Accelerator activities at CEA

2024 European Edition of the International Workshop on the Circular Electron-Positron Collider (CEPC)

Pierre Vedrine

8 April 2024

Outline

Organisation

Programmes

Perspectives

Infrastructures

Conclusions

1. Organisation

CEA Carrying out strategic missions for the future

Defense
and safety
of the country

Nuclear and
renewable
energies

Accelerators at CEA

~ 270 FTE

Technological
research for
industry

Fundamental
research

Accelerators and Magnets at CEA/IRFU

CEA / IRFU - Institute of Research into Fundamental laws of Universe

- Saclay and Ganil Caen
- ~ 270 FTE on accelerators/magnets

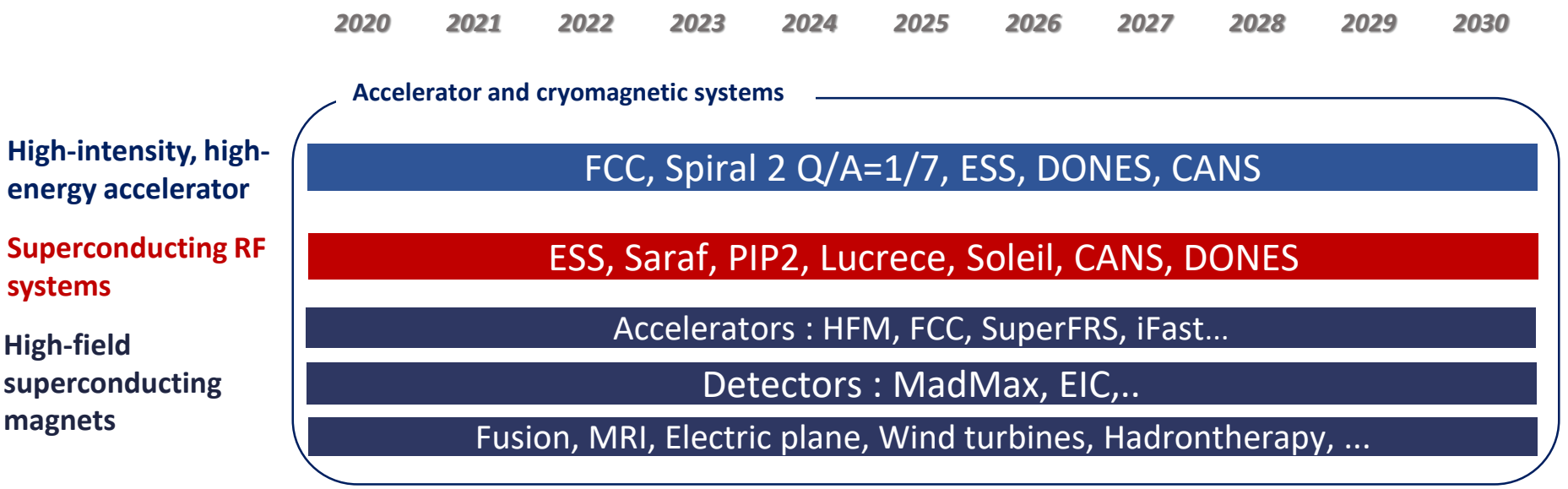
SC technologies for high field magnets	Modelisation/ beam dyn. / num. methods
Innovative cryogenic systems	Superconducting cavities / materials
Understanding high intensity ion beams	RF systems for high power beams

Develop competences on:

- Ion production and acceleration
- SC cavities and high power p and d linacs
- High energy colliders
- High field magnets
- Plasma wakefield acceleration

2. Programmes

Roadmaps – Accelerators and Cryotechnologies



"High-intensity, high-energy accelerators: boosting the energy and intensity of accelerated particle beams; includes developments on « warm" RF sources and injectors, and all studies on current and future linear and circular accelerator systems (ILC, FCC, Muon colliders, ERL, plasma lasers, compact neutron and light sources, etc.).

"Superconducting RF systems" Pushing the gradient limits of superconducting accelerating cavities and reducing their energy consumption; includes all cryomodules and supercavities as well as their RF power supply systems ...We are also starting to develop cryomodules for circular accelerator(Soleil, FCC ee, ILC, etc.) in addition to linear...

"High-field superconducting magnets"; includes all high-field magnets (> 10 T, large size, special, etc.) for physics and societal applications, as well as their cryogenic cooling systems.

Ongoing European Programs

EURATOM : DONES Consolodiation Phase

H2020 - INFRA INNOV-04-2020 Innovation Pilots :

- IFAST Innovation Fostering in Accelerator Science and Technology

H2020 - INFRAIA-02 Integrating Activities for Starting Communities

- HITTRIplus Heavy Ion Therapy Research Integration plus

H2020-INFRA-SERV-01-07: Research infrastructures services advancing frontier knowledge

- Eurolabs EUROpean- Laboratories for Accelerator Based Sciences

H2020 – INFRADEV-01 Design studies :

- FCCIS : FCC ee infrastrucutre

Horizon Europe – Design Studies

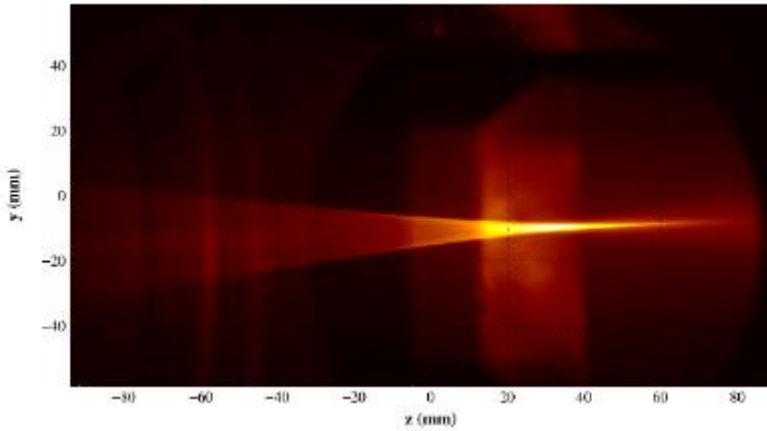
MuCol - Muon Collider complex at 10 TeV center of mass

Ion Production and Acceleration

Highlights:

Record current from the IFMIF ECR deuteron source:

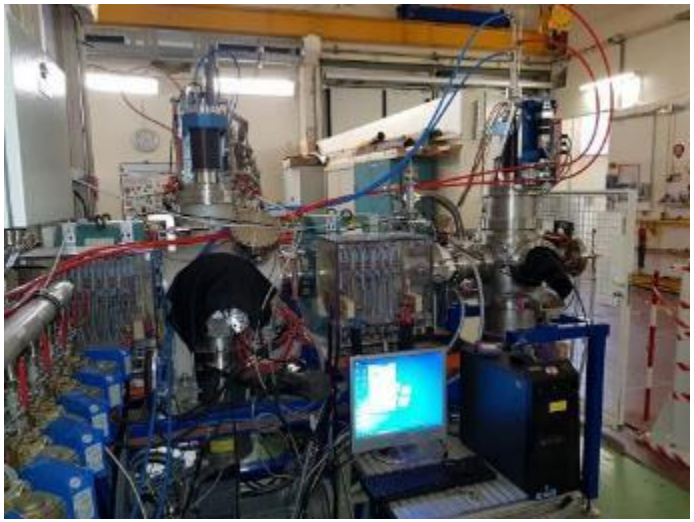
- 140 mA @ 5% duty cycle, emittance < 0.3 p mm.mrad
  90% transmission in RFQ



120 mA 100 keV D beam @ IFMIF

FAIR source + LEBT delivered to GSI

MEBT delivered to Saraf



FAIR source + LEBT @ IRFU

MEBT Saraf @ IRFU

Radio-Frequency Quadrupoles

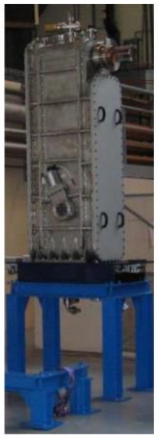
In the past years, IRFU has designed / built / tuned / conditioned / commissioned several high power RFQs

RFQ	Freq. (MHz)	Cont. / pulsed	Current	Energy	First beam
LINAC4	352.2	Pulsed 7.5%	80 mA H^+	3 MeV	2013 at CERN
SPIRAL2	88.05	Continuous	5 mA H+, D^+ 1 mA q/A = 1/3	0.75 MeV / n	2015 at Ganil
IPHI	352.2	Continuous	100 mA H^+	3 MeV	2016 at Saclay
ESS	352.2	Pulsed 4%	70 mA H^+	3.62 MeV	RF cond. July 2021

The ESS RFQ delivered at Lund in August 2019

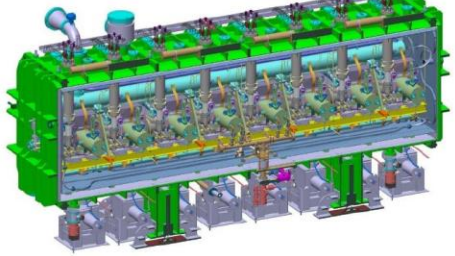
SC cavities and high power proton linacs : History of the Projects @ Irfu

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



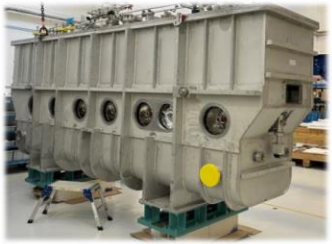
SPIRAL2: design and assembly of 12 cryomodules

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

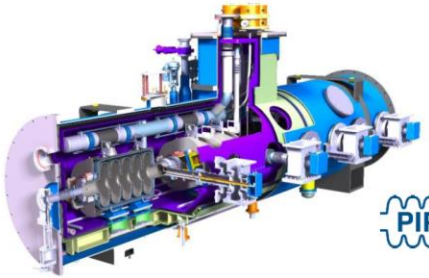


IFMIF/EVEDA: 1 cryomodule

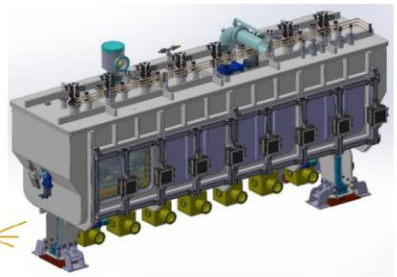
ESS: cavity and coupler design, integration of 30 cryomodules



SARAF Phase 2: 4 cryomodules



PIP-II: 9+1 cryomodules



IFMIF-DONES: 5 cryomodules

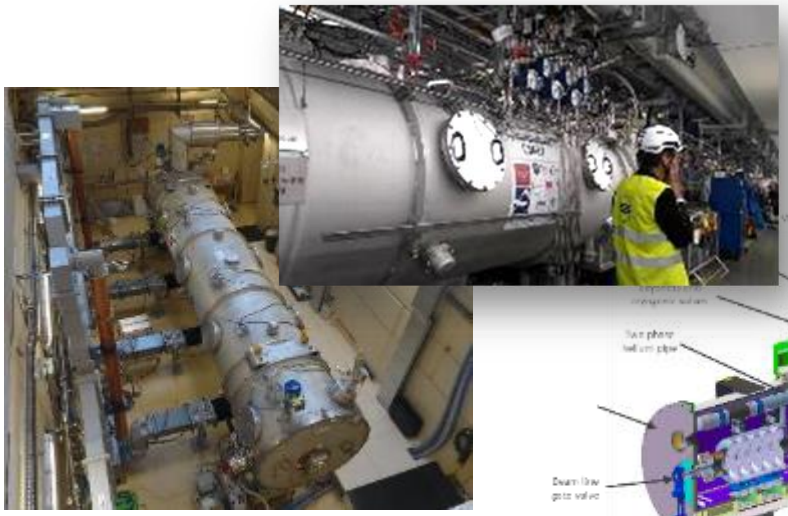
Competences and infrastructures for the design, procurement, assembly, test of SC cavities, ancillary equipments (power couplers, tuners, cryogenics…) and cryomodules assembly

SC cavities and high power proton linacs : Contributions

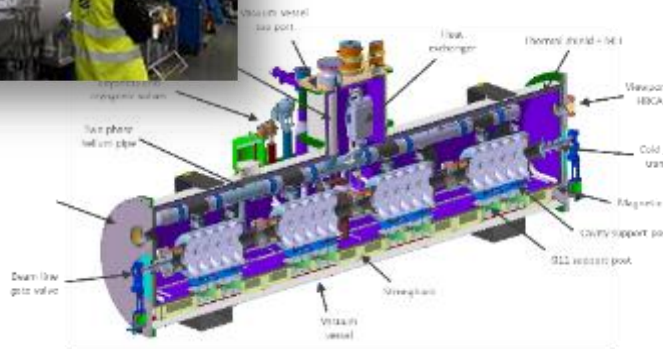
Major contributions to several projects:

- ESS : 30 medium / high beta CM (IRFU) ; 5 cryomodules already installed in the tunnel
- SARAF2: delivery of 4 cryomodules (2 already tested)
- MYRRHA: Prototype CM + involvement in the series (under discussion)
- PIP 2 Linac: 9 « LB650 » (IRFU) cryomodules

Assembly of SARAF CM @ IRFU



Power test of ESS CM @ IRFU and ESS

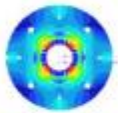


PIP II LB650 CM

Superconducting Magnets

NbTi

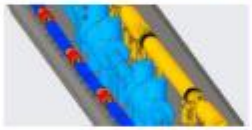
Accelerator magnets for CERN
MQ spares MQYY/MQYYM (Hilumi)


Other accelerator magnets
SARAF Super FRS LEB

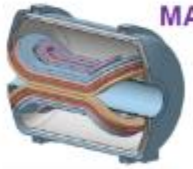


EIC Spin rotators



Detector:
Asterics

MADMAX

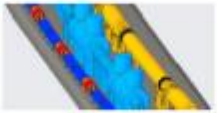


EIC Solenoid

Hybrid solenoid
43T magnet
LNCMI

ISEULT 11.7T
MRI
Neurospin

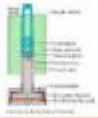
EIC Spin rotators



Nb_3Sn

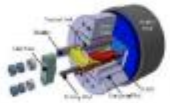
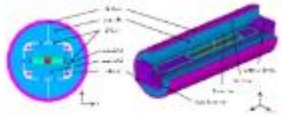
R&D on Nb3Sn coil training and on thermomechanical behavior during Nb3Sn heat treatment






HFM CERN/CEA Collaboration



Suprafusion

Detector and accelerator magnets

HTS HFM
CERN/CEA
Collaboration

GLEAD

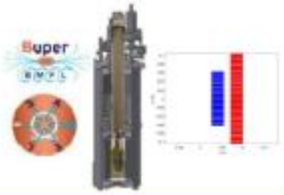
HTS (ReBCO)

R&D on HTS magnet cooling and magnet protection



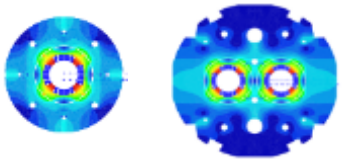

Ultra-high field solenoids

SUPER EMFL /
FASUM

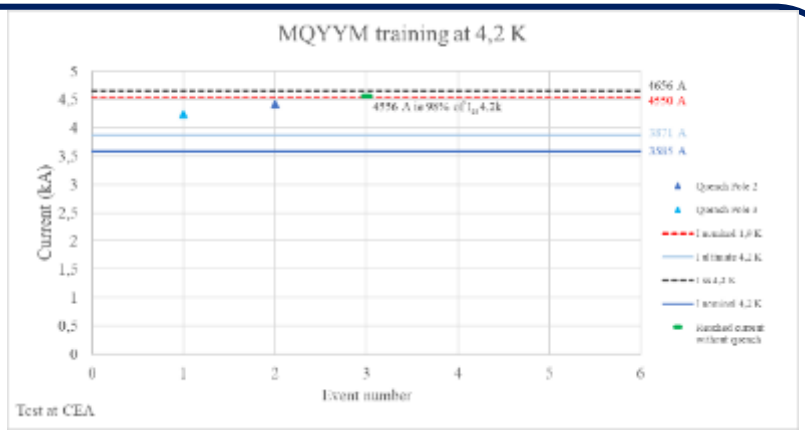


NbTi Magnets

MQYY (Hilumi)

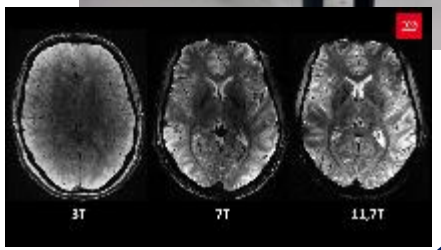


Operating Gradient	120 T/m
Operating current	4550 A
Bpeak at operation	6.42 T



Nominal field reached in April 2021

MRI magnet: ISEULT 11.7 T



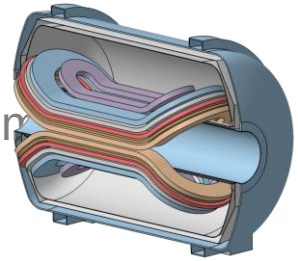
Nominal field reached in 2019

First images in April 2024

Detector magnet

MADMAX (9 T in 1.35 m

Max Planck Institute



High field hybrid magnet: 43 T

LNCMI Grenoble

Signing of CEA - CERN agreements on HFM

March 23, 2023

Collaboration agreement signature between CEA-IRFU and CERN for the High Field Magnets project by CERN Director General Fabiolo Gianotti and CEA Administrator General François Jacq.

The recent update of the European strategy for particle physics recommended a feasibility study for the next generation collider.

One of our objectives is to develop the technologies needed to manufacture the high-field superconducting magnets that will be essential for the future collider: this is the HFM (High Field Magnets) project.

In this context, Irfu has proposed to develop high magnetic field magnets using Nb3Sn and HTS superconductors, with a target of 16 T - 20 T.

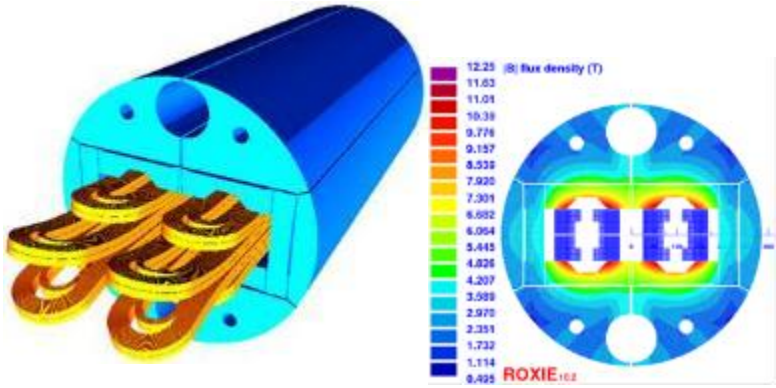
This collaborative project with Cern will last at least 5 years.

Nb_3Sn Magnets

CERN/CEA COLLABORATION AGREEMENT

R&D activities:

- **Thermomechanical behaviour of Nb_3Sn conductors during heat treatment**
- **Mechanical tests of Nb_3Sn cables**



FCC quadrupole

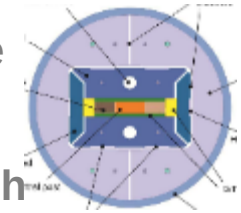
FCC dipole demonstrator

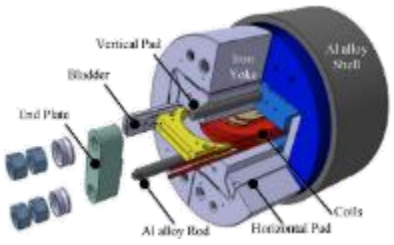
1. SMC 11T (=**S**hort **M**odel **C**oil)

Racetrack coils, 11T-dipole cable

13 T, 15 kA, no aperture

→ **Demonstrate fabrication tech**



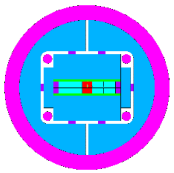


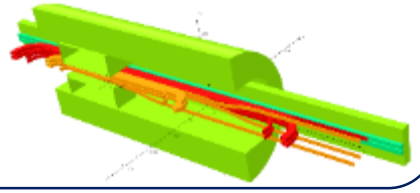
2. R2D2 (=**R**esearch **R**acetrack **D**ipole **D**emonstrator)

Racetrack + 2 Graded cables

11 T, 15 kA, no aperture

→ **Demonstrate grading**





High Temperature Superconductor Magnets

CERN/CEA COLLABORATION AGREEMENT – French ANR and EU FUNDINGS

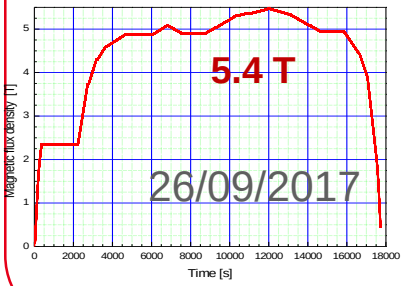
R&D activities:

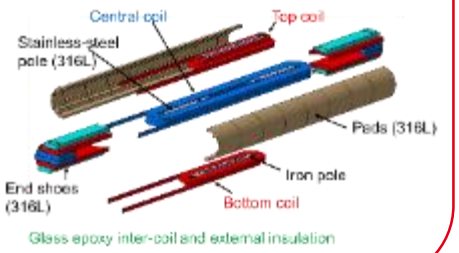
- mechanical study of REBCO metal-as-insulation coils (PhD student)
- understand the redistribution of radial and azimuthal currents during transient operation in non-insulated hts coils
- study of cryogenic fluid cooling disturbances due to magneto- gravitational volume forces in superconducting magnets

NOUGAT

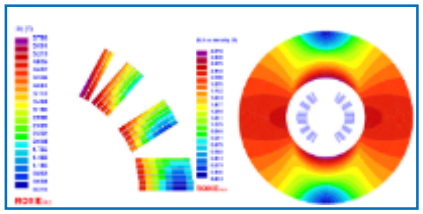
- Insert made of 9 double pancake (ReBCO) (inner diameter of 50 mm) using an innovative MI insulation (Metal-as-Insulation)
- 32.5 T obtained (14,5 T created by the HTS insert with a background field of 18T @ LCNMI Grenoble)

EuCARD: HTS racetrack block design without aperture

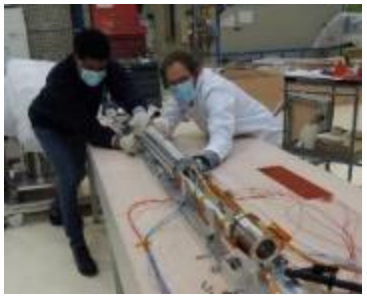




EUCARD 2 – Cos theta HTS dipole



HTS Roebel cable



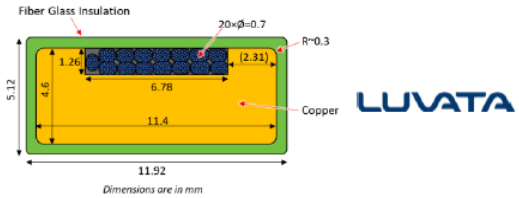
MARCO Solenoid

Solenoid for the EIC ePIC detector @ BNL

Collaboration contract CEA/JLab:

- Conceptual design of a 2T magnet
- Conductor design, support for the procurement

Copper stabilized RIC NbTi conductor
(Iseult inspiration)

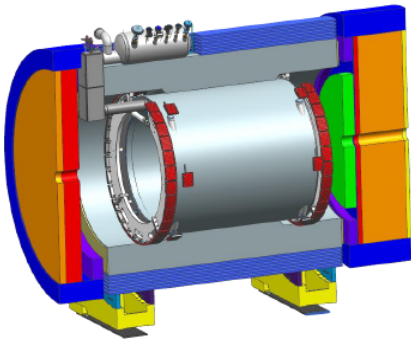


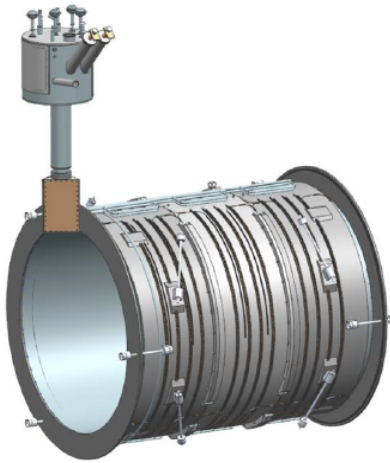
LUVATA

STATUS

- Conceptual design finalized in October 2023
- Ongoing conductor sample development & tests
- Call for tender foreseen in 2024 (build to spec)

Parameter	Parameter Value	Units
Bore diameter	**2.84**	**m**
Coil Rin	1.501	m
Coil thickness	32.7	mm
Coil Length	3492	m
Nominal Current	**3924**	**A**
Turns	1668	
Layers	6	
Modules	3	
B_0	**2.00**	**T**
Bpeak+self field	2.67	T
Stored Energy	**45.3**	**MJ**





MARCO Solenoid

Accelerators Magnets : SPIN ROTATORS

2024

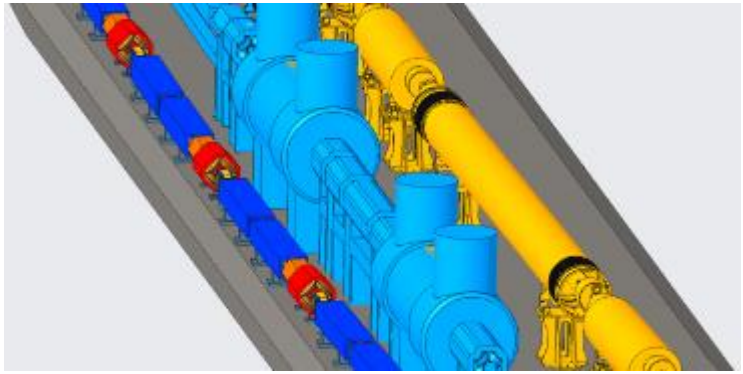
Collaboration CEA, BNL

- Preliminary Design

Activities forecast:

Preliminary design for

- 4 short solenoids (1.5 m – 8.5 T, Ø = 84 mm)
- 4 long solenoids (5.5 m – 8.5 T, Ø = 84 mm)



Difficult magnets due to:

- Limited space in the existing RHIC tunnel
- Synchrotron radiation
- Fringe field requirements

The choice of the conductor (NbTi / Nb_3Sn) will be addressed within this study

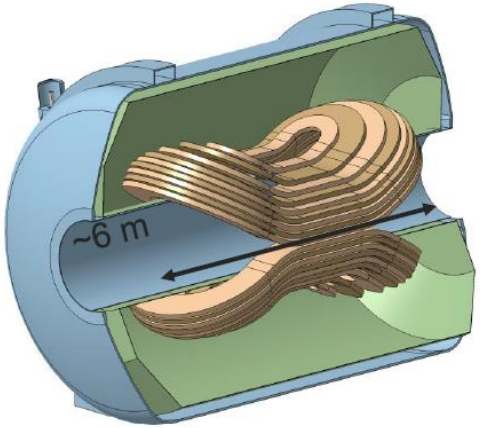
MADMAX: MAgnetized Disk and Mirror Axion eXperiment

Phase 1 : magnet design, cond. R&D, quench mock-up demonstrator (MACQU)

Date

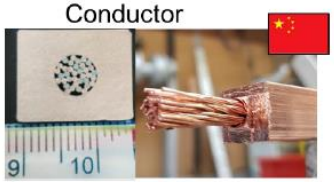
9T dipole magnet

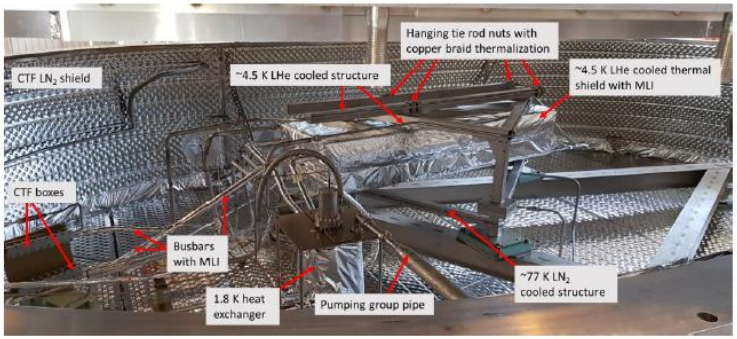
Nb-Ti CICC @ 1.8 K



Φ = 1.35 m

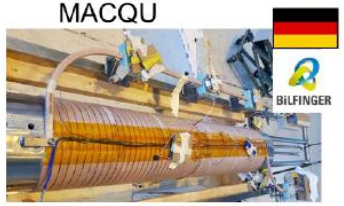
Conductor

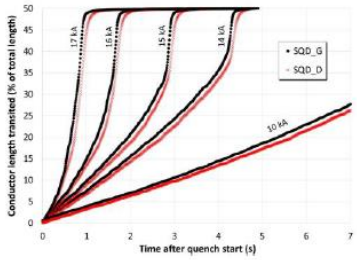




Cryogenic test (JT60 test facility)

MACQU

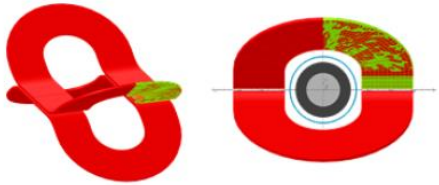




Detection: OK

THQB 1.8 K: revealed

Phase 2 : funding obtained by MPI for a new demonstrator to validate the thermal stability model (dec. 2023)



4. Perspectives

New accelerators

FCC e-e

- Participation in the new FCC - IS design study
- Booster design

Soleil light source

- Participation in the detailed design studies for the upgrade

Compact neutron sources

- feasibility of a compact neutron source at 3 MeV with the option of a solid beryllium target
- In the longer term, consideration of a facility for academic needs at 20-40 MeV **ICONE**

Prospective Laser Plasma

- Member of the Eupraxia collaboration: beam dynamics studies
- Participation in Cilex Appolon; transport line study
- Awake: participation in studies of a laser-plasma injector

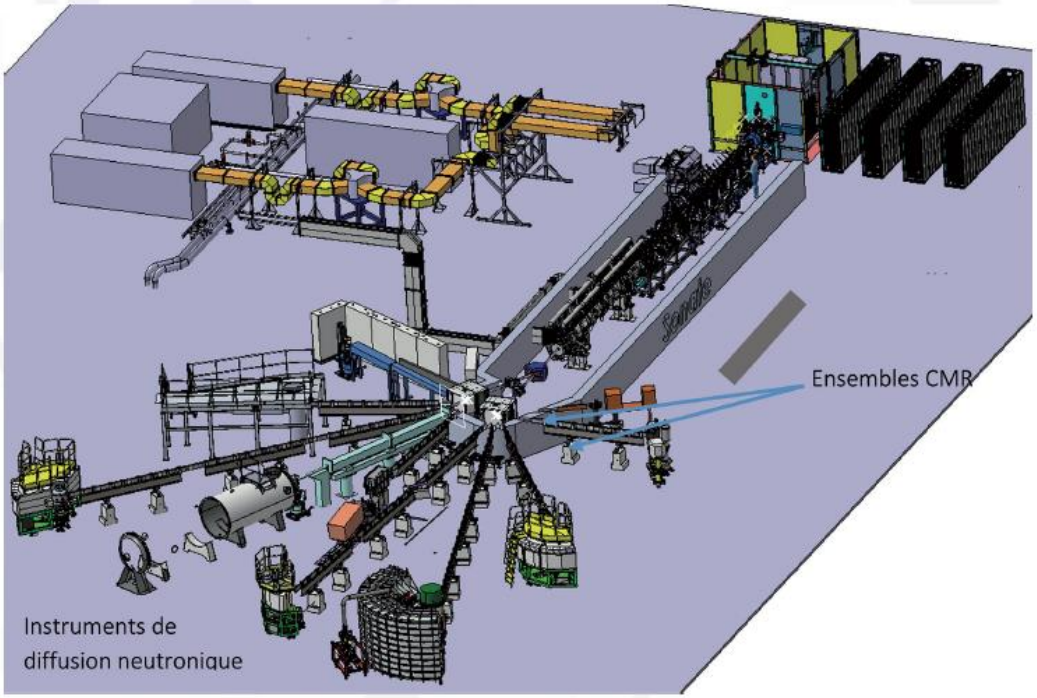
Muon Collider: MuCol collaboration

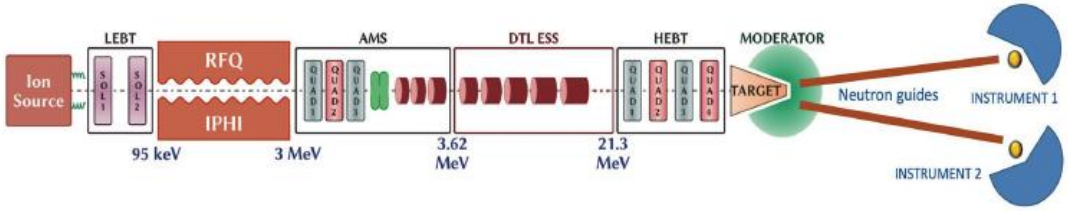
ICONE

ICONE
Neutrons for Materials Sciences

UNE NOUVELLE SOURCE DE DIFFUSION NEUTRONIQUE FRANÇAISE

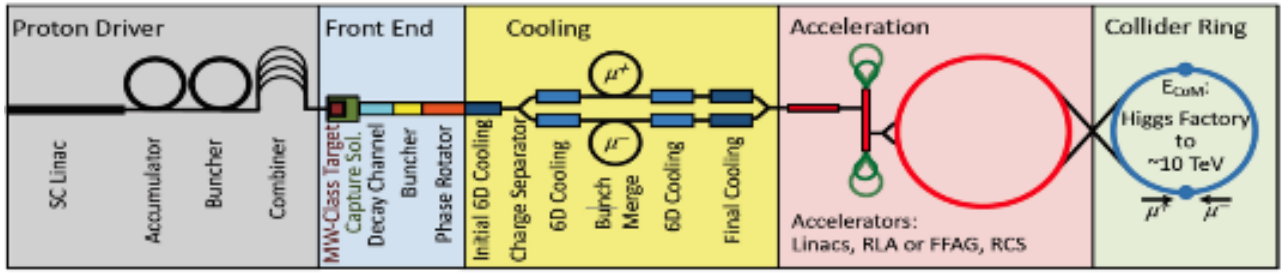
APS/APD to be launched in 2024





Particules accélérées	Protons
Énergie des protons	25 MeV
Courant crête	100 mA
Cycle utile	6 % (4 % + 2 %)
Accélérateur	Source d'ions Section RFQ 4 vanes (3,6 MeV) Section DTL chaud (25 MeV)
Structure temporelle	2ms – 20 Hz 200 µs – 100 Hz
Cibles	Béryllium
Modérateurs	Thermique (H2O) Froid (Méthane) Froid (para-hydrogène)
Instrumentation	5 + 5

R&D: Muon collider



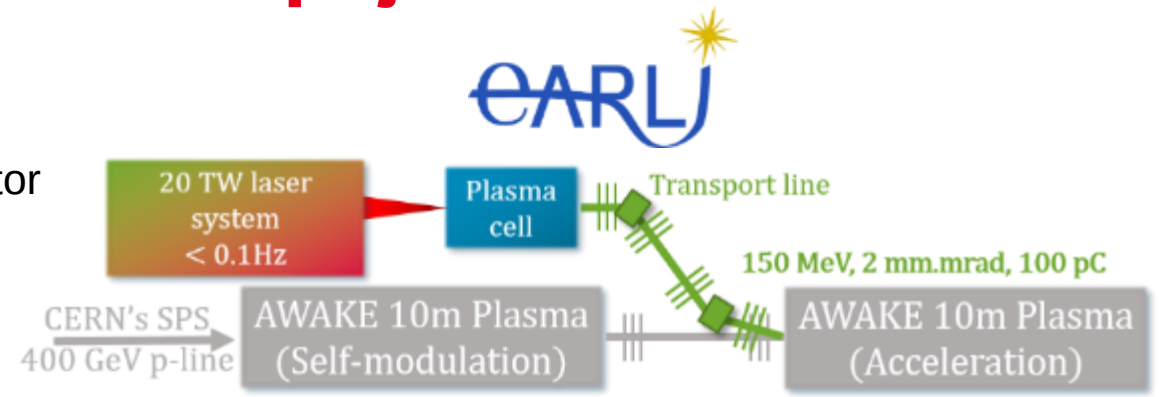
International MUON Collider Collaboration

- **Participation in the MuCol conceptual study proposal (approved summer 2022)**
- **WP5: High Energy Complex**
  - Coordination and design of RCS solution
- **WP6: Radiofrequency Systems**
  - Coordination, study of accelerator cavities, study of cavity behavior under magnetic field for cooling
- **WP7: Magnet systems**
  - Study of very high field magnets (40+ T solenoids, 20 T - 1m magnet), cooling study

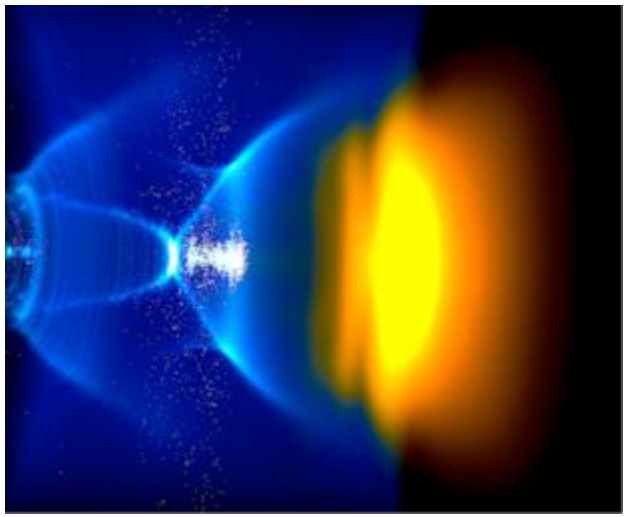
	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8	Total Person-Months per Participant
CERN	x	x	x	x	x	x	x	x	0
DESY	x	12							12
TUDa	x						15		15
UROS	x					12			12
CEA	x	12			24	22	18		76
INFN	x	12		x	12	36	32	18	110
UMIL	x			x			8	38	46
UNIPD	x	24							24
UT-WENTE	x						14		14
LIP	x	12							12
ESS	x		33						33
UU	x		2						2
Imperial	x			22.5				12	34.5
UKRI	x			28.6				x	28.6
UWAR	x			21					21
ULA	x					36			36
SOTON	x						42		42
UOS	x	12							12
PSI	x						x		
UNIGE	x						x		
SYSU	x	x							
KIT	x						x		

R&D: LASER-PLASMA: EARLI project

- EARLI a LWFA-based electron injector
-
  - For AWAKE Run2c (2028)
    - Alternative solution to an RF injector
    - Smaller footprint?
  - Adaptable to other plasma accelerator (EuPRAXIA, etc.)
  - Reproducible, high-quality beams
  - Proposal submitted by CEA-IRFU, LPGP-CNRS-UPS, THALES LAS
- Currently in the design phase



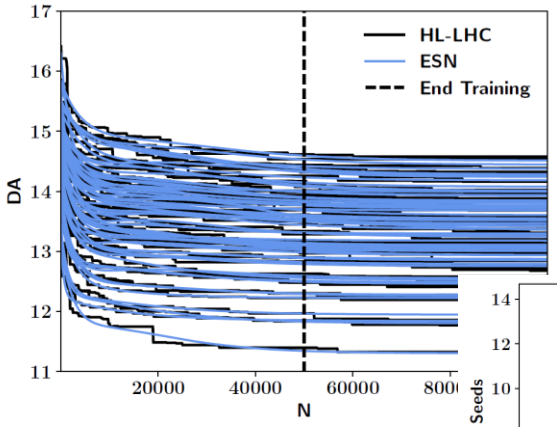
cnrs université PARIS-SACLAY THALES



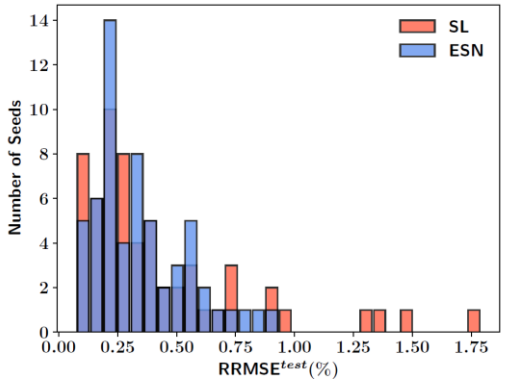
AWAKE targeted beam parameters
100-250 MeV
< 2%
< 2 mm.mrad
a=0
5.75 µm
60 µm
100 pC
0.01-0.1 Hz

R&D: Artificial intelligence techniques for accelerator

- **Using Echo State Networks to predict dynamic opening**
  - Internship in collaboration with Politecnico Milano and CERN



Evolution of dynamic aperture for 60 HL-LHC configurations

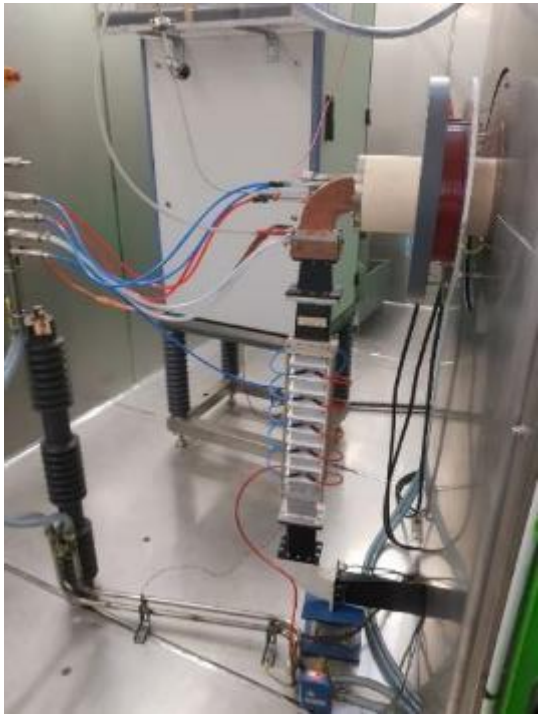


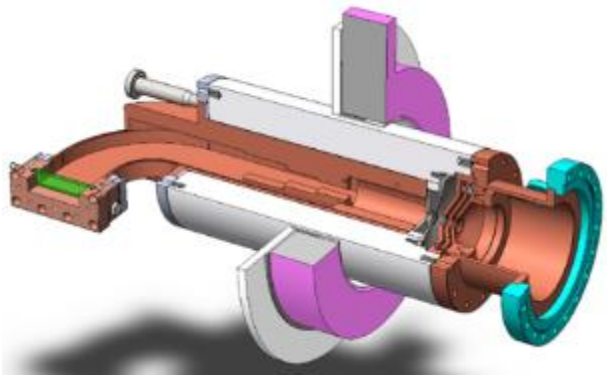
Relative square error

- **Other applications under consideration:**
  - optimizing the design of FCC-ee's high-energy booster
  - BPM noise reduction
  - identification of particle types in emittance measurements
  - improved SARAF linac simulations
  - optimization of LWFA parameters

- **Participation in the French M4CAST network (Multiphysics Modelling, Machine learning and Model-based Control in Accelerator Sciences and Technologies)**
  - exchange of data and methods
  - search for financing
  - in partnership with foreign laboratories (Eurolabs, CERN, MYRRHA, CLARA, ESS, XFEL, SLAC)

R&D: Sources - ALISES on BETSI





ECR Source high intensity :

- A plasma-chamber-cooled copper brazed assembly/ribbed guide/rf elbow
- An insulating ceramic chamber
- 1 extraction system with 5 electrodes
- 1 adjustable coil 0-150A
- 1 extraction chamber

INNOVATIVE ASPECT:

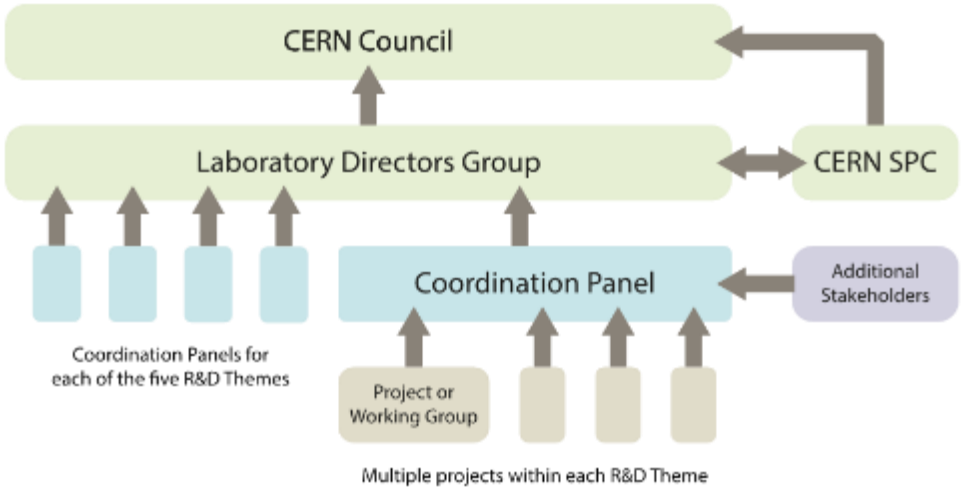
- **Compact**
- **One-piece ceramics**
- **1 adjustable ground coil**
- **Electrode concentricity**
- **Low weight**
- **Easy maintenance**
- **No HT platform**
- **Direct connection to LBE**
- **Φ6μμ plasma electrode for V extraction$_{max}$ 50 kV**

Prospects for superconducting magnets

- **R&D on Nb3Sn accelerator magnets for FCC** - CERN collaboration, European programs
- **HTS 20 T accelerator magnet development** - CERN collaboration
- **High-field magnets** (full superconducting) > 30-40+ T (HTS program) - European programs ,SuperEMFL, Isabel, French Program PIA3 FASUM.
- **MADMAX** (MPI, Germany) - 10 T dipole in a one-metre bore – **Prototype**
- **Glead -** HTS detector for axions
- **R&D in magnet cooling techniques** - European programs and collaborations
- **Gantry magnets** HITRIplus, Ifast

Active participation in the roadmap for the accelerator of the future

High-field magnets 16 T - 20 T
RF Supra
Muon collider
Laser plasma acceleration
ERL



Report published in January 2022

Ongoing projects: Block-Coil 16-T Roadmap

F2D2 Short model → **Planned**

Grading + Flared-ends + Aperture, 16 T

1.5 m, 50 mm bore **with aperture**

FD Demonstrator → **Planned**

Grading + flared-ends, 14 T

1.5 m, No bore **with flared ends**

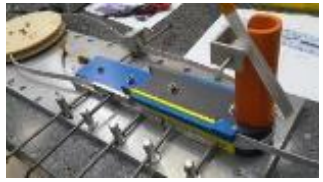
CEA-CERN R2D2 → **Ongoing**

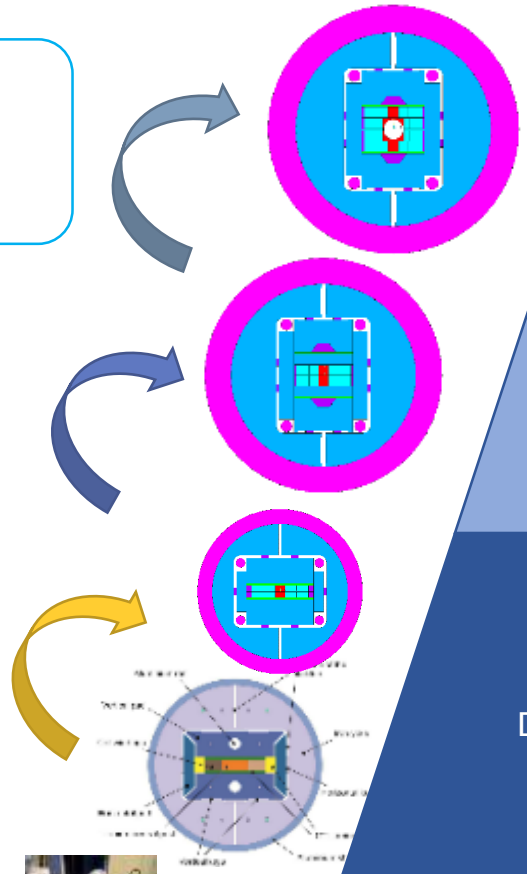
Demonstrate grading ≥ 12 T

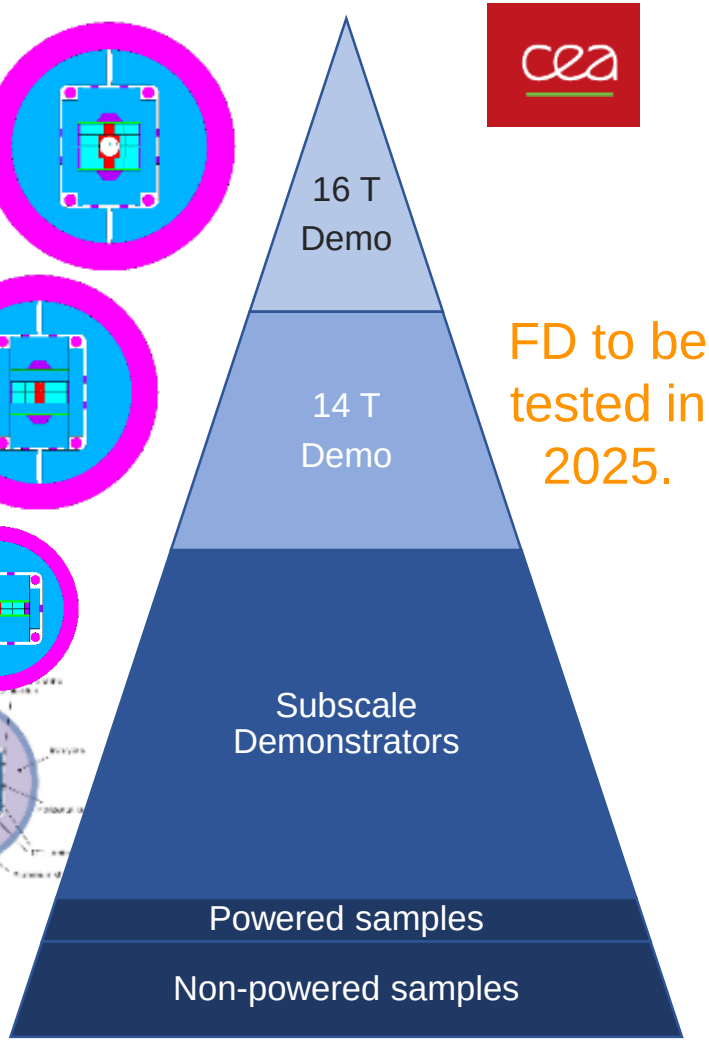
1.5 m, No bore **with grading**

CEA-CERN SMC-13T coil ✓**Done**

Demonstrate Nb_3Sn tech. ≥ 12 T







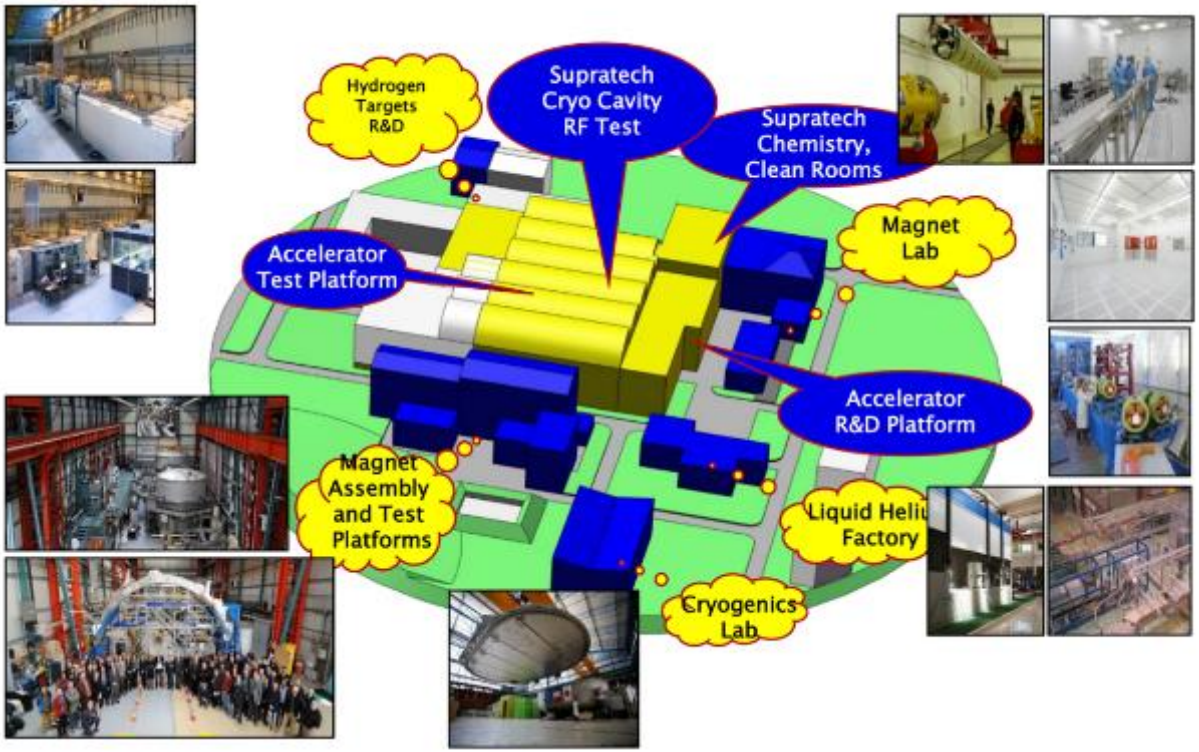
FD to be tested in 2025.

Courtesy of E. Rochepault

5. Infrastructures

SYNERGIUM :EXAMPLE OF CEA TECHNOLOGICAL INFRASTRUCTURE

Equipment for development, integration and testing: manufacturing and assembly platforms, clean rooms, small-scale test stations for materials characterisation and large-scale test stations (coils, superconducting cavities and injectors)



Synergium complex

- ✓ 25 000 m2
- ✓ 100 M€ technical platform
- ✓ 200 FTE
- ✓ 40 M€ / year turnover

Member of the

European project

ACCELERATOR AND MAGNET INFRASTRUCTURE FOR COOPERATION AND INNOVATION EUROPEAN TECHNOLOGY INFRASTRUCTURE

Synergium Technology Infrastructure

The **Synergium Technology Infrastructure** is the **basement** of future large-scale accelerator and SC magnet projects, also covering activities for societal applications.

from *Design* to *Construction* and *Operation*

R&D → *Prototyping* → *Assembly* → *Verification* → *Installation* → *Support*

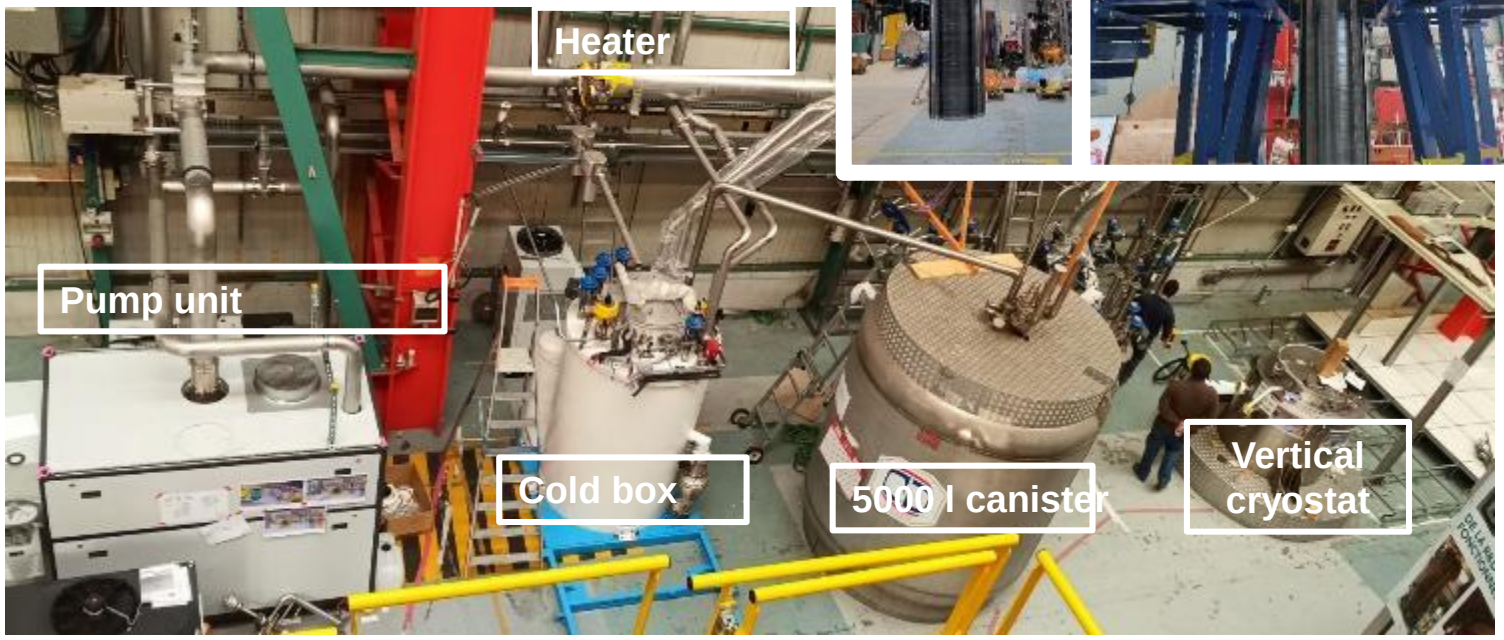
It spans the whole **TRL spectrum**, from R&D to fabrication, with an emphasis on the **Preparation** and **Construction** phases, corresponding to **Prototyping (3-5)** and **Industrial Production (>5)** of components.

STAARQ Station
Quadrupole Magnet Accelerator Test Station

STAARQ status:

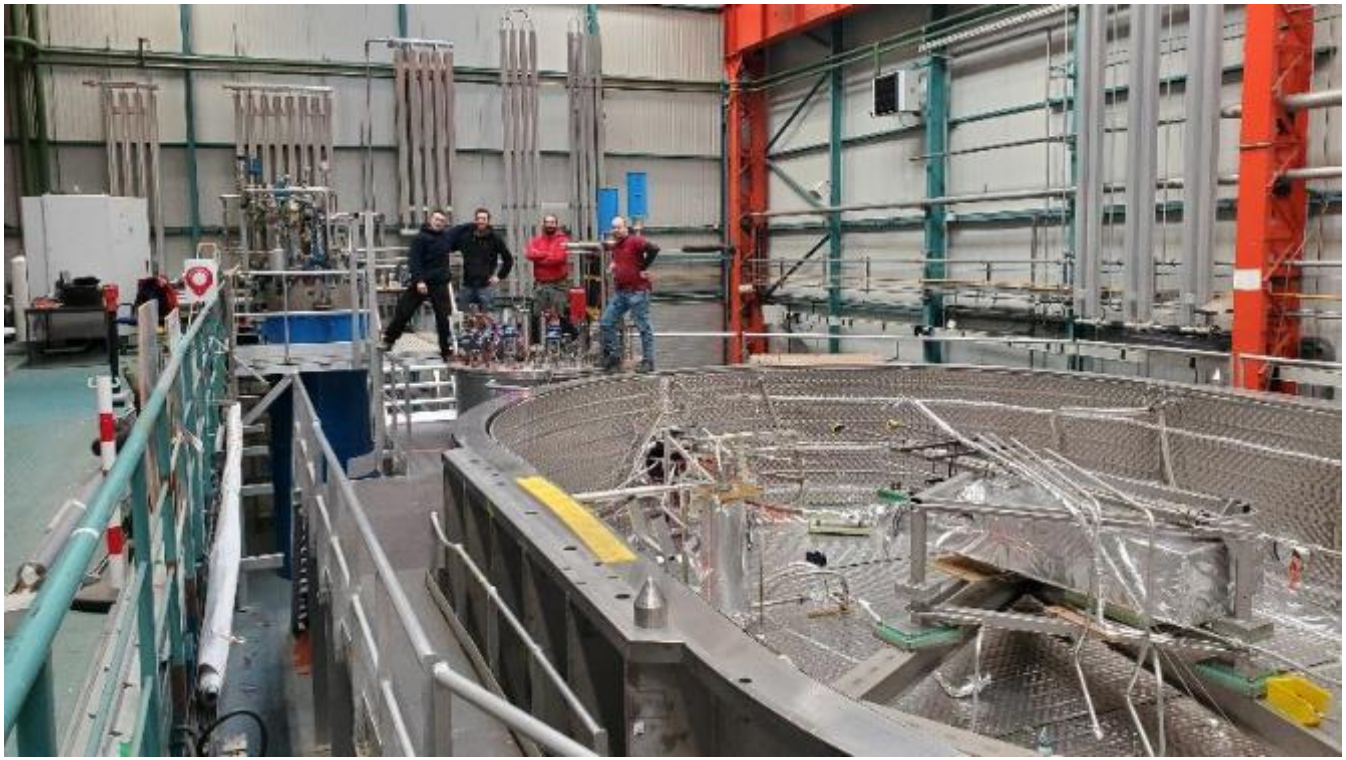
- Cryostat with current leads completed at T°LHe. (1.9 K adjustment required)
- LHe production in progress (80%)
- Power supply and MSS are operational.
- Commissioning (12 months) from September 22 to November 2023 (90% complete)
- MQQYM test estimated in Q2 24
- Scheduled tests: April 2024 to June 2026

Magnet integration platform
Load testing with MOYY



MATTRICS Test Station

Objective: test and qualify future superconducting magnets for detectors (MadMax) and magnetic fusion. R&D for the next generation of superconducting magnets at temperatures of the order of 20 K and under intense working conditions (~40 kA).



6. Conclusions

Conclusions

A wide range of competencies in the field of accelerators and superconducting magnets

Lots of great results on current projects and R&D.

A growing workload with new projects and R&D over the next 10 years.

New prototyping and testing facilities to complement the existing ones will be operational very soon.

A determination to be at the service of major accelerator projects for science around the world.