ACCELERATOR R&D FOR PP

G. BISOFFI AND D. ALESINI, FOR THE INFN-ACCELERATORI PI'S

INFN INPUT FOR ESPP 2025-2026, MILANO 04-FEB-2025

OUTLINE

The study of the next accelerator at CERN is fundamental to the future of PP in Europe.

INFN has already encouraged and supported, with adequate resources, initiatives aimed at feasibility study of the FCC (Future Circular Collider), and R&D projects on innovative accelerator technologies

Others are proposed in a call for expression of interest to the INFN accelerator community

- FCCee: MDI, injector, beam dynamics — FCC-specific
- SC magnets for limiting the size of circular accelerators
- SC cavities for lower-impact accelerators (bulk-Nb and thin films)
- High-I positron sources, high-P couplers, vacuum chamber studies (also FCCee) — FCC and more
- MC: cooling cell, MDI, cavities, HFM — Muon Coll
- EuPRAXIA and plasma-based colliders — Plasma-based Coll

TOPIC
Main message
area

- Need
- Present status
- New goal

- Who
- When
- Risks/benefits

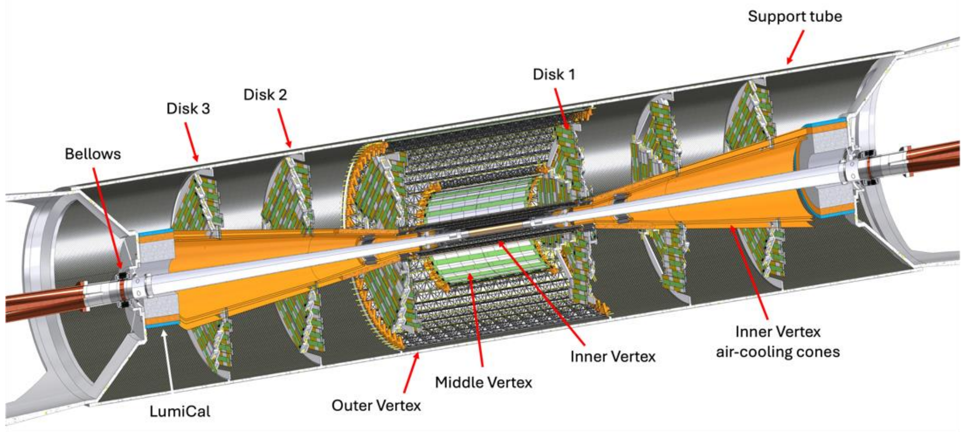
Oggi non parliamo di risorse

INTERACTION REGION DESIGN OF FCC-EE
INTEGRATE IR LIGHTWEIGHT BEAMPIPES

Needs - **FCC-ee interaction region (IR): fulfill accelerator and detector requirements, while maximising $\mathcal{L}$ / background.**
Compact design, integrating light vertex and luminosity detectors, beam and detector diagnostics, IR-magnets, bellows, remote vacuum connection, while guaranteeing UHV and structural integrity (← thickness, material)

Present status (in pre-TDR phase): at LNF technological design solutions for FCC-ee are being shaped: **beam optics/dynamics, beam background, vertex detector design and development, thermo-fluid-dynamics, system integration.** Al for IR mockup beampipes is instrumental for other materials.

New goal Develop the **entire IR design**, including integration with **IR-magnets and the rest** of the experiment. Demonstrate feasibility of **lightweight IR beampipes** in Be, AlBeMet, and carbon fibre composites, including cooling systems, bellows, and remote vacuum connection.



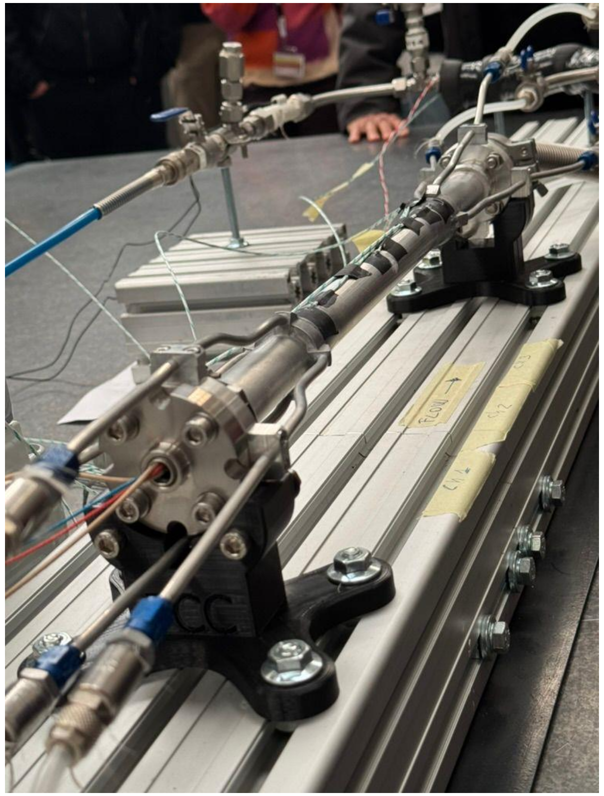
Components that will be assembled for the FCC-ee IR mockup.

FCC - specific

INTERACTION REGION DESIGN OF FCC-EE
INTEGRATE IR LIGHTWEIGHT BEAMPIPES

Who

INFN-LNF, INFN-Pisa, INFN-Perugia. Foreseen/possible collaborations– CERN, IHEP, UNIGE, SLAC, BNL, PSI, R&D of interest in the ECFA-DRD8 WP1.1, KEK, INFN-Roma, UniCal



Schedule

Years 1-2: Definition of **specs**, Market survey of **materials and fabrication technologies**, **Design** studies of accelerator components for different beam energies, **structural and thermal** simulations
Years 2-4: Construction of accelerator IR components prototypes, Vertex detector mockup, **Mechanical tests and integration**
Year 5 – End of pre-TDR Integration studies, **Consolidation** of findings

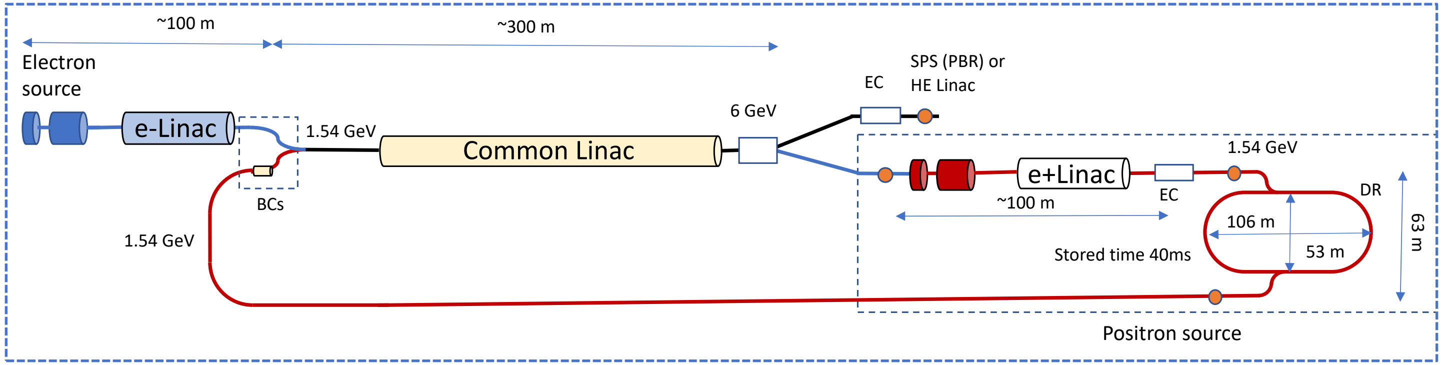
Risks/ Benefits Availability and machining of beryllium/AlBeMet (Mitigation through CERN, IHEP collaboration). Full exploitation of collider performance. Consolidate/boost **expertise of INFN** on accelerator IR at colliders.

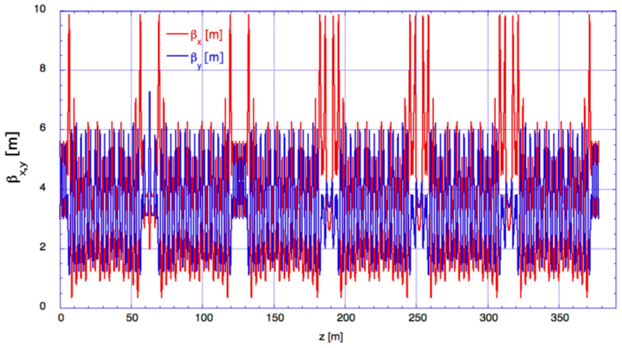
INJECTOR COMPLEX FOR FCC-EE
FEED HIGH-L COLLIDER

Need – **Design FCC-ee injector complex** providing suitable **e⁻ and e⁺ bunch trains for alternating bootstrapping** injection during top-up, every ~ tens of s. Not yet available for ***~ 5 nC e+ bunch charge***

Present status – LNF is providing an **integrated optimized design** for Damping Ring (DR), Transfer Lines (TLs), Energy Compressor (ECS) and Bunch Compressor. (BCS) Mid term review: consider **2.86 GeV DR**, with 100 Hz pulses from linacs (4 bunches every 25 ns) → injector layout revised

New goal **Complete the design** of DR, TLs, ECS and BCS, optimising the high energy (2.86 GeV) 370 m long DR layout, assessing **impedance budget evaluation and collective effects**, with realistic HW. Add start-to-end simulations to be done. Provide a cost assessment.



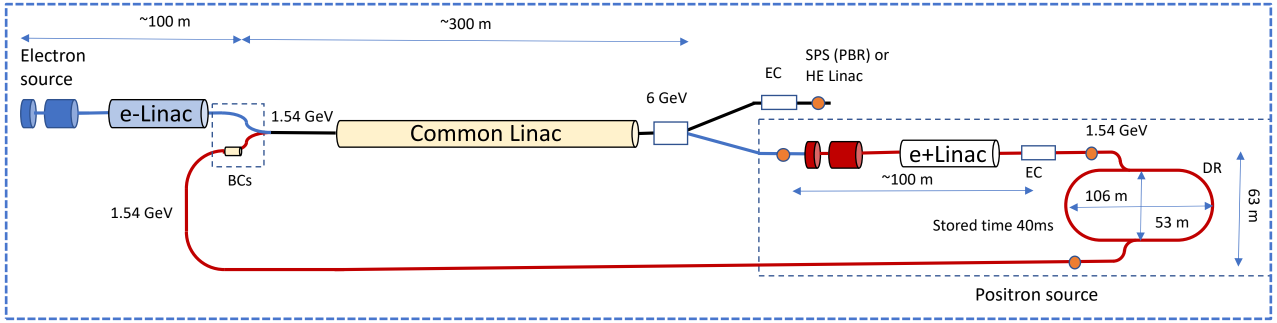


INJECTOR COMPLEX FOR FCC-EE
FEED HIGH-L COLLIDER

Who – INFN-LNF, in collaboration with PSI and CERN, CNRS-IJCLab (Orsay)
INFN – Ferrara has independently started contributing to the e^+ source development with studies on radiation from crystals (see later).

Schedule
FCC-ee Injector TDR 2025-2028: with pre-TDR by mid-2027 (→ machine/infrastructures for the initial CE design)

Risks – (recruitment of enough skilled scientific personnel in due time)



HIGH-INTENSITY BEAM DYNAMICS IN FCC-EE

CONTROL COLLECTIVE EFFECTS IN HIGH-L COLLIDERS

Need: With the **crab waist scheme**, already successfully tested at Frascati, to **increase** $\mathcal{L}$, collisions at the FCC IP will be challenging (low ε, low β-function, high-I, large ϕ_{PIW}): **severe beam-beam and conventional collective effects** expected. Mandatory to carefully **assess machine impedance**, collective effects and their interplay

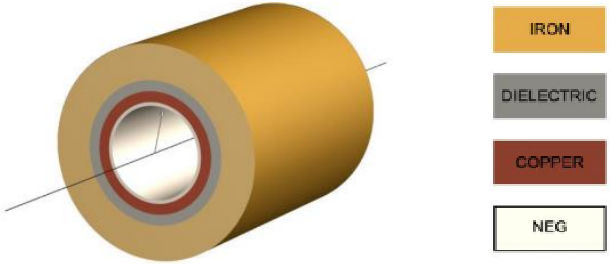
Present status: A machine **impedance model** for studying beam instabilities **exists**; FCCee vacuum chambers **evolve** → coupling Z → beam stability regions

New goal: **Keep FCC impedance model updated**, help in device design, evaluate impact on instability thresholds, look for mitigations

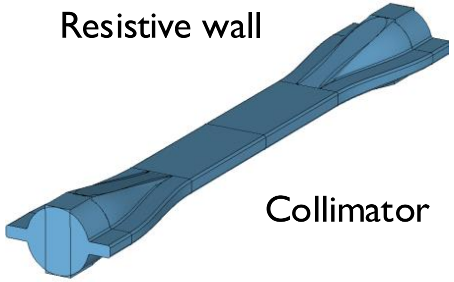
Who: Sapienza and INFN – Roma1, INFN – LNF, w/PhDs and post-docs. Collaborations with CERN, IHEP and KEK; FCC-ee collective effects study group (CERN, GANIL, IHEP, KEK)

Schedule: **Follow evolving** FCC design. Beam dynamics **measurements at SuperKEKB** to validate simulation tools (if possible)

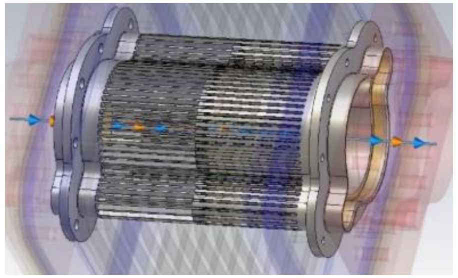
Risks: (Many devices being finalized at the same time, resources).



Resistive wall



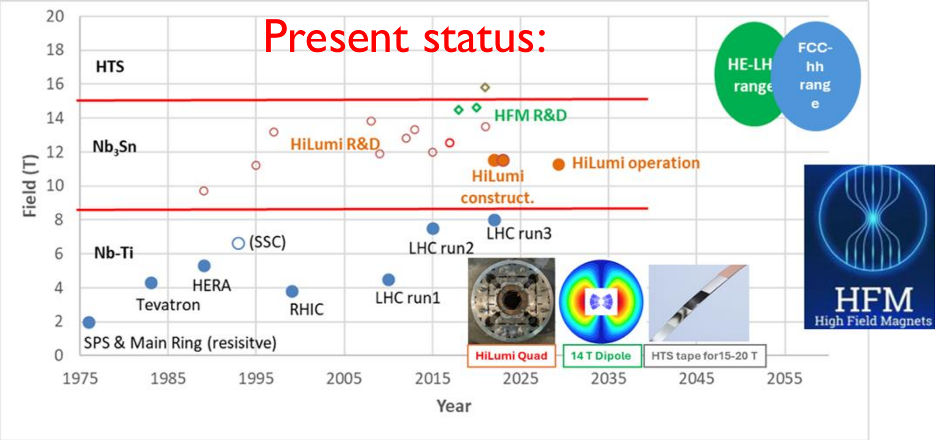
Collimator



Bellow – SuperKEKB model w/sliding contacts

HIGH FIELD MAGNETS – ITALY
CONTAIN THE SIZE OF CIRCULAR MACHINES

Need: **Critical for FCChh and MC** (1st bullet of ESPP2020), 80-120 TeV in a 91 km **FCChh require 12-20 T dipoles; MC requires large-aperture 12-16 T dipoles**; **Nb_3Sn-HFM at 4.2 K** would reduce FCC cryopower 300 →150 MW or less; **HTS-HFM at 20 K** would make it drop to 30-50 MW (~ @LHC)



- ✓ Operational NbTi magnets.
- ✓ HiLumi Nb_3Sn magnets
- ✓ Range needed for FCC-hh and HE-LHC (equal to the one of a HE-LHC).
- ✓ Scope of the CERN–led HFM R&D program.
- ✓ HTS attempt towards >14 T at 20 K. Likely needed at least in critical zones as inner triplets region, dispersion suppressor and lattice correctors (sextupoles)

New goal: **A bolt step above the status of-the-art.**

- ✓ **14 T Nb_3Sn dipole single aperture** (1 m long, full cross section; FCC-hh baseline) -1.9 K design, INFN-tests at 4.2 K.
- ✓ **2-in-1 dipole in Nb_3Sn** (based on 12 T "Falcon-D"). Tests: 10-12 T@4.2 K at INFN and @1.9 K at CERN.
- ✓ **Absolute-first HTS dipole** of accelerator quality, 10 T @20 K (cryogen-free): milestone for operational 14-20 T @20 K

HIGH FIELD MAGNETS – ITALY
CONTAIN THE SIZE OF CIRCULAR MACHINES

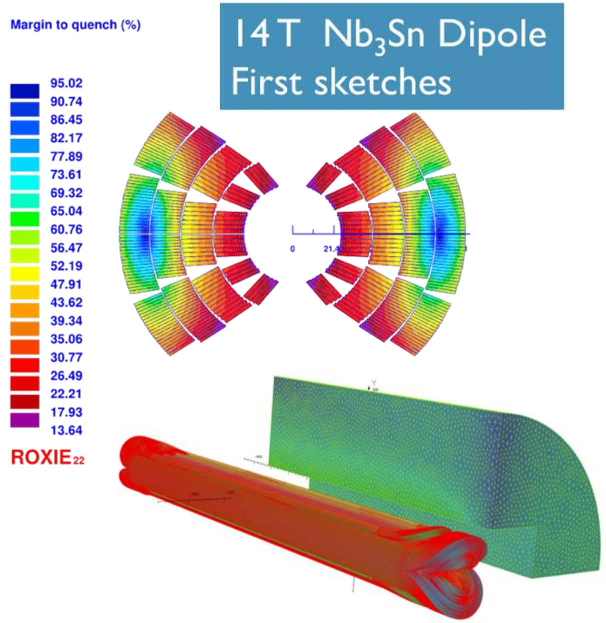
Participants
INFN-Genova, Milano LASA, Uni-Milano (INFN-Napoli-Salerno). CERN main partner (50% of funds – *approved FC, Dec'24*). Collaboration MoU: CERN, CEA, CIEMAT, INFN, KIT, PSI, RAL-STFCM, and various Universities.

Plan: if CERN-INFN HFM collab. contract is signed in spring 2025:

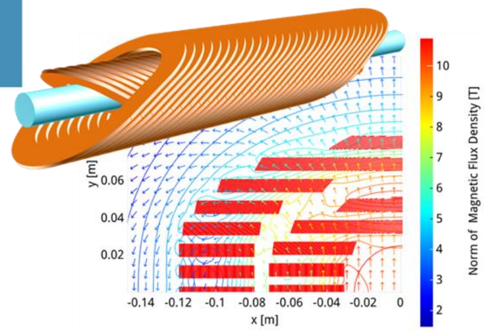
I. 14 T dipole : 1st July 2025 – 30th June 2031 , 6 years; It is the main driver of the whole program;
II. 12 T double aperture dipole: 1st July 2025 – 30th June 2029, 4 years;
III. 10 T@20K HTS dipole: 1st July 2025 – 30th June 2028, 3 years; if successful, followed by a further *14-20 T HTS dipole program*

Risks: Mission-oriented R&D: main risk is **not-reaching-full-performance**, various mitigations devised. Higher risk for **HTS (an absolute first!** and "accelerator quality"), whatever is achieved is worth for less demanding colliders, in terms of field quality (MC)

14 T Nb_3Sn Dipole
First sketches



10 T HTS Dipole
CCT type



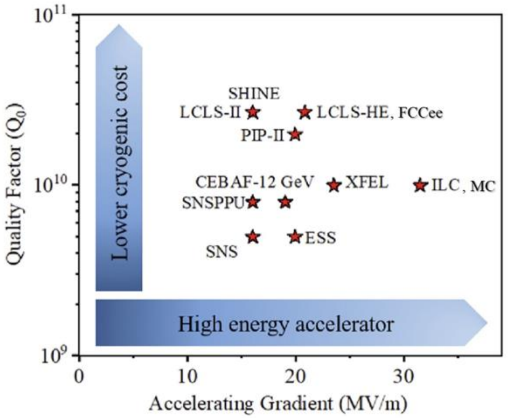
BULK-NB SC RESONATORS FOR FUTURE COLLIDERS

LOWER IMPACT AND SHORTER ACCELERATORS - I

Need – **Reduced power** consumption (higher Q_0) and **smaller** footprint (higher G), for FCC, ILC, MC

Present status

- ✓ HighQ/HighG studies (on 1.3 GHz single-cells): surface treatment, thermal treatments, cold VTs at LASA and internationally
- ✓ Migration to multiple-cell, industrialization
- ✓ New cryostat at LASA faster tests, magnetic hygiene and FE diagnostics



New goal Specific focus on: future HEP collider; ERL (CW, high current, HOM damping); new horizontal test facility at LASA for test (in operational conditions!)

Who- INFN-LASA, in collaboration with JLab, FNAL, Cornell, KEK, CERN, NZB, DESY, CEA, IJCLab, IHEP, SHINE); more broadly TESLA, MC and iSAS; Zanon Research & Innovation" (IT), "Research Instruments" (D)

Schedule – extend recipes to **next collider multi-cell** type (**2-3 y**); extend know-how to **ERL high-I_{ave}** structures (**6-8 y**); construct/operate a horizontal test facility (**HTF**) to qualify cavities and RF in operational conditions (**8-10 y**)

Risks/Benefits - HTF inherently linked to the new **cryogenic infrastructure at LASA**

Keep INFN leading role in SRF bulk-Nb cavities and their series production

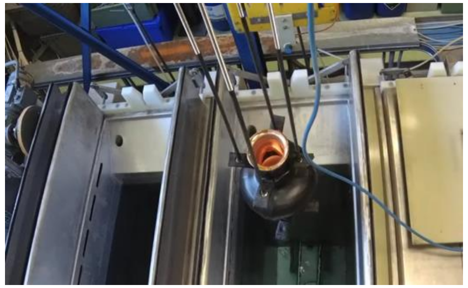
HTS makes LASA a European reference lab for CM testing

THIN FILM SC RESONATORS FOR ENERGY SAVING

LOWER IMPACT AND SHORTER ACCELERATORS –2

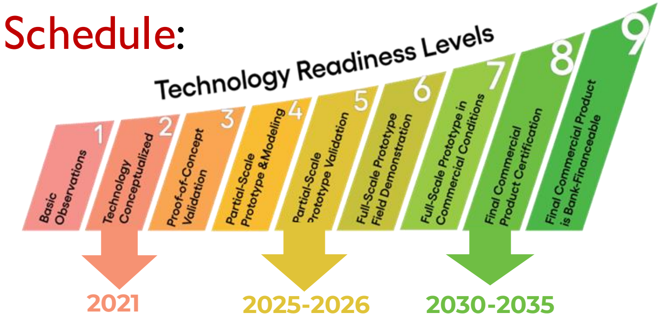
Need: Moving from bulk Nb @2K to **Nb_3Sn @4 K reduces cryogenic power by x 3**

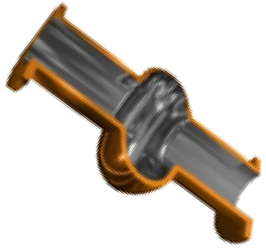
Present status/ New goal: **Plasma Electrolytic Polishing** and **Nb_3Sn/Cu coating by PVD** (1.3 GHz validation → 800/400 MHz for FCCee; → multi-cell; industrial TRL; study of new layers)

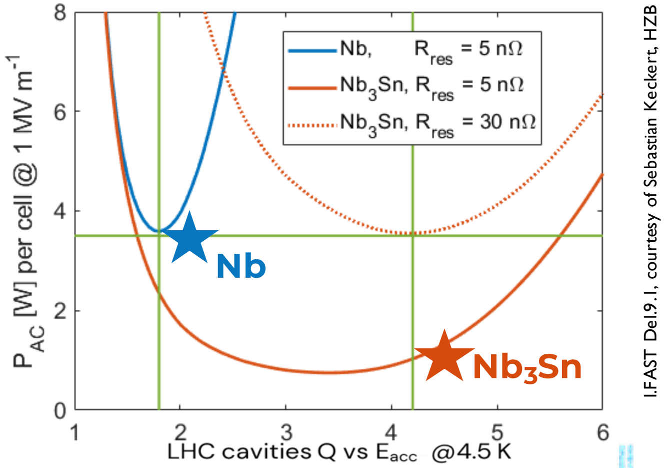


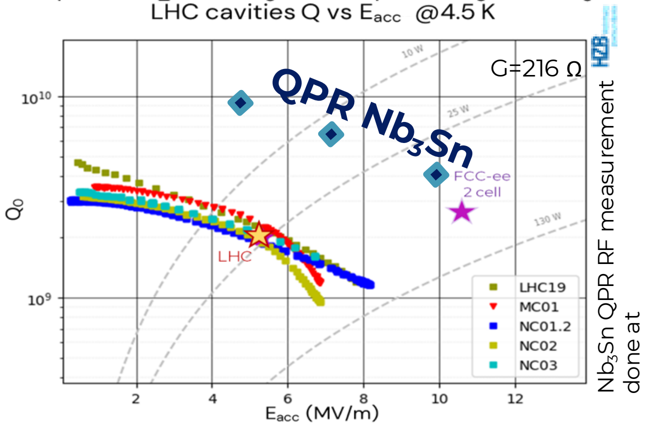
PEP on 1.3 GHz (Aug-24!)

Schedule:









Who: INFN-LNL, LASA; CERN, CEA, UKRI, HZB, Zanon, RI; INFN ESPP20 funding, RD_FCC, SAMARA; I-FAST, iSAS

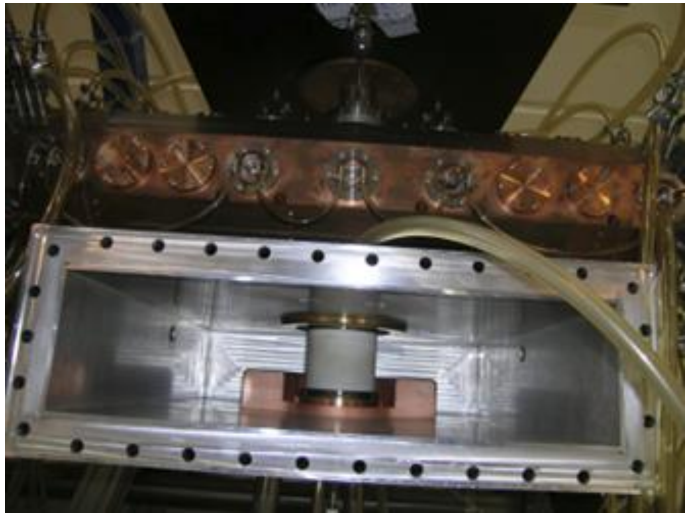
Nb_3Sn on small Nb planar resonator meets FCC-ee specs
Scaling to 1.3 GHz: exp H2-2025

Risks/benefits: lower than expected performaces (mitig.:liaise with CERN, STFC, Jlab)
PEP and Nb3Sn films game changer for SRF cavities (also: conduction cooling, easier to build/operate linacs for huge range of applications.

R&D FOR RF WINDOWS AND COUPLERS
ENABLE HIGH-G/I CAVITY OPERATION IN FCC AND OTHER COLLIDERS

Need – Build reliable **high-P couplers con FCCee and other colliders**

- 1. 400 MHz, 1 MW-CW and 800 MHz, 250 kW CW: disk window in WG
- 2. 800 MHz version, coax window close to beam axis (0.5 MW CW).



Present status - ~ **x2 away from present state of the art** on power couplers. **Lack of resources and competences** on a Europea/world scene. ~100-kW-CW developments at CERN, CEA, DESY, STFC.

INFN-LNL: ~100 kW CW for IFMIF, ESS, DONES, ANTHEM

New goal – *RF design and **Multipacting** studies (*optimization loop between RF ad particle tracking) - *Alumina* Ti(N) ***Coating*** discs, coaxial, cylindrical - *Mechanics/**Brazing*** - *High-power **tests***

Who – INFN-LNL, LNF, Na, CERN, CEA.

Schedule – Along 4 years

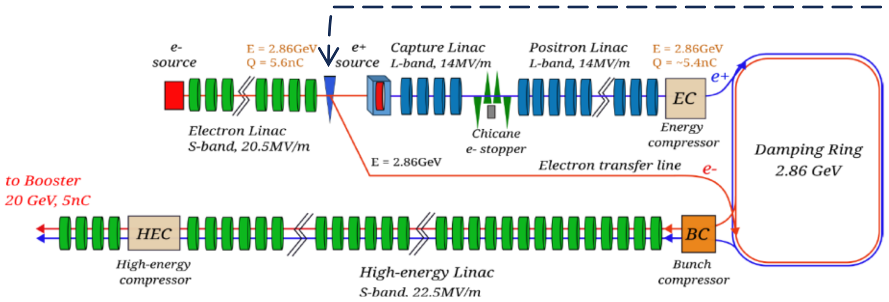
Risks – Disk **window thermal** handling. Metal-to-ceramic successful **brazing**

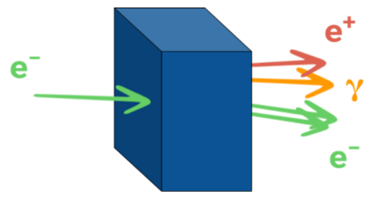
POSITRON SOURCES FOR FUTURE COLLIDERS

INCREASE LUMINOSITY AT LOWER COST AND IMPACT

Need: **Increase collider $\mathcal{L}$** with higher I(e+); **energy saving** (for FCCee, CLIC, ILC)

Present status - e^- → e^+ in a thick target (FCCee baseline). $\mathcal{L}$ limited by target heating/mechanical stresses



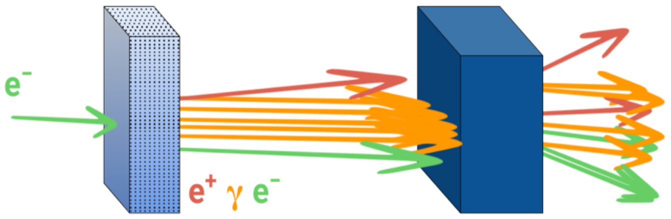


Thick amorphous high-Z target

New goal – e+ via: gamma-quanta radiator | gamma-to-e+ converter (R. Chehab, A.Variola,…)

Channeling radiation from thin axially oriented crystal (more photons vs standard Bremsstrahlung) → **increase in the number of e+** at the converter target (in a hybrid scheme:only photons reach the converter), **low dep. energy**

Result: Higher $\mathcal{L}$ and better sustainability (smaller I(e-) current -> smaller cost)



Thin crystal radiator Thick converter

(soft e+ easily captured in matching systems)

Who – INFN Ferrara, LNL, Milano, MiB, Napoli; IJCLab

Current: CSN1 RD-FCC, Past: CSN1 RD-MUCOL, CSN5 STORM

Schedule - **Design** different configurations; **target resistance tests** and @PSI with beam

VACUUM CHAMBER IMPROVEMENT
MITIGATE VACUUM WALLS EFFECTS IN HIGH-L COLLIDERS

Need: **Interaction beam-walls** (electron clouds, particle-emitted photons, …) is paramount on FCCee, FChh, MC, all colliders - issues of **static (UHV material, preparation, cleanliness) and dynamic vacuum (beam-wall)**

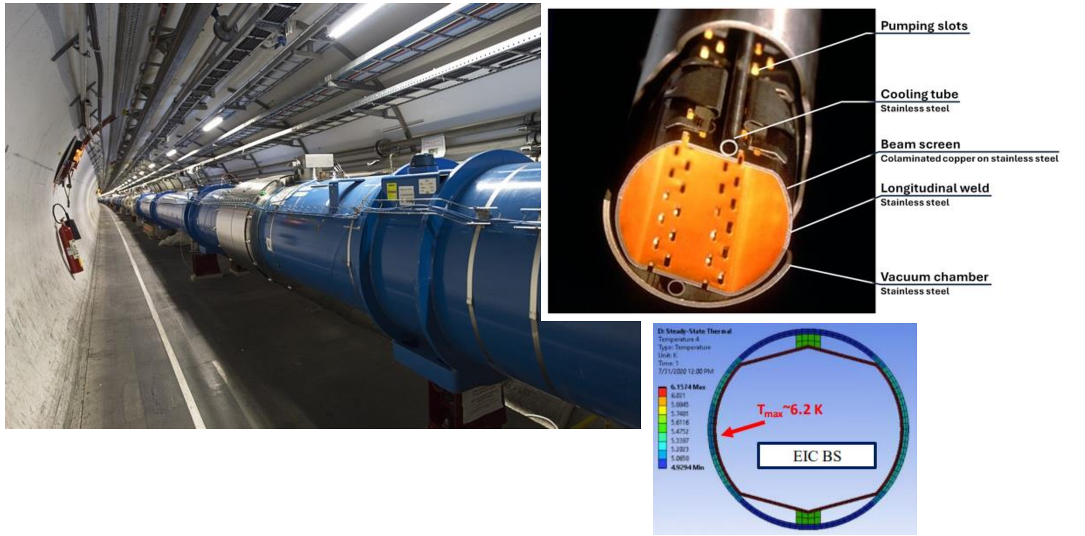
Present status/New goal – Strong INFN-LNF competences for higher-performance design.

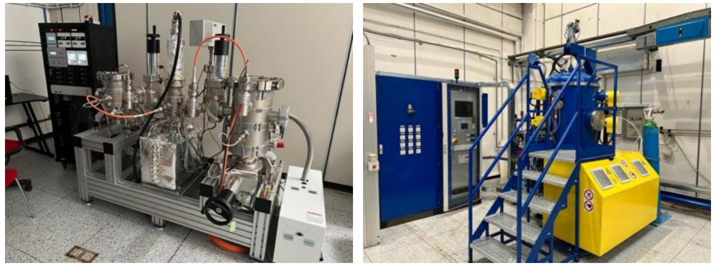
Who – **LNF with CERN (LHC and FCChh)**; originally developed for Dafne, then supported by CSN5; Collaboration with BNL-EIC (USA), synergies with ET

Work plan– To be defined, in correlation with definite collider scheme

Risks – No specific

Benefits – To many R&D areas where challenging vacuum specs needed





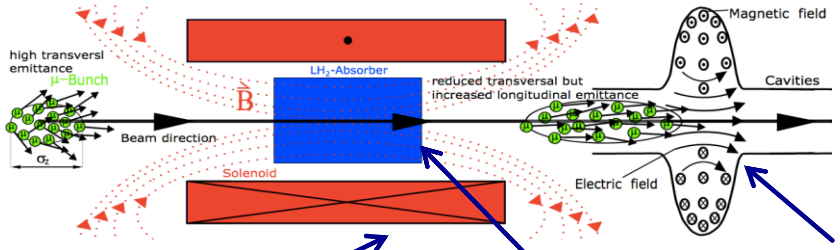
LNF: Outgassing TF, Vacuum furnace

R&D FOR THE MUON COLLIDER
DEMONSTRATE E-H OVERLAPPING IN THE MUON COOLING CELL

Need - R&D for the **muon cooling cell** and its test infrastructure: **improve RF breakdown in high-H conditions** (~30 MV/m in >7 T)

Present status – **Initial studies on-going** in INFN-Mi-LASA with first INFN funding: 30 MV/m NC-RF integrated in a HTS large bore solenoid field.

New goal – **Design and experimental tests** of RF cavities in high-H field. EM, thermomechanical, and BD simulations.
Higher-then-needed-f cavities **1.3÷12 GHz** (smaller, easier!) can be tested **in existing infrastructure** (H > 5 T and various configurations).
Installations at INFN-Mi-LASA (in IMCC Muon Cooling Demonstrator Program).

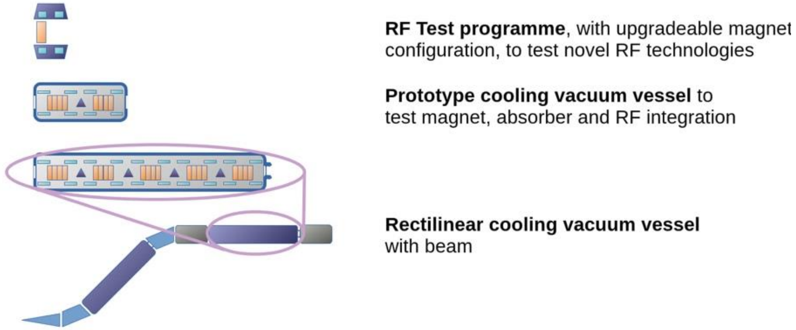


High-field, superconducting solenoid

Robust absorbers

High-G NC cavities

Muon Cooling Demonstrator Program



R&D FOR THE MUON COLLIDER
DEMONSTRATE E-H OVERLAPPING IN THE MUON COOLING CELL

Who - INFN-LASA, LNF, LNS, To within RD_MUCOL (CSN1), EU-MuCol and ESPP-A-MUCOL (INFN Executive Board dedicated funds), collaboration – IMCC: CERN, CEA, UKRI, and more recently SLAC

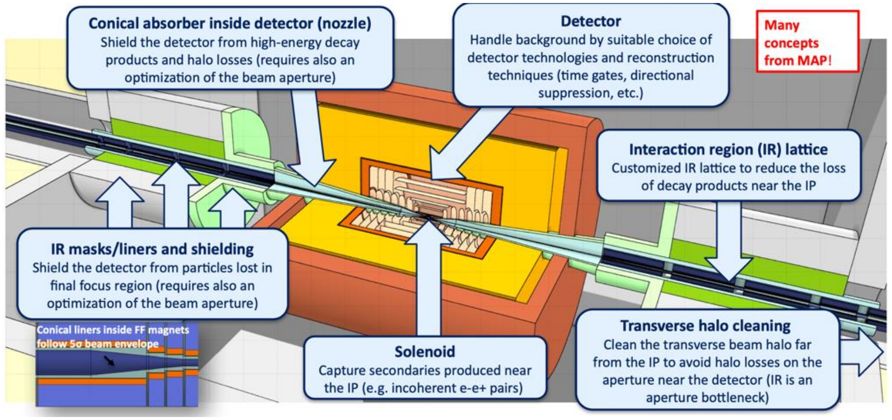
Schedule -
1) **3 GHz RF cavity and 5 T** magnetic solenoid designs – material test @ LASA
2) 5 T solenoid procurement – **C, X band RF power test @ LNF**
3) **704 MHz RF cavity** design and procurement and tests
4) **HTS coil** design
5) HTS coil and 704 MHz RF cavity: **integration, operation and test @ LASA**

Risks – Not achieving the required performance within the R&D program. **Understanding the limits is paramount.** Mitigation: involving national and international major experts in the sector.

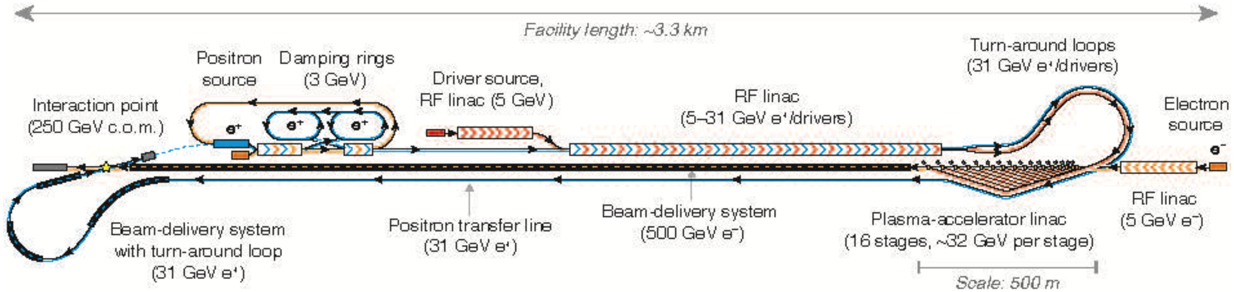
Benefits – Availability of **test stands** to study materials and their properties to reduce breakdown strengthens INFN leadership in the sector. **HTS coil at >5 T (bore ~200 mm)** will be an unrivaled experimental set-up.

MUON COLLIDER R&D: MACHINE DETECTOR INTERFACE (MDI) STUDIES AND DESIGN

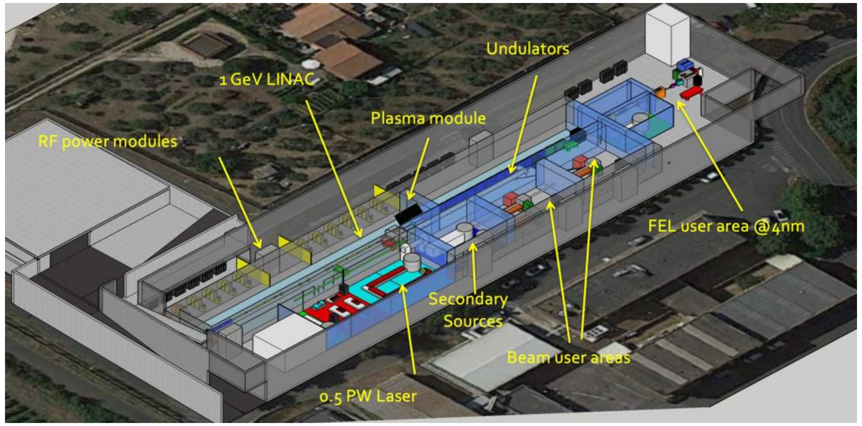
- Need- Integrated design of **machine interaction region (IR), detectors and magnet**, to **mitigate the effect of the machine backgrounds (Beam-Induced and Incoherent Pair Production) on the Detector**..
- Present status- **Proof of concept designs** @ 3 TeV and 10 TeV c.o.m. energy exists. (CERN and INFN-UniPD).
- New goal- Design of **shielding structure** (IR, shapes, materials, support). **Integration** studies/simulations. Design and test of **moke-ups**.
- Who - INFN: PD, Ge, RM-1, To, Ts;   within RD_MUCOL (CSN1) and ESPP-A-MUCOL within IMCC CERN.
- Schedule - **Design of shielding** structure (IR, shapes, materials, support) – **2 years** (DEL: material choice, baseline design); moke-ups and performances studies (**~ 2 years**)
- Risks - **Shielding material** availability, handling, machining (W or compound material) - Structure **constraints**
- Benefits - Advancement on shielding design structure for high radiation level facilities



ACTIVITIES FOR FUTURE PLASMA-BASED COLLIDERS
LEVERAGE ON EUPRAXIA TO DEVELOP COMPACT COLLIDERS



The Hybrid Asymmetric Linear Higgs Factory Project - HALHF



EuPRAXIA @ SPARC_LAB

- Need - **More compact, less expensive** high-energy (plasma-based) linear collider with >10 GV/m **accelerating field (x10–100** times vs conventional technology). Muon acceleration. Smaller footprint, less concrete, **smaller P/$\mathcal{L}$**.
- Present status - EuPRAXIA at LNF, AWAKE at CERN, HALHF (see Figure) in Europe, FACET II in the US, the large CEPS collider developed in China. Similar plans exist for PETRA4. EuPRAXIA may well provide important results to de-risk any plasma-based collider concept.
- New goal – **R&D on advanced plasma components towards plasma-based LC feasibility**. (WP1) theory and simulations, (WP2) high rep-rate module prototypes, (WP3) beam manipulation for high-η acceleration, (WP4) e^+ production/ acceleration, (WP5) scalable laser driver technology, (WP6) **design and test of a staging module at EuPRAXIA_SPARC_LAB** (most important to support any plasma-based Collidear Design)

ACTIVITIES FOR FUTURE PLASMA-BASED COLLIDERS
LEVERAGE ON EUPRAXIA TO DEVELOP PBC

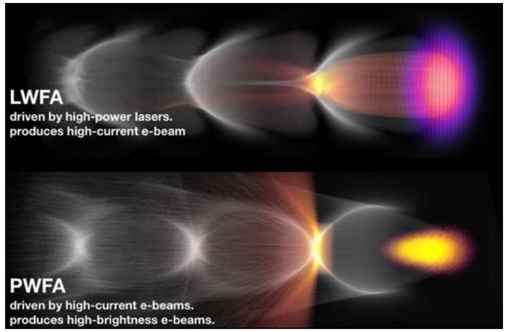
Who - **INFN - LNF** leads WP6, WP3, WP4 and WP2 (new plasma-based components) and contributes to WP1. **LNS** develops the capillary system for optimizing electron beam acceleration (WP2). **Roma-1** on WP1, WP2, WP3 and WP4. **Roma-2**: WP1, WP4. **Milano**: WP1, WP3. **Pisa**: WP5 (leader), WP1. **Queen's University Belfast:** WP4, (leader) pioneers on laser-driven positron generation and detection. **IST Lisbon:** beam dynamics studies in support of WP2 and WP3.

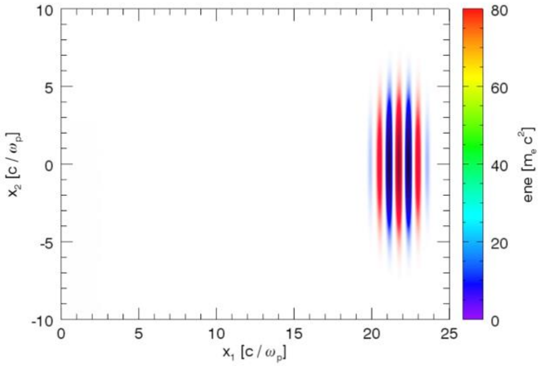
Schedule

WP1 - Plasma accelerator theory, simulations (2025-2028) synergic with EuPRAXIA@SPARC_LAB activities.
WP2 - High repetition rate plasma module (2025-2029) synergic with EuPRAXIA/PACRI activities.
WP3 – High-η plasma acceleration, high transformer ratio mode (2025-2028) preliminary test on going at SPARC_LAB.
WP4 - Positron source and acceleration (2025-2028) preliminary design study in progress at SPARC_LAB.
WP5 - Scalable laser driver technology (2025-2029) synergic with EuPRAXIA/PACRI activities.
WP6 - Design and Test of a staging module at EuPRAXIA_SPARC_LAB (2025 => 2031), fundamental for LC but not supported.

Risks – Underlined WPs are high risk-high gain, most critical component for any LC design.

Plasma Capillary Module





Plasma Acceleration Simulation

OUTLOOK

With the FCC-integrated approach (FCC-ee, followed by FCC-hh) as the next major flagship collider project for Europe, and for CERN, very sound proposals were presented (on FCC, MC, PBC):

FCC

- R&D distinctively for FCC-ee: R&D on the **interaction region, injector design and damping ring**, and studies of **collective effects**.
- **High-field magnets and RF cavities** (bulk Nb; thin films) are transverse technological sectors, fundamental for FCC and other colliders (and more), where INFN has a very relevant profile.
- R&D on **power couplers, materials for vacuum chambers, high-intensity positron sources** concur to shorten technical improvements for FCC and have vast applications

MC

- Muon collider is the main longer-term collider option. Developing a **muon-cooling-cell demonstrator** is a key challenge, and INFN has a leading role in IMCC

PBC

- A plasma-based collider is an even farther prospect, with **EuPRAXIA** as a key platform for paramount developments.

SPUNTI PER LA DISCUSSIONE

1. Le proposte di linee di R&D sugli acceleratori ci appaiono: 1. su temi critici 2. sufficientemente ben inserite nel contesto internazionale

- Commenti/osservazioni/integrazioni?

2. Ad alta priorità le attività FCC-related (ee ed hh)

Alcune più specifiche (IR, BD, Iniettore) Alcune con un significativo impatto anche sulla sostenibilità/fattibilità del progetto stesso (HFM e cavità-SC, couplers, vuoto, sorgenti di positroni) e con validità più generale.

- Commenti/osservazioni/integrazioni?

3. MuColl: la fattibilità di un dimostratore suscita un grande interesse.

- L'attività per la cooling cell potrebbe presto avere bisogno di un peso più significativo; la attività per magneti e cavità SC sembrano tasselli di programmi ben più vasti; i tests su una beam facility saranno il vero banco di prova. Siamo adeguatamente preparati ad uno scenario di eventuale ramp-up del programma?

4. Plasma collider: più a lungo termine, ma ben inserita nei programmi dell'INFN (LNF-PNRR) e che occuperanno i LNF nei prossimi 10-15 anni (almeno...)

- Quali sviluppi in sovrapposizione, sinergia, quale «competizione» con EuPRAXIA?