Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

TRANSFORMING THE BNL 200 MeV H^- LINAC: 10^3 LOWER LOSSES, 2× HIGH-CURRENT TRANSMISSION, AND 2× LOWER EMITTANCE

Deepak Raparia, BNL

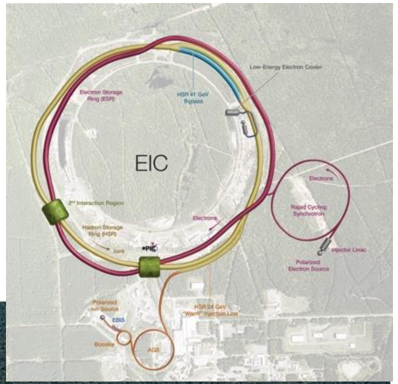
MSU-ASES Seminar

March 27, 2027

Outlines

- Introduction
- BNL Linac
- Losses in BNL H^- linac
- Mitigation for beam losses
  - Lattice changes
  - Collimators
  - Simulation assisted beam tuning
- Results
- Conclusion

Overview of the BNL Hadron Complex

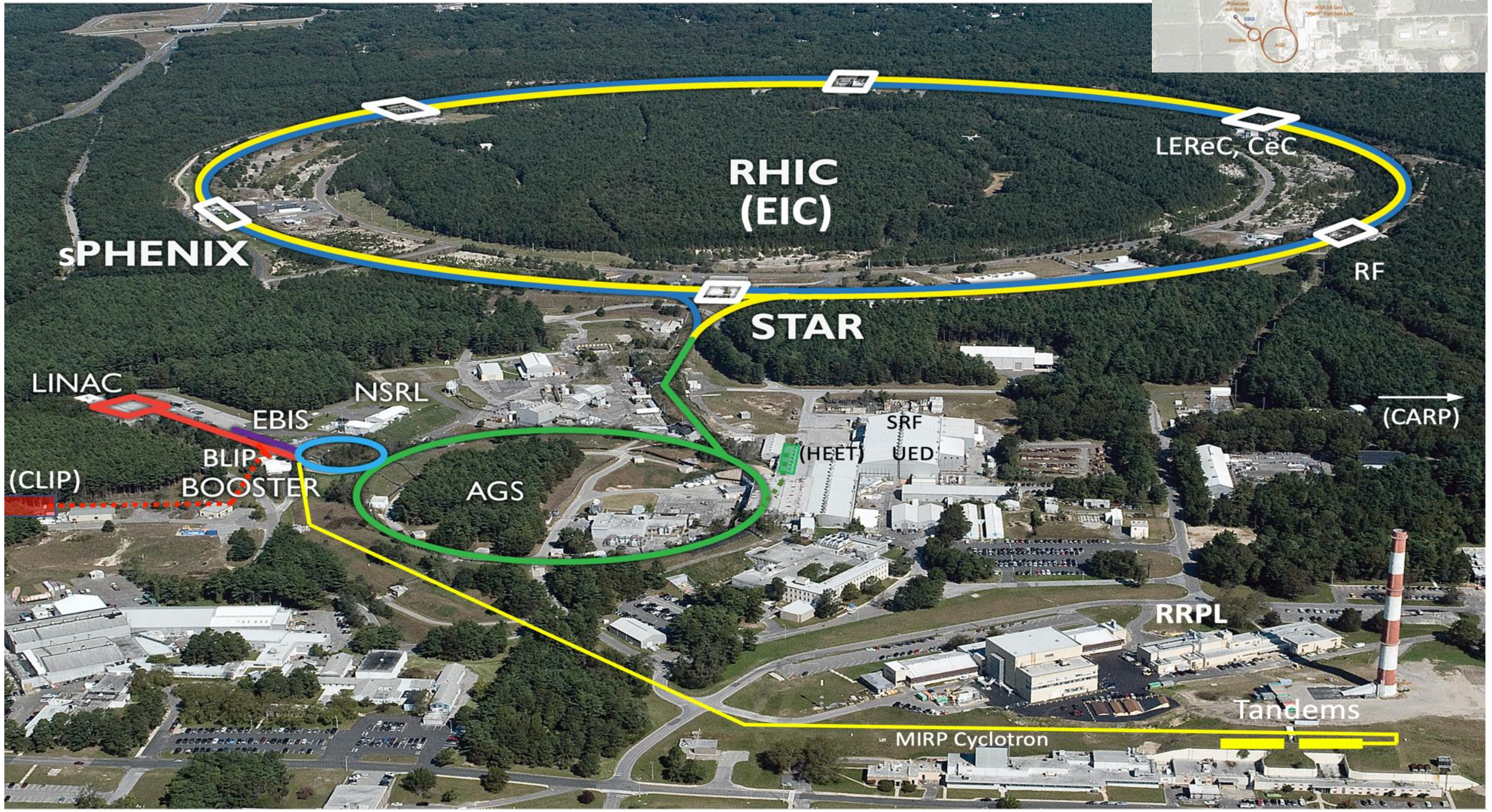


Uniquely flexible and only hadron collider in US for exploration of QCD phase diagram and proton spin

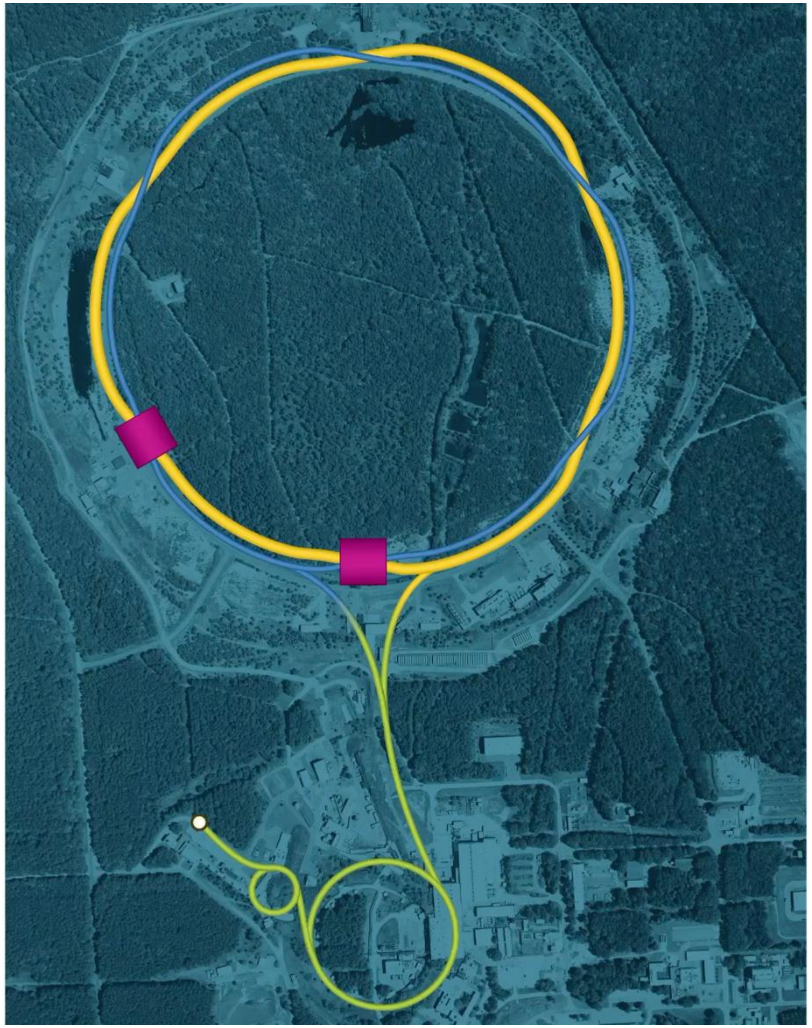
Injectors also used for application programs:

- Linac/BLIP for isotope production
- Booster/NSRL for space radiation studies
- Tandem for industrial/academic users

R&D for future facilities and application sources, pol. beams, …

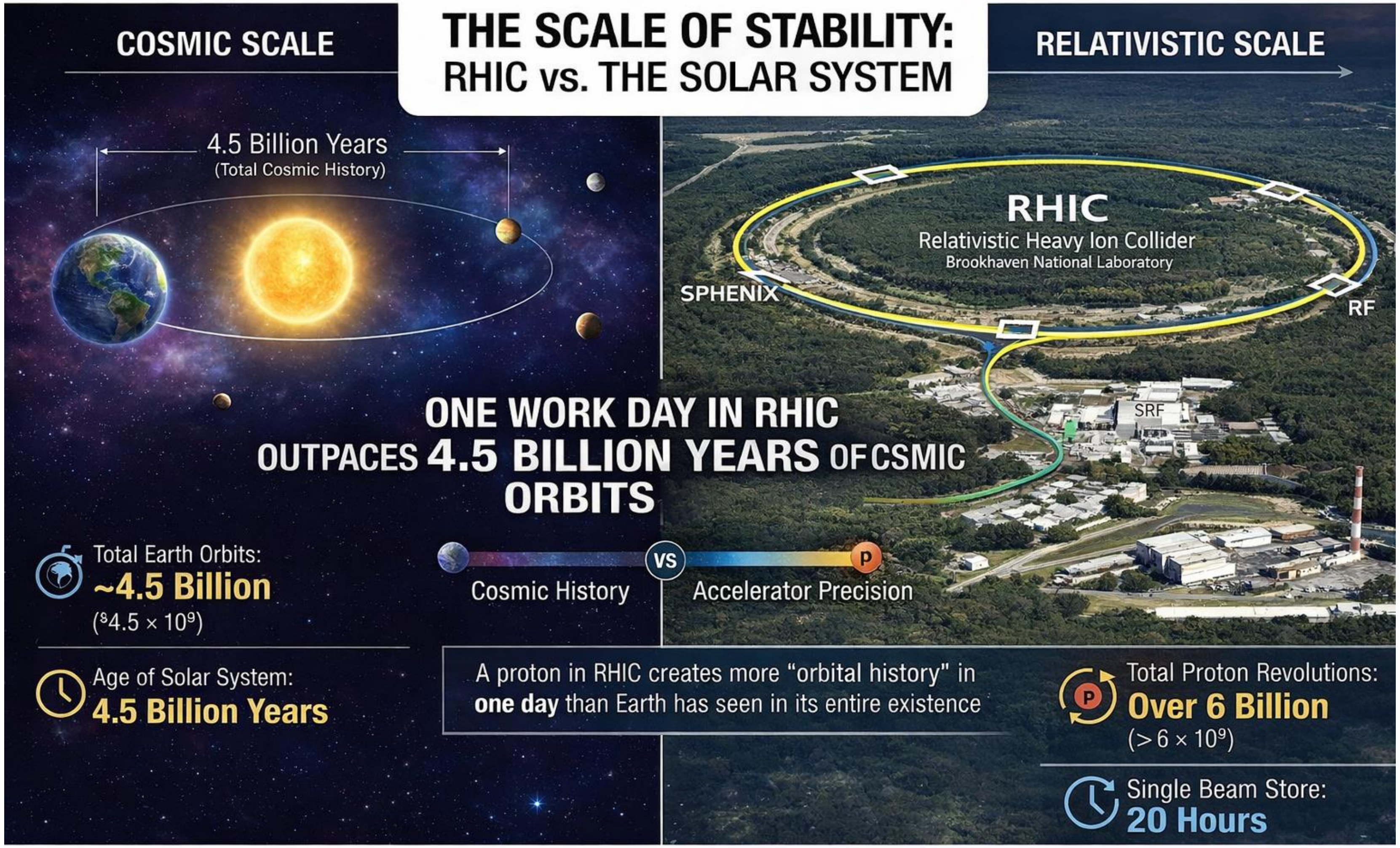


RHIC: The World's Most Versatile Collider



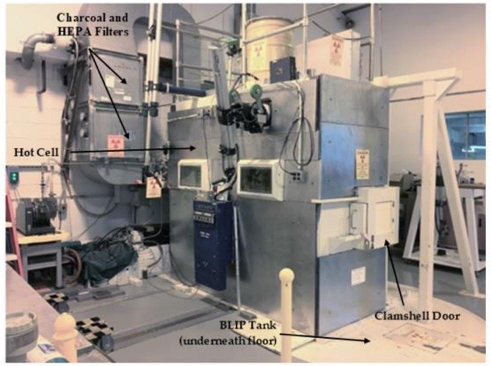
- High-intensity, high-brightness ion and proton sources
- 49 different combinations of energy, ions, and collision configurations
- 10 different ion species
- 18 center-of-mass energies
- Innovative accelerator technologies
- Gold-gold collision rates 44 times higher than design
- Only polarized proton collider in the world

Abhay Deshpande, RHIC Capstone Event, MCR, 6 Feb 2026

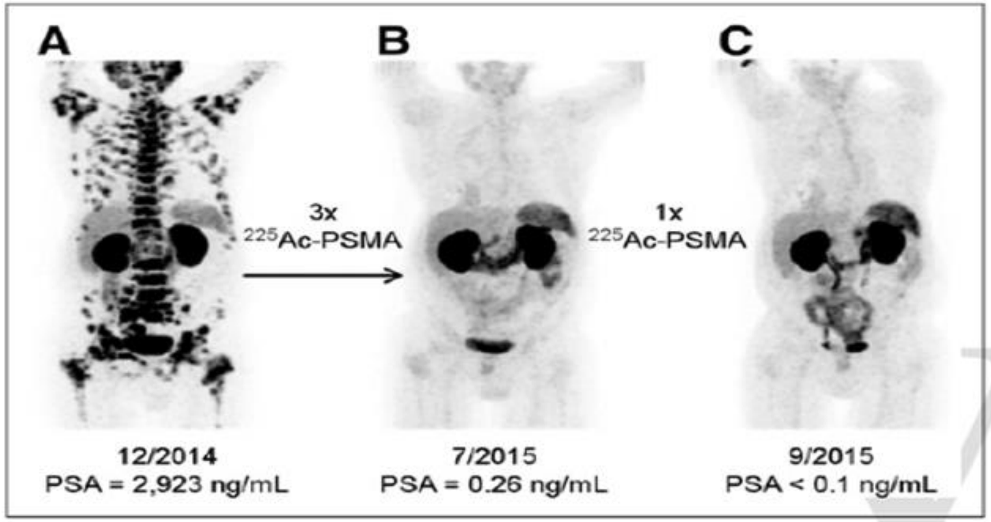


RHIC Stability: Where 20 hours of accelerator physics outpaces 4.5 billion years of planetary motion.

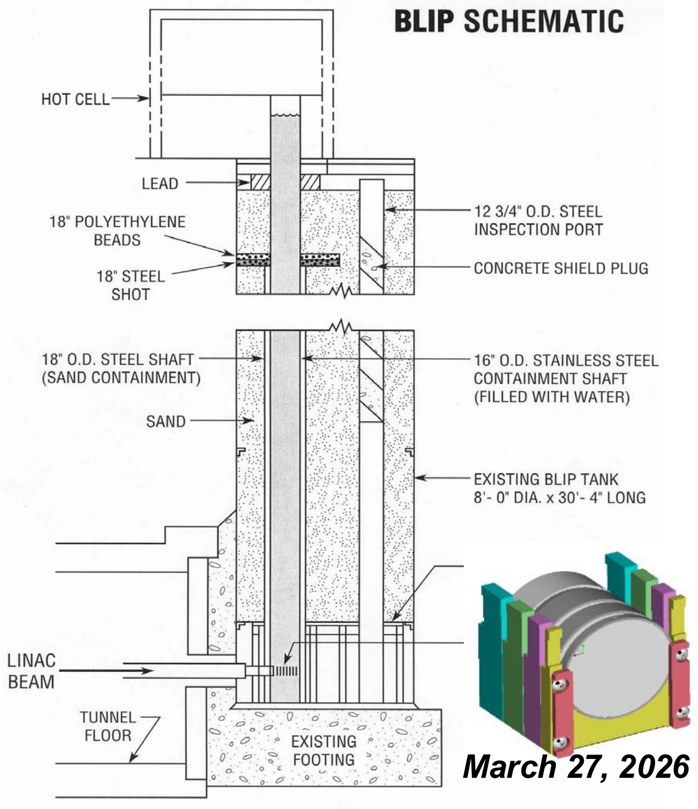
Brookhaven Linac Isotope Producer (BLIP)



- Target irradiation with 66 – 200 MeV, 200 μA proton beam
- Radioisotope production for therapeutic and diagnostic use



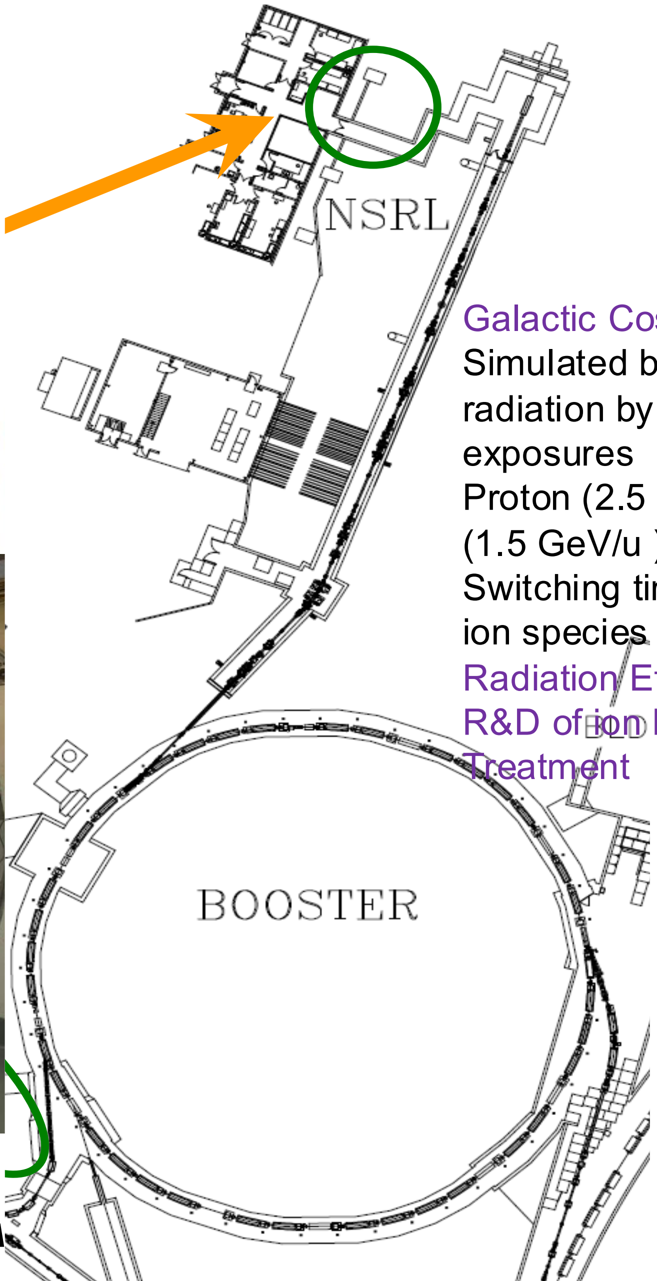
Ac-225: Alpha emitter for treatment of metastatic prostate cancer



NASA Space Radiation Laboratory (NSRL)

Towards Safer Spaceflight

A joint Brookhaven Lab/NASA facility to study the effects of cosmic radiation



Galactic Cosmic Ray

Simulated by mixed radiation by sequences of exposures

Proton (2.5 GeV) and ions (1.5 GeV/u)

Switching time between ion species ~ 40 sec

Radiation Effect Studies

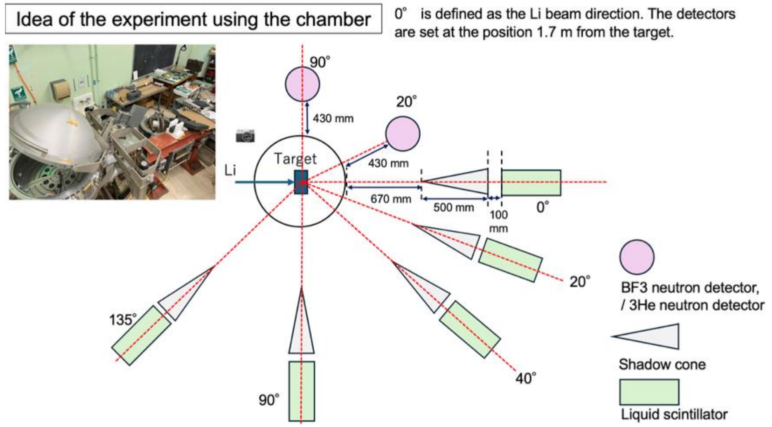
R&D of ion beam cancer Treatment

Tandem Van de Graff Facility

- Radiation Effects testing and Calibration
- Sigle Event Upset Test facility
- Ion irradiation/implantation
- Radiobiology Research Facility
- Also, backup for EBIS

Neutron production experiment at Tandem

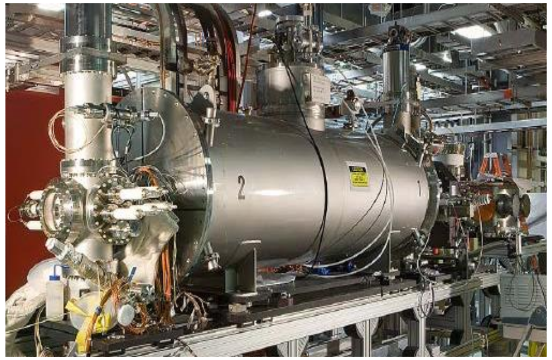
Masahiro, Toshiro, Madhawa, Antonino, Takeshi, Shunsuke, Dannie, Benedikt (Germany), Phillip (Germany)



Very high directivity was confirmed using Shadow Cone technique

Hadron Preinjector at BNL

Linac (1970) | EBIS injector (2010) | Tandem (1970)

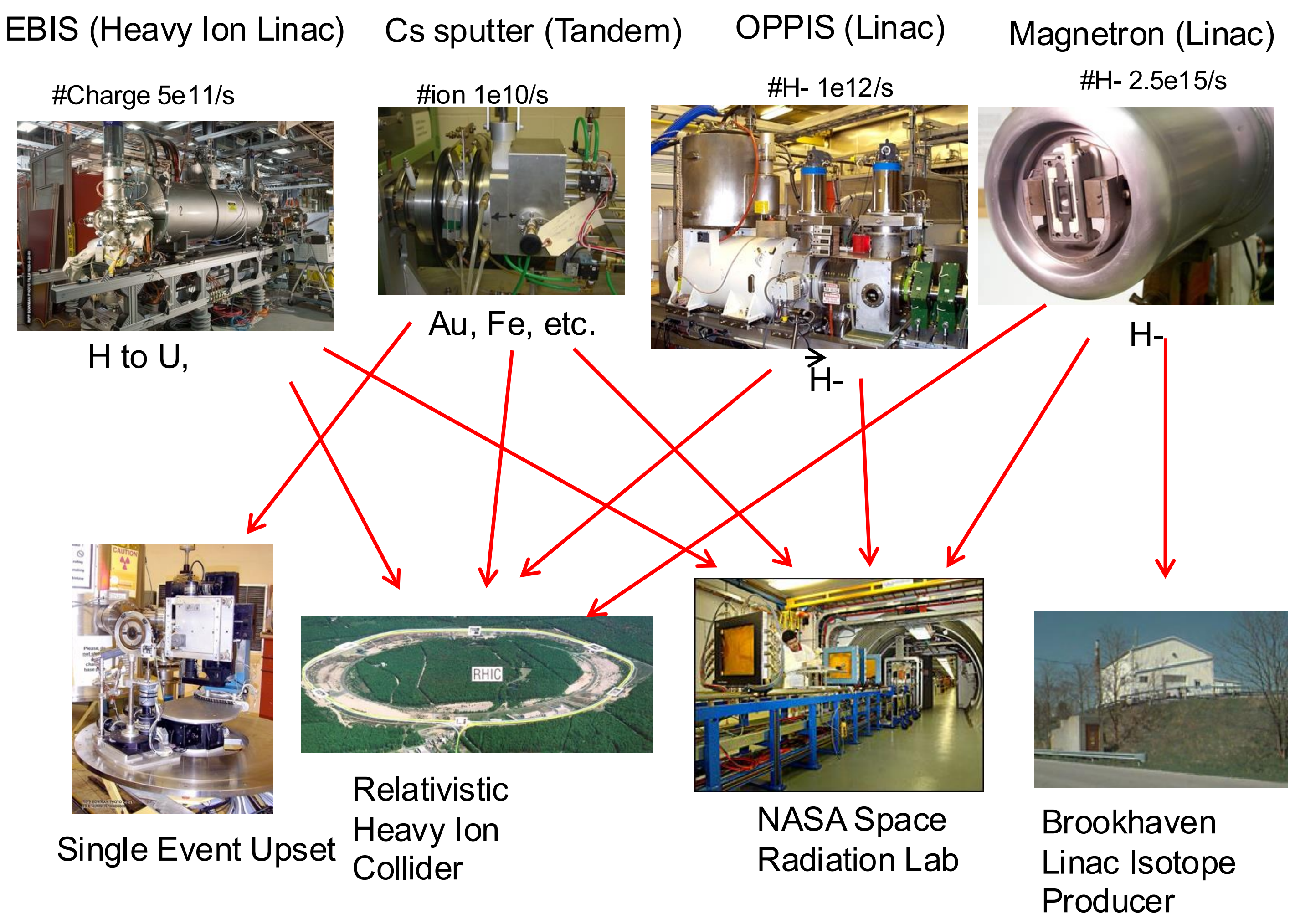


Ion:	H^-, $H^{-\wedge}$	H-U	H-U
E:	10 -200 MeV	2 MeV/u	14 MV(1+q)
I_{ave} :	200uA,	~150 nA	~10 μA
RR:	10 Hz	5 Hz	dc/pulsed
User:	**BLIP,** NSRL, RHIC	NSRL, RHIC	SEU, NSRL RHIC,

Can serve all users simultaneously

Brookhaven National Laboratory

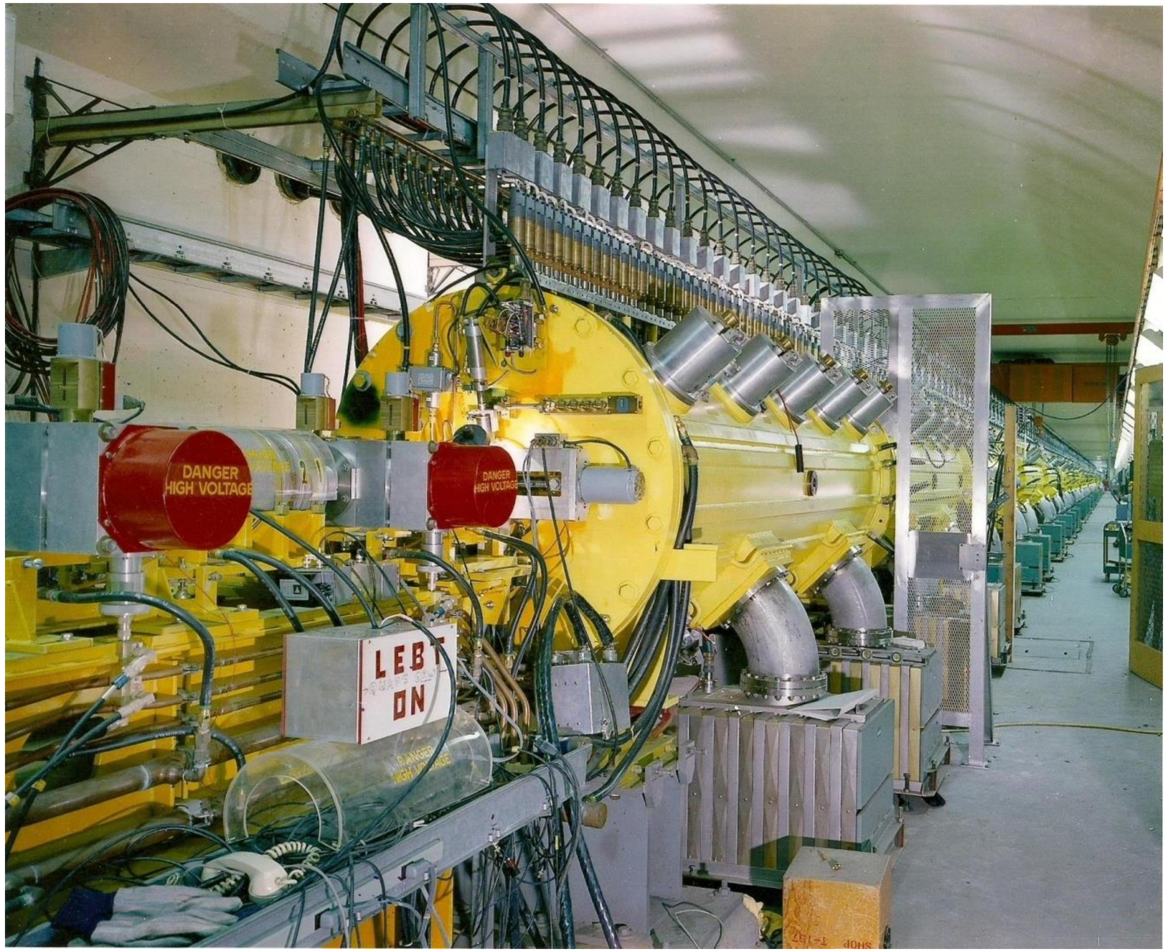
All sources can serve all users simultaneously



Laser Ion sources for the new application

1972 BNL Linac 200 MeV

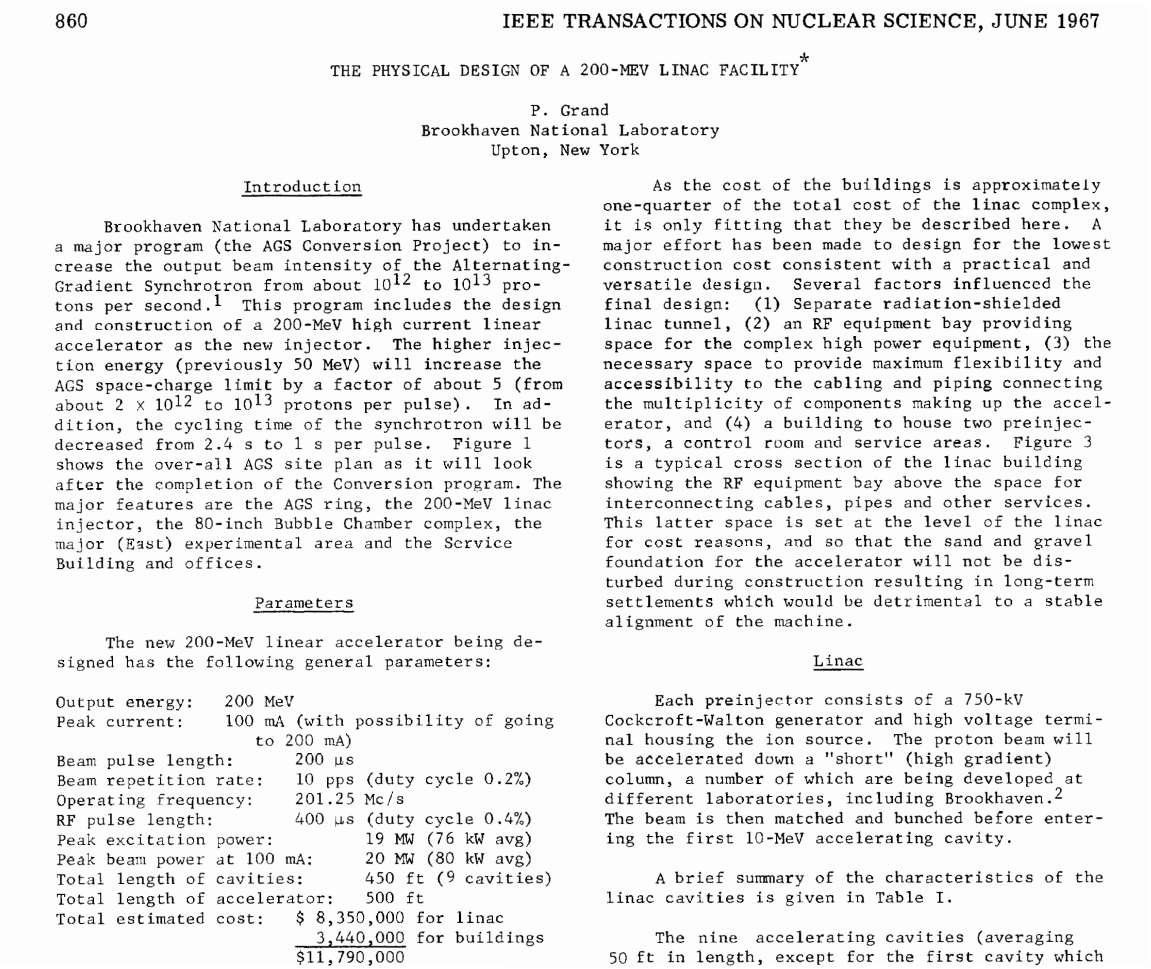
Cockcroft-Walton 750 KeV



Drift Tube Linac (Alvarez Linac) 200 MeV

J. D. Cockcroft and E.T.S Walton, Proc. Roy. Soc. 136A, 619 (1932)
L. W. Alvarez, et al, Rev. Sci. Ins. 26, 111 (1955)

BNL LINAC Design



THE PHYSICAL DESIGN OF A 200-MEV LINAC FACILITY*

P. Grand
Brookhaven National Laboratory
Upton, New York

Introduction

Brookhaven National Laboratory has undertaken a major program (the AGS Conversion Project) to increase the output beam intensity of the Alternating-Gradient Synchrotron from about 10^{12} to 10^{13} protons per second.[1] This program includes the design and construction of a 200-MeV high current linear accelerator as the new injector. The higher injection energy (previously 50 MeV) will increase the AGS space-charge limit by a factor of about 5 (from about 2×10^{12} to 10^{13} protons per pulse). In addition, the cycling time of the synchrotron will be decreased from 2.4 s to 1 s per pulse. Figure 1 shows the over-all AGS site plan as it will look after the completion of the Conversion program. The major features are the AGS ring, the 200-MeV linac injector, the 80-inch Bubble Chamber complex, the major (East) experimental area and the Service Building and offices.

Parameters

The new 200-MeV linear accelerator being designed has the following general parameters:

Output energy: 200 MeV
Peak current: 100 mA (with possibility of going to 200 mA)
Beam pulse length: 200 μs
Beam repetition rate: 10 pps (duty cycle 0.2%)
Operating frequency: 201.25 Mc/s
RF pulse length: 400 μs (duty cycle 0.4%)
Peak excitation power: 19 MW (76 kW avg)
Peak beam power at 100 mA: 20 MW (80 kW avg)
Total length of cavities: 450 ft (9 cavities)
Total length of accelerator: 500 ft
Total estimated cost: $ 8,350,000 for linac
3,440,000 for buildings
$11,790,000

As the cost of the buildings is approximately one-quarter of the total cost of the linac complex, it is only fitting that they be described here. A major effort has been made to design for the lowest construction cost consistent with a practical and versatile design. Several factors influenced the final design: (1) Separate radiation-shielded linac tunnel, (2) an RF equipment bay providing space for the complex high power equipment, (3) the necessary space to provide maximum flexibility and accessibility to the cabling and piping connecting the multiplicity of components making up the accelerator, and (4) a building to house two preinjectors, a control room and service areas. Figure 3 is a typical cross section of the linac building showing the RF equipment bay above the space for interconnecting cables, pipes and other services. This latter space is set at the level of the linac for cost reasons, and so that the sand and gravel foundation for the accelerator will not be disturbed during construction resulting in long-term settlements which would be detrimental to a stable alignment of the machine.

Linac

Each preinjector consists of a 750-kV Cockcroft-Walton generator and high voltage terminal housing the ion source. The proton beam will be accelerated down a "short" (high gradient) column, a number of which are being developed at different laboratories, including Brookhaven.[2] The beam is then matched and bunched before entering the first 10-MeV accelerating cavity.

A brief summary of the characteristics of the linac cavities is given in Table I.

The nine accelerating cavities (averaging 50 ft in length, except for the first cavity which

First Beam

Letter to the Editor

SIR,

Initial Performance of New Brookhaven Linac†

The first section of the BNL 200-MeV proton linac has been successfully operated, accelerating a current of 200 mA to 10 MeV. The linac is very similar to the NAL injector‡ so will not be described here in detail. Briefly, the operational equipment consists of the Cockcroft–Walton generator, duoplasmatron source, high gradient accelerating column, beam transport from column to first cavity (including two bunchers), the cavity with its 201.25 MHz rf system and quadrupole focusing system and a 10-MeV analysis station. All of the equipment is in its final position in the linac building. The 10-MeV analysis station was a temporary setup in the location which now is occupied by the second cavity.

Complete beam monitoring and analysis equipment has been installed. Both before and after the cavity there are current transformers, quartz viewing flags and emittance devices for both horizontal and vertical planes. In addition, following the cavity there was a magnetic spectrometer for recording beam momentum and momentum spread.

A beam was first accelerated to 10 MeV in March and was followed by several months of careful measurement and optimization studies before peak performance was obtained. The most important feature in tuning up is the proper matching of beam emittance to the acceptance at the beginning of the cavity.

The optimum beam conditions are given in the table below.

Operations were carried out at pulse rates of 1 and 10 pulses per second and pulse lengths from 20 to 150 μsec. In addition, deuterons were accelerated in the $2\beta\lambda$ mode to 5 MeV using 400 kV injection energy. A peak current of 18 mA was achieved without complete optimization of the system.

George W. Wheeler, Kenneth Batchelor and Th. J. M. Sluyters
Brookhaven National Laboratory,
Upton, New York, USA

† Work performed under the auspices of the U.S. Atomic Energy Commission.
‡ C. D. Curtis *et al.*, *Particle Accelerators*, **1**, 93 (1970).

Injection energy:	780 kV	Current at base of column	0.400 A
Emittance at input, Horiz.	19.5π cm-mrad	Current entrance of cavity	0.270 A
Vert.	19.5π cm mrad	Current at 10 MeV	0.210 A
Emittance at 10 MeV, Horiz.	6π cm-mrad	Energy	10.4 MeV
Vert.	7.5π cm-mrad	Energy Spread (FWHM)	0.5 MeV
Cavity synchronous phase	− 32°	Cavity Transmission	79%

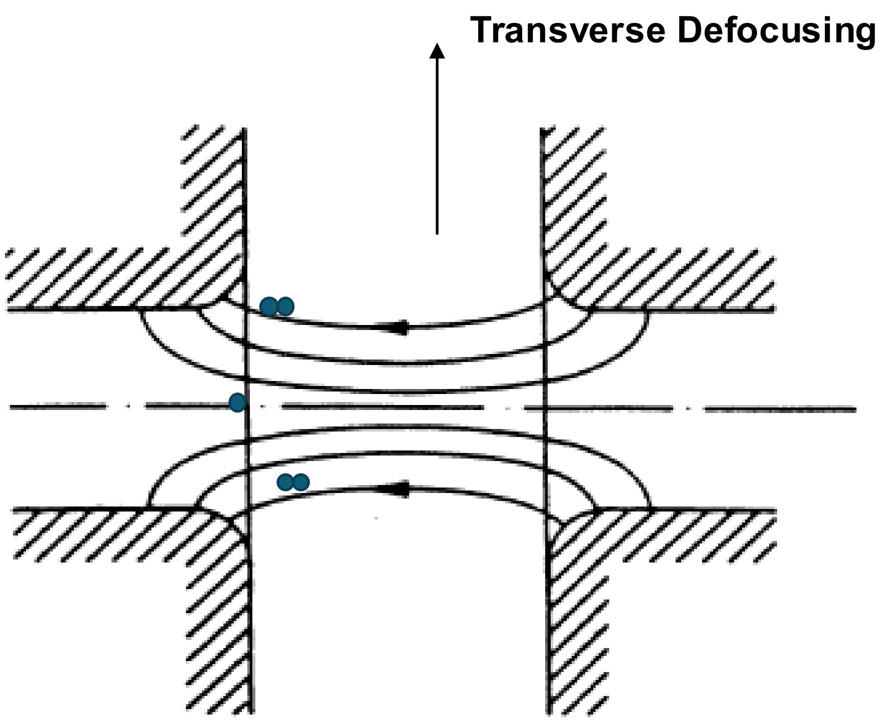
Received 10 August 1970

Working of BNL linac

- LEBT: strong transverse space charge
- MEBT: longitudinal space charge and mismatch
- DTL injection sensitivity

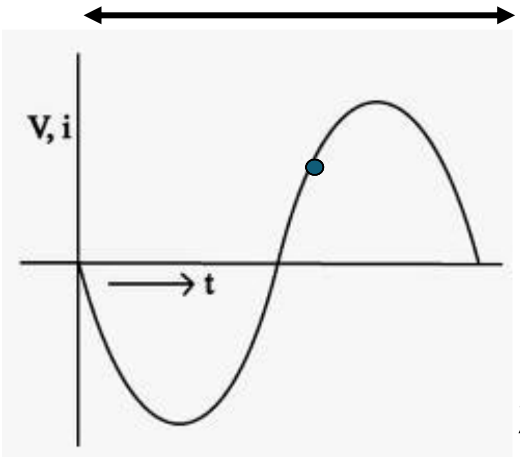
(1) Acceleration

Accelerating Gap Always comes with defocusing in transverse direction



Accelerating Gap

d=βλ

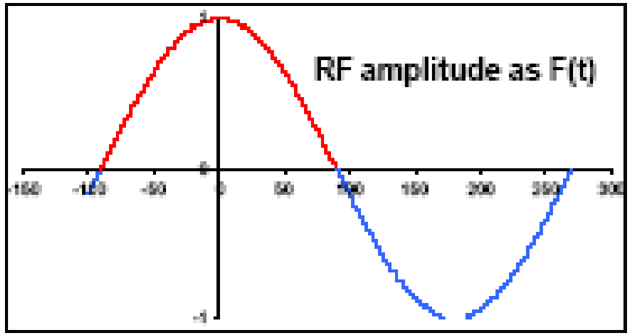


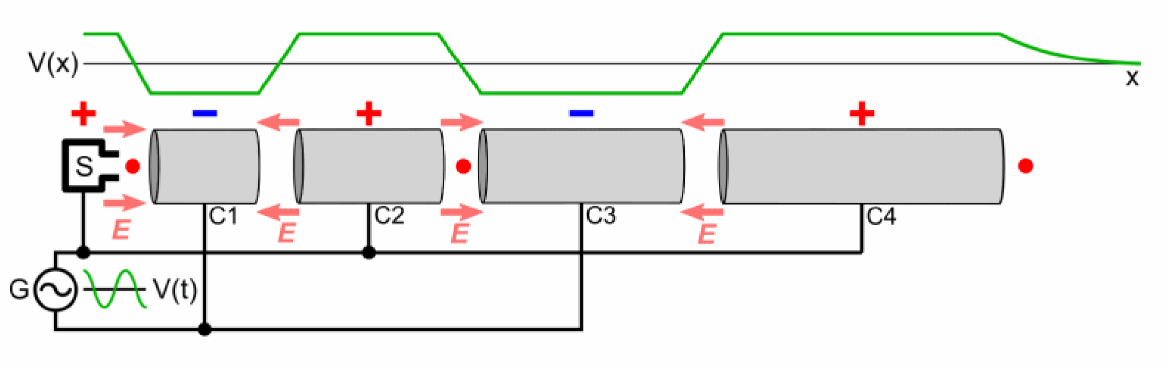
β=velocity/speed of light
λ= wave length

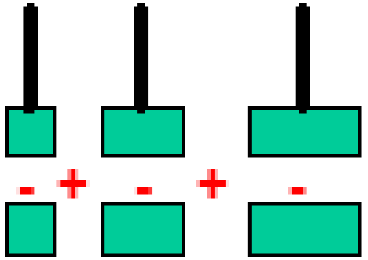
RF field rising in time=> RF defocusing

Working of Drift Tube Linac

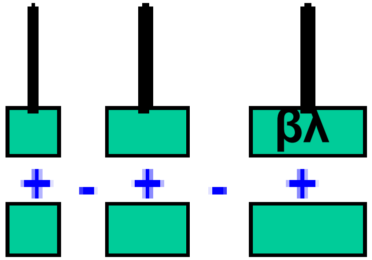
RF transmitter power excites the cavity causing alternating EM field: in the cavity (SNS: f = 402.5 MHz)





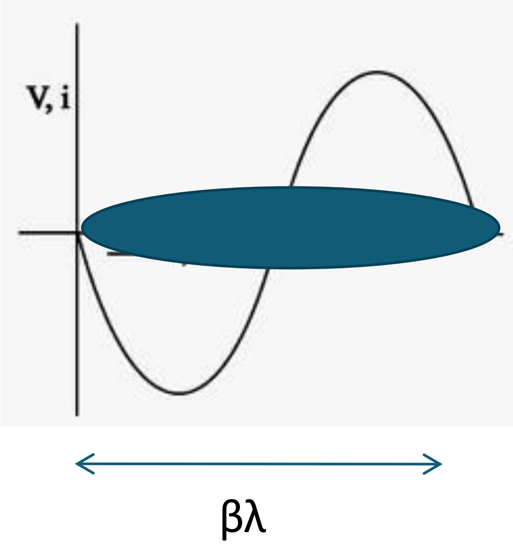


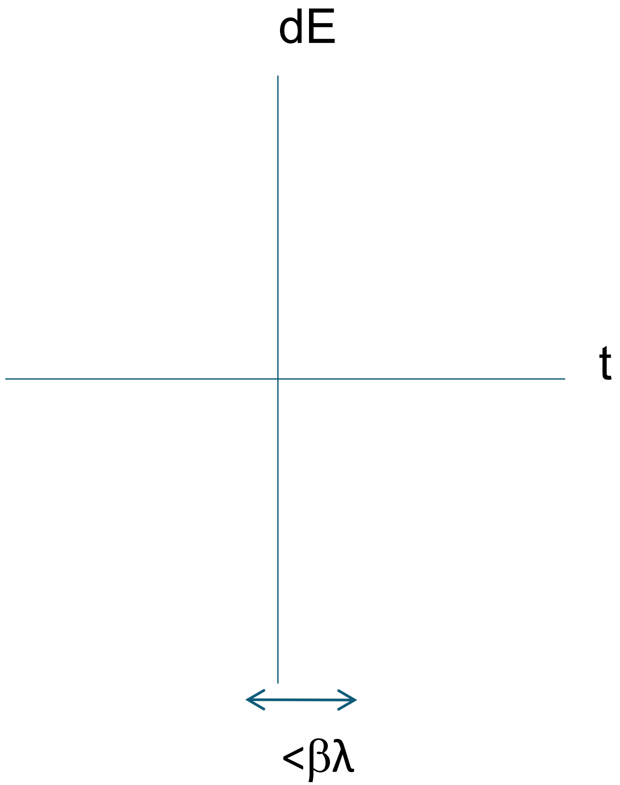
Charged particles gain energy in the gaps between drift tubes during the accelerating half of the RF field



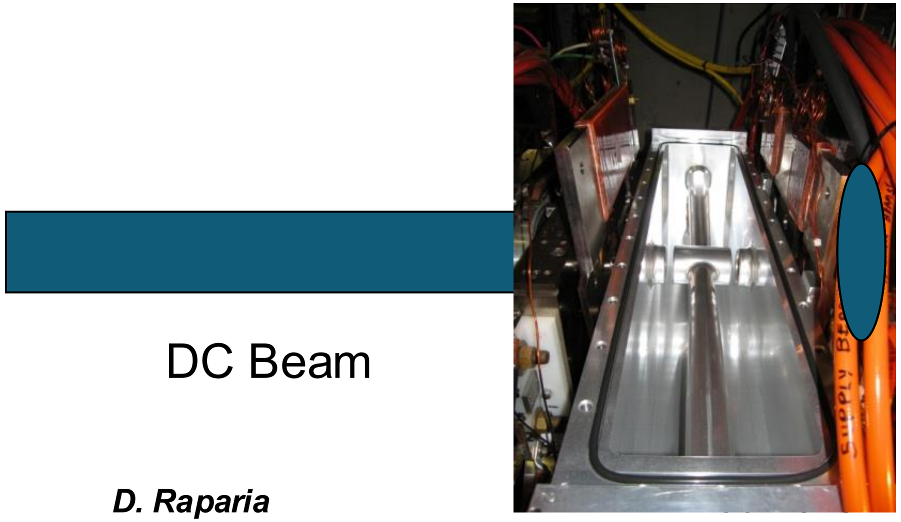
Drift tubes shield beam from de-accelerating RF field

(2) Bunching





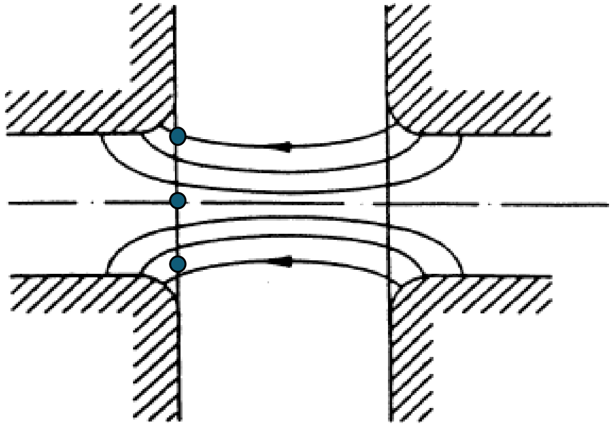
Buncher

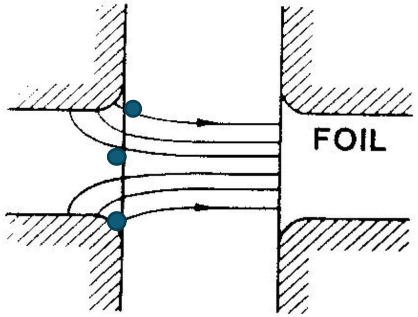


DC Beam

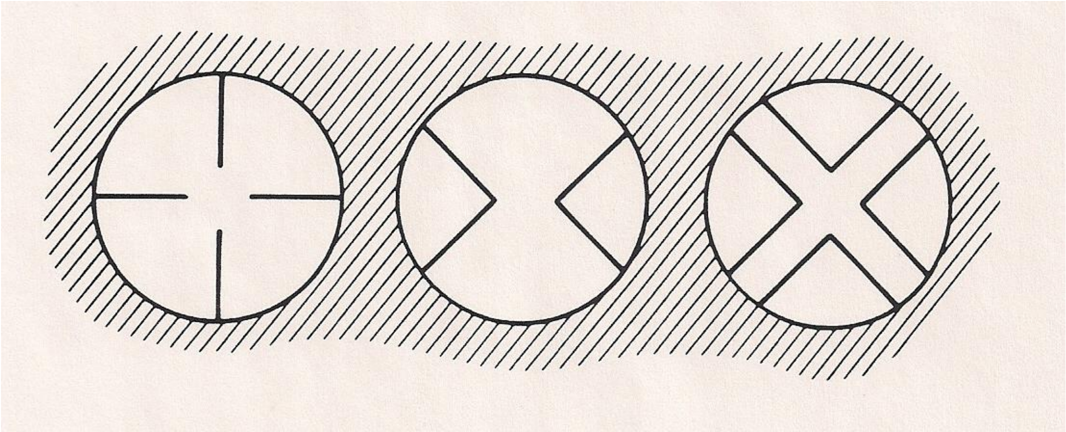
Bunched Beam
Higher Charge Density

(3) Focusing





Before 1970s

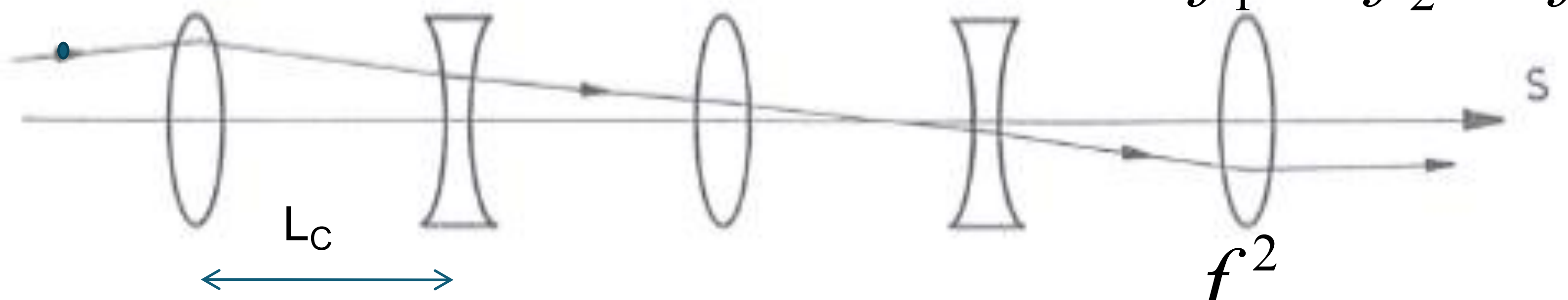


Foils used for focusing low intensities

(3) Focusing

To transport charge particles, one needs to provide external forces (focusing) to keep them within the beam pipe

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} + \frac{L_c}{f_1 f_2}$$

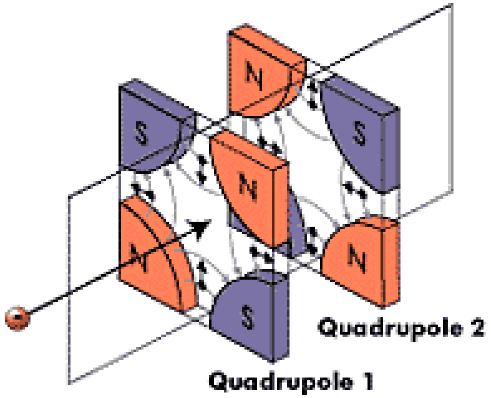


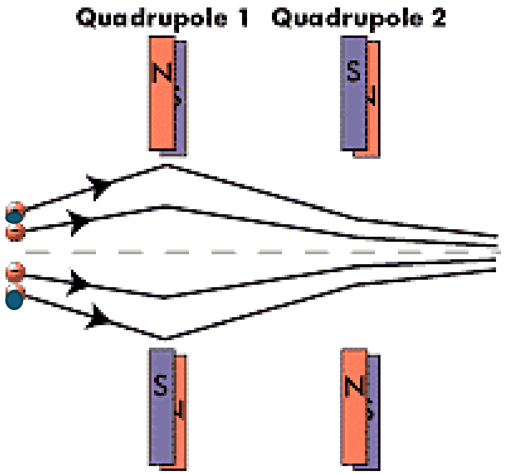
$$F = \frac{f^2}{L_c}; f_1 = -f_2$$

Focusing + Defocusing + Focusing +Defocusing + Focusing = Focusing

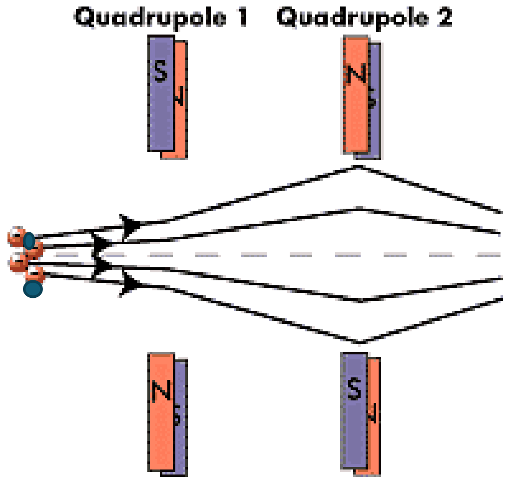
Focusing with Quadrupole Magnets

Magnetic quadrupole
Strong focusing, higher energies
In a DTL LINAC they are located inside the drift tubes





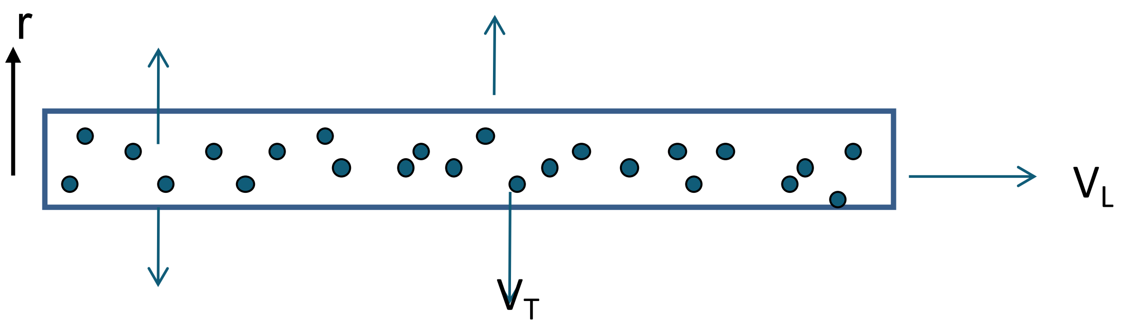
Side View

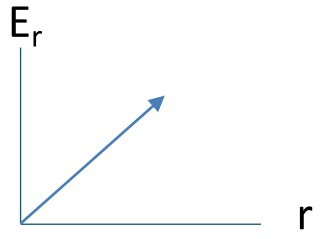


Top View

(4) Coulomb Repulsive Force
Continuous Beam

Dominates low-energy beam physics





- **Similar charge repel each other and try to blow up the beam**
- **Higher the charge larger the repulsive force**
- **Measure of charge density called space charge potential V_s**

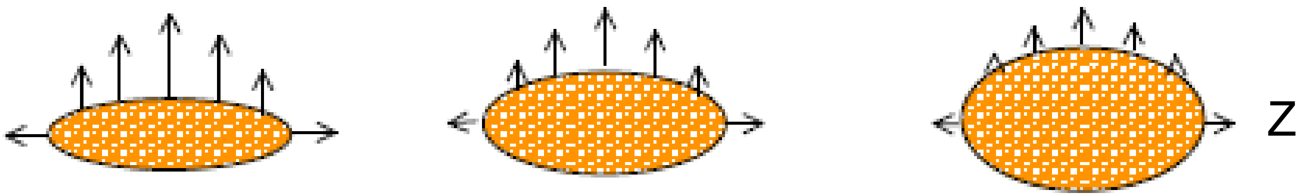
$$V_s = \frac{30I}{\beta}$$

I= current

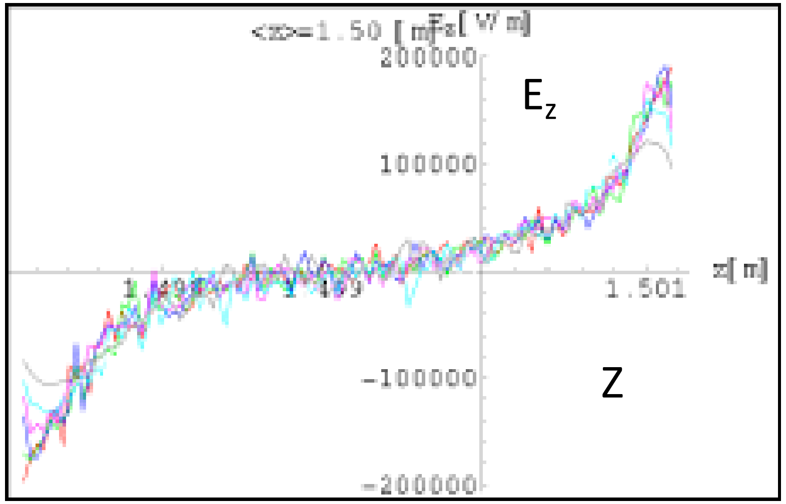
Higher the velocity lower the space charge effect

(4)Repulsive forces for bunch beam

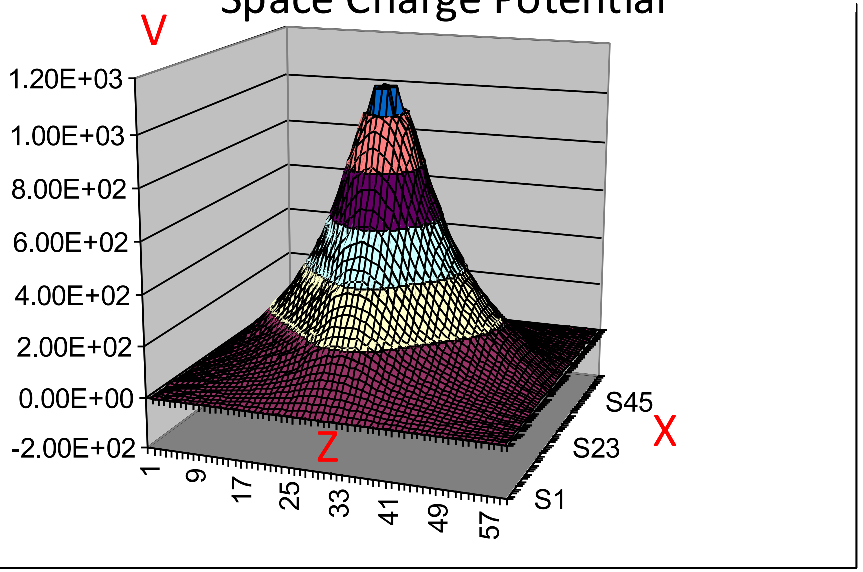
longitudinal space charge and mismatch



Longitudinal Electric field due to space charge



Space Charge Potential



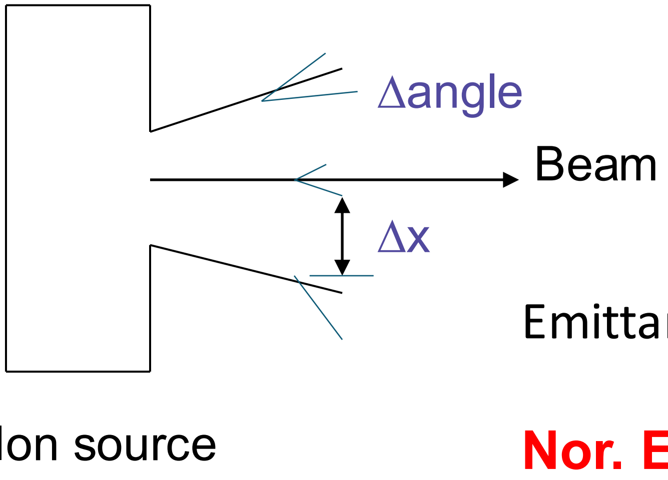
Transverse space charge force is linear with radius

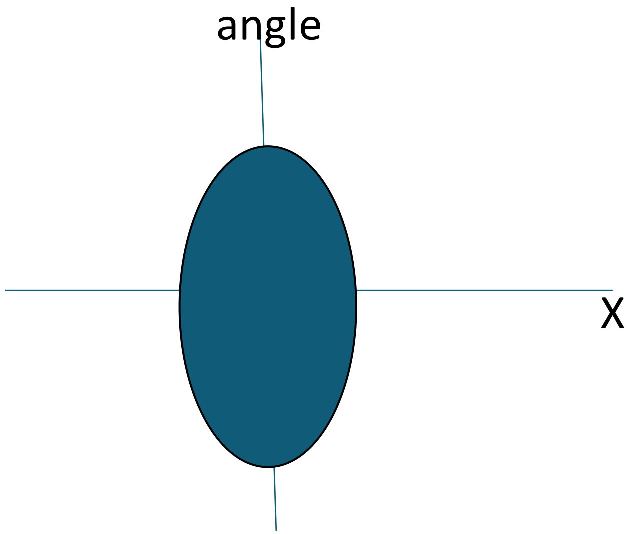
Longitudinal space charge force is not linear with length

Linear accelerator
(5)Emittance- Figure of Merit

Emittance (ε) = $\Delta x * \Delta angle$ = area of Ellipse

Nor. Emittance (ε_N) = $\beta\gamma\varepsilon$





Emittance define quality of beam, smaller is better

Nor. Emittance (ε_N) is preserve during the acceleration

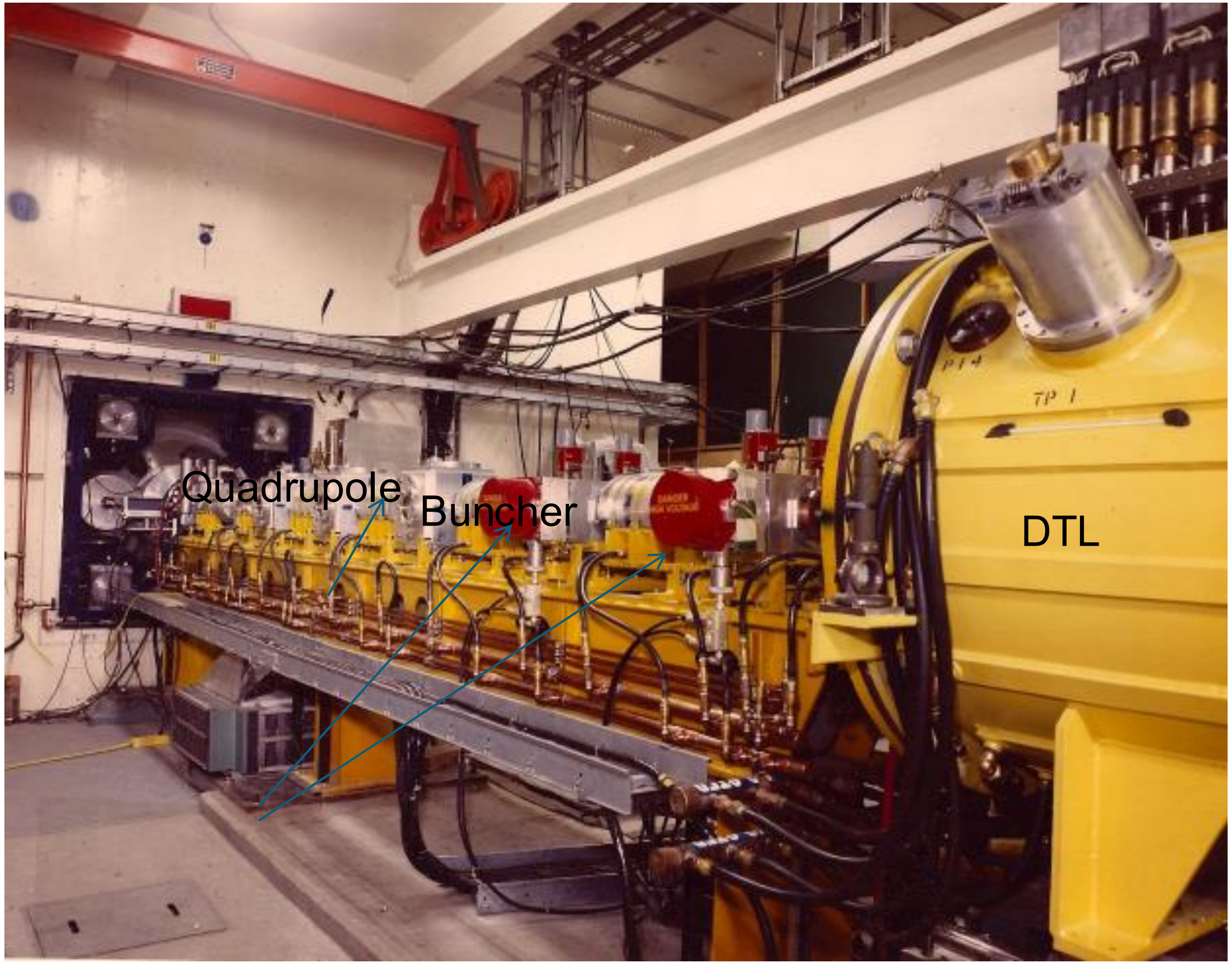
It also specify aperture and length between lenses

Emittance ~ (aperture)^2/Length between Lenses (L_C)

BNL Linac

A 55-year-old linac significantly improved through space charge control

1970s BNL Low Energy Beam Transport (LEBT)



BNL LINAC Beam Parameters

Frequency	**201.25 MHz**
Injection Energy	**0.750 MeV**
Final Energy	**10-200 MeV**
Peak Current	**~60 mA/ ~ .5 mA P^**
Pulse Length	**600 μs**
Repetition Rate	**6.67 Hz**
Number of cavities	**9**
Length	**144.8 m**
Total Peak RF Power	**22 MW**

RHIC Program
Energy: 200 MeV ,
Intensity: ~400 μA ,
Pulse length: 300 μs
Pol: 85%
goals: max. pol. & min. emit.

BLIP Program
Energy: 66–200 MeV
Pulse length :~600 μs
Intensity 60 mA
Goals: uniform beam & min. losses.

NSRL Program:
Energy : 200 MeV
Intensity: ~350 μA ,
Pulse length: 300 μs
Goal: schedule

Can be serve all programs simultaneously

R F Power for Linac

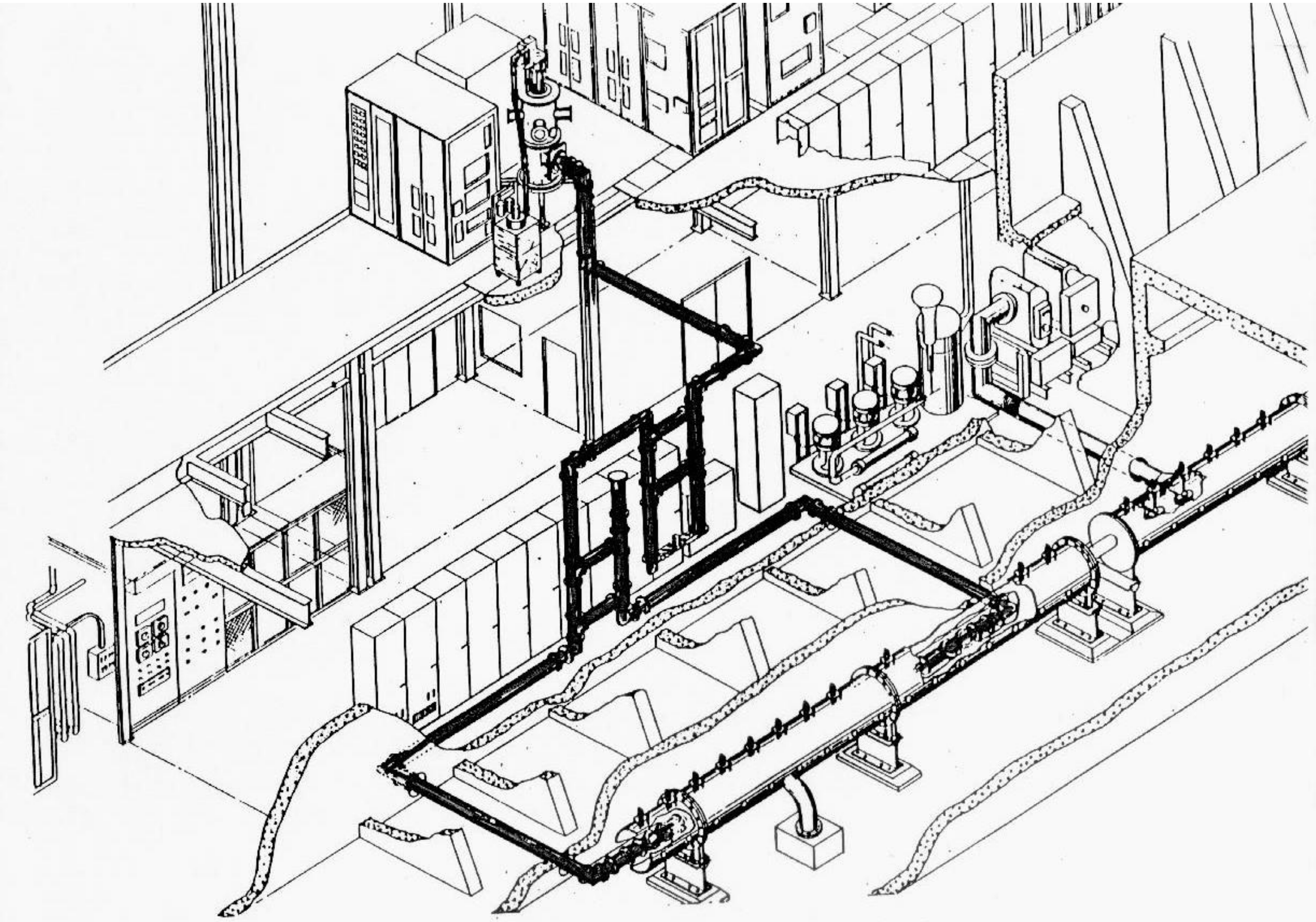
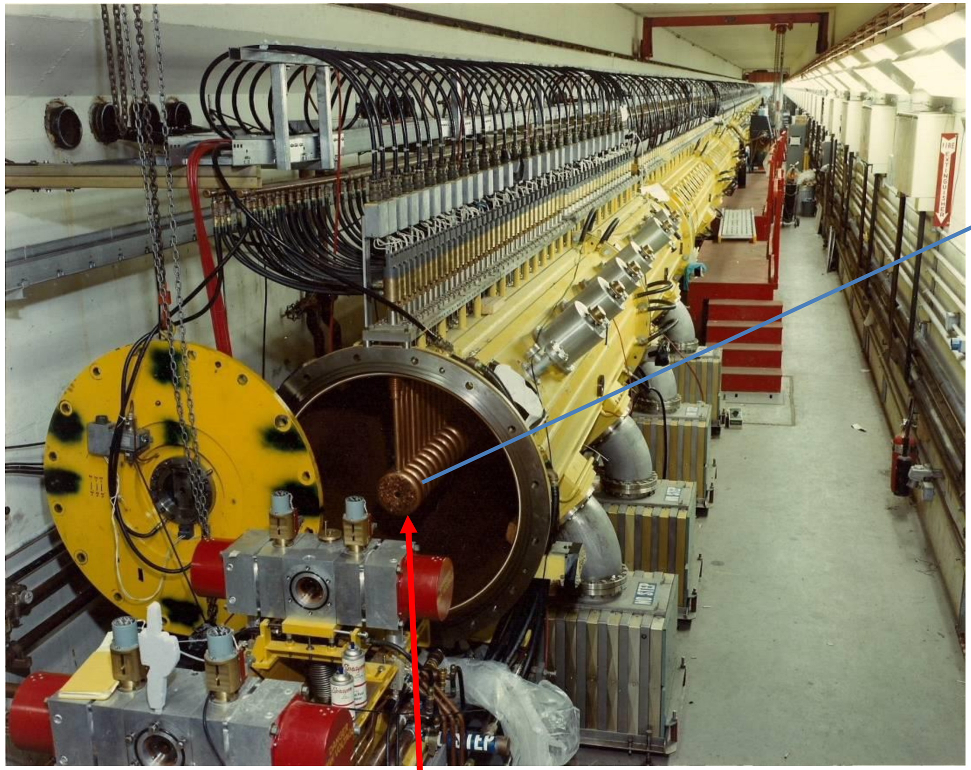


FIGURE III.3.b.2 RF transmission-line layout.

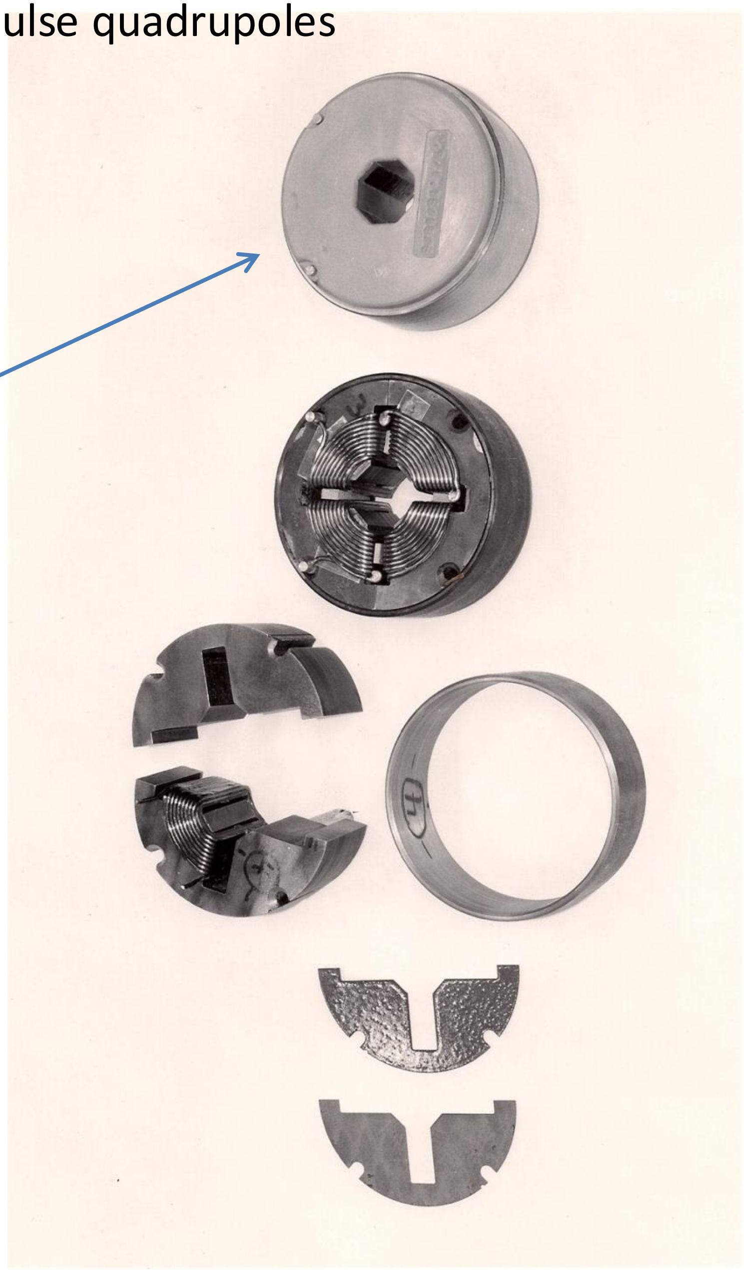
RF Tubes for BNL LINAC

Transverse Focusing

Pulse quadrupoles

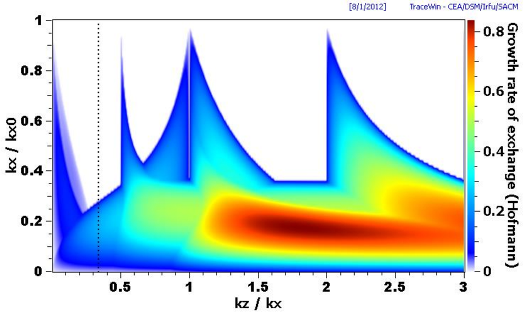


Drift Tube



Beam Losses in BNL Linac

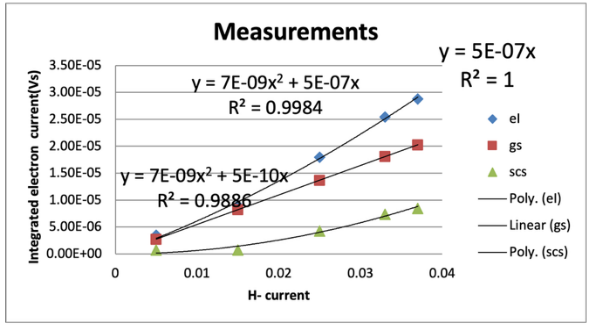
Beam Losses in BNL H^- linac



Beam loss mechanisms

- Continuous beam losses

- Beam halo/tails (Mismatch, collective effects, resonances, etc.) ~ 4-5 10^{-1}
- Residual gas stripping. ~ 10^{-5}
- Intra-beam stripping. ~ 10^{-6}
- H^+ capture and acceleration ~10^{-7}
- Magnetic field stripping of H^- ~ 10^{-11}
- Black body radiation stripping ~0
- RF transient ~ 10^{-2}



- Occasional Beam losses (e.g equipment fault) ~ 10^{-2}

Beam Loss Mitigation

- Continuous beam losses
- Lattice design change: Matching
- Equipment modification (beam loss monitor, replace vacuum pumps)
- Beam Tuning (simulation assisted, space charge neutralization)
- Beam dump for doubly stripped H^+
- Collimation

Beam Loss Mitigation (cont..)

- Occasional Beam losses : Modernization of technology

- Replacement of 5 kW peak power amplifiers with solid-state units,
- pressurized coax,
- Migration from TTL/analogue to digital low-level RF (LLRF) controls,
- Integration of pulsing logic, RF malfunction diagnostics, tank and timing control,
- Implementation of real-time fault warnings and automated system recovery,
- New timing system,
- Vacuum ion pump replacement.

Mitigation
Lattice Changes

200 MeV Linac – converted from Cockcroft-Walton to RFQ in 1989

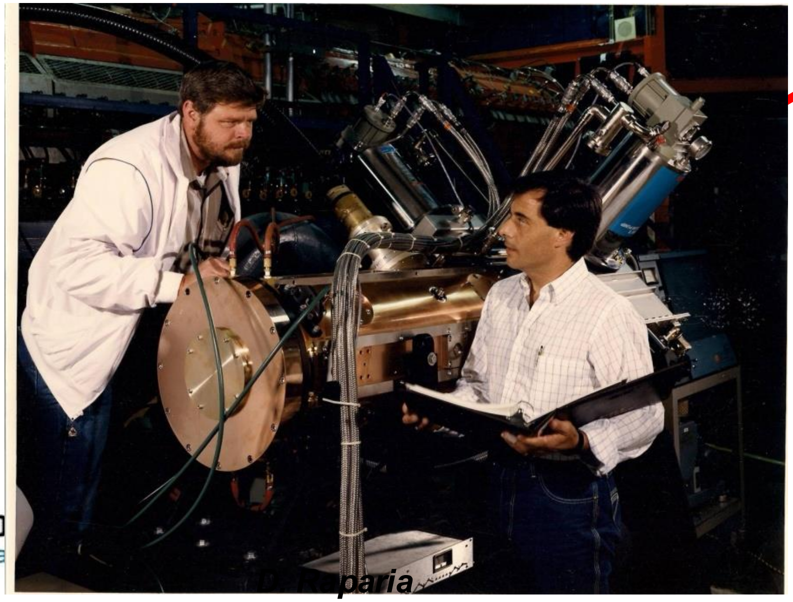
Cockcroft-Walton/ Buncher System 750KeV → LEBT → Drift-Tube Linac (DTL) 200 MeV

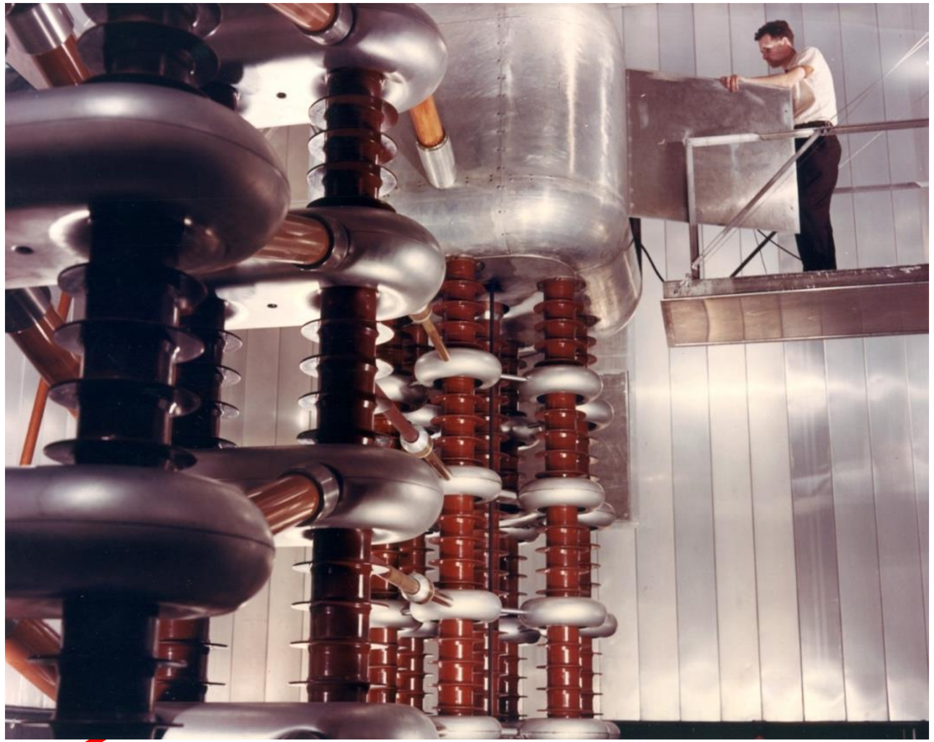
1970s

1990s

Ion Source 35 KeV → LEBT → RFQ 750 keV → MEBT → Drift-Tube Linac (DTL) 200 MeV

RFQ





Cockcroft-Walton

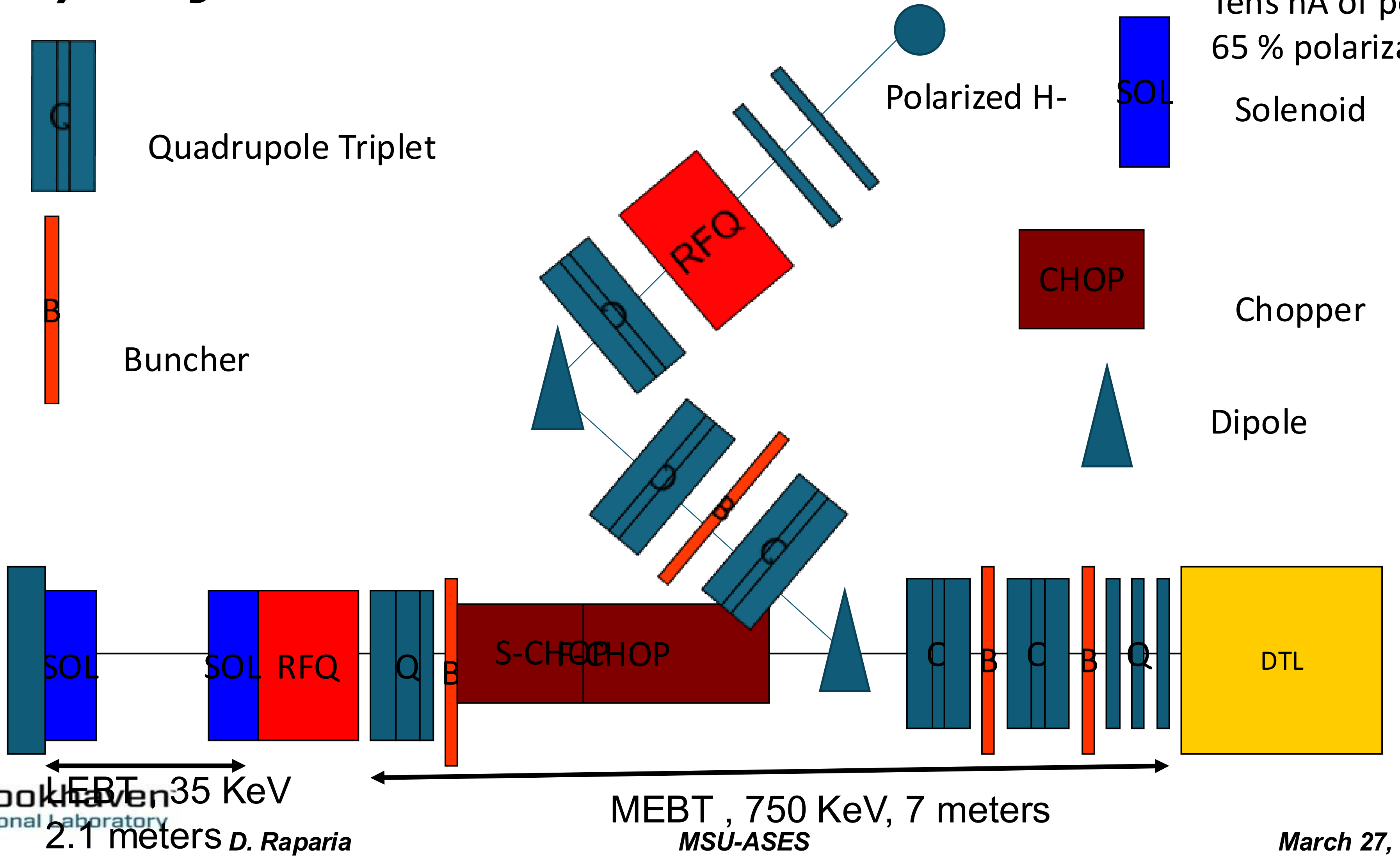
- Space charge neutralization (SCC)
- Time-dependent beam behavior
- Matching into RFQ critical

Low and Medium Energy Beam Transport (LEBT-MEBT) Layout

Polarized H-

Tens nA of polarized current

65 % polarization, 20 keV



Linac Performance after RFQ 1989

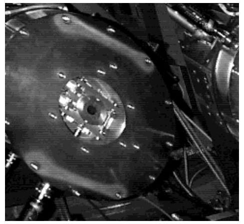
- RFQ was much more reliable and required less maintenance than Cockcroft-Walton
- But capture efficiencies in the linac did not improve as advertise
- Neither emittance nor intensity improved out of linac
- Beam losses did not change

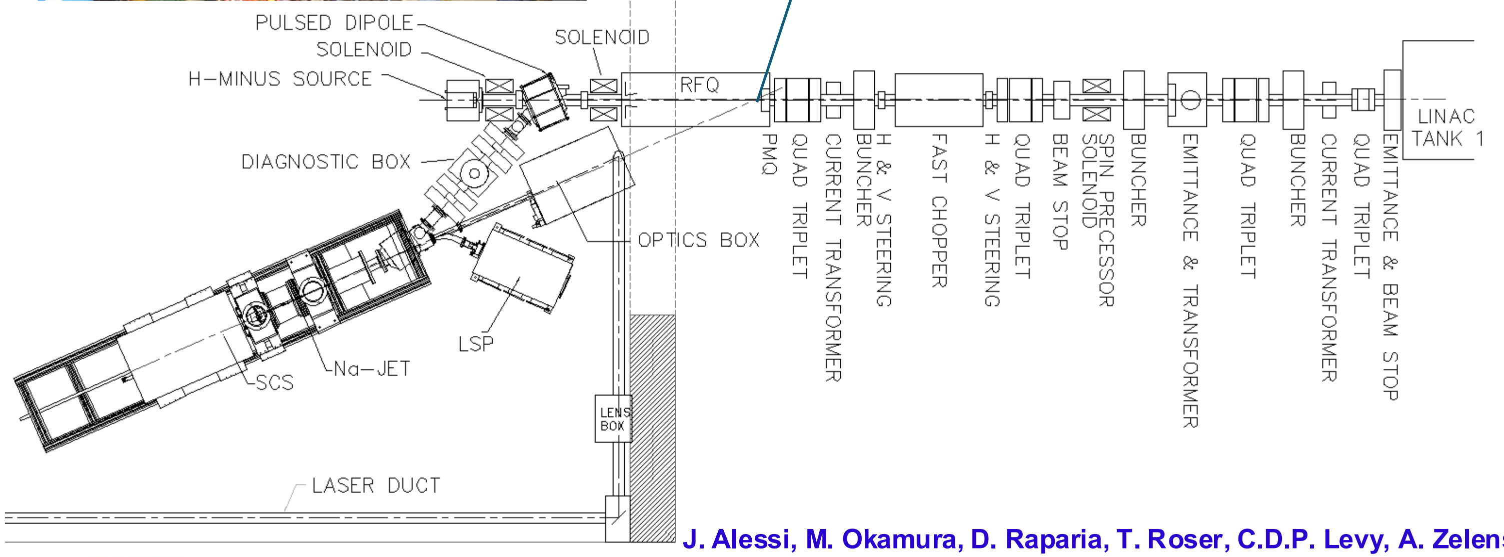
At BNL, the full potential of the RFQ had not been realized….

J. Alessi, J. M. Brennan, J. Brodowski, H. N. Brown, A. Kponou, V. LoDestro, P. Montemurro, K. Prelec, R. Witkover, R. Gough, J. Staples, `` Performance of the New AGS RFQ Preinjector", IEEE Tran. Nucl. Sci. 1989

Addition of Optically Pumped Polarized H- ion Source (OPPIS) 1996-2000

Reducing Transverse Space Charge Effects and Matching



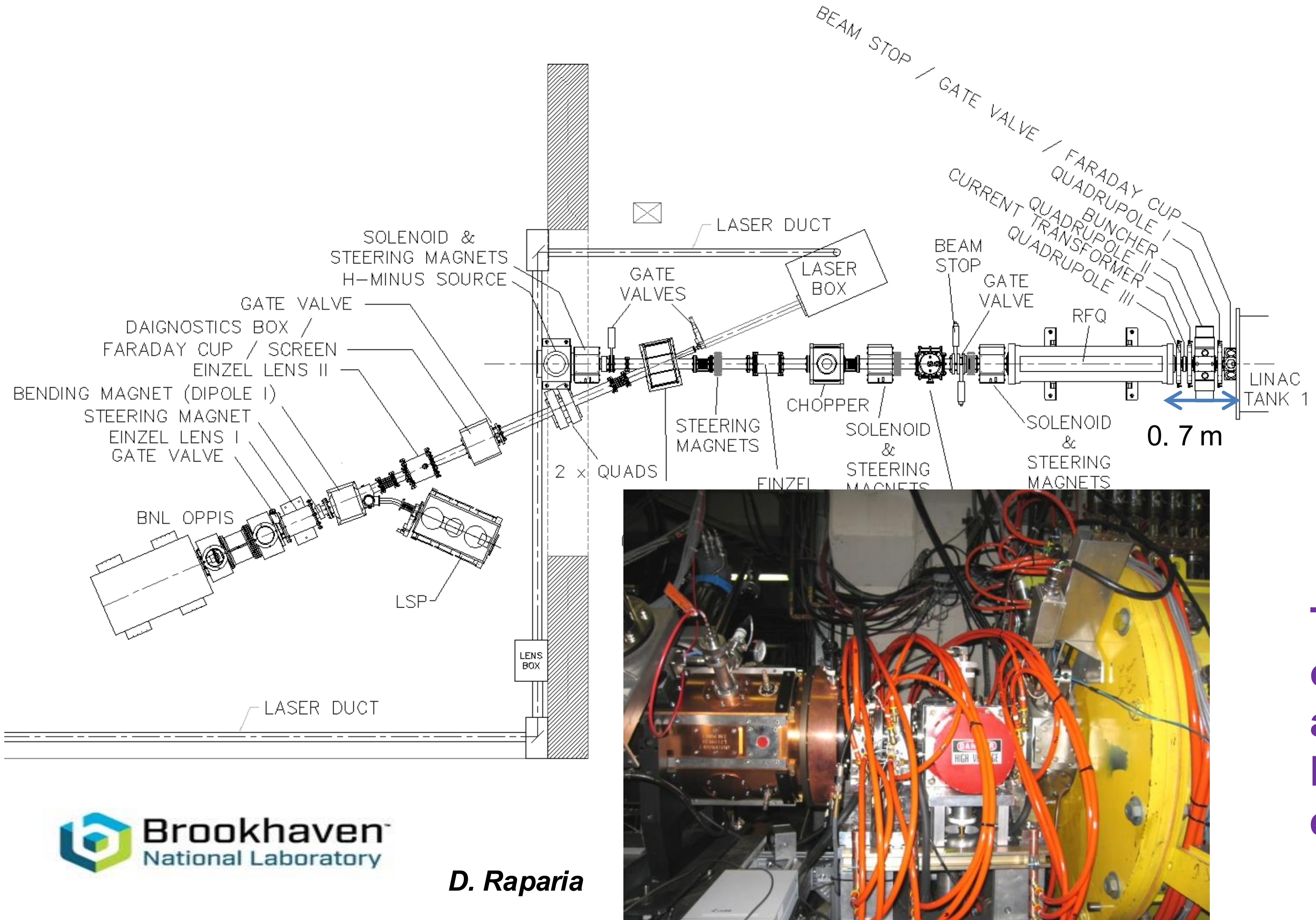


J. Alessi, M. Okamura, D. Raparia, T. Roser, C.D.P. Levy, A. Zelenski, T. Takeuchi, Y. Mori, `` Design of a 35 keV LEBT for the New High Intensity OPPIS at BNL”, PAC 1999

- Shorting (2.2 -1.4 m) 35 keV line by removing diagnostics and adding PMQ in the end-flange of the RFQ.
- These changes resulted in a 50% higher peak beam current and about 45% lower emittance.
- **Transverse Mismatch:** Both RFQ and DTL use FODO lattices with $\beta\lambda \approx 6$ cm. In contrast, the MEBT incorporated drift spaces 15–20 times longer to accommodate chopper, dipole, and diagnostics.
- **Longitudinal mismatch**: Three unequally spaced bunchers. The bunch length grew more rapidly due to longer longitudinal focusing periods and nonlinear sinusoidal restoring forces, which caused beam losses at higher energies

Shorter MEBT -2009

Reducing Longitudinal Space Charge Effects



- MEBT was changed from 7 meters to 0.7 meters
- LEBT was changed from 1 to 4 meters

-Emittance for polarized H- was reduced by factor of two

-Higher Transmission through Linac

-Much lower radiation through out the linac

-Lower Transmission through RFQ

LEBT was too long and more

Buncher needed more rf power

This emittance reduction was observed through out the accelerator chain up to RHIC. At RHIC collision energy emittance was reduced by 25 %

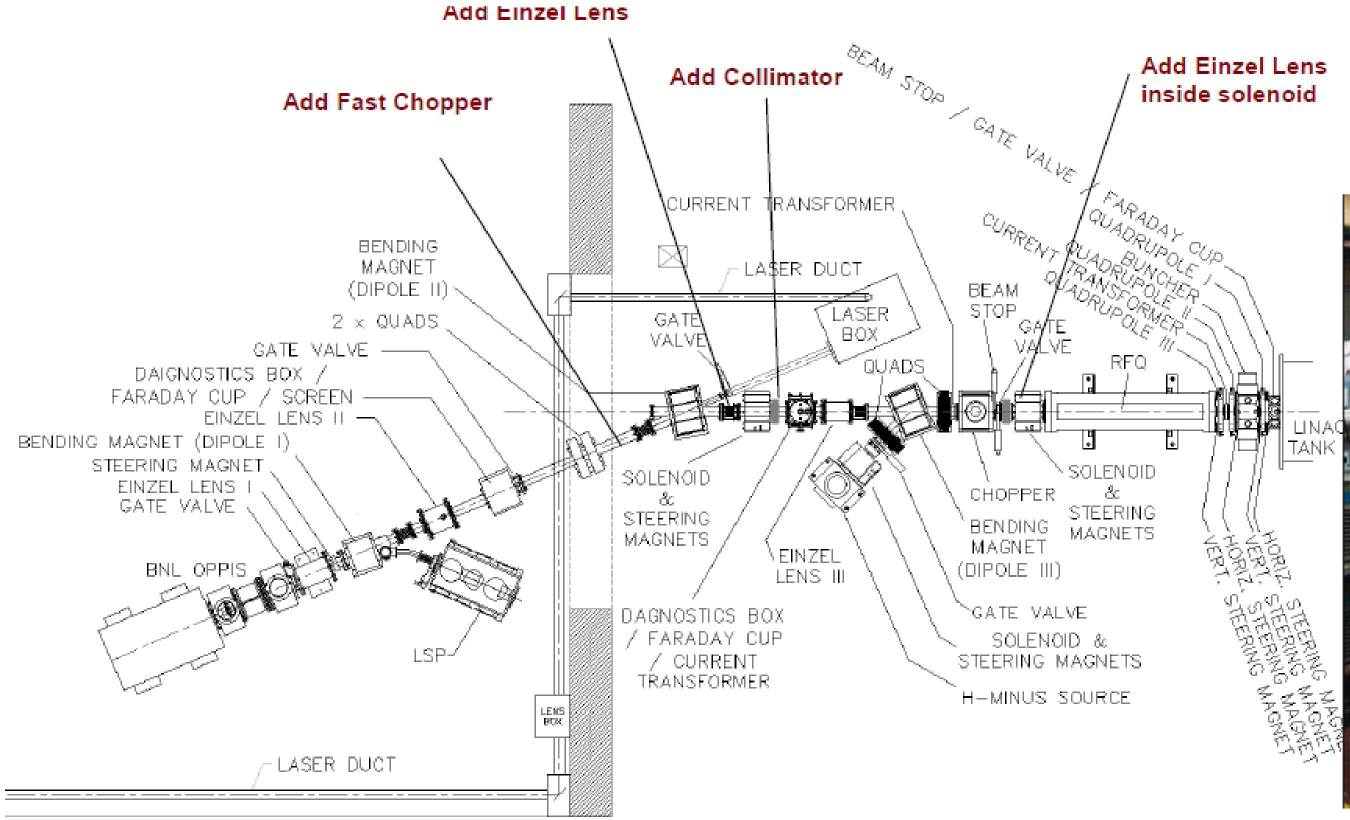
Shorter LEBT -2010

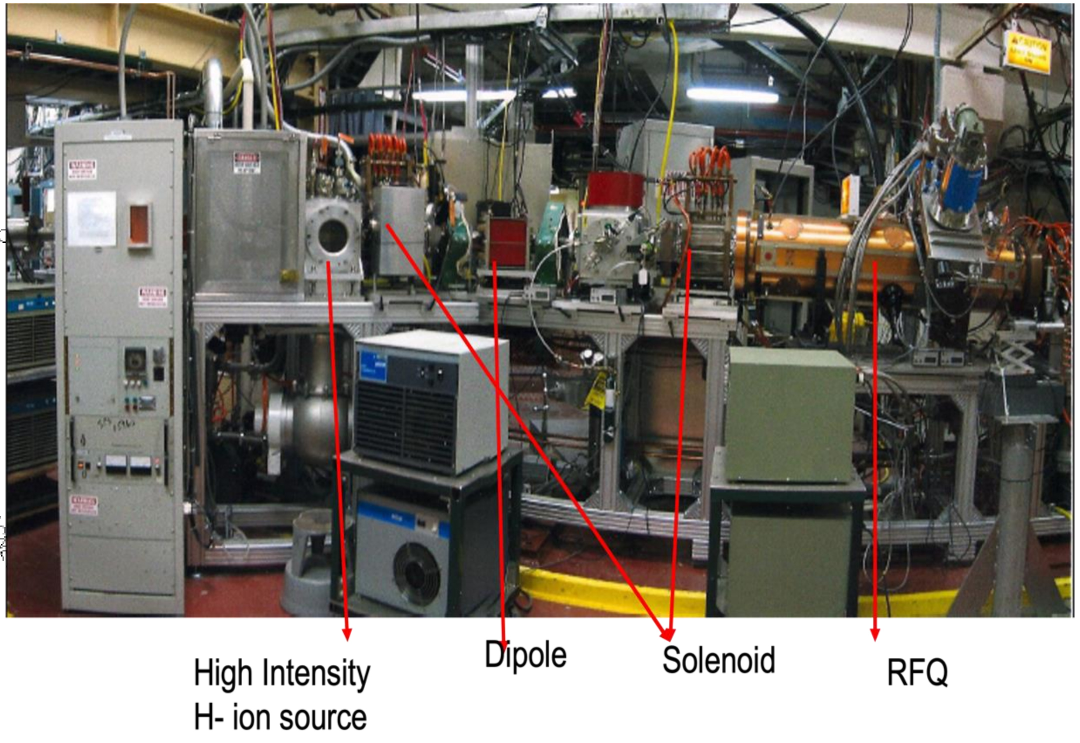
Reducing Transverse Space Charge Effects

Reduced MEBT length to 2 meter from 5 meters

-Increased peak current 32 to 39 mA

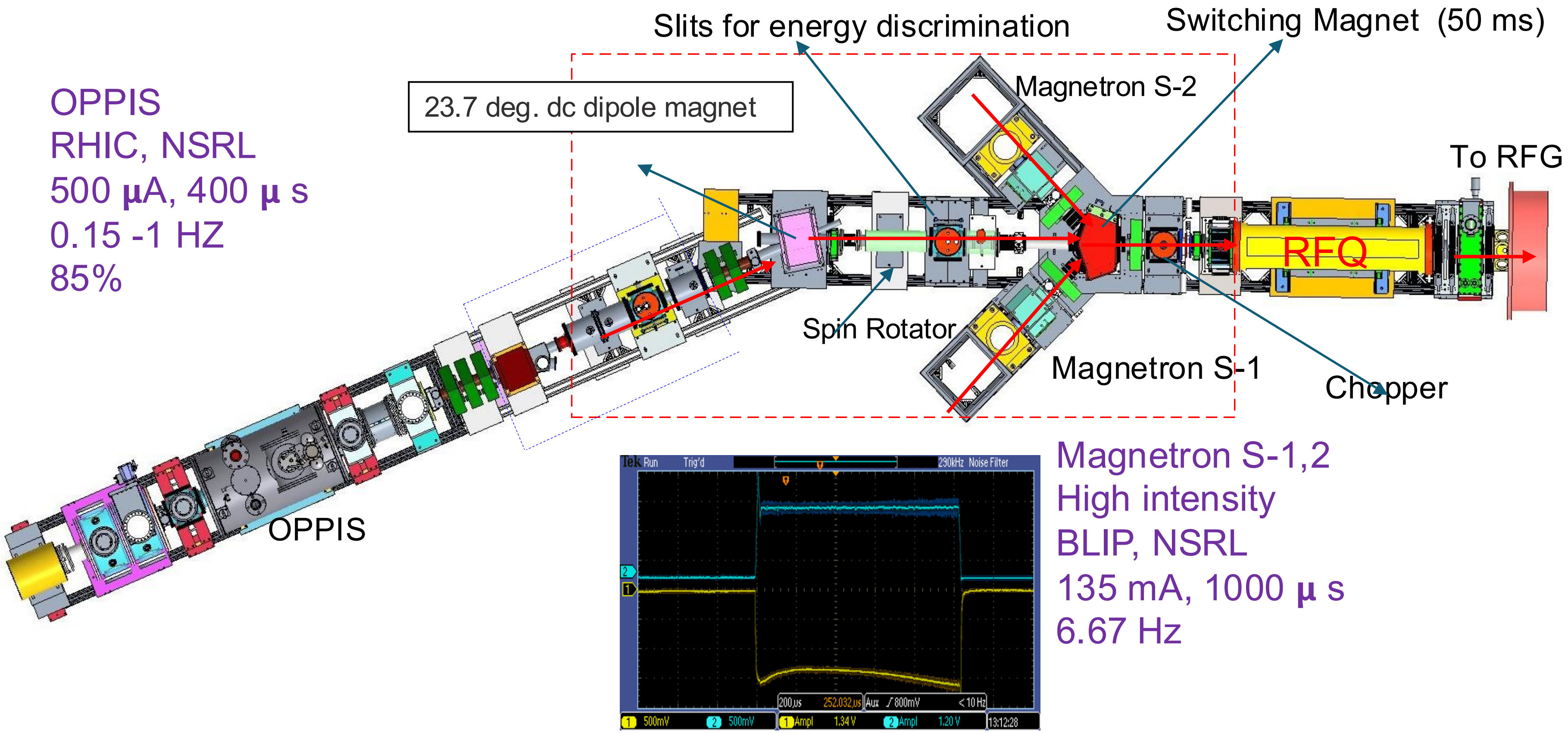
-In spite of higher current lower radiation



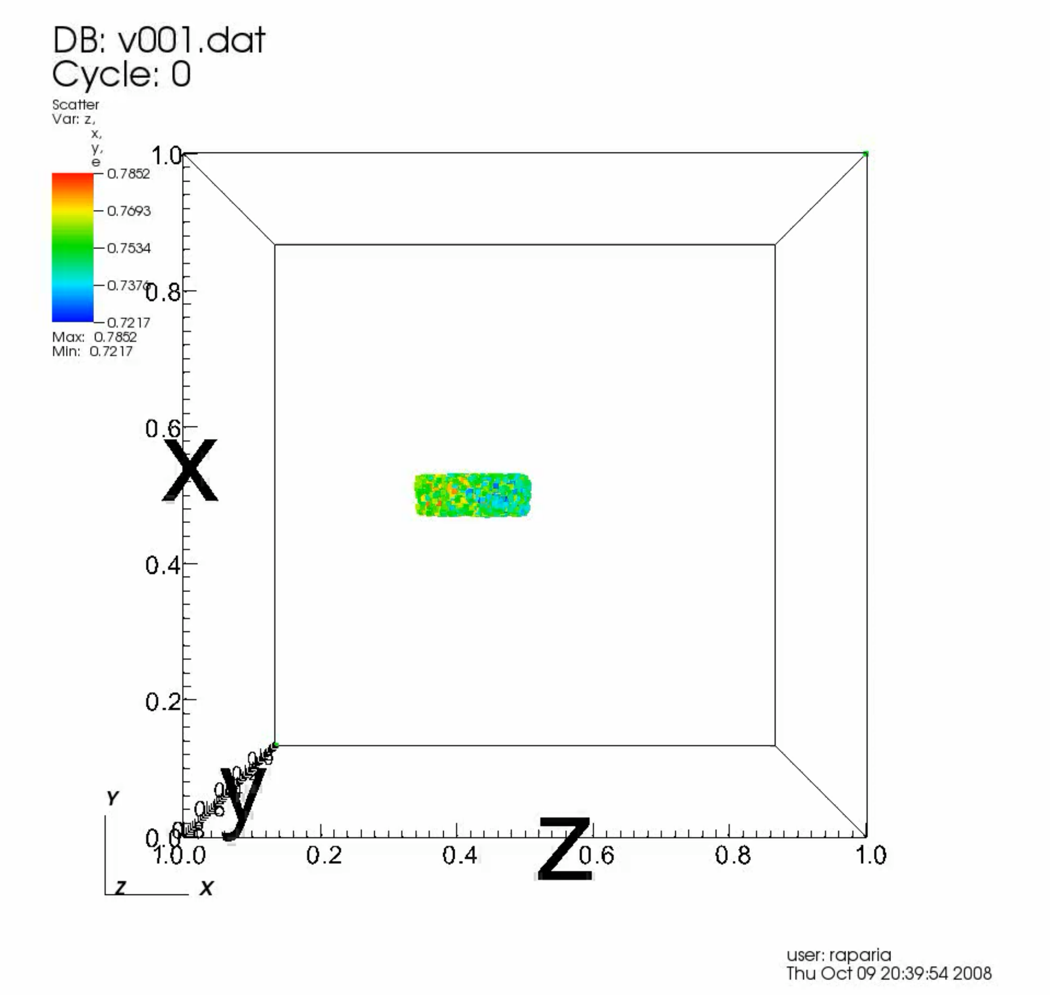


Three Sources Configuration of LEBT

The Low Energy Beam Transport (LEBT) lines combine three beams. The first line is the polarized OPPIS beam-line, and the second and third lines are the high-intensity unpolarized beam lines.

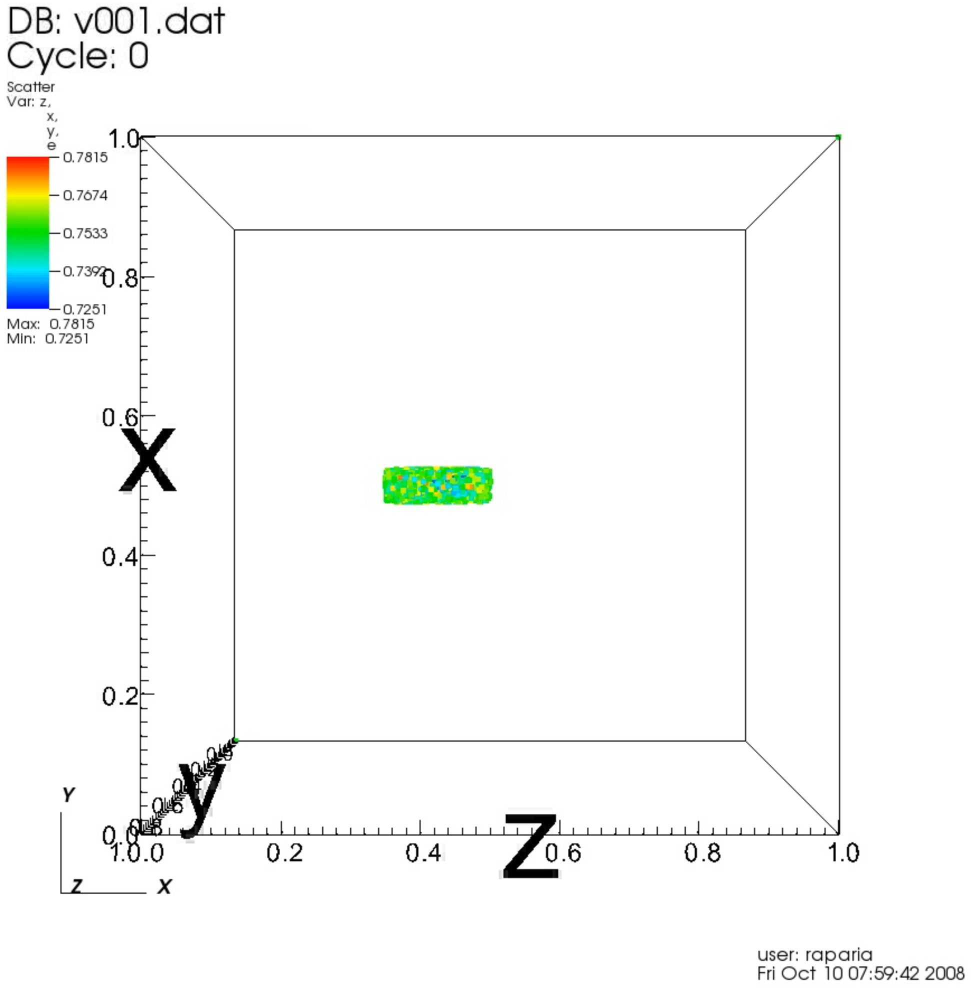


Bunch Through OLD MEBT and LINAC



$\beta\lambda$

Bunch Through New MEBT and Linac



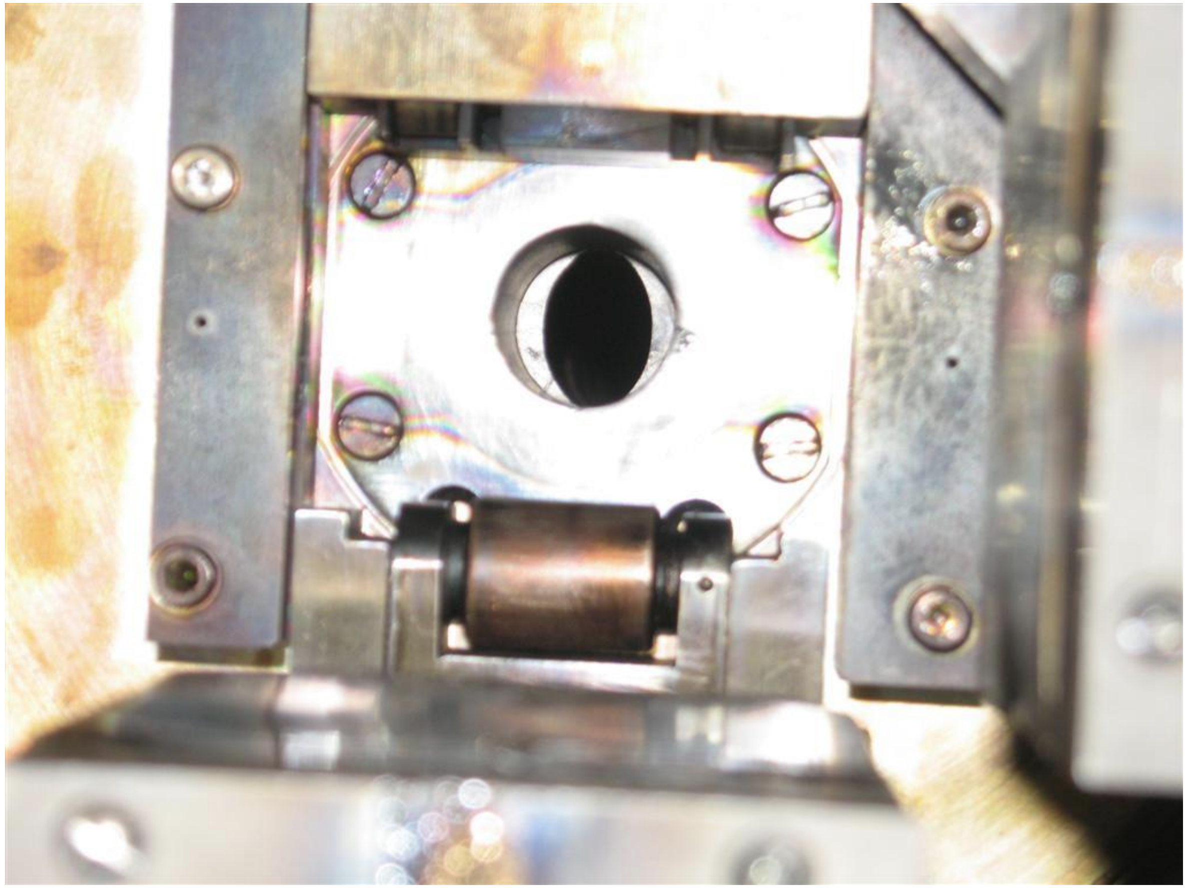
$\beta\lambda$

Mitigation

Collimation

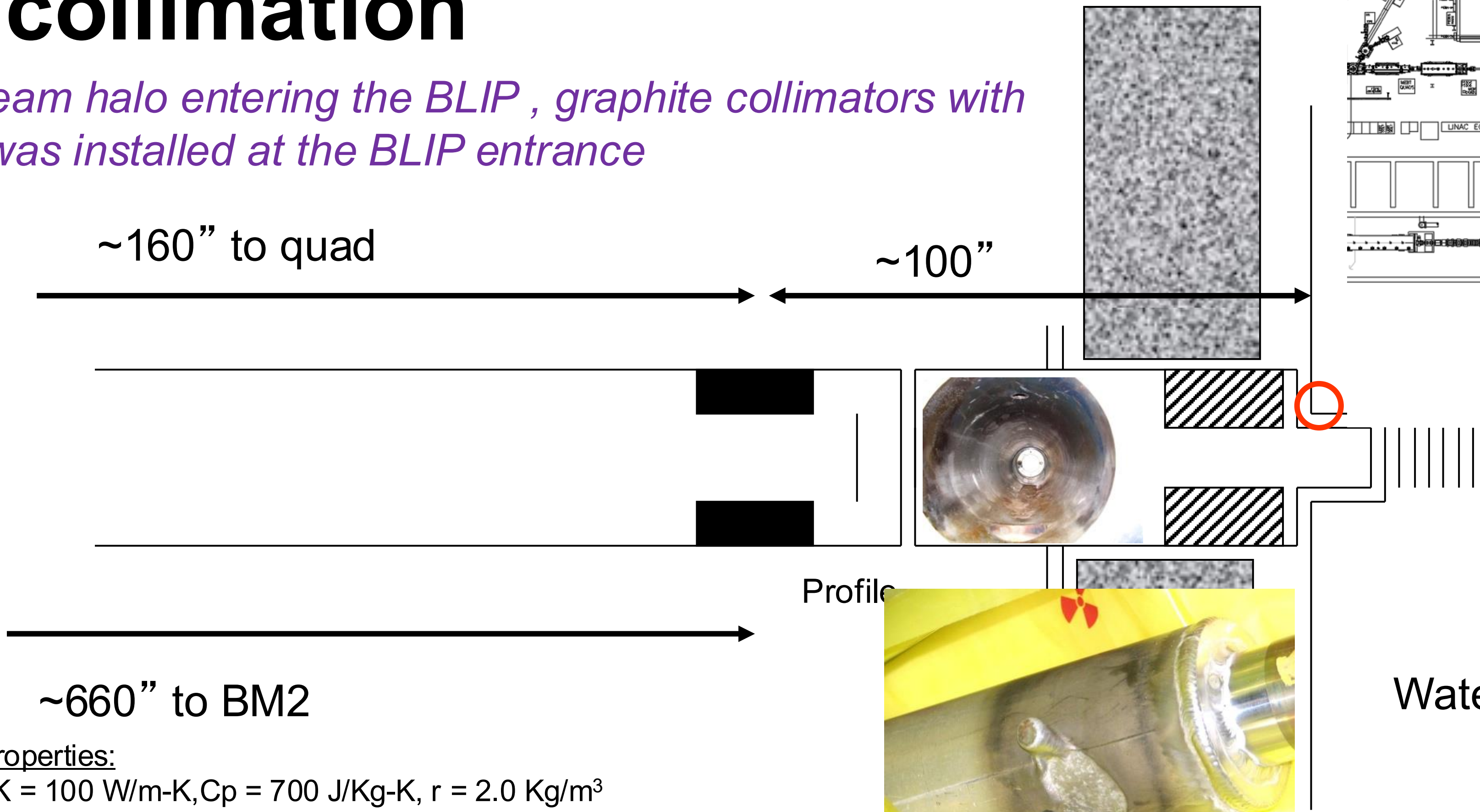
Collimation at tank 1 entrance

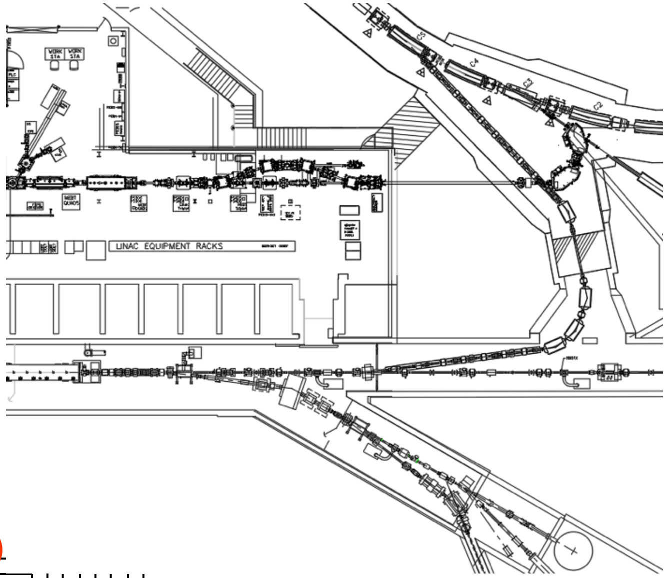
To reduce beam halo entering the DTL, a graphite collimator (0.8 x 1.6 cm) was installed at the DTL entrance

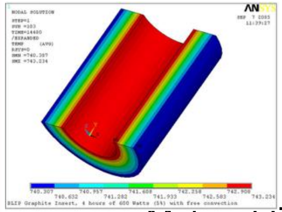


BLIP collimation

To reduce beam halo entering the BLIP , graphite collimators with 800 mm ID was installed at the BLIP entrance







Material Properties:
Graphite, K = 100 W/m-K,Cp = 700 J/Kg-K, r = 2.0 Kg/m^3
Geometry:,I.D. = 3.12 (79.2 mm,O.D. = 5.70 (144.8 mm),L = 7.0 (177.8mm)
Heat Load:
5% of total 12KW beam = 600 Watts, Applied on approximately 30mm radius from Inner wall all around

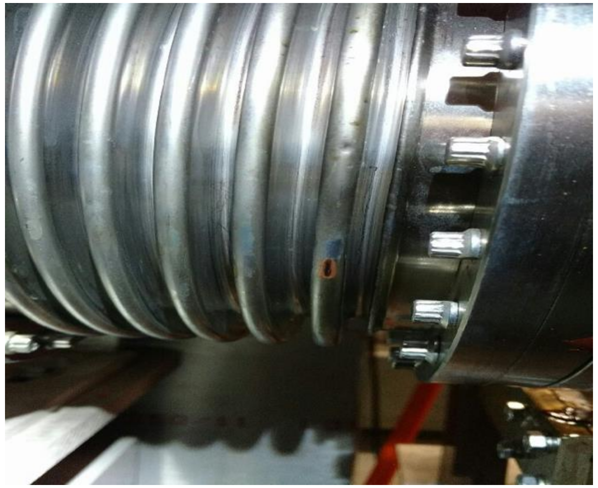
Summary of Calculations:
The temperature of the graphite and aluminum can rise within hours to the melting point of aluminum. The total heat transfer by natural convection and radiation at or near the melting point is roughly 5% or so of the total beam power.

Brookhaven National Laboratory

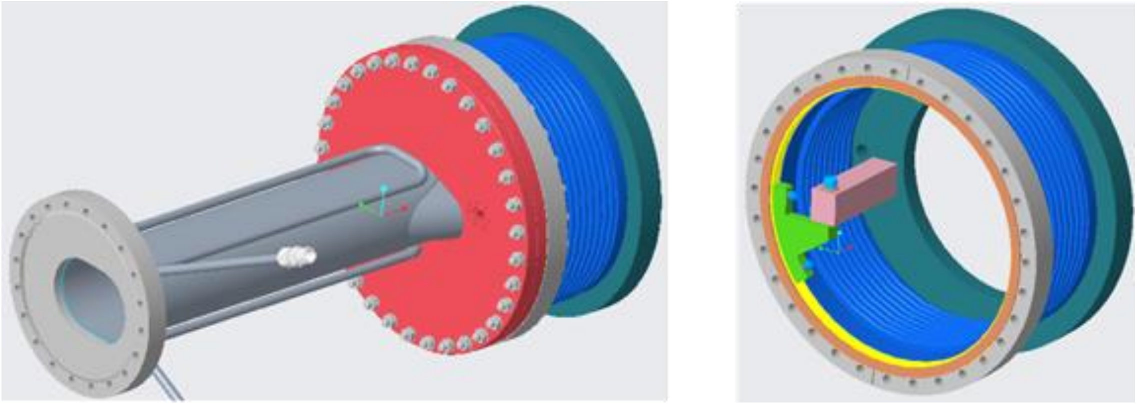
Acceleration of double stripped P

To capture doubly strip Proton, a tungsten beam dump is being install in the BM1

Protons formed in LEBT are captured 180° out of phase in the RFQ and accelerated to full energy. After exiting the 200 MeV DTL, they are bent in the opposite direction of the H^- beam by the first bending magnet (BM1). The estimated H^+ fraction reaching BM1 is ~1.7×10^{-5}, while linac losses due to this process are two orders of magnitude lower



Vacuum leak due to doubly stripped P and BM1 in 2015

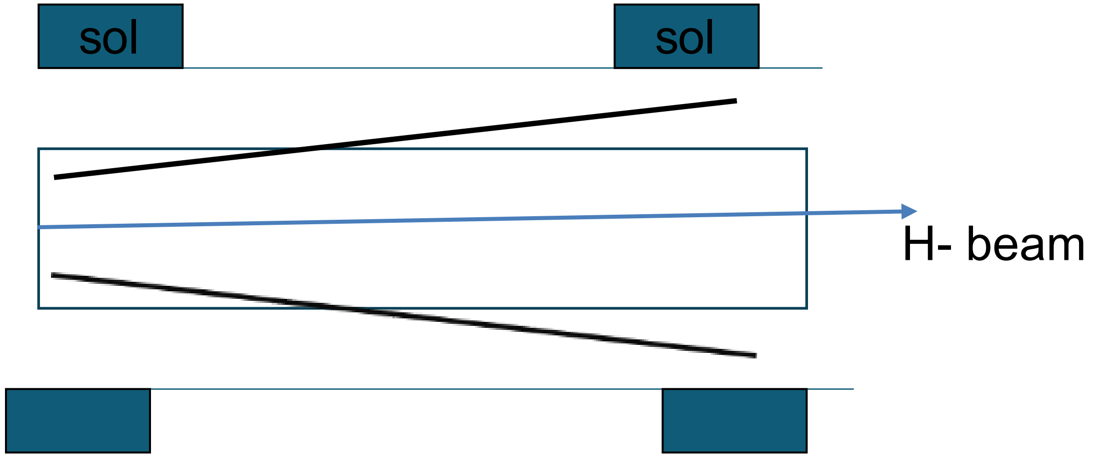


The 3-D model of the BM1 vacuum chamber with bellow containing doubly stripped proton beam dump which can measure proton intensity

Mitigation
Beam Tuning

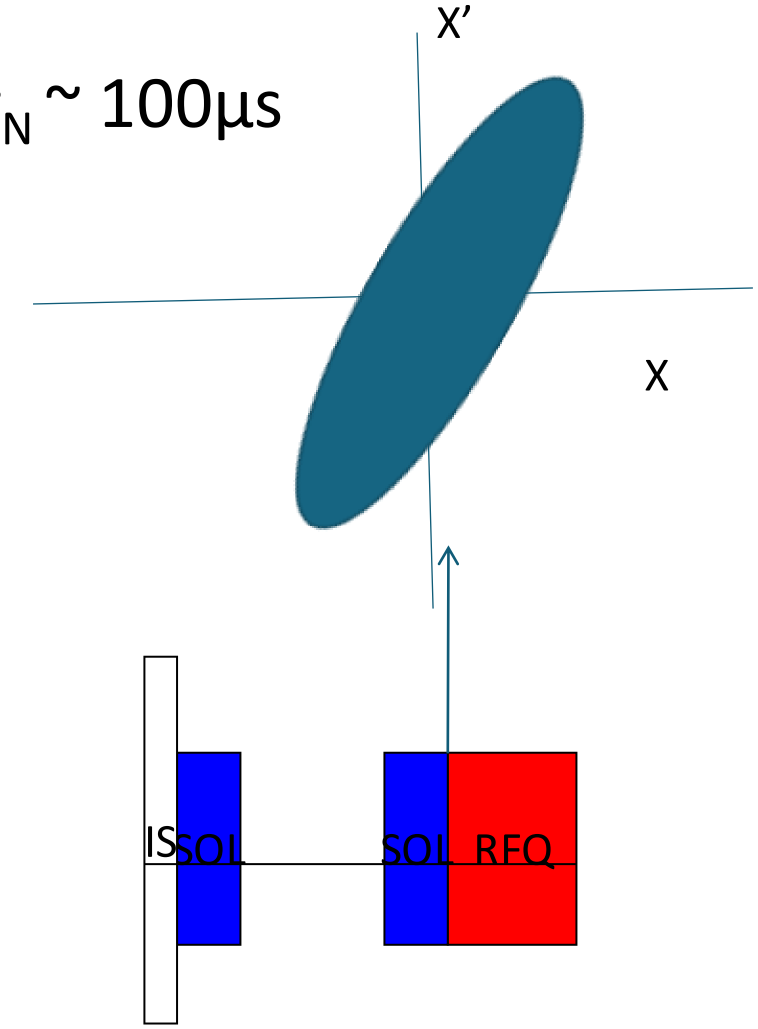
LEBT at 35 keV with 130 mA of H^-

To reduce transverse space charge effect, emittance control



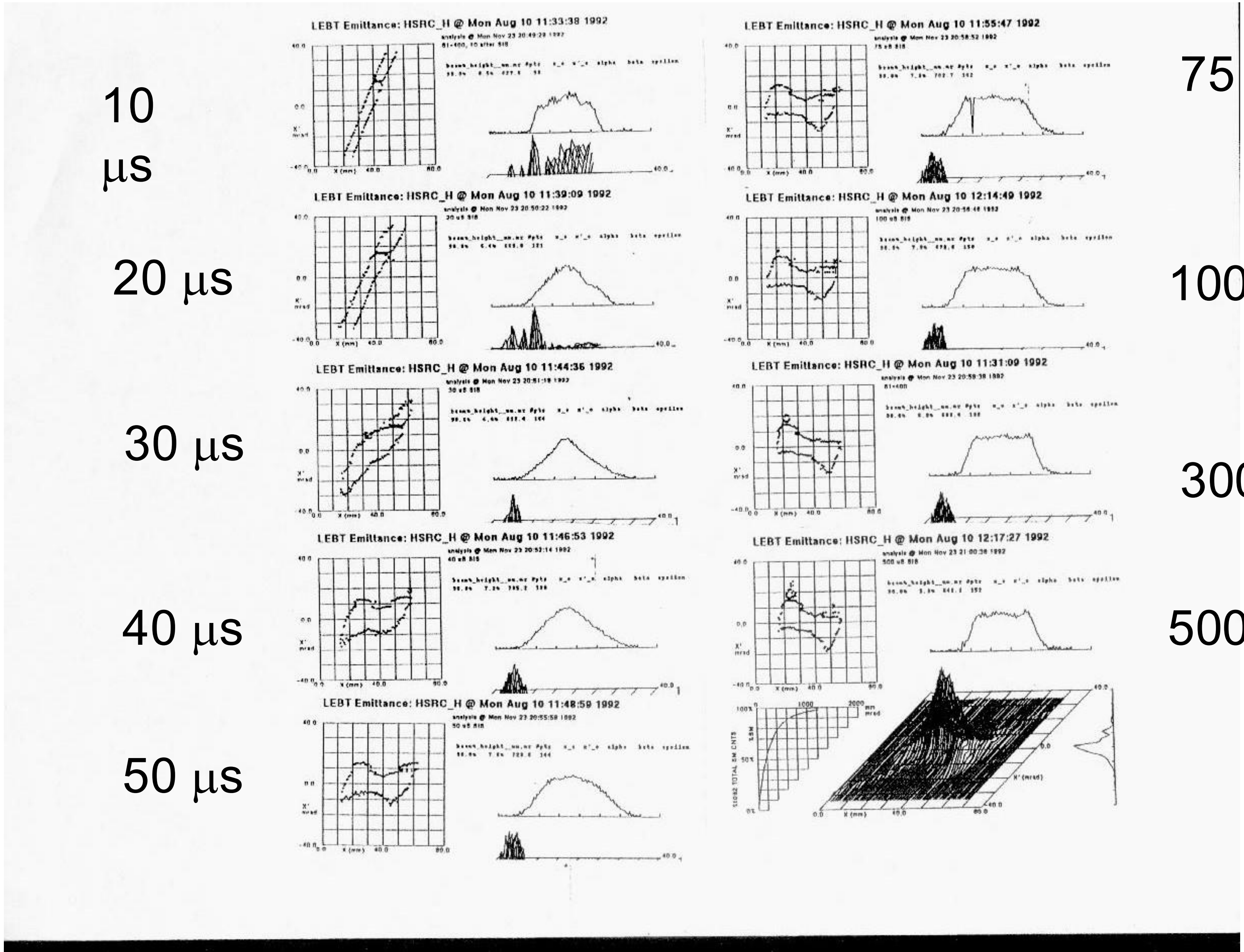
During Neutralization time phase space rotate

$\tau_N \sim 100\mu s$

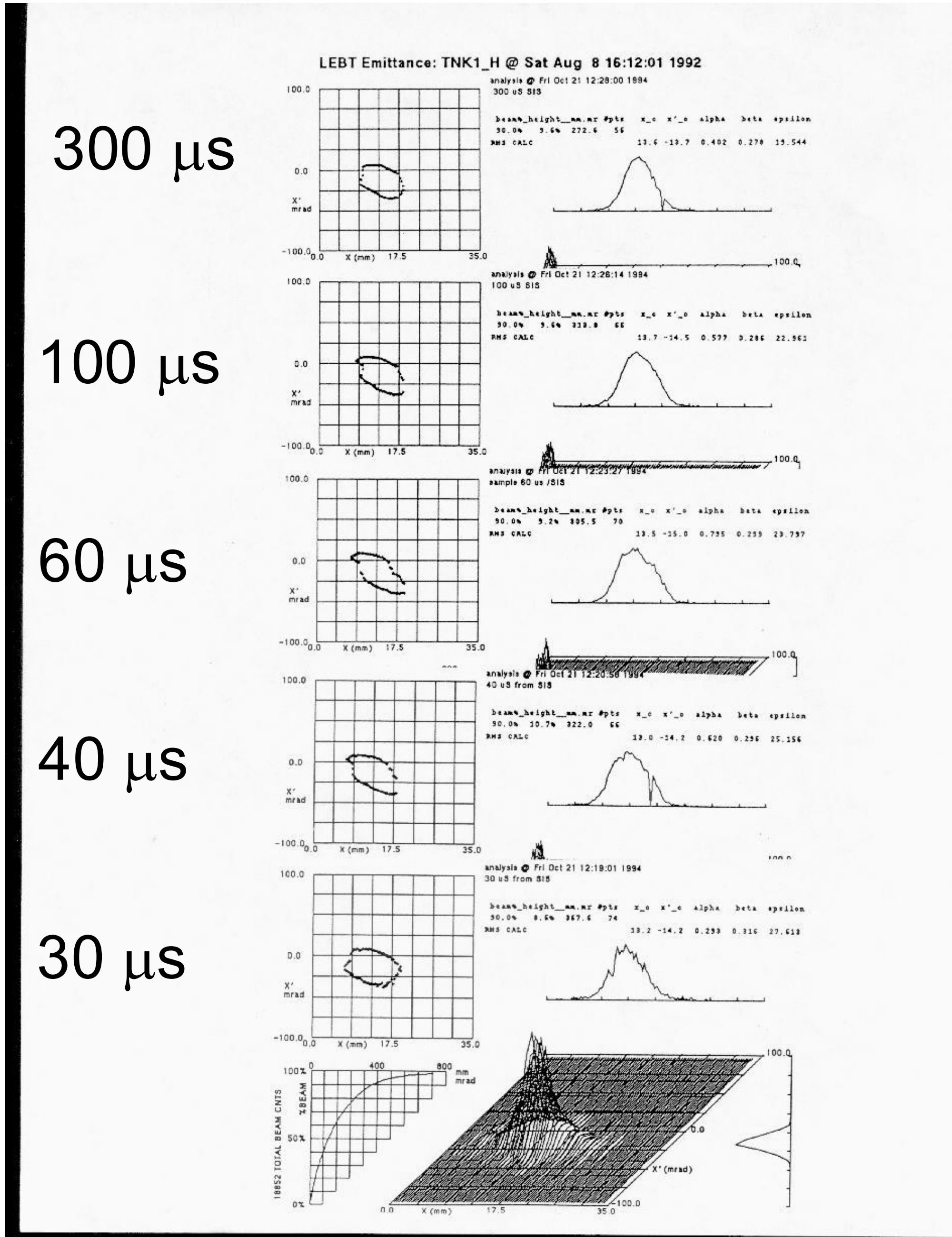


- LEBT for 130 mA H-
- Magnetic (solenoid) focusing
- H^- ionizes residual gas and capture positive nucleus this is called space charge neutralization
- H^- stripping

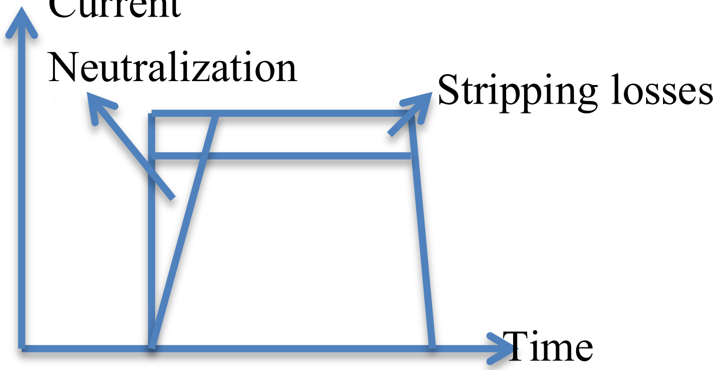
Neutralization in LEBT (35 keV)



Neutralization in MEBT (750 keV)

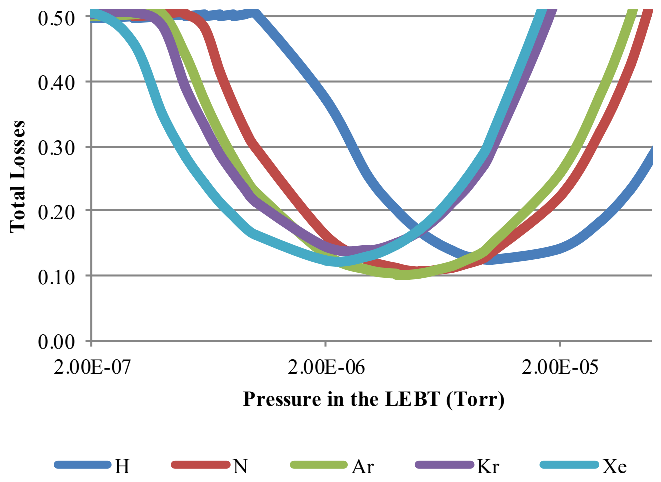


H- Stripping and Neutralization (cont..)

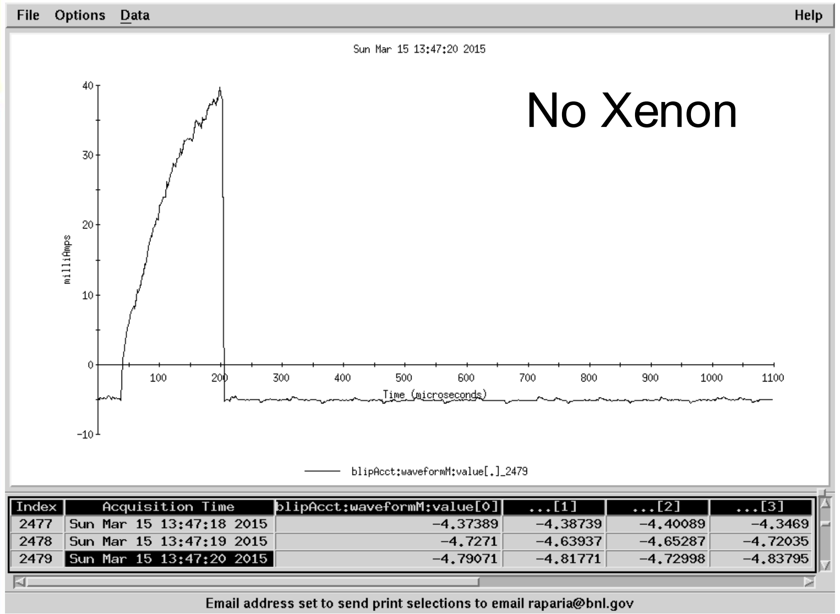


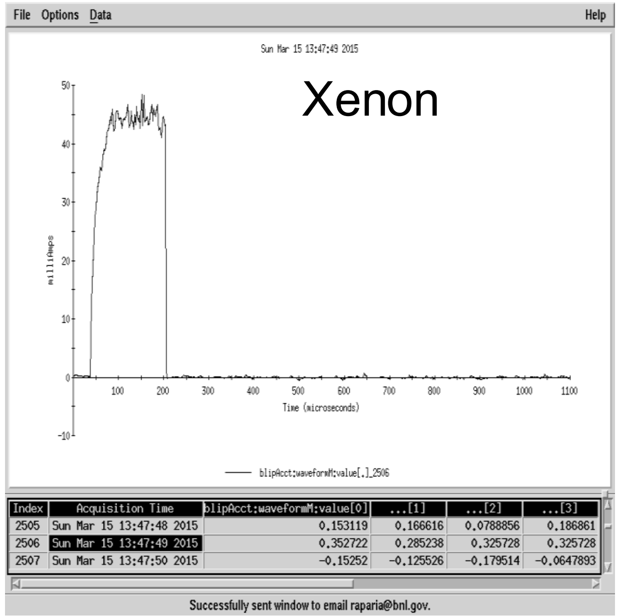
Left Triangular are represents Losses due to Neutralization. Top rectangular are represent Losses due to the stripping

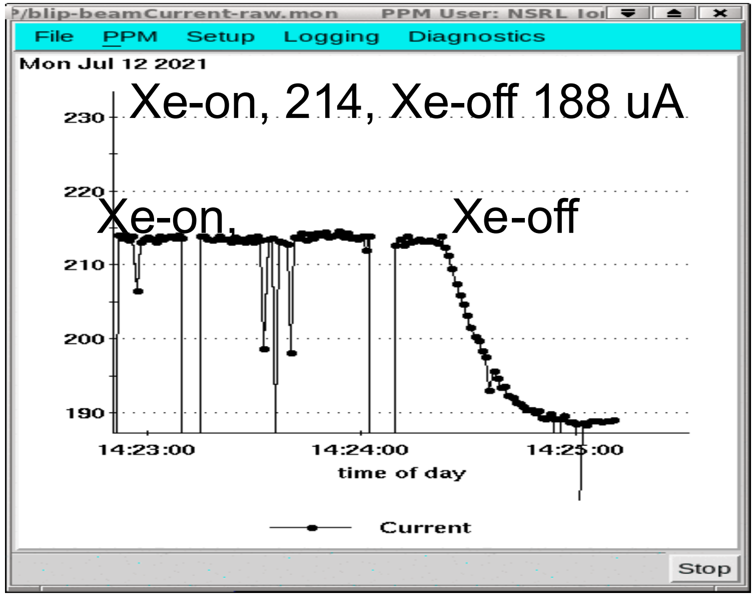
Total losses due to stripping And neutralization as function Of residual gas pressure for 200 cm long LEBT and 500 us long beam pulse length.

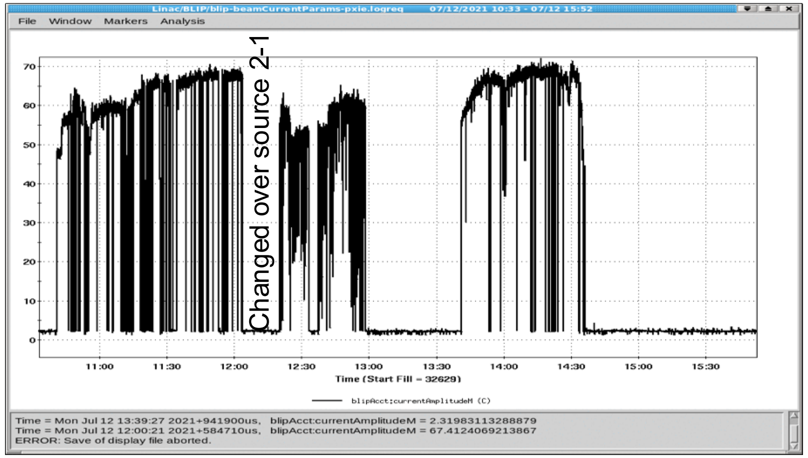


Xenon Gas Effect







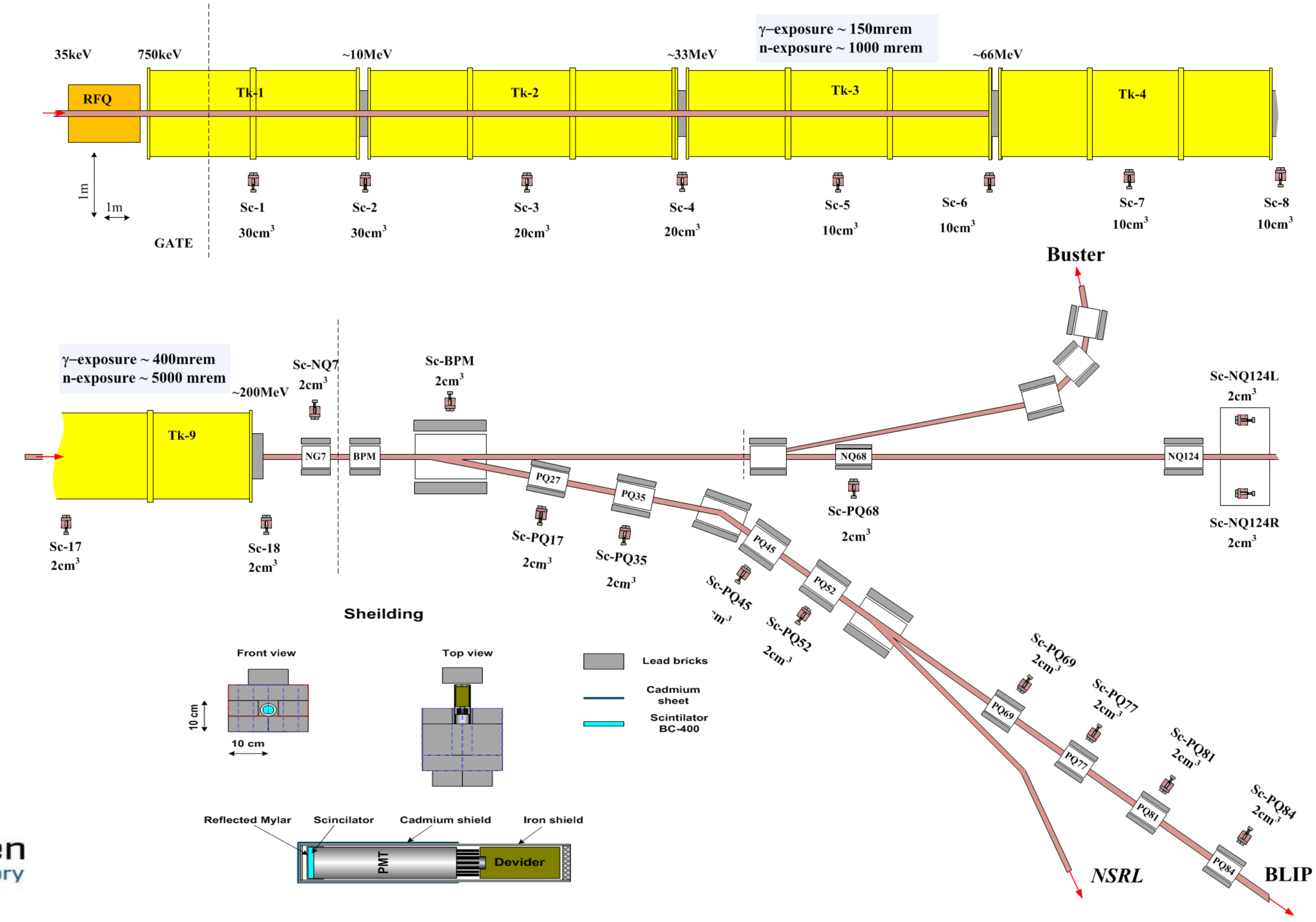


Brookhaven National Laboratory

Beam Loss Monitor

To reduce mismatch , steering and beam halo

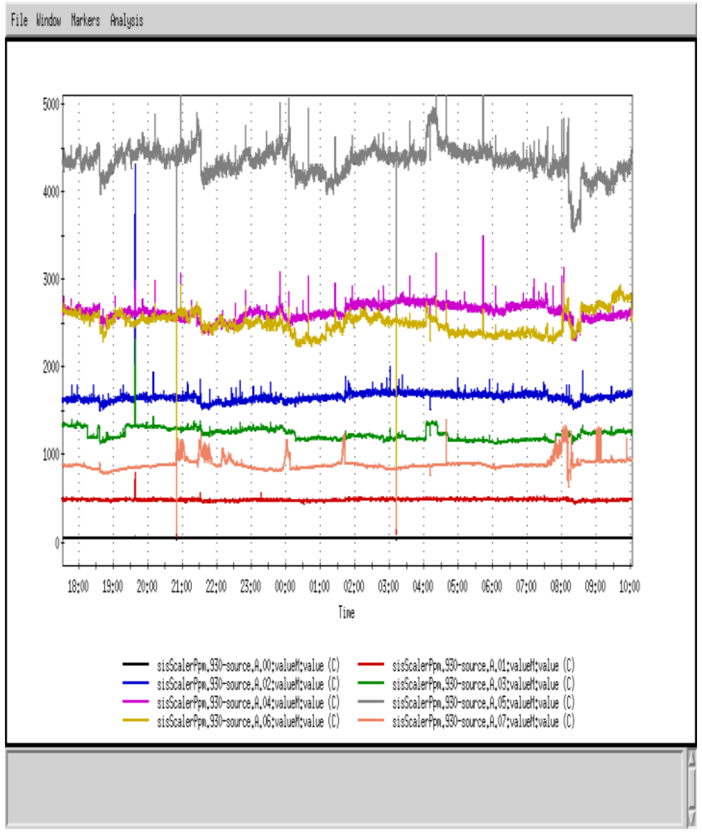
Beam Lost monitor (BLM)



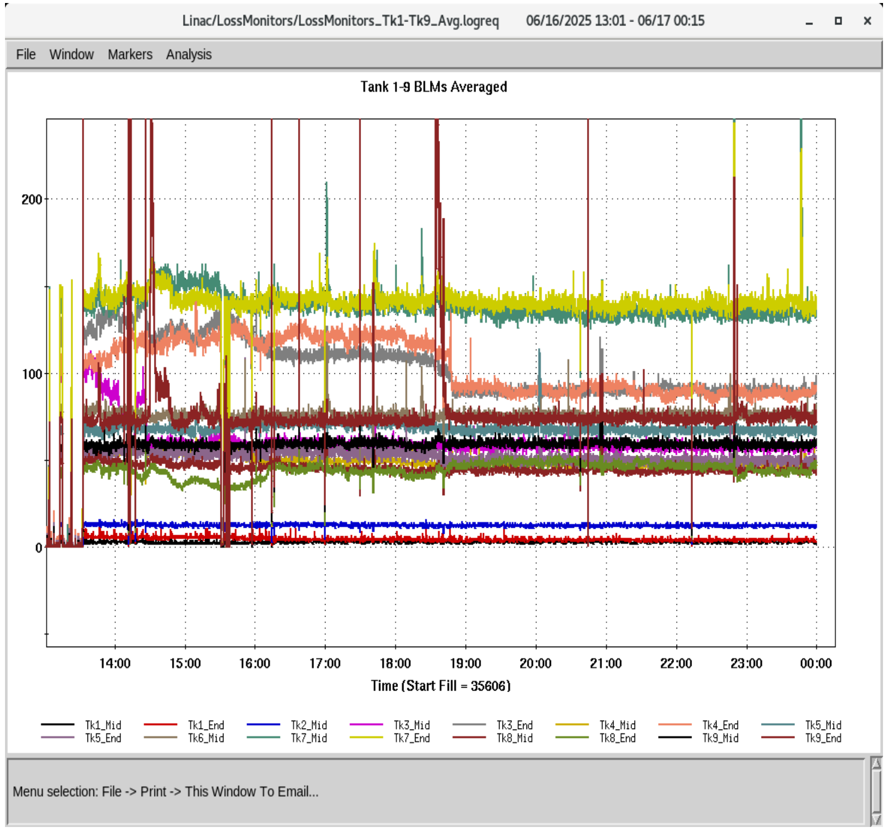
Brookhaven National Laboratory

Beam Loss Monitor

To reduce mismatch , steering and Halo



2015 Beam Current 120 uA



2025 Beam Current 170 uA

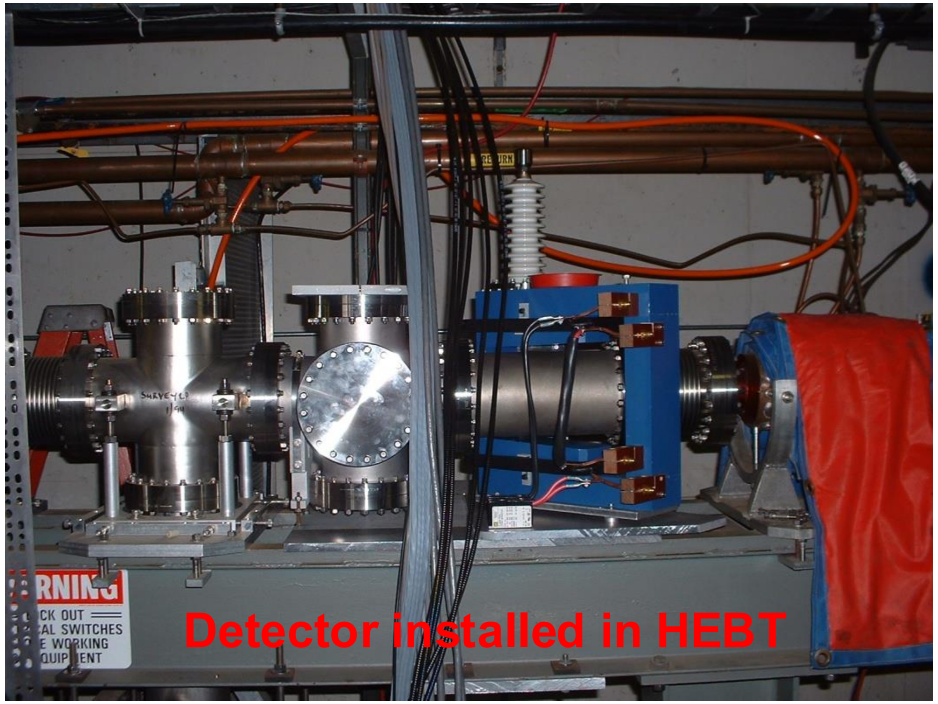
Laser Beam Profile Monitor

Energy and transvers profile: To reduce transvese and longitudinal mismatch , steering

First ionization potential for H- ions is 0.75 eV

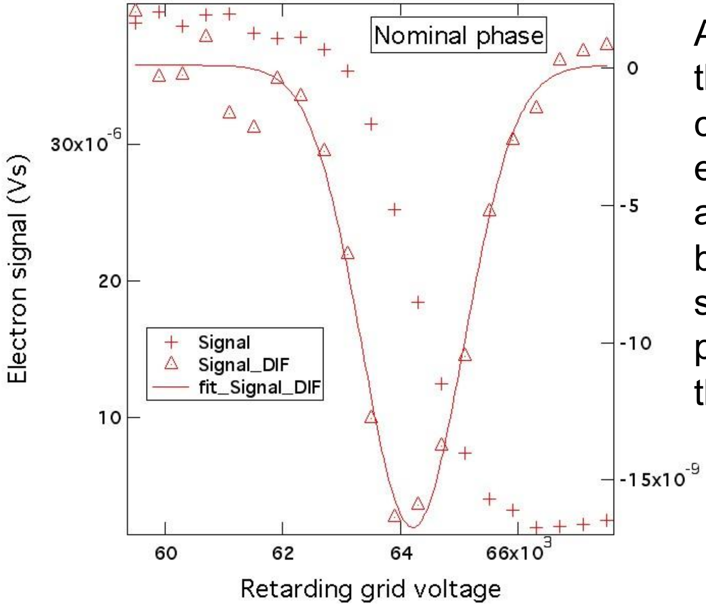
Photons with $\lambda \leq$ 1500 nm can separate H- ions into **free electron** and neutral H

The H- ion has no excited states so the electron is removed into the continuum



Detector installed in HEBT

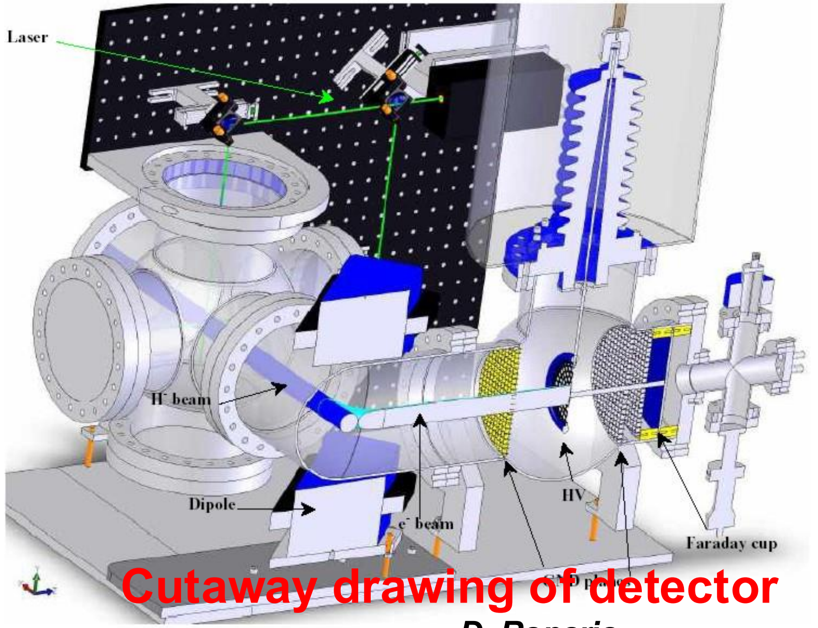
energy scan



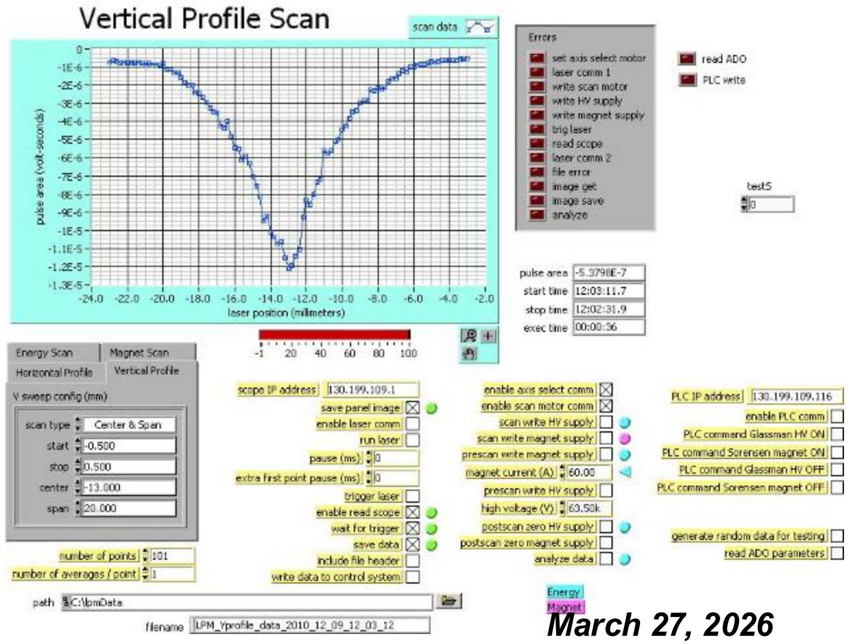
A Gaussian is fitted to the derivative of the signal vs. grid voltage data. The center (64.2kV) is the average electron energy from the beam motion and the width (σ=0.87kV) is from beam-energy spread and from the space-charge potential spread. The proton energy is m_p/m_e=1836 times the measured electron energy:

E_p = 118 MeV

σ_p = 1.6 MeV



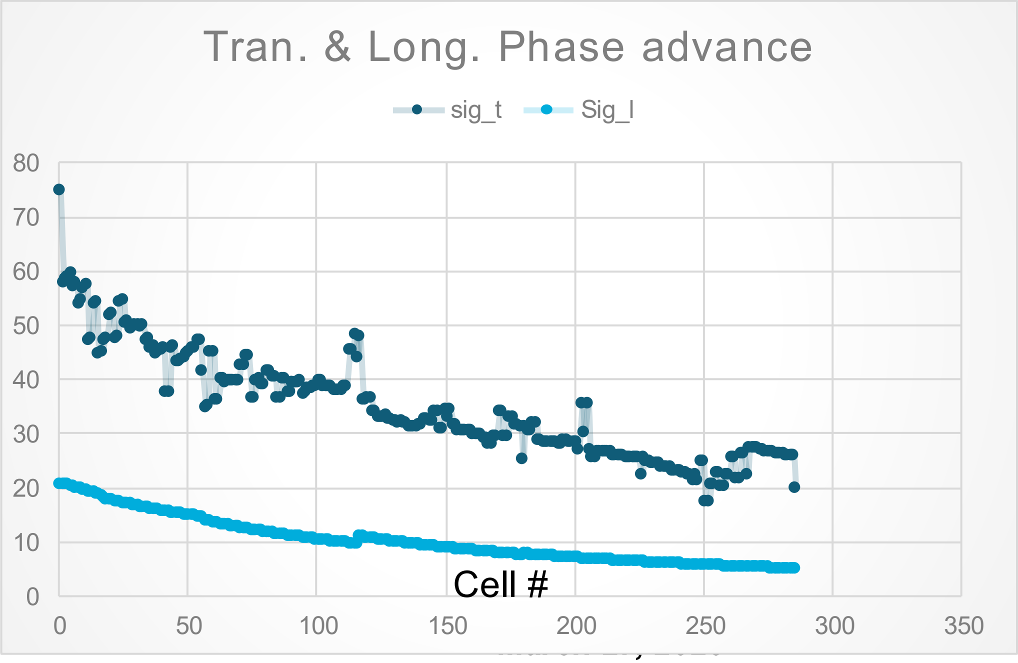
Cutaway drawing of detector



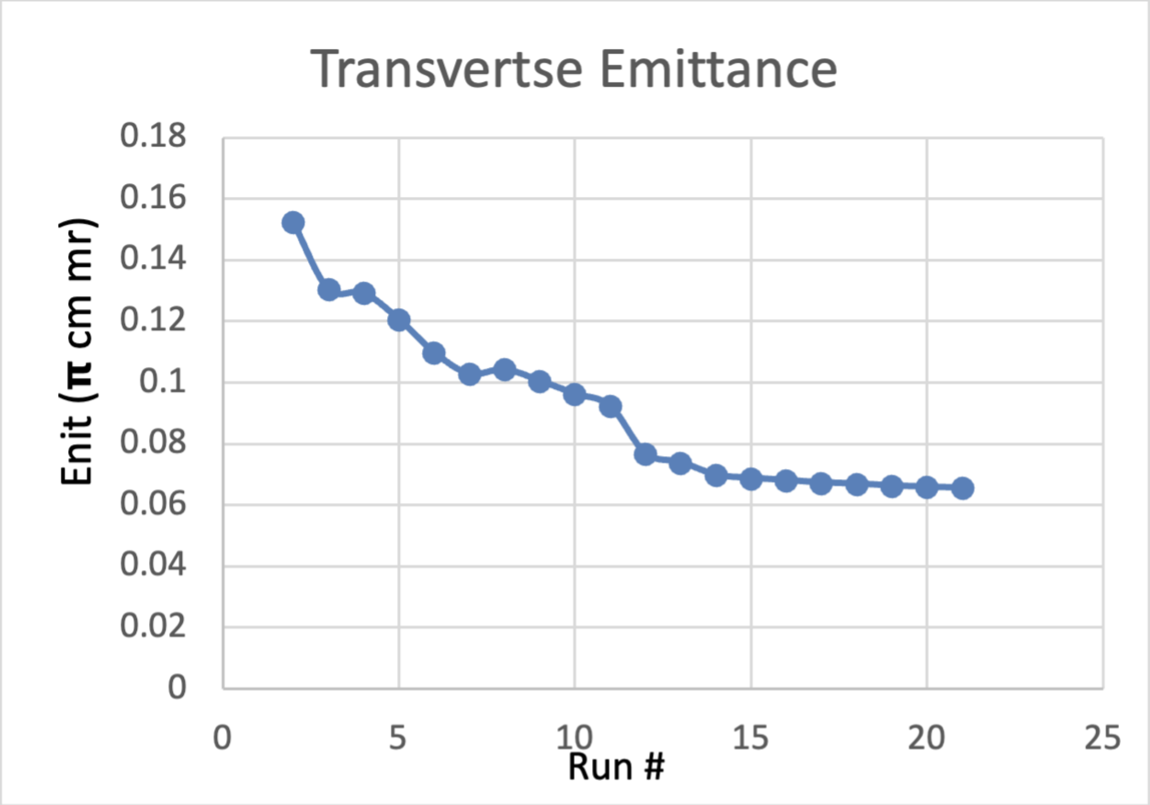
Simulation Assisted Tunning

Transverse and Longitudinal Matching

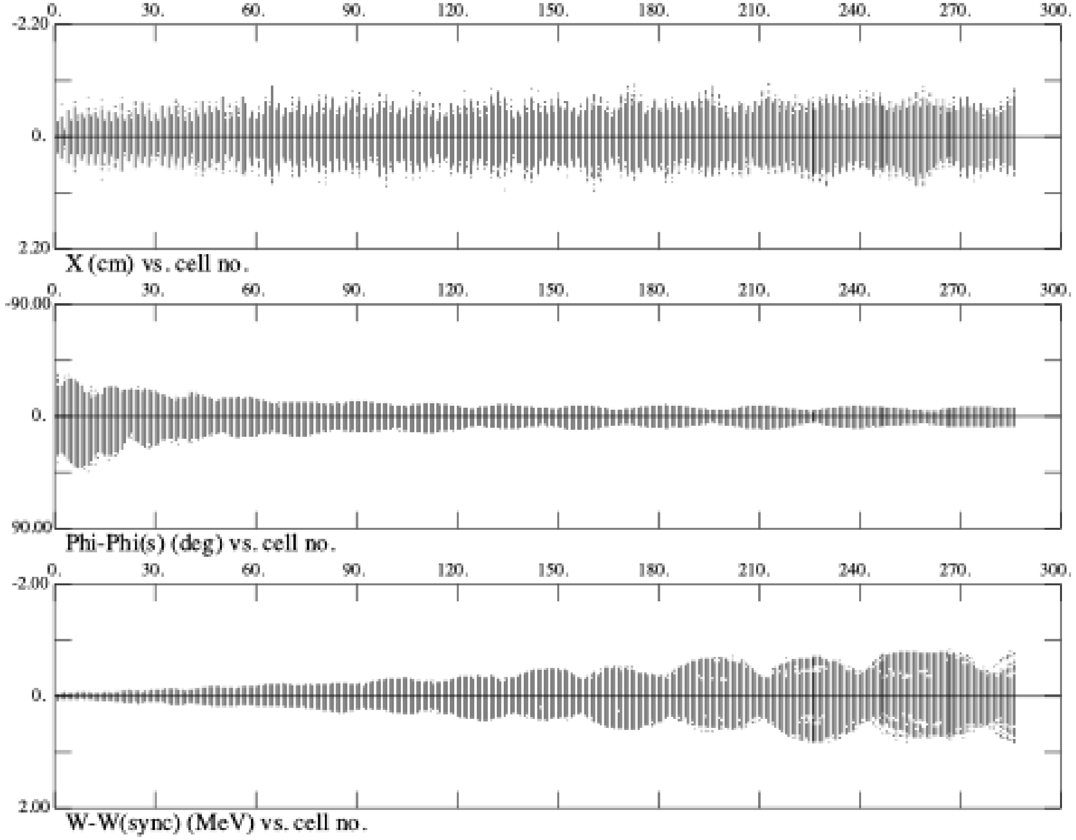
- No steering 0.750 MeV to 200 Mev(150 m)
- 55 years old quadrupole PS , calibration ??
- In FODO configuration, two adjacent quad powered by one PS
- Tk_n-Q_n- Tk_{n+1} - Q_1 ; One PS
- Only neutron beam loss monitor in the linac
- Diagnostic are located before and after linac



Simulation Assisted Tunning and



Emittance reduction in PARMILA iterative simulations using operational lattice settings

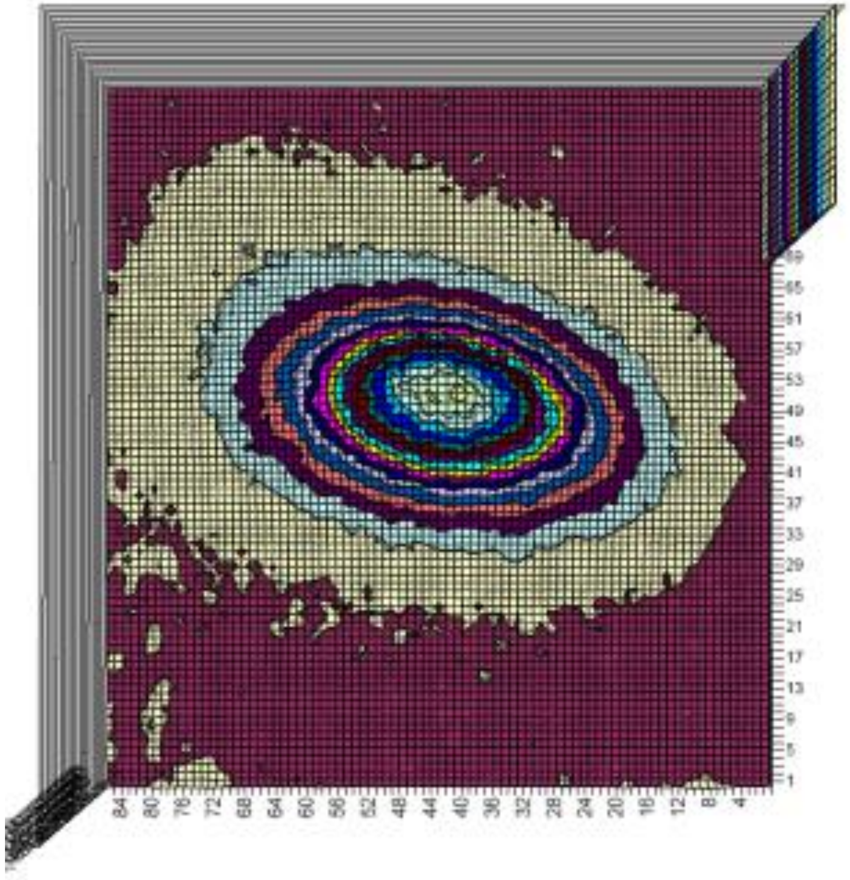


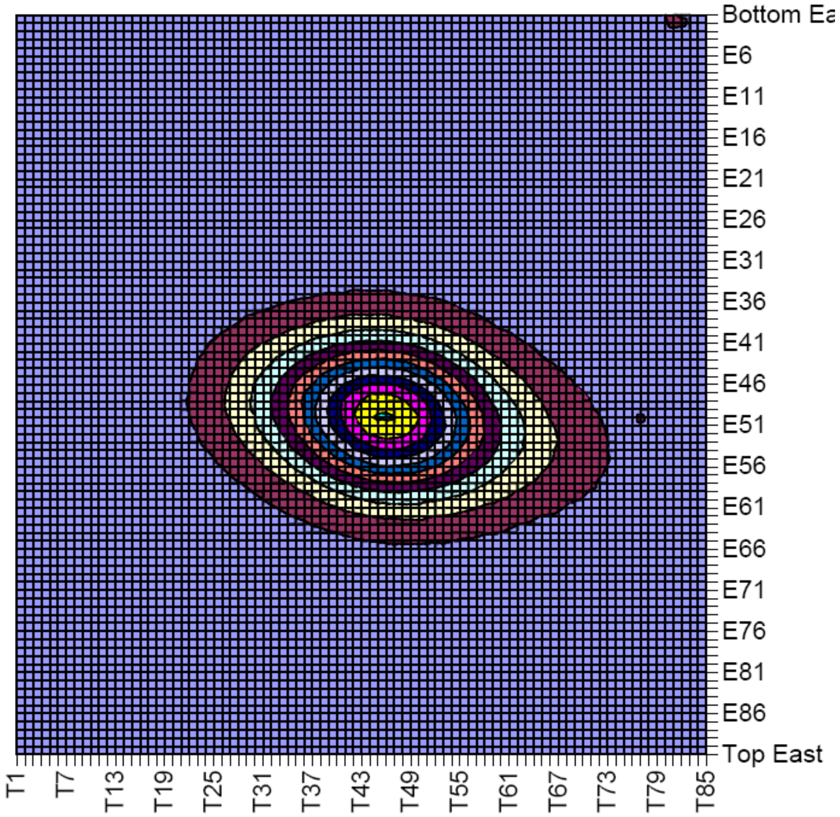
Parmila Simulation for 60 mA peak current

Results

- 10^3 reduction in beam losses
- 2× higher transmission
- 2× lower emittance

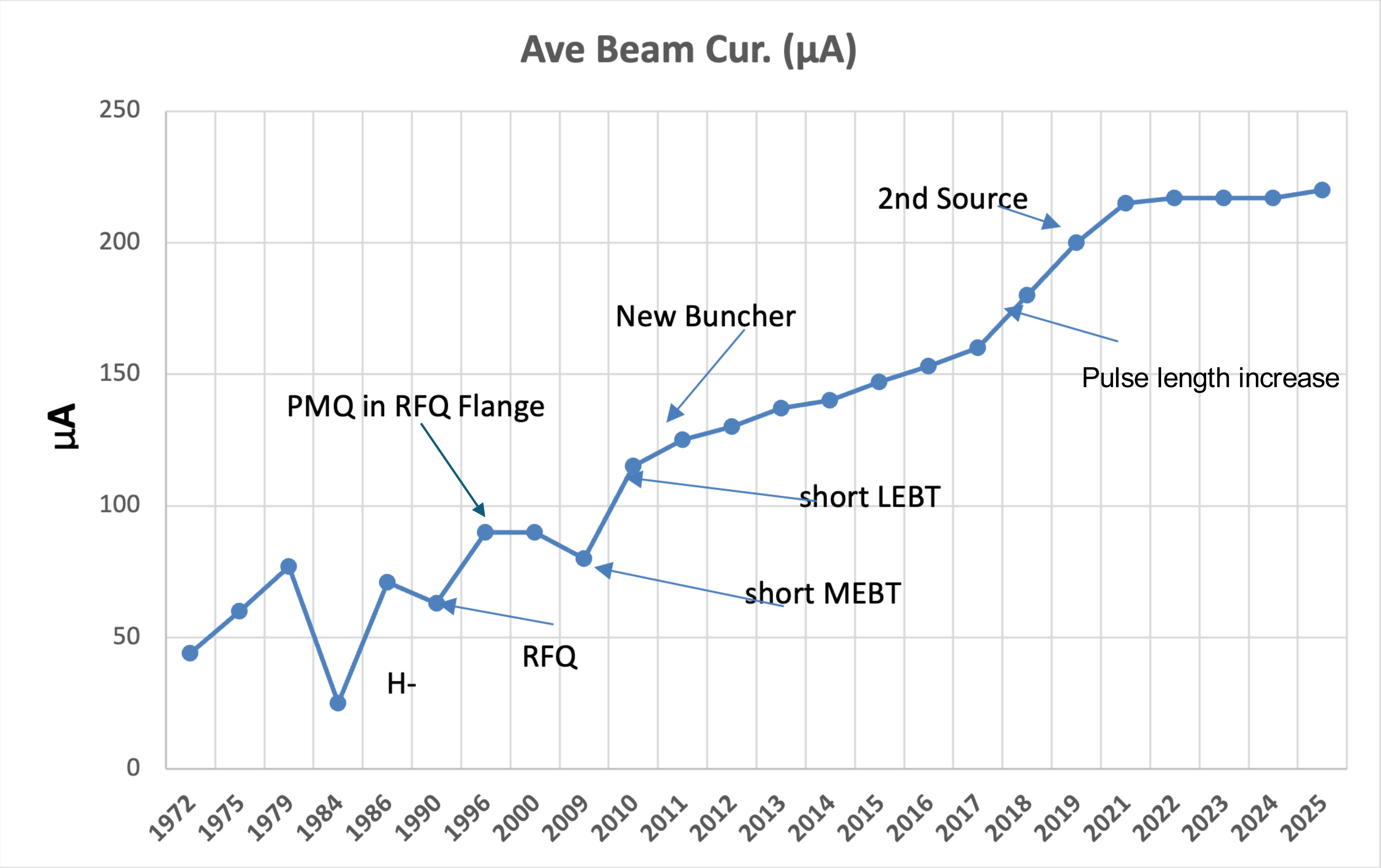
Beam Footprint at the BLIP Target



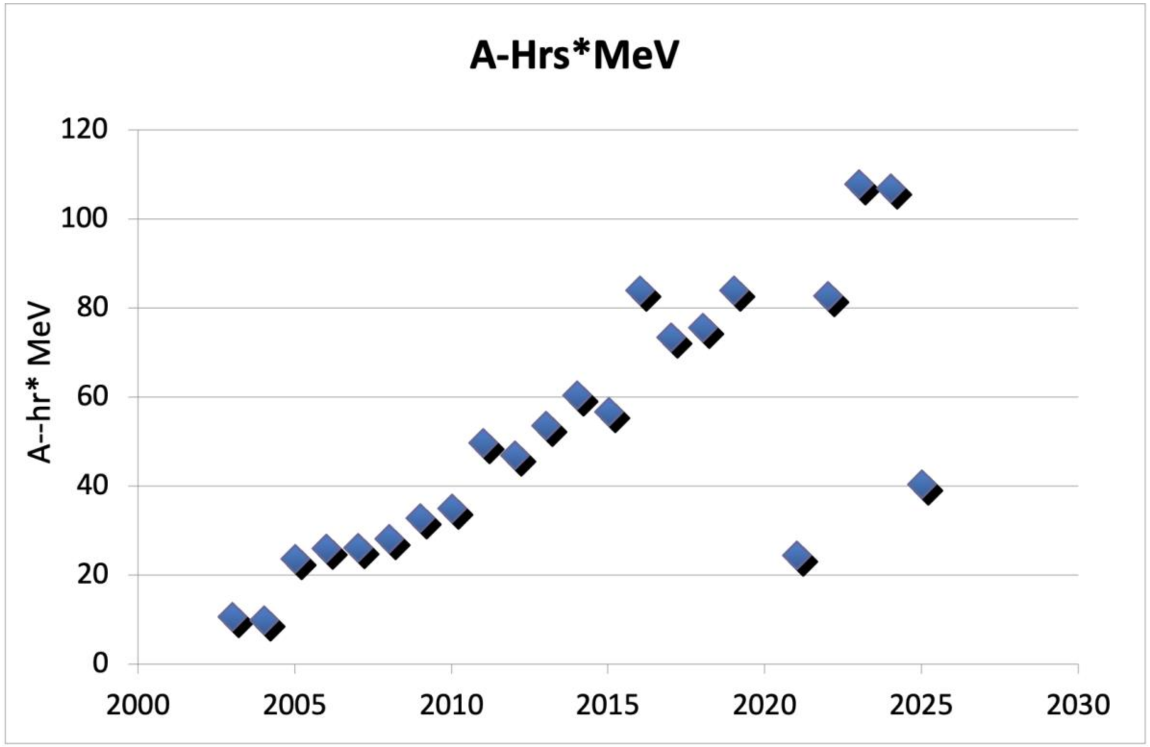


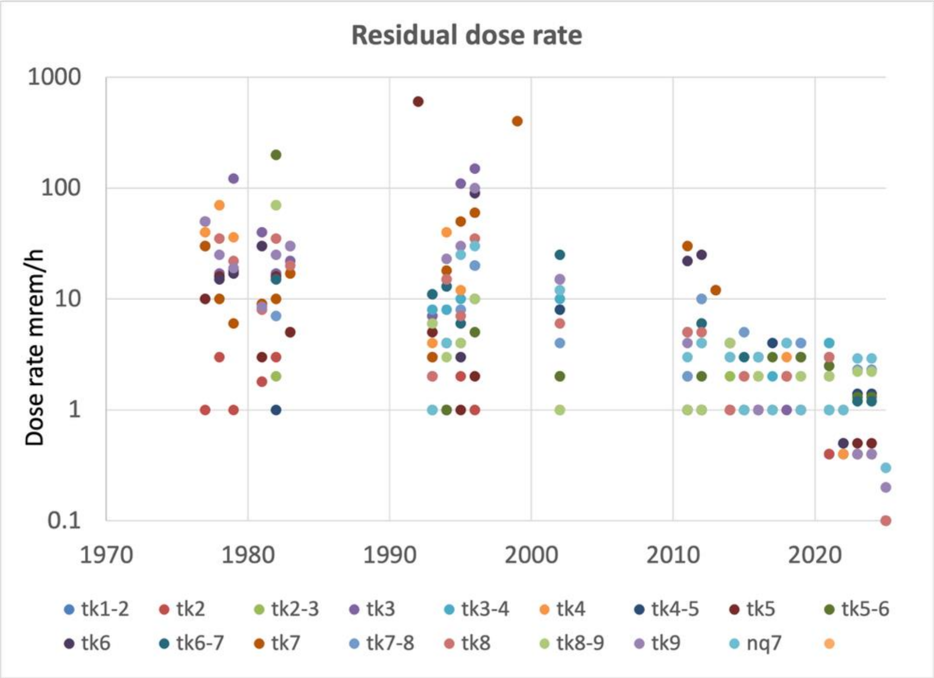
Beam footprint at BLIP target 2008 (left), and 2016(right)

Average Current at BLIP (1970-2025)

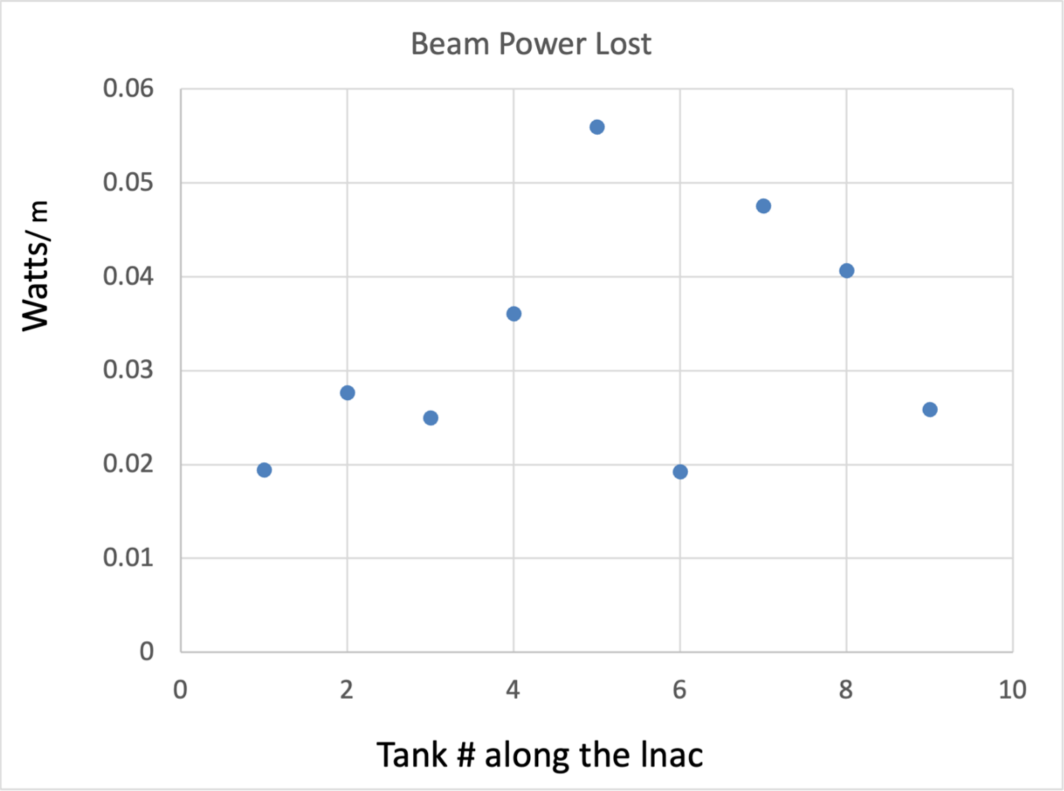


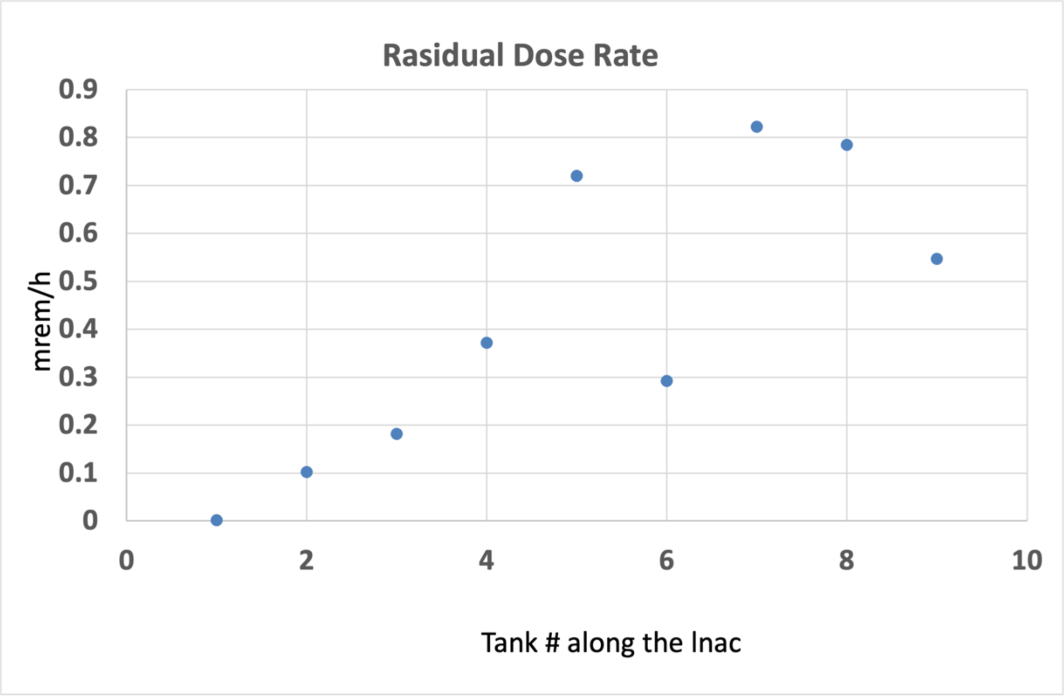
Beam Power and Residual Dose Rate





Power Loss and Residual Dose Rate due Residual Gas Stripping of H^-



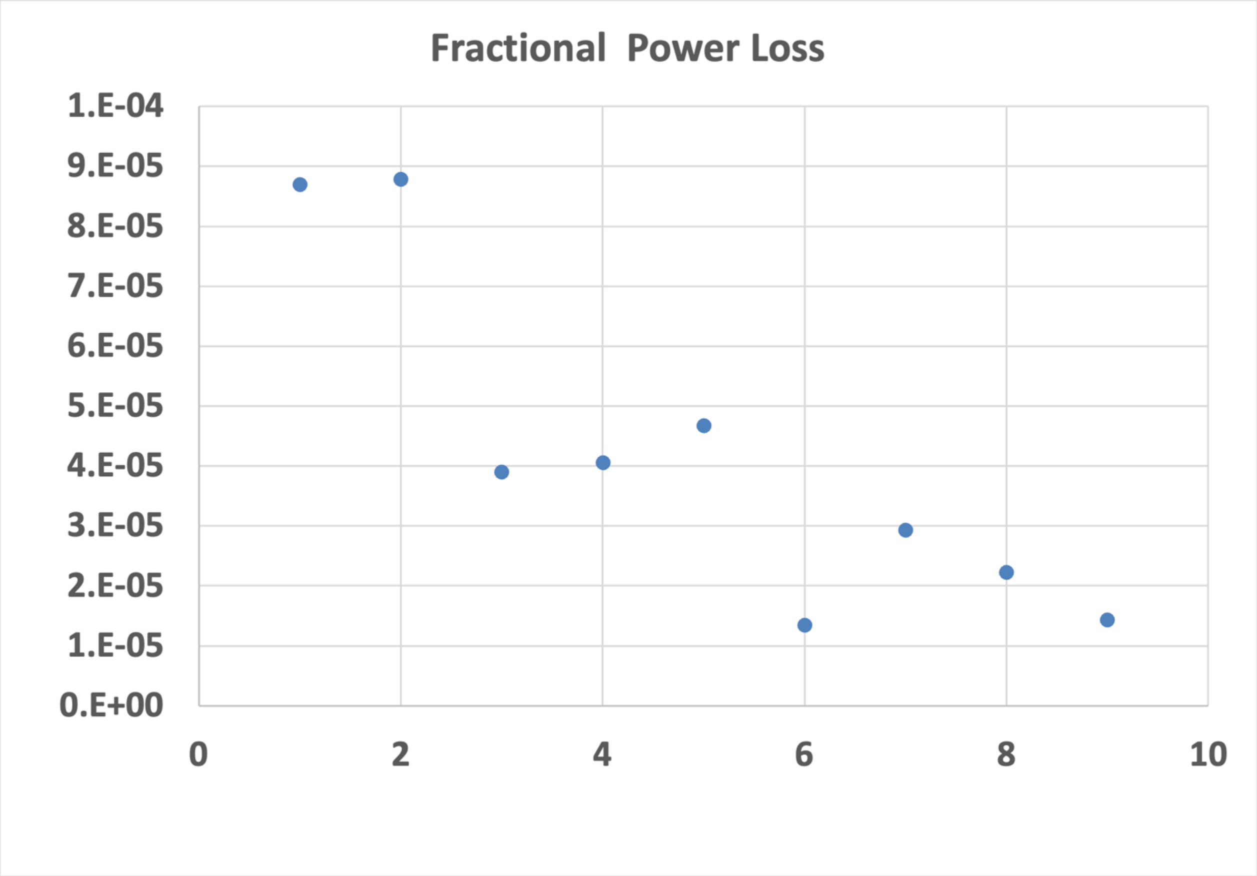


$$P_{per\ unit\ length} = E_{beam}\ I_{beam} \rangle\ d \int / d\wedge$$

Dose Rate (mrem/h)=0.33P_{lost} (W) [E(MeV)-9]$^{1.8}$ /E(MeV)

(J. Galambos et al., Snowmass, July 7, 2001)

Fractional Power Loss



Reducing Beam Losses

- Reducing length of MEBT to 0.7 meter from 7 meter
- Reducing LEBT to 2 meter from 4 meter
- Neutron beam loss monitor
- Optimizing H^- beam neutralization in LEBT
- New buncher design
- Simulation assisted tunning
- **Now most of the beam losses in the linac is due to gas stripping of H^-**
- *Linac tunnel was recently reclassified from a* ***High Radiation Area*** *to a* ***Radiation Area***

Summary

- Fifty-five years of operations , performance still improving.
- Severing multiple users simultaneously, BLIP, RHIC, NSRL, 200 MeV Polarimeter.
- **Losses better understood, Four order of magnitude less losses with 10-fold increase in beam power.**
- **Reliability > 95%.**
- **This demonstrates that even in a legacy linac, careful control of space-charge-dominated beam dynamics—through a combination of experimental diagnostics, modeling, and operational optimization—can significantly extend performance.**

Thank You

Questions ?

Linac Upgrades History

1970: Built for Proton beam pulse length 200 μs, RF pulse length 400 μs, 10 Hz

1977: 5 Hz operation

1982: Switch to H-

1986: Add Polarized H-

1990: Replacement of Cockcroft-Walton By RFQ

1996: Pressurized coax, RF system:50 kV power supply, new RF control system, new amplitude phase servo, and LEBT modification, 6.67 Hz

1999: New timing system

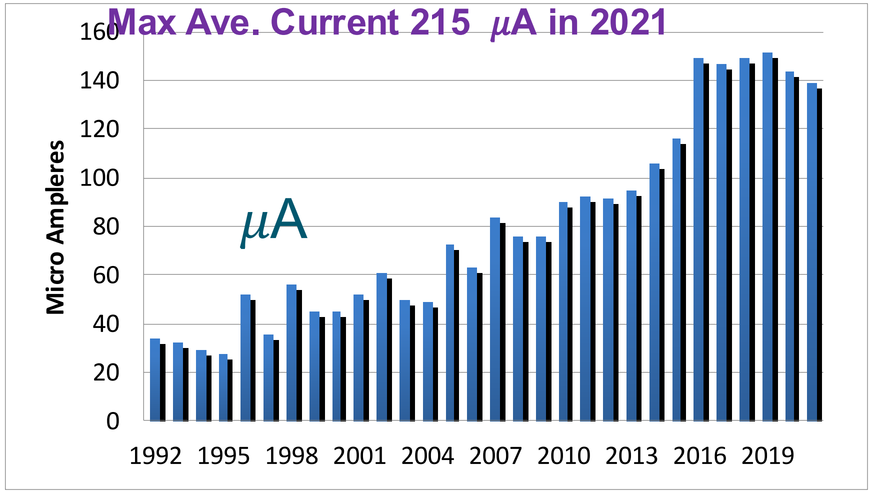
2000: addition of OPPIS

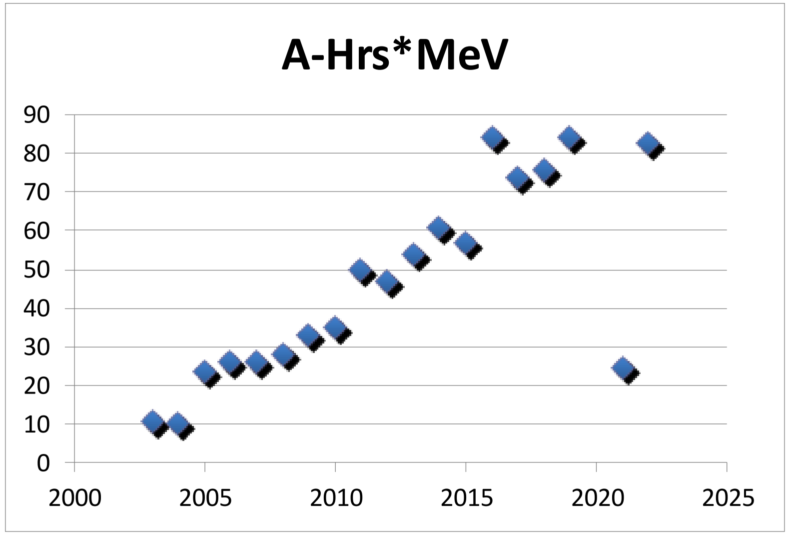
BNL Linac Upgrades (Cont.)

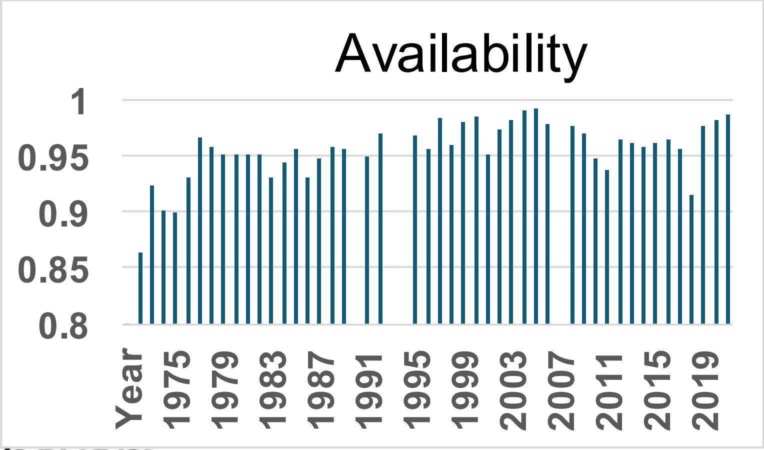
2009: LEBT/MEBT reconfiguration short MEBT (7m to 0.7m)
2010: Short LEBT at 45 deg (4m to 2m)
2015: New beam loss monitor ,replacement of tetrode 7651 with 5 kW solid state amplifiers
2016: Intensity upgrade phase I, Beam raster system
2017: Upgrade to digital LLRF
2019: High intensity sources
2020: Vacuum upgrade replace all ion pumps

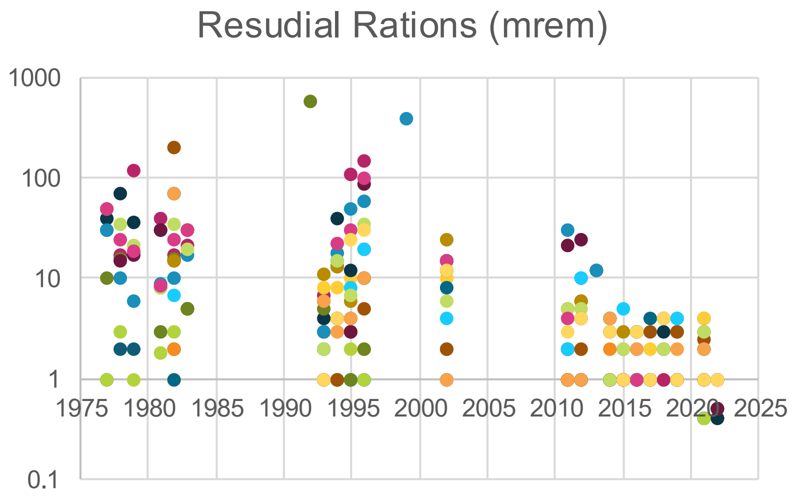
Most of the sub system has been upgraded to modern technology

Yearly Ave. Current and Beam Power, Availability and Residual Radiation



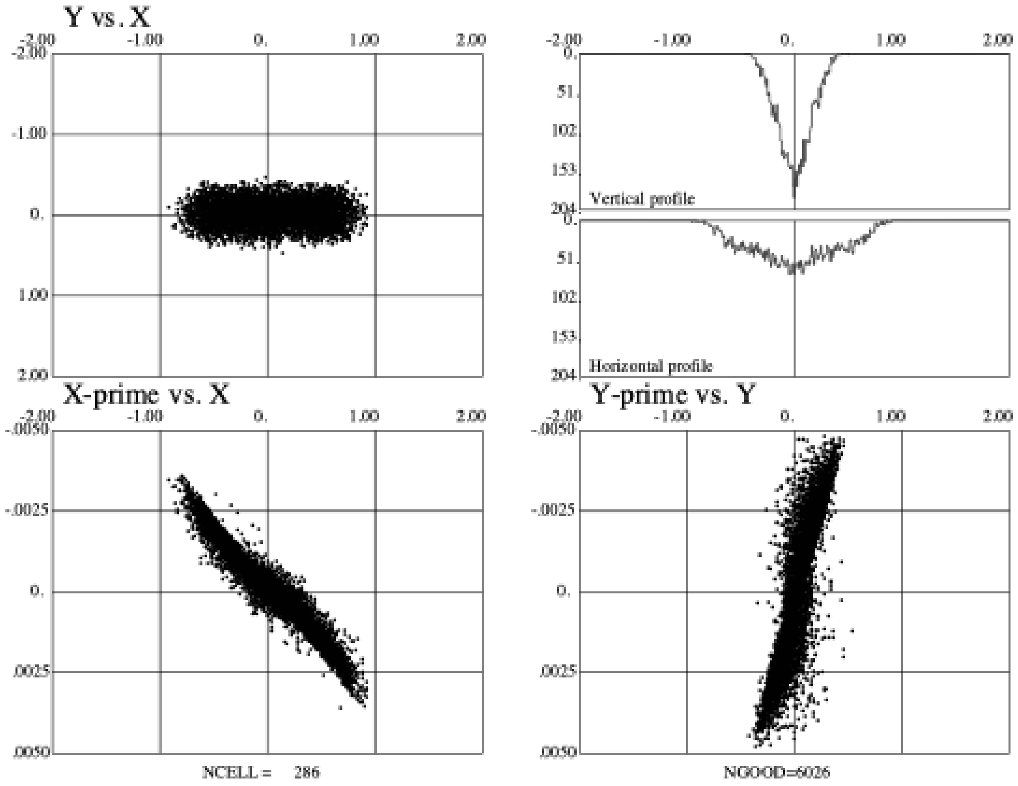




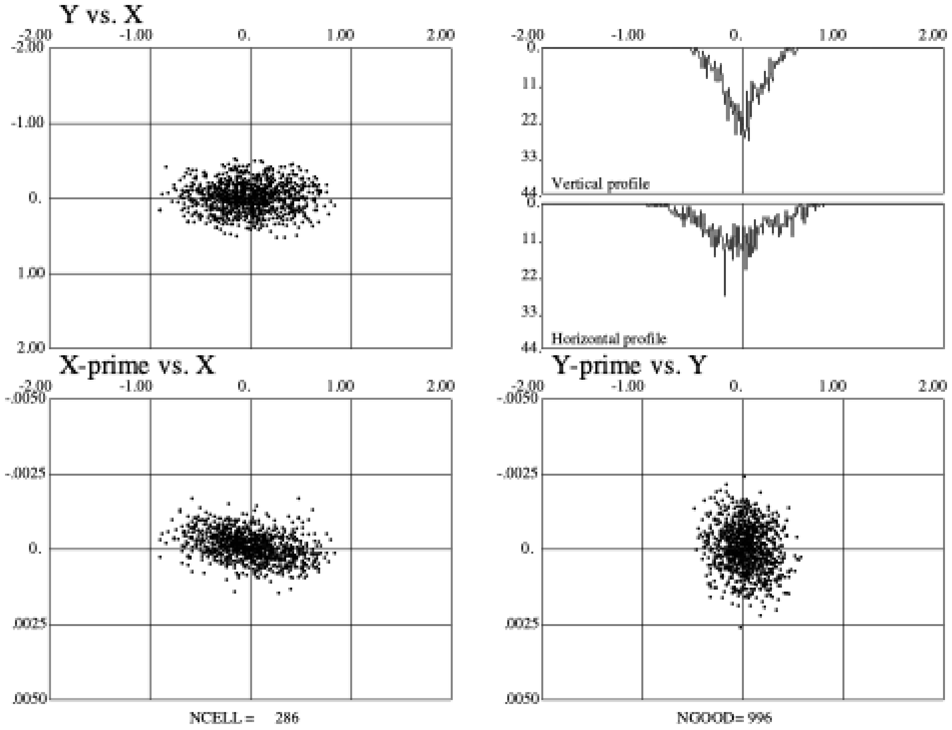


Brookhaven National Laboratory

Emittances at tank 9



2008



2025