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

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Outline

- Project Goal & Accomplishments so far
- Previous Years Accomplishments (FY10-FY14)
- More Recent Developments (FY15-FY16)
- Current Status of the Injector Linac Design
- Proposed Future Work
  - High Power Pulsed Operation of QWRs and HWRs
  - Alternative Design Approach for the JLEIC Ion Complex
- Summary

Project Goal & Accomplishment so far

- Goal of ANL Contribution: Development of the Ion Accelerator Complex for MEIC/JLEIC Design

- Accomplishments FY10-FY12: Design of the Ion Complex for MEIC Original Baseline (2012)
  - Injector Linac Design
  - Pre-booster Design
  - Beam formation schemes in the ion complex

- Accomplishments FY13-FY14:
  - Significant code development for space charge and longitudinal effects
  - Setup of Injection Schemes in the Booster ring

- Accomplishments FY15-FY16:
  - More Compact Linac Design
  - More Compact Pre-booster Design

Budget Summary and Expenditures Over the Years

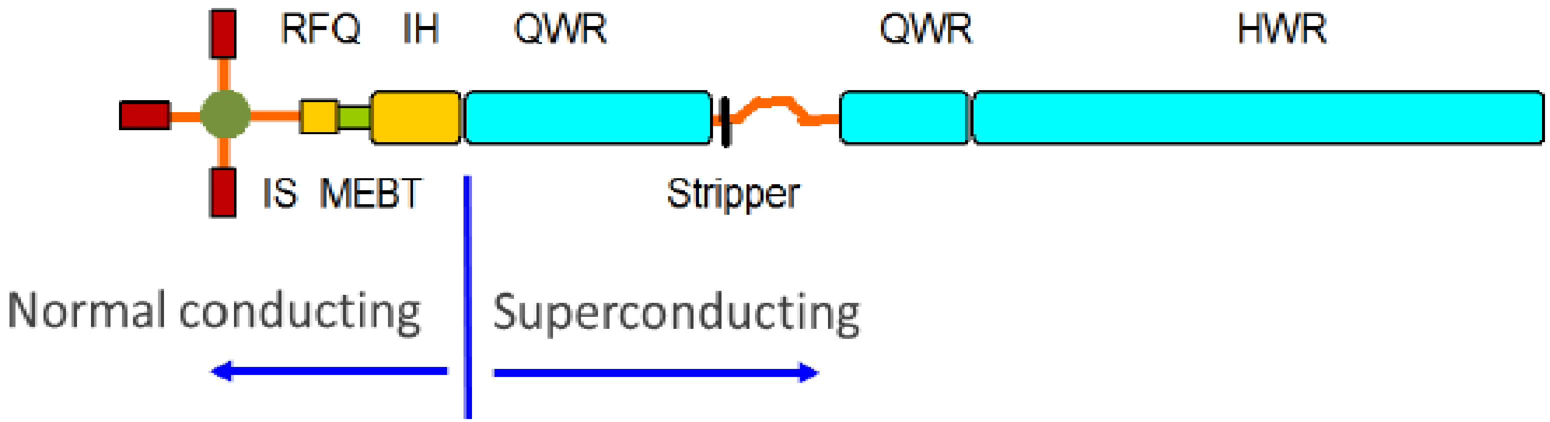
	FY10+ FY11	FY12+ FY13	FY14+ FY15	FY16+FY17	Total
Funds allocated	0+440k	100k+98k	50k+50k	55k+100k	$893k
Actual costs to date	0+316.8k	142.2k+115.2k	53.7k+64.1k	55k+50k	$843k

✓ FY-17 Milestones

	Milestones
Q1FY17	Conceptual Design of the Room-Temperature Front-End: RFQ and IH-DTL Structures
Q2FY17	MEBT Design connecting the light-ion and heavy-ion RFQ injectors to the common IH-DTL Section.
Q3FY17	Design of the stripper section for heavy-ion beam including the chicane for charge state selection and collimation
Q4FY17	End-to-end simulations in the linac for at least one light-ion and one heavy-ion beam.

Accomplishments of Previous Years (FY10-FY14)

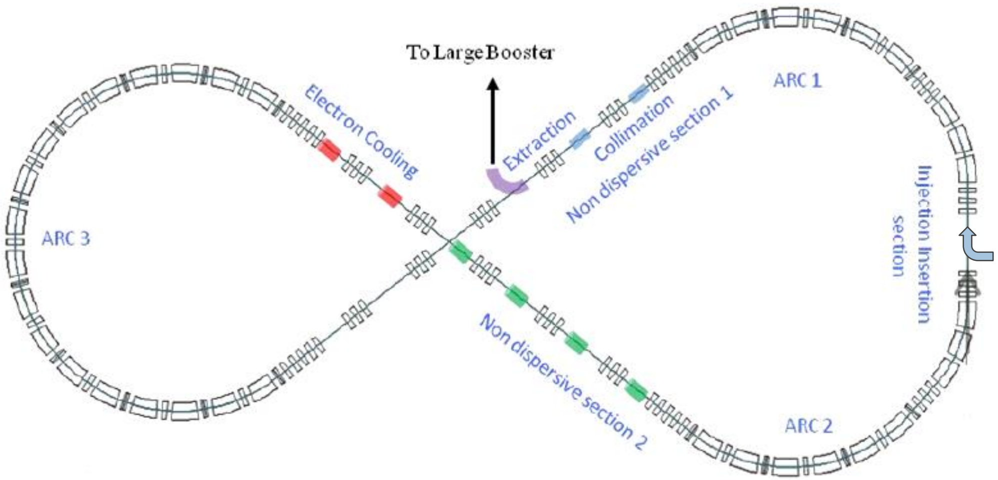
Linac Design (2012) – MEIC/JLEIC Baseline



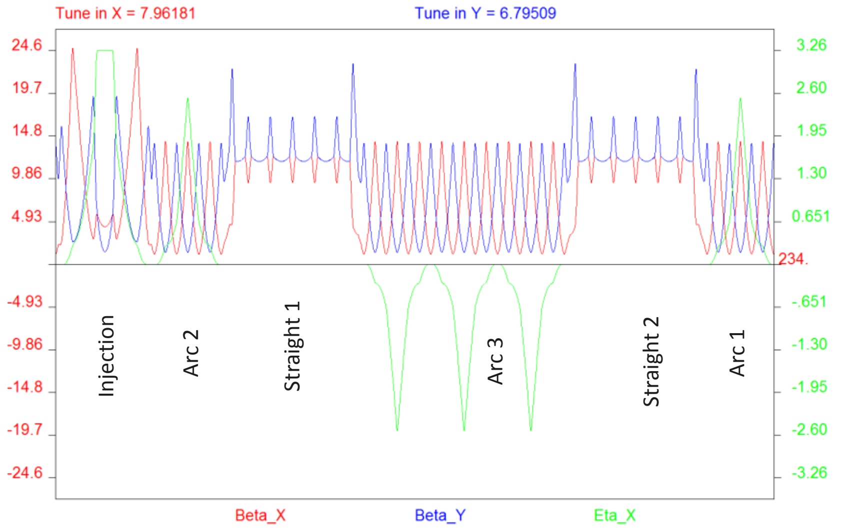
- Warm front-end up to ~ 5 MeV/u for all ions
- SC QWR section up to 13 MeV/u for Pb ions
- A stripper for heavy ions for more effective acceleration: $Pb^{28+} \rightarrow {}^{67+}$
- SC high-energy section (QWR + HWR) up to 280 MeV for protons and 100 MeV/u for Pb ions
- Total linac length of ~ 130 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 (2012) – Original MEIC Baseline

3 GeV – 234 m – RT Pre-booster



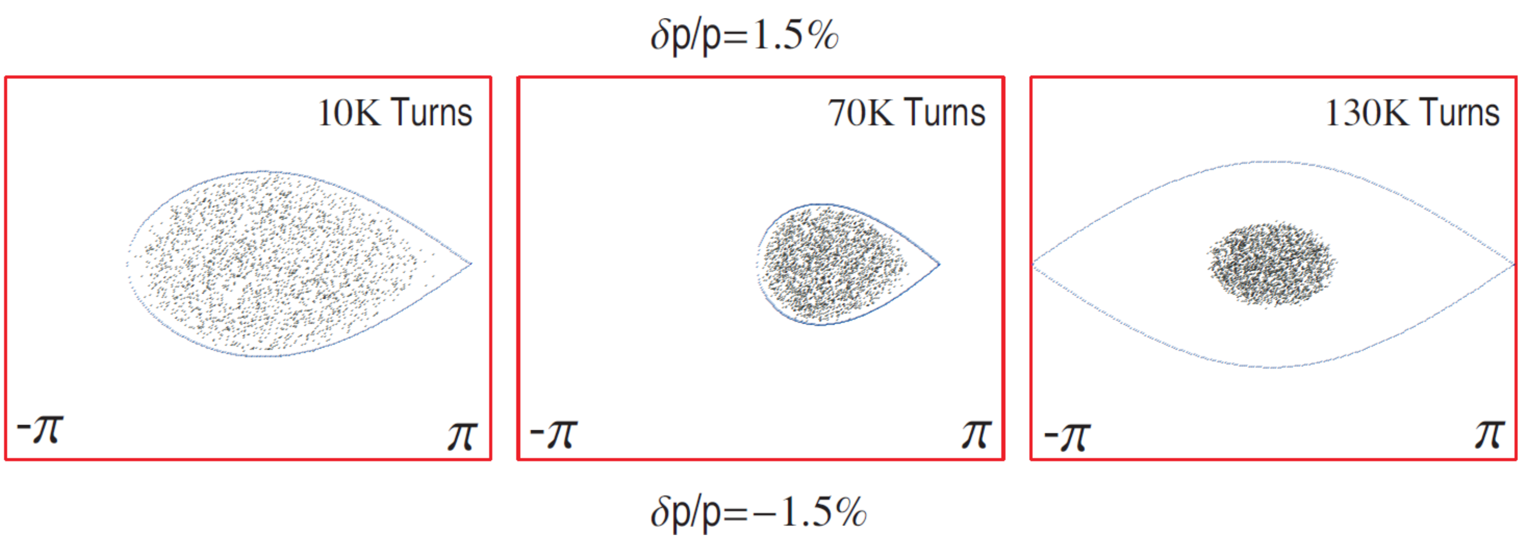
Linear Optics of Pre-Booster Ring: Lattice Plot



- 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



Lead Ion Beam Formation in the MEIC Ion Complex

		Source	Linac	Pre-booster		Large booster		Collider ring
		ECR	After stripper	At injection	After boost	before injection	After Boost	After boost
Charge status		$^{208}Pb^{30+}$	$^{208}Pb^{67+}$			$^{208}Pb^{82+}$		
Kinetic energy	MeV/u	~0	13.2	100	670	670	7885	23653
γ and β				1.11 / 0.43	1.71 / 0.81	1.71 / 0.81	9.4 / 0.99	26.2 / 1
Pulse current	mA	.5	0.1					
Pulse length	ms	0.25	0.25					
Charge per pulse	μC	0.125	0.025					
Ions per pulse	10^{10}	1.664	0.332					
Number of pulses				28				
Efficiency			0.2	0.7		0.75		
Total ions	10^{10}			4.5		3.375x5		
Stored current	A			0.26	0.5	0.447	0.54	0.54

Published Work …

- “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.

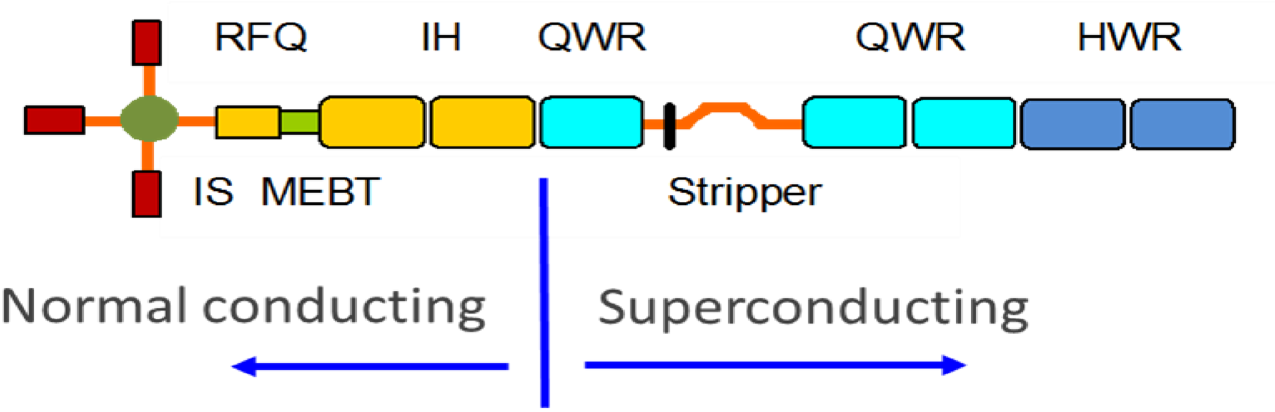
- ”An accumulator/Pre-Booster for the Medium-Energy Electron Ion Collider at Jlab”, B. Erdelyi, S. Abeyratne, Y.S. Derbenev, G.A. Krafft, Y. Zhang, S.L. Manikonda, P.N. Ostroumov, PAC-2011, New York.

- “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.

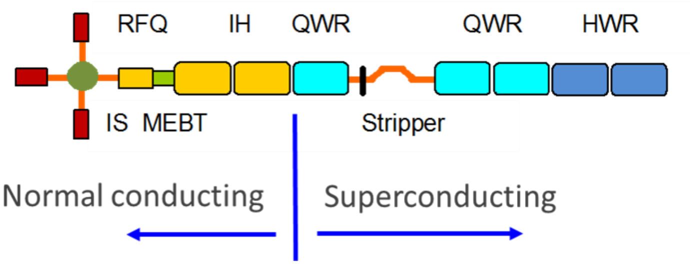
More Recent Developments (FY15-FY16)

More Compact Linac Design (2015)

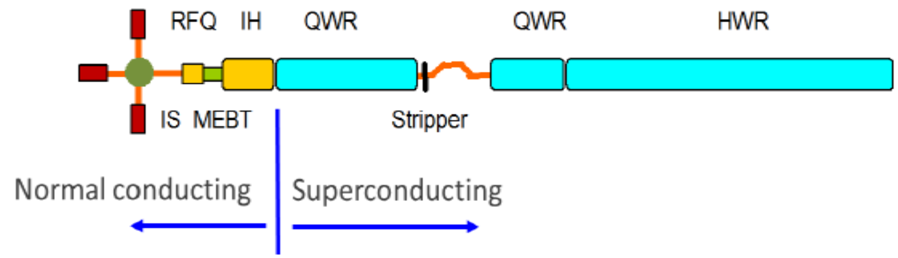


- The same warm front-end up to ~ 5 MeV/u for all ions
- A single high-performance QWR module up to 8.2 MeV/u for Pb ions
- A stripper for heavy ions for more effective acceleration: $Pb^{30+ \rightarrow 61+}$
- High-energy SC section (QWR + HWR) up to 130 MeV for protons and 42 MeV/u for Pb ions
- Total linac length of ~ 55 m with a total pulsed power of 260 kW

New vs. Original Linac Design



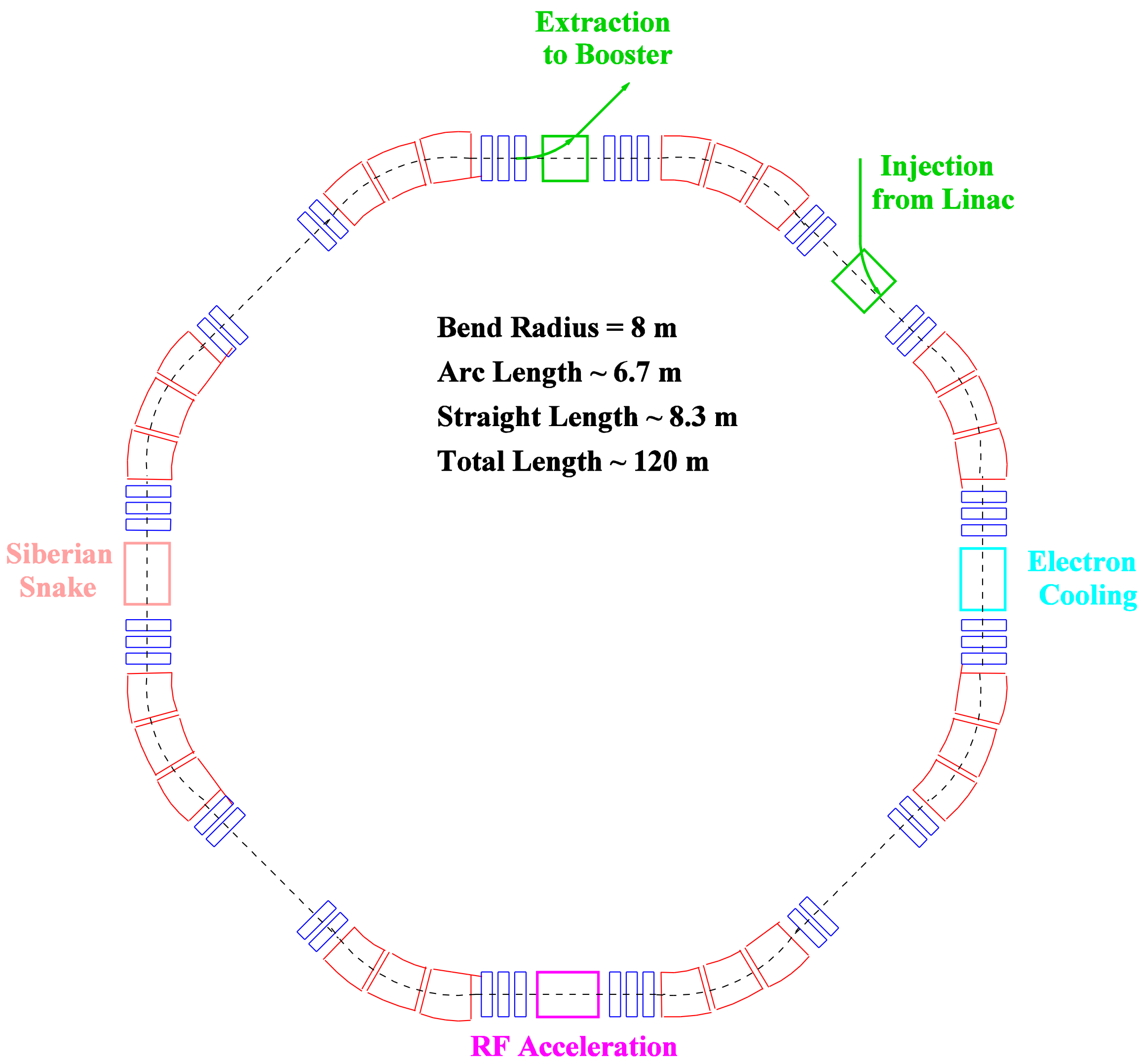
VS



Item / Parameter	Original	New	Comments
Frequency (MHz)	115	100	-
Stripper at (MeV/u)	13	8.2	Depends on W out
Protons (MeV)	280	130	Lower output W
Pb (MeV/u)	100	42	Lower output W
SC modules	16	5	~ 1/3 Cost
Total Length	130	55	~ 1/2 Tunnel cost
Total Power (kW)	560	260	

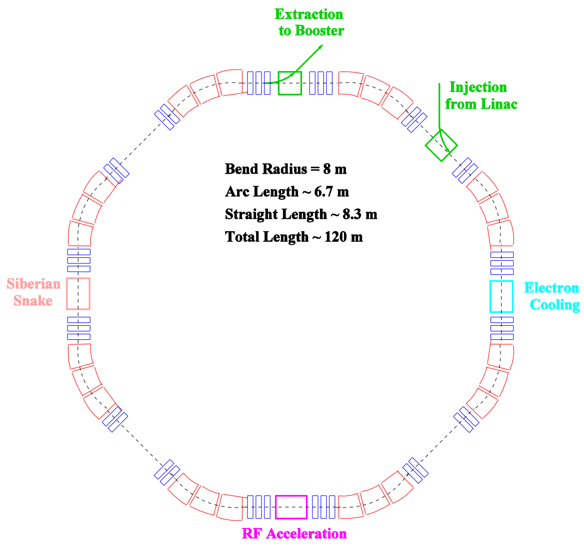
- The new design is ~ 1/3 the construction cost of the original

More Compact Pre-Booster Design (2015)

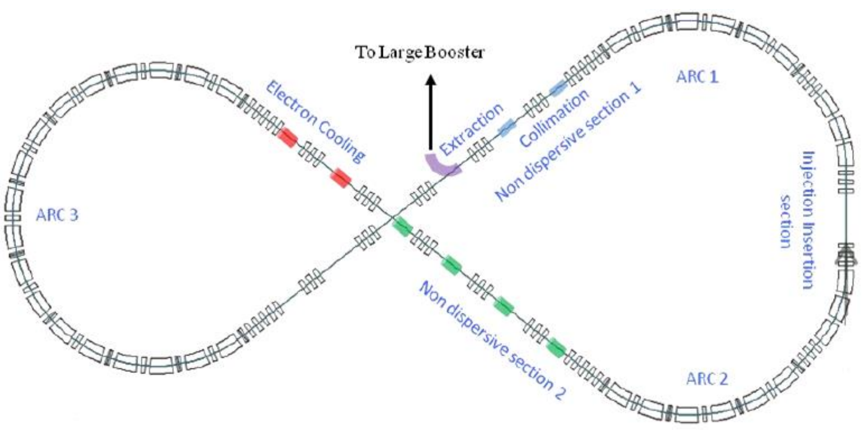


- A 120 m long Octagonal Design
- Same injection and extraction features as the original design
- Four dispersion-free sections
- Will require Siberian snakes for polarization
- Injects to e-ring as large booster for the ions

New vs. Original Pre-Booster Design



VS



Item / Parameter	Original	New	Comments
N. of 15^o Dipoles	36	24	-
N. of Quads	95	40	-
Total N. of Magnets	131	64	1/2 Cost
Total Length	234	120	1/2 Tunnel cost

➢ The new design is ~ 1/2 the construction cost of the original

Published Work …

- “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

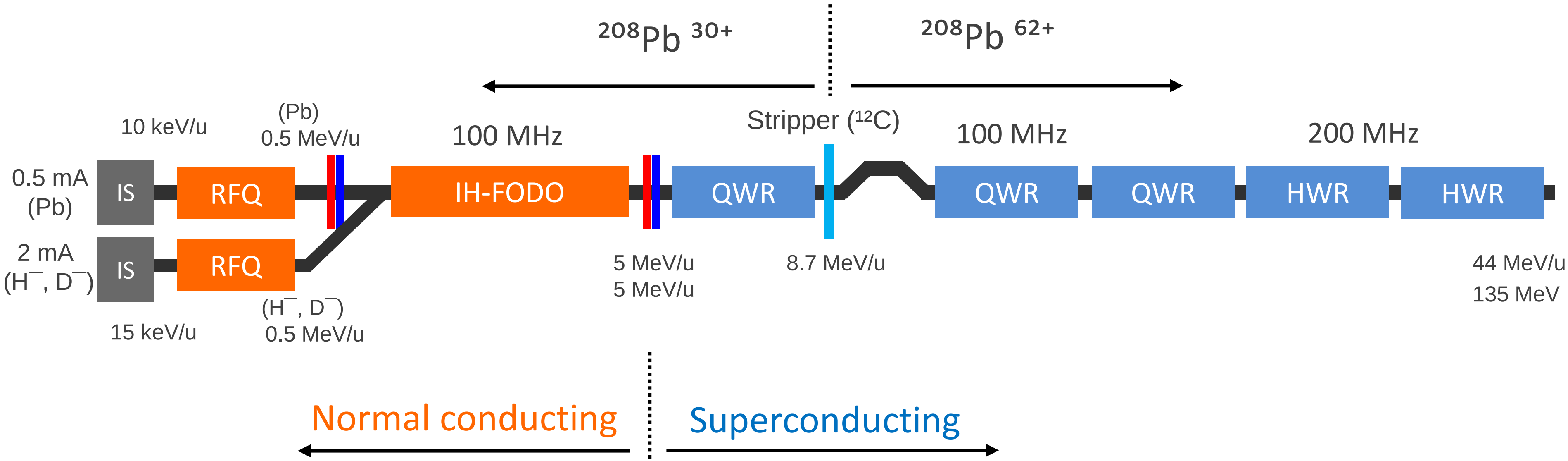
- “Design and Beam Dynamics Studies of a Multi-Ion Linac Injector for the JLEIC Ion Complex”, P. Ostroumov et al, Proceedings of Hadron Beams 2016 Workshop (HB-2016), Malmo, Sweden, July 3-8, 2016.

- “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.

- “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, Chicago, Illinois.

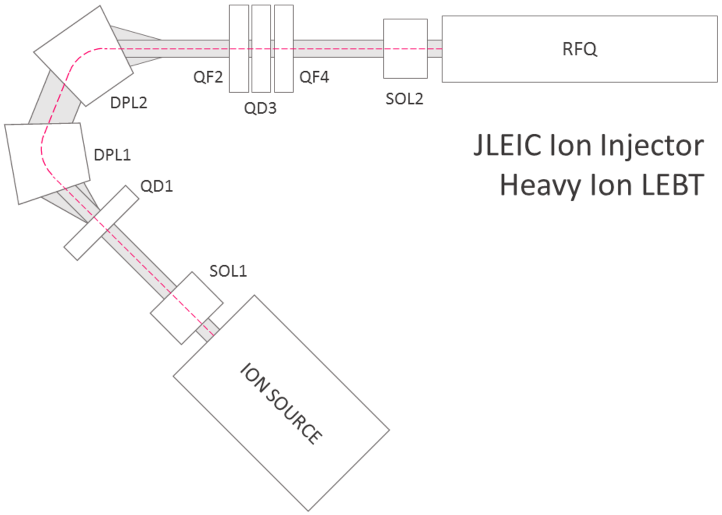
Current Status of the Multi-Ion Injector Linac Design

Multi-Ion Pulsed SRF Linac Injector

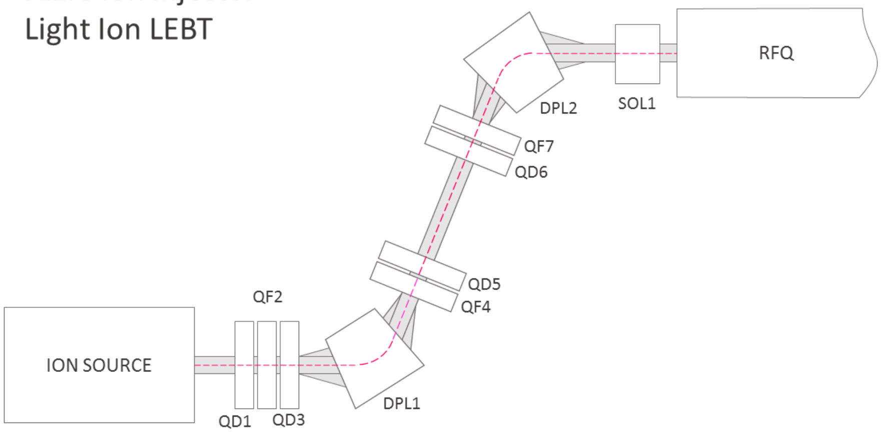


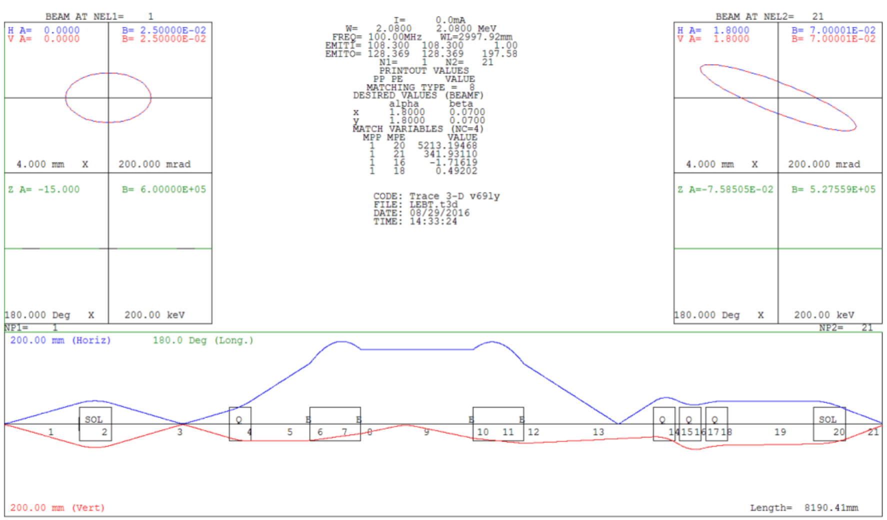
- Two RFQs: For light ions (q/A ~ 1/2) and for heavy ions (q/A ~ 1/7)
  - Different emittances and voltage requirements for polarized light ions and heavy ions
- Selected RT Structure: IH-DTL with FODO Lattice instead of Triplets
  - No Frequency jump & FODO focusing → Significantly better beam dynamics
- Separate LEBTs and MEBTs for light and heavy ions
- IH and SRF sections common to all beams
- Pulsed Operation: 10 Hz (0.25 ms / 0.5 ms pulse for heavy/polarized light ions)

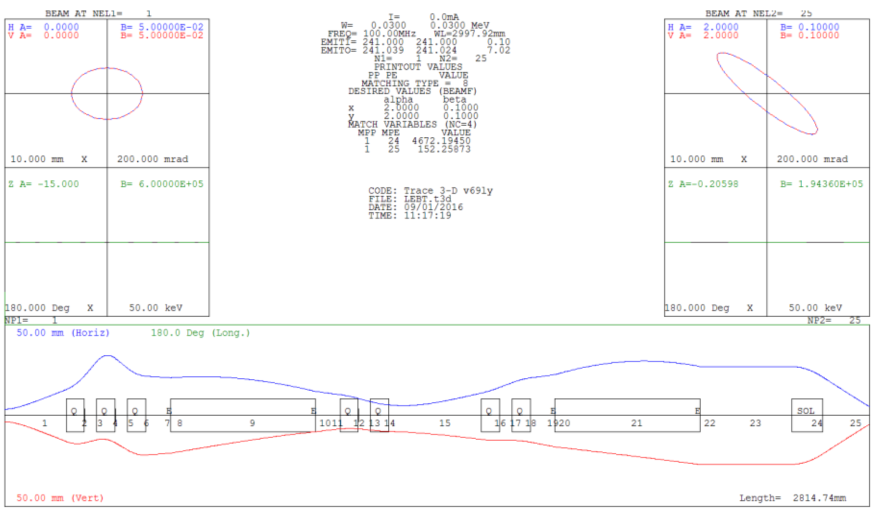
LEBTs: From Ion Sources to the RFQs



JLEIC Ion Injector
Light Ion LEBT



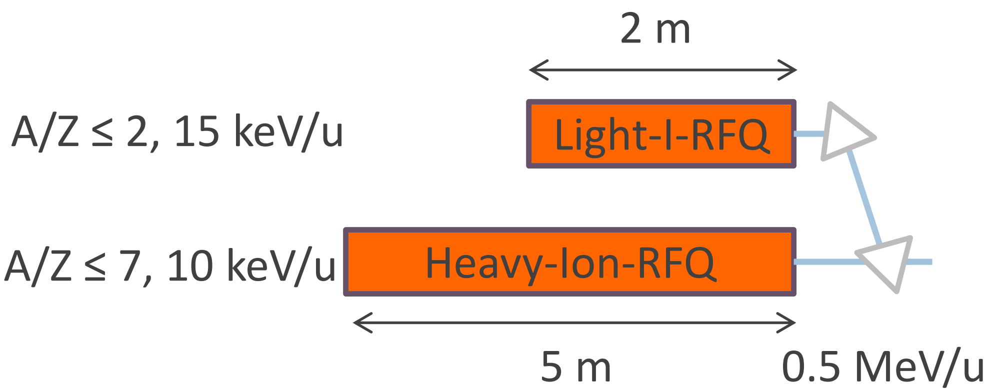




Similar to CERN Linac3 LEBT

Similar to BNL LEBT

Two Separate RFQs for Light Ions 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 Z/A ≤ 7 with **0.5 π** mm mrad normalized transverse emittance

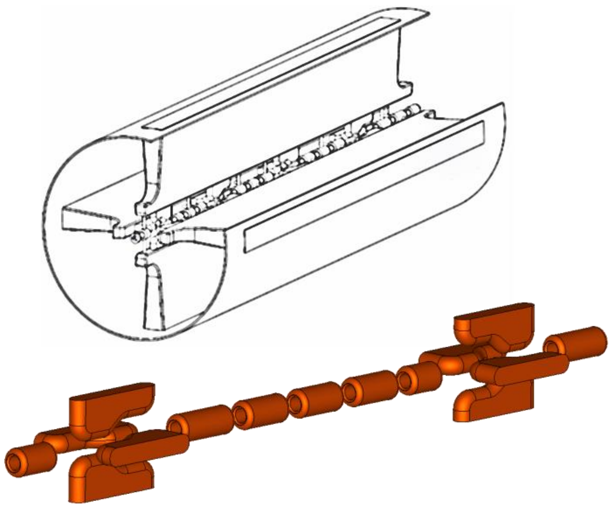
Parameter	Heavy ion	Light ion	Units
Frequency	100		MHz
Energy range	10 - 500	15 - 500	keV/u
Highest - A/Q	7	2	
Length	5.6	2.0	m
Average radius	3.7	7.0	mm
Voltage	70	103	kV
Transmission	99	99	%
Quality factor	6600	7200	
RF power consumption (structure with windows)	210	120	kW
Output longitudinal emittance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

FODO Focusing Lattice for the IH-DTL Section

✓ **Options Investigated**

BNL EBIS Injector 100 MHz IH Structure
(Courtesy of J. Alessi)

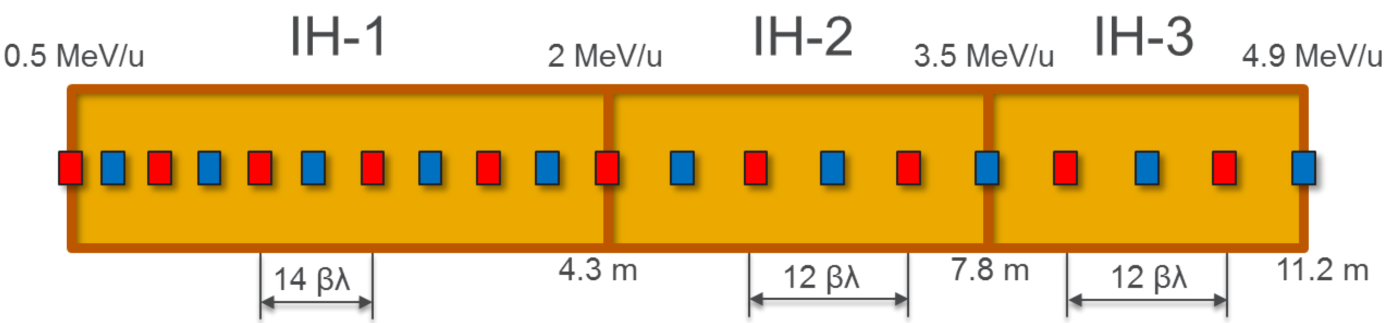
+ Highest efficiency
- Limited acceptance for polarized ions



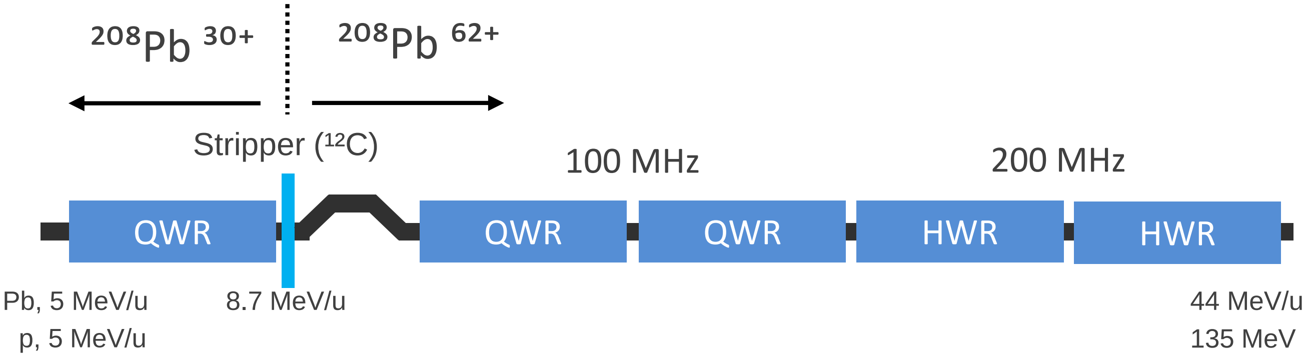
RF Quadrupole Focusing 4-vane DTL

+ Large acceptance
- Low Shunt Impedance

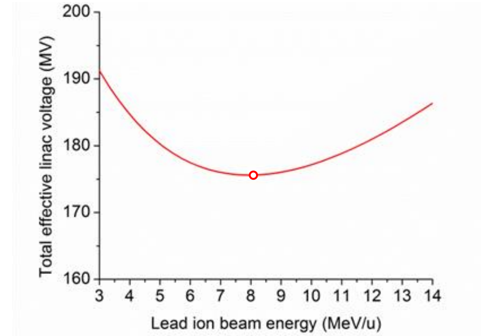
➢ **Better solution: IH-DTL with FODO focusing lattice**



Stripper and SRF Linac Section



Stripping Energy & Charge



@ 8.7 MeV/u: 30+ → 62+ → 44 MeV/u

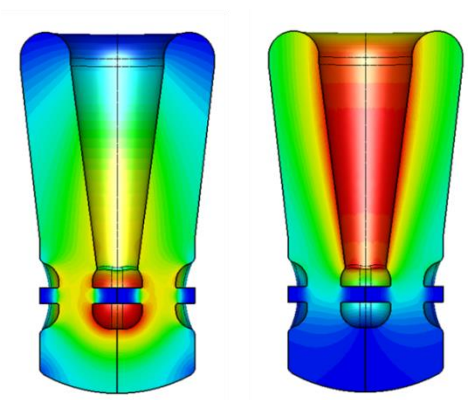
@ 13.3 MeV/u: 30+ → 67+ → 40 MeV/u

QWR Module

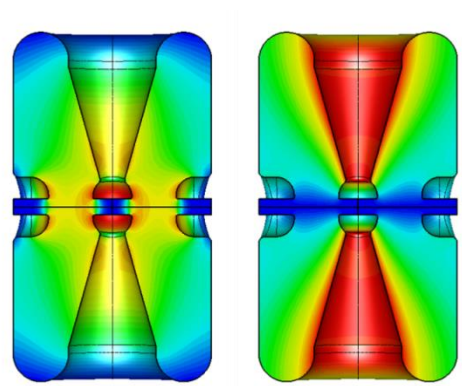
HWR Module

Horizonal orientation of cavities

QWR Design

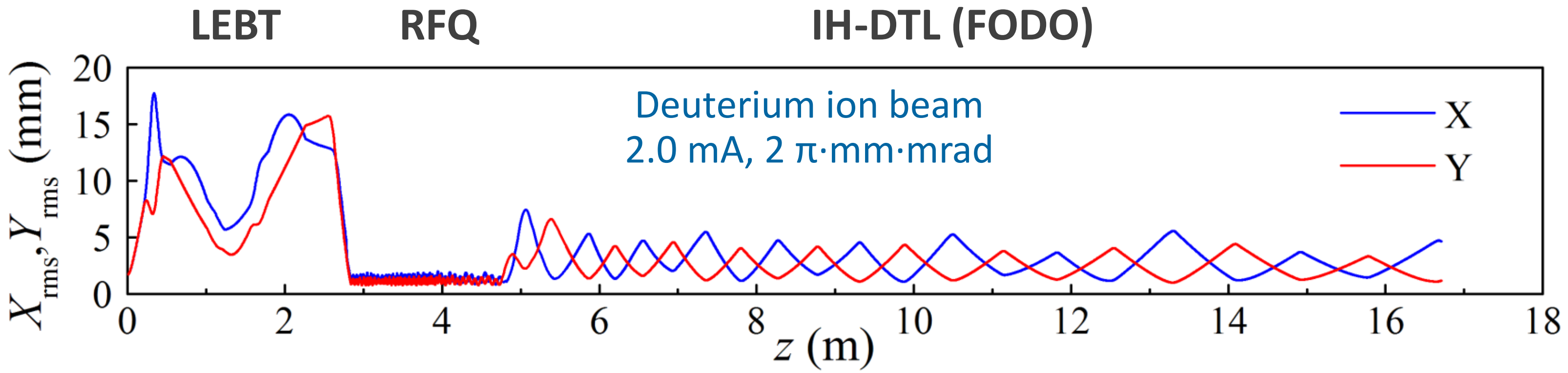


HWR Design

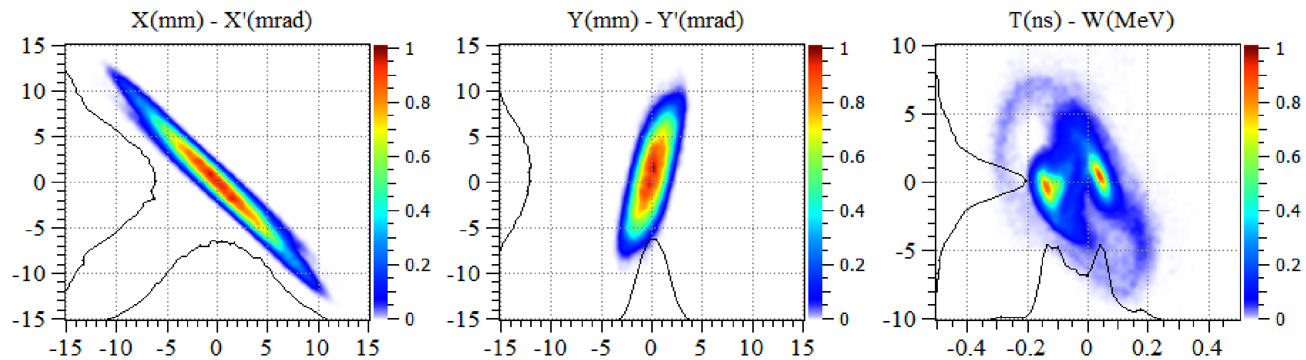


Parameter	QWR	HWR	Units
β_{opt}	0.15	0.30	
Frequency	100	200	MHz
Length ($\beta\lambda$)	45	45	cm
E_{PEAK}/E_{ACC}	5.5	4.9	
B_{PEAK}/E_{ACC}	8.2	6.9	mT/(MV/m)
R/Q	475	256	Ω
G	42	84	Ω
E_{PEAK} in operation	**57.8**	**51.5**	**MV/m**
B_{PEAK} in operation	**86.1**	**72.5**	**mT**
E_{ACC}	**10.5**	**10.5**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

Light Ion Beam Dynamics in the RT Linac Section

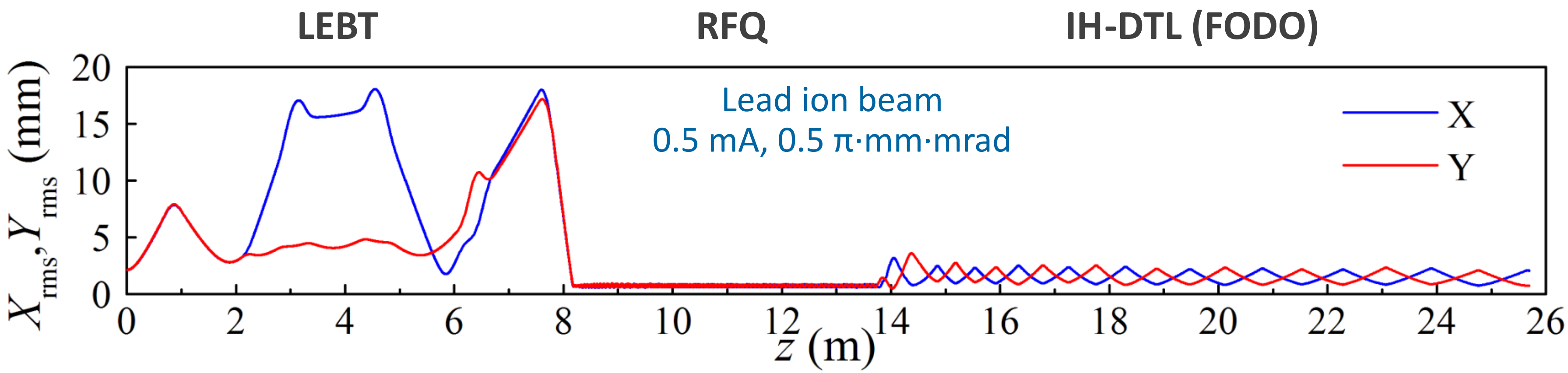


Output Phase Space

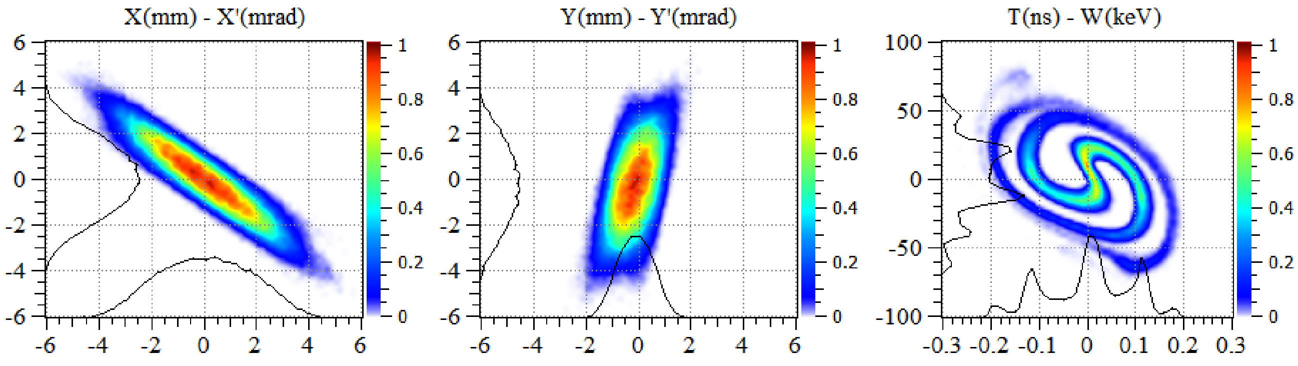


- ✓ Input beam: 0.5 MeV/u, polarized deuterons, 2 π.mm.mrad and 2 mA
- ✓ Output beam: ~ 5 MeV/u, 13% Transverse emittance growth – 0% Longitudinal

Heavy Ion Beam Dynamics in the RT Linac Section



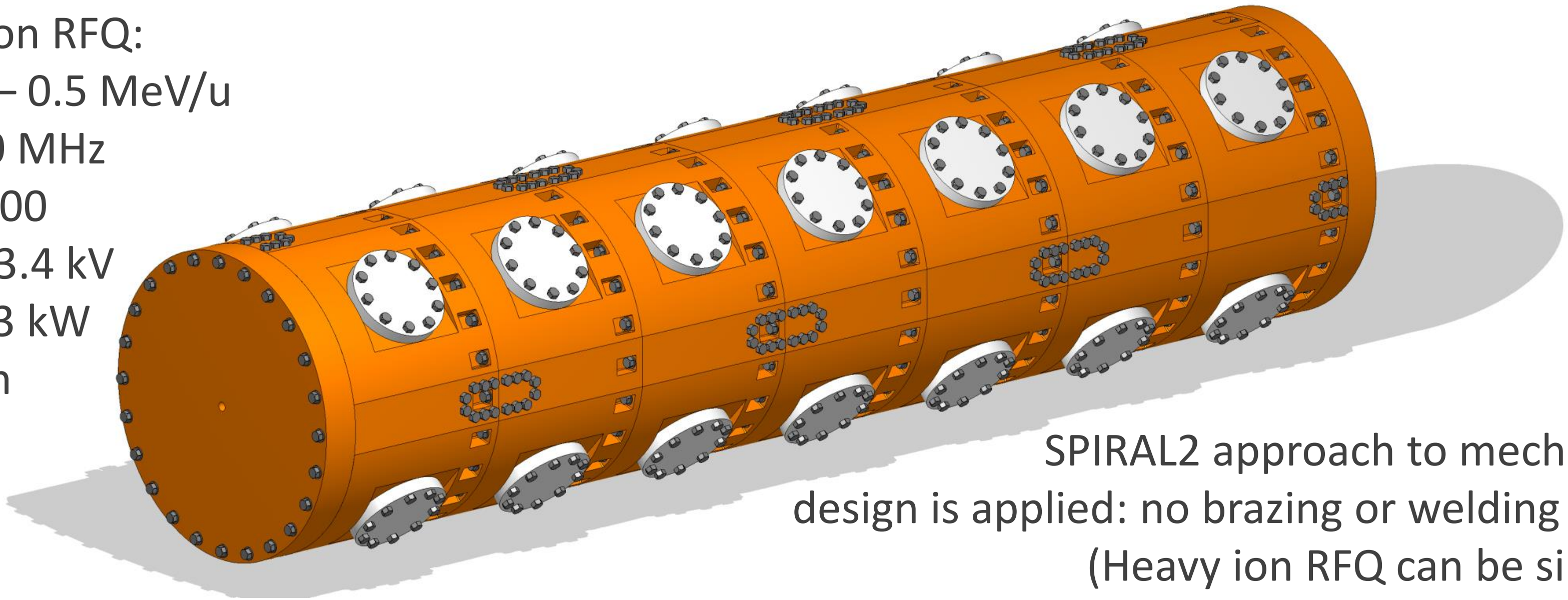
Output Phase Space



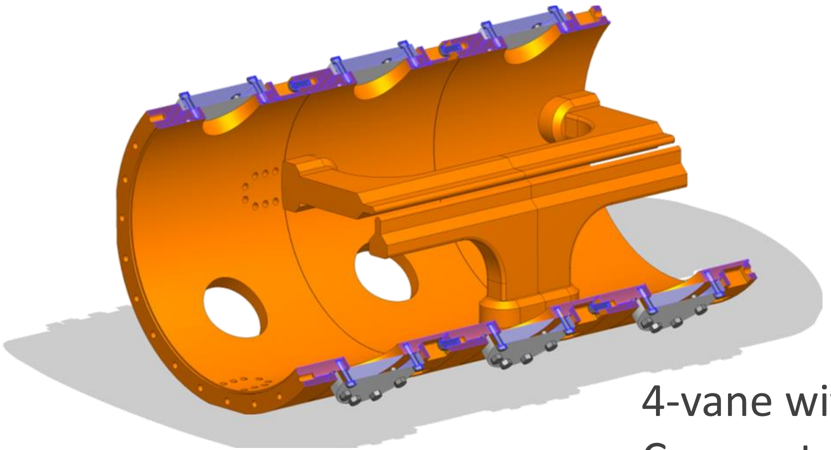
- ✓ Input beam: 0.5 MeV/u, lead ions, 0.5 π.mm.mrad and 0.5 mA
- ✓ Output beam: ~ 5 MeV/u, 17% Transverse emittance growth – 0% Longitudinal

Proposed Structure for the RFQs

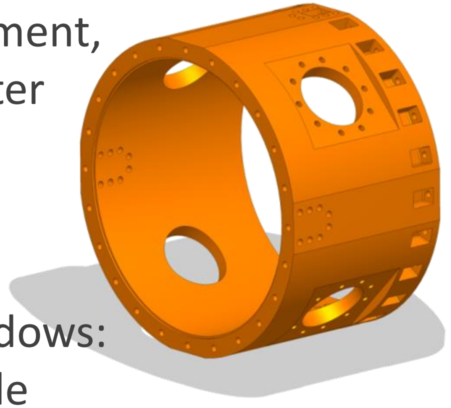
Light Ion RFQ:
0.015 – 0.5 MeV/u
f = 100 MHz
Q = 9700
V = 103.4 kV
P = 113 kW
L = 2 m



SPIRAL2 approach to mechanical design is applied: no brazing or welding joints (Heavy ion RFQ can be similar)



One RFQ segment, 40 cm diameter

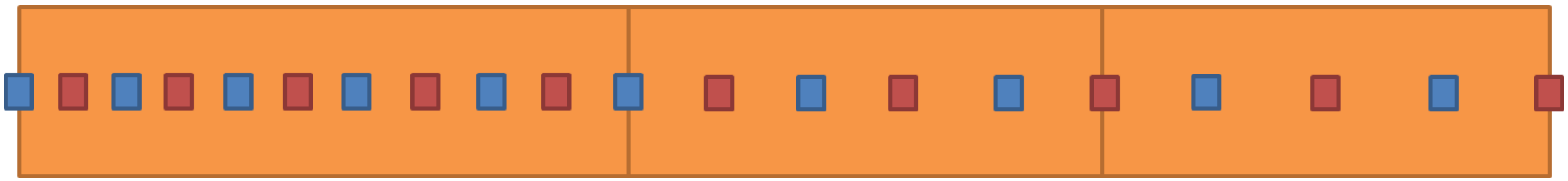


4-vane with magnetic coupling windows: Compact & Suitable for pulsed mode

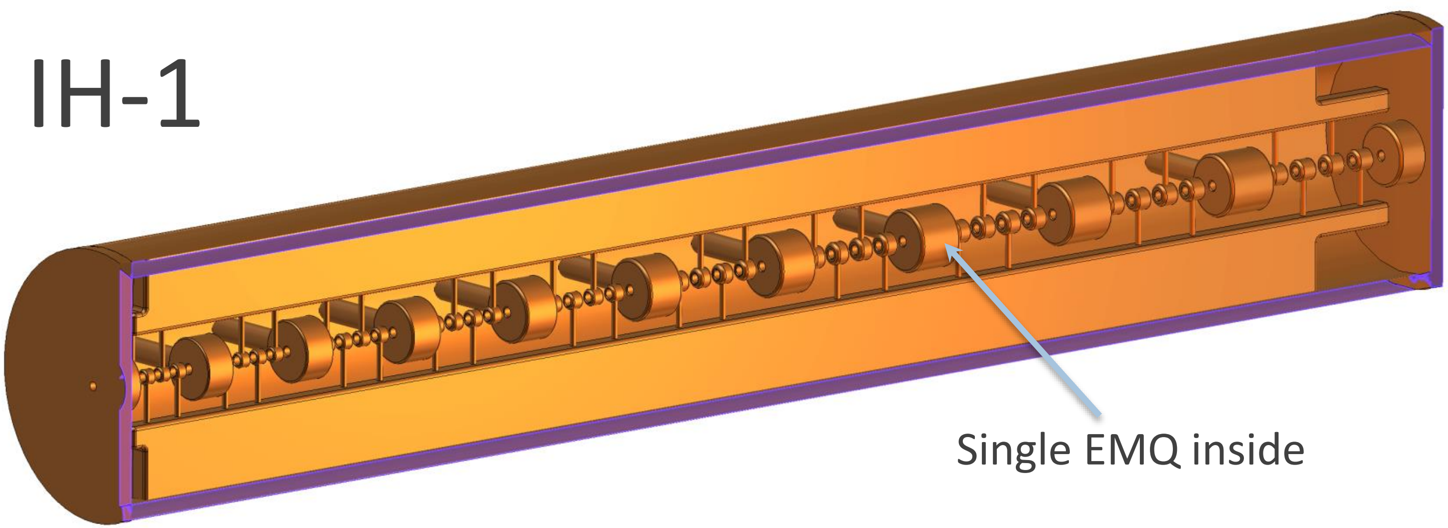
Proposed Design for the IH-DTL with FODO Focusing

✓ 3 Tanks – 20 Quadrupoles in FODO arrangements

IH-1 IH-2 IH-3



✓ 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



Design Parameters for the RT Front-End

Parameter	Units	Light Ion RFQ	Heavy Ion RFQ	IH-1	IH-2	IH-3	Total
Energy range	MeV/u	0.015 – 0.5	0.010 – 0.5	0.5 – 2.0	2.0 – 3.5	3.5 – 4.9	0.01 - 4.9
Length	m	2.0	5.6	4.3	3.5	3.4	
Diameter	m	0.47	0.44	0.7	0.7	0.7	
Number of cells / gaps		136	264	50	30	24	
Number of quads				11	5	4	20
Voltage	kV	103.4	70.0	200 - 500	500	570	
Aperture (R_0)	mm	7.0	3.7	12.5	12.5	12.5	
Quality factor		9500	9200	18000	18000	18000	
RF power losses	kW	110	180	280	400	620	1480 (max)
Peak surface electric field	Kilpat. units	1.84	2.05	2.0	2.0	2.0	
Norm. transverse emittance (90%)*	π·mm·mrad	1.47	0.35	1.62 / 0.40	1.66 / 0.41	1.66 / 0.41	+13% / +17%
Norm. longitudinal emittance (90%)*	π·ns·keV/u	4.9	4.5	4.9 / 4.5	4.9 / 4.5	4.9 / 4.5	+ 0%
Transmission*		99.9%	99.7%	99.8%	100%	100%	99.7%
Beam current*	mA	2.0	0.5	2.0 / 0.5	2.0 / 0.5	2.0 / 0.5	2.0 / 0.5

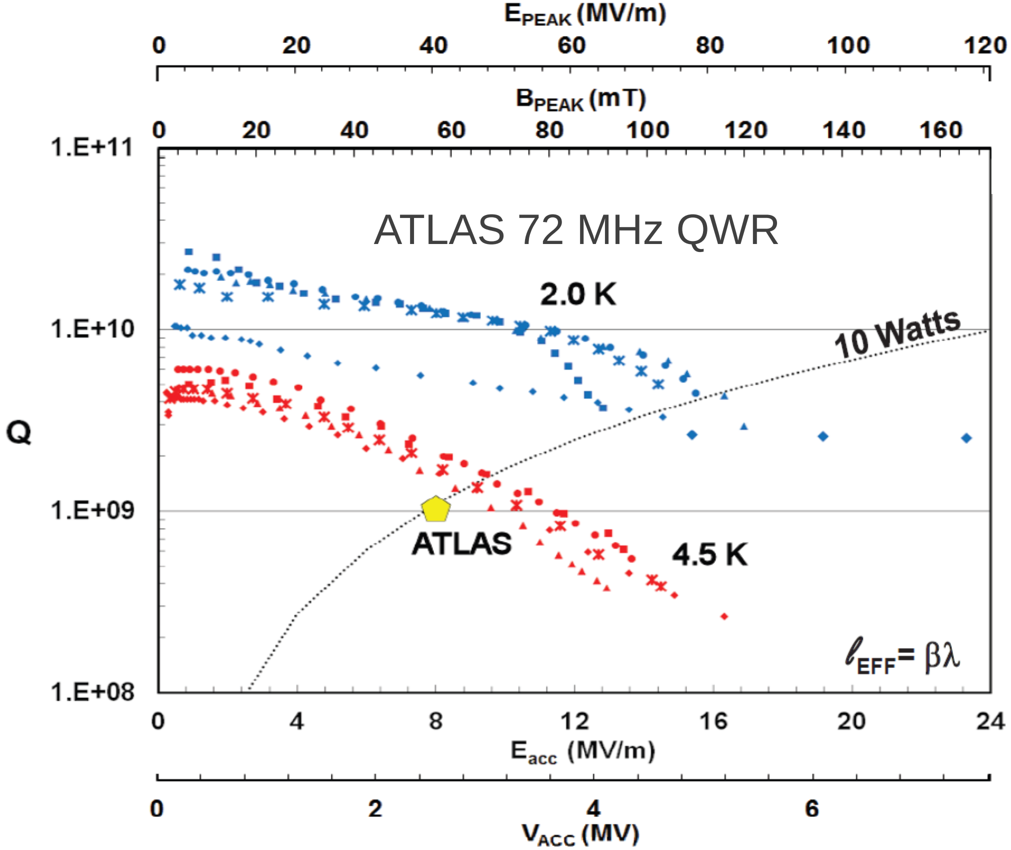
* Deuterium ion beam / Lead ion beam

Proposed Future Work

High-Performance QWRs Developed at ANL

ATLAS
72 MHz QWR

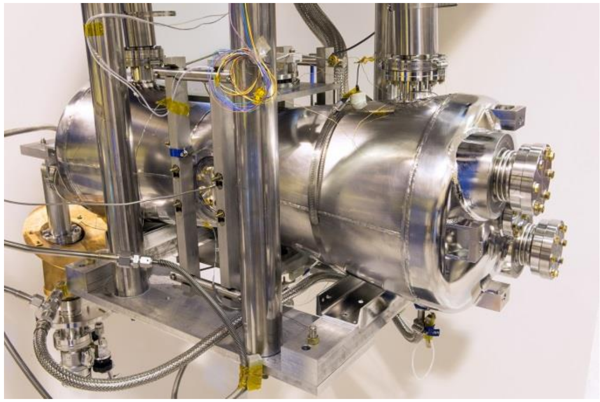
SC section will operate at 4.5K in pulsed mode



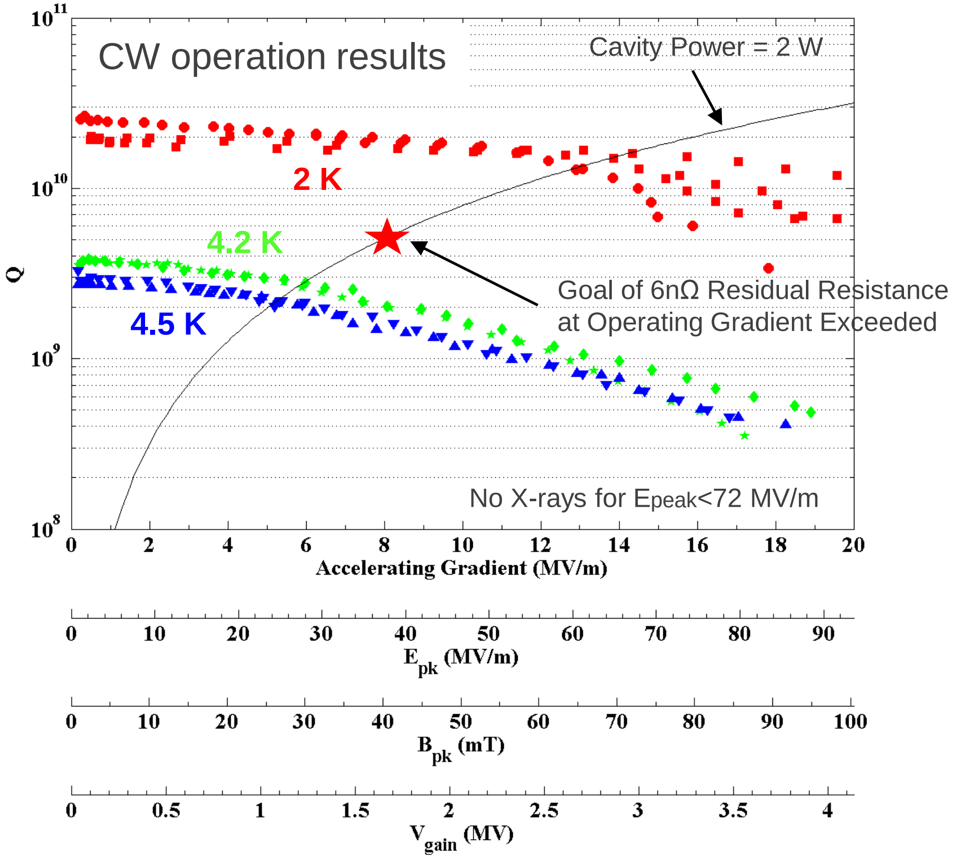
- ✓ A 72 MHz β=0.077 QWR is capable of delivering 4 MV @ E_{peak} ~ 64 MV/m and B_{peak} ~ 90 mT in CW mode
- ✓ Scaled to 100 MHz and β_{opt} = 0.15, the QWR designed for JLEIC could deliver up to 5.6 MV.
- ✓ JLEIC QWRs will operate in pulsed mode @ 4.7 MV per cavity

High-Performance HWRs developed at ANL

FNAL - 162 MHz HWR



SC section will operate at 4.5K in pulsed mode



- ✓ A 162 MHz β=0.11 HWR is capable of delivering 3 MV @ E_{peak} ~ 68 MV/m and B_{peak} ~ 72 mT in CW mode
- ✓ Scaled to 200 MHz and β_{opt} = 0.3, the HWR designed for JLEIC could deliver up to 6.6 MV
- ✓ JLEIC HWRs will operate in pulsed mode @ 4.7 MV per cavity

High Voltage Pulsed Operation of QWRs and HWRs

- In CW mode, QWRs and HWRs are usually operated at moderate voltages
- For the JLEIC Injector Linac, they are designed to operate at relatively high-voltage in pulsed mode
- Based on CW tests of similar cavities at ANL, the QWRs and HWRs proposed for JLEIC are capable of delivering their design voltage
- Developments required to demonstrate high-power pulsed operation
  - Study the dynamic detuning inherent to the pulsed operation of QWRs
  - Development and testing of fast mechanical tuners for QWRs
  - High-power couplers suitable for pulsed operation of SRF cavities
  - High-power tests using similar QWRs and HWRs existing at ANL

Alternative Design Approach for JLEIC Ion Complex

Motivations

- Reduce the footprint of the Ion Complex
  - Compact ring as pre-booster (3 GeV, RT, no figure-8 required)
  - Consolidate: Use electron ring as large ion booster (12-15 GeV)

- Lower the risk
  - Use proven technology of RT or SC magnets when possible
  - Avoid transition crossing for all ions

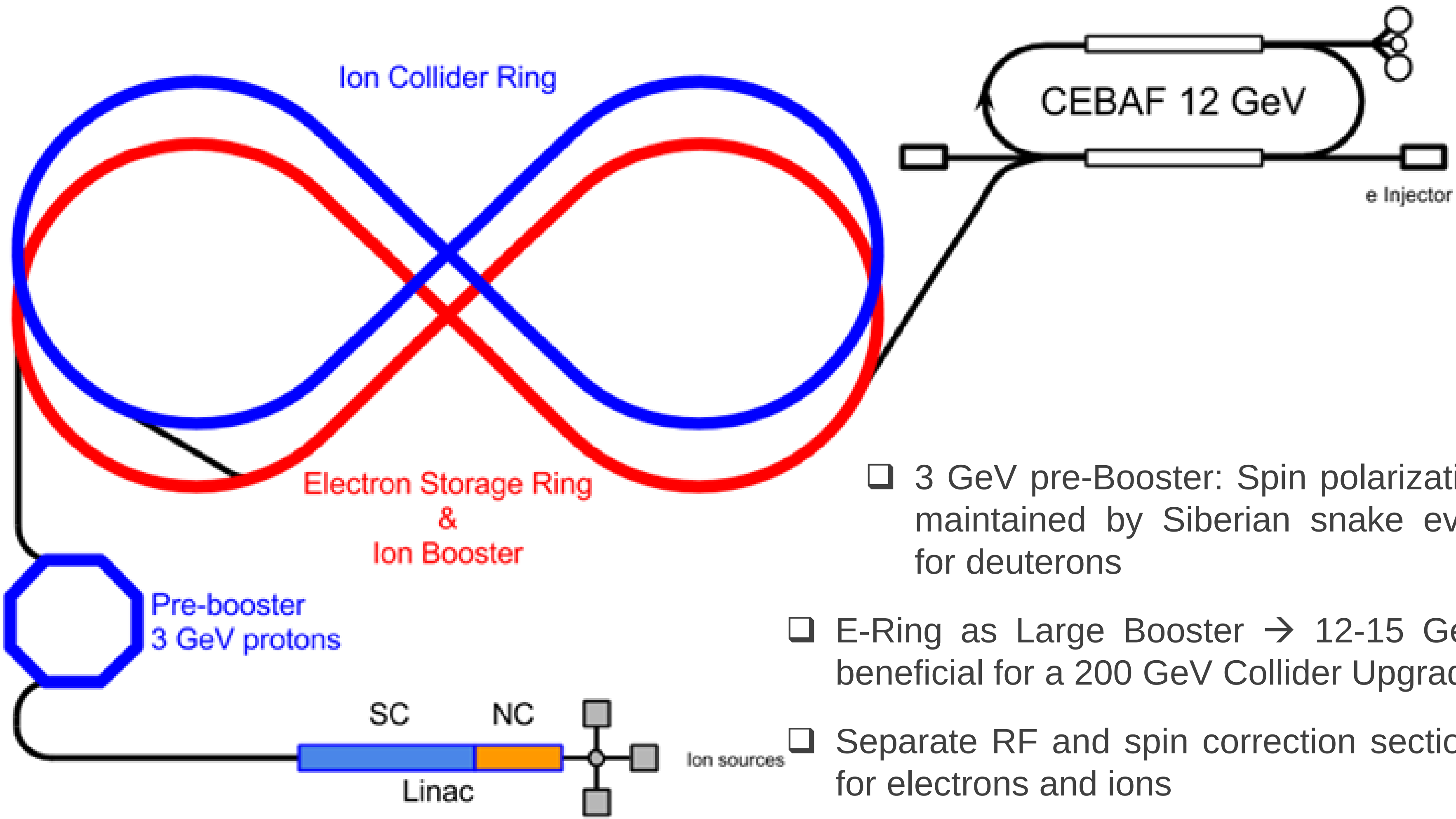
- Options for Staging
  - First Stage: 60 GeV Collider with RT magnets only (Cost effective)
  - Second Stage: Upgrade to 200 GeV with fully superconducting

Original Ideas …

- ❑ More Compact Linac … Yuhong & Fulvia
- ❑ More Compact Pre-Booster … P. Ostroumov
- ❑ Use Electron Ring As Large Booster for the Ions … Y. Derbenev
- ❑ 60 GeV RT Ion Collider Ring … Original design by V. Morozov
- ❑ …

➢ The idea is not to replace the baseline design but rather to investigate alternative options for the different components of the accelerator complex that have the potential of lowering the cost, mitigating the risk, or to be ready for eventual staging of the project

Layout of A Possible Alternative …



- ❑ 3 GeV pre-Booster: Spin polarization maintained by Siberian snake even for deuterons
- ❑ E-Ring as Large Booster → 12-15 GeV, beneficial for a 200 GeV Collider Upgrade
- ❑ Separate RF and spin correction sections for electrons and ions

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

Very Preliminary: E-Ring As Large Ion Booster

Table 1: Options for the e-Ring as Large Ion Booster

Parameter	**Baseline design**	**Low-emittance design**	**TME design with SF/SC quads**
Cell length (m)	15.2	11.4	22.8
Transition γ	15	20	33
proton (GeV)	12	15	30
Pb (GeV/u)	4.8	6	12
Dipole (T)	0.36	0.5	1.1
Quad (T/m)	15	25	60
Limitation	Dipoles	Quads	-

✓ "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, Chicago, IL.

Possible Staging with RT then SC Magnets

- First Stage: Fully RT Magnets → 60 GeV Collider, possible with
  - 130 MeV Linac
  - 3 GeV Pre-Booster
  - 12 GeV Large Booster (E-ring with PEP-II Magnets)
  - 60 GeV Ion Collider Ring

- Second Stage: SC Magnets in Collider Ring → 200-250 GeV Collider
  - 130 MeV Linac
  - 3 GeV Pre-Booster
  - 12-15 GeV Large Booster (E-ring with New Magnets)
  - 200-250 GeV Ion Collider Ring with SC Magnets (6-8 Tesla)

Summary

- Significant progress has been made in the design and simulations of the MEIC/JLEIC Ion Accelerator Complex
- More recently, ANL effort was mainly focused on the Injector Linac design, both the room temperature front-end and the SRF sections
- We now have a good solution and robust design for the JLEIC Injector Linac
- Further developments are required to demonstrate reliable high voltage operations of superconducting QWRs and HWRs
- An alternative design approach is being proposed to reduce the foot-print of the JLEIC ion complex, mitigate the risk and for possible staging of the project …