Detailed Beam Dynamics Studies for an SRF-Based Multi-Ion Injector Linac

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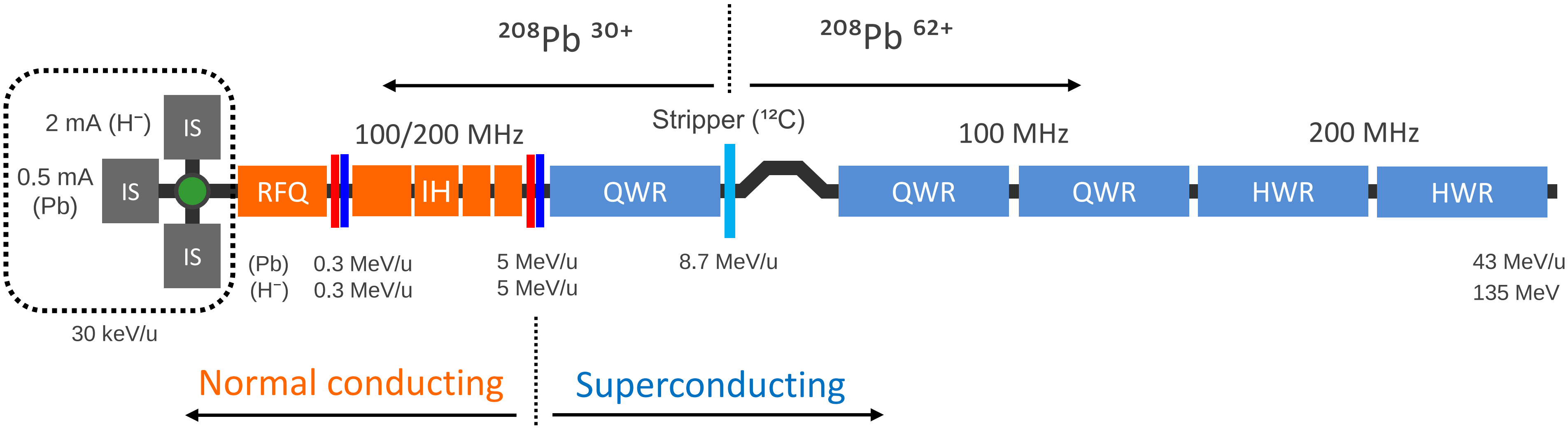
JLEIC Collaboration Meeting
JLab, March 31, 2016

Outline

- JLEIC Injector Linac Layout
- Design of Key Linac Components
  - Normal Conducting RFQ
  - IH Structure / RF Focusing Structure
  - High Performance Superconducting QWRs and HWRs
- Optimized Stripping Energy & Charge State
- End-to-End Beam Dynamics & Linac Output Beam Parameters
- Layout of Ion Accelerator Complex
- Tools for End-to-End Beam Simulations of JLEIC Ion Complex
- Summary & Future Work

New Compact Linac Design: Layout & Key Components

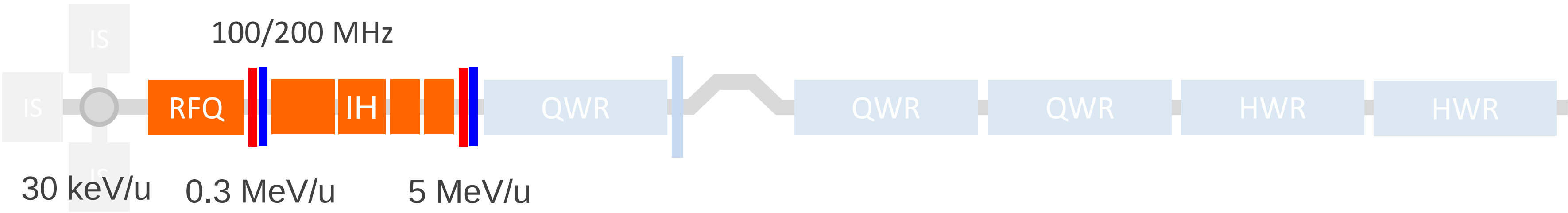


QWR

HWR

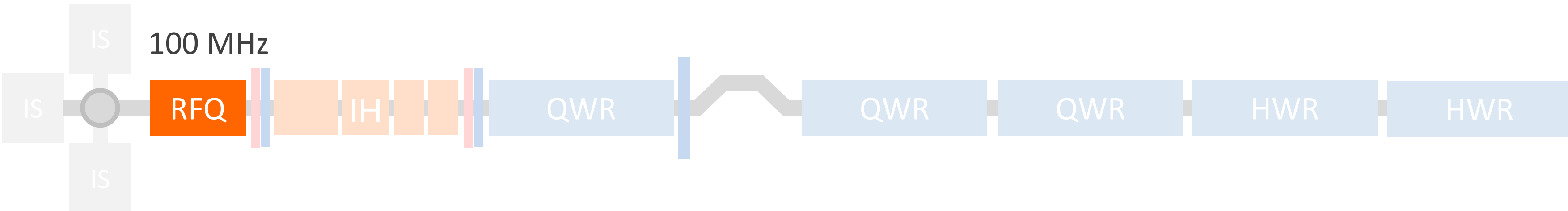
Horizonal orientation of cavities

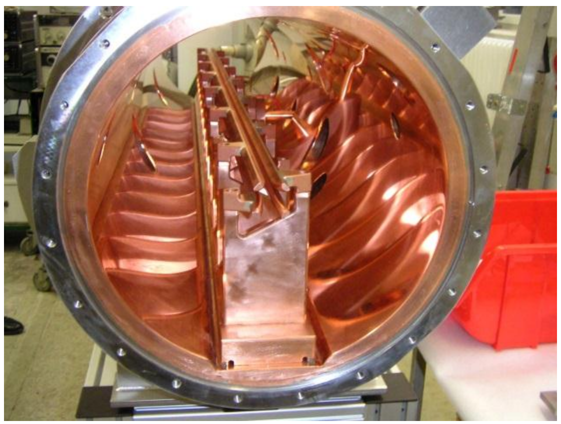
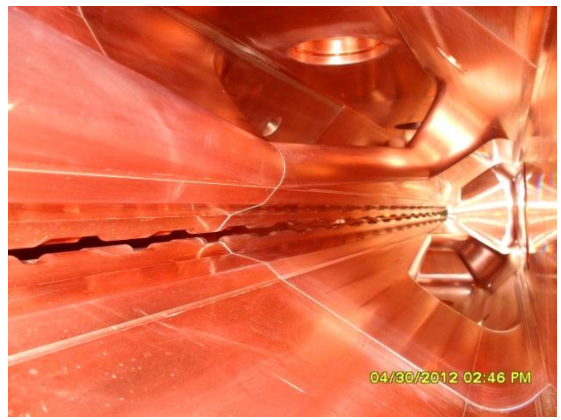
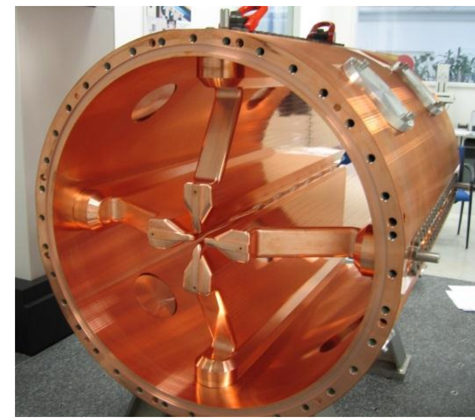
- A stripper for heavy ions for more effective acceleration: $Pb^{30+ \rightarrow 62+}$
  - An option of stripping to Pb^{67+} is also investigated
  - H^{-} and light ions will be polarized
- Repetition rate: 10 Hz (Pb) and 5 Hz (H^{-})
- Total linac length is ~ 50 m


100/200 MHz
IS
IS
RFQ
IH
QWR
QWR
QWR
HWR
HWR
30 keV/u
0.3 MeV/u
5 MeV/u

RT section

Normal Conducting Front-End: RFQ



4-rod	✓ 4-vane with coupling windows	4-vane
		
RIKEN RFQ	ATLAS RFQ	SPIRAL-2 RFQ
High power consumption	Flexible design	Large diameter

Maximum A/Q:	~ 7
Frequency:	100 MHz
Energy:	30 – 300 keV/u
Voltage:	70 kV
Average radius:	3.6 mm
Length:	3 m
Power consumption:	100 kW

Examples of Operating 4-vane Window-Coupled RFQs

The structure is proven by operation of several linacs:

ATLAS CW RFQ, 60 MHz, A/Q=7 (ANL, USA)

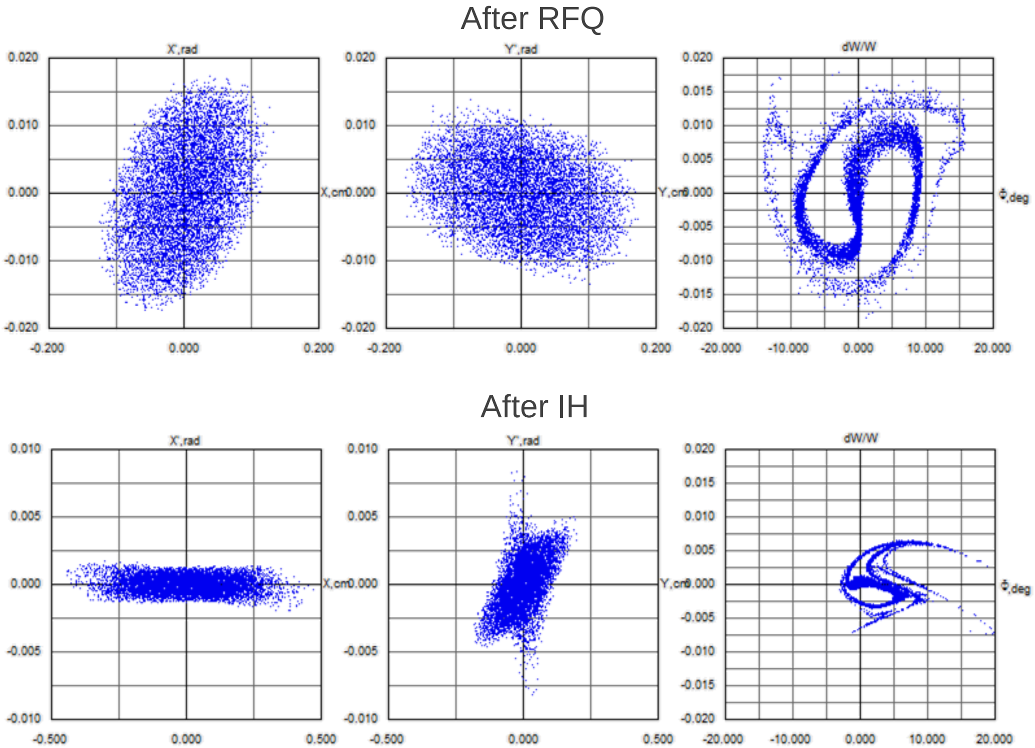
Heavy Ion Prototype, 27 MHz, A/Q=60 (ITEP, Moscow)

Heavy Ion Injector, 81 MHz, A/Q=3 (ITEP, Moscow)

Light Ion Injector, 145 MHz, A/Q=3 (JINR, Dubna)

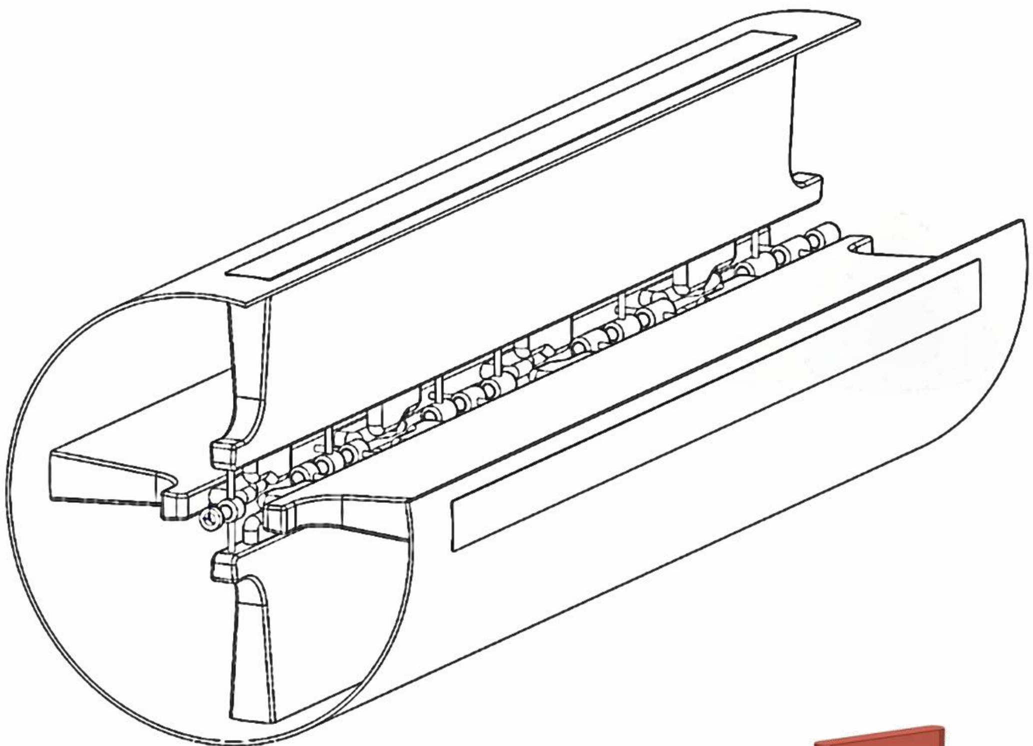
Normal Conducting Front-End: IH Structure

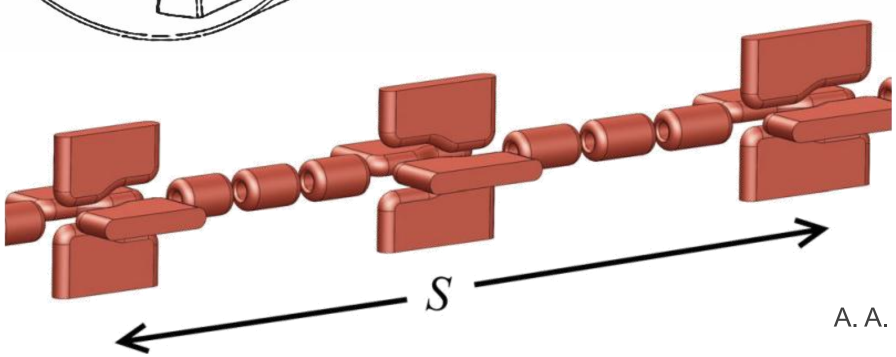
BNL EBIS Injector 100 MHz IH Structure
(Courtesy of J. Alessi)



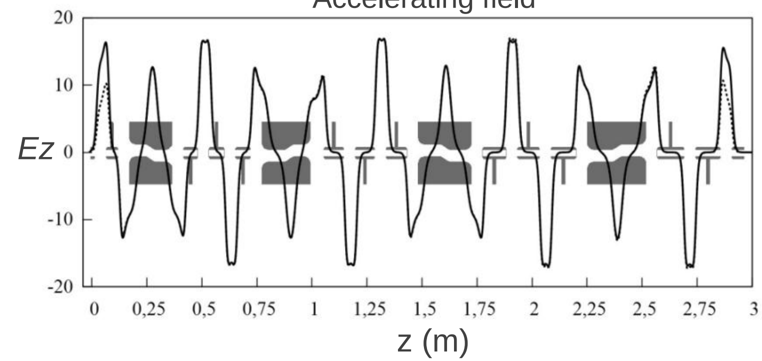
RF Focusing Structure: Alternative Option to IH-DTL

Spatially Periodic RF Quadrupole Linac

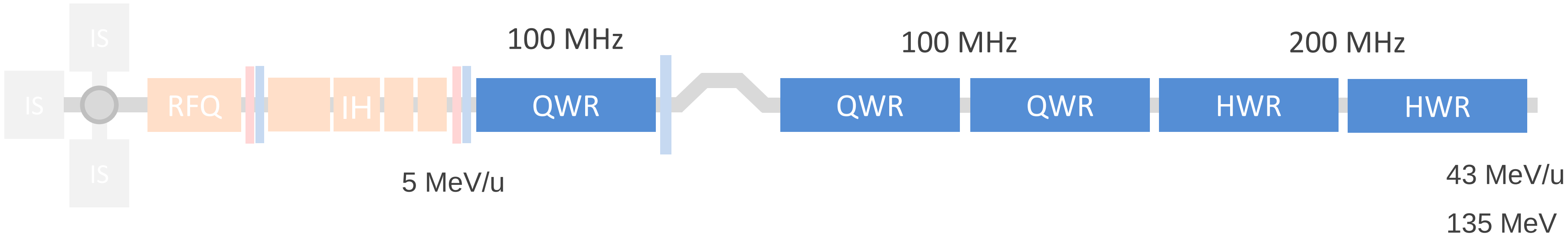




- In this velocity range, focusing by RF fields is very efficient
- Conventional longitudinal beam dynamics can be applied
- Real-estate accelerating gradient can be high as in IH structure
- Beam quality is better than in IH structure
- The resonator is 4-vane type as in a conventional RFQ



Spatially periodic radio-frequency quadrupole focusing linac
A. A. Kolomiets and A. S. Plastun, Phys. Rev. ST Accel. Beams **18**, 120101



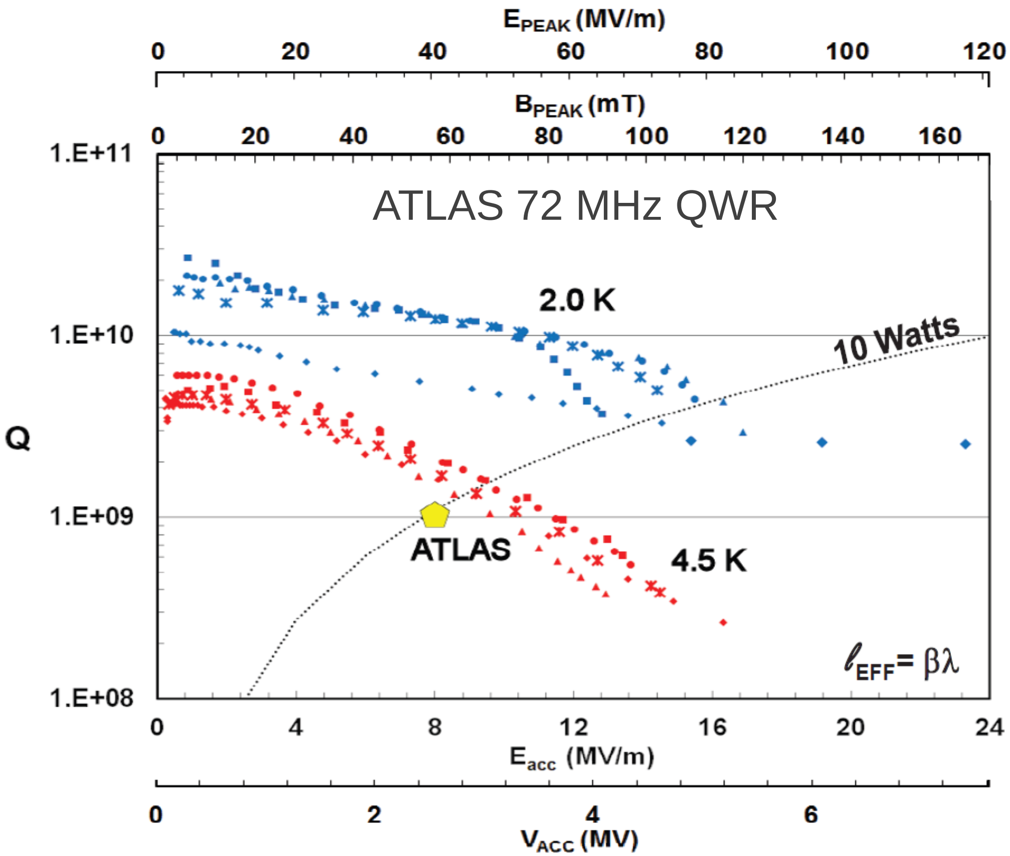
SC section

will operate at 4.5K in pulsed mode

High-Performance QWRs developed at ANL

ATLAS
72 MHz QWR

SC section will operate at 4.5K in pulsed mode

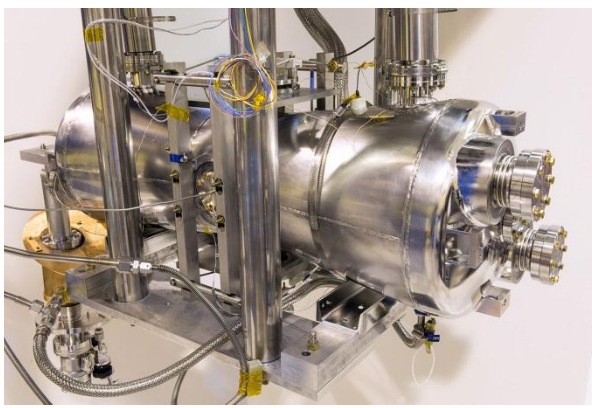


A single 72 MHz β=0.077 QWR is capable of delivering 4 MV voltage @ E_{peak} ~ 64 MV/m and B_{peak} ~ 90 mT in CW mode which corresponds to 5.6 MV @ 100 MHz and βopt = 0.15.

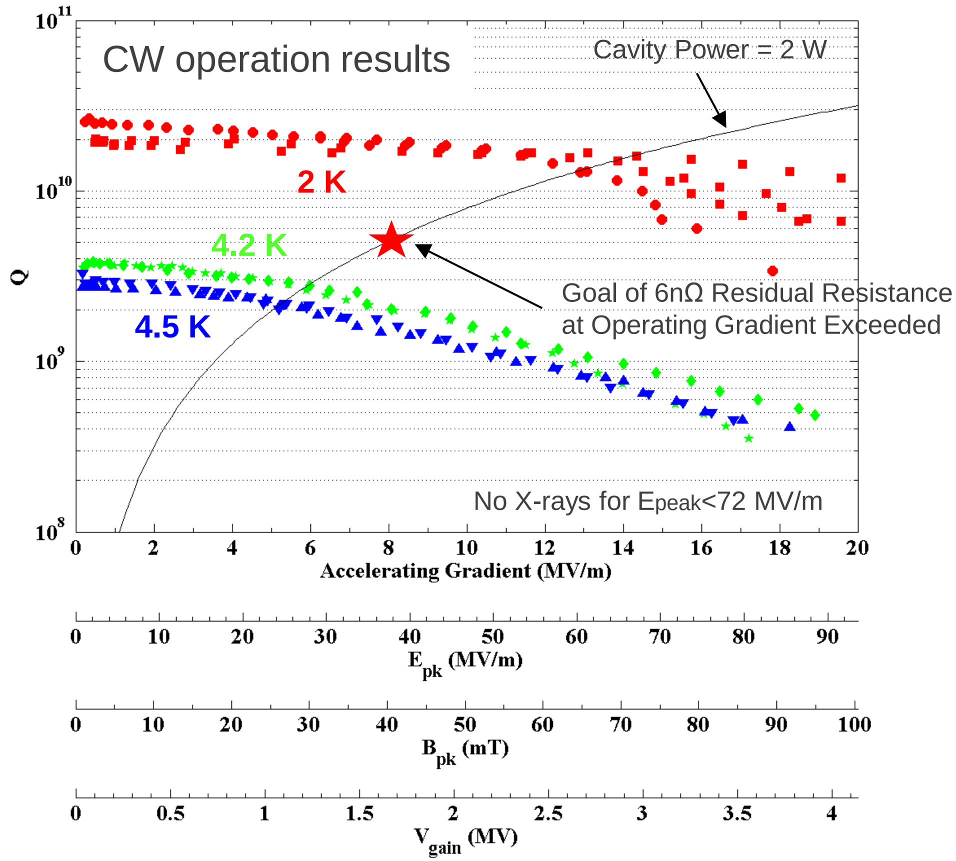
We propose to operate 100 MHz β=0.15 QWRs in pulsed mode to produce 4.7 MV per cavity

High-Performance HWRs developed at ANL

FNAL - 162 MHz HWR



SC section will operate at 4.5K in pulsed mode

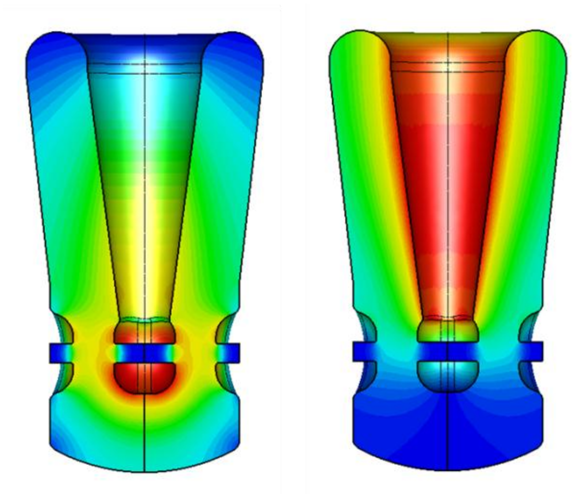


A single 162 MHz β=0.11 HWR is capable of delivering 3 MV voltage @ E_{peak} ~ 68 MV/m and B_{peak} ~ 72 mT in CW mode which corresponds to 6.6 MV @ 200 MHz and βopt = 0.3.

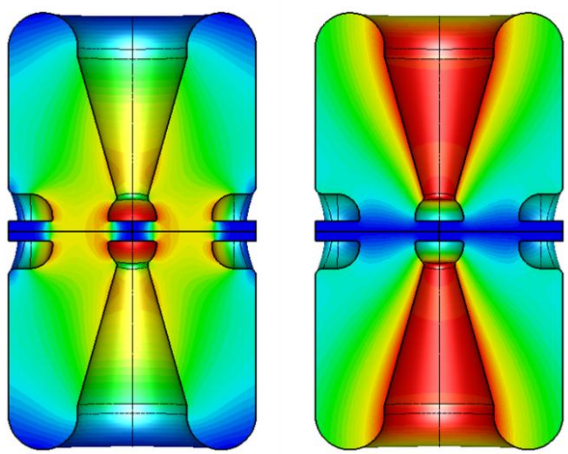
We propose to operate 200 MHz β=0.3 HWRs in pulsed mode to produce 4.7 MV per cavity

Preliminary QWR and HWR Design for JLEIC Linac

JLEIC QWR Design



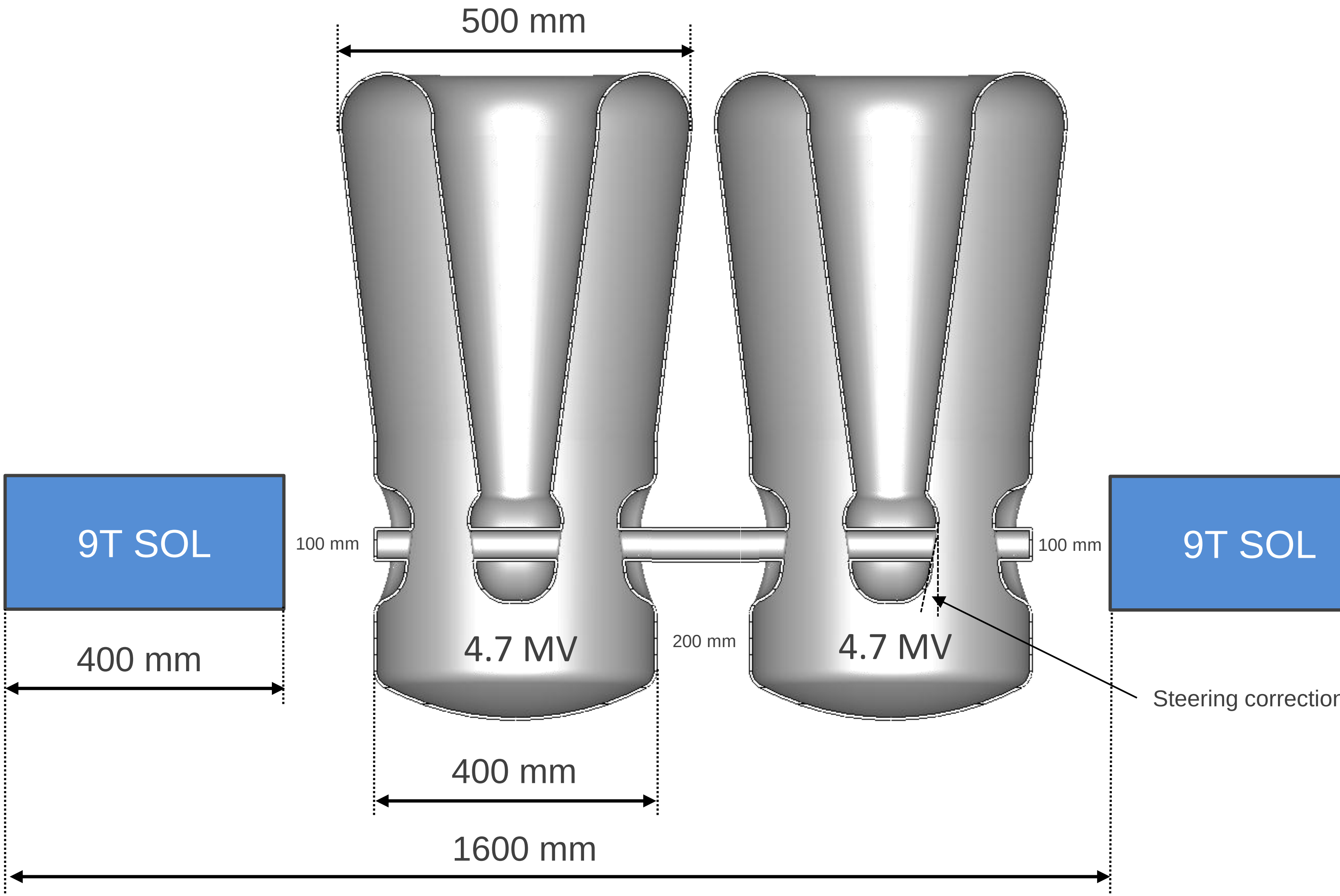
JLEIC HWR Design



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	

Period Structure in SRF Section

QWRs are optimized to compensate beam transverse RF steering by tilting the drift tube faces

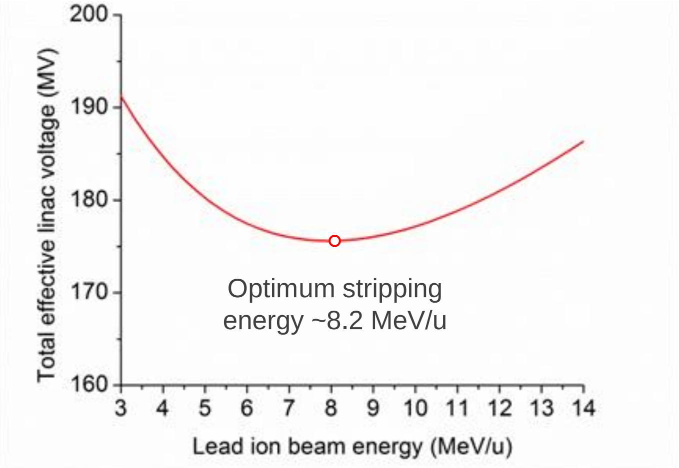


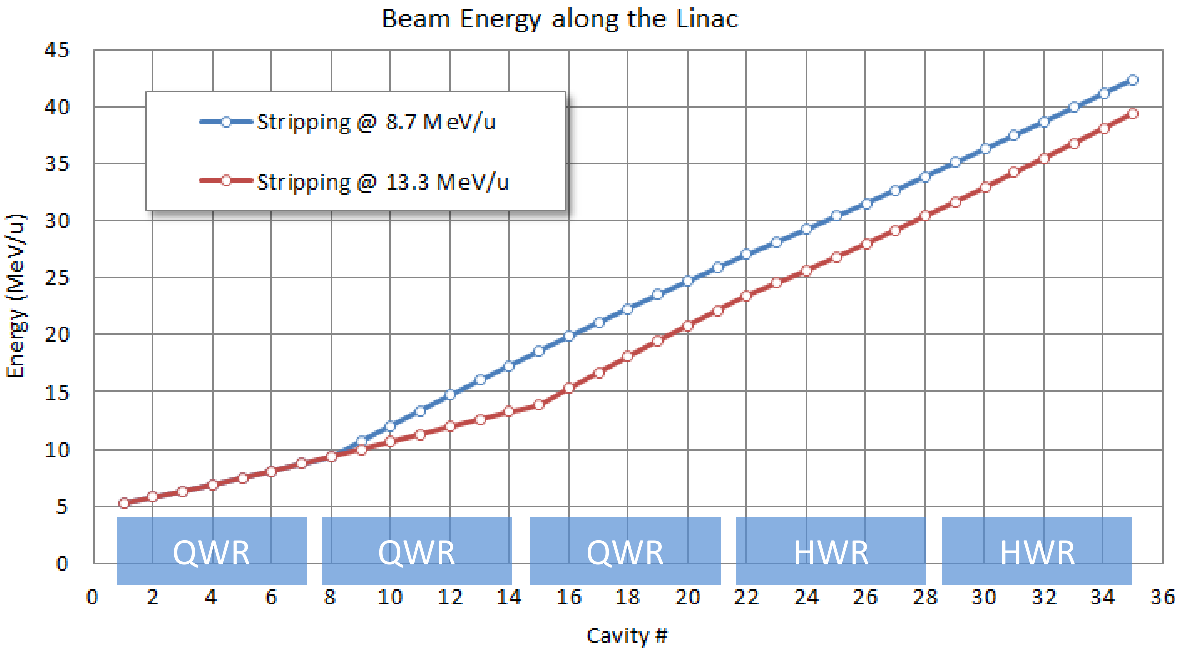
Optimized Stripping Energy & Charge State

Stripping efficiency:
(30+) → (62+) : 17.5% @ 8.7 MeV/u
(30+) → (67+) : 22% @ 13.3 MeV/u

$$U_{total} = \frac{\Delta W_1}{Q_1} + \frac{\Delta W_2}{Q_2}$$

1 – before stripping, 2 – after stripping

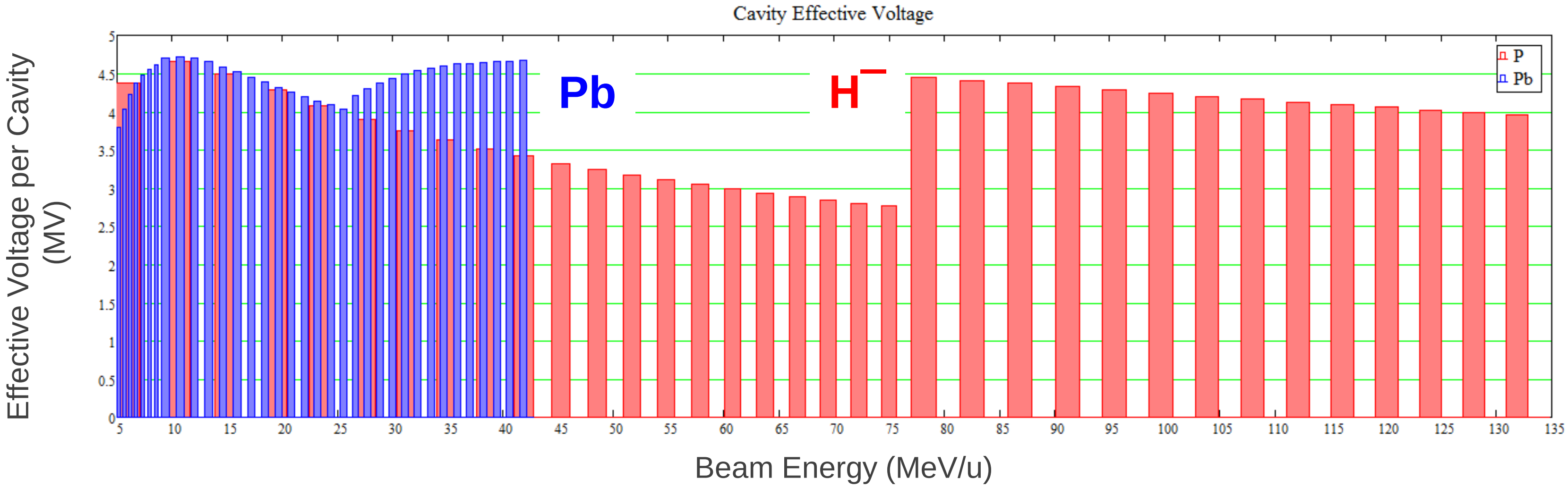




42.4 MeV/u (62+)

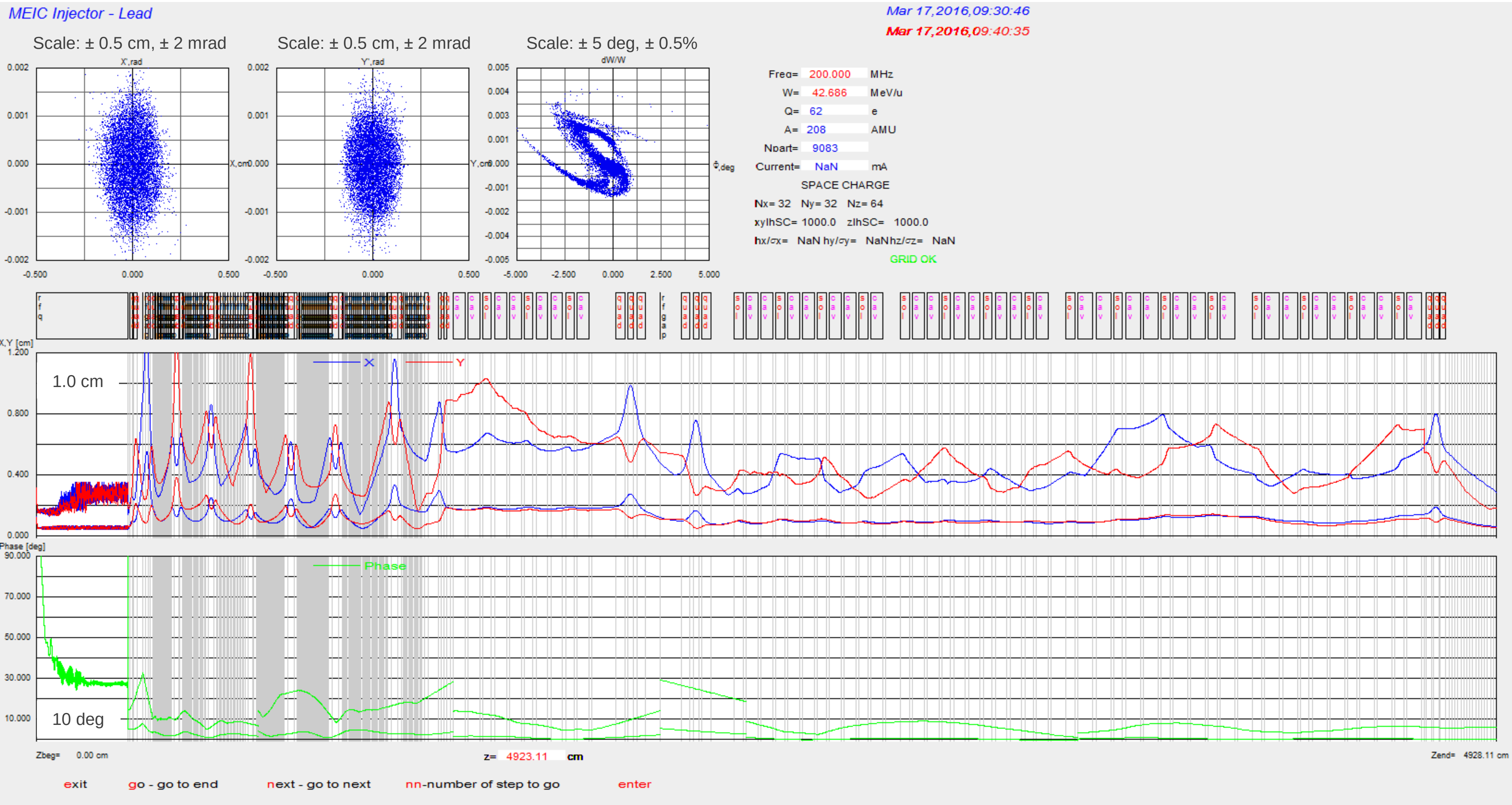
39.4 MeV/u (67+)

Voltage Profile & SRF Performance

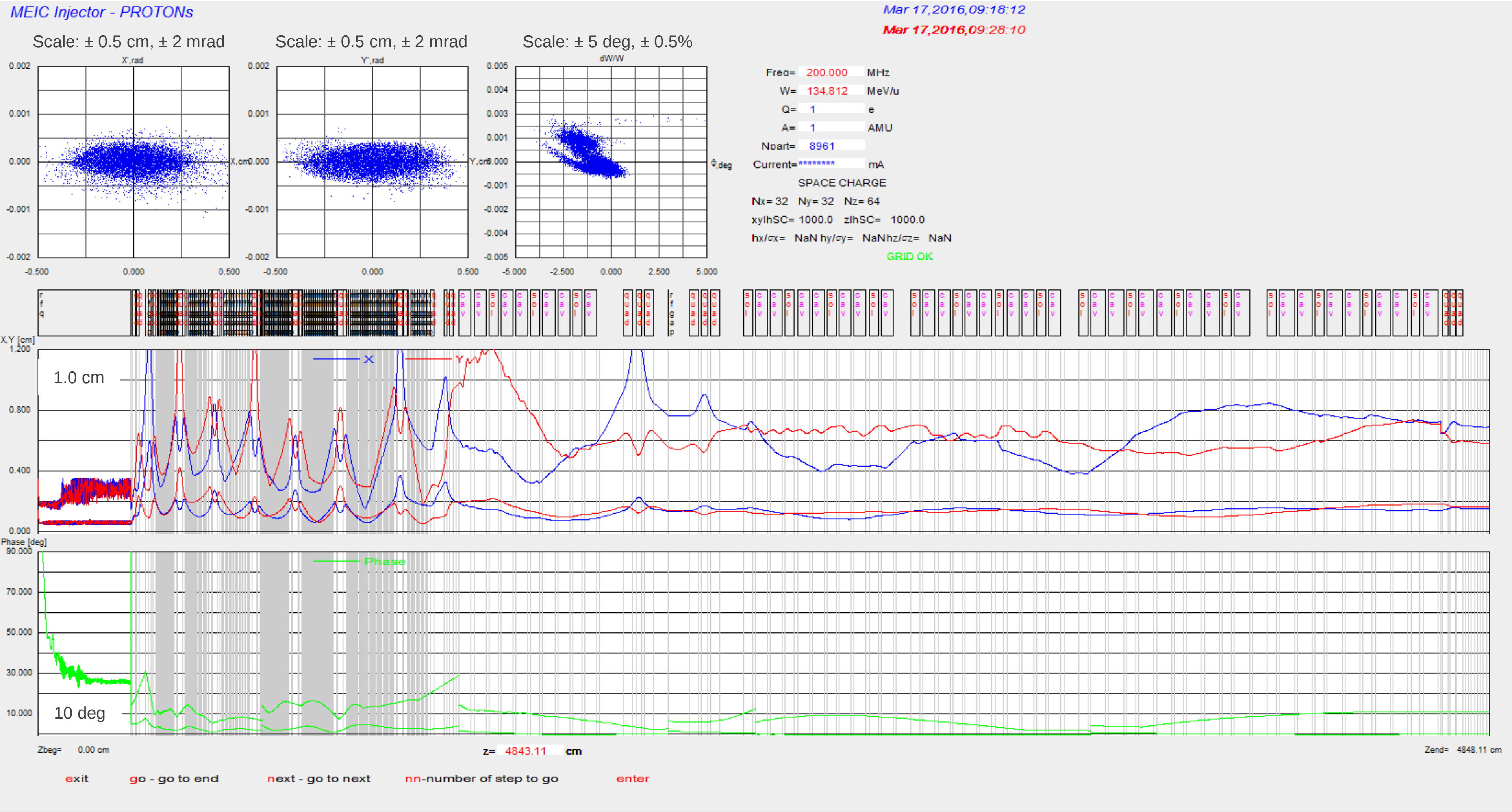


- SC Cavity Voltage profile optimized for both lead ions and protons/H^-
- SC Cavity re-phasing produces much higher energy for protons/H^-
- SC linac will operate in pulsed mode to reduce dynamic cryogenics load
  - 10% duty cycle during the booster filling time, SC cavities will be equipped with fast tuners to compensate for Lorentz detuning
  - 4.5K operation temperature
  - Total ~75 Watts of static load for 5 cryomodules
  - Can be used for other applications during the collider operation
    - Booster beam to fixed target experiments
    - Isotope production, for example, molibdenium-99

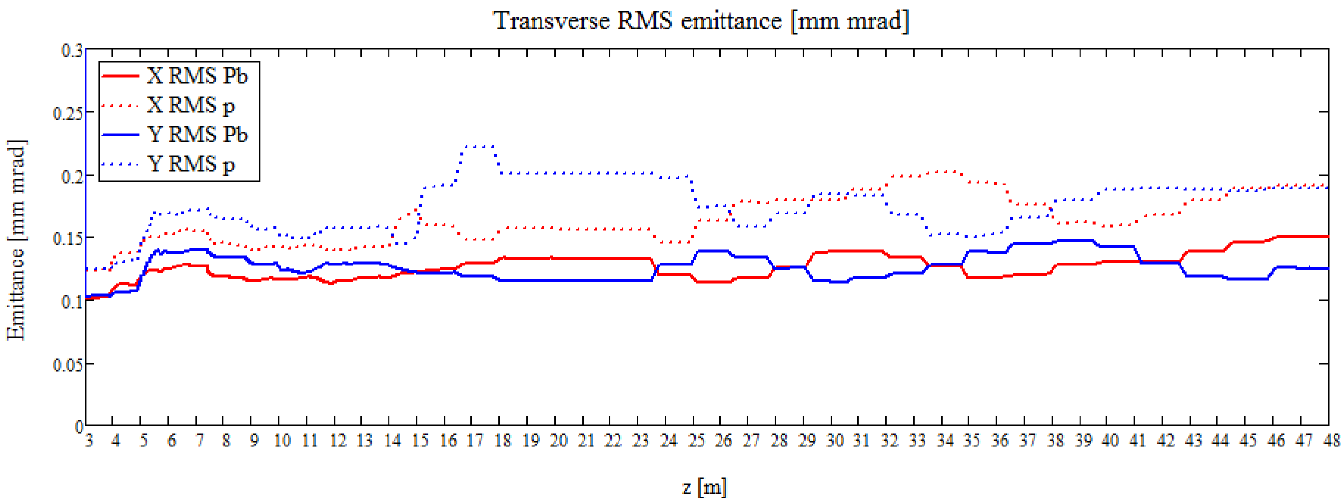
End-to-End Beam Dynamics Simulation - Lead Ions

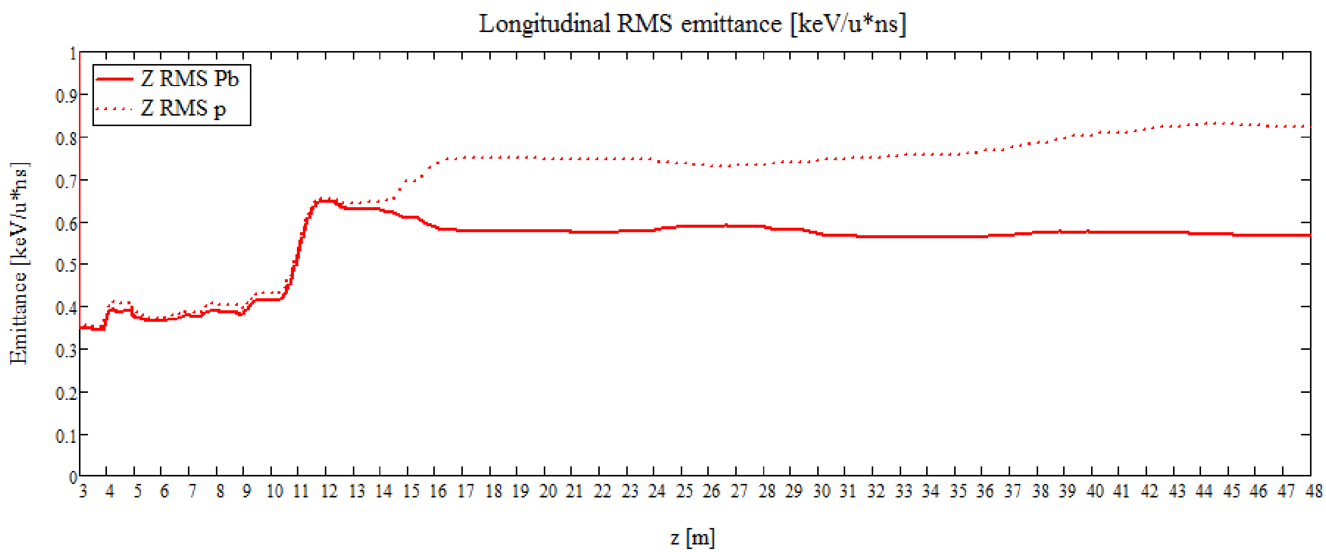


End-to-End Beam Dynamics Simulation - Protons/H⁻



RMS Emittance along the injector



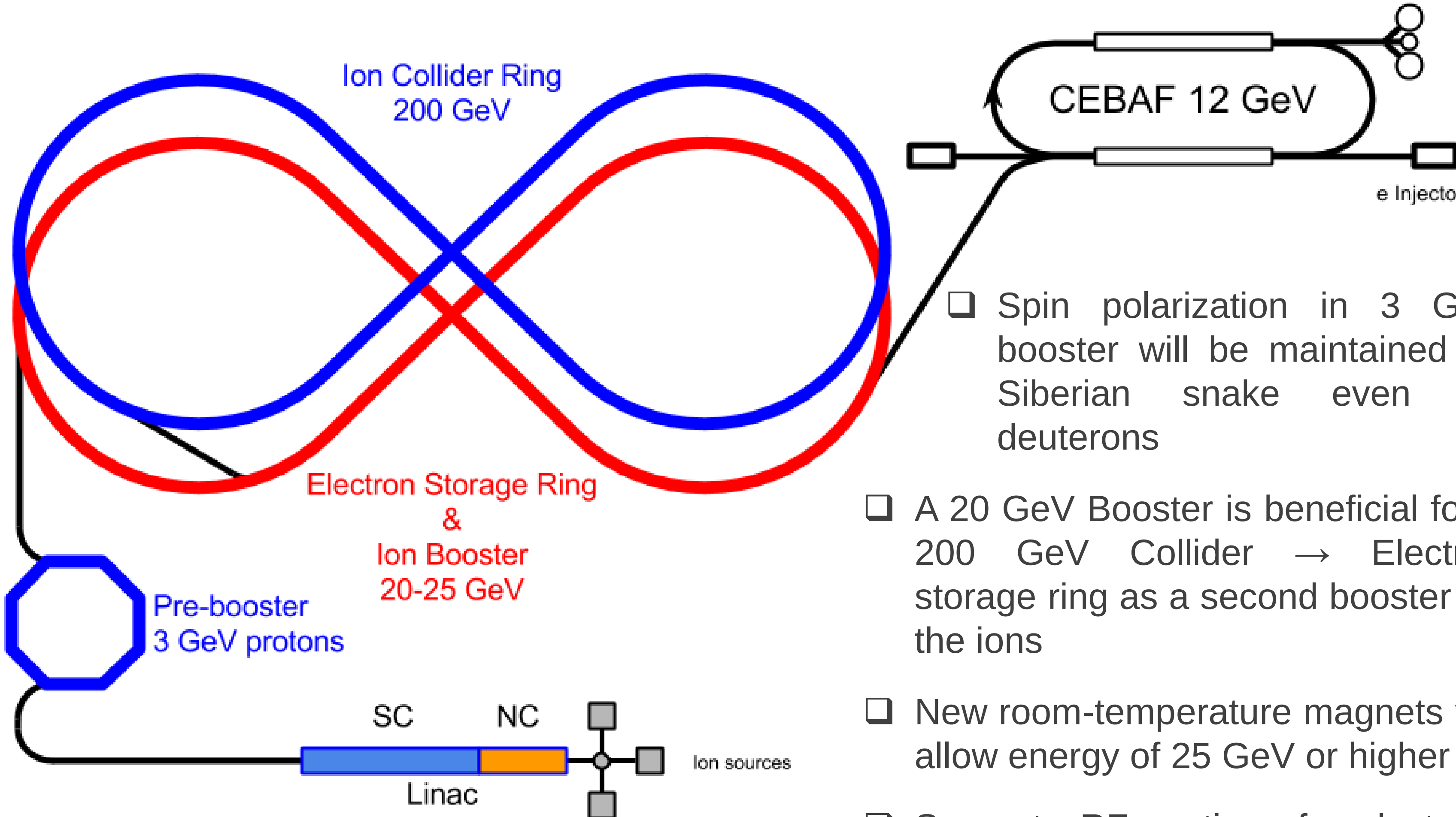


Linac Output Beam Parameters

Parameter	$^{208}Pb^{62+}$	p / H^-
Energy	42.7 MeV/u	134.8 MeV
Pulse current	0.5 mA	2 mA
Pulse length	0.25 ms	0.5 ms
Repetition rate	10 Hz	5 Hz
Input transverse normalized RMS emittance	0.1 π·mm·mrad	0.122 π·mm·mrad
Output transverse normalized RMS emittance (X / Y)	0.15 / 0.13 π·mm·mrad	0.19 / 0.19 π·mm·mrad
Twiss α and β (X / Y)	0.024, 1.11 mm/mrad 0.011, 1.12 mm/mrad	0.061, 7.60 mm/mrad 0.017, 9.11 mm/mrad
Output longitudinal normalized RMS emittance	0.57 π·keV/u·ns	0.82 π·keV/u·ns
Twiss α and β (longitudinal)	0.53, 9.9 deg/%	0.68, 16 deg/%
RMS energy spread	0.11%	0.06%
RMS time spread in the bunch	13 ps	10 ps

Discussion of Ion Accelerator Complex

Ion Accelerator Complex Option to be Investigated



- ❑ Spin polarization in 3 GeV booster will be maintained by Siberian snake even for deuterons
- ❑ A 20 GeV Booster is beneficial for a 200 GeV Collider → Electron storage ring as a second booster for the ions
- ❑ New room-temperature magnets will allow energy of 25 GeV or higher
- ❑ Separate RF sections for electrons and ions

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

Tools for End-to-End Simulation of JLEIC Ion Complex

ANL and NIU has been in the EIC collaboration for about 6 years. During this time we developed beam simulation tools.

- Most of the Ion Complex in the JLEIC baseline design was developed using an updated version of COSY Infinity
- This new version of COSY Infinity, mainly developed using EIC R&D funds, is capable of:
  - Linac simulation
  - Synchrotron design and simulation
  - Interaction region design and simulation
  - 3D beam dynamics, space charge effects and spin tracking
- MADX(CERN) was used to design a compact octagonal 3 GeV pre-booster and benchmark COSY's original results
- TRACK is being used for the Linac design and detailed beam dynamics simulations including error simulations

Summary & Future Work

- The combination of room temperature front-end (low-beta) and SC linac is a flexible option for the acceleration of ions with a wide range of A/Q ratios
- A detailed computer model of this linac was developed and preliminary beam dynamics for H- and lead ion beams was studied
- Future Linac Work
  - Improvement of bean dynamics in the IH sections
  - EM design for the RFQ and RF-focusing sections
  - Error Studies
  - Testing of existing QWR and HWR in pulsed mode operation
- Proposed Ion Complex Work for a High-Energy Collider Option
  - Optimize the design of the pre-booster
  - Develop the modifications necessary to utilize the existing electron ring as a booster for ions
  - We have the tools to study the beam formation and perform end-to-end simulations in the Ion Accelerator Complex

Thank you!