SRF Challenges and R&D for the EIC

Bob Rimmer

For the EIC RF design team

FCC week, 11.20
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  - J. Fox (Stanford University)
  - C. Rivetta (SLAC)

- **Crab Cavity HOM Damping Simulations**
  - Z. Li (SLAC)

The Future Circular Collider Innovation Study (FCCIS) project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant No 951754.
Outline

• Dedication
• Overview of EIC
• SRF systems overview
  – ESR
  – HSR
  – Crabbing
  – RCS
  – Strong Hadron Cooling
• LLRF
• Critical component R&D
• RF power
• Alternative materials
• Conclusions
Glen Lambertson, whose Berkeley Lab career in accelerator science and technology spanned more than half a century, passed away August 30 in Oakland, CA at the age of 94.

Raised in Colorado in a farmhouse without electricity, Lambertson would become known for seminal contributions to some of the most advanced and nuanced aspects of particle accelerators, making possible the infrastructure of discovery.

A great but humble man who was a mentor to me and many many others

His ideas live on in machines like these.

https://atap.lbl.gov/in-memoriam-glen-r-lambertson-1926-2020/
EIC RF systems

- Electron - 591 MHz electron storage cavity
- Hadron - 591 MHz bunch compression cavity
- Hadron Cooling - 591 MHz acceleration cavity
- Both rings - 394 MHz crab cavity
- Hadron - 24.5 MHz acceleration cavity
- Hadron - 49.2 MHz and 98.5 MHz bunch splitter cavity
- HSR 197 MHz crab cavity
- Injector - 571 MHz bunch compression cavity
- Rapid Cycling Synchrotron - 591 MHz acceleration cavity
- Electrons
- Ions
- Possible Detector Location
- IR10
- IR8
- IR6
- Electron Storage Ring
- Ion Transfer Line
- IR12
- injector Linac
- Electron Cooler
- Polarized Electron Source
- 41 GeV Arc
- 100 meters
# EIC RF Systems (By The Numbers)

<table>
<thead>
<tr>
<th>RF System</th>
<th>Sub System</th>
<th>Freq [MHz]</th>
<th>Type</th>
<th>Location</th>
<th># Cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Storage Ring</td>
<td>Fundamental</td>
<td>591</td>
<td>SRF, 1-cell</td>
<td>IR-10</td>
<td>18</td>
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<tr>
<td>Rapid Cycling Synchrotron</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>Bunch Merge 1</td>
<td></td>
<td>295</td>
<td>NCRF, Reentrant</td>
<td>IR-4 or IR-10</td>
<td>2</td>
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<tr>
<td>Bunch Merge 2</td>
<td></td>
<td>148</td>
<td>NCRF, Reentrant</td>
<td>IR-4 or IR-10</td>
<td>1</td>
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<tr>
<td>Hadron Ring</td>
<td>Capture / Accel</td>
<td>24.6</td>
<td>NCRF, QWR</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>NCRF, QWR</td>
<td>IR-4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Bunch Split 2</td>
<td>98.5</td>
<td>NCRF, QWR</td>
<td>IR-4</td>
<td>2</td>
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<tr>
<td></td>
<td>Store 1</td>
<td>197</td>
<td>NCRF, Reentrant</td>
<td>IR-4</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Store 2</td>
<td>591</td>
<td>SRF, 5-cell</td>
<td>IR-10</td>
<td>2</td>
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<tr>
<td>Strong Hadron Cooling</td>
<td>Bunch Comp.</td>
<td>197</td>
<td>NCRF, Reentrant</td>
<td>IR-2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>SRF Booster</td>
<td>197</td>
<td>NCRF, Reentrant</td>
<td>IR-2</td>
<td>6</td>
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<tr>
<td></td>
<td>Linearization</td>
<td>591</td>
<td>NCRF, Reentrant</td>
<td>IR-2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Fundamental</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>3</td>
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<tr>
<td>Crab Cavity</td>
<td>Hadron</td>
<td>197</td>
<td>SRF, DQW/RFD</td>
<td>IR-6</td>
<td>8 (4 CM)</td>
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<tr>
<td></td>
<td>Hadron/Electron</td>
<td>394</td>
<td>SRF, DQW/RFD</td>
<td>IR-6</td>
<td>6</td>
</tr>
</tbody>
</table>
EIC Proton and Electron Beam Parameters

- Example: CDR Table 3.3 - Highest luminosity operation

<table>
<thead>
<tr>
<th>Species</th>
<th>proton</th>
<th>electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>275</td>
<td>18</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>140.7</td>
<td>104.9</td>
</tr>
<tr>
<td>Bunch intensity [$10^{10}$]</td>
<td>19.1</td>
<td>6.2</td>
</tr>
<tr>
<td>No. of bunches</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.69</td>
<td>0.227</td>
</tr>
<tr>
<td>RMS norm. emit., h/v [µm]</td>
<td>5.2/0.47</td>
<td>845/71</td>
</tr>
<tr>
<td>RMS emittance, h/v [nm]</td>
<td>18/1.6</td>
<td>24/2.0</td>
</tr>
<tr>
<td>$\beta^*$, h/v [cm]</td>
<td>80/7.1</td>
<td>59/5.7</td>
</tr>
<tr>
<td>IP RMS beam size, h/v [µm]</td>
<td>119/11</td>
<td>95/8.5</td>
</tr>
<tr>
<td>$K_\delta$</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>RMS $\Delta \theta$, h/v [µrad]</td>
<td>150/150</td>
<td>202/187</td>
</tr>
<tr>
<td>BB parameter, h/v [$10^{-3}$]</td>
<td>3/3</td>
<td>93/100</td>
</tr>
<tr>
<td>RMS long. emittance [$10^{-3}$, eV·s]</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>RMS bunch length [cm]</td>
<td>6</td>
<td>0.9</td>
</tr>
<tr>
<td>RMS $\Delta p/p$ [$10^{-4}$]</td>
<td>6.8</td>
<td>10.9</td>
</tr>
<tr>
<td>Max. space charge</td>
<td>0.007</td>
<td>neglig.</td>
</tr>
<tr>
<td>Piwinski angle [rad]</td>
<td>6.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Long. IBS time [h]</td>
<td>2.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Transl. IBS time [h]</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>Hourglass factor $H$</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>Luminosity [$10^{33}$cm$^{-2}$s$^{-1}$]</td>
<td>1.54</td>
<td></td>
</tr>
</tbody>
</table>
ESR RF system

- Up to **70 MV** using new **591 MHz** SRF cavities
  - maintain 1.2% Bucket height from 5-18 GeV
- Naturally short bunch length ~1cm
- **10MW** maximum beam power, **2.5A** maximum current
- Two fundamental power couplers per cavity, ~**400kW** ea.
- Beam loading effects will be significant.

Alternate single-cell design
(JLab style cryostat)
# 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>18</td>
<td>32</td>
</tr>
<tr>
<td>#Amplifiers (eSR)</td>
<td>14</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>impedance</td>
<td>least</td>
<td>reference</td>
<td>most</td>
</tr>
<tr>
<td>Est. HOM power (kW)</td>
<td>264</td>
<td>528</td>
<td>704</td>
</tr>
<tr>
<td>3H freq</td>
<td>1182</td>
<td>1773</td>
<td>2364 (1572 2\textsuperscript{nd}?)</td>
</tr>
<tr>
<td>Comments:</td>
<td>Synergy with LHC/FCC (e.g. crabs)</td>
<td>unique</td>
<td>Synergy with PERLE/FCC (e.g. crabs)</td>
</tr>
<tr>
<td>size</td>
<td>New cavity, cryostat, infrastructure</td>
<td>CDR reference design (fits in Jlab mod. 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>
</tbody>
</table>

Baseline for CDR
394 MHz cavity dimensions

Jlab 400 MHz cavity
Feisi He thesis project
SRF2013, Paris, France

Will keep studying as a back up option

394 MHz 1-cell concept

591 MHz 1-cell concept
HSR RF system

- Keep existing RHIC 12 MV 12x197 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 28 MV 591 MHz SRF system
- Up to 1A beam, up to 1160 bunches
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
- HSR system 197 MHz 34 MV each side
  - Need second harmonic for linearization
- IR 6 total 8x 197 MHz cavities, 4x 394 MHz cavities
- **LHC crab cavity tests in SPS are invaluable!**
- Two candidates under consideration based on LHC experience, DQW and RFD
  - Both meet voltage requirements
  - Both can meet pressure code (even at 197 MHz)
  - Both have been fabricated at 400 MHz
  - Both need improved HOM damping for EIC
Crabbing Systems

DQW 394 MHz crab cavity

RFD 197 MHz crab cavity

“WOW” crab cavity
Courtesy: Zhenghai Li

DQW 197 MHz crab cavity

RFD 197 MHz crab cavity

Courtesy: Qiong Wu, Silvia Verdú-Andrés, Doug Holmes, Binping Xiao

Courtesy: Suba Da Silva, HyeKyoung Park, Jean Delayen, ODU, Jim Henry Jlab.
Crabbing RF systems HOM damping

- 290 bunches 0.74A, and 1160 bunches 1A, are considered, with 6cm bunch length.
- HOM power is <3.41kW, with more than 80% from longitudinal modes.

Impedance thresholds:
\[ Z_l = 3750 \, \Omega, \quad Z_t = 1.35 \times 10^6 \, \Omega/m \]
Crab cavity packaging

- Waveguides can be folded
- HOM loads in warm region outside thermal shield

Also looking at coax transitions
Rapid Cycling Synchrotron

- 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
- Fast tuning during ramping

\[ E_{\text{acc}} : \ 15.8 \ \text{MV/m} \]
\[ P_{\text{dyn}} : \ 32 \ \text{W} \]
\[ U_{\text{sync}} = 36 \ \text{MeV / turn (18 GeV)} \]
\[ \Delta f_{\text{acc}} = 500 \ \text{Hz from 400 MeV} - 18 \ \text{GeV}. \]

RF Power Amplifiers
- 3x 591 MHz, 65 kW CW, IOT
- Solid State looks very promising
Strong Hadron Cooling (SHC)

- Single Pass 150 MeV ERL (1 up, 1 down)
- 8x 591 MHz, 5-cell elliptical, 2K
- Maximum 180 MV, Eacc 15.8 MV/m
- 9x 591 MHz, 65 kW CW RF Power Amplifiers
- 100 mA single pass current
- 98.5 MHz bunch frequency
- HOM power well below the 20 kW per absorber rating.

Courtesy of Erdong Wang
LLRF controls

- High currents, abort gaps require state of the art LLRF
- Will benefit from experiences at LHC, PEP-II, Super KEK-B etc.

- Simulations by T. Xin and G. Bassi with full RF beam physics.
- Working with collaborators to develop the LLRF control requirements.
  - T. Mastoridis (Cal Poly), C. Rivetta (SLAC), J. Fox (Stanford University)
  - Utilizing and further developing proven tools to understand transient beam loading, optimal detuning, coupled bunch thresholds, feedback architecture and power requirements.
  - Will include real-world effects (loop delay, linearity, noise, dynamic range, etc.).
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

T. Mastoridis (Cal Poly)
500 kW CW, Variable Q_{ext} Couplers

- Use existing fixed 500 kW CW coupler design.
- Vary Q_{ext} using adjustable waveguide tuner section.
- Initial funding by BNL LDRD.
- Testing delayed by Covid19.
High Power SIC HOM Absorber

• Requirement and challenge
  — High power, broadband HOM damper
  — Large size of SiC HOM damper for low frequency

• Initial LDRD program on SiC HOM absorber:
  — Low power test on a cavity to test effective damping bandwidth
  — High power test to test the power handling capability

• Results:
  — Tests were delayed due to CoVID-19.

• Inspiration
  — Instead of one solid piece HOM damper, fabrication and RF study of piece-by-piece (tile) type HOM damper
  — HOM damper suitable for various temperature environments
RF power options

Super-power klystrons
  Limited vendors, high cost, low efficiency
Combined IOT’s
  Better efficiency, becoming obsolete
Combined SSA’s
  High efficiency, redundancy, costs falling

PEP-II 1.2 MW klystron and HVPS

50 kW SSA module

400 kW SSA module
**Scope Detail: RF1010 Building**

- 2020: RF1010 Support Building with **14.4 MW** total SSA based high power RF, interface to IR-10 and IR-10 cryomodule layout.**
  - Remarkable power densities becoming realistic for solid state power across the digital TV broadcast frequencies.
  - 3D model is based on one of the vendor budgetary proposals.

- **591 MHz, 400 kW modular amplifier unit.**
  - 36 = 18 * 2 shown.
  - 7.2m (L) x 1.4m (D) x 2.2m (H)

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* 14.4 MW is just the result of showing 36x 400 kW “units”. Vendor budgetary quote in this case is based on 400kW = 4x 100kW per amplifier.

** This layout is a conceptual layout to explore the space requirements for 18x single cell 591 MHz ESR cryomodules. The 18 cryomodules fit in the available IR space. The SSA power density leads to reduced building space needs.
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 who knows?

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

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

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

PI: Uttar-Pudasaini

PI: Anne Marie Valente Feliciano
Conclusions

• Making good progress on EIC design
• Taking full advantage of community knowledge
  – Combined BNL and JLab RF team
  – Modern light-source practices (e.g. impedances)
  – LHC crab cavity, beam loading, FCC studies
  – T. Mastorides, J. Fox on transients and RF controls
  – PEP-II and KEK-B experience
  – Recent large scale SRF projects
• Developing the RF systems as an integrated set
• High degree of modularity in cryomodule design.
• Many challenges ahead and much synergy with FCC

Thank You