Overview of Potential UK Contributions to EIC Accelerators

Peter Williams, Daresbury Laboratory & Cockcroft Institute

EIC Workshop – Promoting Collaboration on the Electron-Ion Collider

Session 3.1  13:10 BST / 12:10 UT  8th October 2020
Electron-Ion Collider: Origins of UK Interest

• Obviously the big historical influence in the UK has been the ~40 year involvement with HERA! Strong in Physics/Detector/Theory but pre-2004 not in accelerators. This changed with the foundation of the Cockcroft and John Adams Institutes in 2004.

• The ex-HERA community (led by U Glasgow) initiated the first UK workshop on EIC in October 2016 at Ross Priory on beautiful Loch Lomond. This brought together UK theory, detector and accelerator communities, and BNL & JLab for the first time. I represented Cockcroft due to links with BNL on the EMMA FFAG project and JLab on the ALICE ERL-FEL project.

• We agreed to campaign for the UK funding agencies (STFC and UKRI) to recognise EIC as a unique opportunity for Physics, Detector R&D and Accelerator R&D.
Electron-Ion Collider: UK Accelerator 2020 Status

• Project status (our understanding!): DOE Budget is for one detector and one IR - Second detector and IR from international contributions + US NSF – **International contributions to accelerator could offset cost of second detector/IR** - construction 2023/24 – 2029/30

• First formal request by UKRI/STFC for expressions of interest from UK community: **“UKRI Infrastructure Process” April 2020**: with 3 strands: Physics, **Accelerator** & Detector:
  • Cockcroft proposed accelerator contributions (ASTeC - Daresbury, Lancaster, Liverpool, Manchester):
    1. Energy Recovery Linacs for Hadron Cooling
    2. Crab Cavities
    3. SRF Component design & build
    4. Polarised Electron Source
    5. Second Interaction Region
  • Activity split into **preliminary** (2021 - 2024) – accelerator £5.4M of total £12.6M and **full** (2024 – 2030) – accelerator £43M of total £96M
  • It should be noted that this proposal only represented part of what a wider UK effort could potentially contribute – a “testing the water” exercise
Electron-Ion Collider: UK Accelerator Interest / Status

- Decision on “UKRI Infrastructure Process”: June 2020: STFC shortlisted EIC to be taken forward to UKRI 😊 … but without accelerator component 😞 at the preliminary stage. Crab cavities only retained as option for full phase.

- Nevertheless, further funding exercises are anticipated for which we are now well prepared

- 27/28 July 2020: “UK Workshop on Physics, Detector and Accelerator Opportunities at the EIC” considered next steps https://indico.cern.ch/event/934314/overview

- In the bid we highlighted our strong relevant historical interactions and emphasised synergies with other UK priority projects / subjects – for example…
  - Light sources – including Free-Electron Lasers and Compton sources, particularly the UK-XFEL proposal for a domestic ~£1 Bn facility for science and industry https://www.clf.stfc.ac.uk/Pages/UK-XFEL-science-case.aspx#
  - High energy physics facilities – High-Luminosity LHC, LHeC, FCC, DUNE/PIP-II
  - Neutron Sources - ESS
Electron-Ion Collider: Priority Accelerator R&D from 2017 Review

IV. Priority List of R&D

General Comments

The panel considers the R&D elements identified in the General Comments section of Part III of this report (Charge Element 3) to be high priority but notes that they can be sorted in the order of importance.

The panel received a self-assessment of the priorities of 37 R&D items identified by JLAB and 19 R&D items identified by BNL – these were binned into the categories of High, Medium and Low.

The panel cross-referenced the elements identified in Charge Element 3 with the self-assessment provided by the proponent laboratories – there was substantial agreement but some differences were noted.

In particular the panel identified 9 items it considered high priority that were not identified for action by the proponent laboratories. These items are identified in bold italic text below.

Technologies and/or design concepts that address technical risks common to all concepts that must be demonstrated

- Crab cavity operation in a hadron ring  
- Strong hadron cooling  
- Validation of magnet designs associated with high-acceptance interaction points by prototyping
- High-current single-pass ERL for hadron cooling  
- Benchmarking of realistic EIC simulation tools against available data
- Polarized $^3$He source

Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

February 13, 2017

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Energy Recovery Linacs
Electron-Ion Collider Needs Hadron Cooling

- Intrabeam scattering = Lorentz boosted multiple Coulomb scattering within bunches
- IBS is dominant limit on both luminosity and luminosity lifetime because emittance increases with time
- IBS growth rate \( \frac{1}{\tau_{ibs}} \propto \frac{N_p}{\varepsilon_x \varepsilon_y \varepsilon_S} \)

Start: maximum luminosity without cooling
Then: increase luminosity, for example by
- Increase \( n_b \) \( \rightarrow \) \( N_p \), \( 1/t_{ibs} \) scales with \( n_b \) \( \rightarrow \) need cooling
- Decrease \( \beta \) \( \rightarrow \) need to decrease \( \sigma_s \) by incr \( U_{rf} \) \( \rightarrow \) \( \sigma_e \) larger + more nonlin beam-beam \( \rightarrow \) need cooling

Table:

<table>
<thead>
<tr>
<th>Species</th>
<th>Nominal Design (with cooling)</th>
<th>Risk Mitigation (no cooling)</th>
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<tbody>
<tr>
<td></td>
<td>p</td>
<td>e</td>
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<tr>
<td>Bunch frequency [MHz]</td>
<td>112.6</td>
<td>56.3</td>
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<td>Bunch intensity [10^11]</td>
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<tr>
<td>Number of bunches</td>
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<tr>
<td>Beam current [A]</td>
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<td>2.5</td>
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<tr>
<td>Rms norm. emit. h/v [um]</td>
<td>2.7/0.38</td>
<td>391/20</td>
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<tr>
<td>Rms emittance h/v [nm]</td>
<td>9.2/1.3</td>
<td>20/1</td>
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<tr>
<td>( \beta^* ) h/v [cm]</td>
<td>90/4</td>
<td>42/5</td>
</tr>
<tr>
<td>IP rms beam size h/v [um]</td>
<td>91/7.2</td>
<td></td>
</tr>
<tr>
<td>IR rms angular spread h/v [urad]</td>
<td>101/179</td>
<td>219/143</td>
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<td>b-b parameter (IP) h/v</td>
<td>0.013/0.007</td>
<td>0.064/0.099</td>
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<td>Rms bunch length [cm]</td>
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<td>Rms energy spread, 10^4</td>
<td>4.6</td>
<td>5.5</td>
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<tr>
<td>Max space charge parameter</td>
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<td>neglig.</td>
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<tr>
<td>IBS growth time tr/long, h</td>
<td>2.1/2.0</td>
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<td>Polarization, %</td>
<td>80</td>
<td>70</td>
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<tr>
<td>Hourglass and crab crossing factor</td>
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<td>0.85</td>
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<tr>
<td>Peak luminosity [10^33 cm^-2s^-1]</td>
<td>10.1</td>
<td>4.4</td>
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<tr>
<td>Integrated luminosity/week, fb^-1</td>
<td>4.51</td>
<td>1.12</td>
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</table>
Electron-Ion Collider – How to Cool?

- Proton and electron beams must have identical relativistic gamma, for example $100 \text{ GeV} \Rightarrow 54 \text{ MeV e}^-$, $275 \text{ GeV} \Rightarrow 150 \text{ MeV e}^-$

- These electron energies are well beyond capabilities of standard DC coolers used since 1960s - **new technology required**

- Of the cooling methods currently under study (from Ferdi Willeke – 2018 EIC Accelerator Meeting) 4 of the 8 listed utilise an Energy Recovery Linac (ERL) (others: 2 storage ring, 1 laser, 1 induction linac)

- All need **high power**: tens or hundreds of mA = e-beam power 1 MW to 50 MW and excellent quality = **small energy spread**

- It is this combination that makes ERLs attractive solutions – perhaps 2 are required! 1 for incoherent at low energy + 1 to drive CeC at high energy?

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**Cooling Methods Under Study**

- Bunched beam (incoherent) electron cooling using ERL (e current requirements exceed present capabilities)
- Bunched beam (incoherent) electron cooling with recirculatory ring, ERL electron beam source (JLEIC design is based on recirculating cooler)
- Bunched beam (incoherent) electron cooling with electron storage ring for the cooling beam (under study, FOA 8/19)
- Coherent electron cooling with FEL amplifier (PoP experiment at BNL)
- Coherent electron cooling with ERL electron beam and multi-stage micro-bunching amplifier (under study, FOA 19/19)
- Coherent electron cooling with micro-bunching amplifier and with electron storage ring (under study, FOA 19/19)

And more ....

- Optical stochastic cooling
- Coherent electron cooling with induction linac driver ...
Why are we well placed to engage in ERLs?

- From 2004 – 2016 Daresbury conceived, designed, built, commissioned, operated for users and then decommissioned ALICE

- **ALICE** (initially called ERLP) was Europe’s first ERL, and the second of only four SC-ERLs worldwide – so unlike linacs & storage rings, ERL operational experience is rare – we ran is as a **user facility** for 5 years

- Situated under the old NSF tower at Daresbury, ALICE successes include:
  - First SCRF linac operating in the UK
  - First DC photoinjector gun in the UK
  - First ERL in Europe
  - First FEL driven by ERL in Europe
  - First transmission IR-SNOM imaging
Why are we well placed to engage in ERLs?

• Since ALICE decommissioning in 2016 we remain at the forefront of ERL development

• UK-XFEL Science Case https://www.clf.stfc.ac.uk/Pages/UK-XFEL-science-case.aspx – potential of a UK based XFEL facility of ~£1Bn scale. Case includes science that could be addressed by incorporating a ~1 GeV ERL into the larger facility


“In particular, only ERL technology currently seems capable of producing the beam power required to efficiently cool ions at the Electron-Ion Collider (EIC)”
Why are we well placed to engage in ERLs?

- Part of PERLE collaboration to construct facility at IJC, Orsay in support of LHeC – a proposed ERL to enable e-p at HL-LHC.

For example: “Implications of beam filling patterns on the design of recirculating energy recovery linacs” S. Setiniyaz, R. Apsimon, and P. H. Williams, Phys. Rev. Accel. Beams 23, 072002 – Published 17 July 2020

Filling pattern [1 4 3 6 5 2]

- ER@CEBAF: part of experimental effort to demonstrate GeV-scale multipass ERL through adaptation of CEBAF, JLab – scheduled for 2021

See Rob Apsimon’s talk later
Crab Cavities
<table>
<thead>
<tr>
<th>eRHIC RF system</th>
<th>RF sub system</th>
<th>Freq [MHz]</th>
<th>Type</th>
<th>Location</th>
<th># of Cavities</th>
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<tr>
<td>Electron Storage Ring</td>
<td>Fundamental</td>
<td>591</td>
<td>SRF, 2-cell</td>
<td>IR-10</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Third Harmonic</td>
<td>1773</td>
<td>SRF, 1-cell</td>
<td>IR-10</td>
<td>5</td>
</tr>
<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>Pre-Injection LINAC</td>
<td>Bunch Compression 1</td>
<td>114</td>
<td>Copper, capacitor loaded</td>
<td>IR-2</td>
<td>1</td>
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<tr>
<td></td>
<td>Bunch Compression 2</td>
<td>571</td>
<td>Copper, 1-cell</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>8 x 3m sections</td>
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<td>Hadron Ring</td>
<td>Capture/Acceleration</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 Splitter 1</td>
<td>49.2</td>
<td>Copper, Quarter Wave</td>
<td>IR-4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Bunch Splitter 2</td>
<td>98.5</td>
<td>Copper, Quarter Wave</td>
<td>IR-4</td>
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<td>Bunch Compression 1</td>
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<td>Copper, 1-cell</td>
<td>IR-4</td>
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<tr>
<td></td>
<td>Bunch Compression 2</td>
<td>591</td>
<td>SRF, 5-cell</td>
<td>IR-10</td>
<td>2</td>
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<tr>
<td>Crab Cavity</td>
<td>Hadron</td>
<td>394</td>
<td>SRF, Double Quarter Wave</td>
<td>IR-6</td>
<td>8</td>
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<tr>
<td></td>
<td>Electron</td>
<td>394</td>
<td>SRF, Double Quarter Wave</td>
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<td>Hadron Cooling</td>
<td>SRF Booster</td>
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<td>SRF, Quarter Wave</td>
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<tr>
<td></td>
<td>Fundamental</td>
<td>591</td>
<td>SRF, 5-cell</td>
<td>IR-2</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Third Harmonic</td>
<td>1773</td>
<td>SRF, 5-cell</td>
<td>IR-2</td>
<td>2</td>
</tr>
</tbody>
</table>
**394 MHz EIC Crab Cavity**

- Operates in a TE/TEM-like mode
- Deflecting/Crabbing mode is the lowest operating mode
- Net deflection is mainly due to the transverse electric field

![E Field](Image)

![H Field](Image)

- US are evaluating the possibility to open the beampipe port of the cavity to damp HOMs by propagating to external absorbers.
- HOM ports/couplers (circled) can be eliminated, using SiC absorbers outside the cryomodule instead (same as ESR cavities for example).
Existing Experience: SPS Crabs – HL-LHC-UK Contributions and leadership

- Cavity vertical testing
- HOM coupler design and measurements
- Warm & Cold magnetic shield design and manufacture
- Cavity supports and microphonics
- Thermal shield design
- LLRF measurements
- Impedance measurements
- Multipoles
- Beam measurement and control

Double quarter-wave (DQW)

RF Dipole (RFD)
HL-LHC Crab Cavity Cryomodules

- A cryomodule is required to efficiently keep the cavity at 2K and maintain cavity support vibration free
- The UK are delivering half the cryomodules for the project. We are currently building the pre-series LHC cryomodule
Protons meet Crabs! First HL-LHC CC Test on SPS@CERN – May 2018

First injection – 12:55, May 23
Cavity 1 only
Single bunch
$0.2 − 0.8 \times 10^{11}\text{p/b}$

Crabbing reconstruction (assuming Gaussian transversely)
Superconducting Linac RF Technology
ESS High Beta Cavities (2015 – 2022)

- Similar to CEBAF/SNS cryomodule concept with 4 cavities per cryomodule
- Common cryomodule design for medium and high beta cavities

<table>
<thead>
<tr>
<th></th>
<th>Medium-β</th>
<th>High-β</th>
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<tbody>
<tr>
<td>Geometrical β</td>
<td>0.67</td>
<td>0.86</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>704.42</td>
<td></td>
</tr>
<tr>
<td>No. of Cryomodules</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>Cavities /Cryomodule</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>No. of Cavities</td>
<td>36</td>
<td>84</td>
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<tr>
<td>Cryomodule length (m)</td>
<td>6.584</td>
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<tr>
<td>Nominal Accelerating gradient (MV/m)</td>
<td>16.7</td>
<td>19.9</td>
</tr>
<tr>
<td>Nominal Accelerating Voltage (MV)</td>
<td>14.3</td>
<td>18.2</td>
</tr>
<tr>
<td>$Q_0$ at nominal gradient</td>
<td>&gt; 5e9</td>
<td></td>
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</table>
ESS Cavity Manufacture

- Niobium deliveries complete (Ningxia OTIC):
  - 924 sheets delivered; Eddy current scanned at DESY.
  - Only 2% rejected, replaced by vendor.

- Cavity manufacturing strategy (Research Instruments):
  - 4 pre-series cavities (H001 – H004) used to qualify vendor processes:
    - Pre-series cavities cold test ‘undressed/dressed’ at DESY and ‘dressed’ at Daresbury.
  - Series manufacturing (H005 – H088):
    - During pre-series fabrication/testing, continue preparing component series parts.
    - Manufacture release of full batch production after pre-series tests successful.

<table>
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<tr>
<th>Cavity</th>
<th>Status</th>
<th>Cold test at DESY</th>
<th>Dressed cold test at DL</th>
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<tbody>
<tr>
<td>H001</td>
<td>Being prepared for test @ DL</td>
<td>Completed Mar 20</td>
<td>Exp Aug 2020</td>
</tr>
<tr>
<td>H002</td>
<td>Being prepared for test @ DL</td>
<td>Completed Mar 20</td>
<td>Exp Aug 2020</td>
</tr>
<tr>
<td>H003</td>
<td>Being prepared for shipment to DL</td>
<td>Completed Jul 20</td>
<td>Exp Oct 2020</td>
</tr>
<tr>
<td>H004</td>
<td>Being prepared for shipment to DL</td>
<td>Completed Jul 20</td>
<td>Exp Oct 2020</td>
</tr>
</tbody>
</table>
ESS Testing Infrastructure at Daresbury

- Currently commissioning with ESS prototypes: Good performance agreed with tests from CEA.
- RF performance: LLRF tracking validated & HPRF successfully tested up to 200W.
- Cryogenics: Excellent static T, P stability ($\pm 1\text{mK}$, $\pm 0.1\text{mBar}$); dynamic stability being refined.
- Cleanroom and HPR facility: Completed installation in June/July 2019; started commissioning in July/August 2019, awaiting cavity for final HPR commissioning.
- Target ‘series’ testing readiness Q2/Q3 2020.
ESS First Pre-Series Tests @ Daresbury

**H001 DESY Test**

**H002 DESY Test**

Pre-series cavities @ DL 23/07/20
Fermilab Proton Improvement Plan II (2019 – 2025)

US-DoE set timescales to deliver 1.2 MW proton beam over the energy range 60 – 120 GeV for first LBNF/DUNE operations in 2026.

Establish a platform for future upgrades to multi-MW capability.
Room Temperature

- FNAL design and integration.
- DAE India providing cavities & CM components.
- STFC & DAE contributing to CM design review processes.
- STFC & DAE to undergo CM assembly training at FNAL.

CM-1:
- FNAL design and integration.
- DAE India providing cavities & CM components.
- STFC & DAE contributing to CM design review processes.
- STFC & DAE to undergo CM assembly training at FNAL.

CM-2 to CM-4:
- STFC to input into FNAL cavity & CM manufacturing readiness reviews.
- STFC to procure, qualify and assemble all CM components.

**UK Responsibility**

**PIP-II HB650 Cryomodules**

<table>
<thead>
<tr>
<th>CM type</th>
<th>No. of CMs</th>
<th>Cavities Per CM</th>
<th>Magnets Per CM</th>
<th>Energy gain (MeV)</th>
<th>(Current) CM style</th>
<th>Transports</th>
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<tr>
<td>HWR</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>2</td>
<td>Bathtub</td>
<td>ANL to FNAL</td>
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<td>SSR1</td>
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<td>8</td>
<td>4</td>
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<td>Strong-back</td>
<td>FNAL internal</td>
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<td>SSR2</td>
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<td>5</td>
<td>3</td>
<td>5</td>
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<td>FNAL internal</td>
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<td>LB650</td>
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<td>3</td>
<td>0</td>
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<td>CEA to FNAL</td>
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<td>HB650</td>
<td>4</td>
<td>6</td>
<td>0</td>
<td>19.9</td>
<td>Strong-back</td>
<td>3: STFC to FNAL 1: FNAL internal</td>
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<tr>
<td>Totals</td>
<td>25</td>
<td>116</td>
<td>37</td>
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UK Delivery of PIP-II HB650 Cryomodules

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<th>PIP-II</th>
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<td>Frequency (MHz)</td>
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<td>Cavity Beta</td>
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<tr>
<td>Gradient (MV/m)</td>
<td>19.9</td>
</tr>
<tr>
<td>Quality Factor Qo</td>
<td>$3 \times 10^{10}$ (N2 Doped)</td>
</tr>
<tr>
<td>Number of Cells</td>
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<tr>
<td>Cavity Dynamic Load (W)</td>
<td>&lt;22</td>
</tr>
<tr>
<td>Cavity Length (m)</td>
<td>1.42</td>
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<tr>
<td>Number of Cavities</td>
<td>18 (+2)</td>
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**HB650 Cryomodule**

- Cryogenic Interface Stub
- Cavity Input Coupler Locations (x6)
- Cavity Support and Alignment Fixture
- 6 x HB650 Cavities
- Cryomodule End-Cap (x2)
- Cryomodule Support Stand (x2)
- Cryomodule & Helium Vessel

**HB650 Cavity**

- Helium jacket
- Tuner
- 5-cell high-purity Niobium cavity
- Coupler interface

**Develop UK industry SRF fabrication capability**
- First ever complete UK SRF cavity manufacture

**Partnership with:**
- The Welding Institute
- Nuclear Advanced Manufacturing Research Centre
- Shakespeare Engineering
SRF Infrastructure Evolution
Superconducting RF Lab (SuRFLab) – PIP-II

- String to support & shields
- Outer vessel integration
- Cavity string assembly
Polarized Electron Source
Polarized Electron Source

- Scientific and technological challenges of PES’es:
  - Photocathode
    - Maximum polarisation
    - Potential Quantum Efficiency (QE)
    - Response time
    - Life time
  - Photocathode activation infrastructure:
    - Extra High Vacuum (EHV) conditions ($p<1.0\cdot10^{-11}$ mbar with $O_2$ pressure $<1.0\cdot10^{-16}$)
    - Activation procedure (traditional Cs-O or new Cs-Sb)
    - Resulting QE ($>0.1\%$)
    - Photocathode transport system
  - Photocathode gun
    - EHV vacuum conditions at any regime
    - Accurate HV design ($E<10$ MV/m)
    - Accurate beam optics design

- Daresbury GaAs design, build and characterisation infrastructure developed for FEL projects, now being applied to Polarised Electron Source for PERLE (see Walid Kaabi’s talk)
Second Interaction Region

• Pool of expertise in interaction region design at JAI (Oxford, RHUL) and CI (Liverpool, Manchester, Daresbury), projects include…

• HL-LHC: Developed optics for the “squeeze”: the transition from injection (relaxed $\beta^*$) to collision (minimized $\beta^*$) optics.

• ERL-Ring LHeC optics, to be integrated into HL-LHC
  “Modelling the effects of high-luminosity optics in the upgrades of the Large Hadron Collider”, E. Cruz-Alaniz, PhD Thesis (University of Liverpool), 2016.

• LHeC Ring-ring IR design

Snapshots of HL-LHC IR optics during the “squeeze” M. Korostelev et al, proceedings of IPAC’13.

Figure 1: LHeC interaction region with a schematic view of synchrotron radiation. Beam trajectories with $5\sigma$ and $10\sigma$ envelopes are shown.

The high luminosity interaction region for a ring–ring Large Hadron Electron Collider

R B Appleby$^{1,2}$, L. Thompson$^{1,2}$, B Holzer$^3$, M Fitterer$^3$, N Bernard$^4$ and P Kostka$^5$

IOP Publishing JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
Electron Beam Diagnostics
Electron Beam Diagnostics – JAI (Oxford, RHUL)
Also see Stephen Gibson’s talk

Stripline BPMs

Excellent temporal + spatial resolution

ATF

Cavity BPMs

CLIC main beam/CTF3 (15 GHz)

ATF2 (6.5 GHz)

Nanometre-resolution

<table>
<thead>
<tr>
<th>Resolution calculation method</th>
<th>Single sampling</th>
<th>Integration sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric</td>
<td>49 ± 1</td>
<td>21.5 ± 0.4</td>
</tr>
<tr>
<td>Fitting Γ</td>
<td>49 ± 1</td>
<td>19.9 ± 0.4</td>
</tr>
<tr>
<td>Fitting Γ, Q’</td>
<td>43 ± 1</td>
<td>19.5 ± 0.4</td>
</tr>
<tr>
<td>Fitting Γ, Q’, q</td>
<td>43 ± 1</td>
<td>19.5 ± 0.4</td>
</tr>
<tr>
<td>Fitting Γ, Q’, q and x</td>
<td>42 ± 1</td>
<td>19.2 ± 0.4</td>
</tr>
</tbody>
</table>
High power / bandwidth, low latency amplifiers

Digital & Analogue feedback / feedforward

Feedback using nanometer resolution BPMs

<table>
<thead>
<tr>
<th>Bunch</th>
<th>Feedback off (nm)</th>
<th>Feedback on (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106 ± 16</td>
<td>106 ± 16</td>
</tr>
<tr>
<td>2</td>
<td>96 ± 10</td>
<td>41 ± 4</td>
</tr>
</tbody>
</table>
Conclusions: Electron-Ion Collider: UK Potential Accelerator Contributions

• UK involvement in e-p/A colliders has a long history and there is an established user community

• EIC accelerator R&D is highly synergetic with other UK priority accelerator projects: Light sources, high-energy physics and neutron sources

• EIC is seen as strategically important by UKRI / STFC – recently shown by the success of detector R&D in the April 2020 UKRI Infrastructure Process – **now need to build on this to secure commitment to accelerator R&D**!

• Potential topics identified:
  • ERLs for cooling
  • Crab cavities & cryomodules
  • SRF design & build
  • Polarized electron source
  • Second IR design
  • Electron diagnostics
  • ......
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