CEPC International Workshop
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The FCC program

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Outline

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.

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Disclaimer

To prepare these slides I used content from many friends and colleagues, whom I wholeheartedly wish to thank. Any mistake or misinterpretation is entirely my fault!

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Analogy: Explore new worlds (Star Trek)

We have now identified more than 6000 exoplanets.

Imagine one day we are ready to seek out new life and civilizations,

and dare to go where no one has gone before…

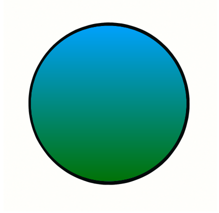
What would be your strategy?

F. Maltoni

Phase I : Observe

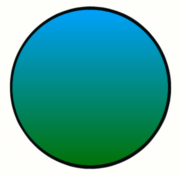
F. Maltoni

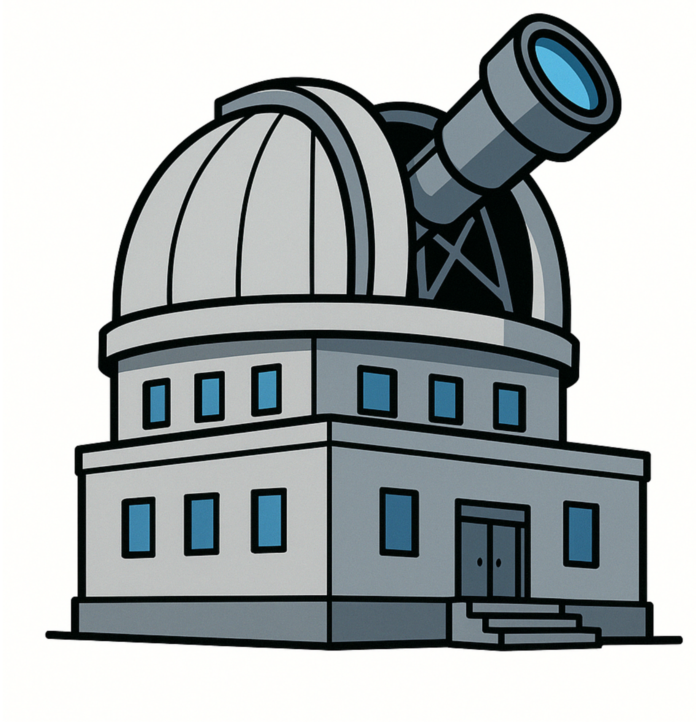
Phase I : Observe



F. Maltoni

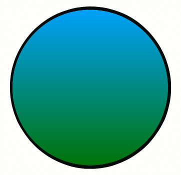
Phase I : Observe

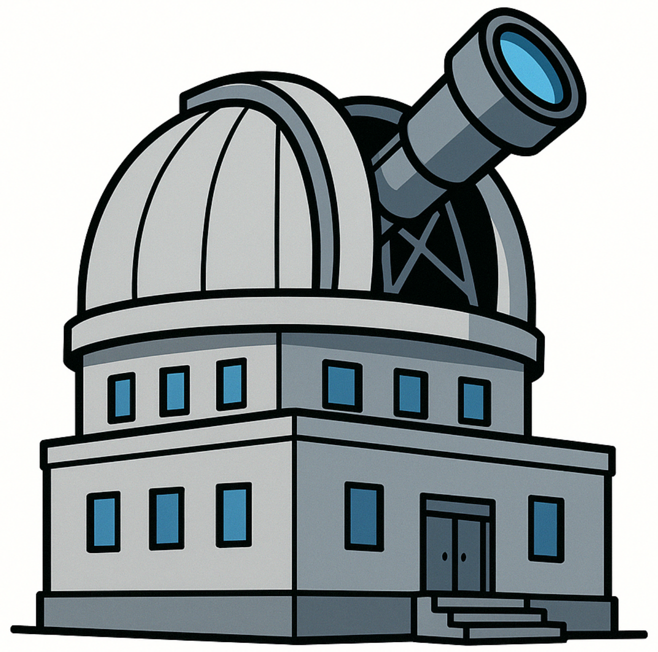


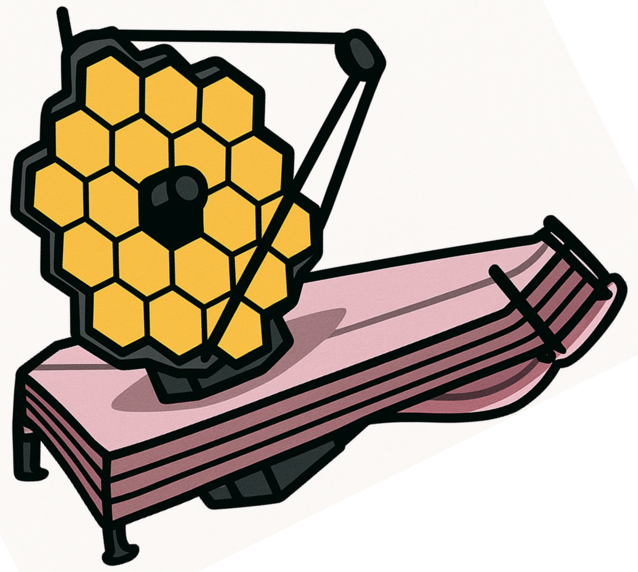


F. Maltoni

Phase I : Observe







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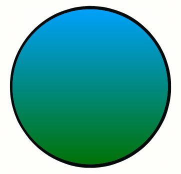
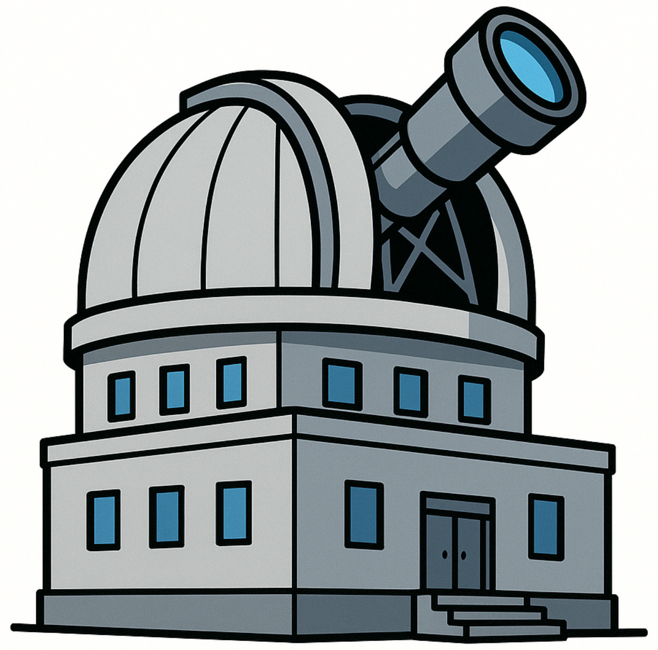
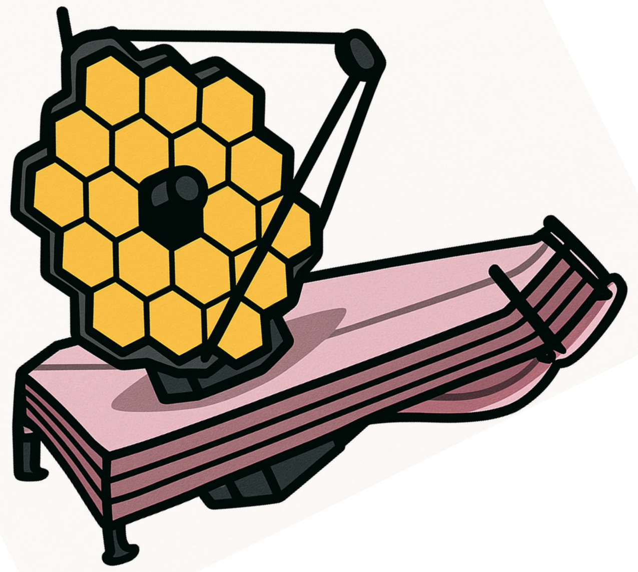


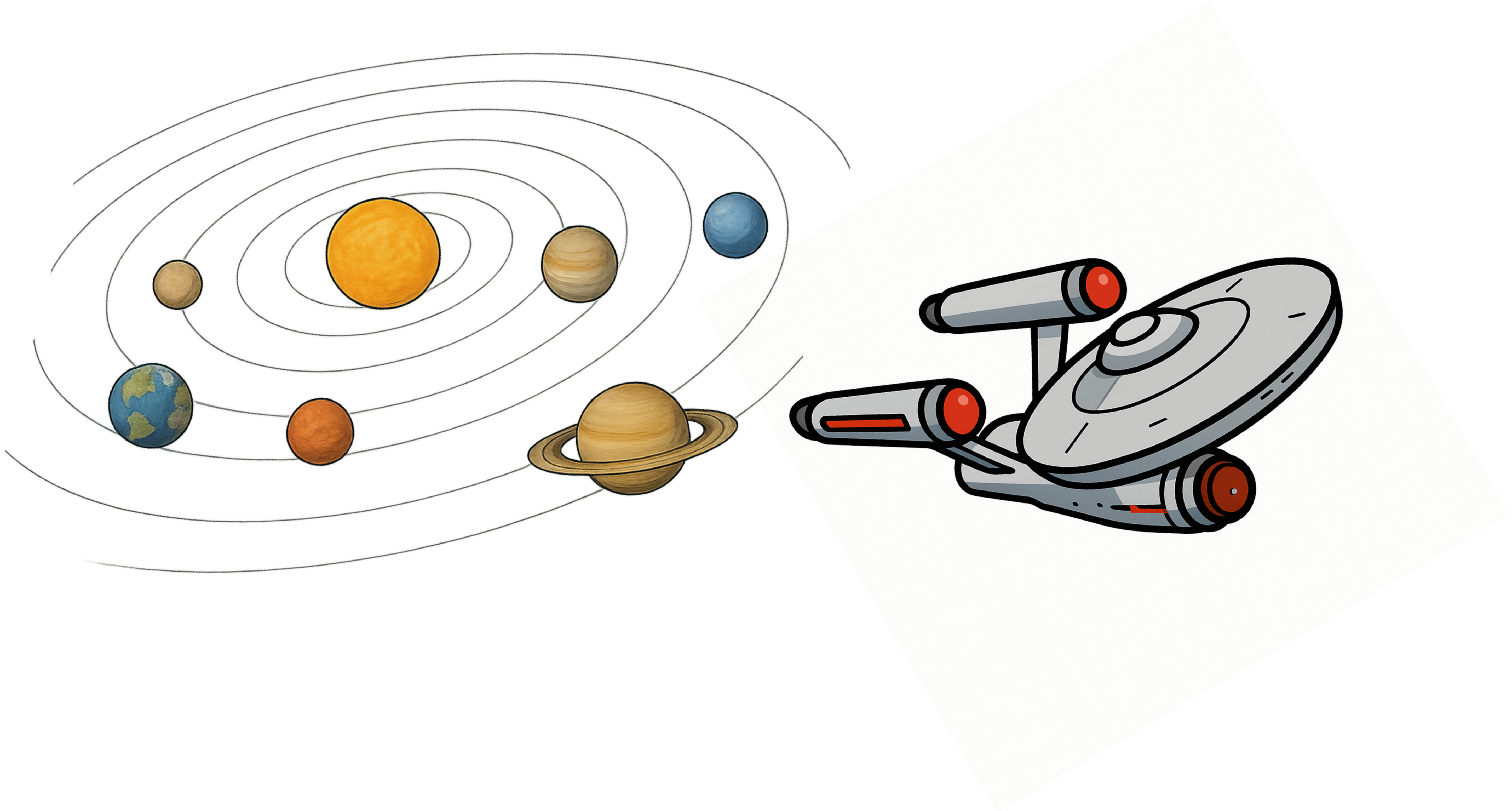




Build telescopes with better and better resolution to make the observations and identify the best candidates for life and civilizations…

F. Maltoni

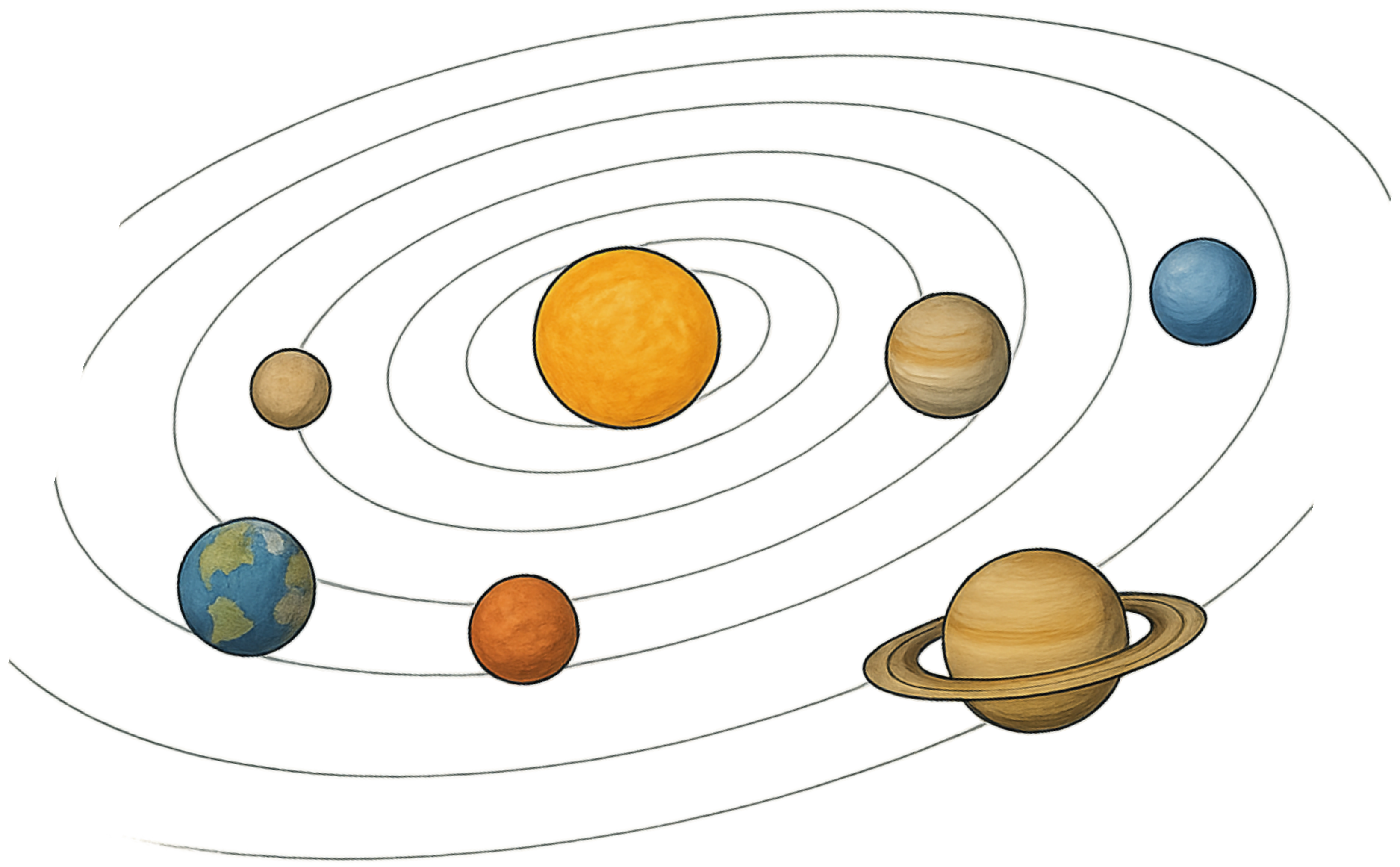
Phase II : Go there!



Develop new technologies to allow space travel and then…. go there!

F. Maltoni

Phase II : Go there!



Develop new technologies to allow space travel and then…. go there!

F. Maltoni

FUTURE CIRCULAR COLLIDER

Where do we go from here?

We are in an interesting situation

- No experimental hint to the origin of these observed phenomena
- No clear theoretical hint to indicate the best direction to go

We have no clear energy scale for new physics
We don’t know its coupling strength to the SM particles

- **Next facility must be versatile**
  - With a reach as broad as possible

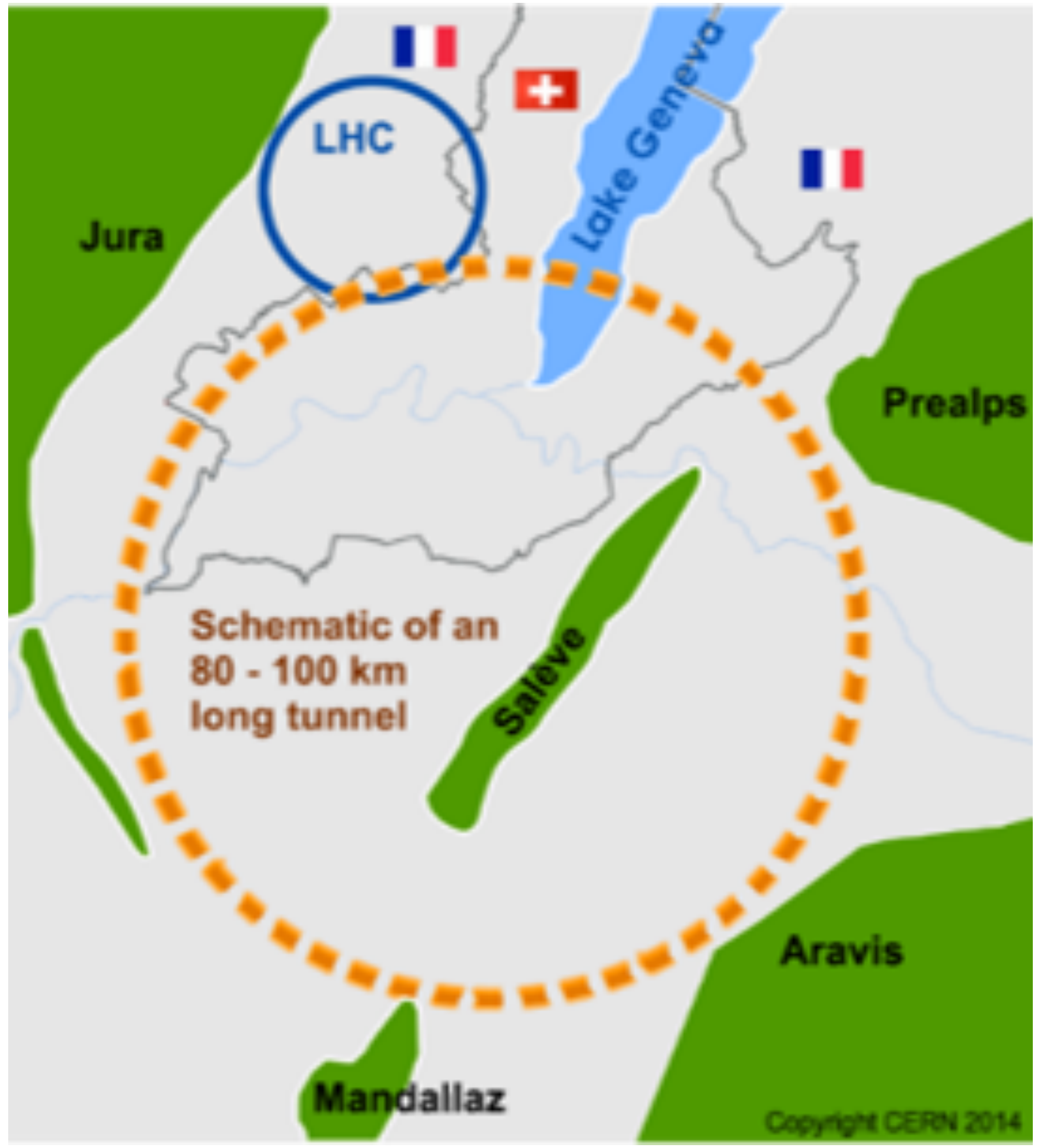
More Sensitivity, more Precision, more ENERGY

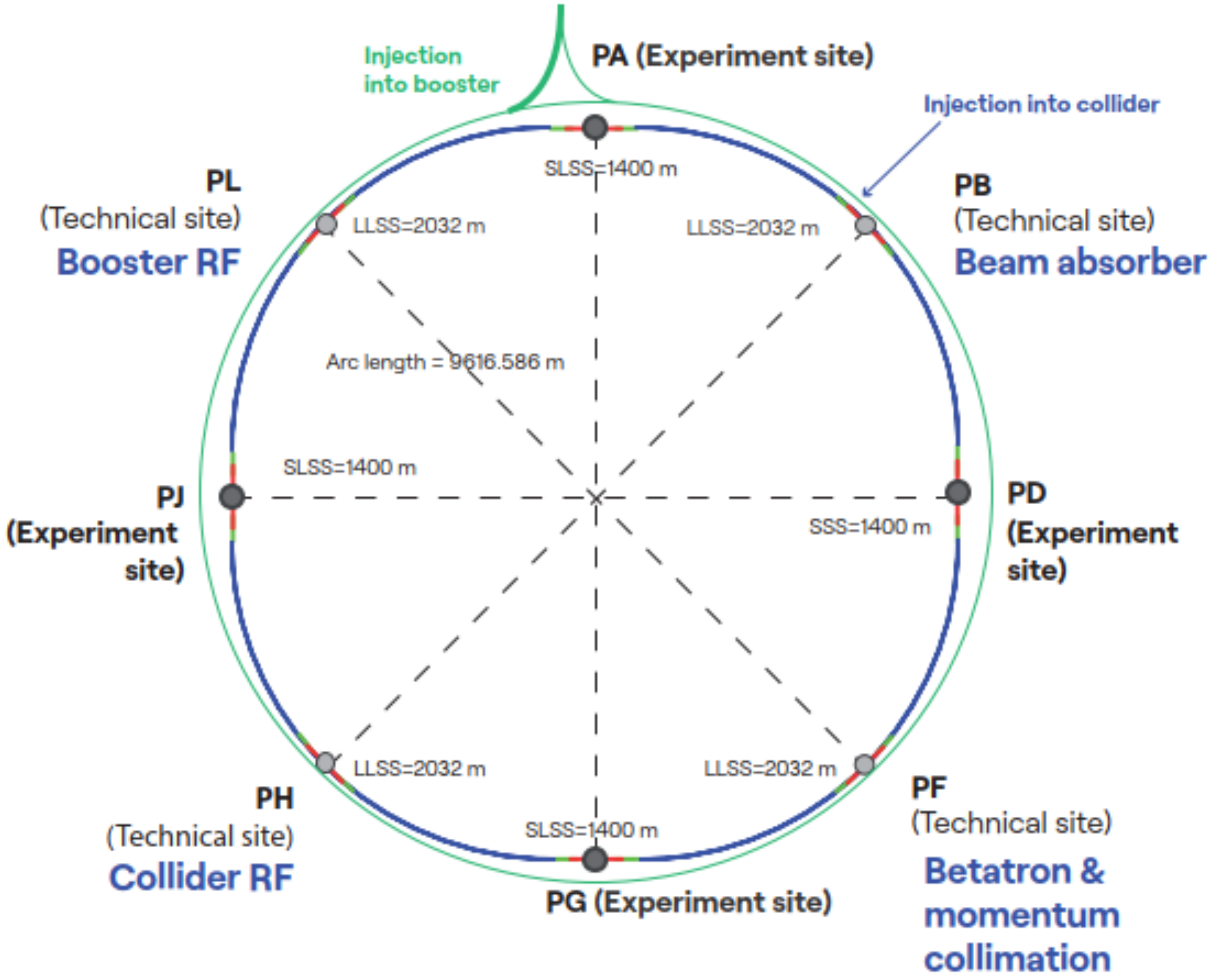
- A high precision, high intensity lepton collider, later followed by a high energy hadron collider offers the **best** solution

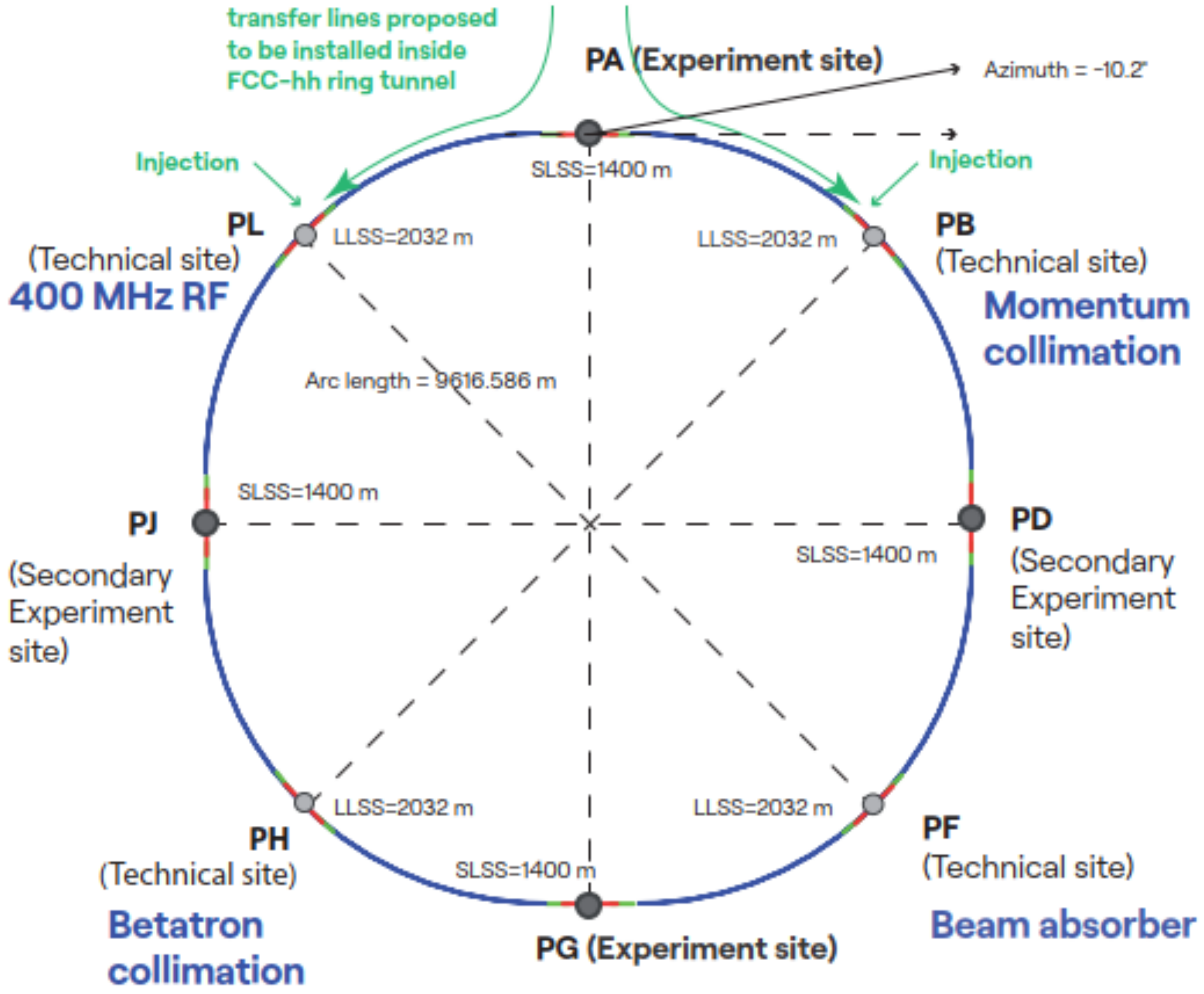
P. Janot

FCC Program

- stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within few years of the end of HL-LHC exploitation







2020 - 2045 | 2048 - 2062 | 2079 - 2104

M. Benedikt

FUTURE CIRCULAR COLLIDER

FCC integrated program – timeline

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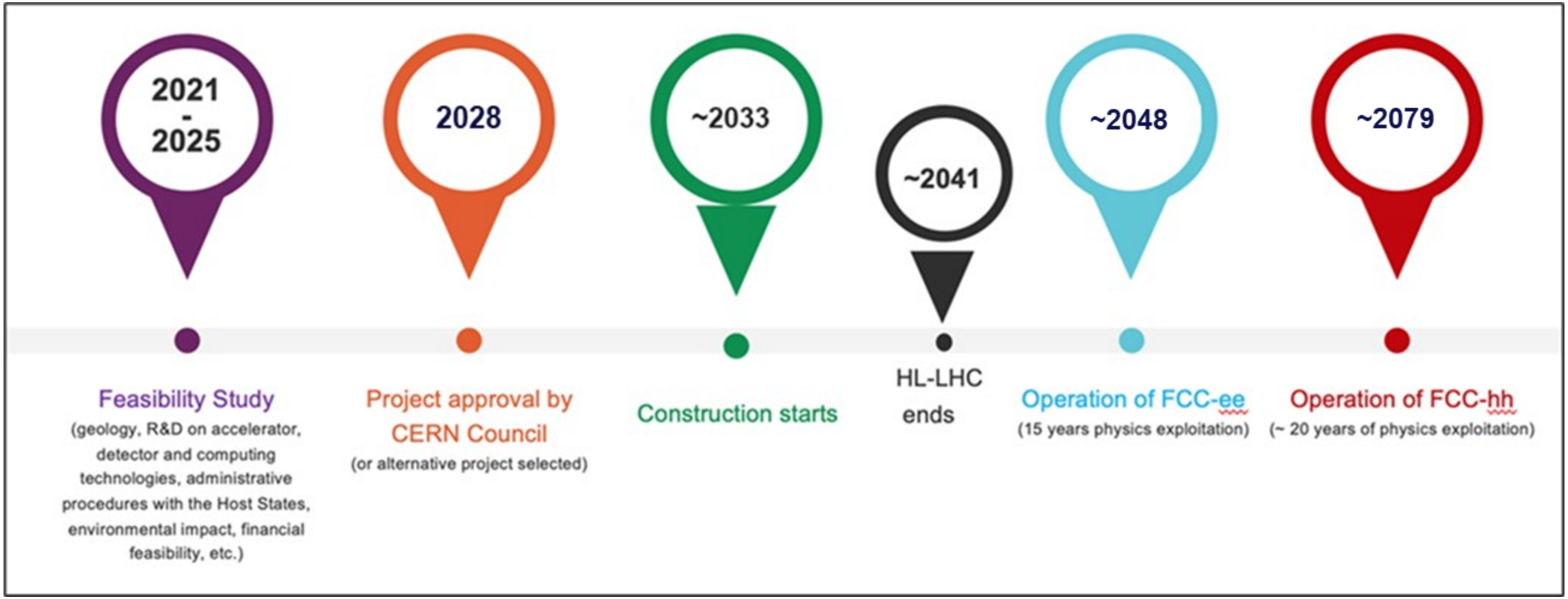


Ambitious schedule taking into account:

- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041
- **constraints imposed by present assumptions in funding model**
- **project preparatory phase with adequate resources immediately after Feasibility Study**

M. Benedikt

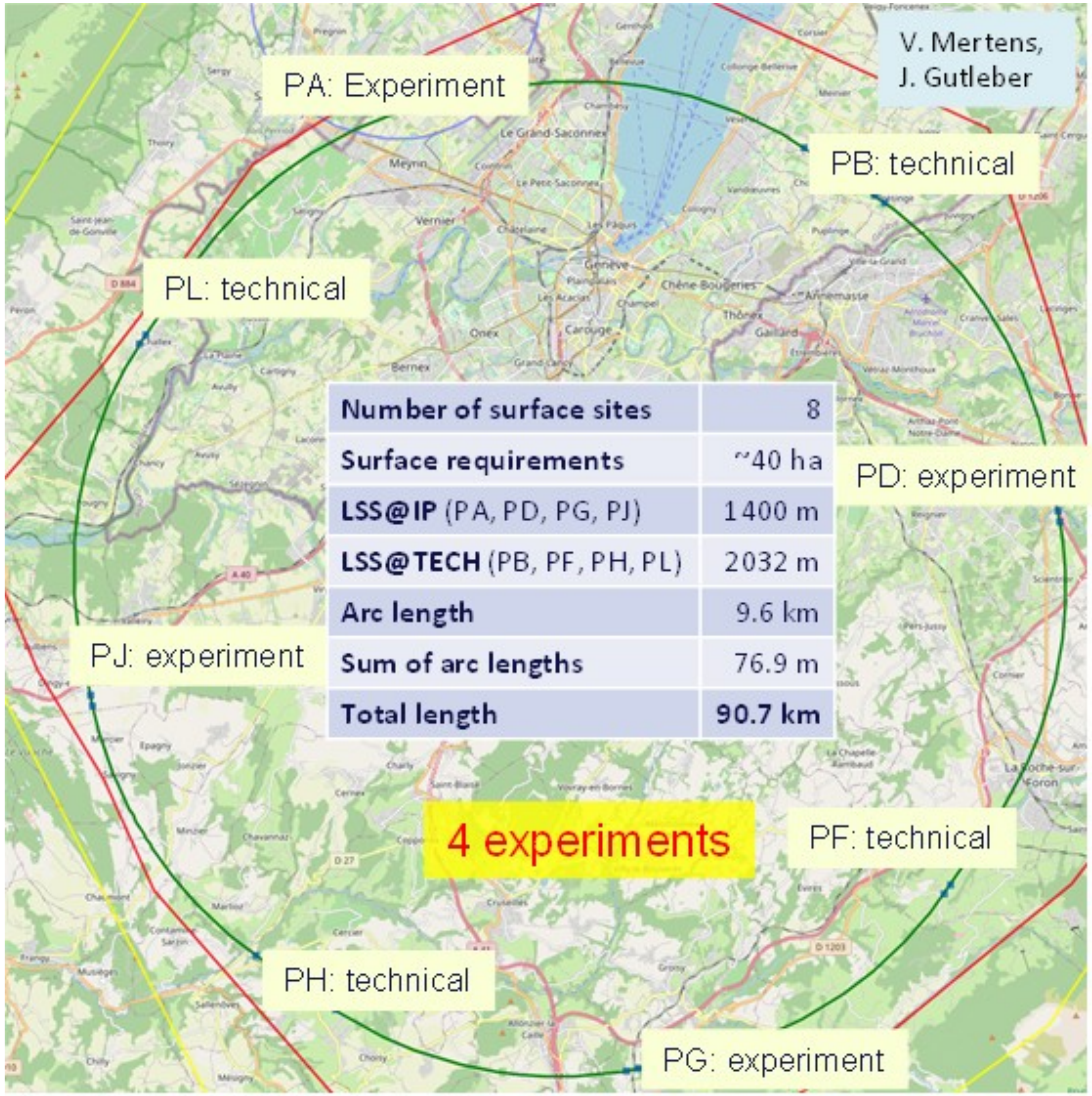
Reference layout and implementation:PA31 - 90.7 km

Layout chosen out of ~ 100 initial variants, based on several criterias:

- **geology,**
- **surface constraints** (land availability, urbanistic, etc.),
- **environment,** (protected zones),
- **infrastructure** (electricity, transport),
- **machine performance**

"Avoid-reduce-compensate" principle of EU and French regulations.

Overall lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold symmetry



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FUTURE CIRCULAR COLLIDER

Surface site locations 7 FR and 1 CH

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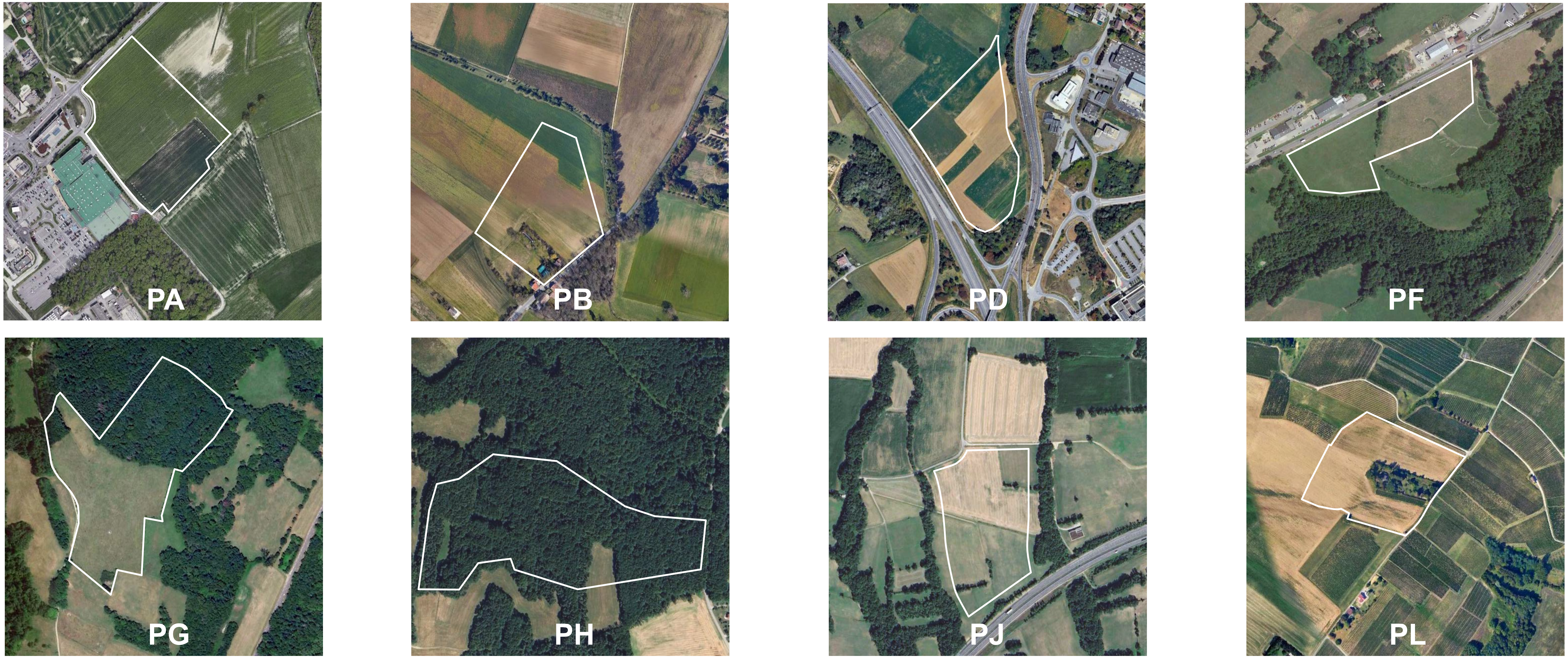
Optimisation done with communes

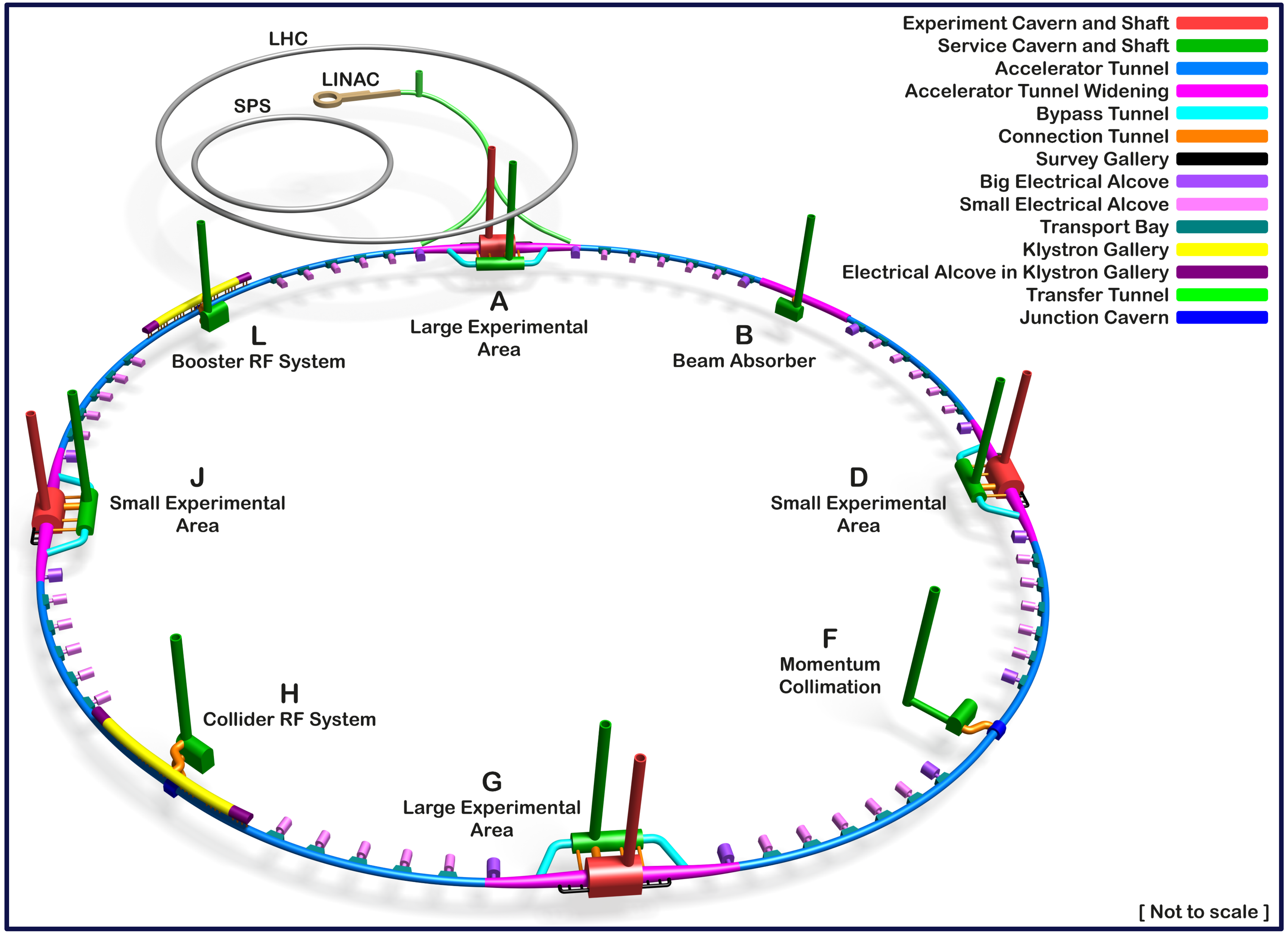


- land plot needs communicated to Host States,
- process in FR: «prise en consideration», landplot in CH owned by Canton of Geneva

M. Benedikt

Key features of the Underground Civil Engineering Baseline

- Tunnel Circumference: 90.7 km
- Excavated vol: 6.25M m^3 (*in-situ* volume)
- Access shafts: 12
- Construction shafts: 1
- Large experiment sites: 2
- Small experiment sites: 2
- Technical sites: 4
- Deepest shaft: 400m
- Average shaft depth: 243m
- Total concrete volume: 2 M m^3



Schematic of FCC-ee Baseline Underground Civil Engineering

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Optimum placement of FCC tunnel and geology

Tunnelling mainly in molasse layer (soft rock), well suited for fast, low-risk TBM construction.

6 million m³ excavated volume → 8.5 million m³ excavation material on surface

CE Designs of all underground structures developed

Average shaft depths ~240 m

To fix the vertical position of the tunnel, interfaces between geological layers have to be known

M. Benedikt

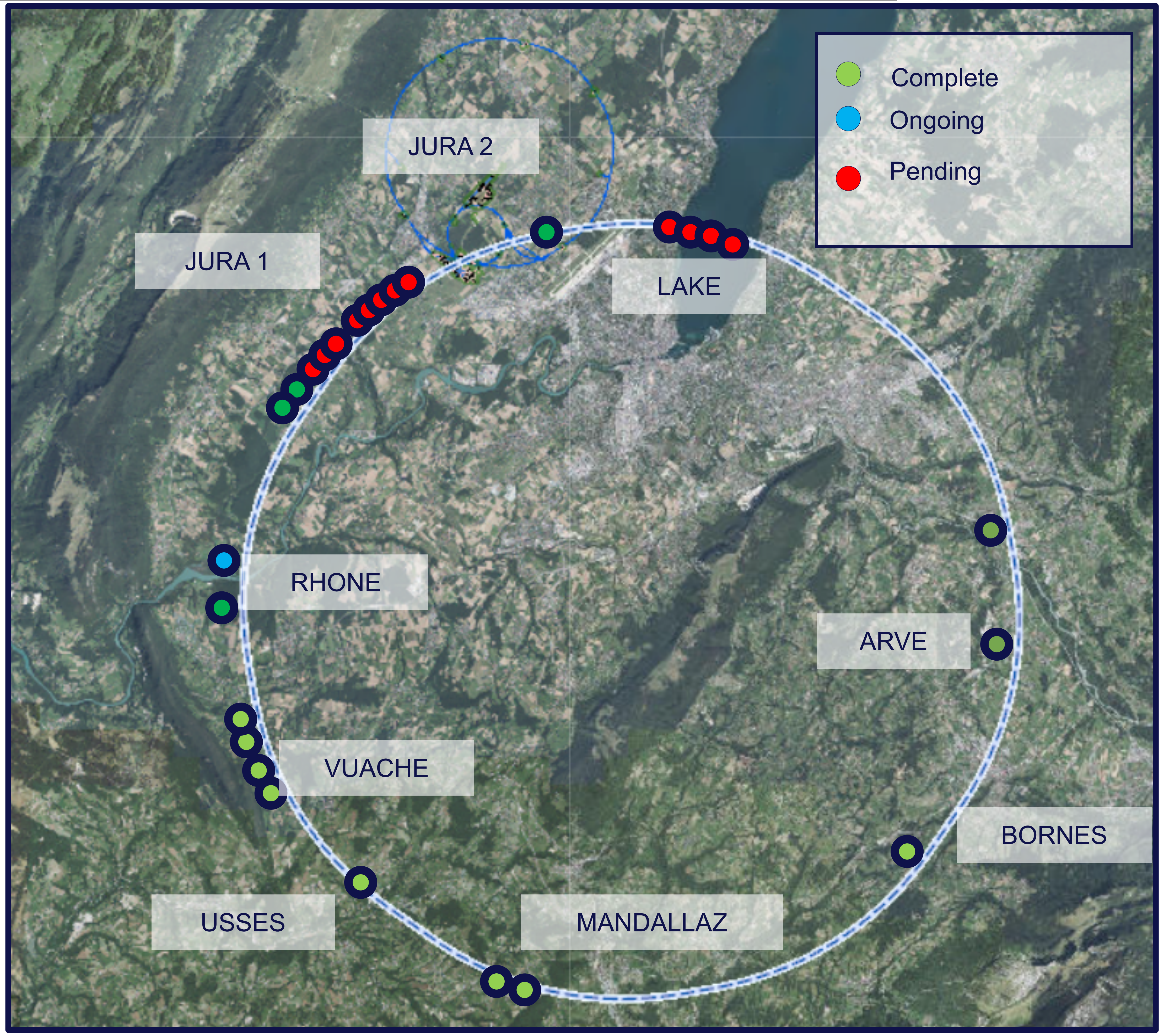
Site Investigation Phase 1

South-western work package SGS3

- Works began in October 2024
- Geophysics acquisition complete and interpretation ongoing
- Drilling activities complete for all 10 boreholes
- Testing complete and report preparation ongoing

North-eastern work package GEOTEC-IOI

- Works began in France in April 2025
- Two boreholes completed and one ongoing
- Geophysics 25% complete
- 4 lake drillings starting and permits for last 8 boreholes imminent.



Status of drilling 1/09/2025

Preliminary results

- Results to date do not indicate any deviation from the baseline assumptions made for the rock conditions and the location of the moraine/molasse interface and molasse/limestone interface being as expected or more favourable.
- The length of tunnel in the Mandallaz limestone is now expected to be close to 3 km compared to 5 km as assumed prior to the phase 1 site investigation.

M. Benedikt

Reuse of excavated materials: OpenSkyLab project

- Develop a quality-managed process to transform excavated materials into fertile soil
- Permit reuse in renaturalisation, agriculture, etc.
- Additives as compost etc. in various mixtures
- Location: 1 ha field, LHC P5 CMS Cessy (FR)
- Applicable to entire alpine molasse region!

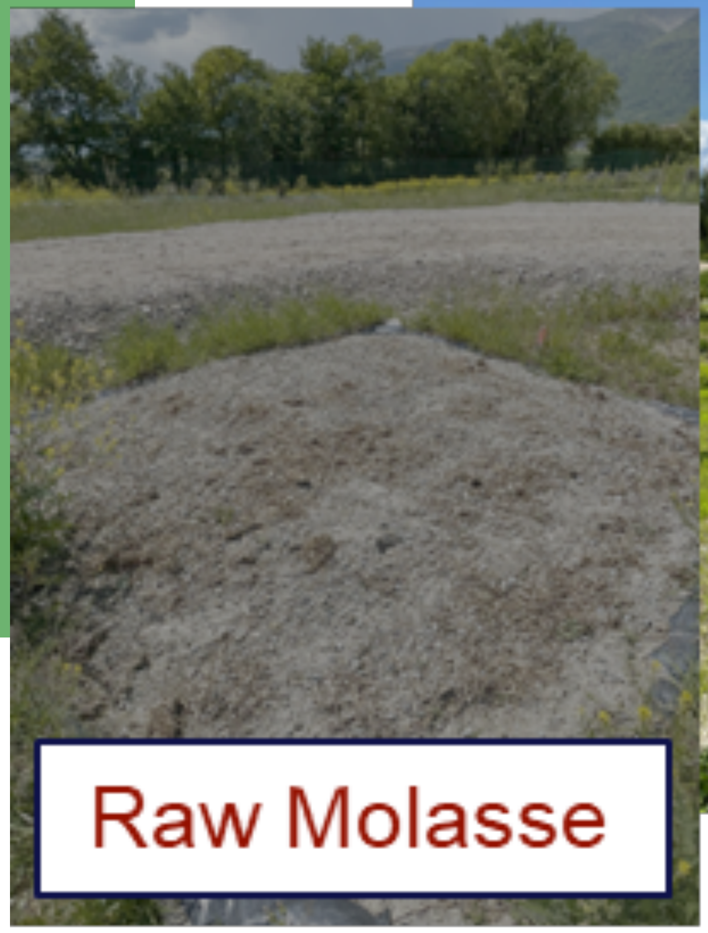
<u>Estimate of reuse quantities:</u>

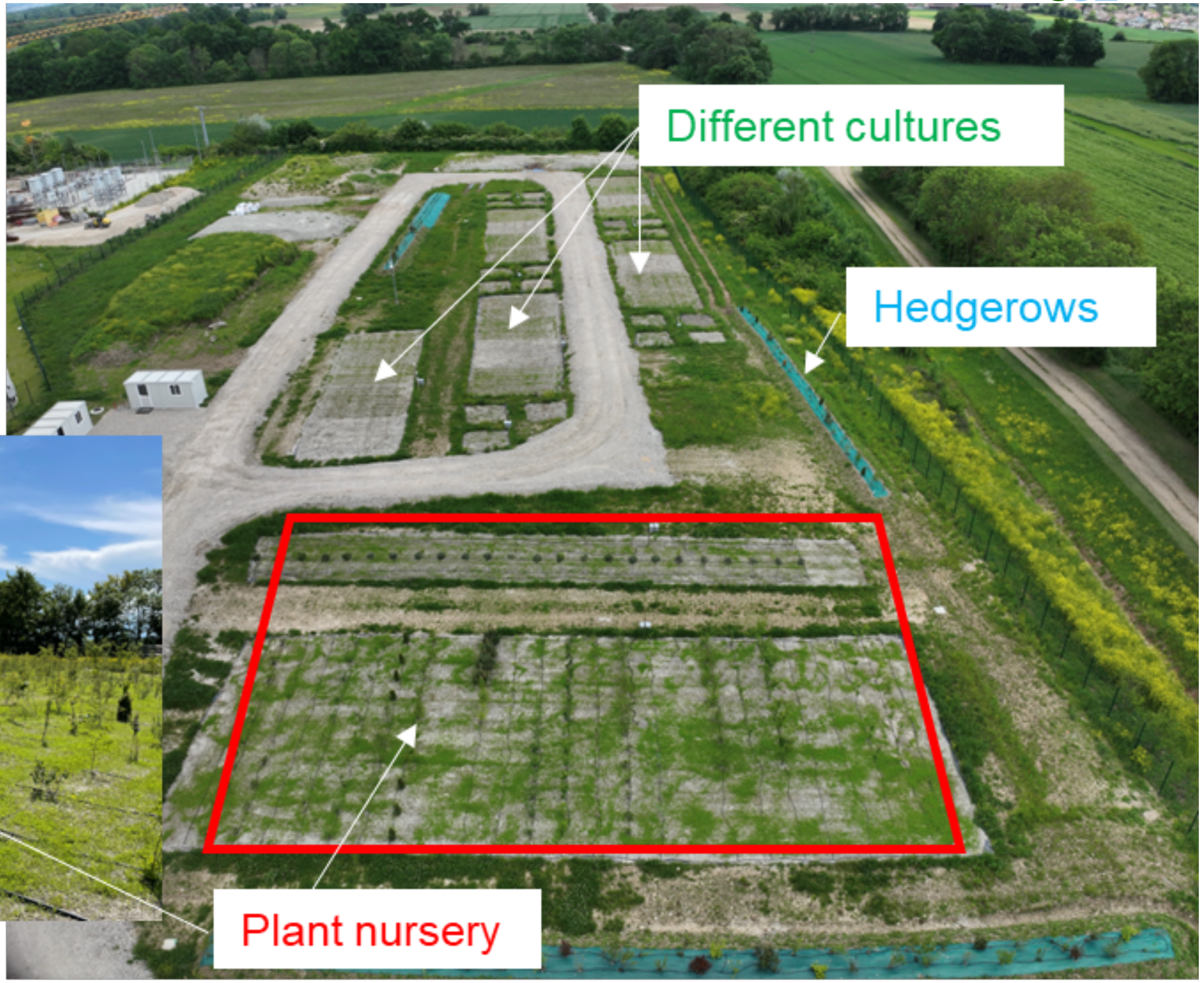
40% refill of quarries (~ 7.5 Mt)

25% reconstituted soil (~ 4 Mt)

30% deposit (~ 5 Mt)

5% other reuse





hepia Haute école du paysage, d'ingénierie et d'architecture de Genève · brgm Géosciences pour une Terre durable · EDAPHOS ENGINEERING · BOKU UNIVERSITY · microhumus · MONTAN UNIVERSITÄT LEOBEN · BECC · wsp

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FCC – main tunnel integration – 5.5 m inner diameter

FUTURE CIRCULAR COLLIDER

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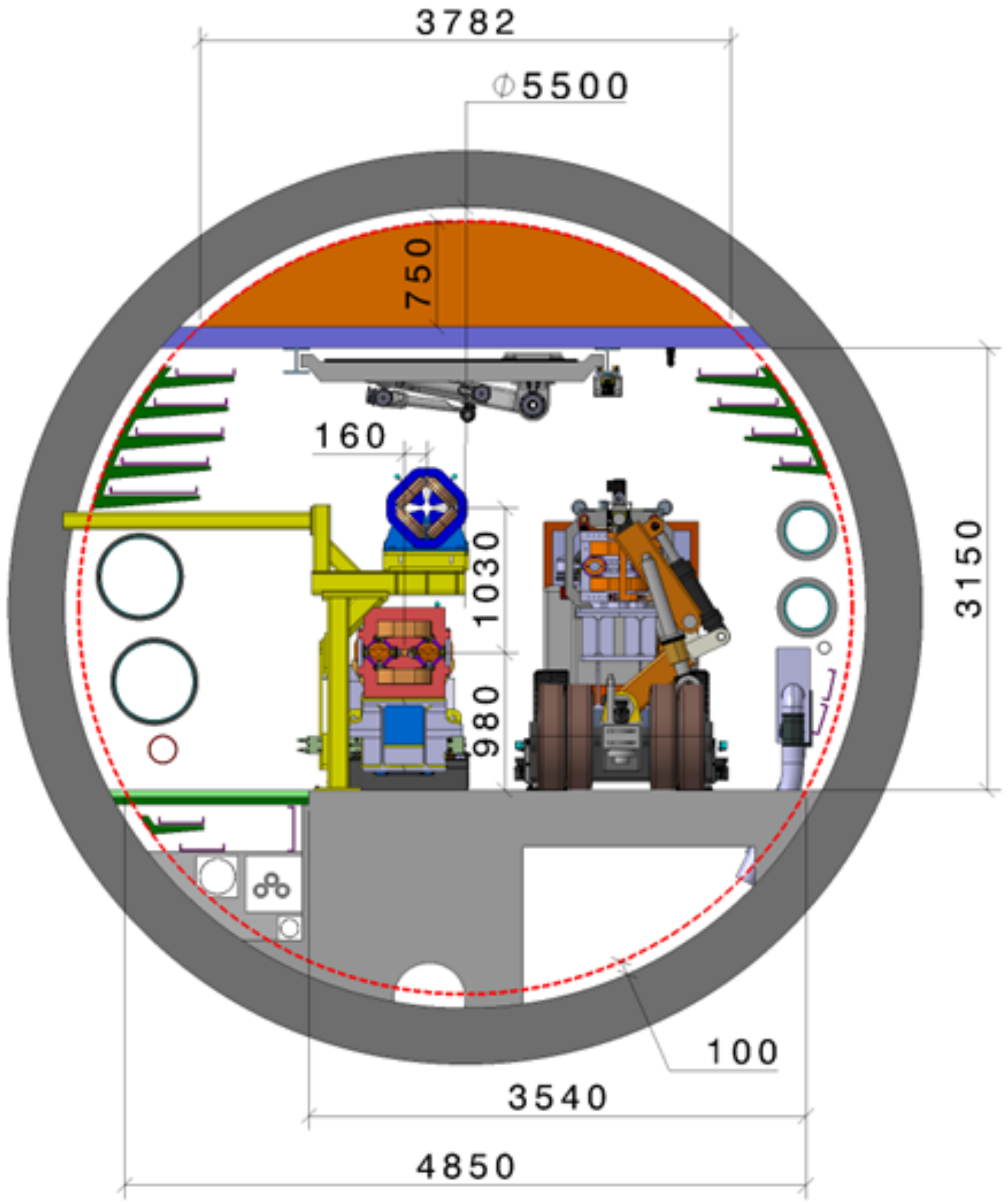

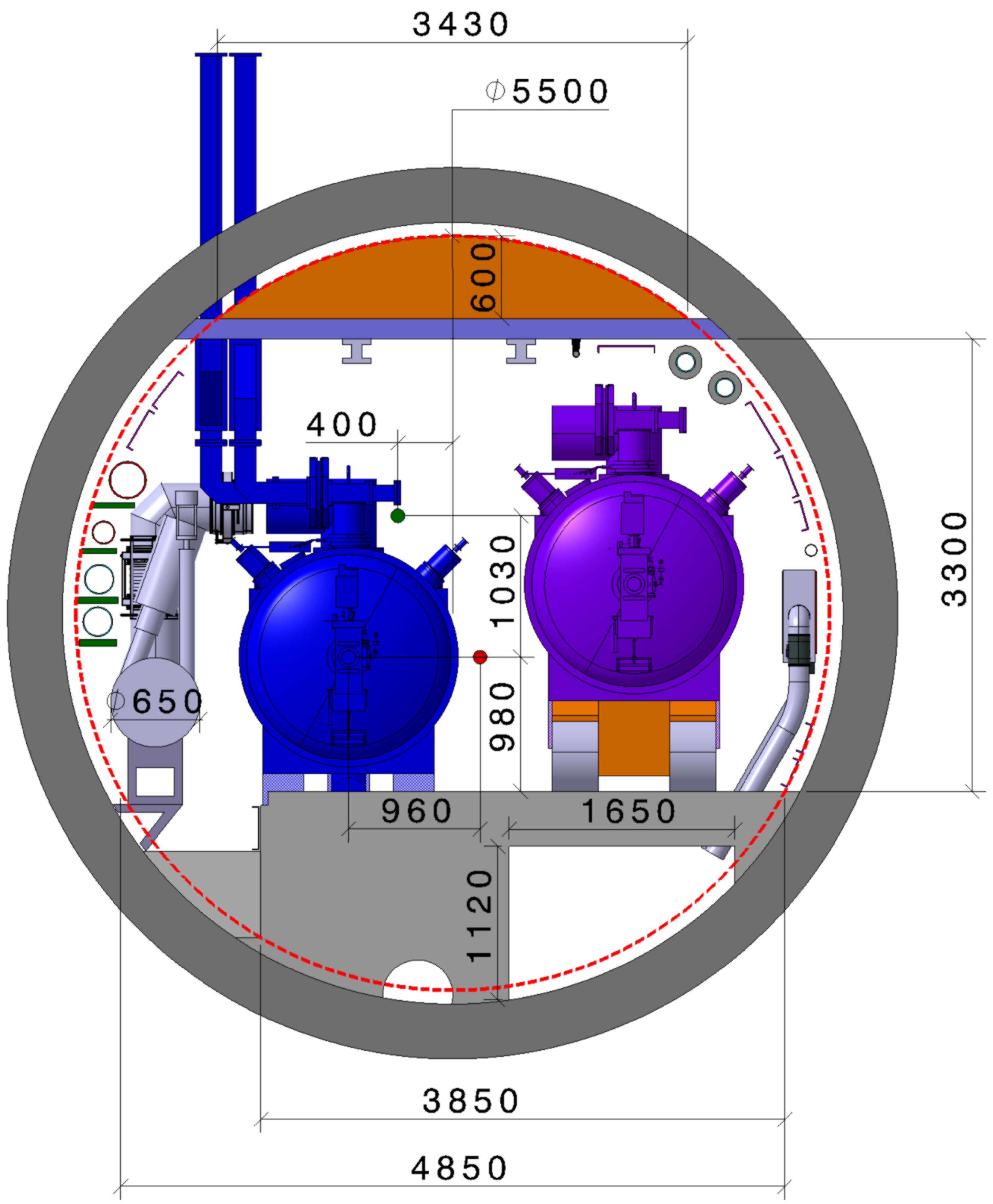

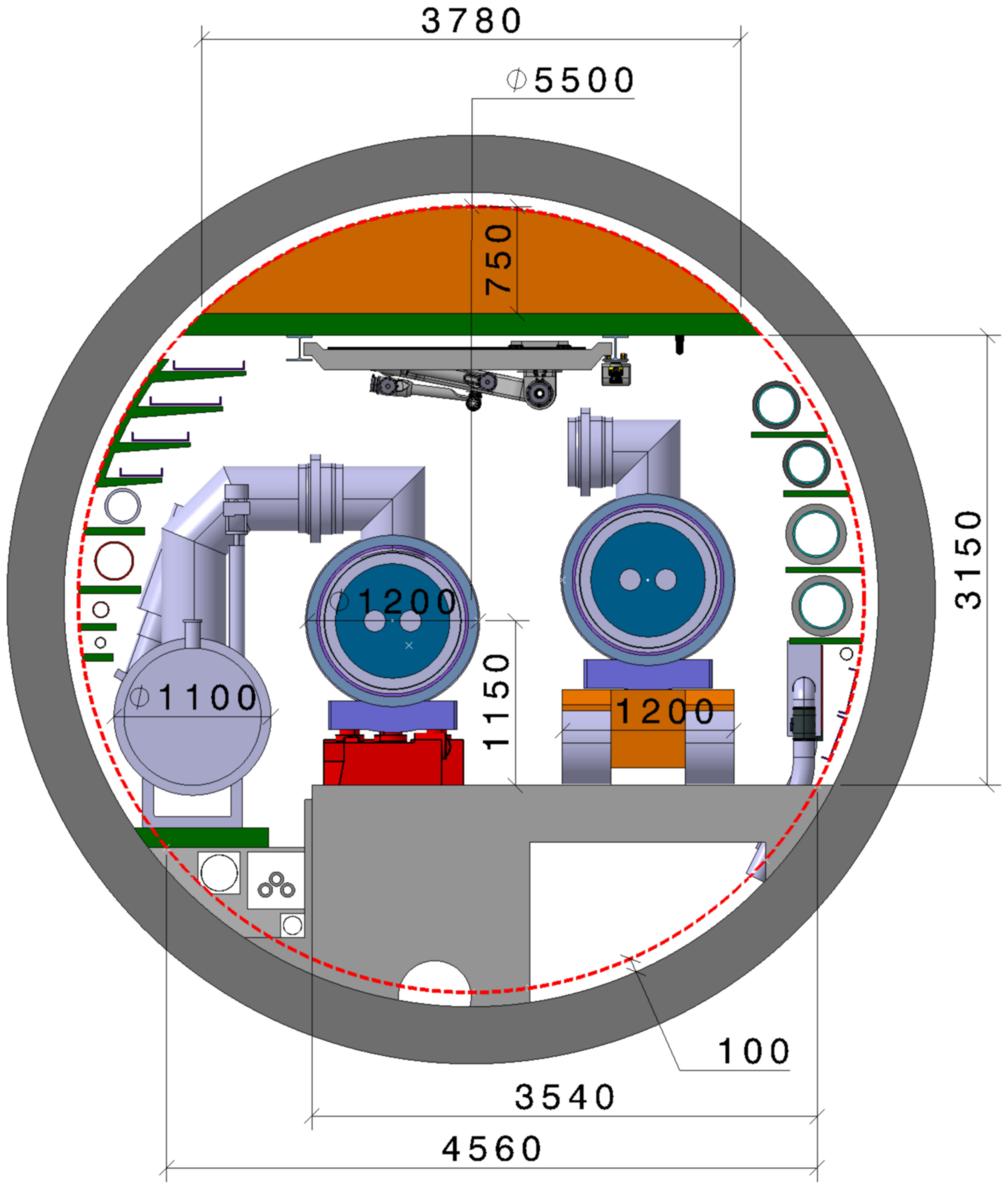

Integration & logistics studies for installation, safety concept reviewed, to confirm 5.5 m

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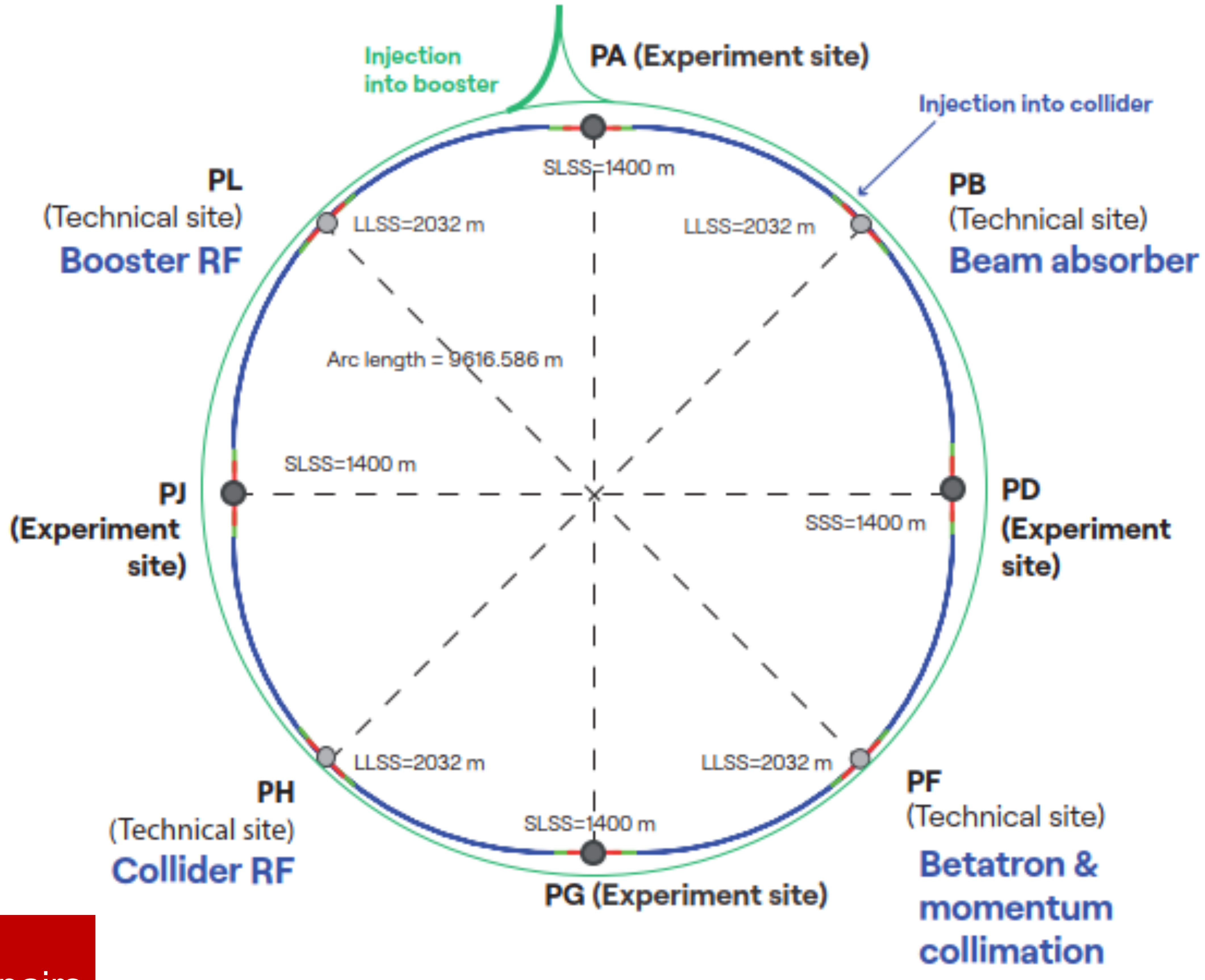
Stage 1: e^+e^- collider FCC-ee

Consolidated main parameters

parameter	Z	WW	H (ZH)	
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [10^{34} cm^{-2}s^{-1}]	145	20	7.5	1.4
total integrated luminosity / IP / year [ab^{-1} / yr]	17	2.4	0.9	0.17
electrical power operation [MW]	250	275	297	381
electrical energy per year [TWh]	1.17	1.32	1.41	1.85
	4 years 6 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years > 2x10^6 H	5 years 2 x 10^6 tt pairs

FCC-ee functional layout



10^4 (@WW) - 10^5 (@Z) x luminosity/energy of LEP → sustainable physics

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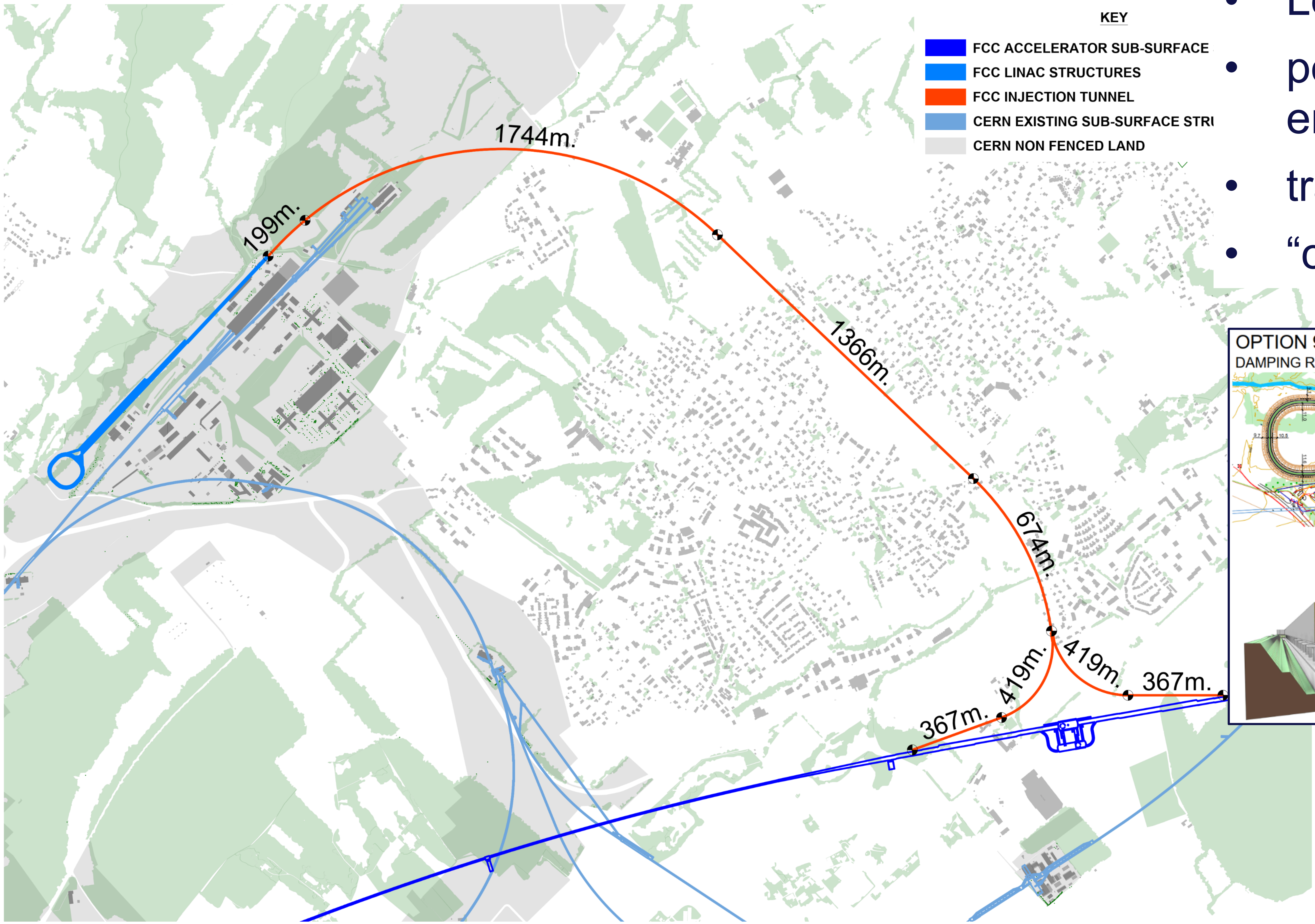
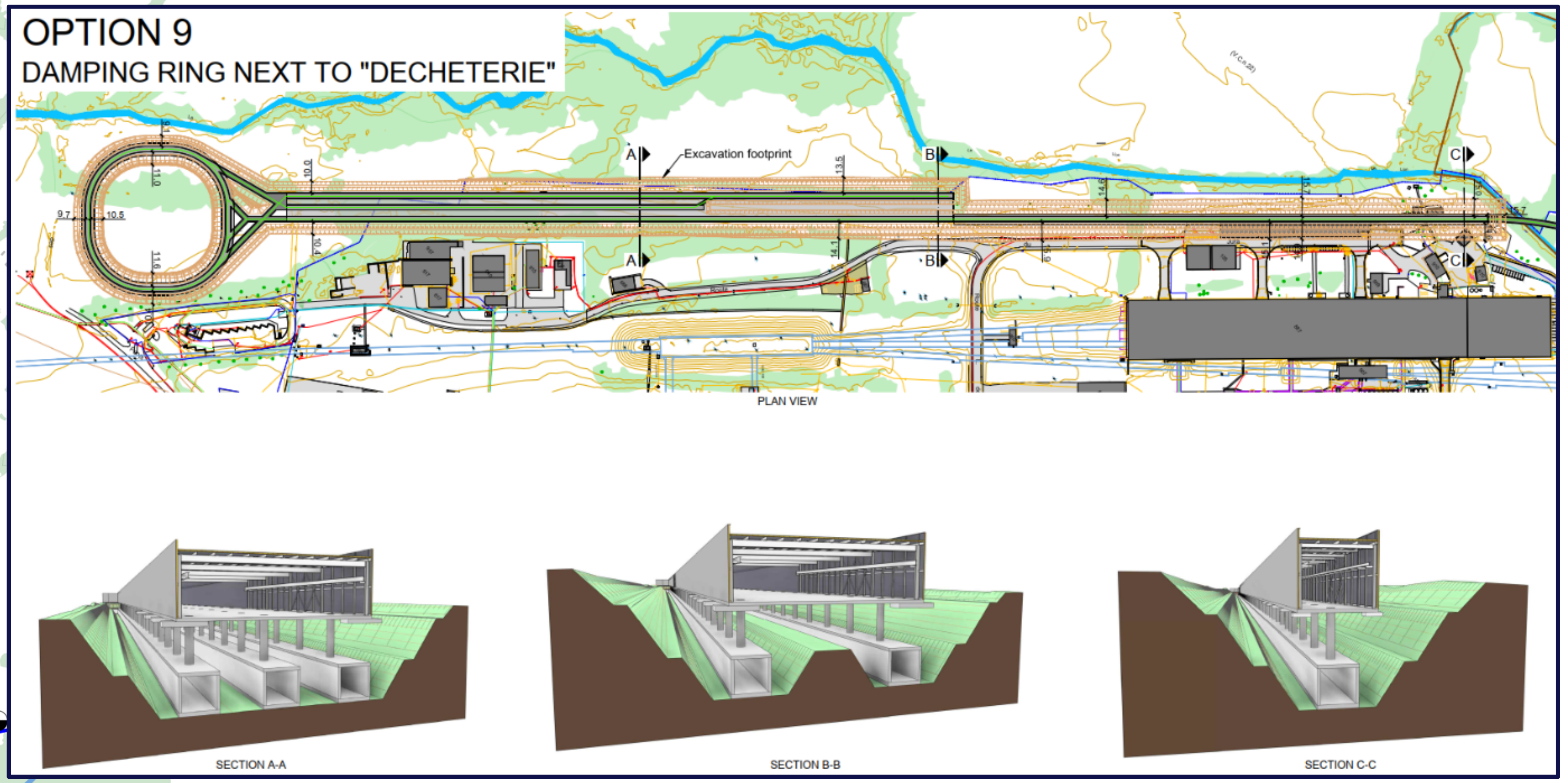
FCC-ee injector with HE Linac



- Located on CERN Prévessin site
- possible connection to North Area to enable non-collider physics
- transfer line to FCC PA (LHC P8)
- “cut and cover” construction



- Since MTR overall parameter optimization to reduce electrical power to < 30 MW

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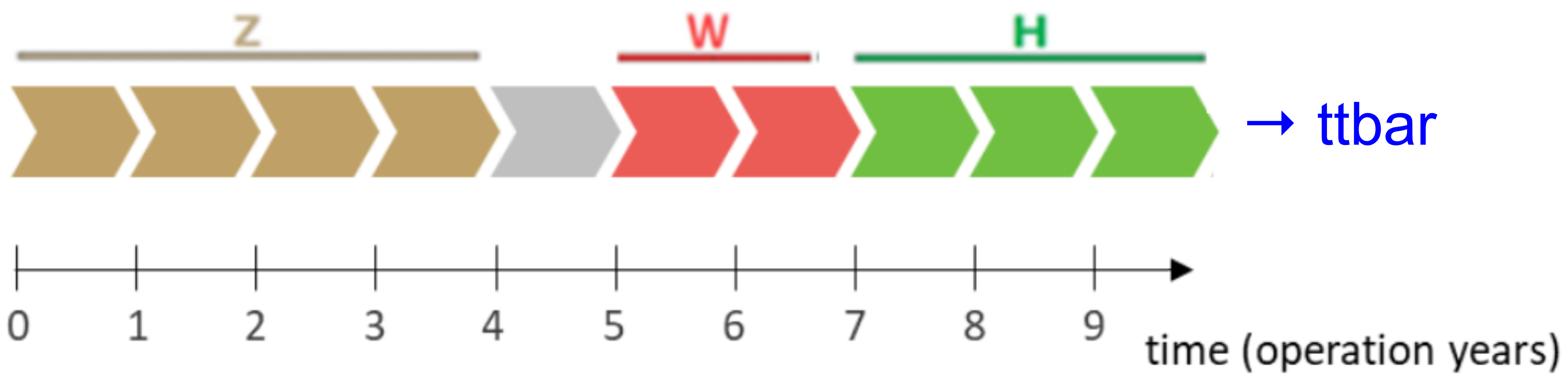
Operation modes for RF

- Physics at 4 different energy points:
  Z^0, W^+W^-, Higgs (ZH), t-tbar production
- Same SR power for all 4 modes
  P_{SR}= **50 MW** per beam



Lowest energy:
- Low RF voltage
- High beam current

⬇

- Few cavities
- Low voltage per cavity
- **High power** per cavity
- Significant HOM power
- Instabilities

⬇

- 1- or 2-cell cavities at low RF frequency (400MHz)

Highest energy:
- High RF voltage
- Low beam current

⬇

- Many cavities
- **High voltage** per cavity
- Low power per cavity
- Low HOM power
- High SR damping

⬇

- Multi-cell cavities at higher RF frequency (800MHz)

M. Benedikt - F. Zimmermann

Operation modes for RF

- Physics at 4 different energy points:
  Z^0, W^+W^-, Higgs (ZH), t-tbar production
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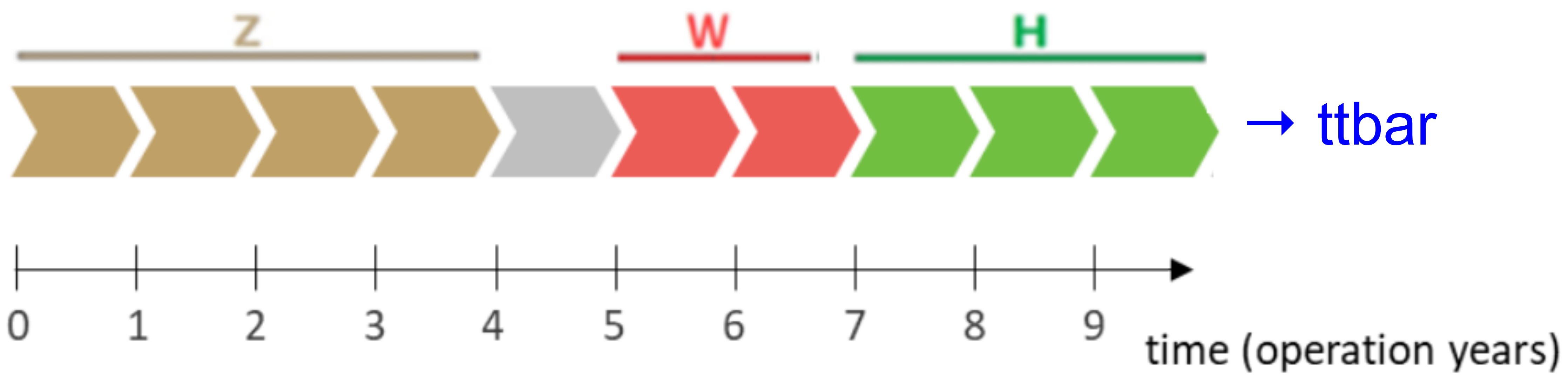

Lowest energy:
- Low RF voltage
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Highest energy:
- High RF voltage
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- Many cavities
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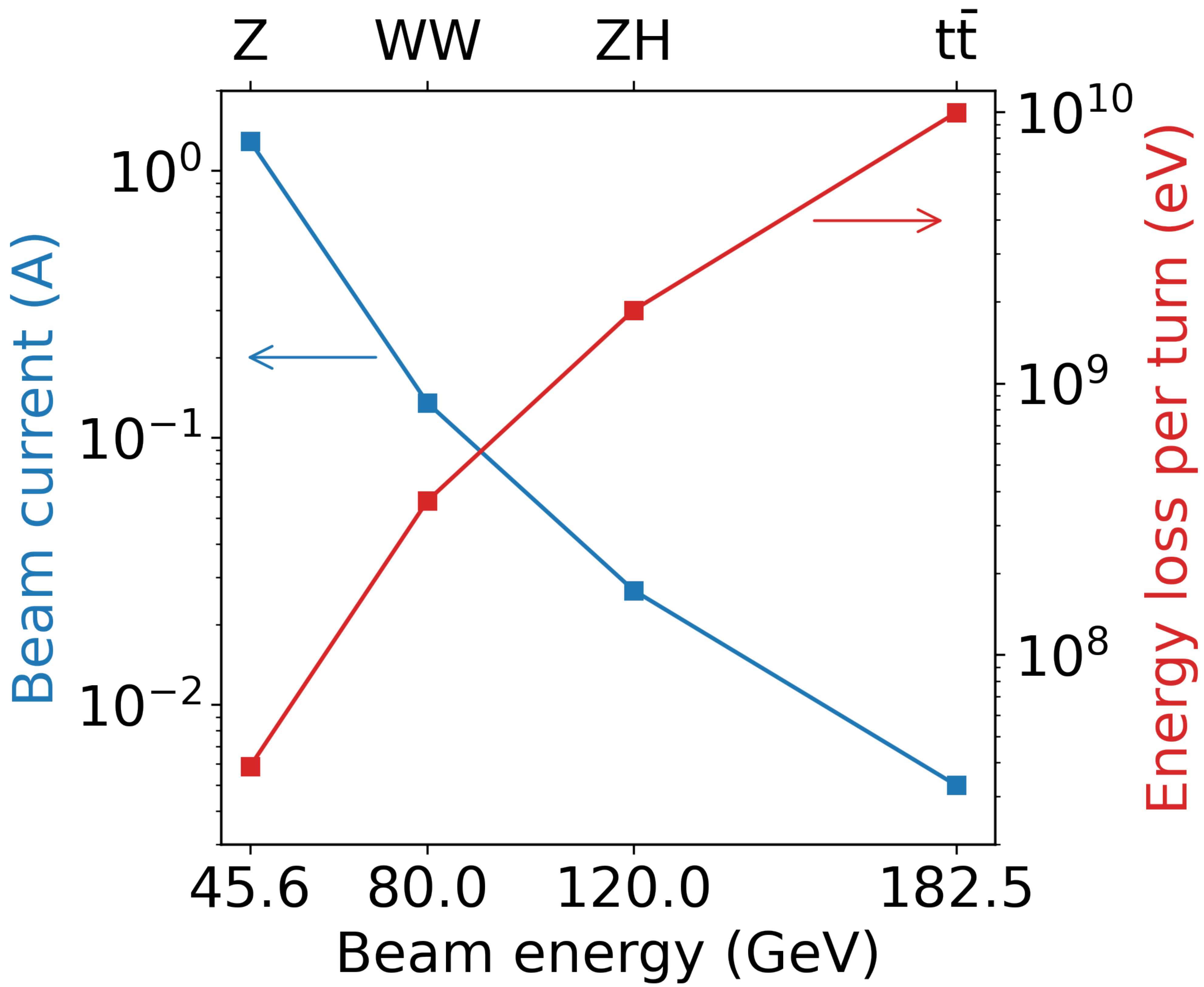

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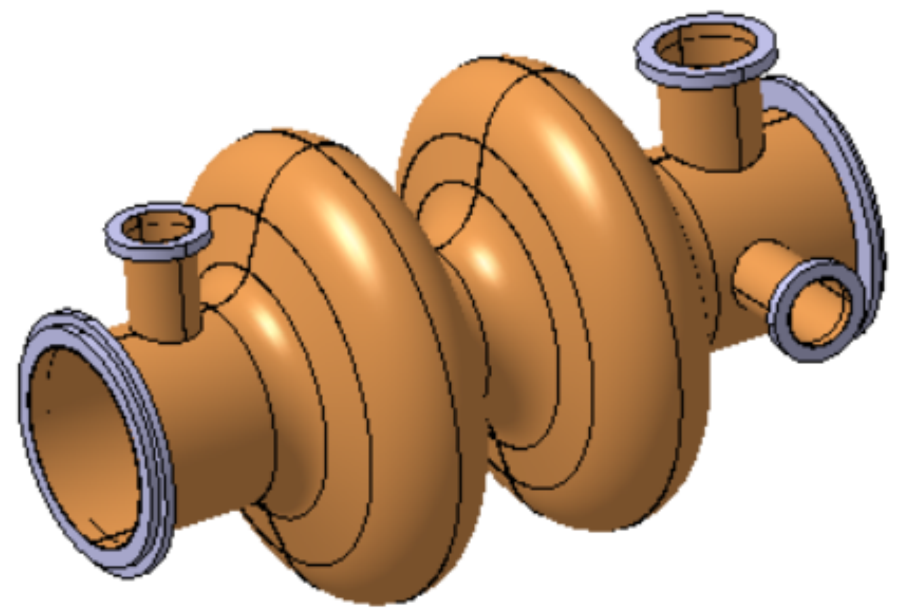
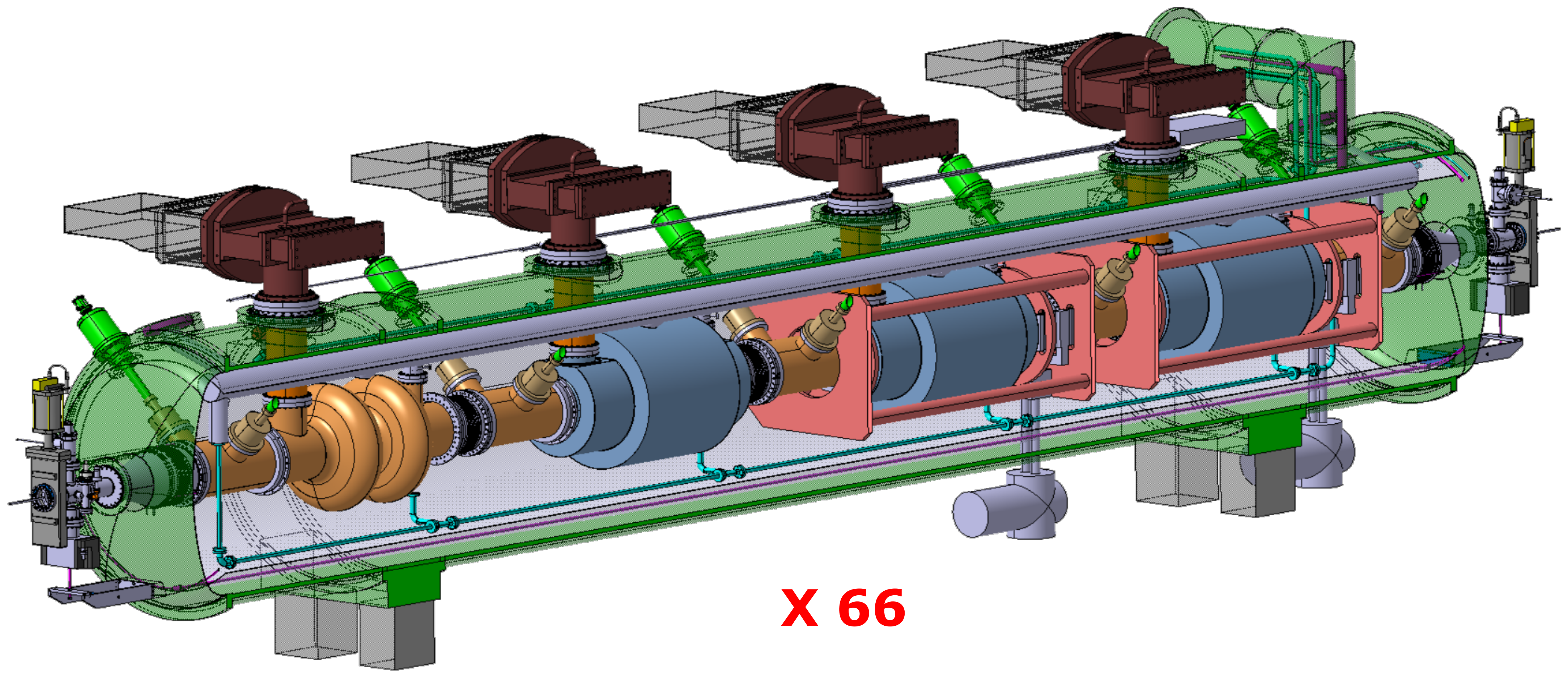
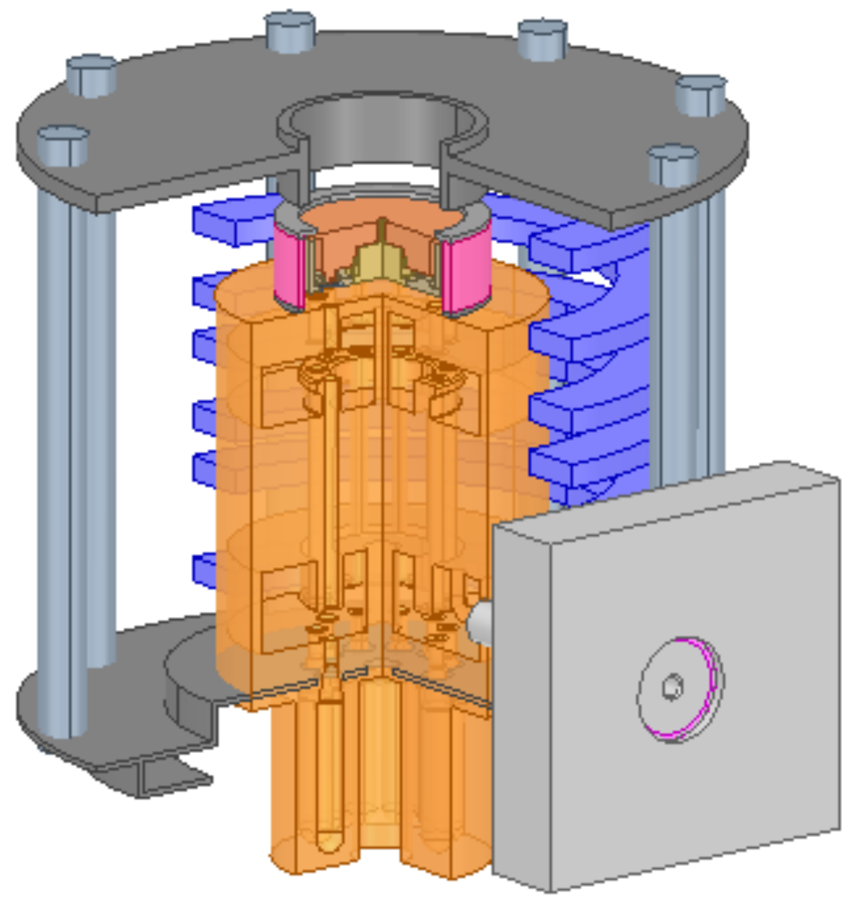
400 MHz system – collider Z, W, ZH



X 264



X 66



X 264

Superconducting elliptical cavity

- 400 MHz, 2-cell
- 1.5 m. long
- Electropolished and seamless RF surface
- Niobium thin film with HiPIMS

Cryomodule

- Segmented design, 4 cavities
- Vertical FPC, HOM damping and extraction
- Frequency tuning system
- Thermal and magnetic shielding

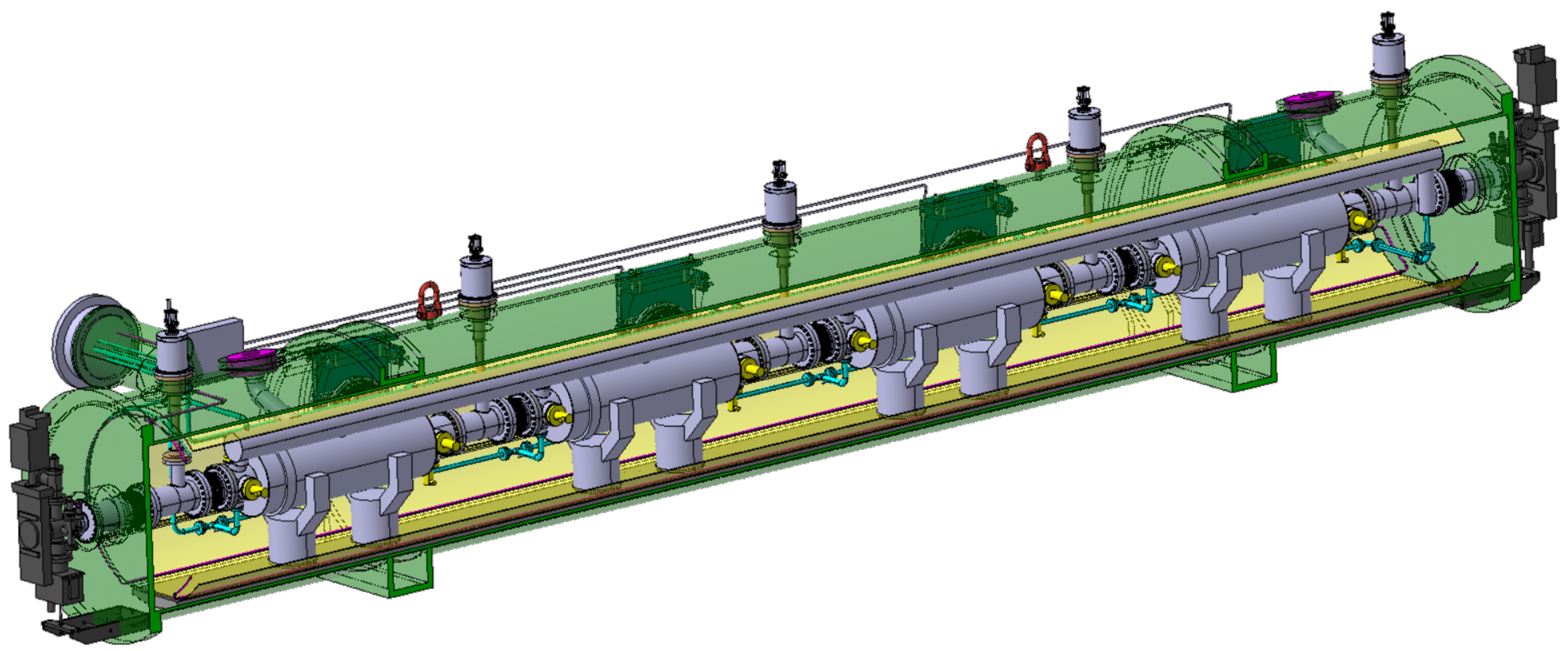
Multibeam Tristron

- **400 MHz**
- 46 kV
- 500 kW, CW
- ~ 90% efficiency

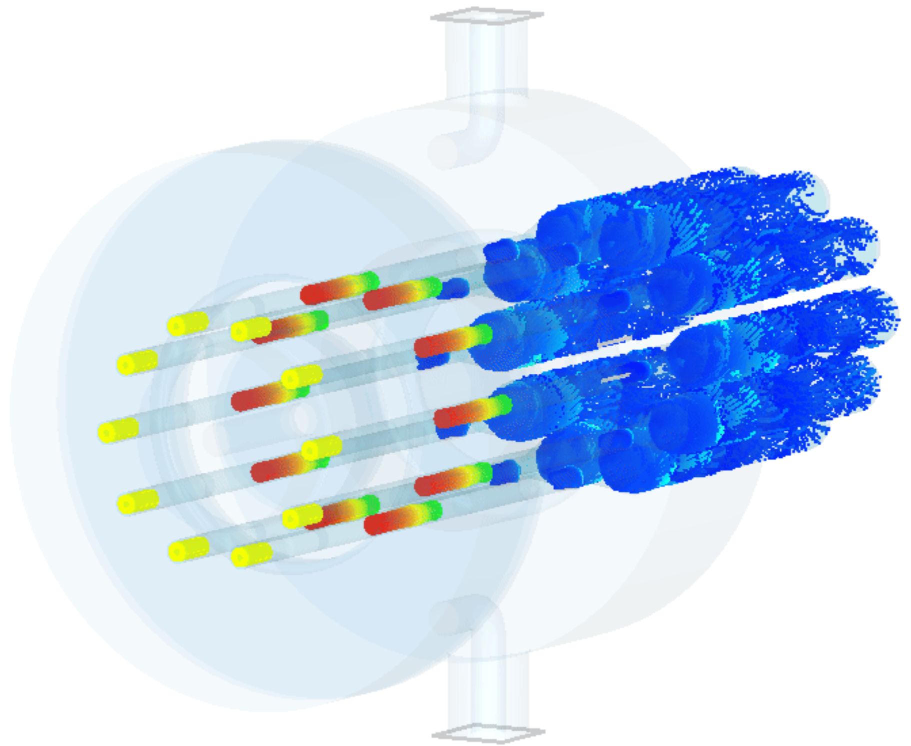
I. Syratchev

800 MHz system – ttb (collider and booster)

X (408 + 448)



X (102 + 112)



Multibeam Tristron
- 800 MHz
- 250 kW, CW

X 408

Superconducting elliptical cavity
- 800 MHz, 6-cell
- Nb3Sn if R&D is successful

Cryomodule
- Segmented design, 4 cavities, 2 K
- Operation at 4.5 K if R&D successful

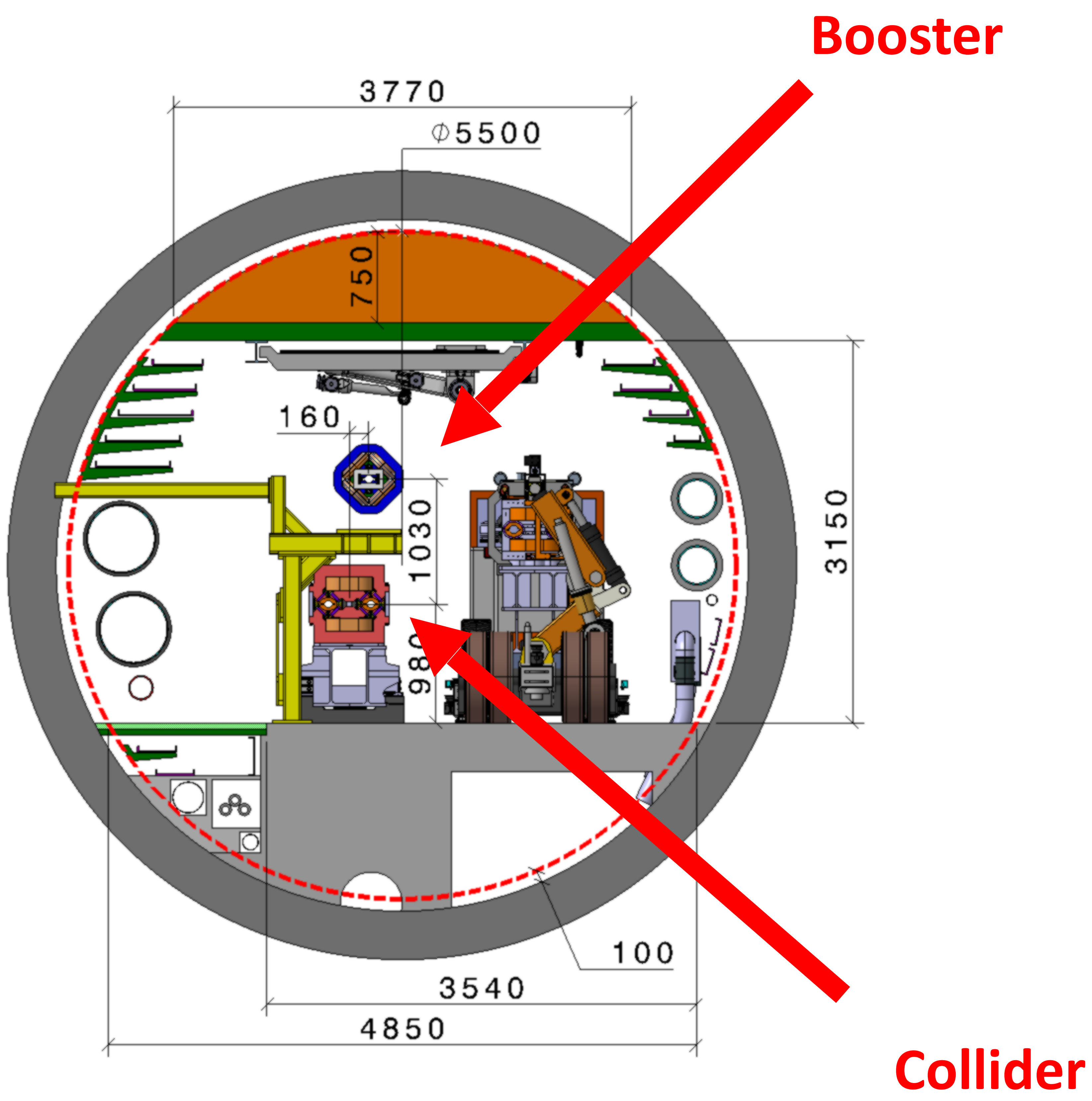
Solid State Amplifier (SSA)
- 800 MHz
- 10-15 kW pulsed

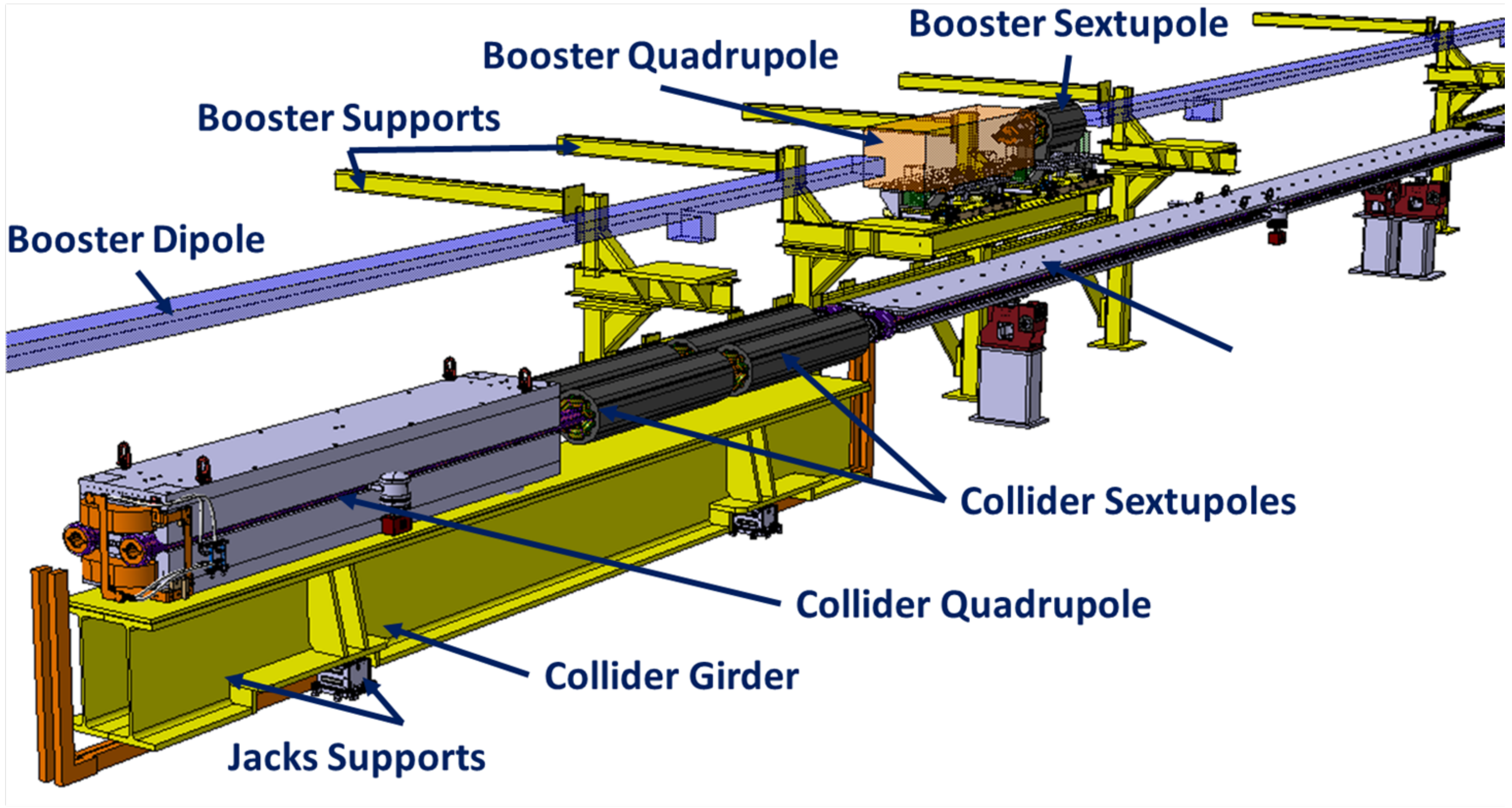
X 448

A. Butterworth

FCC-ee booster

full energy booster, ramping from 20 GeV to 46 GeV – 182.5 GeV; injection ~every minute to keep collider beam currents constant; booster intensity ~1% of collider; full RF voltage as in collider





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FCC-ee cost estimate (FSR 2025)

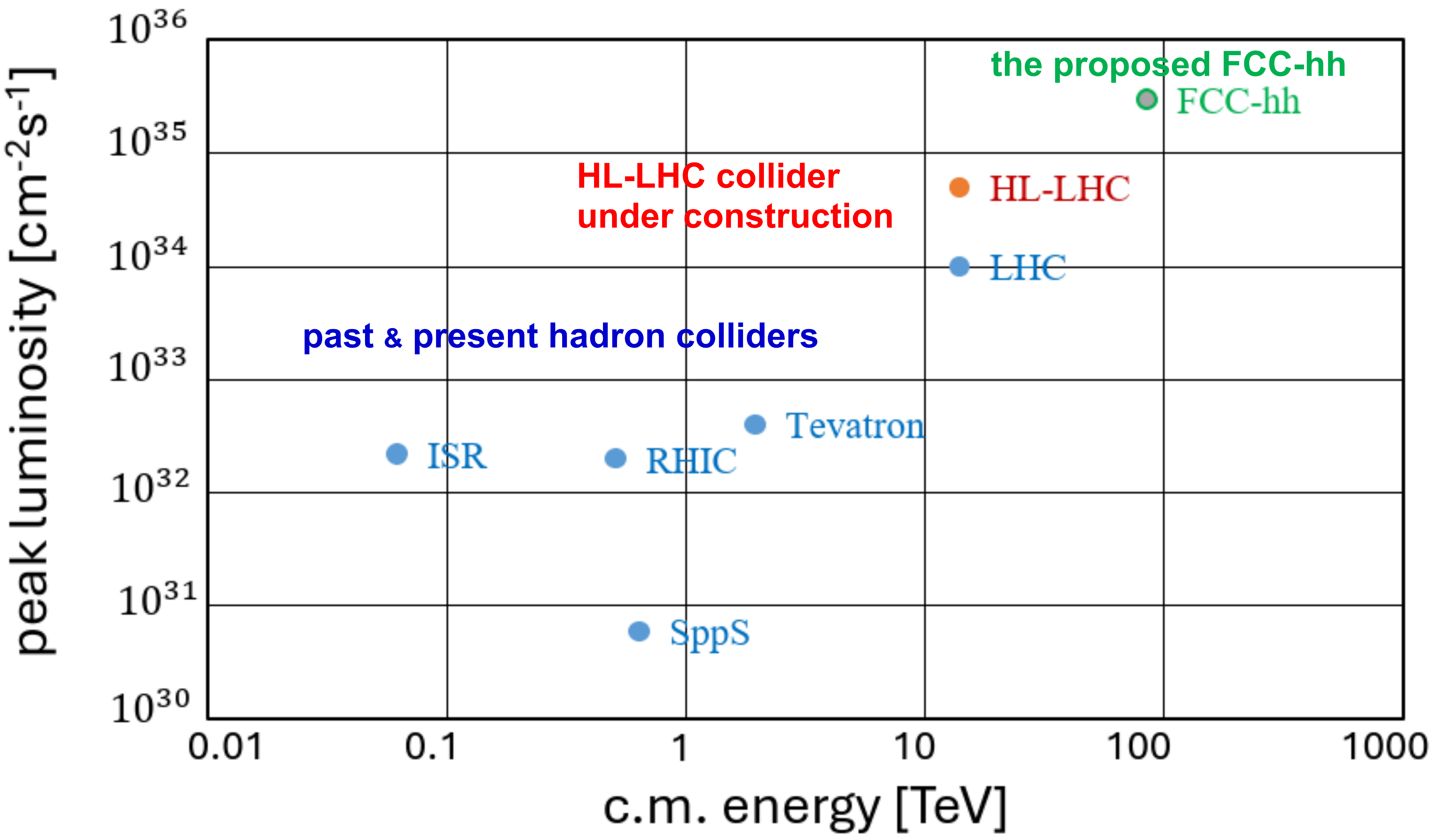
Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF.

M.Benedikt

Hadron collider peak luminosity vs. c.m. energy



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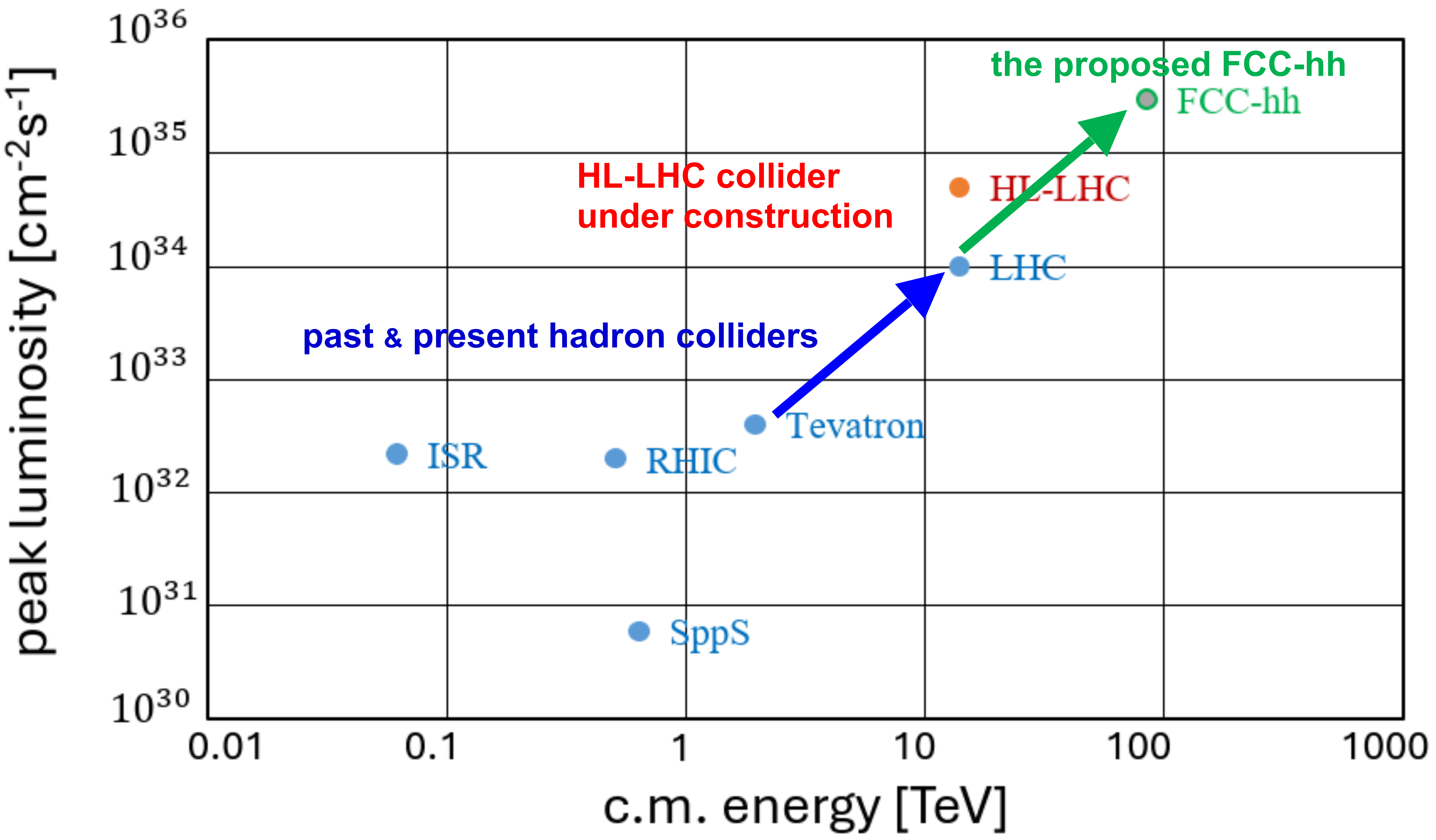
Hadron collider peak luminosity vs. c.m. energy



M. Benedikt - F. Zimmermann

Stage 2: hadron collider FCC-hh

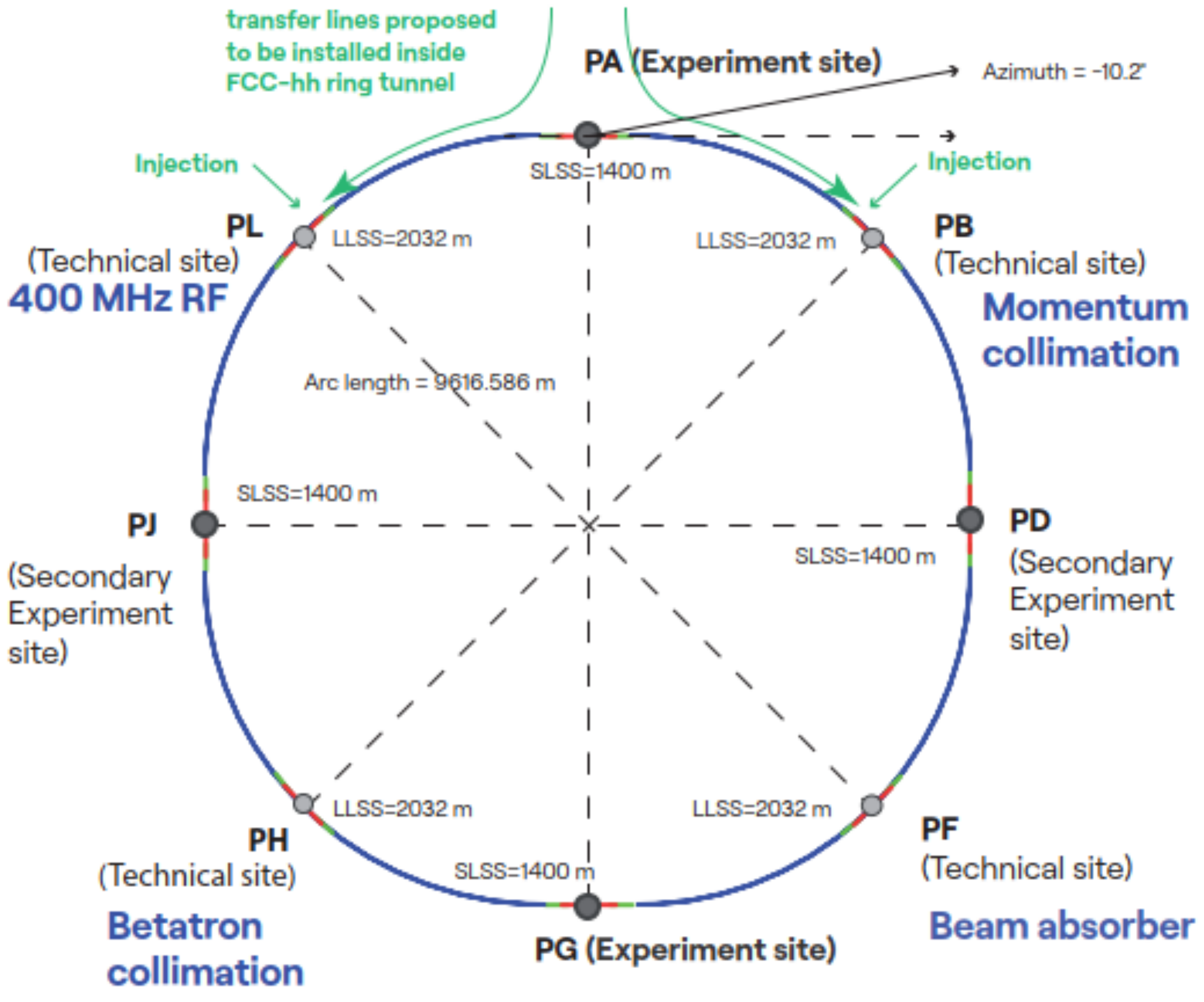
- Parameter optimization to lower electricity consumption (~max. consumption of FCC-ee)
- Magnetic field considered realistic with today's technologies (Nb_3Sn, ~14T, 1.9 K)

Main parameters FSR 2025

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [10^{34} $cm^{-2}s^{-1}$]	30	30	5 (lev.)
integr. luminosity / IP [fb^{-1}]	20000	20000	3000

- **For Nb_3Sn @ 1.9 K: 355 MW el, consumption and 2.3 TWh/y**
- **For Nb_3Sn @ 4.5 K potential to reduce to ~1.8 TWh/y as FCC-ee.**

FCC-hh functional layout



M.Benedikt

Status of the FCC Global Collaboration

Increasing international collaboration is a prerequisite for success:

→links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of the FCC

→Next step is preparation of a plan with national laboratories for in-kind contributions to the project

38 Participating Countries

Austria – Belgium – Brazil – Canada – Chile – Colombia – Czech Republic – Denmark – Estonia – Finland – France – Georgia – Germany – Greece – Hungary – India – Iran – Italy – Japan – Latvia – Malta – Mexico – Netherlands – Norway – Pakistan – Poland – Portugal – Republic of Korea – Romania – Serbia – Spain – Sweden – Switzerland – Thailand – Türkiye – Ukraine – United Kingdom – United States of America

162 Institutes

38 Countries + CERN

FUTURE CIRCULAR COLLIDER *Feasibility Study*

FUTURE CIRCULAR COLLIDER

European Strategy for Particle Physics: 2026 Update

INFN Istituto Nazionale di Fisica Nucleare

- Strategy process was initiated by the CERN Council in 2024

  Motivation: - Large progress towards future colliders at CERN (FCC feasibility study) and beyond
  - International landscape of the field (CEPC, ILC, P5 in the US)
  - Accomplishments in physics (LHC, HL-LHC and elsewhere)
  - Long timescales (community engagement)

- *Aim: develop a* ***visionary and concrete plan*** *that greatly advances human knowledge in fundamental physics through the* ***realisation of the next flagship project at CERN****. This plan should attract and value* ***international collaboration*** *and should* ***allow Europe to continue to play a leading role in the field.***

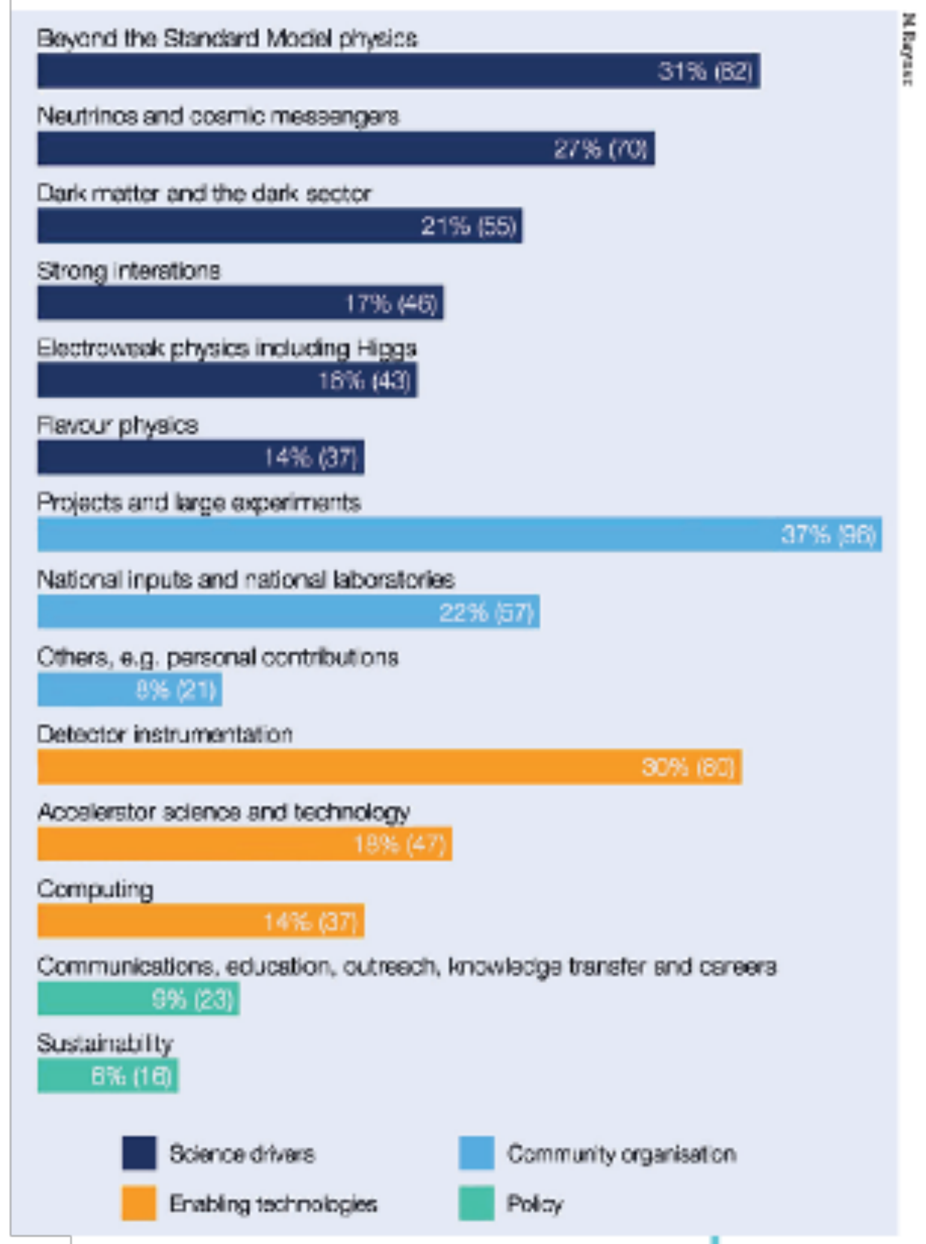
- *The Strategy update should include the* ***preferred option for the next collider at CERN*** *and* ***prioritised alternative options*** *to be pursued if the chosen preferred plan turns out not to be feasible or competitive.*

- *The Strategy update should also* ***indicate areas of priority for exploration complementary to colliders*** *and for other experiments to be considered at CERN and at other laboratories in Europe, as well as for participation in projects outside Europe.*

K. Jakobs

European Strategy for Particle Physics: 2026 Update

Timeline for the update of the European Strategy for Particle Physics



266 submissions received

- *Major flagship projects*
- *Many projects in other physics areas*
- *Input from national HEP communities*
- *National labs*
- *Early career researchers*
- …

31 March 2025 — **Deadline** for the submission of main input from the community

26 May 2025 — **Deadline** for the submission of additional national input in advance of the **Open Symposium**

23-27 June 2025 — **Open Symposium (in Venice)**

End September 2025 — Submission of the "Briefing Book" to the **ESG**

14 November 2025 — **Deadline** for the submission of final national input in advance of the **ESG Strategy Drafting Session**

1-5 December 2025 — **ESG Strategy Drafting Session (Monte Verità / Ascona, CH)**

End January 2026 — Submission of the draft strategy document to the Council

March and June 2026 — Discussion of the draft strategy document by the Council and **updating of the Strategy**

More details on ESPP web page: https://europeanstrategyupdate.web.cern.ch/

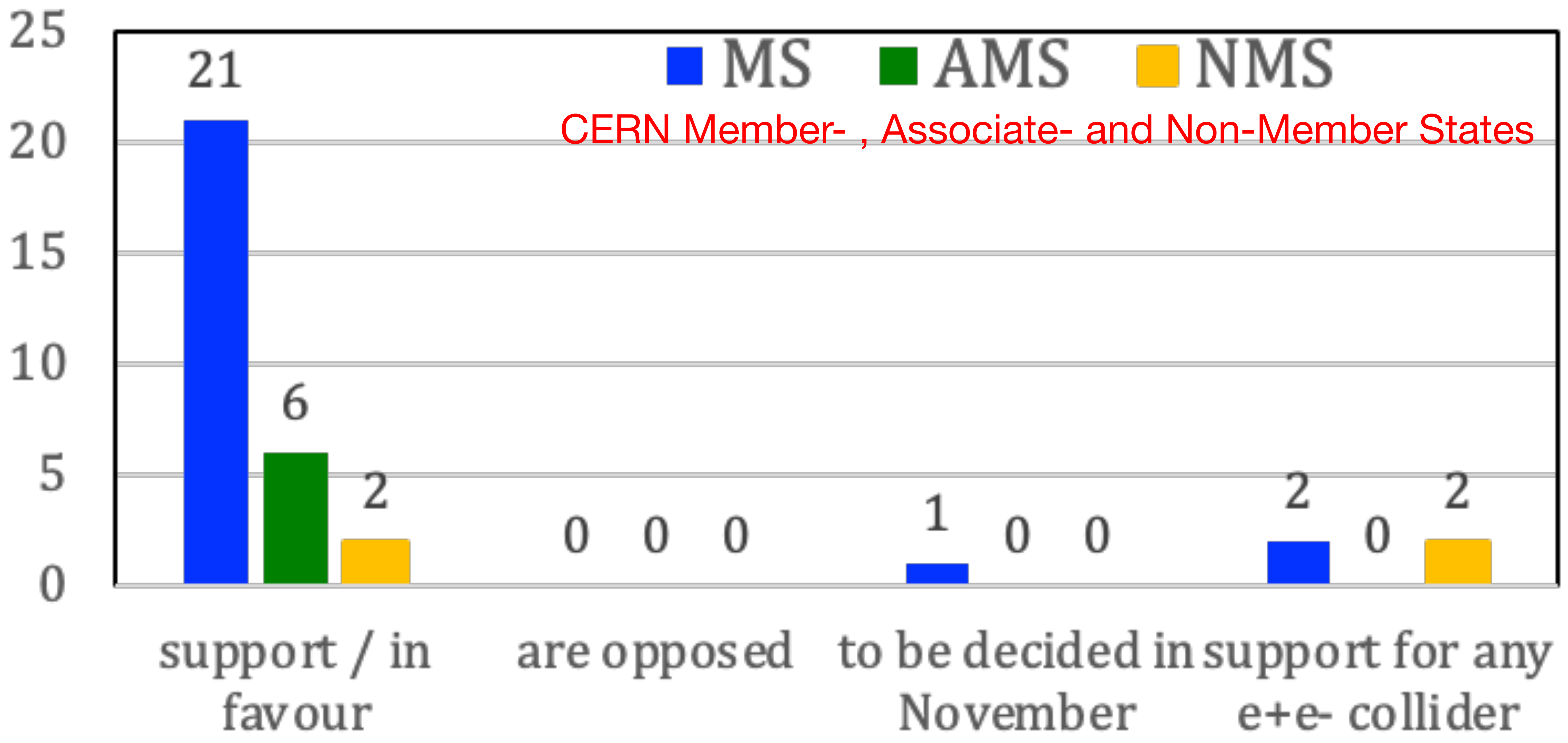
K. Jakobs

Open Symposium in Venice

https://agenda.infn.it/event/44943/overview

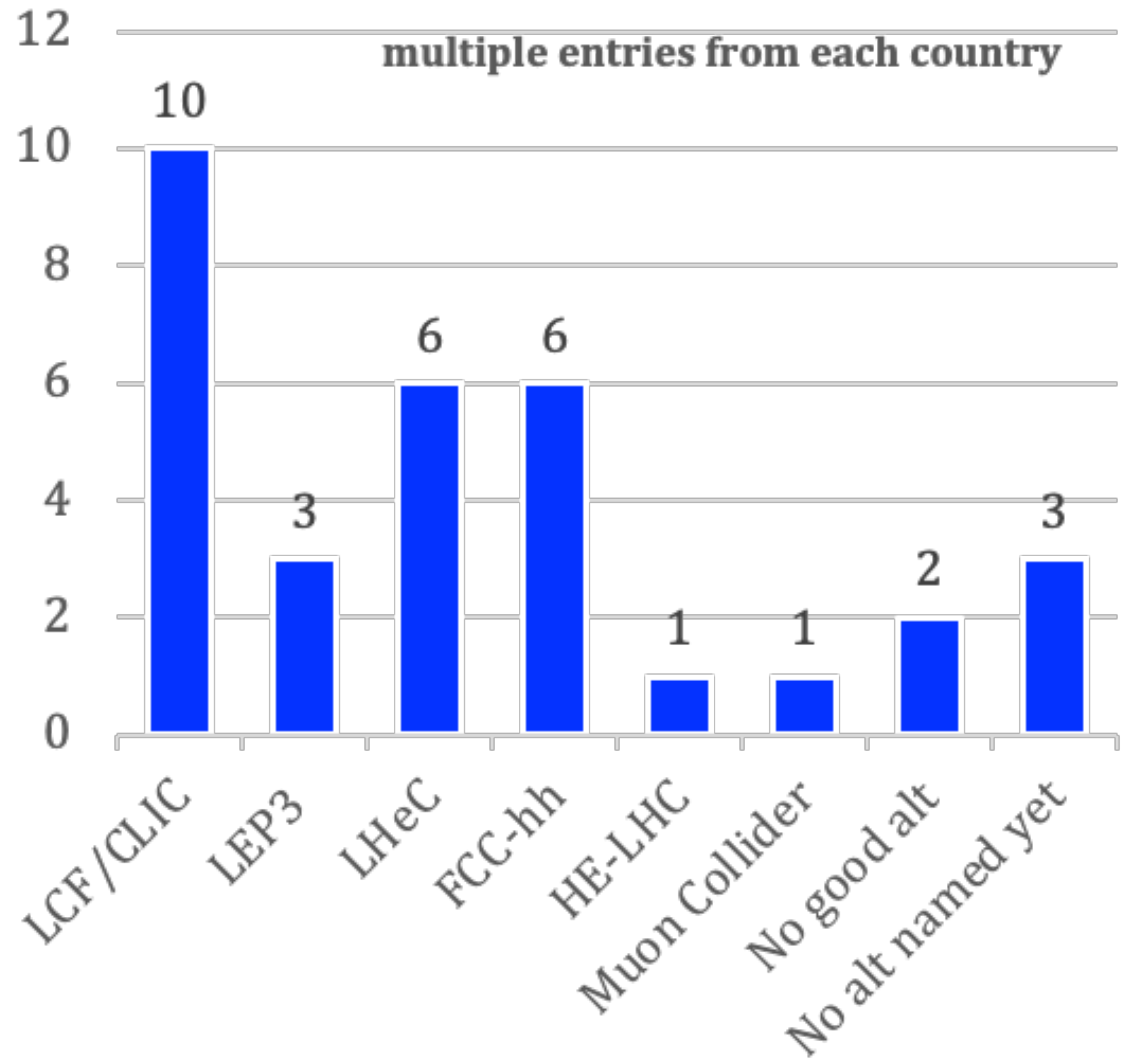
View of the national HEP communities

What is the preferred large-scale accelerator for CERN?



- Overwhelming support (21/24 CERN Member States HEP communities) in favour of the integrated FCC-ee/hh programme
- Support as well from Associate Member States (AMS) and Non-Member States (NMS)

What is the alternative if the preferred option is not feasible?



- No consensus on an alternative (yet)

K. Jakobs

FUTURE CIRCULAR COLLIDER

Towards the recommendations for the next CERN flagship project

INFN Istituto Nazionale di Fisica Nucleare

(i) Physics Potential

Physics Briefing Book (→ 30 Sept. 2025)

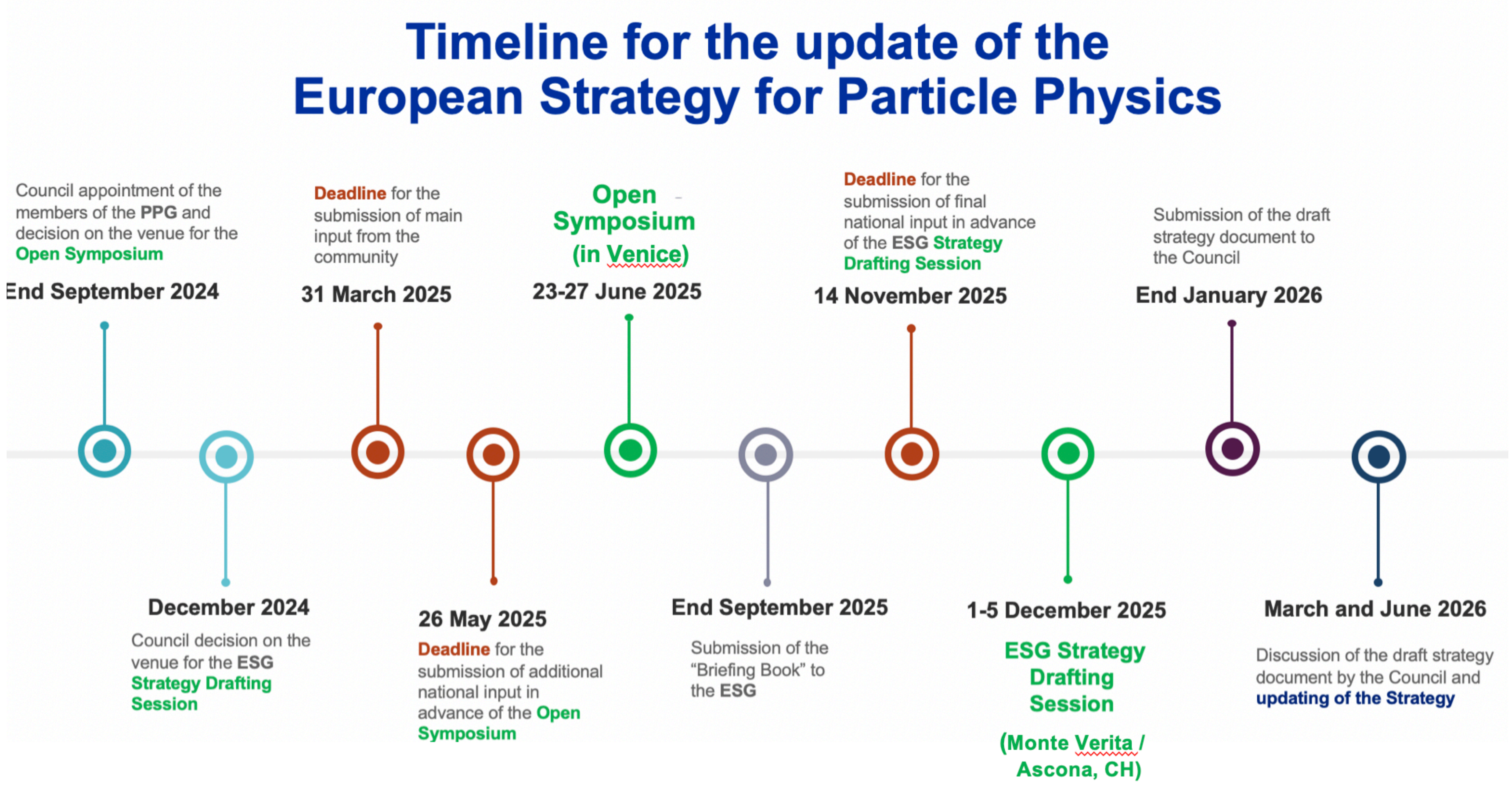
→ Assessment of overall Physics Potential **(ESG Working Group 2b)**

(ii) Project assessment

Technical feasibility, required R&D, risks, timeline, costs and human resources (including estimates for the associated detectors), environmental impact

(ESG working group 2a)

Preliminary finding will be shared with the community around mid October



More details on ESPP web page: https://europeanstrategyupdate.web.cern.ch/

(iii) Final input by the National HEP communities

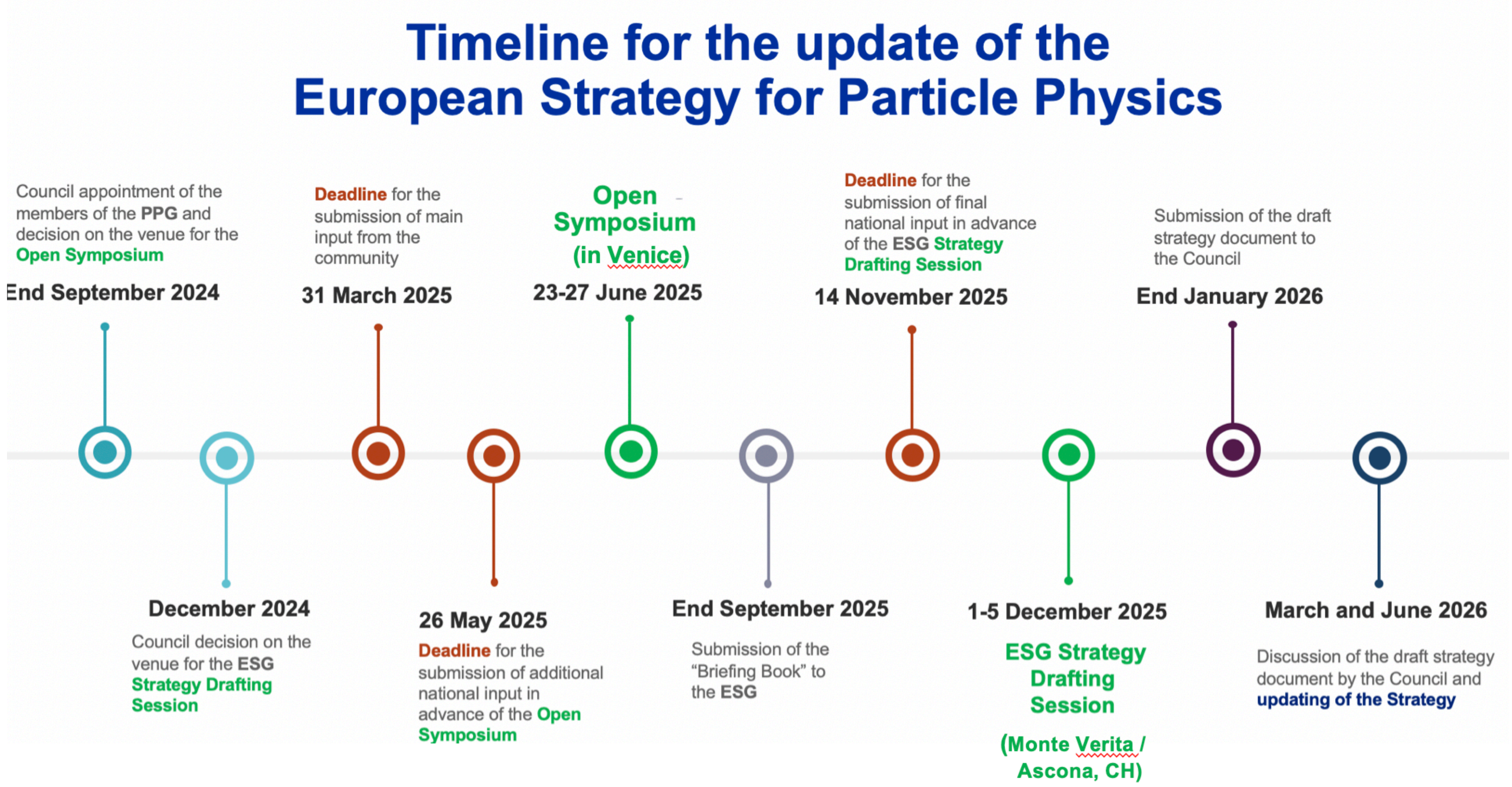
(→ 14 Nov. 2025)

Towards the recommendations for the next CERN flagship project

(iv) ESG Strategy Drafting Session, 01 – 05 Dec 2025
in Ascona / Monte Verità

→ ESG recommendations;

Will be submitted to the CERN Council



More details on ESPP web page: https://europeanstrategyupdate.web.cern.ch/

(v) Update of the European Strategy for Particle Physics by the CERN Council
(Discussions in March 2026, final meeting in Budapest in May 2026)

(vi) Final deliberations on **project approval** by the CERN Council during 2027/2028

Physics requirements

Higgs Factory Programme

- At √s=240 and √s=365 GeV collect 2.6M HZ and 150k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (~4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \rightarrow H$ at 125 GeV

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6×10^{12} Z and 2×10^8 WW events
- × 500 improvement of statistical precision on EWPO: $m_Z, \Gamma_Z, \Gamma_{inv}, \sin^2\theta_W, R_b, m_W, \Gamma_W$, …
- 2×10^8 tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

- **Absolute normalisation of luminosity to 10^{-4}**
- **Relative normalisation to $\lesssim 10^{-5}$ (e.g. Γ_{had}/Γ_ℓ)**
  - Acceptance definition to $\mathcal{O}$(10 μm)
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2×10^{12} ττ (clean and boosted): 10 × Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/√E**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

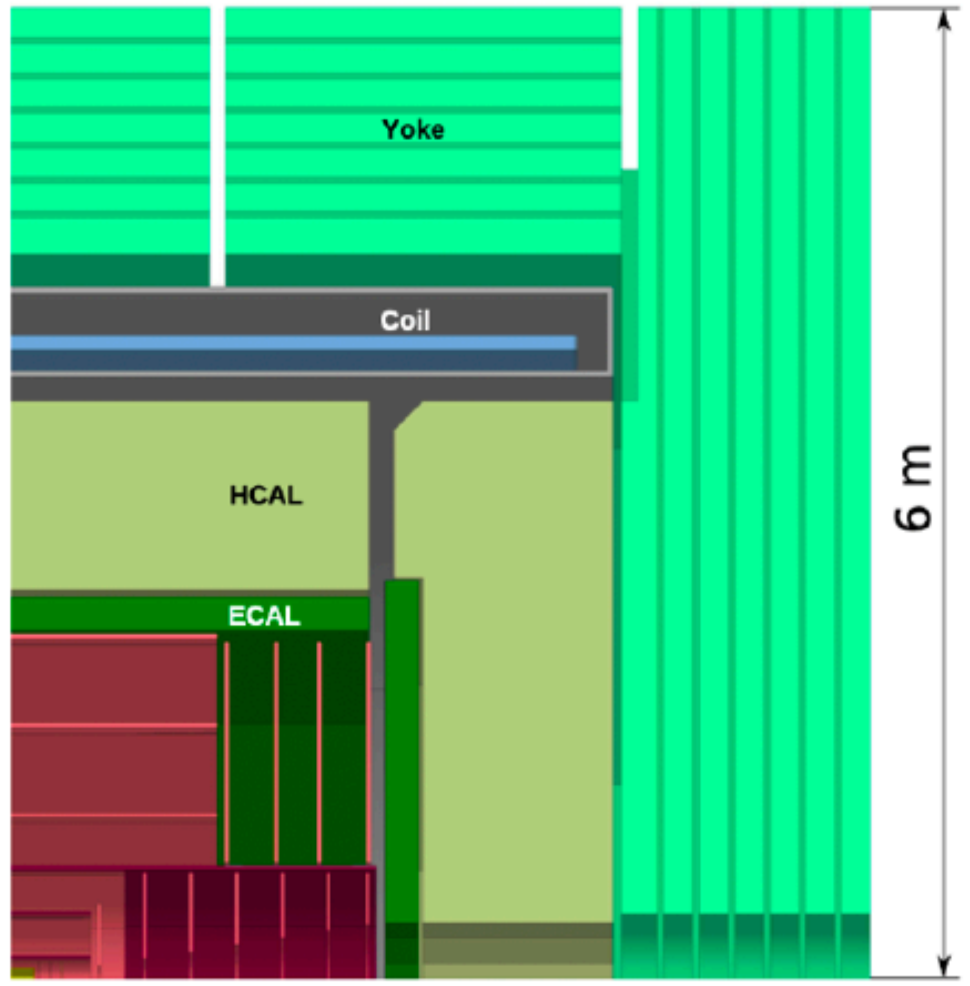
- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, ”continous” tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

M. Dam

FCC-ee Detector concepts

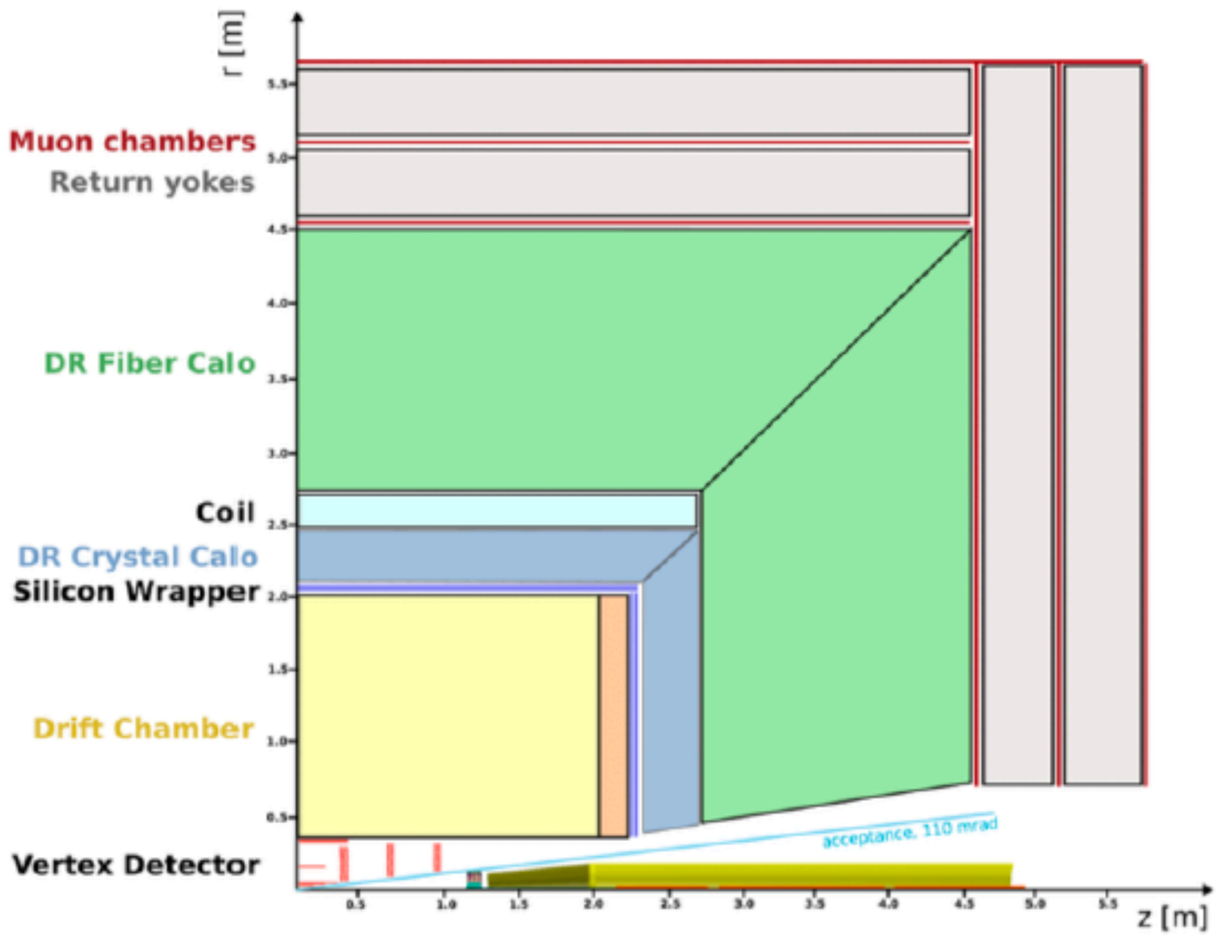
CLD



- Well established design
  - ILC → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

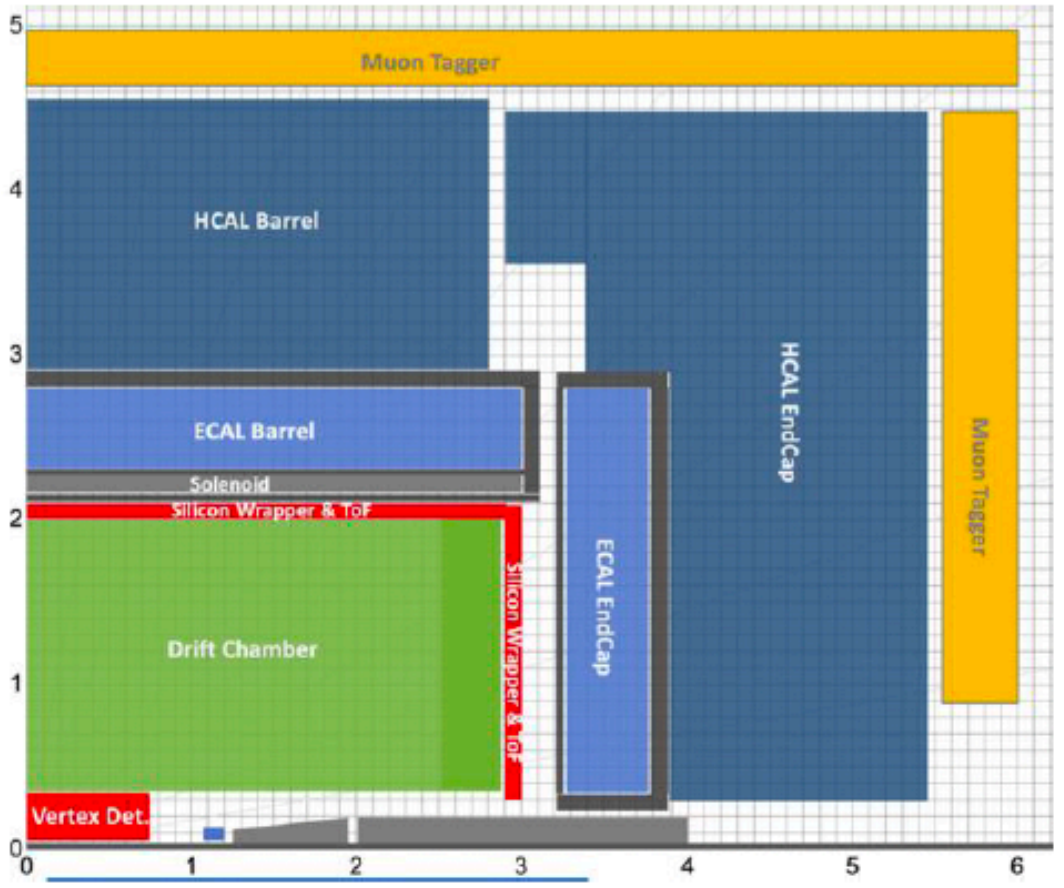
IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VXD; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

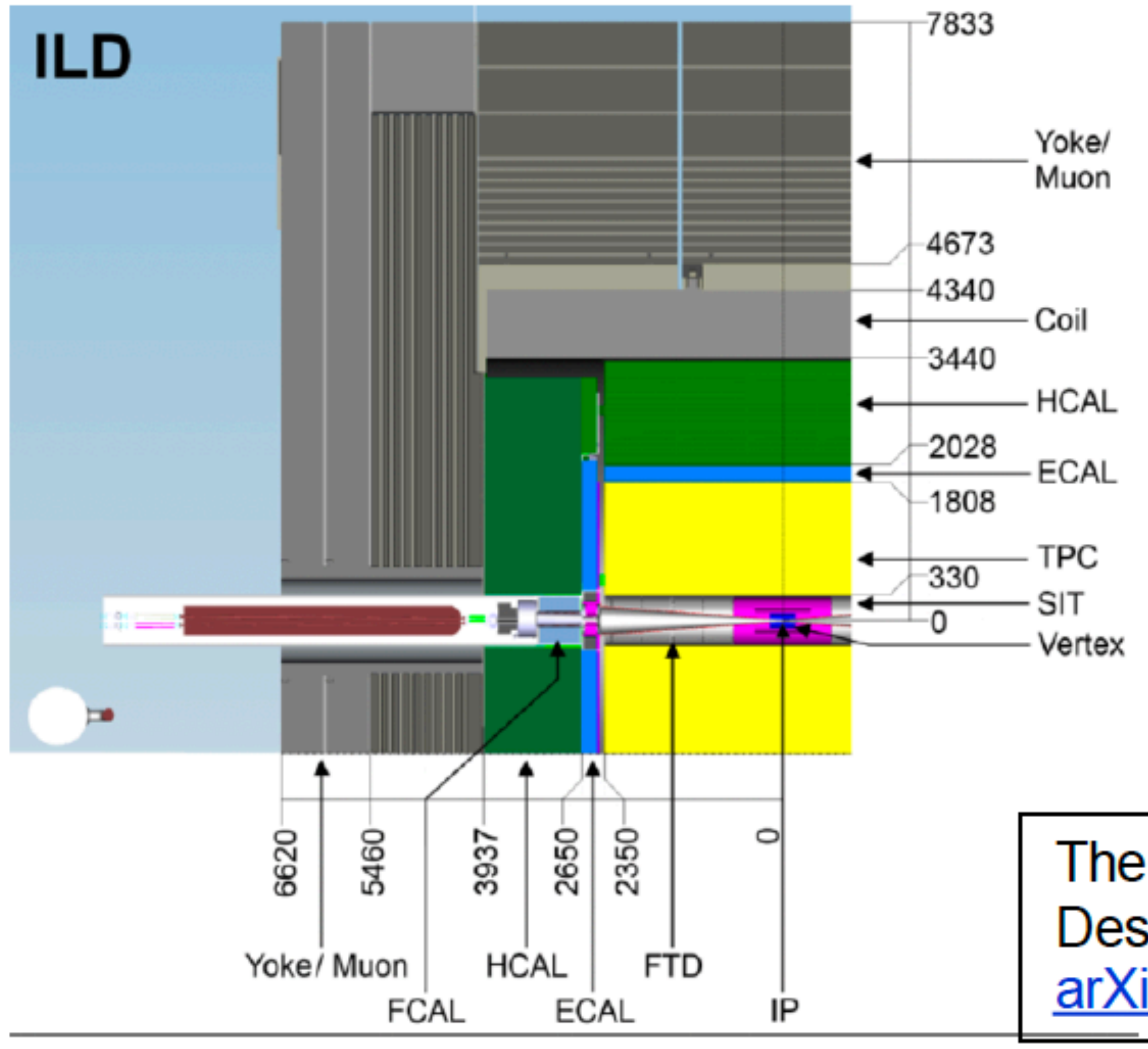
https://doi.org/10.48550/arXiv.2502.21223

Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VXD
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
  - Large-volume time projection chamber (TPC)

The International Linear Collider Technical Design Report - Volume 4: Detectors
arXiv:1306.6329

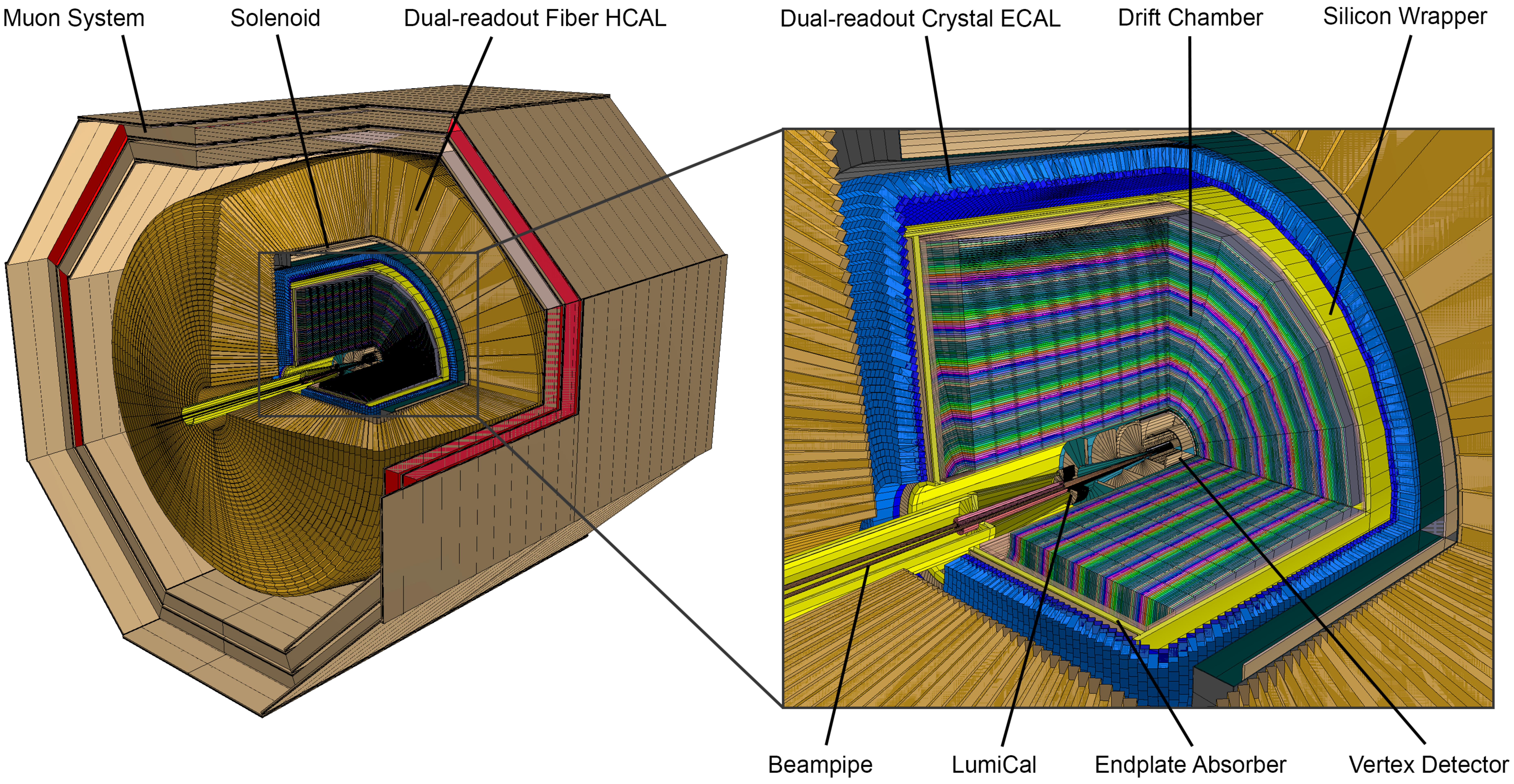
M. Dam

Innovative Detector for E+e- Accelerator (IDEA)

IDEA was proposed some years ago by several INFN researchers.

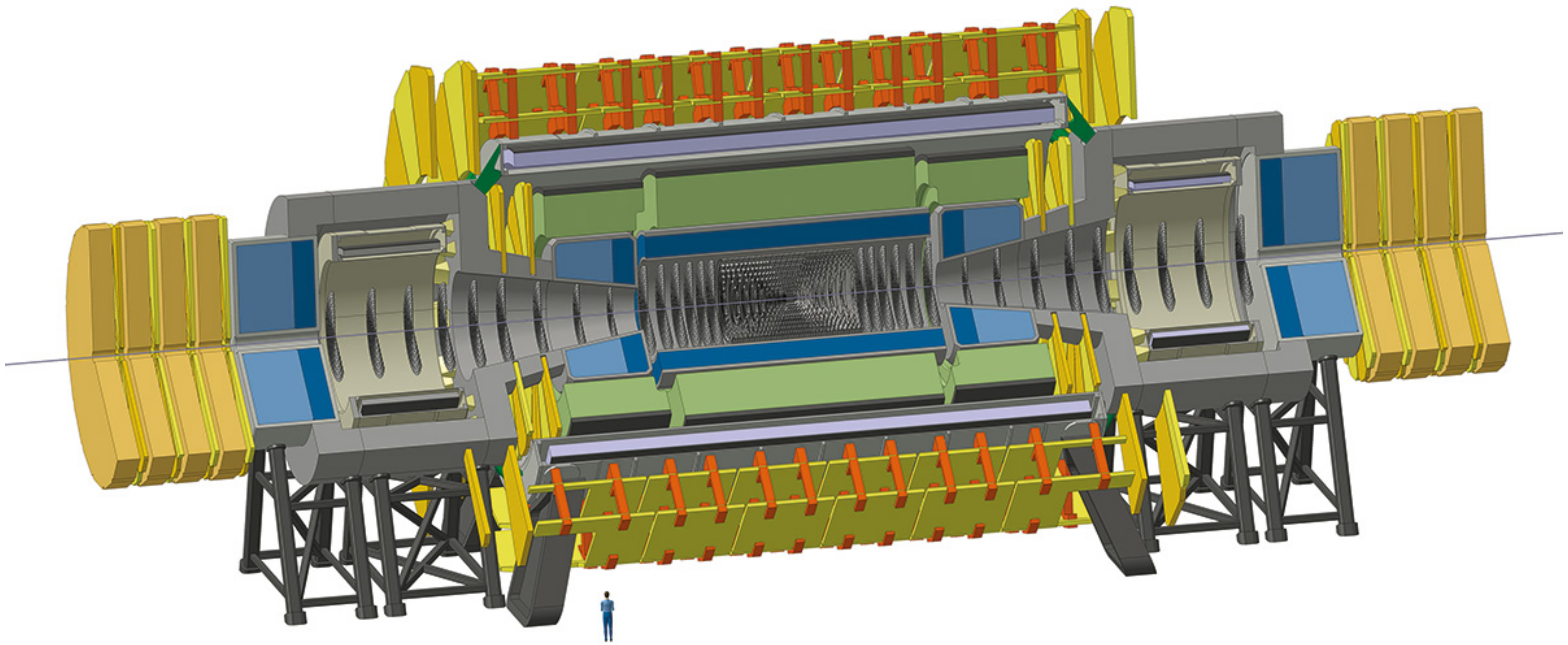
It was the first detector conceived specifically for FCC-ee.

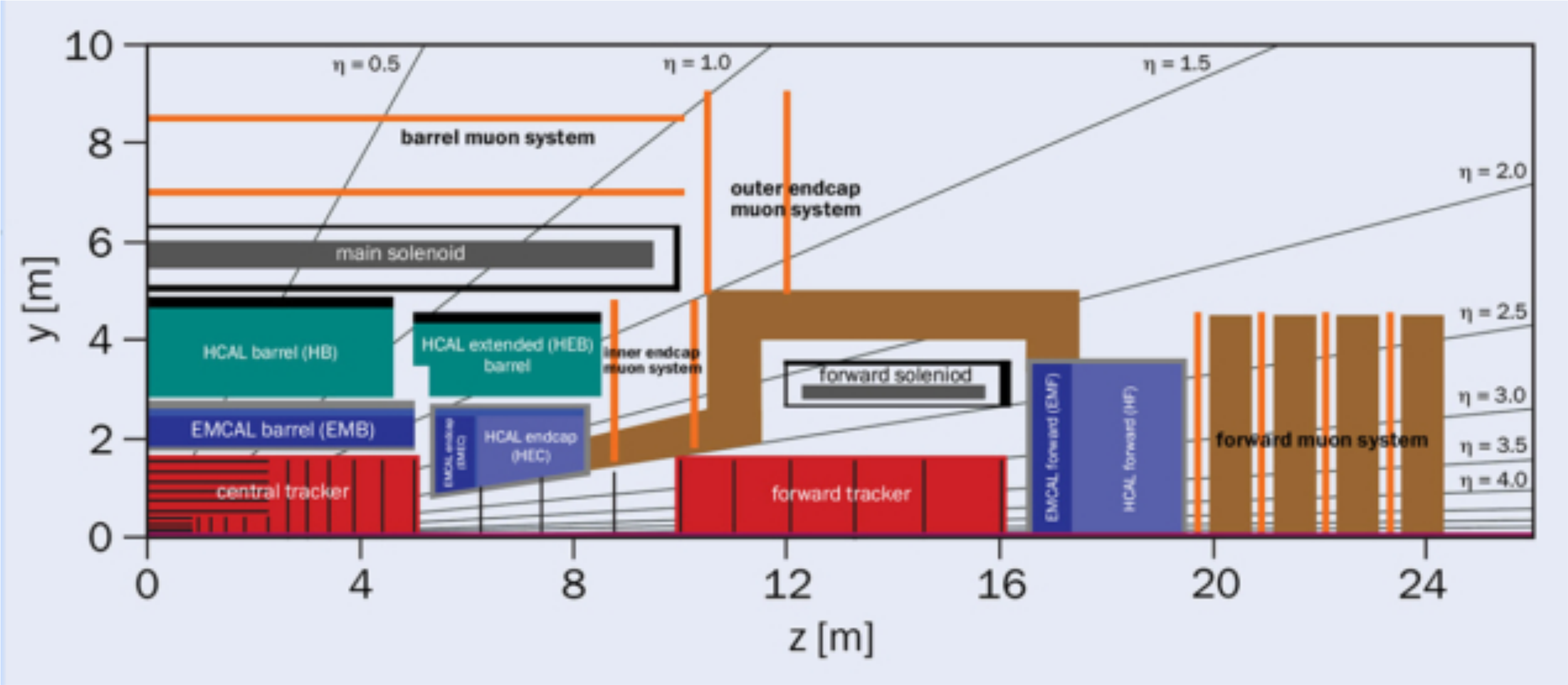
It is probably the most ambitious of all 4 detector concepts.



FCC-hh detector concept

- pp collisions at $\sqrt{s} > 100$ TeV, luminosity up to 3×10^{35} cm^{-2} s^{-1} (up to 1000 pileup events)
- Central detector houses tracking, e.m. and hadron calorimetry inside a 4T solenoid with a free bore of 10 m diameter
- Forward parts are displaced by 10m from the interaction point, with two forward magnet coils
- The muon system is placed outside the magnet coils
- Overall length ~**50m**, diameter ~**20m**





→ No field return yoke for FCC-hh reference detector

Conclusions

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FUTURE CIRCULAR COLLIDER

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FUTURE CIRCULAR COLLIDER

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- We are living in very interesting times, especially for our young collaborators
- **We are open to cooperation and collaboration, there are plenty of opportunities**
- **Hopefully we will be able to realise such a great project somewhere in the world, for the benefit of science!**

Backup

FCC-ee layout

4 experimental areas

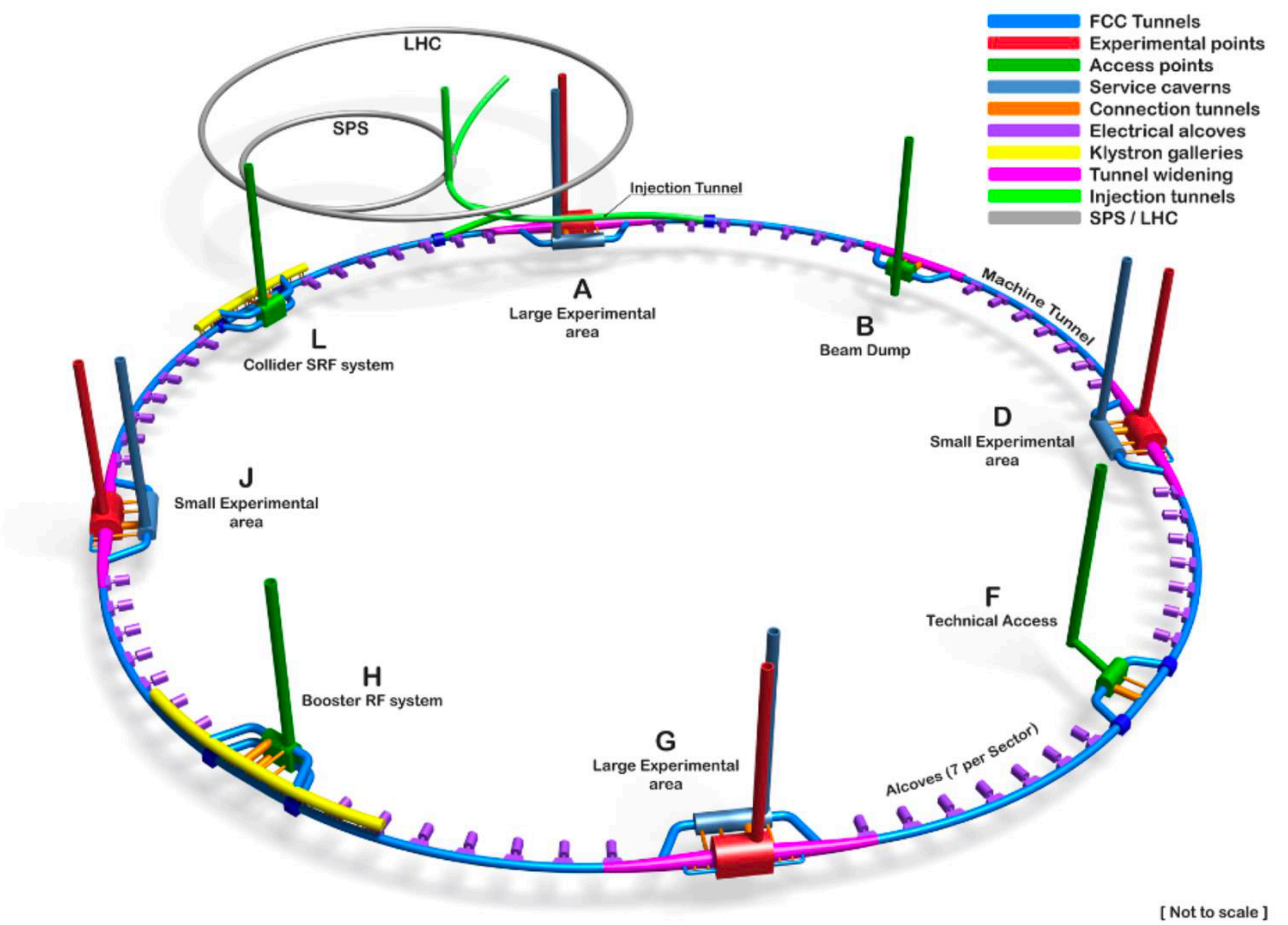
(4 experiments)

Point A

Point D

Point G

Point J



IDEA Detector concept

- Many sections of INFN teamed up and proposed the IDEA detector concept several years ago
- IDEA was designed to fulfil all the physics and detector requirements foreseen for FCC-ee
  - Provide outstanding performances at all FCC-ee centre-of-mass energy points
    - Z^0 peak
    - W^+W^- threshold
    - HZ peak production
    - ttbar threshold
  - It is an innovative and highly challenging detector concept with beyond the state-of-the-art technologies

Resource needs & connections to regional infrastructure

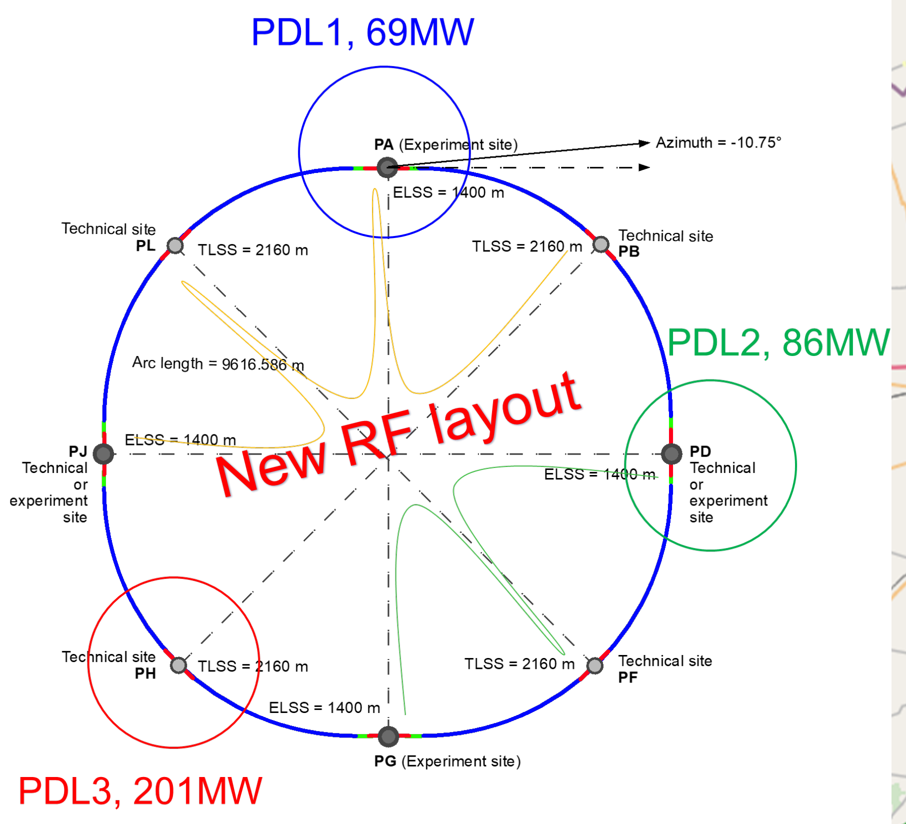
Electricity consumption 1.1 – 1.8 TWh/year

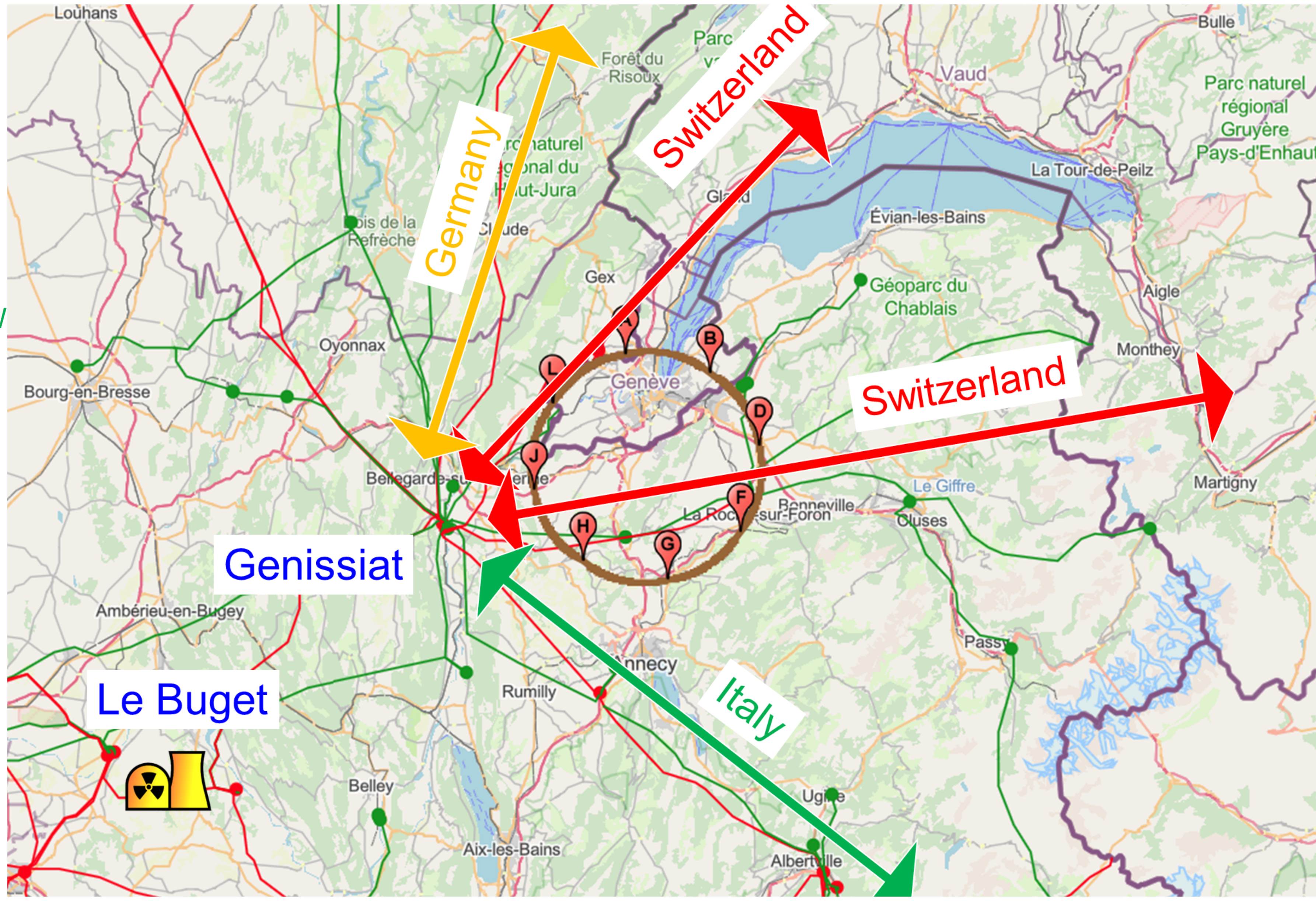
Three supply points

- Two new substations from existing HV grid

- Reuse of present CERN station

Feasibility confirmed with RTE (FR operator)





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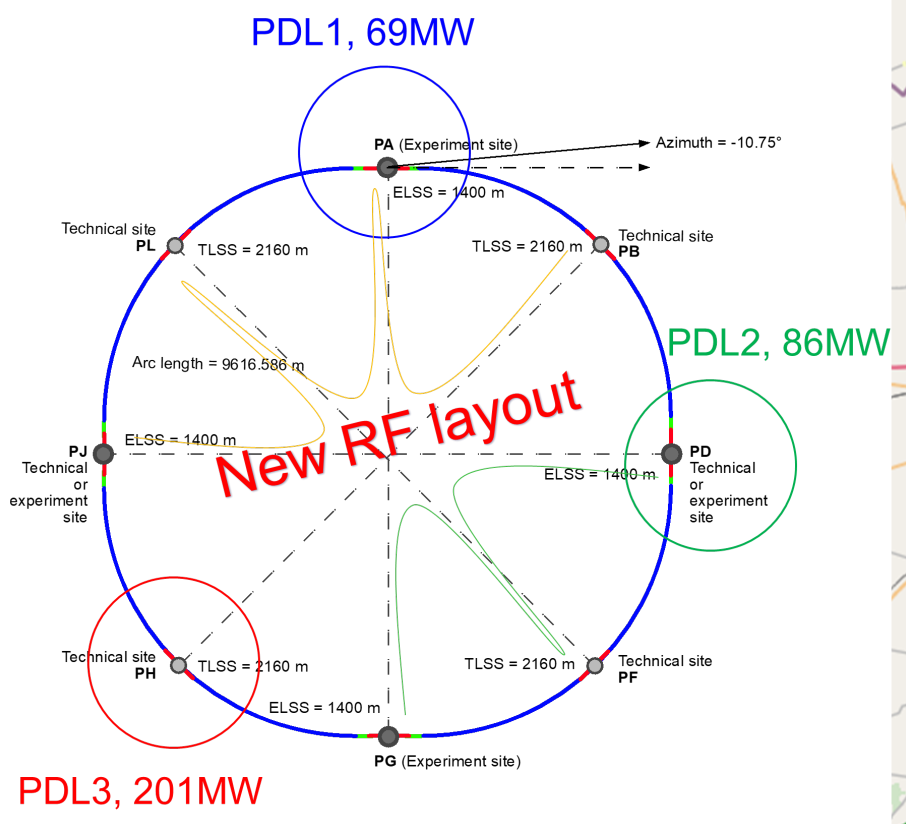

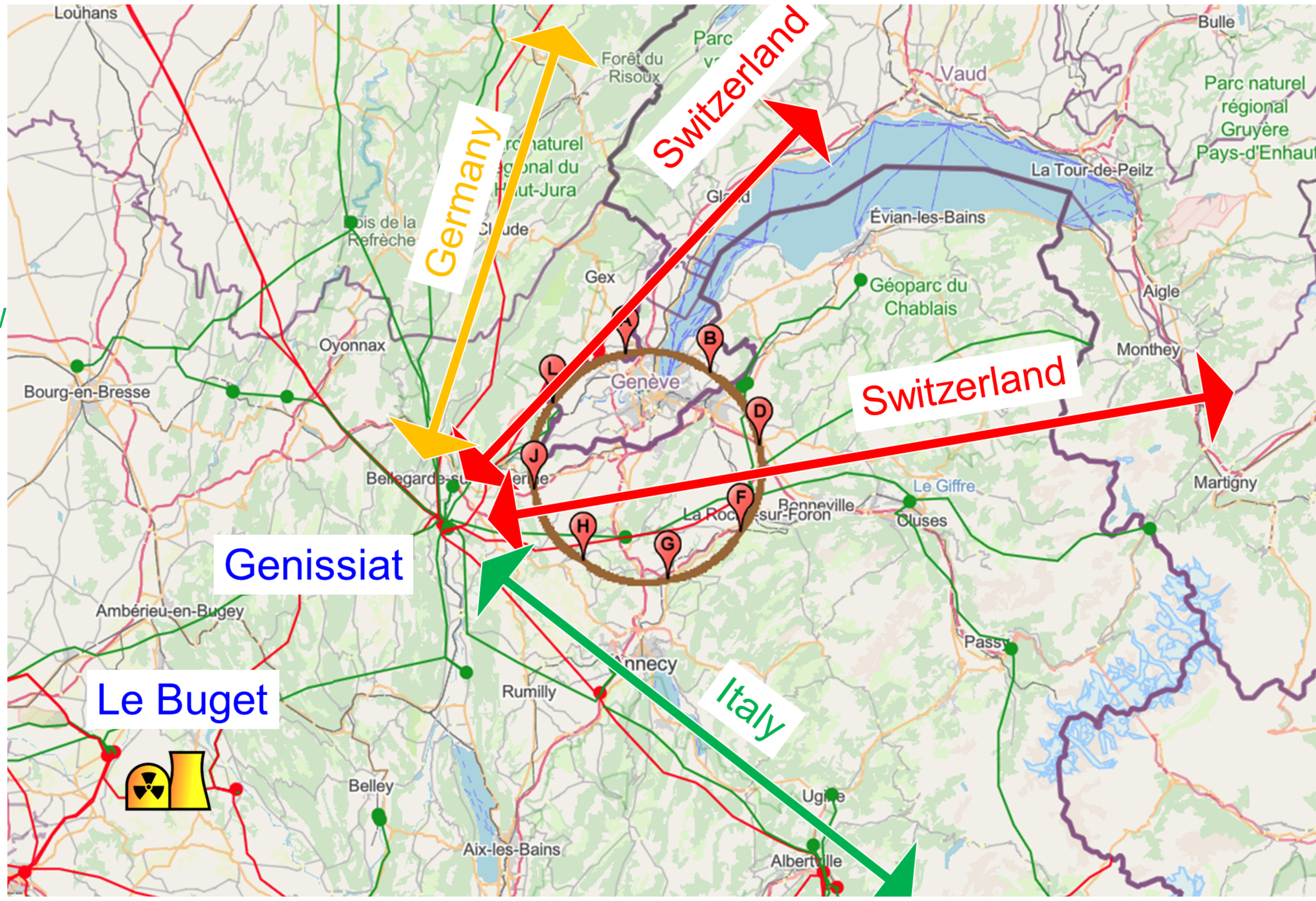

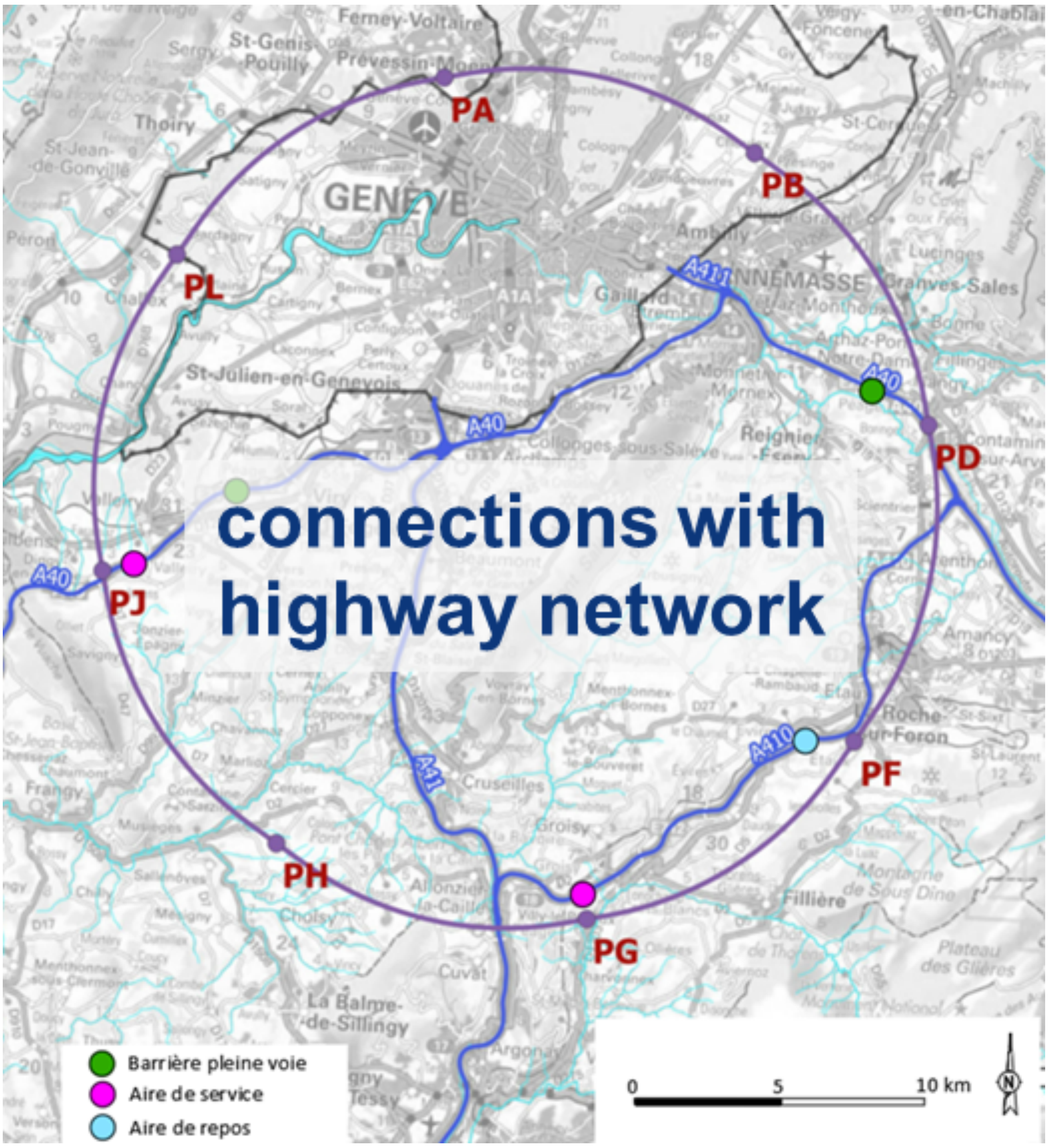

Road access
developed for all 8 surface sites

Four possible highway connections defined

Less than 4 km of new roads required

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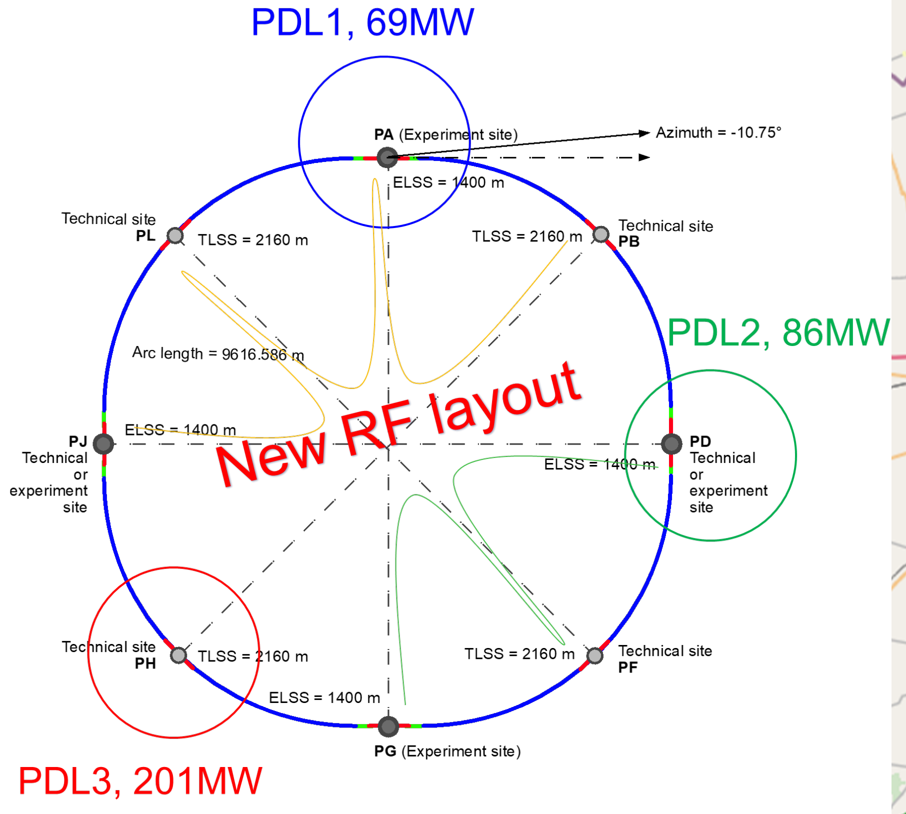

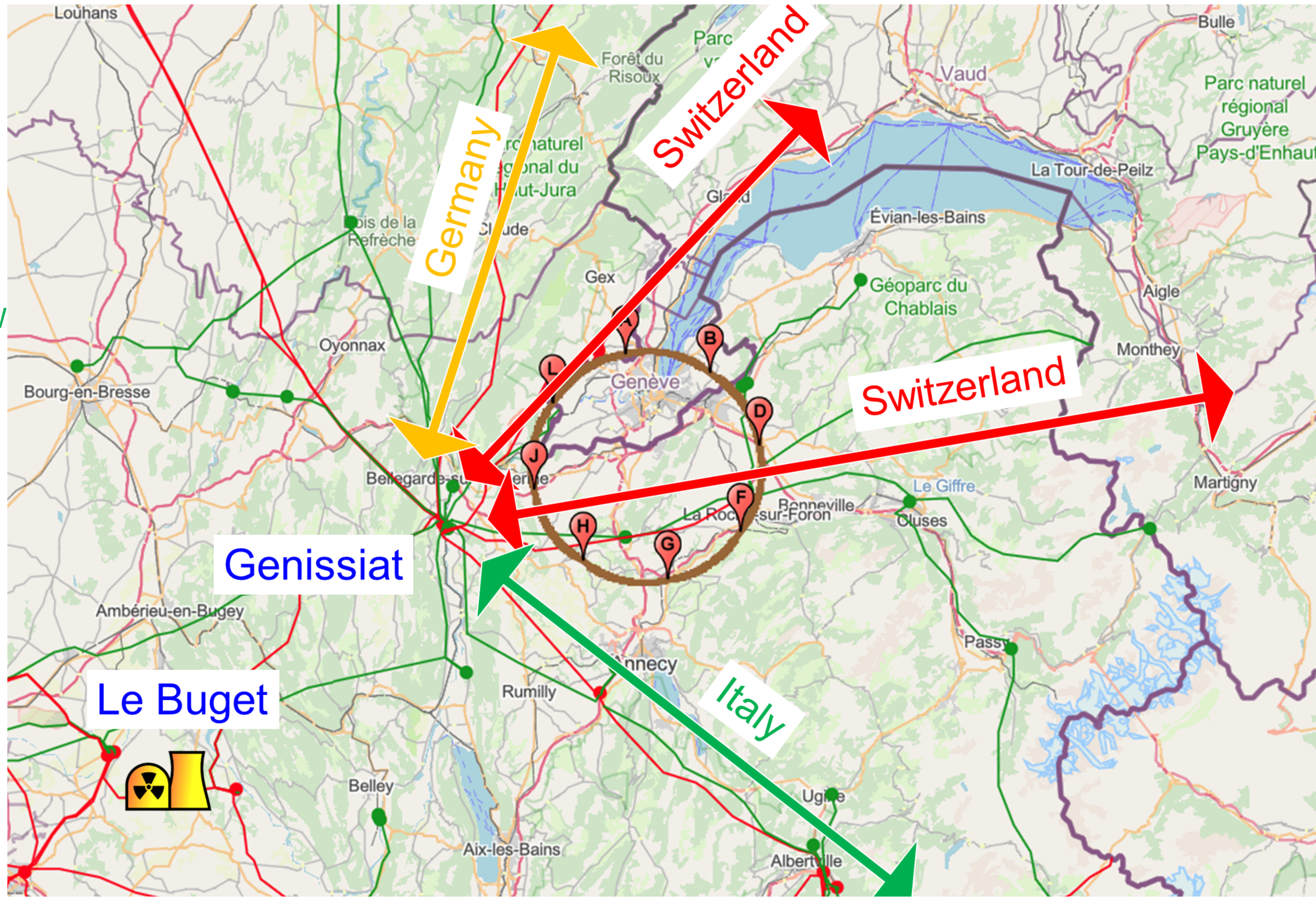

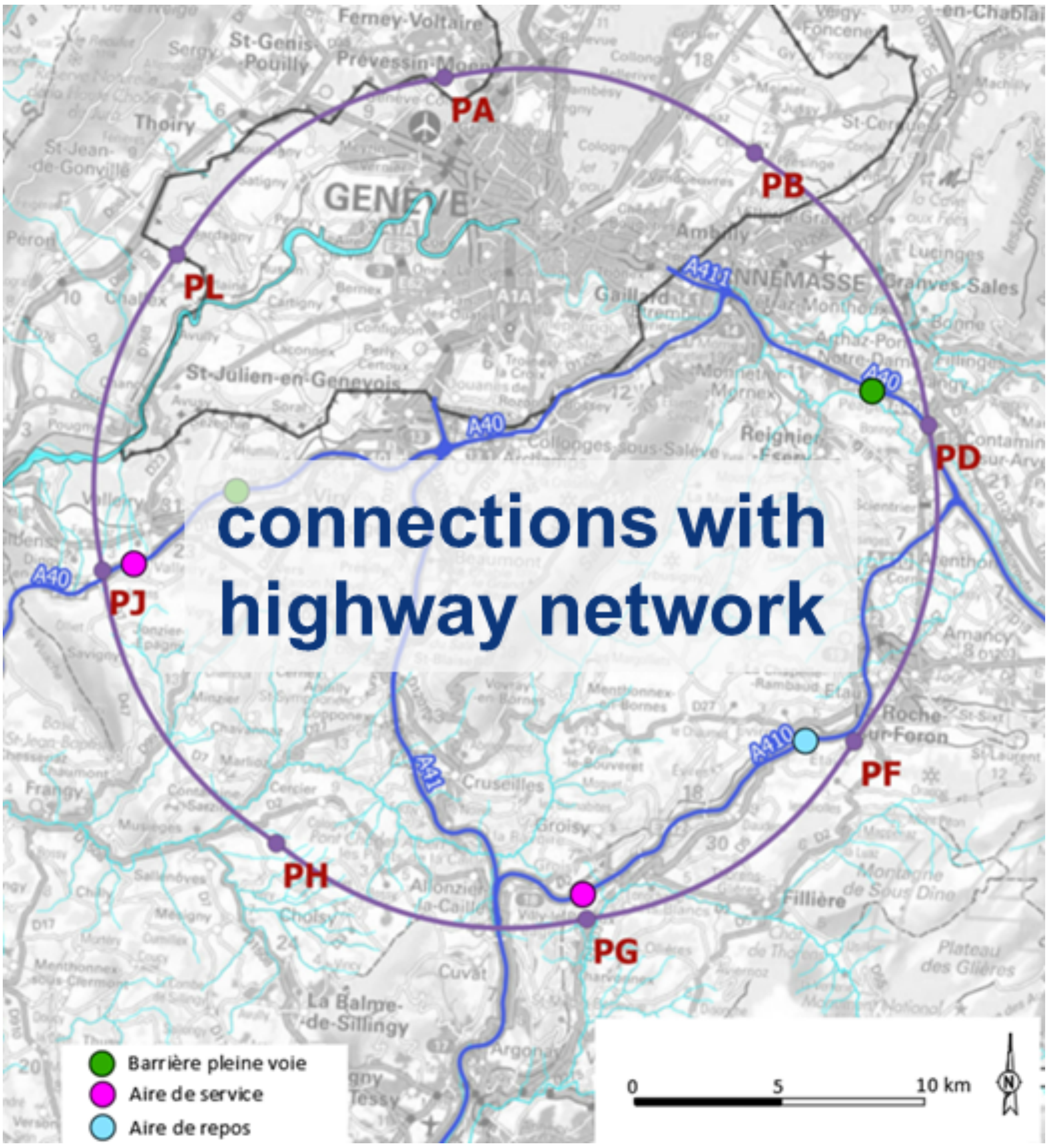

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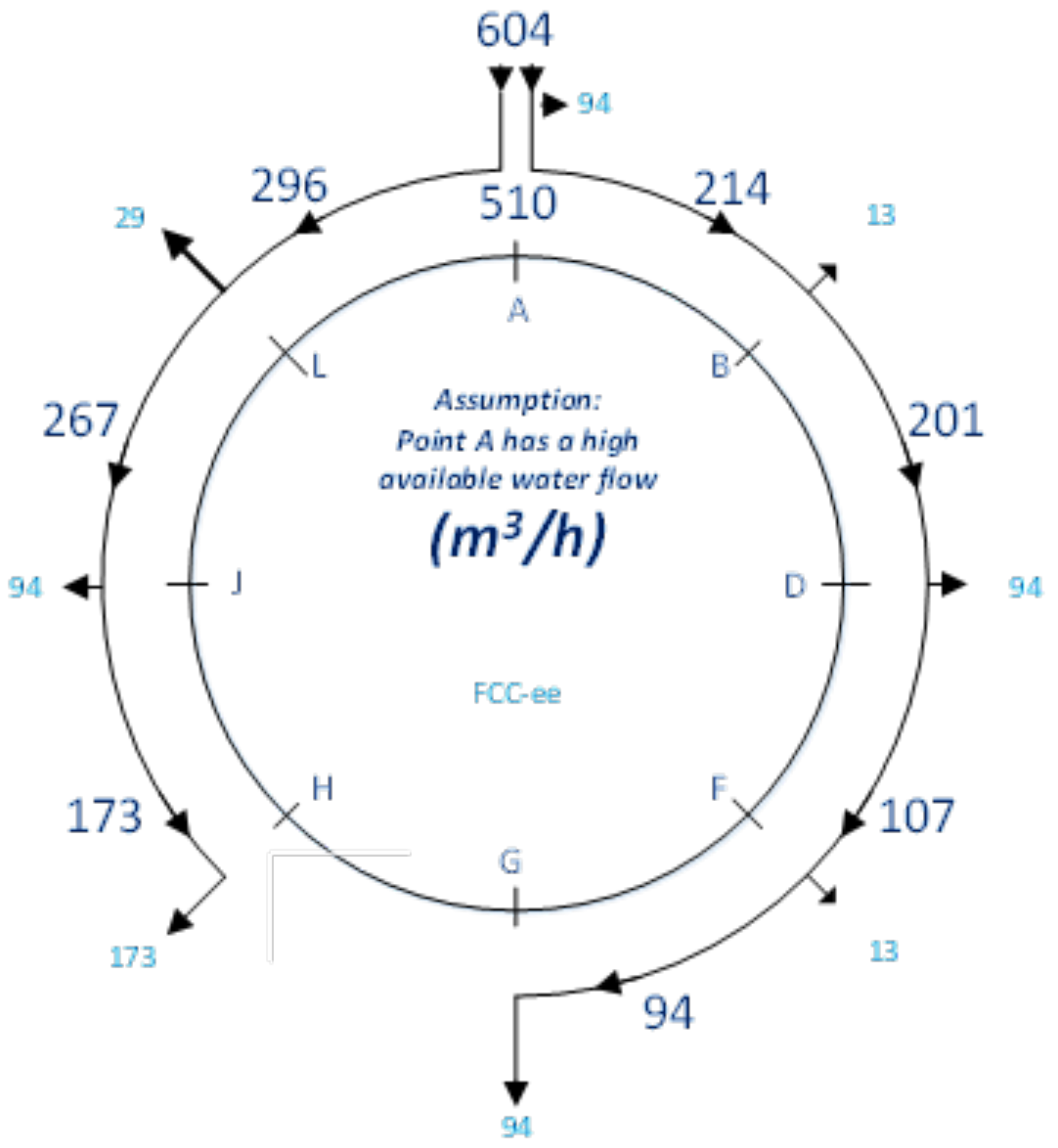
Raw water need:

1 – 3 million m³/year

Water supply from lake Geneva via existing SIG supply to CERN

Distribution via tunnel



Stage 1 FCC-ee schedule

Overall FCC-ee schedule

- 04/2025 – 06/2027 pre-TDR entire project
- 01/2026 – 12/2030 environmental evaluation and project authorisation
- **2028 assumed project approval by CERN Council**
- 01/2028 – 06/2032 CE design and tendering
- 01/2032 TDR for collider and technical infrastructure
- **01/2033 – 06/2041 CE construction work**
- 07/2039 – 12/2043 technical infrastructure installation
- **07/2041 – 06/2045 accelerator installation**
- 06/2046 HW commissioning completed
- **07/2046 start of beam commissioning and operation**
- **01/2048 nominal beam operation**

Injector Project schedule

- 12/2028 TDR injector project
- 01/2028 – 12/2030 CE design and tendering
- 01/2029 – 12/2031 Accelerator and technical infrastructure engineering designs
- **01/2031 – 12/2034 Civil construction work**
- 01/2032 – 12/2040 Component production (rates for RF structures as for SwissFEL)
- 01/2034 – 12/2036 Technical infrastructure installation
- **01/2035 – 12/2040 Component installation and testing**
- **01/2041 HW commissioning**
- **01/2042 Beam commissioning**

FCC-ee construction and installation schedule