0} [1 - \cos(\theta'_1 - \theta'_0)]}, \quad \tan \theta = \frac{\sin \theta'}{\gamma(\cos \theta' + \beta)}, \quad \phi = \phi'$$

Incoherent Scattering

The total incoherent scattered flux of the radiation is

$$n_s = \frac{n_e n_L}{\Sigma} f \sigma \quad \left\{ \begin{array}{l} n_e = \text{no. of electrons} \\ n_L = \text{no. of laser photons} \\ \Sigma = \text{common transverse area} \\ f = \text{frequency of encounters} \\ \sigma = \text{cross section (Thomson)} \end{array} \right.$$

$$\sigma_{\text{max}} = 2r_0^2 = \quad r_0 = \frac{\mu_0 e^2}{4\pi m}$$

- Laser photons collide with electrons in any position inside the electron beam that takes part in the scattering.
- Uniform density of the electron beam:
Phases of the scattered photons are random.

Coherent scattering

In the impulse approximation, the total electromagnetic field produced by scattering by an ensemble of N electrons is given by the Fourier transform of the density

$$\mathbf{E}_T = \mathbf{E}F(\mathbf{q}), \quad F(\mathbf{q}) = N \int_V \rho(\mathbf{r}) e^{i\mathbf{q} \cdot \mathbf{r}} d\mathbf{r}, \quad \begin{cases} \rho(\mathbf{r}), \text{ density distribution} \\ V, \text{ normalization volume} \\ \mathbf{q} = \mathbf{k} - \mathbf{k}', \text{ momentum transfer} \end{cases}$$

158

$\mathbf{E}$, average amplitude radiated by the single scatterer at the position $\mathbf{r}$
 $F(\mathbf{q})$, form factor of the distribution.

The radiated flux is proportional to $|\mathbf{E}_T|^2$

When $\mathbf{q}$ is small enough that $\mathbf{q} \cdot \mathbf{r} \ll 1$ over V , the total flux is N^2 larger than from a single electron.

If the wavelength ($2\pi/q$) is much shorter than the linear dimension of the electron bunch, the exponent can be large and with ample oscillations:

$F(\mathbf{q})$ falls down very rapidly with increasing $\mathbf{q}$, and only the incoherent scattering survives.

in the ERF:

§ To increase the coherent contribution to the scattering at small wavelength, we will examine two possibilities:

(i) modulate the electron beam intensity so that in the form factor $F(\mathbf{q})$ there will be a substantial contribution from the harmonic content of periods of the order of $|\mathbf{q}|^{-1}$, and

(ii) perform the scattering at large angles (say, 90°) so the linear dimension of the scattering volume are very small in the reference frame of the electrons.

It is important to observe that collective scattering and coherence in the scattered beam are not necessarily synonymous. In collective scattering, in the ERF the intensity of the scattered beam increases with the square of the number of electrons. However, in the LAB scattering angles and photon energies Lorentz transform and the radiation may lose its spatial coherence.

Longitudinally modulated electron beam density

The electron beam is equivalent to a moving grating: Bragg Diffraction

- enhances the X-ray intensity in some directions and
- produces some degree of coherence in the scattered beam.

Extreme case: electron beam as a linear array of N charge blobs at equal intervals a

$$\rho(z) = \sum_{n=1}^N \delta(z - na), \quad F(q_z) = \sum_{n=1}^N e^{inaq_z}$$

In the Bragg condition $q_z = 2\pi m/a$ (m , an integer) obtain complete coherence

$$|\mathbf{E}_T|^2 = N^2 |\mathbf{E}|^2$$

In practice, the electron beam can be modulated by passing through an undulator together with a laser beam of frequency equal to the fundamental or to one of the odd harmonics of the spontaneous undulator radiation.

Klystron diagram

Scattering by a modulated electron beam

Energy modulation of the electrons → drift space → modulation of the longitudinal charge.

In the modulated beam, an originally gaussian shows a series of harmonics (in the ERF)

$$\left\{ \begin{array}{l} \rho(x, y, z) = \rho_0(x, y, z) \sum_{n=0}^{\infty} a_n(\eta) \cos(n\chi_b z) \\ \rho_0(x, y, z) = \frac{1}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} e^{-\frac{1}{2} \left[\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2} \right]} \\ a_n(\eta) = 2J_n(n\eta) e^{-\frac{1}{2} \left(\frac{n}{n_c} \right)^2}, \quad a_0 = 1 \end{array} \right.$$

J , Bessel functions of the harmonic number n and of a quantity $\eta = \eta(z, ct)$ that depends on the modulator geometry.

The a coefficients rapidly decrease with increasing n .

n_c is a critical number that depends on the emittance of the beam and on the accuracy of the undulator.

The frequencies (ERF) are obtained by Lorentz transformation of the frequency of the modulating laser in the LAB

$$\chi_b = \frac{2\pi}{\lambda_{b,L}\beta\gamma}$$

Generalize the linear array example

Head on scattering between a laser (a different laser than used for the modulation) and the modulated electron beam.

See what happens in a region of length Δz around the drift distance where the bunching is a maximum.

$$F(\mathbf{q}) = N \sum_{n=0}^{\infty} \iint dx dy \int_{\Delta z} dz \rho_0(x, y, z) a_n \cos(n\chi_b z) e^{i\mathbf{q} \cdot \mathbf{r}}$$

Separate the integrals in the transverse coordinates, x, y , and in the longitudinal, z .

The radial integral vanishes everywhere, except in two narrow cones, forward and backward, respectively, since the momentum transfer $\mathbf{q}$ in the exponent is inversely proportional to the scattering laser wavelength, and the radial components of $\mathbf{r}$ at least extend to the electron beam dimensions

$$\sigma_x, \sigma_y / \bar{\lambda}_s \gg 1$$

The z-integral will be evaluated in these two narrow cones.

Result:

only for the backscattered radiation this integral is not negligible. The contribution to F of the n -th harmonic (length of interaction set $=\sigma_z$), is proportional to N .

The number of coherent photons in the backward cone of angular aperture $\Delta\Omega$ is

$$N_X^{coh} = \sqrt{\pi} \left[\frac{Na_n}{\sqrt{2\pi}\gamma_n} \right]^2 I_0(\pi) \frac{\sigma_z}{\beta c} \Delta\Omega, \quad \begin{cases} I_0(\mathbf{q}), \text{ intensity scattered by one electron} \\ \Delta\Omega = \frac{1}{4\pi\sigma_x\sigma_y} \left[\frac{\lambda_s}{(1+\beta)\gamma_n} \right]^2, \text{ cone solid angle} \\ [\bullet], \text{ no. of electrons in the } n \text{ mode,} \\ \text{all scattering in phase} \end{cases}$$

For comparison, rewrite the number of incoherent photons in the same cone

$$N_X^{inc} = 2 \frac{N}{\gamma_n} I_0(\pi) \frac{\sigma_z}{\beta c} \Delta\Omega$$

Coherent to incoherent ratio, or coherent fraction

$$\mathfrak{R} = \frac{1}{4\sqrt{\pi}} \frac{Na_n^2}{\gamma_n}$$

Comparison with undulator radiation

Coherent X-rays are obtained in undulators, by selecting a narrow cone of radiation on axis.
The process is similar to the one we have just discussed.
Comparison useful to better understand the basic physical process.

Undulator formulæ: On axis

The energy of a photon in a line of order n is a multiple of the energy of the fundamental

(Compare with CS)

$$\hbar\omega_1 = \hbar\omega_0 \frac{2\gamma^2}{1 + \frac{1}{2}k^2}, \quad \omega_0 = \frac{2\pi}{\lambda_0}, \quad k = \gamma\theta_{\max}$$

λ_0 , period of the undulator

k , deflection parameter, proportional to the max. angle of deflection of the electron trajectory .

$$\left\{ \begin{array}{l} \frac{\delta\omega}{\omega} \approx \frac{1}{nN_0}, \text{ spectral width of line} \\ \delta\theta = \frac{1}{\gamma} \sqrt{\frac{1 + \frac{1}{2}k^2}{2nN_0}} \end{array} \right.$$

N_0 , number of periods

Intensity of the n -th line

$$\frac{d^2 n_n}{d\theta d\phi} = \alpha N_0 \gamma^2 \frac{I}{e} F_n(k), \text{ photons per sec and per mrad}^2$$

$$\alpha = \frac{1}{"137"} = \frac{\mu_0}{4\pi} \frac{e^2 c}{\hbar}, \text{ fine structure constant}$$

I , electron beam current

$F_n(k)$, a certain combination of Bessel functions

Undulator radiation described as Scattering

In the ERF

the undulator is an incoming e.m. wave traveling at the speed βc .

by relativistic transformation, also a transverse electric field appears

$$\text{LAB:} \begin{cases} \mathbf{E} = 0 \\ B_x = B_z = 0 \\ B_y = B_0 \cos \omega_0 t \end{cases} \quad \text{ERF:} \begin{cases} E'_x = -\gamma \beta c B_0 \cos \omega_0 t & B'_x = 0 \\ E'_y = E'_z = 0 & B'_y = \gamma B_0 \cos \omega_0 t \\ & B'_z = 0 \end{cases}$$

Phase of the wave in the LAB and in the ERF frames (primed quantities)

$$\omega(t - z/c) = \omega'(t' - z'/c)$$

Time, space and frequency transform from LAB to ERF

$$t' = \gamma_z \left(t - \frac{\beta_z z}{c} \right), \quad z' = \gamma_z (z - \beta_z c t), \quad \omega' = \gamma_z \omega_0$$

Since the phase is an invariant, obtain

$$\omega = \omega_0 \frac{1 + \beta_z}{1 - \beta_z^2} \cong \omega_0 \frac{2\gamma^2}{1 + \frac{1}{2}k^2}, \quad \left[\beta_z^2 = 1 - \frac{1}{\gamma^2} - \theta^2 \right]$$

Number of equivalent photons in one period of the undulator
(magnetic energy in a volume $\lambda_0 \times \Sigma$) / (energy of an "undulator photon")

$$n_u = \frac{1}{4} \frac{\epsilon_0 c^2 B_0^2}{\hbar \omega_0} \lambda_0 \Sigma$$

B_0 , peak magnetic field in the undulator

$$n_e = \frac{I}{e \beta c} \lambda_0, \text{ number of electrons in } \lambda_0, \quad f = 2 \frac{\beta c}{\lambda_0}, \text{ frequency of collisions}$$

$$\sigma = 2 \left(\alpha \frac{\hbar}{mc} \right) \left(\frac{\mu_0 e^2}{4 \pi m} \right), \text{ Thomson cross section, } \Delta \theta \Delta \phi \cong \frac{1}{2 \gamma^2 N}, \text{ cone of fundamental}$$

169

Combine and obtain for for the photon flux

$$\frac{n_1}{\Delta \theta \Delta \phi} \cong \alpha N_0 \gamma^2 \frac{I}{e} k^2$$

(the incoherent flux in the fundamental is due to the scattering from a region of length λ_0)

How about coherence from an undulator?

Undulator radiation is not intrinsically very coherent, however experiments of X-ray Microscopy and Holography performed using undulators.

Spatial coherent radiation has been obtained by imaging a pinhole illuminated by the undulator at large distance from the subject, within the diffraction limit

$$\sigma \times \theta \ll \lambda$$

σ , pinhole radius. θ , collection angle

Temporal coherence by the use of a monochromator

Advantage of using an undulator over the ordinary arc source since, because of interference, a higher photon flux is concentrated in a small cone region

Limits on coherence due to the finite emittance of the electron beam

Coherent scattering at 90°

Collective effects also arise if the e. bunch length is $\ll$ that the incoming radiation wavelength. Here, all the electrons radiate in phase.

In the ERF (where the formalism is simpler), the electron bunch appears longer by a factor of γ (the laser wavelength shorter by a factor $1/\gamma$ (time transforms), then to achieve a sizeable coherent bunch should be made as short as λ/γ^2 (the wavelength of the scattered radiation).

For optical or shorter wavelengths, this is difficult to achieve in head-on collisions

A possibility: electron and photon beams cross each other at a large angle

¹⁷¹ In this case, a fraction of photons is continually scattered in phase in the forward direction of the slice of the electron beam (a true reflection). However, the scattering done by successive slices does not add in phase, since there is no phase relation between the scattering by successive slices; by successive slices add incoherently, until the electron bunch is gone.

Form factor for scattering at 90° in the LAB

Perform the calculations in the ERF. Here, the incoming and scattered wavelengths are the same. We must perform two Lorentz transforms: from LAB to ERF and back to LAB

Laser beam of wavelength λ_s focused on the electron trajectory, with elliptical spot size $\eta \times \xi$ of half axes

Minimum spot size limited by the momentum/position uncertainty principle (the laser beam cannot be focused down to linear sizes less than $\lambda/2\pi$).

Results

After the relativistic transformation, for each value of ℓ, m in the LAB, the photon density in the ERF appears concentrated in a cylindrical volume almost perpendicular to the y - z plane and sweeping across the electron pulse at the speed βc .

But, since the Lorentz transformation acts differently on the spatial coordinates and the photon momenta, we obtain the interesting result that the photons inside each cylinder appear to travel in a direction almost parallel to the z axis.

Since the Lorentz compression factor γ squeezes the cylinder along the z direction, the laser light collides only against a tiny slice of the electron bunch.

¹⁷⁴ Form factor for scattering at 90°

$$F(\mathbf{q}) = \iiint_{-\infty, +\infty} \rho_e(x, y, z) e^{-\Gamma} e^{i\mathbf{q} \cdot \mathbf{r}} dx dy dz$$

with Γ a certain function of the position and angles.

Electrons in volume V scatter in phase because they have been selected in a region of linear dimensions along the z axis of the same order of the photon wavelength

The radiation is essentially confined to a forward diffraction limited solid angle

$$\Delta\Omega = \frac{1}{16\pi\beta^2} \frac{(\lambda_L/\gamma)^2}{\sigma_x\sigma_y} \frac{\sqrt{\xi^2 + \sigma_y^2}}{\xi}$$

The aperture angle is $\gamma \times$ the ratio of the X-ray wavelength to the electron beam transverse dimension, i.e. $\gamma \times$ the cone aperture used in X-Ray Microscopy with undulator radiation.

The radiation is made of photon pulses of length $\sigma_z/\sqrt{2}\beta$ that propagates (ERF) along the direction

$$\cos\theta = \frac{1}{\gamma}, \quad \phi = \frac{\pi}{2}$$

Coherent fraction within the forward solid angle

$$\Re(\theta_L \cong 0) = \frac{N}{4\pi} \frac{(\lambda_L/\gamma^2)}{\sigma_{z,L}} e^{-4\beta^2}, \quad \text{when} \quad \xi = \eta = \sigma_y = \frac{\lambda_L}{2\pi}$$

directly proportional to the number of electrons contained in a scattered wavelength in the LAB.

Example of Coherent Scattering by a Modulated Electron Beam

<u>Electron Beam (Recirculated Van de Graaf)</u>		
Electron energy	E	9.30 MeV
Current	$\langle I \rangle$	40 μ A
Energy spread ^a	σ_E	$7 \cdot 10^{-7}$
Bunch length	$\sigma_{z,L}$	15 cm
Beam transv. dimensions	$\sigma_{x,y}$	0.15 mm
<u>Bunching: Undulator</u>		
Period ^b	λ_0	3.48 mm
Peak field	B_0	0.41 T
No. of periods	N_0	24
Deflection parameter	k	0.134
<u>Bunching and Scattering: Laser (CO₂, pulsed, doubled)</u>		
Laser wavelength	λ_L	5.3 μ m
Laser pulse length		1 nsec
Peak Power for Bunching	P_b	36 KW
Peak Power for Scattering	P_s	5 GW
<u>X-Rays</u>		
Wavelength	λ_X	4 nm
Coherent fraction	$\mathfrak{R}$	$1.41 \cdot 10^4$
Coherent photons per pulse	n_X^{coh}	$5.3 \cdot 10^6$
Coherent cone	$\Delta\Omega$	$5.66 \cdot 10^{-11}$ sterad
^a Advertised energy spread for edge-of-technology machines		
^b Micro undulators. E.g. NSLS-Brookhaven		

Example of Coherent Scattering at 90°

<u>Electron Bunch</u>		
Number of electrons	N	$5 \cdot 10^{11}$
Electron energy	E	33 MeV ($\gamma = 64.5$)
Bunch Length (LAB)	$\sigma_{z,L}$	3 mm (10 psec)
Emittance	ε	$2 \cdot 10^{-7}$ m-rad
<u>Laser (CO₂), pulsed</u>		
Wavelength	λ	10.6 μm
Power, pulse length	W	1 Joule/100 psec
Repetition Rate		1 KHz
<u>Scattering</u>		
X-ray Energy	$\hbar\omega$	1 KeV
Laser and beam spot size	$\xi = \eta = \sigma_x = \sigma_y = \frac{\lambda}{2\pi}$	1.68 μm
Central cone aperture	$\Delta\theta_L$	10°
No. of passes in cavity		100
Coherent Enhancement	$\mathfrak{R}$	620
Coherent photons	n_x^{coh}	$5.7 \cdot 10^{10} \text{ sec}^{-1}$
X-ray beam direction	(θ, ϕ)	(89.1°, 90°)

Undulator radiation. Example for a Scanning Microscope

<u>Storage Ring: APS-Argonne</u>		
Electron energy	E	7 GeV
Beam current	I	200 mA
Emittance	ϵ	74 nm-rad
<u>Undulator</u>		
Period	λ_0	3.3 cm
Number of periods	N_0	72
Peak field	B_0	0.75 T
Deflection parameter ^a	k	2.312
Fundamental wavelength ^b	λ_1	0.323 nm (3.84 KeV)
Natural linewidth	$\delta\omega/\omega$	0.0139
<u>Scanning Microscope</u>		
Pinhole aperture	σ	=vertical beam size
Angle of coherence	λ/σ	$3.78 \cdot 10^{-6}$ rad
Solid angle	$\Delta\Omega$	$4.49 \cdot 10^{-11}$ sterad
Photon flux in $\Delta\Omega$	n_{ph}	$1.27 \cdot 10^{15}$ sec ⁻¹
Coherent fraction ^c	$\mathfrak{R}$	$1.98 \cdot 10^{-4}$
^{a)} $k = \frac{e}{2\pi mc} \lambda_0 B_0$ ^{b)} $\lambda_1 = \lambda_0 \frac{1 + \frac{1}{2}k^2}{2\gamma^2}$ ^{c)} $\mathfrak{R} = \frac{(\lambda/\pi)^2}{\epsilon_x \epsilon_y} = \frac{1}{\pi^2} \left[\frac{\lambda(1 + \chi^2)}{\chi \epsilon} \right]^2$		

THE LHC PROJECT

L. EVANS
CERN

V

THE LHC PROJECT

L. EVANS /CERN.

1. Introduction
2. Lattice
3. Magnet
4. Cryogenics
5. Vacuum.
6. Injector chain
7. Schedule.

MAIN LHC PARAMETERS (June 1993)

COLLISIONS	p p	Pb ions
OPERATIONAL ENERGY TeV	14	1148
DIPOLE FIELD (MAX) T	8.65 (9.0)	
LUMINOSITY cm-2 s-1	10^{34}	10^{27}
LUMINOSITY @ BEAM-BEAM	($2.5 \cdot 10^{34}$)	
BUNCH INTERVAL m / ns	7.5 / 25	40.5 / 135
PARTICLES per bunch	10^{11}	10^8
PARTICLES per beam	$2.8 \cdot 10^{14}$	$4.7 \cdot 10^{10}$
NUMBER of EXPERIMENTS	2	1

(+ 1 B - Experiment.

Figure 1. Today's Livingston plot for colliding beams expressed in the average constituent centre of mass energy. Circles for e^+e^- , squares for hadron colliders. Operating machines are shown with full symbols.

Figure 2: The LEP tunnel cross-section

P187

fig 3 : LHC schematic layout

Fig 5a : Schematic representation of arcs (even sectors)

Figure 7: Schematic representation of a half-cell (even sector)

Figure 15: Optics functions of insertion 1 (tuned low-beta)

Power deposited in machine elements near a high luminosity interaction region

Estimates using the program FLUKA

$$\text{Luminosity} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

DIPOLE MAGNETS

TEVATRON
 $B = 4 \text{ T}$
 Bore : 76 mm

HERA
 $B = 4.5 - 6 \text{ T}$
 BORE : 75 mm

SSC
 $B = 6.6 \text{ T}$
 Bore : 50 mm

LHC
 $B = 8.65 \text{ T}$
 Bore : 56 mm

DIPOLE MAGNET PARAMETERS

OPERATIONAL FIELD	8.65	T
COIL APERTURE	56	mm
MAGNETIC LENGTH	13.145	m
OPERATIONAL CURRENT	11470	A

INNER COIL SHELL:

URNS/CHANNEL	30	
No STRANDS	28	
STRAND DIAMETER	1.065	mm
FILAMENT DIAM.	7	μ m
Cu/SC RATIO	1.6	

OUTER COIL SHELL:

URNS/CHANNEL	52	
No STRANDS	36	
STRAND DIAMETER	0.825	mm
FILAMENT DIAMETER	6	μ m
Cu/SC RATIO	1.9	

STRUCTURE:

DISTANCE btw. ORBITS	180	mm
OUTER DIAMETER	560	mm

Critical-current surface for a commercial superconducting alloy of niobium-titanium.

CHARACTERISTICS OF LHC MAGNET MODELS (L = 1.3 m)

MODELS (1.3 m)

Name	Aperture Ø [mm]	Inner Cable		Outer Cable		Collars	B _{ss}	B _o reached	No. of quenches to pass 9 T	First quench field after thermal cycle
		Strand No. x Ø [mm]	Width [mm]	Strand No. x Ø [mm]	Width [mm]	mat.	[T]	[T]		
Single aperture models										
8 TM1	50	30 x 0.84	12.6	30 x 0.84	12.6	Al	9.3	9.3	3	8.9
8 TM2	50	30 x 0.84	12.6	30 x 0.84	12.6	Al	9.4	9.4	3	8.9
MSA 1E	50	26 x 1.29	17	40 x 0.84	17	Al	9.8	9.7	11	not tested
MSA 2 KEK	50	22 x 1.39	15	37 x 0.79	15	Mn/Al	10.2	9.8	4	9.5
Twin-aperture models										
MTA 1/E	50	26 x 1.29	17	40 x 0.84	17	Al (S)	9.8	9.0	12	not tested
MTA1/A	50	26 x 1.29	17	40 x 0.84	17	Al (C)	9.8	9.7	9	8.3
MTA1/H	50	26 x 1.29	17	40 x 0.84	17	Al (C)	10.0	10.0	5	8.9
MTA1/JS	50	26 x 1.29	17	40 x 0.84	17	Al (C)	10.0	10.0	10	8.4
MTA2/KEK	50	22 x 1.39	15	37 x 0.79	15	MnAl	10.2	under test		
MTA3CERN*	50	26 x 1.29	17	40 x 0.84	17	SS (S)	10.5	10.5	0	9.75
MBTRA	56	30x0.808	12.4	36x0.648	11.7	SS (S)	9.4	under construction		
MFISC	56	30 x 1.10	16.7	38 x 0.87	16.7	SS (S)	9.9	under construction		

* With industrially-made coils.

(S): Separate collars.

Al: Aluminium alloy,

B_o = Field in the centre of the aperture.

B_{ss} = Field in the aperture centre at which the conductor placed in the magnet peak field position reaches the short sample limit.

(C): Combined collars.

SS: Austenitic steel,

Mn:

Mn steel.

Results of test
made in May 1993

CHARACTERISTICS OF LHC MAGNET PROTOTYPES (L = 10 m)

Name	No. of units	Aperture. Ø [mm]	Inner Cable		Outer Cable		Collars material	B _{ss} [T]	B _o reached [T]
			Strand No. x Ø [mm]	Width [mm]	Strand No. x Ø [mm]	Width [mm]			
Twin-aperture prototypes									
TAP	1	75	24 x 0.84	10	24 x 0.84	10	Al (C)	8.3	8.3
MTP 1/A	3	50	26 x 1.29	17	40 x 0.84	17	Al (C)	10.0	Under
MTP 1/N	2	50	26 x 1.29	17	40 x 0.84	17	Al (C)	10.0	cons-
MTP 2/AJS	1	50	26 x 1.29	17	40 x 0.84	17	Al (S)	10.0	truc-
MTP 3/EH	1	50	26 x 1.29	17	40 x 0.84	17	SS (S)	10.0	tion

(S): Separate collars, (C): Combined collars.

Al: Aluminium alloy, SS: Austenitic steel.

B_o = Field in the centre of the aperture.

B_{ss} = Field in the aperture centre at which the conductor placed in the magnet peak field position reaches the short sample limit.

AC 8-2-94/18

Dipole Parameters

			Parameters of prototypes under assembly #	
Operational field	<u>8.65</u>	T	<u>9.5</u>	T
Coil aperture	<u>56</u>	mm	<u>50</u>	mm
Magnetic length	13.145	m	10	m
Operating current	11'470	A	13900	A
Operating temperature	1.9	K		
Coil turns per beam channel				
inner shell	30			
outer shell	52			
Distance between aperture axes	180	mm		
Outer diameter of cold mass	560	mm	580	mm
Overall length of cold mass	14085	mm		
Outer diameter of cryostat	980	mm		
Overall mass of cryomagnet	29	t		
Stored energy for both channels	<u>0.55 MJ/m</u>	MJ	<u>0.63 MJ/</u>	
Self-inductance for both channels	110	mH		
Resultant of e-magnetic forces in the				
first coil quadrant ΣF_x (1.80 MN/m)	23.7	MN	<u>2.06 MN/</u>	
inner layer ΣF_y (-0.15 MN/m)	-2.0	MN	<u>-0.21</u>	"
outer layer ΣF_y (-0.62 MN/m)	-8.2	MN	<u>-0.88</u>	"
Axial e-magnetic force on magnet ends	<u>0.55</u>	MN	<u>0.63</u>	"

* The first one delivered
on 1/2/1994

MAIN QUADRUPOLE CROSS-SECTION QUADRUPOLE LHC : COUPE TRANSVERSALE

LHC Quadrupole Performance

Two-in-one type, constructed in Saclay, France

Design current	15060 A
Design gradient	252 T/m
Nominal Gradient (white book)	220 T/m
Nominal Excitation	13150 A
Short sample current	17000 A
Coil aperture	56 mm
Magnetic length	3.05 m

Quench History:

Figure 45: Cross-section of MSBH & MSBV corrector

Figure 44: Combined tuning quadrupole and octupole

LONGITUDINAL SECTION OF THE LHC SHORT STRAIGHT SECTION

PHASE DIAGRAM OF HELIUM

LHC magnet string cooling scheme

BOUCLE CRYOHYDRAULIQUE A HELIUM SUPERFLUIDE POUR LHC LHC SUPERFLUID HELIUM CRYOLOOP TEST

Figure 53: Cryogenic flow scheme of half-cell

Figure 61: The H₂ adsorption isotherm at 4.2 K on the stainless-steel Cu-plated surface

VACUUM.

Figure 62: A schematic diagram of the square-section beam screen

PSB Tune Diagram

Laslett tune shift for LHC beam in PSB at 50 MeV. $N=2E12$ p, $B_f = 0.55$.

Emittances (physical) in $4\sigma^2/\beta$

$$\epsilon_{h \text{ r.m.s.}}^* = 3.0 \mu\text{m}$$

$$\epsilon_{v \text{ r.m.s.}}^* = 2.0 \mu\text{m}$$

"DESIGN" "BEAM-BEAM LIMIT"

LHC	T (TeV)	7.0	7.35	
↑↑...↑	B(τ)	8.65 ₃₄	9.0 ₃₄	TWO AREAS
12 PULSES	$\mathcal{L}$ (cm ⁻² sec ⁻¹)	10 ³⁴	2.5 10 ³⁴	
...	p/bunch	10 ¹¹	1.67 10 ¹¹	25ns SPACING
	$\epsilon^*(1\sigma)$ (μm)		3.75	
SPS	p/pulse	2.5 10 ¹³	4.2 10 ¹³	80 MHz
↑↑↑	$\epsilon^*(1\sigma)$		3.5	
3 PULSES				
PS	p/pulse	0.84 10 ¹³	1.4 10 ¹³	40 MHz
↑↑	$\epsilon^*(1\sigma)$		3.0	80 MHz
2 pulses				NEW RF SYSTEM
				↓
PSB	p/ring	1.05 10 ¹²	1.75 10 ¹²	h=1
1 ⇒ 1.4 GeV	$\epsilon^*(1\sigma)$		2.5	h=2

LINAC2
50 TeV

180 mA
for ≥ 20 μs
1.2

RFQ2
750 keV

200 mA
0.5 ... 1.0

NEW HARDWARE

Bunch Shapes @ Injection

7/12/93

G. SCHNEIDER

W10 + 3 u.s.

BF = 0.52

+ 3 u.s.

BF = 0.56

W10 + 4 u.s.

W10 + 3 u.s.

REFLECTION

1 Beamscope	1.4 GeV
2 S-G PS	1.4 GeV Injection
3 Fil PS C220	1.4 GeV Debut polier
4 Fil PS C1400	1.4 GeV Fin de polier
5 Fil PS C1620	3.5 GeV/c
6 Fil Ps C2397	26 GeV/c
7 S-G TT2	26 GeV/c

Nominal LHC emittance
has been achieved with
ultimate intensity
Dec. 1993.

fig 43 : Lead ion : injector layout

Figure 1 - LHC Dipole fabrication planning - Optimum scenario

**OPTIMIZATION OF THE
PHOTOCATHODE-LINAC SEPARATION
FOR THE ATF INJECTION SYSTEM**

***Z. PARSA
BNL***

and

S.K. KO

UNIVERSITY OF ULSAN 680 -- 749 KOREA

VI

Optimization of the Photocathode-Linac Separation for the ATF Straight-ahead-Injection System

Z. Parsa and S.K. Ko

We present some of our Simulation results with PARMELA, for the ATF Injectin System. The new Solenoid-Gun-Solenoid--Drift-Linac Scheme would improve the beam quality needed for FEL and other experiments at ATF. To optimize the gain in the beam quality we have to consider and optimize various parameters e.g., the Solenoid field strengths and the separation between the gun and entrance to the linac. The effects of the change in these parameters on the beam emittance is also given.

Outline:

- ATF (Original Design) Injection System (Fig 1)
- Gun - Solenoid - Gun Injection Scheme for ATF (Fig 2)

PARMELA Simulations for Gun - Solenoid - Gun Injection Scheme

- Emittance and beam size optimization with respect to:
- Variation in the Solenoid field (current I)
- Variation in the separation distance (d) between the Gun and Linac.
- Discussion on the effects of initial beam distributin : Flat vs Gaussian.

Reference: Z. Parsa, *Development of the Alternate Entry Port for the ATF*, IEEE 1993, 0-7903-1203-1/93, p. 2723 (1993), and Refs therein.

We present some of the results obtained with Program PARMELA (modified version on the UNIX Workstation, which gives slightly different results than the version we regularly have used in collaboration with L. Young. This version is used as a test for comparison with other calculations using this program version at ATF).

For convenience in Table 1 we have included (the labling of) the elements in the beam line utilizing PARMELA format.

Here we present the change in the beam emittance (beam profile) due to effects of variation of the Solenoid current (field strength) and change in the distance from the cathode .

In Table 2, the variation of emittance at the gun exit at $z=7.9$ cm, with the change in the Solenoid field strength (and current I) is illustrated for the case of 66 MV/m field (on the cathode). In Table 3. the variation in emittance from element no 1 ($z=0$) through element 35 distance of $z=95$ cm from cathode is given for the case of 100 MV/m field on the cathode. Cmparison of these tables shows clearly the effects of the increase in the field on the cathode from 66 to 100 MV/m. We also note the dependance of the emittance as with Z for a given solenoid and with variation in the solenoid field strength. Figures 3 -1 to 3-10 shows the beam profile at various element locations (distance z from the cathode), with solenoid current of $I=2100$ amp. Figures 4 -1 to 4-9 shows the beam profile at various element locations (distance z from the cathode) for $I=2800$ amp solenoid. Additional figures and beam profiles for the new injection scheme with solenoids field variations as well as the results obtained with various initial particle distributions (e.g flat beam vs. Gaussian distribution) will be included in follow up notes.

Figure captions:

- Figure 1 Sketch of the BNL ATF injection System (original Design)
- Figure 2 Sketch of a New BNL ATF injection System (new Design)
- Figure 3 -1 shows the beam profile at element no. 1 ($z=0$) with $I=2100$ amp.
- Figure 3 -2 shows the beam profile at element no. 2 ($z=2.6$) with $I=2100$
- Figure 3 -3 shows the beam profile at element no. 3 ($z=5.2$) With $I=2100$
- Figure 3 -4 shows the beam profile at element no. 4 ($z=7.9$) with $I=2100$
- Figure 3 -5 shows the beam profile at element no. 5 ($z=10.0$) with $I=2100$
- Figure 3 -6 shows the beam profile at element no. 10 ($z=20$) with $I=2100$.

Figure 3 -7 shows the beam profile at element no. 20 ($z=40$) with $I=2100$
Figure 3 -8 shows the beam profile at element no. 27 ($z=58$) with $I=2100$.
Figure 3 -9 shows the beam profile at element no. 30 ($z=70$) with $I=2100$
Figure 3 -10 shows the beam profile at element no. 35 ($z=95$) with $I=2100$
Figure 4 -1 shows the beam profile at element no. 1 ($z=0$) with $I=2800$ amp.
Figure 4 -2 shows the beam profile at element no. 2 ($z=2.6$) with $I=2800$
Figure 4-3 shows the beam profile at element no. 3 ($z=5.2$) with $I=2800$
Figure 4-4 shows the beam profile at element no. 4 ($z=7.9$) with $I=2800$.
Figure 4-5 shows the beam profile at element no. 5 ($z=10.0$) with $I=2800$
Figure 4-6 shows the beam profile at element no. 10 ($z=20$) with $I=2800$
Figure 4-7 shows the beam profile at element no. 20 ($z=40$) with $I=2800$
Figure 4 -8 shows the beam profile at element no. 30 ($z=70$) with $I=2800$
Figure 4-9 shows the beam profile at element no. 34 ($z=90$) with $I=2800$

Figure 1: Sketch of the BNL ATF injection system. The transport beamline from the gun to the linac entrance showing the positions of the magnetic elements.

The high brightness laser driven photoelectron beams (with low emittance and high current) are required for new methods of acceleration such as FEL, IFEL (an inverse free-electron laser) and future development of linear colliders. To achieve high brightness and rapid acceleration, an rf gun operating at 2.856 GHz, with 1-1/2 cells, π - mode resonant, disc-loaded structure (with cathode placed at the start of the first 1/2 cell), has been designed and operating as the injector for the two S-band linac sections at the BNL Accelerator Test Facility (ATF). The cathode is illuminated with a frequency quadrupled Nd:YAG laser with photon energy of 4.65 MeV at the gun exit.

The Accelerator Test Facility at BNL is an experimental Facility for accelerator and beam physics experiments. A major research interest is in the interaction of laser driven photoelectrons with the electromagnetic fields. ATF's present injection system consist of a photoelectron gun and a low energy transport beamline which consists of two sets of quadrupole triplets and a 180° achromatic double bend, (Fig. 1). The photoelectrons are ejected from a photocathode rf gun into the transport beam line and then accelerated through 2 S - band linac sections to 50 MeV [1,2]. The linac consists of two $\pi/3$ - mode, 3.05 m long, disc loaded, travelling wave SLAC linear accelerator sections that was produced at IHEP, Beijing, China. The gun and the linac are driven by the same XK5 klystron, delivering about 25 MW of peak power with a 3.5 micro-second pulse at 2.856 GHz [2].

With the *original* injection system, the beam diverges quickly at the gun exit and gets large in going through the double bend transport line into the linac [3,4]. We have considered and studied various schemes [6] and will present some results for the proposed ATF *new* injection

a solenoid + a gun + solenoid

(straight-ahead) INJECTION SYSTEM

We have considered various schemes to improve the beam quality and preserve the low emittance and high brightness beam needed for experiments at ATF [6]. In this section we present some of our calculations and simulation results obtained for a (straight-ahead) injection system.

Figure 2: Sketch of a new injection system for ATF. A solenoid + gun + solenoid (gun+s) combination is placed in line with the linac. (Not scaled).

This scheme would allow the production of the low emittance and high brightness beam needed for the experiments and preserves the *original* injection system which can be used alternatively for diagnostic measurements etc. Where the beam is injected from a *new* entry port (using a 2nd gun) directly into the linac without going through the bending magnets.

Selections of "d" the distance from the gun (cathode) to the linac entrance and solenoid strength are important and would effect beam quality (see Section II). For other injection schemes and a more detailed analysis see references. In this analysis the fields off axis for solenoids are calculated to sixth order using the expansions:

$$B_z(z, r) = B_z(z, 0) - \frac{r^2}{4} \frac{d^2 B}{dz^2} + \frac{r^2}{4} \left(\frac{d^4 B}{dz^4} \frac{r^2}{16} - \frac{d^6 B}{dz^6} \frac{r^4}{576} \right)$$

$$B_r(z, r) = -\frac{r}{2} \left(\frac{dB}{dz} - \frac{d^3 B}{dz^3} \frac{r^2}{8} + \frac{d^5 B}{dz^5} \frac{r^4}{192} \right)$$

Table 1. Shows the labling of the elements in the beam line (in PARMELA format) from the Cathode (at $z=0$), through the RF Gun and at various points (distance z from the cathode) to the Linac entrance.

n	z1	element	z2	dz
1	.0	cell	2.6	2.625
2	2.6	cell	5.2	2.625
3	5.2	cell	7.9	2.625
4	7.9	drift	10.0	2.100
5	10.0	drift	12.0	2.000
6	12.0	drift	14.0	2.000
7	14.0	drift	16.0	2.000
8	16.0	drift	17.5	1.500
9	17.5	drift	20.0	2.500
10	20.0	drift	22.0	2.000
11	22.0	drift	24.0	2.000
12	24.0	drift	26.0	2.000
13	26.0	drift	28.0	2.000
14	28.0	drift	30.0	2.000
15	30.0	drift	32.0	2.000
16	32.0	drift	34.0	2.000
17	34.0	drift	36.0	2.000
18	36.0	drift	38.0	2.000
19	38.0	drift	40.0	2.000
20	40.0	drift	42.0	2.000
21	42.0	drift	44.0	2.000
22	44.0	drift	46.0	2.000
23	46.0	drift	48.0	2.000
24	48.0	drift	50.0	2.000
25	50.0	drift	54.0	4.000
26	54.0	drift	58.0	4.000
27	58.0	drift	62.0	4.000
28	62.0	drift	66.0	4.000
29	66.0	drift	70.0	4.000
30	70.0	drift	75.0	5.000
31	75.0	drift	80.0	5.000
32	80.0	drift	85.0	5.000
33	85.0	drift	90.0	5.000
34	90.0	drift	95.0	5.000
35	95.0	drift	100.0	5.000

Table 2. Shows variation of emittance at the gun exit at $z=7.9$ cm, with the change in the Solenoid field strength With 66 MV/m field on the cathode

At $z=7.9$ cm	66.6MV/m	sigmar=0.9mm
I (amp)	Erms	Bmax (gauss)
2100	.4892	2093
2180	.4891	2173
2300	.4891	2293
2400	.4892	2392
2600	.4890	2591
2800	.4890	2790
3000	.4890	2990

Table 3. Shows variation of emittance through the gun, at the the gun exit and ouside of the gun through the drift space(s) to the Linac entrance. With 100 MV/m field on the cathode.

I (amp)	Erms(at 2.6 cm)	Erms(at 5.2 cm)	Erms(at 7.9 cm)
2100	.2391	.3266	.2215
2140	.2391	.3267	.2216
2160	.2392	.3267	.2216
2180	.2392	.3266	.2215
2200	.2391	.3266	.2214
2300	.2391	.3266	.2214
2400	.2391	.3266	.2214
2500	.2391	.3266	.2214
2600	.2391	.3267	.2215
2800	.2391	.3268	.2214
3000	.2391	.3268	.2212
3400	.2391	.3268	.2212
3800	.2391	.3271	.2213

I (amp)	Bmax (gauss)
2100	2093
2140	2133
2160	2153
2180	2173
2200	2193
2300	2292
2400	2392
2500	2492
2600	2592
2800	2792
3000	2991
3400	3389
3800	3787

I (amp)	Erms (at 10 cm)	Erms (at 12cm)	Erms (at 22 cm)
2100	.2233	.2260	.2479
2140	.2235	.2263	.2526
2160	.2234	.2263	.2527
2180	.2234	.2262	.2528
2200	.2233	.2261	.2531
2300	.2234	.2263	.2545
2400	.2234	.2264	.2558
2500	.2234	.2266	.2573
2600	.2236	.2268	.2586
2800	.2236	.2270	.2612
3000	.2236	.2272	.2647
3400	.2239	.2283	.2741
3800	.2244	.2295	.2838

I (amp)	Erms (at 42 cm)	Erms (at 62 cm)
2100	.2640	.2574
2140	.2647	.2551
2160	.2645	.2532
2180	.2645	.2513
2200	.2646	.2492
2300	.2660	.2372
2400	.2669	.2123
2500	.2684	.2060
2600	.2697	.2900
2800	.2678	.3864
3000	.3127	.4835
3400	.4150	.6898
3800	.5232	.8892

Figures 3 -1 to 3-10 shows the beam profile at various element locations (distance z from the cathode). With I=2100 amp.

Figure 3 -1 shows the beam profile at element no. 1 (z=0)
With I=2100 amp.

Table 3. Shows variation of emittance through the gun, at the the gun exit and ouside of the gun through the drift space(s) to the Linac entrance. With 100 MV/m field on the cathode.

I (amp)	Erms (at 2.6 cm)	Erms(at 5.2 cm)	Erms(at 7.9 cm)
2100	.2391	.3266	.2215
2140	.2391	.3267	.2216
2160	.2392	.3267	.2216
2180	.2392	.3266	.2215
2200	.2391	.3266	.2214
2300	.2391	.3266	.2214
2400	.2391	.3266	.2214
2500	.2391	.3266	.2214
2600	.2391	.3267	.2215
2800	.2391	.3268	.2214
3000	.2391	.3268	.2212
3400	.2391	.3268	.2212
3800	.2391	.3271	.2213

I (amp)	Bmax (gauss)
2100	2093
2140	2133
2160	2153
2180	2173
2200	2193
2300	2292
2400	2392
2500	2492
2600	2592
2800	2792
3000	2991
3400	3389
3800	3787

**Figure 3 -2 shows the beam profile at element no. 2 ($z=2.6$)
With $I=2100$ amp.**

**Figure 3 -3 shows the beam profile at element no. 3 ($z=5.2$)
With $I=2100$ amp.**

**Figure 3 -4 shows the beam profile at element no. 4 ($z=7.9$)
With $I=2100$ amp.**

**Figure 3 -5 shows the beam profile at element no. 5 ($z=10.0$)
With $I=2100$ amp.**

**Figure 3 -6 shows the beam profile at element no. 10 (z=20)
With I=2100 amp.**

**Figure 3 -7 shows the beam profile at element no. 20 ($z=40$)
With $I=2100$ amp.**

**Figure 3 -8 shows the beam profile at element no. 27 (z=58)
With I=2100 amp.**

**Figure 3 -9 shows the beam profile at element no. 30 ($z=70$)
With $I=2100$ amp.**

**Figure 3 -10 shows the beam profile at element no. 35 (z=95)
With I=2100 amp.**

Figures 4 -1 to 4-9 shows the beam profile at various element locations (distance z from the cathode). With I=2800 amp.

Figure 4 -1 shows the beam profile at element no. 1 (z=0)
With I=2800 amp.

**Figure 4 -2 shows the beam profile at element no. 2 ($z=2.6$)
With $I=2800$ amp.**

**Figure 4-3 shows the beam profile at element no. 3 ($z=5.2$)
With $I=2800$ amp.**

**Figure 4-4 shows the beam profile at element no. 4 ($z=7.9$)
With $I=2800$ amp.**

**Figure 4-5 shows the beam profile at element no. 5 ($z=10.0$)
With $I=2800$ amp.**

**Figure 4-6 shows the beam profile at element no. 10 ($z=20$)
With $I=2800$ amp.**

**Figure 4-7 shows the beam profile at element no. 20 ($z=40$)
With $I=2800$ amp.**

**Figure 4 -8 shows the beam profile at element no. 30 ($z=70$)
With $I=2800$ amp.**

**Figure 4-9 shows the beam profile at element no. 34 ($z=90$)
With $I=2800$ amp.**

REFERENCES

*Work performed under the auspices of U.S. Dept.of Energy contract DE-AC02-76-CH00016.

1. Z. Parsa, "*Preliminary Emittance Measurements and Calculations of the Laser Excited Beam from the BNL Accelerator Test Facility Radio Frequency Electron Gun*", Vol.II, Sec.II, p1-54, BNL-52292 (1991) and References therein; K. McDonald et al., Proc., EPAC88, June 1988; A. Fisher, J. Fisher, I. Pogorelsky, private communications on laser performance.; Z. Parsa, "*Effects of 3rd Order Maps and Solenoid on a High Brightness Beam*", BNL-48397 (1993) and Proc. IEEE PAC May 17-20, Washington D.C. (1993).
2. K. Batchelor, I. Ben-Zvi, I. Bigio, T.S. Chou, R.C. Fernow, J. Fischer, J. Gallardo, H. Kirk, N. Kurnit, K.T. McDonald, R.B. Palmer, Z. Parsa, C. Pellegrini, J. Sheehan, T. Srinivasan-Rao, S. Ulc, A. Van Steenberg, M. Woodle, "*Operational Status of Brookhaven Accelerator Test Facility*", Proc. March 20-23, 1989 IEEE PAC, Chicago, Ill, #89CH2669-0 (1990).
3. Z. Parsa, "*On Beam Emittance and Invariants - Applications to ATF Beamline*", Proc.2nd EPAC, Nice-France, Nile Ed., Frontiers, (1990); BNL Report BNL-44364 (1990) and Ref.therein.
4. Z. Parsa, and L. Young, "*Modeling of the BNL Photocathode Gun with the Code PARMELA*", Nucl. Inst. & Meths. A318 (1992) 254-258.
5. L. Young, (Private comms.), PARMELA, 1993 version; We thank L. Young for helpful discussions, modifications to the programs and collaborations.
6. Z. Parsa, "*An Alternate Injection System for the BNL Accelerator Test Facility*", BNL-48403, APS April 12-15, Washington D.C. (1993); Z. Parsa, "*Interactions Between Charged Particles and RF Space Charge and Wake Fields in an Accelerating Structure*", Particles and Fields 91, Vol. 2, 1073, Ed. David Axen, Douglas Bayman and Martin Comyn; Z. Parsa, Accelerator Physics and Modeling, BNL- Report BNL-52379, 65-165 (1993). Z. Parsa, "*Development of the Alternate Entry Port for the ATF*", IEEE 1993, 0-7903-1203-1/93, p. 2723

ON CEBAF COMMISSIONING FIRST RESULTS

L. Merminga
CEBAF

VII

CEBAF COMMISSIONING:

FIRST RESULTS

Lia Merminga

CONTENTS

- CEBAF: Overview
 - Accelerator Description
 - Status Breakdown
- Commissioning Schedule
- Injector to Hall C Commissioning
 - Injector
 - North Linac Recommissioning
 - South Linac Commissioning
- Conclusions

MACHINE CONFIGURATION

CEBAF

264

0.4-GeV Linac
(20 Cryomodules)

45-MeV Injector
(2 1/4 Cryomodules)

Helium
Refrigerator

Recirculation
Arcs

0.4-GeV Linac
(20 Cryomodules)

Extraction
Elements

End
Stations

Machine Configuration 1/10/94

SIMULTANEOUS COMPLEMENTARY EXPERIMENTS

CEBAF

◀ HALL A (Start of physics: 4Q FY95)

- ▷ Nuclear structure at small inter-nucleon separations
- ▷ Nuclear medium effects on bound nucleon structure
- ▷ Precision measurements of high Q^2 form factors of nuclei and nucleons

HALL B (Start of physics: 3Q FY96)

- ▷ Baryon and meson structure and spectroscopy
- ▷ Gluonic degrees of freedom
- ▷ Multinucleon correlations in nuclei

◀ HALL C (Start of physics: 3Q FY94)

- ▷ Strange-quark content of proton
- ▷ "Color transparency"
- ▷ Neutron electric form factor
- ▷ Exploratory ($e, e' K$)

HALL C HMS SUPERCONDUCTING DIPOLE
MAGNET AND FORM FOR SOS DETECTOR HUT

HG

ACCELERATOR SITE

SUMMARY ACCELERATOR DESCRIPTION

- Beam performance objectives:
 - ≥ 4 GeV, 200 μ A, CW
 - Emittance and energy spread: $\epsilon \sim 2 \cdot 10^{-9} \text{ m}^*$, $\sigma_E/E \sim 2.5 \cdot 10^{-5}$ at 1 GeV
 - 3 simultaneous beams, independent energy and current adjustment
- Design concept: recirculating, superconducting cw linac
 - CW for high beam quality
 - RF superconductivity for efficiency
 - 5 pass beam recirculation for cost optimization, multi-energy operation
- Key design features:
 - 1 RF system per cavity for control of microphonics and operational flexibility
 - 2 K operation for cost optimization
 - Isochronous, achromatic beam recirculation arcs
 - Strong focusing optics to minimize synchrotron radiation effects

* Emittance is quoted as unnormalized emittance of the whole beam at 1 GeV ($\sigma_x^2 = 1/4 \beta_x \epsilon_x$)

CEBAF

The Continuous Electron Beam Accelerator Facility

cnc[Hutton/Talks]Control System Review

4 May 1994

STATUS BREAKDOWN

SRF Acceleration System

- Scope
 - 338 cavities in 42 1/4 cryomodules
- Status
 - Completely installed
 - Exceeds G, Q specs twofold

RF System

- Scope
 - 340 klystrons in 43 HPAs
 - 344 low level control modules
 - Master oscillator and distribution
 - 3 beam injector
 - RF separators, HPAs, controls
- Status
 - Linac system installed, meets specs
 - 3 beam injector completed
 - RF separator prototype being tested

CEBAF

The Continuous Electron Beam Accelerator Facility

cnc[Hutton/Talks]Control System Review

4 May 1994

CEBAF

The Continuous Electron Beam Accelerator Facility

E and Q at usable gradient for all 338 cavities

CEBAF CAVITY VERTICAL TEST

AH

RK

CLEAR TOPPER

SOUTH LINAC CRYOMODULES

AH

STATUS BREAKDOWN (cont'd)

Cryogenic System

- Scope
 - 4800 W, 2 K CHL (Central Helium Liquifier)
 - ESR (End Station Refrigerator)
 - Transfer lines
- Status
 - CHL operational at 2.1 K, 3750 W transfer lines complete
 - ESR complete

I&C

- Scope
 - 25,000 hardware devices controlled (100,000 EPICS records)
 - Beam diagnostics devices (28 harps, 108 viewers, 494 BPMs)
 - Safety systems
- Status
 - Control system operational
 - Undergoing transformation to EPICS
 - Beam diagnostics installed, electronic upgrades ongoing

CEBAF

The Continuous Electron Beam Accelerator Facility

cnc[Hutton/Talks]Control System Review

4 May 1994

EAST ARC MAGNET INSTALLATION

HG

COMMISSIONING OVERVIEW

- **Phase 1 Pre-Operational Tests - low power (< 17 kW)**
 - Stage 1 Front End Test (*completed*)
 - Stage 2 North Linac low power beam test (*completed*)
 - Stage 3 East Arc low power beam test (*completed*)
- **Phase 2 Pre-Operational Tests - high power (< 120 kW)**
 - Stage 1 North Linac high power beam test (*completed*)
 - Stage 2 South Linac high power beam test
- **Phase 3 Commissioning**
 - Stage 1 Commission single - pass operation
Start delivery of nominal 800 MeV, 200 μ A beam to Hall C
 - Stage 2 Tests of 2, 3, 4 and 5 pass operation to 4 GeV (nominal)
 - Stage 3 Three-beam distribution tests

BEAM SCHEDULE

3/94	INJECTOR
4/94	NORTH LINAC
6/94	TO HALL C
6/95	TO HALLS A & B
8/94	WEST ARC/MULTIPASS

CERN

Accelerator Commissioning Schedule

[illegible]

Accelerator Commissioning Schedule

Activity Name	Start Date	Finish Date	Jul '94				Aug '94				Sept '94				Oct '94				Nov '94				Dec '94					
			3	10	17	24	31	7	14	21	28	4	11	18	25	2	9	16	23	30	6	13	20	27	4	11		18
Machine Downtime (convert East Arc to EPICS)	7/6/94	7/17/94	▲	→																								
24 Hour Operation First try at second pass in North Linac	7/18/94	7/31/94																										
Machine Downtime - budget driven (complete installation of all BPM electronics))	8/1/94	9/11/94				▲	→																					
24 Hour Operation Dellver CW beam to Hall C	9/12/94	9/26/94																										
24 Hour Operation Beam to Hall C for Spectrometer tests	9/26/94	10/2/94																										
24 Hour Operation Set up second turn with pulsed beam at 1.6 GeV	10/3/94	10/16/94																										
24 Hour Operation Beam to Hall C for Spectrometer tests	10/17/94	10/23/94																										
Machine Downtime (necessary repairs or	10/24/94	10/30/94																										
24 Hour Operation Set up third turn with pulsed beam at 2.4 GeV	10/31/94	11/14/94																										
24 Hour Operation CW Beam to Hall C for Spectrometer tests	11/14/94	11/23/94																										
Holiday	11/24/94	11/27/94																										
24 Hour Operation Set up CW beam to BSY	11/28/94	12/4/94																										
24 Hour Operation First production run of Commissioning experiment for Hall C	12/5/94	12/22/94																										
Holiday	12/23/94	1/2/95																										

Injector to Hall C Commissioning Procedure (1 Pass)

Contact: D. Douglas (7512)

Purpose: Deliver 800 MeV single-pass beam to end Hall C and verify accelerator model agrees with performance. Establish procedures for normal machine operation.

Machine Parameters:

Injector at 45 MeV, North Linac at 445 MeV and South Linac at 845 MeV.

Beam pulsed with parameters to allow BPMs to be used and G. Krafft's new canonical setting.

Test Plan:

- 1) Setup the Injector using the Injector Metaprocedure.
- 2) Download quad values and thread beam through the betatron phase match region (0L10).
Perform the 45 MeV beam properties measurements:
measure beam energy and energy spread with the 45 MeV spectrometer,
and emittance at 0L10.
Set betatron match into the NL.
- 3) Activate orbit lock into the chicane.
- 4) Download values and set up the chicane as a spectrometer.
Determine beam energy and perform gradient calibration of the injector cavities with beam.
- 5) Setup the chicane in the nominal mode.
Check chicane optics.
- 6) Activate energy lock into the chicane.
- 7) Thread beam to the NL using the NL recommissioning metaprocedure (up to step 18).
- 8) Perform NL gradient calibration with beam.
- 9) Readjust spreader to be achromatic.
- 10) Perform a save/restore test.
- 11) At this point the program deputy will decide whether to thread the beam to the high power dump or thread it into the East arc. If the beam is

- threaded into the East arc, go to step 16. Else,
- 12) Park the beam at the dump for 4 hours and archive signals that carry signature of beam instabilities.
 - 13) RF checkout with beam.
 - 14) Perform beam properties measurements at 445 MeV.
 - 15) Perform quad/BPM alignment.
 - 16) Transport beam through the east arc and recombining and check east arc optics.
 - 17) Transport beam through the South Linac.
 - 18) Perform SL gradient calibration with beam.
 - 19) Set up nominal West spreader, download values and transport beam to the BSY recombining.
 - 20) Activate energy lock into the West spreader.
 - 21) Measure beam properties at 845 MeV.
Match to West arc/BSY.
 - 22) Perform BPM/quad alignment.
 - 23) Download values and transport beam to the BSY dump.
Check optics to BSY dump.
 - 24) Park the beam at the dump for 4 hours.
 - 25) SL RF checkout with beam.
 - 26) Download values and transport beam into Hall C transport.
 - 27) Beam properties measurements in Hall C phase matching region.
Calculate matching into the arc.
 - 28) Download values and transport beam through Hall C arc.
 - 29) Download values and transport beam through phase matching to target.

Injector Metaprocedure

Contact: G. Kraft (7557)

Test Plan:

- A1 and A2 setup
- Chopper setup
- Buncher phase setup. Set bunch G_{set} to 15.7
- Steer through buncher center (Procedure is at the end of this document)
- Capture section phase setup. Set G_{set} to 5650
- Steer through capture section center (Procedure is at the end of this document)
- Steer through A3 and A4
- Steer through cryounit, centering beam in the electrical center (Procedure is at the end of this document)
- 1/4 cryo and bypass setup (Procedure written by D. Douglas on 5-17-94)
- Check bunch length at second 6 GHz cavity is less than 1, if not follow standard optimization procedure
- Check beam steered properly through the cryounit, check the unit cavities are still on crest, and recheck the bunch length at the third cavity after any corrections are made. All three conditions must be satisfied simultaneously
- Check that the bunch length at the second 6 GHz cavity is still under 1
- Preaccelerator setup

When we have determined a good golden orbit through the bypass again, bypass steering should become much easier.

Note: Space Charge is not a problem at CEBAF
 due to low charge per bunch: $\sim 10^6$ particles/bunch.

After -1.3° gang phase Bonker Capture, Unit

ALWAYS-Q225 MAY 18

Beam properties measurements

All measurements done at low power
 $\sim 20 \mu\text{A}$ peak current
100 μsec pulse width

Measured

5 MeV ϵ_x, ϵ_y

45 MeV $\epsilon_x, \epsilon_y, \delta p/p$

Results

5 MeV

$$\epsilon_x = 4 \times 10^{-8} \text{ m-rad}$$

$$\epsilon_y = 3 \times 10^{-8} \text{ m-rad}$$

$$\text{Nominal } \epsilon_{x,y} = 10^{-7} \text{ m-rad}$$

45 MeV

$$\epsilon_x = 5 \times 10^{-9} \text{ m-rad}$$

$$\epsilon_y = 2.6 \times 10^{-9} \text{ m-rad}$$

$$\delta p/p \leq 6.7 \times 10^{-5}$$

$$\text{Nominal } \epsilon_{x,y} = 10^{-8} \text{ m-rad}$$

$$\text{Nominal } \delta p/p = 2.5 \times 10^{-5}$$

@ 1 GeV

Adiabatic Damping

5 MeV

45 MeV

$$\epsilon_x = 45 \times 10^{-9} \text{ m-rad} \longleftarrow \epsilon_x = 5.0 \times 10^{-9} \text{ m-rad}$$

$$\epsilon_x = 40 \times 10^{-9} \text{ m-rad} \longrightarrow \epsilon_x = 4.4 \times 10^{-9} \text{ m-rad}$$

$$\epsilon_y = 23.4 \times 10^{-9} \text{ m-rad} \longleftarrow \epsilon_y = 2.6 \times 10^{-9} \text{ m-rad}$$

$$\epsilon_y = 30 \times 10^{-9} \text{ m-rad} \longrightarrow \epsilon_y = 3.3 \times 10^{-9} \text{ m-rad}$$

$$\epsilon_x = 5.0 \times 10^{-9} \text{ m-rad}$$

$$\beta_x^{\text{inject}} = 11.243 \text{ m}$$

$$\beta_x^{\text{QDOLDS}} = 14.091 \text{ m}$$

$$\alpha_x^{\text{inject}} = 1.5569$$

$$\alpha_x^{\text{QDOLDS}} = 3.5724$$

$$\epsilon_y = 2.6 \times 10^{-4} \text{ m-rad}$$

$$\beta_y^{\text{inject}} = 55.372 \text{ m}$$

$$\beta_y^{\text{QDOLDS}} = 137.933 \text{ m}$$

$$\alpha_y^{\text{inject}} = 28234$$

$$\alpha_y^{\text{QDOLDS}} = -18.6491$$

May 31, 1994

12:26:46

Orbit / Energy Lock

Calculates corrector strengths to produce a golden orbit.

Calculations are based on DIMAD model.
User may select any number of available E
Single value decomposition yields
optimum results for any combination
of BPMs and correctors.

Orbit lock keeps beam stable to within 200 μ

For energy lock choose BPMs at high n
and a number of linac cavities.

First select the beam position monitors from the BPM list, after that click the next button to auto-select kickers

Auto select kickers

Next you have a chance to change the kicker selection in the KICK list. After that click the next button to calculate the response matrix

Calculate Response Matrix

Next you can start the lock by clicking the next button

☐ Run Orbit Lock continuously | Run Orbit Lock once

BPMs	Select None	☒ X and Y	☐ Difference	☐ Dimad	☒ Golden
0.1176	☐ y	-666.0000	0		
IPM0L06	☐ x	-666.0000	0		
0.0196	☐ y	-666.0000	0		
IPM0L07	☐ x	-666.0000	0		
0.0000	☐ y	-666.0000	0		
IPM0L08	☐ x	-666.0000	0		
0.0000	☐ y	-666.0000	0		
IPM0L09	☒ x	-666.0000	0		
0.0588	☒ y	-666.0000	0		

MBT0L08H	□	h	□	-0.0313
MBT0L08V	□	v	□	-0.0129
MBT0L09H	■	h	■	-0.1550
MBT0L09V	■	v	■	-0.2155
MBT0L10H	□	h	□	-0.2980

PM1L28

Gradient Calibration with beam

Purpose:

Calibrate cavity gradients to better than 2% and update database for corrected field probe coefficients.

$$E_{acc} = \alpha_c \sqrt{P_t}$$

P_t : power from field probe

Presently $E_{acc} = \alpha \sqrt{P_t}$

where α obtained from Q_{ext} .

Gradient calibration with beam provides

$$\alpha_c = \alpha \frac{E_{actual}}{E_{acc}}$$

by measuring the actual beam energy gain (with the spreader spectrometer magnet) corresponding to cavity gradient E_{acc} .

Dispersion check

Change beam energy by 0.2%
and record BPM (at high n points) readings
before and after energy change.

Checks to be done in Bypass, Chicane
and arcs.

Automated Cavity Tuning

Purpose:

Automated measurement of cavity resonance frequency and tuning of cavities to the operating frequency.

Cavity tuning procedure is accomplished in 3 steps.

1) Burst Mode (Rough tuning)

Cavity resonance frequency f_0 is measured by driving the cavity with a noise spectrum:

Phase of incident signal is modulated with a bandwidth limited (± 5 kHz) pseudo-random signal.

f_0 can be determined from the response signal of the field probe which has a narrow frequency spectrum ($Q_L = 6.6 \times 10^6$) within ± 50 Hz.

Stepper motors bring cavity to tune within 100 Hz.

Burst Mode: Power Spectrum

2) Sweep Mode (Exact tuning)

Single sideband modulation is applied to the carrier while sweeping the modulation frequency over a range of ± 20 in steps of 5 Hz.

The measured detuning angle as a function of modulating frequency is compared to the predicted curve to determine the resonance frequency

$$\psi = \arctan \left\{ 2Q_L \frac{f_0 - f}{f_0} \right\} + \psi_0$$

as well as phase offset.

3) Tracking mode

Uses phase offset determined above to keep cavity tuned to the operating frequency.

Status

Burst and auto-track modes used exclusively to tune NL cavities during April run. Sweep mode operational now.

Sw Mode Data

Date: April 9, 1994

Recommissioning the North Linac to the High Power Dump

Contact: B. Legg (7592)

Purpose:

Recommission the north linac in preparation for beam properties measurements and reliability tests.

Prerequisites:

- 1) RF systems commissioned in north linac.
- 2) Controls software
 - a) Save/Restore settings
 - b) Archiver
- 3) Autotune software
- 4) BPMs in linac, spreader and extraction commissioned
- 5) Injector operational

Machine Parameters:

Beam to QD0L02 from Injector

Beam pulsed with parameters to allow BPMs to be used and G. Krafft's new canonical setting.

Test Plan:

- 1) Turn RF on in zones 1L02 through 1L18 to optimized cavity gradients (See procedure), phases will be arbitrary.
- 2) All North Linac quadrupoles are set to 60 deg. phase advance
Match into the nominal North Linac (see procedure 4/1-5).
- 3) Steer beam through North Linac to zone 1L07 BPM.
- 4) Use "Transient Phasing" (See procedure 4/1-7) to set cavity phases in zones 1L02 through 1L06 to crest. This rough first phasing should be accurate to +/- 10 degrees.
- 5) Steer beam through north linac to entrance of spreader.
- 6) Phase the cavities in zones 1L07 through 1L19.

- 7) Increase quad strength by 50% to obtain 90 deg. phase advance/cell. Ensure that no beam loss occurs.
- 8) Download the calculated quad settings for the whole north linac for the beam energy corresponding to the set cavity gradients, and 120 degrees phase advance per cell.
- 9) Steer the beam to the center of each quadrupole magnet manually, and determine BPM offsets with RF on.
- 10) Save corrector pattern and energy profile for further evaluation and cross-checks with beam-alignment data with RF off.
- 11) Perform a save/restore test.
- 12) Activate orbit lock (see instructions) at the end of the linac.
- 13) Set spreader in spectrometer mode and use the auto-phasing algorithm to phase individual cavities and thus maximize energy (see procedure 4/1-12).
- 14) Determine the beam energy. Compare to expectation.
- 15) Activate energy lock (see instructions) using the spreader as spectrometer.
- 16) Perform a save/restore test.
- 17) Verify optics in the linac lattice using the "Linac Optics Verification" procedure (See procedure 4/1-3).
- 18) Evaluate and resolve discrepancies.
- 19) Readjust spreader to be achromatic according to existing procedure (See procedure 4/1-2).
- 20) Perform a save/restore test.
- 21) Use "Beam transport Setup to NL high power dump" (See procedure) to thread beam through the extractor.
- 22) Park the beam at the dump for 4 hours and archive signals that carry signature of beam instabilities.
- 23) Beam properties measurements
- 24) Gradient cell region (See procedure 4/1-15)

25) RF checkout with beam (See procedure 4/1-8)

26) Cavity alignment

27) BPM and quadrupole alignment (See procedure 4/1-4).

- a) Set Injector quads in "Search light" mode and betatron match into north linac.
- b) Determine maximum transmission distance in linac
 - b1) by changing only the injection conditions
 - b2) by changing injection conditions and compensating for the earth's field.
- c) Perform beam alignment with linac quadrupoles off.
- d) Set Injector quads in nominal mode and betatron match into north linac.
- e) Verify beam alignment and betatron matching with linac quadrupoles on.

Linac Energy Management (LEM)

For a given energy at the end of North or South Linac and available cavities,

- finds cavity gradient distribution which minimizes the heat load using individual cavity characteristics
- calculates energy profile along the linacs
- calculates linac quad values consistent with calculated energy profile for different FODO cells: 60° , 90° , 120° .

Mon May 30 18:36:40 1994	Actions	Selections	Quit	ons
Total Energy at end of Injector: 45.00	MeV	Total Energy at end of North Linac: 325.0		ghigh
				5.000
				5.000

Hysteresis button will bring up TACL dipole/correctors/Quads window.

Hystereris

RCA1L023	0.000	0.00	5.000
RCA1L024	5.000	4.96	5.000
RCA1L025	5.000	4.96	5.000
RCA1L026	5.000	4.98	5.000
RCA1L027	5.000	4.96	5.000
RCA1L028	5.000	4.97	5.000
RCA1L031	4.000	4.20	5.000
RCA1L032	0.000	0.03	5.000
RCA1L033	0.000	0.00	5.000
RCA1L034	0.000	0.00	5.000
RCA1L035	3.000	3.16	5.000
RCA1L036	0.000	0.04	5.000

Transient Phasing

Purpose

Set cavity phases to crest using beam induced transients, to within 5° .

Beam conditions: Pulsed beam

$$I_0 = 250 \mu A$$

$$T_b = 20 \mu sec$$

Beam induced transients in the gradient signal are minimized, thus cavity is set at zero crossing.

Determine the accelerating side and increase cavity phase by 90° .

max. deceleration

max. acceleration

Phasing cavities with
beam induced
transients

$$V_D = 4.1 \text{ V } (\times 1)$$

$$\hat{I}_B = 250 \mu\text{A}$$

$$t_B = 10 \mu\text{s}$$

$$\tau_R = 60 \text{ Hz}$$

PSET = 70°

75°

80°

Phasing cavities using
beam induced transients.

$$\hat{I}_b = 250 \mu A$$

$$t_b = 10 \mu s$$

$$\tau_r = 60 \text{ Hz}$$

Signal: Output from
gradient detector

$$V_D = 4 V \hat{=} 4 \text{ MV/m}$$

Cavity 1Lφ3-8

Gain: 50dB

Signal/Noise ratio:
improved by averaging
(continuous, 61 samples)

← gradient detector
(50dB gain)

← averaged

← Beam sync

SPREADER - EXTRACTION - NORTH STUB

Linac Auto-phasing

Precise cavity phasing is achieved by maximizing the linac energy.

Spreader is set up in spectrometer mode.
Spreader BPM is used as a spectrometer.

Phase of an individual cavity is changed by $\pm 30^\circ$.

Initial beam position and beam position changes are recorded.

Crest phase is found from

$$\phi_{\text{crest}} = \phi_c + c \tan \left\{ - \frac{(y_+ - y_-)}{(y_+ + y_- - 2y_0)} \tan \frac{\Delta \phi}{2} \right\}$$

ϕ_0 : initial phase setting

$y_{\pm}$: beam position at $\phi = \phi_0 \pm \Delta \phi$

y_0 : beam position at ϕ_0

Reproducibility better than 1° .
Phasing time 2 min/cavity.

Cavity AutoPhase**Quit Program**☐ **Set Phases****Wait after change:** **seconds****Number of signals to average:** **Change in Phase:** **degrees****Selection:** **AutoPhase****R121 R122 R123 R124 R125 R126 R127 R128**

Linac Optics Verification

Purpose:

Verify the proper 120° phase advance/cell in the linac.

EAST ARCTEST

ISOCHRONICITY MEASUREMENT

- The linac energy was modulated with a square wave applied to the drive of one of the superconducting RF cavities.
- A 1500 MHz precision phase detector was used to measure the phase difference between a reference signal derived from one of the RF control modules in the linac and a beam signal from a BPM at the 90° point.
- Two optics sets were calculated by Dimad to give different values of M_{56} (change of path length with energy) and measured using this technique.

nominal M_{56} 1 m	measured 1.4 m
nominal M_{56} 0 m	measured 18.5 cm
- Applying small tweaks to the optics corrected the M_{56} of the latter case to

measured 1.8 cm	specification 10 cm
-----------------	---------------------
- The accuracy of the measurement technique is better than 3 mm.

Chao Jb16

CONCLUSIONS

- CEBAF commissioning proceeds on schedule. Beam to Hall C is expected by June 30.
- Detailed procedures have been developed for Injector to Hall C commissioning.
- Conversion to EPICS has been smooth and so far has not impeded operations.
- High level applications software is being prototyped and tested.
- Emphasis is on machine reproducibility.
- Beam quality appears to be within spec.

***THE PROPOSED BOOSTER
APPLICATION FACILITY AT BNL***

***P. THIEBERGER
BNL***

VIII

PROJECT COMPONENTS

- MP6 Tandem upgrade
- MP6 - HITL interconnection
- New Booster extraction system
- Beam transport and conditioning
- New experimental facility
- Instrumentation, controls and dosimetry
- Experimental support hardware and services

Examples of maximum energies estimated intensities
and dose rates for BNL Booster heavy ion beams

Ion	Energy (MeV/AMU)	Average Intensity (Ions/sec x 10 ⁸)	Range in water (cm)	Surface dose-rate in water for a 10 cm ² beam (Gy/min x 10 ²)
⁶ C ¹²	1500	33	185	2.4
⁸ O ¹⁶	1500	24	139	3.1
⁹ F ¹⁹	1500	23	131	3.8
¹⁴ Si ²⁸	1500	15	79	5.9
¹⁵ P ³¹	1500	10	77	4.5
¹⁶ S ³²	1500	10	69	5.2
¹⁷ Cl ³⁵	1500	9	67	5.2
²⁶ Fe ⁵⁶	1248	0.5	36	0.7
²⁹ Cu ⁶³	1127	6	29	10.5
³² Ge ⁷⁰	1097	5	27	10.8
³⁵ Br ⁷⁹	917	6	19	16.0
⁵³ I ¹²⁷	620	4	7.4	27.4
⁷⁹ Au ¹⁹⁷	350	4	2.2	77.5
⁷⁹ Au ¹⁹⁷	445	0.2	3.2	3.5

ALTERED MP-7 MATCHING INJECTION

NEW MP-6 INJECTION

EXISTING MP-7 INJECTION

ALTERNATING BOOSTER CYCLES

a. PROTONS - HEAVY IONS

b. HEAVY IONS (1) - HEAVY IONS (2)

BOOSTER APPLICATIONS FACILITY

BEAM CHARACTERISTICS

TARGET SPOT	0.5 to 10 cm	AREA A
	5 to 100 cm	AREA B
	1 to 20 cm	AREA C
MICROBEAM OPTION	25 to 50 microns (LOW INTENSITY)	
BEAM SPOT UNIFORMITY	+- 10 %	
BEAM SPILL UNIFORMITY	+- 20 %	SLOW SPILL

AGS BOOSTER

TECHNICAL REQUIREMENTS FOR BOOSTER APPLICATIONS FACILITY

EXTERNAL BEAM

**BEAM TRANSPORT SYSTEM AND TUNNEL
WITH BRANCH LINES**

EXPERIMENTAL AREAS

**NEW BUILDING
AND EXPERIMENTAL EQUIPMENT**

BEAM EXTRACTION

SLOW SPILL EXTRACTION SYSTEM

BOOSTER OPERATIONS

**PULSE TO PULSE SWITCHING
CONTROLS & INSTRUMENTATION**

TANDEM SYSTEMS

**MP-6 BEAM TRANSPORT BRANCH
MP-6 VOLTAGE UPGRADE**

LABORATORY BUILDING

- * TOTAL ENCLOSED AREA 6000 sqft
- * TWO SUPPORT ROOMS PER TARGET
- * FOUR OFFICES
- * BEAM CONTROL ROOM
- * MECHANICAL SERVICE EQUIPMENT AREA
- * RADIOACTIVE EQUIPMENT STORAGE
- * MISCELLANEOUS SERVICE ROOM
- * SEPARATE BEAM POWER SUPPLY BUILDING
1200 sqft

C O N C L U S I O N S

- * IT IS FEASIBLE TO SUPPORT A HEALTH RESEARCH PROGRAM AT THE AGS BOOSTER.
- * AFTER AN INITIAL INVESTMENT IN A NEW RESEARCH FACILITY AND A NEW EXTERNAL BEAM LINE THE PROGRAM CAN OPERATE STAND-ALONE OR IN CONJUNCTION WITH THE PHYSICS RESEARCH PROGRAMS OF THE AGS AND RHIC.
- * THE PROGRAMS CAN BE SERVICED SIMULTANEOUSLY BY A RAPID PULSE TO PULSE SWITCHING TECHNIQUE.
- * A SLOW BEAM SPILL CAN BE PROVIDED.
- * FACILITY PLANS CAN BE DEVELOPED IN CLOSE COLLABORATION WITH THE USER COMMUNITY.
- * PRECEDENTS EXIST FOR SUPPORT STRUCTURES AND FUNDING SCENARIOS FOR SUCH PROGRAMS.

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 - Progress Report and a report on LINAC 90 Conf., Albuquerque, NM.

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

11/20/90 I. Ben-Zvi (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 Trasport Beamline, and Possible Quadrupole schems 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 variatin 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?