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

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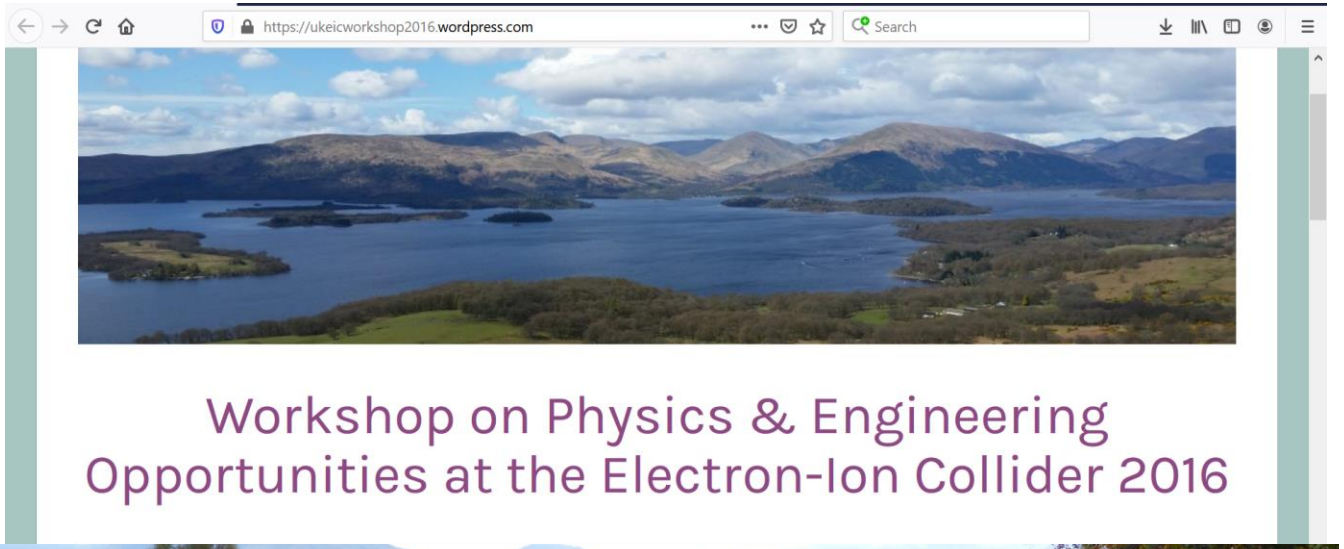
Electron-Ion Collider: Origins of UK Interest

- 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**



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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

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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

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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-walked 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

2017

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Energy Recovery Linacs

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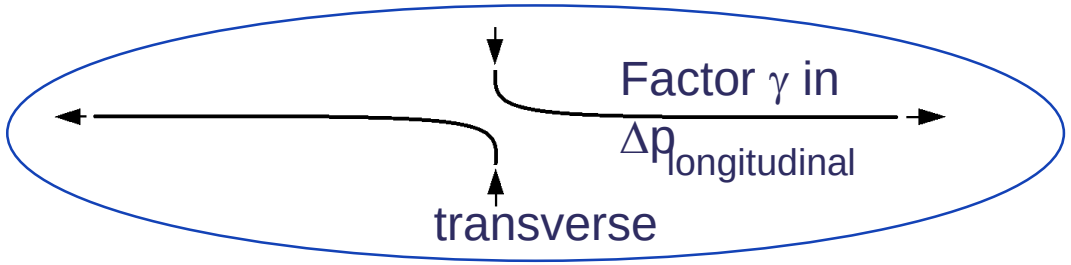
Electron-Ion Collider Needs Hadron Cooling

- 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 ➔ N_p , $1/t_{ibs}$ scales with n_b ➔ need cooling
- Decrease β ➔ need to decrease σ_s by incr U_{rf} ➔ σ_e larger + more nonlin beam-beam ➔ need cooling

	Nominal Design (with cooling)			Risk Mitigation (no cooling)	
Species	p	e		p	E
Bunch frequency [MHz]	112.6			56.3	
Bunch intensity [10^11]	0.6	1.5		1.05	3.0
Number of bunches	1320			660	
Beam current [A]	1	2.5		0.87	2.5
Rms norm. emit. h/v [um]	2.7/0.38	391/20		4.1/2.5	391/95
Rms emittance h/v [nm]	9.2/1.3	20/1		13.9/8.5	20/4.9
β* h/v [cm]	90/4	42/5		90/5.9	63/10.4
IP rms beam size h/v [um]	91/7.2			112/22.5	
IR rms angular spread h/v [urad]	101/179	219/143		124/380	179/216
b-b parameter (/IP) h/v	0.013/0.007	0.064/0.099		0.015/0.005	0.1/0.083
Rms bunch length [cm]	5	1.9		7	1.9
Rms energy spread, 10^-4	4.6	5.5		6.6	5.5
Max space charge parameter	0.004	neglig.		0.001	neglig.
IBS growth time tr/long, h	2.1/2.0			9.2/10.1	
Polarization, %	80	70		80	70
Hourglass and crab crossing factor	0.87			0.85	
Peak luminosity [10^33 cm-2s-1]	**10.1**			**4.4**	
Integrated luminosity/week, fb^{-1}	**4.51**			**1.12**	

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Electron-Ion Collider – How to Cool?

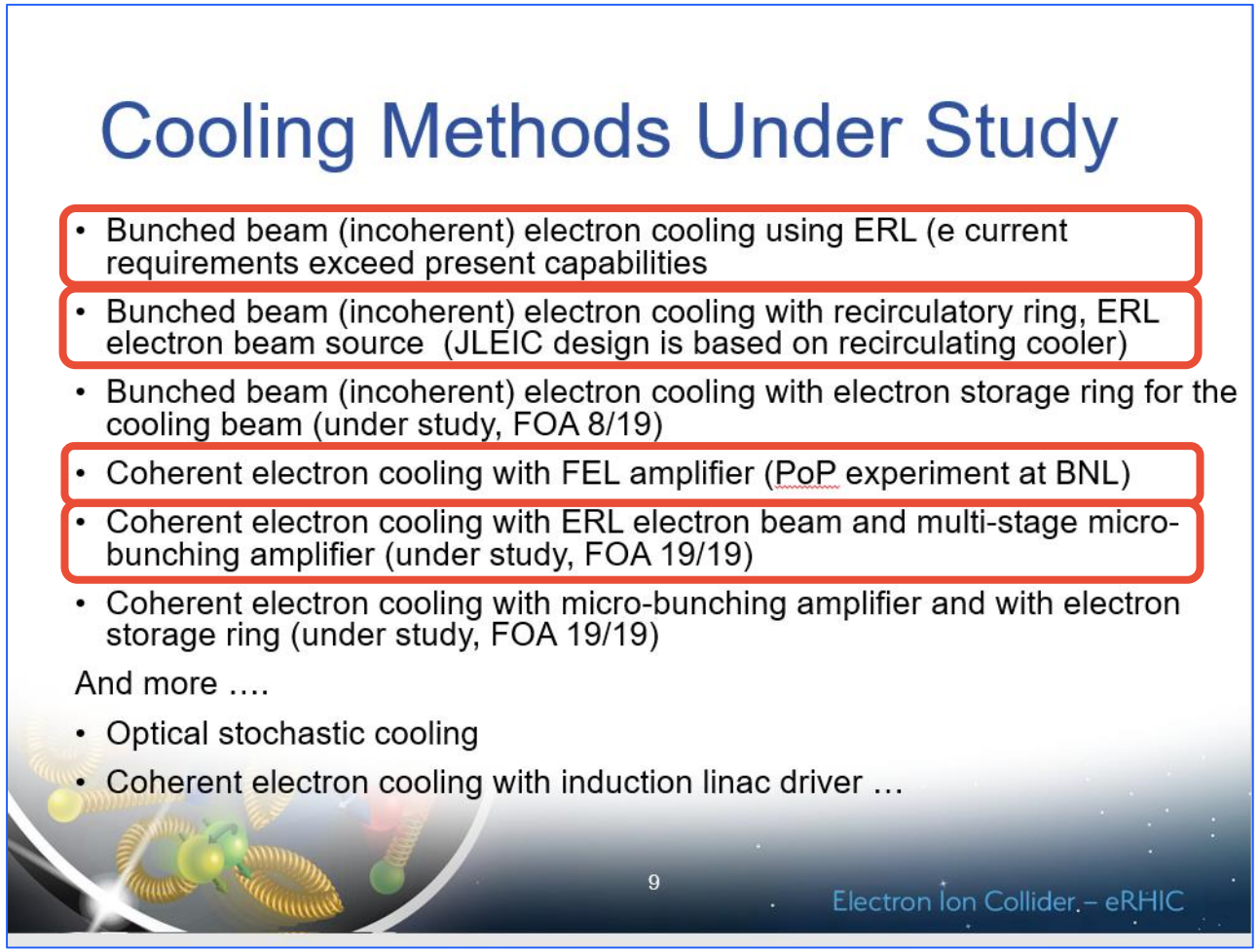
- Proton and electron beams must have identical relativistic gamma, for example 100 GeV p ⇒ 54 MeV e- , 275 GeV p ⇒ 150 MeV e-

- 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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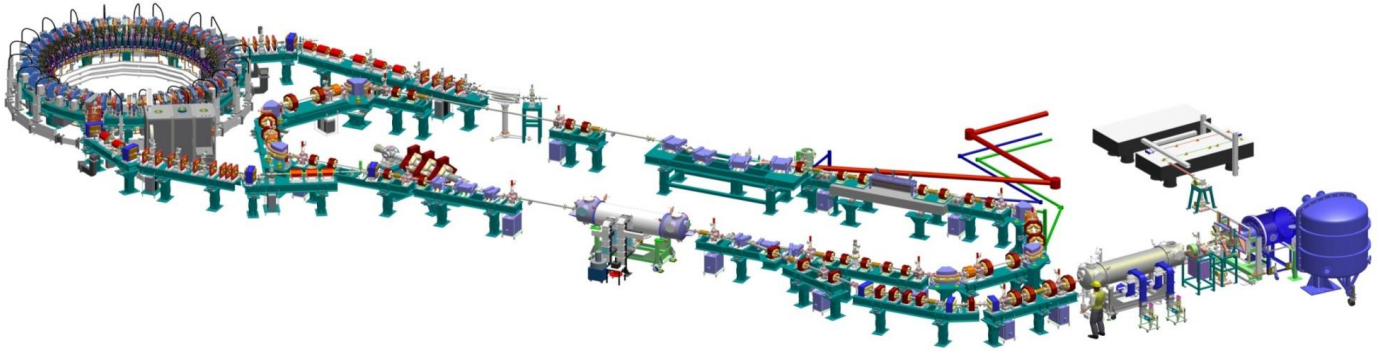
Why are we well placed to engage in ERLs?

- 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

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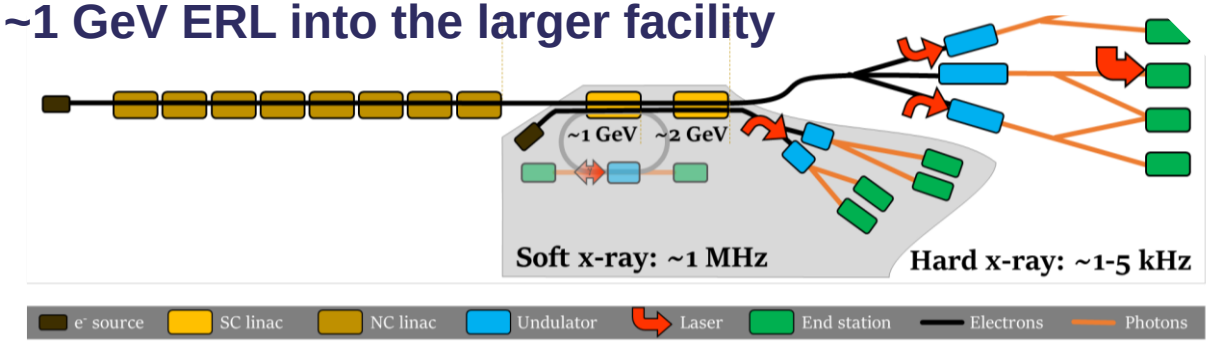
Why are we well placed to engage in ERLs?

- 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**

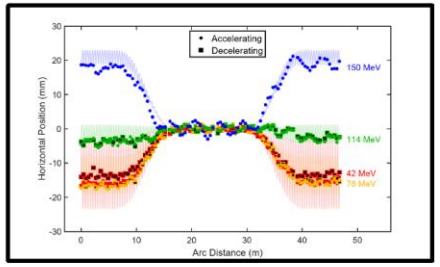


- Existing EIC involvement - CBETA: contributed to 2019 Cornell / BNL multipass ERL demonstration: https://link.aps.org/doi/10.1103/PhysRevLett.125.044803

"In particular, only ERL technology currently seems capable of producing the beam power required to efficiently cool ions at the Electron-Ion Collider (EIC)"

CBETA Multi-pass Commissioning

Joe Crone



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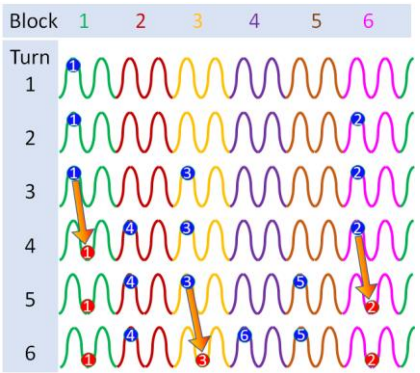
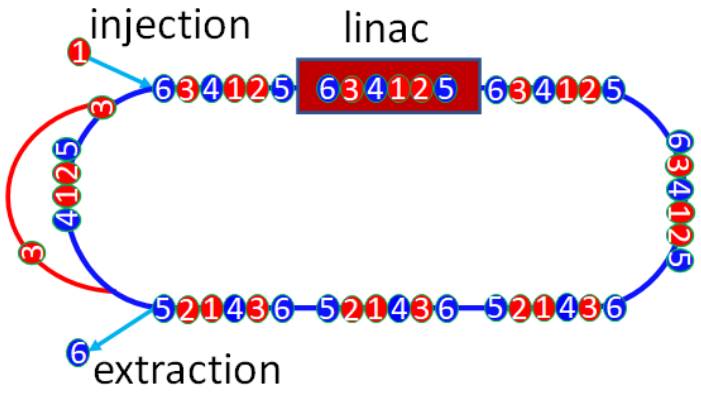
Why are we well placed to engage in ERLs?

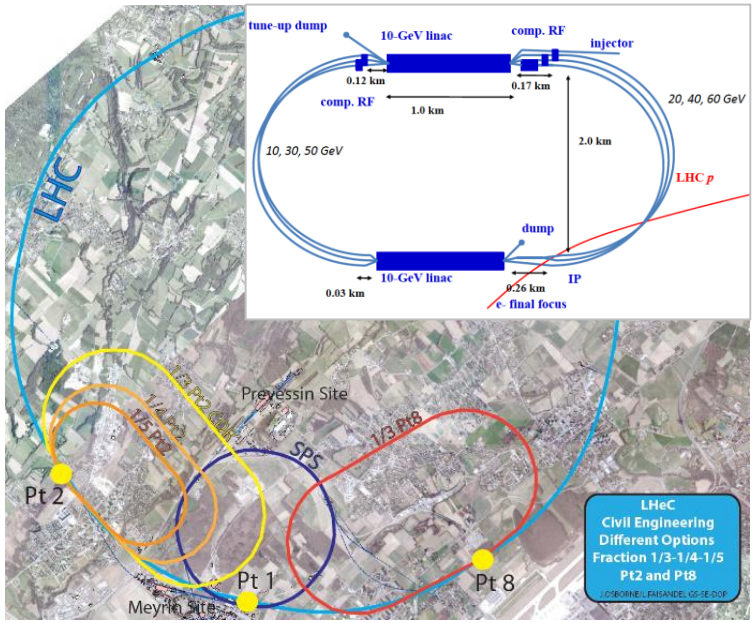
- Part of PERLE collaboration to construct facility at IJC, Orsay in support of LHeC – a proposed ERL to enable e-p at HL-LHC.

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

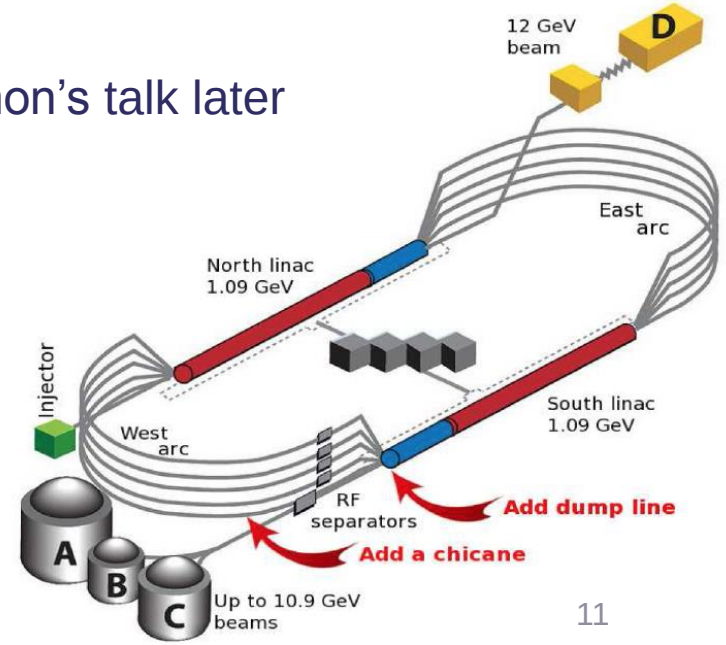
Filling pattern **[1 4 3 6 5 2]**







See Rob Apsimon's talk later



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

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Crab Cavities

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eRHIC RF system	RF sub system	Freq [MHz]	Type	Location	# of Cavities
Electron Storage Ring	Fundamental	591	SRF, 2-cell	IR-10	14
	Third Harmonic	1773	SRF, 1-cell	IR-10	5
Rapid Cycling Synchrotron	Fundamental	591	SRF, 5-cell	IR-10	3
Pre-Injection LINAC	Bunch Compression 1	114	Copper, capacitor loaded	IR-2	1
	Bunch Compression 2	571	Copper, 1-cell	IR-2	1
	400 MHz LINAC	2856	SLAC type LINAC	IR-2	8 x 3m sections
Hadron Ring	Capture/Acceleration	24.6	Copper, Quarter Wave	IR-4	2
	Bunch Splitter 1	49.2	Copper, Quarter Wave	IR-4	2
	Bunch Splitter 2	98.5	Copper, Quarter Wave	IR-4	2
	Bunch Compression 1	197	Copper, 1-cell	IR-4	12
	Bunch Compression 2	591	SRF, 5-cell	IR-10	2
Crab Cavity	Hadron	394	SRF, Double Quarter Wave	IR-6	8
	Electron	394	SRF, Double Quarter Wave	IR-6	2
Hadron Cooling	SRF Booster	118	SRF, Quarter Wave	IR-2	2
	Bunch Compression	591	Copper, 1-cell	IR-2	1
	Fundamental	591	SRF, 5-cell	IR-2	9
	Third Harmonic	1773	SRF, 5-cell	IR-2	2

Electron Ion Collider.

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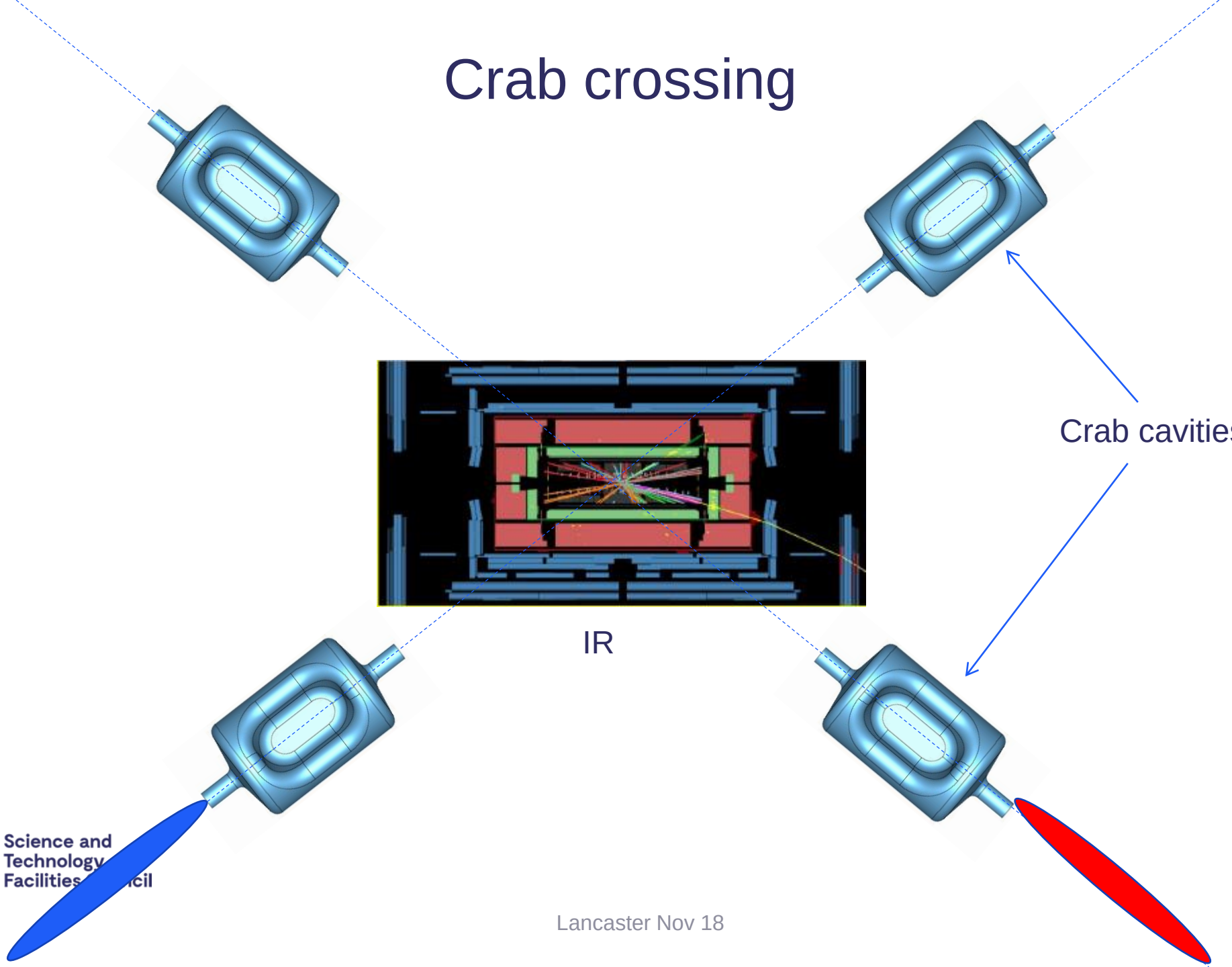
Crab crossing



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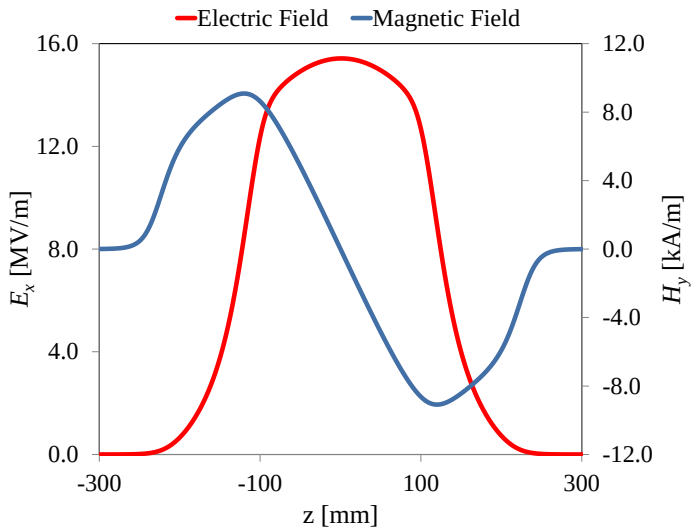
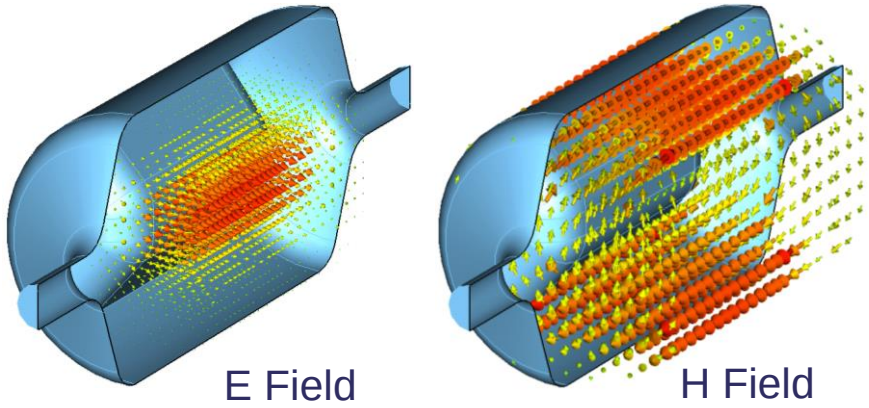
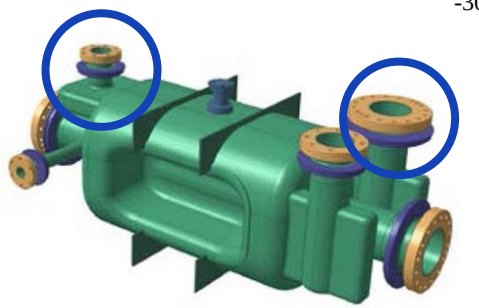
394 MHz EIC Crab Cavity

- 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

Field on axis

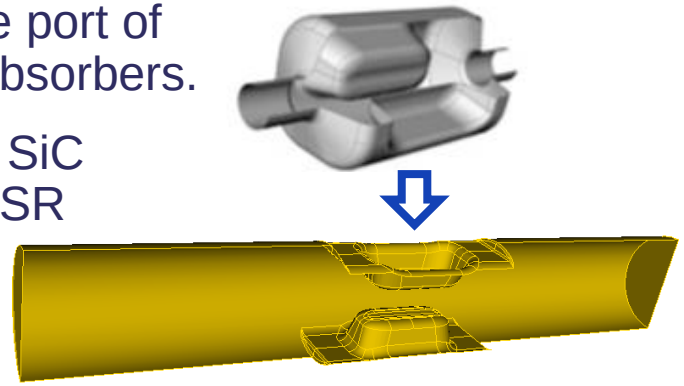


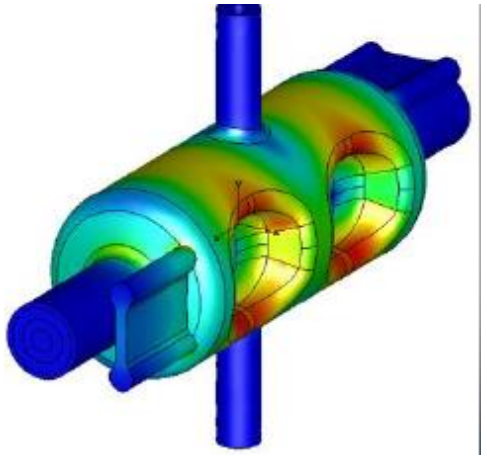




From Binping Xiao

- 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).





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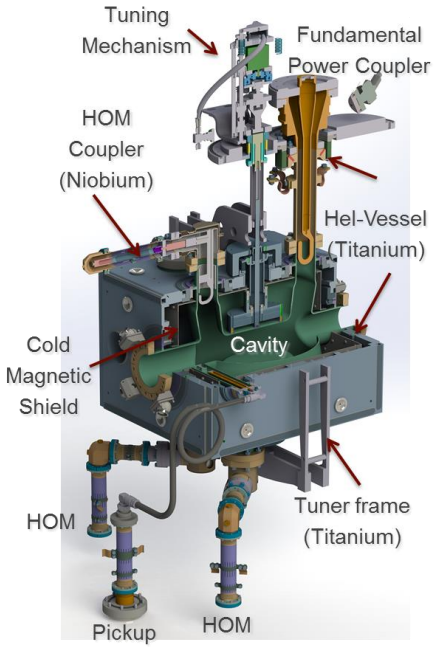
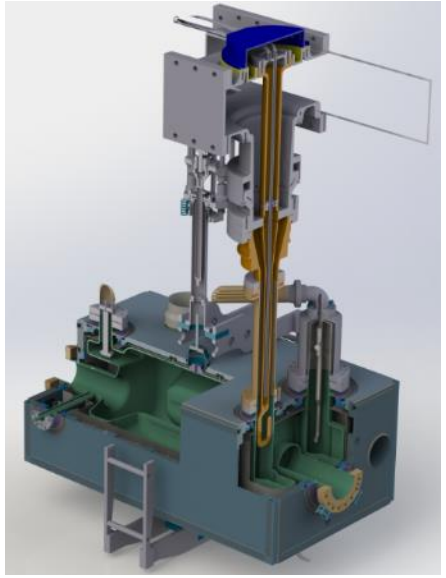
Existing Experience: SPS Crabs – HL-LHC-UK Contributions and leadership

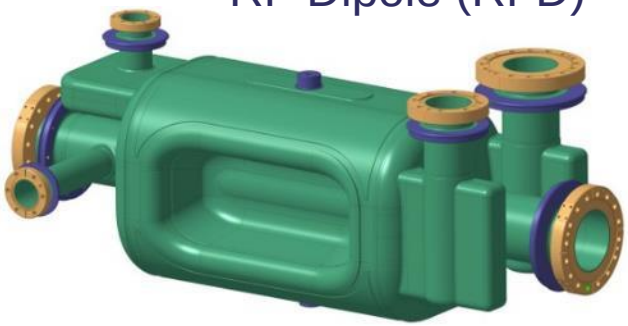
- Cavity vertical testing
- HOM coupler design and measurements
- Warm & Cold magnetic shield design and manufacture
- Cavity supports and microphonics
- Thermal shield design
- LLRF measurements
- Impedance measurements
- Multipoles
- Beam measurement and control

Double quarter-wave (DQW)





RF Dipole (RFD)



Lancaster University

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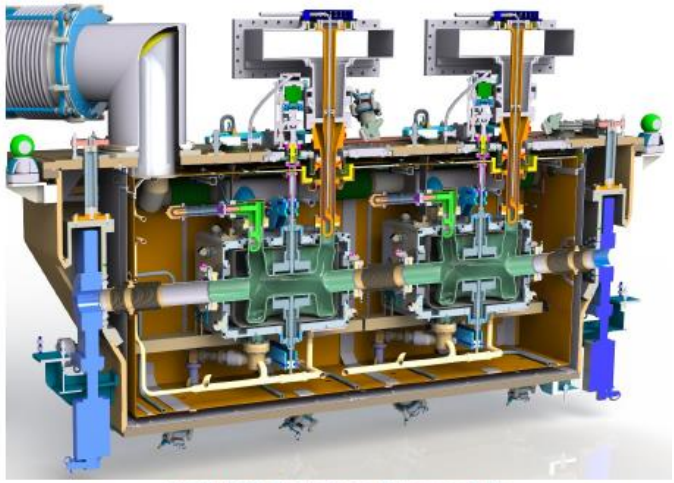
UKRI Science and Technology Facilities Council

MANCHESTER 1824 The University of Manchester

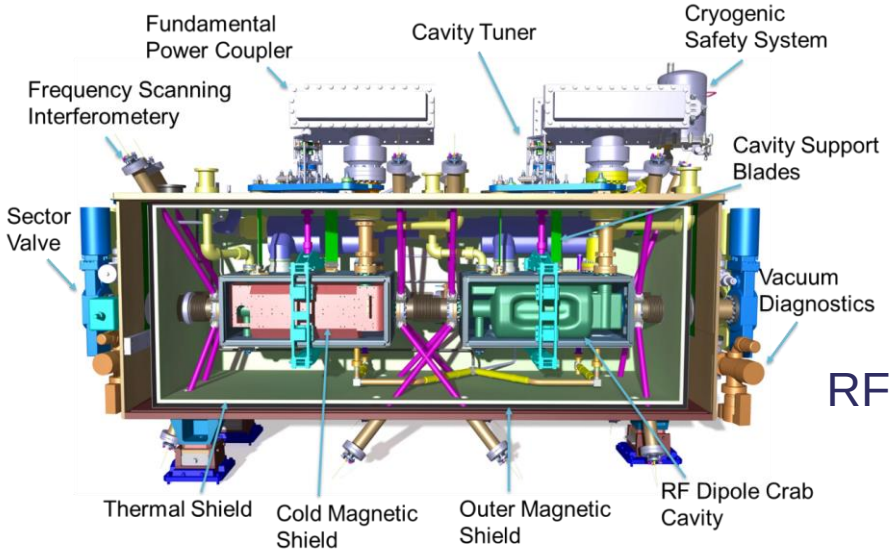
UNIVERSITY OF LIVERPOOL

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

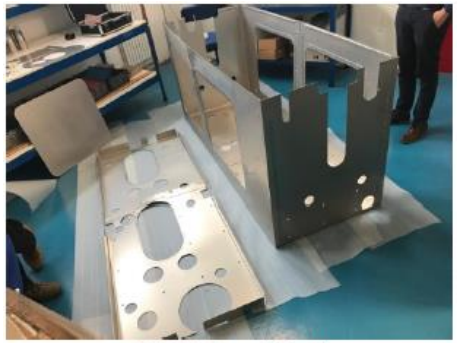


DQW SPS Prototype Cryomodule

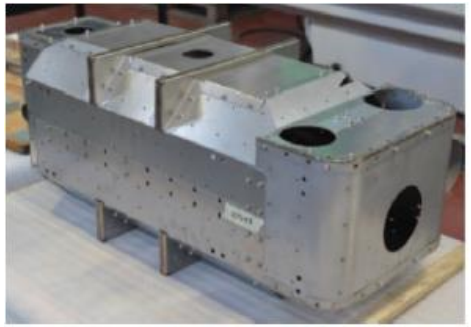


Double quarter-wave (DQW)

RF Dipole (RFD)



DQW Warm Shield



RFD Cold Shield

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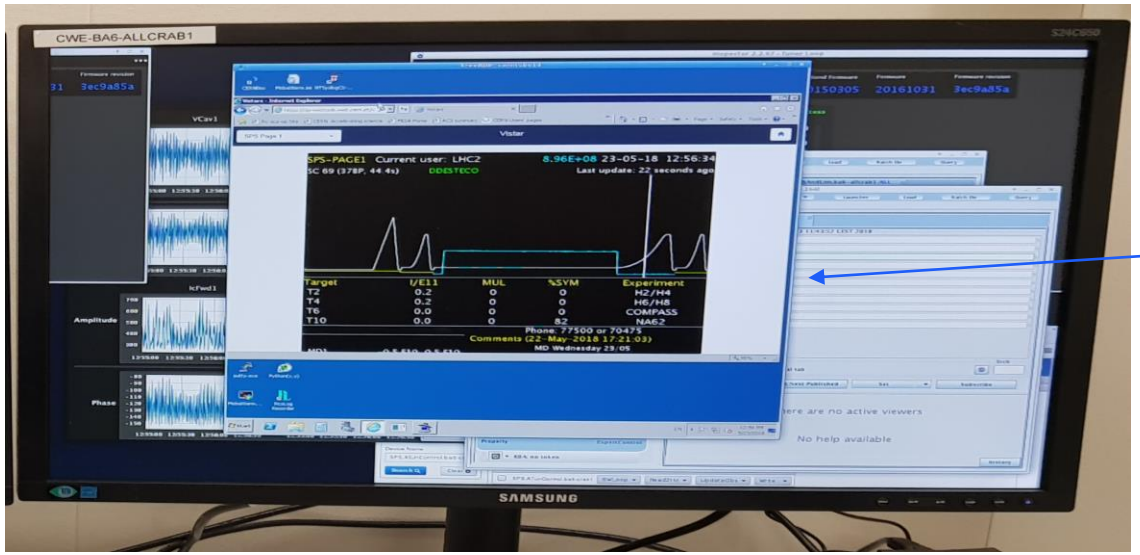
BROOKHAVEN NATIONAL LABORATORY · Fermilab · OLD DOMINION UNIVERSITY · CERN · Jefferson Lab · Science & Technology Facilities Council · Lancaster University · SLAC

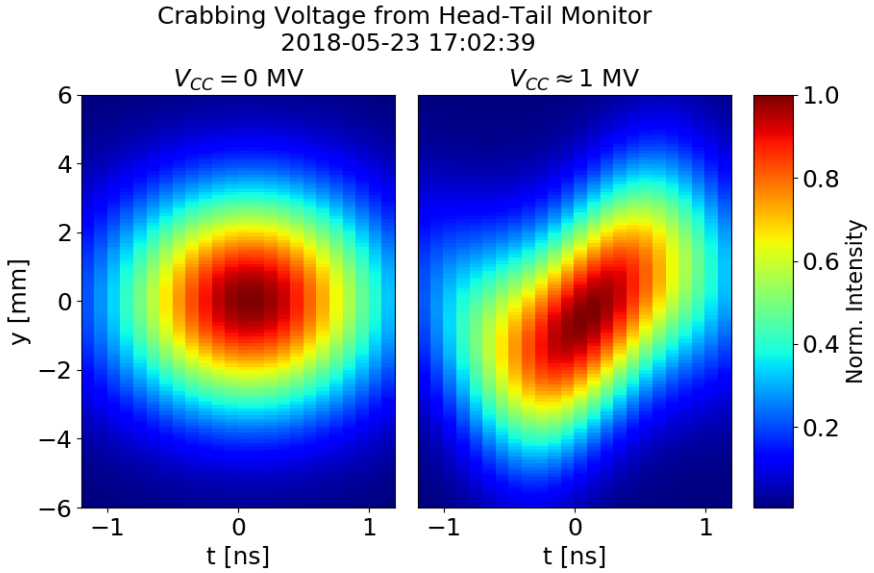
Protons meet Crabs! First HL-LHC CC Test on SPS@CERN – May 2018

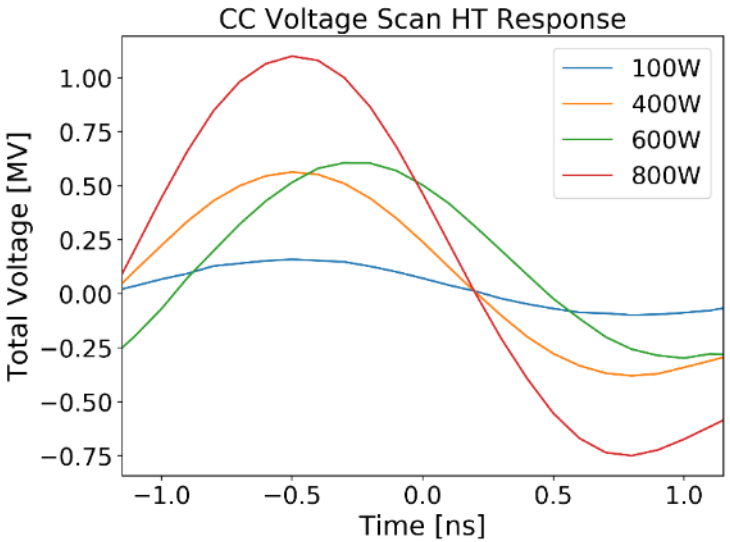


First injection – 12:55, May 23
Cavity 1 only

Single bunch
$0.2 - 0.8 \times 10^{11}$p/b

Crabbing reconstruction
(assuming Gaussian transversely)





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Superconducting Linac RF Technology

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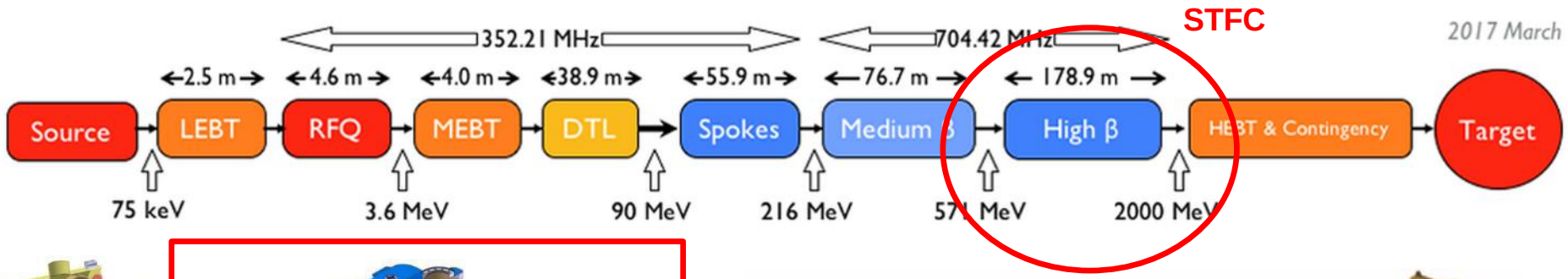
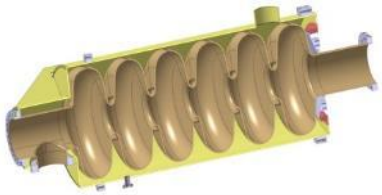
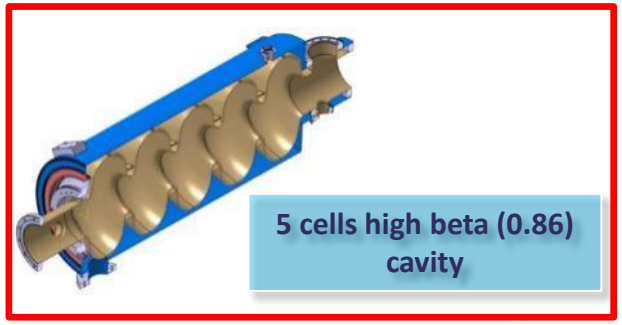
ESS High Beta Cavities (2015 – 2022)





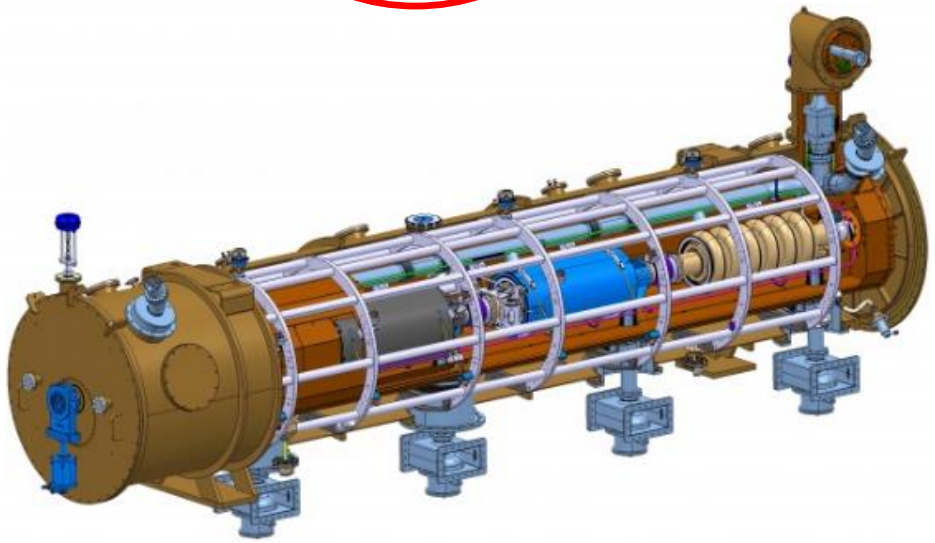
6-cells medium beta (0.67) cavity



5 cells high beta (0.86) cavity

Cavities without HOM coupler

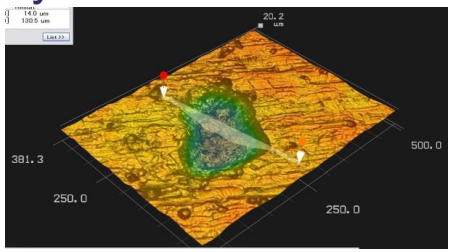
	Medium-β	High-β
Geometrical β	0.67	0.86
Frequency (MHz)	704.42	
No. of Cryomodules	9	21
Cavities /Cryomodule	4	4
No. of Cavities	36	84
Cryomodule length (m)	6.584	
Nominal Accelerating gradient (MV/m)	16.7	19.9
Nominal Accelerating Voltage (MV)	14.3	18.2
Q_0 at nominal gradient	> 5e9	



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

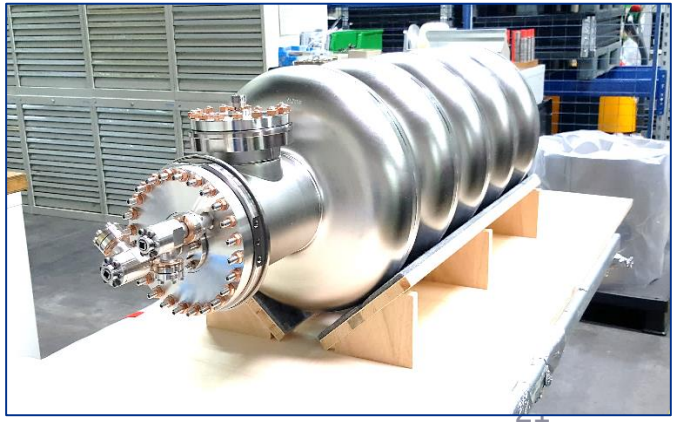
ESS Cavity Manufacture

- 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.



Cavity	Status	Cold test at DESY	Dressed cold test at DL
H001	Being prepared for test @ DL	Completed Mar 20	Exp Aug 2020
H002	Being prepared for test @ DL	Completed Mar 20	Exp Aug 2020
H003	Being prepared for shipment to DL	Completed Jul 20	Exp Oct 2020
H004	Being prepared for shipment to DL	Completed Jul 20	Exp Oct 2020

H001 READY FOR HELIUM JACKET ASSEMBLY



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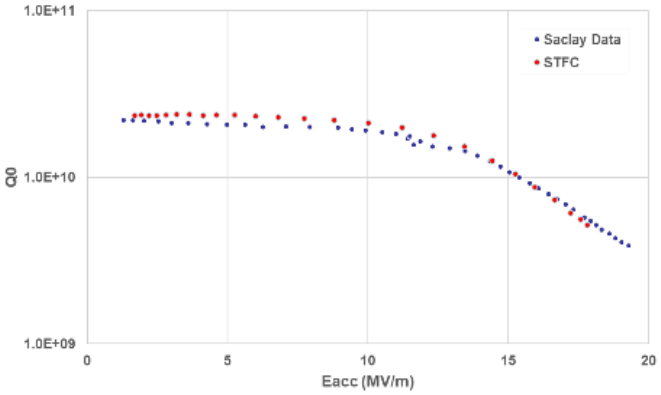
ESS Testing Infrastructure at Daresbury

- 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 (±1mK, ±0.1mBar); 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.



CEA prototype cavity P02 test at DL

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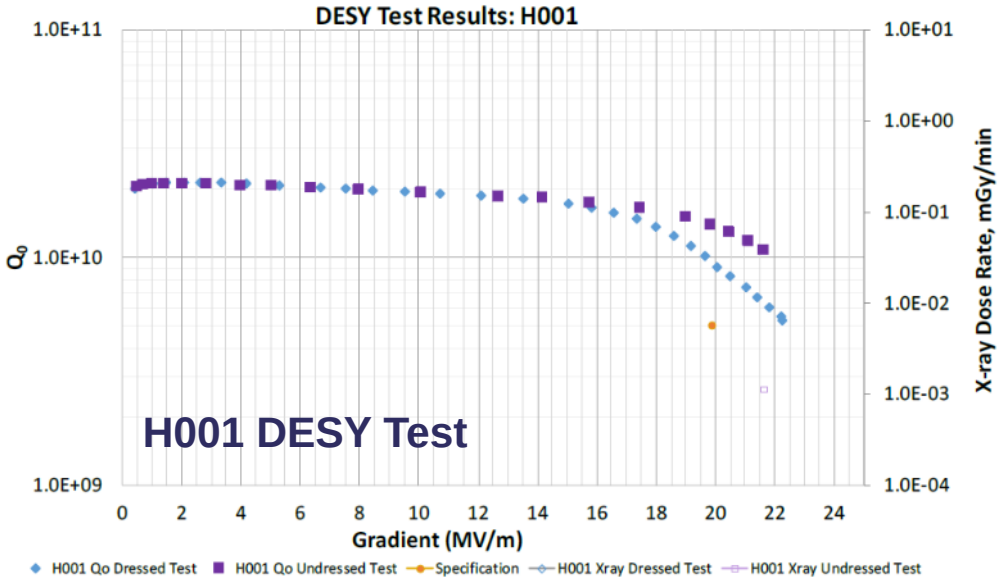
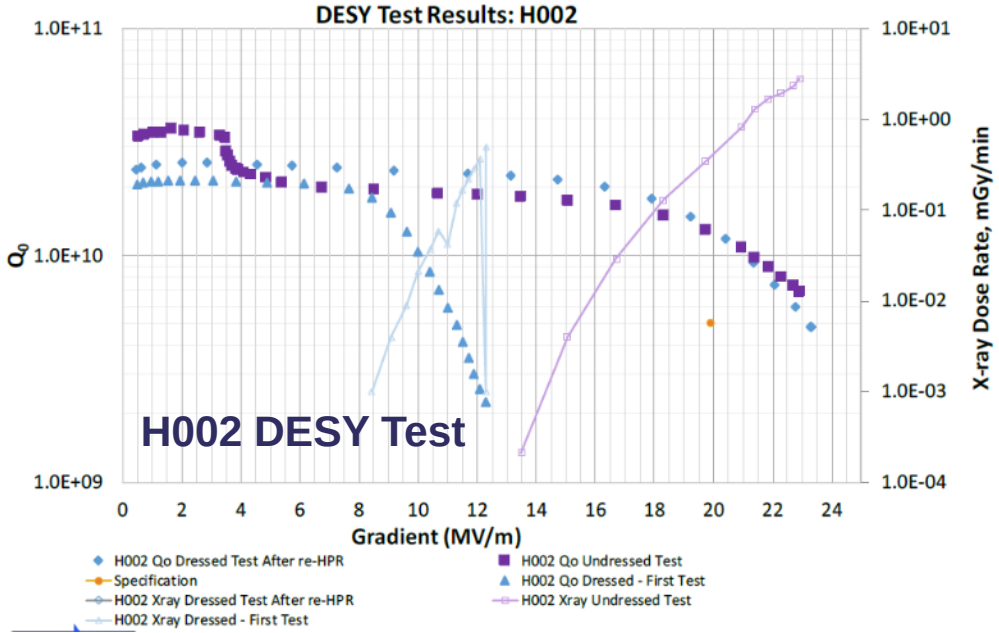
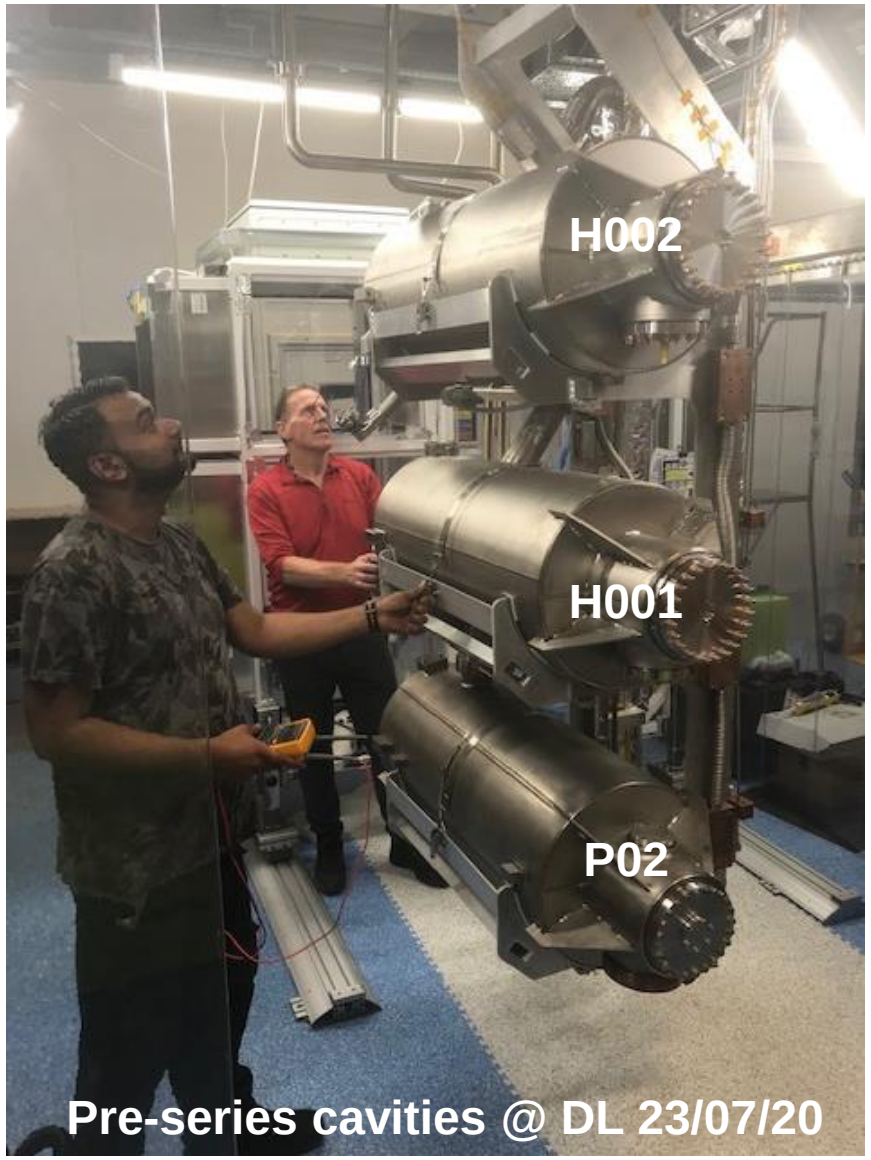
ESS First Pre-Series Tests @ Daresbury







Pre-series cavities @ DL 23/07/20

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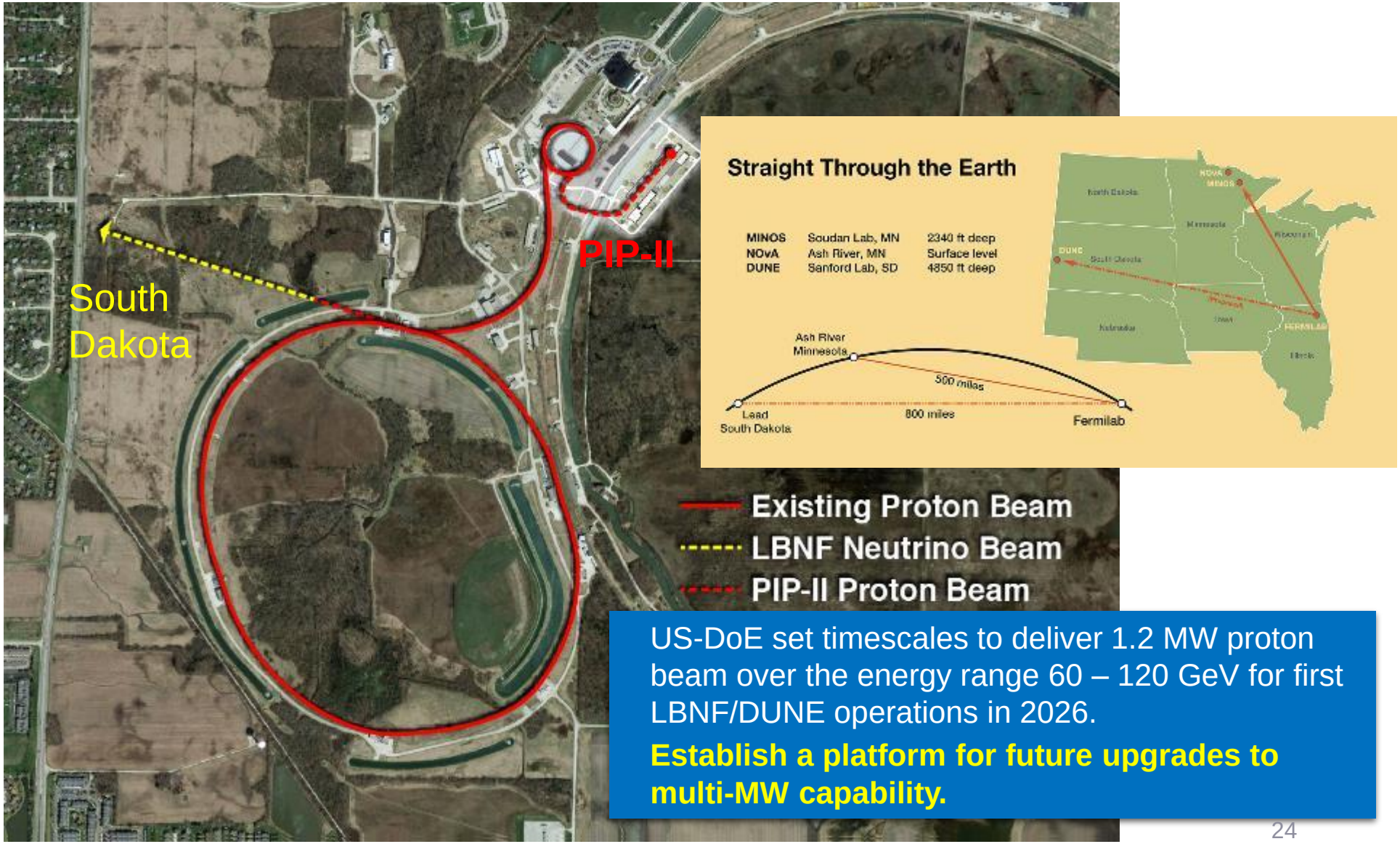
Fermilab Proton Improvement Plan II (2019 – 2025)



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.

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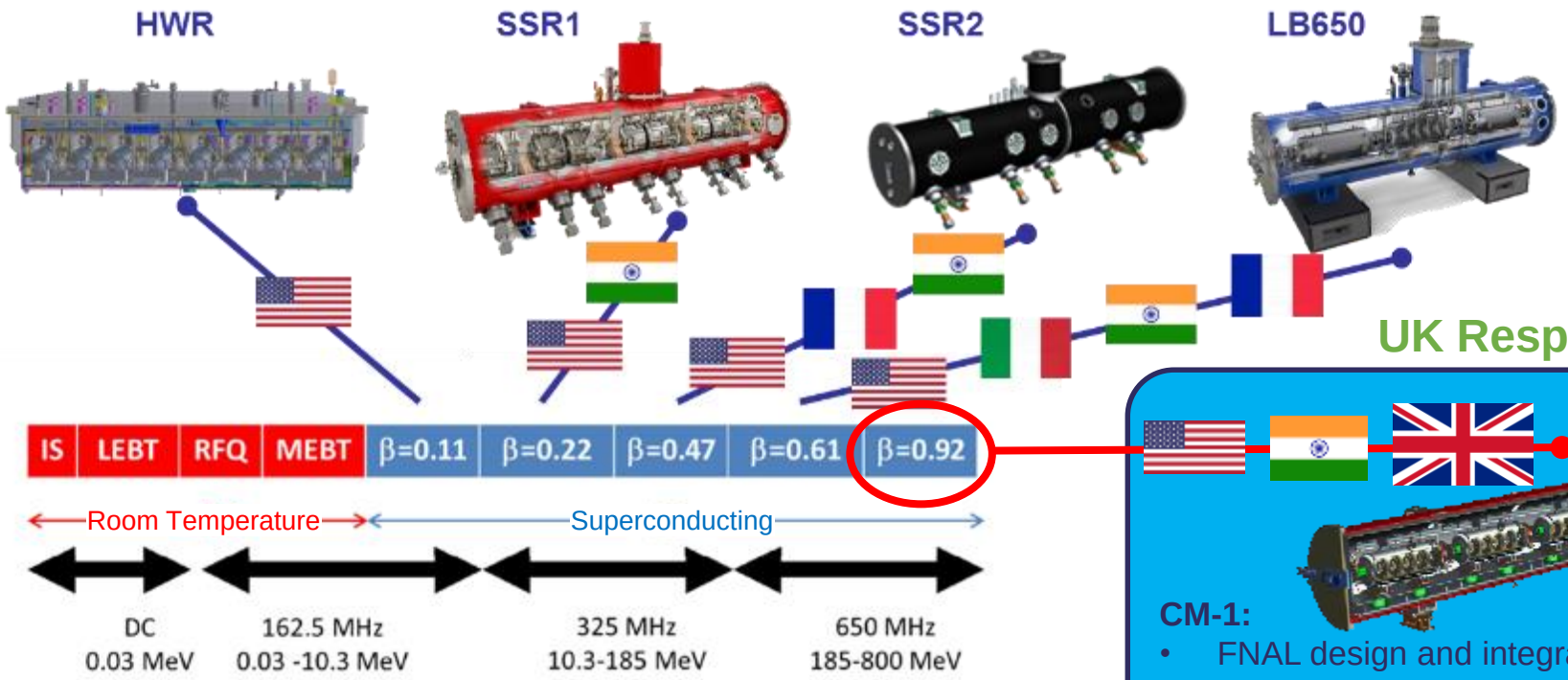
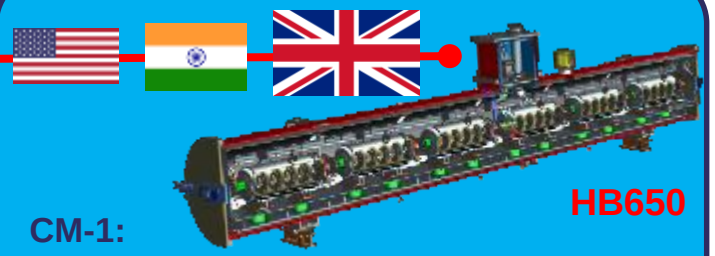
PIP-II HB650 Cryomodules



CM type	No. of CMs	Cavities Per CM	Magnets Per CM	Energy gain (MeV)	(Current) CM style	Transports
HWR	1	8	8	2	Bathtub	ANL to FNAL
SSR1	2	8	4	2.05	Strong-back	FNAL internal
SSR2	7	5	3	5	Strong-back	FNAL internal
LB650	11	3	0	11.9	Strong-back	CEA to FNAL
HB650	4	6	0	19.9	Strong-back	3: STFC to FNAL 1: FNAL internal ***
Totals:	25	116	37			

UK Responsibility



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.

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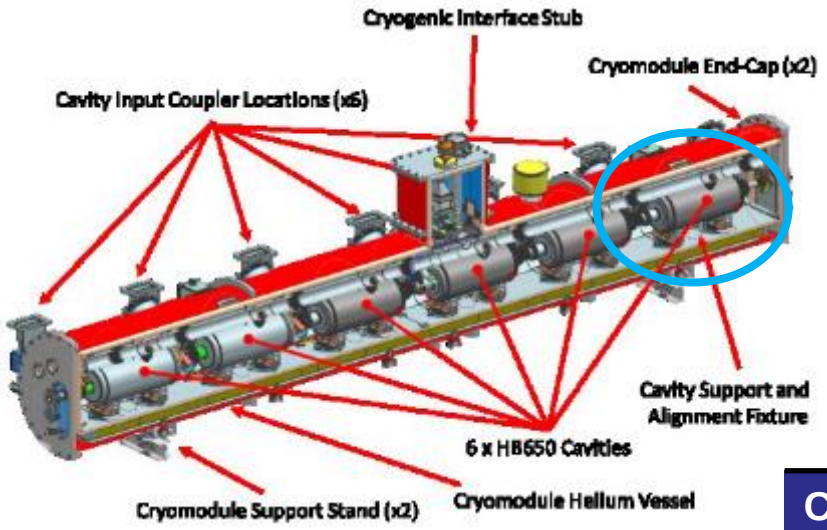
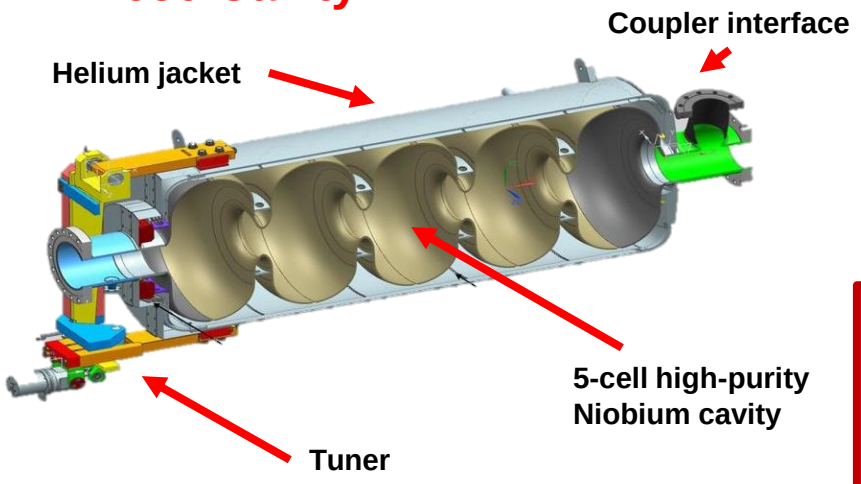
UK Delivery of PIP-II HB650 Cryomodules

HB650 Cryomodule



HB650 Cavity



Cryomodule (CM)	PIP-II
Operating Temperature (K)	2
Number of Cavities	**6**
Energy Gain (MeV)	**~110**
Dynamic Load (W)	130
Static Load (W)	32
CM Length (m)	**9.8**
Number of Cryomodules	**3**

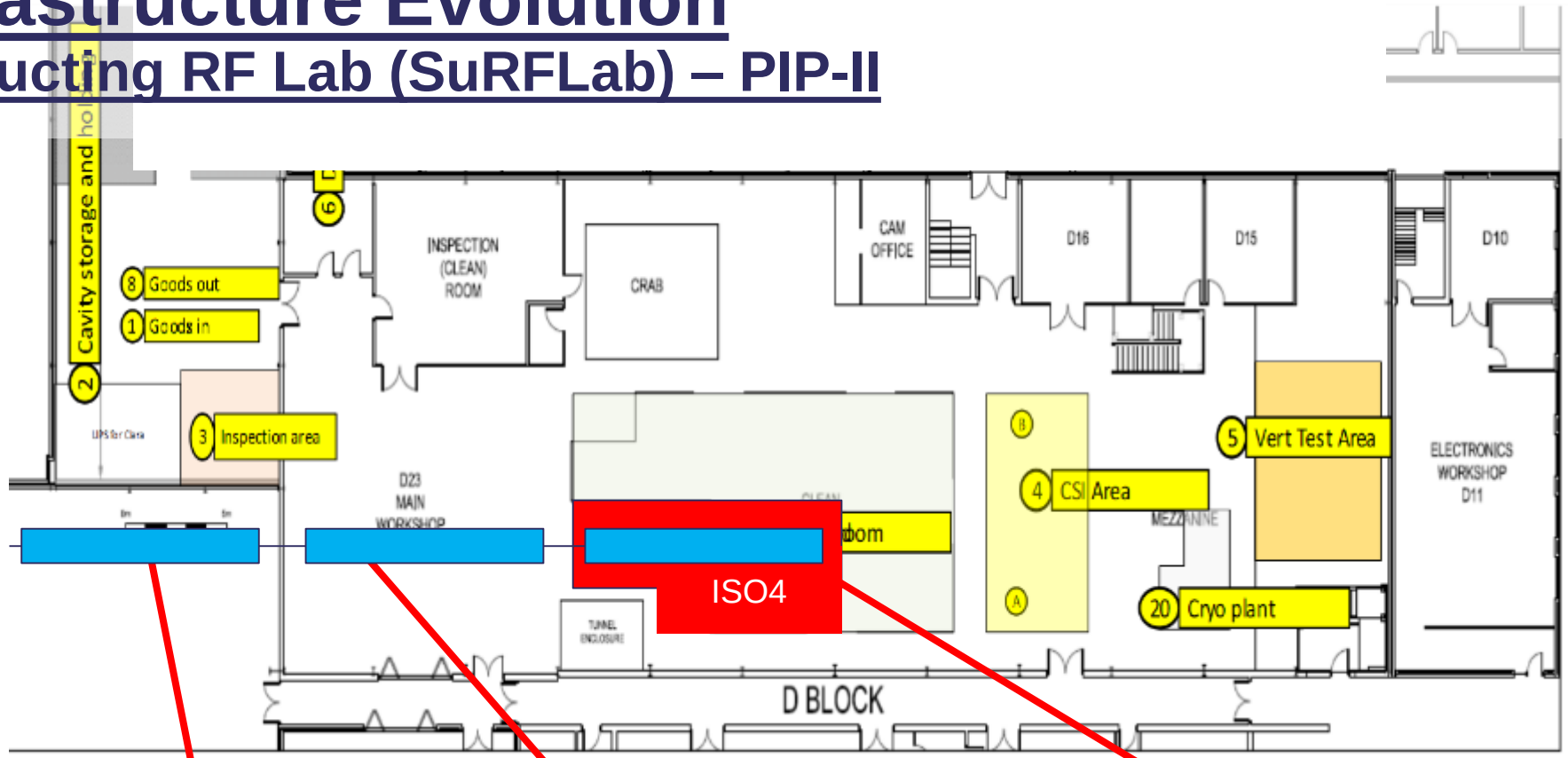
Cavity	PIP-II
Frequency (MHz)	650
Cavity Beta	0.92
Gradient (MV/m)	**19.9**
Quality Factor Qo	**3 x 10^{10} (N2 Doped)**
Number of Cells	5
Cavity Dynamic Load (W)	<22
Cavity Length (m)	**1.42**
Number of Cavities	**18 (+2)**

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



Outer vessel integration

String to support & shields

Cavity string assembly

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Polarized Electron Source

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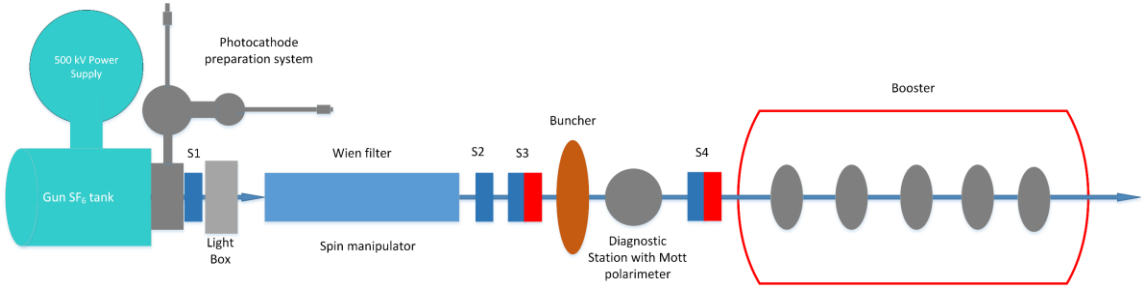
Polarized Electron Source

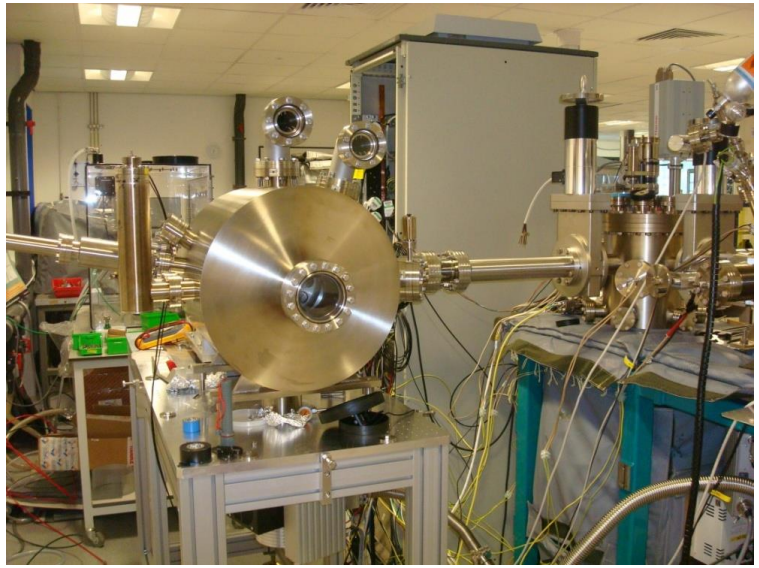
- **Scientific and technological challenges of PES'es:**
- Photocathode
  - Maximum polarisation
  - Potential Quantum Efficiency (QE)
  - Response time
  - Life time
- Photocathode activation infrastructure:
  - Extra High Vacuum (EHV) conditions ($p<1.0\cdot10^{-11}$ mbar with O_2 pressure $<1.0\cdot10^{-16}$)
  - 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)



Extra High Vacuum GaAs photocathode preparation system

Transverse Energy Spread Spectrometer (TESS)



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Second Interaction Region

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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 *β**) to collision (minimized *β**) optics.

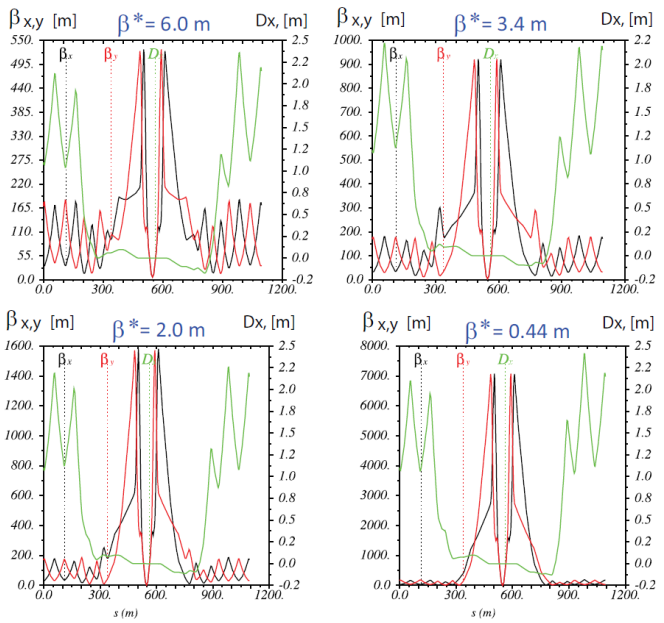
- ERL-Ring LHeC optics, to be integrated into HL-LHC

  "LHeC IR optics design integrated into the HL-LHC lattice", M.Korostelev, E. Cruz-Alaniz, D. Newton, A.Wolski, O. Bruning, R. Tomas, proceedings of IPAC'13.

  "LHeC IR optics design integrated into the HL-LHC lattice", E. Cruz-Alaniz, M. Korostelev, D. Newton, R. Tomas, proceedings of IPAC'14.

  "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.

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **40** (2013) 125004 (20pp) doi:10.1088/0954-3899/40/12/125004

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]

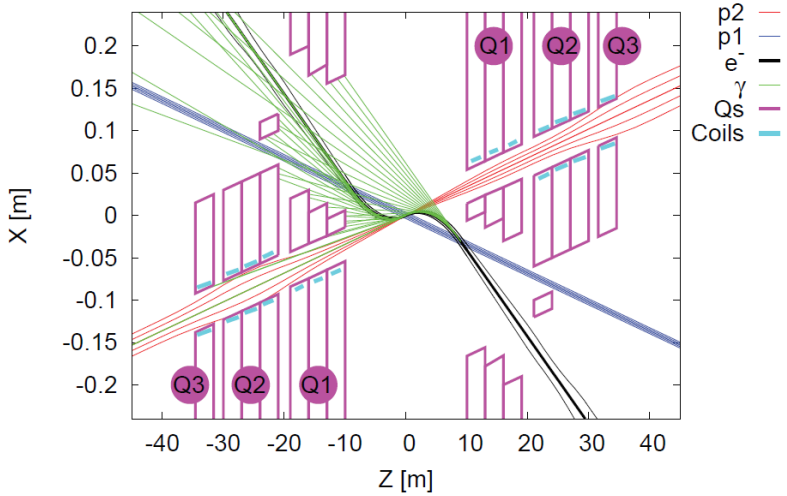


Figure 1: LHeC interaction region with a schematic view of synchrotron radiation. Beam trajectories with 5σ and 10σ envelopes are shown.

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Electron Beam Diagnostics

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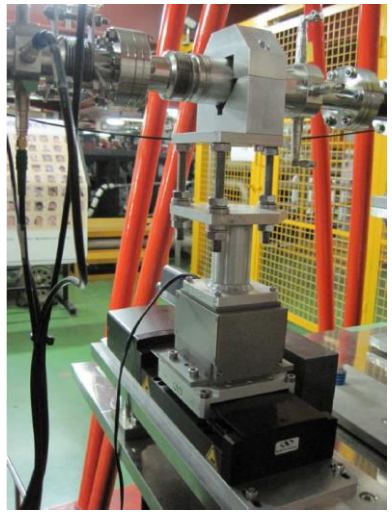
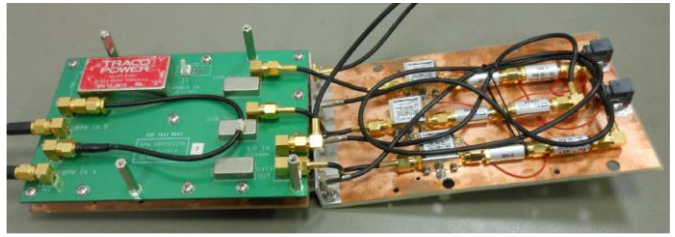
Electron Beam Diagnostics – JAI (Oxford, RHUL)
Also see Stephen Gibson's talk

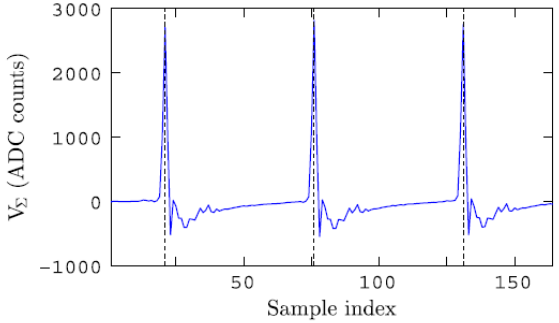
Stripline BPMs



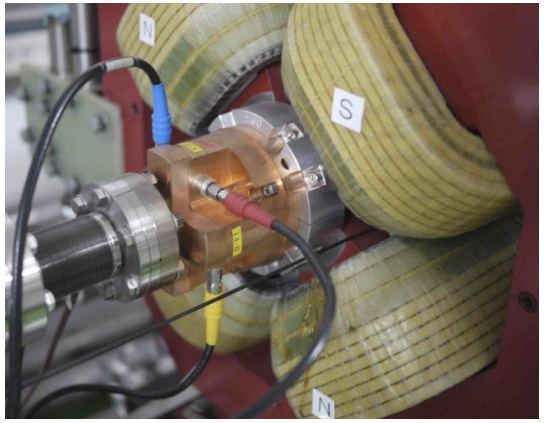
ATF



Excellent temporal + spatial resolution



Cavity BPMs



ATF2 (6.5 GHz)

CLIC main beam/CTF3 (15 GHz)

Nanometre-resolution

Resolution calculation method	Resolution (nm) Single sampling	Resolution (nm) Integration sampling
Geometric	49 ± 1	21.5 ± 0.4
Fitting I'	49 ± 1	19.9 ± 0.4
Fitting I', Q'	43 ± 1	19.5 ± 0.4
Fitting I', Q', q	43 ± 1	19.5 ± 0.4
Fitting I', Q', q and x	42 ± 1	19.2 ± 0.4

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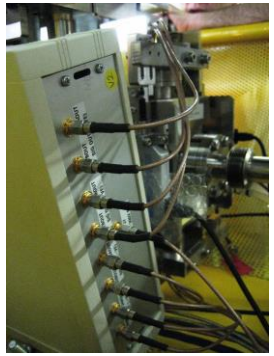
Electron Beam Diagnostics – JAI (Oxford, RHUL)
Also see Stephen Gibson's talk

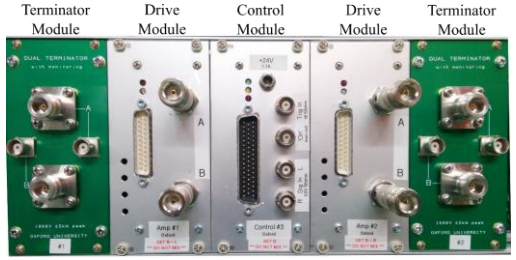
High power / bandwidth, low latency amplifiers

NLCTA



ATF2

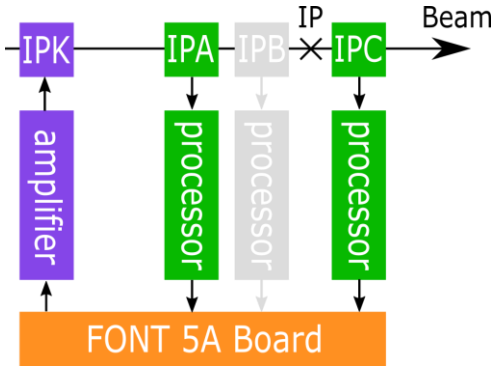
ATF

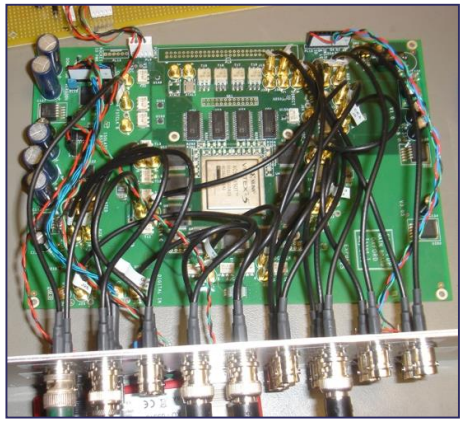


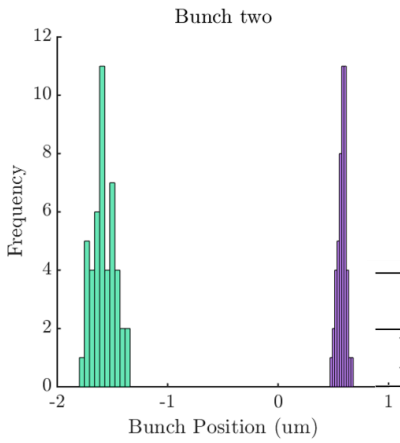
CTF3

Digital & Analogue feedback / feedforward

FONT5: ATF2 + CTF3







Feedback using nanometer resolution BPMs

	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	106 ± 16	106 ± 16
2	96 ± 10	41 ± 4

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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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