Beam Simulations & Code Benchmarking (FY-2017 Project)

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DOE-NP EIC Accelerator R&D PI Meeting
November 13-14, 2018, Gaithersburg, MD
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

<table>
<thead>
<tr>
<th></th>
<th>FY10+ FY11</th>
<th>FY12+ FY13</th>
<th>FY14+ FY15</th>
<th>FY16+FY17</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Funds allocated</strong></td>
<td>0k+440k</td>
<td>100k+98k</td>
<td>50k+105k</td>
<td>100k+0k</td>
<td>$893k</td>
</tr>
<tr>
<td><strong>Actual costs to date</strong></td>
<td>0k+316.8k</td>
<td>142.2k+115.2k</td>
<td>53.7k+119.1k</td>
<td>99.2k+46.8k</td>
<td>$893k</td>
</tr>
</tbody>
</table>
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
- 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

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

\[ \delta p/p = 1.5\% \]

10K Turns

\[ -\pi \text{ to } \pi \]

70K Turns

\[ -\pi \text{ to } \pi \]

130K Turns

\[ -\pi \text{ to } \pi \]

\[ \delta p/p = -1.5\% \]

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Publications …


More Recent Work (FY15-16)
Conceptual Design for the JLEIC Ion Injector Linac

- Two RFQs: One for light ions ($A/q \sim 2$) and one for heavy ions ($A/q \sim 7$)
  - 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 $\rightarrow$ 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 $\sim 0.5$ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Heavy ion</th>
<th>Light ion</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>100</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Energy range</td>
<td>10 - 500</td>
<td>15 - 500</td>
<td>keV/u</td>
</tr>
<tr>
<td>Highest - A/Q</td>
<td>7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>5.6</td>
<td>3.0</td>
<td>m</td>
</tr>
<tr>
<td>Average radius</td>
<td>3.7</td>
<td>7.0</td>
<td>mm</td>
</tr>
<tr>
<td>Voltage</td>
<td>70</td>
<td>103</td>
<td>kV</td>
</tr>
<tr>
<td>Transmission</td>
<td>99</td>
<td>99</td>
<td>%</td>
</tr>
<tr>
<td>Quality factor</td>
<td>6600</td>
<td>7200</td>
<td></td>
</tr>
<tr>
<td>RF power consumption (structure with windows)</td>
<td>210</td>
<td>120</td>
<td>kW</td>
</tr>
<tr>
<td>Output longitudinal emittance (Norm., 90%)</td>
<td>4.5</td>
<td>4.9</td>
<td>π keV/u ns</td>
</tr>
</tbody>
</table>

**Light-Ion RFQ**

- Designed for polarized beams with $2\pi$ mm mrad normalized transverse emittance
- $A/q \leq 2$, 20 keV/u

**Heavy-Ion RFQ**

- Designed for ion with $A/q \leq 7$ with $0.5\pi$ mm mrad normalized transverse emittance
- $A/q \leq 7$, 10 keV/u

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Light-Ion RFQ:
- Frequency: 100 MHz
- Energy range: 10 - 500 keV/u
- Highest - A/Q: 7
- Length: 5.6 m
- Average radius: 3.7 mm
- Voltage: 70 kV
- Transmission: 99%
- Quality factor: 6600
- RF power consumption (structure with windows): 210 kW
- Output longitudinal emittance (Norm., 90%): 4.5 π keV/u ns

Heavy-Ion RFQ:
- Frequency: 100 MHz
- Energy range: 15 - 500 keV/u
- Highest - A/Q: 2
- Length: 3.0 m
- Average radius: 7.0 mm
- Voltage: 103 kV
- Transmission: 99%
- Quality factor: 7200
- RF power consumption (structure with windows): 120 kW
- Output longitudinal emittance (Norm., 90%): 4.9 π keV/u ns
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
SRF Linac & Stripper Section

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

- Pb @ 13 MeV/u: 30+ $\rightarrow$ 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, $\beta$: 0.15 – 0.35
**SRF Section: QWR & HWR Design Parameters**

β₀ = 0.15

QWR Module

β₀ = 0.3

HWR Module

280 MeV protons
100 MeV/u Pb

QWR Design

HWR Design

Optimum stripping energy

Stripping @ 13 MeV/u, Pb: 30+ → 67+

<table>
<thead>
<tr>
<th>Parameter</th>
<th>QWR</th>
<th>HWR</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>β₀öpt</td>
<td>0.15</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>100</td>
<td>200</td>
<td>MHz</td>
</tr>
<tr>
<td>Length (β₀λ)</td>
<td>45</td>
<td>45</td>
<td>cm</td>
</tr>
<tr>
<td>$E_{\text{PEAK}}/E_{\text{ACC}}$</td>
<td>5.5</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>$B_{\text{PEAK}}/E_{\text{ACC}}$</td>
<td>8.2</td>
<td>6.9</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>R/Q</td>
<td>475</td>
<td>256</td>
<td>Ω</td>
</tr>
<tr>
<td>G</td>
<td>42</td>
<td>84</td>
<td>Ω</td>
</tr>
<tr>
<td>$E_{\text{PEAK}}$ in operation</td>
<td>57.8</td>
<td>51.5</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_{\text{PEAK}}$ in operation</td>
<td>86.1</td>
<td>72.5</td>
<td>mT</td>
</tr>
<tr>
<td>$E_{\text{ACC}}$</td>
<td>10.5</td>
<td>10.5</td>
<td>MV/m</td>
</tr>
<tr>
<td>Phase (Pb)</td>
<td>-20</td>
<td>-30</td>
<td>deg</td>
</tr>
<tr>
<td>Phase (p/H⁻)</td>
<td>-10</td>
<td>-10</td>
<td>deg</td>
</tr>
<tr>
<td>No. of cavities</td>
<td>21</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

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Start-to-end Linac Simulations: Polarized Deuterons

No beam loss over the whole linac (10k particles) \( \Rightarrow \) Avoid neutron activation
Start-to-end Linac Simulations: Lead ion beam

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Publications …


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

<table>
<thead>
<tr>
<th></th>
<th>FY10+ FY11</th>
<th>FY12+ FY13</th>
<th>FY14+ FY15</th>
<th>FY16+FY17</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Funds allocated</td>
<td></td>
<td></td>
<td></td>
<td>50k</td>
<td>$50k</td>
</tr>
<tr>
<td>Actual costs to date</td>
<td></td>
<td></td>
<td></td>
<td>45k</td>
<td>$45k</td>
</tr>
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</table>

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

<table>
<thead>
<tr>
<th>Milestones</th>
<th>Development of accelerator lattice conversion tools between codes: MADX, COSY, Zgoubi, TRACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1FY17</td>
<td>Benchmarking beam optics in e-ring as large ion booster</td>
</tr>
<tr>
<td>Q3FY17</td>
<td>Spin dynamics in octagonal pre-booster and benchmarking</td>
</tr>
<tr>
<td>Q4FY17</td>
<td>Spin dynamics in the ion injector linac and benchmarking</td>
</tr>
</tbody>
</table>
Alternative Design Approach for JLEIC Ion Complex

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

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

Excellent agreement between the two codes ...

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A More Compact Booster Ring → Pre-Booster

Original 3-GeV Booster

![Original 3-GeV Booster Diagram]

New Design

![New Design Diagram]

Design Parameters

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

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

Beam Optics

![Beam Optics Graph]

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Spin Dynamics in Pre-Booster: COSY vs. Zgoubi

- Intrinsic resonances (proton)
  - Perfect lattice: End-to-end spin tracking
  - Perfect lattice: 1st intrinsic resonance isolated
  - Perfect lattice: 2nd intrinsic resonance isolated

- Imperfection resonances (proton)
  - Lattice w/ errors: End-to-end spin tracking
  - Lattice w/ errors: Imperfection resonance k=3
  - Lattice w/ errors: Imperfection resonance k=6
  - Lattice w/ 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

<table>
<thead>
<tr>
<th>Option</th>
<th>~ 5 Imperfection</th>
<th>~ 2 Strong Intrinsic</th>
<th>~ 1 Intrinsic</th>
<th>~ 8 Weak Intrinsic</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Orbit corrections</td>
<td>Rf Dipole</td>
<td>Rf Dipole</td>
<td>Nothing/Pulsed Quads</td>
</tr>
<tr>
<td>B</td>
<td>5% Siberian Snake</td>
<td>Rf Dipole</td>
<td>Rf Dipole</td>
<td>Nothing/Pulsed Quads</td>
</tr>
<tr>
<td>C</td>
<td>Orbit Correction</td>
<td>Pulsed Quads</td>
<td>Pulsed Quads</td>
<td>Nothing/Pulsed Quads</td>
</tr>
<tr>
<td>D</td>
<td>5% Siberian Snake</td>
<td>Pulsed Quads</td>
<td>Pulsed Quads</td>
<td>Nothing/Pulsed Quads</td>
</tr>
<tr>
<td>E</td>
<td>40% Siberian Snake</td>
<td>40% Siberian Snake</td>
<td>40% Siberian Snake</td>
<td>40% Siberian Snake</td>
</tr>
</tbody>
</table>

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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

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Deuteron Spin Dynamics in SRF Section

Longitudinal

Vertical

Vertical

Longitudinal

* # SPIN DATA - STORAGE FILE, 12-11-2018 15:44:49 *

* # SPIN DATA - STORAGE FILE, 12-11-2018 15:50:01 *

* # SPIN DATA - STORAGE FILE, 12-11-2018 15:50:01 *
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 result 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 …


• “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 …