Critical Accelerator R&D for Achieving High Performance of a Polarized Medium Energy Electron Ion Collider (MEIC / JLEIC Collaboration)

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DOE-NP Accelerator R&D PI Meeting

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Outline

- Project Goal, Accomplishments & Budget
- Highlights from Previous Years Work (FY10-14)
- Recent Developments (FY15-17)
- Status of the JLEIC Ion Injector Linac Design
- ANL Supported LDRD
- Proposed Future Work
- Summary

Project Goal & Accomplishments

- Goal of the early work (FY10-14): Development of the Ion Accelerator Complex for MEIC/JLEIC

- Goal of most recent work (FY15-17): Design and Simulations of the JLEIC Ion Injector Linac

- Accomplishments FY10-14: Design of the Ion Complex (Baseline – 2012)
  - Preliminary Linac Design
  - Pre-Booster Design
  - Beam injection and formation scheme in the ion complex
  - COSY developments for space charge and longitudinal dynamics

- Accomplishments FY15-17: Injector Linac Design & Simulations
  - Complete conceptual design of the ion linac – Short & full energy versions
  - Start-to-end simulations in the linac and injection to the Booster (in progress)

Budget Summary & Expenditures Over the Years

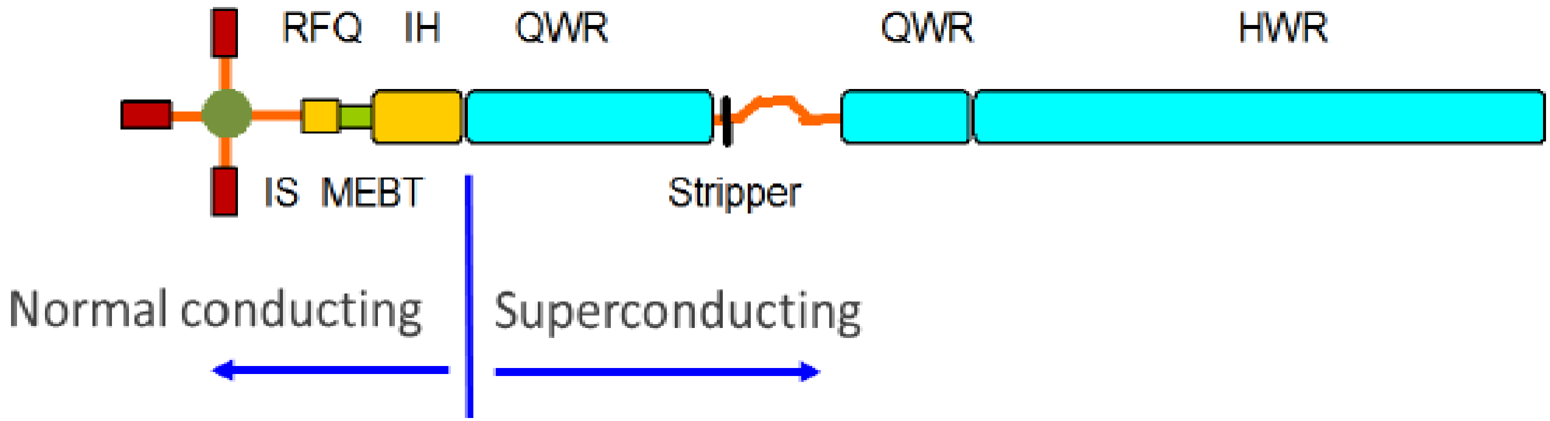
	FY10+ FY11	FY12+ FY13	FY14+ FY15	FY16+FY17	Total
Funds allocated	0k+440k	100k+98k	50k+105k	100k+50k	$943k
Actual costs to date	0k+316.8k	142.2k+115.2k	53.7k+119.1k	99.2k+5k	$851.2k

✓ FY-17 Milestones, using FY-16 funds

	Milestones
Q1FY17	Conceptual Design of the Room-Temperature Front-End: RFQ and IH-DTL Structures
Q2FY17	LEBT and MEBT Design for the light-ion and heavy-ion RFQ injectors leading to the common IH-DTL Section.
Q3FY17	End-to-end simulations in the linac for at least one light-ion and one heavy-ion beam.
Q4FY17	Extension of the Linac to the full Baseline energy of the JLEIC Injector

Highlights from Previous Years (FY10-14)

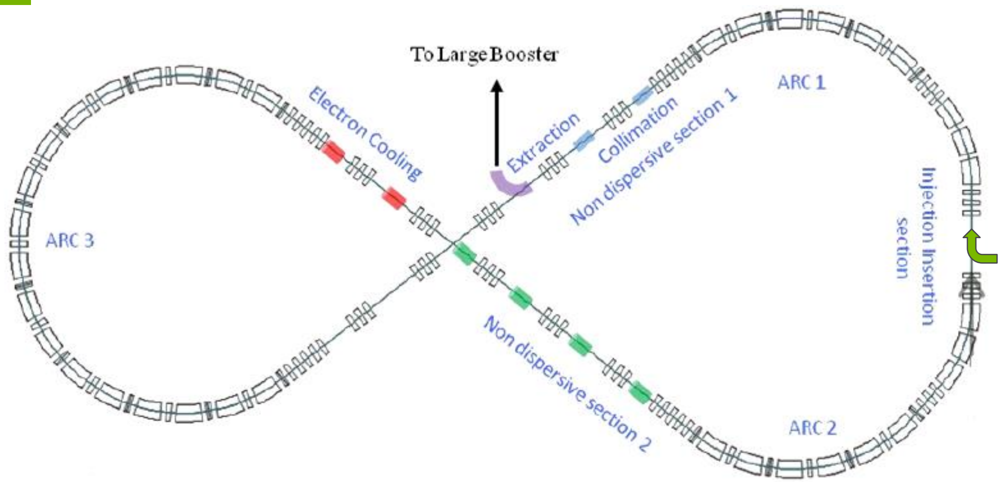
Original Linac Design (2012) – MEIC/JLEIC Baseline



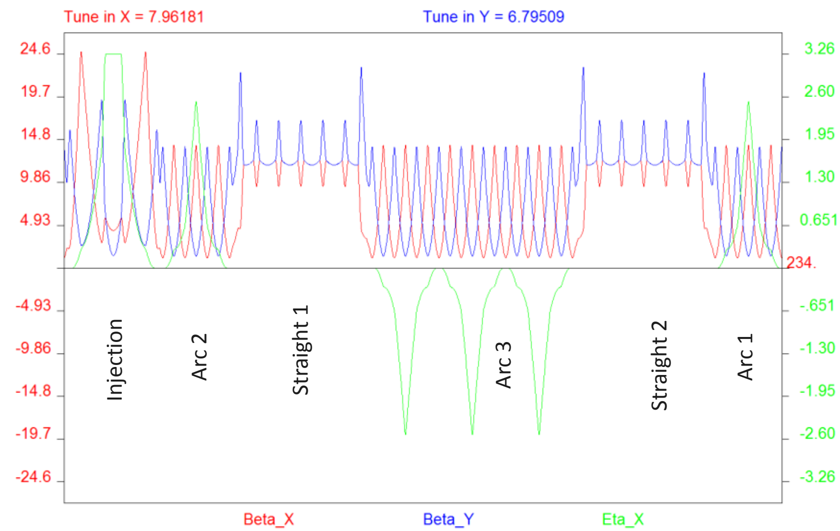
- Warm front-end up to ~ 5 MeV/u for all ions
- SC QWR section up to 13 MeV/u for Pb ions
- A stripper for heavy ions for more effective acceleration: Pb $^{28+} \rightarrow ^{67+}$
- SC high-energy section (QWR + HWR) up to 280 MeV for protons and 100 MeV/u for Pb ions
- Total linac length of ~ 130 m with a total pulsed power of 560 kW (2012)
- A first version of the linac design in 2011 included 3 types of cavities (QWR, HWR and DSR) with a total length of 150 m

Pre-Booster Design – Original MEIC Baseline (2012)

3 GeV – 234 m – RT Pre-booster



Linear Optics of Pre-Booster Ring: Lattice Plot

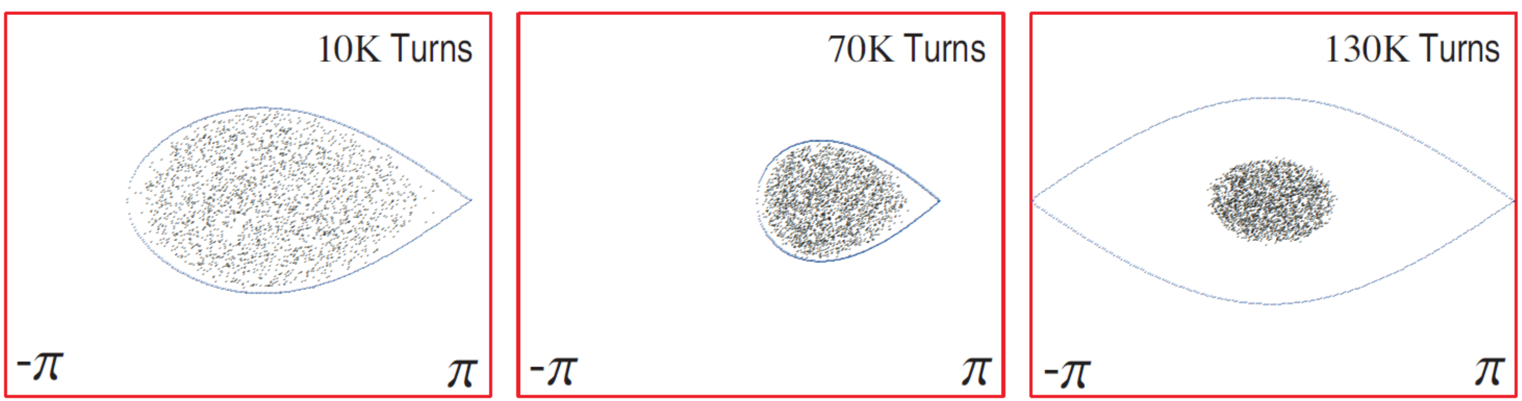


- Figure-8 design to preserve beam polarization
- Below transition energy: 3 GeV for protons, 670 MeV/u for Pb ions
- 234 m circumference with adequate space for insertions: e-cooling, RF system, injection, extraction, correction and collimation

Polarized Proton Beam Formation in the MEIC Ion Complex

		Source	Linac	Pre-booster		Large Booster	Collider Ring
		ABPIS	At exit	At Injection	After boost	After boost	After boost
Charge status		H^-	H^-	H^+	H^+	H^+	H^+
Kinetic energy	MeV/u	~0	13.2	285	3000	20000	60000
γ and β				1.3 / 0.64	4.2 / 0.97	22.3 / 1	64.9 / 1
Pulse current	mA	2	2	2			
Pulse length	ms	0.5	0.5	0.22			
Charge per pulse	μC	1	1	0.44			
Ions per pulse	10^{12}	3.05	3.05	2.75			
Pulses				1			
Efficiency				0.9			
Total stored ions	10^{12}			2.52	2.52	2.52x 5	2.52x5
Stored current	A			0.33	0.5	0.5	0.5

$\delta p/p = 1.5\%$



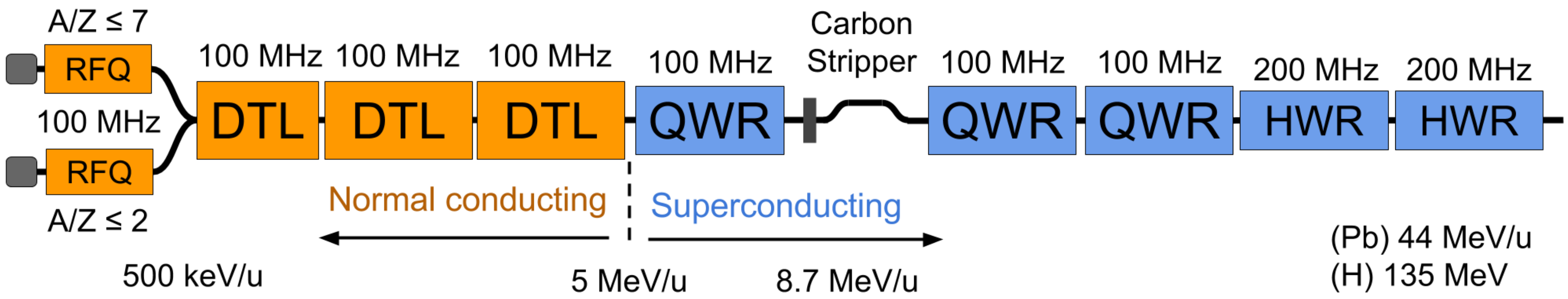
$\delta p/p = -1.5\%$

Publications …

- “Design Studies of Pre-Boosters of Different Circumference for an Electron Ion Collider at Jlab”, S. Abeyratne, B. Erdelyi, S.L. Manikonda, PAC-2011, New York.
- ”An accumulator/Pre-Booster for the Medium-Energy Electron Ion Collider at Jlab”, B. Erdelyi, S. Abeyratne, Y.S. Derbenev, G.A. Krafft, Y. Zhang, S.L. Manikonda, P.N. Ostroumov, PAC-2011, New York.
- “Formation of Beams in the Ion Accelerator Complex of the Medium Energy Electron Ion Collider Facility at Jlab”, S.L. Manikonda, P.N. Ostroumov, B. Erdelyi, IPAC-12, New Orleans.
- “An improved transfer map approach to longitudinal beam dynamics”, B. Erdelyi, S. Manikonda, P.N. Ostroumov, Nuclear Instruments and Methods in Physics Research A694 (2012) 147–156.

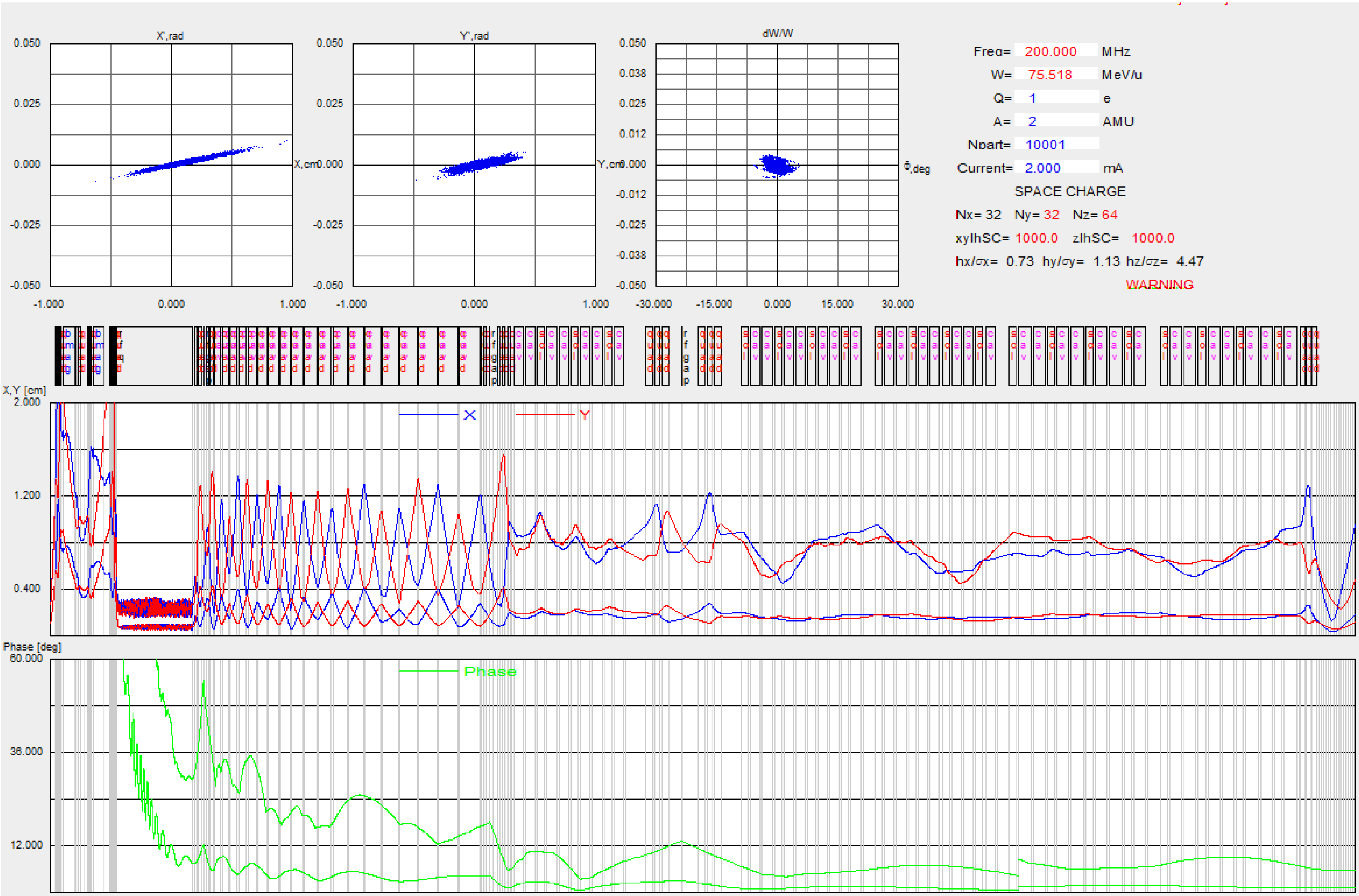
Recent Developments (FY15-17)

Conceptual Design for the JLEIC Ion Injector Linac



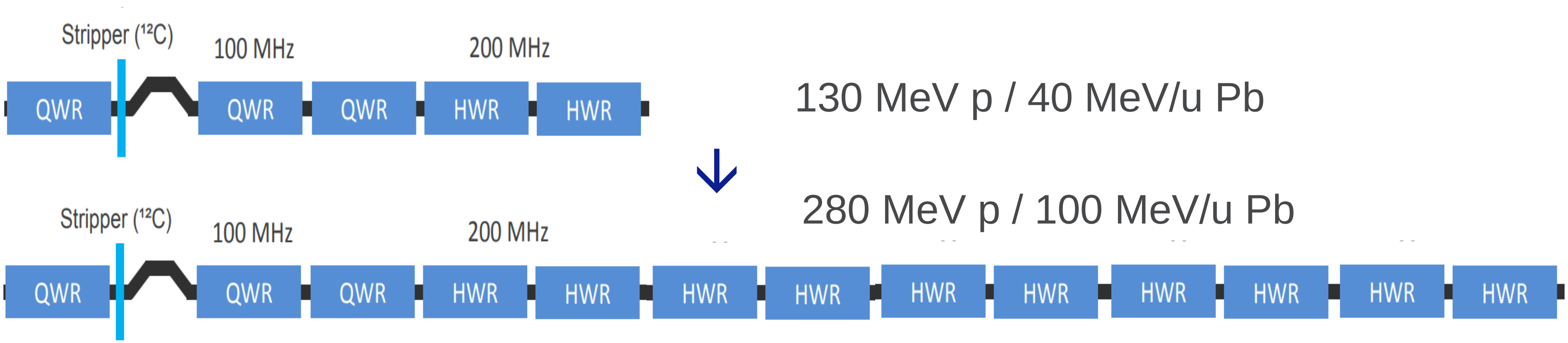
- ❑Two RFQs: One for light ions (A/q ~ 2) and one for heavy ions (A/q ~ 7)
  - Different emittances and voltages for polarized light ions and heavy ions
- ❑Separate LEBTs and MEBTs for light and heavy ions
- ❑RT Structure: IH-DTL with FODO Focusing Lattice
  - FODO focusing → Significantly better beam dynamics
- ❑SRF Linac made of QWR and HWR, based on recent ANL developments
- ❑Stripper section for the heavy-ions
- ❑Pulsed Linac: up to 10 Hz repetition rate and ~ 0.5 ms pulse length

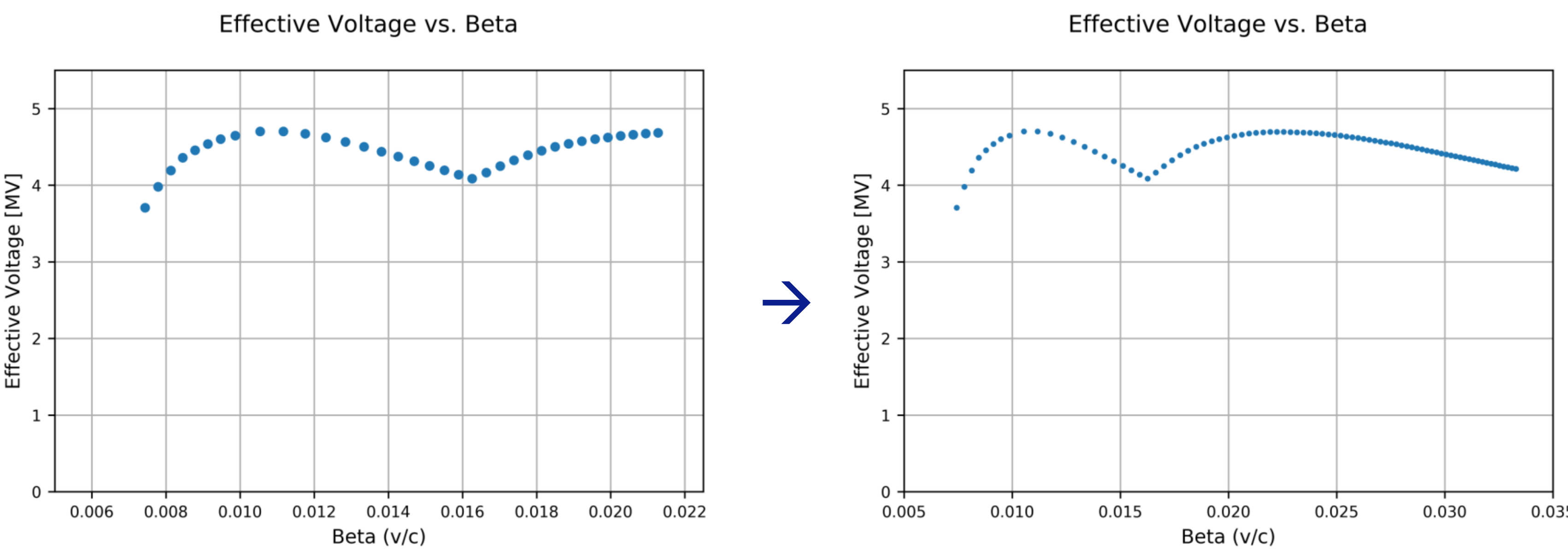
Start-to-end Linac Simulations: Polarized Deuterons



No beam loss over the whole linac (10k particles) → Avoid neutron activation

Extension / Upgrade to full Baseline Design Energy





➢ Same type of HWR still efficient → No need for a new cavity type

Publications …

- “Pulsed SC Ion Linac as an Injector to Booster of Electron Ion Collider”, P.N. Ostroumov, Z.A. Conway, B. Mustapha, B. Erdelyi, Proc. of SRF-2015, Vancouver, Canada, September 2015

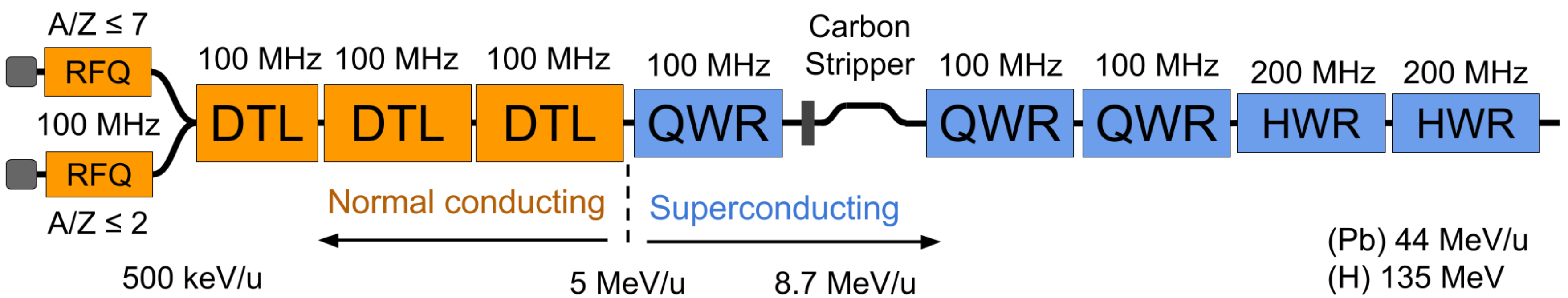
- “Design and Beam Dynamics Studies of a Multi-Ion Linac Injector for the JLEIC Ion Complex”, P. Ostroumov et al, Proceedings of Hadron Beams 2016 Workshop (HB-2016), Malmo, Sweden, July 3-8, 2016.

- “Design of the Room-Temperature Front-End for a Multi-Ion Linac Injector”, A. Plastun, B. Mustapha, Z. Conway and P. Ostroumov, Proceedings of NAPAC-2016, October 9-14, Chicago, Illinois.

Status of the JLEIC Ion Injector Linac

Status of the JLEIC Ion Injector Linac Design

- We have developed designs for all sections of the linac
  - Two RFQs: One for light ions (A/q ~ 2) - one for heavy ions (A/q ~ 7)
  - Separate LEBTs and MEBTs for light and heavy ions
  - IH-DTL with FODO Focusing Lattice
  - SRF Linac made of QWR and HWR
  - Stripper section for the heavy-ions (in progress)



- Brief overview of the different linac sections …

Ion Sources

- Polarized Light Ions: Desired vs. Available H-/D- beams (A. Sy & V. Dudnikov)

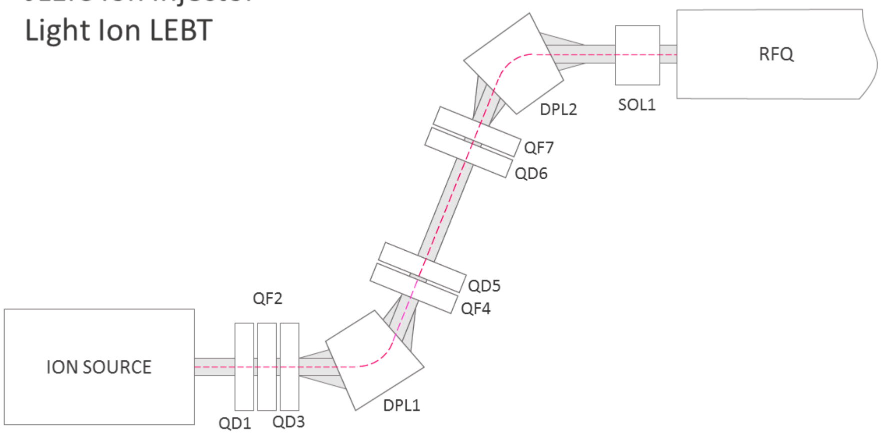
	(units)	Desired value	ABPIS+	OPPIS*
Charge state		H-/D-	H-/D-	H-/D-
Pulse current	mA	2	3.8	4 (0.7)
Pulse length	ms	0.5	0.17	(0.3)
Polarization	%	100	91	85

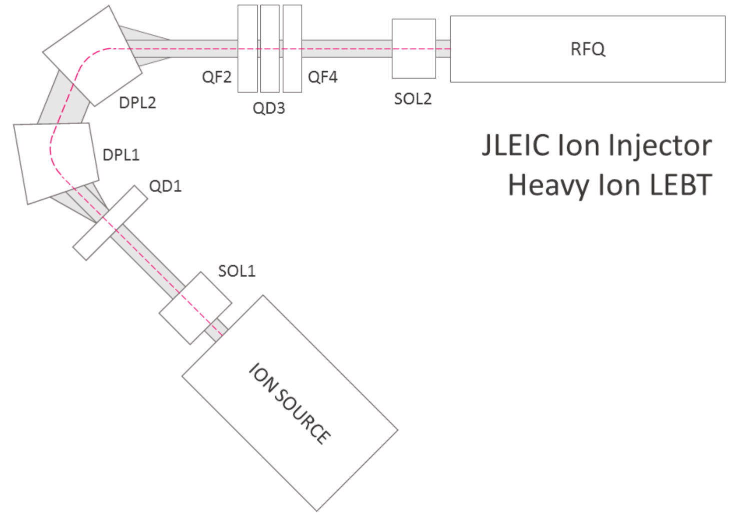
- Heavy ions: ECR + Chopper or pulsed EBIS may be used

Ions	A / Q	Source	Current, mA	Emittance, π·mm·mrad
$^{208}Pb^{30+}$	~ 7	ECR	0.5	0.5

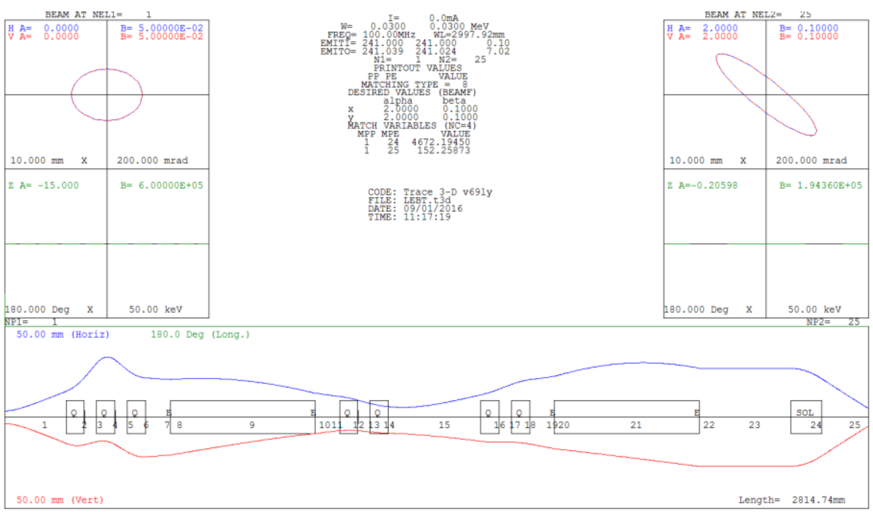
LEBTs Design: Light and Heavy ions LEBT

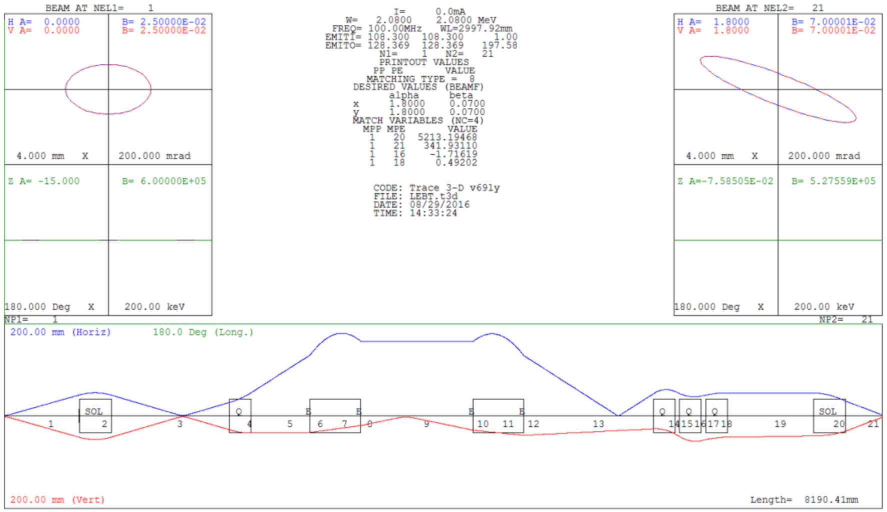
JLEIC Ion Injector
Light Ion LEBT





JLEIC Ion Injector
Heavy Ion LEBT

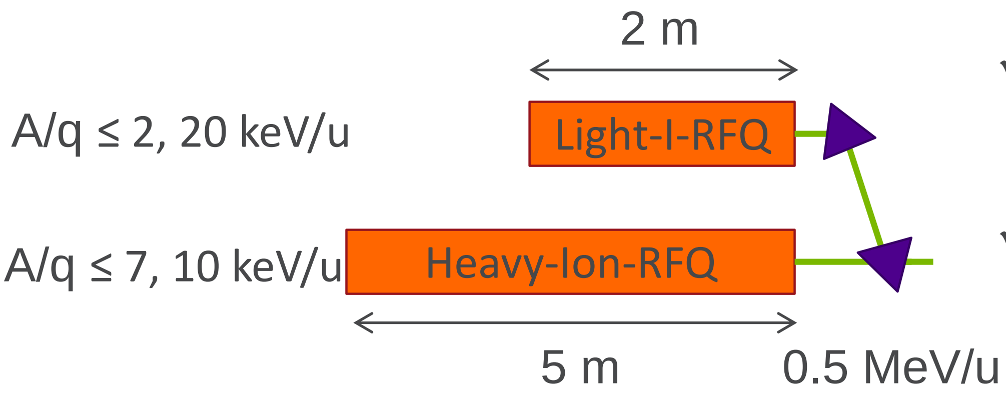




Similar to BNL LEBT

Similar to CERN Linac3 LEBT

RFQs: Light and Heavy ions

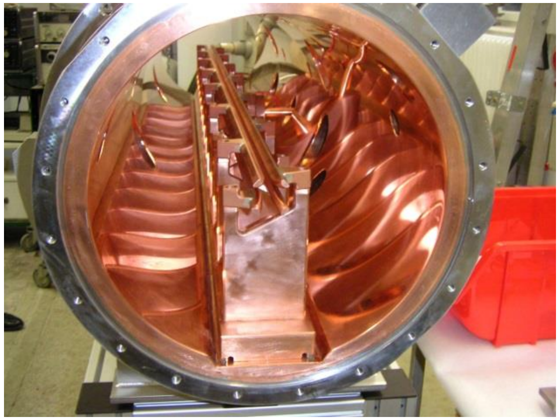


- ✓ Light-Ion RFQ is designed for polarized beams with **2 π** mm mrad normalized transverse emittance
- ✓ Heavy-Ion RFQ is designed for ion with A/q ≤ 7 with **0.5 π** mm mrad normalized transverse emittance

Parameter	Heavy ion	Light ion	Units
Frequency	100		MHz
Energy range	10 - 500	15 - 500	keV/u
Highest - A/Q	7	2	
Length	5.6	2.0	m
Average radius	3.7	7.0	mm
Voltage	70	103	kV
Transmission	99	99	%
Quality factor	6600	7200	
RF power consumption (structure with windows)	210	120	kW
Output longitudinal emittance (Norm., 90%)	4.5	4.9	π keV/u ns

Choice of RFQ Structure

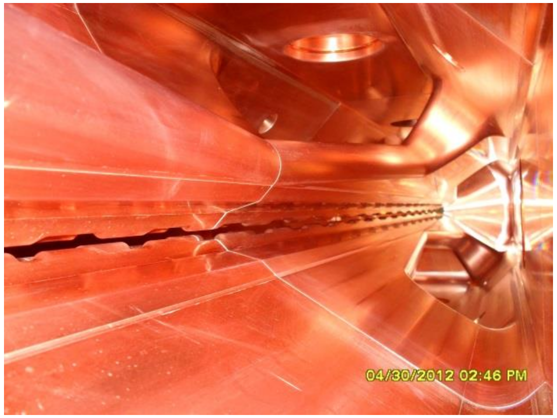
4-Rod



RIKEN RFQ

High power consumption

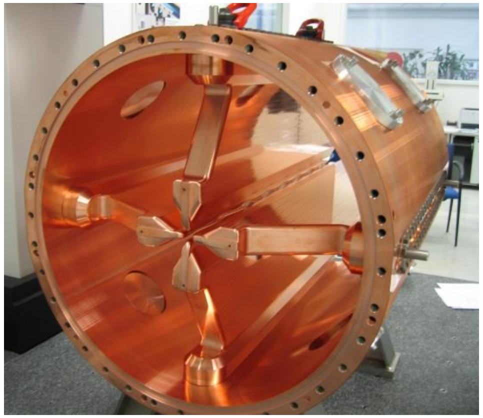
4-Vane window coupled



ATLAS RFQ

Flexible design

4-Vane

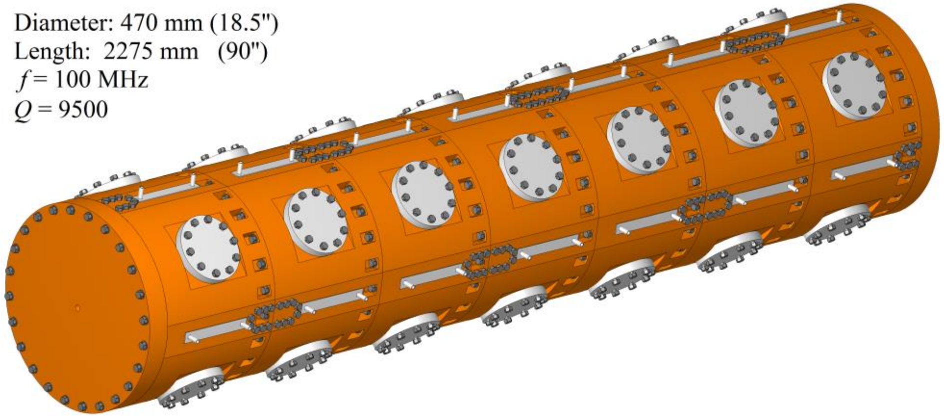


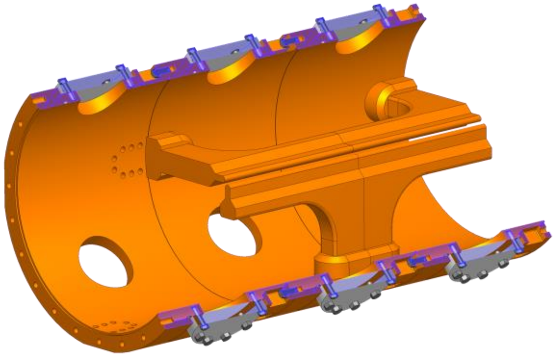
SPIRAL-2 RFQ

Large diameter

- 4-vane bolted or brazed structure (windows or not …)

Diameter: 470 mm (18.5")
Length: 2275 mm (90")
f = 100 MHz
Q = 9500

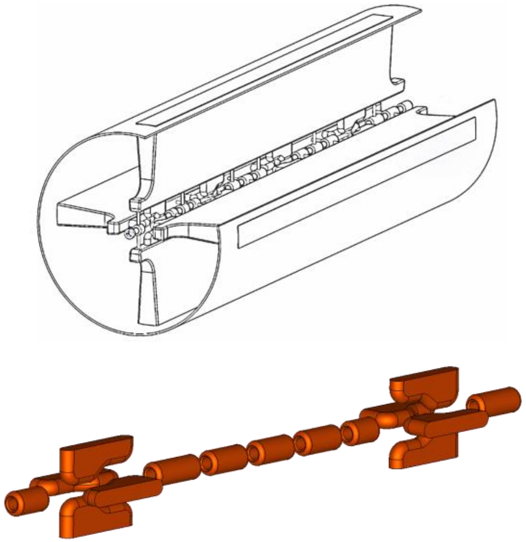


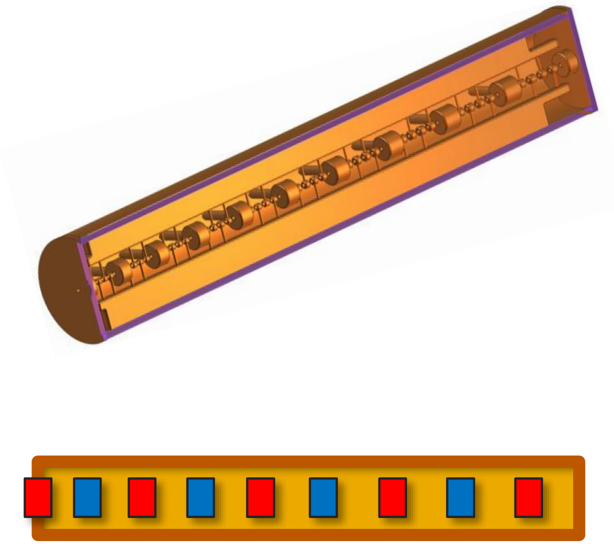


Choice of IH Structure

IH-DTL with Triplets | DTL with RF Quad focusing | IH-FODO with EMQs

BNL
EBIS
Injector





- Most efficient
- Small acceptance

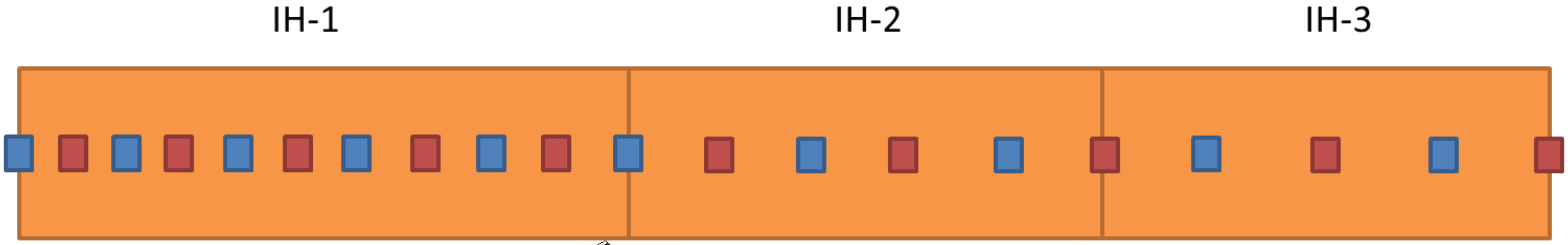
- Largest acceptance
- Less efficient

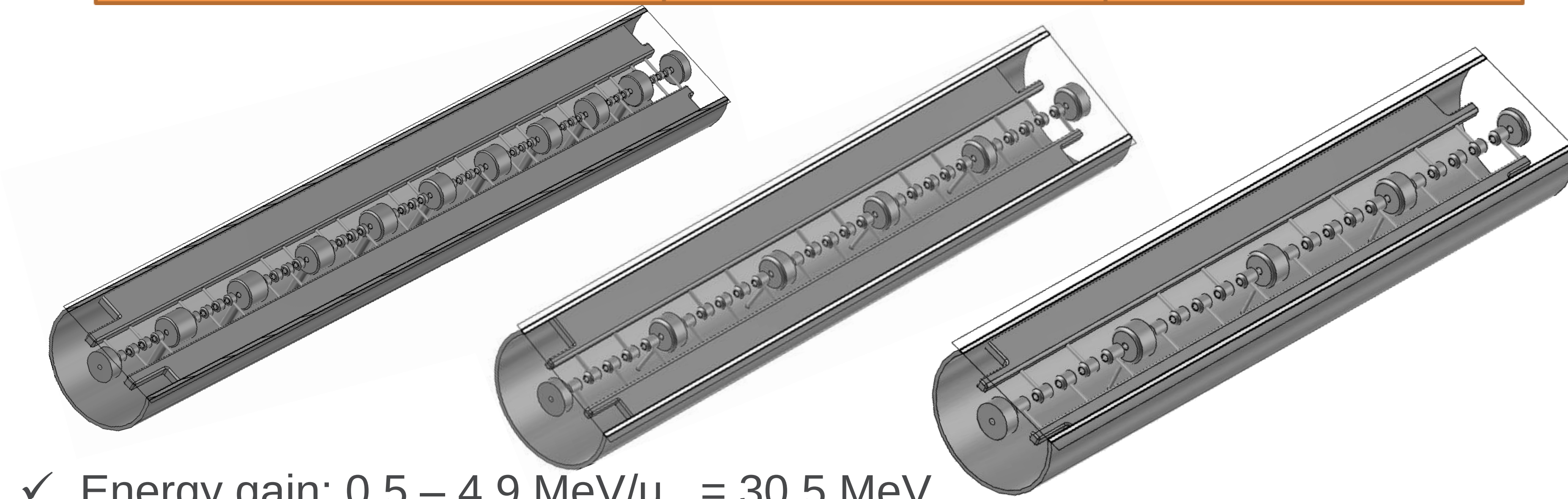
- Large acceptance
- Good efficiency

➢ IH-DTL with FODO: Larger acceptance for polarized light ions

IH – DTL with FODO Focusing

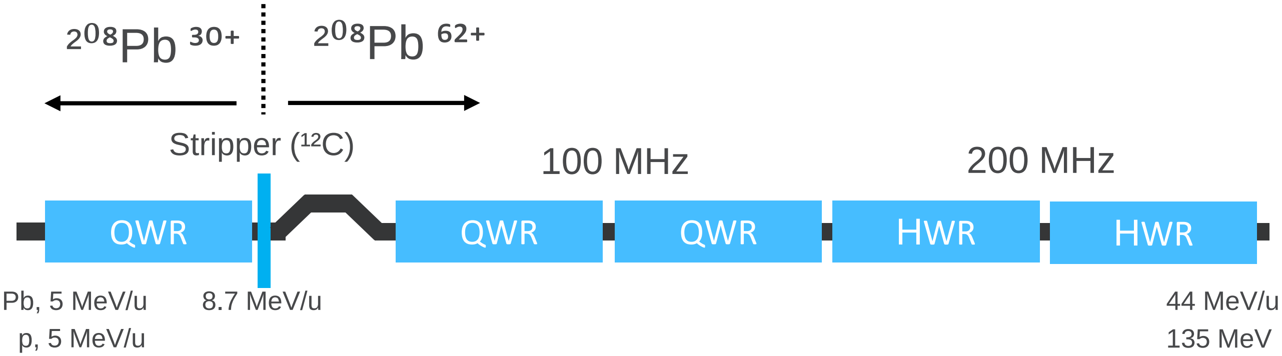
- ✓ 3 Tanks – 20 Quadrupoles in FODO arrangements



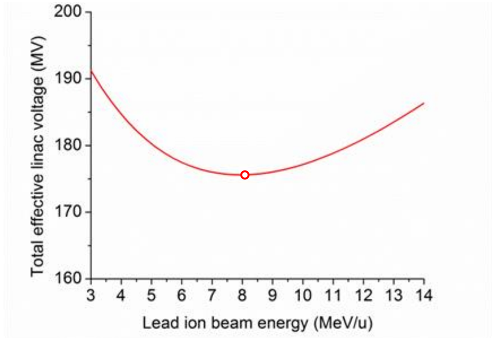


- ✓ Energy gain: 0.5 – 4.9 MeV/u = 30.5 MeV
- ✓ Total length: 4.3 + 3.5 + 3.4 m = 11.2 m
- ✓ Real-estate accelerating gradient: 2.72 MV/m
- ✓ RF Power losses: 280 + 400 + 620 = 1.3 MW

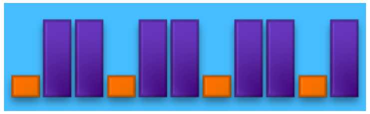
SRF Section: QWR, HWR, Stripper for heavy ions



Stripping Energy & Charge



QWR Module



HWR Module

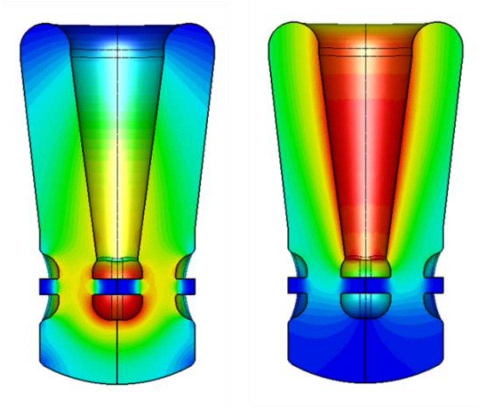
Horizonal orientation of cavities

@ 8.7 MeV/u: 30+ → 62+ → 44 MeV/u

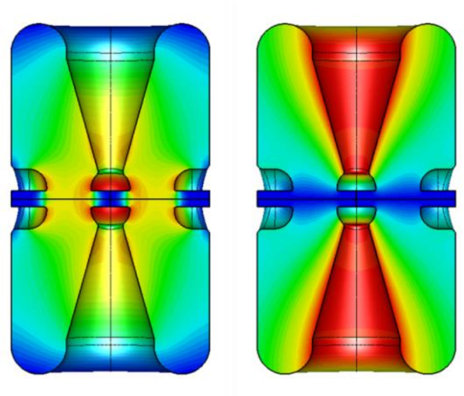
@ 13.3 MeV/u: 30+ → 67+ → 40 MeV/u

Parameter	QWR	HWR	Units
β_{opt}	0.15	0.30	
Frequency	100	200	MHz
Length ($\beta\lambda$)	45	45	cm
E_{PEAK}/E_{ACC}	5.5	4.9	
B_{PEAK}/E_{ACC}	8.2	6.9	mT/(MV/m)
R/Q	475	256	Ω
G	42	84	Ω
E_{PEAK} in operation	**57.8**	**51.5**	**MV/m**
B_{PEAK} in operation	**86.1**	**72.5**	**mT**
E_{ACC}	**10.5**	**10.5**	**MV/m**
Phase (Pb)	-20	-30	deg
Phase (p/H⁻)	-10	-10	deg
No. of cavities	21	14	

QWR Design



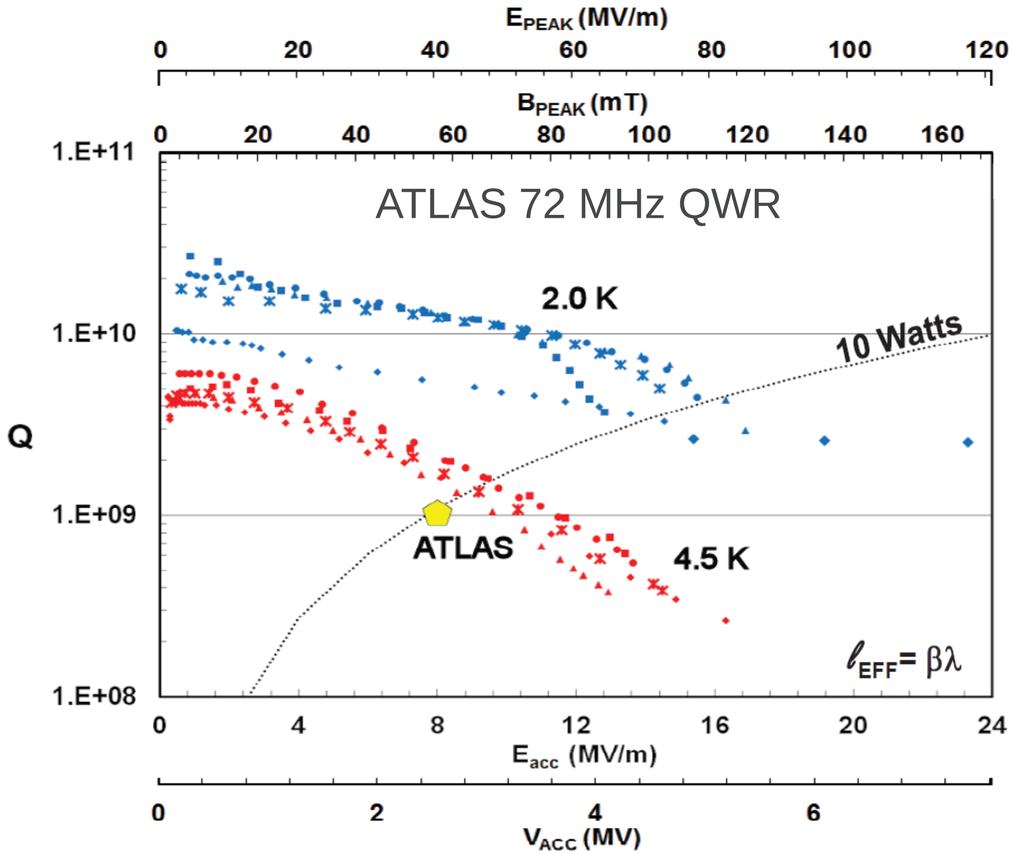
HWR Design



High-Performance QWRs Developed at ANL for ATLAS

ATLAS
72 MHz QWR

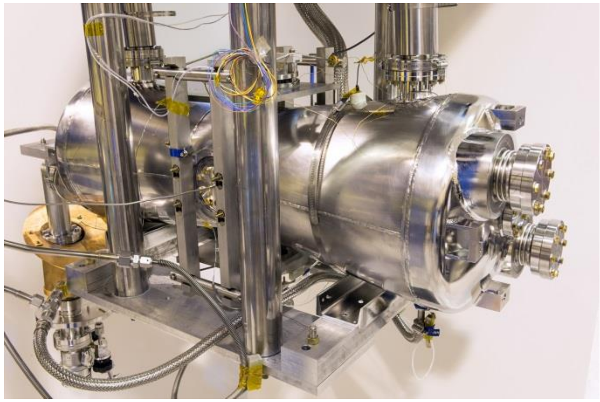
SC section will operate at 4.5K in pulsed mode



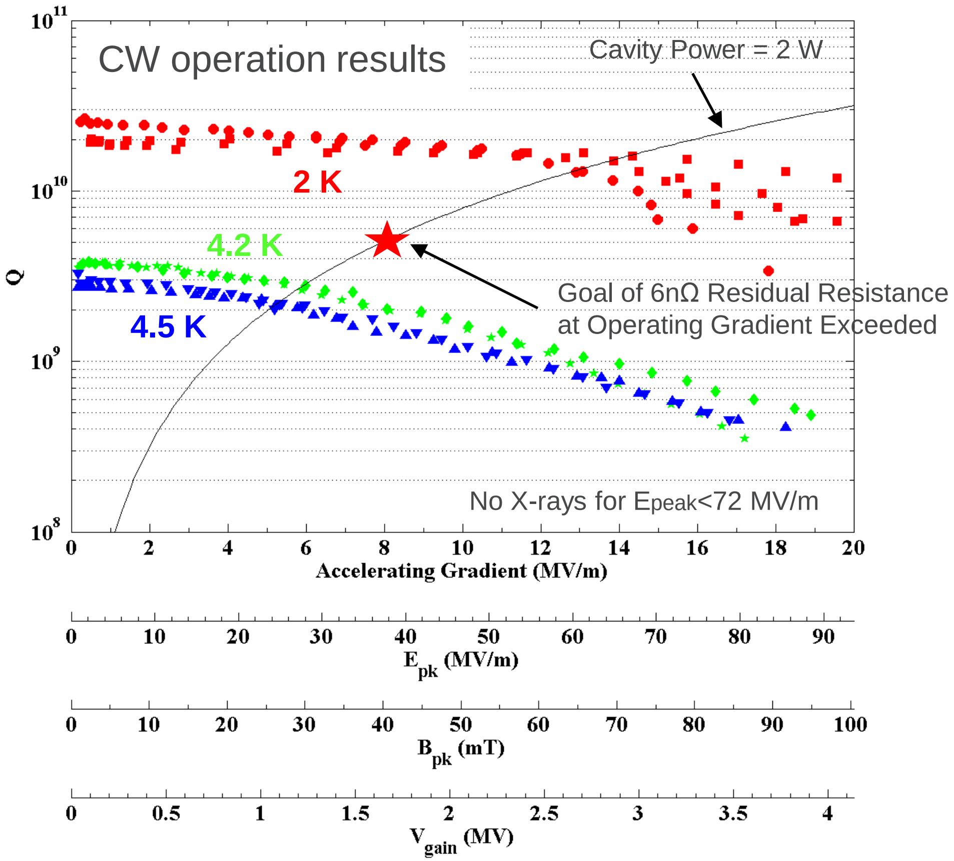
- ✓ CW mode: A 72 MHz β=0.07 QWR can deliver 4 MV voltage (E_{peak}~64 MV/m, B_{peak}~90 mT)
- ✓ JLEIC: Pulsed operation of 100 MHz β=0.15 QWRs @ 4.7 MV per cavity (5.5 MV possible)

High-Performance HWRs Developed at ANL for PXIE

FNAL - 162 MHz HWR



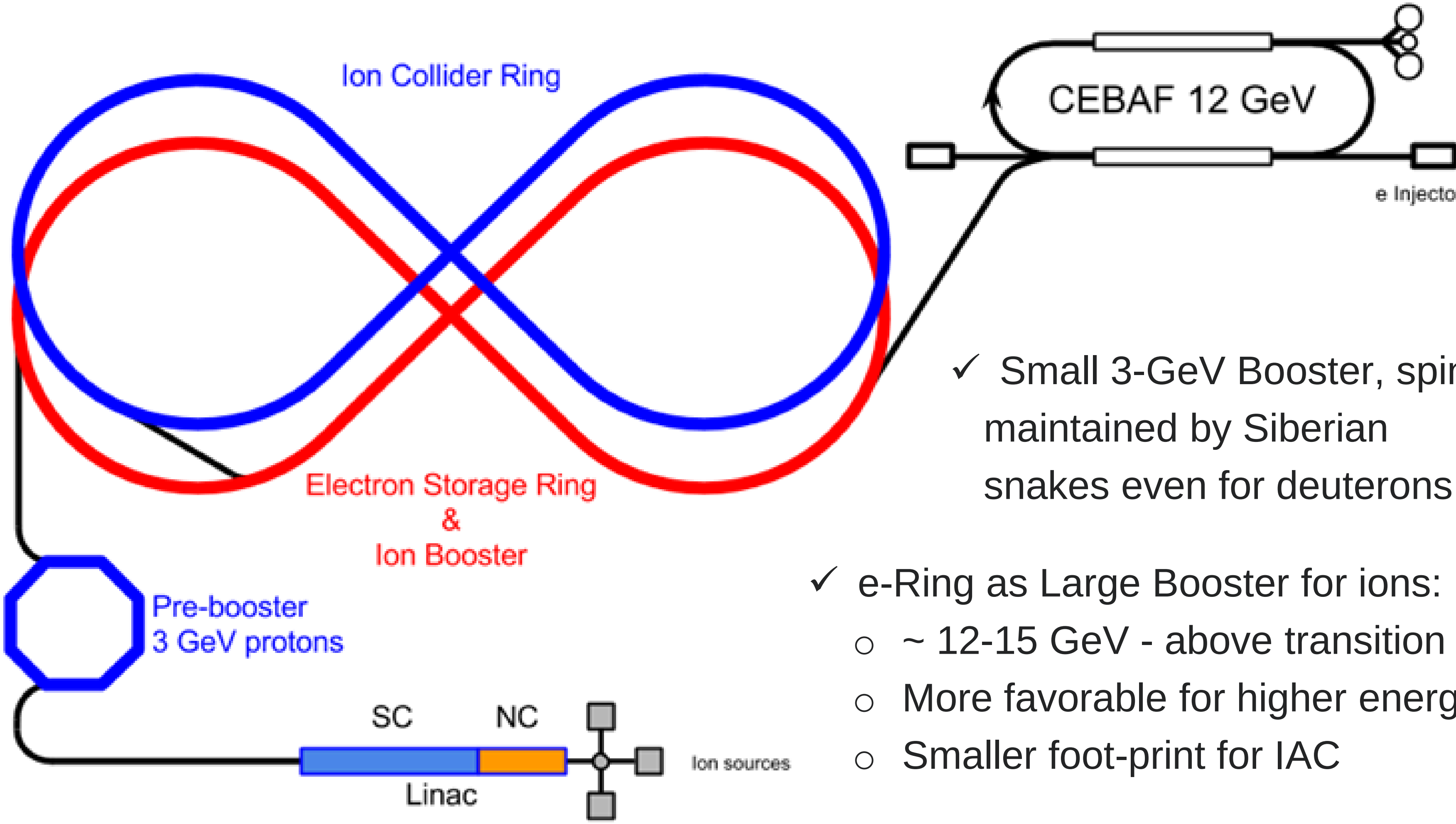
SC section will operate at 4.5K in pulsed mode



- ✓ CW mode: A 162 MHz β=0.11 HWR can deliver 3 MV voltage (E_{peak}~68 MV/m, B_{peak}~72 mT)
- ✓ JLEIC: Pulsed operation of 200 MHz β=0.3 HWRs @ 4.7 MV per cavity (6.6 MV possible)

ANL Supported LDRD

Alternative Design Approach for JLEIC Ion Complex



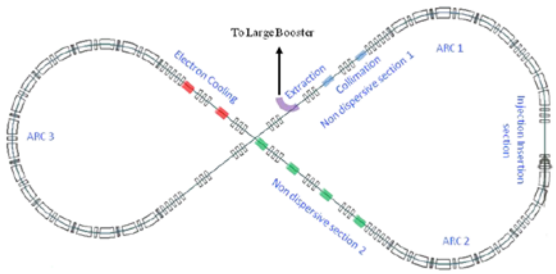
- ✓ Small 3-GeV Booster, spin maintained by Siberian snakes even for deuterons

- ✓ e-Ring as Large Booster for ions:
  - ~ 12-15 GeV - above transition
  - More favorable for higher energy
  - Smaller foot-print for IAC

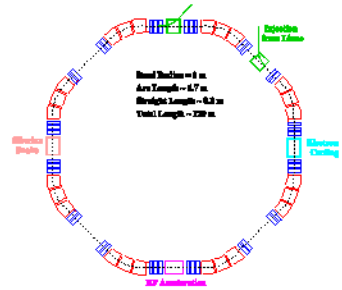
- The Electron Storage Ring and Ion Collider Ring are stacked vertically
- Ion injection from the booster (e-ring) to the ion collider ring is a vertical bend

A More Compact Booster Ring

Original 3-GeV Booster



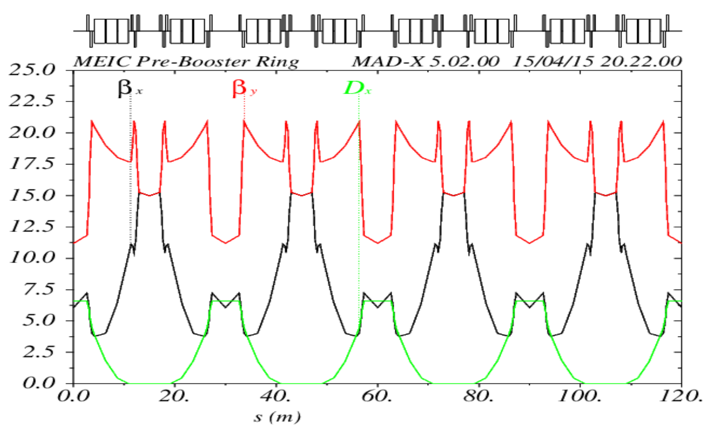
New Design



Item / Parameter	Original	New
N. of 15° Dipoles	36	24
N. of Quads	95	40
Total N. of Magnets	131	64
Total Length	234	120

At 3 GeV, figure-8 is not required, spin correction with Siberian snakes

Beam Optics

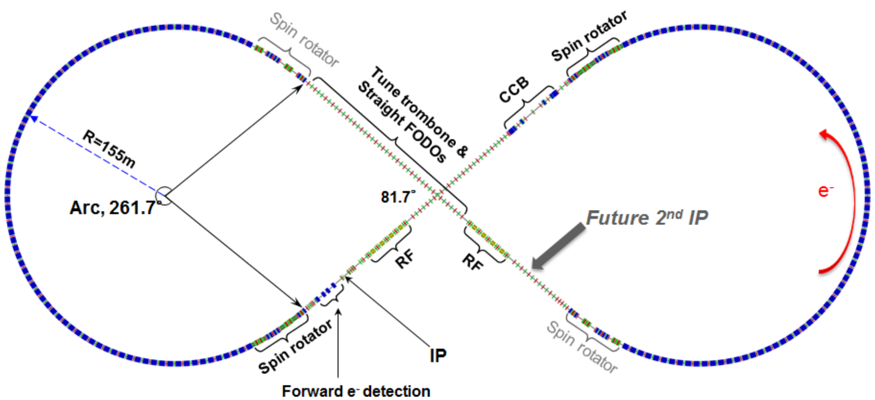


Design Parameters

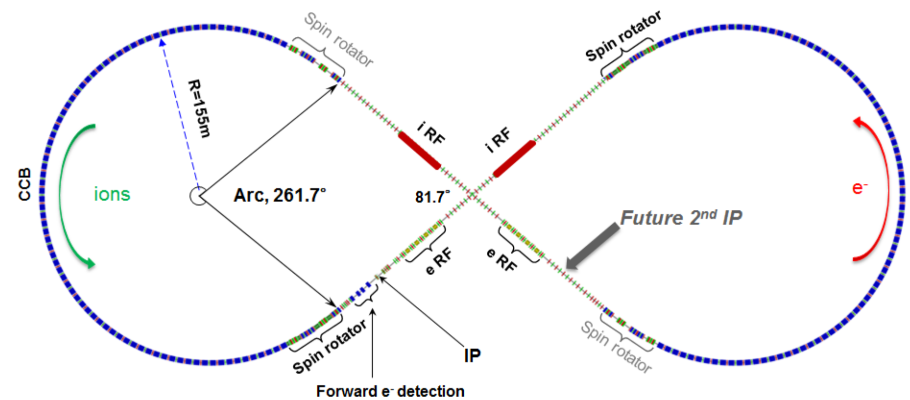
Parameter	Octagonal
Circumference, m	120
Arc length, m	6.7
Straight section length, m	8.3
Maximum β_x	15.3
Maximum β_y	21.0
Maximum dispersion	4.2
β_x at injection	6.0
Normalized dispersion at injection: $D/\sqrt{\beta_x}$	1.71
Tune in X	3.01
Tune in Y	1.18
Gamma transition	4.7
Gamma at extraction (3 GeV)	4.22
Momentum compaction factor	0.045
Number of quadrupoles	40
Quadrupole length, m	0.4
Quadrupole half aperture, cm	5
Maximum quadrupole field, T	1.5
Number of dipoles	24
Dipole bend radius, m	8
Dipole angle, deg	15
Dipole full gap, cm	5
Maximum dipole field	1.6

E-Ring As Large Booster for the Ions - Added Accelerating / RF Sections for Ions

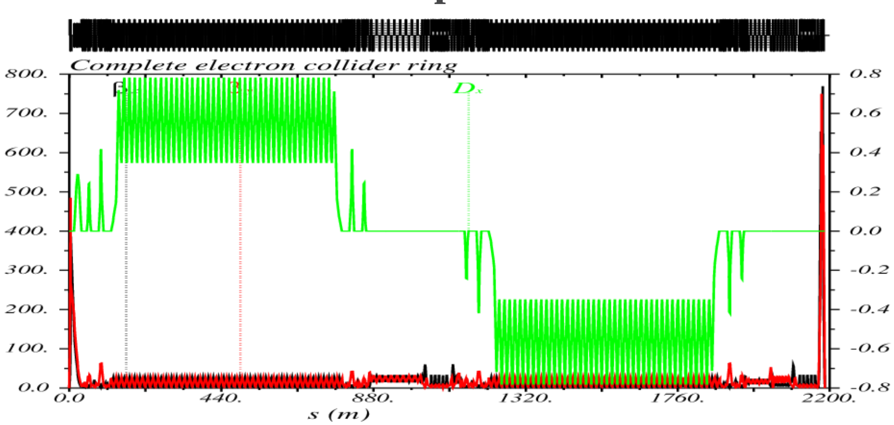
Electrons Only



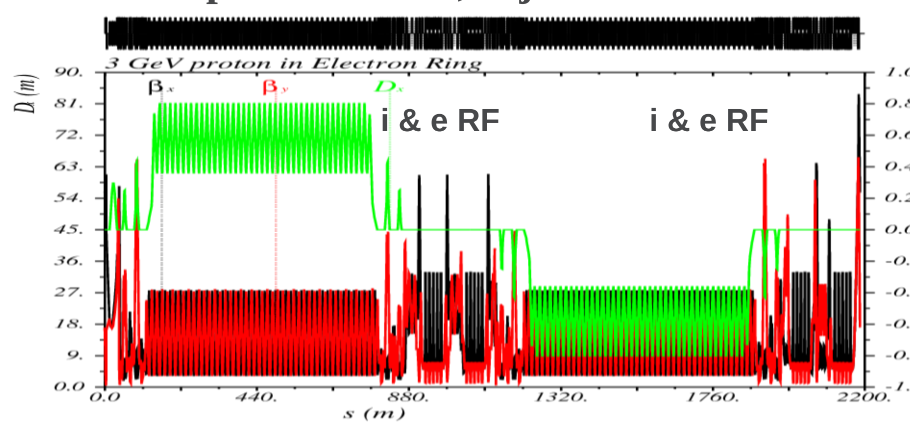
Electrons & Protons



e- Collision Optics at 5 GeV



Proton optics at 3 GeV, Injection from Booster



- ✓ Ion RF sections were inserted in the straight sections, across from electron RF
- ✓ Proton beam optics studied at the injection energy of 3 GeV

Characterization of Pulsed Operation of QWRs & HWRs

- QWRs & HWRs
  - Needed for the ion injector linac for acceleration in the range of β from 0.1 to 0.5
  - Currently produced QWRs and HWRs are operating in continuous wave (cw) mode

- Operation in pulsed mode
  - Required for JLEIC
  - Reduces cryogenic refrigeration requirements
  - Increases resonator operating gradient
  - Issue: dynamic mechanical deformation leading to detuning

➢ **Needs to be tested/characterized …**

Publications …

- “A More Compact Design for the JLEIC Ion Pre-Booster Ring”, B. Mustapha, P.N. Ostroumov and B. Erdelyi, Proceedings of NAPAC-2016, October 9-14, 2016, Chicago, Illinois.

- “An Alternative Approach for the JLEIC Ion Accelerator Complex”, B. Mustapha, P. Ostroumov, A. Plastun, Z. Conway, V. Morozov, Y. Derbenev, F. Lin and Y. Zhang, Proceedings of NAPAC-2016, October 9-14, 2016, Chicago, IL.

- “Adapting the JLEIC Electron Ring for Ion Acceleration”, B. Mustapha, J. Martinez Marin, Z. Conway, P. Ostroumov, F. Lin, V. Morozov, Y. Derbenev and Y. Zhang, Proceedings of IPAC-2017, May 14-19, 2017, Copenhagen, Denmark.

Proposed Future Work

Future Work: Beam Simulation & Benchmarking

- Use and build upon the recent simulation features added to the COSY and TRACK code specifically developed for application to the EIC

- These tools differ from the software being used at both JLab and BNL and could be effectively used for independent code-code and code-data benchmarking

- These tools include
  - Longitudinal beam dynamics for beam formation schemes
  - Space charge effects and nonlinear beam dynamics
  - Spin tracking for electrons and light ions (built-in in COSY)

- The developed beam simulation tools could be used for either the JLEIC or eRHIC concepts, for either electron or ion beams. (priority rows # 4, 12 & 37 in Jones Report)

Summary

- We have completed the conceptual design for the JLEIC multi-ion injector linac
- The design is optimized in terms of both performance and cost-efficiency – It includes a RT front-end followed by a SRF linac
- Optimization of beam dynamics and fine tuning of the linac parameters with the rest of the accelerating chain is underway …
- Stripping for heavy ions & spin tracking for light ions is next …
- Future work will focus on beam simulations and benchmarking, taking advantage of already existing tools and new developments
- These tools will be instrumental for code-code and code-data benchmarking …