End-to-End Beam Simulations for MSU RIA Driver Linac

Xiaoyu Wu
NSCL
Michigan State University

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Beam Dynamics studies for RIA at MSU

- Established 10th sub-harmonic (80.5 MHz) RIA driver linac design option
  - Beam power: 400 kW
  - Uncontrolled beam loss: 1W/m
  - Adequate acceptances and limited emittance growths
- Beam simulations for all sub-systems of MSU RIA driver linac design
- End-to-end beam simulation studies
  - Realistic input beams
  - Alignment and dynamic rf errors through all segments of RIA driver linac
  - Charge-stripping foil model
Beam Simulation Tools

- **RIA front end**:
  - PARMELA – beam transport with space charge
  - PARMTEQ – RFQ beam dynamics

- **Driver linac segments and charge-stripping sections**
  - LANA – end-to-end 3-D simulations
  - DIMAD – transverse focusing lattice, misalignment and correction scheme
  - COSY INFINITY – high order aberrations and corrections
  - TRIM – Charge-stripping foil modelling

- **In progress**
  - PARMTEQm + IMPACT – end-to-end simulations
RIA Layout at NSCL/MSU
RIA Driver linac Lattice

- **Segment I: 0.292 – 11.8 MeV/u**
  - 80.5 MHz (0.041, 0.085) SRF QWC, 30 mm aperture
  - SC solenoid magnets, L=0.1 and 0.2 m
- **Segment II: 11.6 – 88.9 MeV/u**
  - 322 MHz (0.285) SRF HWC, 30 mm aperture
  - SC solenoid magnets, L=0.5 m
- **Segment III: 83.8 – 400 MeV/u**
  - 805 MHz (0.49, 0.63, 0.83) 6-cell elliptical cavities, 77 mm aperture
  - Room-temperature quadrupole magnets, L=0.25 m

- THP70 – T.L. Grimm, “Experimental Study of an 805MHz Cryomodule for the Rare Isotope Accelerator”
VENUS Source (LBNL)
Bismuth Emittance Measurements

Measured Bi\textsuperscript{27+} RMS emittance
\sim 0.08 \pi\text{-mm-mrad}

Courtesy of D. Leitner
RIA Front End Simulation Results

- Two charge-state $^{238}$U beam acceleration
- Beam intensity: 8 pA
- 100kV high voltage platform
- Phase spaces based on LBNL emittance measurement
- Small transverse emittance growth
- Beam emittance at SCL entrance

<table>
<thead>
<tr>
<th>$\varepsilon_{n,T}$ (rms)</th>
<th>$\sim$0.09 $\pi$ mm-mard</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{n,T}$ (99.5%)</td>
<td>$\sim$0.9 $\pi$ mm-mard</td>
</tr>
<tr>
<td>$\varepsilon_{n,L}$ (rms)</td>
<td>$\sim$0.1 $\pi$ keV/u-ns</td>
</tr>
<tr>
<td>$\varepsilon_{n,L}$ (99.5%)</td>
<td>$\sim$1.2 $\pi$ keV/u-ns</td>
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</tbody>
</table>
## Misalignment and rf Errors

<table>
<thead>
<tr>
<th>RIA Driver Linac</th>
<th>Misalignment $\sigma_{x,y}$ [mm]</th>
<th>Maximum rf Errors for SRF Cavity*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SRF Cavity</td>
<td>Focusing Element</td>
</tr>
<tr>
<td>Segment I</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Segment II</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Segment III</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- Gaussian distribution with a cut-off at $2\sigma$ for misalignment
- Uniform distribution for rf errors

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* A. Facco, “High Gradient Locking of Beam Loaded QWRs”, presented at *RIA Driver Workshop II*, May 2002, ANL.

* THP66 – T.L. Grimm, “Measurement and Control of Microphonics in High Loaded-Q Superconducting RF Cavities”

* TUP76 – T. Kandil, “Adaptive Feedforward Cancellation (AFC) of Sinusoidal Disturbances in Superconducting RF (SCRF) cavities”
Alignment Correction Scheme

- Segments I, II – Horizontal/vertical dipole windings for each focusing solenoid magnet
- Segment III – Warm dipole correctors beside focusing quadrupole doublet
- All BPMs in the warm region between cryomodules
- Central orbit distortions limited within ± 5mm after corrections in all three segments of driver linac

![Graph showing orbit distortion before and after corrections](image)
Charge-Stripping Foils

- Stripping foil model
  - Based on simulation results from code TRIM
  - Elastic and inelastic scattering
  - Energy loss and straggling
- Small transverse beam spot (~3mm) and Short bunch length (~8°) achieved on both foils
- Carbon foils* used in simulation
- Foil thickness variation : ± 5%

<table>
<thead>
<tr>
<th>Stripping Foil</th>
<th>Stripping Energy</th>
<th>Thickness</th>
<th>Emittance Growth Transverse/Longitudinal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>11.87 MeV/u</td>
<td>1.78 µm</td>
<td>~21%, ~64%</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>83 MeV/u</td>
<td>64 µm</td>
<td>~45%, ~103%</td>
</tr>
</tbody>
</table>

*Charge-stripping foil experiments at MSU
Simulation Results: Segment I

Segment I lattice without errors

Beam phase spaces at the end of Segment I

Beam transverse and longitudinal rms emittances in Segment I

No transverse rms emittance growth
Small longitudinal rms emittance growth
Simulation Results: Segment I

- Segment I with misalignment and rf errors
  - Alignment correction applied
  - 100 random seeds
  - No beam loss observed in simulations
  - Transverse and longitudinal emittance growths

Confidence plots of Beam rms emittances at the end of Segment I

- Beam continued through charge-stripping sections and Segment II and III with errors
End-to-End Simulations Summary

- No beam loss observed
- Transverse and longitudinal emittance growths acceptable

Transverse emittances and acceptances comparison

<table>
<thead>
<tr>
<th></th>
<th>Segment I Entrance</th>
<th>Segment II Entrance</th>
<th>Segment III Entrance</th>
<th>Segment III Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_T$ (rms) ($\pi$ mm-mrad)</td>
<td>0.09</td>
<td>0.16</td>
<td>0.24</td>
<td>0.25</td>
</tr>
<tr>
<td>$\varepsilon_T$ (99.5%) ($\pi$ mm-mrad)</td>
<td>0.9</td>
<td>1.4</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Rmax (mm)</td>
<td>10.4</td>
<td>9.6</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>Radial Aperture (mm)</td>
<td>15.0</td>
<td>15.0</td>
<td>25.0 (38.5)</td>
<td></td>
</tr>
<tr>
<td>Aperture/Rmax</td>
<td>1.4:1</td>
<td>1.6:1</td>
<td>2.1:1 (3.2 :1)</td>
<td></td>
</tr>
</tbody>
</table>
End-to-End Simulations Summary

Longitudinal emittances and acceptances comparison

<table>
<thead>
<tr>
<th></th>
<th>Segment I Entrance</th>
<th>Segment II Entrance</th>
<th>Segment III Entrance</th>
<th>Segment III Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_L$ (rms) ($\pi$ keV/u-ns)</td>
<td>0.10</td>
<td>0.64</td>
<td>1.8</td>
<td>2.2</td>
</tr>
<tr>
<td>$\varepsilon_L$ (99.5%) ($\pi$ keV/u-ns)</td>
<td>1.2</td>
<td>6.2</td>
<td>20.2</td>
<td>25.8</td>
</tr>
<tr>
<td>Acceptance ($\pi$ keV/u-ns)</td>
<td>3.5</td>
<td>20.0</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>Acceptance/ $\varepsilon_L$ (99.5%)</td>
<td>2.9:1</td>
<td>3.2:1</td>
<td>5.6:1</td>
<td></td>
</tr>
</tbody>
</table>

Longitudinal acceptance for 805 MHz 6-cell elliptical cavity lattice
Conclusions

• End-to-end beam simulations for RIA
  • Experimentally based input beams
  • Misalignment and rf errors
  • Charge-stripping foil model

• 10th sub-harmonic (80.5 MHz) RIA driver linac option proposed by MSU has adequate transverse and longitudinal performance for multi-charge state beam acceleration
Current and future beam dynamics studies

- Equipment loss scenarios – accelerating structures, focusing & steering elements
- Developing an automated SRF cavity tuning procedure for multi-charge beam acceleration
- Introducing PARMTEQm + IMPACT tools for beam simulations using supercomputers
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