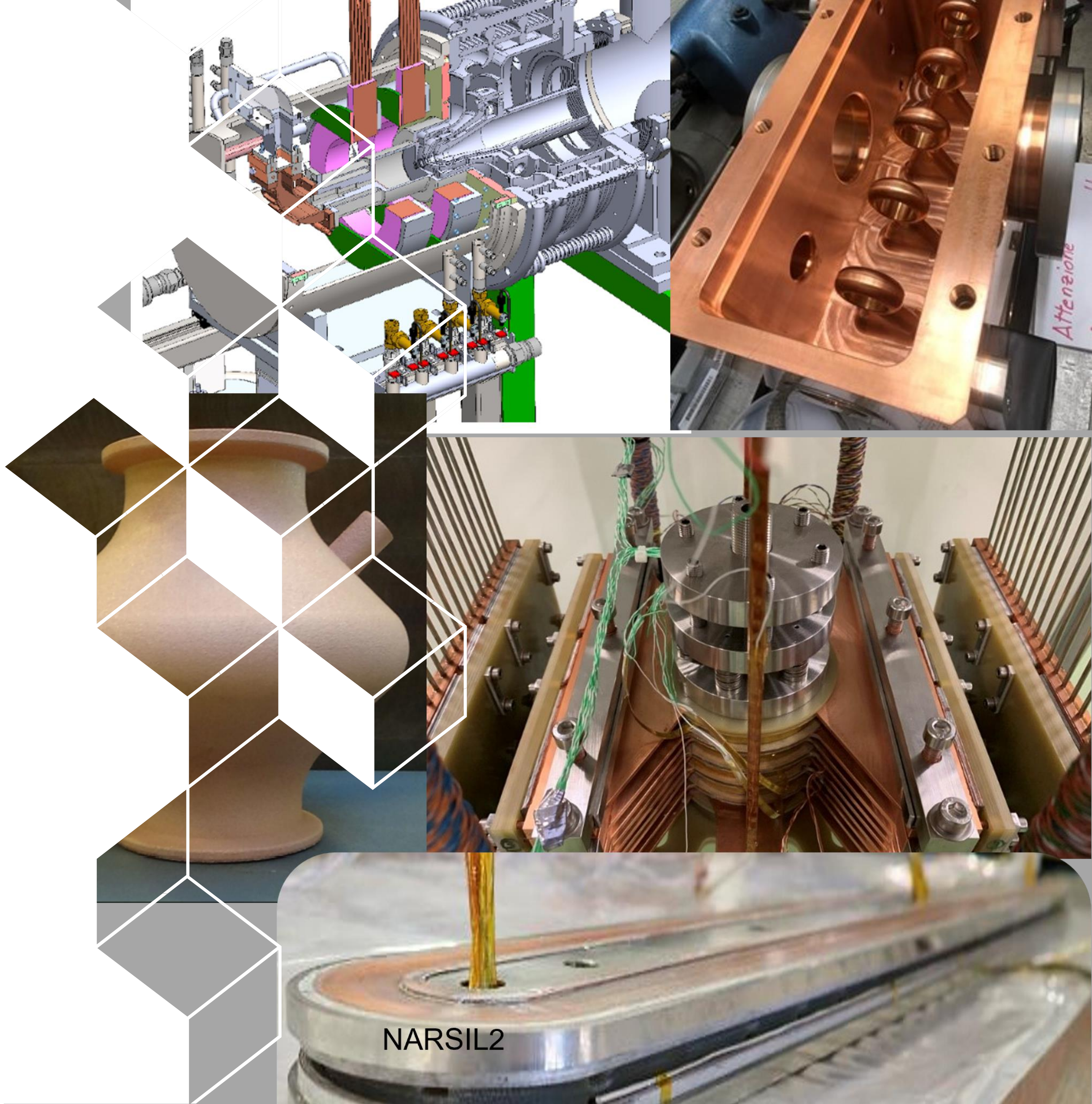
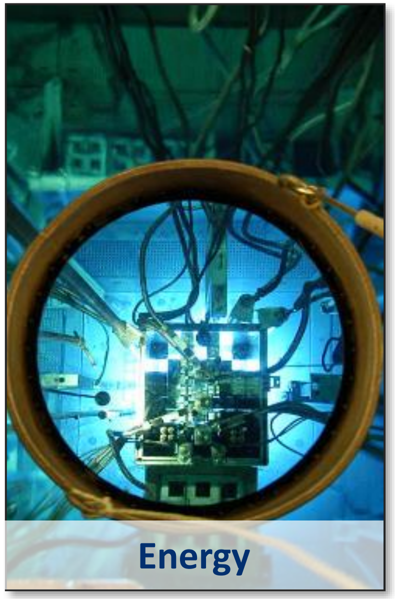
Department of Accelerators, Cryogeny and Magnetism

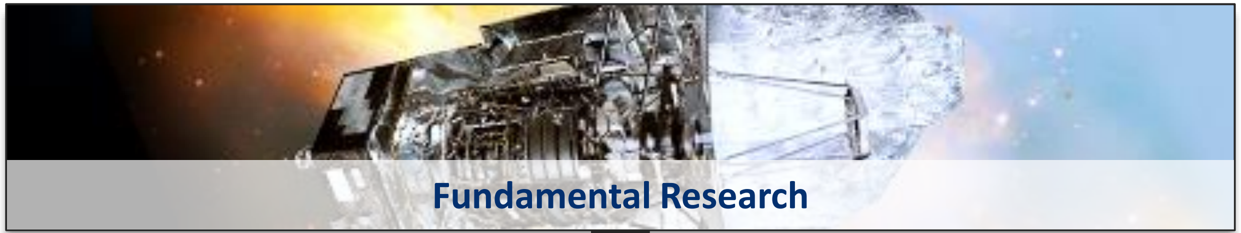
C. Madec

TTC 2026



CEA – The French Alternative Energies and Atomic Energy Commission





cea irfu Institute for Research into the Fundamental Laws of the Universe

22000
employees

7
billion euros

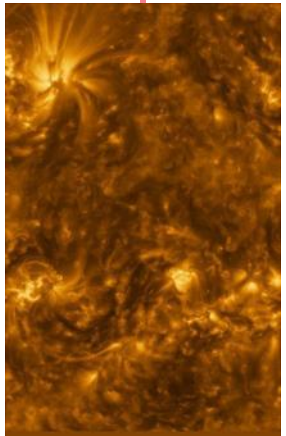
> 5000
publications

> 450
European projets

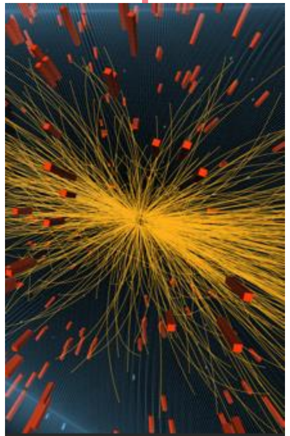
IRFU

cea irfu — Institute for Research into the Fundamental laws of the Universe

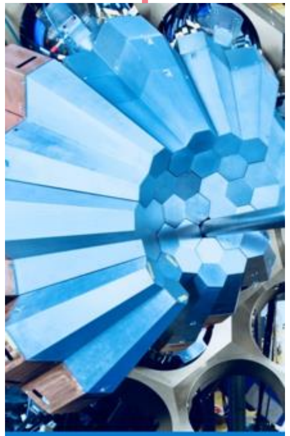
Management Office



DAP
Astrophysics



DPHP
Particle Physics



DPHN
Nuclear Physics

GANIL
Heavy Ion National Accelerator

DEDIP
Detectors Electronics Computing

DACM
Accelerators Cryogenic Magnets

DIS
System Engineering

1150

1000/y

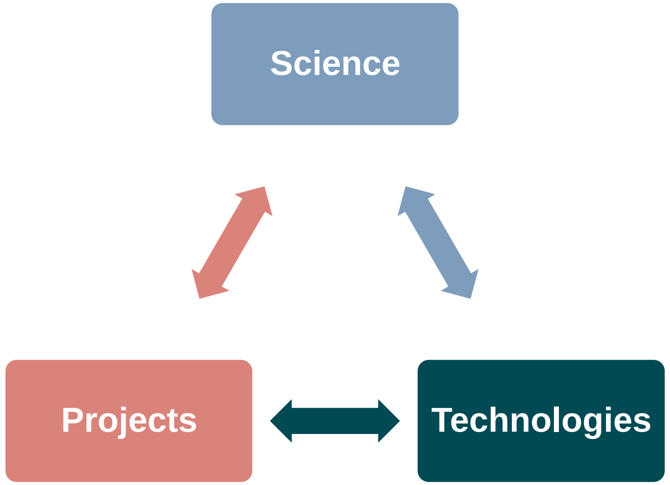
28 ERC
(11 ongoing)

Missions of IRFU

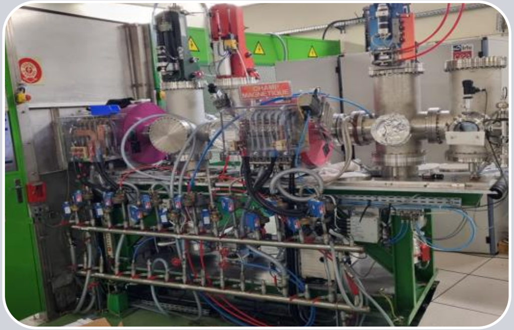
- **Carry out technological and fundamental research** within the framework of CEA's missions, in order to explore the fundamental laws of the universe, from the smallest scales (elementary constituents, nuclear matter) to the largest (energy content and structure of the universe)
- **Apply our technological innovations** to major national or international projects: MRI or fusion magnets, accelerators and neutron sources, medical imaging, etc.

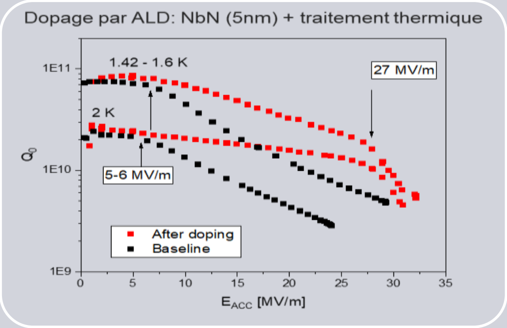
With two specificities due to IRFU's size and the strong integration of its departments:

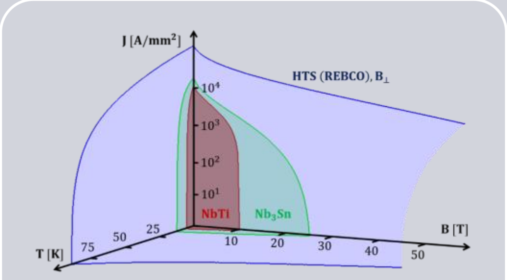
- **Ability to cover the entire research chain**
  - Theory, experiment proposal, simulation, design, construction, operation, data analysis, phenomenology and communication
- **Ability to manage large, innovative and complex projects**
  - Accelerators, magnets, detectors



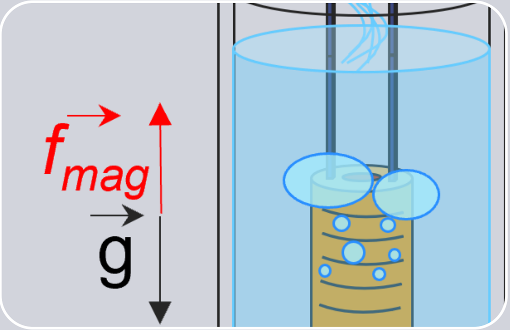
Accelerators, magnets, cryogeny department







Surfaces critiques principaux supraconducteurs



Accelerator developments

Beam dynamics studies

Increase beam currents (200mA)

Commissionning

FCC, Muon collider, Newgain, PACIFICS CANS, ICONE, ESS, DONES,

(S)RF technology

Increase the gradient

Lower the losses

Thin films developments

iFAST, EPITA, ESS, SARAF, PIP-II, IFMIF, DONES, FCC, ITN, ICONE, SOLEIL, CANS

High field magnets

Increase magnetic field for various applications

Operate at higher temperature

HFM, iFAST, EPITA et HTS4SRI Fasum, FCC, EIC, Glead, PEPR SupraFusion

Cryogeny

Cool down with or without cryogens

Cool down with or without gravity

CNES, CryoNEXT, PACIFICS, Audace, HL-LHC, PEPR Suprafusion, Newgain, PIP-II

Accelerators : from the target parameters to machine specifications and components

Accelerator life cycle: from design and simulation to testing, commissioning, and operation, including equipment manufacturing and optimization

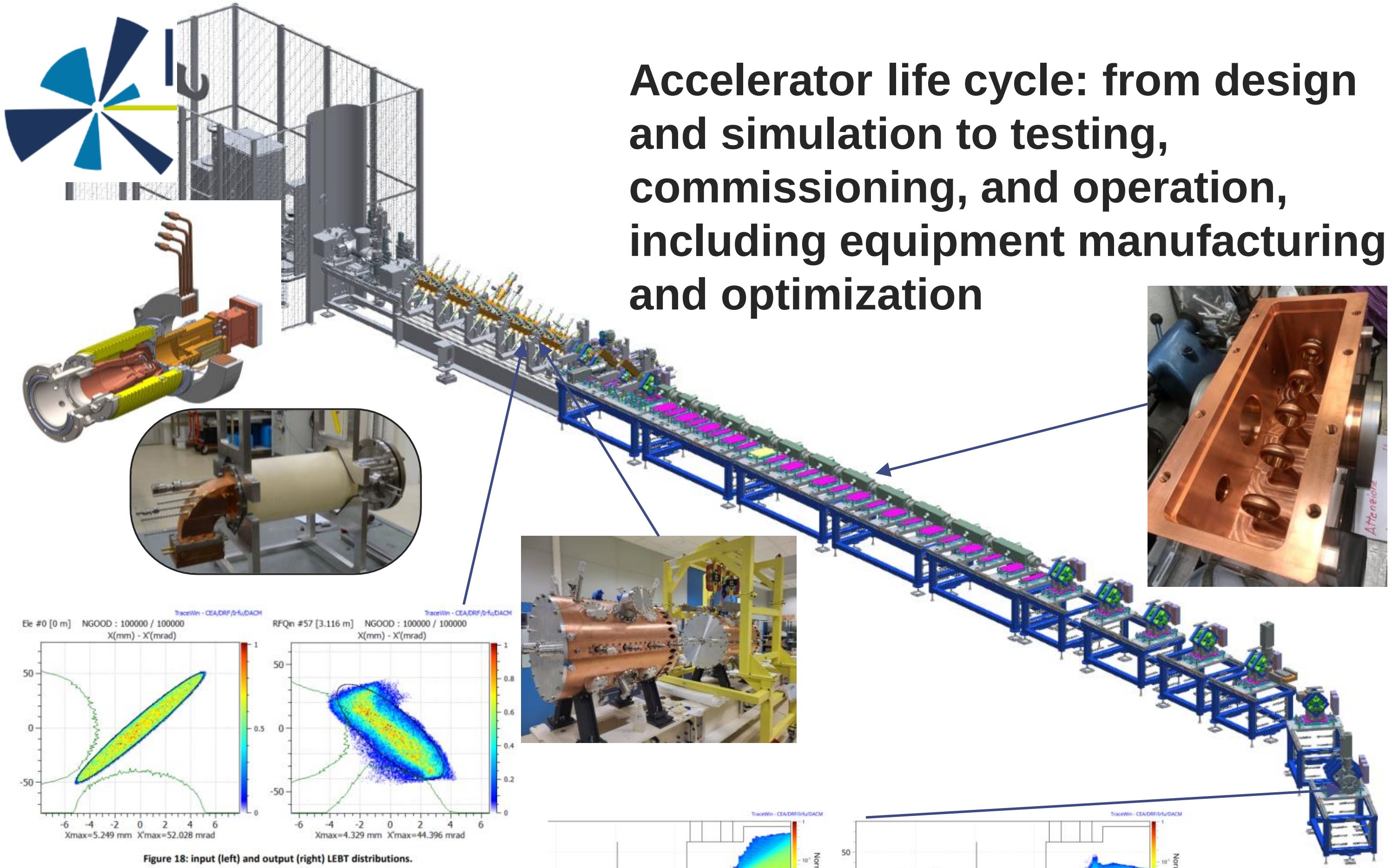


Figure 18: input (left) and output (right) LEBT distributions.

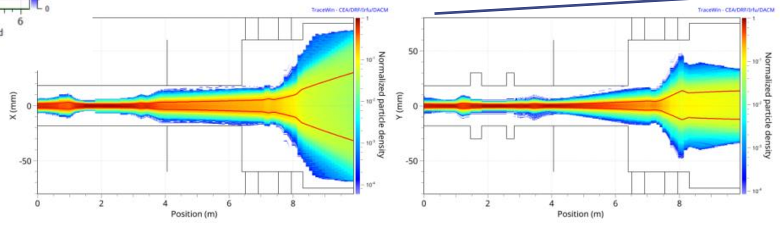
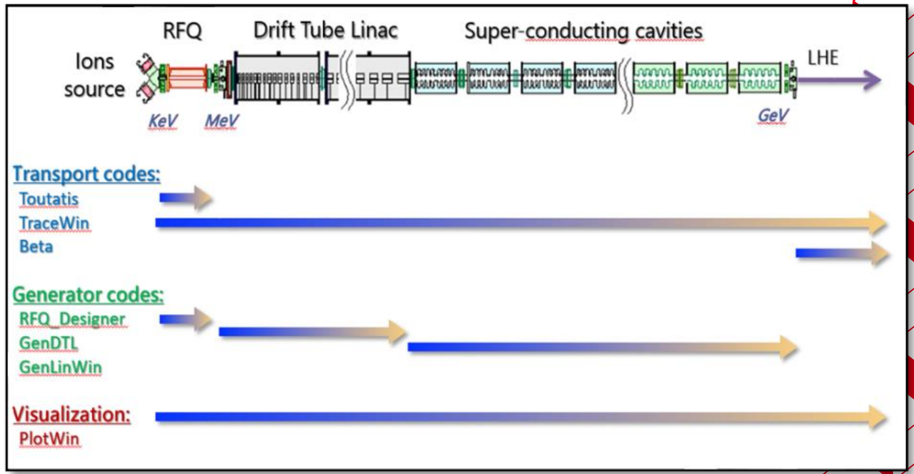
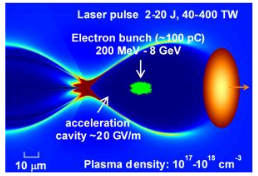
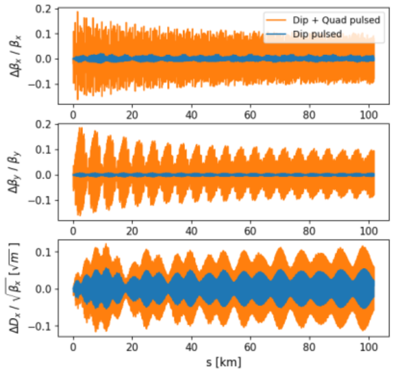
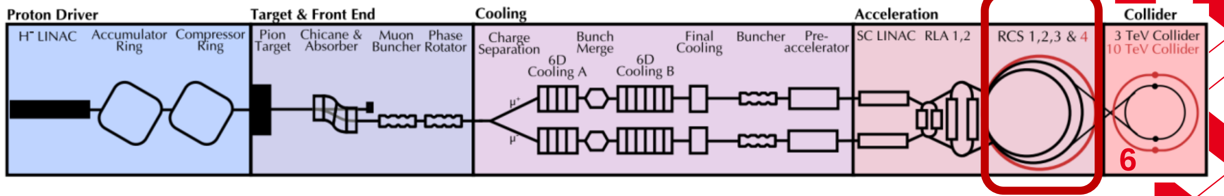


Figure 45: horizontal (left) and vertical (right) beam transport in multiparticle in the HEBT









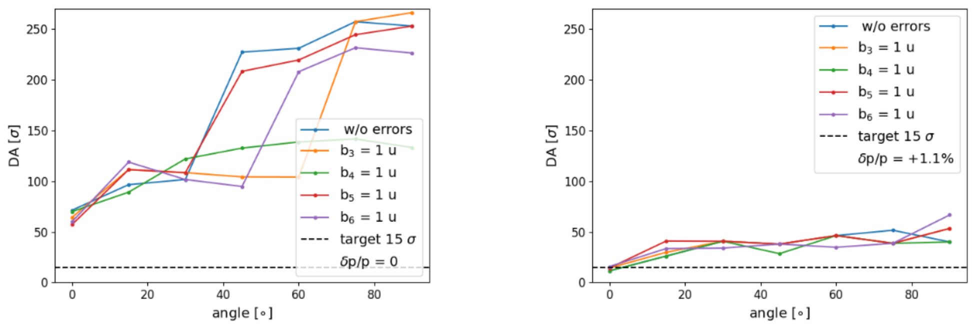
FCC-ee Booster design as an example

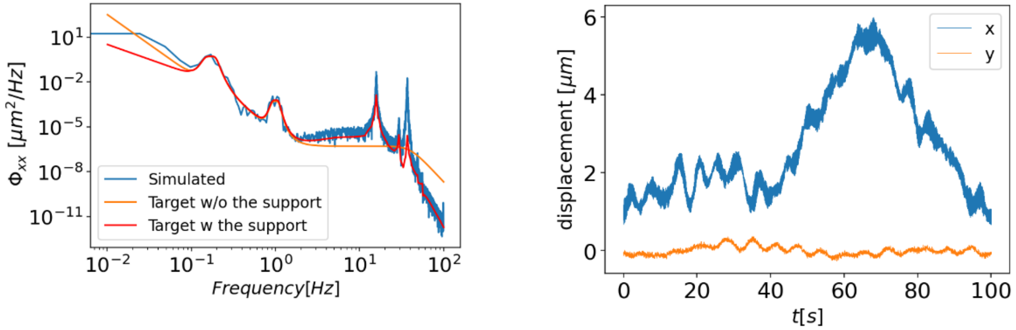
The **high-energy booster** (20 GeV) is the final accelerator injection stage before providing the fresh beam to the collider. The design of the FCC-ee high-energy booster has several challenges: **multi-turn stability**, **top-up** operation, **ramp** of the magnets, **small emittances**.

Tolerance calculation

- Multi-turn tracking simulations to evaluate the impact of **field imperfections** in the magnets to the beam stability (dynamic aperture).
- The **misalignment errors** have a big impact on the beam stability.
- Modelisation of the **vibration** (ground motion, technical noise and mechanical supports) to get a realistic evaluation of the magnet displacements.

Dynamic aperture with systematic errors in the dipoles





FFT model of the vibration to magnet displacement

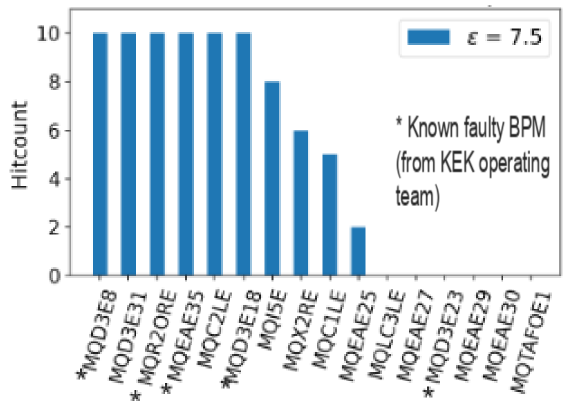
AI developments for accelerators

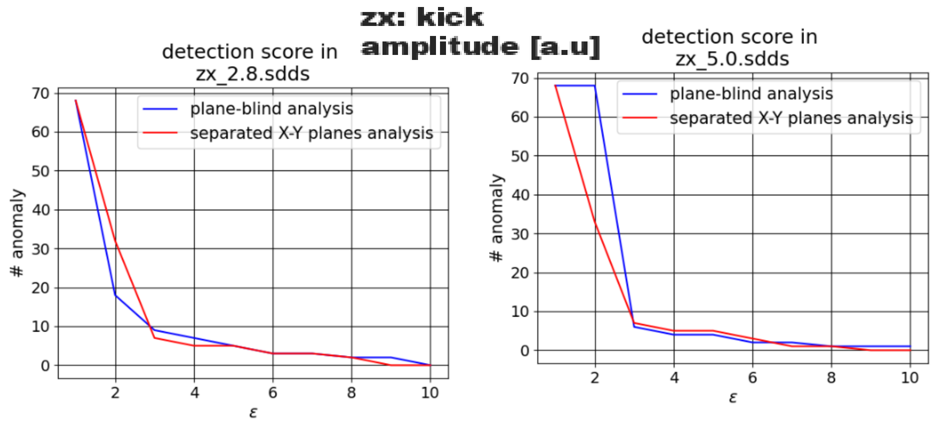
Experimental PoC

➢ SuperKEKB

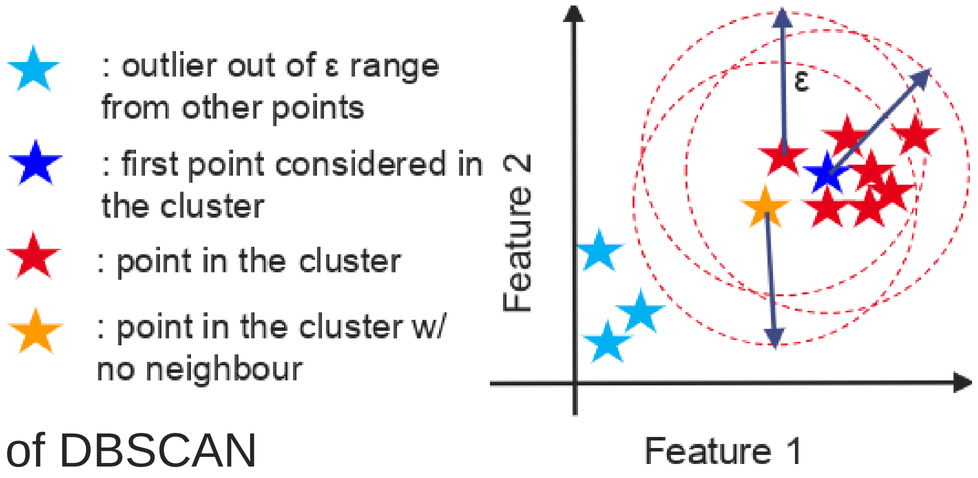
Detection of failed BPMs with IA

- Use of SuperKEKB data to validate the conce
- Complete characterizaton of the algorithm on simulation.
- Run a comprehensive detection campaign on SuperKEKB 2024 data.
- Use an IA algorithm to denoise the validated tracks





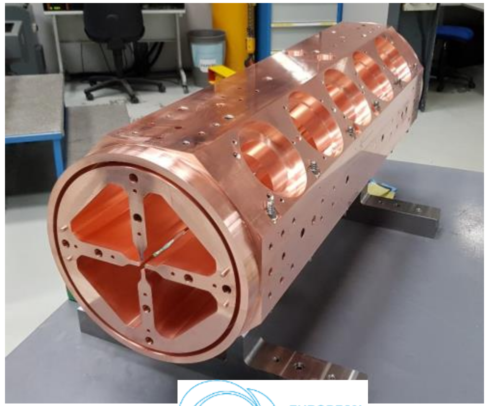
Hit score when BPM considered as faulty

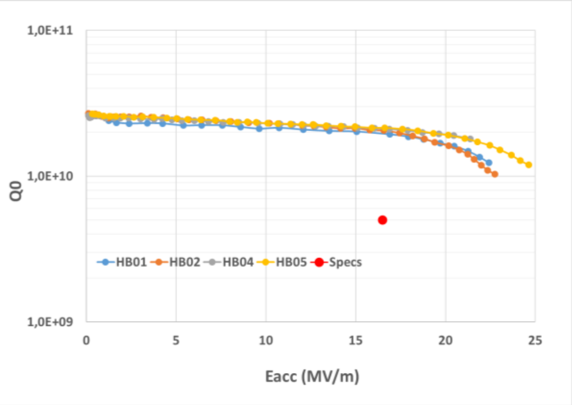


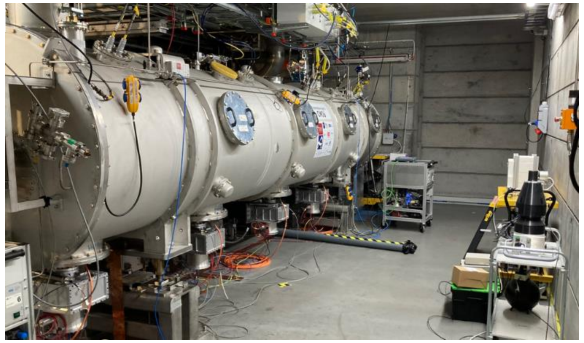
Principle of DBSCAN

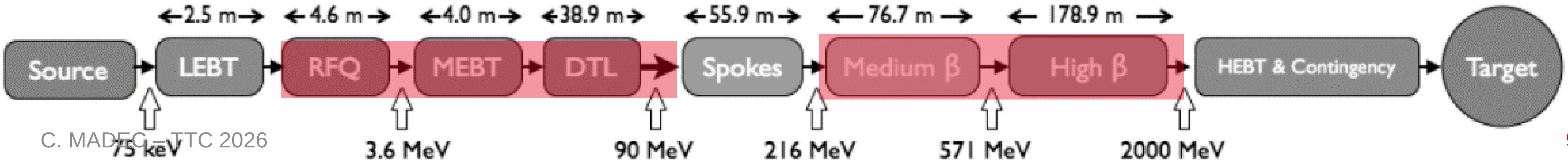
Radiofrequency for accelerators

Design, manufacturing, and qualification testing of high-frequency accelerator components, as well as their implementation on accelerators



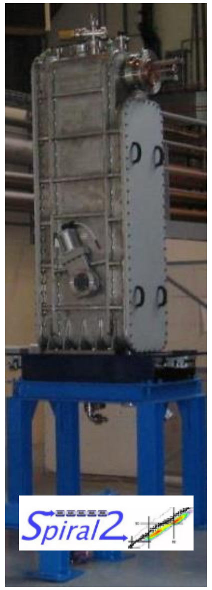






Superconducting cavities and cryomodules @ CEA

Booster → MACSE → SOLEIL TTF, SLS → SPIRAL2 XFEL → ESS, SARAF → IFMIF EVEDA → PIP-II → PERLE → IFMIF DONES → FCCee



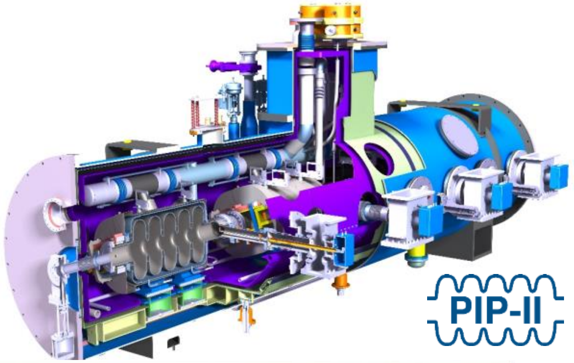
SPIRAL2 : Twelve modules

XFEL: assembly of 103 cryomodules (1 CM/wk)

ESS: Components but
ıd assy of 30
les

IFMIF EVEDA:
1 cryomodule

SARAF : 4 cryomodules

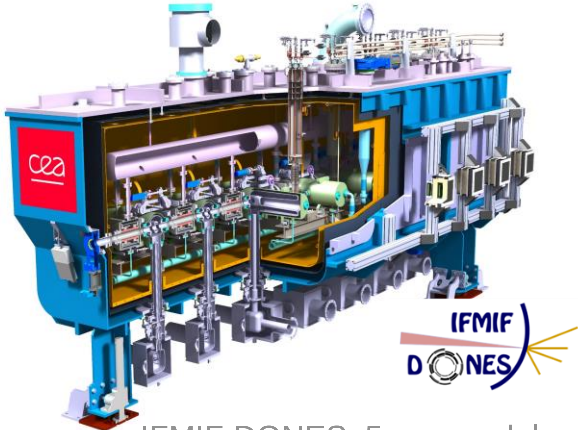


PIP-II: 9+1 cryomodules


Coupler connection with Cobot

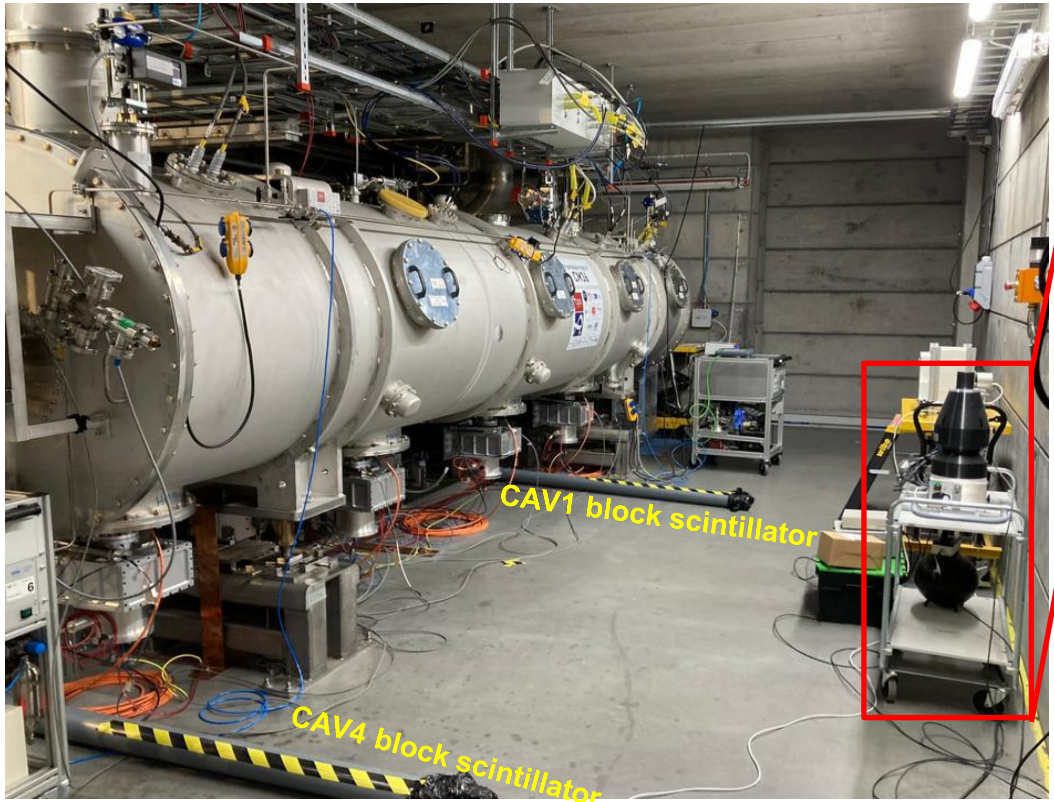

Cavity string assembly

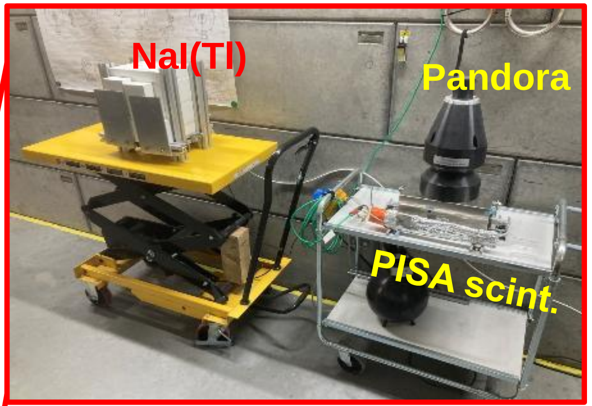
PERLE : 1 cryomodule assembly

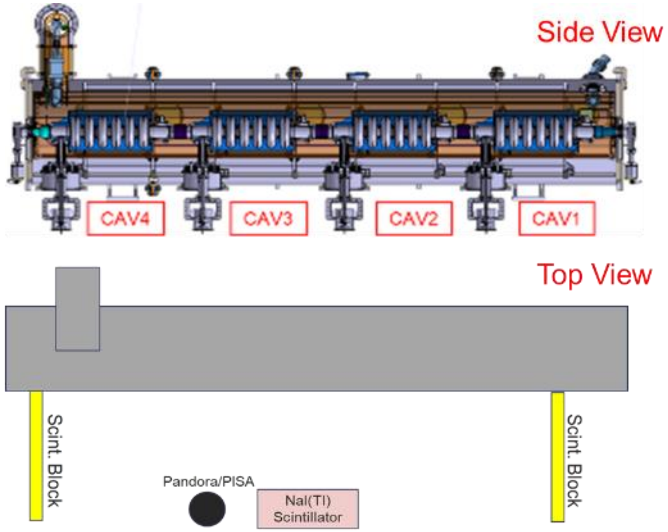


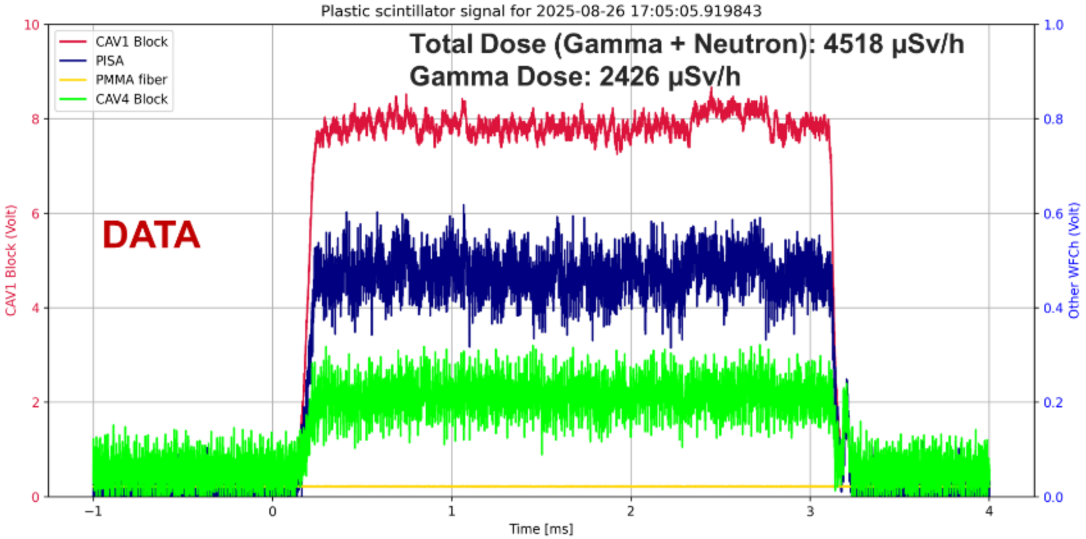
IFMIF DONES: 5 cryomodules

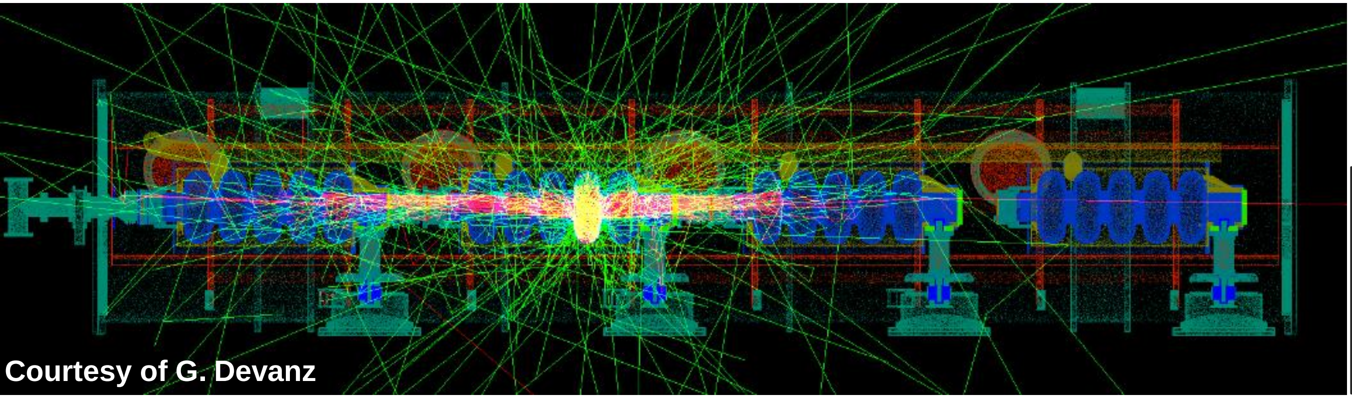
Detector technologies for cavity and cryomodule diagnostics











CEA, ESS and KEK collaboration on the development of various detector technologies for cavity and cryomodule diagnostics, as well as on data analysis and simulation studies.

ITN (CERN-KEK-INFN-CEA)

- ❖ Develop an ILC-style cryomodule as a technology demonstrator.
- ❖ It will include several cavities that are manufactured, processed, and tested within the EU
- ❖ It will strengthen collaboration and network across the European accelerator community, sharing know-how

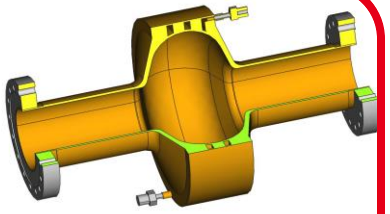
- Two single cells manufactured at RI, to be tested! (+1 cavity from CEA already at KEK)
- 2 cavities delivered to KEK (March 2026) two 9-cells to be compliant with the HPGS regulation in the EU
- Four 9-cell cavities under manufacturing at RI, ready for VT in October

Baseline

- 150µm EP
- 900°C HT
- 10-20µm cold EP (with fresh acid)
- HPR + Assembly
- 75°C 4h 120°C 48h baking

	Vertical Test				Cryomodule Test				
	Eacc nominal [MV/m]	Q0 nominal	max X-ray dose [mSv/h]	Max Eacc (admin limit) [MV/m]	Eacc nominal [MV/m]	Q0 nominal [W calorimetric]	max X-ray dose rate [mSv/h]	Max Eacc (admin limit) [MV/m]	Energy gain [MeV]
Single-cell	35	≥1x10^{10}	No FE (<35MV/m)	at quench					
9-Cell	35	≥1x10^{10}	<10	±20%	31.5	≥1x10^{10}	no perf. degradation	±20%	209-314

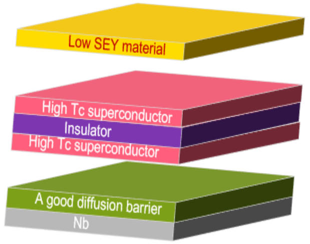
SRF R&D :



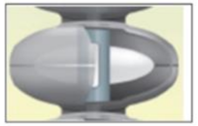
Under fabrication

Material : SRF and qubit

- Surface functionnalisation with ALD, HiPIMS
- Field emission reduction (TEEY)
- Additive manufacturing



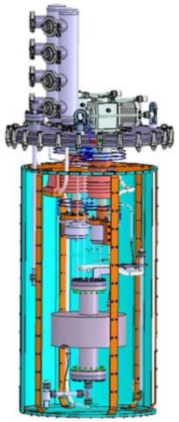
Electropolishing



- Optimisation of surface treatment on mono-cell and multi-cells
- Substrate preparation (Cu, Al)

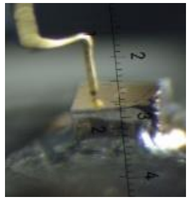
Cobotisation

- Assembly by Cobots : reduction of operator's pain and FE



Measurements tools

- Tunnel spectroscopy(Q-bits and cavities)
- Magnetometry

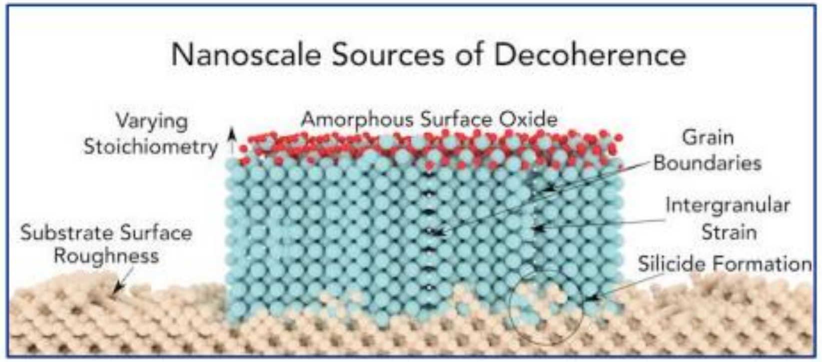


Surface technology for enhanced superconducting qubits lifetimes

▪ Context of the project

2D superconducting qubits suffer from limited coherence times

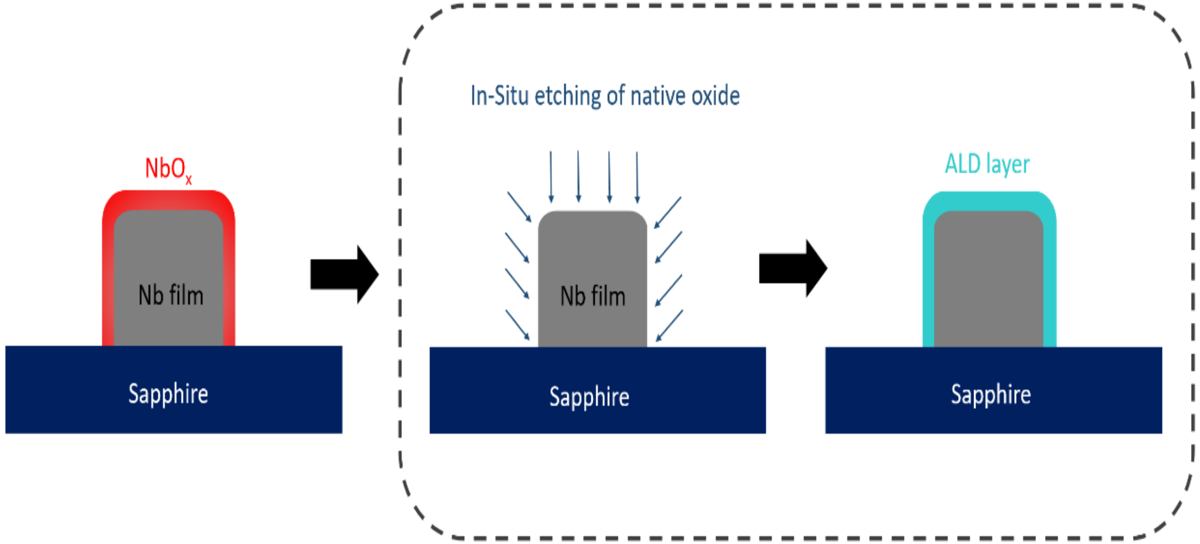
Defects in the oxides layer are the major source of decoherence due to the presence of Two-level system (TLS) defects .



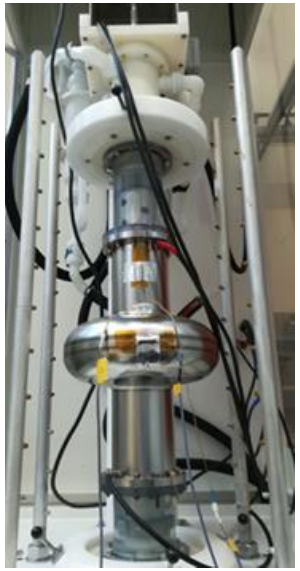
▪ Objectives

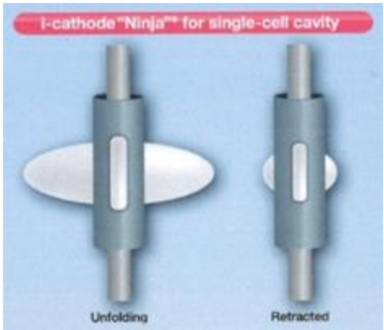
Increase the coherence time of superconducting qubits by reducing the density of two-level system (TLS) defects present in the native oxides covering the superconductor's surface:

The passivation of the superconductor’s surface with thin films deposited by Atomic Layer Deposition (ALD), which inherently have fewer TLS defects, prior in-situ Atomic layer etching (ALE) and thermal treatments when needed designed to dissolve the initially present lossy native oxides



ELECTRO-POLISHING AT CEA Saclay



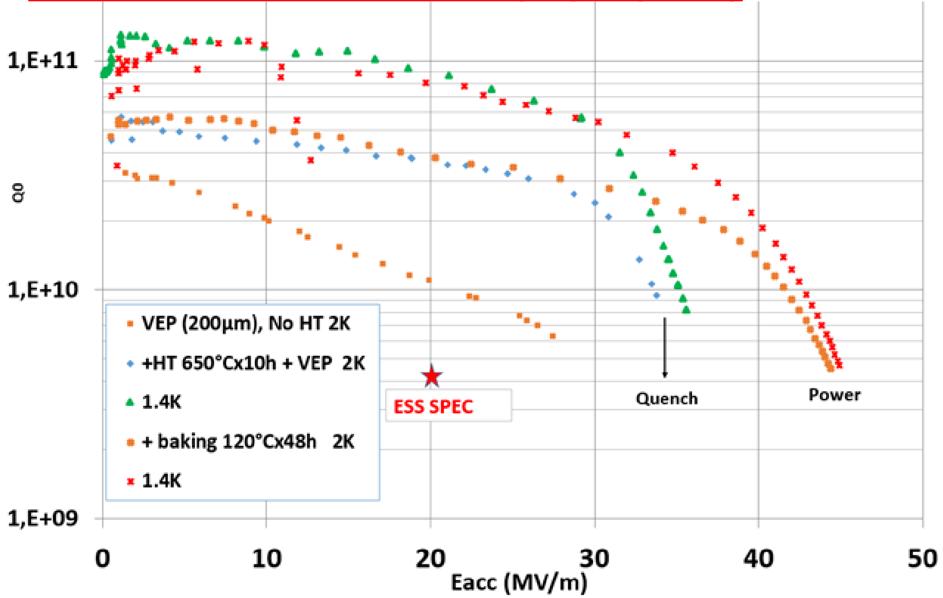


Vertical EP Technology:

- ❖ Designed for large cavities
- ❖ Circulating acid
- ❖ Injected from bottom
- ❖ 300L acid capacity
- ❖ Rotative cathode: uniform removal rate
- ❖ Cooling system (heat exchanger in acid tank)
- ❖ Emptying by gravity
- ❖ Nitrogen blowing in top of cavity/acid tank

Blueish surface observed on ESS geometry 1Cell cavity

Record gradient on single-cell ESS geometry with modified HF concentration (ongoing R&D)



Eacc > 45 MV/m

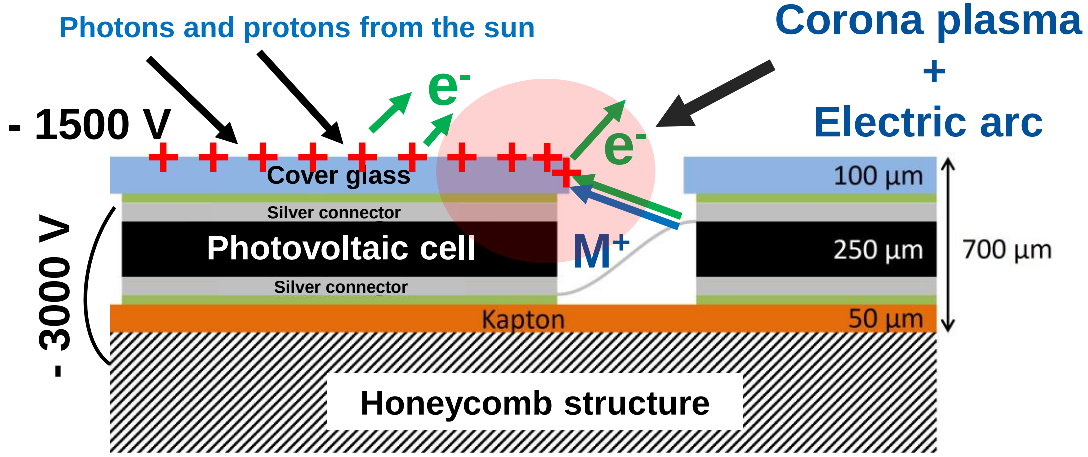
Proceedings of LINAC22, THPOGE23, pp. 844-847

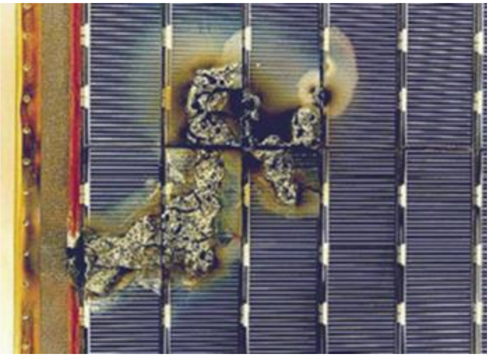
- EP of 1300 MHz and 704 MHz activities
- EP Parameters R&D
- Record gradient achieved on 1Cell cavities
- Preparation of cavities for several R&Ds:
  - Thin film coatings
  - Doping
  - Heat treatments

The challenge of electronic emission yield

Electrostatic discharge on orbiting satellites

Potential difference between dielectric and conductive areas



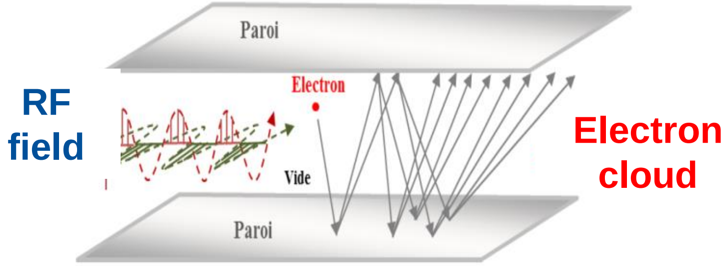


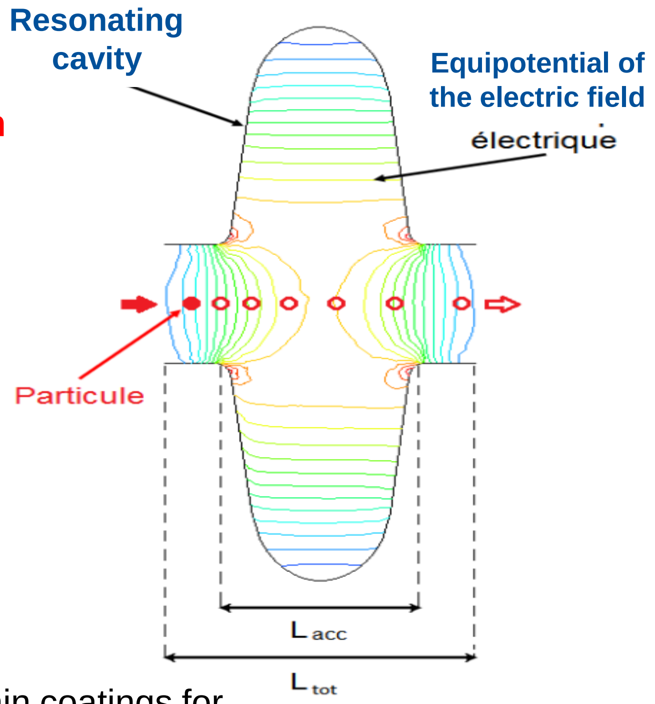
EURECA satellite solar array sustained arc, damage
Credits: ESA

Multipactor Effect in RF components

Synchronisation between electronic emission and RF field

Exponential dependency on TEEY





Solution :

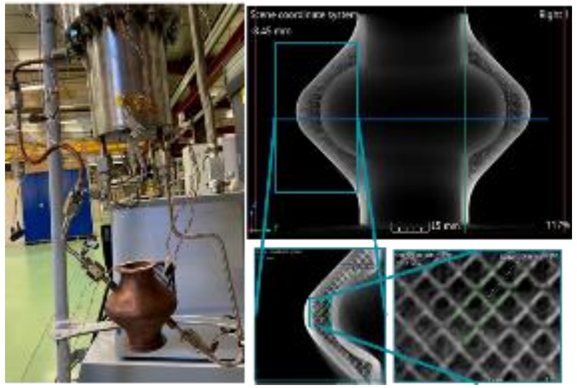
To use Atomic Layer Deposited coatings with tunable TEEY and electrical conductivity

Other developments in SRF

Fab Add by Laser Powder Bed Fusion

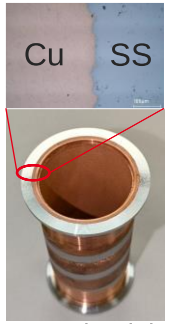
6 GHz Cu cavity – vacuum and cryo tested

Cavité Cu par impression 3D



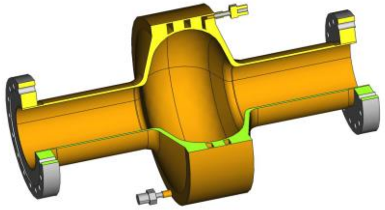
Fab Add by Cold Spray

1,3 GHz Cu cavity under manufacturing



Multimaterial potential

Sample trial



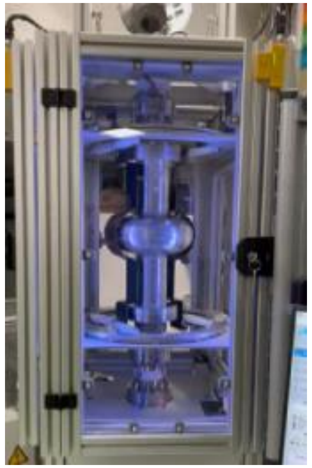
EP on Fab Add substrate

surface roughness ~ 0,1µm

Thin Films

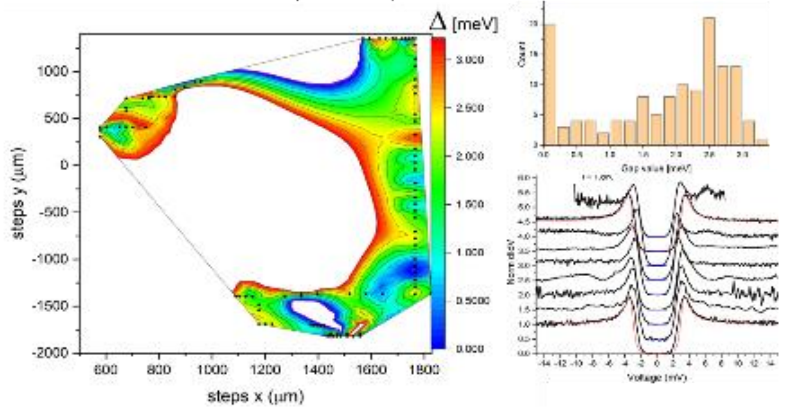
-ALD processes: diffusion barrier, thermocurrents, TEEY, …

-HIPIMs: under development

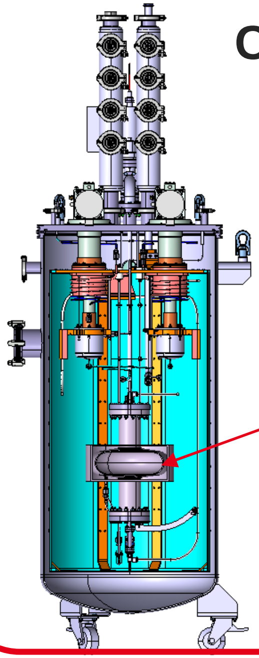


Characterization of SC properties

Spectroscopie tunnel de Nb_3Sn/Cu



Cryostat with cryocooler



-Design completed

-Under manufacturing

Fab add cavity with « helium tank »

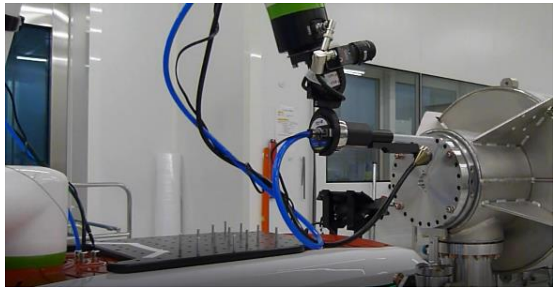
Cobot development for cleanroom activities

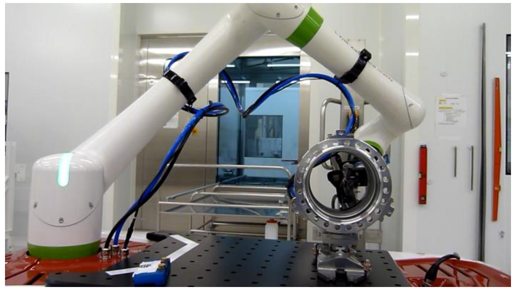
Main goals
- Reduce the tedious work of cleaning component in cleanroom
- Reduce the risk of particulate contamination caused by the operators during critical assembly phases

Development of toolings designed for various operations and programming of associated trajectories

ESS PROJECT

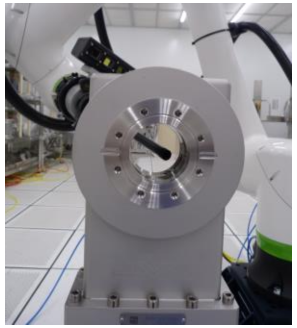
- Use of a FANUC CRX10iAL cobot arm (10kg payload) on 14 ESS cavity strings on **blow cleaning steps of components and flanges holes**
- Cobot and operators can work in parallel
- Path programming in cleanroom with the components
- Cobot can perform particle counting for each blow cleaning
- Time-saver for ESS string assembly in the clean room : ~ 1/3 of assembly time (work in hidden time)

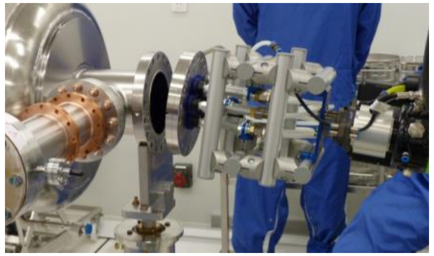




PIP-II PROJECT

- Use of a FANUC CRX25iAL cobot arm (25kg payload) to extend the use of cobot in assembly steps
- Improved vision system to improve accuracy of cobot operations
- Path programming outside the cleanroom with a digital mockup
- The blow cleaning/particle counting operations are extended to couplers, gate valves, …
- The PIP-II **bellows and couplers are assembled on cavity with cobot**
  - Handling, alignment and positioning of component on cavity
- A cold RF test of a PIP-II cavity with coupler assembled by cobot has shown no field emission at project acceleration field limit (19,6 MV/m)

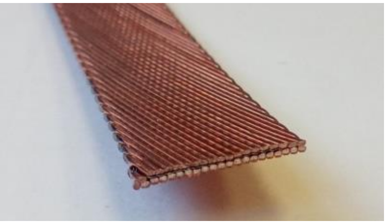




Perspective :
Continue to expand the range of tasks performed by the cobot by enhancing collaboration between the two cobots arms and the operators

From acceleration to focalisation and beyond

Superconducting materials (NbTi, Nb_3Sn, REBCO) for specific magnetic systems

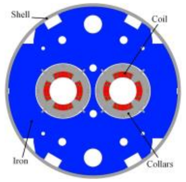


Fundamental sciences related to accelerators and detector magnets

LHC accelerator magnets (CERN/ CEA)

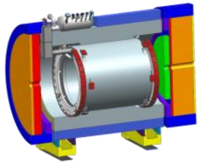
MQ spares

MQYY/MQYYM (Hilumi)

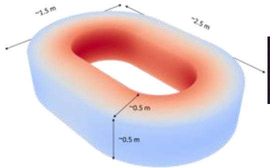


Detectors magnet

EIC MARCO

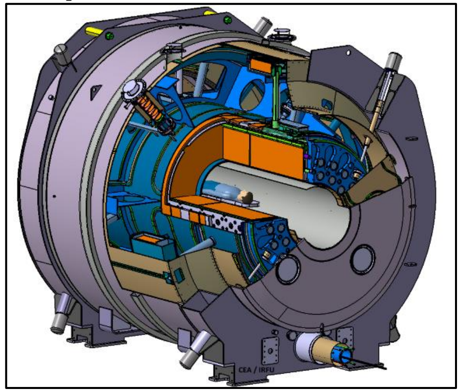


Energy with developments for nuclear fusion



PEPR SupraFusion (Démonstrateur PC4)

Health, with projects focused on the development of MRI (Iseult – 11T) and NMR



Laboratory magnets with projects focused on ultra-high field magnets (FASUM)

Magnets for High field > 30 T

SUPER EMFL / FASUM

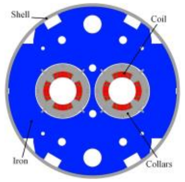
3 superconductors serving detectors, accelerators or societial developments

Nb-Ti

LHC accelerator magnets (CERN/ CEA)

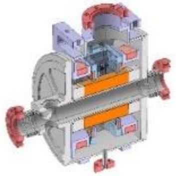
MQ spares

MQYY/MQYYM (Hilumi)

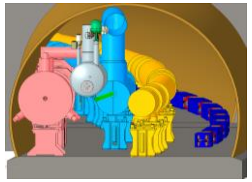


Other accelerator magnets

SARAF



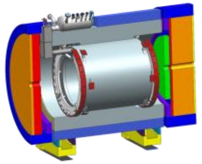
EIC Spin Rotators



Super FRS

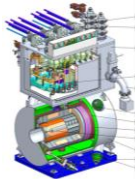
Detecors magnet

EIC MARCO



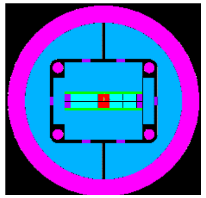
Ion source magnet

Asterics



Nb_3Sn

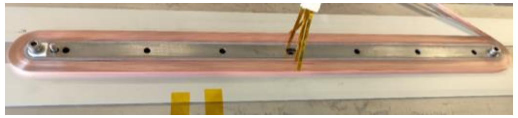
Accelerator magnets



CERN/CEA

R2D2

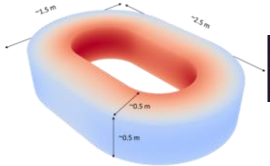
HTS



CERN/ CEA

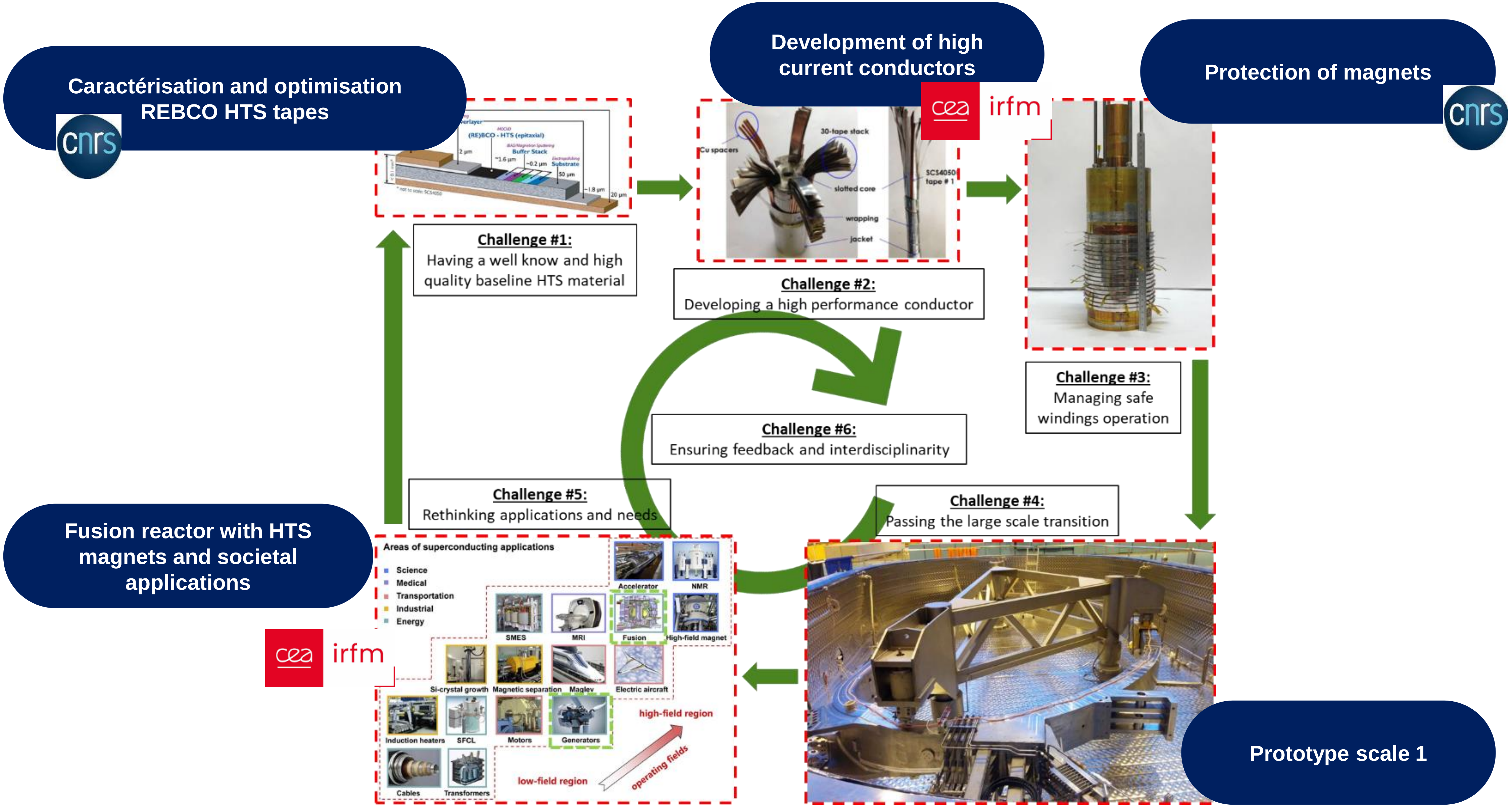
Magnets for High field > 30 T

SUPER EMFL / FASUM



PEPR SupraFusion (scale 1 prototype PC4)

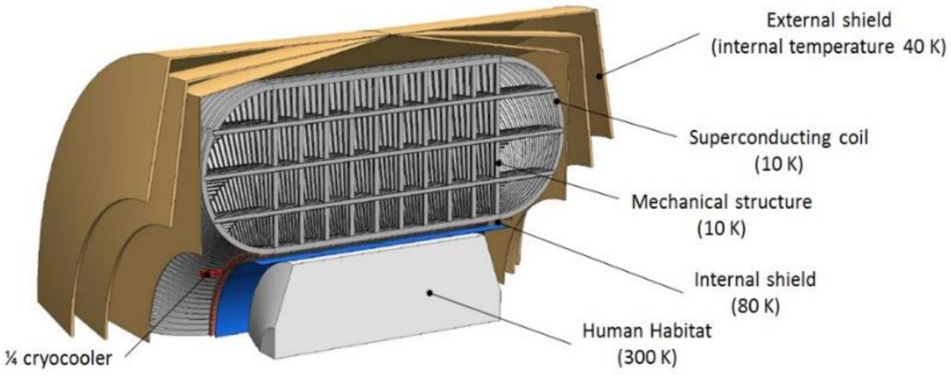
SupraFusion : towards energy produced by fusion



Cooling in specific environments :

Heat transfert in zero gravity environment

- Cooling down of superconducting for space applications
- Cooling down of superconducting magnet in high hield environment (B>20 T) where magnetic force conterbalance gravity



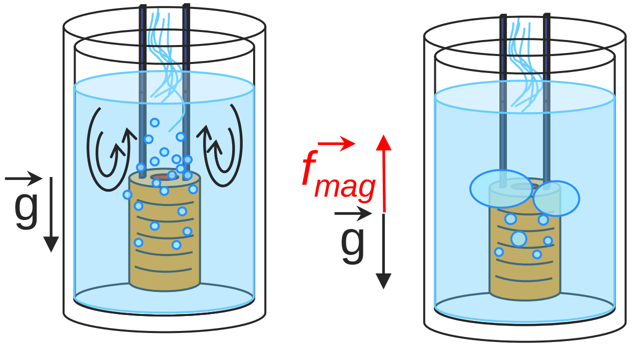
European Commission Grant ID:313224,
Project duration 2013 – 2015

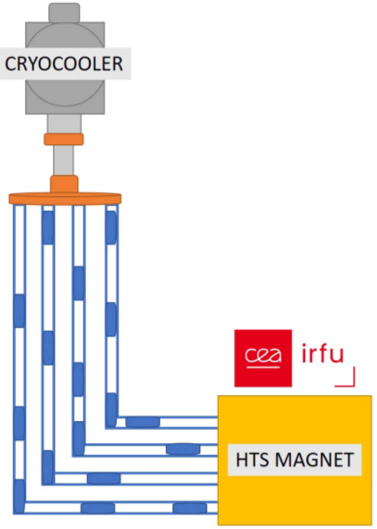
Cooling down of a thermal shield for space craft carrier

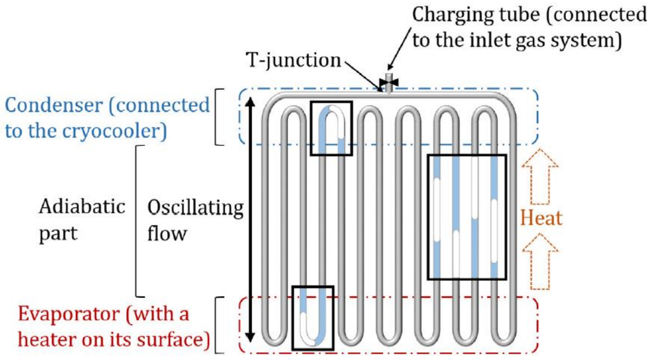
HTS 32,5 T solenoid (NOUGAT) cooled in He bath

Fazilleau et al., Cryogenics 106 (2020) 103053

$$\overrightarrow{f_{mag}} \propto \frac{\chi}{2\mu_0}\overrightarrow{grad}(B^2)$$







Cool down at 4,2 – 1,8 K : tests stations

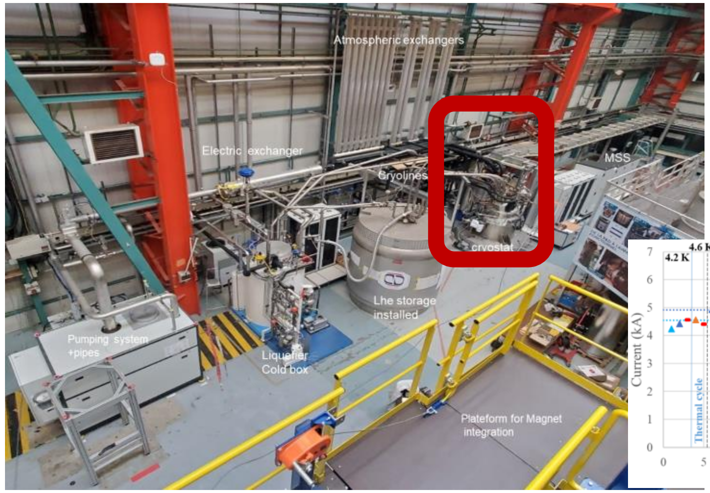
Magnets test stand

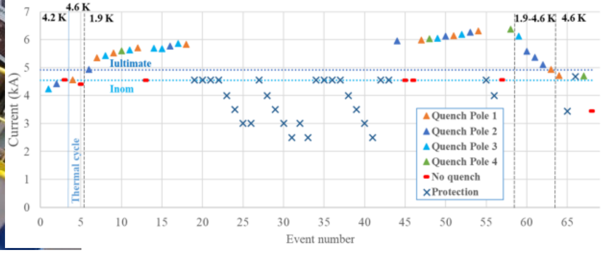
HL-LHC PROJECT

Cool down and test quadrupoles for HL-LHC (4,5-1,9K)

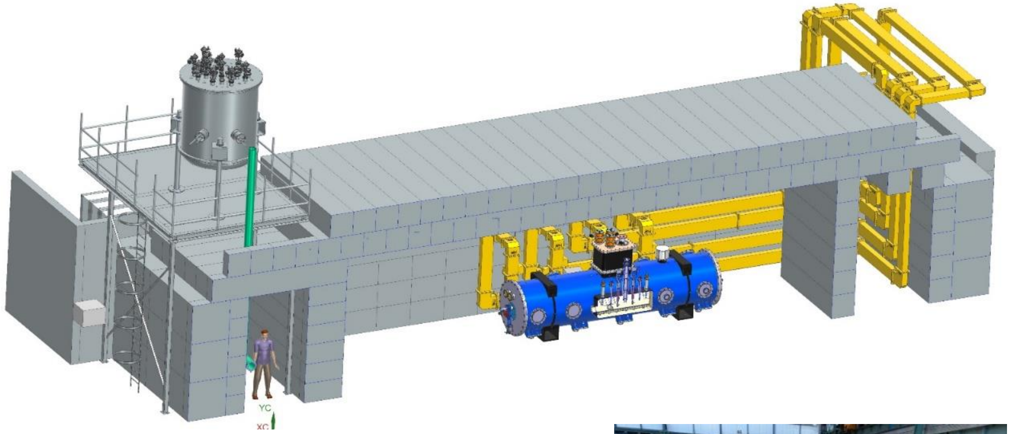
STAARQ

cea - Irfu



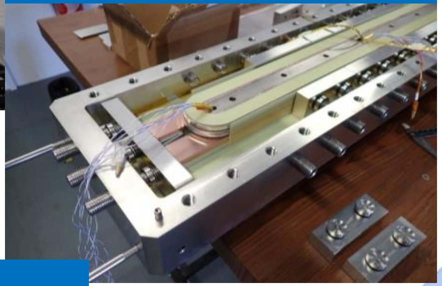


Cryomodule test stand



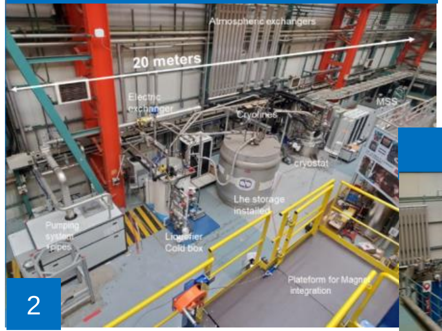
HTS development

HTS development



R2D2

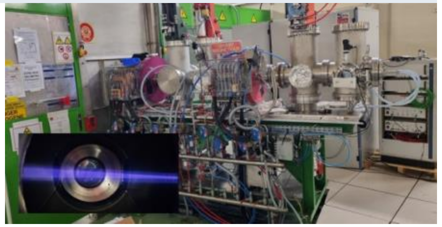
Stations d’essais STAARQ



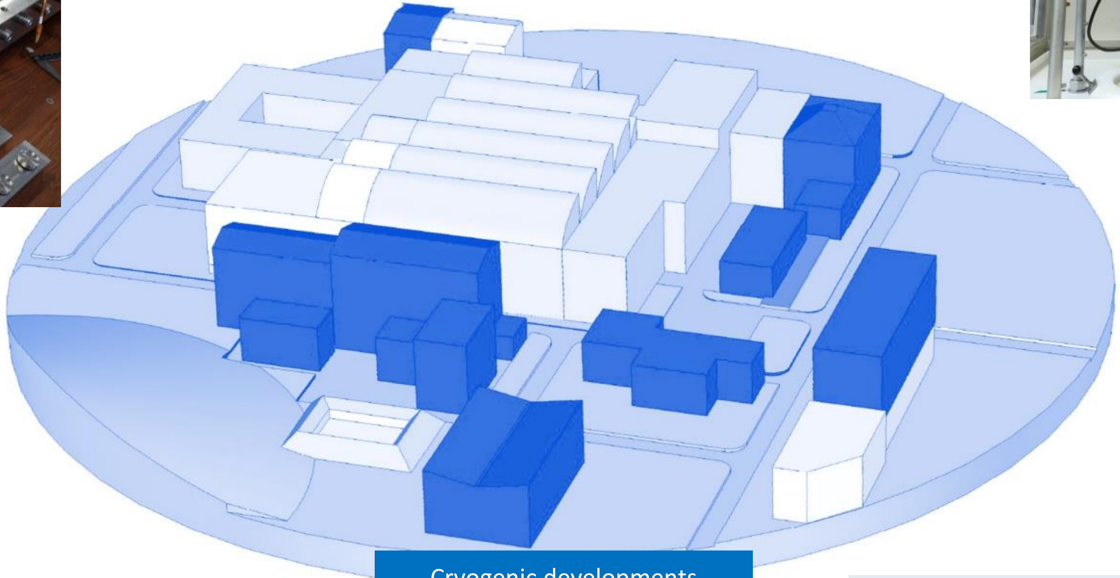
2

Test station for magnets

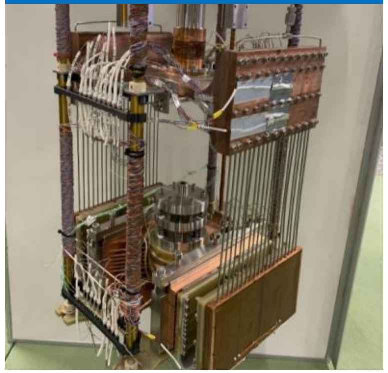
Proton source



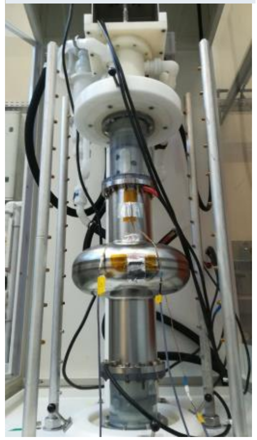
Cobot



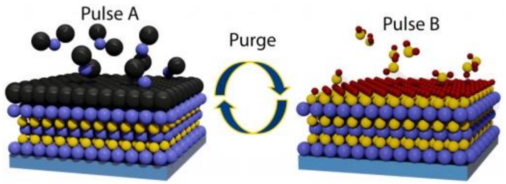
Cryogenic developments



Cavity preparation



Thin films developments



Cryomodule assembly

Supratech / Cryo HF

Coupleurs ESS

“ END