SRF Systems for the Jefferson Lab Electron Ion Collider (JLEIC)

Presented by
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MOXA06
• What is JLEIC?
• Why is it challenging?
  – High level parameters, frequency choice
• Storage ring cavities
  – HOM damping options
• Cooler
  – ERL Linac and injector
  – Cooler Circulator Ring (CCR) and Harmonic fast kicker
• Crab cavities (ODU)
• Gap transient mitigation experiments
• Modular cryostat
• Conclusions
JLEIC Design Update (Apr. 2017)

energy range:

- $E_e$: 3 to 12 GeV
- $E_p$: 40 to 100-400 GeV
- $\sqrt{s}$: 20 to 65- 140 GeV

(upper limit depends on magnet tech. choice)

- **Electron complex**
  - CEBAF
  - Electron collider ring

- **Ion complex**
  - Ion source
  - SRF linac
  - Booster
  - Ion collider ring

- Fully integrated IR and detector
- DC and bunched beam coolers

arXiv: 1504.07961
April 2017 Update
JLEIC energy reach and luminosity

![Graph showing luminosity vs. CM energy](image)

- Luminosity (cm\(^{-2}\)s\(^{-1}\))
  - 10\(^{33}\) to 10\(^{35}\)
- CM Energy (GeV)
  - 20 to 140
- Curves for different magnetic fields:
  - Max dip field 3 T
  - 6 T
  - 8.4 T (LHC magnets)
  - 12 T
- Points indicating energy:
  - 40x3 GeV
  - 100x5 GeV
  - 100x10 GeV
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electron Ring NCRF</th>
<th>Proton SRF</th>
<th>Lead Ion SRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>4, 5, 10 GeV</td>
<td>30, 100 GeV/u</td>
<td>40 GeV/u</td>
</tr>
<tr>
<td>Frequency</td>
<td>476.3, 476.3, 476.3</td>
<td>952.64, 952.77, 952.57 MHz</td>
<td></td>
</tr>
<tr>
<td>Beam Average Current</td>
<td>3.00, 3.00, 0.708 A</td>
<td>0.50, 0.50 A</td>
<td></td>
</tr>
<tr>
<td>SRpower/ring (= power to beam)</td>
<td>1.08, 2.65, 10.00 MW</td>
<td>0.50, 0.50, 0.50 A</td>
<td></td>
</tr>
<tr>
<td>Energy Loss per Turn</td>
<td>0.362, 0.883, 14.124 MeV</td>
<td>0.00, 0.00, 0.00 degree</td>
<td></td>
</tr>
<tr>
<td>Vpeak, Total</td>
<td>1.82, 3.59, 21.69 MV</td>
<td>11.64, 44.66, 42.27 MV</td>
<td></td>
</tr>
<tr>
<td>Syn. Phase</td>
<td>11.5, 14.2, 40.6 degree</td>
<td>0.00, 0.00, 0.00 degree</td>
<td></td>
</tr>
<tr>
<td>Vgap, 1K2C</td>
<td>0.45, 0.45, 0.79 MV</td>
<td>0.73, 1.12, 1.06 MV</td>
<td></td>
</tr>
<tr>
<td>Vgap, 1K4C</td>
<td>0.47 MV</td>
<td>1.06 MV</td>
<td></td>
</tr>
<tr>
<td>Gradient, 1K2C</td>
<td>1.44, 1.43, 2.51 MV/m</td>
<td>4.62, 7.10, 6.72 MV/m</td>
<td></td>
</tr>
<tr>
<td>Gradient, 1K4C</td>
<td>1.49 MV/m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PowerToBeam per Cavity, 1K2C</td>
<td>271.18, 331.03, 363.90 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PowerToBeam per Cavity, 1K4C</td>
<td>215.62 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity Wall Loss Power, 1K2C</td>
<td>29.50, 28.76, 89.03 kW</td>
<td>0.3, 0.7, 0.7 W</td>
<td></td>
</tr>
<tr>
<td>Cavity Wall Loss Power, 1K4C</td>
<td>31.26 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward Power Per Cavity, 1K2C</td>
<td>316.15, 399.76, 459.76 kW</td>
<td>24.00, 56.54, 50.65 kW</td>
<td></td>
</tr>
<tr>
<td>Forward Power Per Cavity, 1K4C</td>
<td>249.22 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reflected Power, 1K2C</td>
<td>15.47, 39.97, 6.83 kW</td>
<td>24.00, 56.54, 50.7 kW</td>
<td></td>
</tr>
<tr>
<td>Reflected Power, 1K4C</td>
<td>2.35 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qext</td>
<td>4615, 4615, 4615</td>
<td>5.24E+04, 5.24E+04, 5.24E+04</td>
<td></td>
</tr>
<tr>
<td>Cavity Number, Total</td>
<td>4, 8, 34</td>
<td>16, 40, 40</td>
<td></td>
</tr>
</tbody>
</table>

Need high efficiency RF sources. Possibly magnetrons?
JLab EIC RF Systems

- **Electron ring**: PEP-II warm RF adopted
  - Proven technology, low cost
  - Enough cavities and klystrons available
  - 476.3 MHz buckets can be filled from CEBAF linac with simple timing
  - Upgrade to 952.6 MHz SRF in future

- **Ion ring**: new 952.6 MHz SRF bunching system
  - Plus low frequency capture, splitting and acceleration cavities

- **Cooler source and ERL** 952.6 MHz
  - Cooler baseline became *circulator ring*

- **Crab cavity system** 952.6 MHz

- Ion injector chain as developed by ANL
### First 952.6 MHz Cavity Fabrication Status

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Qty.</th>
<th>Material</th>
<th>Nb blanks for half cells</th>
<th>Nb blanks for beam tubes</th>
<th>Half cells deep-drawn</th>
<th>Beam Tubes</th>
<th>Flanges</th>
<th>Endgroups</th>
<th>Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-cell</td>
<td>1</td>
<td>Nb</td>
<td>2/2 – wire EDM completed</td>
<td>wire EDM completed</td>
<td>2/2 - completed</td>
<td>Completed/ machined</td>
<td>Completed/ machined (Nb flanges)</td>
<td>2/2 Welding completed</td>
<td>Waiting for RF trim fixture</td>
</tr>
<tr>
<td>1-cell</td>
<td>2</td>
<td>Cu</td>
<td>4/4 – wire EDM completed</td>
<td>wire EDM completed</td>
<td>4/4 - completed</td>
<td>Rolled/ not machined yet</td>
<td>SS CF flanges - to be ordered</td>
<td>Not yet Started</td>
<td>-</td>
</tr>
<tr>
<td>5-cell</td>
<td>1</td>
<td>Nb</td>
<td>10/10 – wire EDM completed</td>
<td>wire EDM completed</td>
<td>2/10 (new fixture in place to ease release of cells)</td>
<td>Completed/ machined</td>
<td>In stock – not yet used</td>
<td>Not yet started</td>
<td>-</td>
</tr>
</tbody>
</table>

- Single-cell Nb cavity endgroups ready, getting close to complete cavity
952.6 MHz SRF: HOM damping

- New 952.6 MHz high-current cavity shape
- 1-cell prototype in progress
- HOM damping schemes under evaluation
- Full RF system parameter tables defined

1) 3WG.  
2) 3 x coax dampers.  
3) enlarged beam pipes (ref)  
4) on-cell dampers

Cooler needs 5-cells in the ERL, 1-cells in the injector.  
Ion ring might use 2-cells
Impedance and feedback

- Broadband damping of cavity HOMs is essential.
- PEP-II feedback systems allowed running above threshold. Similar systems are now commercially available.
- JLEIC needs a high level system design and performance simulation for pre-CDR.
- Many other ring components need to be considered.
- Reliable high-power *kickers* are needed.

F. Marhauser, “Next Generation HOM-damping”, Special Issue on Superconducting RF for Accelerators, to be published.
Progress has been made to design of a heavily damped 952.6 SRF single-cell cavity with on-cell waveguide dampers.

The effective and broadband HOM damping with a similar arrangement of three waveguide dampers is well proven with normal-conducting cavities (e.g. BESSY 500 MHz cavity and PEP-II 476 MHz cavity).

The magnetic field enhancement at the surface (openings) can be limited to a factor of ~2 compared to standard elliptical cavities, around ~15 MV/m are feasible.

High Energy Cooling

- High energy cooling is a high priority R&D item
- Experiments at IMP suggest bunched-beam cooling works!
  top ring: CCR

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Multi-Turn High Energy Electron Cooler Baseline Design

- Developing the **ERL linac** and **injector** (similar to FELs)
- CCR Harmonic Fast injection/extraction kicker (**New**)
- Impedance and wakefield calculations are important
Individual HOM power values are summed up.

- Note that the spectral lines are weighted by the nominal 20 mm flat top bunch length, which produces the roll-off at the high frequency end (beyond 10 GHz however there will be a ripples due to the beer-can distribution, i.e. peak currents will raise again to some extent).

- The monopole HOM power up to 9.5 GHz is 137 Watts @ 2nC bunch charge.
- The HOM power is 350 Watts @ 3.2nC bunch charge.
Harmonic Fast Kicker R&D

138 kV kick voltage (2.5 mrad@55 MeV)
Baseline cavity design:
- six odd harmonics of 86.6 MHz to 952.6 MHz + possible DC, one cavity design for all harmonics, one pair for CCR
- High shunt impedance, ~3 kW @138 kV per cavity
- Asymmetric inner conductor design for the 952.6 MHz mode to minimize the beam loading effect

Compatible for future proposal of beam based tests at UITF/LERF Gun needs to operate at 136 MHz rep rate


New! 11 scheme

Ex & Ez vs z

Improved symmetry in gap, Sarah Overstreet summer student project 2017
JLEIC Crab cavity

Design by ODU
- 952.6 MHz “RF dipole” like LHC
- Modest RF system (no beam loading)
- Must have good HOM damping
- Cryostat may be similar to other cavities
- Multi-gap RF dipole would be very desirable

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Electron</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Bunch frequency</td>
<td>MHz</td>
<td>952.6</td>
<td></td>
</tr>
<tr>
<td>Crossing angle</td>
<td>mrad</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Betatron function @ IP</td>
<td>cm</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Betatron function @ crab cavity</td>
<td>m</td>
<td>~200</td>
<td>363.44</td>
</tr>
<tr>
<td>Integrated kicking voltage per IP side</td>
<td>MV</td>
<td>~2.8</td>
<td>20.82</td>
</tr>
<tr>
<td>Number of cavities per IP side (single cell RFD)</td>
<td></td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>Number of cavities per specie</td>
<td></td>
<td>6</td>
<td>36</td>
</tr>
</tbody>
</table>

Parameters still evolving

Location in IP

LARP/LHC prototype*

Multi-gap concept

EFFECTS OF CRAB CAVITY MULTIPOLES ON JLEIC ION RING DYNAMIC APERTURE, Salvador Sosa, V. Morozov, S. U. De Silva, J. R. Delayen, WEPIK044 proceedings of IPAC2017, Copenhagen, Denmark
CRAB CAVITY R&D, Jean Delayen, JLEIC Collaboration Meeting Spring 2017

*L. Ristori HL-LHC AUP Director’s Review – June 13 2017
Beam Transients in collider rings

Gaps in high current rings cause strong transients (e.g. KEK-B, PEP-II). Cannot be corrected by RF alone.

Does Fill Pattern Modulation Work? YES!

Collaboration with LBNL, JLab, IHEP and DimiTel.

D. Teytelman, Dimtel, Inc., San Jose, CA, USA.
“Transient beam loading in FCC-ee (Z)”, FCC Week 2017

Modular cryostat

- Take the best features of previous JLab designs
- Modular approach to hold various different cavities
- Design suitable for industrial production
- Simple concepts, low parts count to reduce costs

4 x 1-cell cavities
On-cell HOMs

4 x 2-cell cavities

2-cell “pair”
Modular helium vessel

1 to 5 cells, coax, WG or on-cell dampers
Modular cryostat: other examples

Concept is very versatile!

- 650 MHz 5-cell cavity?
- 400 MHz Double spoke β=1 cavity
- LCLS-II magnet package
- LCLS-II production cavity
- 802 MHz LHeC/FCC cavity?
- 400 MHz DQW?
- 476.3 MHz RFD Crab cavity?
Conclusions

• JLEIC has several challenging SRF cavity needs
• 952.6 MHz cavity designs are progressing
  – First prototype nearing completion
  – HOM damping schemes being refined
• Strong Cooling baseline ERL and CCR require
  – 5-cell and 1-cell cavities (similar to FEL’s)
  – Fast harmonic kicker (looks very promising)
• ODU “RF dipole” crab cavity looks good
• e-ring and i-ring system stability looks OK
  – Continue optimization, study feedback, transients
• Modular cryostat can hold many types of cavity
• Concepts may be useful for other projects
Thank you for your attention!