DESIGN OF THE MULTI-ION INJECTOR LINAC FOR JLEIC

Brahim Mustapha
Physics Division, ANL

Contributors: A. Plastun, P. Ostroumov and Z. Conway

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Outline

- ❑ The Electron Ion Collider (EIC) – The next machine in the US
- ❑ The Jefferson Lab EIC (JLEIC)
- ❑ JLEIC Ion Injector Linac: Design Requirements & Choices
- ❑ Design of the Different Linac Sections
- ❑ Beam Simulations – Short linac version
- ❑ Summary

The Electron Ion Collider – The next machine in the US

- An Electron Ion Collider (EIC) is the highest priority for future U.S. accelerator-based nuclear physics facility following the completion of the Facility for Rare Isotope Beams (FRIB).

- Design Requirements of the EIC
  - High collision luminosity: ~ 10^{34} $cm^{-2}s^{-1}$

    2-3 orders of magnitude higher than HERA, the last e-p collider

  - High spin polarization: > 70% for electrons and light ions

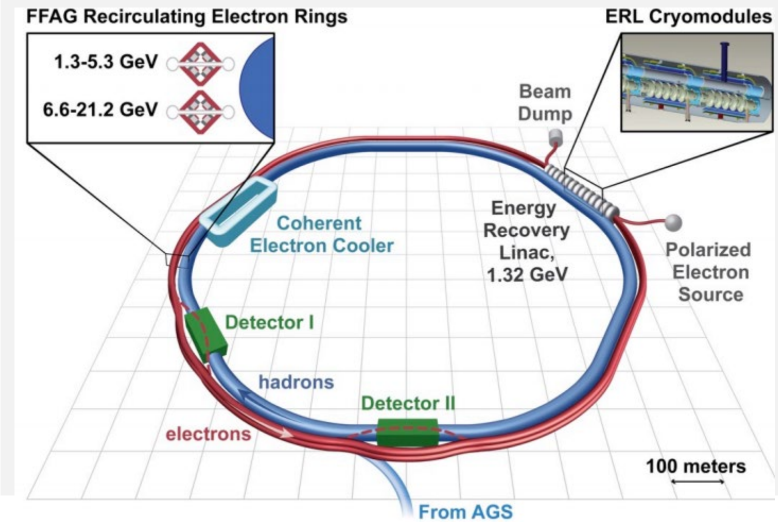
  - Wide range of collision energies: 20-140 GeV CM energy

    5-18 GeV electrons & 60–250 GeV protons / ion equivalent

Two Design Concepts Proposed

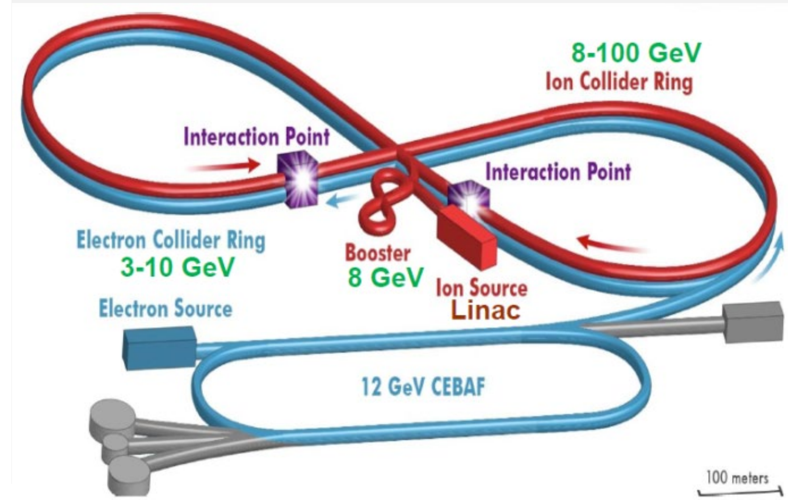
eRHIC

Has a **proton/ion machine** (RHIC)
Needs an **electron ring**



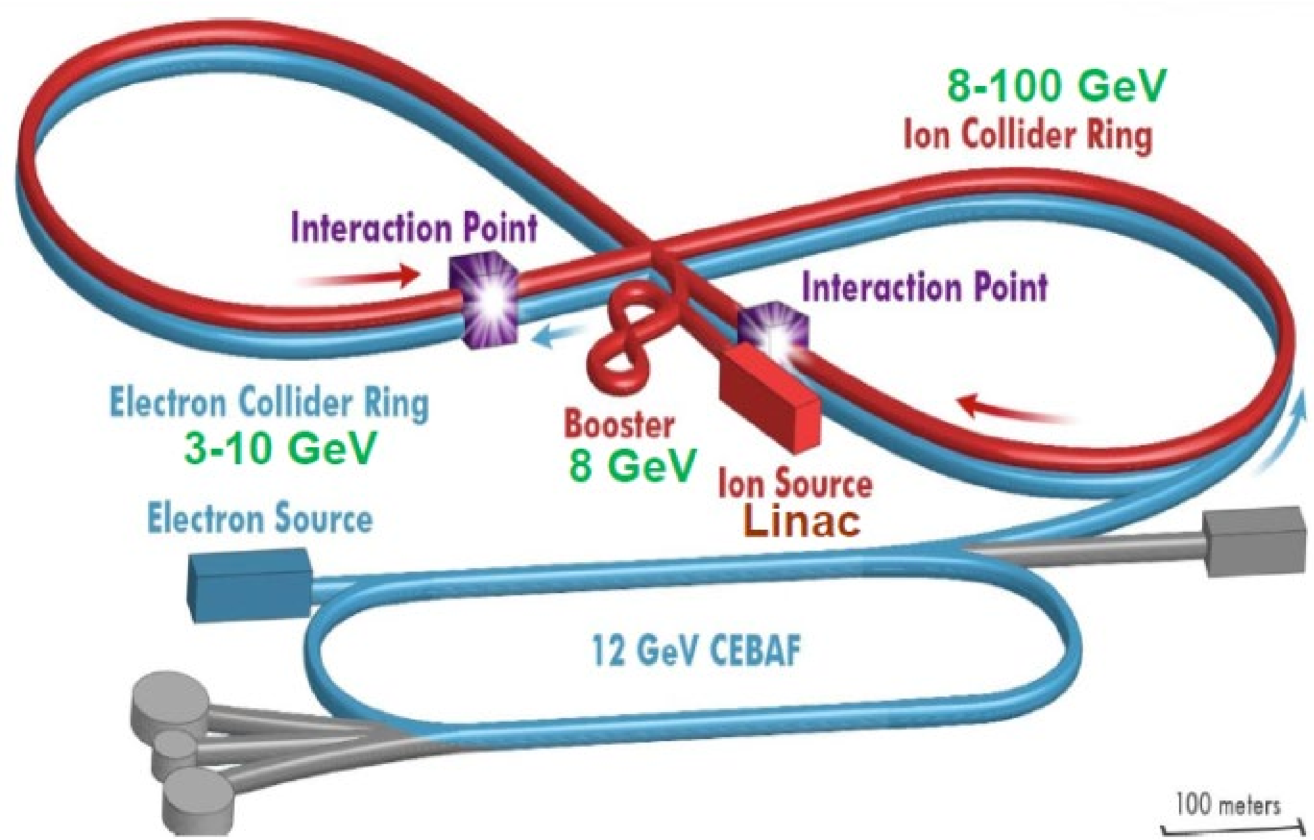
JLEIC

Has an **electron machine** (CEBAF)
Needs a **proton/ion ring**



Possible timeline: **2019** – Mission need (CD-0)
2021 – Site selection
2022 – Start of construction
2030 – First beam collision

The Jefferson Lab EIC (JLEIC) Concept



- ✓ Pulsed SC Linac up to 280 MeV p - 100 MeV/u Pb
- ✓ 8 GeV Booster followed by 100 GeV ion Collider Ring
- ✓ CEBAF is full energy injector for the e Collider Ring
- ✓ All rings are figure-8 to preserve spin polarization

JLEIC Injector Ion Linac: Design Requirements

- ❑ Capable of accelerating all beams: protons to lead ions – polarized / un-polarized light ions and un-polarized heavy ions
- ❑ Baseline Design energy: p - 280 MeV / Pb - 100 MeV/u
- ❑ Pulsed Linac: up to 10 Hz and 0.5 ms pulse length
- ❑ Pulse Current: ~ 2 mA Light ions / ~ 0.5 mA Heavy ions
- ❑ Pulse Length: ~ 0.5 ms Light ions / ~ 0.25 ms Heavy ions
- ❑ Compact and Cost-efficient …

JLEIC Linac - Design Choices

Different Ion Source Parameters → Separate RFQs

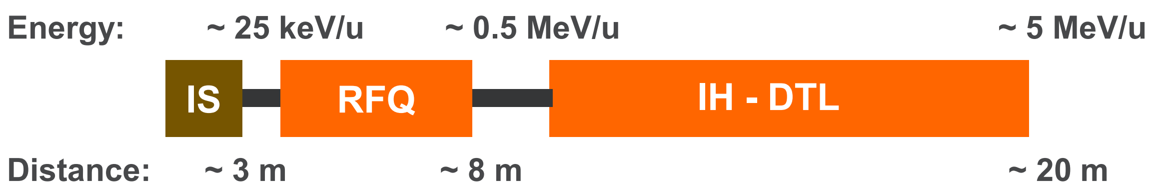
Ions	A / Z	Source	Current, mA	Polarization	Emittance, π·mm·mrad
$^{1}H^{-}$	1	ABPIS / OPPIS	2	> 90%	1.0
$^{2}H^{-}$	2	ABPIS / OPPIS	2	> 90%	2.0
$^{3}He^{2+}$	1.5	EBIS	1	70%	< 1
$^{6}Li^{3+}$	2	ABPIS	0.1	70%	< 1
$^{208}Pb^{30+}$	~ 7	ECR	0.5	0	0.5

- Light ions
  - Large emittance of polarized beams requiring **larger acceptance**
  - **Minimum losses** for deuteron beam to avoid activation
- Heavy ions
  - Heaviest ions (A/q ~ 7) define the RFQ acceptance, Not sufficient for polarized light ions

➢ Two separate RFQs: One for A/q ≤ 2, another for A/q > 2

RT Section to ~ 5 MeV/u – followed by SRF Linac

- RT front-end up to ~ 5 MeV/u → Most efficient and cost-effective option for pulsed linacs, ex: CERN Lead linac and BNL EBIS injector

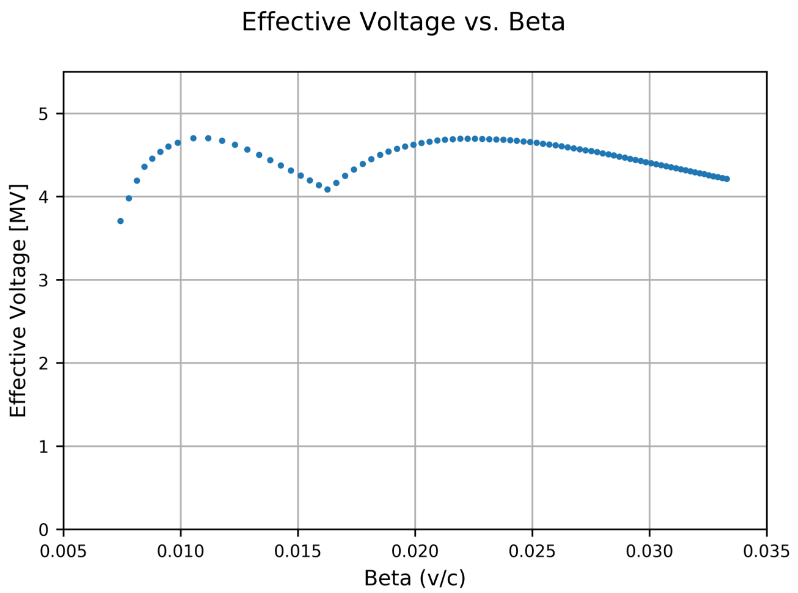


- SRF Linac to full energy
  - Larger acceptance & more flexibility for light and heavy ion beams
  - More compact and cost-effective than the full RT or full SC options (Ref. P. Ostroumov, MEIC meeting 2015; R. York, JLEIC meeting 2016)
  - Take advantage of state-of-the-art performance of QWRs and HWRs
  - Pulsed SRF cavities can run higher voltage → Shorter linac
  - Pulsed RF power is not as expensive as CW

SRF Linac & Stripper Section

➢ Stripping at 13 MeV/u to get Pb^{67+} for Injection to the Booster

- ❑ Pb @ 13 MeV/u: 30+ → 67+, ~ 20% stripping efficiency
- ❑ SRF section made of 3 QWR modules and 9 HWR modules
- ❑ Each module is made of 7 cavities and 4 superconducting solenoids
- ❑ QWR and HWR operated at 4.7 MV



➢ One type of HWR covers the whole velocity range, β: 0.15 – 0.35

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Linac Sections Design

Ion Sources

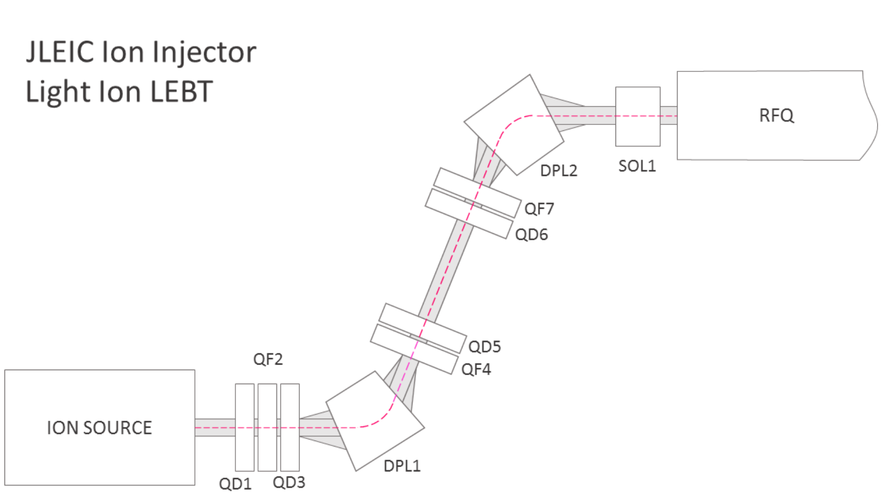
- Polarized Light Ions: Desired vs. Available H-/D- beams (A. Sy & V. Dudnikov)

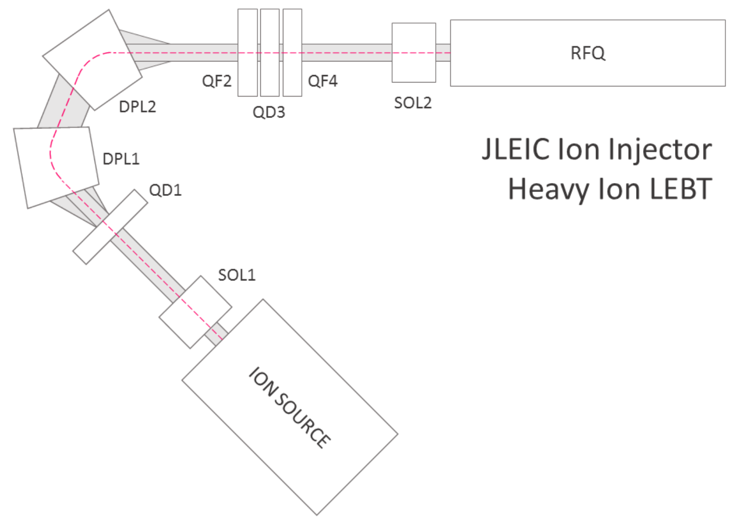
	(units)	Desired value	ABPIS[+]	OPPIS*
Charge state		H-/D-	H-/D-	H-/D-
Pulse current	mA	2	3.8	4 (0.7)
Pulse length	ms	0.5	0.17	(0.3)
Polarization	%	100	91	85

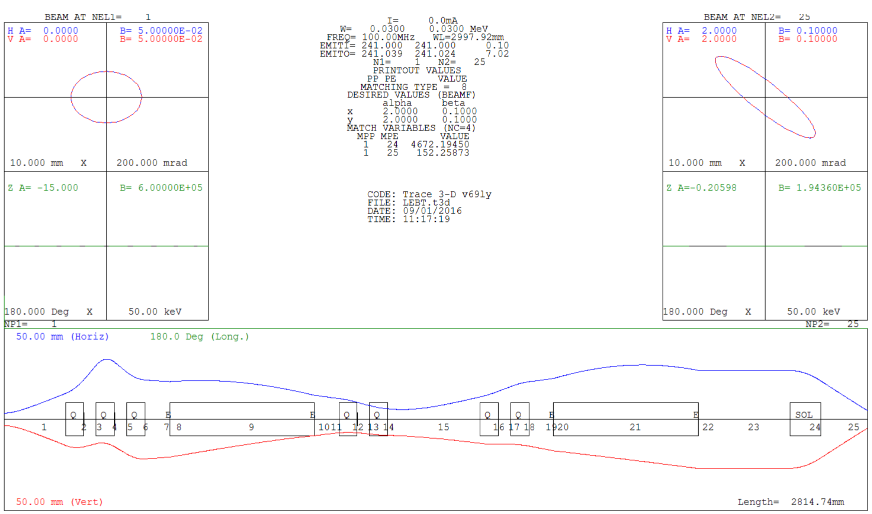
- Heavy ions: ECR + Chopper or pulsed EBIS may be used

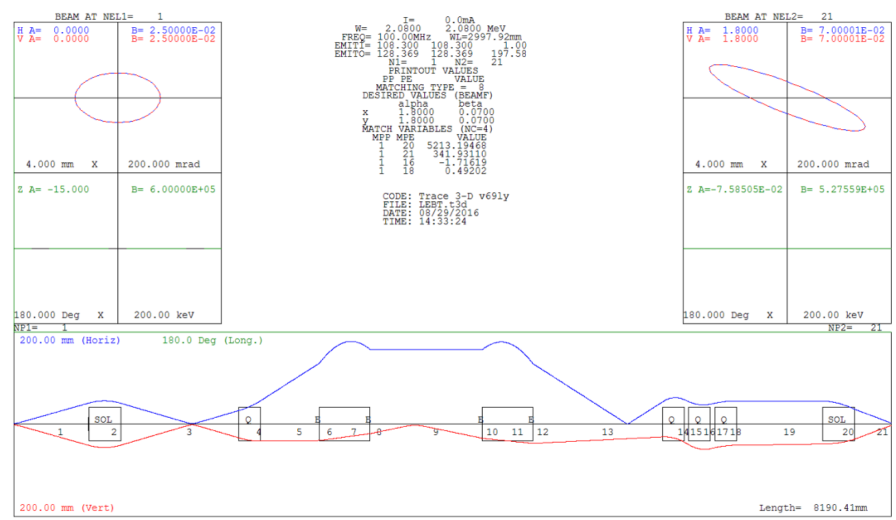
Ions	A / Q	Source	Current, mA	Emittance, π·mm·mrad
$^{208}Pb^{30+}$	~ 7	ECR	0.5	0.5

Light and Heavy Ions LEBTs





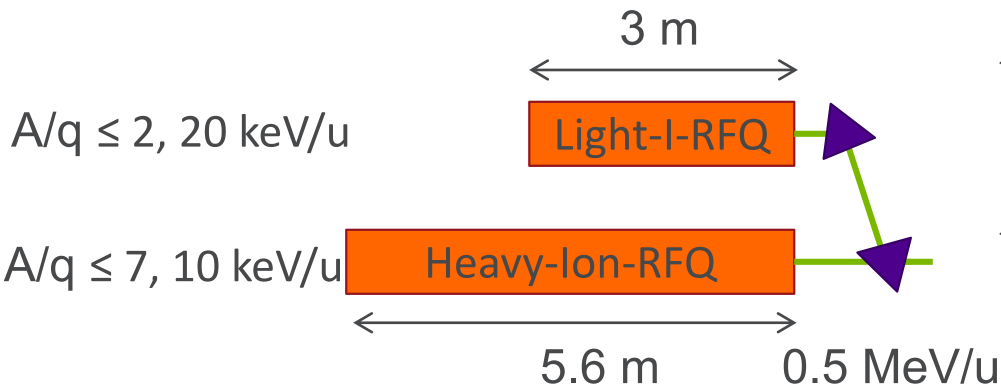




Similar to BNL LEBT

Similar to CERN Linac3 LEBT

Light and Heavy Ions RFQs

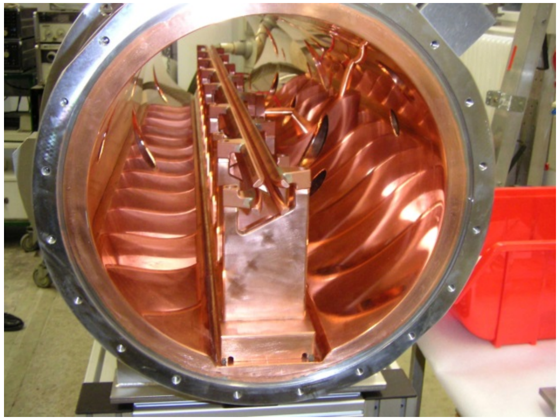


- ✓ Light-Ion RFQ is designed for polarized beams with **2 π** mm mrad normalized transverse emittance
- ✓ Heavy-Ion RFQ is designed for ion with A/q ≤ 7 with **0.5 π** mm mrad normalized transverse emittance

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	3.0	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

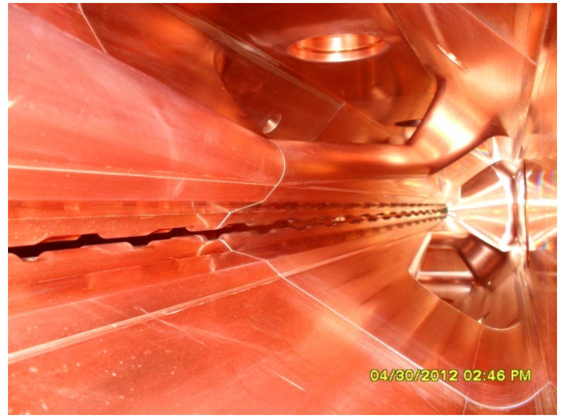
Options for RFQ Structure

4-Rod | 4-Vane window coupled | 4-Vane



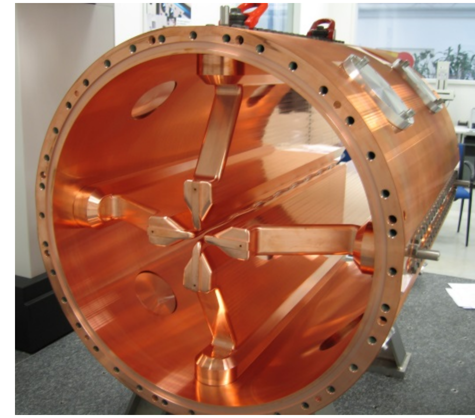
RIKEN RFQ

High power consumption



ATLAS RFQ

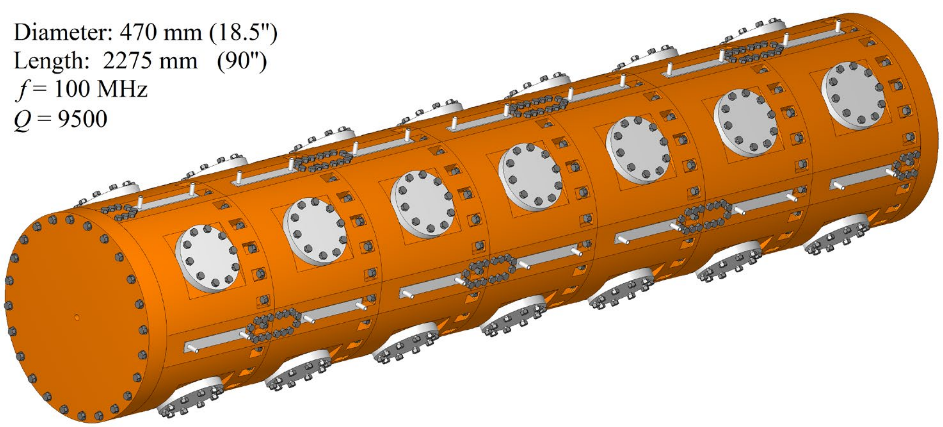
Flexible design

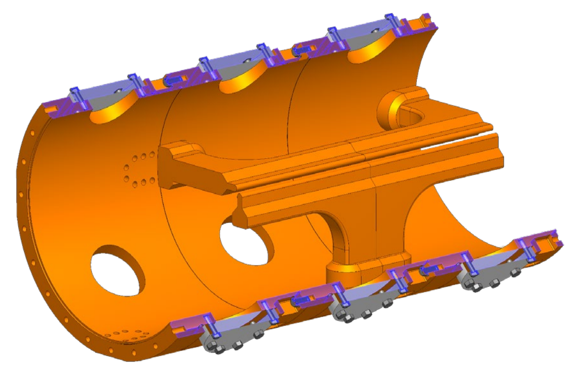


SPIRAL-2 RFQ

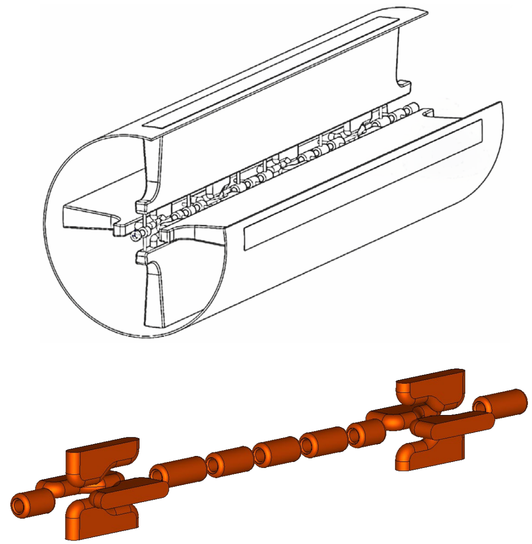
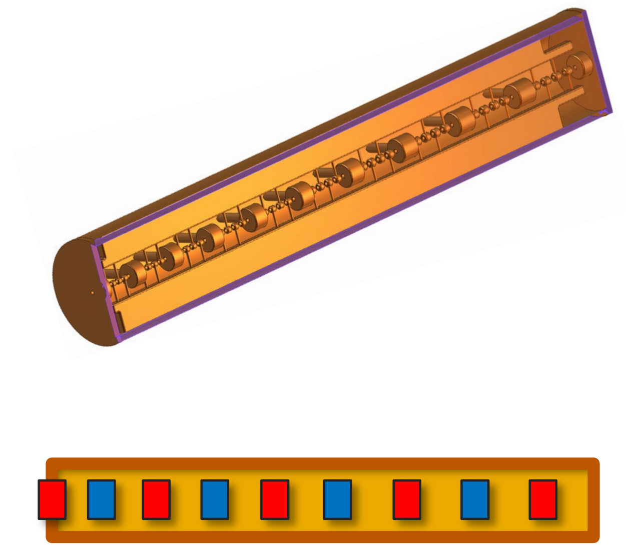
Large diameter

➢ 4-vane bolted or brazed structure with windows or not …





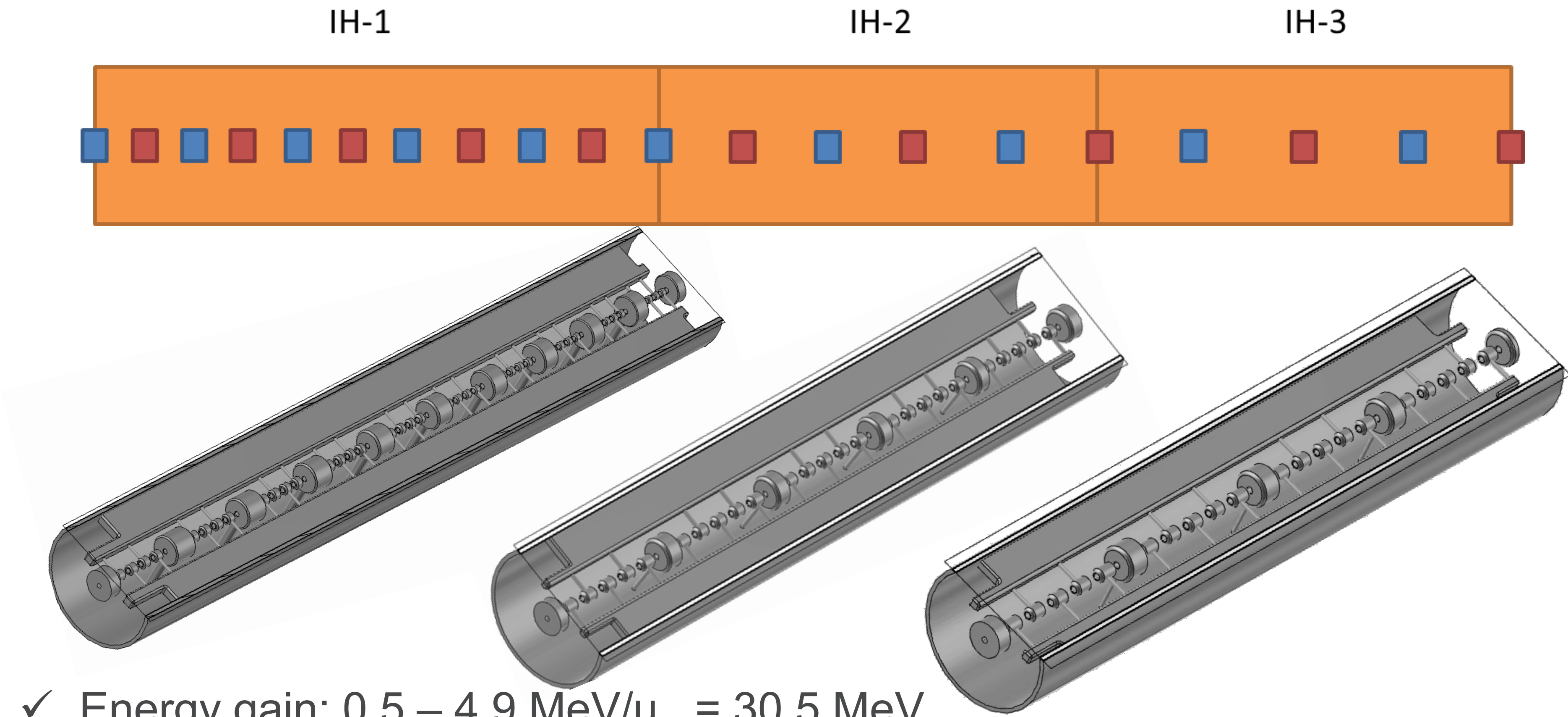
Options for IH Structure

	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

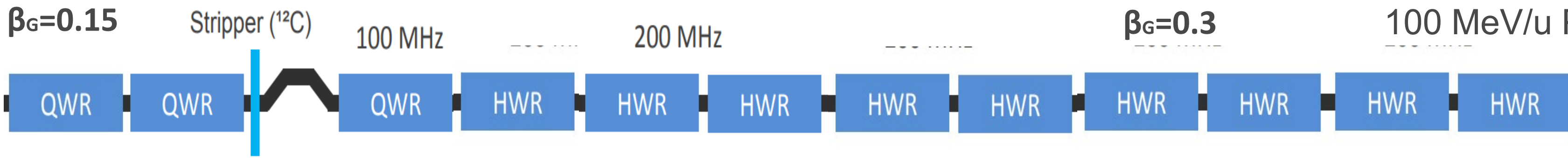
- ✓ 3 Tanks – 20 Quadrupoles in FODO arrangements



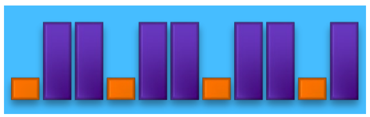
- ✓ Energy gain: 0.5 – 4.9 MeV/u = 30.5 MeV
- ✓ Total length: 4.3 + 3.5 + 3.4 m = 11.2 m
- ✓ Real-estate accelerating gradient: 2.72 MV/m
- ✓ RF Power losses: 280 + 400 + 620 = 1.3 MW

SRF Section: QWR & HWR Design Parameters

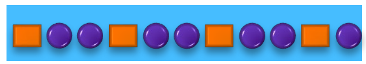
280 MeV protons
100 MeV/u Pb



QWR Module



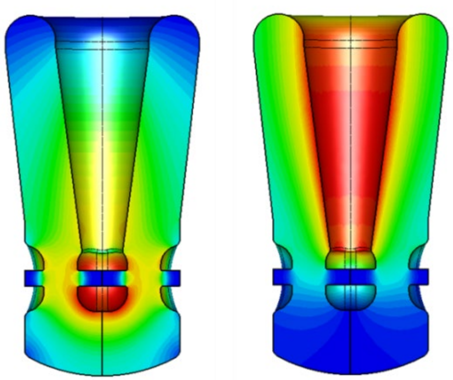
HWR Module



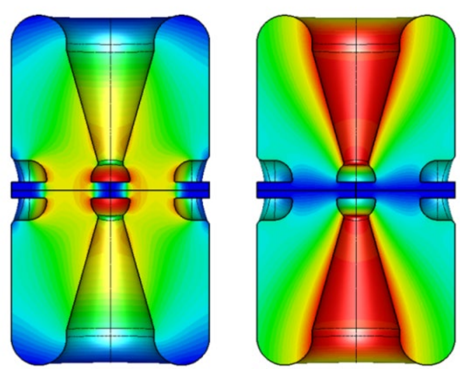
Horizonal orientation of cavities

Stripping @ 13 MeV/u, Pb: 30+ → 67+

QWR Design



HWR Design

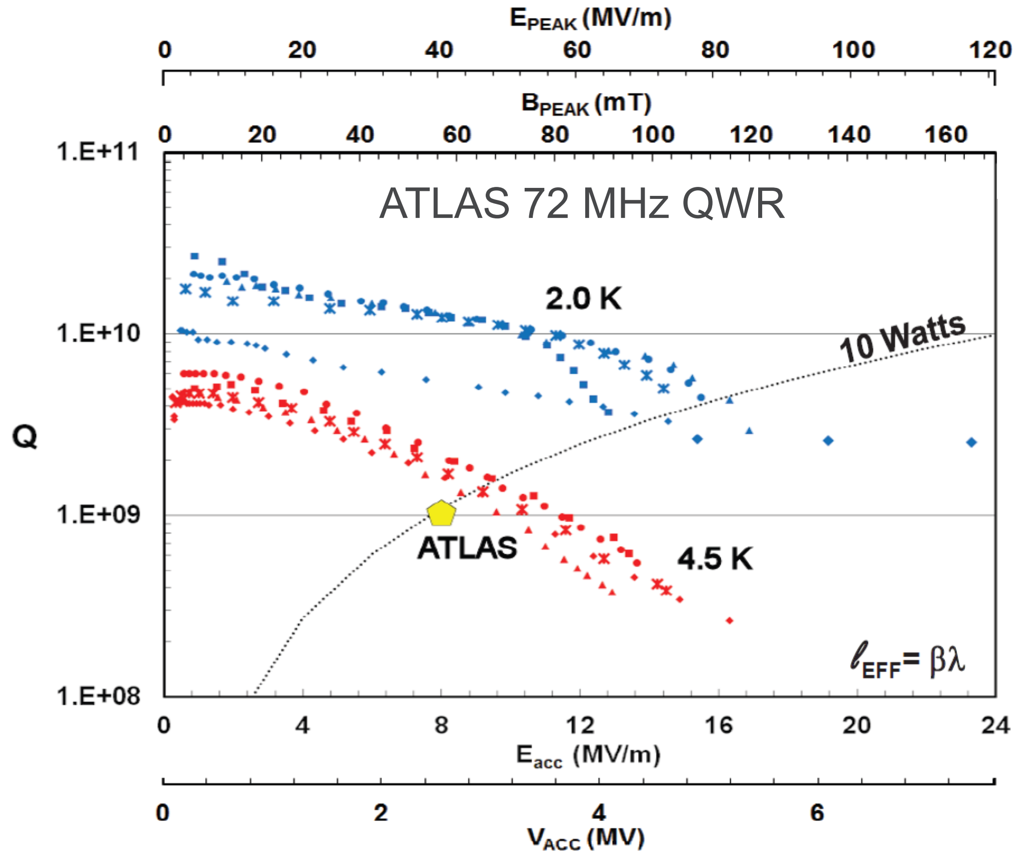


Parameter	QWR	HWR	Units
β_{opt}	0.15	0.30	
Frequency	100	200	MHz
Length (βλ)	45	45	cm
E_{PEAK}/E_{ACC}	5.5	4.9	
B_{PEAK}/E_{ACC}	8.2	6.9	mT/(MV/m)
R/Q	475	256	Ω
G	42	84	Ω
E_{PEAK} in operation	**57.8**	**51.5**	**MV/m**
B_{PEAK} in operation	**86.1**	**72.5**	**mT**
E_{ACC}	**10.5**	**10.5**	**MV/m**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

High-Performance QWRs Developed at ANL for ATLAS

ATLAS
72 MHz QWR

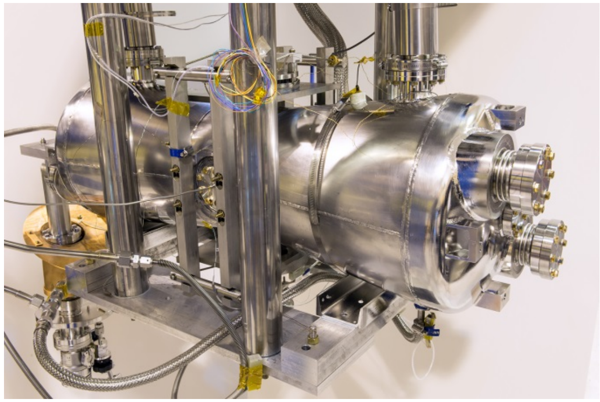
SC section will operate at 4.5K in pulsed mode



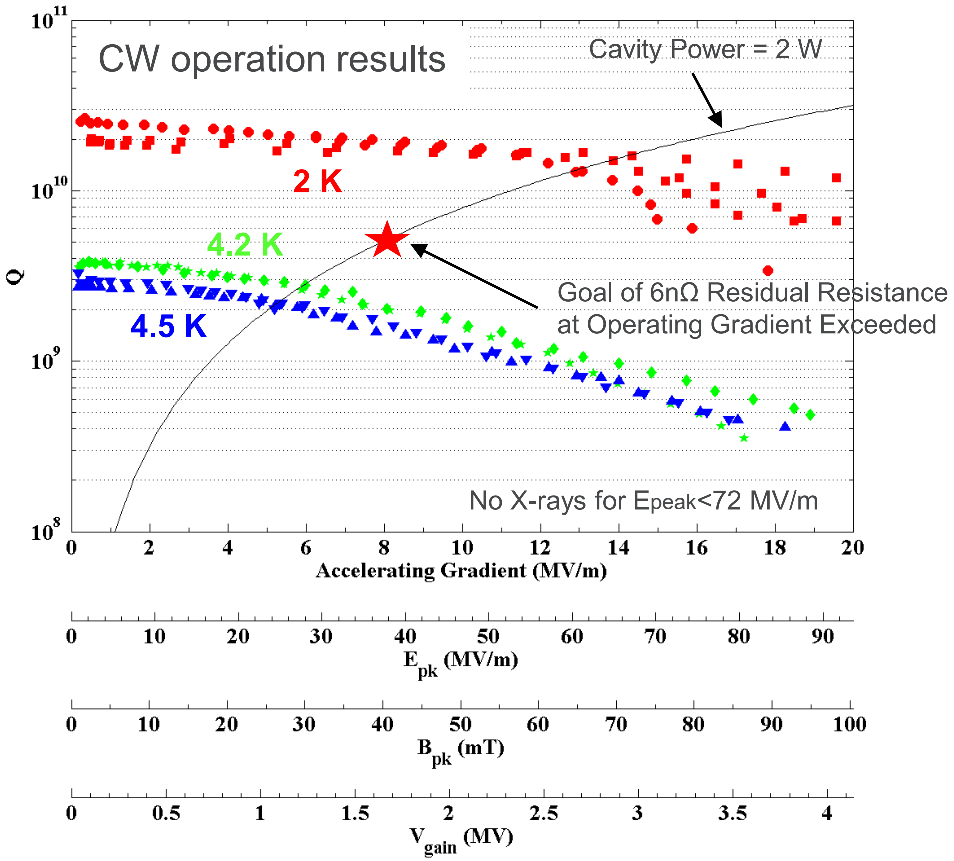
- ✓ CW mode: A 72 MHz β=0.07 QWR can deliver 4 MV voltage (E_{peak}~64 MV/m, B_{peak}~90 mT)
- ✓ JLEIC: Pulsed operation of 100 MHz β=0.15 QWRs @ 4.7 MV per cavity (5.5 MV possible)

High-Performance HWRs Developed at ANL for PXIE

FNAL - 162 MHz HWR



SC section will operate at 4.5K in pulsed mode

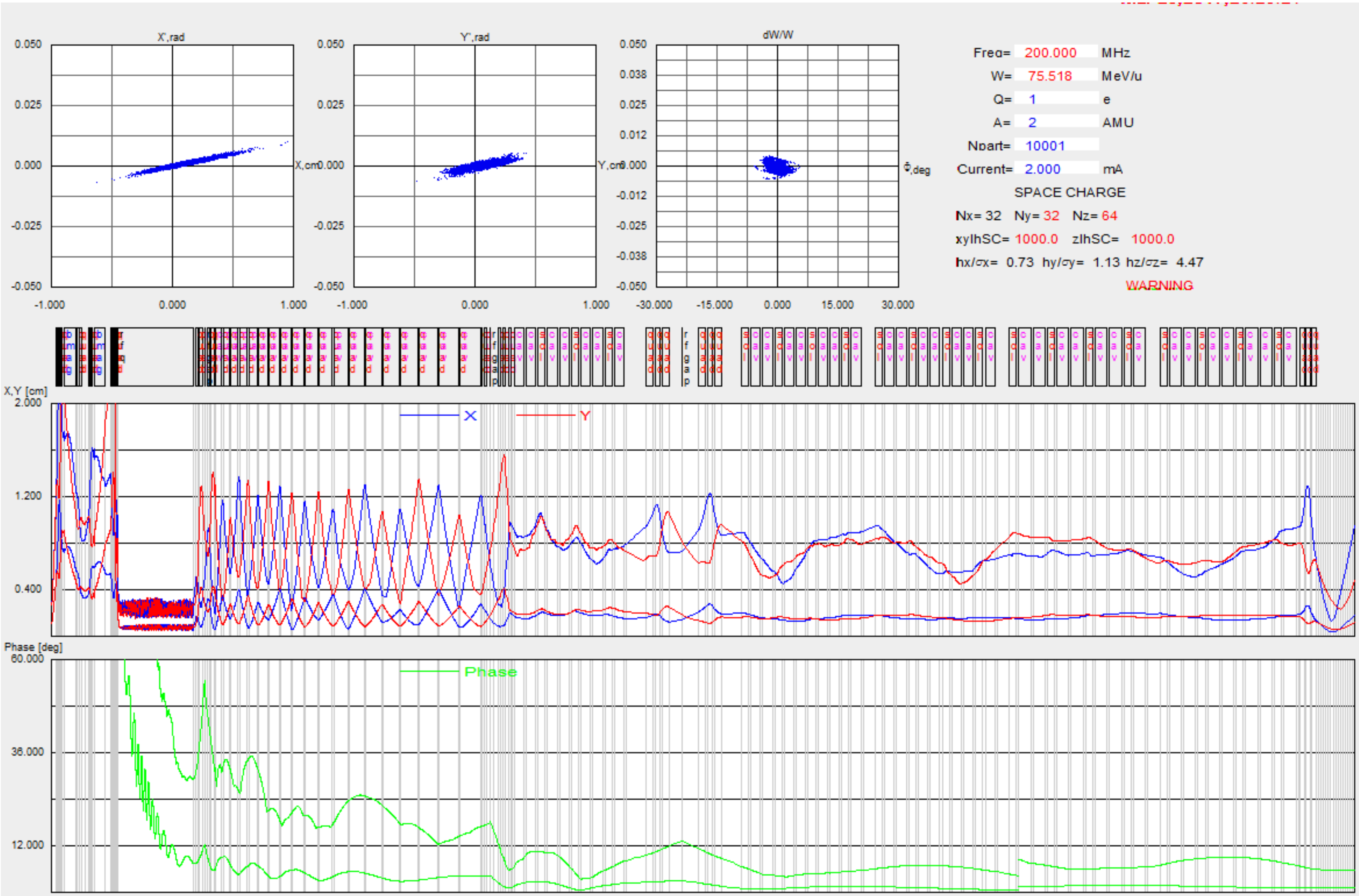


- ✓ CW mode: A 162 MHz β=0.11 HWR can deliver 3 MV voltage (E_{peak}~68 MV/m, B_{peak}~72 mT)
- ✓ JLEIC: Pulsed operation of 200 MHz β=0.3 HWRs @ 4.7 MV per cavity (6.6 MV possible)

End-to-End Beam Simulations

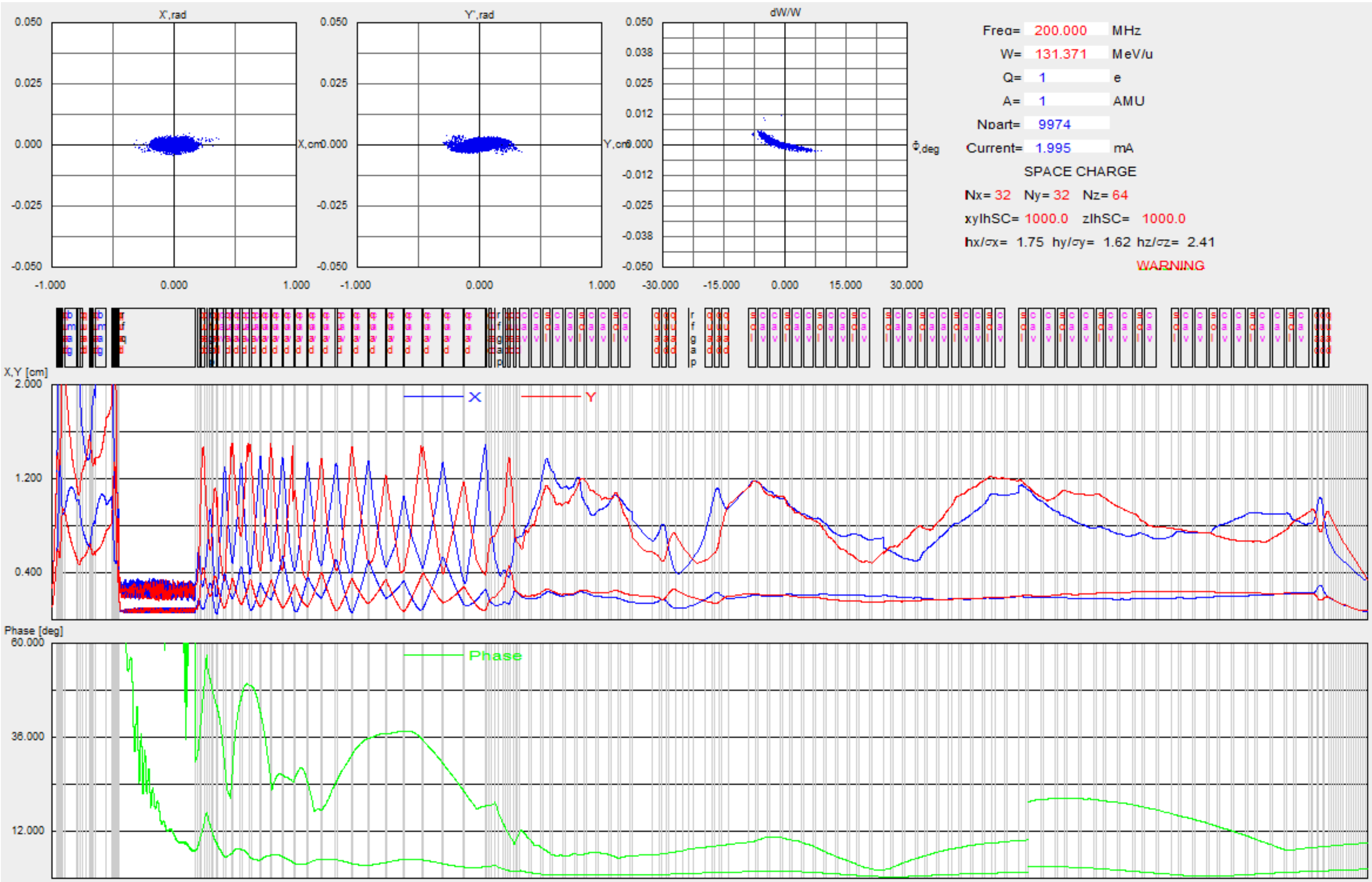
(Short Linac Option)

End-to-end Simulation of a 2 mA Deuteron beam



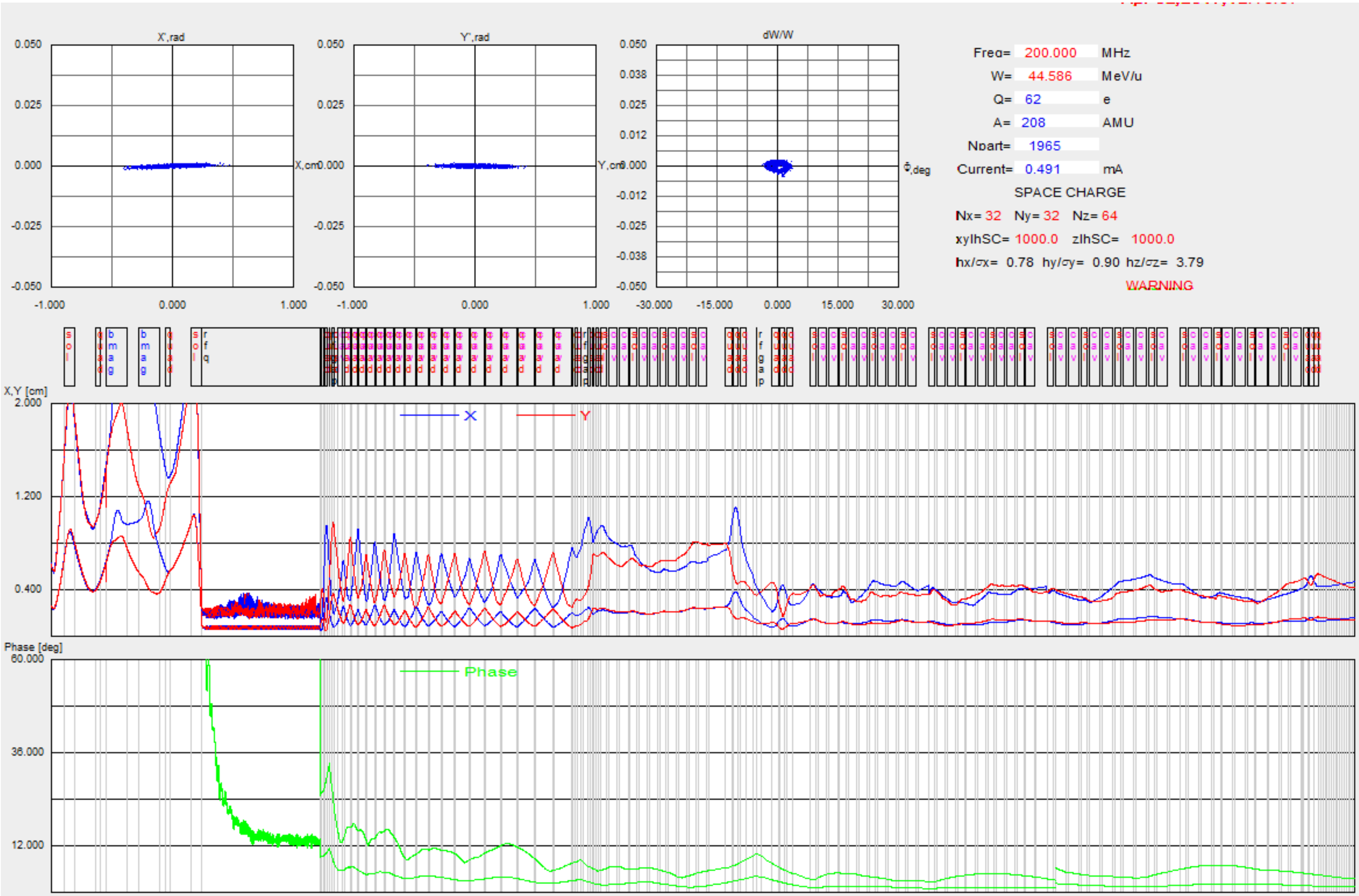
No beam loss over the whole linac (10k particles) – Important to avoid activation

End-to-end Simulation of a 2 mA Proton beam



Some beam loss in the RFQ - normal

End-to-end Simulation of a 0.5 mA Lead beam



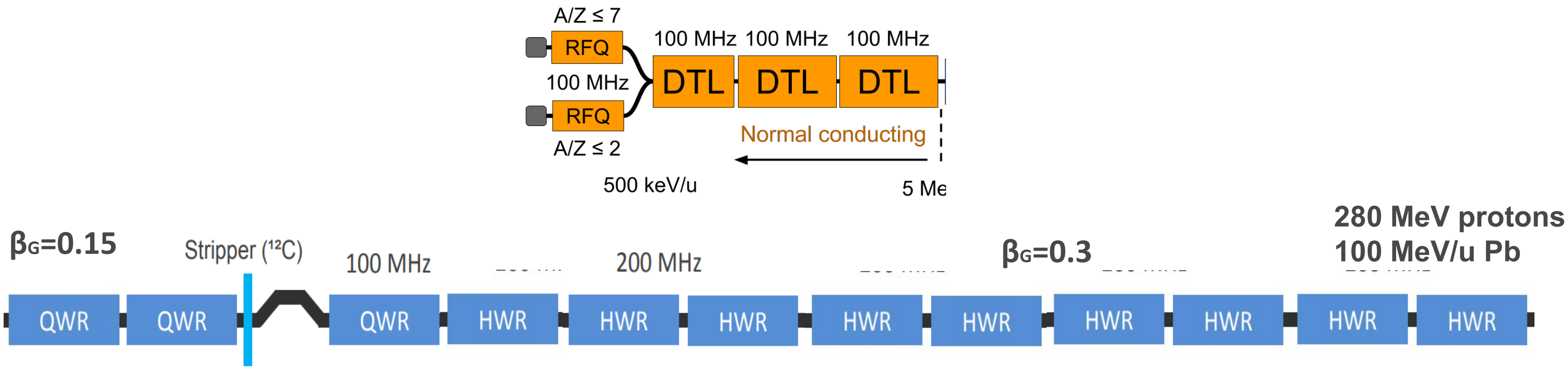
Some beam loss in the RFQ …

Output Beam Parameters

Parameter	Units	H-	D-	Pb67+
Energy	MeV/u	131	75.5	44.5
Transmission	%	99.7	100%	98.3
Norm. transverse emittance (90%)	π·mm·mrad	2.3	1.3	0.8
Norm. longitudinal emittance (90%)	π·ns·keV/u	8.8	7.1	4.6
Energy spread (rms)	%	0.13	0.12	0.1

- ✓ Beam dynamics is being optimized, especially for light ions …
- ✓ Stripper effect is being included for the heavy ions …

JLEIC Linac Design – Summary



- Separate LEBTs and MEBTs for light and heavy ions
- Two RFQs: One for light ions (A/q ~ 2) and one for heavy ions (A/q ~ 7)
  - Different emittances and voltage requirements for polarized light ions and heavy ions
- RT Structure: IH-DTL with FODO Focusing Lattice
  - FODO focusing → Significantly better beam dynamics
- SRF section made of 3 QWR and 9 HWR modules
- Stripper section for heavy-ions after 2nd QWR module
- Pulsed Linac: up to 10 Hz repetition rate and ~ 0.5 ms pulse length

Thank you!