Overview of the EIC RF system and synergies with FCC-ee

R. Rimmer (Jlab)

On behalf of the EIC RF team

FCC week, June 29, 2021
Outline

• Overview of EIC
• SRF systems overview
  – ESR
  – HSR
  – Crabbing
  – RCS
  – High energy electron cooling
  – Polarized electron injector

• Notable challenges
• Critical component R&D
  – FPC
  – HOM absorbers
  – RF power

See also:
AN OVERVIEW OF RF SYSTEMS FOR THE EIC
R.A. Rimmer et. al., MOPAB385 IPAC21
**EIC RF systems**

- **Electron - 591 MHz electron storage cavity**
- **Electron - 1773 MHz 3rd harmonic cavity**
- **Rapid Cycling Synchrotron - 591 MHz acceleration cavity**
- **Electron - 591 MHz bunch compression cavity**
- **Hadron Cooling - 591 MHz acceleration cavity**
- **Injector - 571 MHz bunch compression cavity**
- **Hadron - 197 MHz bunch compression cavity**
- **Hadron - 24.5 MHz acceleration cavity**
- **Hadron - 49.2 MHz and 98.5 MHz bunch splitter cavity**
- **Both rings – crab cavities**
IR-10 Tunnel: Cryomodule Space Allocation

- Space constraints will contribute to the challenge for the integrated coupler/cryomodule design.

c. Doug Holmes
ESR RF system

• Up to 68 MV using 17 new 591 MHz 1-cell SRF cavities
  • maintain 1% Bucket height from 5-18 GeV
• Naturally short bunch length ~1cm
• 10 MW maximum beam power
• ~40 kW HOM power per cavity
• 2.5A maximum current
• Two fundamental power couplers per cavity, ~400 kW ea.
• Strong beam loading requires large detuning frequency (~revolution frequency), advanced RF controls.
• Transient beam loading will be significant.
• At lower energy we can use reverse-phasing method, reducing detuning frequency and transient modulation.
HSR RF system

- Keep existing 6 MV 6x197 MHz NCRF system
- Re-tune existing 2x 28 MHz system to 24.6 MHz
- Add 2x 49.2MHz and 2x 98.5MHz NCRF for binary bunch splitting
- Add 20 MV 591 MHz SRF system
- Up to 1A beam, up to 1160 bunches
- Optimum detuning for reactive power (like LHC)
- Beam loading transient and collective effects studies started
Crabbing Systems

• New SRF crabbing systems for both rings
• Large voltage needed for 25 mRad crossing angle
• ESR system 394 MHz 2.9 MV each side
  • Need second harmonic for linearization
• HSR system 197 MHz 34 MV each side
• IR 6 total 8x 197 MHz cavities, 6x 394 MHz cavities
• RFD type selected for both rings
• HOM damping optimization ongoing
• Noise and RF dynamics studies needed

Binping Xiao, J. R. Delayen, Subashini De Silva, Z. Li, R. Rimmer, S. Verdu-Andres, Qiong Wu, WEPCAV014, SRF 2021
RCS

- Requires rapid acceleration of one or two high charge bunches per cycle for full energy injection
- **3x 591 MHz 5-cell** cavities, same as HSR and ERL
- Bunch merging to achieve peak bunch charge
- Harmonic injection kicker into RCS
- Fast kickers for injection into ESR
High energy electron cooling

- Single Pass **150 MeV ERL**, 98.5 MHz bunch frequency
- **8 x 591 MHz, 5-cell** elliptical + **1.77 GHz** third harmonic
- Maximum 180 MV installed voltage, Eacc **15.8 MV/m**
- **8 x 591 MHz, 65 kW CW**, SSA RF Power Amplifiers
- **1 nC** per bunch, ~**100 mA** single pass current (like FCC-eh)
- Injector: DC photocathode gun, 197 MHz buncher, 591 MHz acceleration, 1.77 GHz linearizer.

“The accelerator design progress for EIC strong hadron cooling”, E. Wang et. Al., TUPAB036 Proc. IPAC21, Brazil.
Polarized electron injector

- 350 kV DC photocathode gun
- 118 MHz buncher
- 591 MHz buncher
- 2856 MHz SLAC-type linac to 400 MeV
- 1182 MHz de-chirper
Notable challenges

- High currents
  - HOM power, BBU, RF stability, resonant heating
- High bunch charge
  - Single bunch instabilities, wakefields, CSR, resistive wall heating
- High beam power
  - RF power, couplers, collimators
  - Gap transients
- Crabbing
  - High voltage, HOMs, linearity, synchronization, noise

simulations of the RF system-beam interaction in the EIC electron ring
Critical component R&D
EIC FPC: 400 kW CW, Variable $Q_{\text{ext}}$ Couplers

- EIC will use new fixed 500 kW CW coupler design.
- Vary $Q_{\text{ext}} \times 10$ using adjustable waveguide tuner section.
- Initial funding by BNL LDRD
- Now on project funds.

Courtesy Wencan Xu
ESR Cavity/Cryomodule Concept with 500 kW Fixed Coupler

- Coupler is an evolution from the KEK / SNS / BNL high power fixed coupler design
- Goals: High power, broadband and physically robust window

End view of the cryomodule, cut on the mid-plane of the couplers. Courtesy: Jim Henry, F. Marhauser.

FCC-ee FPC needs:

- Power need at FCC-ee Z-pole: 1 MW/single-cell cavity.
- FCC baseline: use 2x 500 kW power couplers (LHC-type)
- R&D towards 1 MW CW power couplers is only starting
- Complication: to use the same 4-cell cavities in FCC-ee “WW” and FCC-ee “ZH”, the coupling must be changed.

\( Q_{\text{ext}} \) variable by a factor 20.

Tested up to 500 kW CW forward.

E. Montesinos
EIC High Power SIC HOM Absorber

• Requirement and challenge
  • High power (~20 kW ea.), broadband HOM dampers
  • Large size of SiC HOM damper for low frequency
• Initial LDRD program, now on project
  • Low power test on a cavity to test effective damping bandwidth
  • High power test to test the power handling capability
• Design approach:
  • Solid one-piece HOM damper, Simple shrink-fit assembly based on ANL design
RF power options

Super-power klystrons
Limited vendors, high cost, low efficiency

Combined IOT’s
Better efficiency, becoming obsolete

Combined SSA’s
High efficiency
Reliability and redundancy
Costs falling, supply growing

50 kW SSA module
2x400 kW SSA module

Approximately 70 ft, 22m.

IOT
MW klystron

SPS 200 MHz, 4.6 MW SSPA
Advanced structure R&D

- Conservative baseline choices (KEK-B and LHC type)
  - Asymmetric EIC cavity under study to ease packaging
- On-cell damped JLEIC concept
  - Jlab LDRD funded
  - “Extreme” HOM damping
- CERN SWELL concept
  - Novel fabrication approach

Igor Syratchev et al.
Alternative materials

- **Thin film Nb on copper (HIPIMS)**
  - Significant cost savings at 197 MHz or 394 MHz
- **Multilayers (Nb, NbN, NbTiN)**
- **Nb$_3$Sn**
  - Potential for high Qo at 4K
- **HTS?**
  - In time for FCC perhaps?

Research to understand the fundamental growth mechanism of Nb$_3$Sn linked with RF performance

Factors contributing to Q-slopes in Nb$_3$Sn cavities

Grain-boundary diffusion primarily controls thin-film growth. Patchy regions lack grain boundaries resulting in thin regions.

PI: Uttar-Pudasaini

PI: Anne Marie Valente Feliciano
Conclusions

• EIC project is making good progress
• Pushing the state of art on many frontiers
• RF systems being developed as an integrated set
• High degree of modularity in design
• Many challenges ahead and much synergy with FCC

Thank You For Your Attention!

Back up
Introduction to EIC at BNL

Hadron Ring based on RHIC
- Up to 275 GeV Proton Store Energy
- 1 A maximum beam current
  - 1160 bunches, 11 nC per bunch

ESR: new electron Storage Ring
- 5 GeV – 18 GeV
- 2.5 A maximum beam current (10 GeV)
  - 1160 bunches, 28 nC per bunch
- Up to 10 MW synchrotron radiation power
- Up to 38 MeV loss per turn (18 GeV)

Strong Hadron Cooling
- ERL, Single Pass Up/Down
- 150 MeV, 100 mA

IR Crab Cavities
- 25 mrad crossing angle
- 8x Hadron Crab Cavities
- 6x electron Crab Cavities

RCS: new Rapid Cycling Synchrotron
- 400 MeV – 18 GeV Full Energy e- Injector
- 1 Hz Repetition Rate
- 100 ms ramp
- Up to 28 nC per bunch
# EIC ESR frequency comparison

<table>
<thead>
<tr>
<th></th>
<th>394</th>
<th>591</th>
<th>788</th>
</tr>
</thead>
<tbody>
<tr>
<td>#cells (eSR)</td>
<td>14</td>
<td>17</td>
<td>32</td>
</tr>
<tr>
<td>#Amplifiers (eSR)</td>
<td>14</td>
<td>17</td>
<td>16</td>
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<tr>
<td>impedance</td>
<td>least</td>
<td>Acceptable (?)</td>
<td>most</td>
</tr>
<tr>
<td>Est. HOM power (kW)</td>
<td>264</td>
<td>580*</td>
<td>704</td>
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<tr>
<td>3H freq</td>
<td>1182</td>
<td>1773</td>
<td>2364 (1572 2\textsuperscript{nd}?)</td>
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<tr>
<td>Comments:</td>
<td>Synergy with LHC/FCC</td>
<td>Synergy with FCC-ee? (SWELL?)</td>
<td>Synergy with PERLE/FCC</td>
</tr>
<tr>
<td>size</td>
<td>Large. New cavity, cryostat, infrastructure</td>
<td>Large but fits in most Jlab infrastructure and modular cryostat</td>
<td>Fits in cryostat and infrastructure</td>
</tr>
<tr>
<td>transients</td>
<td>least</td>
<td>acceptable</td>
<td>most</td>
</tr>
<tr>
<td>Max bunch rate (MHz)</td>
<td>394</td>
<td>197</td>
<td>788</td>
</tr>
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</table>

*still under optimization

EIC baseline
600 MHz option for FCC-ee?

FCC-ee RF systems

Possible candidates for 600 MHz?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>WW</th>
<th>ZH</th>
<th>tt1</th>
<th>tt2</th>
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<tbody>
<tr>
<td>Beam Energy (GeV)</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>182.5</td>
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<tr>
<td>Beam current (mA)</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>6.4</td>
<td>5.4</td>
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<tr>
<td>Number of bunches</td>
<td>16640</td>
<td>2000</td>
<td>328</td>
<td>59</td>
<td>48</td>
</tr>
<tr>
<td>Beam RF voltage (MV)</td>
<td>100</td>
<td>750</td>
<td>2000</td>
<td>9500</td>
<td>10 930</td>
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<tr>
<td>Run time (year)</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

- Z: 400 MHz, 1-cell, strong HOM damping! 2 MV/cavity, 1 MW/cavity!
- WW: 400 MHz, 4-cell, still substantial BL and HOM excitation, 1 MW/cavity
- ZH: 400 MHz, 4-cell cavities, 370 kW per cavity (change FPC)
- tt: realign 400 CMs to share them for both beams, add 800 MHz, 5-cell cavities, operated at 20 MV/m, 175 kW/cavity
## Summary of RF systems for EIC

<table>
<thead>
<tr>
<th>RF System</th>
<th>Sub System</th>
<th>Freq [MHz]</th>
<th>Type</th>
<th>Location</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Storage</td>
<td>Fundamental</td>
<td>591</td>
<td>SRF, 1-cell</td>
<td>IR-10</td>
<td>17</td>
</tr>
<tr>
<td>RCS</td>
<td>Fundamental</td>
<td>591</td>
<td>SRF, 5-cell</td>
<td>IR-10</td>
<td>3</td>
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<tr>
<td>Pre-Injection</td>
<td>Buncher 1</td>
<td>118</td>
<td>Copper, ¼ Wave</td>
<td>IR-2</td>
<td>1</td>
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<tr>
<td></td>
<td>Buncher 2</td>
<td>591</td>
<td>Copper, 1-cell</td>
<td>IR-2</td>
<td>2</td>
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<tr>
<td>De-chirper</td>
<td></td>
<td>1182</td>
<td>Copper LINAC</td>
<td>IR-2</td>
<td>1</td>
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<tr>
<td></td>
<td>400 MHz LINAC</td>
<td>2856</td>
<td>SLAC type LINAC</td>
<td>IR-2</td>
<td>6</td>
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<tr>
<td>Hadron Ring</td>
<td>Capture / Accel</td>
<td>24.6</td>
<td>Copper, Quarter Wave</td>
<td>IR-4</td>
<td>2</td>
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<tr>
<td></td>
<td>Bunch Split 1</td>
<td>49.2</td>
<td>Copper, Quarter Wave</td>
<td>IR-4</td>
<td>2</td>
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<tr>
<td></td>
<td>Bunch Split 2</td>
<td>98.5</td>
<td>Copper, Quarter Wave</td>
<td>IR-4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Bunch Comp. 1</td>
<td>197</td>
<td>Copper, 1-cell</td>
<td>IR-4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Bunch Comp. 2</td>
<td>591</td>
<td>SRF, 5-cell</td>
<td>IR-10</td>
<td>1</td>
</tr>
<tr>
<td>Crab Cavity</td>
<td>Hadron</td>
<td>197 + 394</td>
<td>SRF, RFD</td>
<td>IR-6</td>
<td>8 + 4</td>
</tr>
<tr>
<td></td>
<td>Electron</td>
<td>394</td>
<td>SRF, RFD</td>
<td>IR-6</td>
<td>2</td>
</tr>
<tr>
<td>Hadron Cooling</td>
<td>NC Buncher</td>
<td>197</td>
<td>Copper, 1-cell</td>
<td>IR-2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>SRF booster</td>
<td>591</td>
<td>SRF, 1.5-cell</td>
<td>IR-2</td>
<td>1</td>
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<tr>
<td></td>
<td>ERL Linac</td>
<td>591</td>
<td>SRF, 5-cell</td>
<td>IR-2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Third Harmonic</td>
<td>1773</td>
<td>SRF, 5-cell</td>
<td>IR-2</td>
<td>4</td>
</tr>
</tbody>
</table>
Reverse phase operation

- Also known as counter-phasing or RF FODO
- Allows keeping higher cavity stored energy for nominal bunch length at lower beam energy
- Reduces detuning angle
- Reduces range of Qext of FPC
- Reduces gap transients at low beam energy
- R and N cavities have slightly different gap transients
- R cavity reflected power increases after a beam trip

Yoshiyuki Morita, KEK, Presentation at EIC workshop 6-9 Oct 2020
https://indico.cern.ch/event/949203/

Y. Morita et al., IPAC’10, p. 1536