Beam Simulations & Code Benchmarking (FY-2017 Project)

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Outline

- ❑ Overview of ANL's Contribution to EIC R&D
- ❑ Highlights from Previous Years Work (FY10-16)
- ❑ New FY-17 Project: Beam Simulations & Code Benchmarking
- ❑ Motivations & Goals
- ❑ Framework & Progress
- ❑ Summary

Overview of ANL's Contribution to EIC R&D

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

- 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

- Goal of the later work (FY15-16): Design and Simulations of the JLEIC Ion Injector Linac

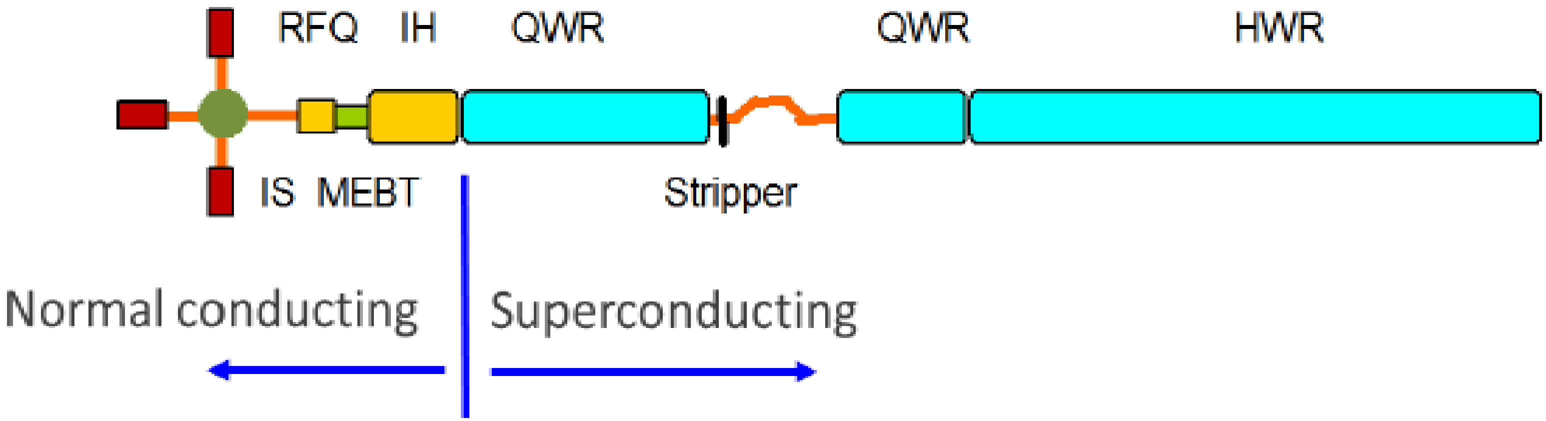
- Accomplishments FY15-16: Injector Linac Design & Simulations
  - Complete conceptual design of the JLEIC ion injector linac
  - Start-to-end simulations in the linac

Budget Summary & Expenditures Over the Years

	FY10+ FY11	FY12+ FY13	FY14+ FY15	FY16+FY17	Total
Funds allocated	0k+440k	100k+98k	50k+105k	100k+0k	$893k
Actual costs to date	0k+316.8k	142.2k+115.2k	53.7k+119.1k	99.2k+46.8k	$893k

Highlights from Early Years (FY10-14)

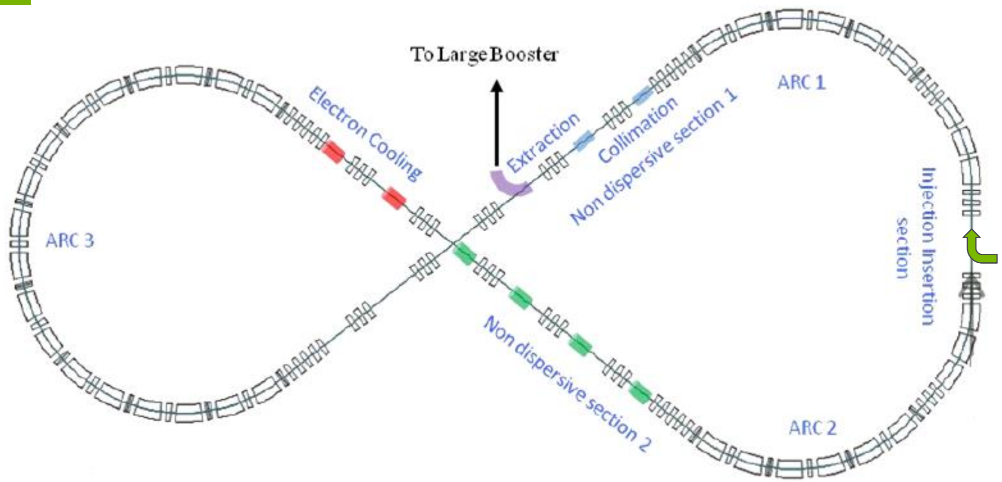
Original Linac Design (2012) – MEIC/JLEIC Baseline



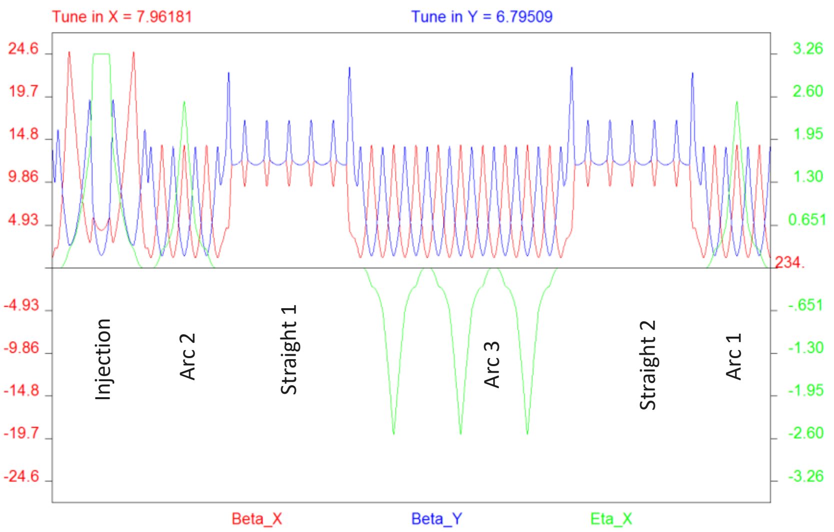
- Warm front-end up to ~ 5 MeV/u for all ions
- SC QWR section up to 13 MeV/u for Pb ions
- A stripper for heavy ions for more effective acceleration: Pb $^{28+} \rightarrow {}^{67+}$
- SC high-energy section (QWR + HWR) up to 280 MeV for protons and 100 MeV/u for Pb ions
- Total linac length of ~ 130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



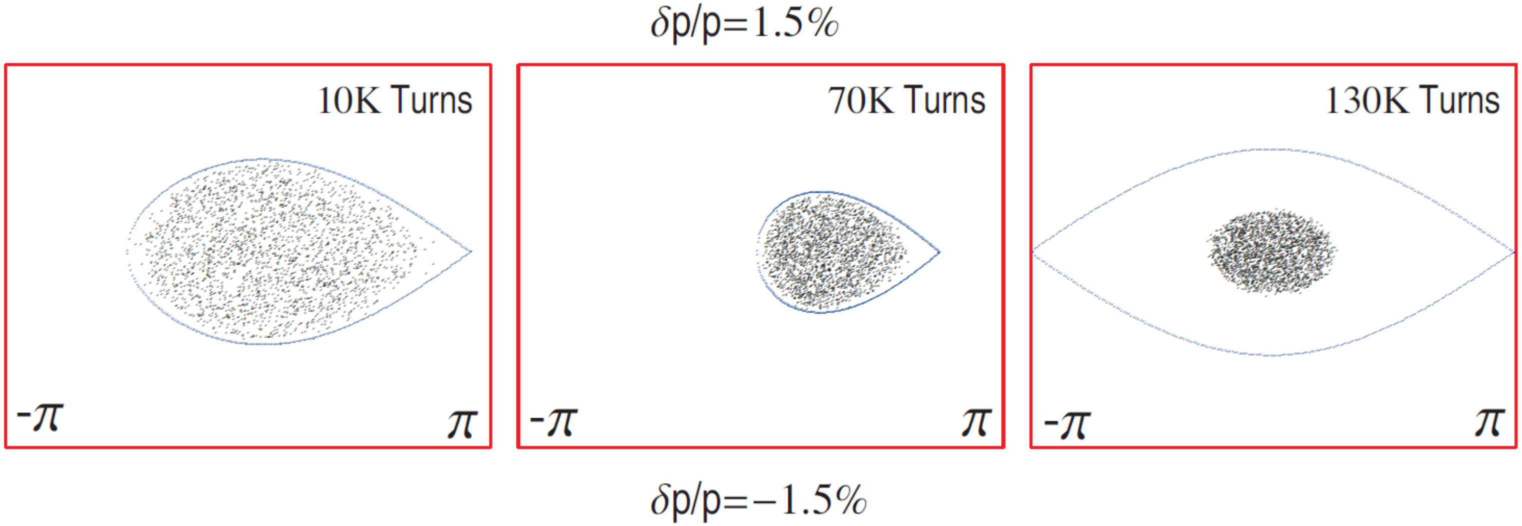
Linear Optics of Pre-Booster Ring: Lattice Plot



- ❑ 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



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.

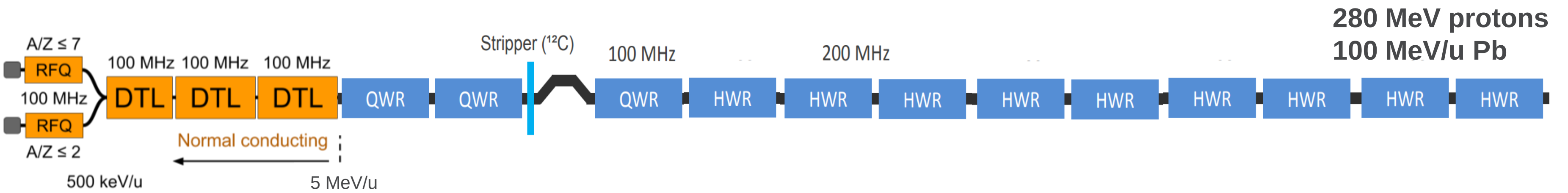
- "An accumulator/Pre-Booster for the Medium-Energy Electron Ion Collider at JLab", B. Erdelyi, S. Abeyratne, Y.S. Derbenev, G.A. Krafft, Y. Zhang, S.L. Manikonda, P.N. Ostroumov, PAC-2011, New York.

- "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.

More Recent Work (FY15-16)

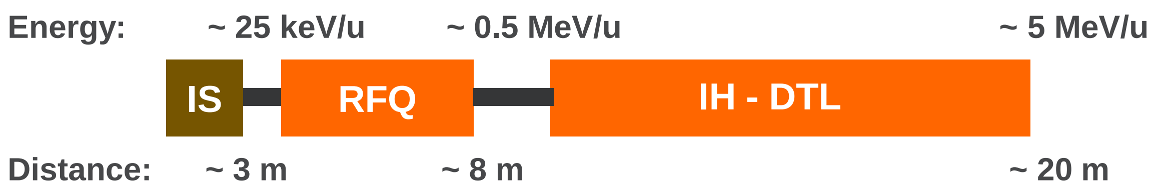
Conceptual Design for the JLEIC Ion Injector Linac



- ❑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 heavy ions
- ❑Pulsed Linac: up to 10 Hz repetition rate and ~ 0.5 ms pulse length

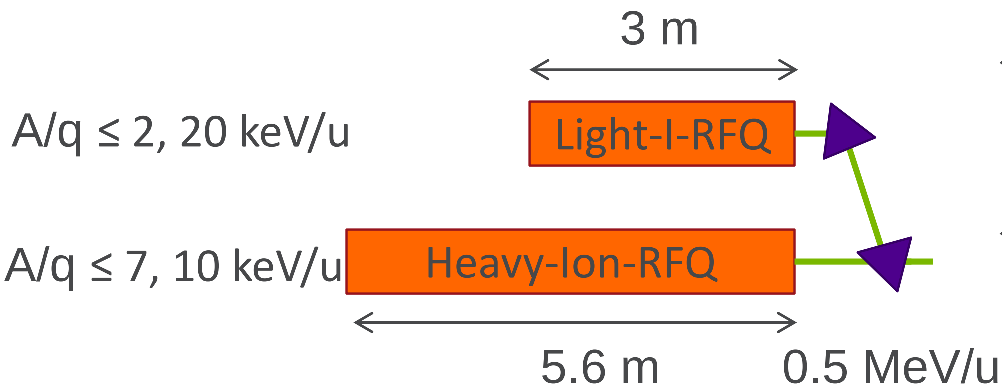
RT Section to ~ 5 MeV/u – followed by SRF Linac

- ❑ 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
  - Large acceptance & more flexibility for light and heavy ion beams
  - More compact and cost-effective than the full RT option (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

Two Separate RFQs: Design Parameters

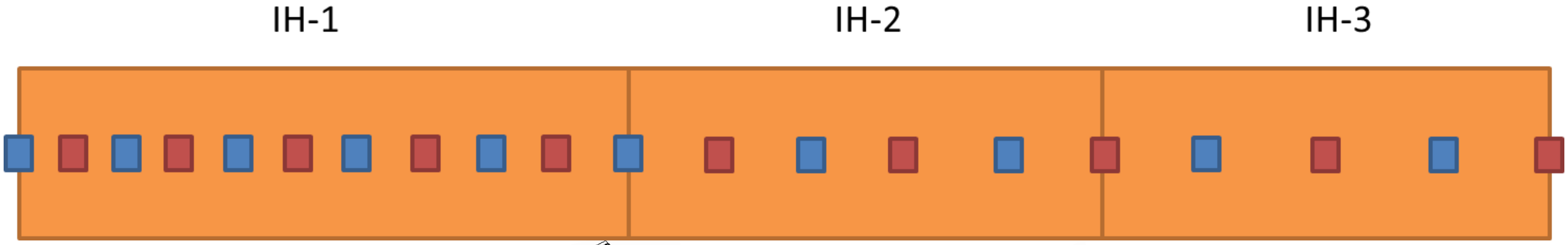


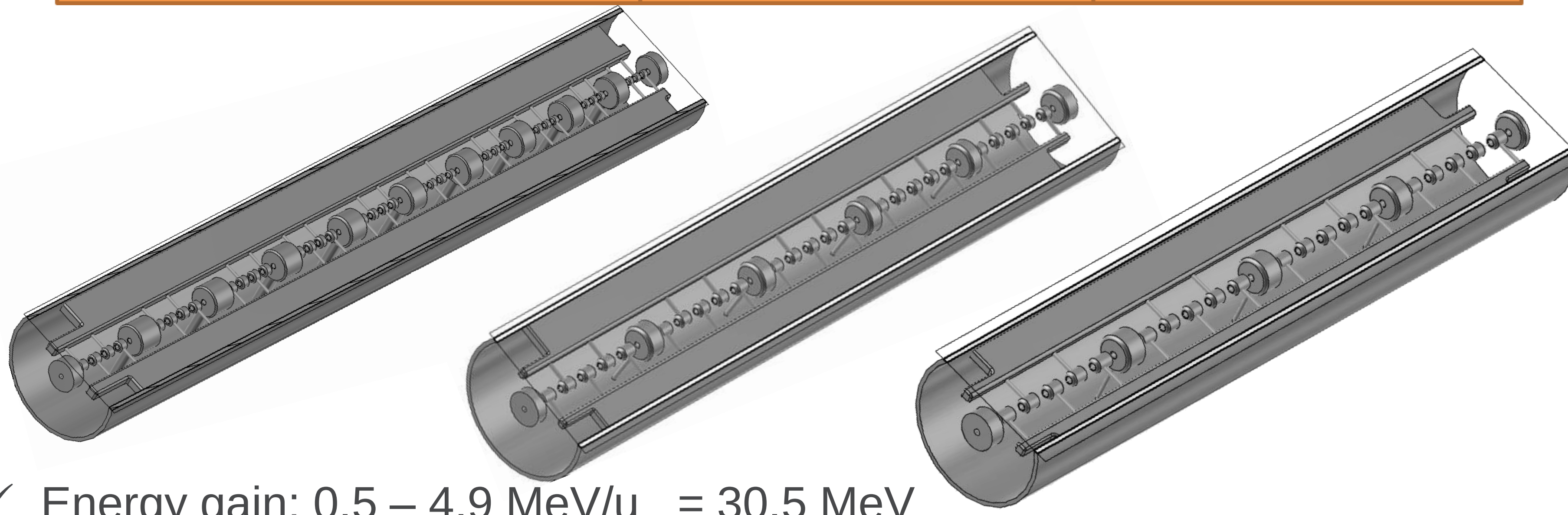
- ✓ Light-Ion RFQ is designed for polarized beams with **2 π** mm mrad normalized transverse emittance
- ✓ Heavy-Ion RFQ is designed for ion with A/q ≤ 7 with **0.5 π** mm mrad normalized transverse emittance

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

IH – DTL with FODO Focusing

- ✓ 3 Tanks – 20 Quadrupoles in FODO arrangements



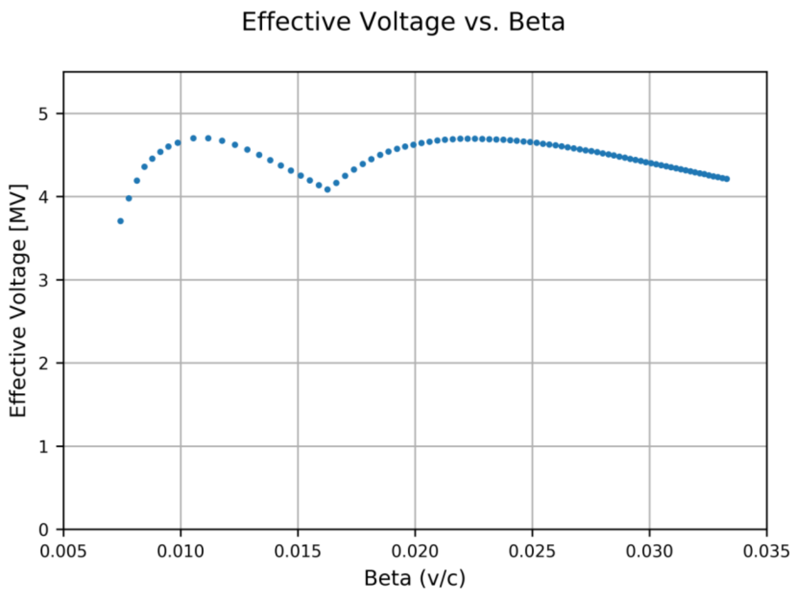


- ✓ Energy gain: 0.5 – 4.9 MeV/u = 30.5 MeV
- ✓ Total length: 4.3 + 3.5 + 3.4 m = 11.2 m
- ✓ Real-estate accelerating gradient: 2.72 MV/m
- ✓ RF Power losses: 280 + 400 + 620 = 1.3 MW

SRF Linac & Stripper Section

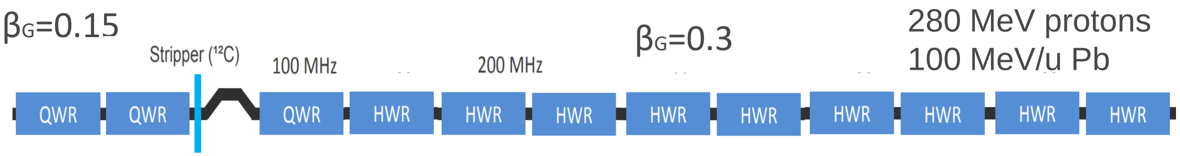
➢ Stripping at 13 MeV/u to get Pb^{67+} for Injection to the Booster

- 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

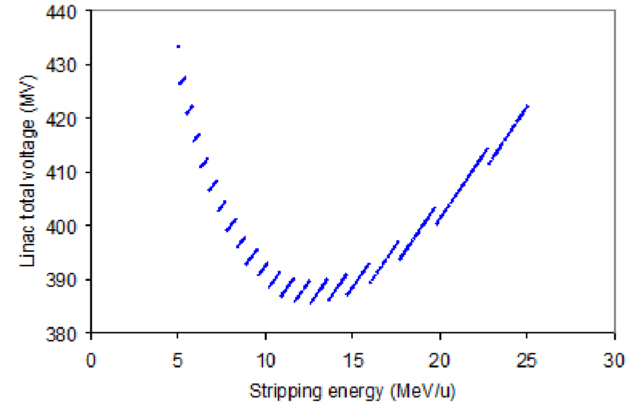


➢ One type of HWR covers the whole velocity range, β: 0.15 – 0.35

SRF Section: QWR & HWR Design Parameters



Optimum stripping energy



QWR Module

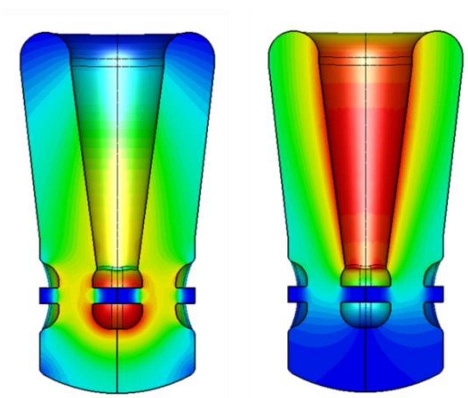
HWR Module

Horizonal orientation of cavities

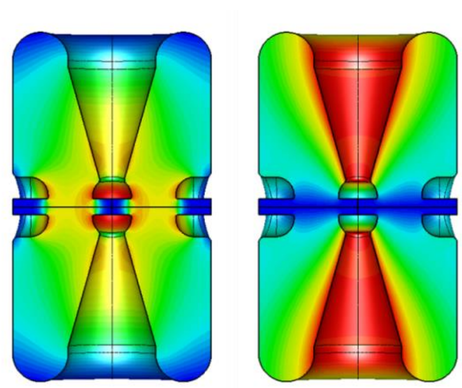
Stripping @ 13 MeV/u, Pb: 30+ → 67+

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	

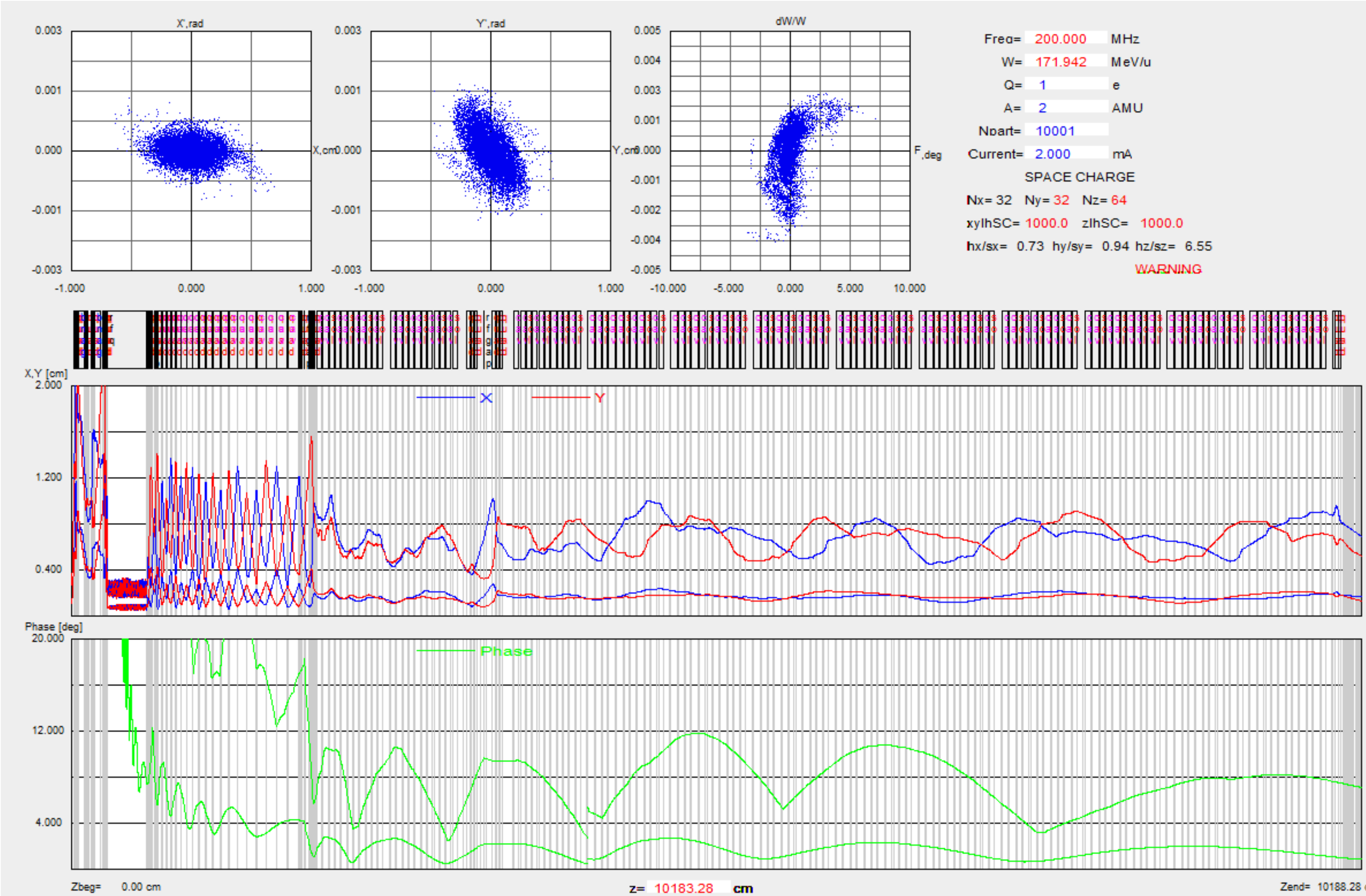
QWR Design



HWR Design

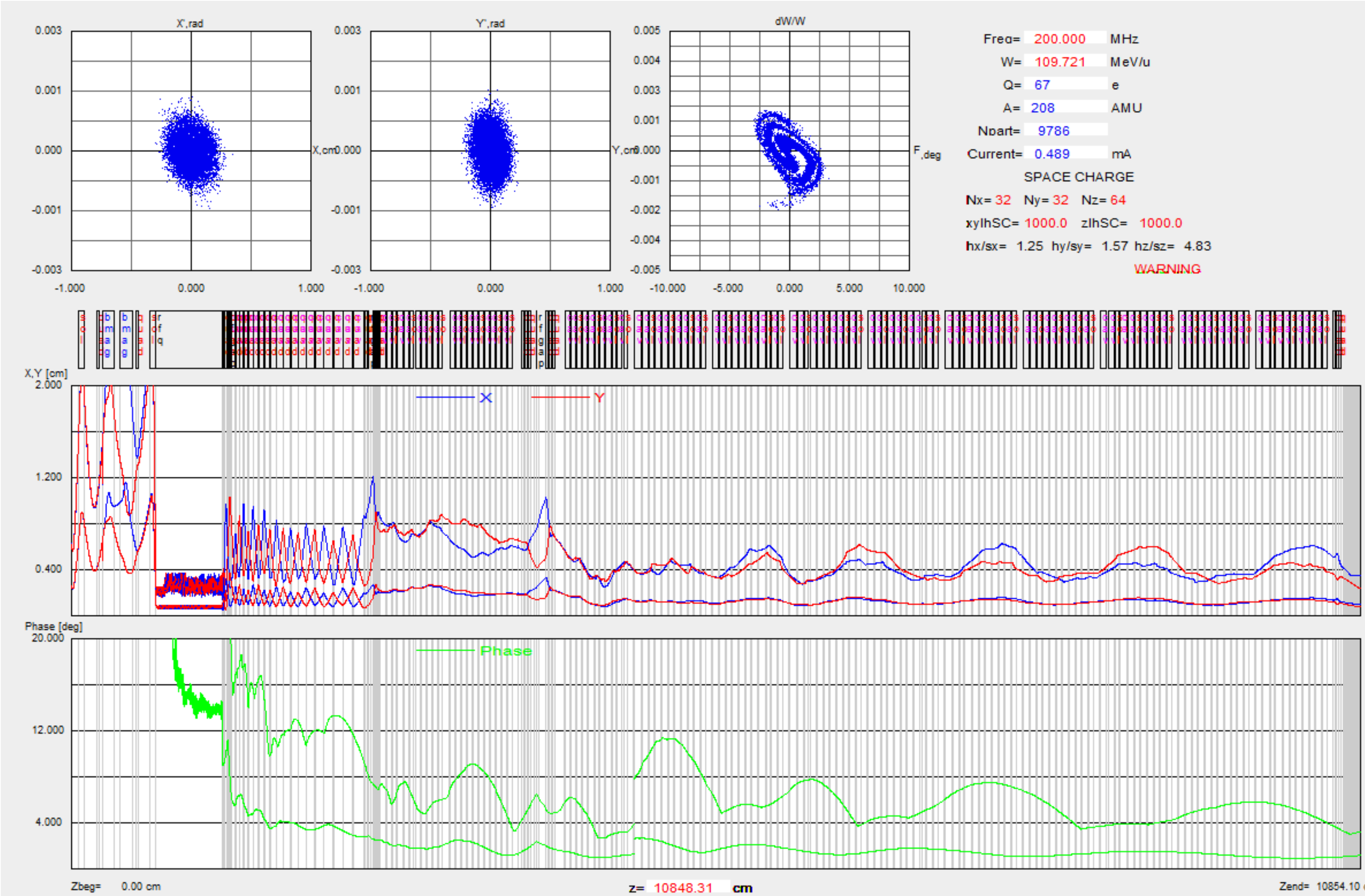


Start-to-end Linac Simulations: Polarized Deuterons



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

Start-to-end Linac Simulations: Lead ion beam



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.

- "Design of the Multi-Ion Injector Linac for JLEIC", B. Mustapha, Z. Conway, M. Kelly, A. Plastun and P. Ostroumov, Proceedings of the HIAT-2018 Conference, October 22-26, Lanzhou, China.

New FY-17 Project:
Beam Simulation & Benchmarking

Motivations & Goals

- 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

Budget Summary & Expenditures Over the Years

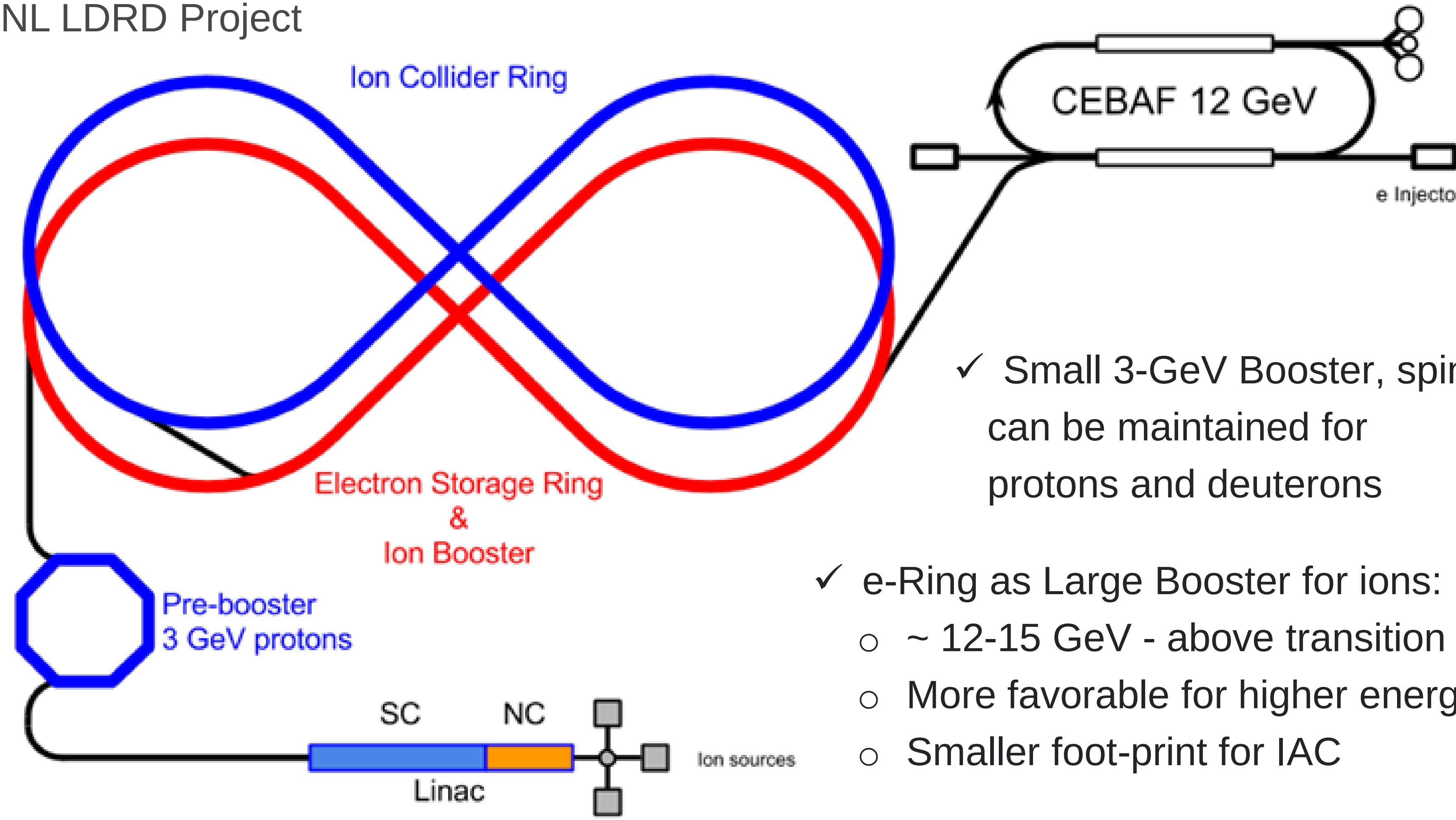
	FY10+ FY11	FY12+ FY13	FY14+ FY15	FY16+FY17	Total
Funds allocated				50k	$50k
Actual costs to date				45k	$45k

✓ FY-17 Milestones: Framework is alternative design for JLEIC ion complex

	Milestones
Q1FY17	Development of accelerator lattice conversion tools between codes: MADX, COSY, Zgoubi, TRACK
Q2FY17	Benchmarking beam optics in e-ring as large ion booster
Q3FY17	Spin dynamics in octagonal pre-booster and benchmarking
Q4FY17	Spin dynamics in the ion injector linac and benchmarking

Alternative Design Approach for JLEIC Ion Complex

ANL LDRD Project

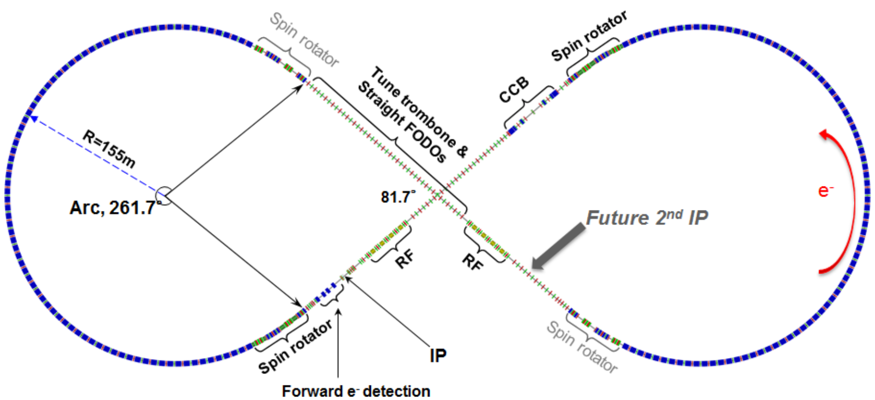


- ✓ Small 3-GeV Booster, spin can be maintained for protons and deuterons
- ✓ e-Ring as Large Booster for ions:
  - ~ 12-15 GeV - above transition
  - More favorable for higher energy
  - Smaller foot-print for IAC

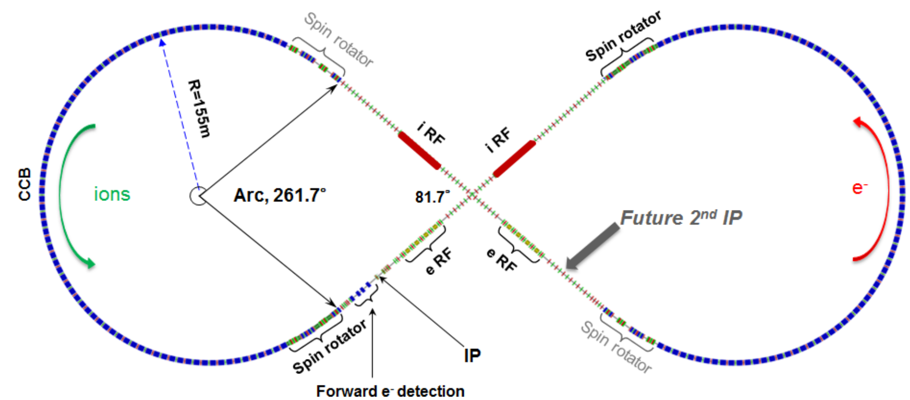
- The Electron Storage Ring and Ion Collider Ring are stacked vertically
- Ion injection from the booster (e-ring) to the ion collider ring is a vertical bend

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

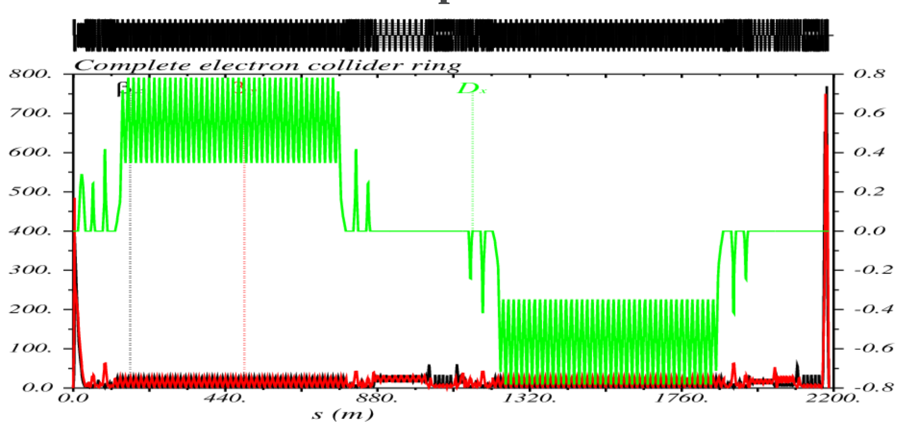
Electrons Only



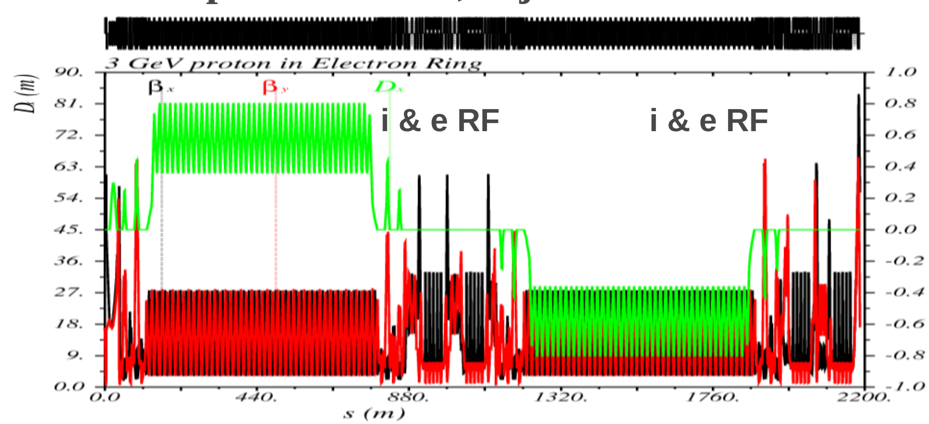
Electrons & Protons



e- Collision Optics at 5 GeV



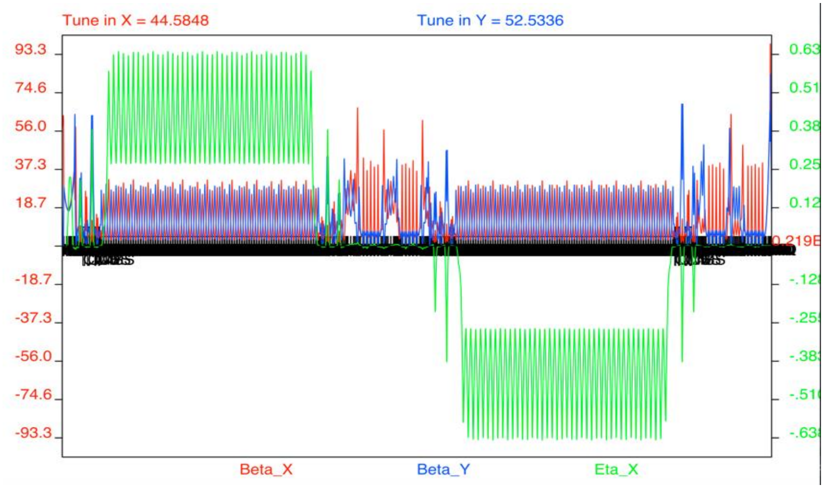
Proton optics at 3 GeV, Injection from Booster



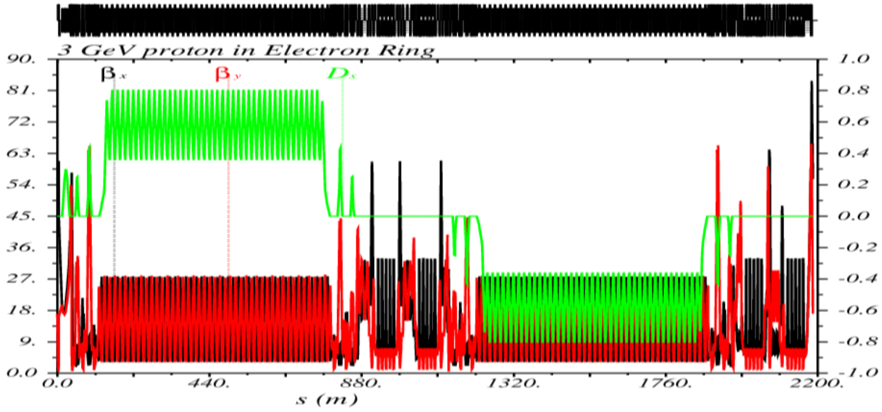
- ✓ Ion RF sections were inserted in the straight sections, across from electron RF
- ✓ Proton beam optics studied at the injection energy of 3 GeV

Benchmarking beam optics in e-ring: COSY vs. MADX

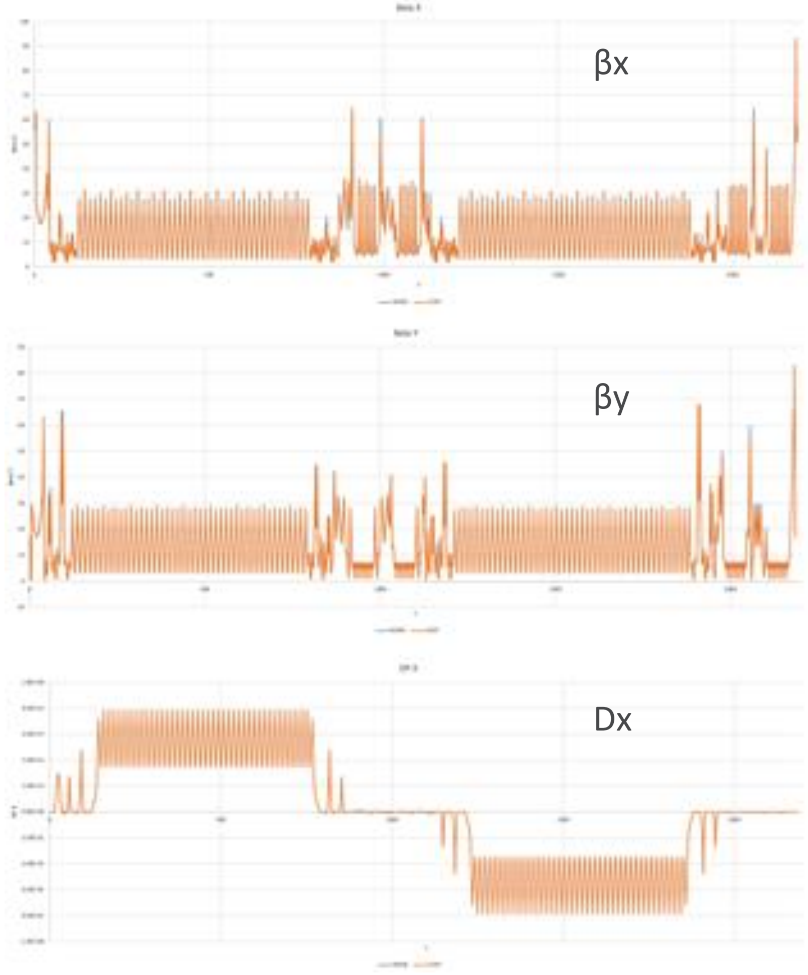
3 GeV proton beam optics in COSY



3 GeV proton beam optics in MADX



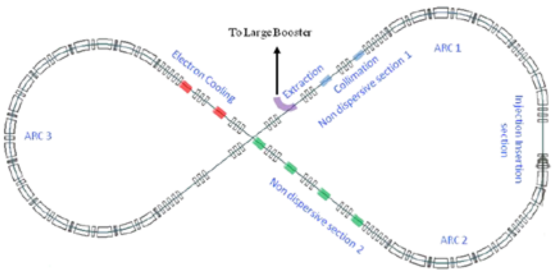
Superposition: COSY in blue, MADX in red



✓ Excellent agreement between the two codes …

A More Compact Booster Ring → Pre-Booster

Original 3-GeV Booster



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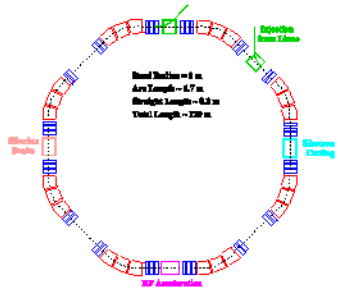
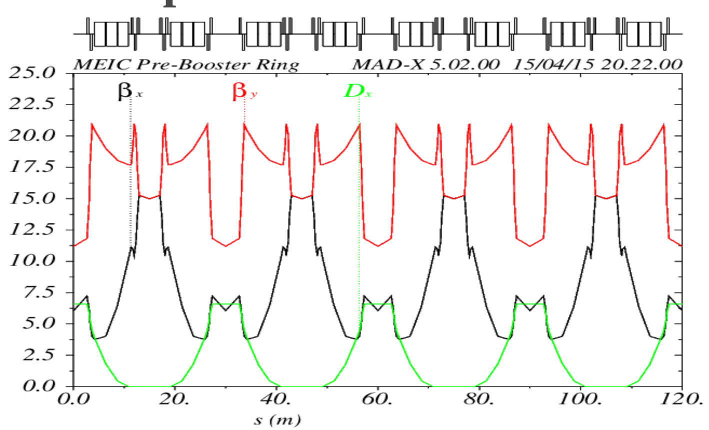
New Design



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 possible

Beam Optics

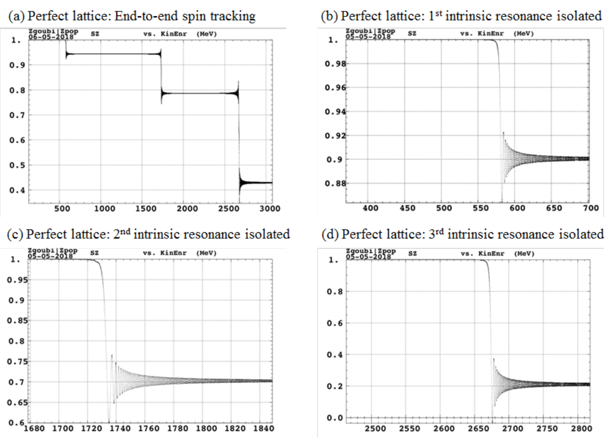


Design Parameters

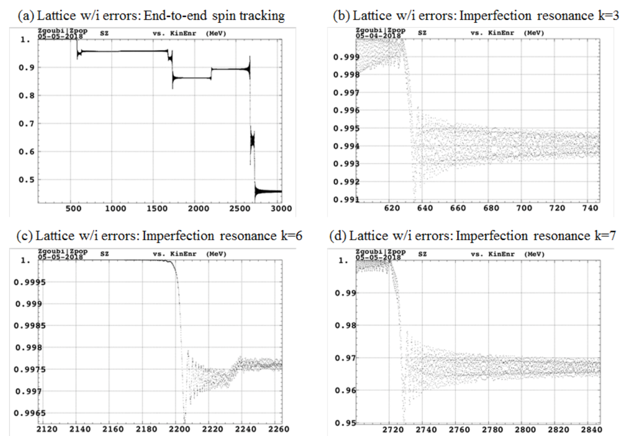
Parameter	Octagonal
Circumference, m	120
Arc length, m	6.7
Straight section length, m	8.3
Maximum β_x	15.3
Maximum β_y	21.0
Maximum dispersion	4.2
β_x at injection	6.0
Normalized dispersion at injection: $D/\sqrt{\beta_x}$	1.71
Tune in X	3.01
Tune in Y	1.18
Gamma transition	4.7
Gamma at extraction (3 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

Spin Dynamics in Pre-Booster: COSY vs. Zgoubi

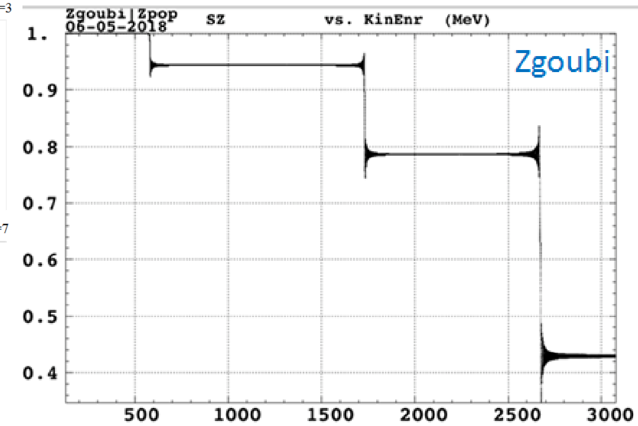
Intrinsic resonances (proton)

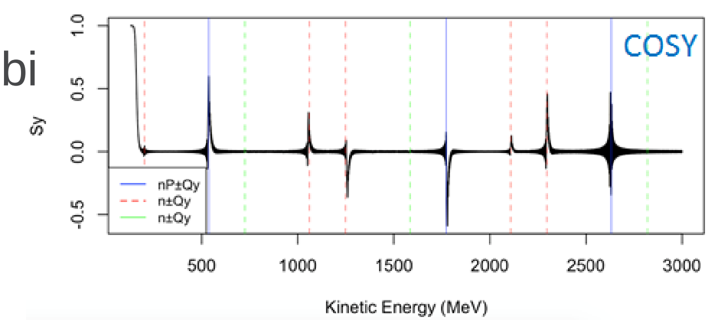

(a) Perfect lattice: End-to-end spin tracking
(b) Perfect lattice: 1st intrinsic resonance isolated
(c) Perfect lattice: 2nd intrinsic resonance isolated
(d) Perfect lattice: 3rd intrinsic resonance isolated

Imperfection resonances (proton)


(a) Lattice w/i errors: End-to-end spin tracking
(b) Lattice w/i errors: Imperfection resonance k=3
(c) Lattice w/i errors: Imperfection resonance k=6
(d) Lattice w/i errors: Imperfection resonance k=7

Intrinsic : COSY vs. Zgoubi





- ✓ Good overall agreement between COSY and Zgoubi
- ✓ No resonances observed for deuterons, first one expected at ~ 5.6 GeV/u
- ✓ Possible spin correction schemes for protons are listed in table below

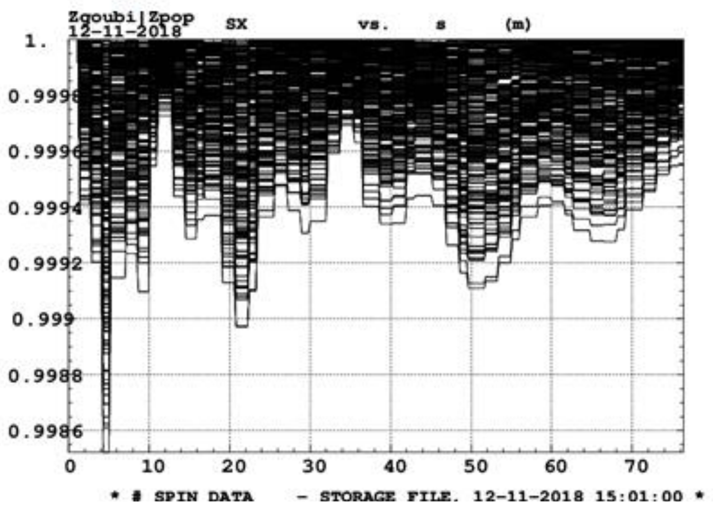
Option	~ 5 Imperfection	~ 2 Strong Intrinsic	~ 1 Intrinsic	~ 8 Weak Intrinsic
A	Orbit corrections	Rf Dipole	Rf Dipole	Nothing/Pulsed Quads
B	5% Siberian Snake	Rf Dipole	Rf Dipole	Nothing/Pulsed Quads
C	Orbit Correction	Pulsed Quads	Pulsed Quads	Nothing/Pulsed Quads
D	5% Siberian Snake	Pulsed Quads	Pulsed Quads	Nothing/Pulsed Quads
E	40% Siberian Snake	40% Siberian Snake	40% Siberian Snake	40% Siberian Snake

Spin Dynamics in the Injector Linac

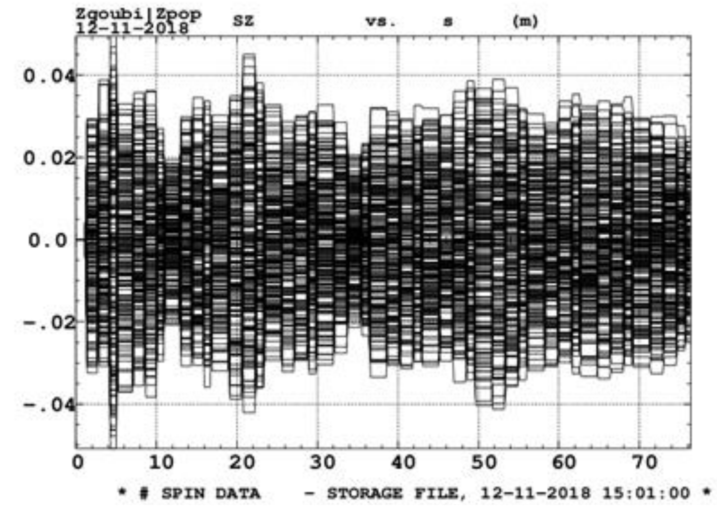
- ✓ Quadrupole focusing in RT section → Transverse spin is more favorable
- ✓ Solenoid focusing in SRF section → Longitudinal spin is more favorable
- ✓ We investigated both options and possible spin correction schemes for both protons and deuterons

Proton Spin Dynamics in SRF Section

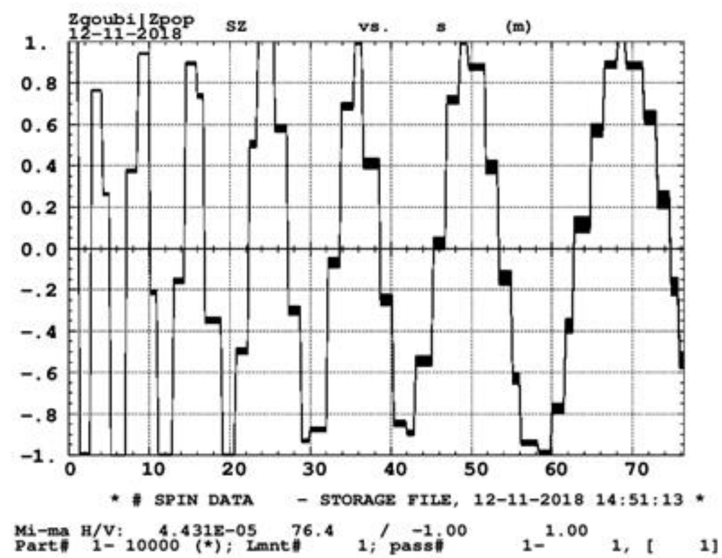
Longitudinal



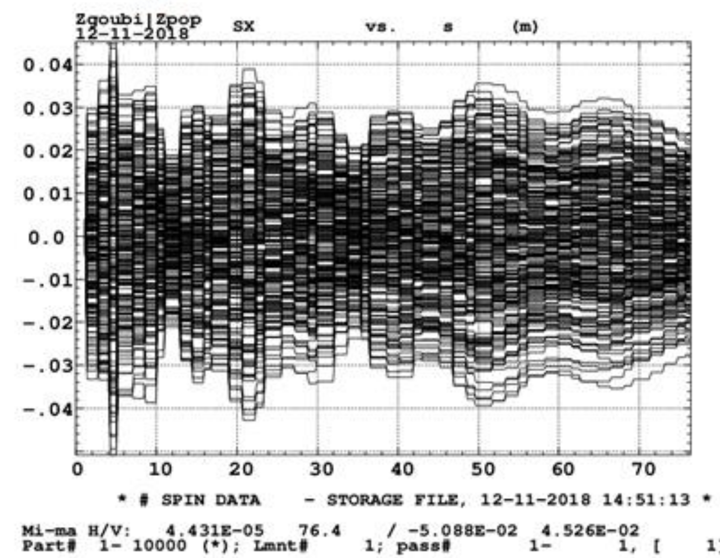
Vertical



Vertical

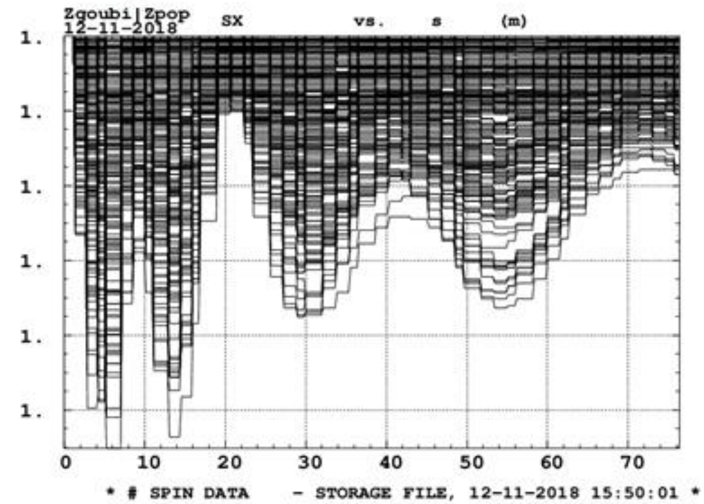


Longitudinal

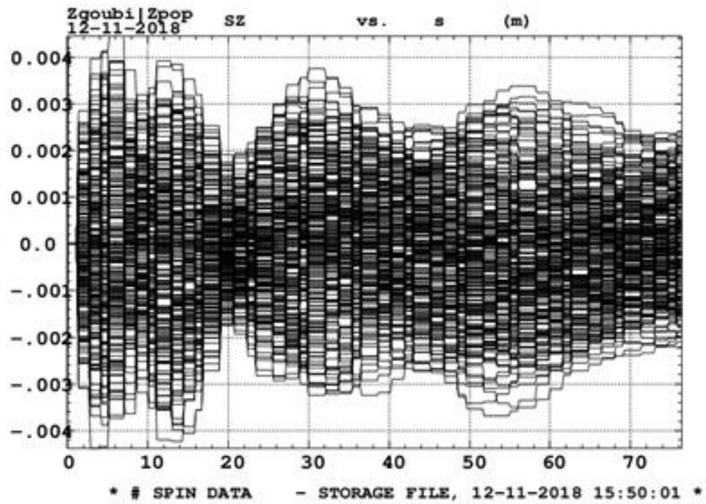


Deuteron Spin Dynamics in SRF Section

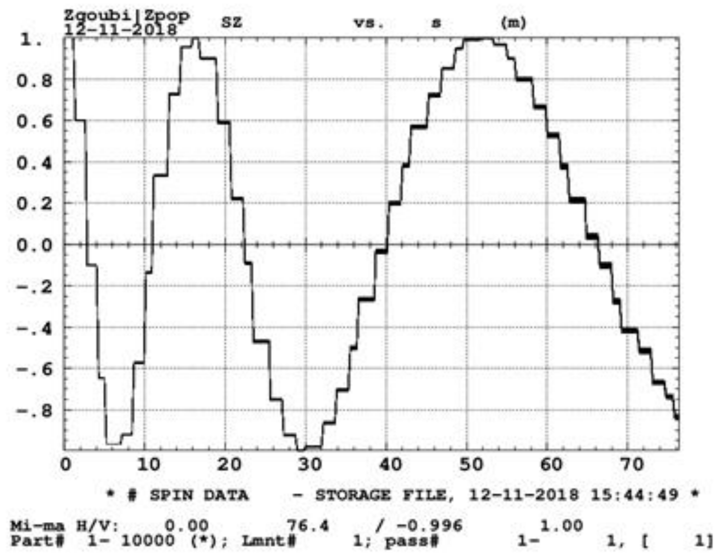
Longitudinal



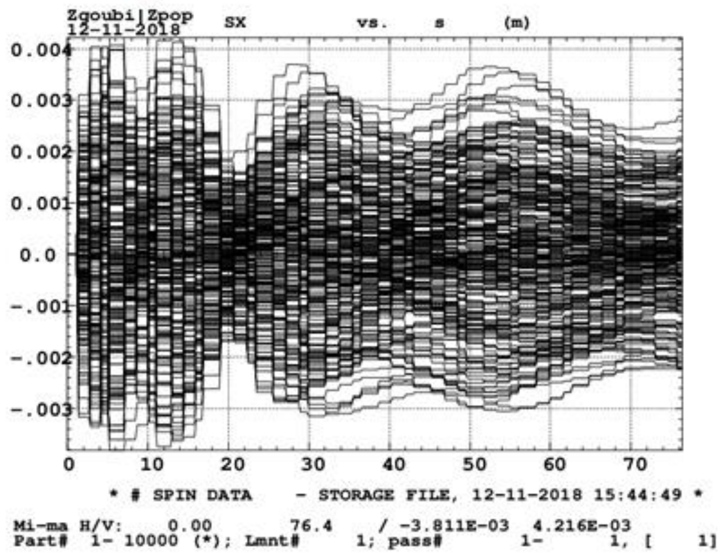
Vertical



Vertical



Longitudinal



Possible Spin Correction Schemes in the Linac

✓A longitudinal spin orientation will be preserved in solenoid focusing but will require spin rotators before and after the SRF section → more space

✓A vertical (transverse) spin orientation will not be preserved but can be restored at the end of the linac using an 8 T – 30 cm long solenoid for protons, but will require a 1.4 m long solenoid for deuterons

✓Another potential scheme (not yet investigated) is to alternate the solenoid field throughout the linac which may results in only a residual spin rotation that could be corrected with a much shorter solenoid

✓Zgoubi's results agree well with analytical estimates

✓Benchmarking with COSY is underway …

Publications …

- “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.

- “Beam Formation in the Alternative JLEIC Ion Complex”, B. Mustapha et al, Proceedings of IPAC-18, April 29 – May 4, 2018, Vancouver, Canada

- “Spin Dynamics in the JLEIC Alternative Pre-booster Ring”, J. Martinez and B. Mustapha, Proceedings of IPAC-18, April 29 – May 4, 2018, Vancouver, Canada

Summary

- Significant progress has been made in beam simulations and code benchmarking under the framework of the alternative design approach for the JLEIC ion complex

- We propose to continue the development and benchmarking of these simulation tools and make them available for the simulation of both the eRHIC and JLEIC concepts of the EIC …