The FCC Feasibility Study

also see A. Blondel, "FCC: a (heavy) neutrino factory", NuFACT21 WG5

Cagliari, 9 September 2021

Frank Zimmermann

gratefully acknowledging input from FCC coordination group, global FCC design study team and all other contributors especially M. Benedikt & A. Blondel

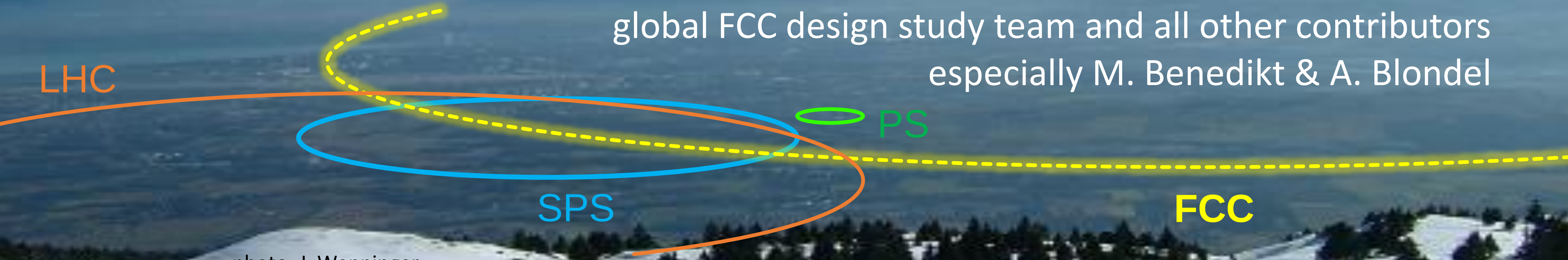


photo: J. Wenninger

http://cern.ch/fcc

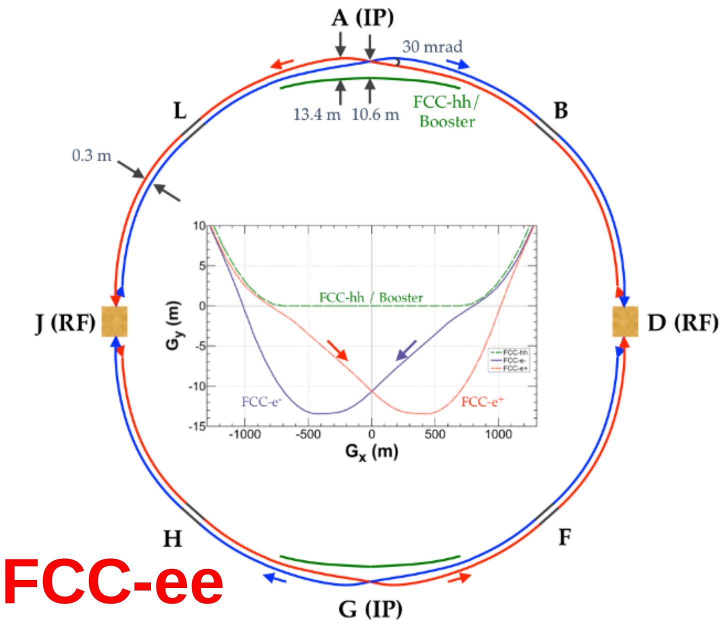
*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **ARIES**, grant agreement 730871, **FCCIS**, grant agreement 951754, and **I.FAST,** grant agreement 101004730.*

European Commission | Horizon 2020 European Union funding for Research & Innovation

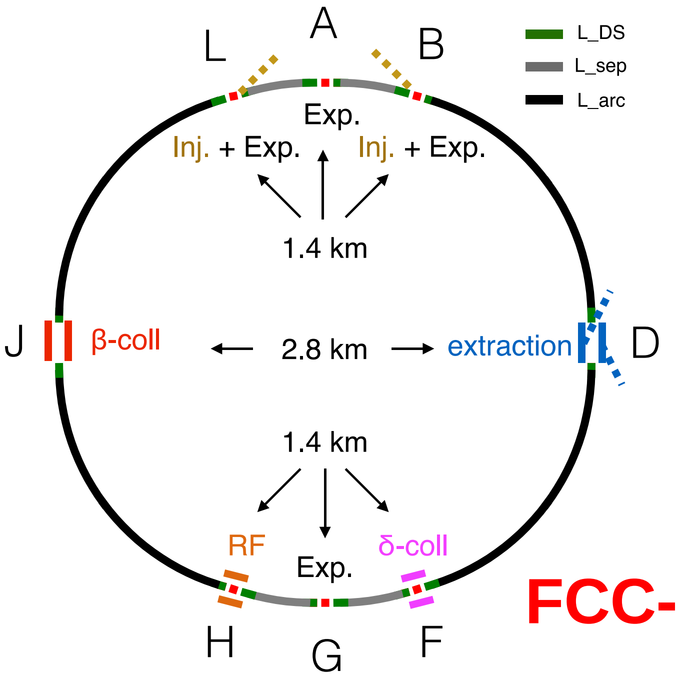
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive long-term program, maximizing physics opportunities

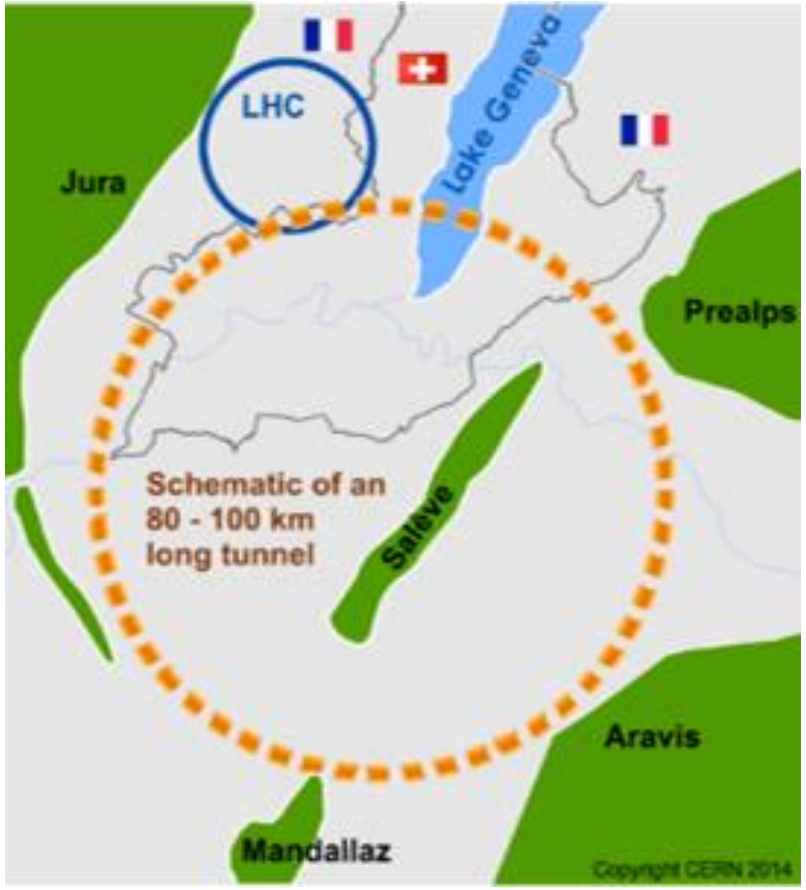
- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC



FCC-ee



FCC-hh



FCC-ee basic design choices

Double ring e^+e^- collider

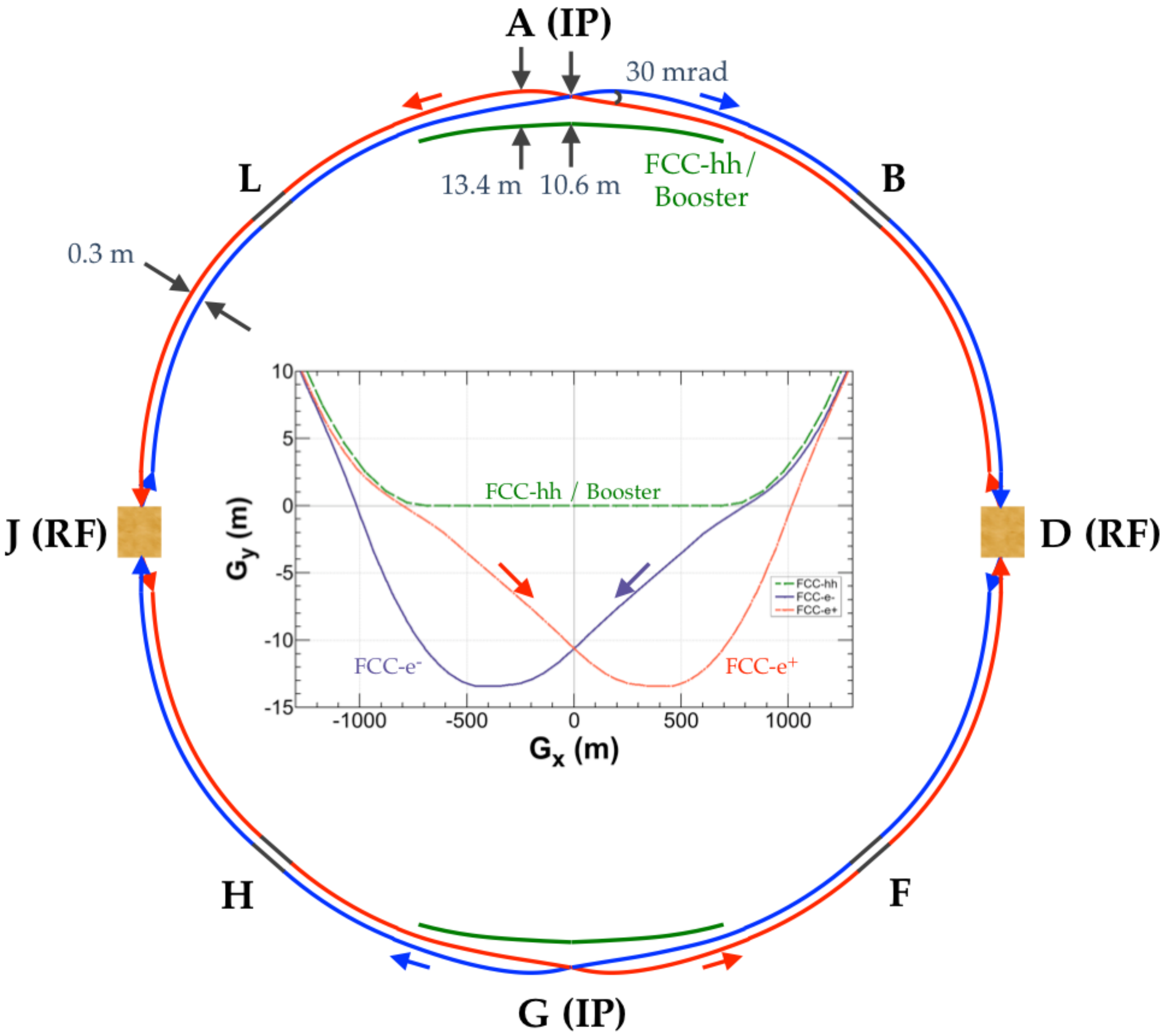
Common footprint with FCC-hh,
except around IPs

Asymmetric IR layout and optics to limit synchrotron radiation towards the detector

2 IPs, large horizontal crossing angle **30 mrad, crab-waist collision optics** (alternative layouts with 4 IPs under study now)

Synchrotron radiation power 50 MW/beam
at all beam energies

Top-up injection scheme for high luminosity;
requires **booster synchrotron in collider tunnel**



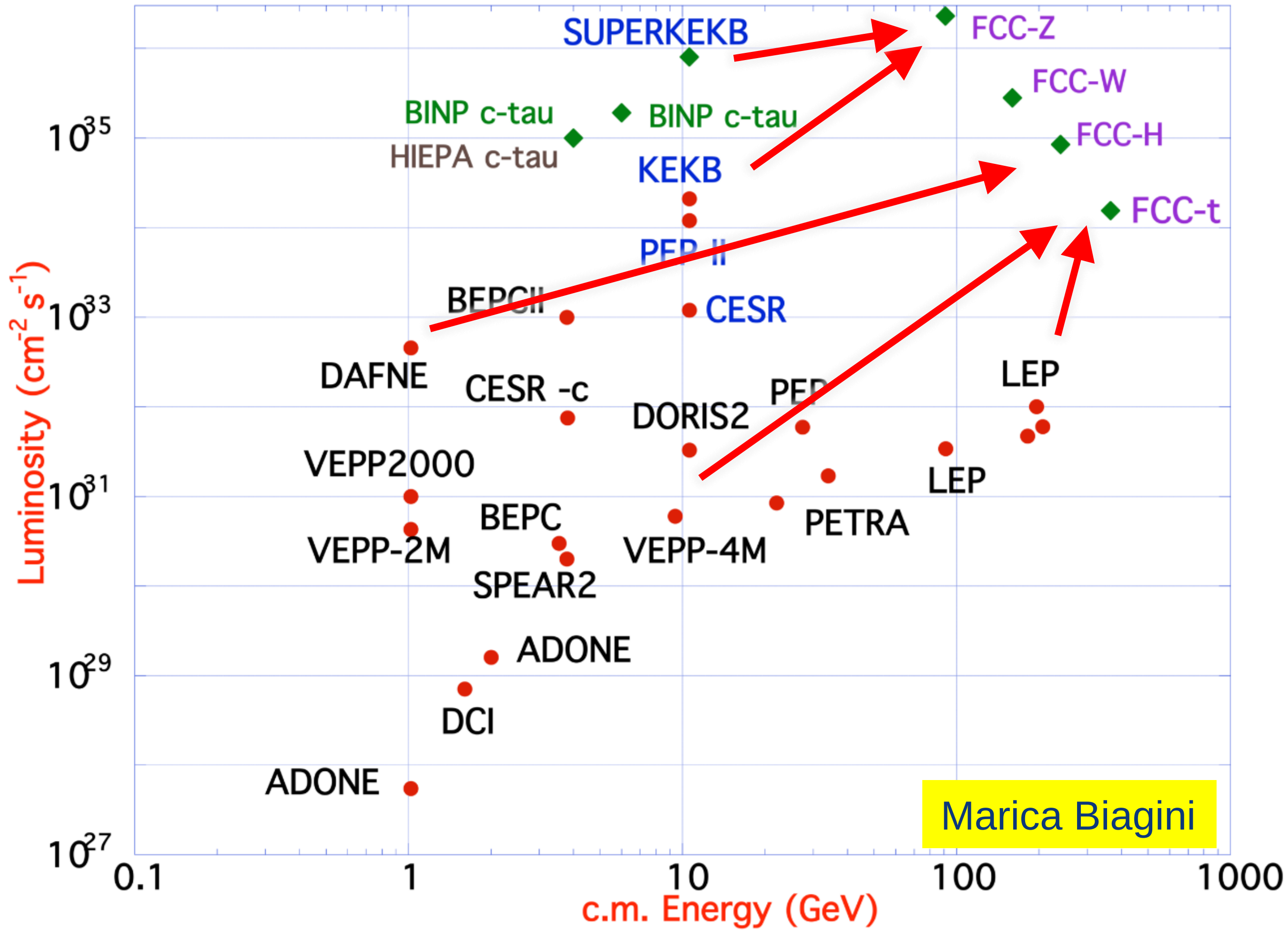
K. Oide, A. Bondel, F. Zimmermann et al.

FCC-ee collider parameters (stage 1)

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee design concept

based on lessons and techniques from past colliders (last 40 years)



B-factories: **KEKB & PEP-II:**
- double-ring lepton colliders,
- high beam currents,
- top-up injection

DAFNE: crab waist, double ring

S-KEKB: low β_y^*, crab waist

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

combining successful ingredients of several recent colliders → highest luminosities & energies

FCC-ee RF staging scenario

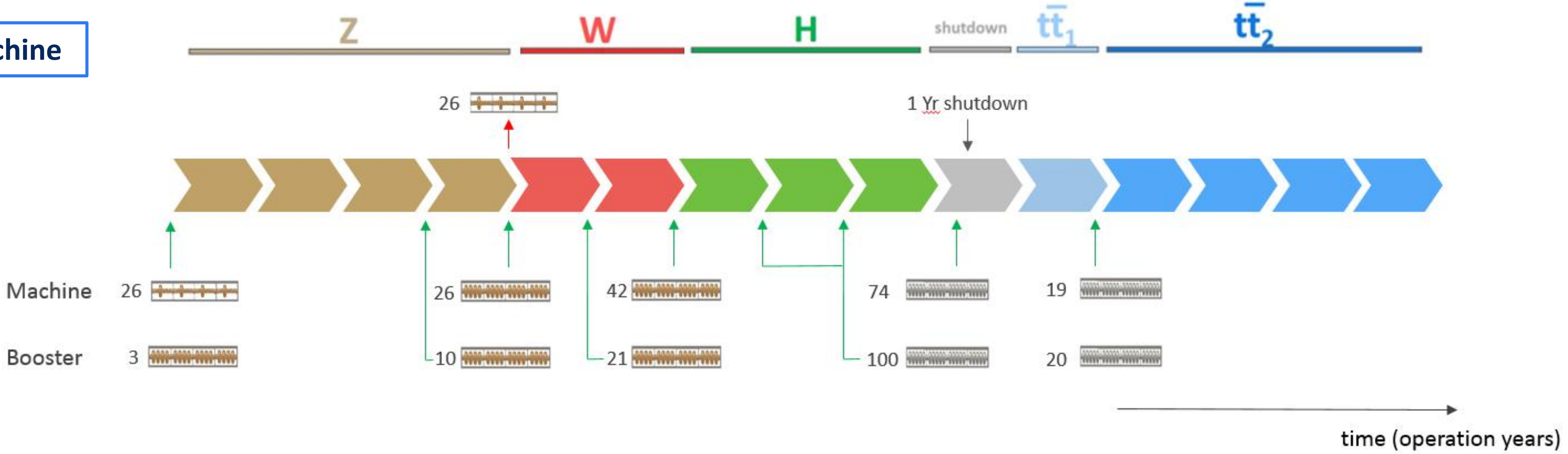
"Ampere-class" machine

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

"high-gradient" machine

three sets of RF cavities to cover all options for FCC-ee & booster:

- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**
- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**

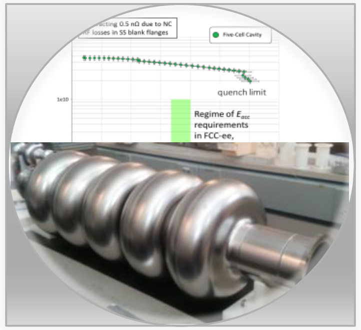


O. Brunner

FCC SRF R&D Program Structure in a Nutshell

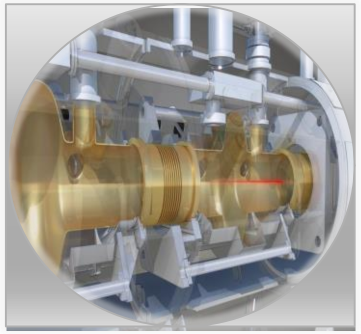
Cavity Studies

- Optimized Cavity Shape, Technology and Operating Temperature (complexity, power consumption, Q_o, E_{acc})
- Design 1- & 4-cell Cavities
- Beam-Cavity Interaction
- Cavity Control System (LLRF)



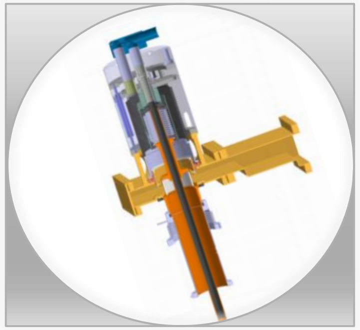
SRF & Substrate Technologies

- Improved Cavity Engineering: New SC Materials, Novel Fabrication Methods, Substrate Surface Preparation, Coating Techniques
- Fabrication & Testing of 1-l & 4-cell cavities for new cryomodule
- Collaboration with international Partners



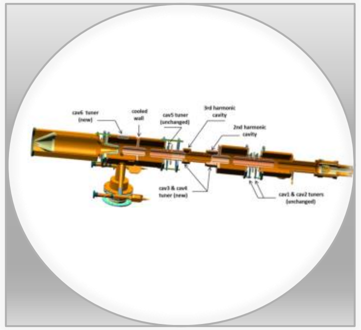
Cryomodule Development

- Engineering design of 400 MHz cryomodule including ancillaries
- Building a 2 cavity CM which can host 1-/4-cell 400 MHz cavities
- R&D Collaboration with int'l Partners (e.g. JLAB)
- 800 MHz CM: Profit from Ongoing Development @ PERLE in Paris



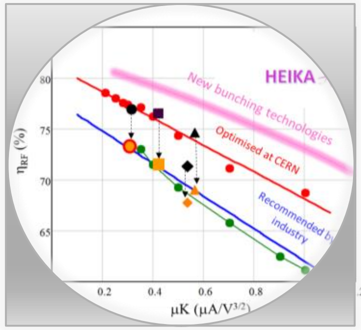
FPC & HOM RF Couplers

- Improved design, fabrication and testing of 400 MHz Fundamental Power Coupler (FPC)
- FPC R&D towards 1MW CW fixed/movable FPC
- 'Adjustable' FPC (external large adaptation of Q_{ext})
- HOM coupler production



RF Power Sources

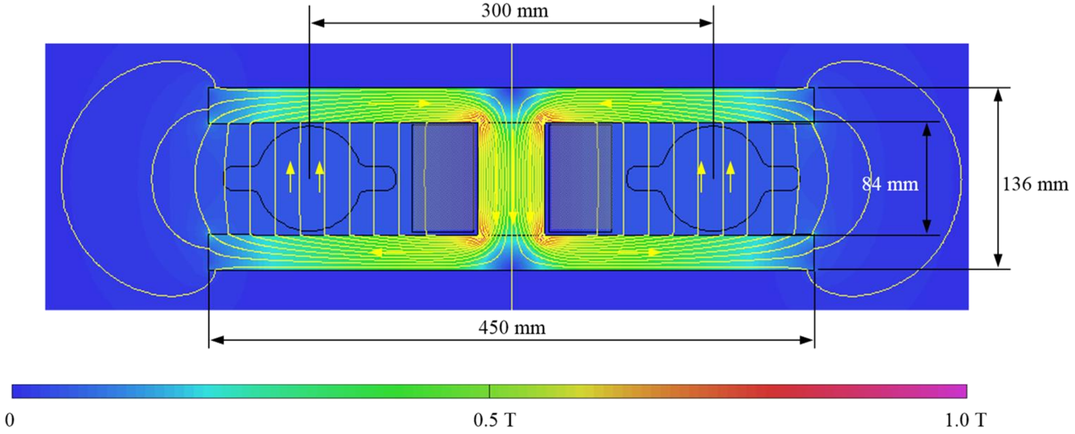
- novel klystron bunching methods
- LHC klystron retrofit as proof of principle
- prototype design, fabrication and testing

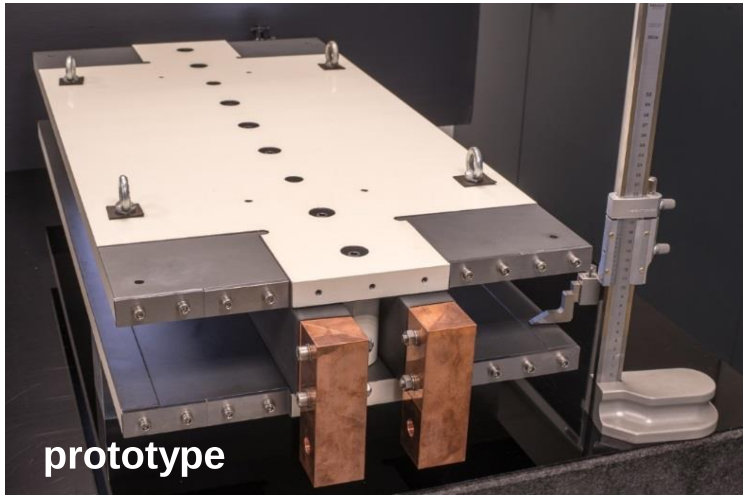


O. Brunner, F. Gerigk, E. Jensen et al.

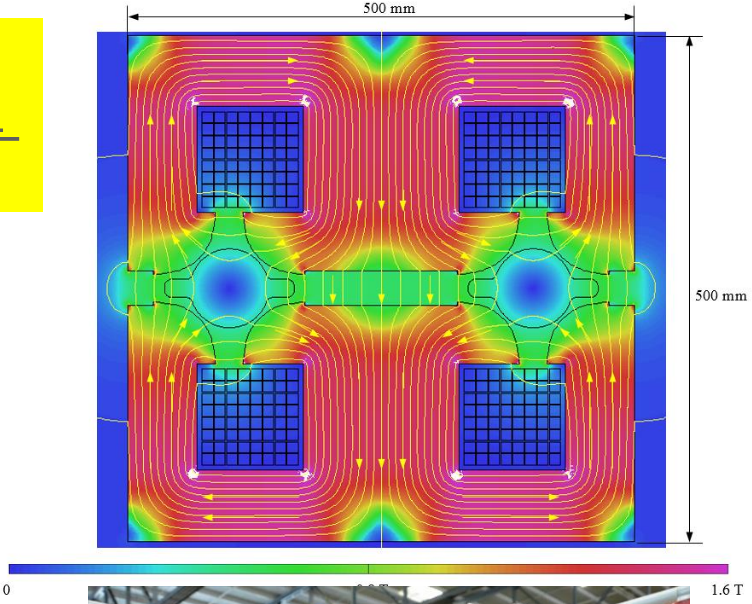
Prototypes of FCC-ee low-power magnets

Twin-dipole design with 2× power saving 16 MW (at 175 GeV), with Al busbars

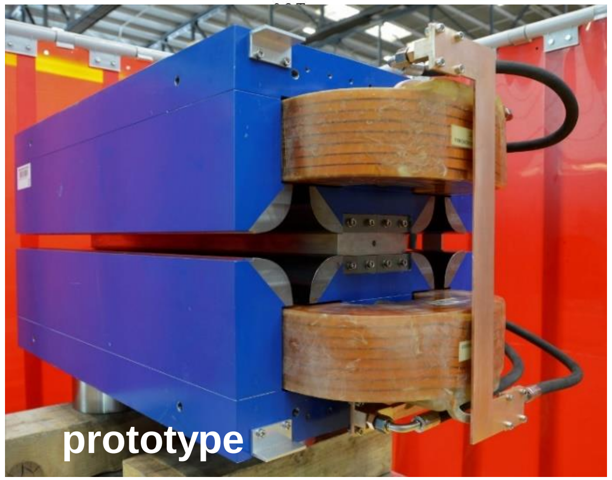




A. Milanese, PRAB 19, 112401 (2016)



Twin F/D arc quad design with 2× power saving 25 MW (at 175 GeV), with Cu conductor



FCC-ee figures of merit

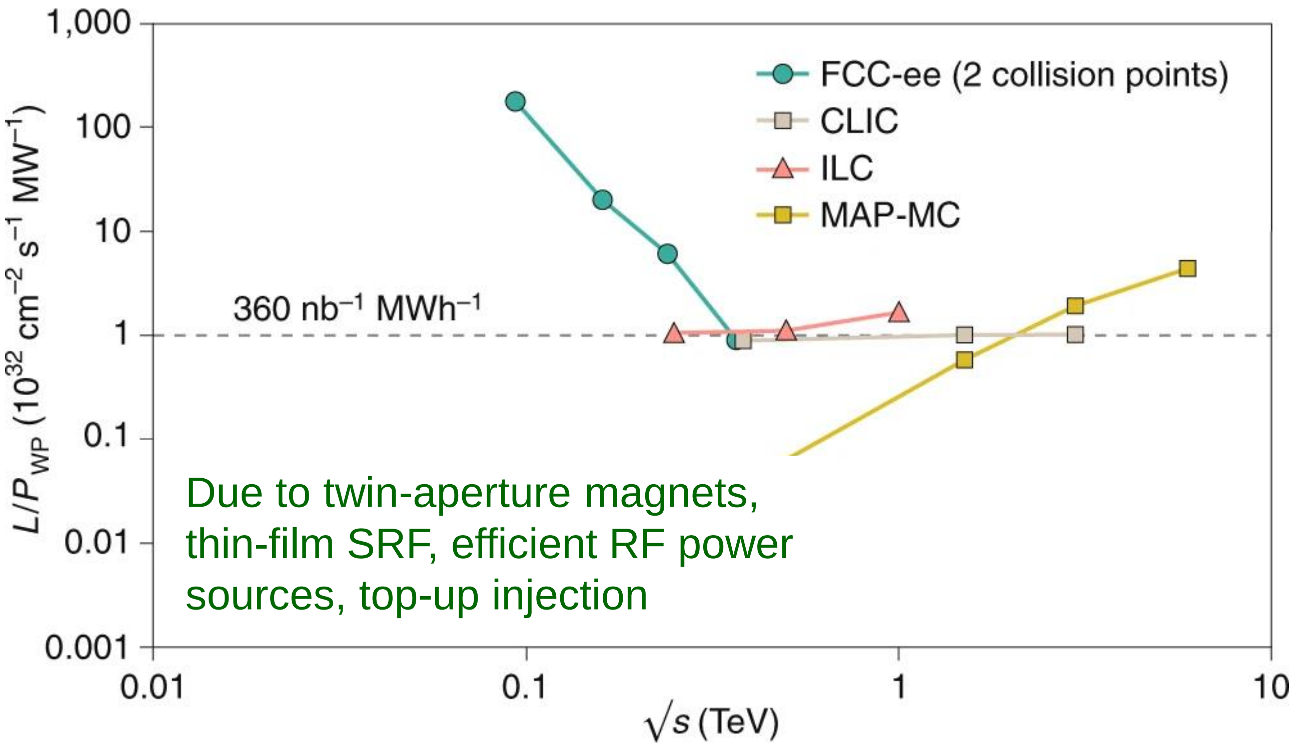
Luminosity vs. capital cost

- for the H running, **with 5 ab^{-1} accumulated over 3 years and 10^6 H produced**, the total investment cost (~10 BCHF) corresponds to → **10 kCHF per produced Higgs boson**
- for the Z running with **150 ab^{-1} accumulated over 4 years and $5x10^{12}$ Z produced,** the total investment cost corresponds to → **10 kCHF per $5×10^6$ Z bosons** (or **10 kCHF per ~10^6 ν's**)

This it the number of Z bosons collected by each experiment during the entire LEP programme !

Capital cost per luminosity dramatically decreased compared with LEP !

Luminosity vs. electricity consumption

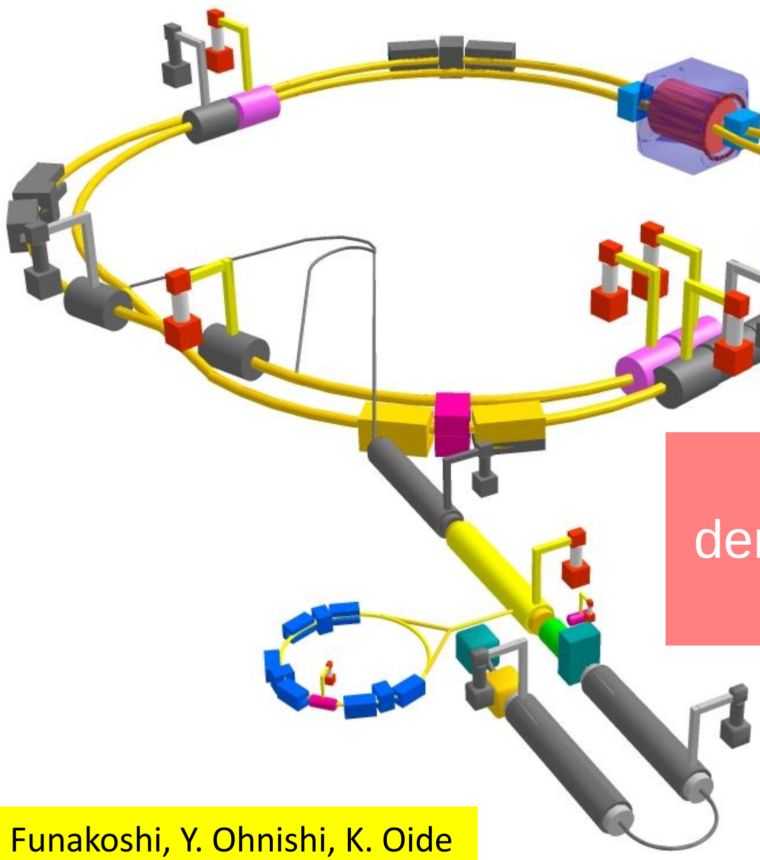


Highest lumi/power of all H fact proposals Electricity cost ~200 CHF per Higgs boson

M. Benedikt, A. Blondel, P. Janot, et al., **Nat. Phys. 16**, 402-407 (2020), and
European Strategy for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

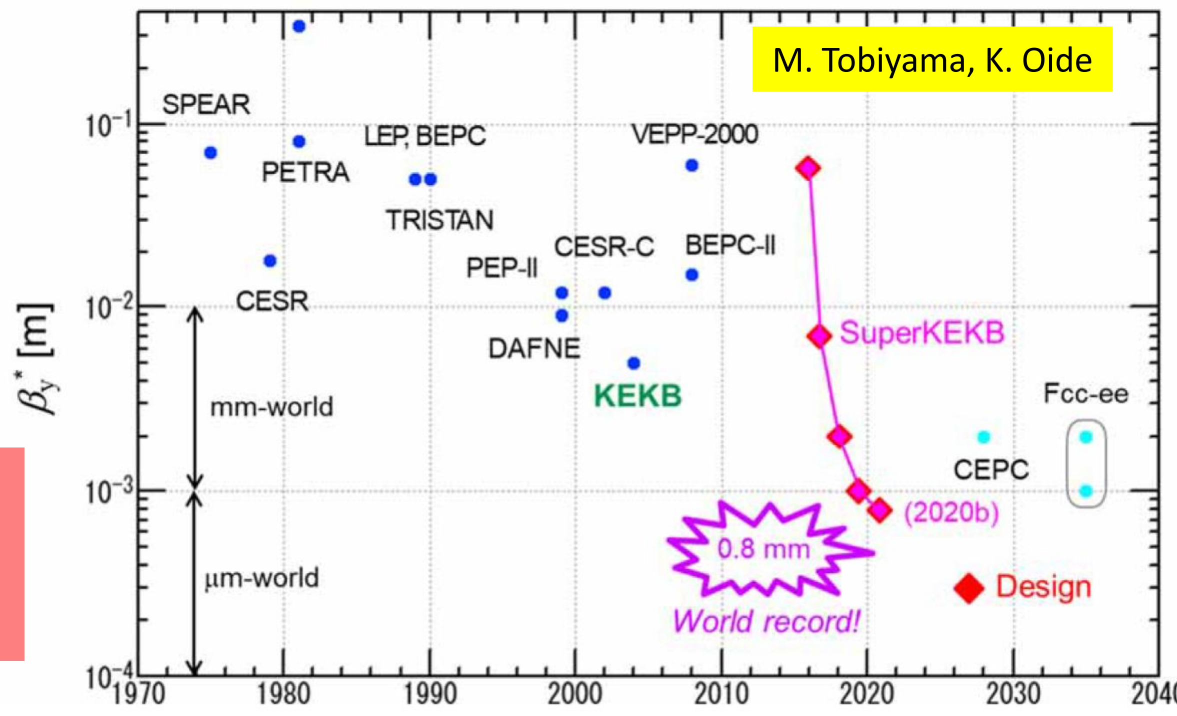
SuperKEKB – "FCC-ee demonstrator"

Design: **double ring e^+e^- collider as *B*-factory** at 7(e^-) & 4(e^+) GeV; **design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$**; **β_y^* ~ 0.3 mm; nano-beam – large crossing angle** collision scheme **(crab waist w/o sextupoles)**; **beam lifetime ~5 minutes**; **top-up** injection; **e^+ rate up to ~ 2.5 10^{12} /s** ; **under commissioning**



SuperKEKB is demonstrating FCC-ee key concepts

Y. Funakoshi, Y. Ohnishi, K. Oide



β_y^* = 0.8 mm achieved in both rings – using the FCC-ee-style "virtual" crab-waist collision scheme

new world record L = 3.12 x 10^{34} $cm^{-2}s^{-1}$ on 22 June '21

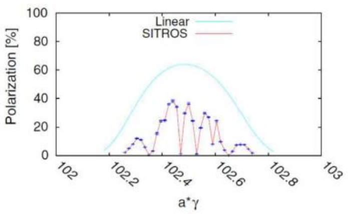
energy calibration by resonant depolarisation

FUTURE CIRCULAR COLLIDER

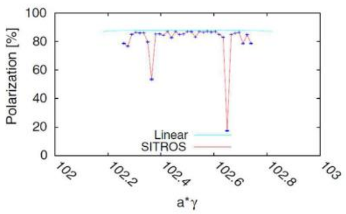
Z pole with polarisation wigglers

E. Gianfelice-Wendt, *Investigation of beam self-polarization in the future e^+e^- circular collider*, **Phys. Rev. Accel. Beams 19**, 101005 (2016).

orbit correction



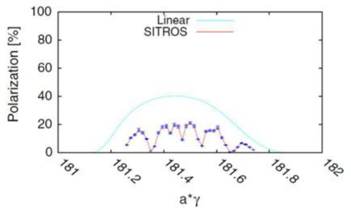
+ harmonic bumps



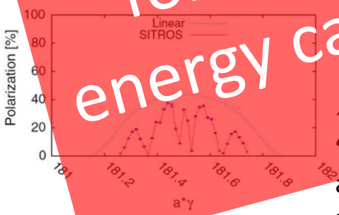
Z pole: 8 asymmetric wigglers per beam lower the polarisation rise time to 12 hours allowing a level of 10% (5%) beam polarisation, sufficient for the energy calibration by RDP, to be obtained in 90 (45) minutes.
W pair threshold: **spontaneous polarisation** with a rise-time of around 10 hours without wigglers.

WW threshold

orbit correction



+ harmonic bumps

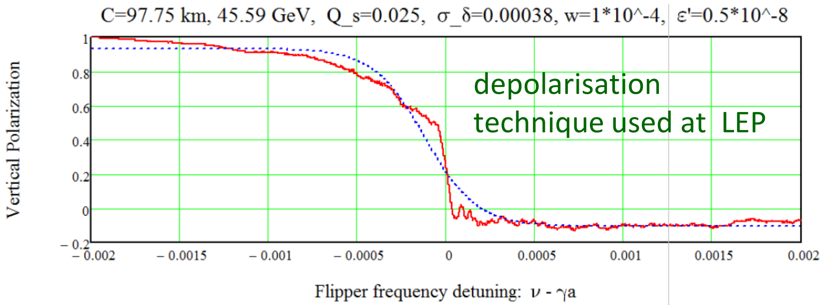


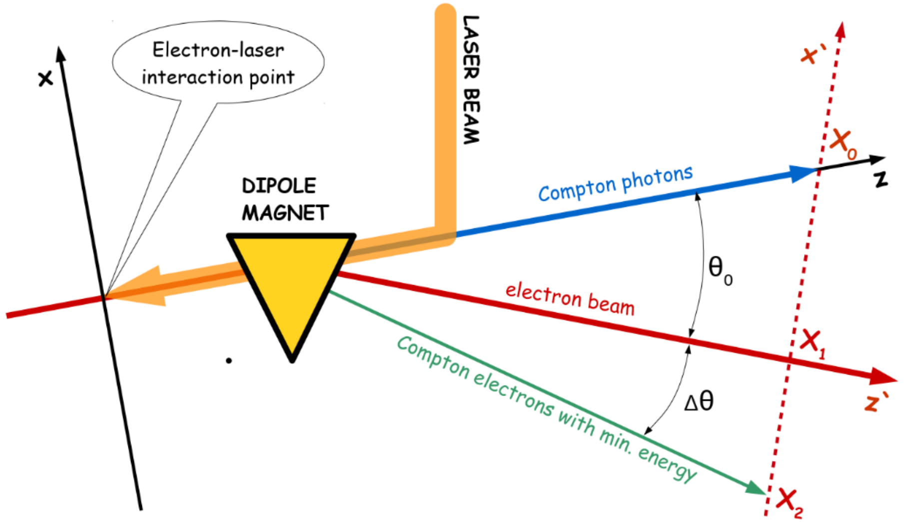
for Z and W: precise energy calibration at 10^{-6} level

RF located in one point ! Largest remaining systematic error:
vertical closed-orbit distortions - at the Z, 300 μm error will induce a possible systematic shift of around 45 keV.

~200 **non-colliding 'pilot' bunches** injected at start of fill and polarised using wigglers

simulated frequency sweep with depolariser





N. Muchnoi, arXiv:1803.09595 (2018).

luminosity-averaged centre-of-mass uncertainty:

~100 keV at Z pole
~300 keV at W pair threshold

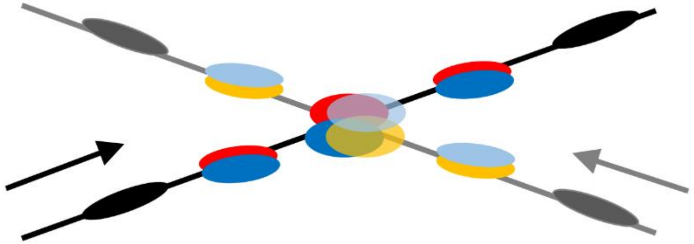
A. Blondel, P. Janot, J. Wenninger et al.

monochromatized direct Higgs production to measure the e⁻ Yukawa coupling ?

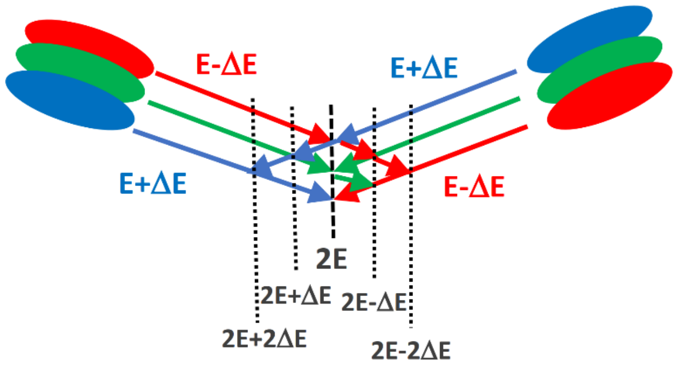
$D_x^* \neq 0$

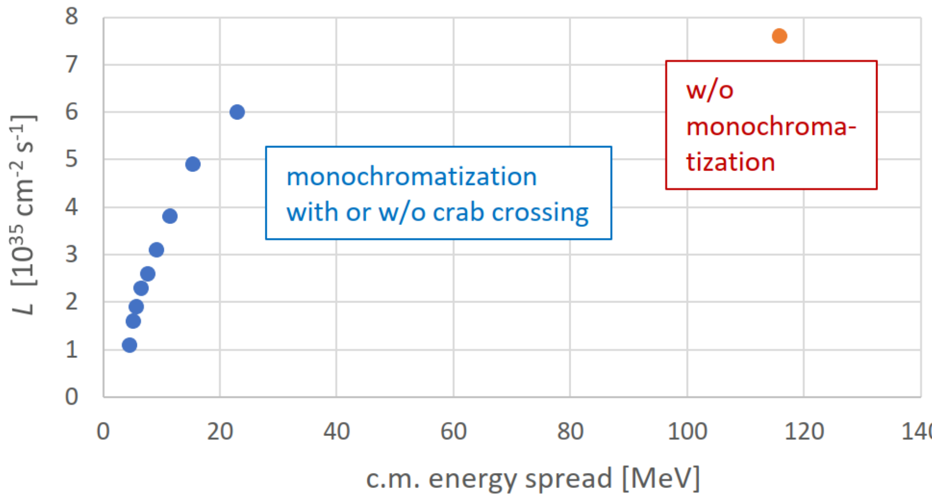
M.A. Valdivia Garcia,
A. Faus-Golfe, A. Blondel,
F. Zimmermann et al.

w crab cavities

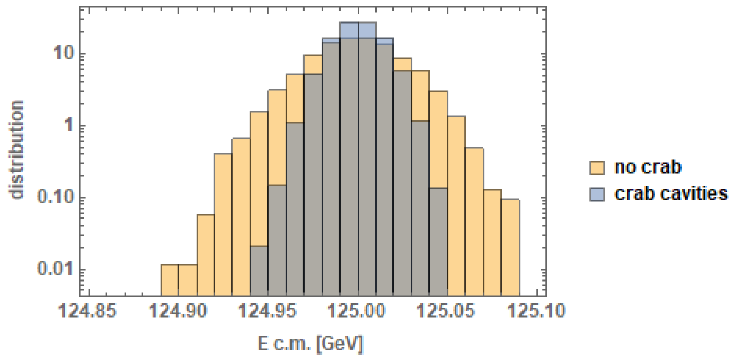


w/o crab cavities

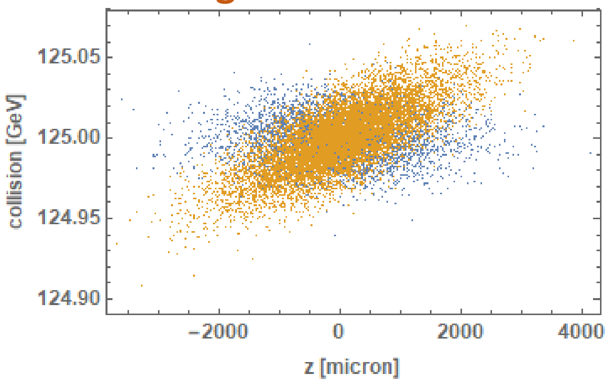




including beamstrahlung



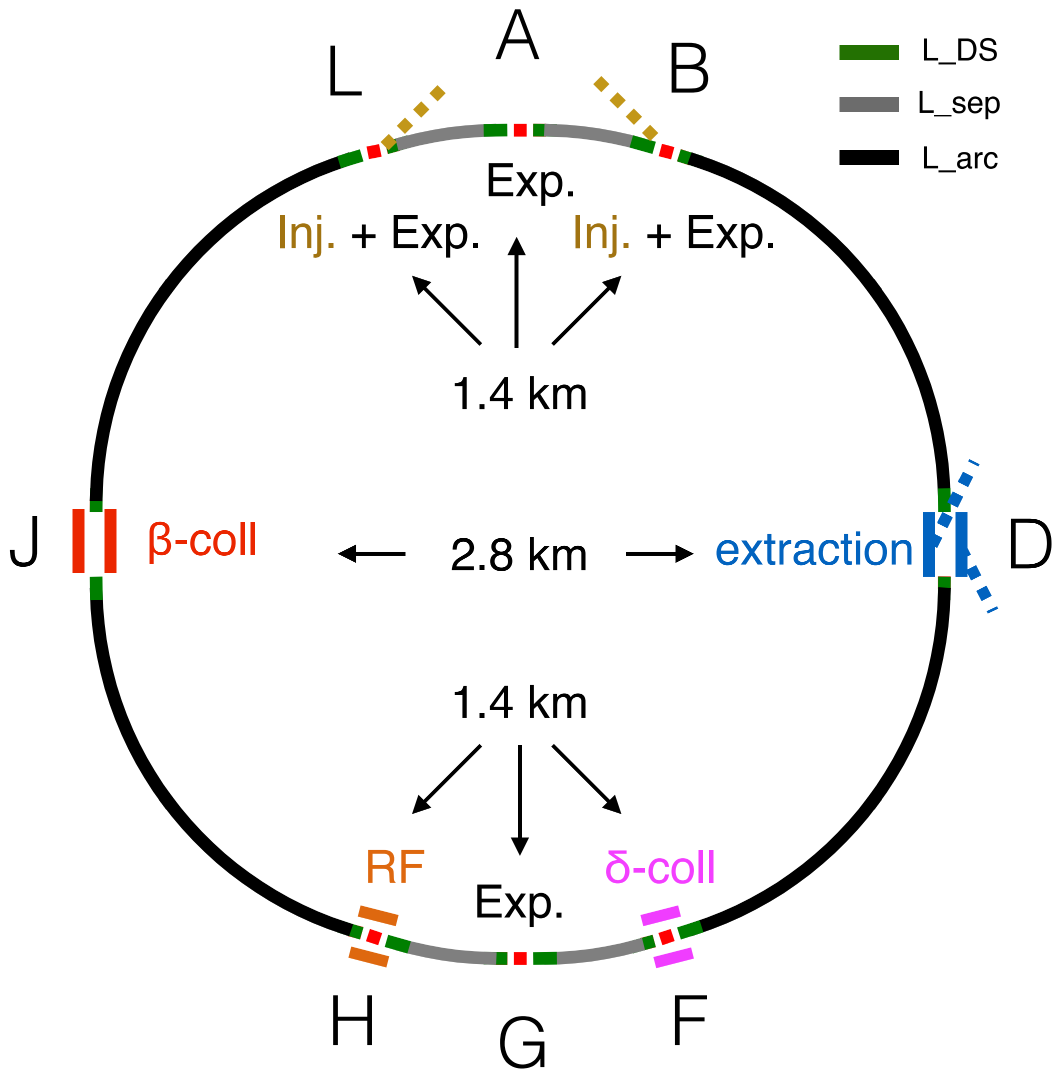
integrated resonance scan



a few times higher Higgs production rate thanks to monochromatization

possibly the only available approach to measure the electron Yukawa coupling !

FCC hh basic design choices



- **dual aperture superconducting magnets**
- **two high-luminosity experiments (A & G)**
- **two other experiments (L & B)** combined with **injection upstream** of experiments
- **two collimation insertions**
  - betatron cleaning (J)
  - momentum cleaning (F)
- **extraction/dump insertion (D)**
- **RF insertion (H)**
- **Injection from LHC (~3 TeV) or scSPS (~1.2 TeV)**
- **Alternative layouts under study**

D. Schulte, A. Chance

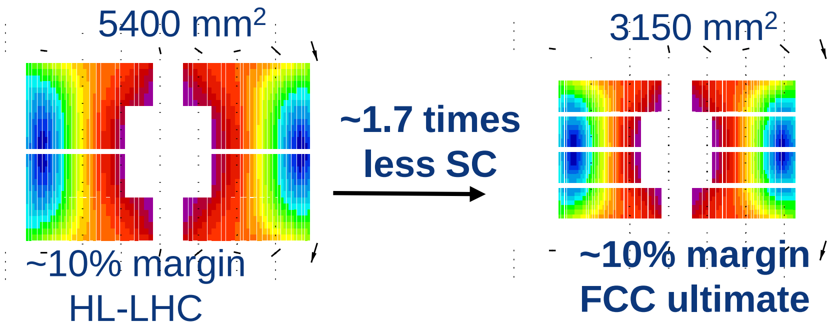
FCC-hh (pp) collider parameters (stage 2)

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity $[10^{11}]$	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [µm]	2.2		2.5	3.75
peak luminosity $[10^{34}\ cm^{-2}s^{-1}]$	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

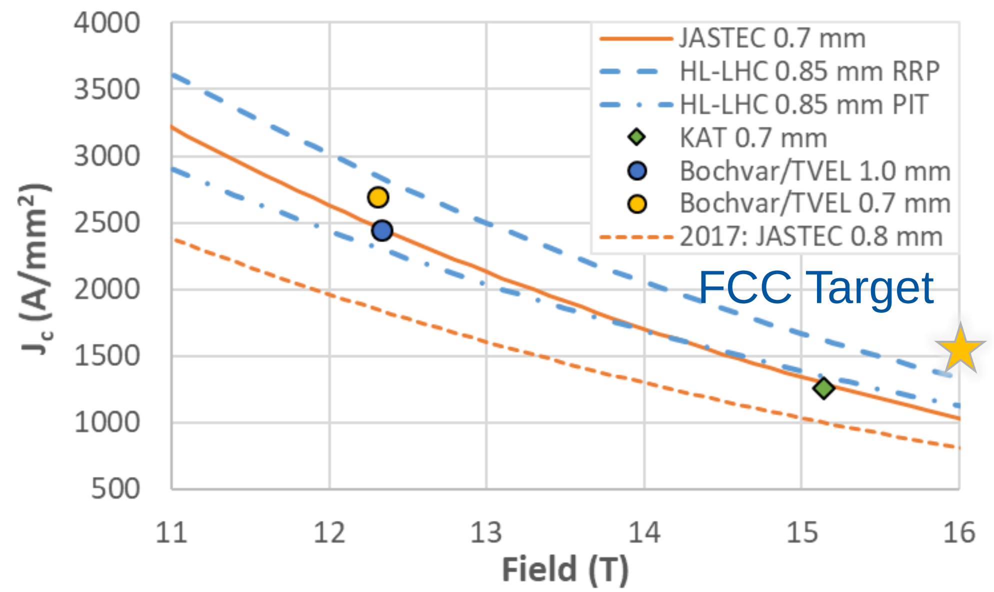
worldwide FCC Nb_3Sn program

Main development goal is wire performance increase:

- **J_c (16T, 4.2K) > 1500 A/mm^2 →50% increase wrt HL-LHC wire**
- **Reduction of coil & magnet cross-section**



After 1-2 years development, **prototype Nb_3Sn wires from several new industrial FCC partners already achieve HL-LHC J_c performance**



FCC conductor development collaboration:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **Bruker**, **Germany**, **Luvata Pori**, **Finland**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT**, **Korea**, **Columbus**, **Italy**
- **University of Geneva**, **Switzerland**
- **Technical University of Vienna**, **Austria**
- **SPIN**, **Italy**, **University of Freiberg**, **Germany**

2019/20 results from US, meeting FCC J_c specs:

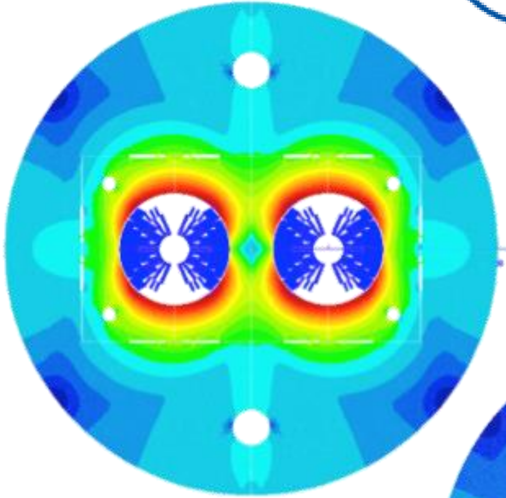
- **Florida State University:** high-J_c Nb_3Sn via Hf addition
- **Hyper Tech /Ohio SU/FNAL**: high-J_c Nb_3Sn via artificial pinning centres based on Zr oxide.

https://arxiv.org/abs/1811.08867 https://arxiv.org/abs/1903.08121

16 T dipole design activities and options

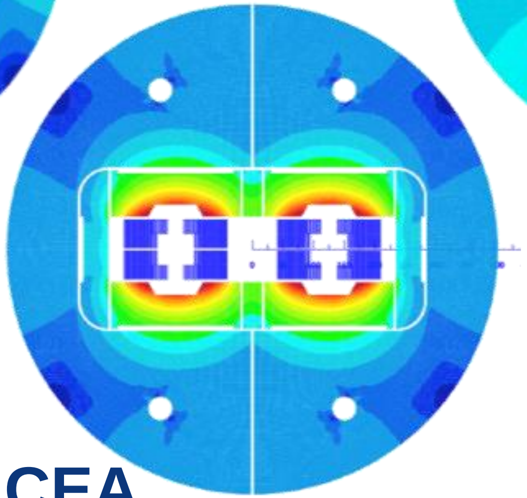
H2020 EuroCirCol – A key to New Physics

Cos-theta



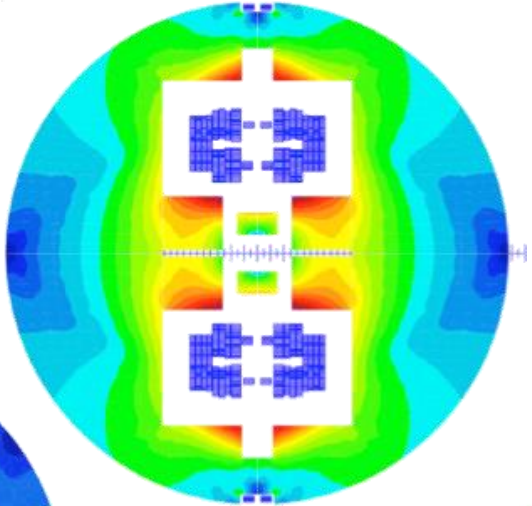
INFN

Blocks



CEA

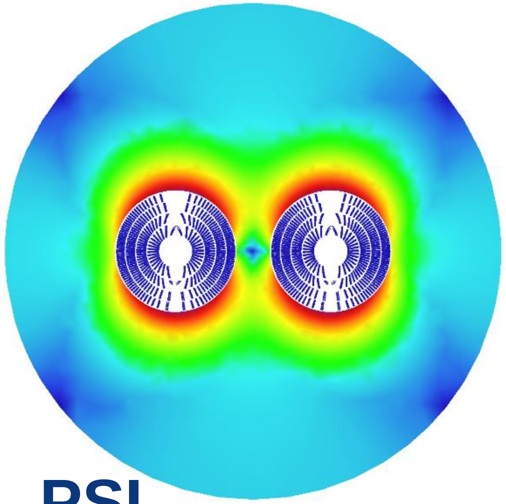
Common coils



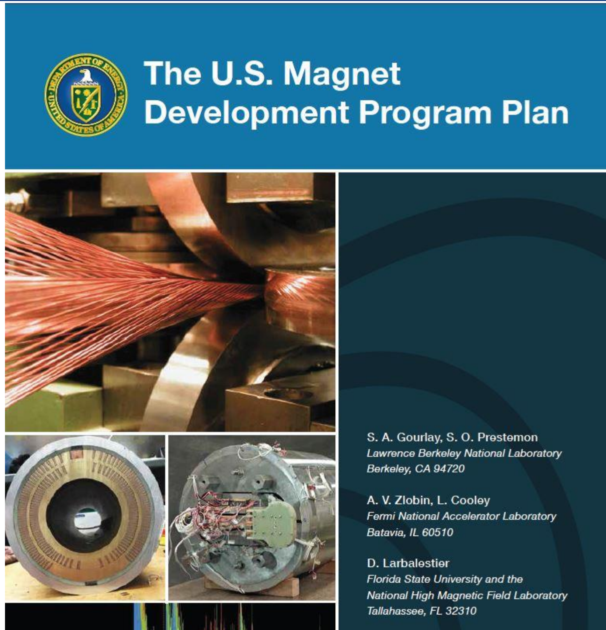
CIEMAT

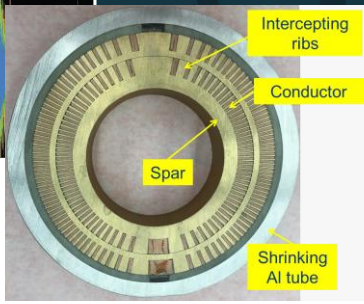
Swiss contribution

Canted Cos-theta



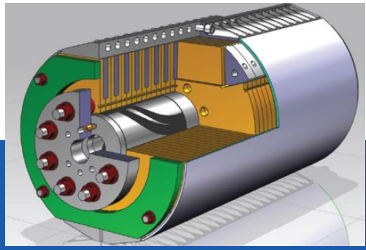
PSI





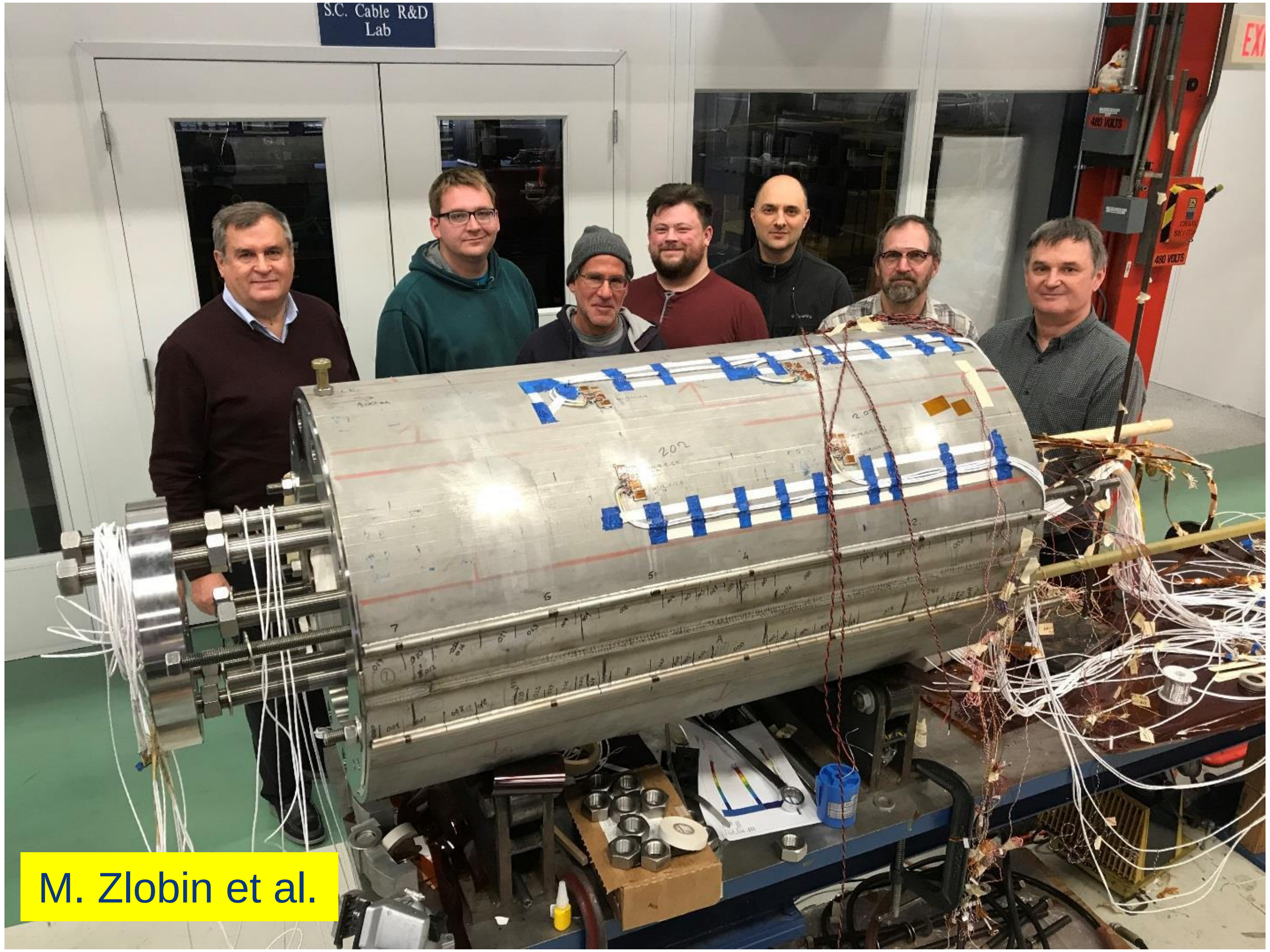
LBNL

FNAL

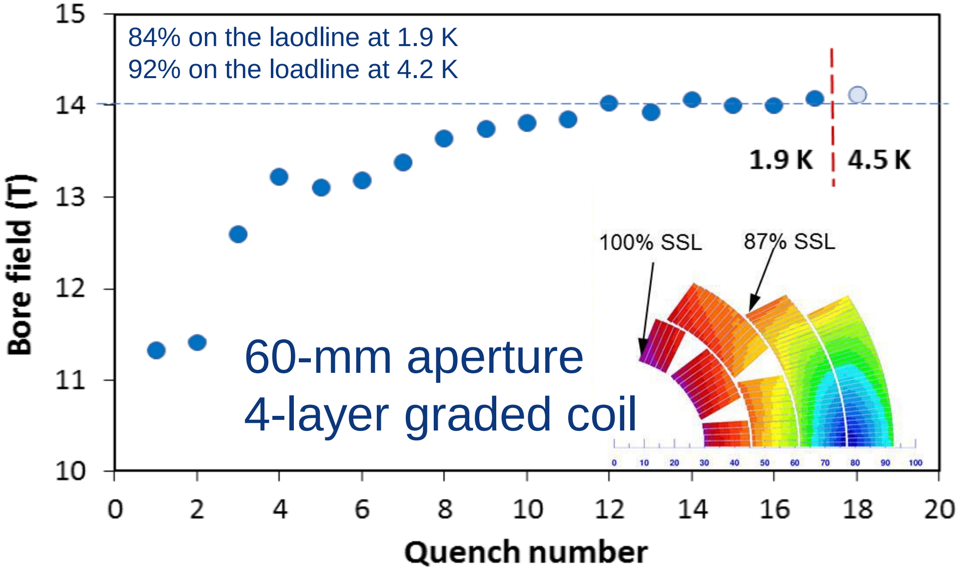


Short model magnets (1.5 m lengths) will be built until 2025

US – MDP: 14.5 T magnet tested at FNAL



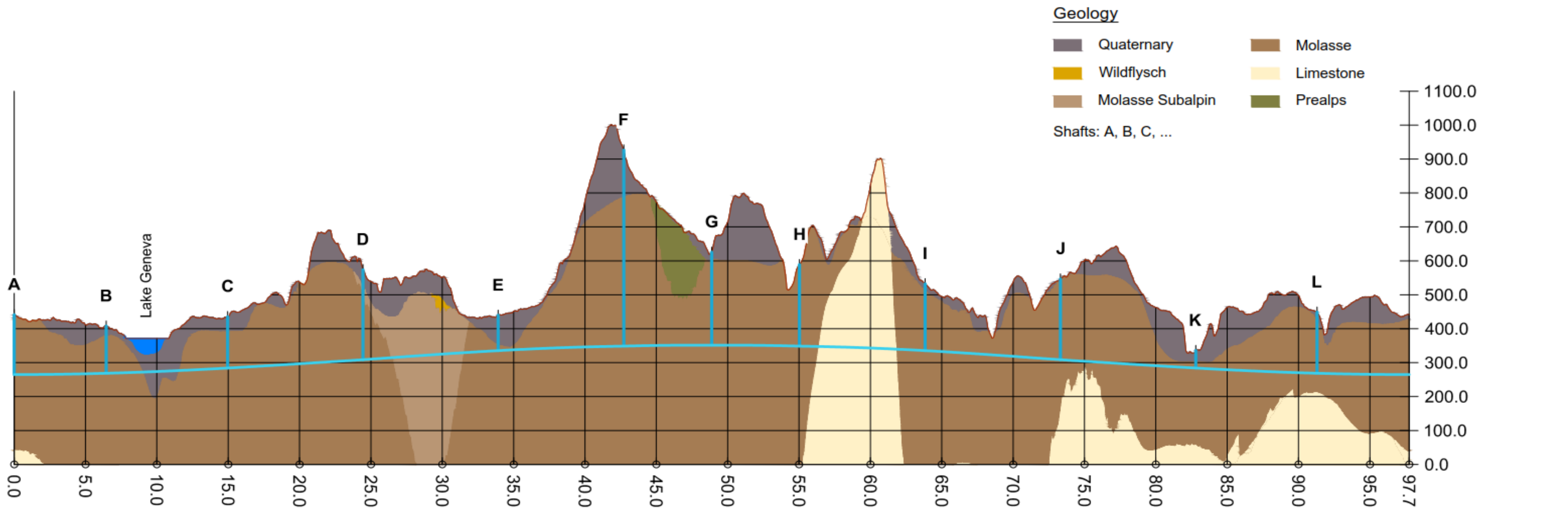
M. Zlobin et al.

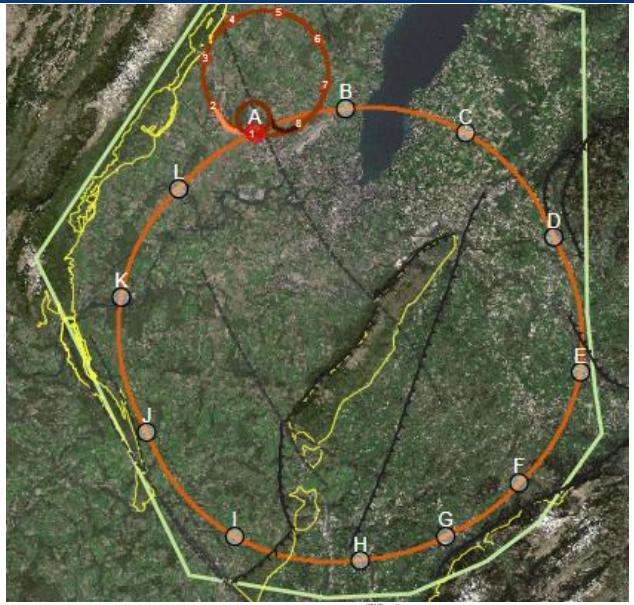


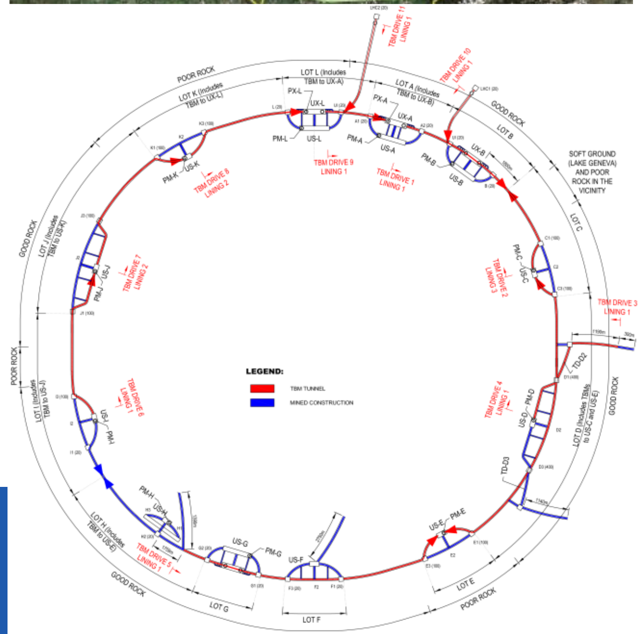
- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T

Fermilab achieves 14.5-tesla field for accelerator magnet, setting new world record | acceleratingnews.web.cern.ch

FCC implementation - footprint baseline







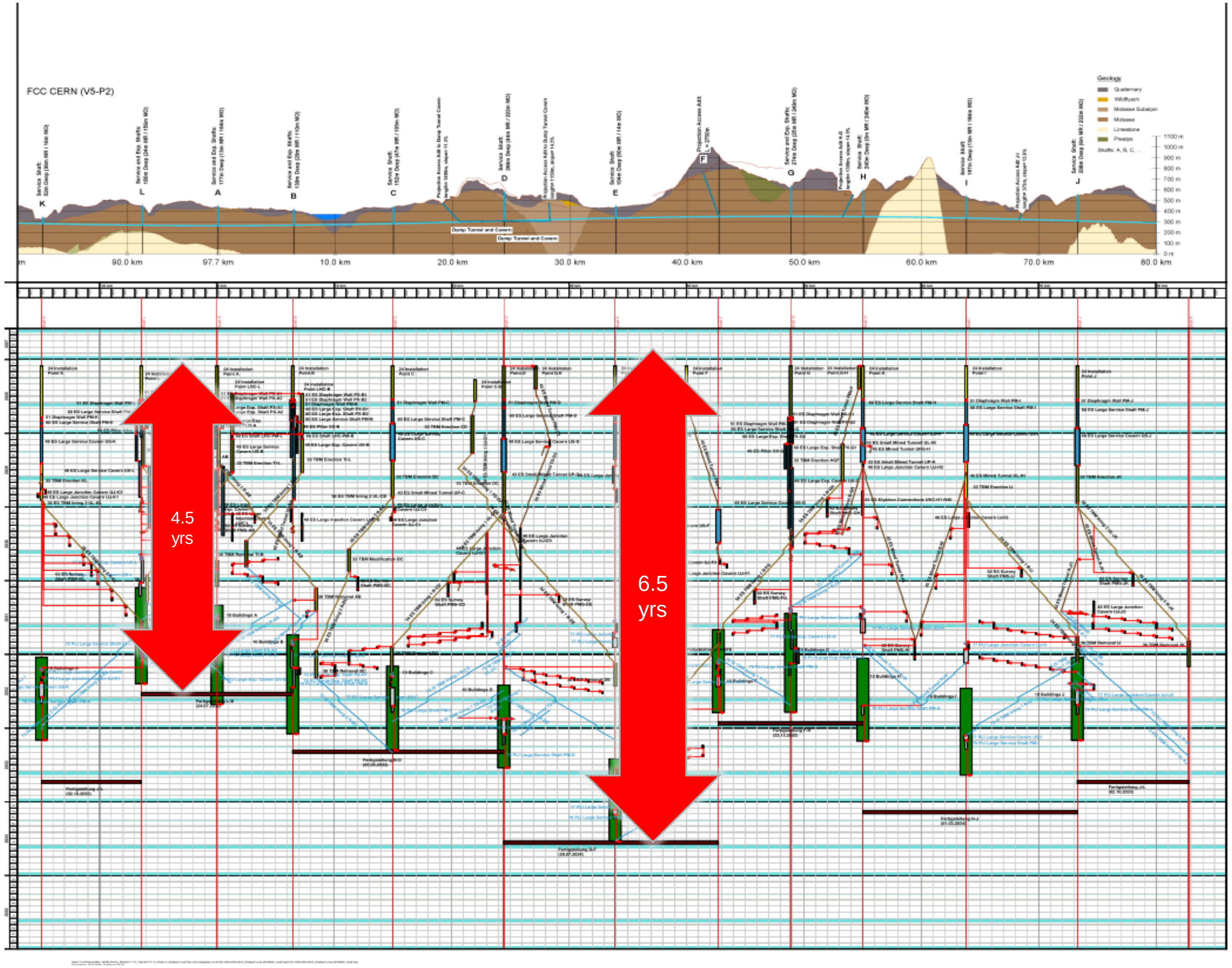
Present baseline position was established considering:

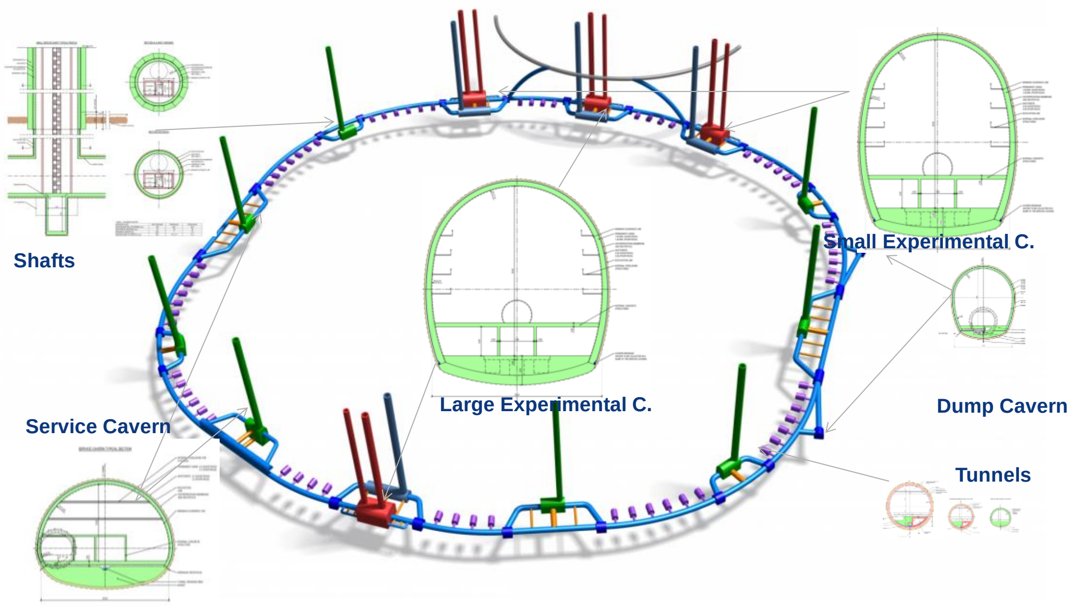
- Molasse rock preferred for tunnelling, avoid limestone with karstic structures
- low risk for construction, fast construction

- **90 – 100 km circumference**
- **12 surface sites with few ha area each**

J. Osborne et al.

civil engineering studies





- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

J. Osborne et al.

FUTURE CIRCULAR COLLIDER

FCC CDR and Study Documentation

- **FCC-Conceptual Design Reports:**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

  EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 ,

  EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

- **Summary documents provided to EPPSU SG**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

FUTURE CIRCULAR COLLIDER

from ESPP Update 2020

High-priority future initiatives:

- An **electron-positron Higgs factory is the highest-priority next collider**. For the longer term, the European particle physics community has the ambition to operate a **proton-proton collider at the highest achievable energy**.

- “Europe, together with its international partners, should investigate the **technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV** and with an **electron-positron Higgs and electroweak factory as a possible first stage**.
- Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be **completed on the timescale of the next Strategy update**..”

FCC feasibility study 2021 – 25 & roadmap

FUTURE CIRCULAR COLLIDER

Highest priority goals:

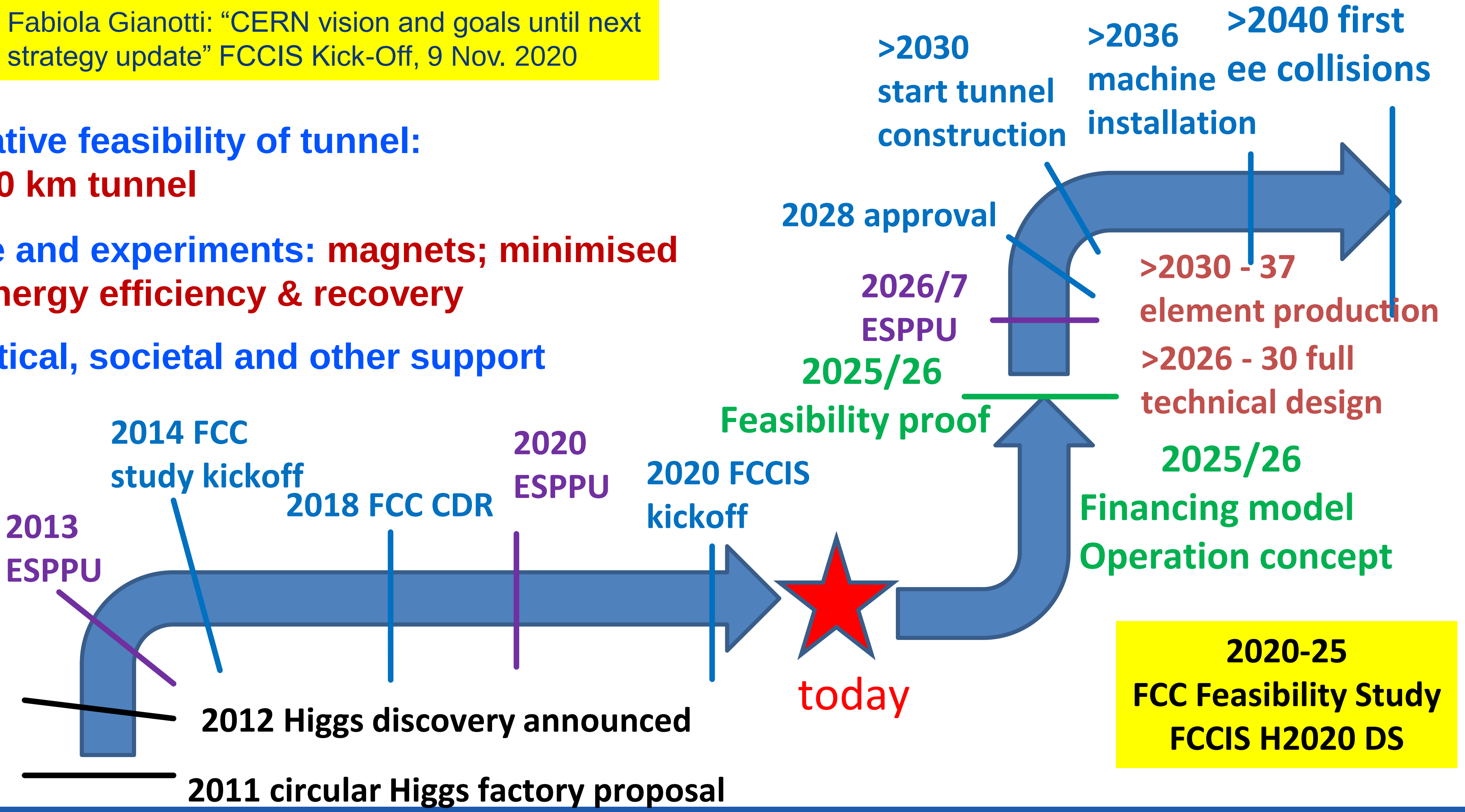
Fabiola Gianotti: "CERN vision and goals until next strategy update" FCCIS Kick-Off, 9 Nov. 2020

Financial feasibility

Technical and administrative feasibility of tunnel:
no show-stopper for ~100 km tunnel

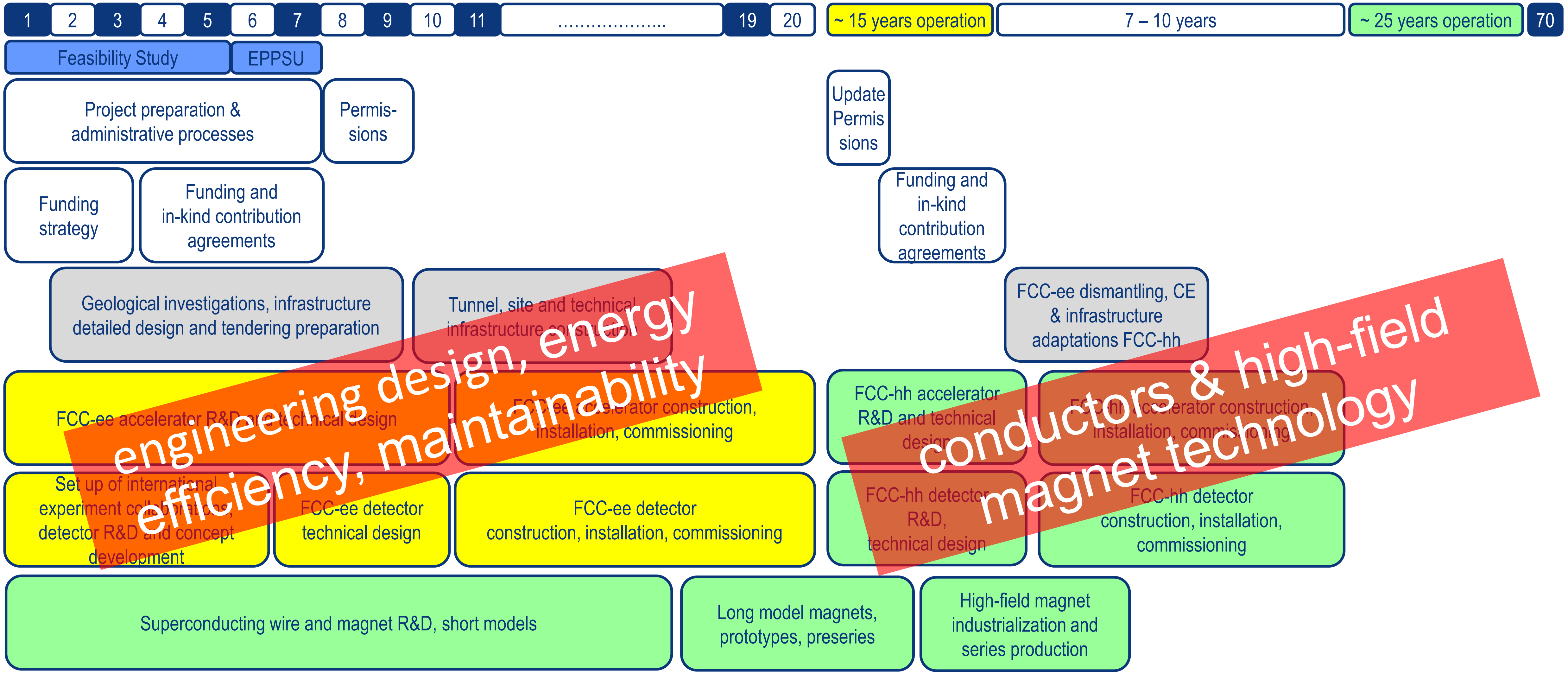
Technologies of machine and experiments: magnets; minimised environmental impact; energy efficiency & recovery

Gathering scientific, political, societal and other support



2020-25
FCC Feasibility Study
FCCIS H2020 DS

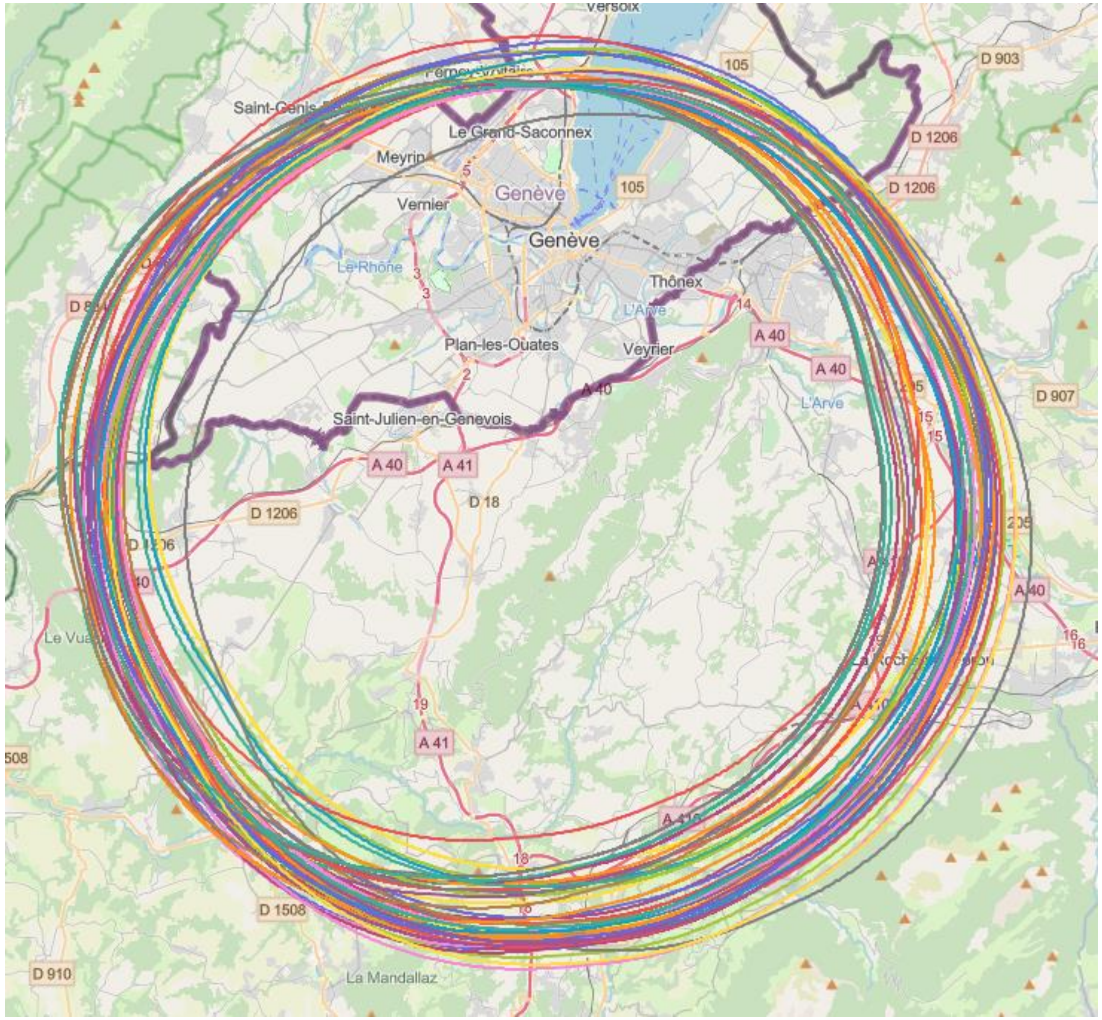
FCC integrated project technical schedule



M. Benedikt, J. Gutleber

Implementation studies with host states

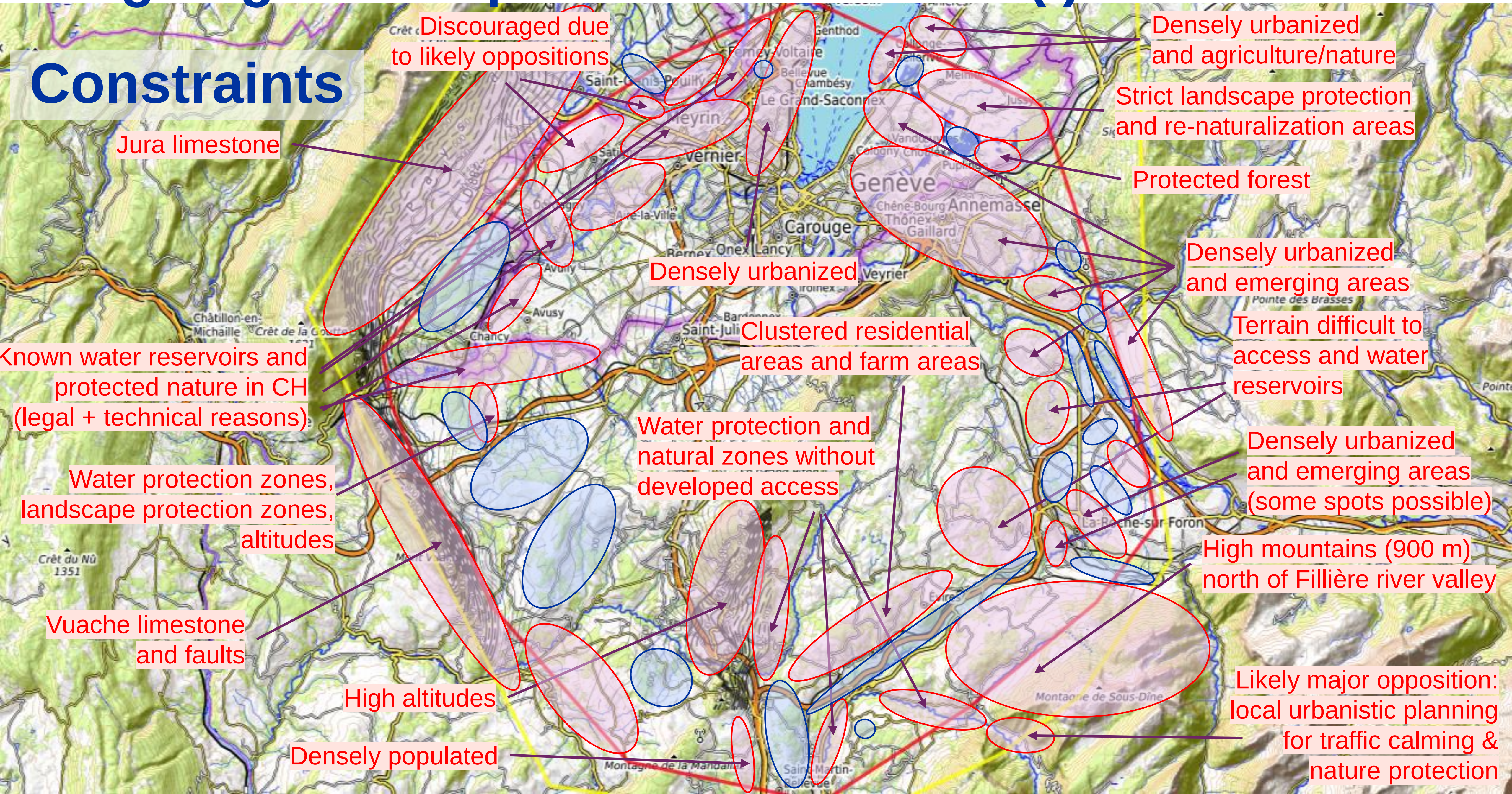
- layout & placement optimisation across both host states, Switzerland and France;
- following "avoid-reduce-compensate" directive of European & French regulatory frameworks;
- diverse requirements and constraints:
  - **technical feasibility of civil engineering** and subsurface geological constraints
  - **territorial constraints on surface** and subsurface
  - **nature, accessibility**, technical infrastructure, resource needs & constraints
  - **optimum machine performance and efficiency**
  - economic factors including benefits for, and synergies, with the **regional developments**
  - …
- collaborative effort: FCC technical experts, consulting companies, government-notified bodies



M. Benedikt, J. Gutleber, V. Mertens

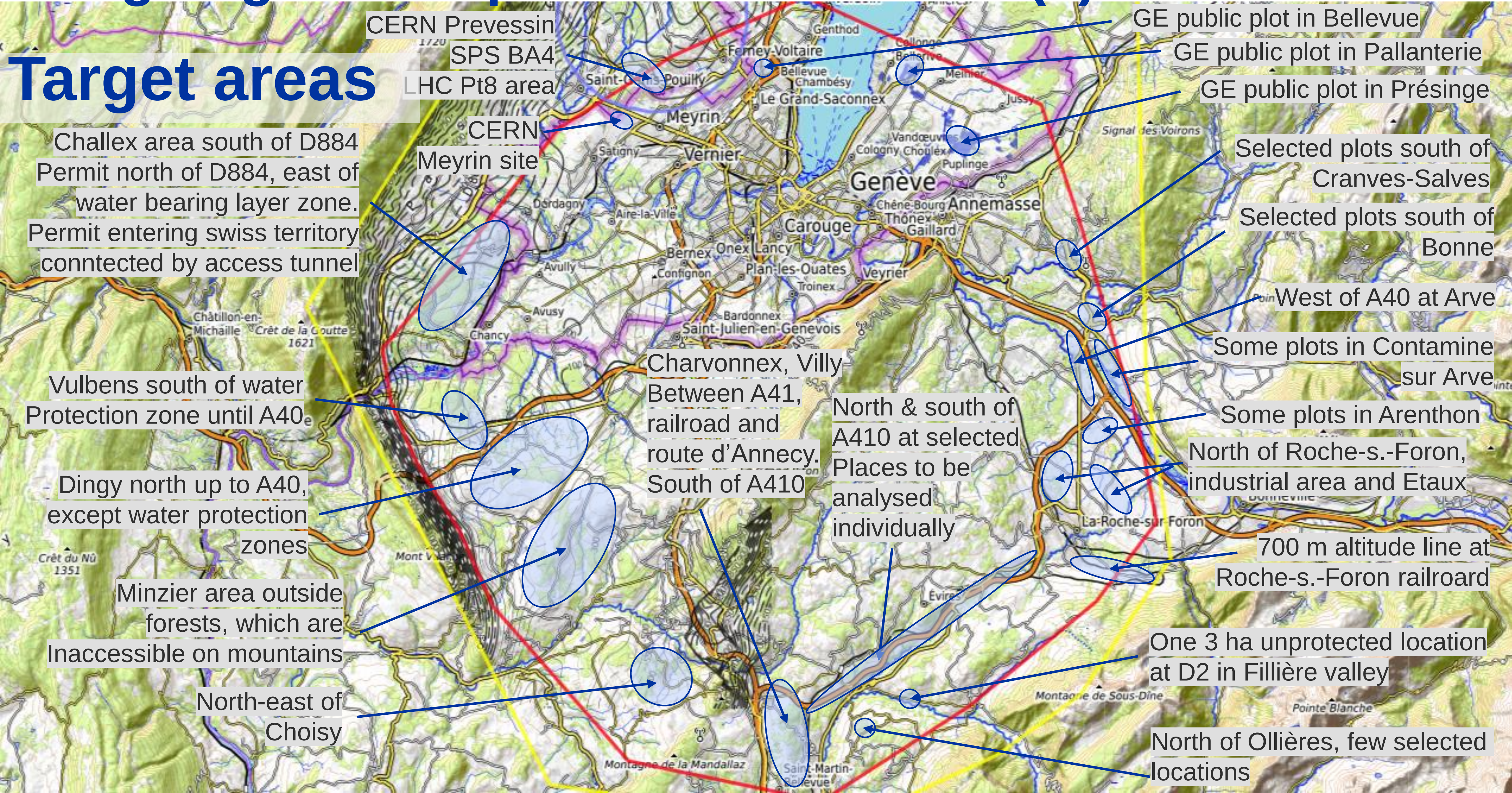
Ongoing work – placements studies (i)

J. Gutleber, V. Mertens



Ongoing work – placements studies (ii)

J. Gutleber, V. Mertens



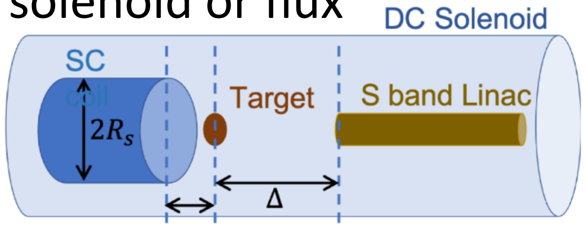
(some) FCC-ee key deliverables by 2025

400 MHz SRF cryomodule,
+ prototype multi-cell cavities
for FCC ZH operation
High-efficiency RF power sources

O. Brunner, I. Syratchev

high-yield positron source

target with DC SC solenoid or flux concentrator



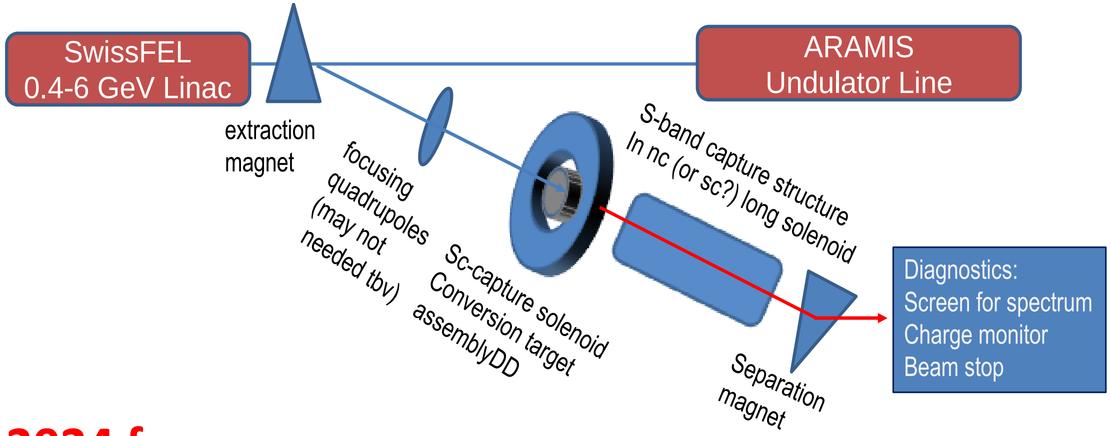
positron capture linac

large aperture S-band linac

- Freq : 2.856 GHz
- 90 cells per structure
- Length: 3.254 m
- Distance between two TWs: 45 cm
- Gradient: 20 MV/m
- Aperture: 30 mm

H. Braun,
P. Craievich

beam test of e$^+$ source & capture linac at SwissFEL – yield measurement

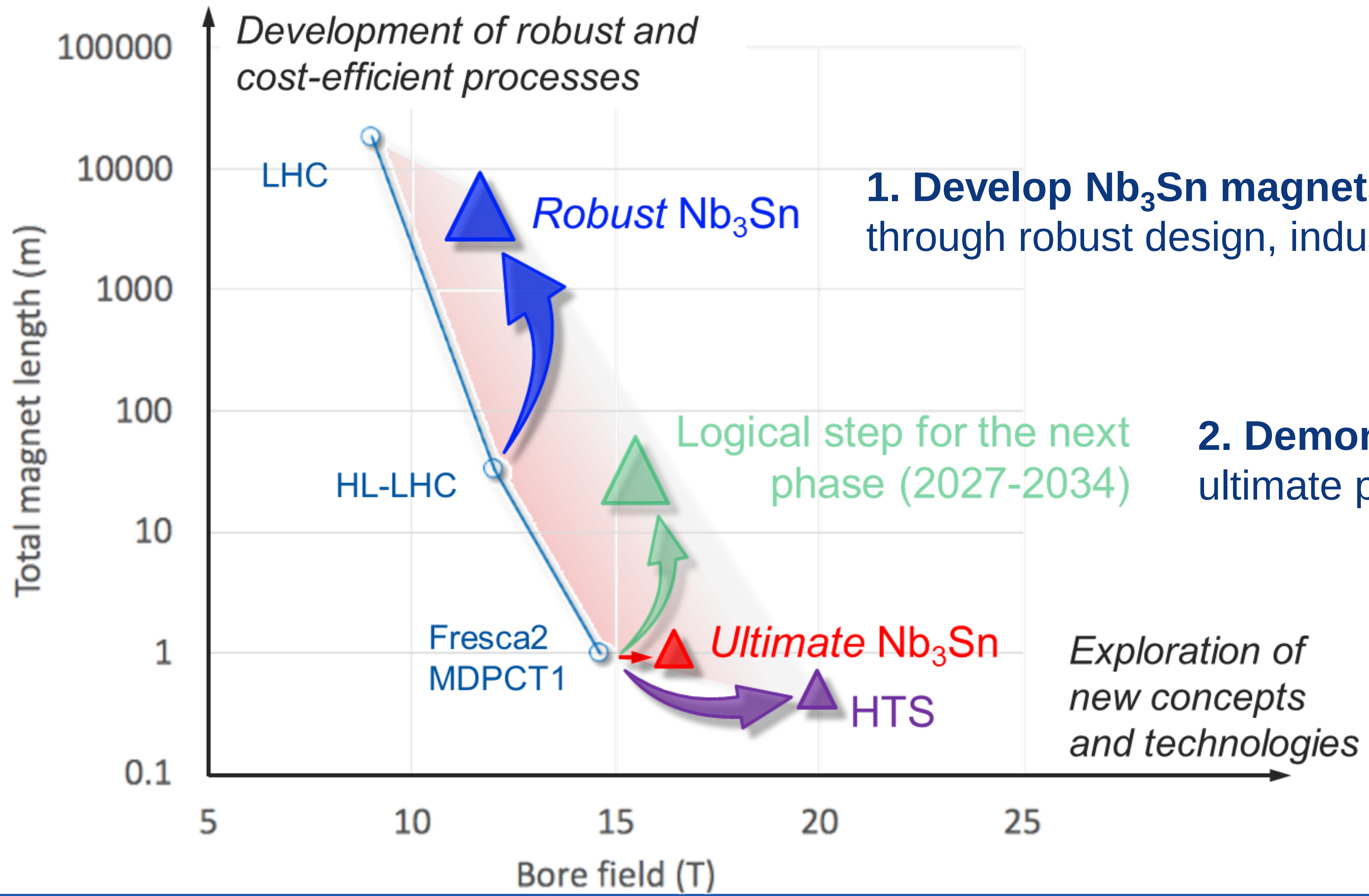


strong support from Switzerland via CHART II program 2019 – 2024 for FCC-ee injector, HFM, beam optics developments, geology and geodesy activities.

H. Braun,
P. Craievich, A. Grudiev,
I. Chaikovska

High Field Magnet program goals until 2027

L. Bottura



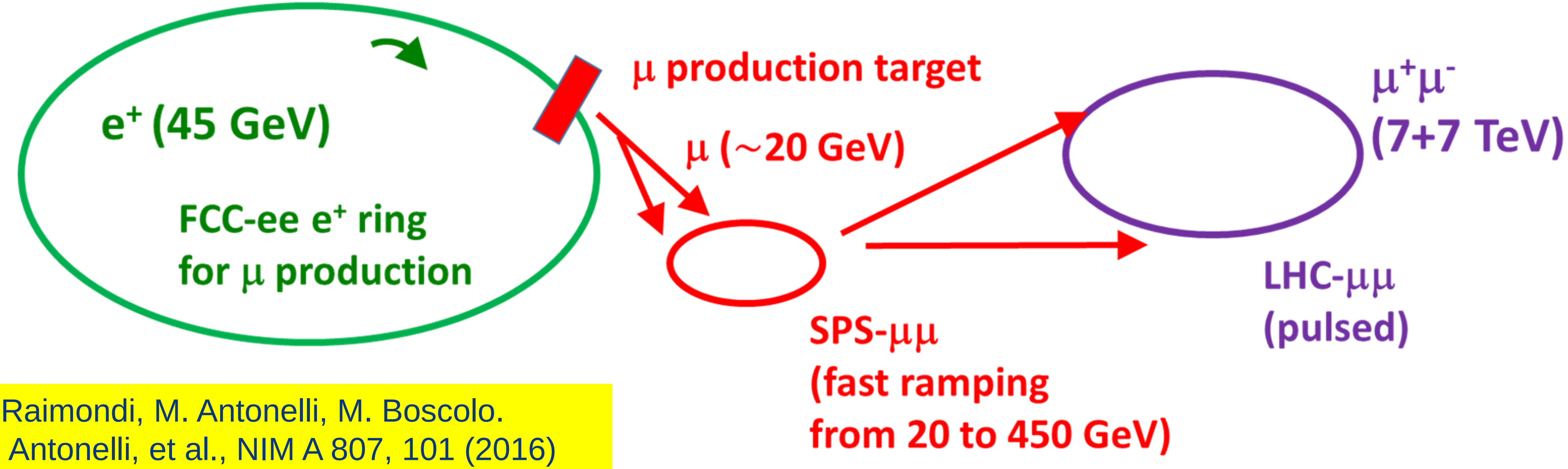
1. Develop Nb_3Sn magnets for collider-scale production, through robust design, industrial processes and cost reduction

2. Demonstrate Nb_3Sn full potential in terms of ultimate performance (short model programs)

3. Provide a proof-of-principle for HTS magnet technology

post FCC-ee option: feeding μ collider

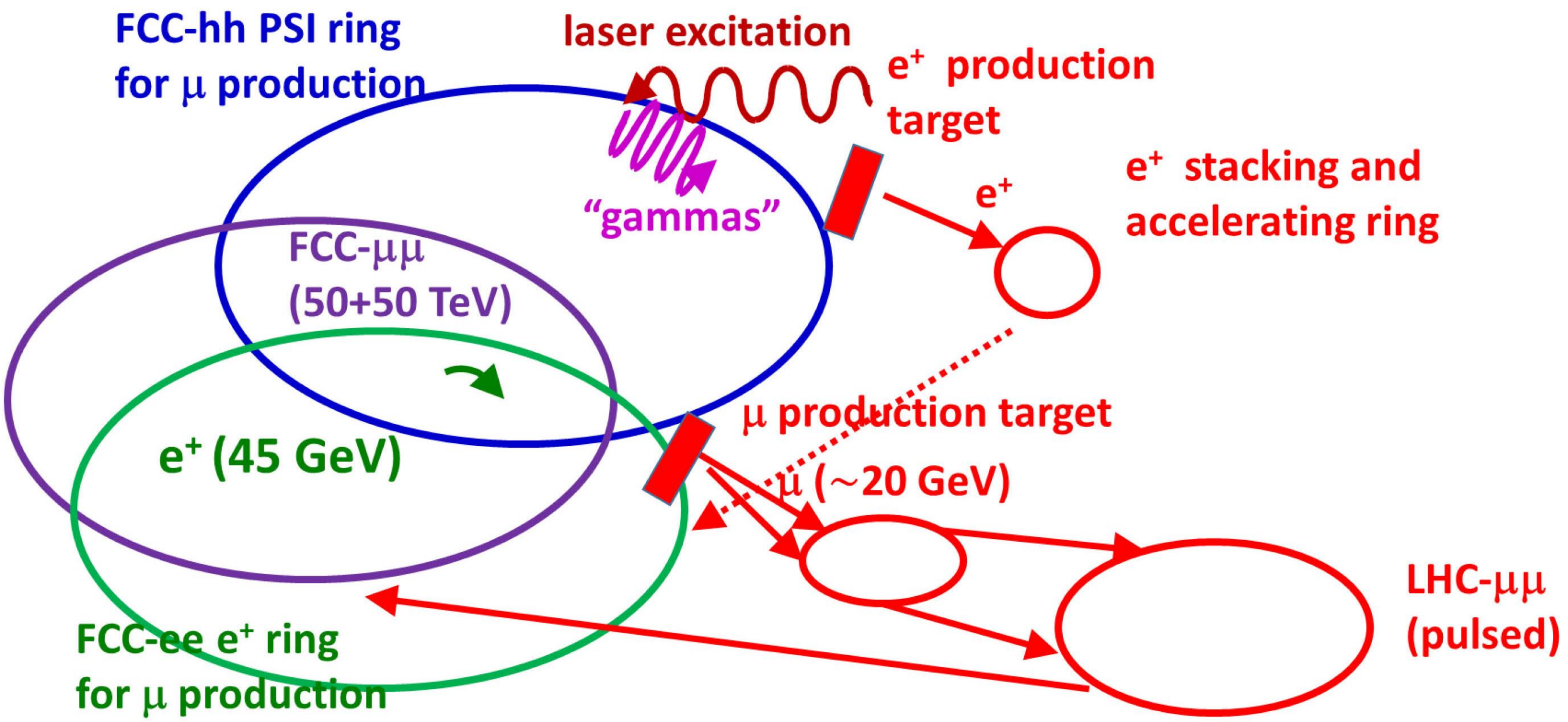
14 TeV μ collider LHC-μμ with FCC-ee $\mu^{\pm}$ production



P. Raimondi, M. Antonelli, M. Boscolo.
M. Antonelli, et al., NIM A 807, 101 (2016)
M. Boscolo et al., PRAB 23, 051001 (2020)

F. Zimmermann 2018 *J. Phys.: Conf. Ser.* **1067** 022017

after FCC-hh: FCC-μμ, a 100 TeV μ collider?



W. Krasny, https://arxiv.org/abs/1511.07794

PSI: partially stripped ion ("Gamma Factory")

F. Zimmermann 2018 *J. Phys.: Conf. Ser.* **1067** 022017

Status of Global FCC Collaboration

increasing international collaboration as a prerequisite for success

34 Countries

EC H2020

30 Companies

147 Institutes

93 member states
16 associate member states
21 non-member states with observer status
17 other non-member states

Summary

- The European Strategy Update 2019/20 issued the **request for a feasibility study of the FCC integrated programme to be delivered by end 2025.**
- **The main activities of the FCC Feasibility Study are:**
    - **concrete local implementation scenario** in collaboration **with host state authorities**,
    - accompanied by **machine optimization, physics studies and technology R&D**,
    - performed **via global collaboration,** supported by **CHART & H2020 DS FCCIS,**
    - in parallel **High Field Magnet R&D program** as separate line, to prepare for FCC-hh.
- Long term goal: **world-leading HEP infrastructure for 21st century** to push the particle-physics **precision and energy frontiers** far beyond present limits.
- **FCC-ee & -hh also are ν factories ! Synergies & options for μ collider (FCC-$\mu\mu$)**
- **Success of FCC relies on strong global participation. Everybody interested is warmly welcome to join the effort !**

FCC Week 2022

In Paris 30 May to 3 June 2022

We are looking forward

to seeing you there !