RF System Challenges in Circular Colliders

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Jlab
(with thanks to many colleagues worldwide for examples and materials)

Tuesday January 22nd, 2019, HKUST
Outline: Collider challenges (using examples from JLEIC and other machines)

- High energy
  - Many cavities/cells
  - High synchrotron radiation power (e+e-)

- High currents, many bunches
  - High beam power
  - Detuning
  - Instabilities
  - High power couplers/windows
  - Coupled-bunch modes, BBU, feedback

- Gaps
  - Ion clearing or abort gaps
  - Transients
  - Complex beam spectrum

- Interaction regions
  - Impedance/heating
  - Crab crossing

- Conclusions
Introduction to JLEIC

- **JLab electron ion collider**
- Figure 8 to preserve polarization
- High currents (3A e-, 750 mA p+)
- Many bunches
- Modest charge per bunch
- e-cooling for ions
- Synchrotron damping for e-
- Injection, top-off from CEBAF for e-
- New ion injection complex

**Beam Design**
- High repetition rate
- Low bunch charge
- Short bunch length
- Small emittance

**IR Design**
- Small $\beta^*$
- Large beam-beam
- Crab crossing

**Damping Design**
- Synch. radiation
- Beam cooling

**Electron complex**
- CEBAF as a full energy injector
- Electron collider ring

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

RF System Challenges in Circular Colliders
High energy requirements

- Many cavities/cells
  - Multi-cell cavities may be desirable if possible

- High synchrotron radiation power (e+e-)
  - May push coupler limits
  - Coupler power may limit the number of cells per cavity (typically 1-5 cells)
  - Practical limit of affordable power?

- Reliable operation
  - Moderate gradients, try to avoid field emission
  - Safety factor on power coupler
  - Strong cooling/thermal management
High currents, many bunches

- High beam power
  - Ampere level currents
  - 10’s to 100’s of MW beam power
  - Achieved through moderate current per bunch, many bunches
  - Requires synchrotron radiation absorbers, chamber cooling (e+e-)
  - Need collimation to protect the detector, active beam abort to protect the machine (gaps)

- Detuning
  - Heavy beam loading may require detuning over multiple revolution harmonics

- Instabilities
  - Longitudinal and transverse HOMs, detuned fundamental
  - Many possible CB modes, broad-band bunch by bunch feedback systems needed

- High power couplers/windows
  - MW class windows have been designed (not so many vendors left)
  - Typically de-rated ~50% for storage ring use (PEP-II, KEK-B, ~500 kW)

- HOM damping/power
  - HOM power can be many kW per cell
  - Cell shape should be optimized to reduce BBU, minimize power
  - High-power broad-band absorbers needed
Effect of detuning and RF feedback

**PEP-II type digital LLRF** system had additional loops for comb filter, klystron equalization and ripple, low mode LFB, gap loop, saturation loop, etc.

“Beam loading compensation for Super B-factories”, Dmitry Teytelman, PAC05

Cavity detuned for beam loading

Direct loop on

Comb loop on
Coupled Bunch Instabilities

This instability happens when single bunch coherent motion gets coupled among bunches when there is long range wakefield.

- **Single bunch modes in longitudinal phase space**
  - Rigid bunch oscillation
  - Higher order bunch shape oscillation

- **Coupled Bunch Modes**

PEP-II actual bunch rate $\leq \frac{476}{2} = 238$ MHz, 119 MHz BW needed (kickers built)
Transverse FB electronics DC-238 MHz
W. Barry, PAC95
LFB cavity 952-1190 MHz
(1071 MHz center frequency, 238 MHz BW)
P. McIntosh, PAC03
Impedance and feedback

- Broadband damping of cavity HOMs is essential
- Many other ring components need to be considered
- PEP-II feedback systems allowed running above threshold. Similar systems are now commercially available
- System will be coupled to main RF for low modes
- Reliable high-power kickers are needed

Figure 1: Transverse feedback system concept.

PEP-II Longitudinal Feedback system concept

APS type transverse kicker

DAPHNE type kicker
Narrowband Impedance Estimation: JLEIC e-Ring

- RF cavity in e-Ring (PEP-II cavities)

PEP II cavity
476 MHz, single cell, 1 MV gap with 150 kW, strong HOM damping, >400 kW RF to beam
• 956 MHz 2-cell Cavity (F. Marhauser)

as tradeoff between accelerating and HOM-damping efficiency

causes LCBI

Unstable!
JLEIC ion-Ring new baseline

- 956 MHz 2-cell Cavity (F. Marhauser)
- Waveguide HOM dampers

Stable!

RF System Challenges in Circular Colliders
Prototype EIC cavity

- Prototype EIC high-current cavity shape, vertical test January 2019
Beam Gaps

- Ion clearing or abort gaps
  - High stored beam energy requires abort gaps and special beam dump lines
  - Gap length is determined by kicker rise time
  - Gaps may also be needed for ion clearing or electron cloud

- Transients
  - Gaps cause transient beam loading
  - Can saturate klystron if high gain direct loop is used
    - Klystron small signal gain goes to zero, feedbacks stop working
  - Causes phase transient along the beam fill
  - Modulates arrival time of bunches at IP (and at crab cavities)
  - Introduces bunch length variation and synchrotron tune spread along the train

- Complex beam spectrum
  - Causes spectral lines at revolution harmonics in between RF lines
  - May induce significant power in some HOMs
  - May induce significant power in beam chamber components (bellows, IR chamber etc.)
Gap transient mitigations:

- Superconducting RF cavity has potential for higher stored energy, smaller transients
- Alternate Idea - used at KEKB - NC ARES energy storage cavity system
- Feed-forward, avoids saturating klystron due to direct feedback
- Match transients in both rings (PEP-II)
- Fill pattern shaping?
Fill pattern modulation

Add charge either side of the gap to reduce transient over most of the fill.

**Does Fill Pattern Modulation Work?**  YES!

What about ions?

**Baseline:** ions binary bunch splitting. Results in long gaps

**Alternative:** barrier bucket rebunching?

Can we shorten the gap?

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D. Teytelman, Dimtel, Inc., San Jose, CA, USA.

*Transients beam loading in FCC-ee (Z)*, FCC Week 2017


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**ALS data (electrons)**

**Phase transient**

**Reduced transient**

**Injection and acceleration**

**Debunching and coasting**

**Rebunching**

**Baseline:** ions binary bunch splitting.

**Results in long gaps**

**x7**

**RF System Challenges in Circular Colliders**
Interaction regions

• Impedance/heating
  - IR chamber has complex geometry and may have high loss factor and trapped modes
  - Masks and collimators may make the problem worse
  - May drive BBU instabilities
  - May couple unacceptable power from the beam
  - Should minimize impedance by design
    • Avoid trapped/re-entrant volumes
    • Smooth tapers
    • Damp residual modes with absorbing material
  - Manage remaining heat with active cooling

• Crab crossing
  - Avoid parasitic crossings for closely spaced bunches
  - Avoid e+ or e- bends close to IP
  - Need crab cavities with high voltage and good HOM damping
  - Tight alignment tolerance to minimize beam loading
  - May experience (or need to follow) gap transients

Possible to get ~100% acceptance for the whole event
Narrowband Impedance: IR Chamber first look

JLEIC IR Chamber CAD Model (Marhauser)

Many trapped modes! Needs optimization

Monopole Modes

Dipole Modes

RF System Challenges in Circular Colliders
Crab Crossing

- Electron and ion beams have to cross at an angle in an EIC
  - Create space for independent electron and ion IR magnets
  - Avoid parasitic collisions of shortly-spaces bunches
  - Improves detections
  - Improves detector background

- Without compensation, geometric luminosity loss is about a factor of 12 and there is potential for dynamic instabilities

- Crabbing restores effective head-on collisions

- Local compensation scheme
  - Set of crab cavities upstream and downstream of IP

- Deflective crabbing
  - Demonstrated at KEK-B
  - Tested with ions at CERN SPS
  - JLEIC Prototype being developed by ODU
Conclusions

• High current and high energy colliders provide many RF system challenges
• Techniques from light sources and “Factories” can be adapted and updated
• New SRF cavity designs can advance the state of the art
• RF power costs are significant
• Gap transients are challenging and not completely solved
• Crab crossing brings its own challenges
  - SPS test with protons very encouraging!
• These problems are common to all new circular colliders

Thank you for your attention
RF System Challenges in Circular Colliders

JLEIC

- Define RF system requirements
- Support the pre-CDR
- Cooler ERL injector, and harmonic kicker
- New Ion ring cavities
- New e-ring cavities (?)
- Cavity prototyping
- Fast feedback
- Impedance (incl. IR)
- CEBAF as injector

476.3 MHz e-ring (NCRF PEP-II)

952.6 MHz crab (SCRF)

952.6 MHz i-ring (SCRF)

Future IP

Electron Injector

12 GeV CEBAF

Halls A, B, C

JLEIC Collider Rings

Cooling

i-SRF + NCRF

Crab

IP

SRF Linac

Booster

ODU

Future IP

Harmonic Fast kicker for cooling ring

952.6 MHz booster (SCRF)
Cooler ERL 5-cell cavity

- Evaluated coax and WG end groups
- Estimated HOM power for various fill patterns including gaps
- Worst case ~6 kW so prefer WG
- 5-cell bare prototype tested

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>f_{RF} (MHz)</td>
<td>952.636</td>
</tr>
<tr>
<td>Cooling bunch rate (MHz)</td>
<td>119.075</td>
</tr>
<tr>
<td>Gun laser rate (MHz)</td>
<td>10.825</td>
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<tr>
<td>bunch train repetition rate (MHz)</td>
<td>0.349</td>
</tr>
<tr>
<td>CCR circumference (m)</td>
<td>213.955</td>
</tr>
<tr>
<td>ER L path length (m)</td>
<td>2573.32</td>
</tr>
<tr>
<td>Laser bucket pattern</td>
<td>7 on, 1 off, 7 on, 1 off, 6 on, 1 off</td>
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<tr>
<td>bunch train repetition rate (MHz)</td>
<td>0.349</td>
</tr>
<tr>
<td>Charge per bunch (nC)</td>
<td>3.2</td>
</tr>
<tr>
<td>Average ERL injection current (mA)</td>
<td>30</td>
</tr>
<tr>
<td>HOM power per cavity (kW)</td>
<td>0.33</td>
</tr>
<tr>
<td>HOM power per cavity scaled to CCR current 1.5A (kW)</td>
<td>6.7</td>
</tr>
</tbody>
</table>

RF System Challenges in Circular Colliders

Q₀ at 2K corrected for SS flange losses
Crab Cavity – RFD 2-cell cavity (HyeKyoung Park)

- After design survey, the prototype is converging to 952.6 MHz 2-cell RFD cavity.
- 10 GeV electron beam and 200 GeV proton beam.
- Input power coupling through beam pipe provides the QL range.

<table>
<thead>
<tr>
<th></th>
<th>protons</th>
<th>electrons</th>
<th>Units</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>952.6</td>
<td>952.6</td>
<td>MHz</td>
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<tr>
<td>Required total kick</td>
<td>37.34</td>
<td>2.8</td>
<td>MV</td>
</tr>
<tr>
<td>$V_t$ per cavity/side</td>
<td>2.7</td>
<td>1.4</td>
<td>MV/m</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>14</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Peak electric field</td>
<td>48.6</td>
<td>25.2</td>
<td>MV/m</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>99.9</td>
<td>51.8</td>
<td>mT</td>
</tr>
<tr>
<td>Surface resistance</td>
<td>95.0</td>
<td>95.0</td>
<td>nΩ</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>0.26</td>
<td>0.26</td>
<td>MΩ</td>
</tr>
<tr>
<td>Dissipated power/cav</td>
<td>27.8</td>
<td>7.5</td>
<td>W</td>
</tr>
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</table>
i-ring: new 952.6 MHz SRF Cavities

New 952.6MHz High-current cavity shape
- 4 different HOM damping schemes evaluated
- Focus on 3 waveguide damper design for ion ring
- Possibly on-cell damper for e-ring
- 1-cell prototype tested

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

Cooler needs 5-cells in the ERL, 1 or 2 -cells in the injector.
Ion ring might use 2-cells.
Collider Ring Impedance Thresholds

- Broadband damping of HOMs with on-cell dampers better than with any other design including enlarged tubes to un-trap low frequency modes
- PEP-II type feedback systems allow running above threshold.
- Beam tube absorbers might still be needed outside of cryomodules for high frequency power

F. Marhauser, “Next Generation HOM-damping”, Special Issue on Superconducting RF for Accelerators, to be published
## JLEIC e-p Parameters and Luminosity Performance

**October 29 – November 1, 2018**

**Fall 2018 EIC Accelerator Collaboration Meeting**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CM Energy</th>
<th>GeV</th>
<th>21.9 (low)</th>
<th>44.7 (medium)</th>
<th>63.3 (high)</th>
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<tr>
<td></td>
<td>p</td>
<td>e</td>
<td>p</td>
<td>e</td>
<td>p</td>
</tr>
<tr>
<td>Beam energy</td>
<td></td>
<td></td>
<td>40</td>
<td>3</td>
<td>100</td>
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<tr>
<td>Collision frequency</td>
<td>MHz</td>
<td></td>
<td>476</td>
<td>476</td>
<td>476</td>
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<tr>
<td>Particle per bunch</td>
<td>A</td>
<td></td>
<td>0.75</td>
<td>2.8</td>
<td>0.75</td>
</tr>
<tr>
<td>Polarization</td>
<td></td>
<td></td>
<td>80</td>
<td>80</td>
<td>80</td>
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<tr>
<td>Bunch length, RMS</td>
<td>cm</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Norm. emitt., horiz./vert.</td>
<td>μm</td>
<td></td>
<td>0.3</td>
<td>24</td>
<td>0.5/0.1</td>
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<tr>
<td>Horiz. &amp; verti. β*</td>
<td>cm</td>
<td></td>
<td>8/8</td>
<td>13.5/13.5</td>
<td>6/1.2</td>
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<tr>
<td>Vert. beam-beam param.</td>
<td></td>
<td></td>
<td>0.015</td>
<td>0.09</td>
<td>0.015</td>
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<tr>
<td>Laslett tune-shift</td>
<td></td>
<td></td>
<td>0.06</td>
<td>0.055</td>
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<tr>
<td>Detector space, up/down</td>
<td>m</td>
<td></td>
<td>3.6/7</td>
<td>2.96/2.2</td>
<td>3.6/7</td>
</tr>
<tr>
<td>Hourglass(HG) reduction</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td>0.87</td>
</tr>
<tr>
<td>Lumi./IP, w/HG, cm⁻²s⁻¹</td>
<td></td>
<td></td>
<td>2.5</td>
<td>21.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Similar high performance for electron-ion (e-A) collisions**
Some NCRF high current cavities

- **ATF cavity**, 714 MHz, 250 kV, 1.8 MΩ
- **PEP-II cavity**, 476 MHz, 850 kV, 3.7 MΩ
- **KEK ARES cavity**, 508 MHz, 500 kV, 1.75 MΩ
- **Daphne cavity**, 368.26 MHz, 250 kV, 2 MΩ
- **NLC DR**, 714 MHz
- **BESSY cavity**, 500 MHz, 3.7 MΩ
SCRF high current cavities

Cornell CESR-B type 500 MHz

KEK-B 508 MHz
Low Frequency RF examples

Needed to capture and accelerate ions in booster and collider ring

- Low frequency (~1 MHz)
- Tunable for ramping

CSNS cavity (ferrite loaded)

JPARC cavity (Metglass loaded).

Used as basis for JLEIC.
JLEIC ion bunch formation injects \( h=56 \), \( E=2 \) GeV (Pb) to 8 GeV (p) long bunches into the ion ring, then perform binary RF splitting 6 times into \( h=3584 \).

<table>
<thead>
<tr>
<th>Cavity function</th>
<th>( \beta ) range</th>
<th>Energy (GeV)</th>
<th>Frequency (MHz)</th>
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<tbody>
<tr>
<td>Collider ring acceleration</td>
<td>0.957-0.999</td>
<td>2.0-20</td>
<td>7.05-7.44</td>
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<tr>
<td>Collider ring bunch splitting</td>
<td>0.999</td>
<td>20</td>
<td>14.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>29.75</td>
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<td>59.49</td>
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<td></td>
<td></td>
<td></td>
<td>118.98</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>237.96</td>
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<tr>
<td>Collider ring bunch splitting, bucket</td>
<td>0.999-1.000</td>
<td>20-100</td>
<td>475.9-476.4</td>
</tr>
<tr>
<td>manipulation, acceleration, bunching</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CERN PS 13.3-20MHz low Q Ferrite loaded cavity, as a reference for JLEIC ion ring 7 MHz acceleration cavities and ion booster acceleration/bunching cavities.

A sliding beampipe shields the cavity from HOM excitation when the cavity is not in use.

May use as a reference for most of the bunch splitting cavities.
Other crab cavity examples

“RF Dipole developed by ODU for LHC
• Compact transverse dimensions
• NO low order mode (LOM)
• Must have good HOM damping
• Multi-gap RF dipole may be very desirable

Squashed elliptical crab cavity (e.g. KEK-B, SPX)
• Large size for a given frequency (952 OK?)
• Strong LOM, must be damped
• High LOM power must be absorbed at room temp
• Multi-cell version impractical

JLab waveguide damped RFD concept

A. Lunin et. Al.
ANL/FNAL multi-gap concept

Z.A. Conway et. al. IPAC14

reality

ODU RFD concept

Elliptical concept

Beam pipe
Elliptical electrodes
Power coupler

reality