Multi-Ion Linac and Pre-Booster for the JLAB based EIC

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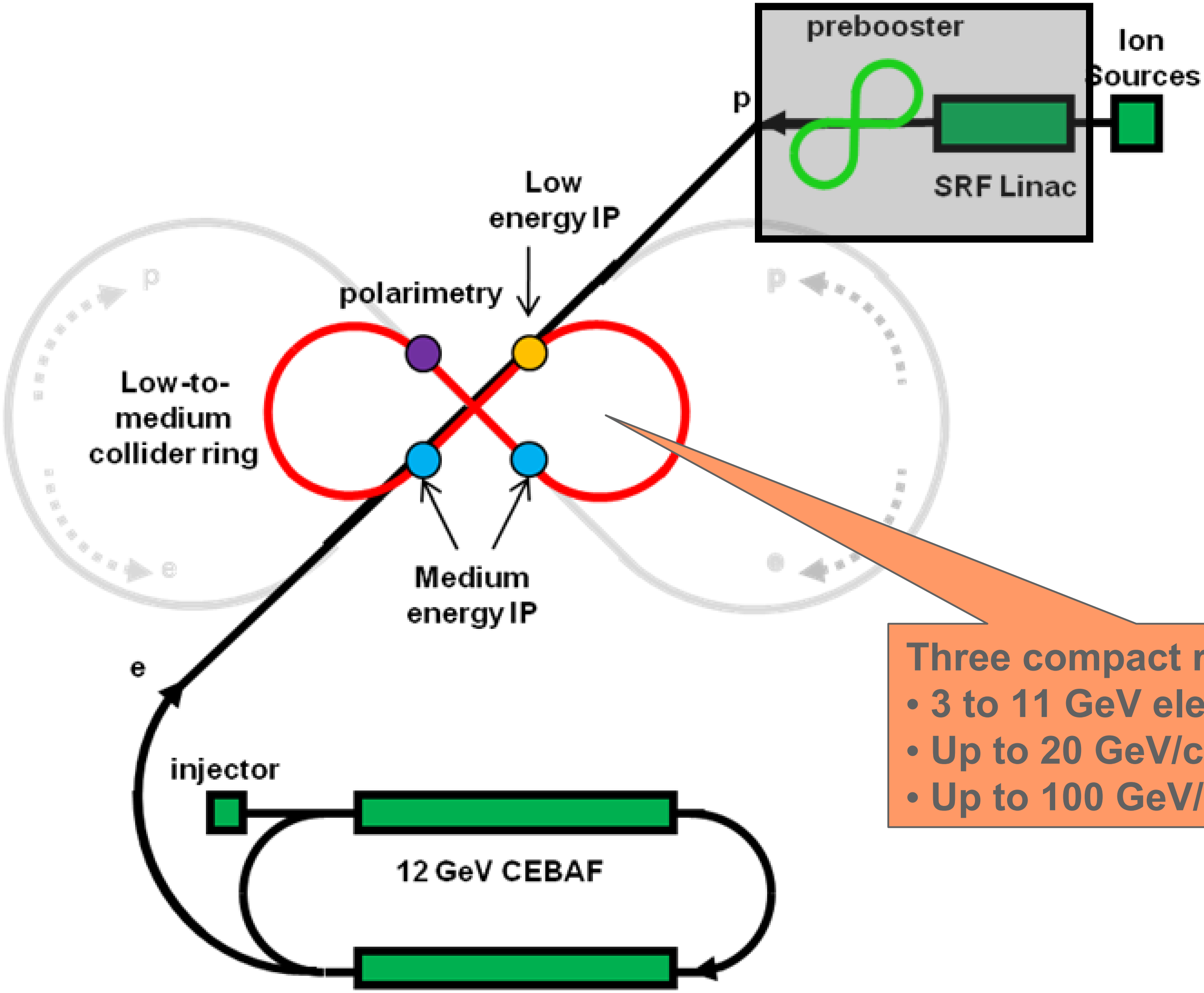
Acknowledgements

- Joint Work with
  - P. Ostroumov, S. Manikonda (ANL)
  - S. Abeyratne (NIU student)
  - Y. Derbenev, Y. Zhang, G. Krafft (JLab)

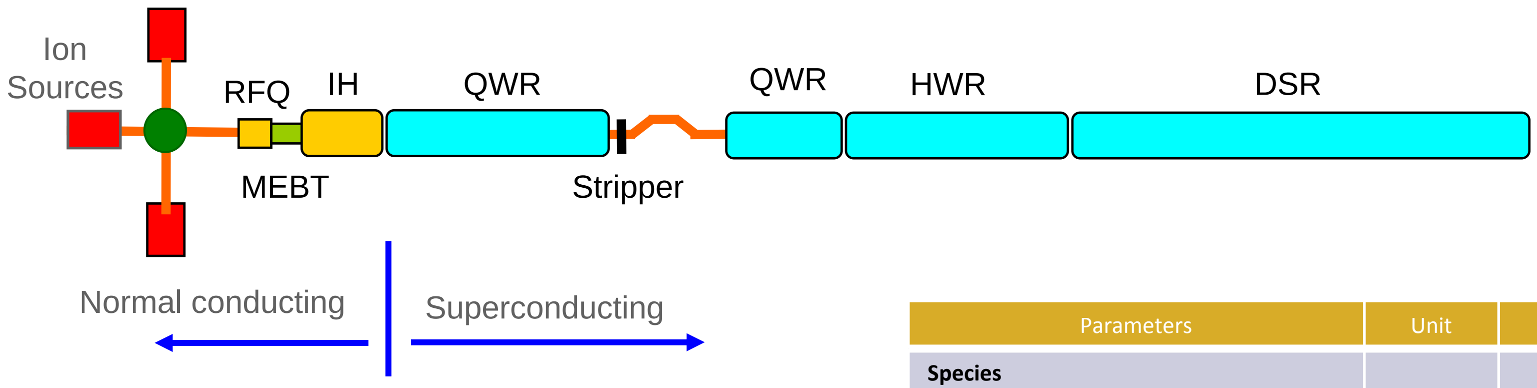
MEIC Conceptual Layout



Three compact rings:
- 3 to 11 GeV electron
- Up to 20 GeV/c proton (warm)
- Up to 100 GeV/c proton (cold)

Ion Linac

Layout



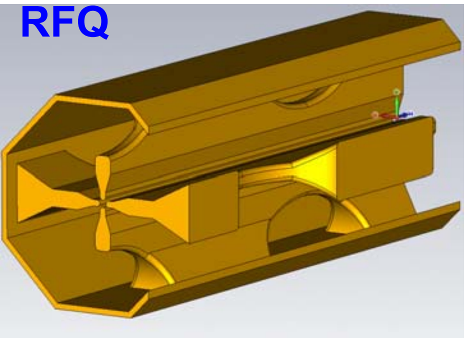
Parameters	Unit	Value
Species		**p to lead**
Reference Design		**^{208}Pb**
Kinetic energy	**MeV/u**	**100**
Max. averaged pulse current	**mA**	**2**
Pulse repetition rate	**Hz**	**10**
Pulse length	**ms**	**0.25**
Max. beam pulsed power	**kW**	**680**
Fundamental frequency	**MHz**	**115**
Total length	**M**	**150**

- Originally developed as a heavy-ion driver accelerator for ***Rare Isotope Beam Facility***
- All technical sub-systems are either ***commercially available*** or based on ***well-developed technologies***
- Adopted for MEIC ion linac for
  - Satisfying MEIC ion linac requirement
  - Covering similar energy range and variety of ion species
  - Excellent and matured design
  - Great saving on time and cost
  - Only minor adjustments required

	Q ion source	Energy at the stripper MeV/u	Q after the stripper	Total energy MeV/u
Proton	1	55	1	285
Dueteron	1	32.8	1	169
^{40}Ar	12	22.4	18	150
^{132}Xe	26	16.5	48	120
^{208}Pb	30	13.2	67	102

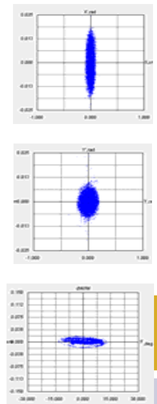
Components of the Ion Linac

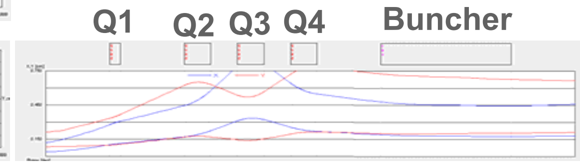
A Segment of the RFQ

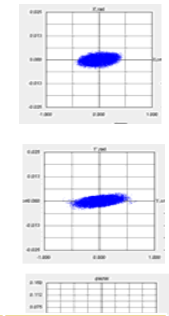


Frequency	115 MHz
Total length	3.6 m
Voltage	85 kV
Average radius	7 mm
# segments	4
Input energy	25 keV
Output energy	500 keV/u

Example of a short MEBT







	Length (mm)	Gradient (T/m)
Q1	20	23
Q2	50	-22
Q3	50	32.75
Q4	50	-16.5

Quad Parameters

Cavity	Unit	1/4 Wave
Volt.	MV	0.8
Freq.	MHz	117.3
Length	mm	340

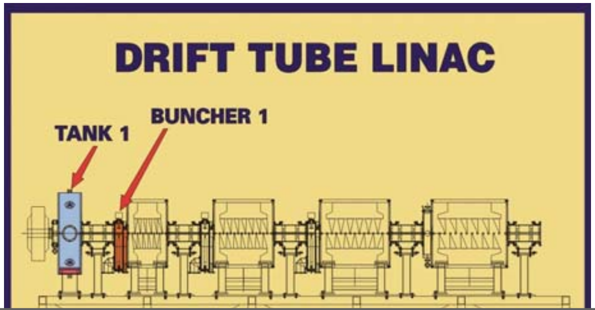
Buncher Parameters

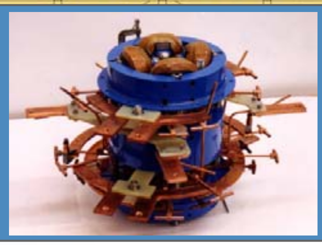
Normal Conducting IH structure

100 MHz

Accelerates the beam from 300 keV/u to 2 MeV/u

Normal Conducting IH cavities

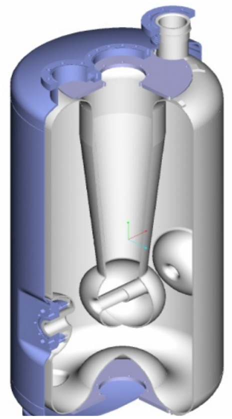




SRF Components of the Ion Linac

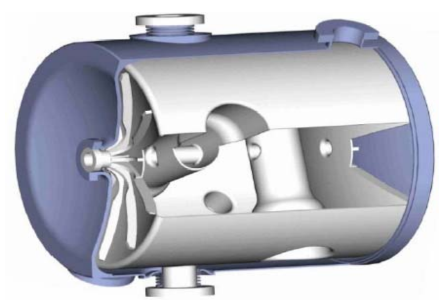
Superconducting cavities

- 119 cavities
- 21 cryostats



Quarter Wave Resonator (QWR)

Half-Wave Resonator (HWR)

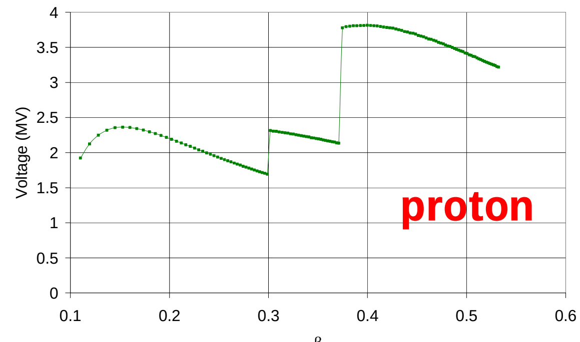


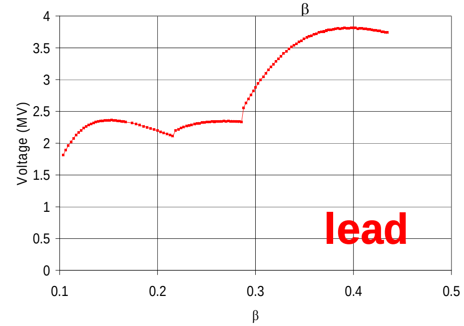
Double Spoke Resonator (DSR)

Heavy-Ion Linac - SC Resonator Configuration

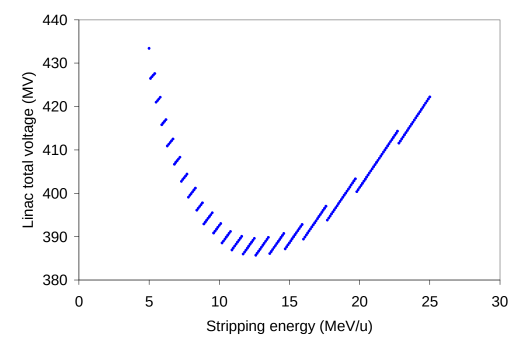
Beta	Type	Freq (MHz)	Length (cm)	at 1 MV/m Epeak		R/Q	G	Esurf	Eacc	Phase	# Cav
0.151	QWR	115.0	25.0	3.2	57	509	42	30	9.46	20	28
	STRIPPER								Subtotal		28
0.151	QWR	115.0	25.0	3.2	57	509	42	30	9.46	20	14
0.263	HWR	230.0	22.5	2.9	78	241	58	30	10.31	30	28
0.393	2SPOKE	345.0	38.1	3.0	69	444	71	30.0	10.00	30	63
									Subtotal		91
									Total Cavity Count =		119

Voltage gain per SRF cavity





Stripping energy (lead)



Accumulator/Pre-Booster Concept

- Purpose:
  - Inject from linac
  - Accumulate ions
  - Accelerate them
  - Extract and send to large booster

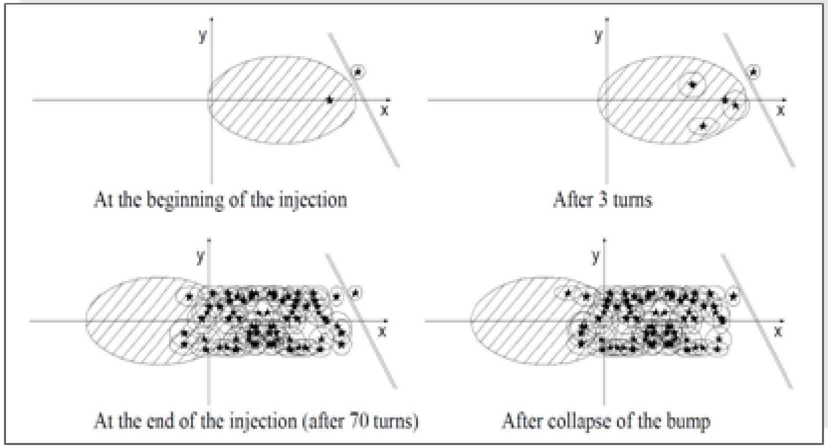
- Concepts:
  - Figure-8 shape for ease of spin transport, manipulation and preservation
  - Modular design, with (quasi)independent module design optimization
  - FODO arcs for simplicity and ease of implementation of optics correction schemes
  - No dispersion suppressors
  - Matched injection insertion
  - Triplet straights for long dispersion-less drifts and round beam
  - Matching/tuning modules in between

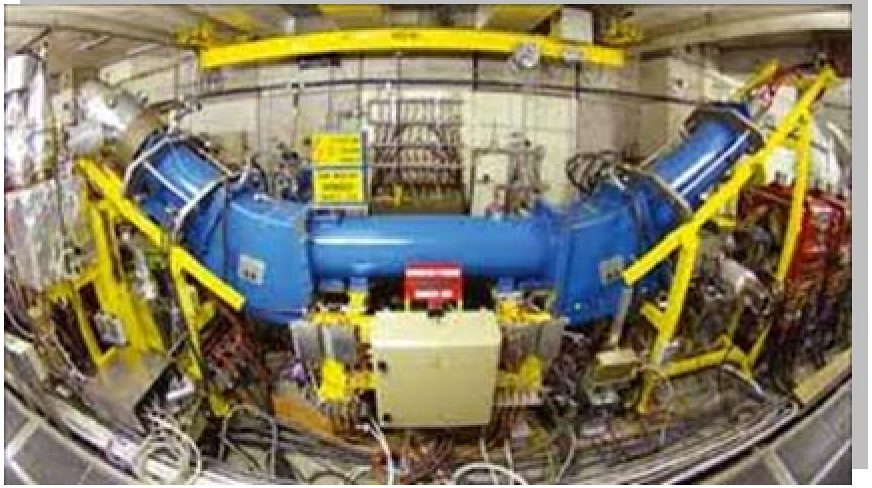
Constraints

- Figure-8 shaped; circumference as short as possible
- Maximum bending field: 1.5 T
- Maximum quadrupole gradient: 20 T/m
- Momentum compaction smaller than 1/25
- Maximum beta functions less than 35 m
- Maximum full beam size less than 3 cm, and 1 cm vertically in dipoles
- 5m m long dispersion-less sections for RF cavities, electron cooling, collimation, extraction, and possibly decoupling
- Sizable (normalized) dispersion for/at injection
- Working point chosen such that tune footprint does not cross low order resonances (tunability)

Injection & Accumulation

- Protons (and possibly light ions)
  - Stripping injection
  - Possibility of emittance reduction with electron cooling
- Heavy ions
  - Repeated multi-turn injection
  - Transverse (horizontal and possibly also vertical) and longitudinal painting
  - Electron cooling for stacking/accumulation





- Intensities needed to achieve design luminosity, with some safety factors included for possible losses during
  - Stripping
  - Capturing, re-capturing
  - Transfers

- Proton current: up to 1A ($6x10^{12}$ total particles in the ring)
- Heavy-ion current: ~0.5 A ($1x10^{11}$ total particles in the ring)

Acceleration

- h=1
  - RF swing necessary is [0.4,2] MHz
- 8-10 kV per cavity
- 50kV/turn => 5-6 cavities
- Average synchronous phase ~ -25°
- ~10^5 turns from 200MeV -> 3 GeV
- ~100 ms acceleration time
- Allows acceleration with h=2

with the same cavities, if needed

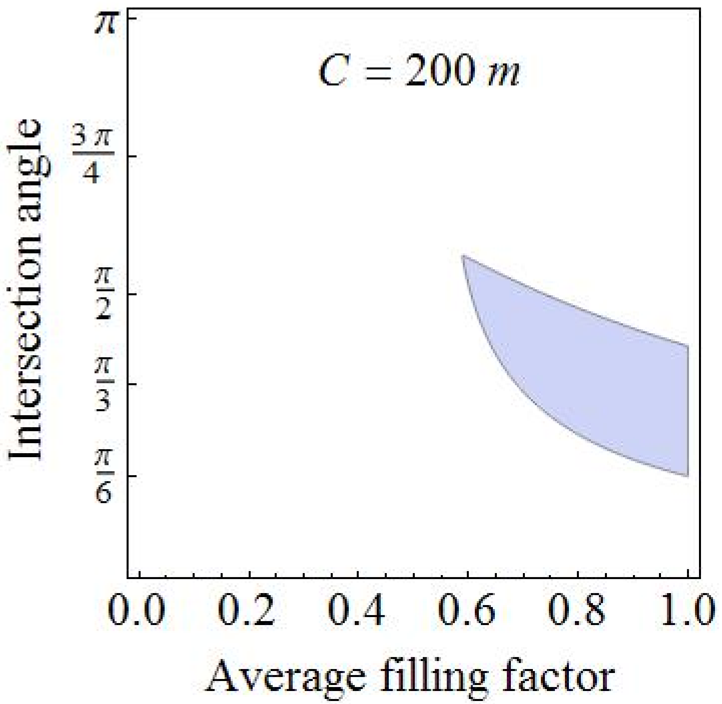
- Finemet cavities
- 0.5 m long
- 4kV/cavity, upgradable
- [0.35,5] MHz frequency swing
- Practically no maintenance needed (CERN-LEIR)

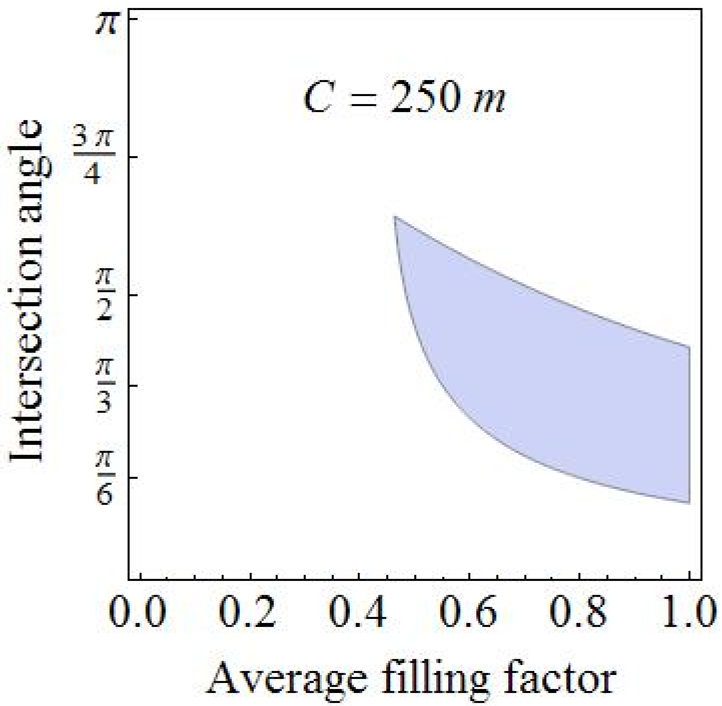
Extraction and stripping

- Conventional single-turn fast extraction
- To minimize heavy-ion loss, strip once in linac and once <u>after</u> the pre-booster to maximize fully stripped fraction
  - Advantages:
    - Less beam-loss to reach fully stripped state
    - Less severe space charge in pre-booster
  - Drawback: lose some energy gain

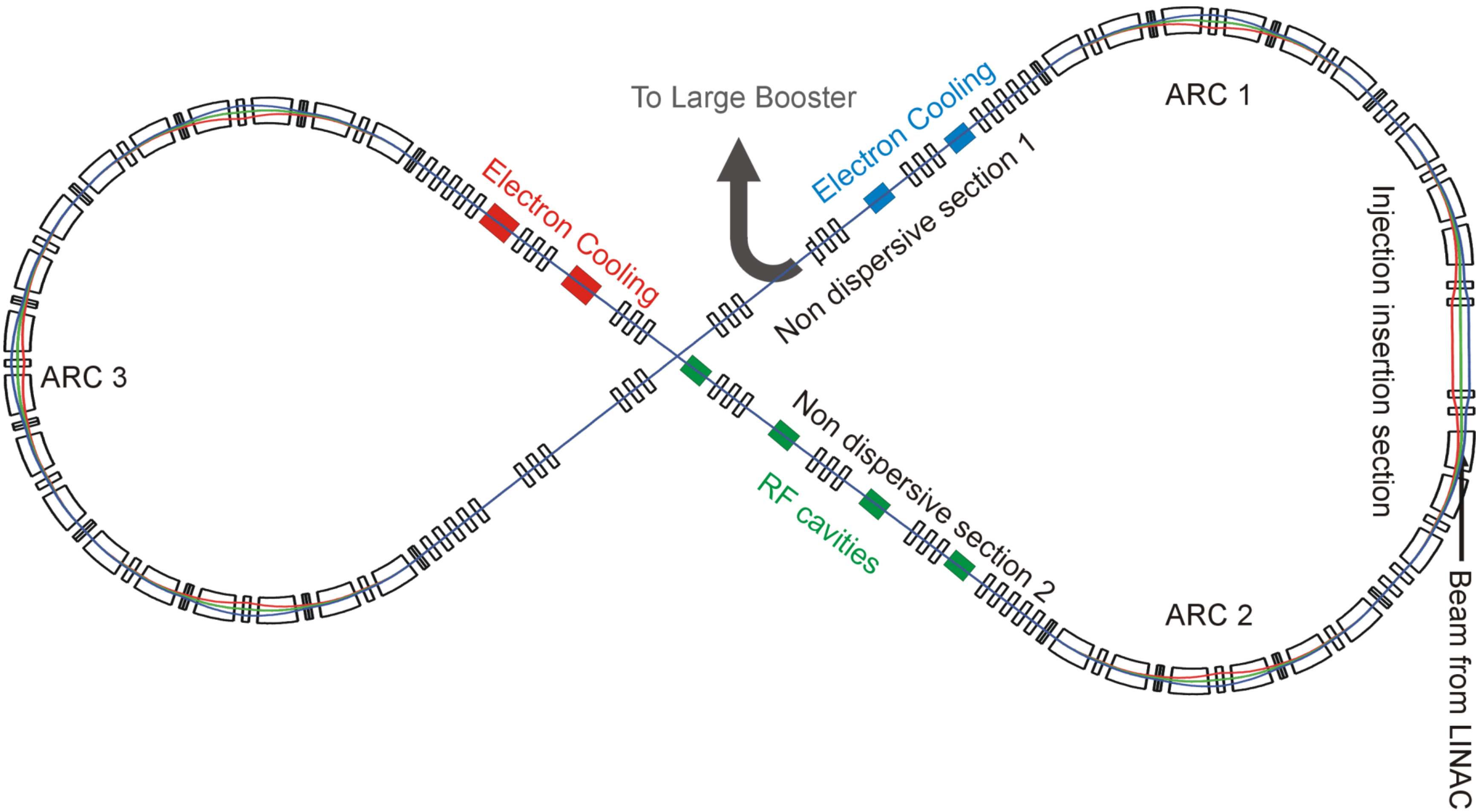
Circumference

Total length of the long drifts in the straights = 20m

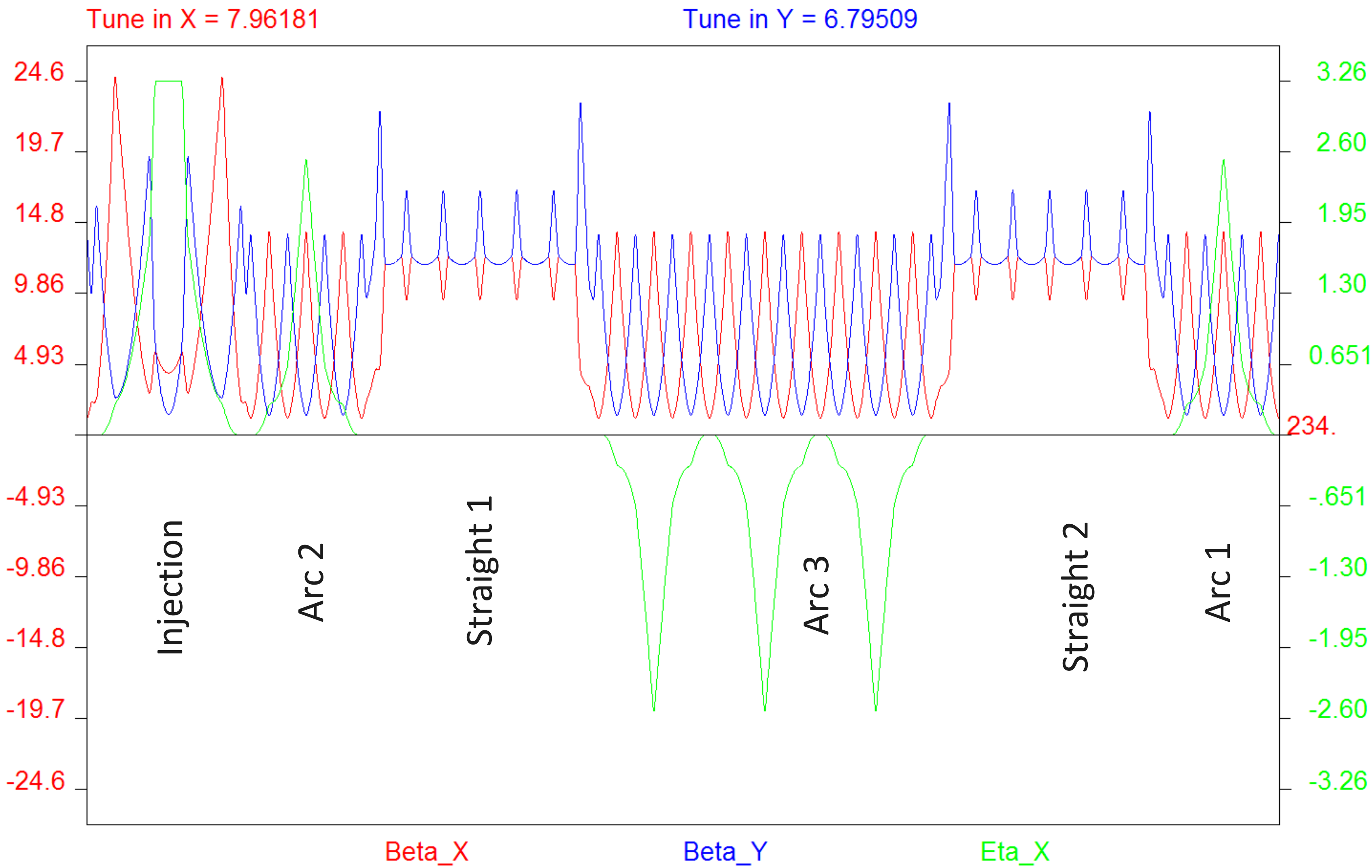




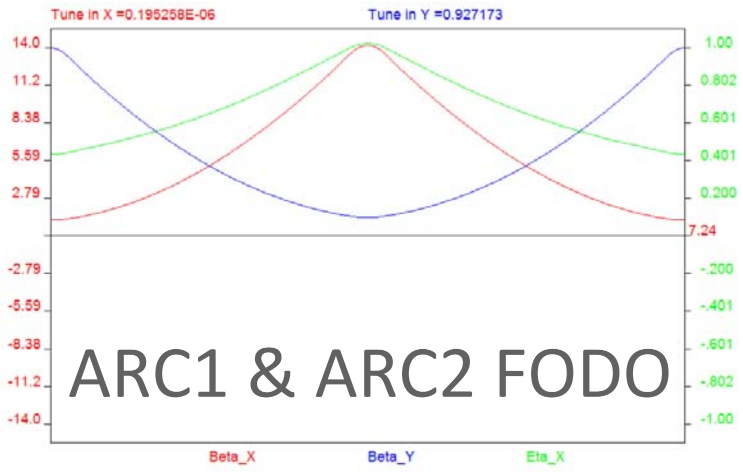
Pre-Booster Layout

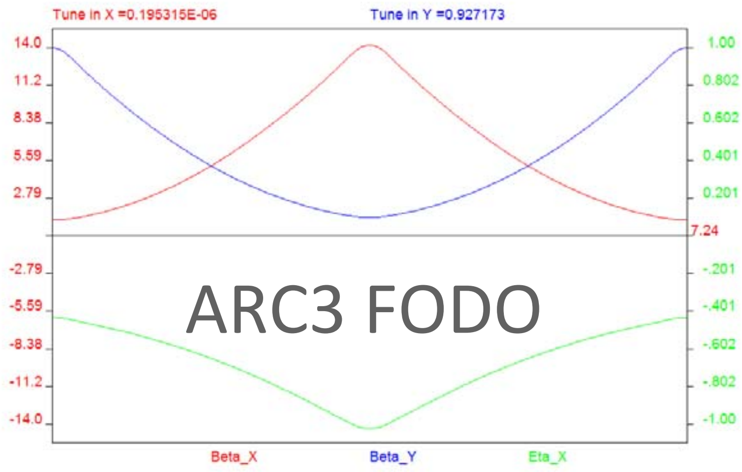


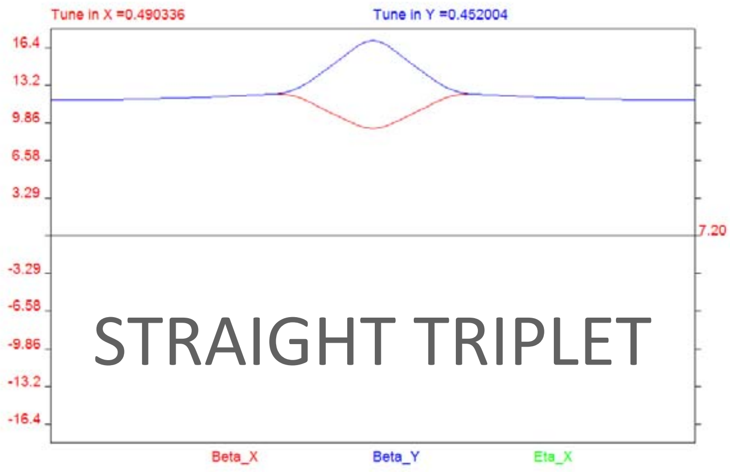
Linear Optics of Pre-Booster Ring: Lattice Plot

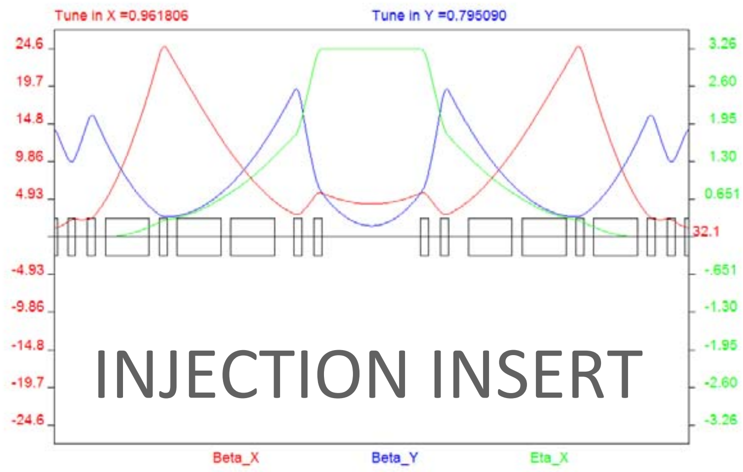


Modules for Building the Lattice





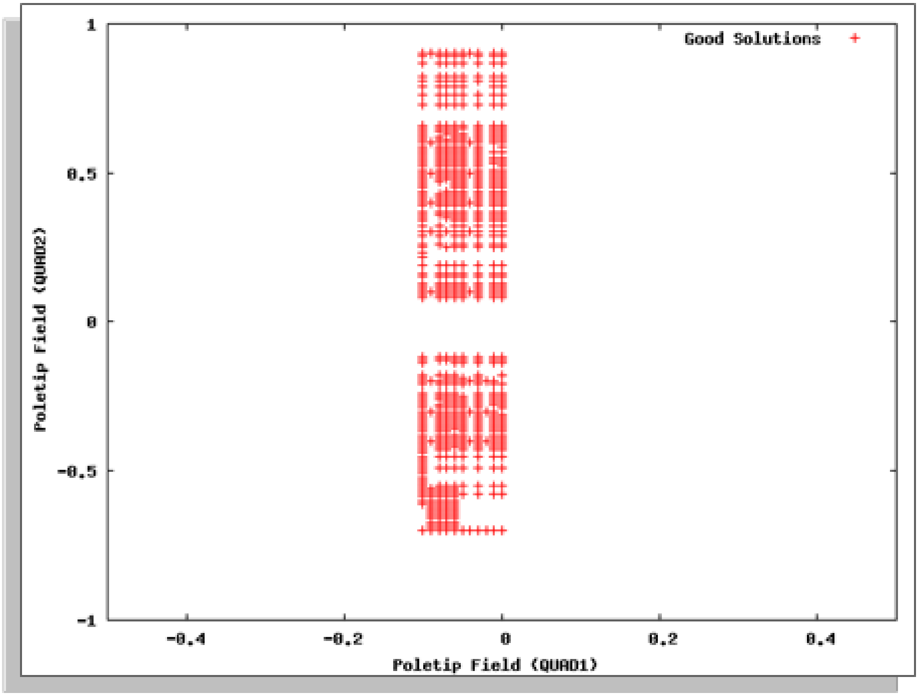


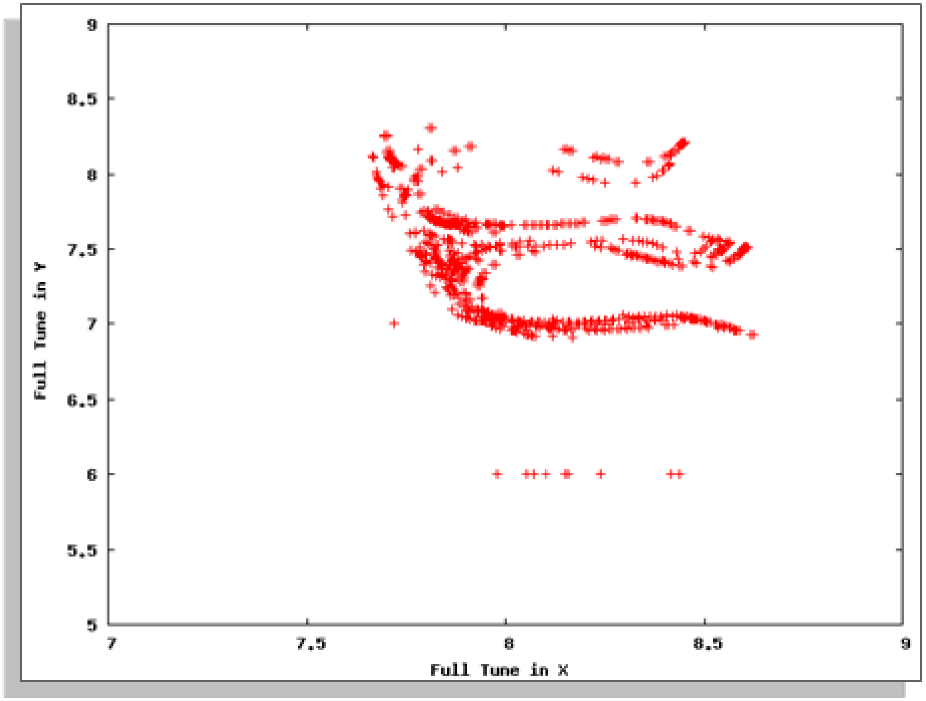


Lattice Parameters

Lattice Parameters	Units	Value
Total length	m	234
Angle at crossing	deg	75
Number of dispersive FODO cells (Type I)		6
Number of dispersive FODO cells (Type II)		9
Number of triplet cells		10
Number of matching cells		4
Minimum drift length between magnets	cm	50
Drift lengths in the insertion region	m	5.0
Drift lengths between triplets (RF, collimation and electron cooling)	m	5.0
Beta maximum in X	m	25
Beta maximum in Y	m	23
Maximum beam size	cm	3.2
Maximum beam size in the dipole magnets	cm	0.6
Maximum Dispersion $(x\| \delta_p)$		4.6
Normalized dispersion at injection $(x\|\delta_p)/\sqrt{\beta_x}$		2.68
Tune in X		7.96
Tune in Y		6.79
Gamma of particle (proton at 3 GeV)		4.22
Gamma at Transition Energy		5
Momentum compaction factor		0.04
Number of quadrupole Magnets		93
Quadrupole magnet Length	cm	40
Quadrupole magnet Half Aperture	cm	5
Quadrupole maximum pole tip field	T	1.00
Number of Dipoles		36
Dipole Vertical full gap	cm	3
Dipole Max Strength	T	1.5
Dipole Bending Radius	m	9
Dipole Angle	deg	14.13

Tunability


Good Solutions
Poletip Field (QUAD2)
Poletip Field (QUAD1)
1
0.5
0
-0.5
-1
-0.4
-0.2
0
0.2
0.4


Full Tune in Y
Full Tune in X
9
8.5
8
7.5
7
6.5
6
5.5
5
7
7.5
8
8.5
9

Proton Beam Parameters

Proton Beam Parameter	Units	Value
Injection Energy	MeV	285
Extraction Energy	MeV	3000
Current at Extraction	A	0.5
Total Number of protons in the ring	10^{12}	2.52
Beam from Linac		
Pulse Length	ms	0.22
Frequency	MHz	115
Number of Bunches in Pulse		25300
Average Current per Pulse	mA	2
Charge per Pulse	μC	0.44
Number of Protons per Pulse	10^{12}	2.75
Injection Efficiency		0.9
Number of Pulses		1
Timing		
RF Acceleration Time	s	0.12
Pre-booster Cycle Time	s	0.2
Beam profile at Injection		
Acceptance in x (ε_x) (normalized)	π mm · mrad	92
Acceptance in y (ε_y) (normalized)	π mm · mrad	50
Momentum Acceptance ($\Delta p/p$)	%	±0.3
Beam profile at Extraction		
Momentum Spread ($\Delta p/p$)	%	±0.27
Bunch Length	μs	0.166
Space Charge		
RMS Emittance Un-normalized x	mm.mrad	26
RMS Emittance Un-normalized y	mm.mrad	14
RMS Emittance Un-normalized z	eV.s	0.016
Laslett Tune Shift (after injection)		-0.025
Max Laslett Tune Shift		-0.038
Laslett Tune Shift (at extraction)		-0.006

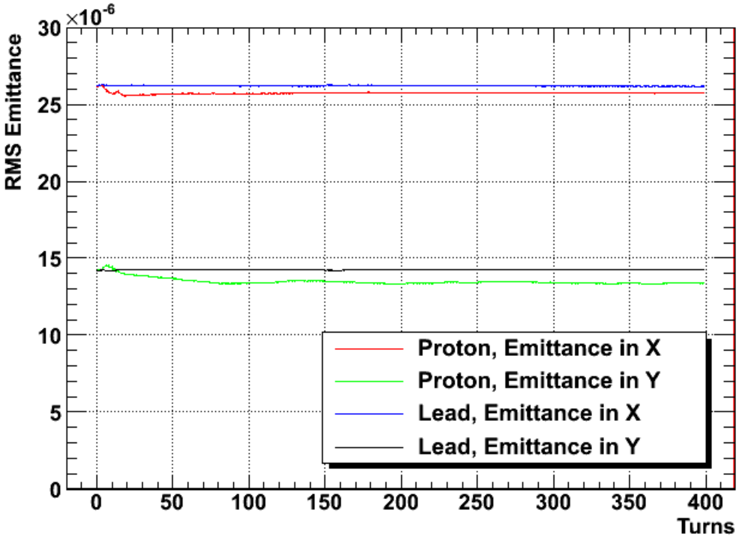
Lead Beam Parameters

Lead Beam Parameter	Units	Value
Injection Energy	MeV/u	100
Extraction Energy	MeV/u	670
Charge State of Lead Ions		+67
Current at Extraction	A	0.5
Total Number of Lead Ions	10^{10}	4.5
Beam from Linac		
Pulse Length	Ms	0.25
Frequency	MHz	115
Number of Bunches in Pulse		28750
Average Current per Pulse	mA	0.1
Charge per Pulse	μC	0.025
Number of Lead Ions per Pulse	10^{9}	2.4
Injection Efficiency		0.7
Number of Pulses		28
Timing		
Electron Energy (for e^- Cooling)	MeV	[.56,.88]
Electron Cooler Current	A	0.3
Electron Cooler Length	M	3
Transverse Cooling Time	Ms	16
Longitudinal Cooling Time	Ms	55
RF Acceleration Time	Ms	144
Pre-booster Cycle Time	S	3.1
Beam Profile at Injection		
Acceptance in x (ε_x) (normalized)	π mm · mrad	92
Acceptance in y (ε_y) (normalized)	π mm · mrad	50
Momentum Acceptance ($\Delta p/p$)	%	±1
Emittance in x (ε_x) (normalized)	π mm · mrad	50
Emittance in y (ε_y) (normalized)	π mm · mrad	25
Momentum Spread ($\Delta p/p$)	%	±0.3

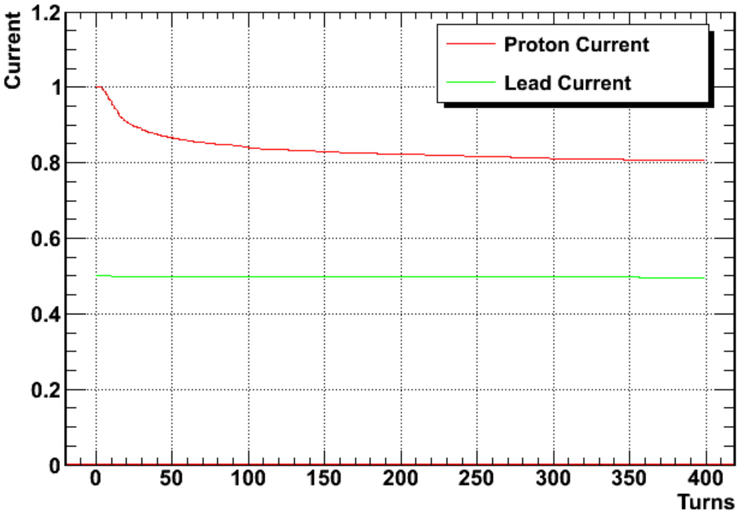
Lead Beam Parameters Cont….

Lead Beam Parameter	Units	Value
Beam Profile after Cooling and Accumulation		
Emittance in x (ε_x) (normalized)	π mm · mrad	20
Emittance in y (ε_y) (normalized)	π mm · mrad	10
Momentum spread ($\Delta p/p$)	%	±0.054
Beam Profile at Extraction		
Emittance in x (ε_x) (full, normalized)	π mm · mrad	20
Emittance in y (ε_y) (full, normalized)	π mm · mrad	10
Momentum spread ($\Delta p/p$) (95% capture efficiency)	%	±0.11
Bunch Length	µs	0.386
Space Charge		
Laslett Tune Shift (at injection)		-0.16
Max Laslett Tune Shift		-0.3
Laslett Tune Shift (at extraction)		-0.09

Transverse space charge effects in the pre-booster

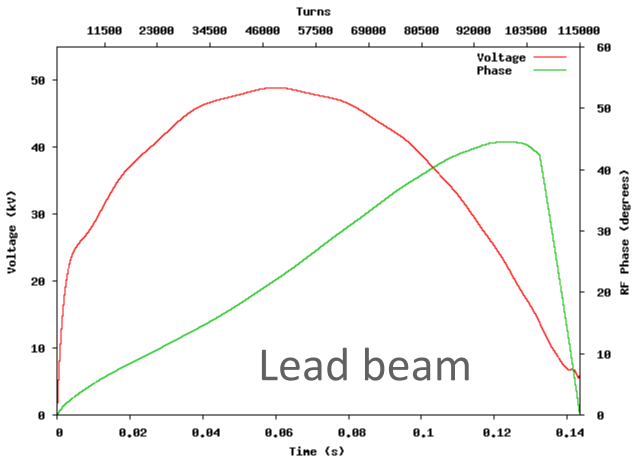


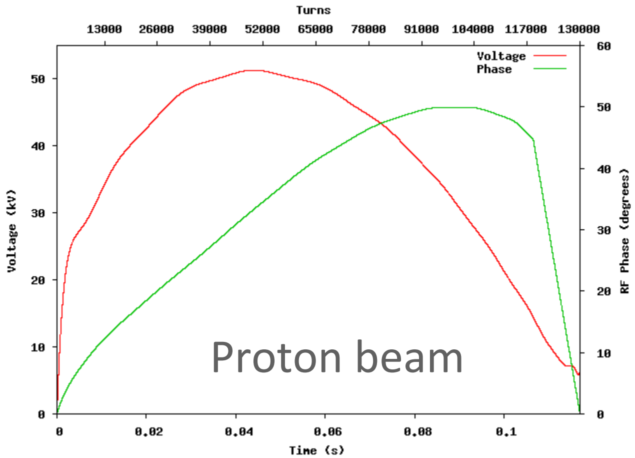
RMS Emittance vs. turns for proton and lead beams due to space charge effects.

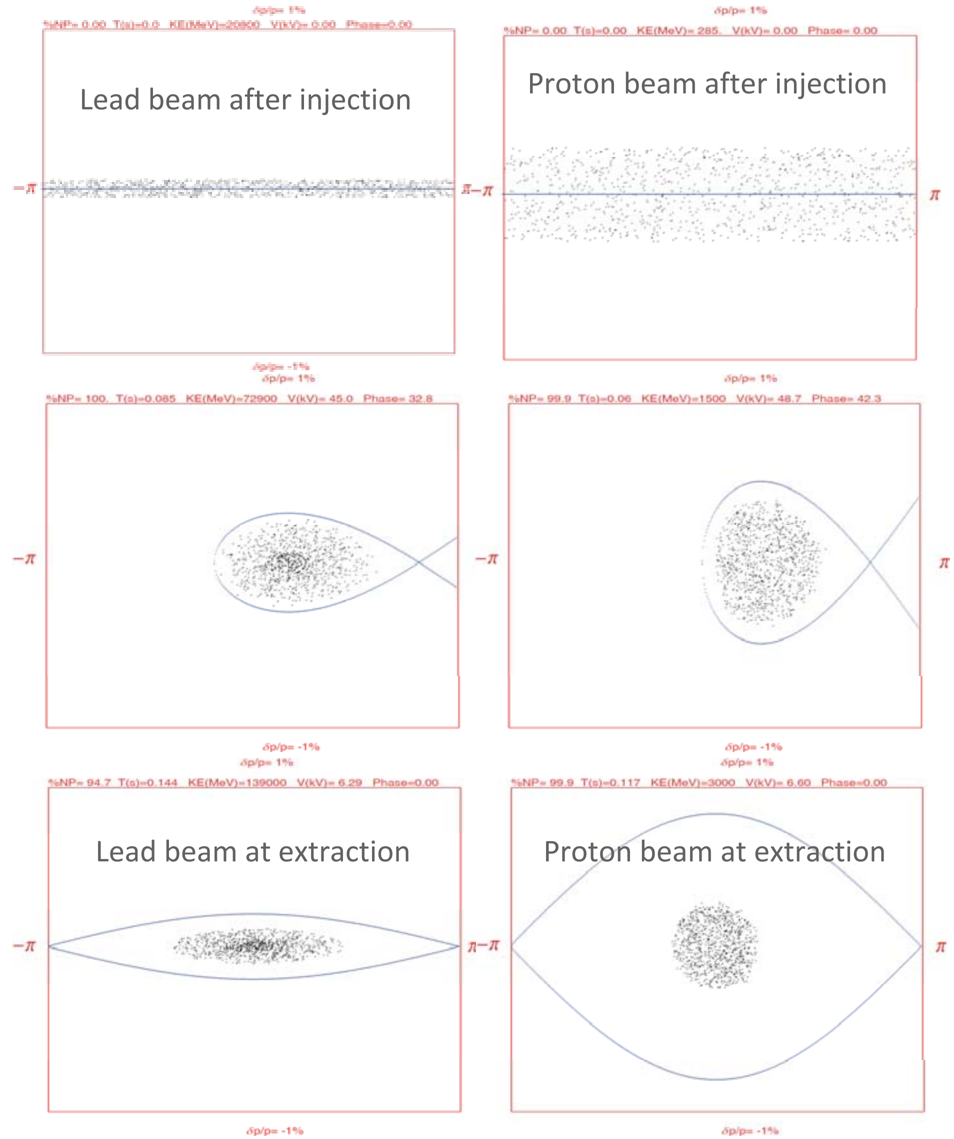


Change in current for proton and lead beams due to 2D space charge effects.

RF Acceleration in the Pre-Booster





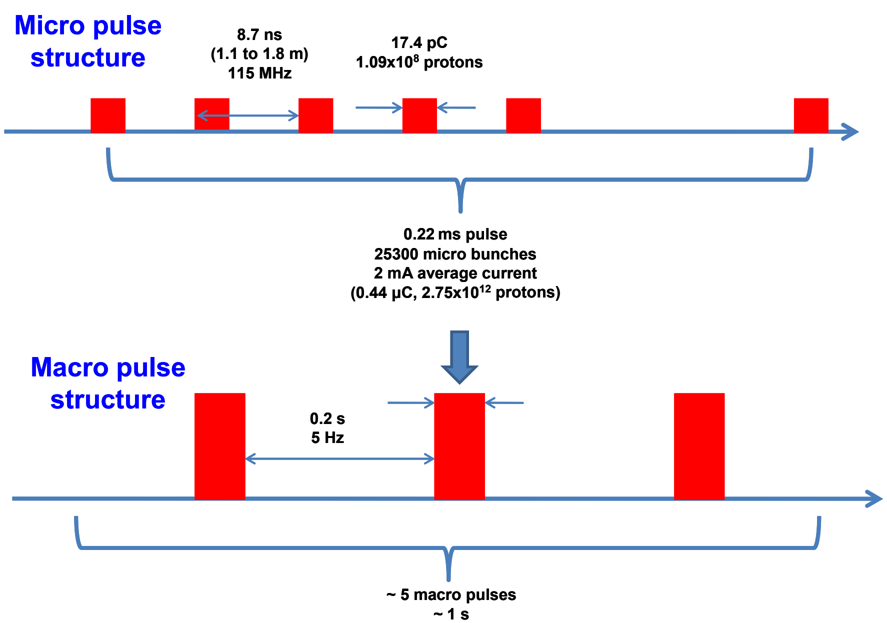


RF voltage and synchronous phase values over the acceleration time.

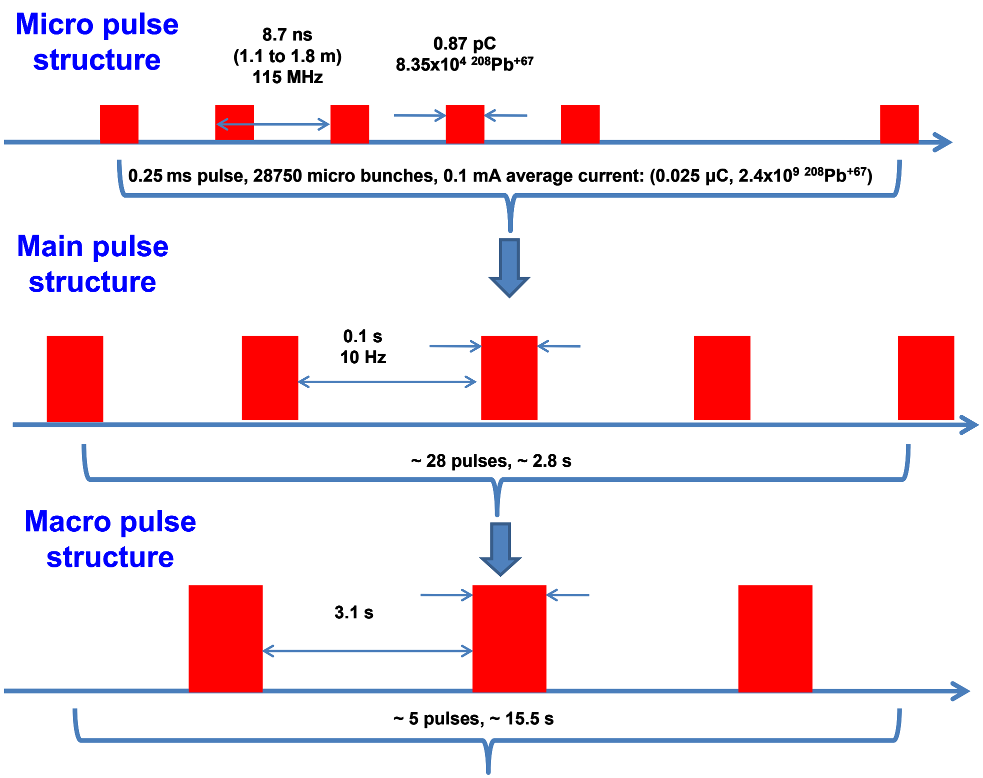
Acceleration and RF parameters in the Pre-Booster

Parameters	Units	Value	Value
Particle		Proton	Lead
Initial Kinetic Energy	MeV/u	285	100
Final Kinetic Energy	MeV/u	3000	670
Initial momentum spread	%	±0.3	±0.054
Initial Beam emittance (RMS)	eV·s	0.295	6.48
RF harmonic number		1	1
RF frequency	MHz	[0.82,1.25]	[0.55,1.04]
Maximum RF voltage	kV	51.2	48.8
Maximum phase	deg	50	50
Momentum Compaction		0.039	0.039
Final capture efficiency factor		0.999	0.999
Final momentum spread	%	±0.27	±0.11
Final Beam emittance (RMS)	eV·s	0.295	6.48
Total turns		130000	115000
Acceleration period	ms	117	144
Bunch Length	μs	0.166	0.386

Bunch structure in the linac, pre-booster and large booster.

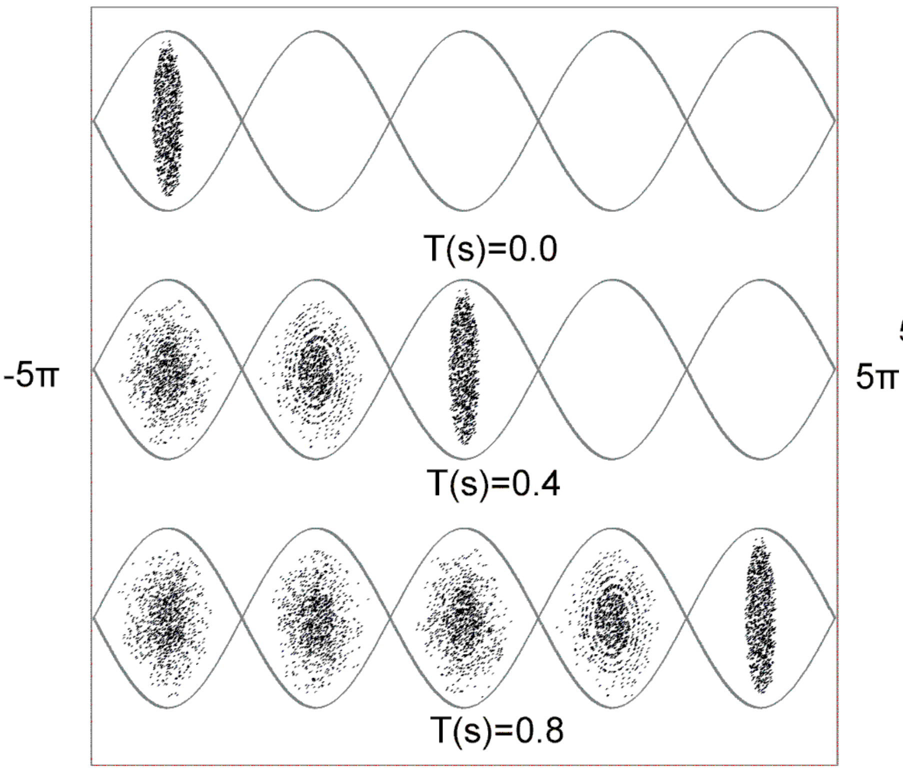


Proton Beam

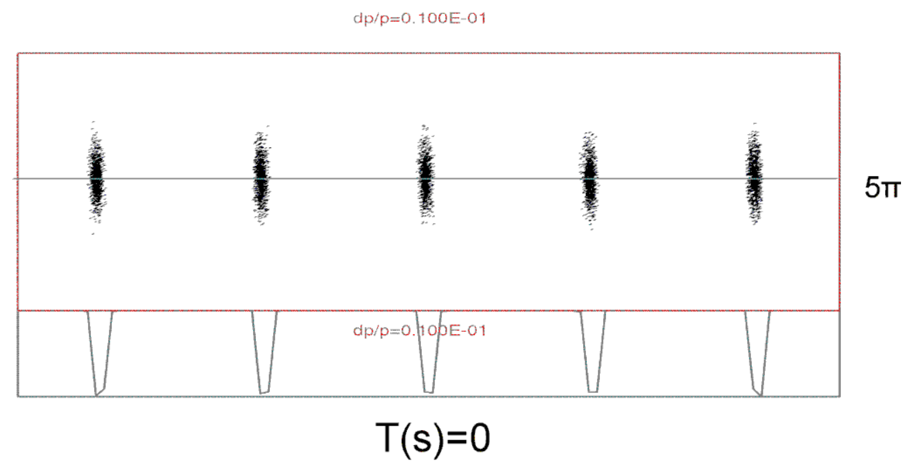


Lead Beam

Beam formation in the large booster: Proton Beam



Accumulation in Large Booster Ring

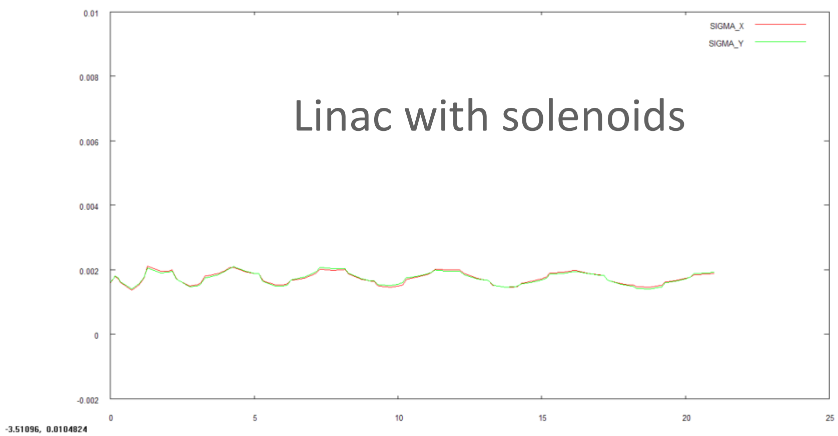


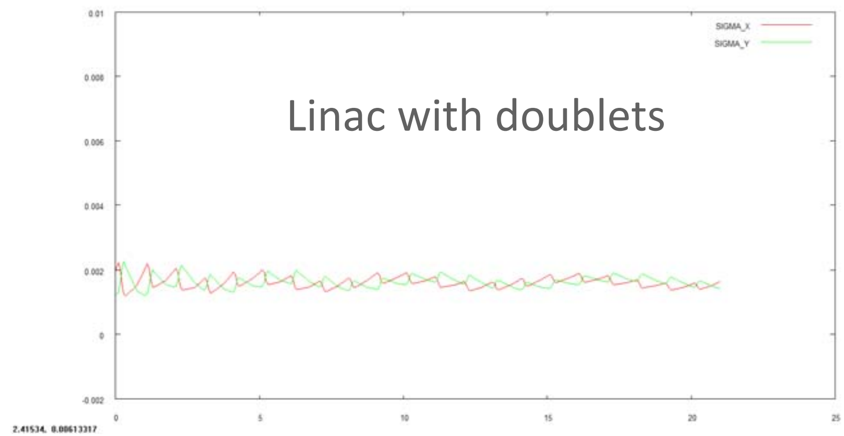
Proton Beam after acceleration to 20GeV in the Large Booster

Accumulation and acceleration parameters of protons in the large booster

Parameters	Units	Value
Initial Kinetic Energy	MeV/u	3000
Final Kinetic Energy	MeV/u	20000
Assumed Momentum Compaction		0.039
Accumulation Stage		
Initial momentum spread	%	±0.27
Initial Beam emittance (RMS)	eV·s	0.19
RF harmonic number		5
RF frequency	MHz	1.21
Maximum RF voltage	kV	15
Final capture efficiency factor		1
Total turns		194172
Accumulation time	s	0.8
Minimum bunch separation	μs	0.25
Maximum bunch separation	μs	0.48
Acceleration Stage		
RF harmonic number		5
RF frequency	MHz	[1.21,1.24]
Maximum RF voltage	kV	208
Final capture efficiency factor		1
Final momentum spread	%	±0.4
Final Beam emittance (RMS)	eV·s	0.38
Total turns		200000
Acceleration period	ms	806
Average bunch separation	μs	0.71

Spin tracking in the LINAC





Initial Polarization Direction	Final Polarization in Linac with Solenoids (Direction of polarization changes)				Final Polarization in Linac with Doublets (Direction remains same as initial)			
	Emittance		5*Emittance		Emittance		5*Emittance	
	(%)	Spread	(%)	Spread	(%)	Spread	(%)	Spread
X	99	3×10^{-2}	98	2×10^{-1}	99	1×10^{-2}	99	5×10^{-2}
Y	99	3×10^{-2}	98	2×10^{-1}	99	1×10^{-2}	99	5×10^{-2}
Z	99	4×10^{-2}	96	3×10^{-1}	99	1×10^{-2}	99	7×10^{-2}

Summary

- The Medium-Energy Electron Ion Collider design, as envisioned to be sited at JLAB, has undergone tremendous progress over the last year
- We participated in the Ion Accelerator Complex pre-conceptual designs
- We lead the front end (linac and pre-booster) work
- Developed some new tools aimed at improved understanding of the beam dynamics and methods that allow enhanced design optimizations
- Will continue to participate in future R&D, such as electron cooling and space charge effects