



Science and
Technology
Facilities Council

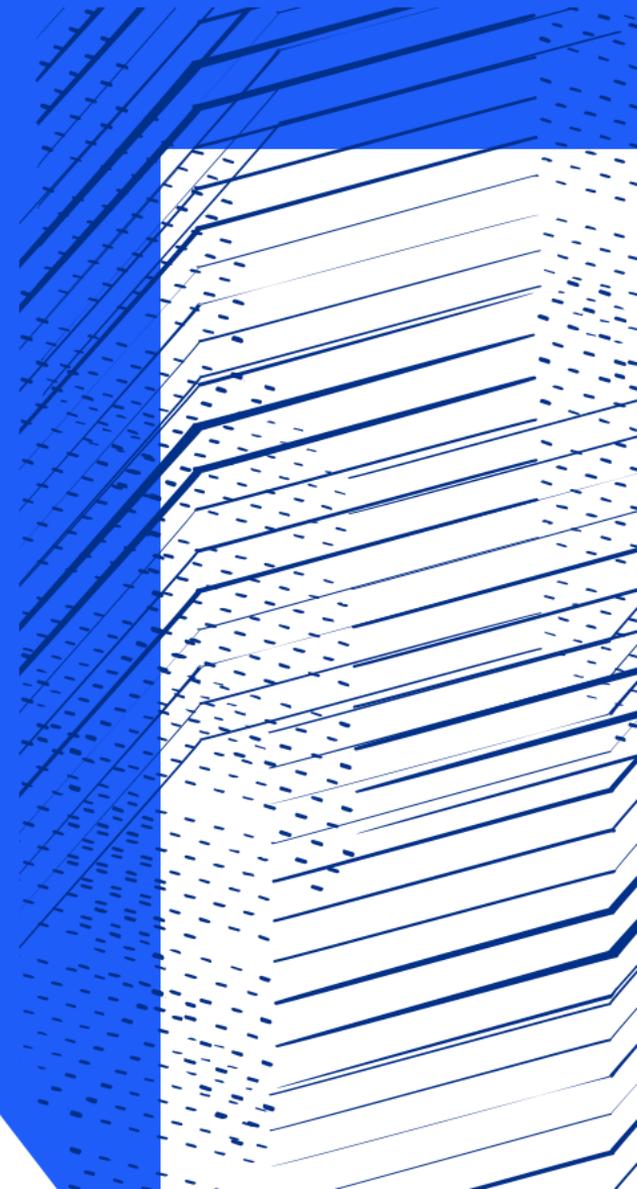
Superconducting RF

Some recent highlights and case studies

European Cryogenics Days &
Cryogenic Heat and Mass Transfer Workshop

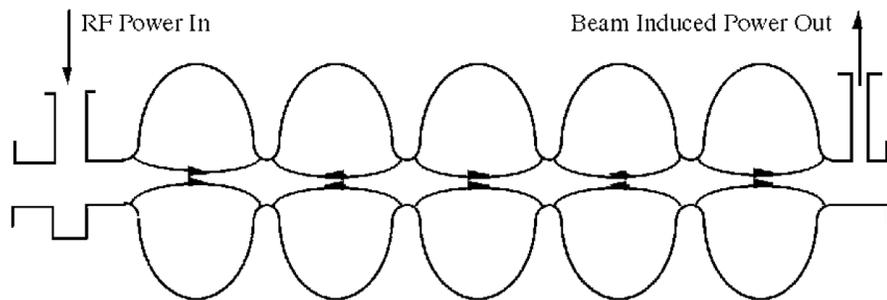
27th-30th Oct 2025
University of Twente

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Why SRF for particle acceleration?

- Superconducting radio frequency (SRF) cavities widely used in modern high energy accelerators to impart energy to the charged particle beam
- Push for increasingly higher beam energies and intensities has been key driver for the considerable progress in SRF technology and associated cryogenic systems that has been made since late 1970s
- E_{acc} that can be achieved is a key figure of merit for a given accelerating structure, proportional to E_{pk} and H_{pk} that can be supported on the cavity surface
- State-of-the-art is bulk Nb at 2 K \Rightarrow ~ 50 MV/m with $Q_0 > 10^{10}$ for 9-cell 1.3 GHz ILC-type cavities



Why SRF for particle acceleration?

Consider wall plug power for normal vs s/c accelerator

Microwave surface resistance of s/c is ~6 orders of magnitude lower than for Cu cavities

Allowing for Carnot at 2 K [$2/(300-2) = 0.0067$] and modern plant at 30% of Carnot (modified Claude-Brayton)

=> net gain on the order of 2000 [= $10^6 * 0.0067 * 0.3$] using SRF

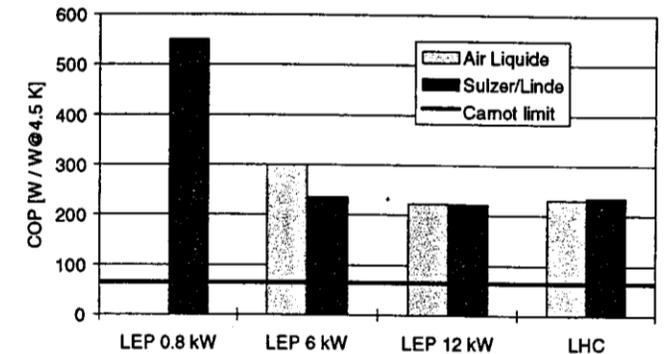
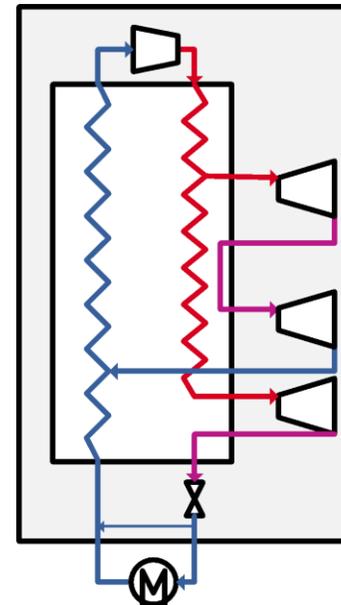
He-II => a) losses $\sim T/T_c$

b) bubble cavitation in He-I induces microphonics

c) excellent temperature stability under high load

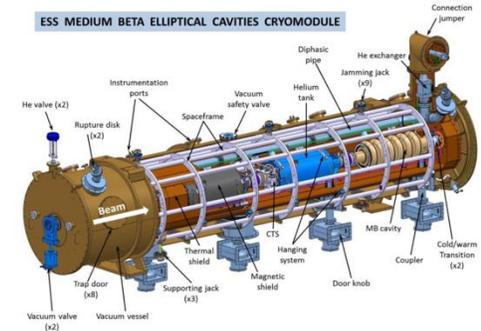
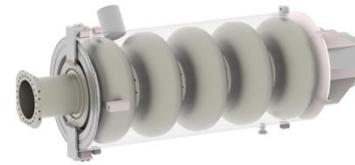
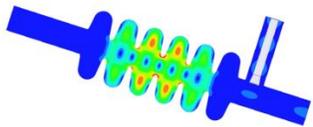
$$Q_0 \equiv \frac{\text{Energy stored in cavity}}{\text{Energy dissipated in cavity walls per radian}} = \frac{\omega_0 U}{P_c}$$

$$P_c = \frac{1}{2} R_s \int_S |H|^2 ds$$



Design to operation

EM modelling → manufacturing → (bare) cavity test → jacketing → cryostating →



→ offline CM testing → CM installation in accelerator → commissioning → operation!



Cavity testing

Cavity performance is extremely sensitive to manufacturing defects and contamination of rf surface throughout build and assembly

Given complexity of cryomodule integration, extensive cavity testing is first required

Following manufacture, initial cavity qualification requires high-power rf testing at 2 K in a specialist vertical test facility (VTF)

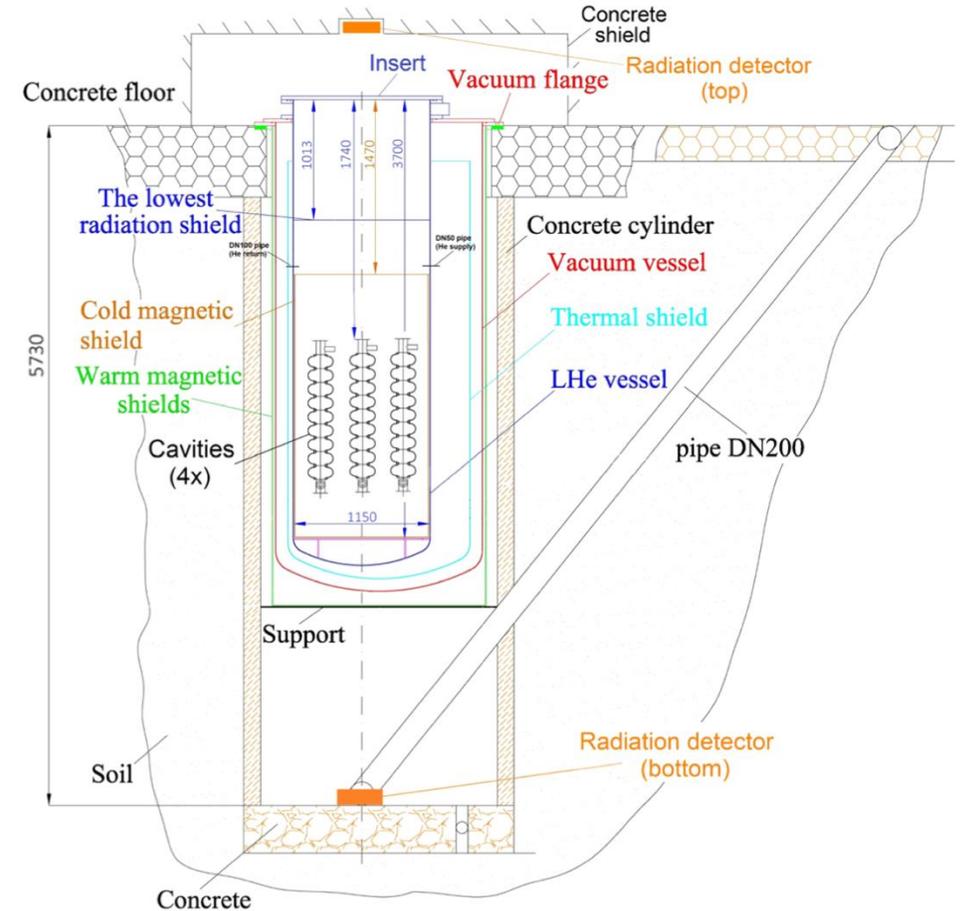
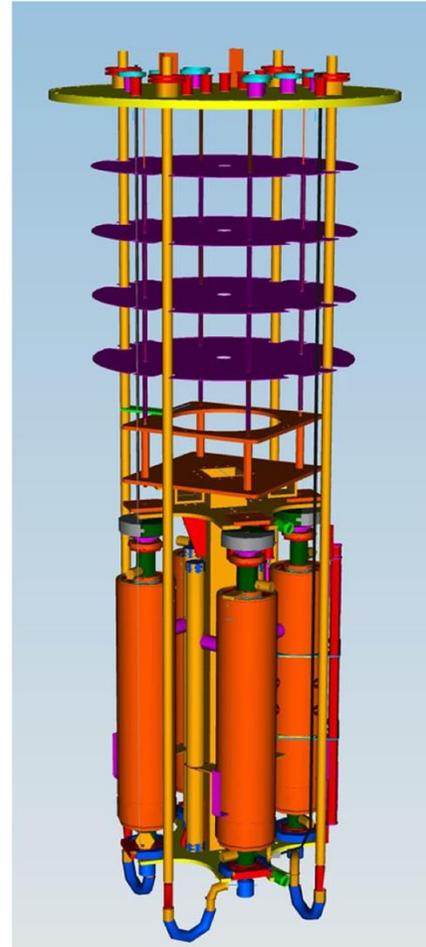
Examples of VTFs currently in operation include those at CERN, DESY, Fermilab, INFN, TRIUMF, JLab, and STFC Daresbury

Example: DESY vertical cavity testing

Conventionally, the cavities (either unjacketed or jacketed) are submerged in a bulk LHe bath

Pumped to 30 mbar (2 K), then 2 K HEX + JT valve to maintain LHe level

Low and high power RF testing of cavity (Q_0 vs E_{acc}) + radiation measurements



'Horizontal' VTF at STFC for jacketed ESS high- β cavities

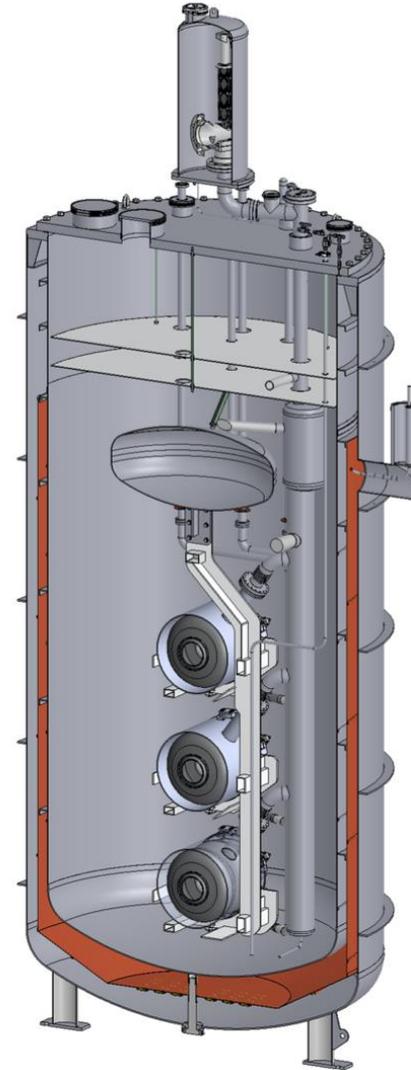
Individual LHe jackets, each ~50 L

Cryostat sized to accommodate horizontal cavity mounting (closer to linac configuration)

3 cavities tested per cooldown

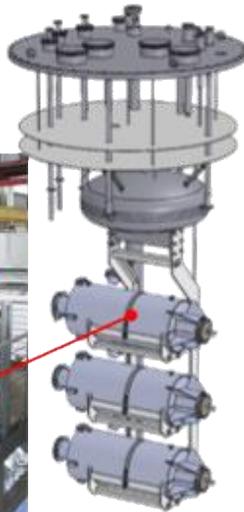
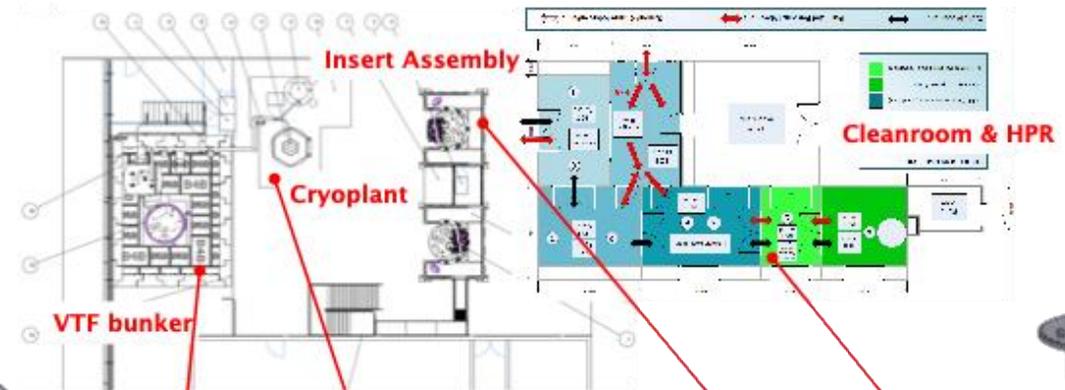
~1500 L required per test (vs 7500 L)

< 2 g/s in steady state under static load (vs 20 g/s)



Daresbury SuRF Lab

- Air Liquide HELIAL ML cryoplant commissioned 2018 (130 L/hr with LN₂ precool)
- Vertical Test Facility (VTF) for SRF cavities commissioned 2019
- Focus on sustainability (uses ~70% less LHe than conventional facility, recovery circuit => closed cycle)
- >60 test runs since 2019 (mainly ESS high-β)
- In 2024, VTF upgraded for PIP-II HB650 tests
- Continuous improvement (e.g., recent grant awarded for helium inventory management)
- Recent visit from the PM and Chancellor!



Cryomodules

Cavities assembled under cleanroom conditions (typically ISO4), typically integrated into cavity strings

Cavities typically have individual tanks welded around them to contain He-II

Trapped flux in Nb decreases $Q \Rightarrow$ shielding required from ambient fields

Couplers installed to provide RF power and HOM pick-up from the cavity, and are generally either coaxial or waveguide with ceramic windows to provide environmental isolation for the cavity

Tuners installed on each cavity are used to ensure operation at the correct frequency

Cavities may be detuned by pressure changes and mechanical stresses, requiring “slow” correction by a mechanical tuner, as well as by Lorentz forces which require “fast” correction by a piezoelectric cartridge

Structural elements such as posts, tension members, and space frames, are required to support the cold mass under mechanical loading from shipping and handling, cooldown, fluid flow, and ground motion

Include input RF power from the amplifiers, RF signals for control, HOM power extraction, electrical feeds for motors and actuators, and instrumentation signals including temperature, vacuum, pressure, and liquid level

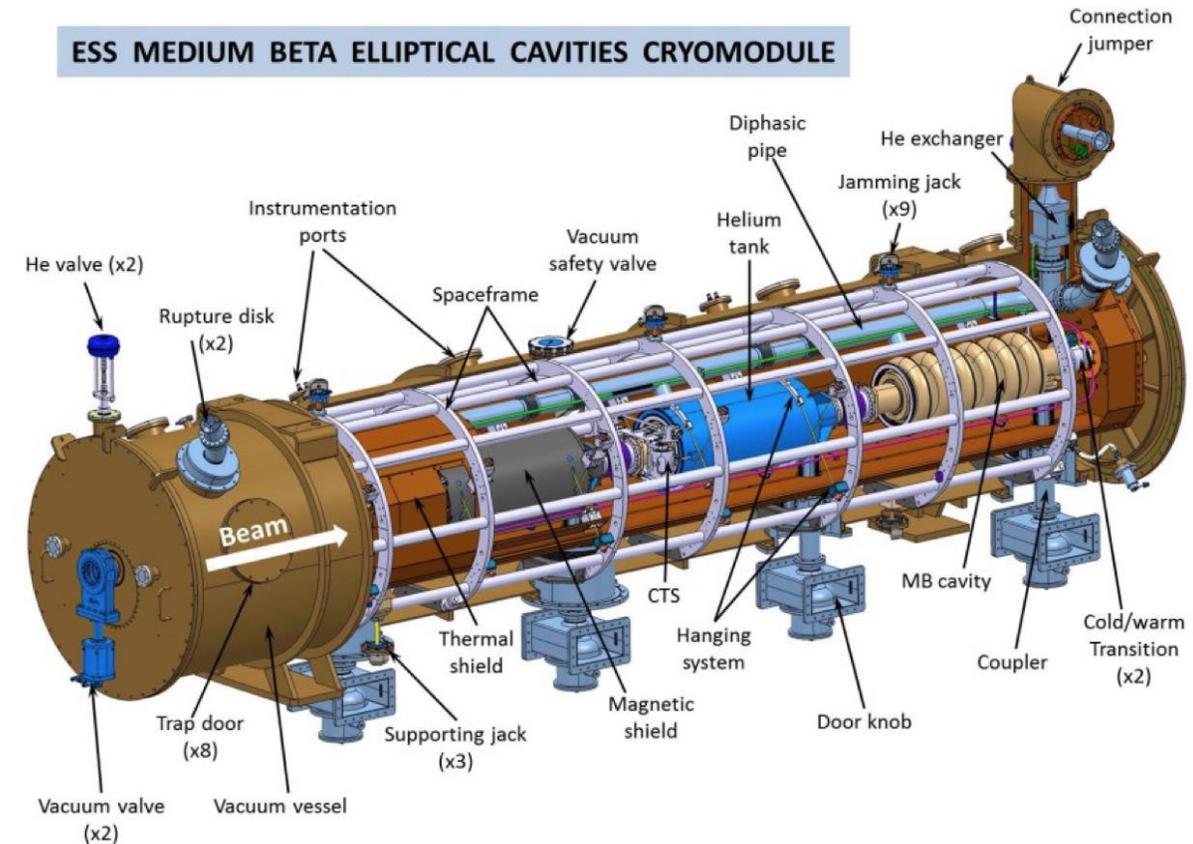
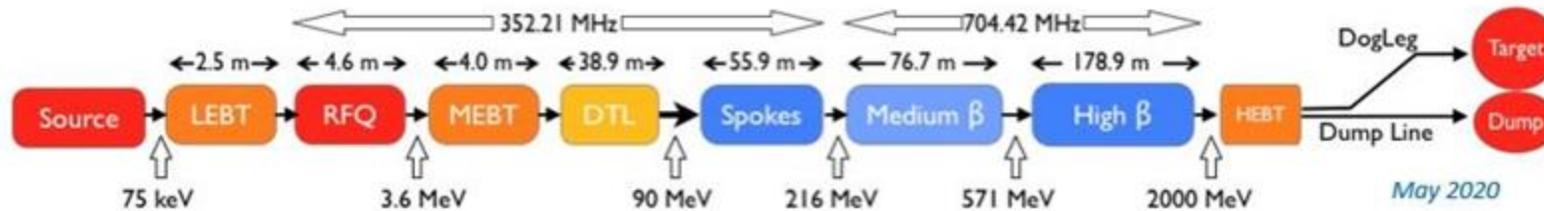


Figure taken from Darve et al. (2017)

European Spallation Source

Long pulse proton linac to drive world's brightest neutron source – design beam power 5 MW



Superconducting linac will have 26 spoke cavities (in 13 cryomodules), 36 medium- β elliptical cavities (in 9 cryomodules) and 84 high- β elliptical cavities (in 21 cryomodules), including IKCs in 42 WPs from 18 institutes in 8 countries (see <https://ess.eu/accelerator> for full list)

Linac installed as far as 5th HBCM => 2 MW beam*



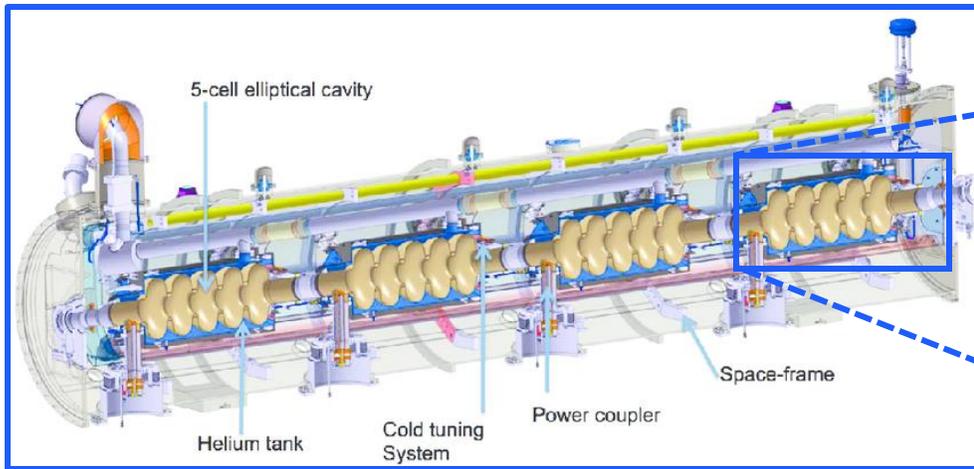
Figs courtesy of ESS

*See Philipp Arnold's talk at this meeting, and Cecilia Maiano's presentation at SRF2025

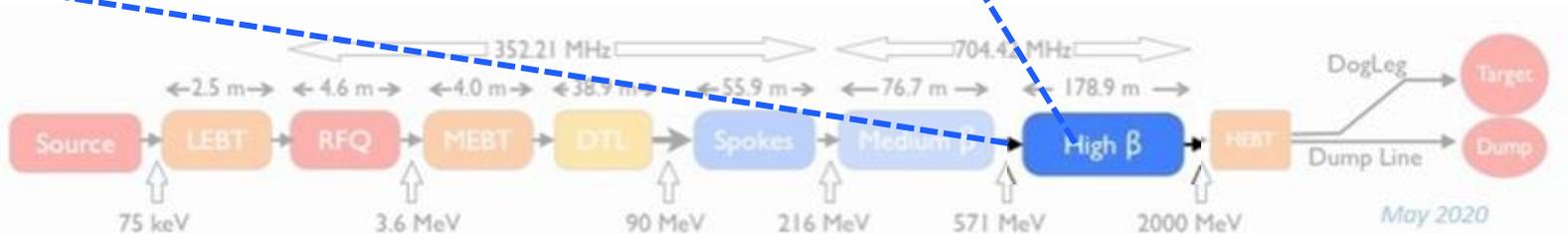
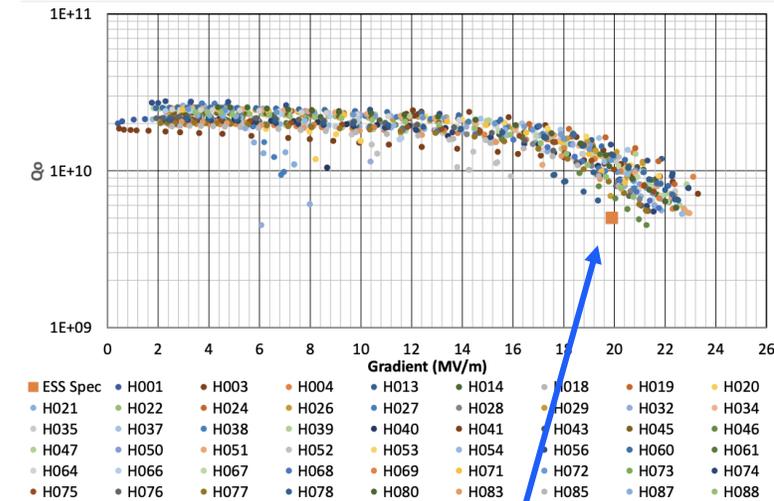
European Spallation Source high- β cavities

84 high- β cavities provided by the UKRI-STFC as IKC (tested at Daresbury and DESY)

→ CMs assembled at CEA-Saclay → shipped to ESS for testing+commissioning+installation



Bulk Nb 5-cell 704 MHz



$E_{acc} > 19.9 \text{ MV/m at } Q_0 > 5 \times 10^9$

PIP-II

800 MeV H- ion srf linac to provide 1.2 MW proton beam in cw to Fermilab accelerator complex; this will be the highest-energy and highest-power superconducting proton linac with continuous wave capabilities ever built

Key to drive neutrino research at the Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE)

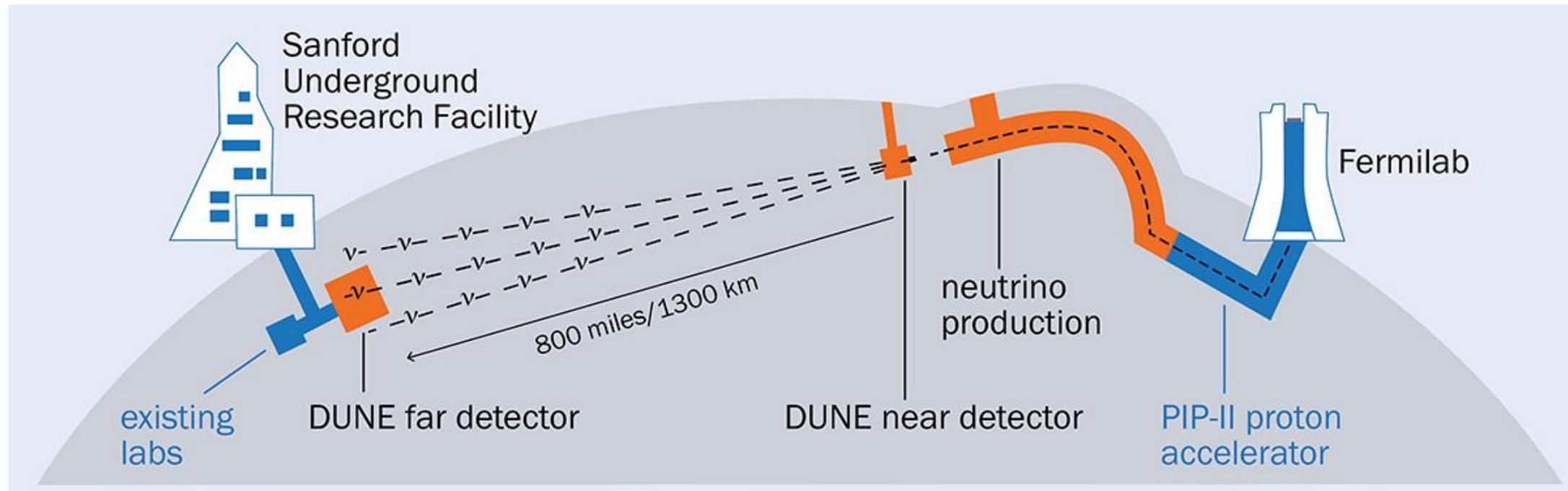
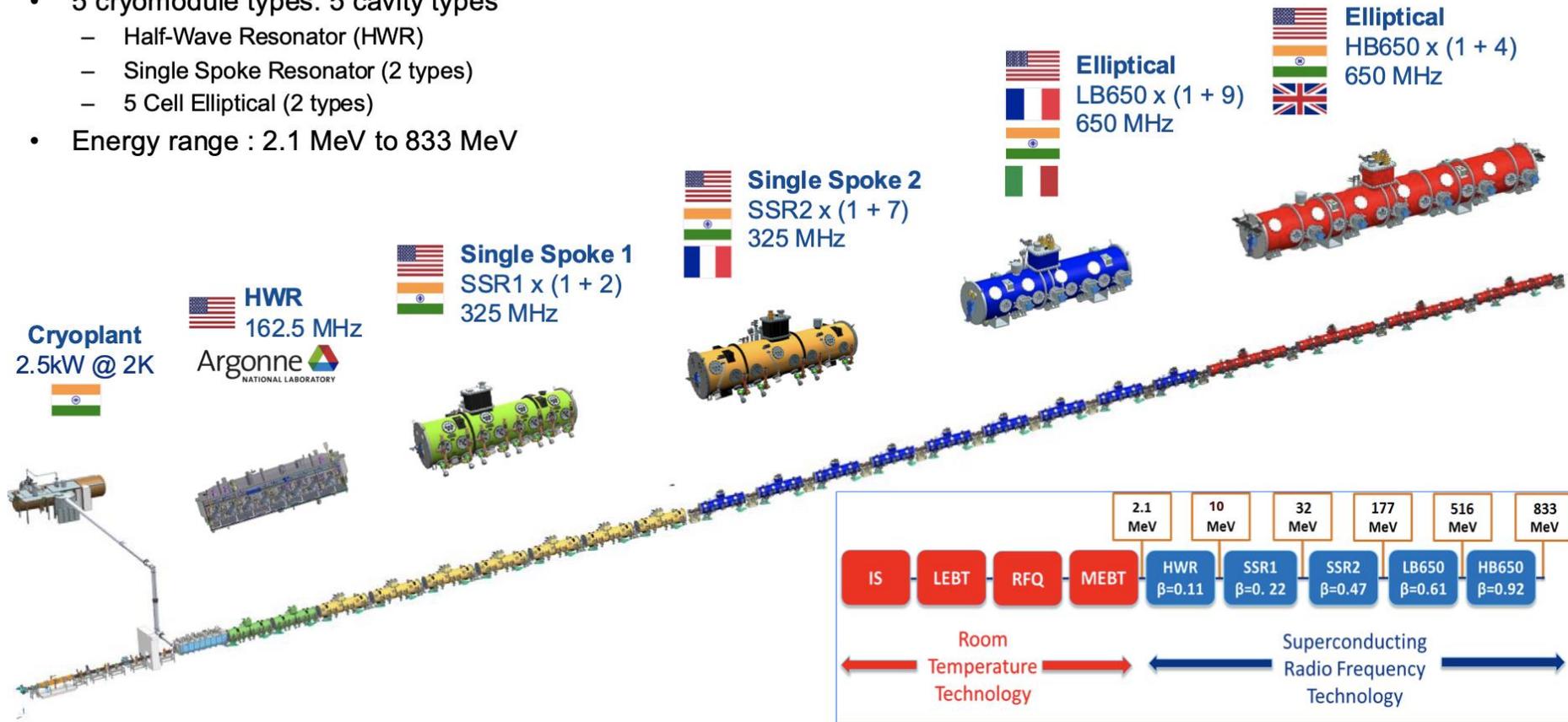


Fig courtesy of FNAL/CERN

PIP-II

- 5 cryomodule types. 5 cavity types
 - Half-Wave Resonator (HWR)
 - Single Spoke Resonator (2 types)
 - 5 Cell Elliptical (2 types)
- Energy range : 2.1 MeV to 833 MeV

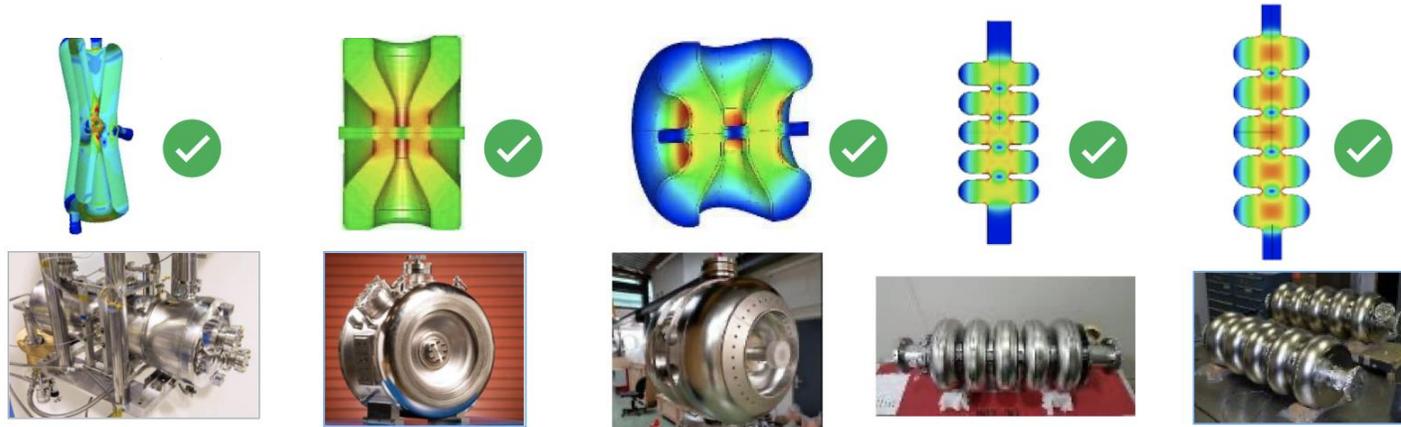


Collaboration includes ANL, LBL, JLab, and SLAC

First US accelerator project to be built with major international contributions!

India, France, Italy, United Kingdom, and Poland

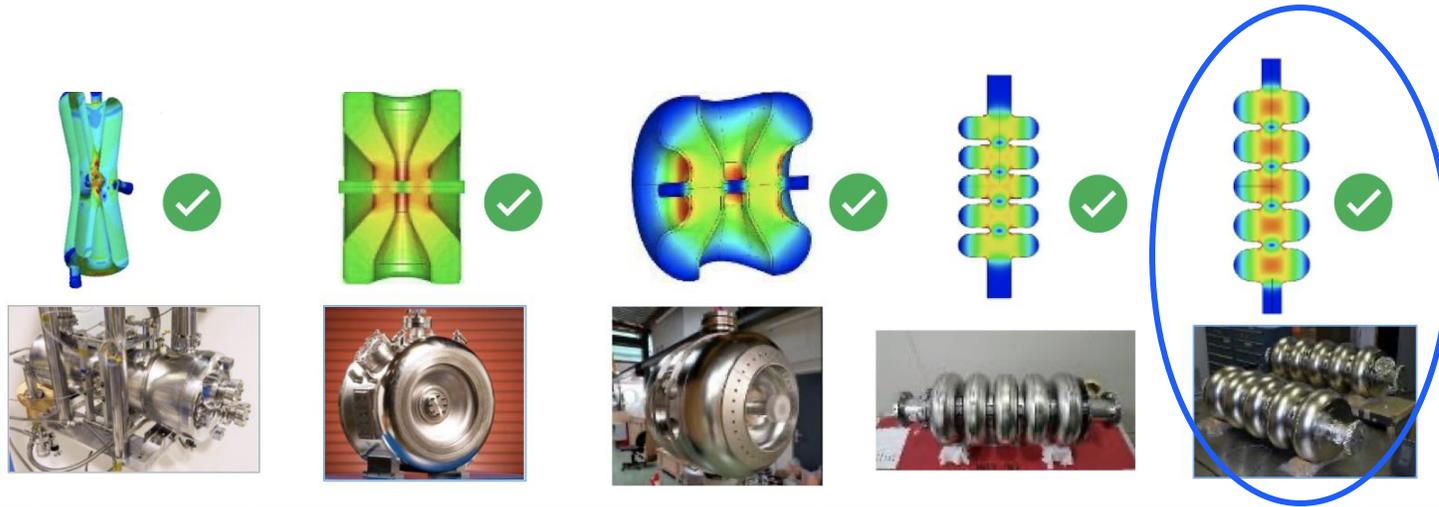
PIP-II



Prototype cavities validated and series production in progress for cavity types!

Name (Qty.)	HWR (8)	SSR1 (16)	SSR2 (35)	LB650 (36)	HB650 (24)	Units
Type	Half-Wave	Single Spoke	Single Spoke	Elliptical	Elliptical	-
β	0.11	0.22	0.47	0.61	0.92	-
Frequency	162.5	325	325	650	650	MHz
Q_0	$8.5 \cdot 10^9$	$8.2 \cdot 10^9$	$8.2 \cdot 10^9$	$2.4 \cdot 10^{10}$	$3.3 \cdot 10^{10}$	-
Gradient	9.7	10	11.5	16.8	18.7	MV/m
Doped	No	No	No	Mid-T bake	Yes	-

PIP-II



Prototype cavities validated and series production in progress for cavity types!

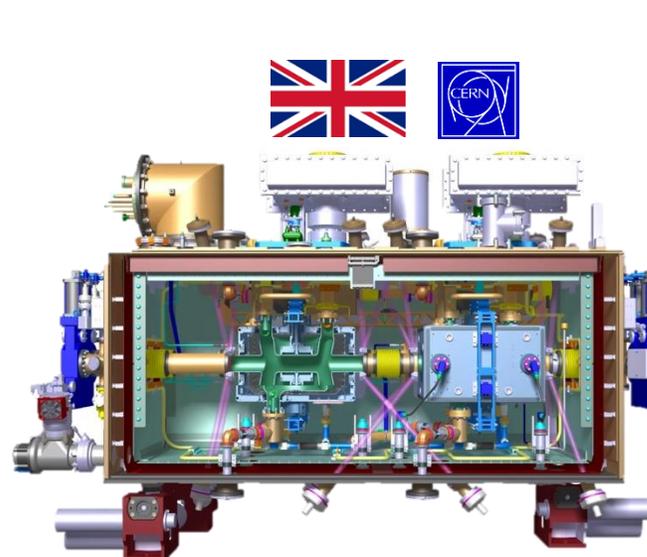
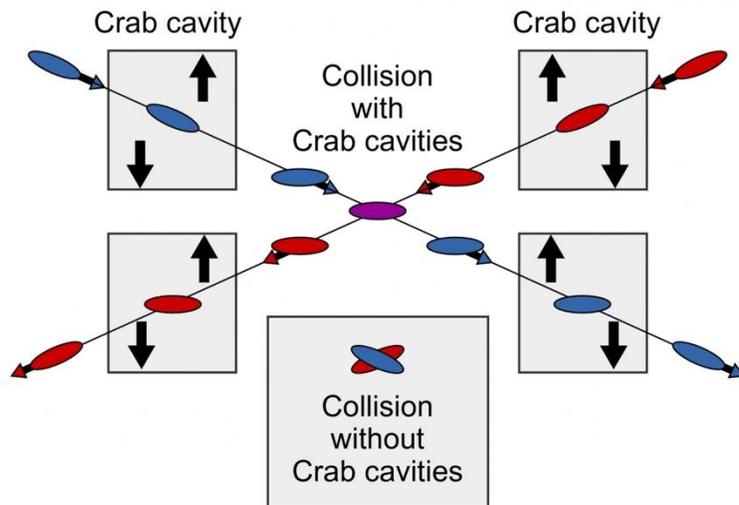
HB650 cavities being tested and CMs assembled at STFC Daresbury!

Name (Qty.)	HWR (8)	SSR1 (16)	SSR2 (35)	LB650 (36)	HB650 (24)	Units
Type	Half-Wave	Single Spoke	Single Spoke	Elliptical	Elliptical	-
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Gradient	9.7	10	11.5	16.8	18.7	MV/m
Doped	No	No	No	Mid-T bake	Yes	-

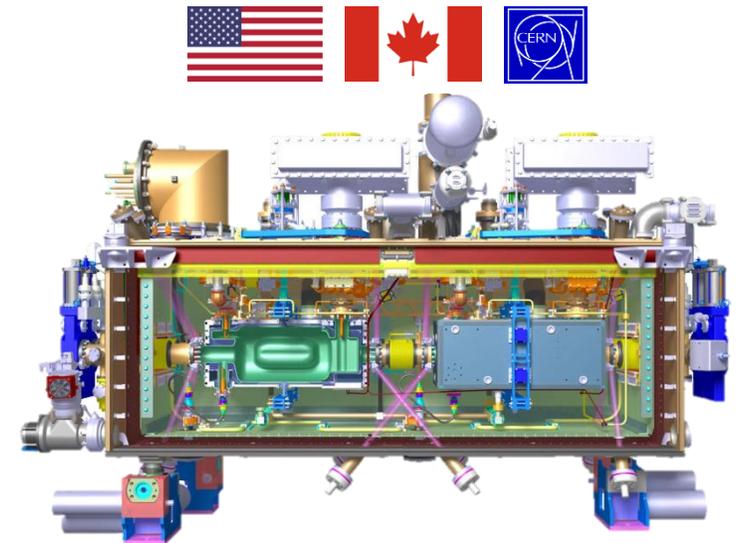
HiLumi LHC compact crab cavities

HiLumi project will increase the integrated luminosity (~number of collisions) by a factor of 10 beyond the LHC's design value: crucial for maximising discovery potential of machine (study Higgs mechanism in greater detail, search for rare particles, etc.)

Includes upgrades to many parts of LHC, one key element is srf crab cavities (transversely deflecting) to rotate proton bunches at interaction points (compensating for crossing angle)



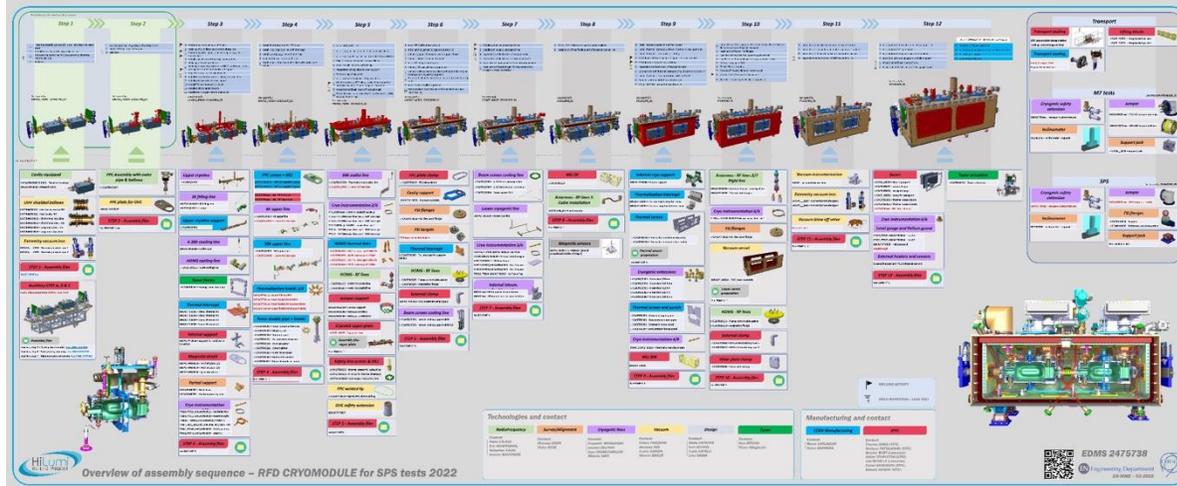
DQW



RFD

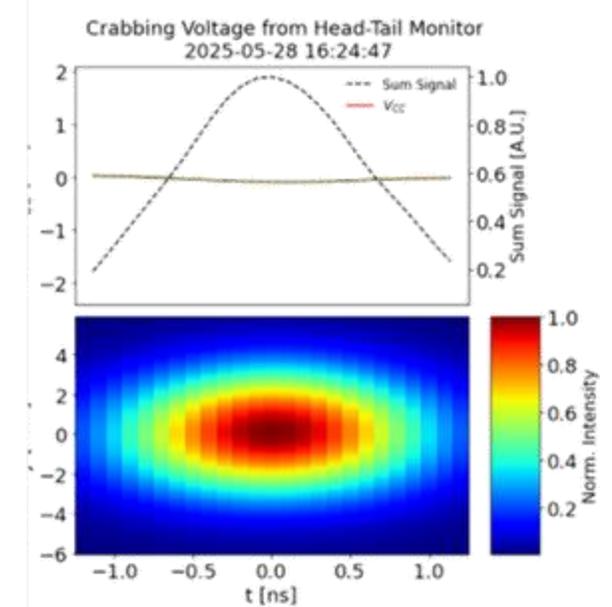
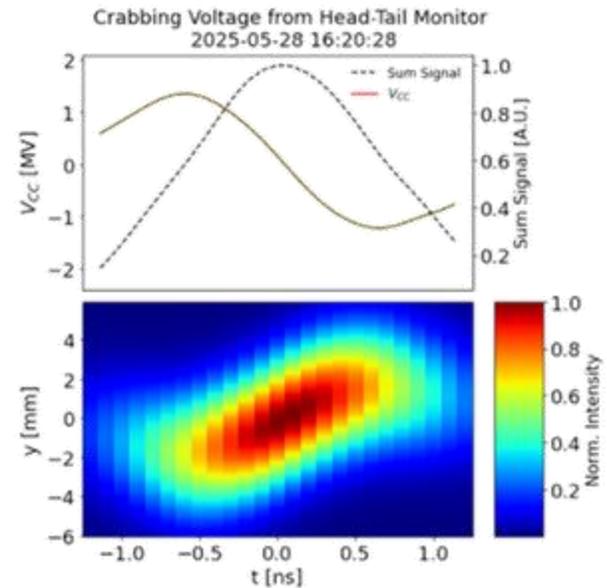
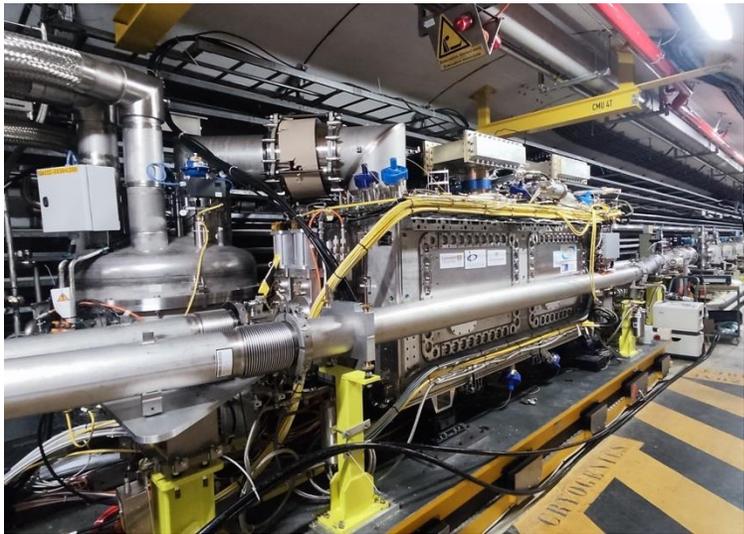
UK contribution to crabs

- STFC and CI working with CERN on project since 2011 (contributions to early cavity design work)
- Following 2-year build program*, prototype RFD cryomodule delivered from Daresbury to CERN Oct 2023; coupler repair and CM testing in SM18 in 2024, testing on SPS from 2025
- Series DQW cryomodule build currently underway at Daresbury



HiLumi LHC compact crab cavities

Prototype cryomodules tested with protons in the SPS (DQW tested 2018-2023 and removed in 2023-24 YETS; RFD installed in YETS 2024-25)



16 series cryomodules build by CERN+UK+Canada will be installed in the LHC around ATLAS (horizontal crabbing) and CMS (vertical) before end of LS3 (end of 2029)

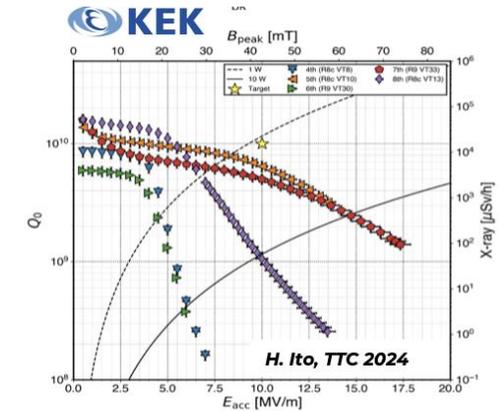
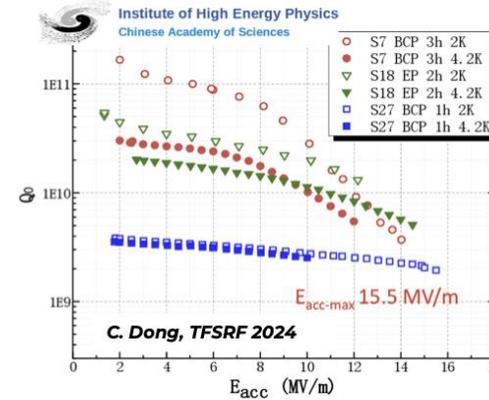
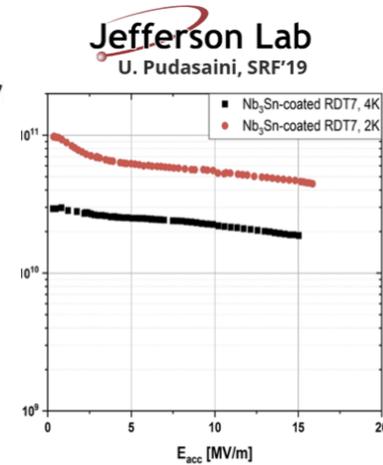
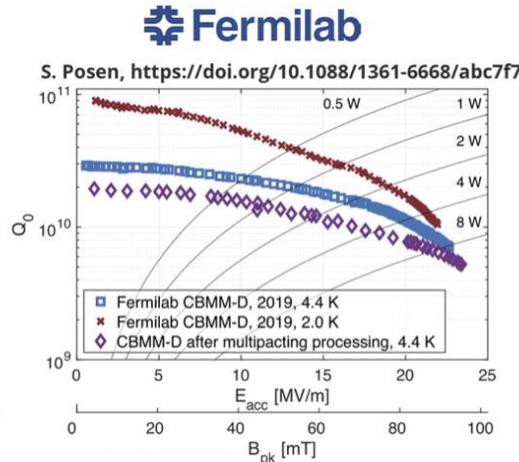
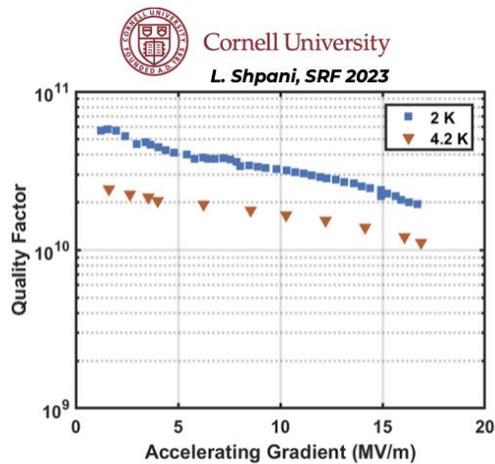
Superconducting RF accelerators

Name	Accelerator Type	Lab	T (K)	Refrigeration Capacity	Status
CEBAF	Electron Linac	JLab	2.1	4.2 kW @ 2.1 K	Operating
12 GeV Upgrade	Electron Linac	Jlab	2.1	4.2 kW @ 2.1 K	Operating
ESS	Proton Linac	ESS	2.0	3 kW @ 2 K	Under Construction
SNS	H ⁻ Linac	ORNL	2.1	2.4 kW @ 2.1 K	Operating
E Linac	Electron Linac	TRIUMF	2.0	288 L/Hr	Operating
S-DALINAC	Electron Linac	TU Darmstadt	2.0	120 W @ 2.0 K	Operating
ERL	Electron Linac	Cornell	1.8	7.5 kW @ 1.8 K	Proposed
XFEL	Electron Linac	DESY	2.0 5 -8 40-80	2.5 kW @ 2 K 4 kW @ 5 -8 K 26 kW @ 40-80 K	Operating
ATLAS	Heavy Ion Linac	ANL	4.7	1.2 kW @ 4.7	Operating
LCLS II	Accelerator	SLAC	2.0 K	8 kW @ 2 K 30.6 kW @ 35 -55 K 2.6 kW @ 4.5 -6 K	Under construction TESLA Tech
ISAC - II	Heavy Ion Linac	TRIUMF	4		Operating
FRIB	Heavy Ion Linac	MSU	2.1 4.5 33/55	3.6 kW @ 2.1 K 4.5 kW @ 4.5 K 20 kW @ 35/55 K	Operating

Thin films

- Bulk Nb is mature technology, reaching limits of performance (E_{acc} , Q_0)
- New materials being investigated to:
 - a) reduce cavity production costs (materials, machining, etc.)
 - b) reduce opex (higher Q_0 , higher operating temp.)
 - c) reduce capex (higher E_{acc} \Rightarrow shorter accelerators)
- S/c alloys such as Nb_3Sn , MgB_2 have higher T_c \Rightarrow higher Q_0 , but brittle so can't form into cavities
- That said, Nb $\lambda_L \sim 50$ nm, so we only need a few hundred nm of s/c \Rightarrow thin films onto some substrate
- Deposition via physical vapour deposition, chemical vapour deposition, thermal diffusion
- Key challenges for thin films are
 - a) fabrication and surface preparation of substrate at least as difficult as bulk Nb
 - b) many parameters can be varied during deposition \Rightarrow large parameter space being explored
 - c) managing microphonics from bubbling at 4 K \Rightarrow fast reactive tuning critical enabling technology

Thin films



Reproducible performance $Q_0 > 10^{10}$ at 4 K, current quench fields: 6 to 24 MV/m (FNAL best results so far)

S-I-S multilayers (first proposed theoretically by Gurevich (2006) for higher E_{acc} ; very interested area of research but fabrication very challenging (see recent work by X. Teng, Temple U.)

Conduction-cooled srf cavities

Work is being done at several institutions including Fermilab (Dhuley et al.), Jlab (Ciovati et al.), and Cornell (Stilin et al.) on operating srf cavities without the use of LHe!

Coupling modified Nb₃Sn-coated cavities with cryocoolers via sufficiently high conductance thermal links, cavity performances approaching 10 MV/m cw have been reported

Designs being developed for standalone srf module ~1m length to deliver e⁻ beams with energies on the order of 10 MeV and average beam powers at least on the order of 10 kW

Emerging e-beam applications:

- pathogen reduction, removal of disinfection byproducts, and removal of pharmaceuticals from water, sewage, and medical waste
- reduction in NO_x, SO_x, and Hg in coal-fired flue gas
- sterilisation of medical devices
- removal of hydrocarbon contaminants in soil
- strengthening of asphalt pavements

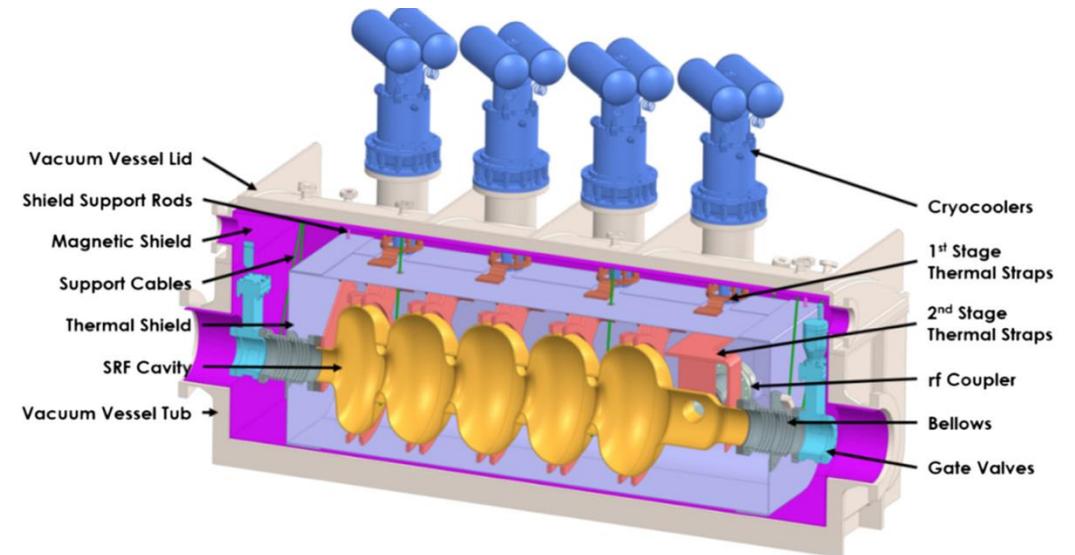


Fig taken from R.C. Dhuley et al, Phys. Rev. Accel. Beams. 25, 041601 (2022).

Quantum information science

Next generation of axion haloscope cavities for dark matter searches (SRF in high DC field, converting axion to microwave photon??) (e.g., Posen et al., 2023, Marconato et al., 2024, Chung et al. 2023)

Dark photon (“light shining through a wall”) searches (e.g., Romanenko et al., 2023)

Quantum computing using SRF cavities (3D resonators) with JJs as qubit platforms (Fermilab SQMS, and others)

Some conferences and meetings

SRF conference series

<https://www.jacow.org/Main/Proceedings?sel=SRF#SRF>

Next meeting: tba

TTC meeting series

<https://tesla.desy.de>

Next meeting: June 2026, Paris, FR

Thin films workshop series

<https://indico.stfc.ac.uk/event/1671/>

Next meeting: Sept 2026, Daresbury, UK



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Questions?



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