Science and Technology Facilities Council

The Cockcroft Institute of Accelerator Science and Technology

John Adams Institute for Accelerator Science

FCC hh ee he

Accelerator opportunities

Stephen Gibson – JAI @ Royal Holloway

on behalf of the UK accelerator community

FCC-UK: discussion on UK involvement in the FCC project

11th September 2020

CERN

ROYAL HOLLOWAY UNIVERSITY OF LONDON

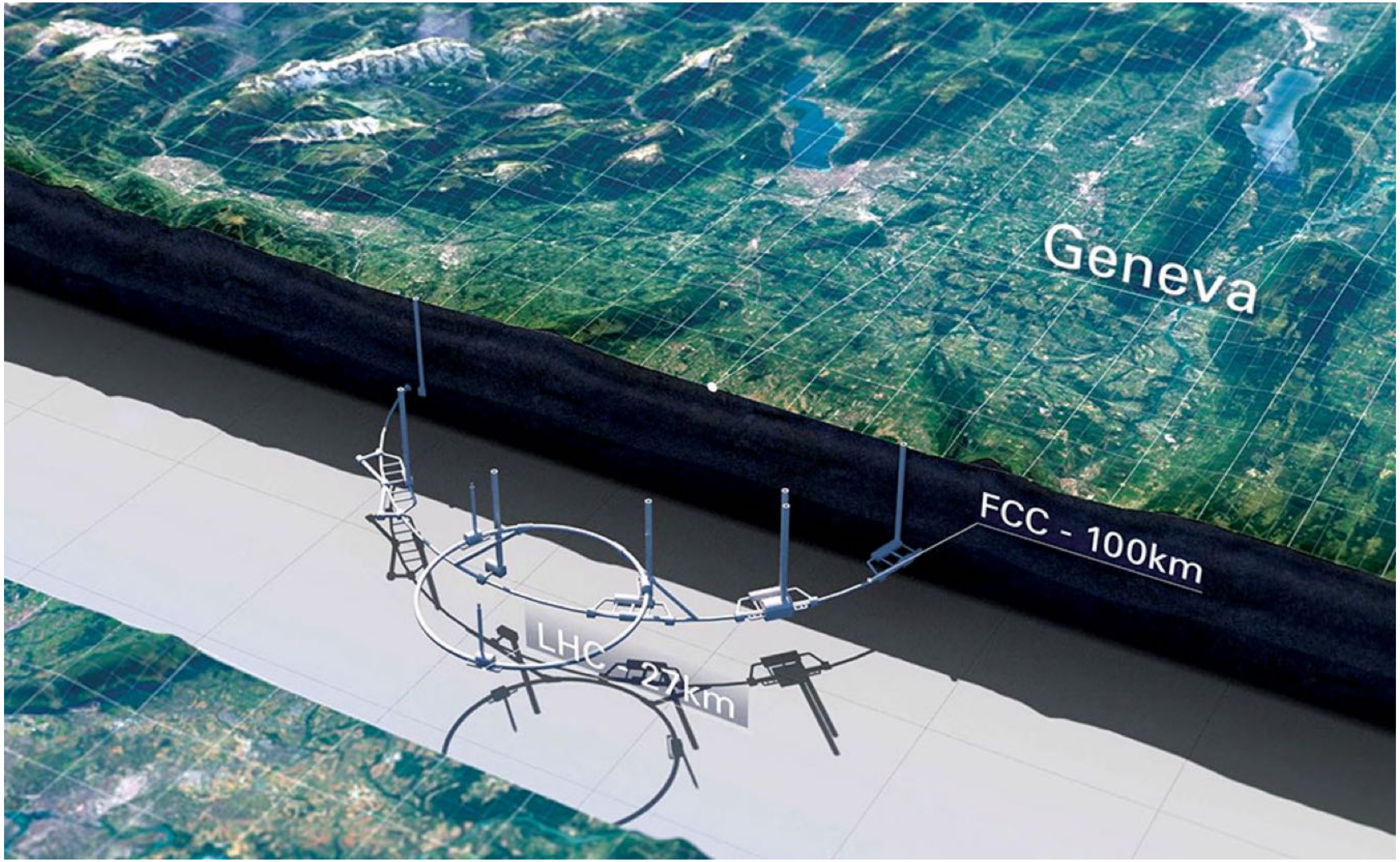
Overview

- ***FCC design study***
  - *Motivation and brief review of UK participation to date*
    - *IR optics design, energy deposition, dynamic aperture & ion collimation for FCC-hh*
  - *Remaining technical challenges for FCC*

- ***Relevant UK accelerator expertise and enabling technologies:***
  - *Superconducting RF, cryogenics & vacuum, klystrons.*
  - *Accelerator simulations, beam dynamics, beam diagnostics.*
  - *Machine protection, novel collimation, IR design & accelerator backgrounds.*

- ***Opportunities and synergies with ongoing accelerator projects:***
  - *e.g HL-LHC, Linear Collider, Diamond-II, XFEL & FEL test facilities, ESS, PIP-II/LBNL, EIC, etc…*

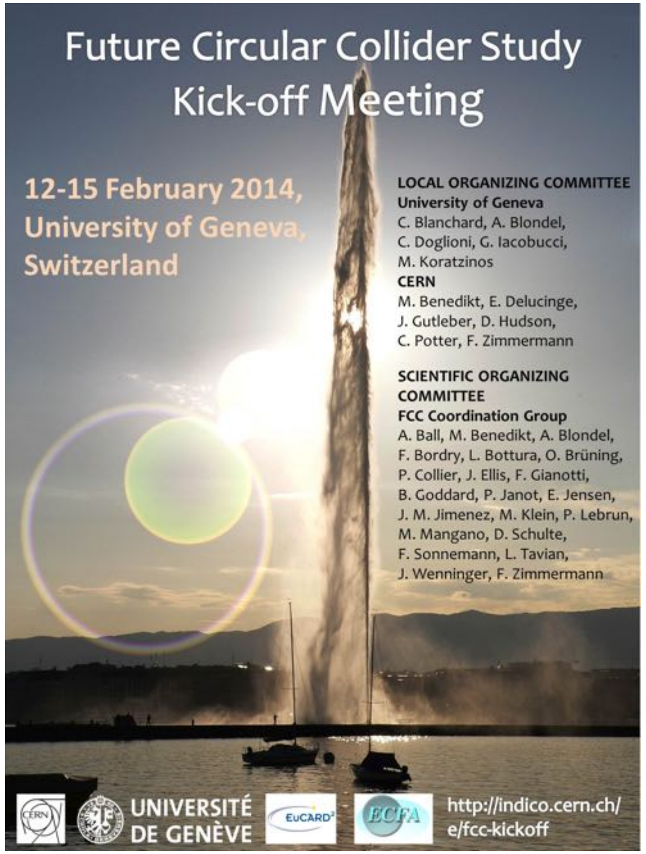
Future Circular Collider Design Study



FCC Design Study: motivation

- ***EU Strategy 2013:***

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide."



- ***Stimulated launch of FCC Design Study:***
  - *2014 kick of meeting in Geneva, + FCC weeks in Brussels, Amsterdam*
- ***UK accelerator community contributed via EU H2020 EuroCircCol***

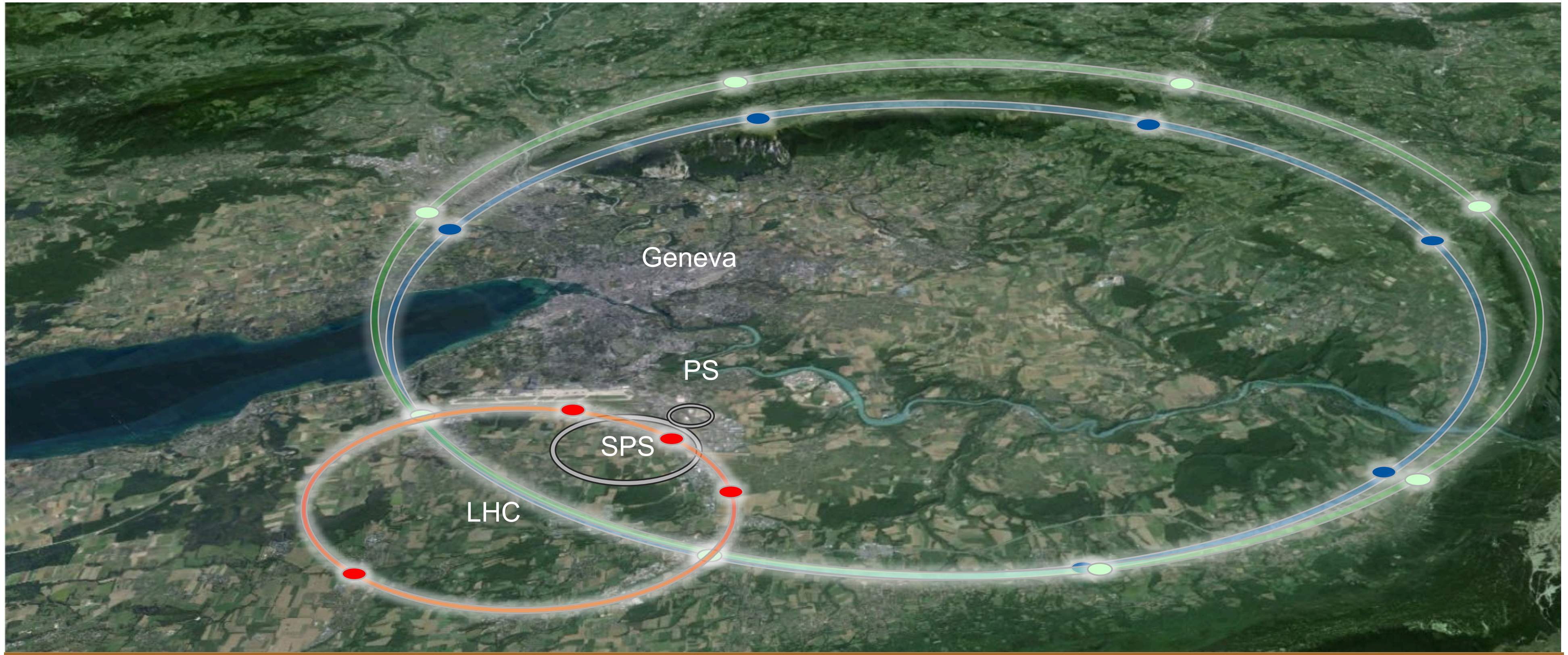
  UK led WP3:
  - ***IR design & inner triplet optics***
  - ***Machine detector interface***

EuroCirCol
A key to New Physics

- ***Culminated in FCC Conceptual Design Reports published in 2019:***
  - ***EPJ C: Vol 1 Physics & EPJ ST: Vol 2 FCC-ee; Vol 3 FCC-hh; Vol 4 HE-LHC.***
  - ***https://fcc-cdr.web.cern.ch/***

FCC weeks 2015 - 2019

FCC Design Study



Full parameters:
FCC-ee → talk by *Tessa Charles*

FCC-hh → talk by *Michael Benedikt*

FCC-he → *talk by Max Klein*

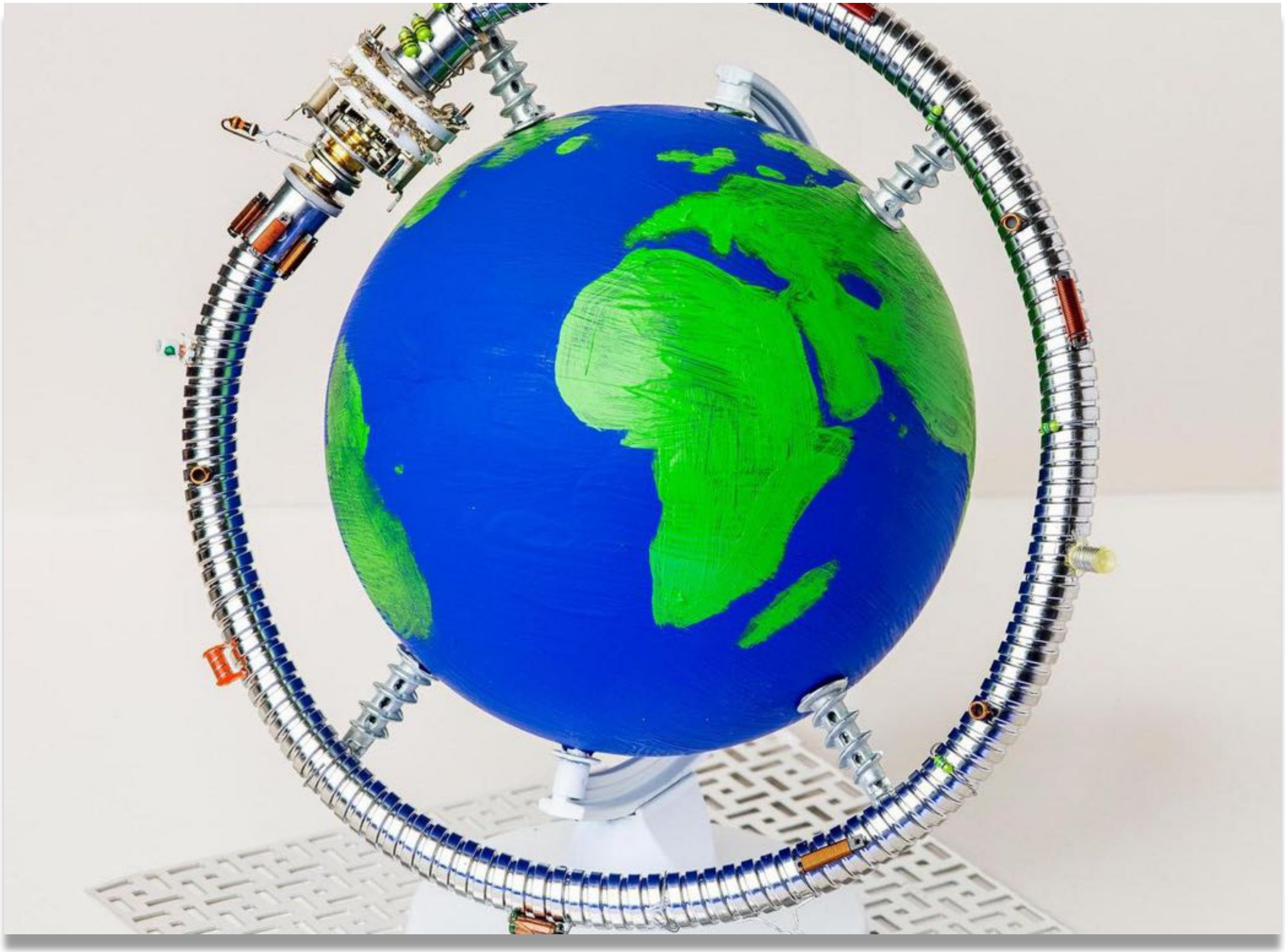
parameter	FCC-hh	HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100	27	14	14
dipole field [T]	16	16	8.33	8.33
circumference [km]	97.75	26.7	26.7	26.7
stored energy/beam [GJ]	8.4	1.3	0.7	0.36

FCC week in Amsterdam, 2018:

Big article in Dutch press:

deVolkskrant

Hoe moet de grootste deeltjesversneller op aarde eruit gaan zien?

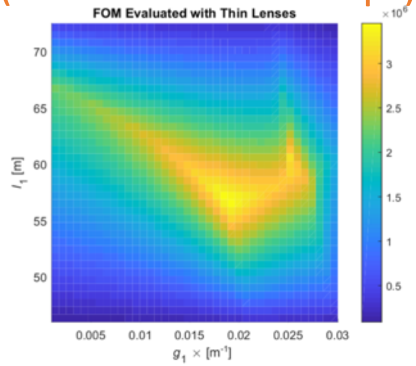


"What might the largest particle accelerator on earth look like?"

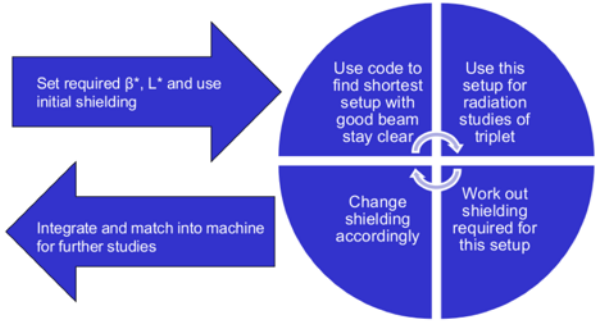
UK contributions to FCC-hh Design Study (e.g. i)

- ***Design of an alternative IR***
  - ***Final focus triplet optimised for length/cost***

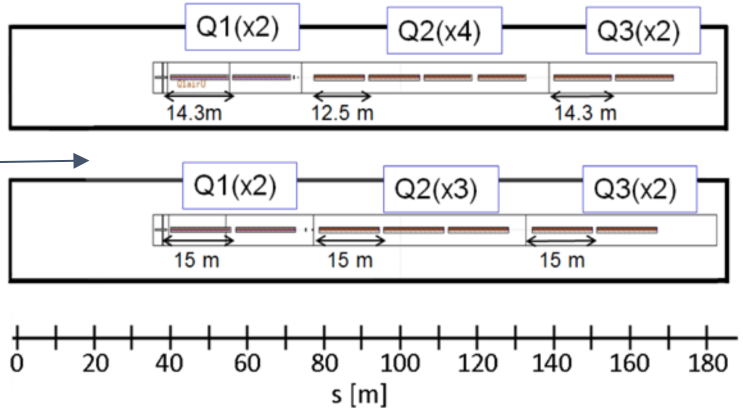
Scan of parameters
(L. Van Riesen-Haupt)



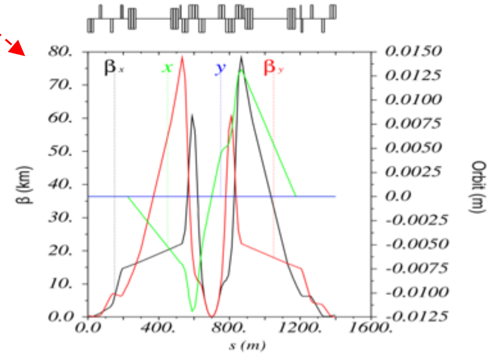
Iterative check of energy deposition (J. Abelleira)

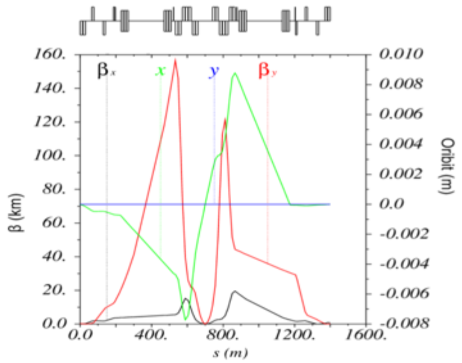


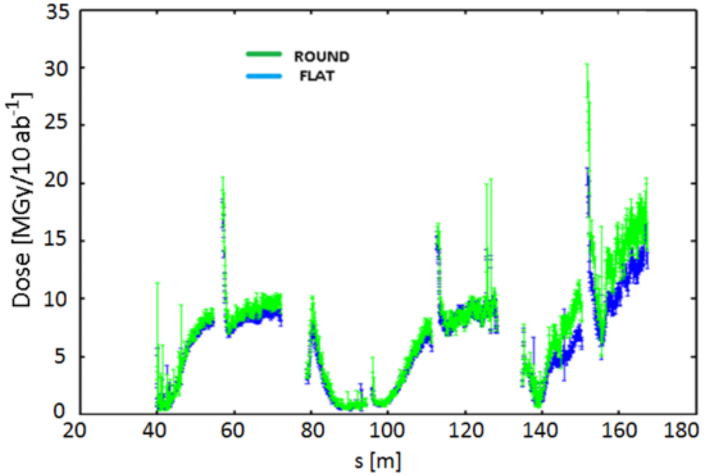
Resulting alternative triplet (down) compared to nominal (up). 4 m shorter



  - ***Validated new triplet optics and energy deposition for both round beams (β*=30 cm) and flat beams (β*=1.2 x 0.15 m)***





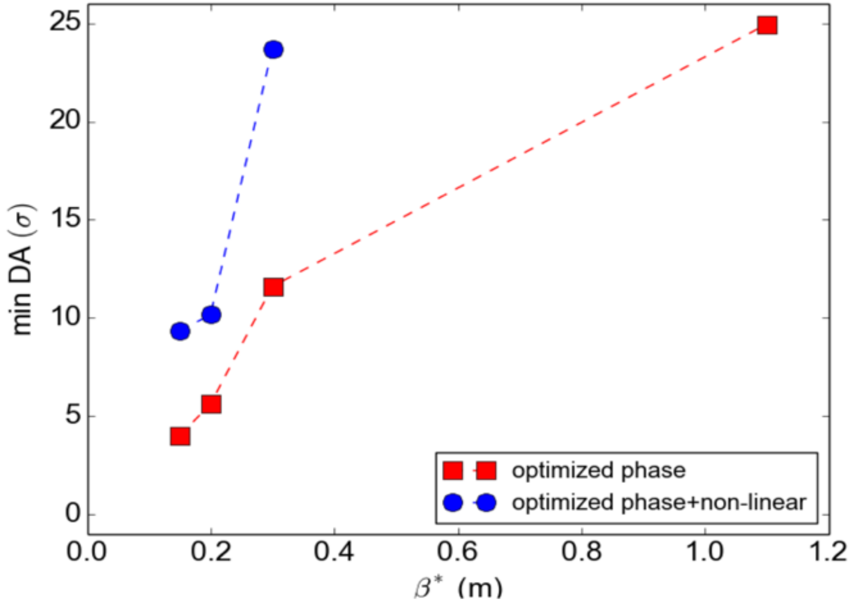


UK contributions to FCC-hh Design Study (e.g. ii)

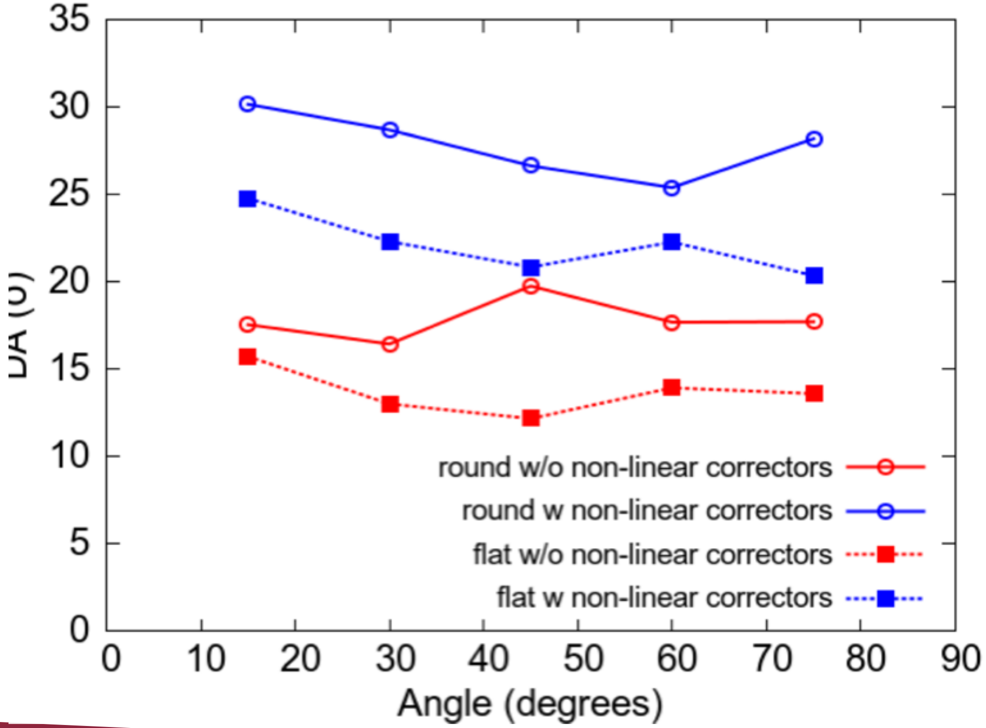
UNIVERSITY OF OXFORD

- ***Study stability of different lattices designs*** *(baseline, different β*, alternative, flat)* *(E. Cruz)*
  - *Study impact of linear and non-linear errors on interaction region*
  - *Analyse dynamic aperture for different lattices*
  - *Determine where non-linear correctors in the interaction region are needed.*

Explore β* options for the baseline design (β*=0.15, 0.2, 0.3, 1.1 m)

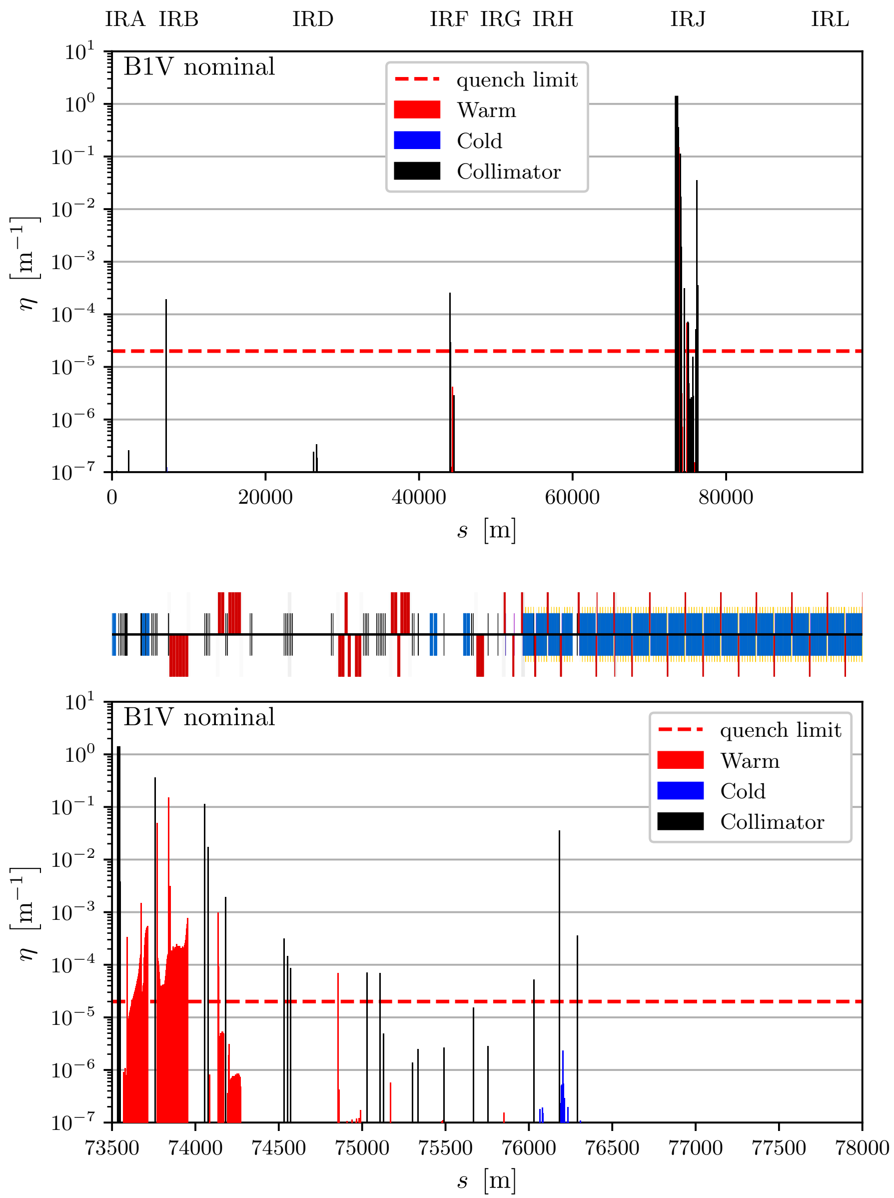


Study dynamic aperture for the alternative design



UK contributions to FCC-hh Design Study (e.g. iiii)

- ***Ion-collimation studies*** ***(A. Abramov)***
  - *FCC-hh has ion operation in the baseline, however, ions can fragment in the collimation system, producing multi-species ion secondaries.*
  - *Detailed studies of ion collimation have been performed for the most challenging collimation scenarios:*
    - *betatron cleaning at top energy*
    - *off-momentum cleaning at injection energy*
  - *Betatron loss maps are shown for the FCC-hh B1V with $^{208}Pb^{82+}$ ions at collision energy, for the full ring (top) and a zoom of the betatron cleaning insertion IRJ.*
  - *A. Abramov, "Ion Beam Collimation for Future Hadron Colliders', PhD thesis 2020.*



ESPP20 update and next steps for FCC

- ***EU Strategy 2020:*** *"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."*

- ***FCC Innovation Study (FCCIS) kickoff meeting in 9-13 November 2020 at CERN, including 4th Physics & Experiments workshop, to begin to address the ESPP20 mandate.***
  - https://indico.cern.ch/event/923801/
  - FCCIS will deliver a conceptual design and an implementation plan for a new research infrastructure, consisting of a 100 km long, circular tunnel and a dozen surface sites. It will initially host an electron-positron particle collider. With an energy frontier hadron collider as a second step, it can serve a world-wide community through the end of the 21st century. This project will validate the key performance enablers at particle accelerators.

- ***Important technical challenges for FCC can be addressed by UK core accelerator expertise.***

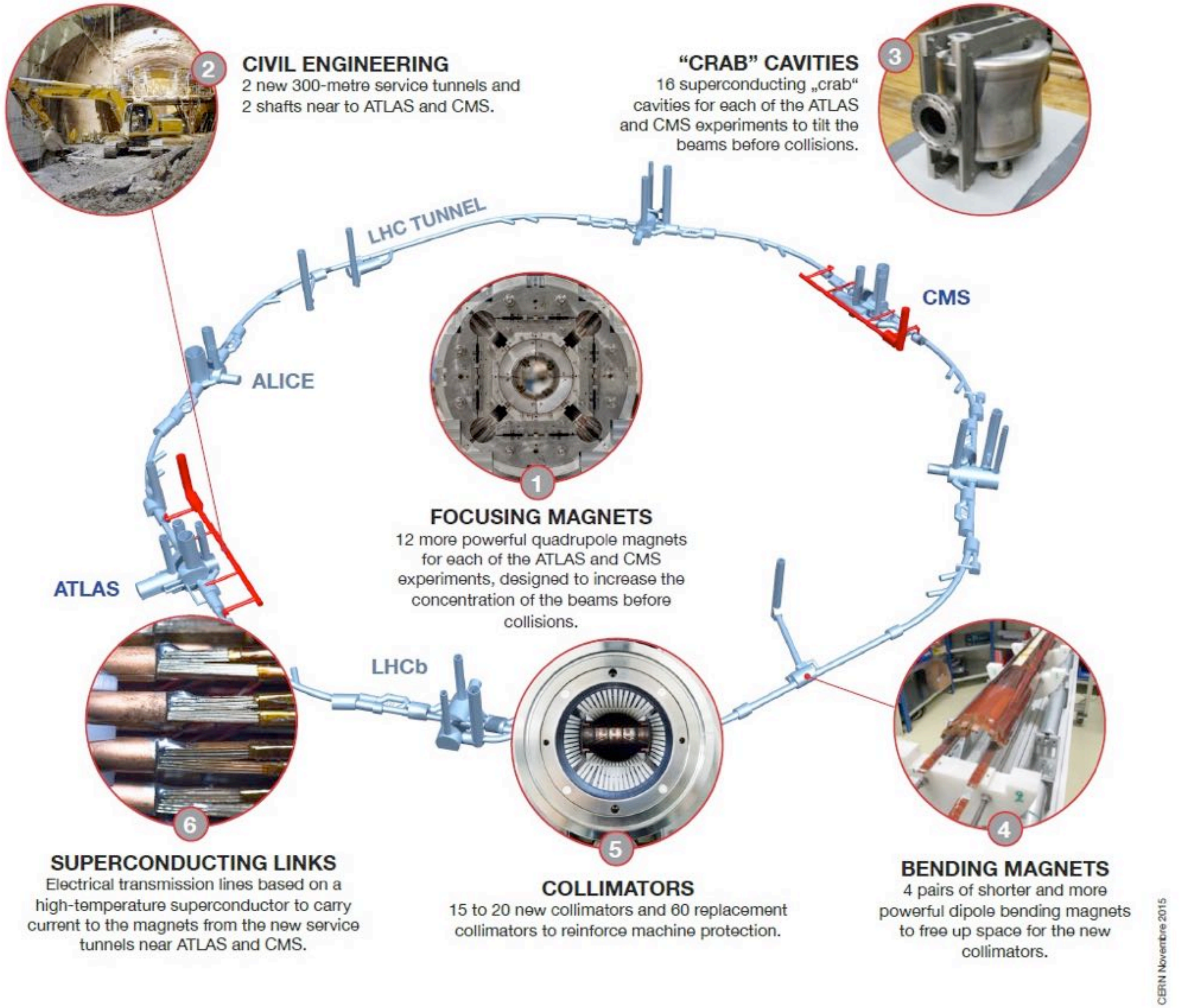
Core UK expertise in accelerators & enabling technology

The UK accelerator community has broad range of relevant expertise ready to deploy, including and not limited to:

- *Beam dynamics simulations; optical lattice design & optimisation*
- *Novel collimation techniques: crystal, hollow electron lens.*
- *Machine detector interface & accelerator backgrounds*
- *Superconducting RF cavities + crab-cavities.*
- *Beam diagnostics, including non-invasive profile & bunch instability monitoring*
- *Nanobeam control and fast feedback*
- *Cryogenic systems, cold powering.*
- *Vacuum systems & electron cloud mitigation*
- *Accelerator alignment systems*
- *Operational experience of low emittance electron storage rings & FEL test facilities…*

*ESPP2020 "Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. … **The European particle physics community must intensify accelerator R&D and sustain it with adequate resources**.*

HL-LHC-UK phase I (2015-2020)



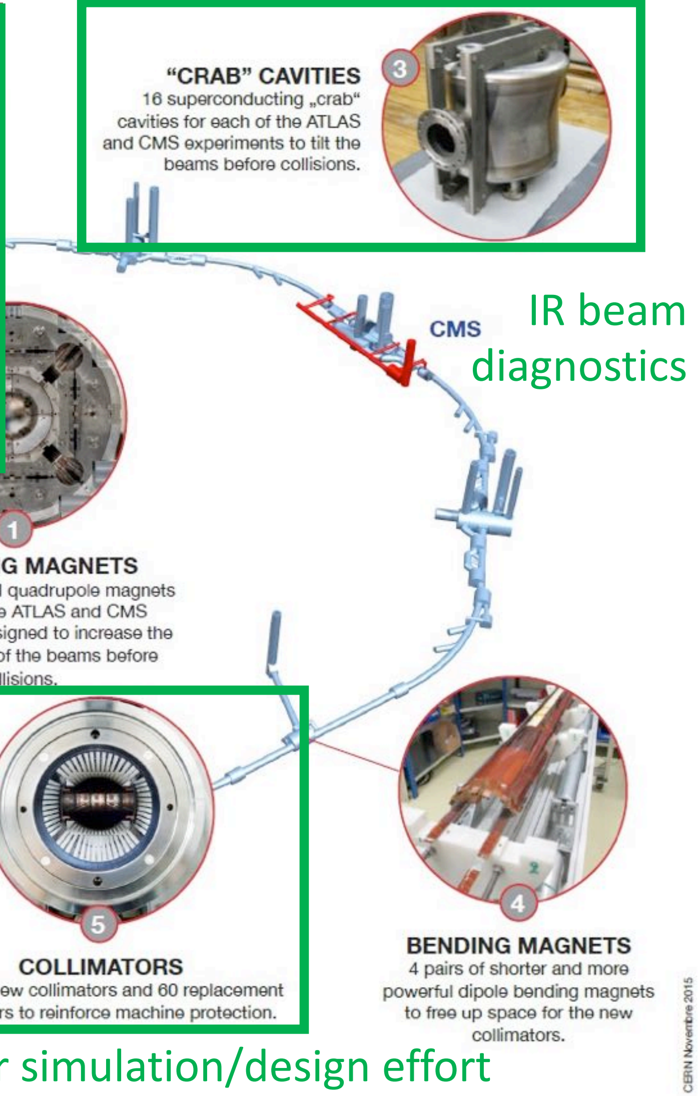
- **Lower beta* (~15 cm)**
  - New inner triplets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
  - Long-range beam-beam compensation
- **Dealing with the regime**
  - Collision debris, high radiation
- **Beam from injectors**
  - Major upgrade of complex (LIU)
  - High bunch population, low emittance, 25 ns beam

HL-LHC-UK phase I (2015-2020)

HiLumi HL-LHC PROJECT

UK delivered crab cavity prototype to SPS


Complete Crab Cavity Cryomodule installed



IR beam diagnostics

UK built prototypes

Major simulation/design effort

UK institutes on ***HL-LHC-UK***

£8M CERN-STFC investment in UK

- The University of Manchester
- The Cockcroft Institute of Accelerator Science and Technology
- Lancaster University
- University of Liverpool
- Royal Holloway University of London
- John Adams Institute for Accelerator Science
- University of Southampton
- University of Huddersfield
- ASTeC

LHC Injectors Upgrade

+ new injector diagnostics

Linac2:
50 MeV protons

Linac4:
160 MeV H^{-} ions
http://home.cern/about/accelerators/linear-accelerator-4

HL-LHC-UK phase II announced today by STFC

https://stfc.ukri.org/news/project-to-upgrade-the-large-hadron-collider-now-underway/

Upgrade to Large Hadron Collider underway

11 September 2020

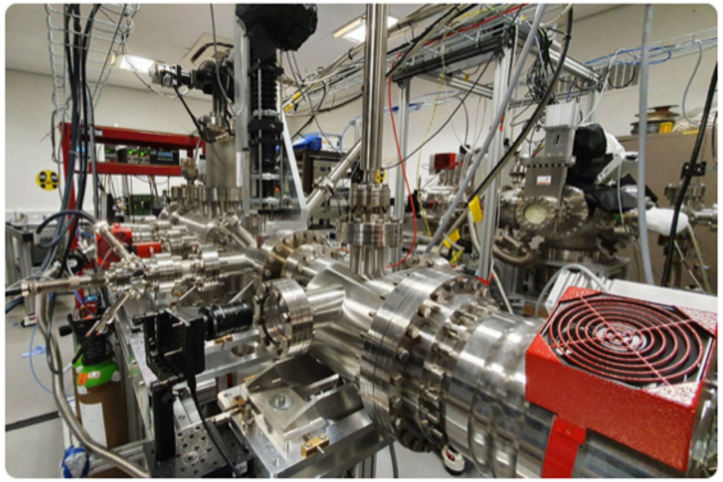
Scientists, engineers and technicians from the UK have embarked on a £26 million project to help upgrade the Large Hadron Collider (LHC) at CERN, on the French/Swiss border near Geneva.

The collaboration is between the Science and Technology Facilities Council (STFC), CERN, the Cockcroft Institute, the John Adams Institute, and eight UK universities. STFC is contributing £13.05 million.

Science Minister Amanda Solloway said:

"Ever since it first switched on in 2008, CERN's Large Hadron Collider has been working to answer some of the most fundamental questions of the universe.

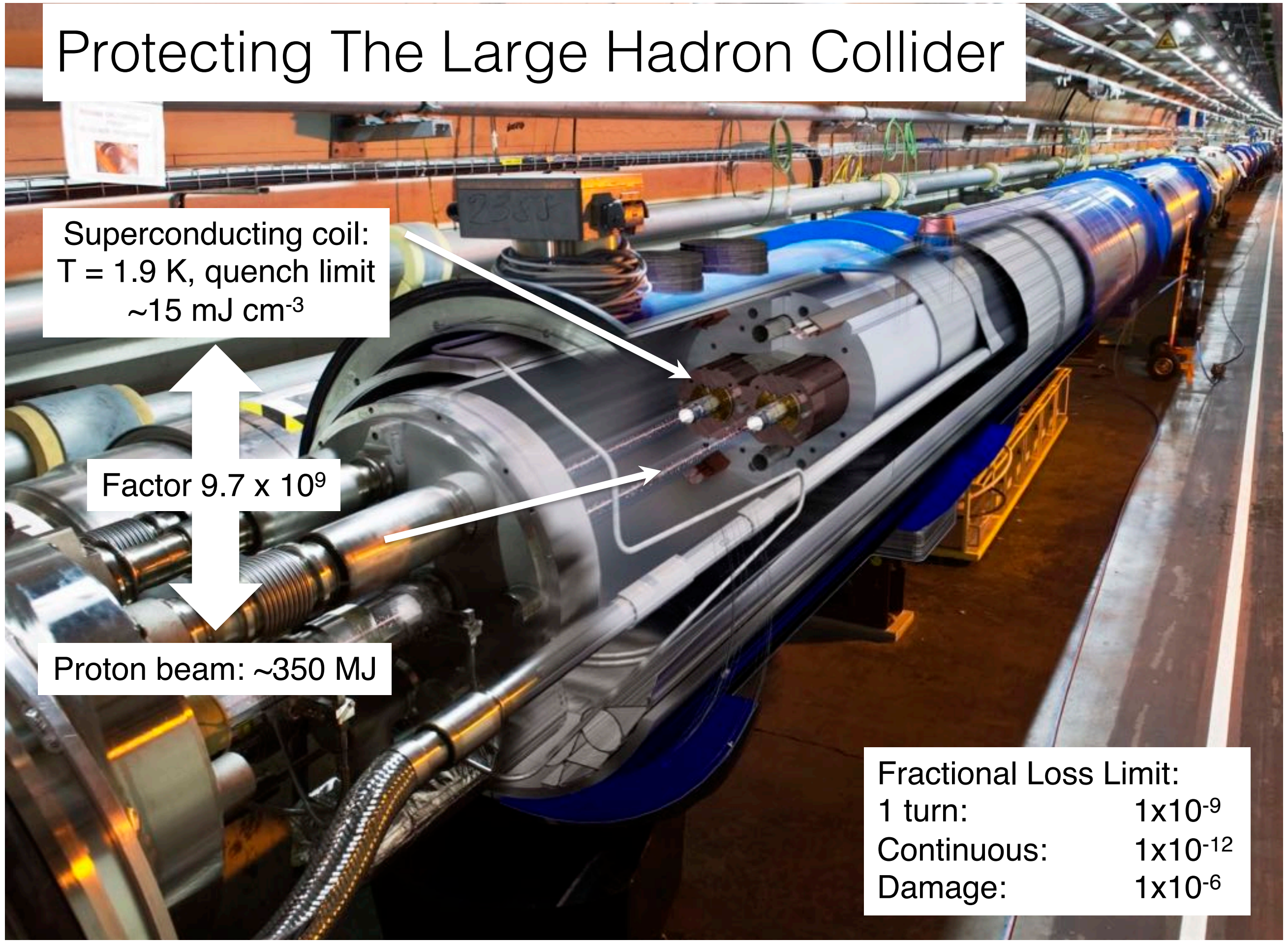
"I am delighted that the UK's science and research industry will play a central role in upgrading what is the world's largest and highest energy particle collider, enabling leading physicists to continue making monumental discoveries."

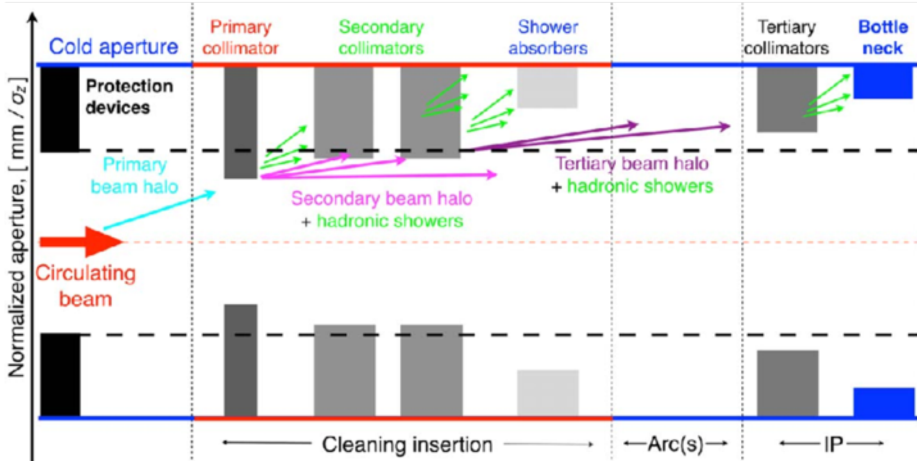


Gas jet beam profile monitor setup at the Cockcroft Institute.

Machine Protection at the LHC, HL-LHC and FCC-hh

- ***Efficient cleaning of proton beam halo is vital to protect the sc magnets***





Stored beam energy:

– ***LHC ~ 350 MJ***

TGV at 150km/h

– ***FCC-hh = 8.4 GJ***

Equivalent to AirBus A380 at 850 km/h

BDSIM model of LHC collimation

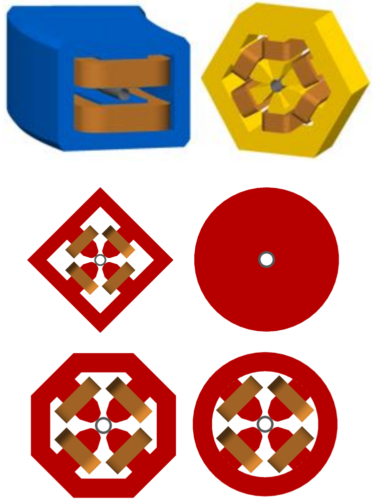
S. Walker, L. Nevay et al

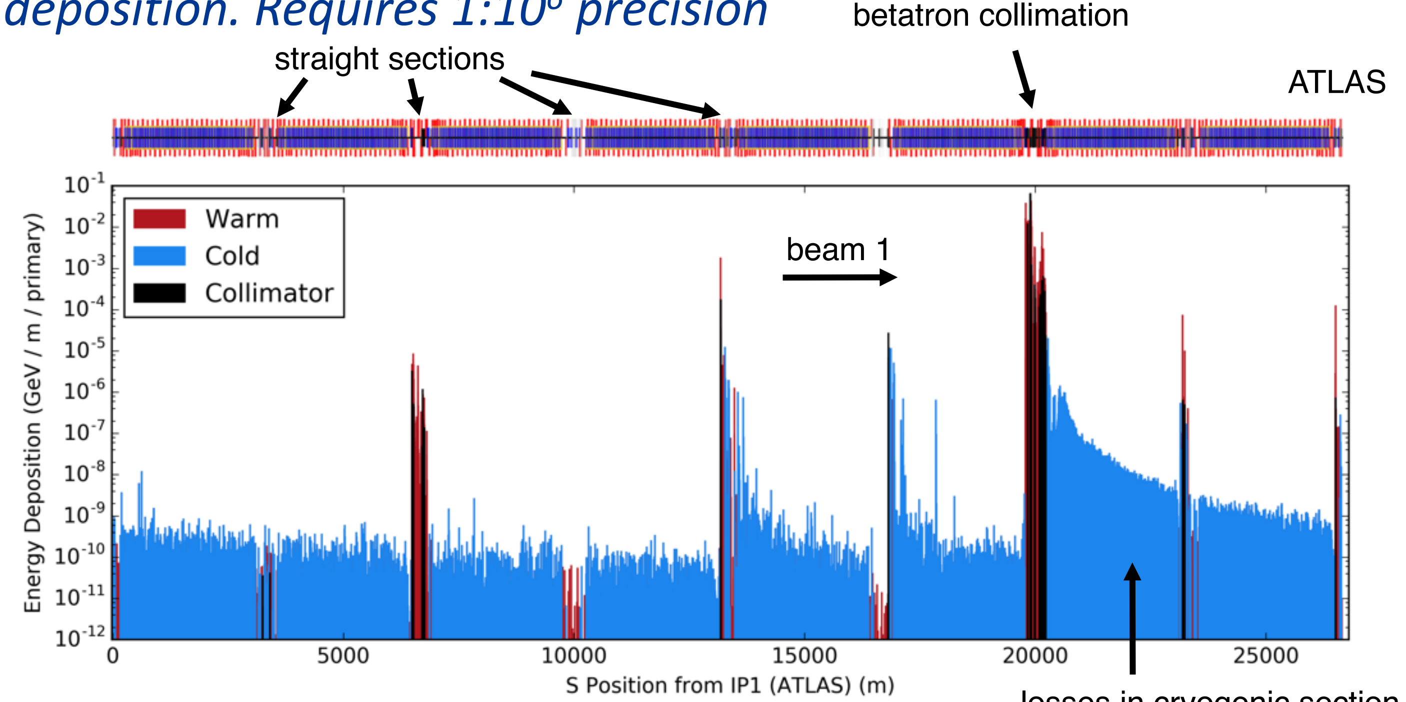
ROYAL HOLLOWAY UNIVERSITY OF LONDON

- BDSIM automatically builds a 3D, Geant4 model, from generic accelerator components.

- *LHC stores unprecedented energy in beams: 350 MJ (80kg of TNT) stored per beams at design energy.*
- *Halo efficiently cleaned by collimation system*
- *LHC model developed to simulate collimation and energy deposition. Requires 1:10^6 precision*

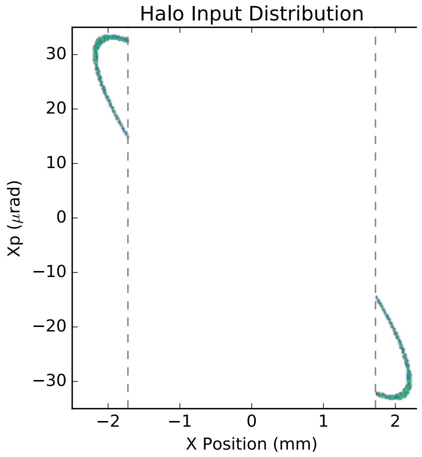
BDSIM
Beam Delivery Simulation

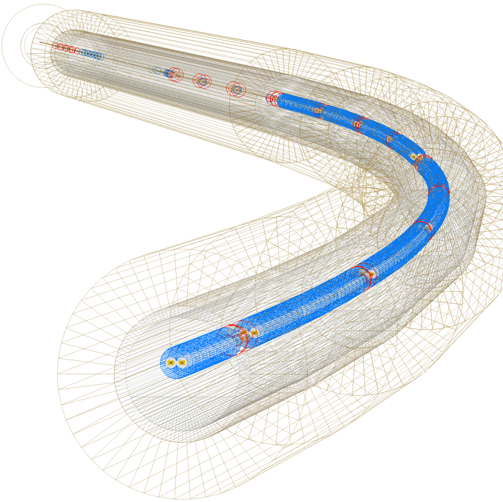




B1 4TeV energy deposition map

Example halo distribution

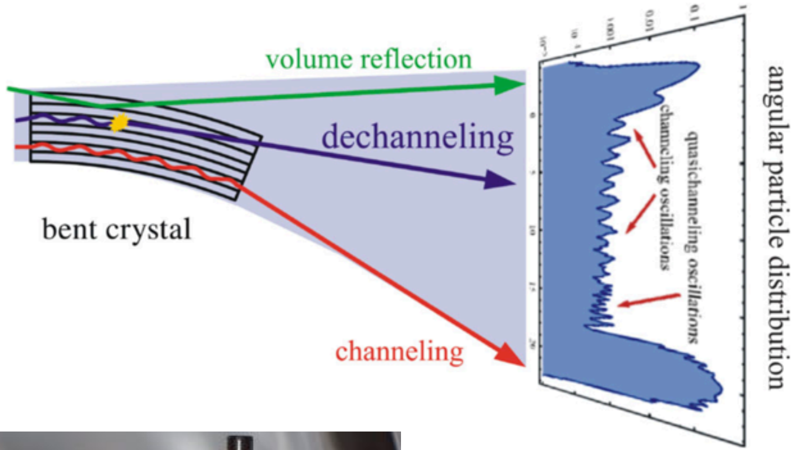


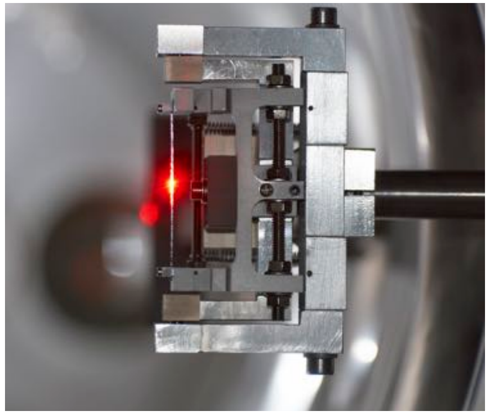


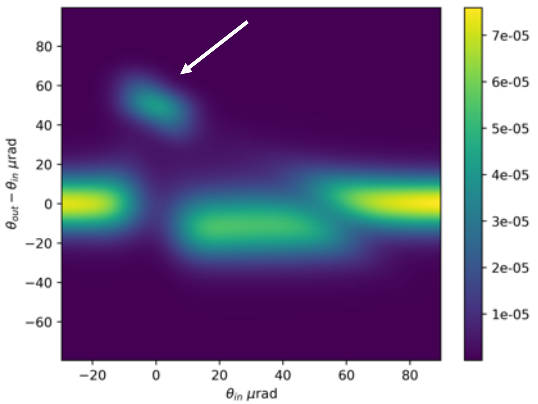
Active halo control & novel collimation

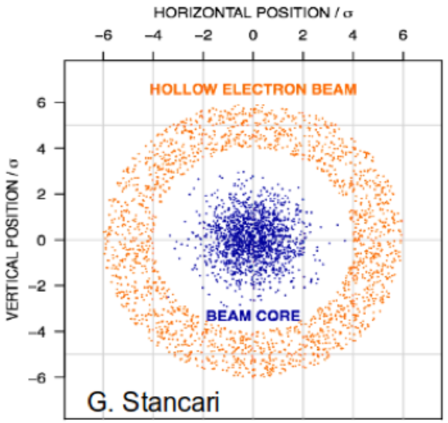
L. Nevay, H. Garcia-Morales et al

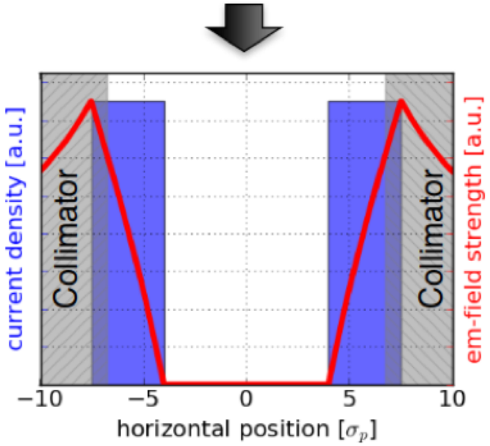
- *How can we **remove halo** particles **without affecting** the **core**?*
- *Novel collimation techniques being developed for HL-LHC:*
  - **Crystal collimation**
  - **Hollow electron lens**

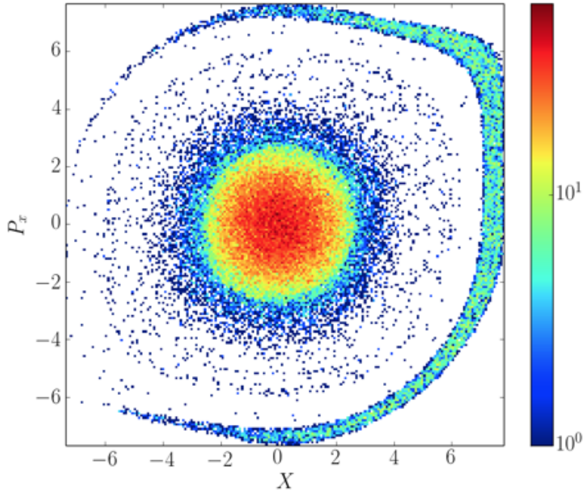


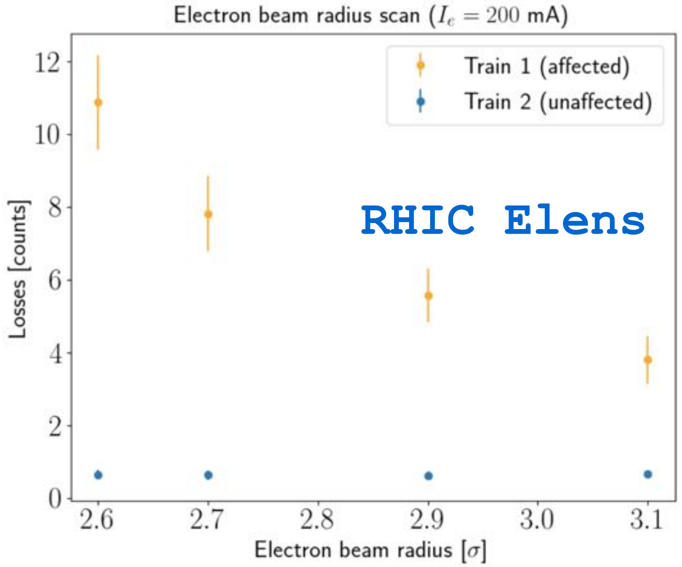












Superconducting RF capabilities

Peter McIntosh, STFC Daresbury Laboratory

- ***ASTeC @ Daresbury hosts major facility for SRF design & fabrication for many projects***

1 ERL SRF Linac
Optimised, high current, flexible CM development

2 Crab Cavity Cryomodule
Collaborative cavity, CM development and infrastructure

3 ESS SRF Contributions
High beta cavity testing and infrastructure

3 PIP-II SRF Contributions
Cavity testing, CM integration and infrastructure

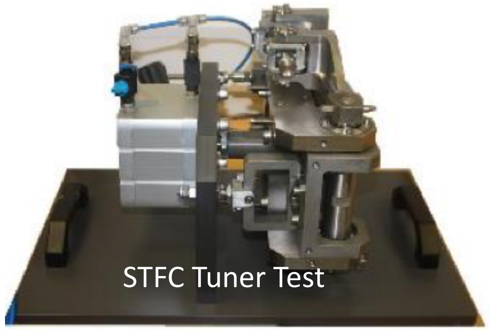
4 UK Industry SRF Developments
Cavity pressing, machining and EBW

5 EIC Opportunities

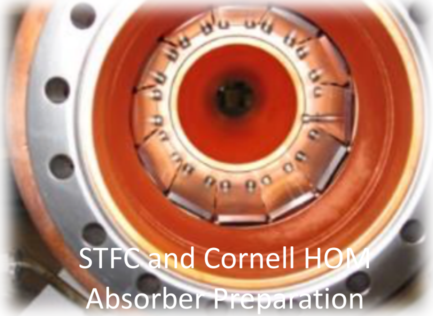

STFC, LBNL and Cornell Cavity Design

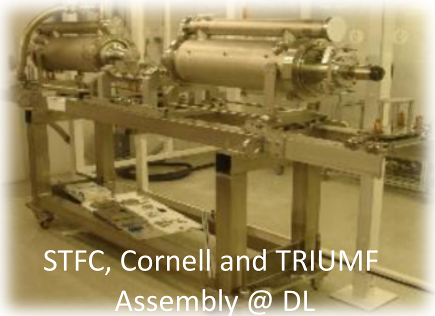

DESY TESLA Superstructure


Cornell Manufacture and Test


STFC Tuner Test


STFC Coupler Test


STFC and Cornell HOM Absorber Preparation


STFC, Cornell and TRIUMF Assembly @ DL

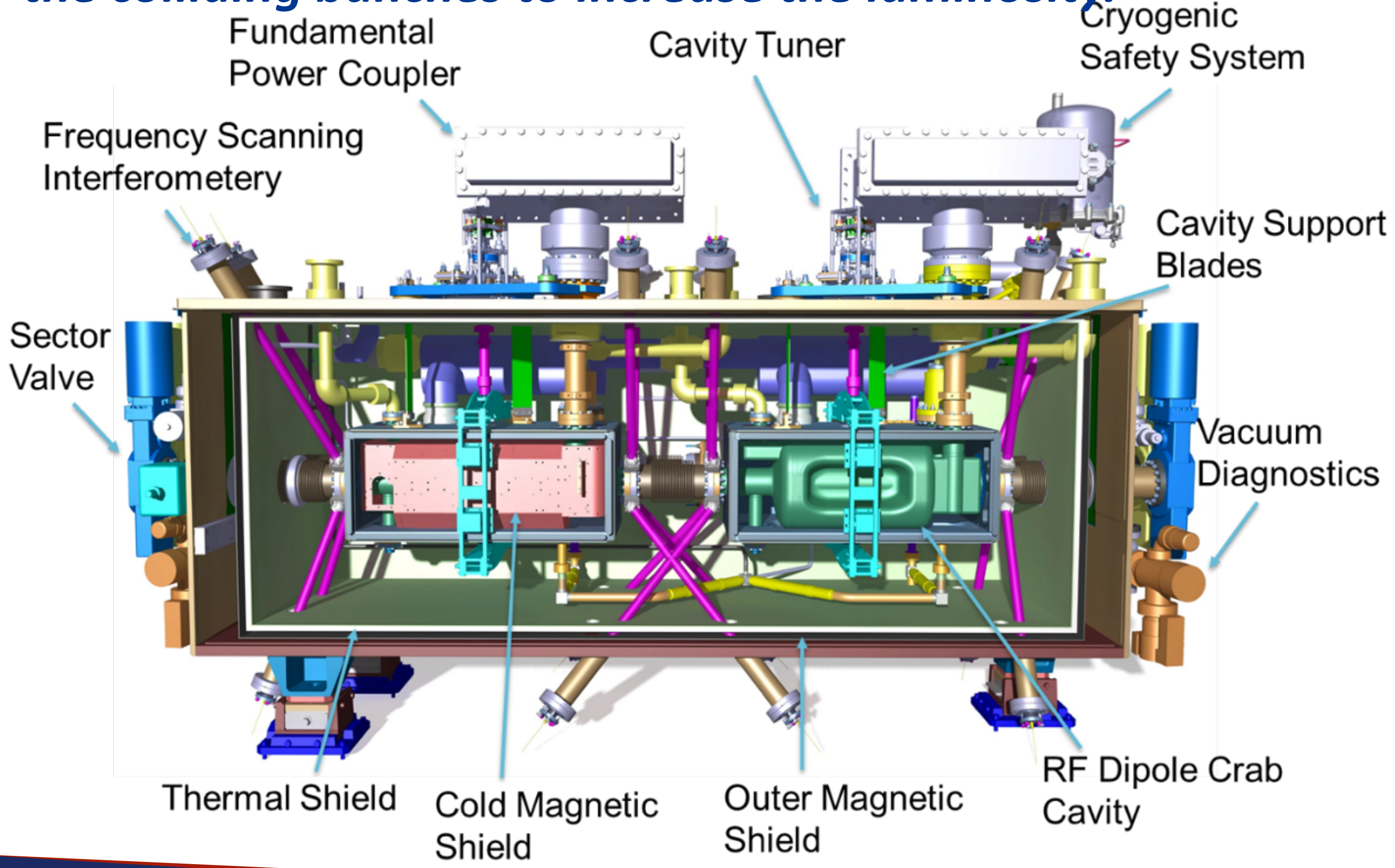

Stanford Outer Cryomodule

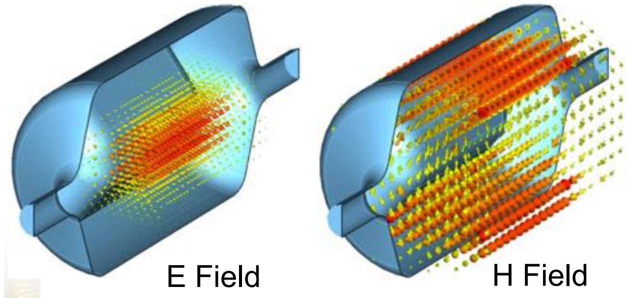

STFC Integration and Installation on ALICE

19

Crab-cavity cryomodules for HL-LHC:

- ***UK contributing cryomodules for crab-cavities, which rotate the colliding bunches to increase the luminosity.***

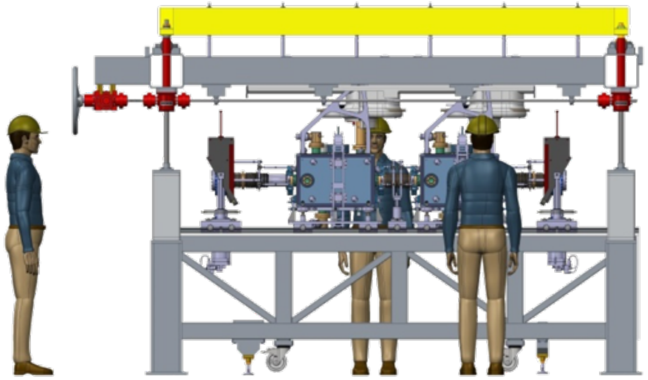




Graeme Burt et al

Cleanroom Assembly

Cryomodule Assembly

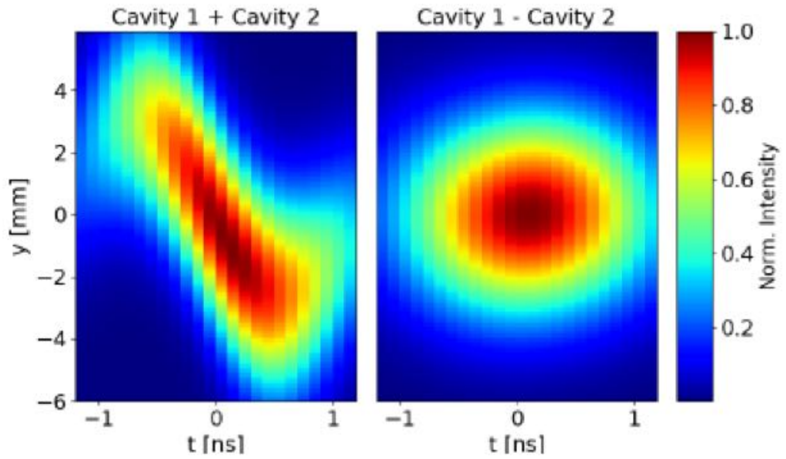


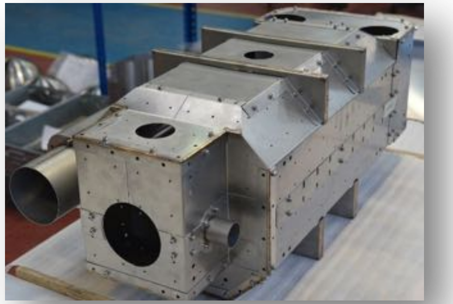
Crab-cavity cryomodules for HL-LHC:

Graeme Burt et al

- First prototype cryomodule (DQW) tests completed on SPS in mid 2018.
- First ever evaluation of crab cavities with a proton beam!
- A 2-cavity pre-series RFD cryomodule design being developed and manufactured at Daresbury (2021).
- Also providing 4 production DQW cryomodules for LS3

UK team responsible for key elements of the design: cold shield, magnetic shield, thermal shield, vacuum vessel, transport modules, HOM coupler + SPS test: machine physics, impedance, diagnostics and played major roles in other areas (LLRF)

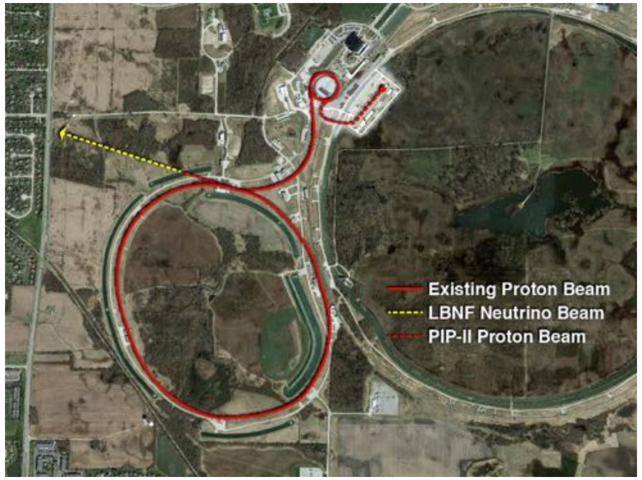




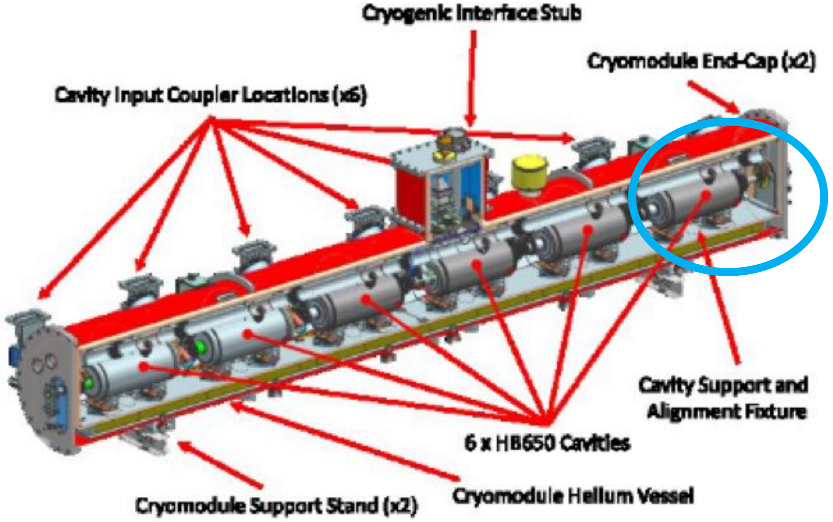
UK Delivery of PIP-II HB650 Cryomodules

Science and Technology Facilities Council

Proton Improvement Plan for **LBNF/DUNE**

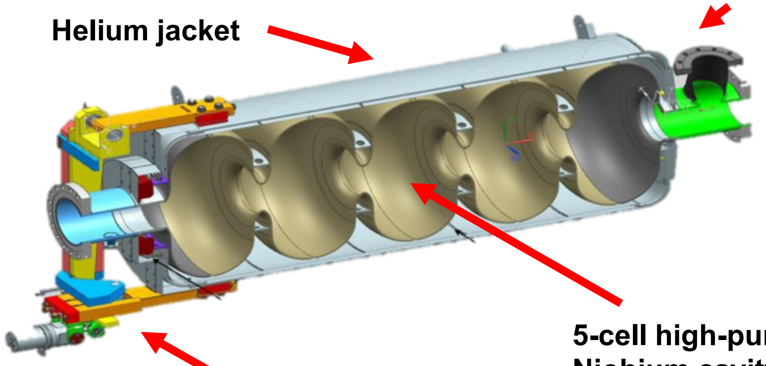


HB650 Cryomodule



HB650 Cavity

Peter McIntosh



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

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	**3×10^{10} (N2 Doped)**
Number of Cells	5
Cavity Dynamic Load (W)	<22
Cavity Length (m)	**1.42**
Number of Cavities	**18 (+2)**

High efficiency Kylstron design for FCC-ee

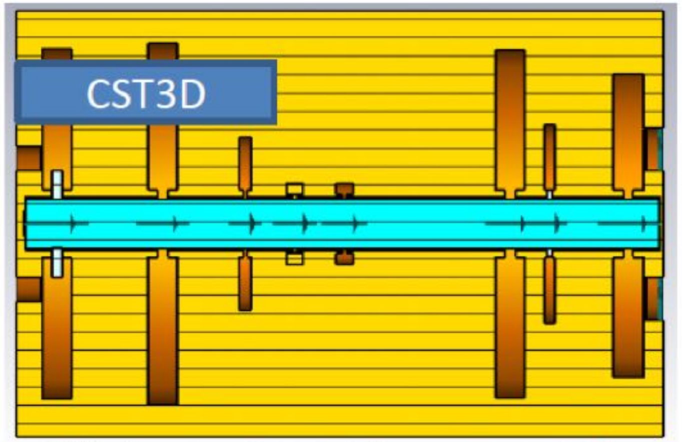
Jinchi Cai & Graeme Burt

0.8GHz,133.9kV×12.5A×**80%**>1.3MW

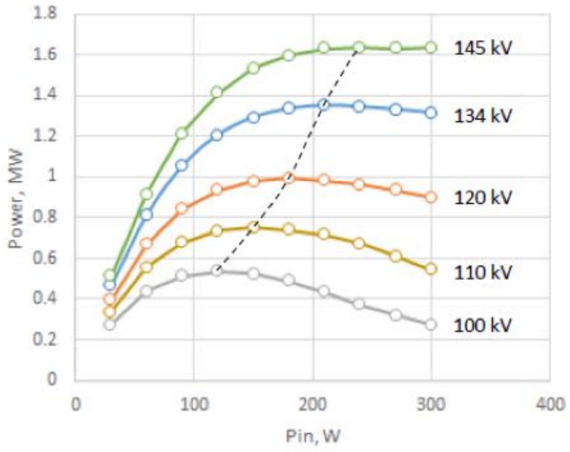
The klystron efficiency impact on the FCC power consumption.
Example of the efficiency upgrade from 60% to 80%.

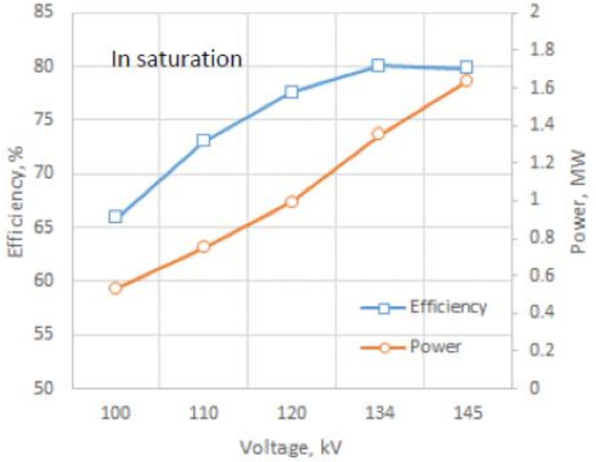
	Klystron eff. 60%	Klystron eff. 80%	Difference
RF power needed for 3TeV CLIC	105 MW		
DC input power	150 MW	123 MW	-27MW
Waste heat	45 MW	18 MW	-27MW
Annual consumption (5500 h assumed)	825 GWh	676 GWh	-149 GWh
Annual cost (60 CHF/MWh assumed)	49.5 MCHF	40.5 MCHF	-9 MCHF

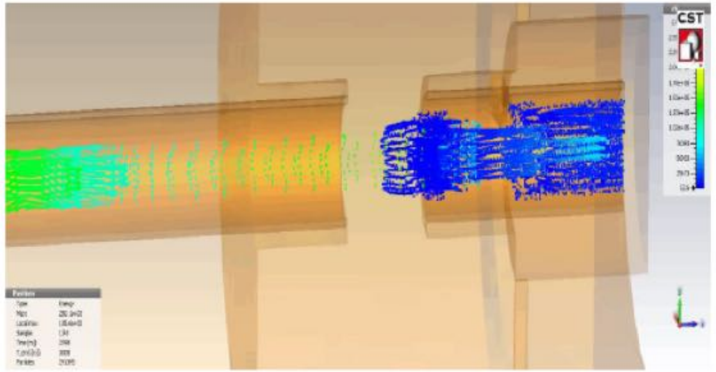
- FCC requires 105 MW of RF power, but the DC power is much higher due to limited efficiency
- Increasing the efficiency by just 20% would save CERN 9 MCHF / year by saving 149 GWh of electricity
- CERN and Lancaster are investigating new methods of increasing klystron efficiency



Efficiency=79%, Time cost=50h



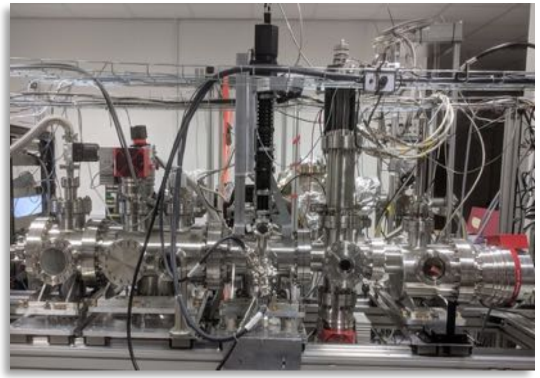


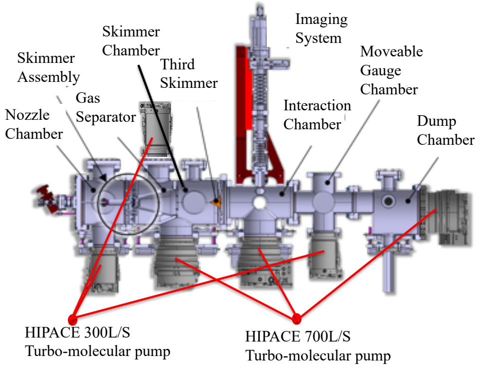


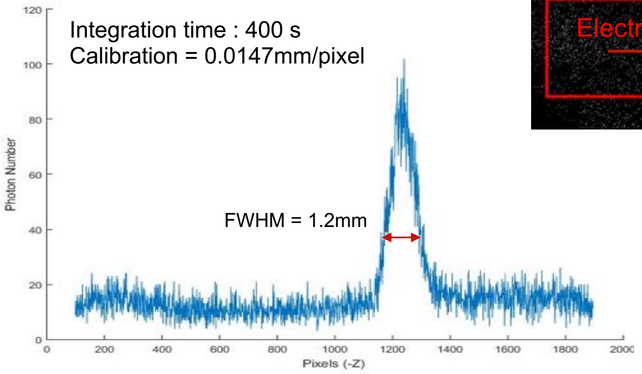
B_z=0.07T (5xBr). **Efficiency 79%**

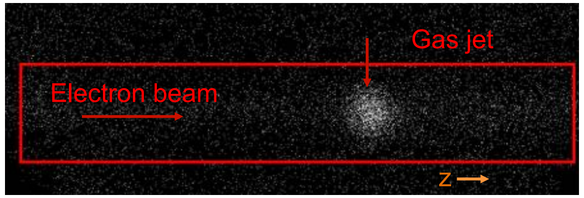
Beam diagnostics for FCC-hh (developed for HL-LHC)

- ***Fully characterizing FCC-hh circulating beams with high intensity requires similar diagnostics to those being developed for HL-LHC. Examples include:***
- ***Beam-gas interactions:***
  - *Continuous, non-invasive 2D beam profile monitoring by a supersonic gas jet monitor for the hollow electron lens collimation.*









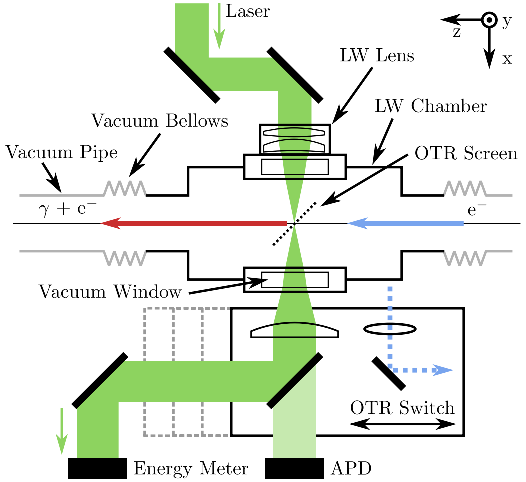
UNIVERSITY OF LIVERPOOL

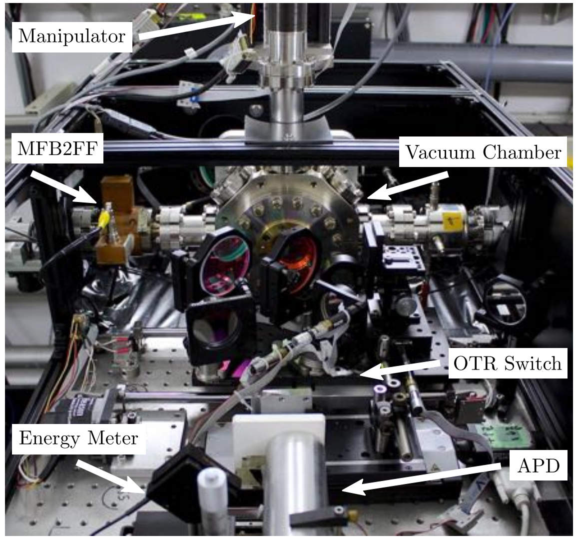
C Welsch et al

- ***Electro optics techniques:***
  - *Electro-optic BPM diagnostics for measurement of crabbed rotation of the hadron bunch [RHUL].*
  - *For FCC-ee, the electron bunch will require sub-ps e-o techniques, as pioneered at ASTeC.*

- ***Developments for 3rd generation light sources and LC are feasible for FCC-ee, though there are opportunities for further R&D:***
- ***Small electron bunches at high energy, and sub ps resolution require novel approaches:***
  - *To measure small transverse beam sizes, **SR interferometric measurements** are under development at LHC, though need to be demonstrated for X-ray wavelengths.*
  - *Bunch lengths of ps, with resolution of 10 fs pose difficulties for streak cameras and e-o sampling techniques due to the relatively long bunch.*
  - *Non-invasive techniques based on **Čerenkov diffraction radiation** may results in a directional beam position monitor and for fast intra-bunch transverse instabilities.*

- ***FCC-ee requires polarimetry based on inverse-Compton scattering (see talk by Tessa Charles)***
  - ***Similar to implementation at LEP and could leverage expertise on electron laserwires developed for Linear Collider at ATF2 in KEK.***



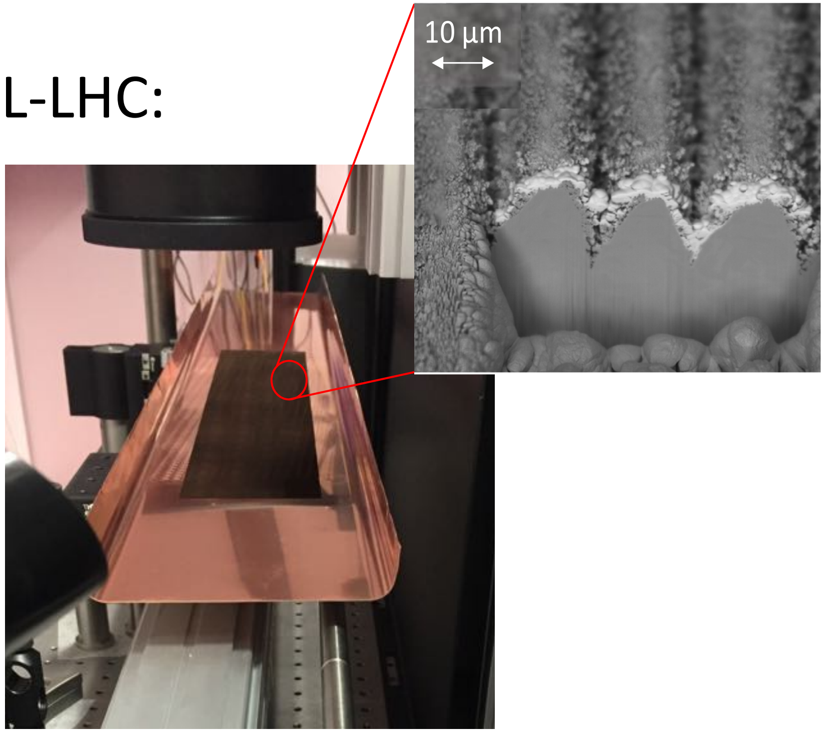


PRSTAB 17, 072802 (2014)

Laser Engineered Surfaces

University of Dundee

- **Electron cloud mitigation:**
  - intense electric field of the proton bunch can accelerate electrons into the beam pipe walls, which liberates secondary electrons. Exponential growth in electrons creating a cloud which heats the superconducting magnets and limits the machine intensity.
- Secondary electron yield can be suppressed by modifying the surface walls with a laser, creating channels to trap the electrons.
- Automated robot for in-situ treatment of beam-screens at HL-LHC:



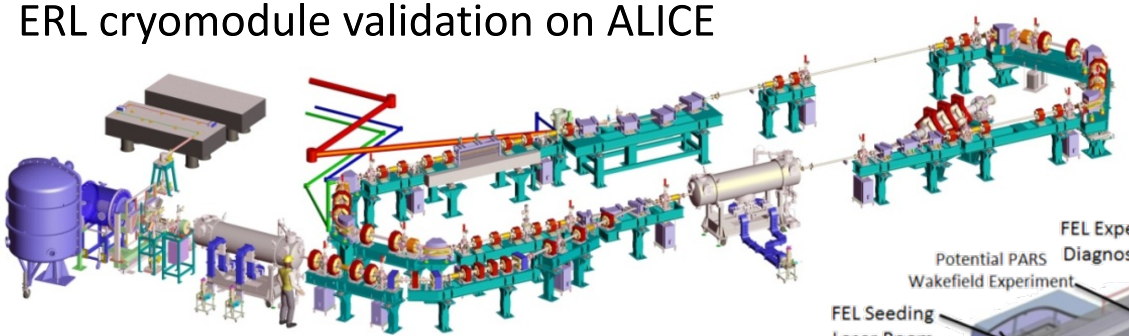
Technical challenges for FCC

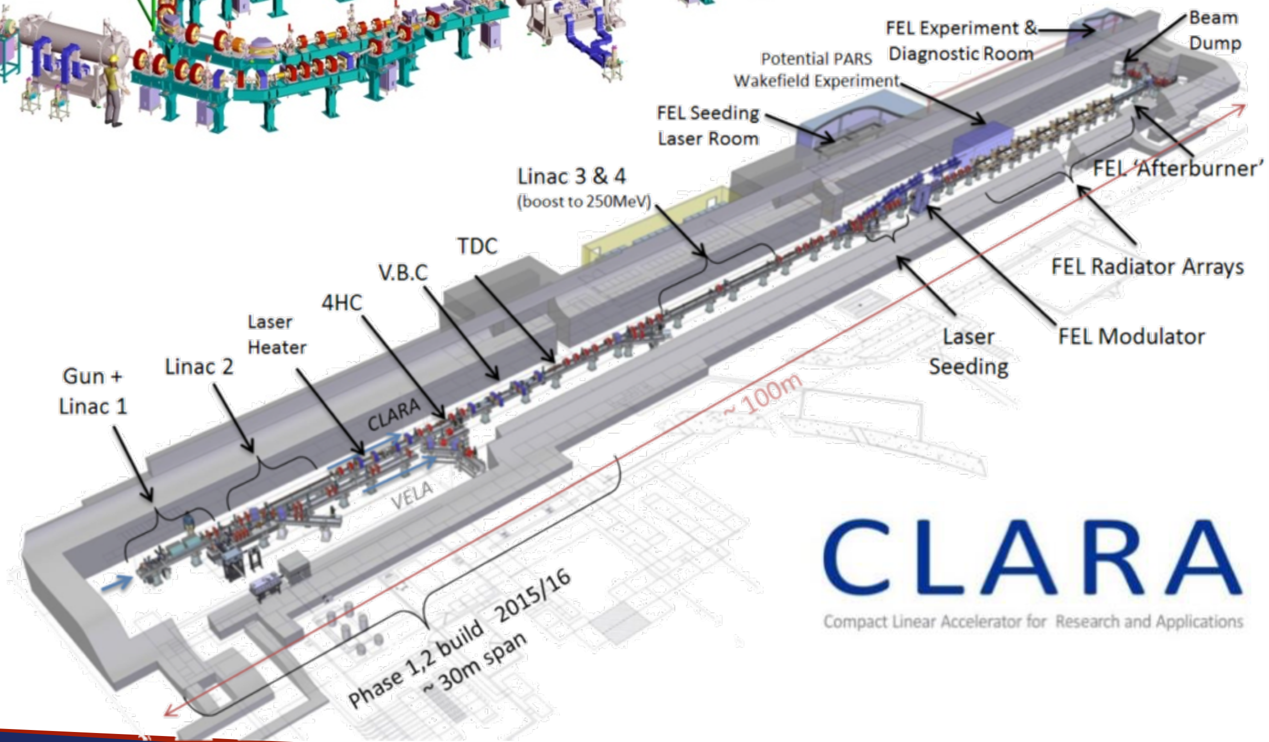
- ***Some of the key technologies required:***
- ***For FCC-ee:***
  - *Synchrotron radiation & beam screen design*
  - *Superconducting RF cavities*
  - *Crab waist scheme*
  - *Nanobeam control, bunch-to-bunch feedback*
  - *Single & multi-bunch instabilities*
  - *Electron bunch diagnostics, inverse-Compton polarimetry*
  - *Electron cloud mitigation*
- ***For FCC-hh:***
  - *Machine protection for unprecedented stored energy (8.4 GJ)*
  - *Cavities for crab-crossing*
  - *Non-invasive, high intensity hadron beam diagnostics*
  - *High-field (>16 T) superconducting magnets*

Operation of electron machines in UK pertinent to FCC-ee / he

- ***Vast experience at ASTeC, Daresbury + STFC RAL in the operation of ERL and FEL test facilities and low emittance electron storage rings:***

ERL cryomodule validation on ALICE

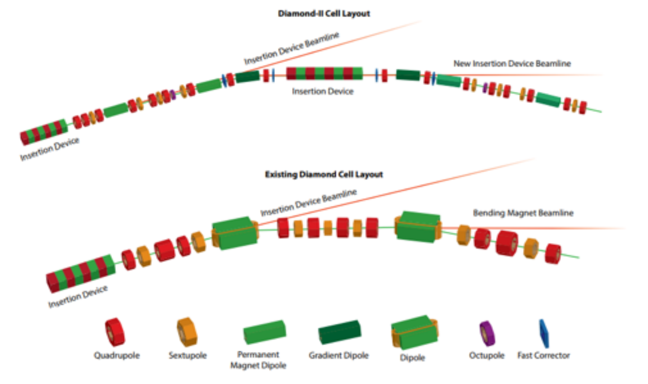




CLARA
Compact Linear Accelerator for Research and Applications

diamond

Diamond-II upgrade



Summary

- ***The UK accelerator community has begun to contribute to the FCC design, with studies of inner triplet layout, energy deposition, dynamic aperture, ion collimation…***
- ***The UK has many more capabilities in accelerator physics and enabling technologies, that can help to underpin the FCC programme.***
- ***There are strong synergies with ongoing developments for other major accelerators that will develop novel technologies and techniques, which will also benefit FCC.***
  - ***Only some topics could be covered here: novel collimation, SRF, cryogenics, vacuum, klystron, beam diagnostics, LESS...***
  - ***Strategic longer term capacity building in relevant technologies (e.g. high field magnets) could be considered in the UK Accelerator Roadmap.***
- ***Discussion...***

Thank you to all contributors!

particularly P. Ratoff, P. Burrows, P. McIntosh