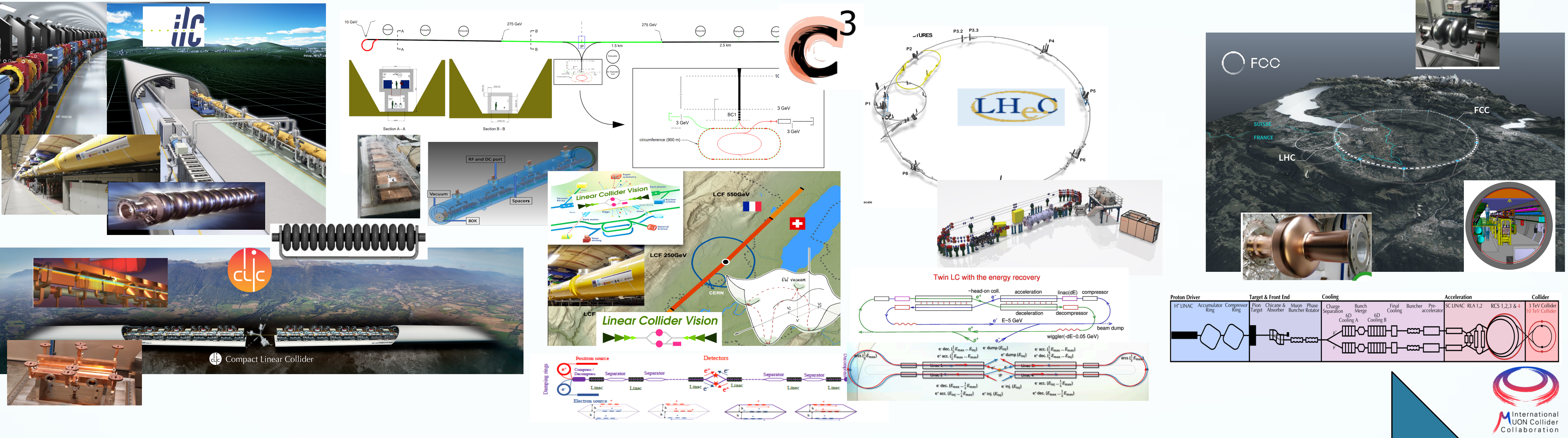


Accelerator R&D French activities for Future Colliders

A. Faus-Golfe & C. Madec

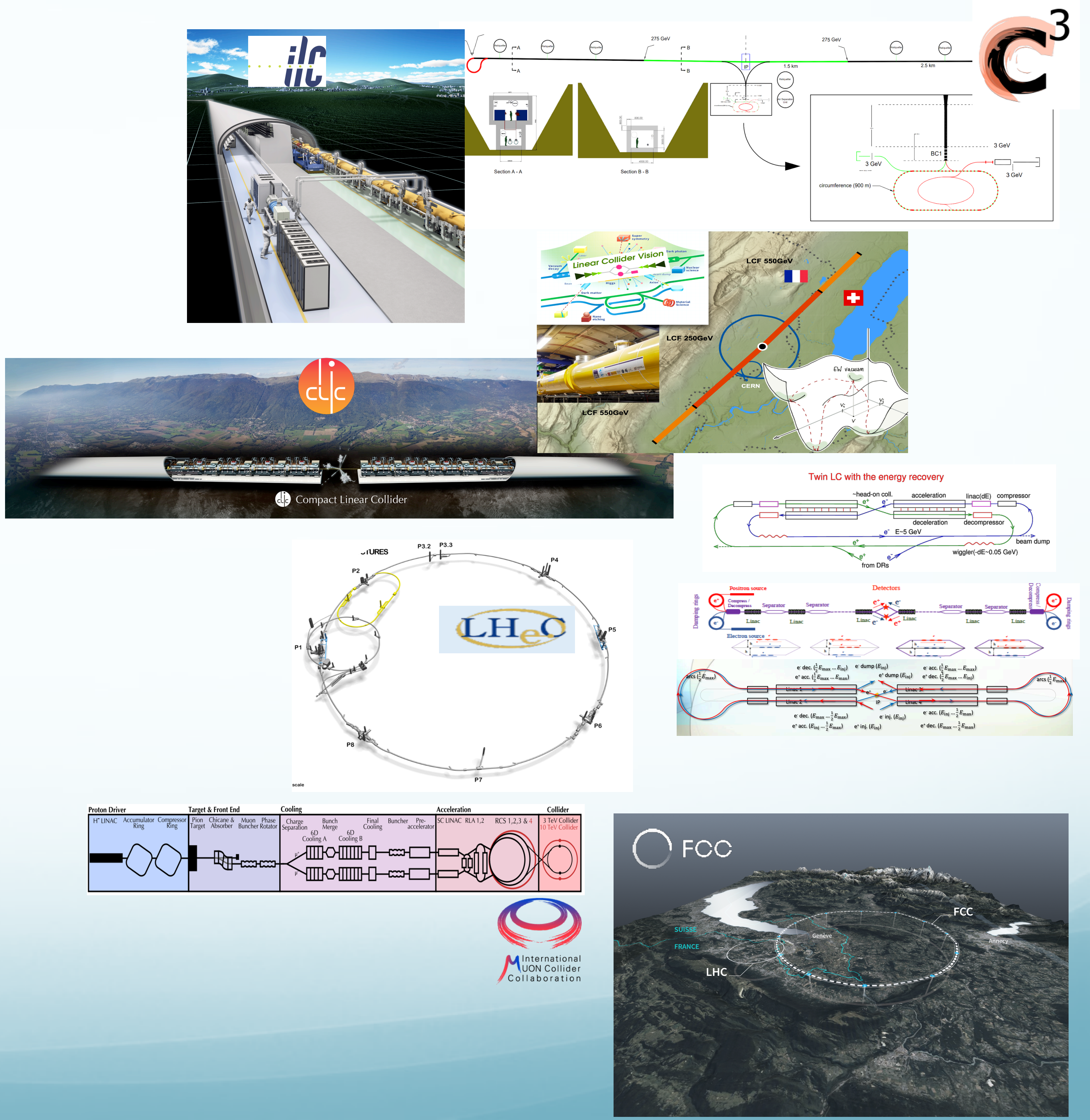
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

cnrs NUCLÉAIRE & PARTICULES

cea

Outline

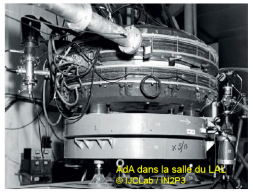
- ❑ **Introduction and Context**
- ❑ **IN2P3 R&D Activities**
  - Interaction Region Design: nanobeams
  - High-intensity e+ sources
  - Luminosity and Backgrounds
  - Stabilization and positioning
  - e+e- polarimetry
  - SRF multipacting and materials
  - IR HTS quads
  - ERLs
- ❑ **CEA R&D Activities**
  - SRF material and industrialization
  - HFM magnets (LTS-HTS)
  - Booster Design
  - AI applications
  - μ colliders: RF and collider design
- ❑ **Outlook and Perspectives:** CERNTECH



French labs has a long tradition in colliders ....

1963:Premier collisionneur du monde à Orsay

AdA: Anello di Accumulazione



Construit en 1961 par une collaboration franco-italienne, à Frascati, puis transporté à Orsay, en 1962

Anneau de 1,60 m
de diamètre
Aimant de 8,5 tonnes
Vide de ~ 10^{-7} Torr

10^7 particules accumulées par faisceau
Collisions e^-e^+ à 500 MeV, au centre de masse => découverte effet Touschek

1965: ACO: Anneau de Collisions d'Orsay

1965 – 1975: Collisionneur électrons-positons
Premières collisions e^-e^+ en 1967: 550 MeV / faisceau

1975 – 1988: Source de lumière synchrotronique

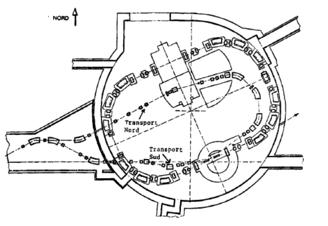
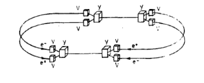
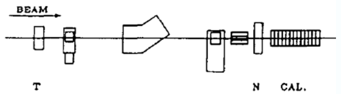
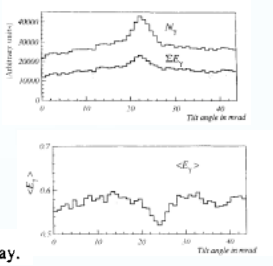


Schéma général du D.C.I.





T: induction monitor
G: goniometer+crystal
A: bending magnet
P: profile monitor (SEM grid)
C: collimator
N: scintillator



Lay-out of the channeling experiment at Orsay.

A new idea: channelling radiation in crystals -> high photon yield (experiments at Orsay, CERN and KEK)

Tube de Crookes | Wideroe (RF) | Cockroft Walton | Cyclotron Joliot Curie | Collège de France | Orsay | AdA Anello di Accumulazione | Frascati | Orsay

Laboratoire de l'Accélérateur Linéaire
Linac 2,3 GeV e-
ACO : e- e+
Anneau de collision d'Orsay
DCI
Dispositif de Collision dans l'igloo

1895 | 1928 | 1932 | 1939 | 1957 | 1958 | 1959 | 1961 | 1962 | 1968 | 1971 | 1976

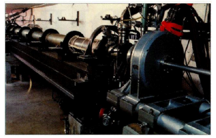
Synchro cyclotron
PS Proton Synchrotron
ISR (Intersecting Storage Rings) p-p p-p̄ Quarks - gluons
SPS Super Proton Synchrotron
CERN

SATURNE 1958 - 1997
CEA – Synchrotron p+ 3 GeV

Cyclotron de Grenoble 1968 - 1993

ALS Saclay 1969 - 1990

LAL: Laboratoire de l'Accélérateur Linéaire d'Orsay



1958: Premier faisceau d'électrons de 3 MeV
1964: Faisceau à 1.3 GeV
1968: Faisceau à 2.3 GeV
Faisceau de positons à 1 GeV
2003: Arrêt définitif du linac.

LAL | Super ACO | **SOLEIL** Source Optimisée de Lumière d'Énergie Intermédiaire du LURE | ...... vers SOLEIL2

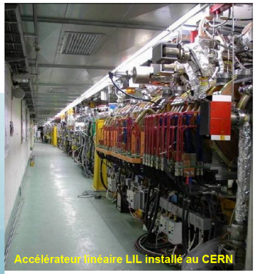
ESRF | EBS Extremely Brilliant source

GANIL | SPIRAL 2

1983 | 1984 | 1987 | 1989 | 1994 | 1995 | 2003 | 2006 | 2008 | 2012 | 2013 | 2019 | 2023 | 20XX

Production $W^\pm$ Z^0
Rubbia Van der Meer (1984)
LIL LEP Injector Linac
LEP Large e^-e^+ collider (1989 – 2000)
Charpak (1992)
LHC Large Hadron Collider
ATLAS-CMS BEH Bosons de Higgs Englert- Higgs (2013)
......vers FCC
CLIC ?
Muons collider ??
CERN

1987: LIL : LEP Injector Linac



Réalisé par le LAL / Orsay

Ce linac produisait et accélérait des électrons et des positons à 500 MeV

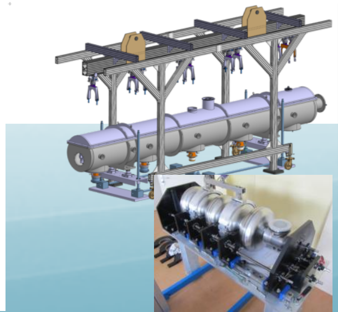
100 m long

f = 2.99855 GHz

LEP operation: 1989- 2000

LEP = Large Electron Positron collider

SMA18 – Stand de cryostating Fermeture de l'enceinte à vide

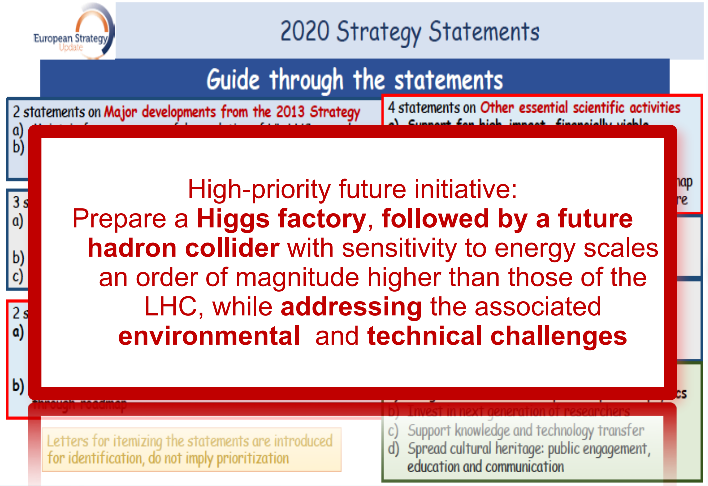


ILC ?
Accélérateurs Laser Plasma ?
.....
.....
A nous d'écrire l'histoire !

SPL - Design et fabrication d'une cavité 5 cellules beta 0.65 et le design et fabrication de l'enceinte à vide du cryomodule et des outillages de montage associés

Courtesy of L. Rinolfi and R. Chehab

French Accelerator contributions to FC



2020 Strategy Statements

Guide through the statements

2 statements on Major developments from the 2013 Strategy

a)

b)

4 statements on Other essential scientific activities

b) Invest in next generation of researchers

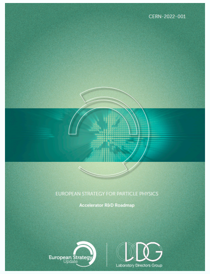
c) Support knowledge and technology transfer

d) Spread cultural heritage: public engagement, education and communication

Letters for itemizing the statements are introduced for identification, do not imply prioritization

High-priority future initiative:
Prepare a **Higgs factory**, **followed by a future hadron collider** with sensitivity to energy scales an order of magnitude higher than those of the LHC, while **addressing** the associated **environmental** and **technical challenges**

+



HFM High Field Magnets

- High-field magnets
- High-gradient accelerations (plasma, SCRF)
- Muon beams
- Energy recovery linacs
- Education and training

\+
Sustainability

A rich R&D program is driving the developing and building of the next colliders projects. A strong cooperation between national institutes, CERN and others global laboratories or collaborations is vital for the progress of the field and also for preserving the expertise.
In this context the main goal of the activities have been to ensure an appropriate contribution to this vibrant and diverse R&D program focusing in areas where we have already demonstrated our know-how and expertise or we are trying to acquire expertise :

IN2P3

- ❑ **Interaction Region**
- ❑ **Luminosity and backgrounds**
- ❑ **High-intensity e+ sources**
- ❑ **e+e- polarimetry**
- ❑ **SRF multipacting / materials**
- ❑ **ERLs**
- ❑ **IR HTS magnets**

CEA

- ❑ **SRF materials/ industry**
- ❑ **HFM magnets**
- ❑ **Booster Design**
- ❑ **AI applications**
- ❑ **μ colliders ; collider / RF**

Currently we are in the process of converging around the 1st next flagship project at CERN (FCCee) and the choice of a 2nd option in case option 1st is not viable…Dec 2025

Update of ESPPU on May2026

After the choice of the options, an R&D phase 2026-2028 will start (pre-TDR for 1st option FCCee, R&D feasibility phase for the 2nd option)

IJCLab 2.5 FTEs

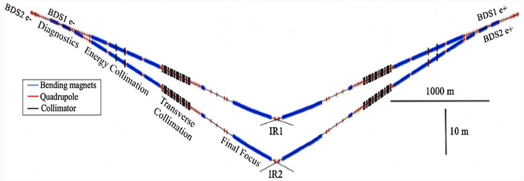
Very **high peak luminosity** needs **nanometre transverse IP beam sizes**
(FCC-ee 30-70 nm, ILC 3-8 nm, CLIC 1-3 nm).
To **demagnify** the beams, complex **IRs** and **FFS** are designed.

$$L = f_{coll}\frac{N_b^2}{4\pi\sqrt{\boxed{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}}$$

Design:

➢ **IRs studies:**

Layout of the two IRs at 380 GeV with 16.5 and 20 mrad crossing angle



➢ CLIC/ILC

Alternatives IR configurations are able to **boost the performances**: Further studies on:

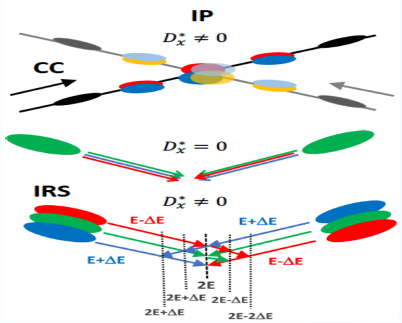
- **Long L*** with **shorter Final Doublet** (FD) outside the detector
- Dual BDS with **two detectors** simultaneously

are being realized to probe the feasibility of this kind of IR schemes.

➢ **FCCee**

Monochromatization scheme

Crossing angle monochromatization scheme featuring IP dispersion of opposite signs.



FCC MoU

In some “special” IR configurations as **monochomatization** the **energy spread** could be **reduced** to **maximize** the **sensitivity** of certain **physics channels**. Further studies on:

- Parameters including Beamsstrahlung (BS) (increased $\varepsilon_x\,\sigma_b$) and crossing angle with ML assistance
- Optics design to generate antisymmetric $D_{x,y}^*$ are needed to probe the feasibility of this kind of IR schemes
- Experimental implementation studies (SuperKEKB, BEPC/BEPCII)

Realistic IR simulations:

- **Beam-Beam instabilities** studies, including more precise wakefield model and possible experimental studies.

IJCLab 2.5 FTEs

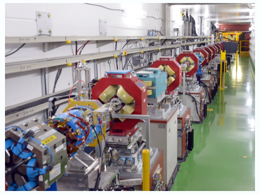
$$L = f_{coll}\frac{N_b^2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

Very **high peak luminosity** needs **nanometre transverse IP beam sizes** (FCC-ee 30-70 nm, ILC 3-8 nm, CLIC 1-3 nm).
To **demagnify** the beams, complex **IRs** and **FFS** are designed.

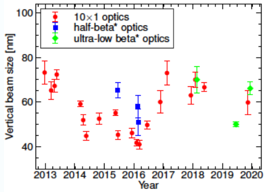
Experimental PoC:

ITN framework

- ➢ **LCs FFS experiments at ATF2-3**



ATF2 @ KEK

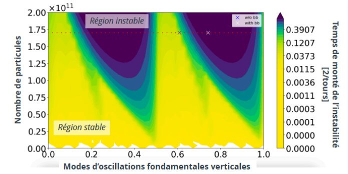


ATF2 beam size story

ATF-ATF2 KEK FFS has verified **experimentally** the **minimal technical feasibility** of **LCs FFS**, to **maximize** the **luminosity potential of LCs.** Further investigation on:

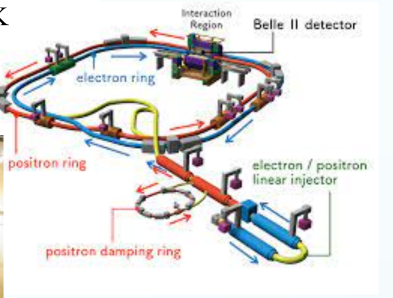
- **Intensity dependence** effects on the IP size
- **High-order optical aberrations** with low and ultra-low β*
- **Long-term stability**

Is being pursued in a follow-on upgraded facility **“ATF3”** (ILC-IDT framed).



Resonances causing horizontal instabilities after beam-beam interactions with Circulant Matrix Model (CMM) semi-analytical model.

SuperKEKB @ KEK



➢ FCCee experiments at SuperKEKB

SuperKEKB is a state-of-the-art facility operated at KEK which is particularly well suited to study some of the main issues and challenges for **future circular colliders**, especially the FCC-ee. The main topics to be addressed are:

- **Beam-beam instability** in strong-strong regime including impedance model and code benchmarking with dedicated experiments with a **reduced number of bunches** varying the **collimator** settings.

High-Intensity e⁺ sources

IJCLab 1.6 FTEs

$$L = f_{coll} \frac{\boxed{N_b^2}}{4\pi\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

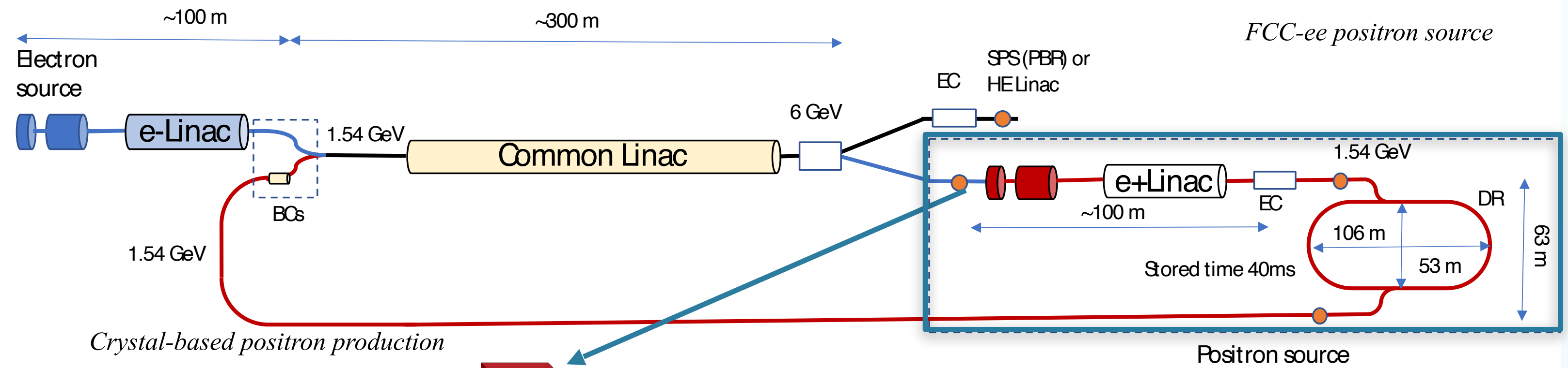
High-beam intensity and **low emittance e⁺** are necessary to achieve high-luminosity (ILC/CLIC 10^{14} -10^{15} e+/s, FCC-ee ~10^{13}e+/s while demonstrated @SLC ~6×10^{12}e+/s)

Design:

➢ LCs - FCCee

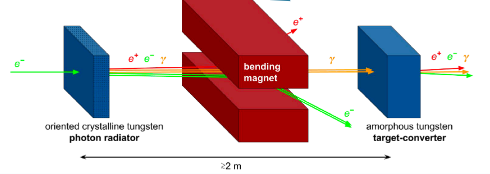
Simulation and **design** studies on :

- **Novel types of e⁺ source** based on the hybrid scheme (channeling in crystals) with new granular targets.
- **Feasibility and R&D studies** of using the **innovative** capture systems (superconducting solenoids)
- Use of the **Artificial Intelligence** (AI) for global **optimisation** of the e⁺ injector parameters

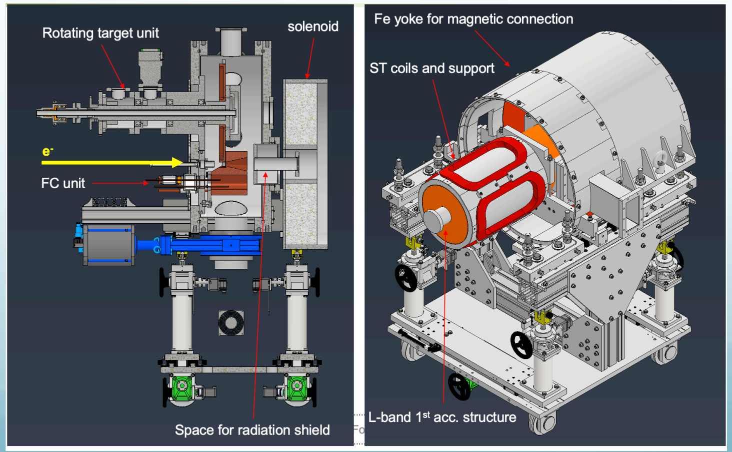


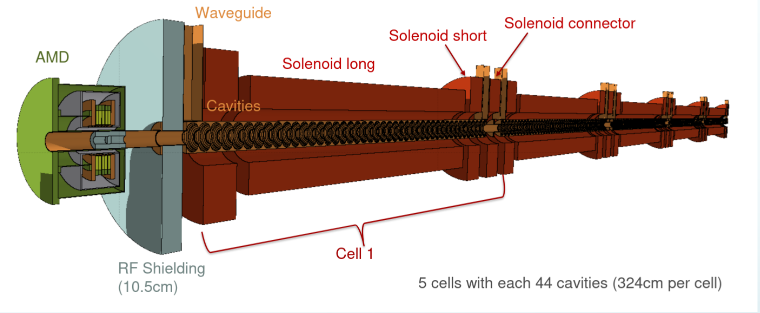
FCC-ee positron source

Crystal-based positron production



ILC e- driven positron source





Positron capture system R&D

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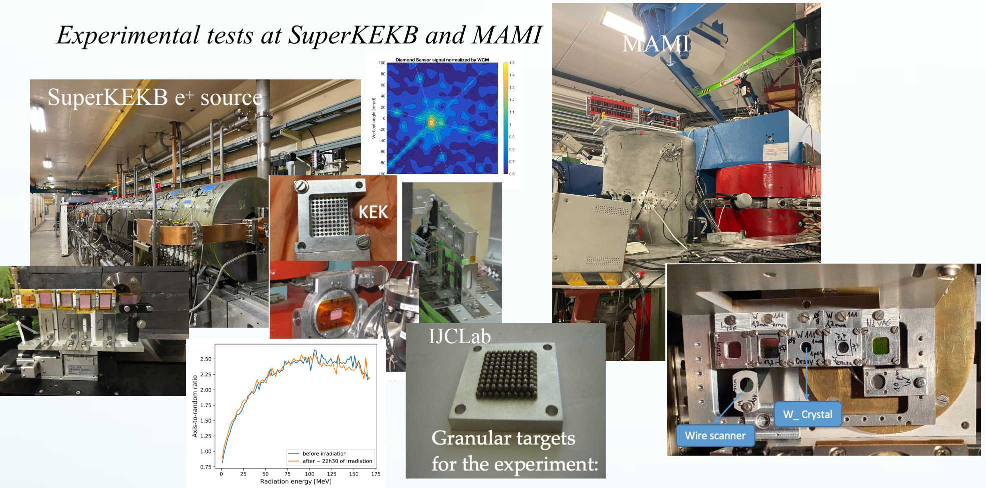
High-Intensity e⁺ sources

IJCLab 1.6 FTEs

High-beam intensity and **low emittance e⁺** are necessary to achieve high-luminosity (ILC/CLIC 10^{14} -10^{15} e+/s, FCC-ee ~10^{13}e+/s while demonstrated @SLC ~6×10^{12}e+/s)

$$L = f_{coll}\frac{\boxed{N_b^2}}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

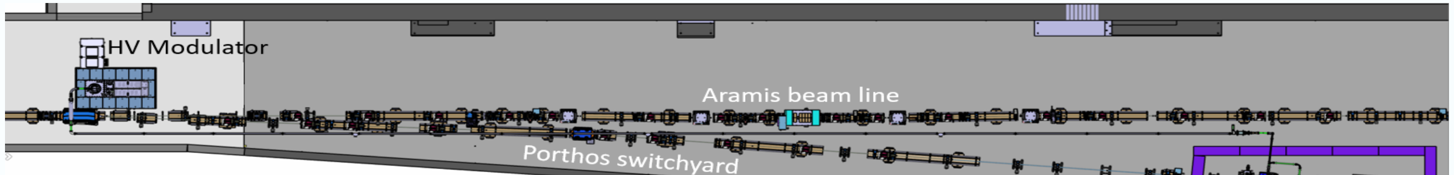
Experimental PoC:

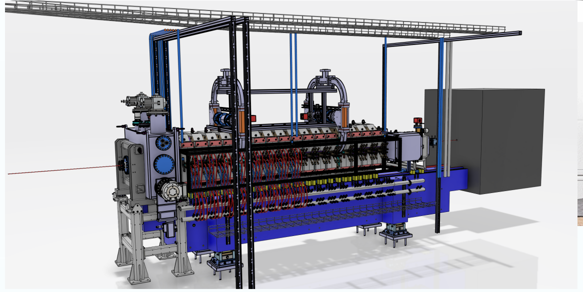

Experimental tests at SuperKEKB and MAMI

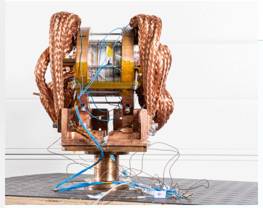
➢ **Characterization e⁺ production and capture systems at SuperKEKB and MAMI**

ITN framework

- **e⁺ production** and **capture**
- **e⁺ injector** beam studies and optimization
- **Target reliability** studies






High-Temperature Superconducting (HTS) solenoid (12.7 T)

P³ PSI e⁺ PRODUCTION

FCC MoU

➢ **Demonstration of an innovative e⁺ production using HTS at SwissFEL**

The **SwissFEL** facility will host the P³ experiment. First beam expected in **2026**. Beam studies up to **2030.**

- **e⁺ source demonstrator** with potential to improve the present state-of-the-art **e⁺ yield** by an **order** of **magnitude.**
- **HTS solenoid** to deliver a peak 12.7 T on-axis field near the target exit

Luminosity and Backgrounds

IJCLab 1.5 FTEs

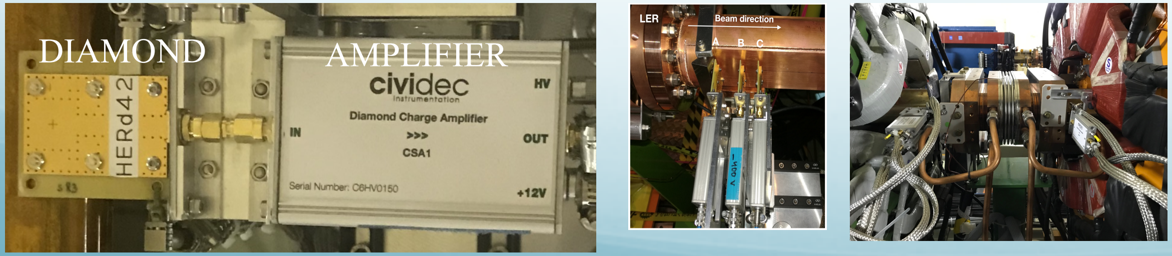
High luminosity implies **continuous correction** of **residual beam offsets and aberrations; fast luminosity measurement** are an essential tool
Background mitigation is increasingly difficult with **ultra-low β*** and very **high currents**.

Experimental PoC:

➢ SuperKEKB

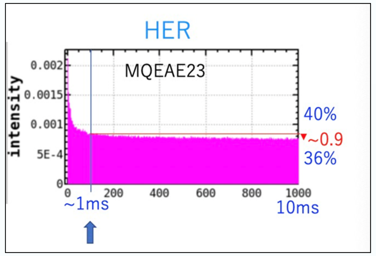
Fast luminometers (1% precision at 1 kHz) designed by IJCLab are deployed at SuperKEKB with large dynamic range, bunch-by-bunch and serve also as beam loss monitors. The measurements are inputs for:

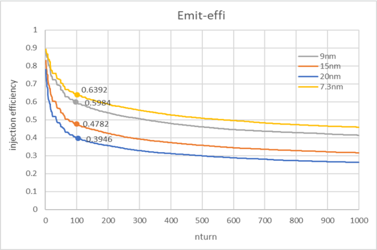
- **Feedback systems**
- **Aberration correction**
- **Luminosity optimization studies**

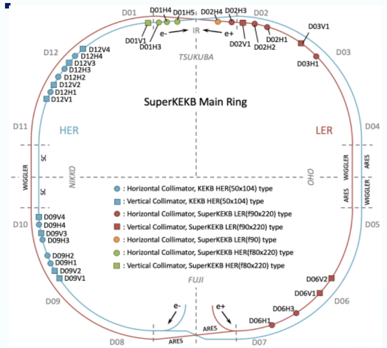


LumiBelle2 fast luminosity monitor at SuperKEKB

Effect of increased input emittance

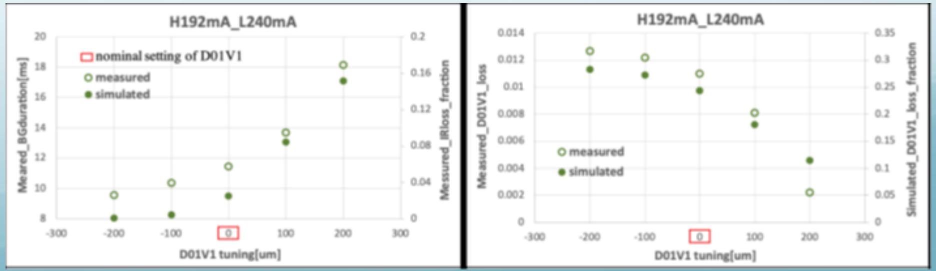






Simulation and **experimental** studies on beam loss backgrounds from continuous top-up injection system:

- **Beam dynamics studies** including: collimators and septum aperture, optics mismatches, injection angle and offset, coupling… of the HER injection efficiency has been carried out
- **Experiments** were conducted and good qualitative agreement with the simulation founded



Nanobeam stabilization and Positioning

LAPP 2.5 FTEs

Vibration mitigation and **misalignments control** are crucial to obtain **high luminosity** (CLIC FFS magnet specification displacements 0.2 nm at 4Hz).

Design:

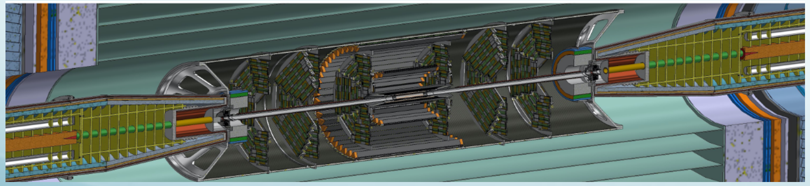
➢ FCCee

- **FCC-ee MDI** : study impact of mechanical behavior of the MDI by integrating the estimated motion of magnets excited by ground generator, including global uncorrelated optics simulation (analytic and XSuite) and the dynamic of the SuperKEKB MDI.
- **FCC-ee uniform waves:** global correlated simulation as function of frequency, phase and direction

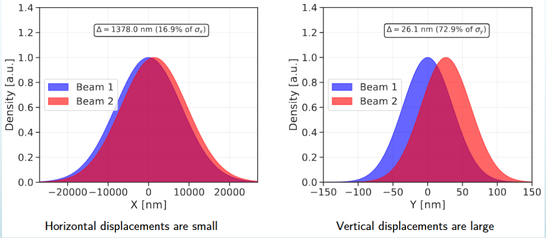
Experimental PoC:

➢ SuperKEKB

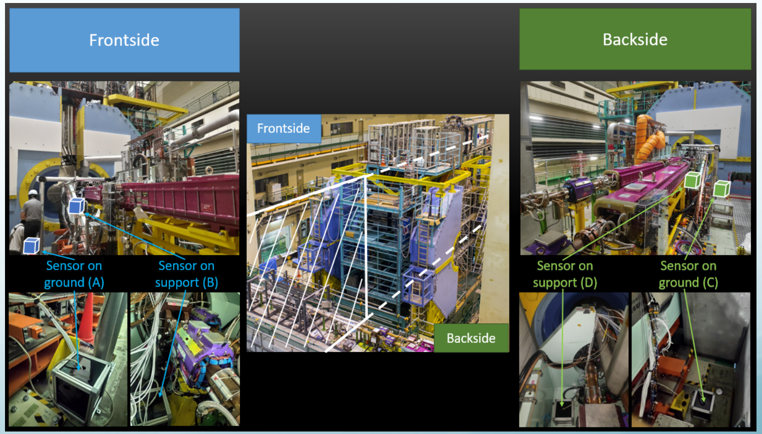
- Analysis of the **vibrations effects** on **beam parameters** on beam parameters (with IJClab) and relevance of the associated optics simulation.



Setup of the MDI



The two beam distributions at the maximum displacements (FCC-ee)



4 seismic sensors (2 each side) BELLE II

e^+e^- Polarimetry

IJCLab 1.35 FTEs

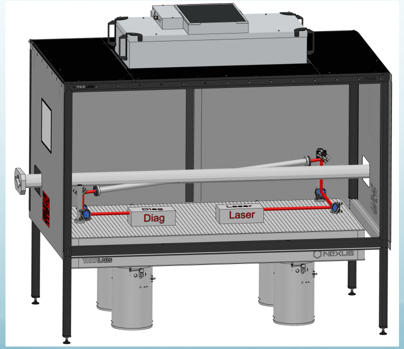
Accurate energy measurements thanks to resonant depolarization is **critical for physics at FCC-ee.**
To optimize collision of highly polarized beams, **rapid measurements of polarization** are a key ingredient.

Design:

FCC MoU

➢ SuperKEKB / FCCee / ILC:

- **Laser systems:**
  - real time monitoring of the laser-beam polarization; critical for ILC, FCC-ee; goal: per-mille accuracy.
  - Absolute measurement of laser polarization never done for modern colliders
- **Photon detectors for SuperKEKB:**
  - 4ns time spacing → dedicated R&D with BaF2
  - DAQ based on IDROGEN ADC board
  - Laser synchronization
- **Pixelized detectors for FCCee**
  - performance and conceptual design



Conceptual implementation for SuperKEKB

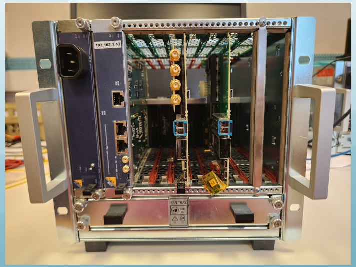
Experimental PoC:

➢ ATF2/3

The challenge is achieving precise synchronization between the laser and RF clocks without disrupting accelerator operations

- **PoC synchronization prototype,** including low-level RF on ATF to validate the system performance in a SuperKEKB-relevant environment.
- WhiteRabbit / IDROGEN card technologies, which enable long-distance, low-jitter clock distribution via fiber, offer a non-invasive solution.

IDROGEN carrier board installed in xTC crate



IDROGEN carrier board with FMC extension

SRF multipacting

LPSC 0.5 FTEs

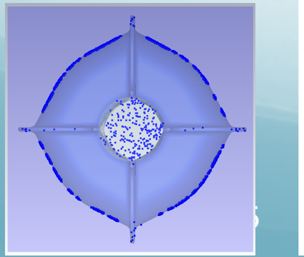
Multipactor phenomena triggered by RF fields present in RF devices under vacuum, such as is one of the potential limitation in in SRF structures for future e^+e^- colliders.

Design:

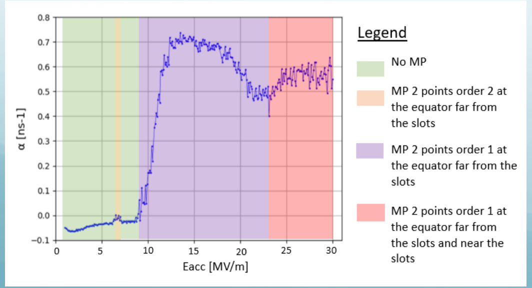
➢ FCCee

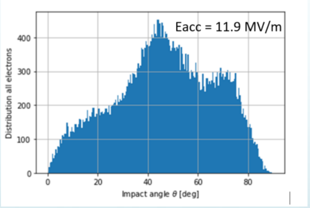
- Studies and test for the Slotted Waveguide Elliptical cavity (SWELL)
- Studies on **multipactor modelling** (locations, impact angle, power ranges, level, SEY impact..):
  - The modified SPL fundamental power coupler (800 MHz)
  - FCCee 800 MHz prototype fundamental power coupler

Multipactor locations

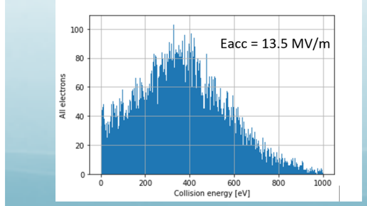


Multipactor energies

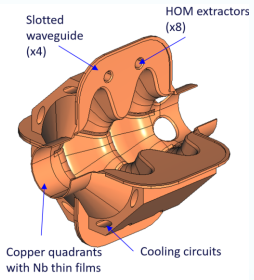




Impact angle



Collision energy

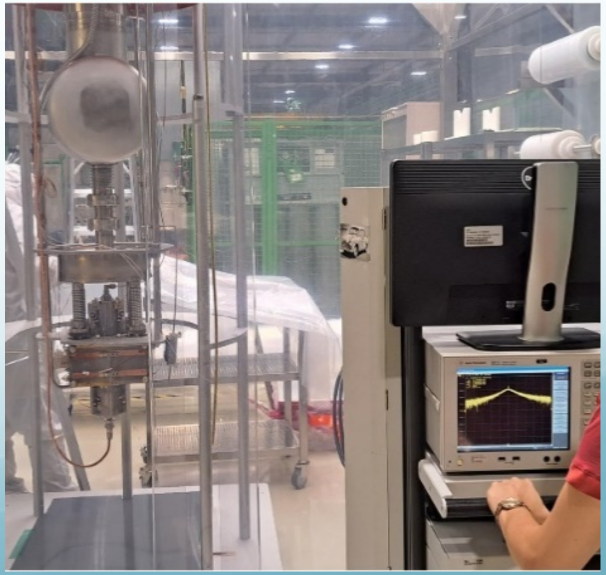


SWELL cavity

Experimental PoC:

- Participation into **cryogenic RF tests** of both RF powers

Tests participation (IJCLab and LPSC)



SRF materials

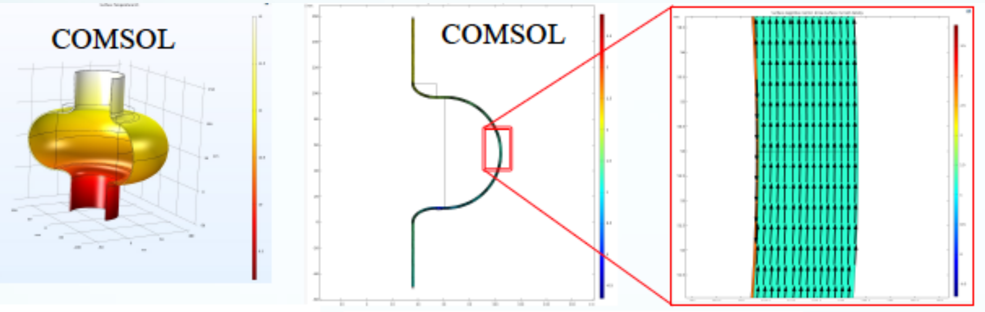
IJCLab 1.1 FTEs

R&D on **High-Q** in bulk niobium cavities and studies in **thermoelectrical material** properties of thin-film cavity performance as well as **higher order mode** handling via absorbers

Design:

➢ **FCCee**

- **High-Q 800 MHz cavity development**
- Study of **thermoelectric current** in bi-metal structure of SRF cavities

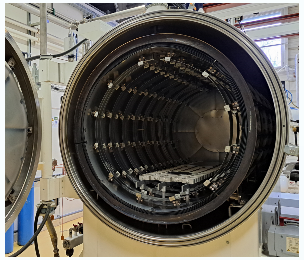


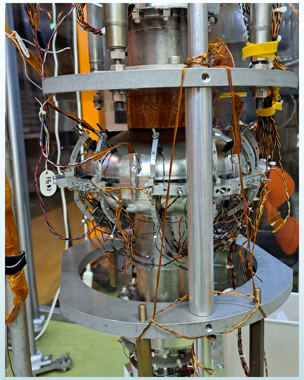
Experimental PoC:

- **Thermal treatments (mid-T baking)**
- **Cold tests**

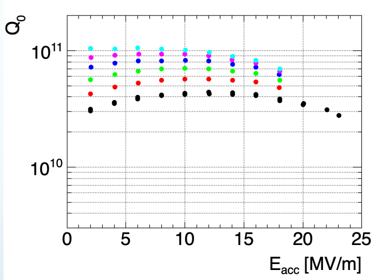
FCC-JLAB prototype 800 MHz @ IJCLab

Furnace @ IJCLab

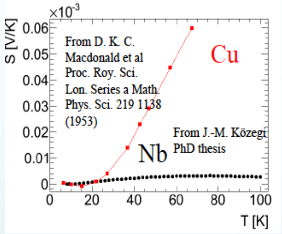




1.3 GHz test @ KEK

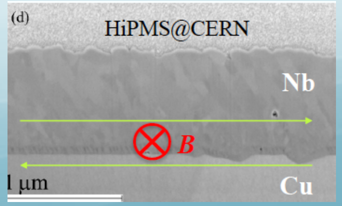


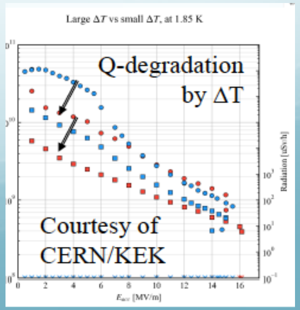
1st high-Q result!



From D. K. C. Macdonald et al Proc. Roy. Sci. Lon. Series a Math. Phys. Sci. 219 1138 (1953)

From J.-M. Közegi PhD thesis





Courtesy of CERN/KEK

Synergies with PERLE 800 MHz SRF

HTS magnet developments

LAPP 1.8 FTEs

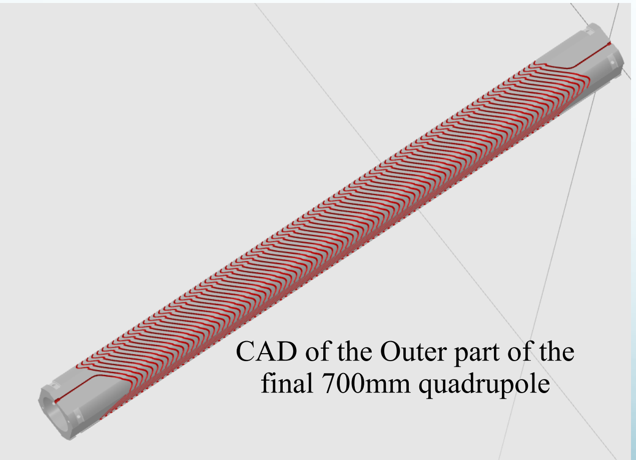
High Temperature Superconductor (HTS) coupled to **Canted Cosine Theta** (CCT) magnets, are a promising way to increase **sustainability, flexibility and compacity** of SC magnets

Design:

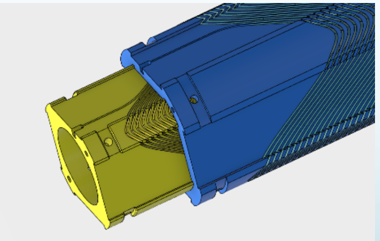
➢ **FCC-ee**

- **Final Focus HTS CCT Magnet QC1L1 :**

CAD design and numerical analysis to the manufacturing and assembling process of short prototype (80 mm) and full 700 mm functioning FF QC1L1 (alternative technology).



CAD of the Outer part of the final 700mm quadrupole

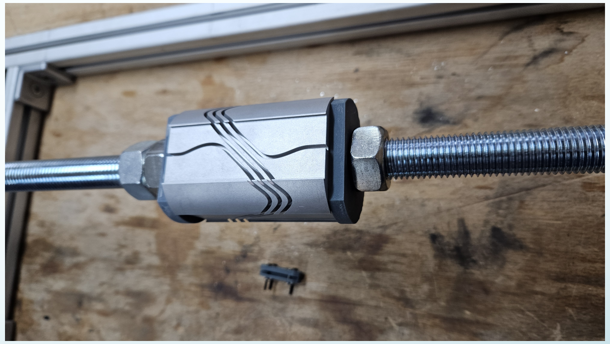


CAD of the inner and outer quadrupole

Experimental PoC:

- **Cryogenics test** at PSI
- **Winding** with the new LAPP winding bench

HTS ribbon in different configuration under resistivity test in Ni bath (77 K)



80 mm magnet prototype

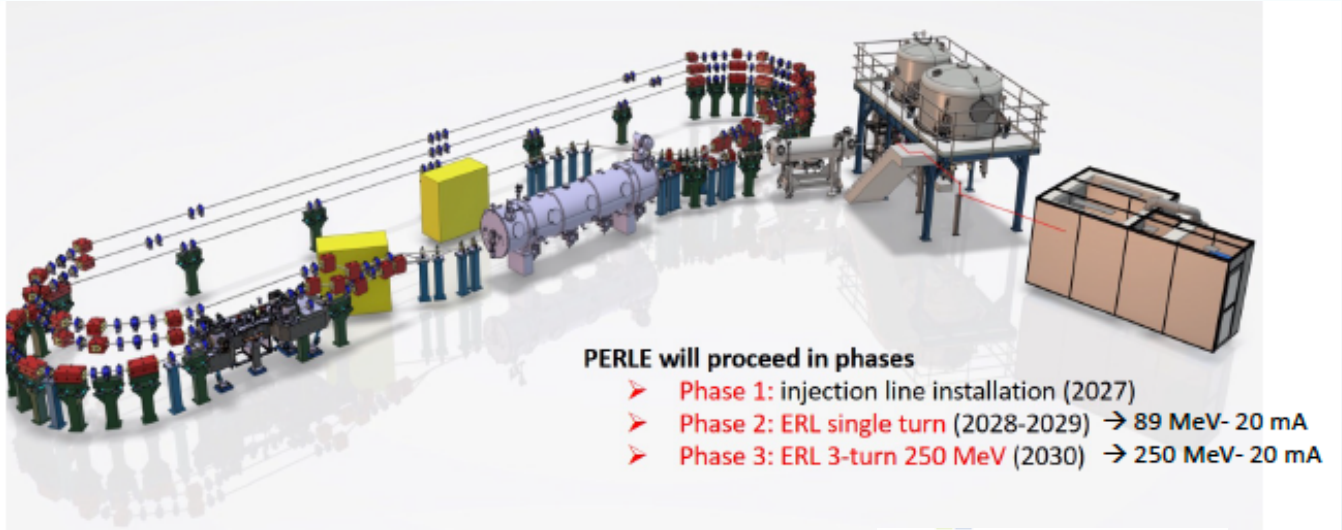
ERLs developments

IJCLab, LPSC 10 FTEs

ERLs linacs are a promising technology for collider applications, offering an important **reduction** of **RF power consumption**, dumping of beams at injection power, **fresh beam** at the IP, **linac-like** beam quality with extremely **flexible time structure** and high operating efficiency.
In **multi-pass configuration** they could achieve **high-current** (no RF power limit) and **high-power** in a **compact** machine

Design:

➢ PERLE

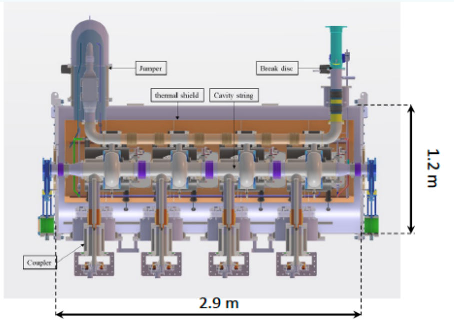


PERLE will proceed in phases

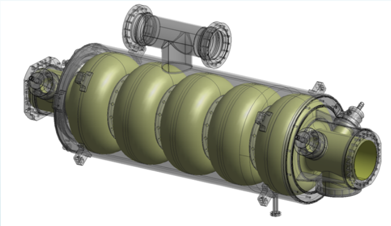
- Phase 1: injection line installation (2027)
- Phase 2: ERL single turn (2028-2029) → 89 MeV- 20 mA
- Phase 3: ERL 3-turn 250 MeV (2030) → 250 MeV- 20 mA

- **Optics** design and **beam dynamics** studies
- Design of the **buncher cavity**
- Design of the **booster cryomodule**
- **SRF cavity** design 800 MHz
- **HOM** studies
- **Power couplers**
- Linac **cryomodule** design (ISAS)

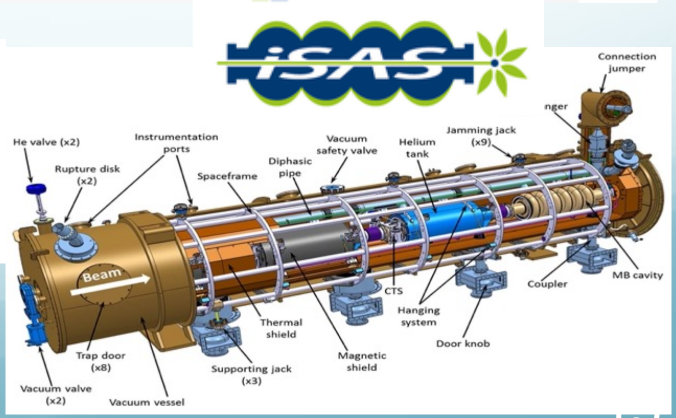
Synergies with FCCee 800 MHz SRF



Boster cryomodule



5-Cell cavity 800 MHz



ERLs developments

IJCLab, LPSC 10 FTEs

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In **multi-pass configuration** they could achieve **high-current** carrying capability (no RF power limit) and **high-power** in a **compact** machine

Experimental PoC:

➢ **PERLE**

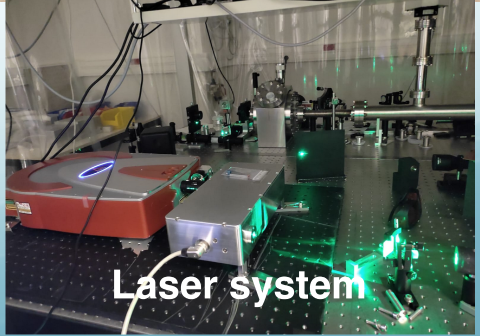
- **Demonstrate multi-turn** and **high-current operation**
  - High-charge electron gun: 500 pC at 40 MHz
  - Optimized 800 MHz SRF system: Maximise the efficiency
  - Common circulation arcs for accelerated and decelerated beams
  - Non-invasive diagnostics

Test bench for FCCee 800 MHz SRF


DC Gun & HV system


Photocathodes Production Facility (PPF)


DC Gun


Laser system

SRF treatments and industrialization

0.5 FTEs

➢ ILC

ITN framework

- **Single-cell R&D**
  - **Material procurement and ECS (Nb):**

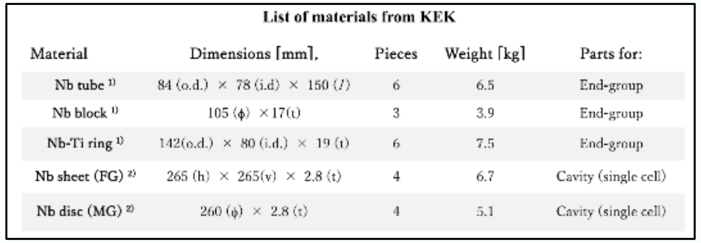
  ✓ **Done**
  - **Mechanical production and treatments:**

✓ Specs prepared by CEA-INFN-CERN (treatments as option)

✓ Order (mechanical + baseline) placed in industry (RI) in March 2025

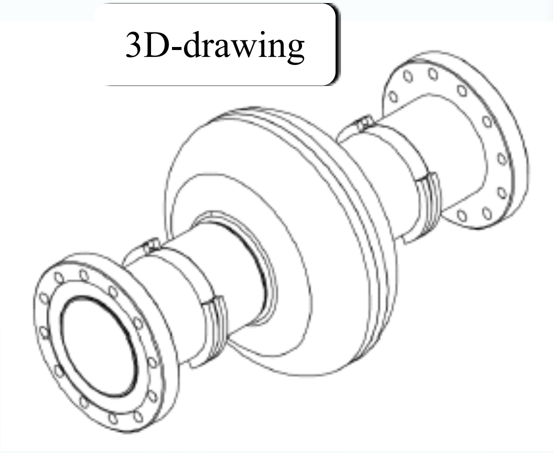
✓ Delivery of materials: expected in November 2025

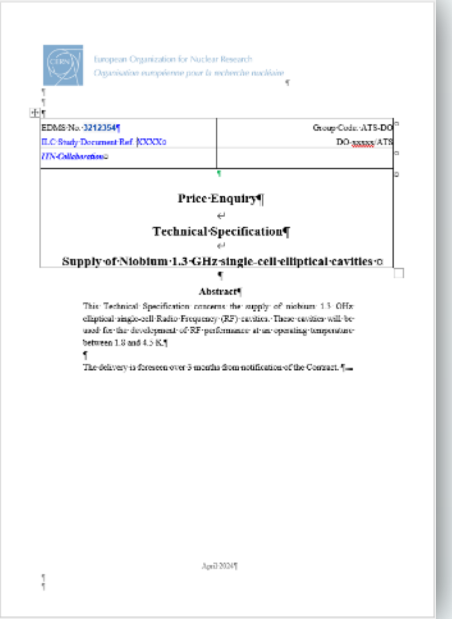
✓ **CEA/INFN** responsible of the **technical support at RI** (QC, etc.)



List of materials from KEK

Material	Dimensions [mm].	Pieces	Weight [kg]	Parts for:
Nb tube [1]	84 (o.d.) × 78 (i.d) × 150 (*l*)	6	6.5	End-group
Nb block [1]	105 (ϕ) ×17(t)	3	3.9	End-group
Nb-Ti ring [1]	142(o.d.) × 80 (i.d.) × 19 (t)	6	7.5	End-group
Nb sheet (FG) [2]	265 (h) × 265(v) × 2.8 (t)	4	6.7	Cavity (single cell)
Nb disc (MG) [2]	260 (ϕ) × 2.8 (t)	4	5.1	Cavity (single cell)





European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

EDMS No. 3212354 ILC Study Document Ref. XXXX ITN-Collaboration	Group Code: ATS-DO DO-xxxxx/ATS

Price Enquiry

Technical Specification

Supply of Niobium 1.3 GHz single-cell elliptical cavities

Abstract

This Technical Specification concerns the supply of niobium 1.3 GHz elliptical single-cell Radio Frequency (RF) cavities. These cavities will be used for the development of RF performance at an operating temperature between 1.8 and 4.5 K.

The delivery is foreseen over 3 months from notification of the Contract.

April 2024

Technical specs for Single-cell fabrication and treatments

- **9-cells cavities:**
  - Production of **9-cells jacketed cavities** at the **EU Industries** (RI and Zanon)
  - **Qualification of EU Industries** in term of pressure vessel code (harmonization with **HPGS Japan**)
  - **Installation** into the **ILC type cryomodule (KEK)** of **2 EU cavities**

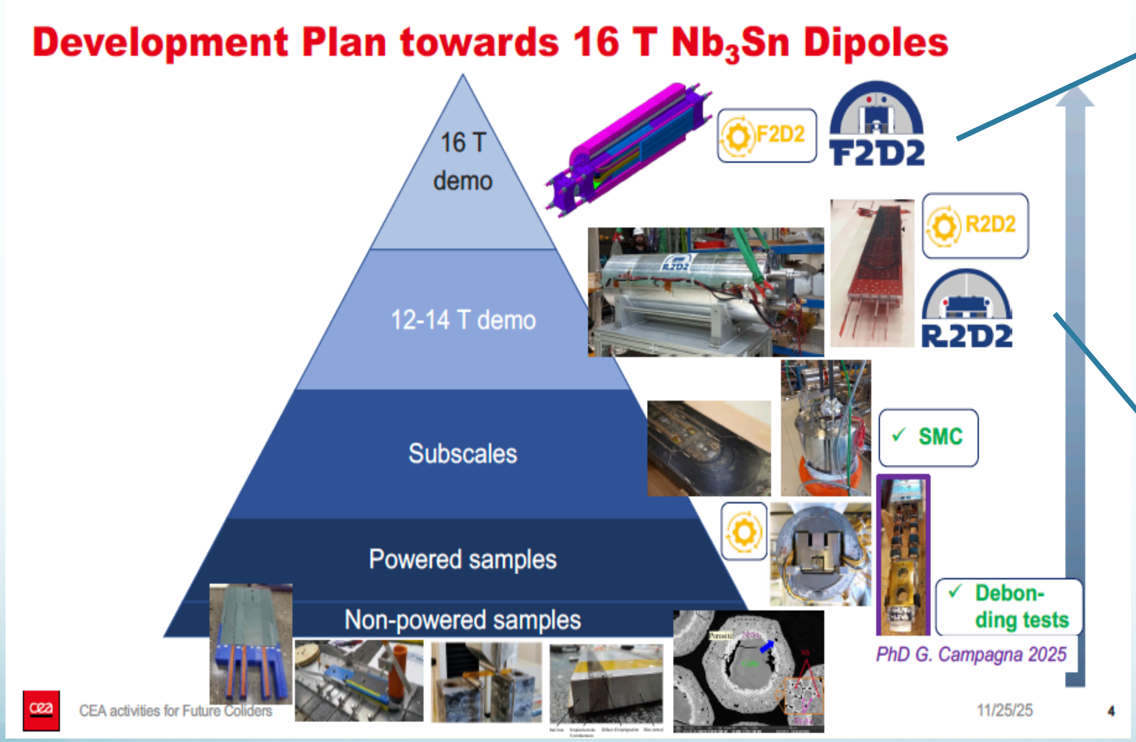
HFM Nb_3Sn dipoles

10 FTEs

HFM FCC program pursue two main goals:

- extend the range of operation of accelerator magnets based on **LTS** up to **16 T**
- explore the technological challenges inherent in the use of **HTS** for accelerator magnets in the **20 T**

➢ FCChh



Development Plan towards 16 T Nb_3Sn Dipoles

16 T demo

12-14 T demo

Subscales

Powered samples

Non-powered samples

F2D2

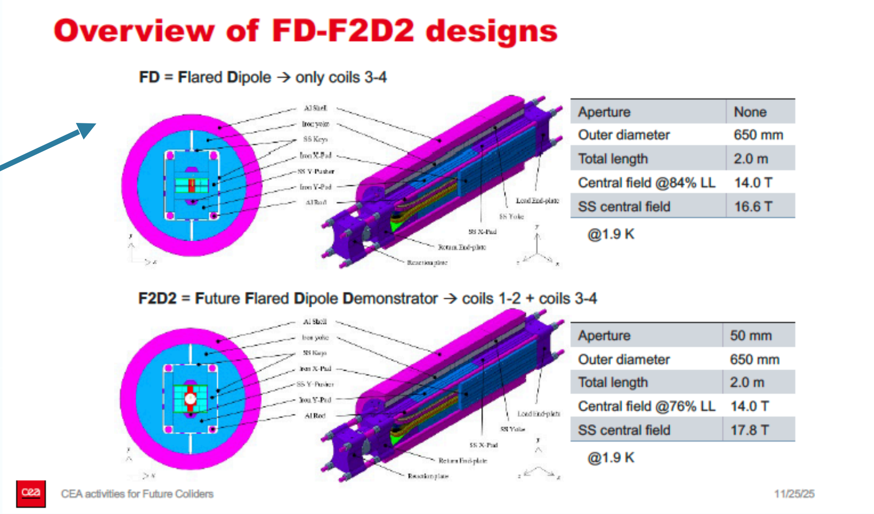
R2D2

✓ SMC

✓ Debonding tests

PhD G. Campagna 2025

CEA activities for Future Coliders 11/25/25 4



Overview of FD-F2D2 designs

FD = **F**lared **D**ipole → only coils 3-4

Aperture	None
Outer diameter	650 mm
Total length	2.0 m
Central field @84% LL	14.0 T
SS central field	16.6 T

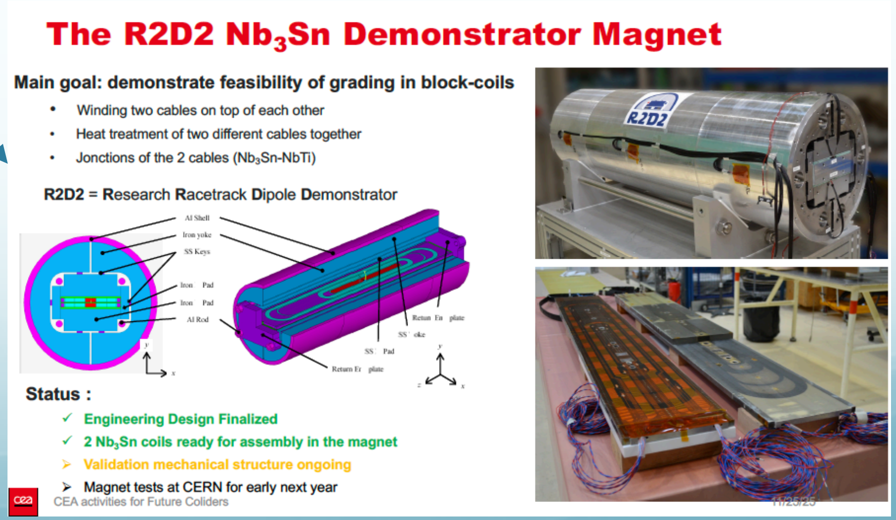
@1.9 K

F2D2 = **F**uture **F**lared **D**ipole **D**emonstrator → coils 1-2 + coils 3-4

Aperture	50 mm
Outer diameter	650 mm
Total length	2.0 m
Central field @76% LL	14.0 T
SS central field	17.8 T

@1.9 K

CEA activities for Future Coliders 11/25/25



The R2D2 Nb_3Sn Demonstrator Magnet

Main goal: demonstrate feasibility of grading in block-coils

- Winding two cables on top of each other
- Heat treatment of two different cables together
- Jonctions of the 2 cables (Nb_3Sn-NbTi)

R2D2 = **R**esearch **R**acetrack **D**ipole **D**emonstrator

Status :

- ✓ **Engineering Design Finalized**
- ✓ **2 Nb_3Sn coils ready for assembly in the magnet**
- ➢ **Validation mechanical structure ongoing**
- ➢ Magnet tests at CERN for early next year

CEA activities for Future Coliders

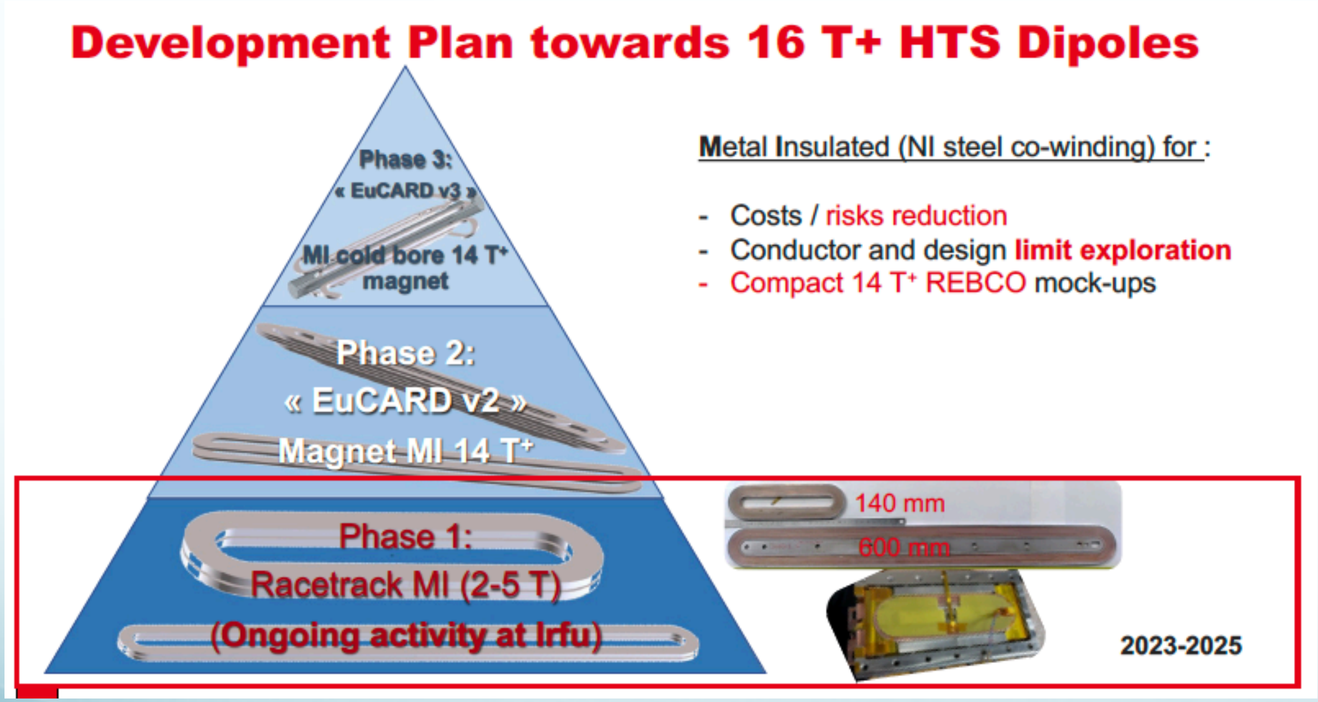
HFM HTS dipoles

10 FTEs

HFM FCC program pursue two main goals:

- extend the range of operation of accelerator magnets based on **LTS** up to **16 T**
- explore the technological challenges inherent in the use of **HTS** for accelerator magnets in the **20 T**

➢ FCChh

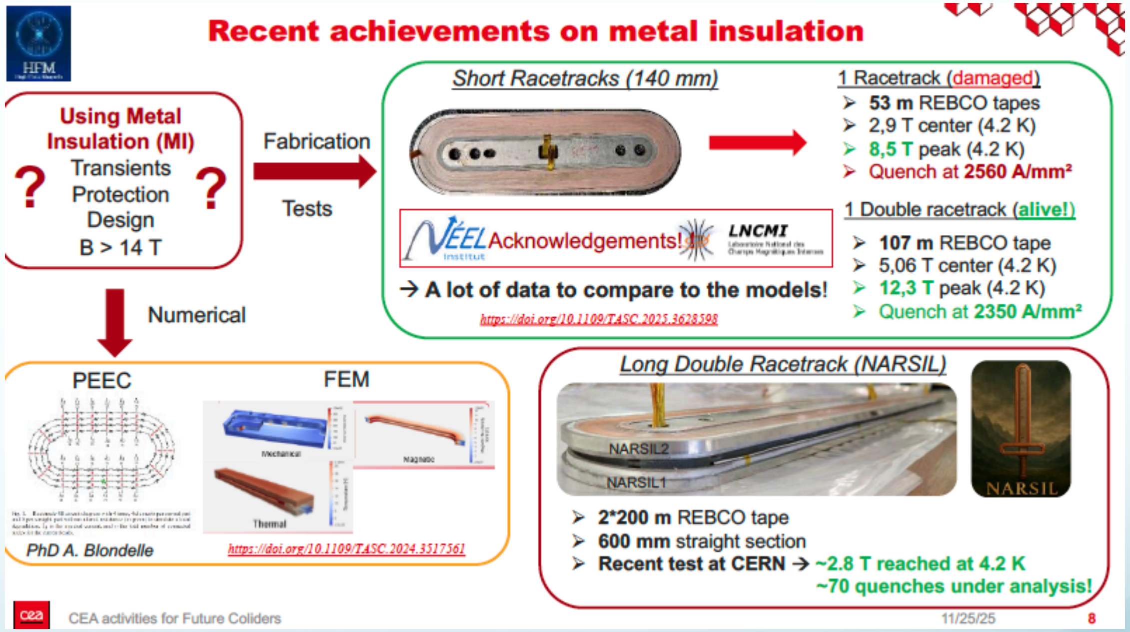


Development Plan towards 16 T+ HTS Dipoles

Metal Insulated (NI steel co-winding) for :

- Costs / risks reduction
- Conductor and design **limit exploration**
- Compact 14 T^+ REBCO mock-ups

2023-2025



Recent achievements on metal insulation

Using Metal Insulation (MI)
? Transients Protection Design B > 14 T ?

Fabrication → Tests

Numerical ↓

Short Racetracks (140 mm)

1 Racetrack (damaged)
- **53 m** REBCO tapes
- 2,9 T center (4.2 K)
- **8,5 T** peak (4.2 K)
- Quench at **2560 A/mm²**

1 Double racetrack (alive!)
- **107 m** REBCO tape
- 5,06 T center (4.2 K)
- **12,3 T** peak (4.2 K)
- Quench at **2350 A/mm²**

NÉEL Institut Acknowledgements! LNCMI

→ **A lot of data to compare to the models!**
https://doi.org/10.1109/TASC.2025.3628598

PEEC

FEM

PhD A. Blondelle
https://doi.org/10.1109/TASC.2024.3517561

Long Double Racetrack (NARSIL)

- **2*200 m** REBCO tape
- **600 mm** straight section
- **Recent test at CERN →** ~2.8 T reached at 4.2 K
  ~70 quenches under analysis!

CEA activities for Future Coliders 11/25/25 8

Booster design

2 FTEs

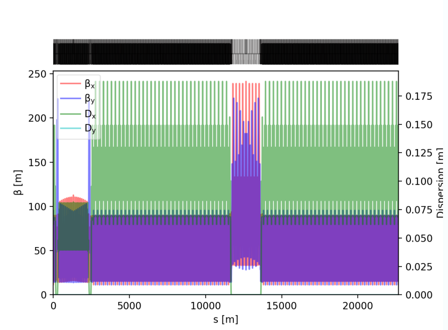
The **high-energy booster** (20 GeV) is the final accelerator injection stage before providing the fresh beam to the collider. The design of the FCC-ee high-energy booster has several challenges: **multi-turn stability**, **top-up** operation, **ramp** of the magnets, **small emittances**.

Design:

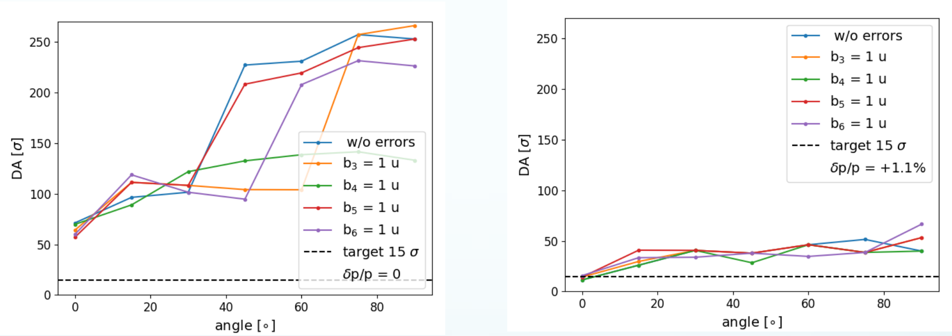
➢ **FCC-ee**

Optics design and Tolerance calculation

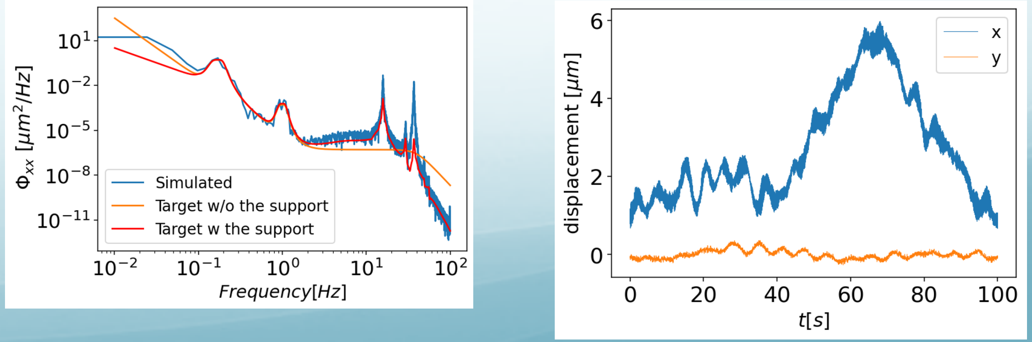
- Multi-turn tracking simulations to evaluate the impact of **field imperfections** in the magnets to the beam stability (dynamic aperture).
- The **misalignment errors** have a big impact on the beam stability.
- Modelisation of the **vibration** (ground motion, technical noise and mechanical supports)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



Optics of 1/4 of booster



Dynamic aperture with systematic errors in the dipoles



FFT model of the vibration to magnet displacement

Booster design

2 FTEs

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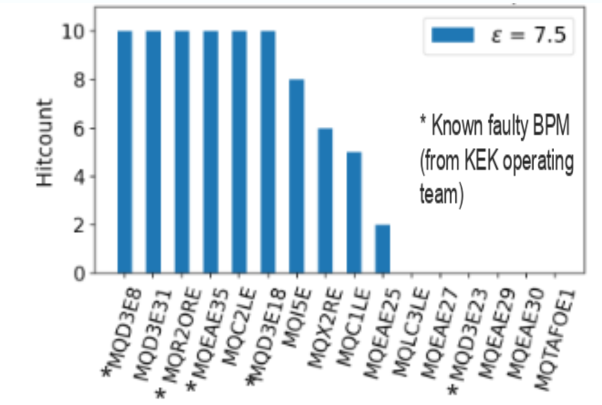
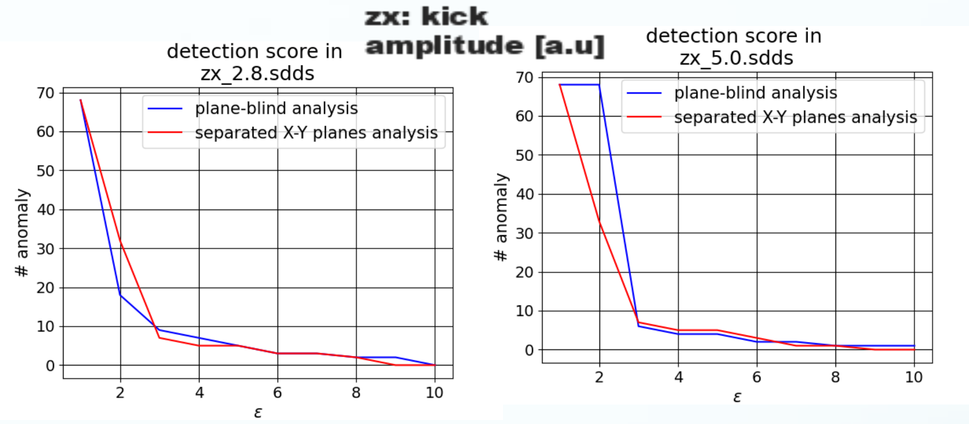
Experimental PoC:

➢ SuperKEKB

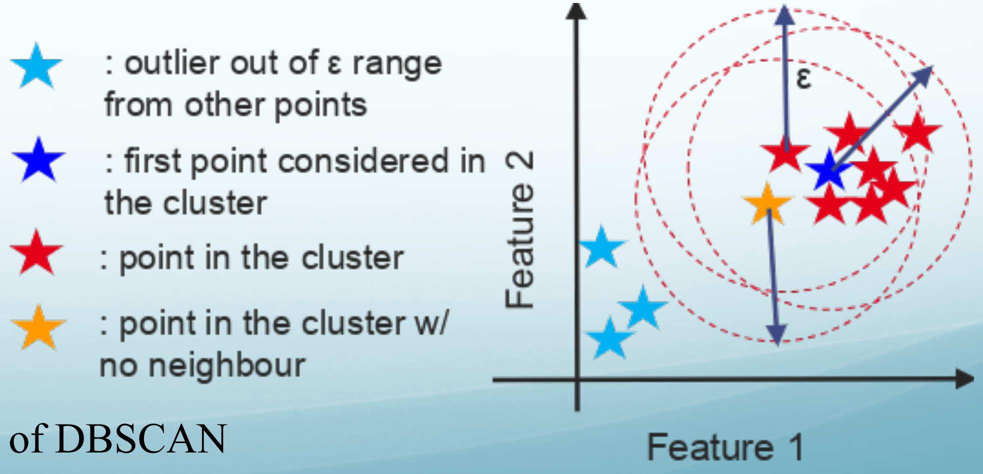
Detection of failed BPMs with IA

- Use of SuperKEKB data BPM turn-by-tu to validate the concept.
- Complete characterizaton of the algorithm on simulation.
- Run a comprehensive detection campaign on SuperKEKB 2024-2025 data.
- Use an IA algorithm to « denoise » the validated tracks.





Hit score when BPM considered as faulty



★ : outlier out of ε range from other points

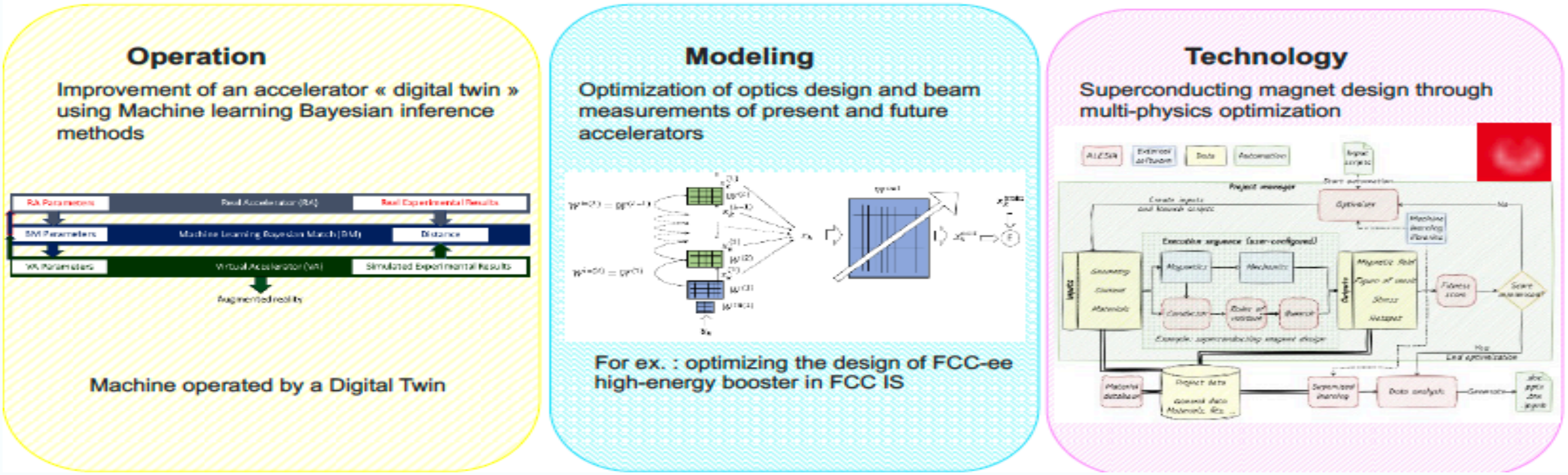
★ : first point considered in the cluster

★ : point in the cluster

★ : point in the cluster w/ no neighbour

Principle of DBSCAN

AI for accelerator developments



Operation

Improvement of an accelerator « digital twin » using Machine learning Bayesian inference methods

Machine operated by a Digital Twin

Modeling

Optimization of optics design and beam measurements of present and future accelerators

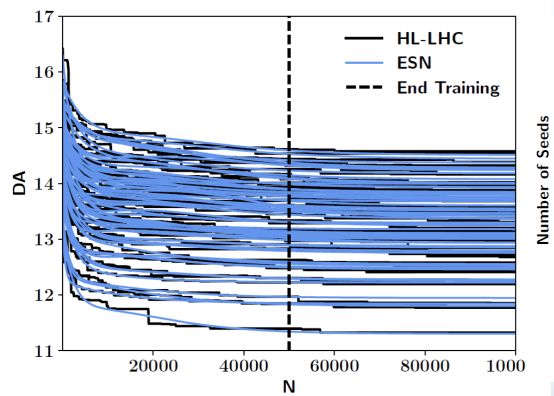
For ex. : optimizing the design of FCC-ee high-energy booster in FCC IS

Technology

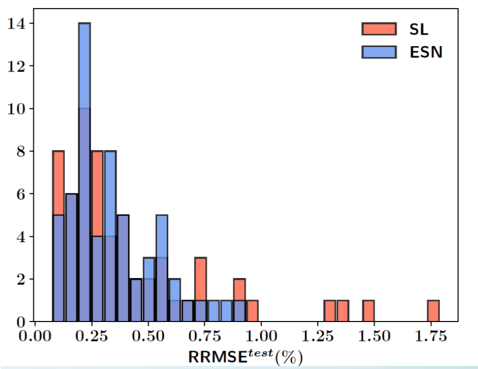
Superconducting magnet design through multi-physics optimization

- **Applications under consideration:**
    - DA optimization
    - optimizing the design of FCC-ee's high-energy booster
    - BPM noise reduction
    - identification of particle types in emittance measurements
    - optimization of LWFA parameters

- Participation in the French **M4CAST network** (Multiphysics Modelling, Machine learning and Model-based Control in Accelerator Sciences and Technologies)



Evolution of dynamic aperture for 60 HL-LHC configurations



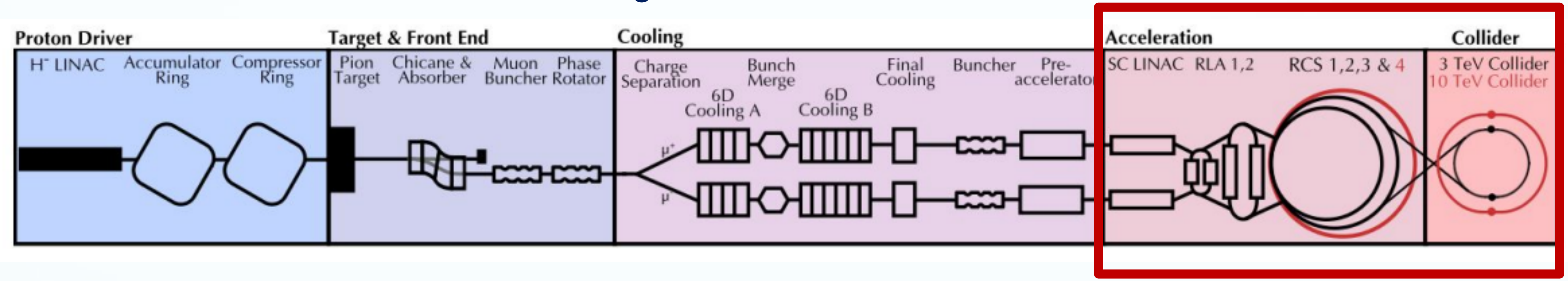
Relative square error

μ collider high-energy complex

2 FTEs

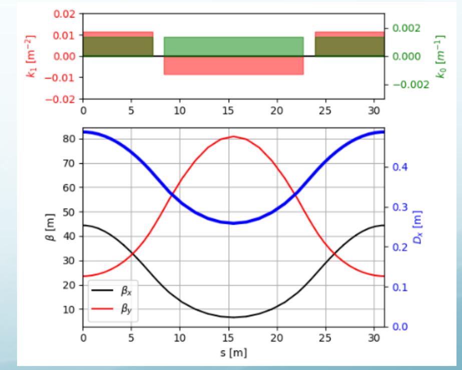
Main R&D topics:

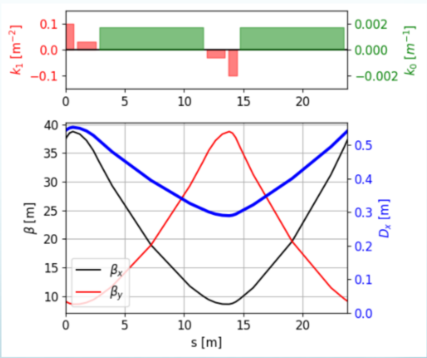
- Produce an **intense beam of muons** (>10^{12} muons/bunch) from a proton beam hitting a target.
- **Collect** muons, **accelerate** and **cool** them quickly to reach low emittances for high luminosity.
- **Accelerate quickly** (< 10 ms) the muons up to 5 TeV.
- **Collisions** of muons in the last ring



- **Design** and comparison of different **optics** to minimize the magnetic energies stored in the arc cells.
- Simulations throughout the very **rapid acceleration process** to verify that the **emittance** is maintained: some magnets may have a static field, which changes the optical properties of the accelerator.
- Initial studies to investigate the **effect** on the **trajectory** of the **variation** in the **dipole** field during transport. An analytical model has been developed that agrees very well with simulations using the Xsuite code.
- Close interaction with our beam dynamics colleagues to verify **beam stability** and limit **emittance magnification**

Combined function





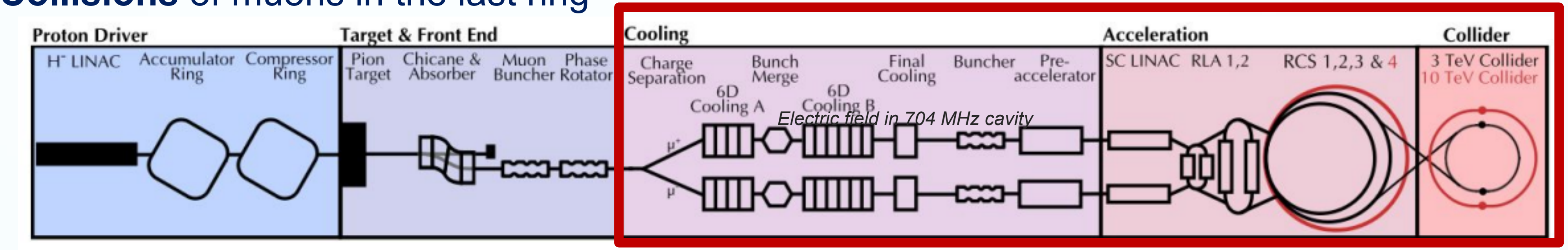
FODO hybride

μ collider RF systems and field emission

2 FTEs

Main R&D topics:

- Produce an **intense beam of muons** (>10^{12} muons/bunch) from a proton beam hitting a target.
- **Collect** muons**, accelerate** and **cool** them quickly to reach low emittances for high luminosity.
- **Accelerate** quickly (< 10 ms) the muons up to 5 TeV.
- **Collisions** of muons in the last ring

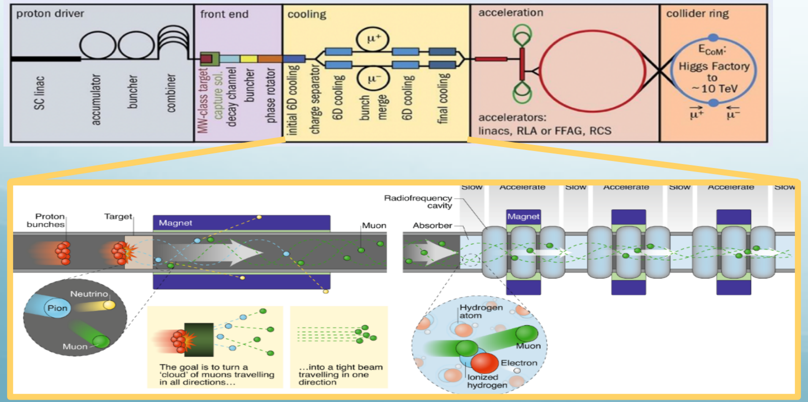


Electric field in 704 MHz cavity

NC accelerating cavities

In the **presence** of a few Teslas **magnetic field**

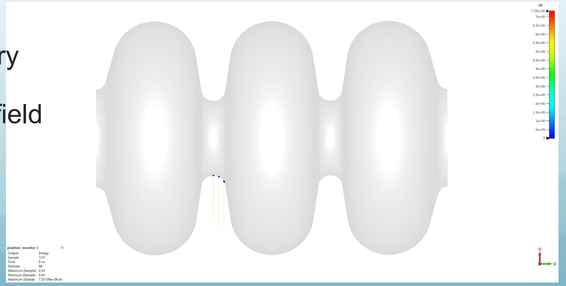
- The **breakdown** threshold is lowered
- The rate of breakdown/time unit is increased



Effect of magnetic field on the trajectory of the material emitted by **field emission** :

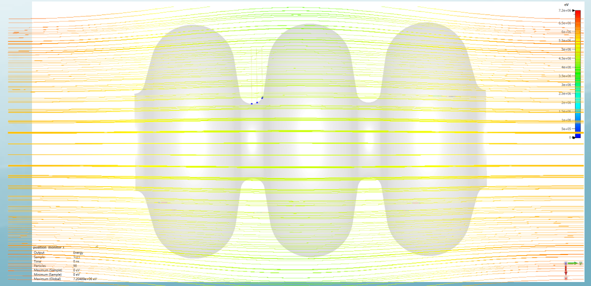
- emitted e- are focused by the B field and the point of impact is more concentrated.
- Increase in temperature
- Higher mechanical stresses on the metal
- Increased RF breakdown effect

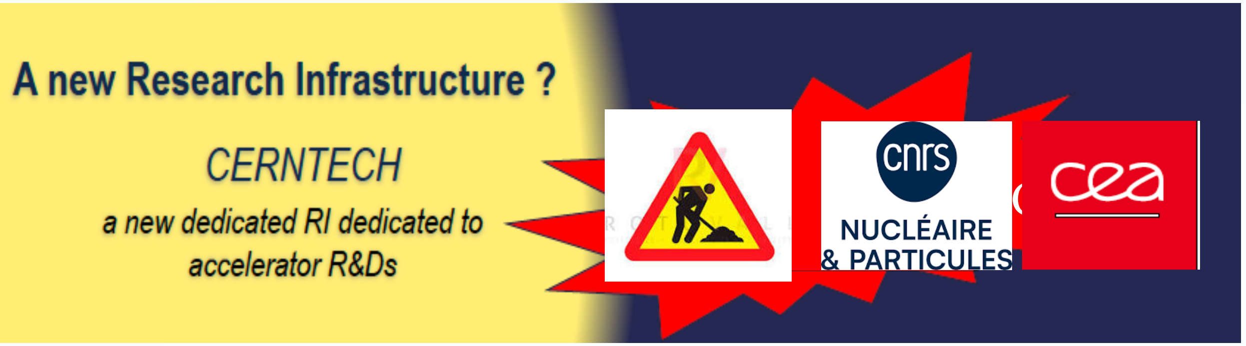
e- trajectory without magnetic field



DC magnetic field lines

e- trajectory with magnetic field

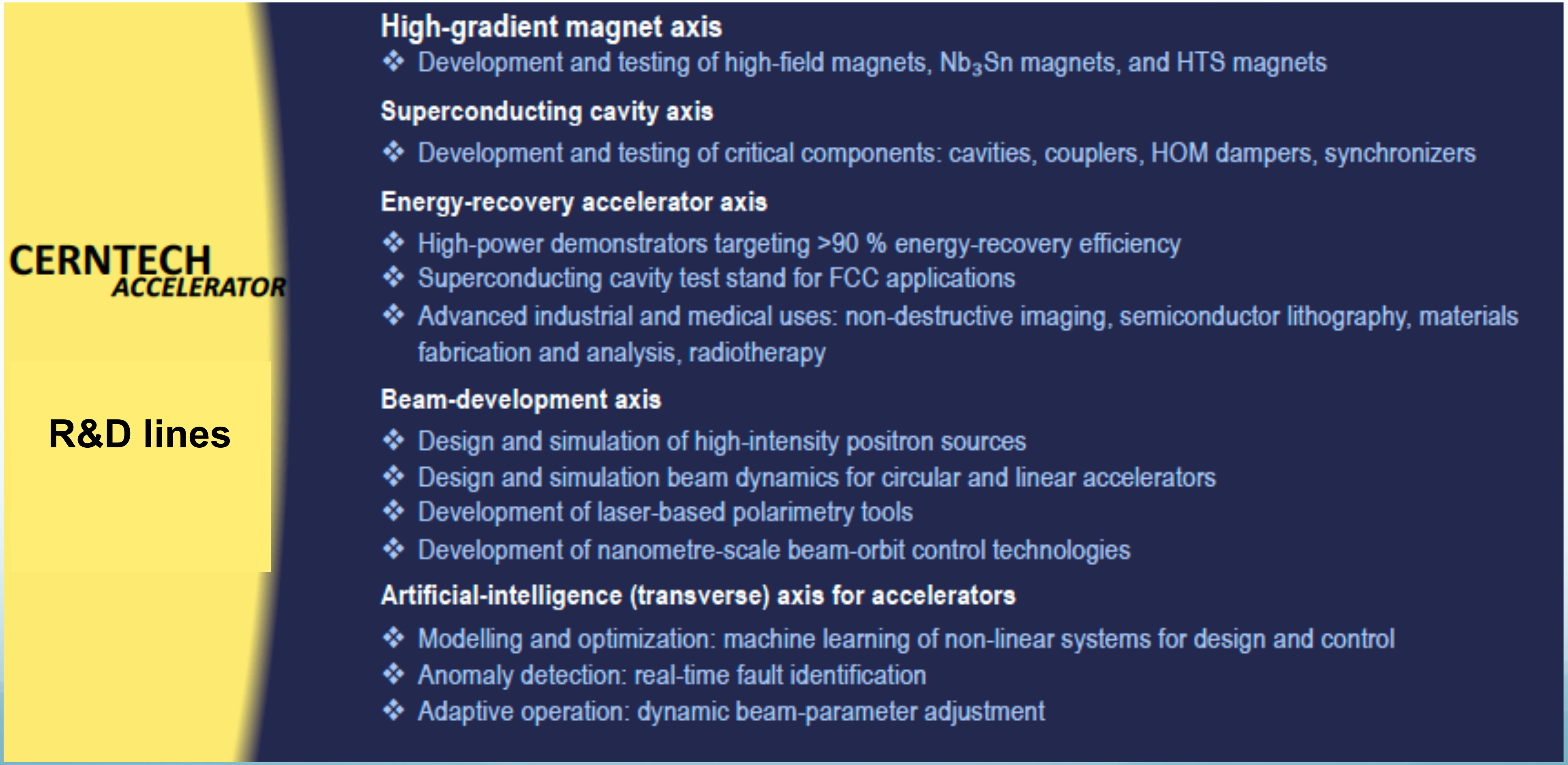




A new Research Infrastructure ?

CERNTECH

a new dedicated RI dedicated to accelerator R&Ds



CERNTECH *ACCELERATOR*

R&D lines

High-gradient magnet axis

- Development and testing of high-field magnets, Nb_3Sn magnets, and HTS magnets

Superconducting cavity axis

- Development and testing of critical components: cavities, couplers, HOM dampers, synchronizers

Energy-recovery accelerator axis

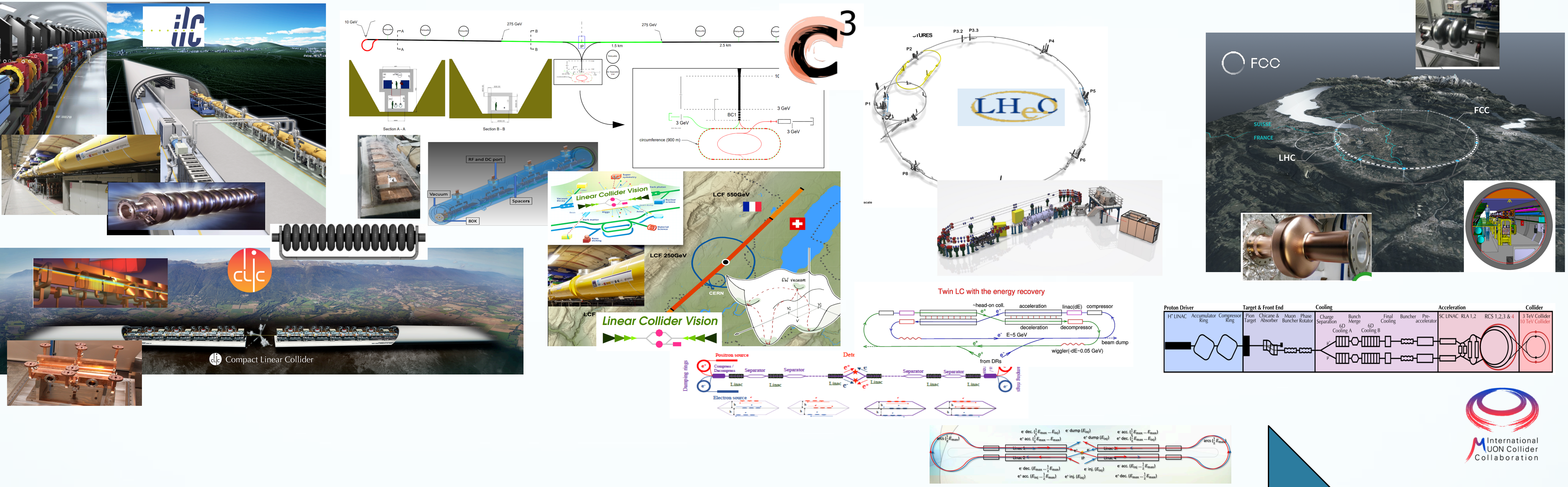
- High-power demonstrators targeting >90 % energy-recovery efficiency
- Superconducting cavity test stand for FCC applications
- Advanced industrial and medical uses: non-destructive imaging, semiconductor lithography, materials fabrication and analysis, radiotherapy

Beam-development axis

- Design and simulation of high-intensity positron sources
- Design and simulation beam dynamics for circular and linear accelerators
- Development of laser-based polarimetry tools
- Development of nanometre-scale beam-orbit control technologies

Artificial-intelligence (transverse) axis for accelerators

- Modelling and optimization: machine learning of non-linear systems for design and control
- Anomaly detection: real-time fault identification
- Adaptive operation: dynamic beam-parameter adjustment



Thanks for your attention