Laboratory Directors Group

Accelerator Research

based on LDG Accelerator Roadmap

EPS HEP Conference, Marseille, July 10, 2025

Mike Seidel, PSI / EPFL

Accelerator R&D - Outline

1) LHC: most performant collider today.

2) Accelerator Technologies:

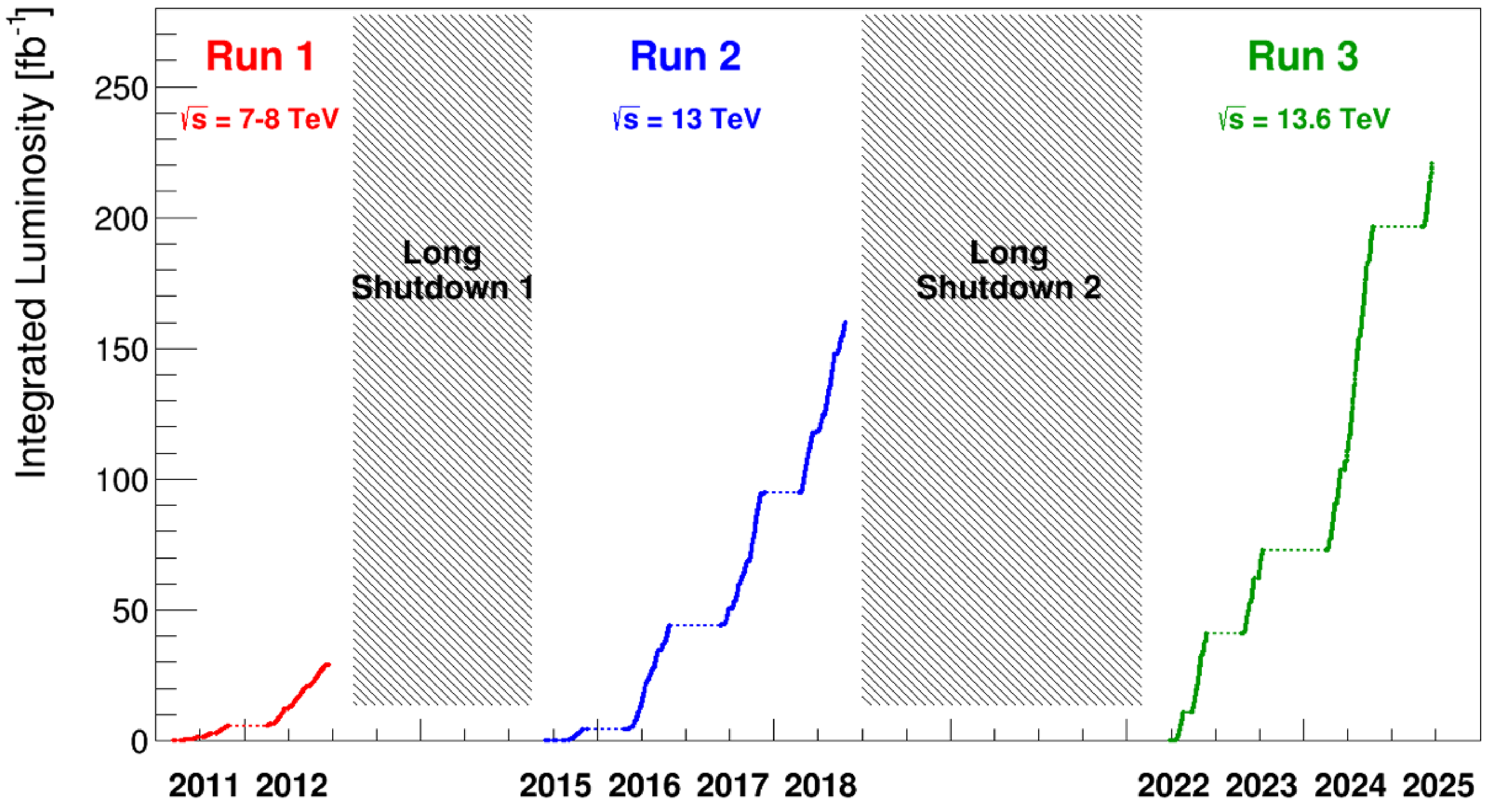
Magnets and RF Systems.

3) Advanced Collider Concepts:

Plasma Acceleration, Muon Collider, Energy Recovery Linac.

LHC / CERN – state of the art for colliders

Large Hadron Collider
- C=27 km, 100 m below ground
- 6.8 TeV per beam
- 1232 bending magnets, 8.3T, 1.9K
- total beam energy: ≈400 MJ
- circulating beam power: 4TW
- ~10^9 collisions/sec; Higgs: ~1/sec
- up to 120 MW grid power, CERN: 1.3TWh/y



Total integrated luminosity to ATLAS and CMS since LHC start: 410 fb-1, of which 380 fb-1 at √s ≥13 TeV

F.Gianotti, 06/2025

major improvements:
- **injector chain: beam brightness (intensity, emittance)**
- **beam size at IP (β*, thanks to collimation system)**
- **ongoing HL-LHC upgrade with new FF system**

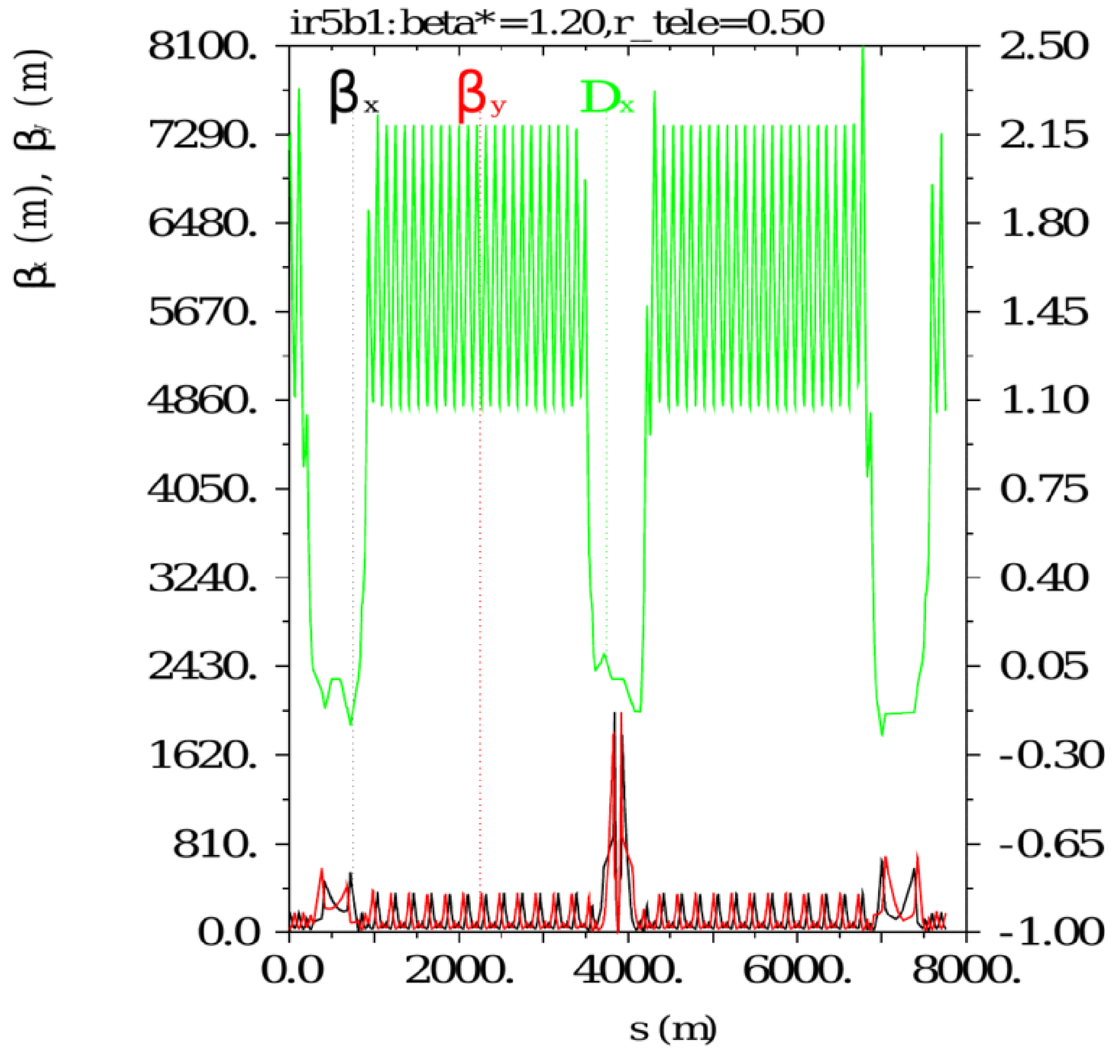
LHC Luminosity Levelling
(example for sophistication)

pile-up control by:

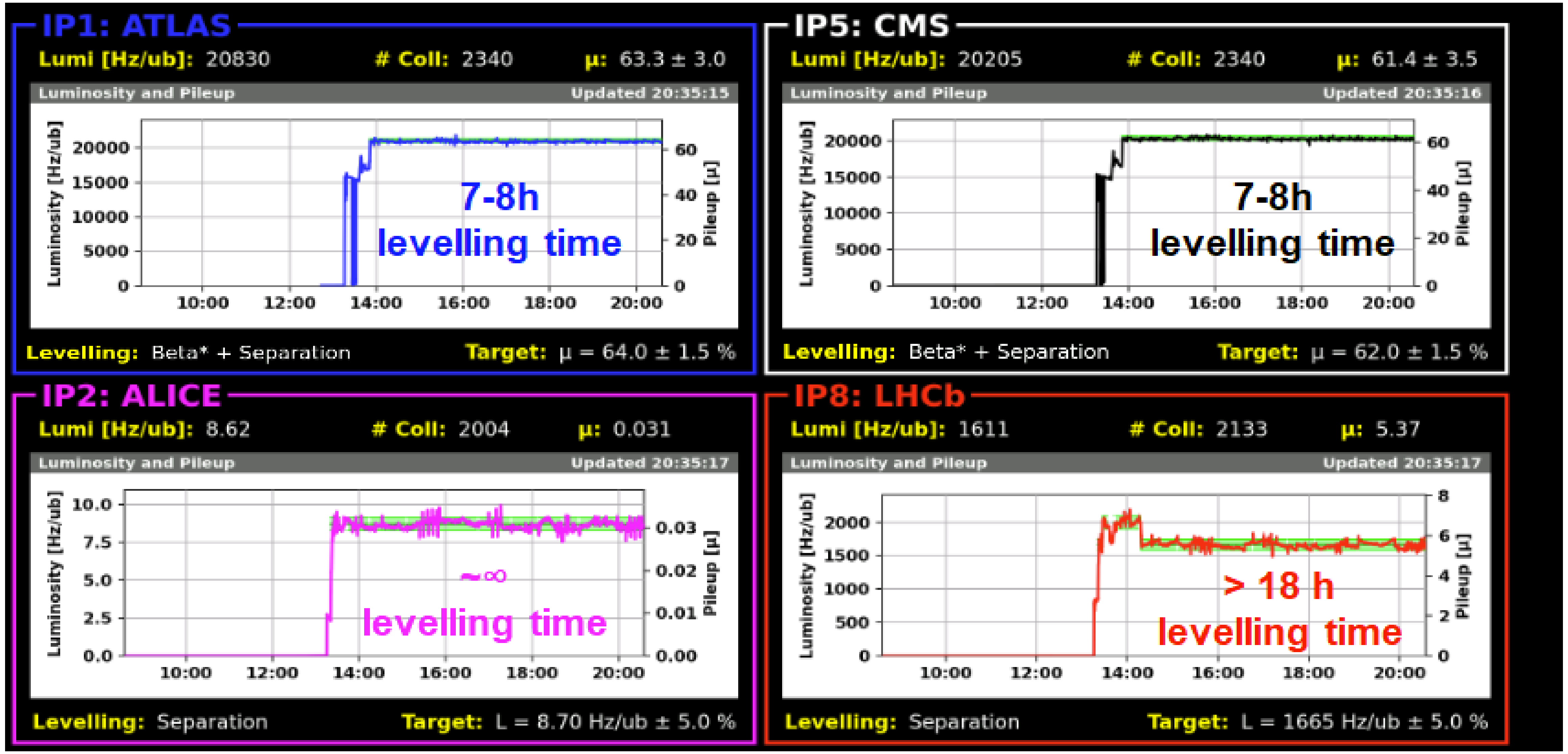
1) varying the beam size at IP

2) varying overlap of beams at IP

Complex but runs flawless!



telescopic β*-levelling
S.Fartoukh et al



luminosity and pile-up at the LHC experiments

Accelerator Roadmap

- 2020 update of ESPP: LDG Roadmap for accelerator R&D: http://arxiv.org/abs/2201.07895 , appr. by council 03/2022
- work packages (technologies, concepts):
  - **1) High Field Magnets**
  - **2) High Gradient RF Structures and Systems**
  - **3) High Gradient Plasma and Laser Accelerators**
  - **4) Bright Muon Beams and Muon Colliders**
  - **5) Energy-Recover**
- February 2025: Review of R&D activities by external committee, chaired by N.Holtkamp (Stanford U./SLAC)

Midterm Review of LDG Roadmap (ESPPU submission)

2022 Accelerator Roadmap

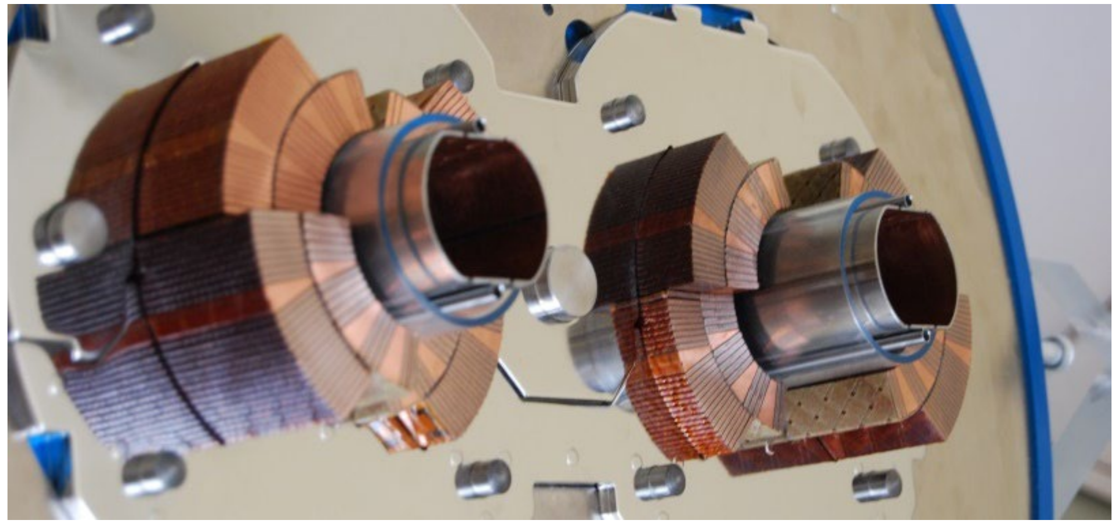
1) Technologies

High Field Magnets,
panel chairs: E.Todesco (CERN), B.Auchmann (PSI)

High Gradient RF Structures and Systems,
panel chairs: G.Bisoffi (INFN LNS), P.McIntosh (STFC)

Superconductivity in Accelerators

s.c. magnets: highest fields

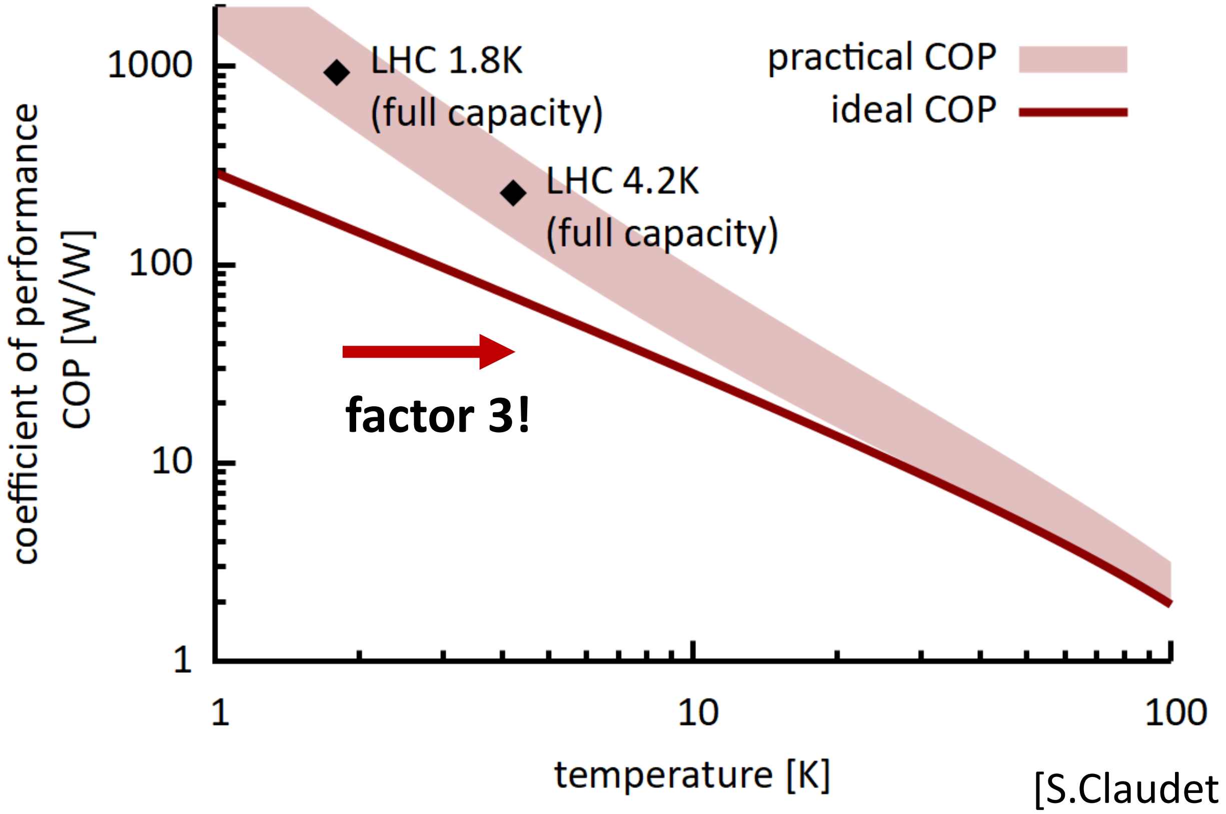


→ **zero losses except ramping**

RF Resonators: highest power transfer

→ small but **non-zero losses due to mass of Cooper pairs**

but: cryogenic efficiency!



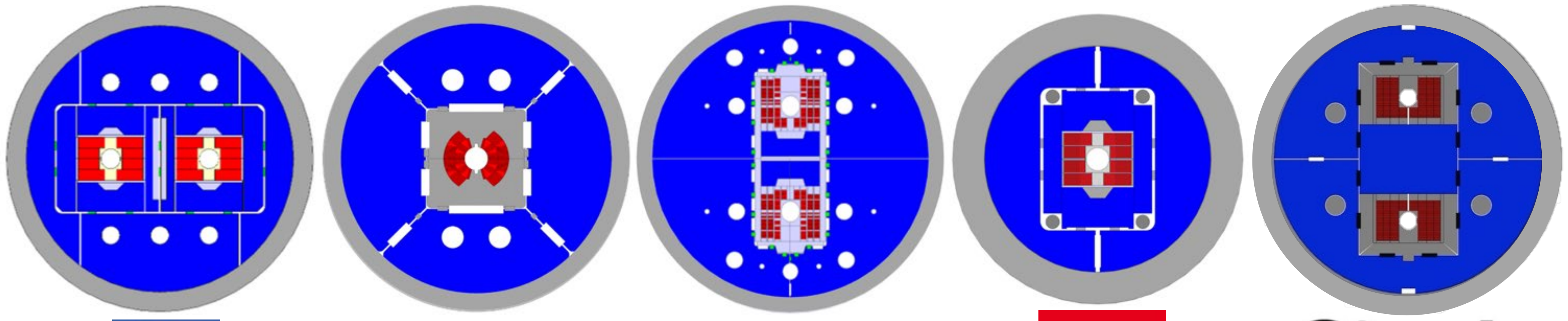
[S.Claudet et al, CERN 2013]

$$P_{\mathrm{cryo}} = \mathrm{COP} \cdot P_{\mathrm{dissip}}$$

COP ≈ 1000@1.8K

HFM: FCC-hh 2025 Updated Baseline Parameters

		CDR 2019	2024-Nb_3Sn
Dipole field	(T)	16.0	**14.0**
Dipole aperture	(mm)	50	50
Magnetic length	(m)	14.3	14.3
Operational temp	(K)	1.9	**1.9**
Tunnel length	(km)	100	90.7
Arc length	(km)	82.0	76.9
Arc filling factor	(1)	0.80	0.83
Energy c.o.m.	(TeV)	50+50	42.5+42.5
Loadline fraction	(1)	0.86	**0.80**
J_c at 16 T and 4.2 K	(A/mm^2)	1500	**1200**
# dipoles	(1)	4587	4463
# quadrupoles	(1)	760	520



options (E.Todesco):

12 T magnet and 77 TeV (15-20% cheaper magnet, for 10% less energy);

…but range extends to 20T variants

Operation at 4.5 K with the same magnet, significant reduction of power consumption of cryogenics (580MW→ 430MW→ ca 330MW)

Hybrid Nb_3Sn/Nb-Ti (large reduction in the mass of Nb_3Sn conductor, even more at 12 T, significant cost reduction)

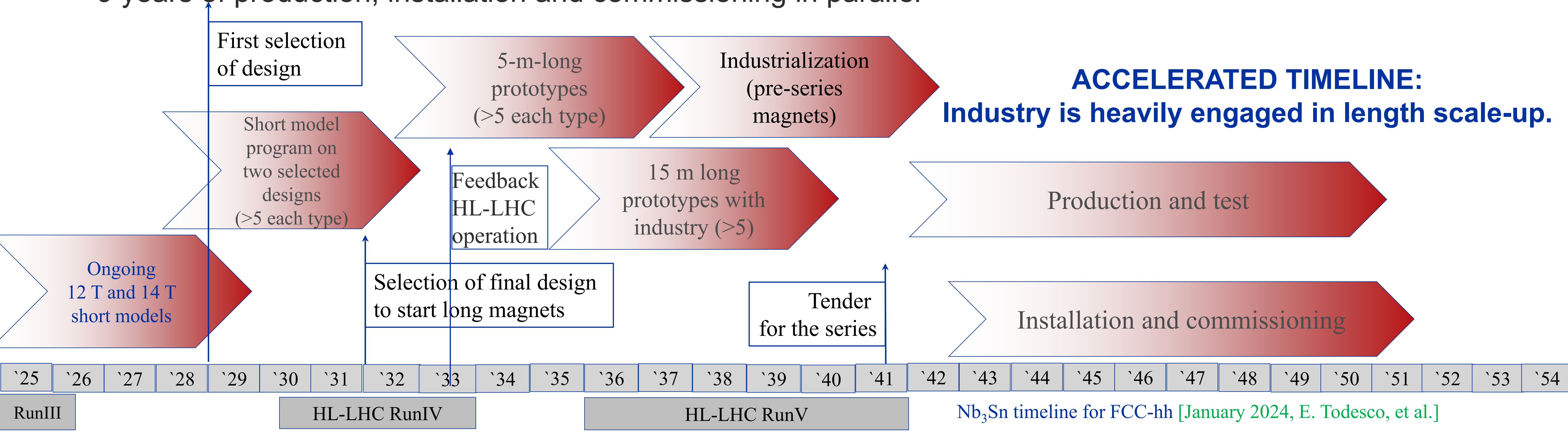
20-m-long magnets (instead 15m, 25% less magnets to produce, plus a few more TeV or a bit more margin, an a bit cheaper magnet)

short model tests in 2026/27, then downselection

HFM High Field Magnets Programme

Timeline for LTS

- Select the design by 2028/29 (first indications from HFM tests in 2026-2027)
- Short model program to verify reproducibility and optimize manufacturing processes: in 2029-2031
- Scaling in length in two steps: TRL 7 achieved between 2032 and 2040
- Industrialization for final magnets, with pre-series
- 9 years of production, installation and commissioning in parallel



ACCELERATED TIMELINE:
Industry is heavily engaged in length scale-up.

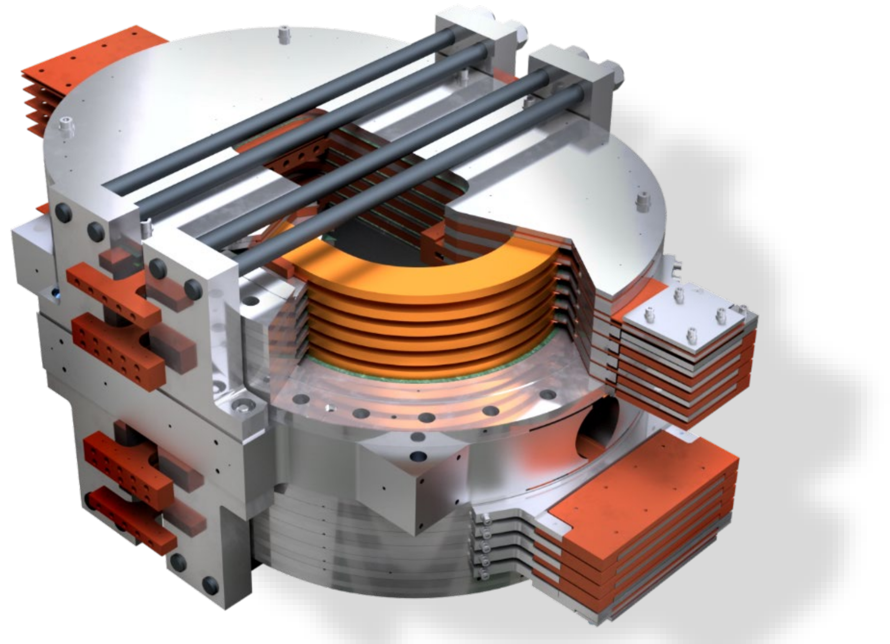
Nb_3Sn timeline for FCC-hh [January 2024, E. Todesco, et al.]

From now to end of 2026: HTS demonstrators

INFN activities: studies on ReBCO demonstrator

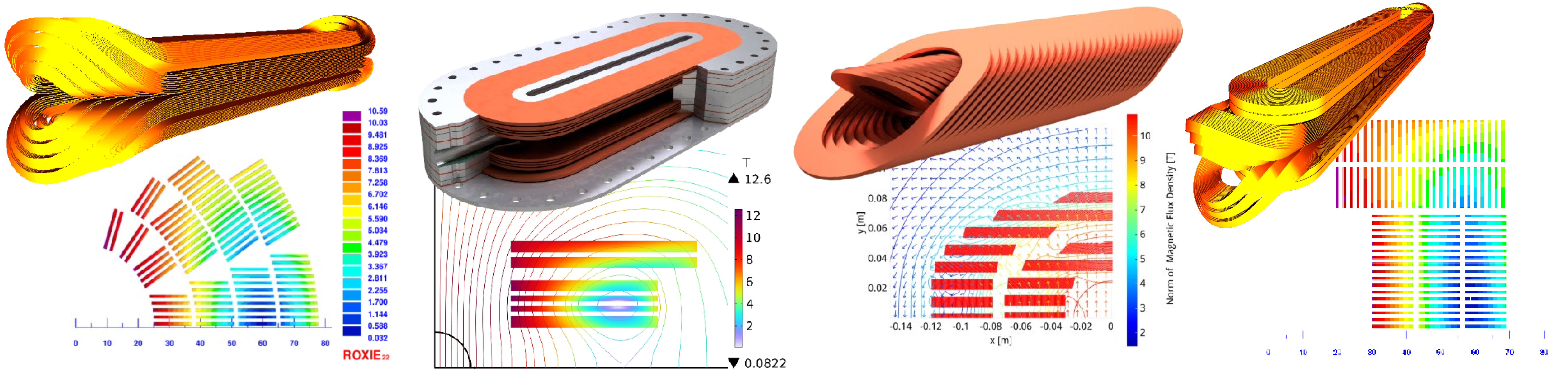
- 10 T field at 20 K, design to be selected bwteeen three variants
- In synergy with other activities in INFN (ESMA, 10 T split racetrack)

Target for end 2026: selection of design (and test of ESMA)



ESMA [M. Statera, L. Rossi et al.]

Different options for 10 T, 20 K dipole [M. Statera, et al.]

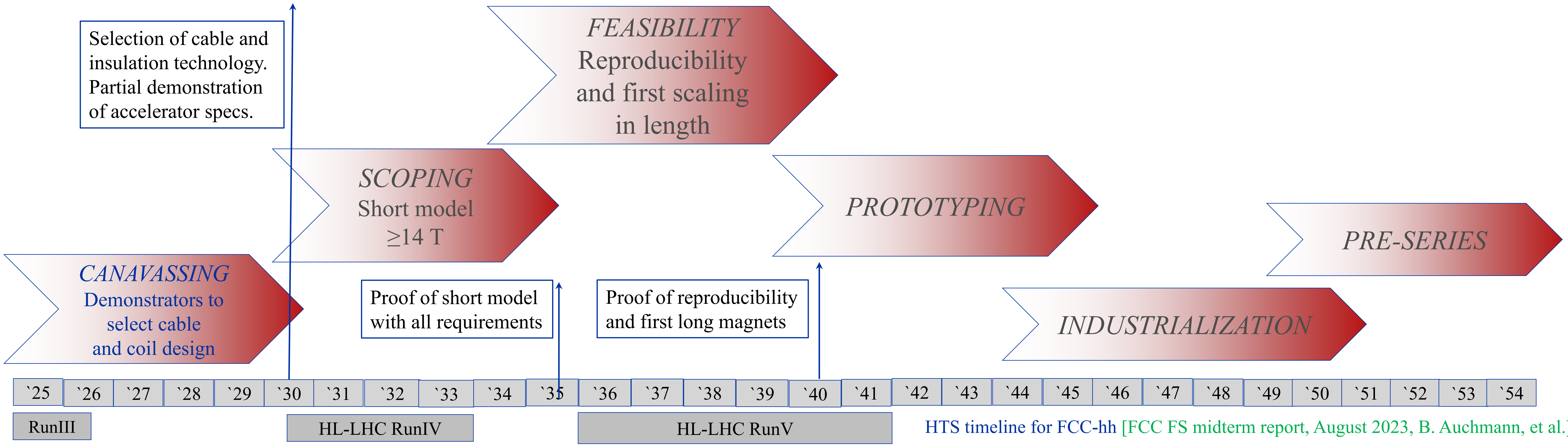


Timeline for HTS

Target: 2035 a proof of a short model dipole with all features for FCC

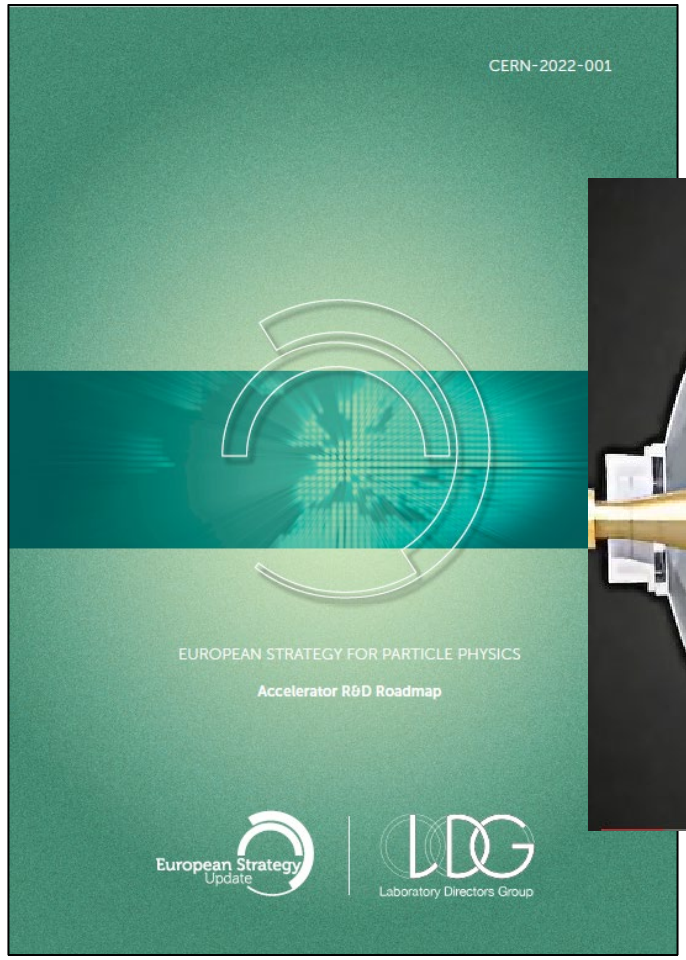
- Aperture, field ≥14T, field quality, protection, …

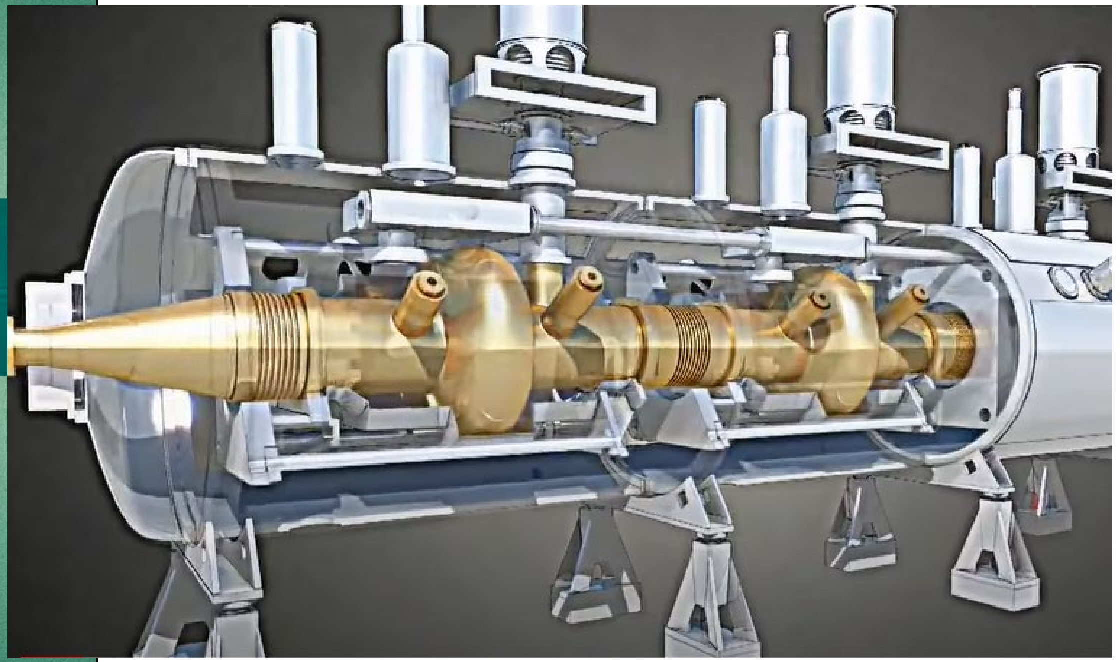
Development of LTS and HTS technology in parallel at least until 2035.



HTS timeline for FCC-hh [FCC FS midterm report, August 2023, B. Auchmann, et al.]

The RF Coordination Panel (RFCP)





RF Panel coordination		G. Bisoffi INFN-I, P. McIntosh STFC-UK
WG1	Bulk Nb	M. Baylac CNRS-F, C. Madec CEA-F, L. Monaco INFN-I
WG2	Thin films	C. Antoine CEA-F, O. Malyshev STFC-UK
WG3	Couplers	F. Gerick CERN, E. Montesinos CERN, A. Neumann HZB-D
WG4	NC High gradient	W. Wünsch CERN, D. Alesini INFN-I
WG5	RF Power sources	I. Syratchev CERN, G. Burt STFC-UK, M. Jensen ESS-S
WG6	LLRF, AI, ML	Z. Geng PSI-CH, W. Cichalewski U-Lodz-P

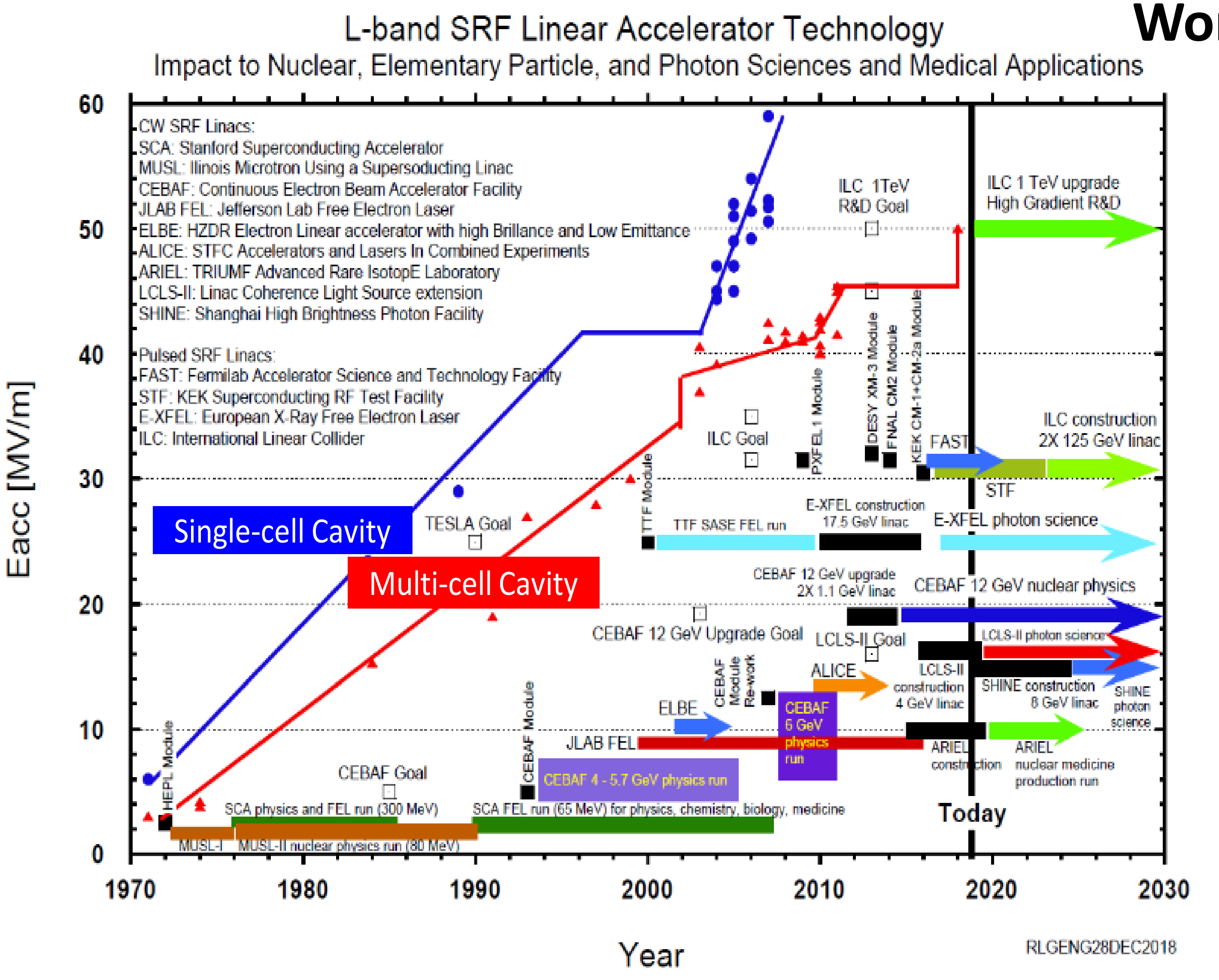
11/2022: RF Coordination Panel nominated, to follow the concrete implementation of the roadmap recommendations":

✓ serve the update of ESPP on benefits, challenges, feasibility, risk and costs, with top priorities to make needed **technology jumps**.

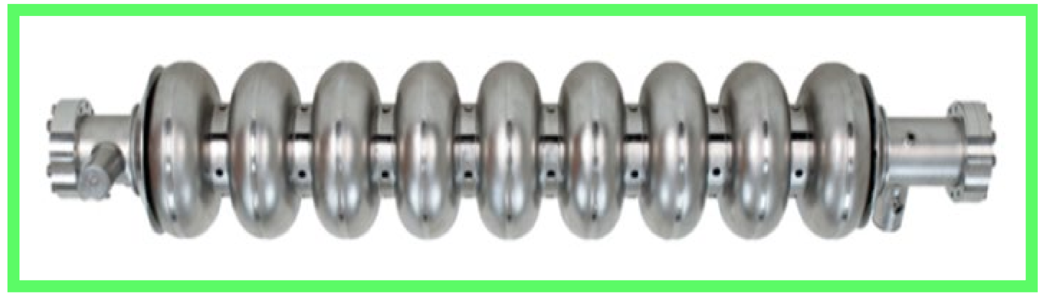
With a significant **SUSTAINABILITY** focus:

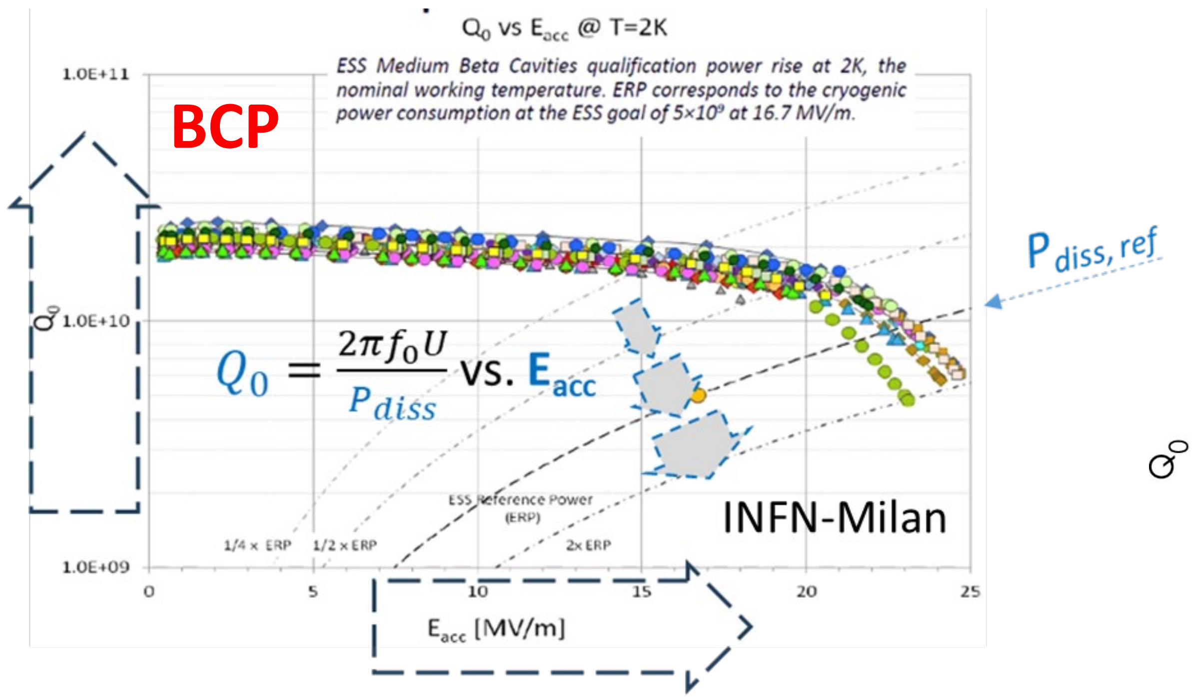
- **Hardware:** Simpler, easier and cheaper to manufacture, more industry sources.
- **Operability:** higher performance, more stable, cheaper to operate.

WG1: Bulk Niobium

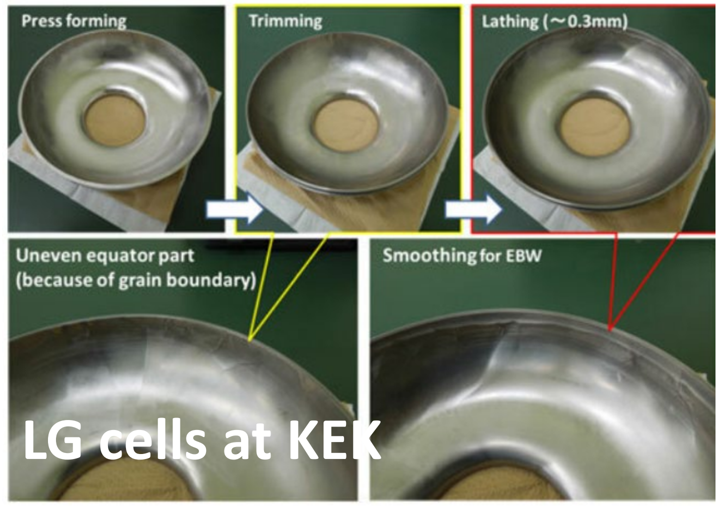


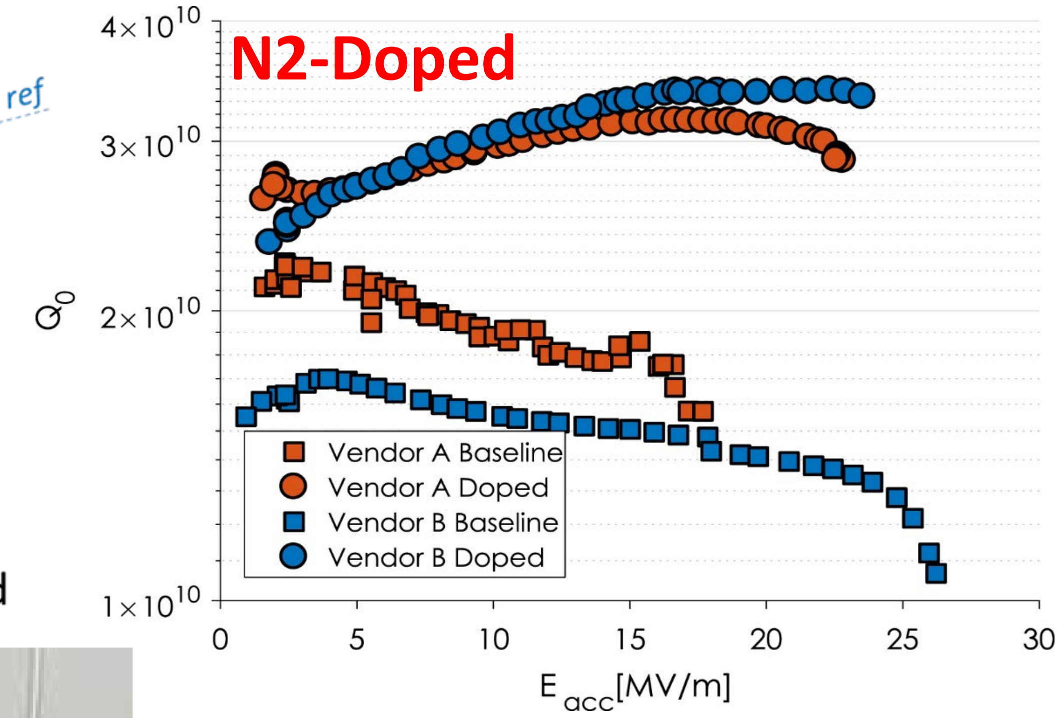
Workhorse: 1.3 GHz SRF , 9-cell cavity (TESLA)



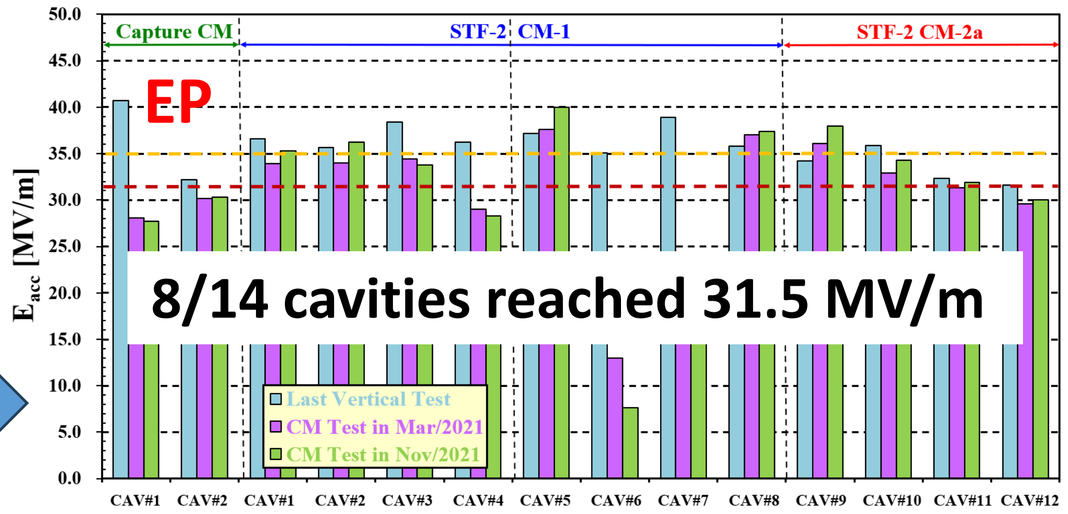


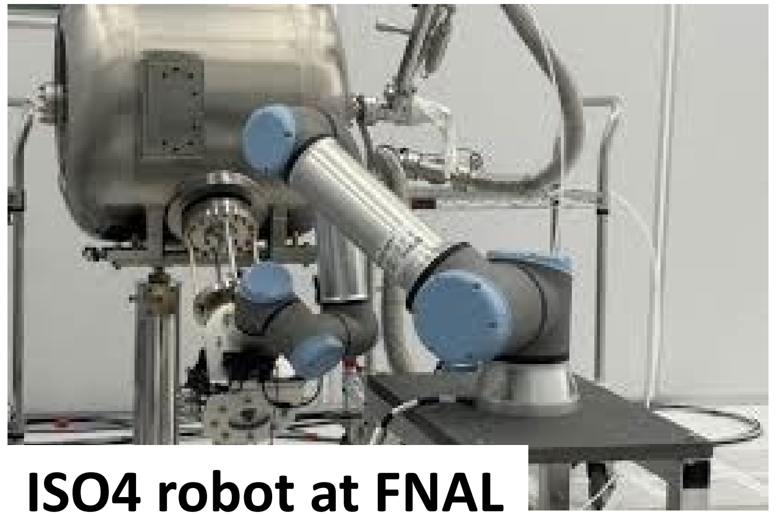
ESS Medium Beta Cavity Dynamic load 2-4 times reduced





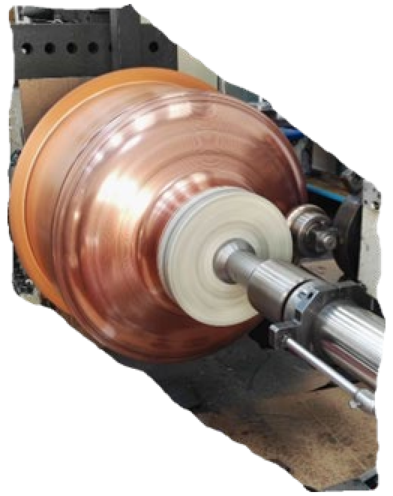
LCLS-II Baseline N2-Doping Verification (>2 times reduced dynamic load)





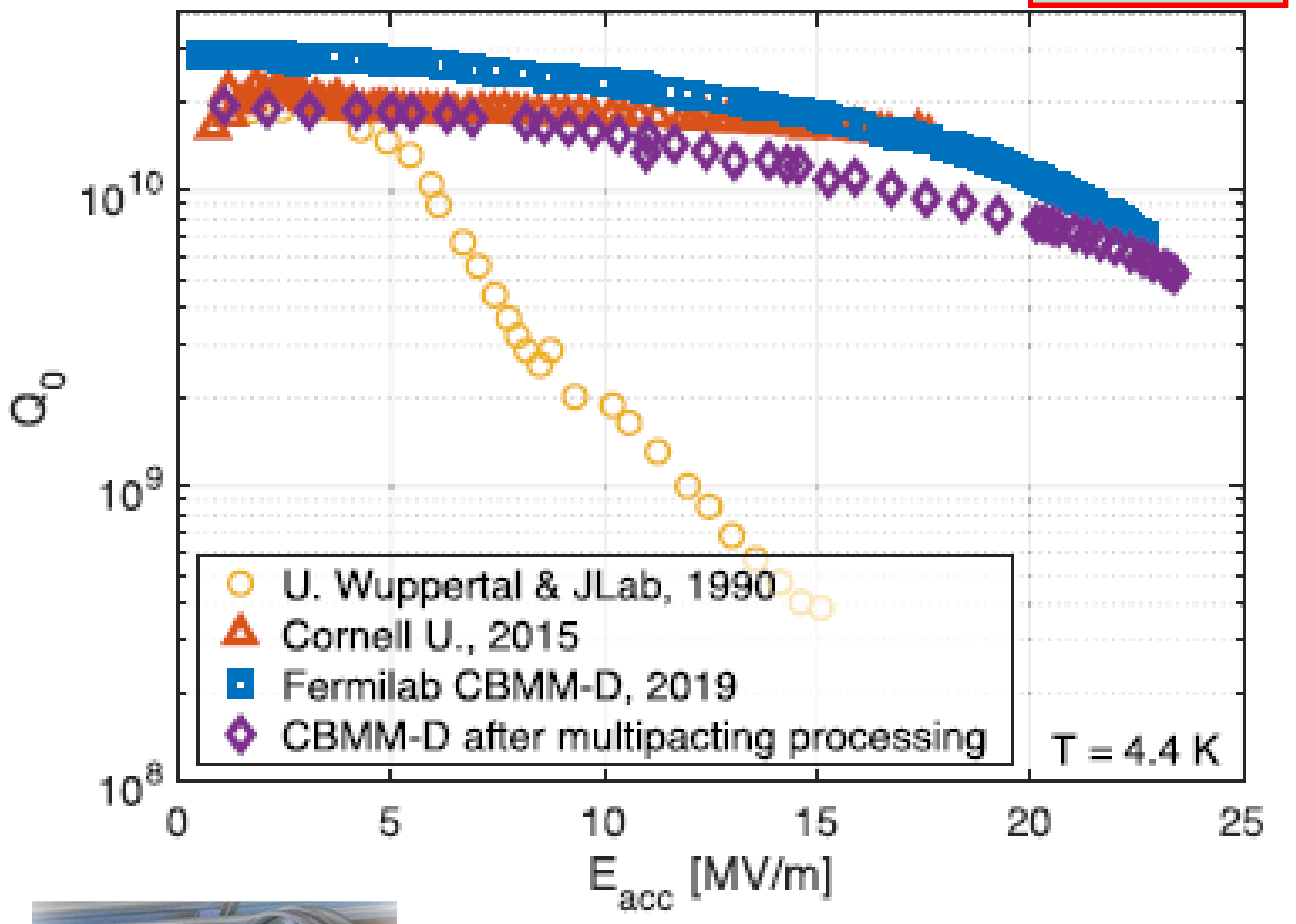
WG2: Thin-films

Seamless copper cavity substrates

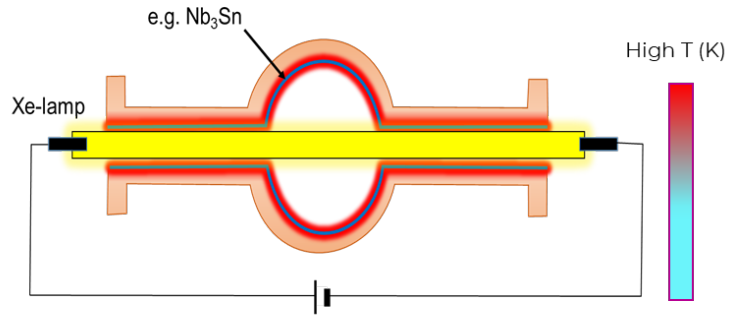


Nb3Sn on Nb at FNAL

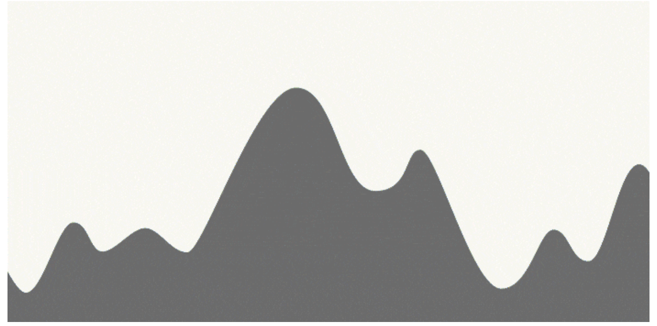
T = 4.4 K



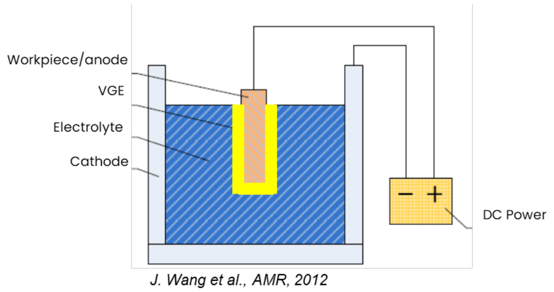
Substrate preparation



Flash Lamp Annealing

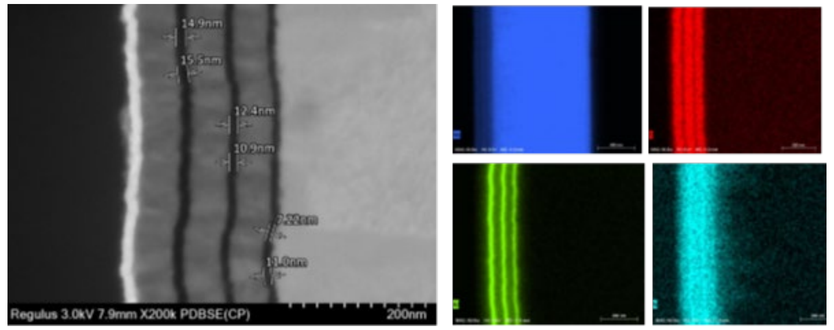


Same EP set-up
Different regime

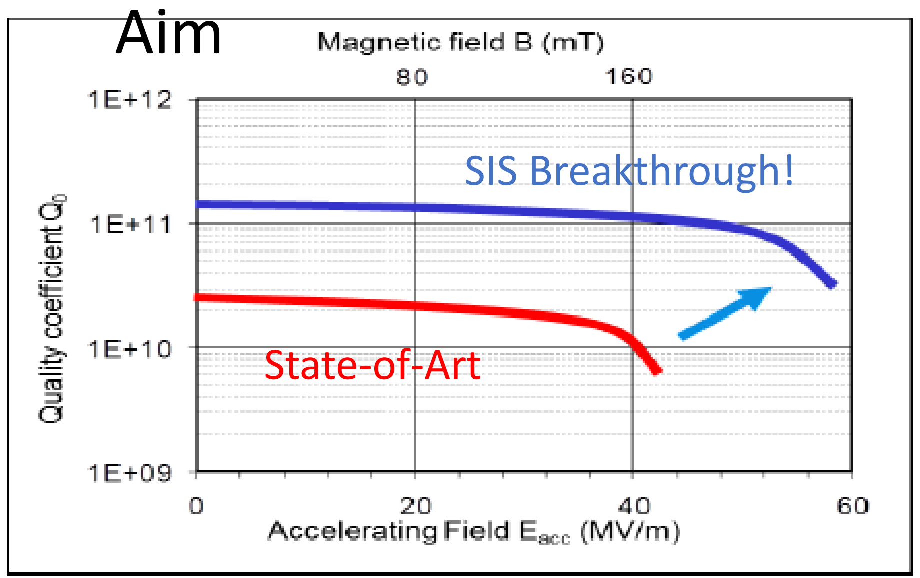


Plasma Electrolytic Polishing

[TFSRF24 – 16 – 20 Sept, Université Paris-Saclay.]



SIS multilayer coating (Nb/AlN/Nb3Sn) on Ta

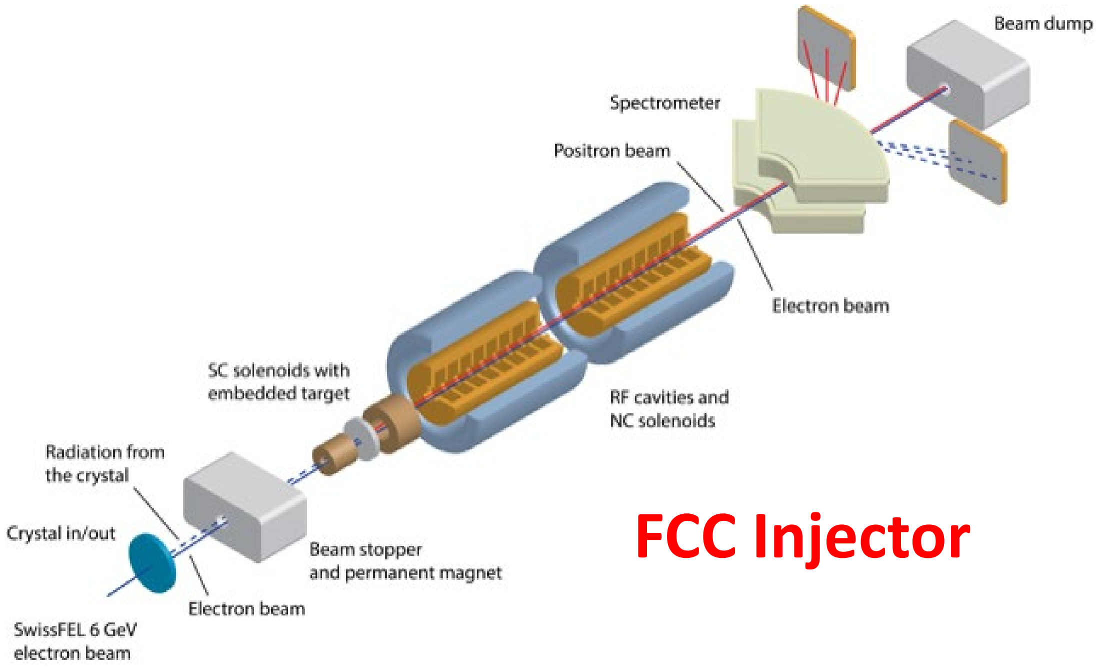


WG4: HG Normal-Conducting RF

CLIC/C^3/FCC: 100 MV/m achieved!

- Deep understanding of fundamental physics (multi-decade HG R&D and funding):
  - Great stimulus for industrial supply of NC RF components/systems.
- **Refine HG designs** - precision mechanics.
- **New materials**, procedures and focus to minimise costs.
- **Test NC structures in high magnetic fields**:
  - Paramount for Muon Collider R&D (major requirement).
- **Fund new and upgrades of existing test infrastructures as priority.**

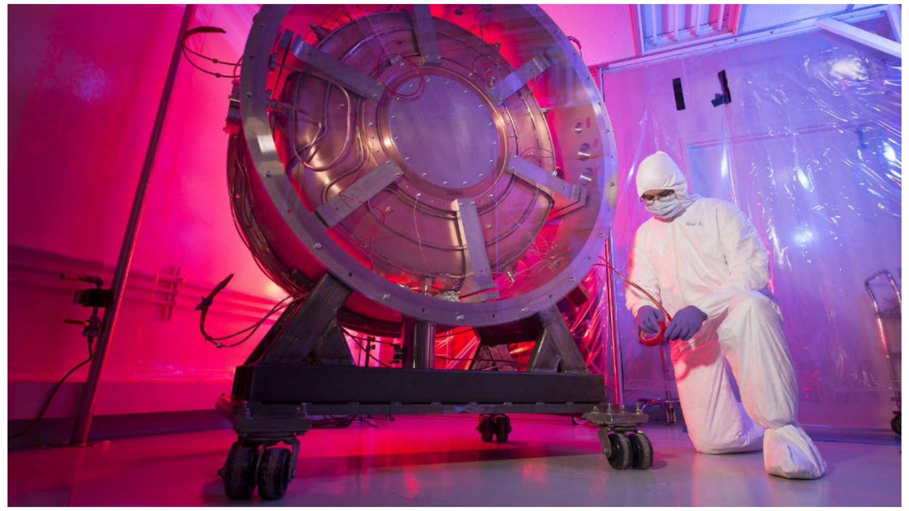
X-Band Cell Manufacture



FCC Injector

Xbox Test Stand at CERN

Muon Collider

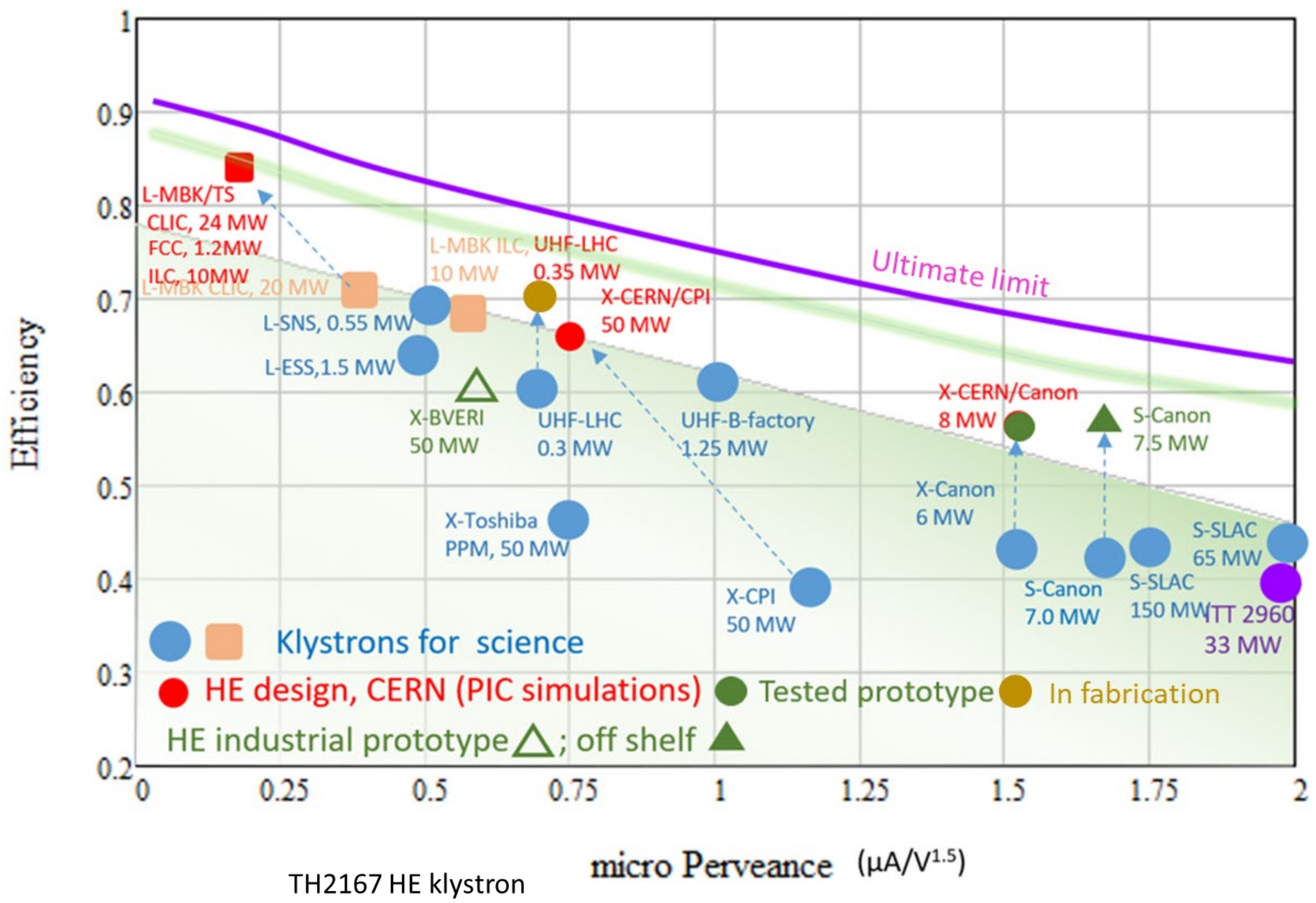


WG5: RF Power Sources & High Efficiency

Strong industry engagement – Thales, CPI and Canon!

System efficiency (400MHz). Z/W/H poles.

Sub-System	TH2167 HE	MB TS klystron	MB Tristron
At cavity	378 kW		
WG efficiency	95% ← 398kW		
Amplifier	70% ← 569kW	86% ← 462 kW	93% ← 427kW
HV converter	98.5% ← 574.7kW	98.5% ← 466.7kW	98.5% ← 431kW
Solenoid	5kW	12kW	2.5kW
Driver	0.1kW	0.1kW	5kW
Heater	1kW	1kW	1kW
Power/cavity	580.8kW / 65%	479.8kW / 78.8%	439.8kW / 85.9%
Grid Power	153.3 MW	126.7 MW	116.6 MW
Grid power cost/ year • *5000 hours* • *80 Euro/MWh*	*61.3ME*	*50.7ME*	*46.7ME*



FCCee

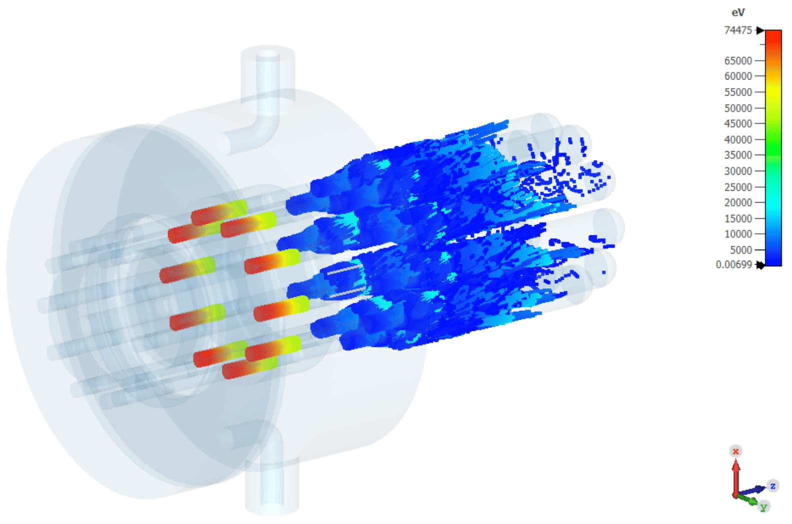
- 380 klystrons and 600 SSPAs.

CLIC

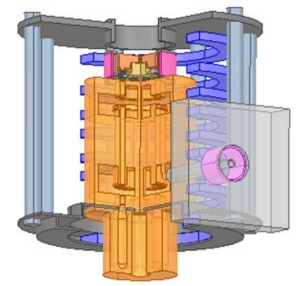
- 200 Multi-beam klystrons.

FCC High Efficiency

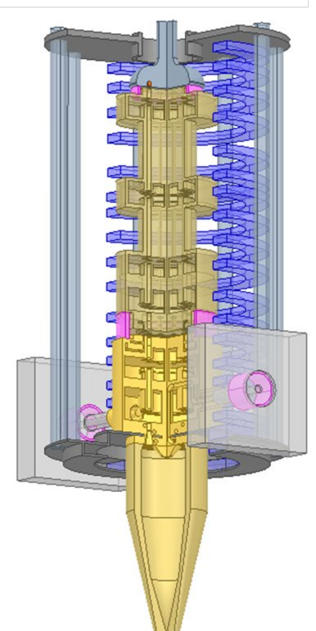
- 400 MHz, 1 MW, **multi-beam (x10) Tristron**
- 86% efficient, <3m long.
- **65% - 85% saves 38 MW electrical power!**



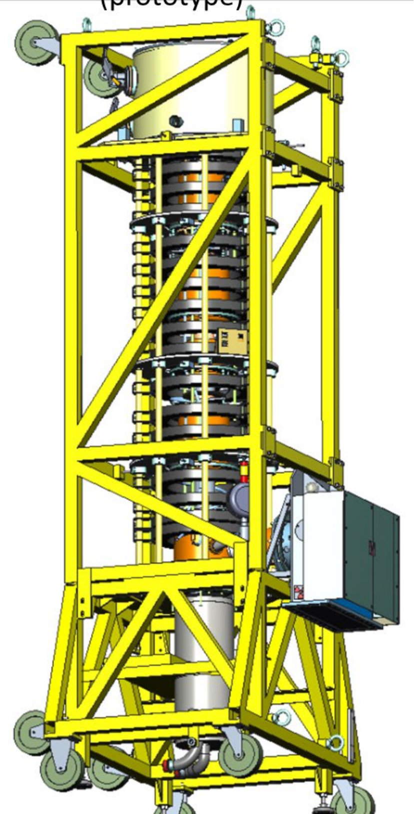
MB Tristron (concept)



MB TS Klystron (design)



TH2167 HE klystron (prototype)



- **Klystron:** R&D costly, primarily done in industry, unless significant investment in infrastructure at Labs (i.e. as at SLAC):
  - **Only 3 qualified vendors w'wide.**
  - Large cost increase, 50 - 100% over ~5 yrs.
- **SSPA:** efficiency increase relies on industry transistor R&D (i.e. GaN).

Summary Technologies

High Field Magnets:

1. LTS: several short prototypes with 12/14 T to be built, concept downselection relies on their performance
2. LTS: prototypes of l=5m by 2037 and full 15m by 2040; ca 4500 magnets $\rightarrow$ industrialization is key
3. HTS: by 2035 a proof of a short model for FCC $\rightarrow$ decision on priority HTS vs LTS
4. HTS: develop suitable cables with ramp capabilities; quench protection concepts

RF Systems:

1. covers a broad spectrum of accelerating resonator technologies and RF power sources
2. particular efforts are invested in superconducting bulk Nb and thin film resonators; a trend towards operation at higher temperature is visible
3. based on the recommendations of the ESPPU the efforts should be focused on prioritized projects

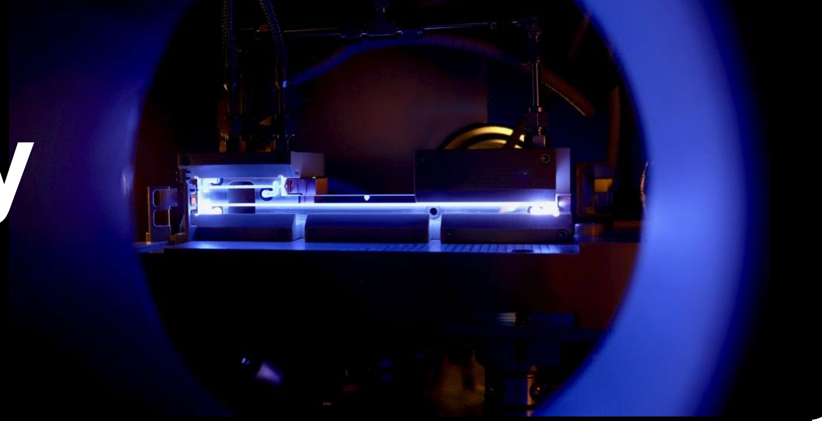
2) Advanced Collider Concepts

High Gradient Plasma and Laser Accelerators,
panel chairs: W.Leemans (DESY), R. Patathill (STFC)

Bright Muon Beams and Muon Colliders,
panel chairs: D.Schulte & S.Stapnes (CERN)

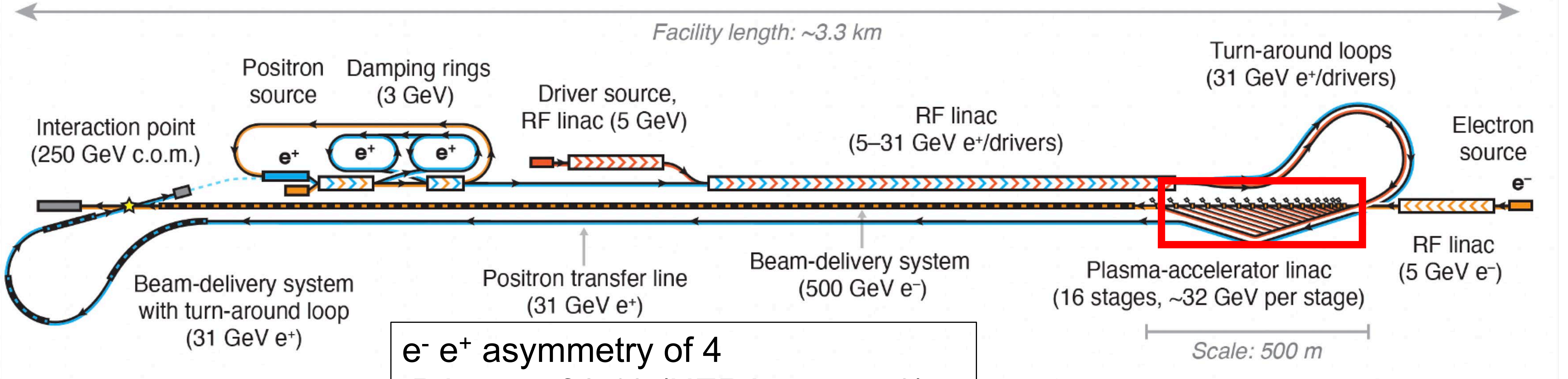
Energy Recovery Linacs,
panel chairs: J.D'Hondt (NIKHEF), A.Stocchi (IJCLab)

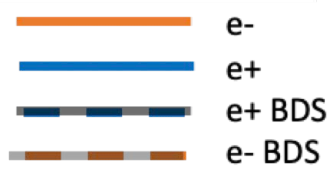
HALHF: A hybrid, asymmetric, linear Higgs factory



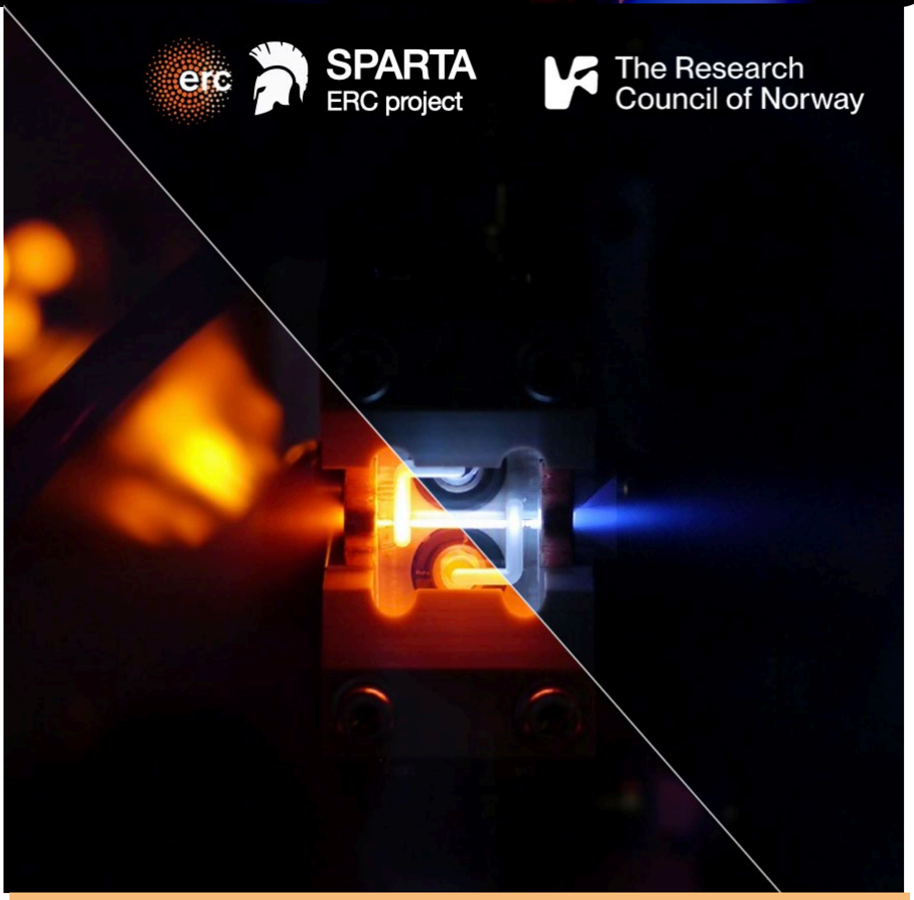
Initial design provides a concept that can fit in many major particle physics labs

WP1.1: Overall Collider Concepts (R. D'Arcy, C.A. Lindstrøm, B. Foster)





e^- e^+ asymmetry of 4
IP boost of 2.13 (HERA was at 3)
e^- ε_{ny} of 0.56 μm
$\mathcal{L}$ ~ $1\text{x}10^{34}/\text{cm}^2/\text{s}$



Supported by ERC grant - C.A. Lindstrøm

Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)
Lindstrøm, D'Arcy and Foster, arXiv:2312.04975

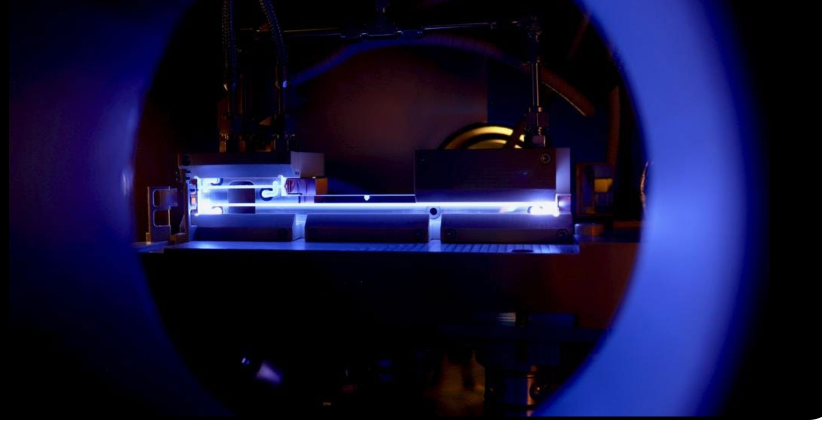
Major themes of work include :

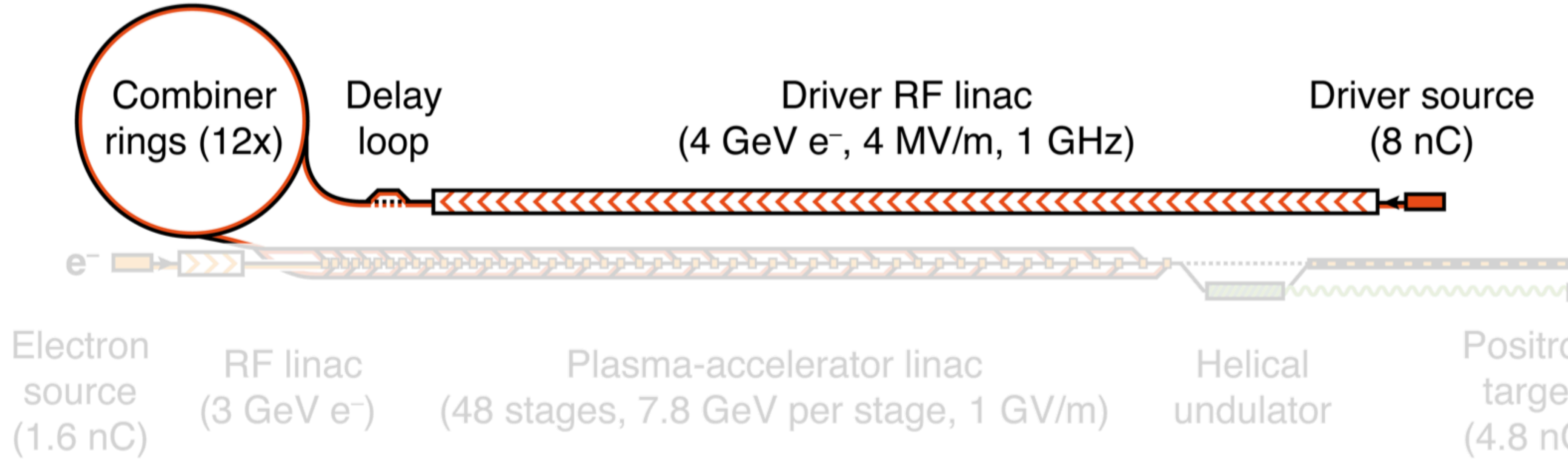
- Performance of the plasma linac (Emittance, efficiency, effective gradient, tolerances, polarization
- Integration of a plasma linac in a collider (linac technology, time structure, drive-beam scheme..)
- Requirements of the plasma source (Rep. rate, time structure, heating..)
- Asymmetric collisions and detector developments (Specific to HALHF)

- no lasers
- no positrons

Drive beam linac design requires development

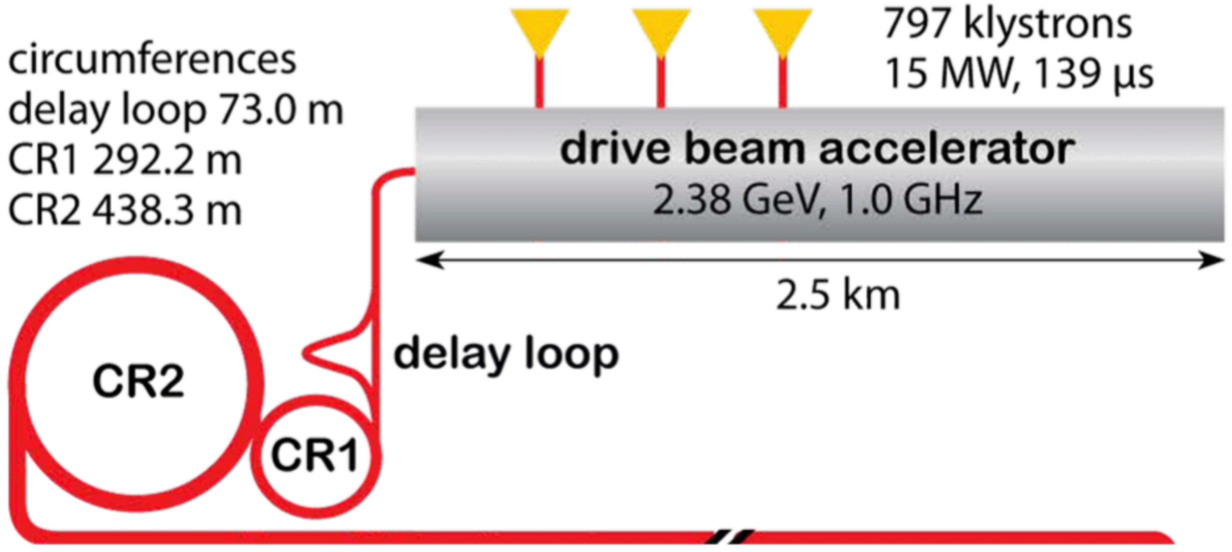
Synergy with other pillars of the roadmap





- The drive-beam linac is the cost driver of the HALHF facility (~40% of the total cost) ➞ klystrons, cavities, rings
- Design and beam parameters are intrinsically linked to the plasma accelerator and its operation

- Very similar to the CLIC drive-beam complex
  - Drive-beam energy: 2.4 GeV (CLIC) ➞ 4 GeV (HALHF)
  - Accelerating gradient (average): 1 MV/m ➞ 3 MV/m
  - Linac length: 2.5 km ➞ 1.3 km
  - Bunch charge: 8.4 nC ➞ 8 nC
  - Final bunch spacing: 0.0167 ns ➞ 0.167 ns



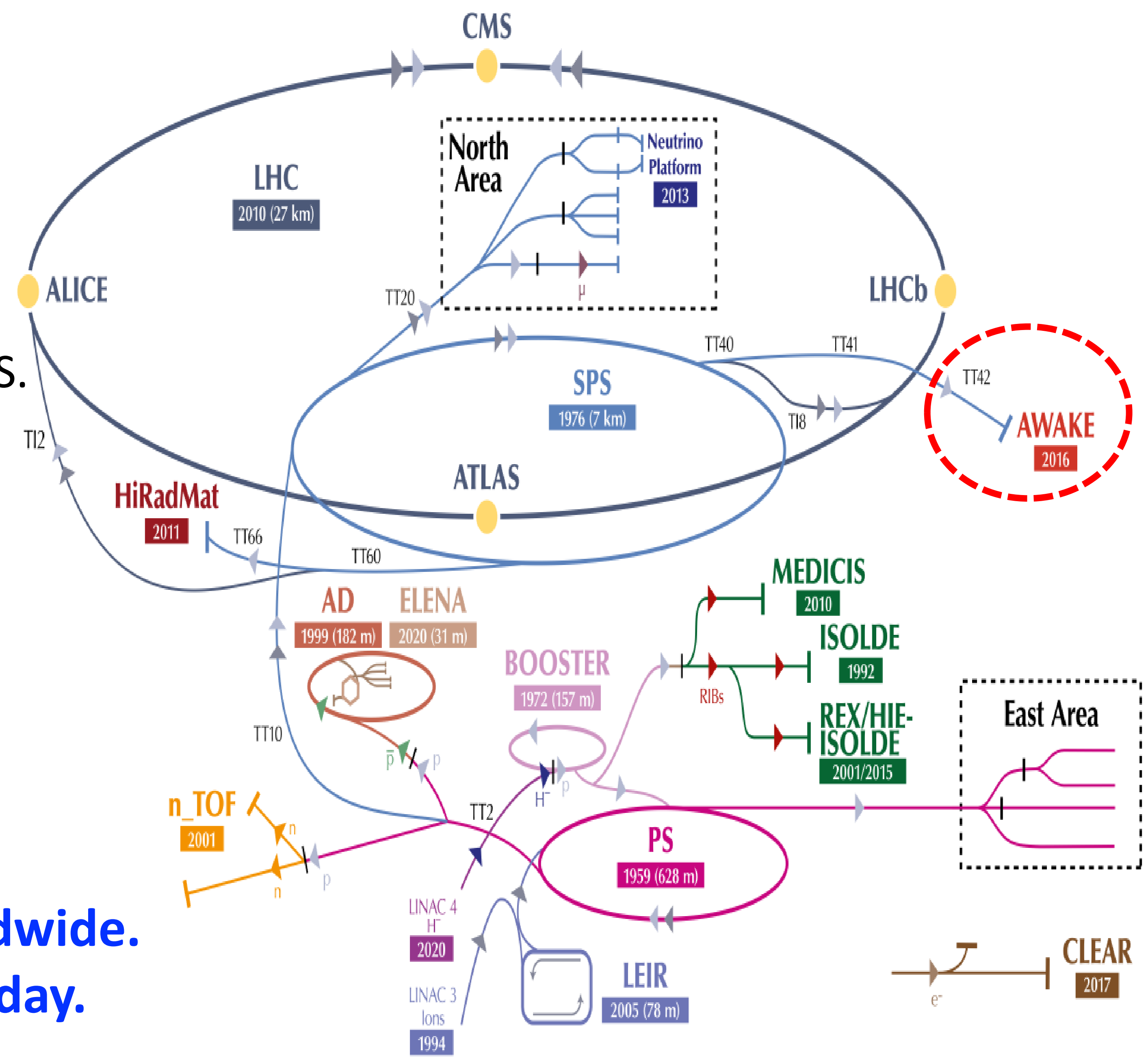
CLIC Drive-Beam Complex. Source: CLIC CDR

AWAKE at CERN

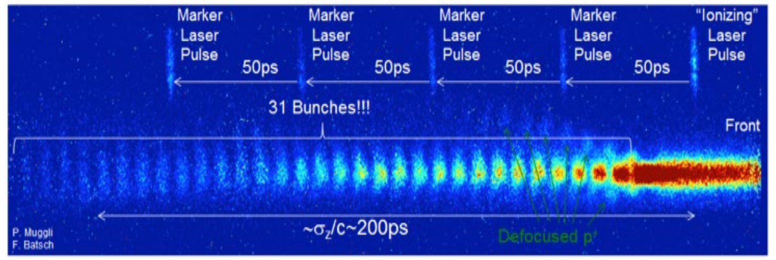
Advanced WAKEfield Experiment

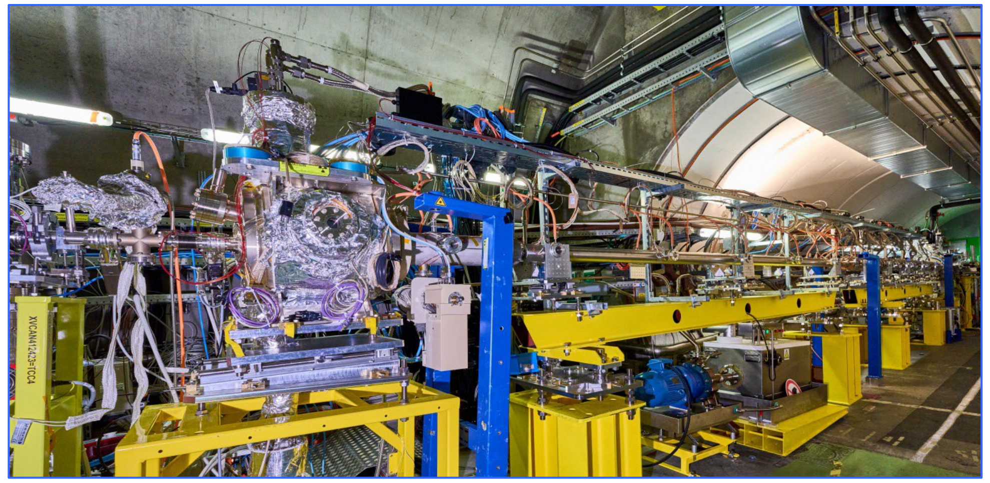
→ Accelerator R&D experiment.
→ International collaboration with 19 institutes.
→ Unique facility driving wakefields in plasma with 400 GeV proton bunch from the SPS.
→ Accelerating externally injected electrons to GeV scale.

→ All milestones achieved.
→ More than 22 high-level publications such as Nature (1), Phys. Rev. Lett. (6), Phys.Rev. E (1), Physics of Plasmas (1), Phys. Rev. A&B (2),…



→ The only proton driven plasma wakefield acceleration experiment worldwide.
→ High energy gain possible because the high-energy driver is available today.





E. Gschwendtner, CERN

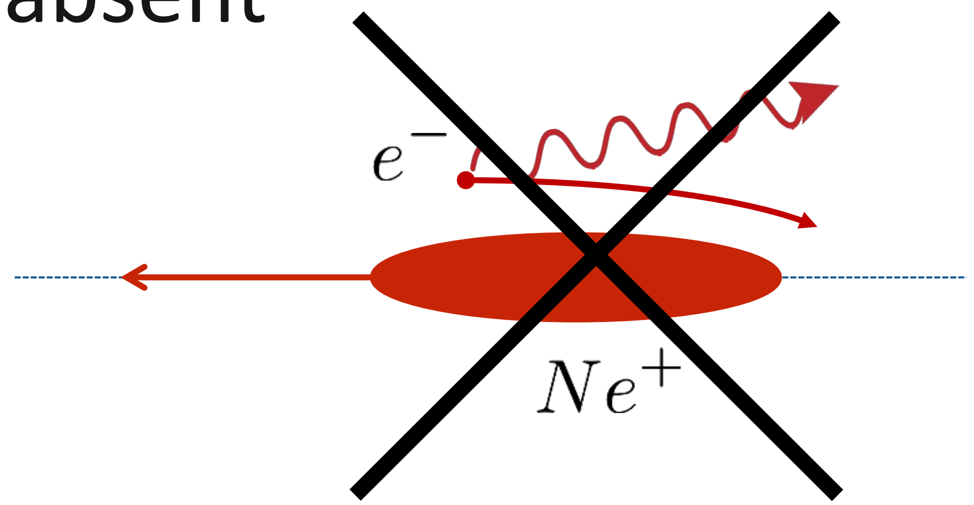
Muon Collider – Efficient at Highest Energies

Muon: E_0 = 106 MeV (200x e-), τ_μ = 2.2 μs

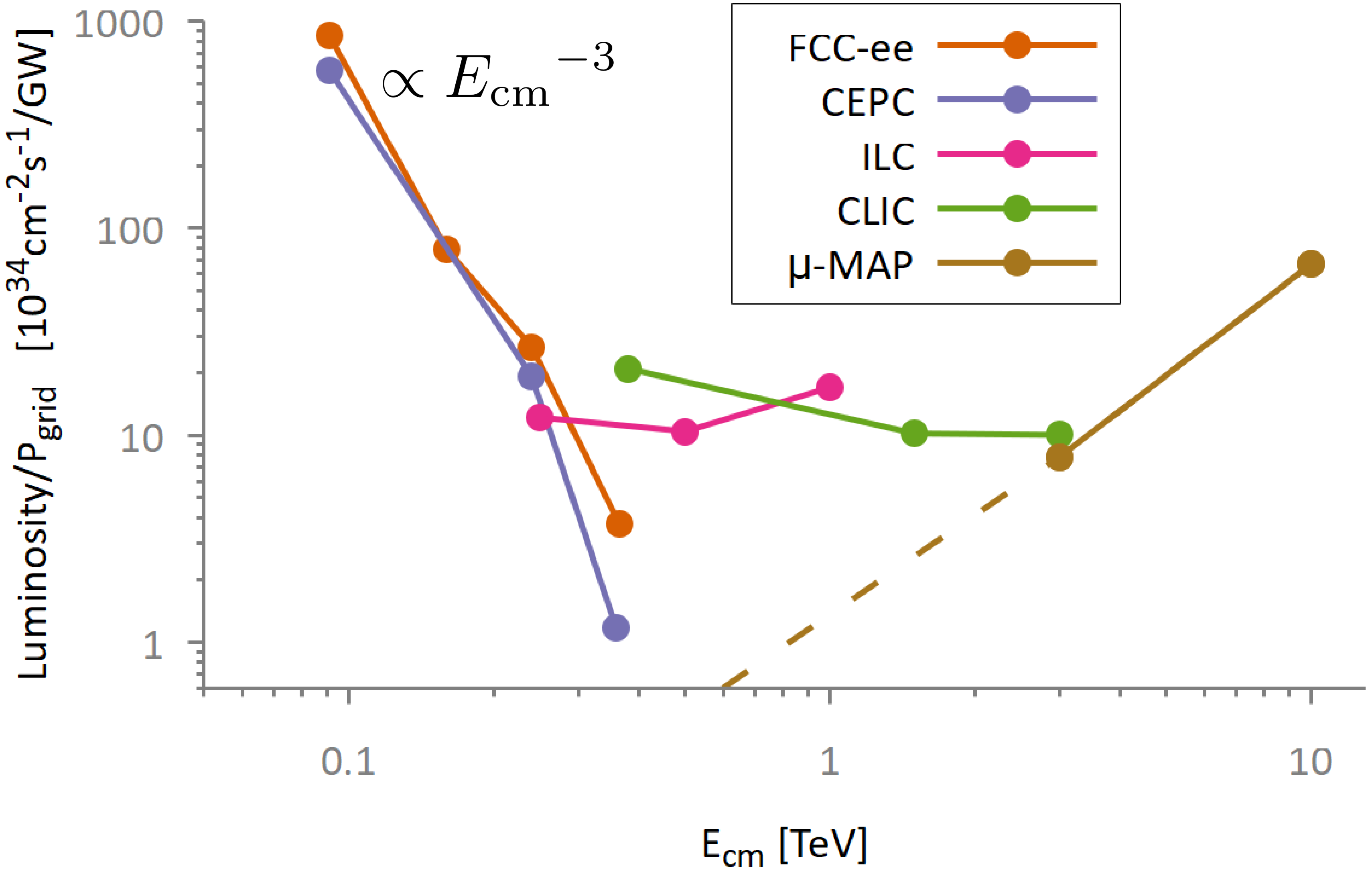
low SR, low beamstrahlung during collisions!

stronger focusing with higher E is possible, thus L/P is increasing with energy

Beamstrahlung absent for muons!



Muon collider: $$\frac{\mathcal{L}}{P_{\text{beam}}} \propto \gamma$$!



Lepton collisions at 3 or 10 TeV CM are in reach.

Muon Collider Roadmap CTEs

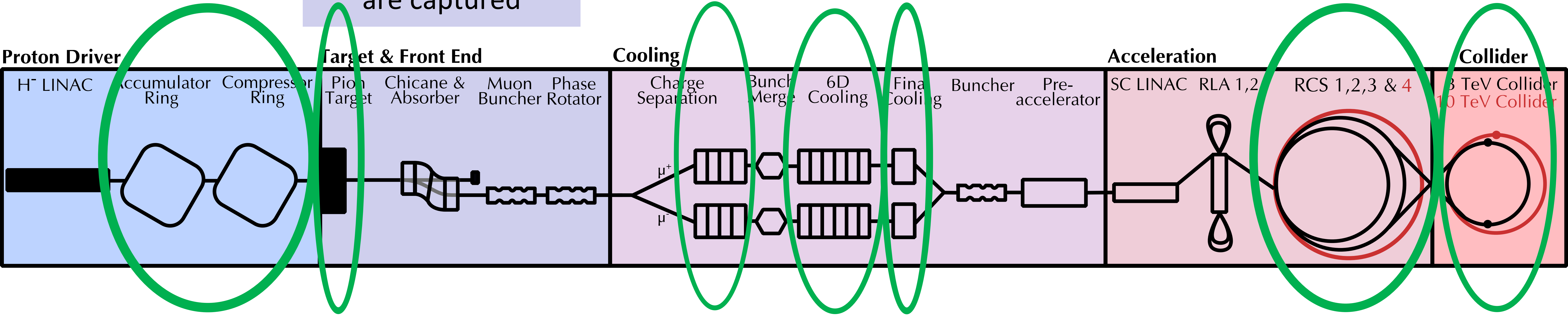
Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision



- Proton driver bunch compression

- Graphite target
- Target solenoid

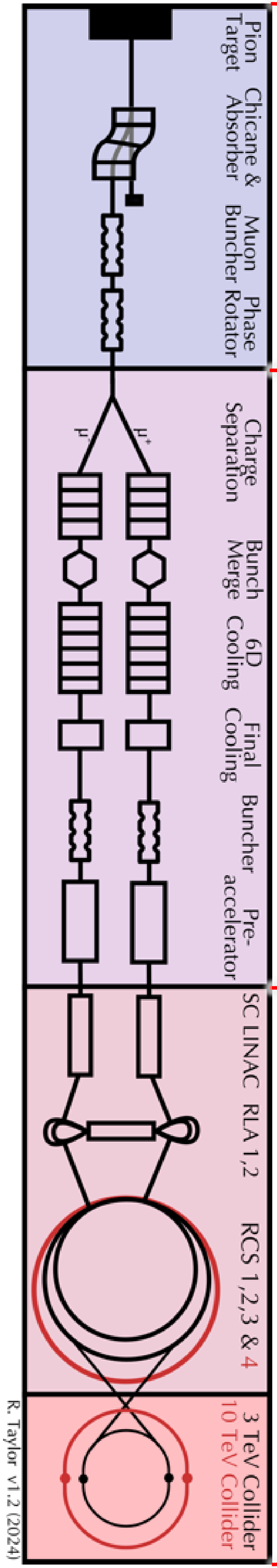
- Muon cooling design
- 6D cooling solenoids
- 6D cooling RF cavities
- Final cooling solenoids

- Pulsed magnets and power converters
- RCS RF system

- Collider ring dipoles
- Final focus quadrupoles

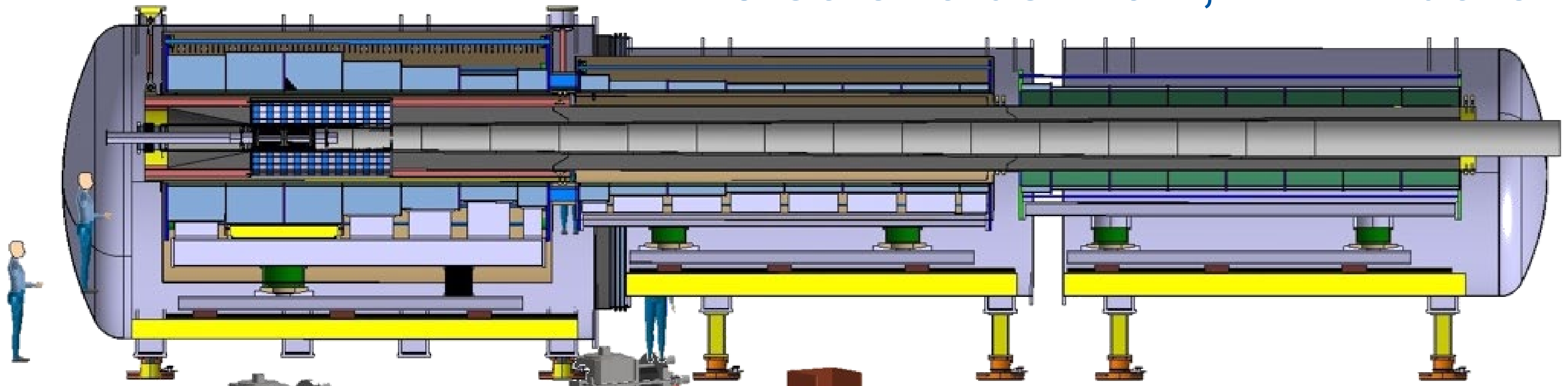
Identified and prioritized with community

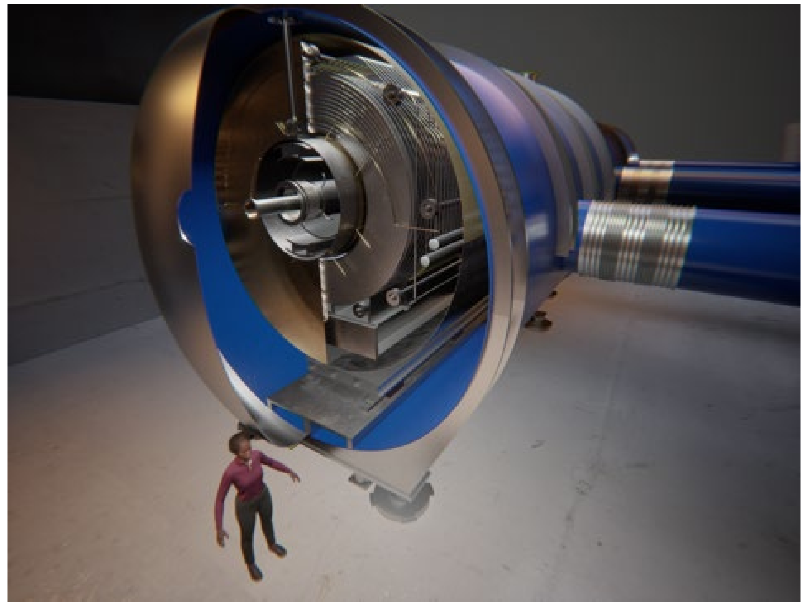
Other areas need now also to be addressed (some work started)



Target and capture solenoid

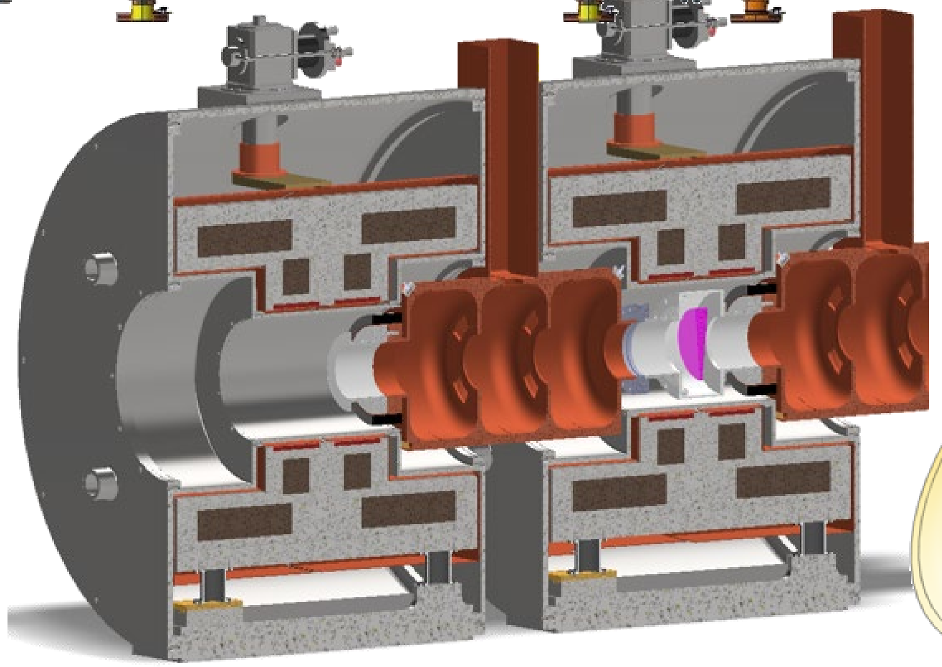
23 solenoids: 20 T, 1.4 m bore

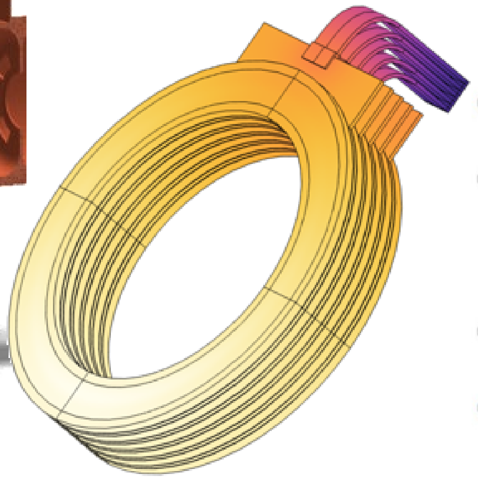


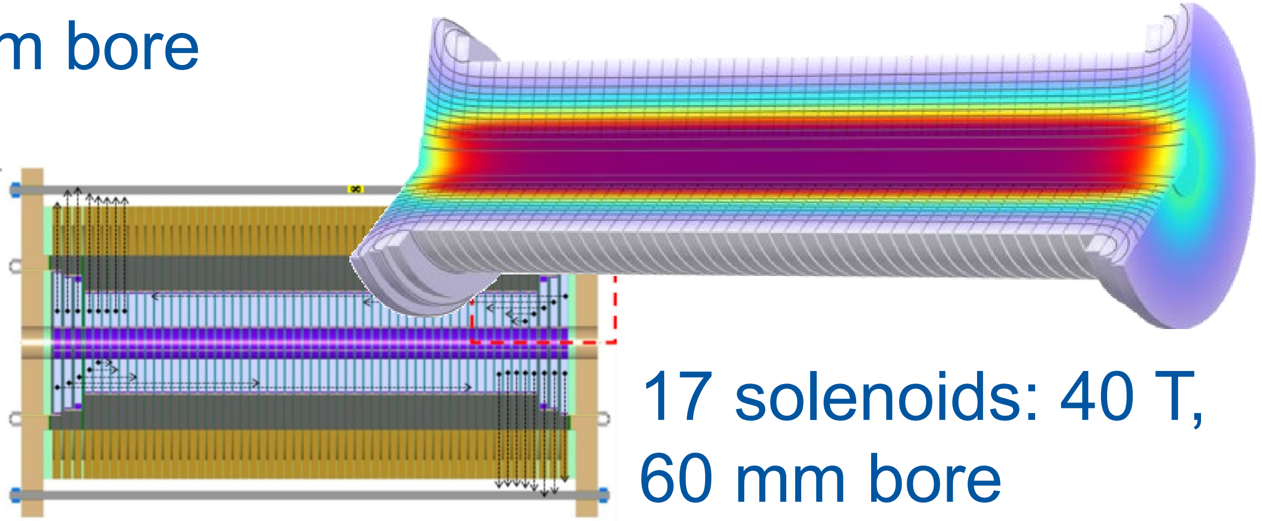


Muon beam cooling solenoids

3000 solenoids: 2 to 14 T, 90 mm to 1.5 m bore

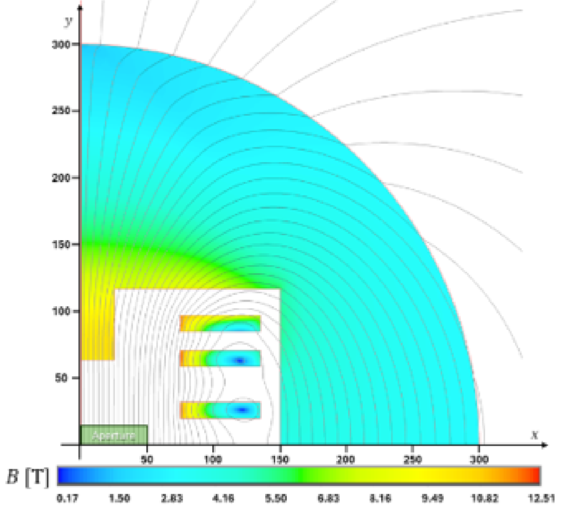


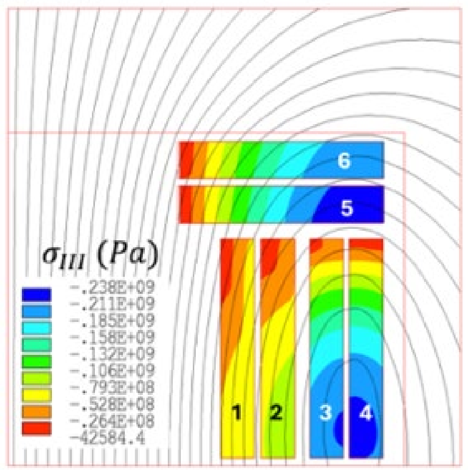




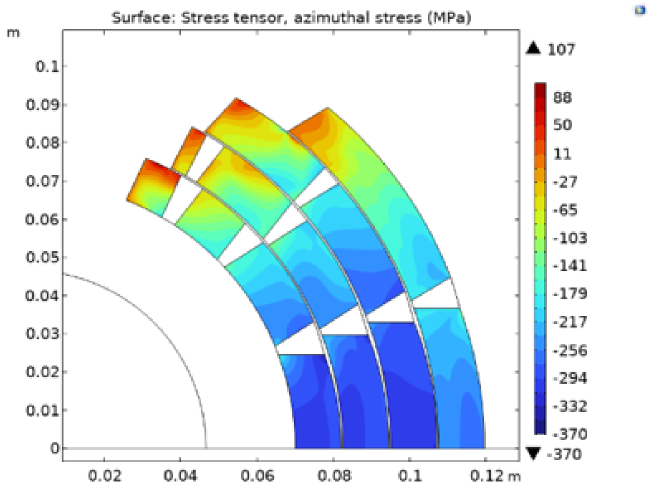
17 solenoids: 40 T, 60 mm bore

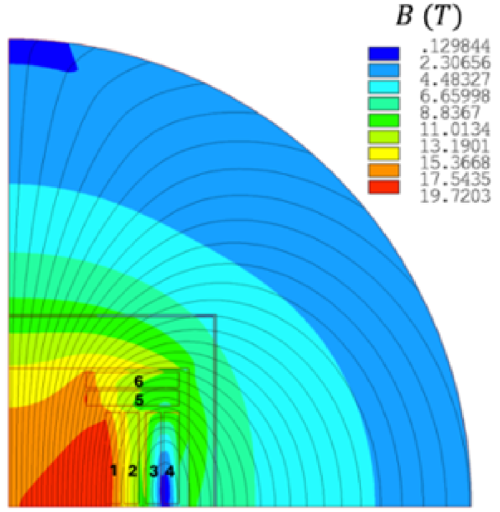
Accelerator and collider magnets





5 km: 10 T, 30(V) x 100 mm (H) dipoles

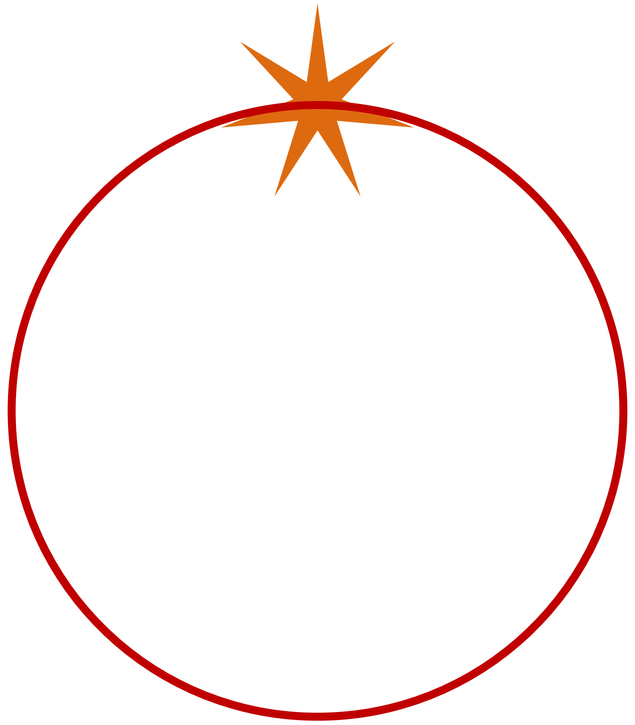




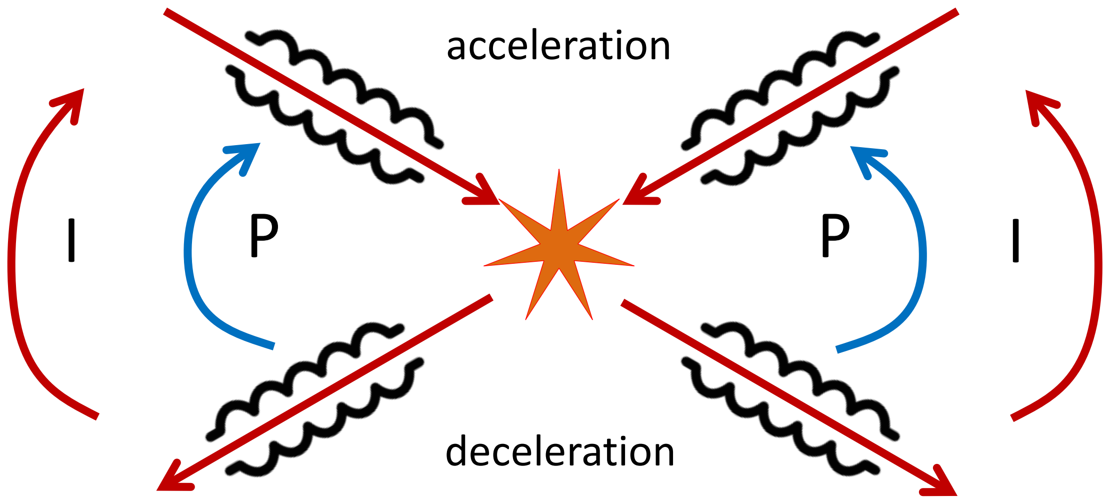
10 km 14 T, 140 mm bore dipoles

ERL vs Ring or Linear Collider

Ring
beam circulates



ERL
power circulates



Linear Collider
high quality beam

- beam (and energy) reused
- synchrotron radiation dominated
- equilibrium beamsize $\rightarrow$ collision parameters limited

- power recirculated, beam recirc. at low E
- benefit from better collision parameters

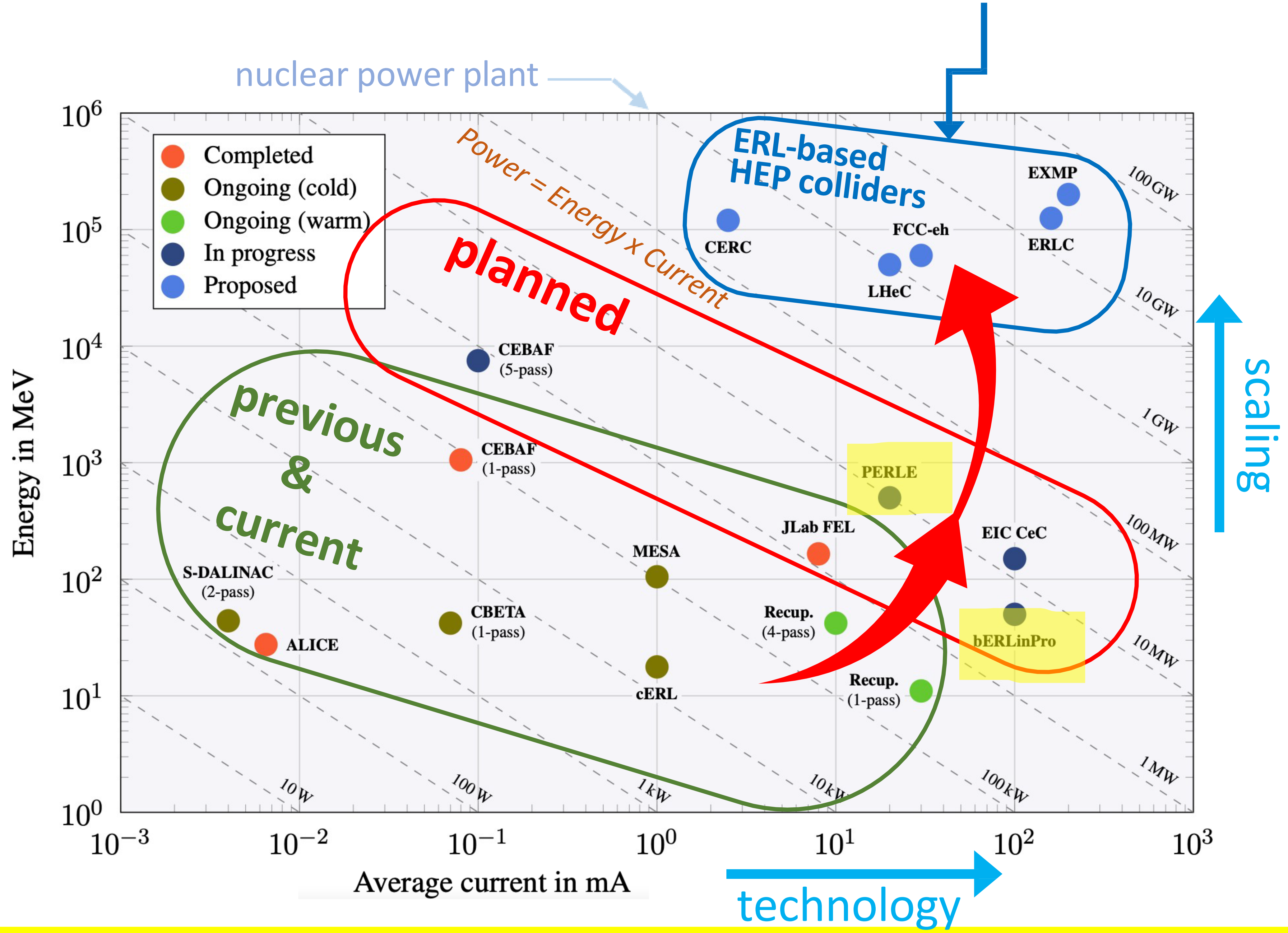
$\rightarrow$ **high L per grid power, but higher investments & complexity**

$\rightarrow$ **main study today e-LHC, but also e+/e- possible**

- beam used only once
- no synchrotron radiation
- ambitious collision parameters possible (no ring dynamics)

DOI: https://doi.org/10.23731/CYRM-2022-001

ERL to enable high-power beams that would otherwise require one or more nuclear power plants



Future ERL-based Colliders

H, HH, ep/eA, muons, …

R&D Roadmap

bERLinPro & PERLE

essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

towards high energy & high power

Energy Recovery demonstrated

great achievements on all aspects and large research infrastructures based on Energy Recovery systems have been operated successfully

Energy Recovery Linacs (ERL): reaching higher luminosities with less power requirements

J.D'Hondt, A.Stocchi et al

Upcoming facilities for Energy Recovery Linac R&D

PERLE @ IJCLab

- *growing international collaboration*
- *all ERL aspects to demonstrate readiness*
- *design, build and operation this decade*
- *for e^+e^- and ep/eA HEP collider applications*

PERLE – Powerful Energy Recovery Linac for Experiments [CDR: *J.Phys.G* 45 (2018) 6, 065003]

Comments advanced concepts

Plasma Acceleration based Collider:

- HALHF avoids plasma acceleration of positrons through an asymmetric collider concept; a Higgs factory with a compact length of 3.3km is proposed
- challenges:

  → staging of accelerator sections; very high intensity drive beam; removal of waste heat from plasma channel
- demonstrator for multi-stage plasma acceleration required, but needs significant funding (>150M, 13y)

Muon Collider:

- path to 10TeV lepton collisions with advantageous energy scaling; operating ca 2050 (decisions in 2035-40)
- challenges:

  → reliable Start-to-End performance simulation, required High-Field HTS development must be defined and funded, RF strategy: clear specifications and performance targets for RF systems
- independent assessment of the scope, schedule and costs is needed for 2026-2036 R&D plans (ca €300M/1800FTEy)

ERL:

- demonstrator PERLE (IJCLab) in multi-turn configuration is important; sufficient funding must be provided
- LHeC: concepts and technologies for dealing with SR power loss and induced energy spread must be developed

Accelerator R&D - Conclusions

- **High Field Magnets and RF Systems form the building blocks for future facilities and technology R&D is focused on those, in particular on superconducting technologies.**
- **energy efficiency and sustainability are key and have a high relevance for public acceptance of particle physics RIs**
- **advanced concepts are promising for medium term collider development:**
  - **plasma acceleration → small footprint**
  - **muon collider → highest lepton energies**
  - **energy recovery linacs → most energy efficient**
- **significant research is needed → the LDG accelerator roadmap will be renewed and aligned with the outcome of the ESPPU; a workshop for adapting priotities is planned for February 2026**