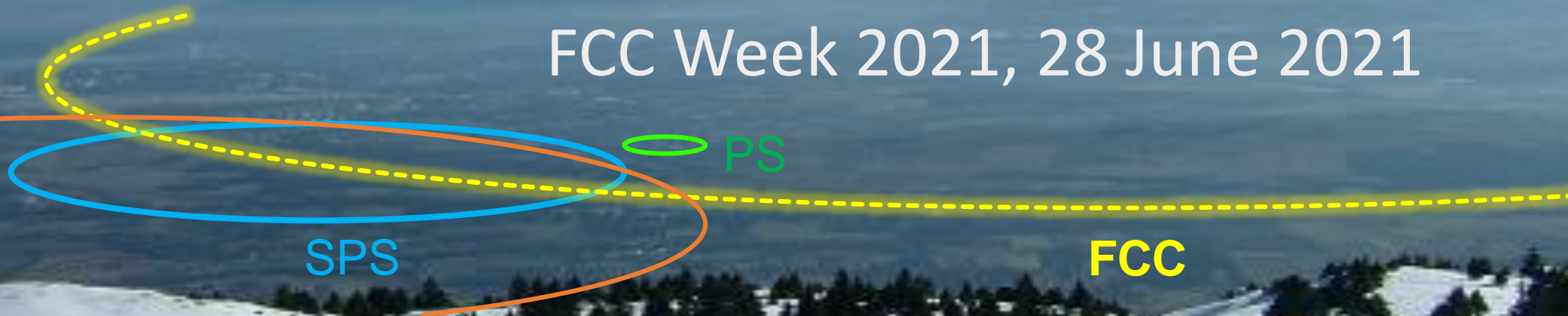


Roadmap for the FCC Feasibility Study

Michael Benedikt, CERN
FCC Week 2021, 28 June 2021

LHC



SPS

PS

FCC



FUTURE
CIRCULAR
COLLIDER
Innovation Study



<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 **E-JADE**, contract no. 645479



European
Commission

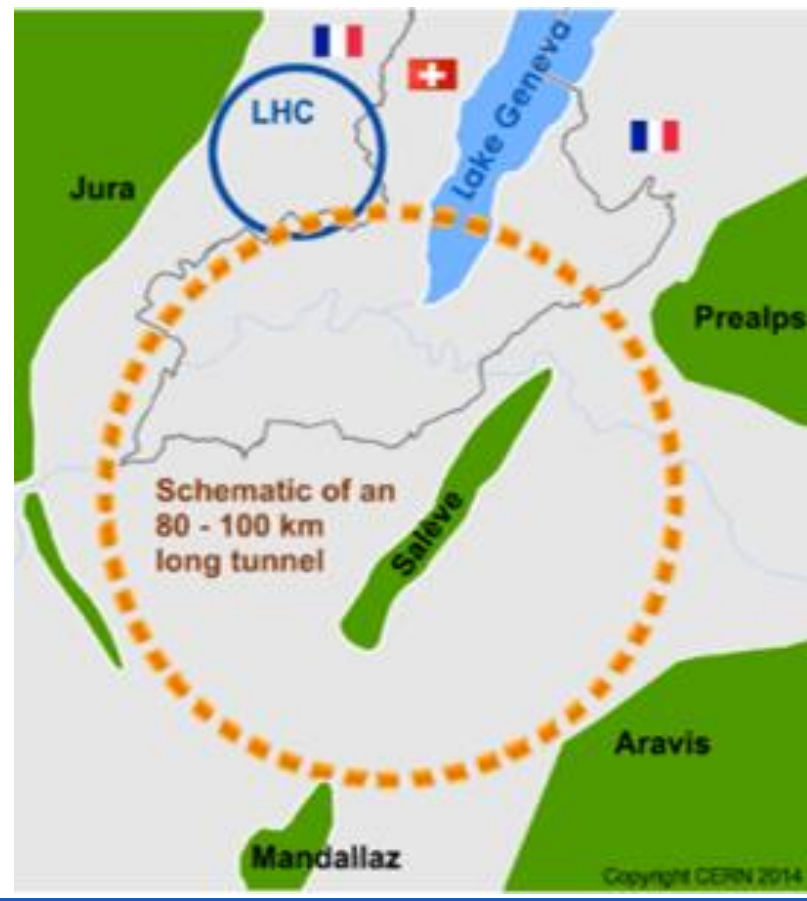
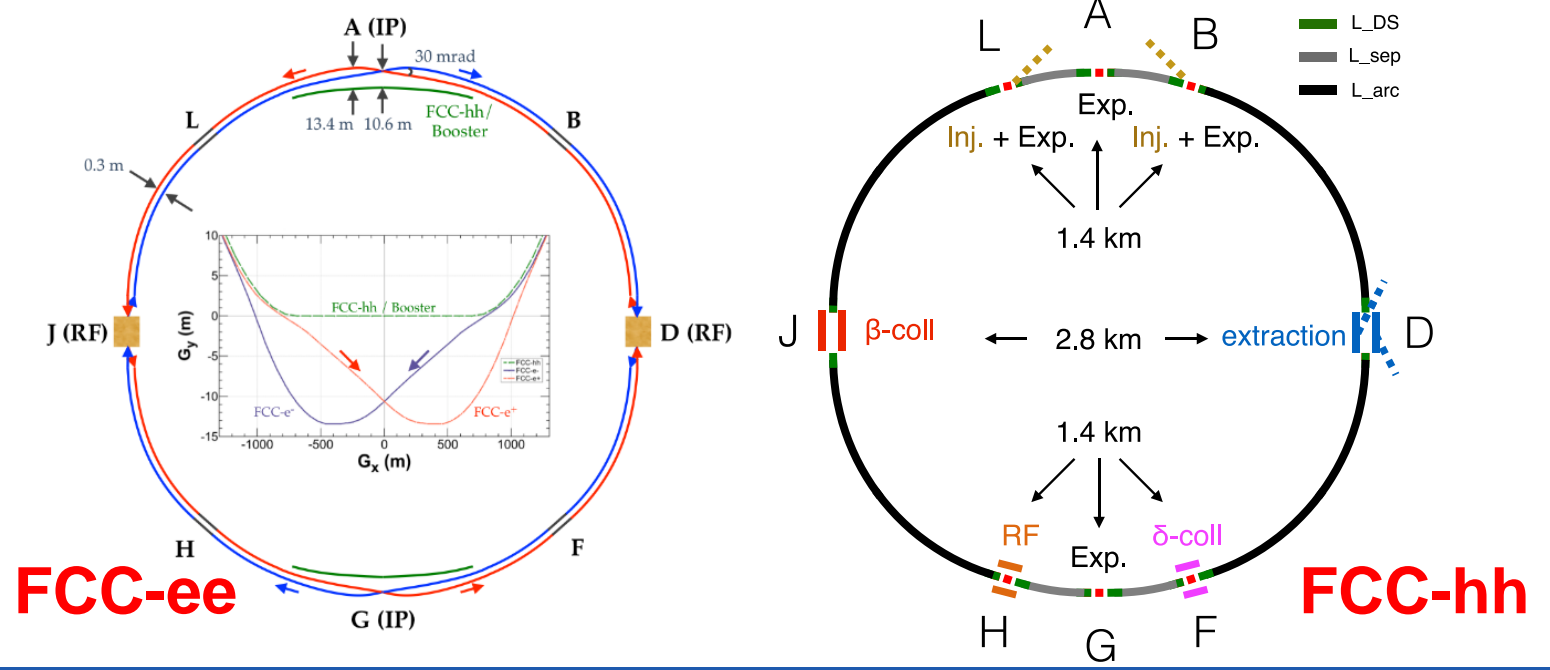
Horizon 2020
European Union Funding
for Research & Innovation

photo: J. Wenninger

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

Comprehensive long-term program, maximizing physics opportunities

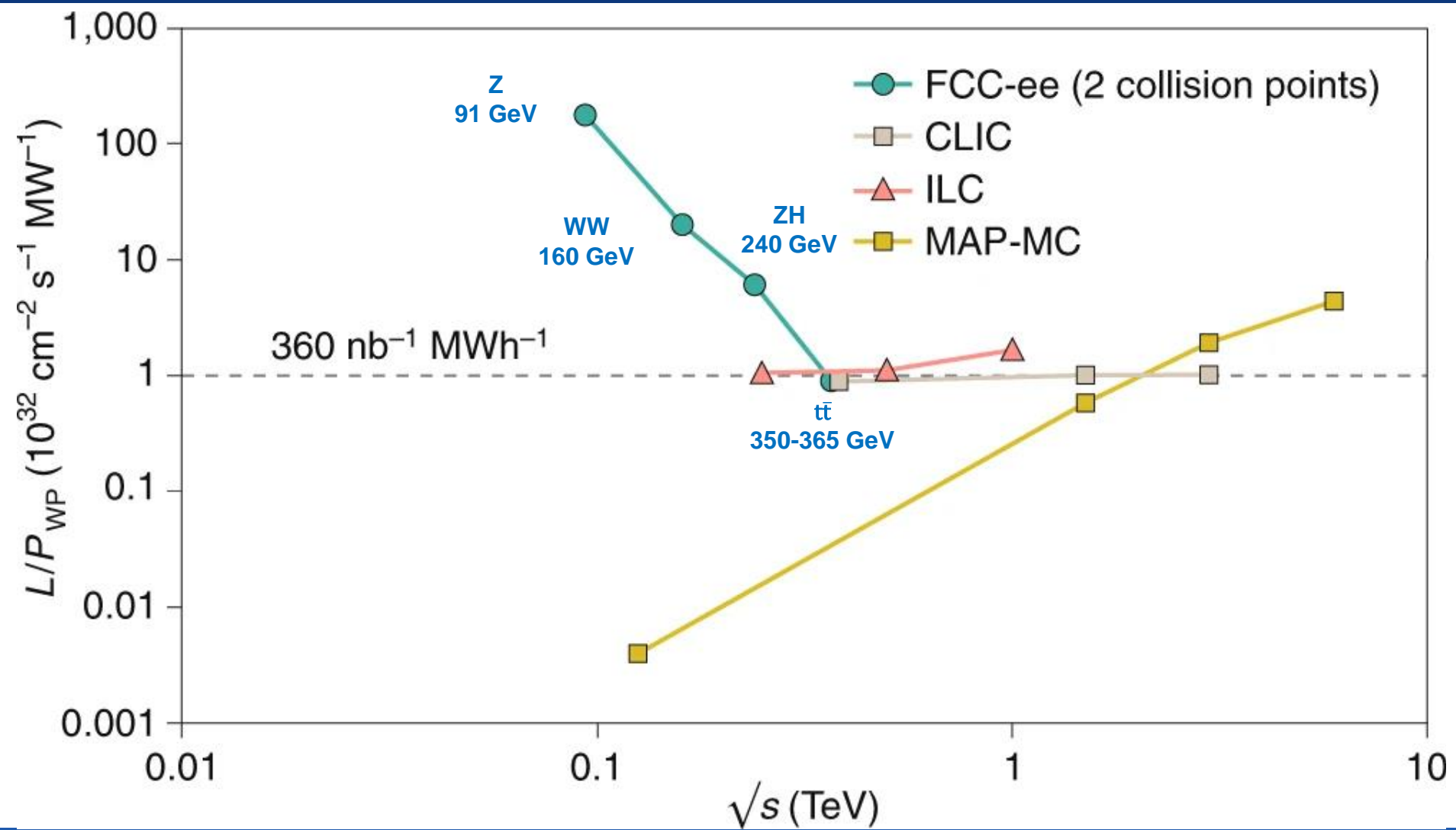
- Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options
- Complementary physics
- Common civil engineering and technical infrastructures
- Building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



FCC-ee 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 [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee: efficient Higgs/electroweak factory

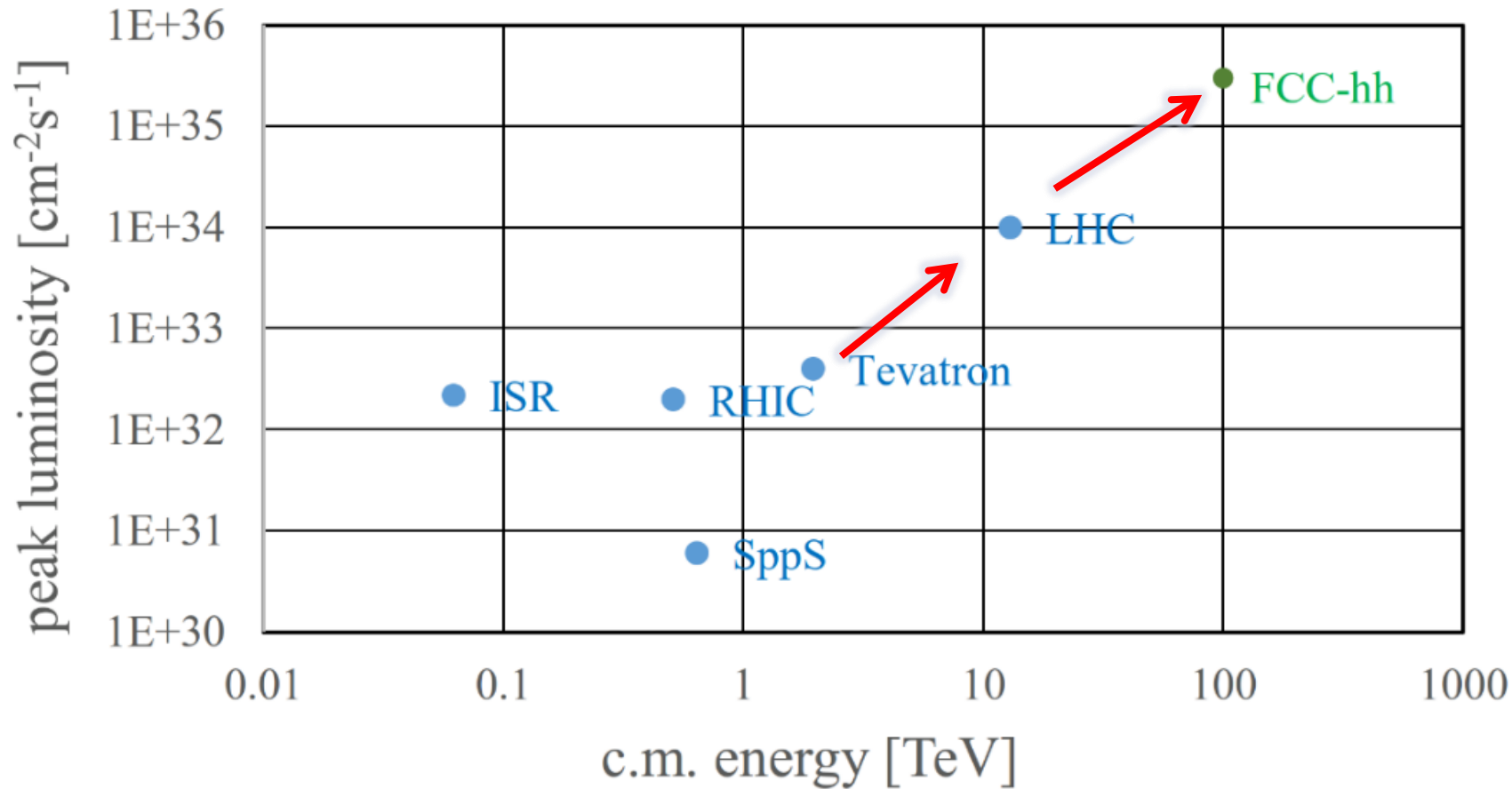


luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders

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 [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

FCC-hh: big step in performance



order of magnitude
performance increase in
energy & luminosity

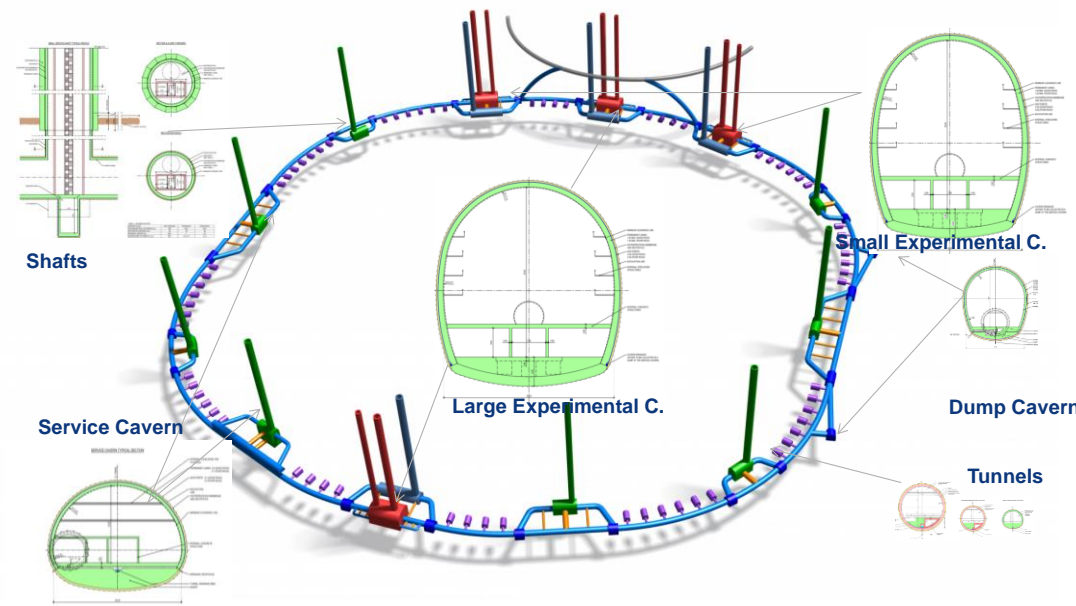
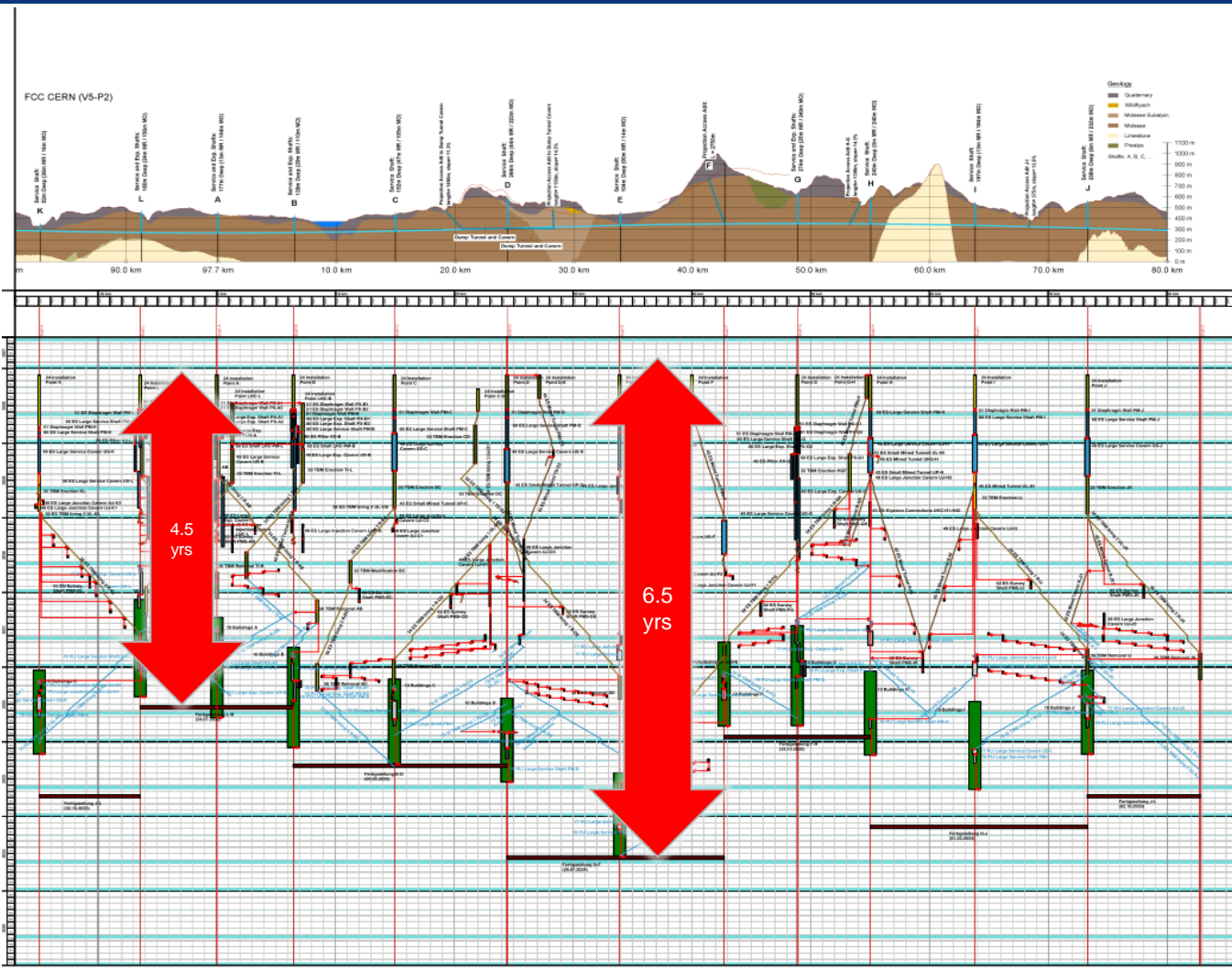
100 TeV cm collision energy
(vs 14 TeV for LHC)

20 ab^{-1} per experiment
collected over 25 years of
operation (vs 3 ab^{-1} for LHC)

similar performance increase
as from Tevatron to LHC

key technology: high-field magnets

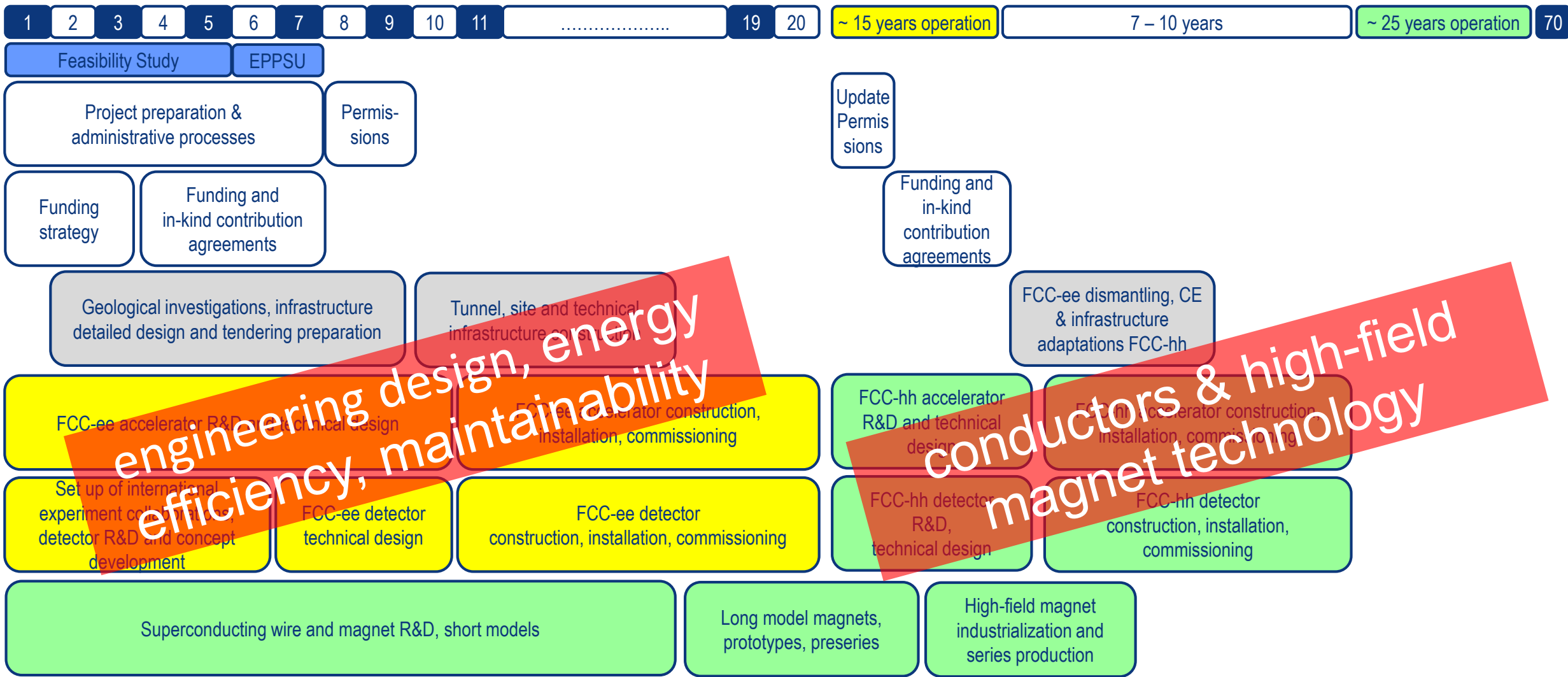
civil engineering studies



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

J. Osborne et al.

FCC integrated project technical schedule



engineering design, energy efficiency, maintainability

conductors & high-field magnet technology

FCC CDR and Study Documentation



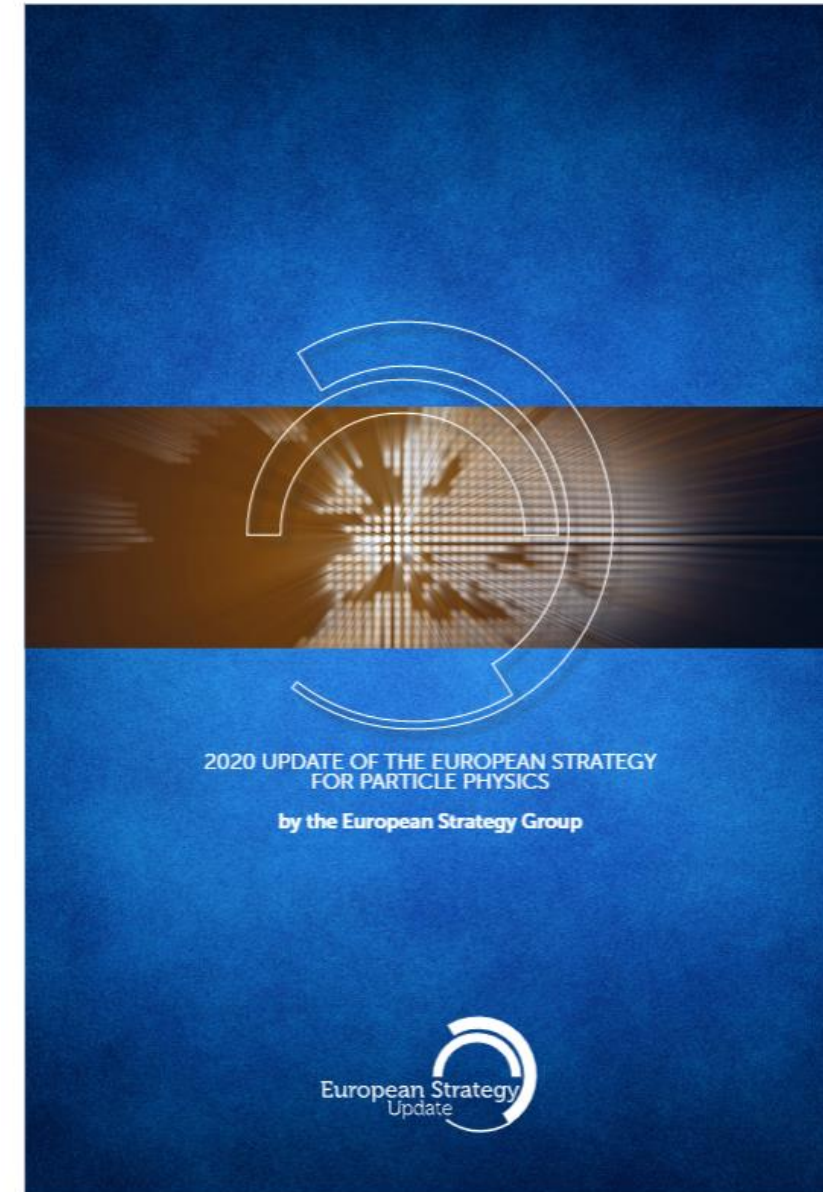
*> 1350 contributors from
> 350 institutes,
a truly global effort as
suggested by EPPSU 2013*

- **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/>

FCC Feasibility Study

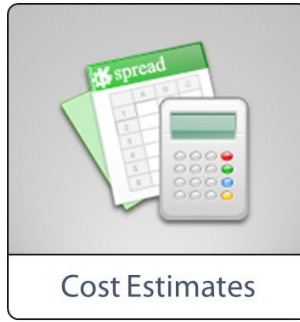
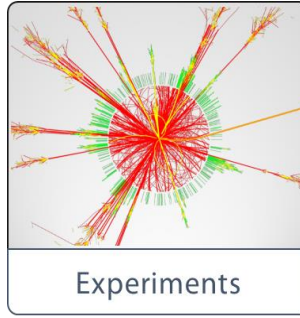
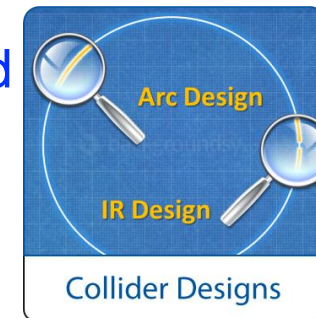
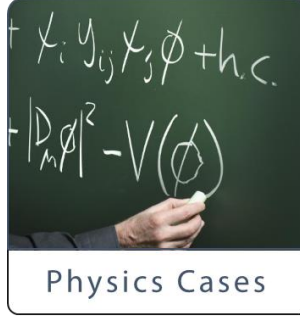
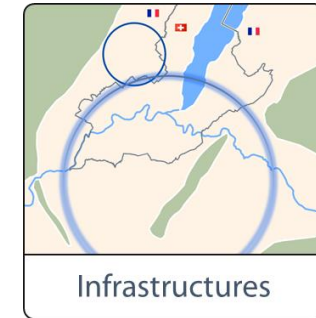
FCC Feasibility Study (FS) will address a recommendation of the 2020 update of the European Strategy for Particle Physics (ESPP):

- “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.”

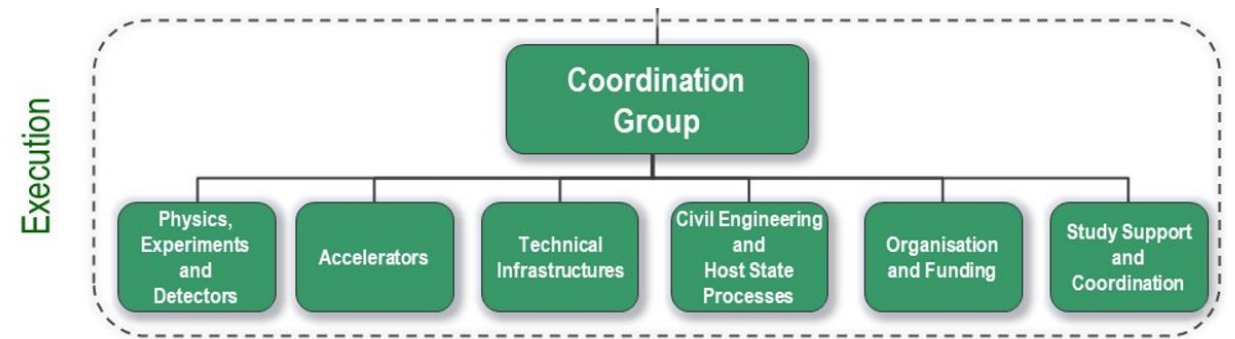


High-level goals of Feasibility Study

- optimisation of placement and layout of the ring and related infrastructure, and demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval, with a focus on identifying and surmounting possible showstoppers;
- optimisation of the design of the colliders and their injector chains, supported by targeted R&D to develop the needed key technologies;
- development and documentation of the main components of the technical infrastructure;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, environmental aspects and energy efficiency;
- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project;
- consolidation of the physics case and detector concepts for both colliders.



Main deliverables and milestones (i):



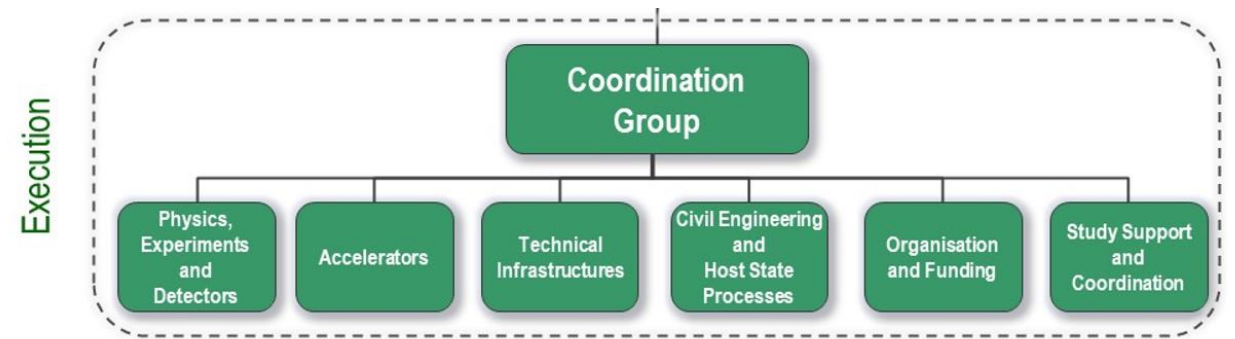
Physics, experiments and detectors

- ❑ consolidation of physics case for full FCC programme;
- ❑ requirements on theoretical calculations, Monte Carlo generators and other software;
- ❑ detector concepts for FCC-ee and FCC-hh (also based on experience with Phase-2 upgrades);
- ❑ detector design and R&D (synergies with “R&D for future detectors” at CERN and ECFA Detector Roadmap);
- ❑ requirements on accelerator performance, technical infrastructure, computing and integration.

Accelerators

- ❑ design of FCC-ee and FCC-hh, and their injectors;
- ❑ development of key technologies for both colliders, including high-field superconducting magnets, SCRF, high-efficiency power production, and other sustainable and environmentally-friendly technologies; milestones will be finalised once Accelerator R&D roadmap available;
- ❑ machine-detector interface for FCC-ee (final focus magnets and compensation solenoids).

Main deliverables and milestones (ii):



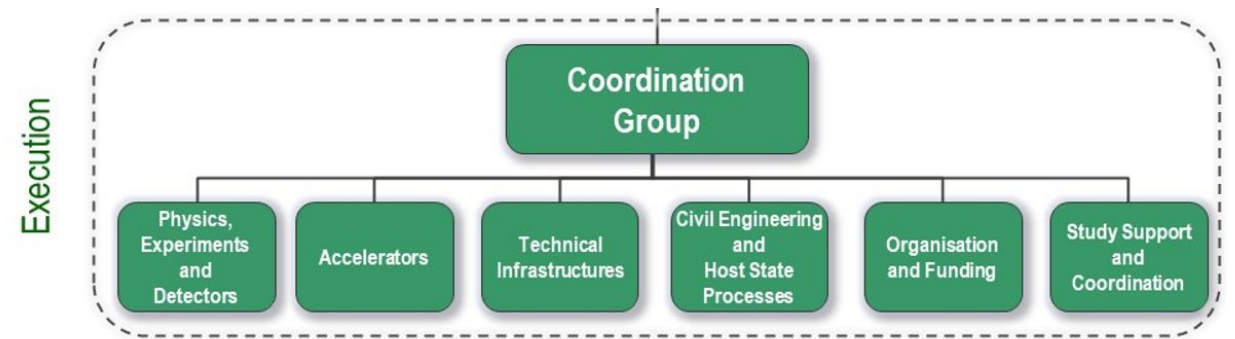
Technical infrastructures

- concepts for electricity supply and distribution; optimise electrical system efficiency and stability;
- design of cooling and ventilation systems; cryogenics systems; efficiency via e.g. waste heat recovery;
- safety and radiation protection;
- integration and logistics: integration of components for installation, maintenance and operation; transport concepts on surface and underground for personnel and materials; etc.

Organisation and funding

- development of organisational models for design, implementation and operation of future project;
- preparation of consolidated cost estimate;
- development of funding concepts and models for the project construction and operation;
- development of procurement strategy/rules for global project (with major contributions from non-Member States);
- development of sustainable operational model for colliders and experiments in terms of human and financial resource needs, environmental aspects and energy efficiency).

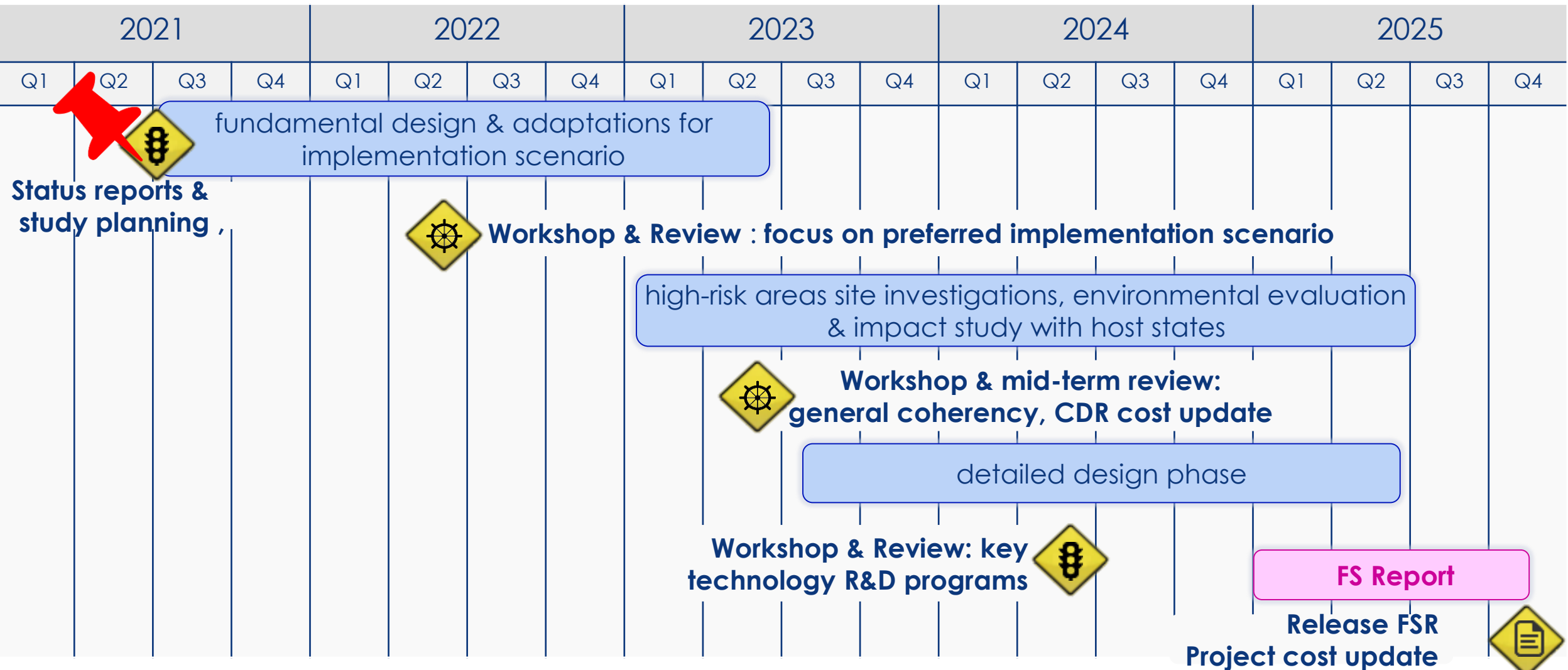
Main deliverables and milestones (iii):



Civil engineering and Host-State processes

- ❑ planning and management of high-risk area site investigations;
- ❑ pre-design of tunnel and underground structures, including shafts and caverns;
- ❑ development of layout concepts for each of 12 foreseen surface sites, taking into account technical requirements and territorial constraints (buildings, streets, parking spaces, storage, integration of general services, etc.);
- ❑ preliminary concepts and requirements for access to each site; pre-design of surface buildings;
- ❑ development and deployment of communications plan for local areas to support the site investigations;
- ❑ identification and execution of Host-State admin processes needed for possible construction start early 2030s;
- ❑ development of integrated process for environmental evaluation in agreement with regulations in both Host States, and first part of environmental evaluation process and impact study from 2023 onwards;
- ❑ roadmaps and plans for processes that will begin after project's possible approval (e.g. acquisition of land plots for surface sites, public debates, environmental impact study and compensation procedures).

Feasibility study timeline



Status of Global FCC Collaboration

increasing international collaboration as a prerequisite for success:
links with science, research & development and high-tech industry will
be essential to further advance with the FCC FS

34
Countries



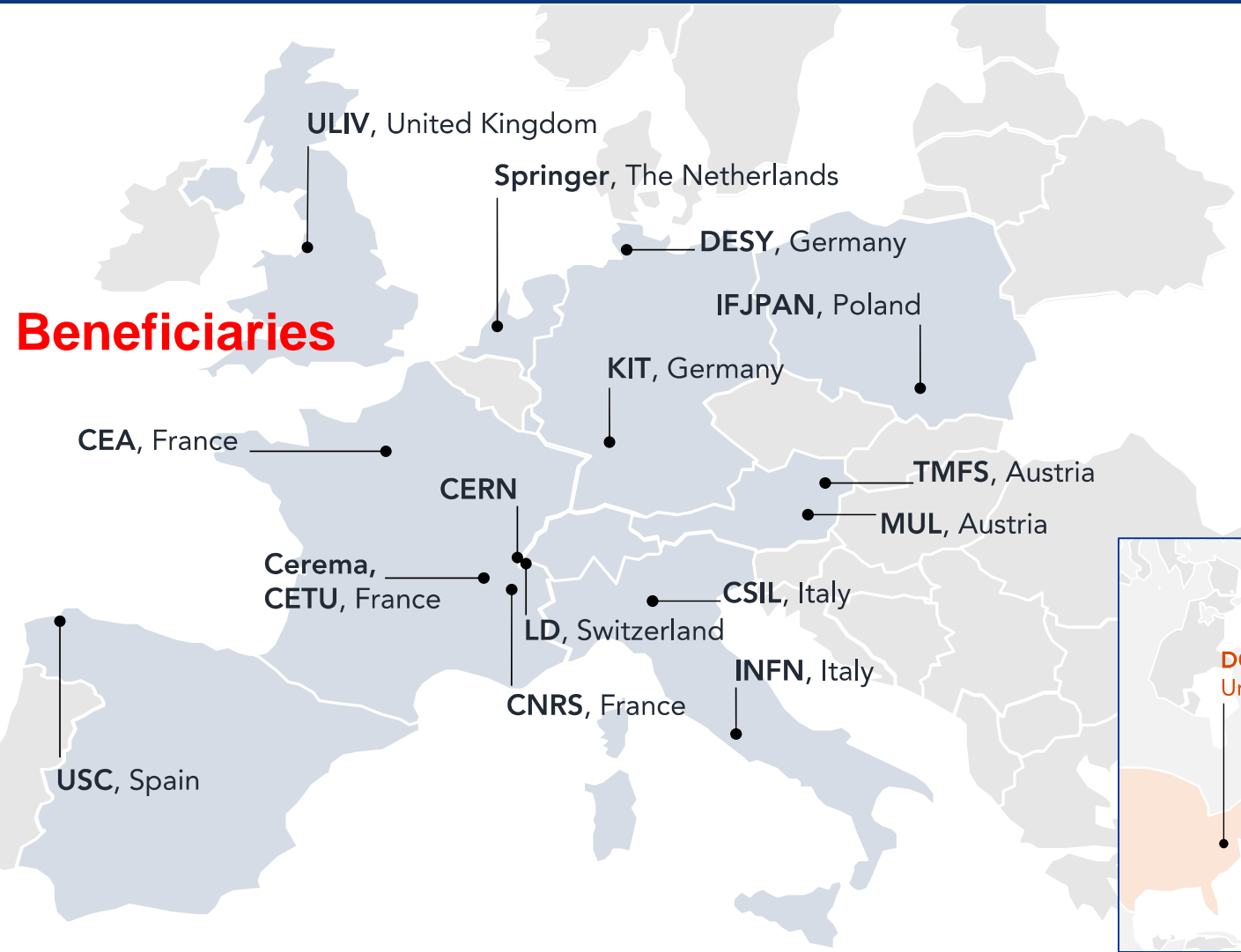
30
Companies

147
Institutes

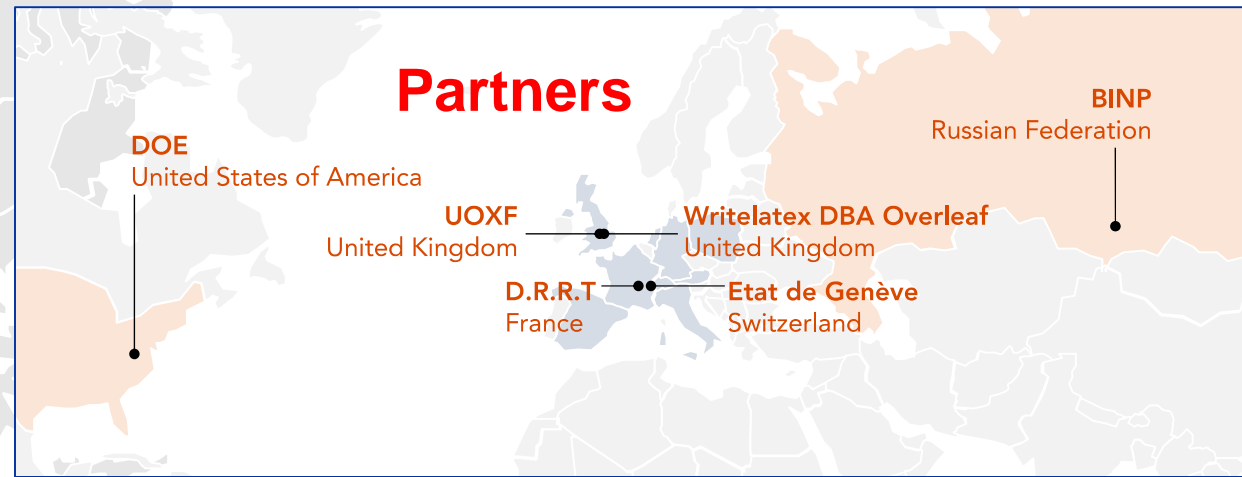
- 93 member states
- 16 associate member states
- 21 non-member states with observer status
- 17 other non-member states

FCC Feasibility Study Governance approved by June Council.
FCC collaboration board meeting in preparation for September 2021.

H2020 DS FCC Innovation Study 2020-24



Grant Agreement	FCCIS 951754
Duration	48 months
From-to	2 Nov 2020 – 1 Nov 2024
Project cost	7 435 865 €
EU contribution	2 999 850 €
Beneficiaries	16
Partners	6



WP1: study management

WP2: collider design

Deliver a **performance optimised machine design**, integrated with the territorial requirements and constraints, considering cost, long-term sustainability, operational efficiency and design-for- socio-economic impact generation.

WP3: integrate Europe

Develop a feasible **project scenario compatible with local – territorial constraints** while guaranteeing the required physic performance.

WP4: impact & sustainability

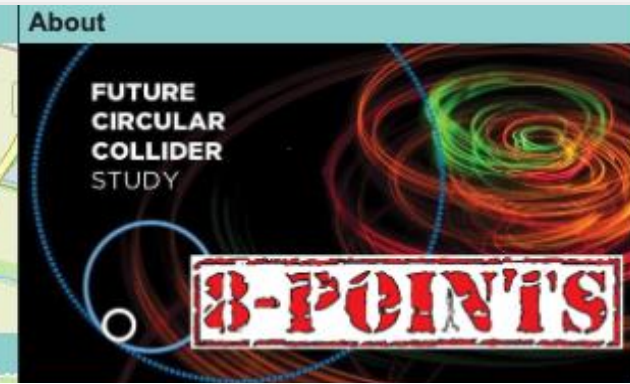
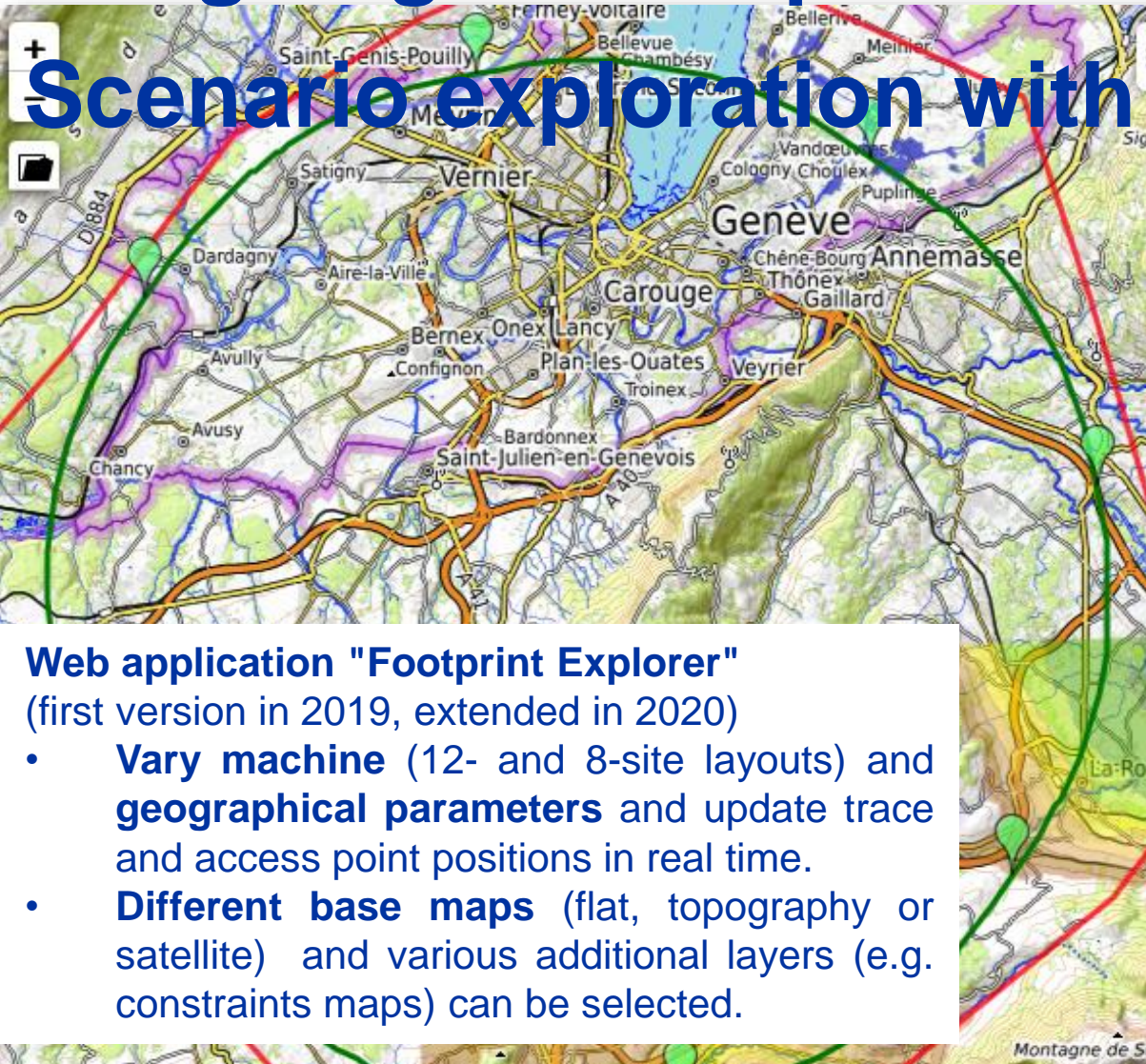
Develop the **financial roadmap of the infrastructure project**, including the analysis of socio-economic impacts.

WP5: leverage & engage

Engage stakeholders in the preparation of a new research infrastructure. Communicate the project rationale, objectives and progress. Create lasting impact by building theoretical and experimental physics communities, creating awareness of the technical feasibility and financial sustainability, forging a project preparation plan with the host states (France, Switzerland).

Ongoing work – placements studies (i)

Scenario exploration with interactive tool



The approach adopted for the layout and placement studies is the one anchored in the French law (Eviter-Reduire-Compenser = Avoid-Reduce-Compensate), which has also been agreed with the Swiss authorities.

The **Multi Criteria Optimisation concept** includes different aspects:

- subsurface aspects (geology, construction technology, etc.)
- surface aspects (land availability, access, etc.)
- nature environment aspects (protected zones, water resources,)
- infrastructure aspects (electricity and water availability, transport,)
- access aspects for different project phases (roads, train)
- synergies (tourism, water re-use, sharing of electricity lines, etc.)

Web application "Footprint Explorer"

(first version in 2019, extended in 2020)

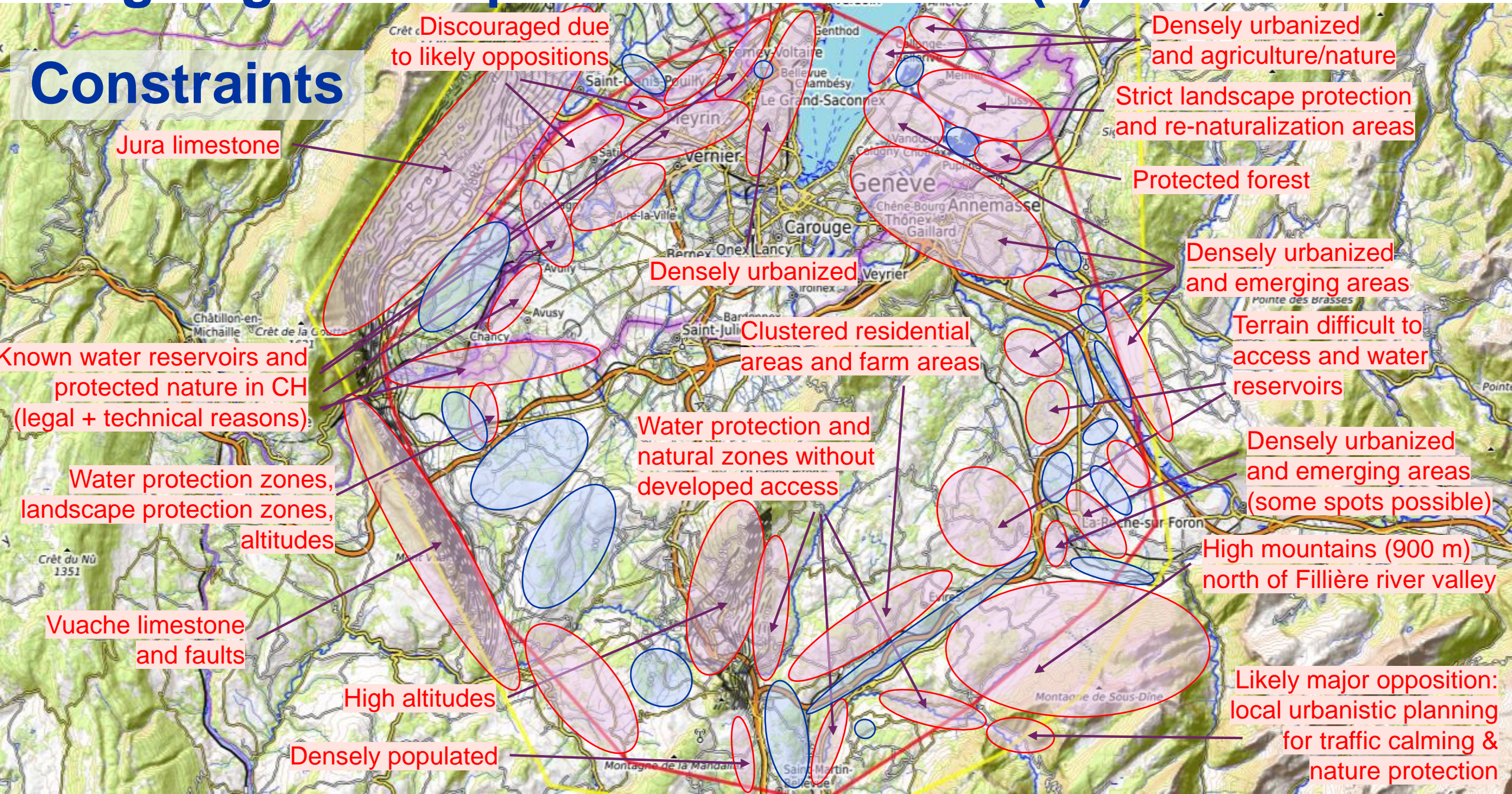
- **Vary machine** (12- and 8-site layouts) and **geographical parameters** and update trace and access point positions in real time.
- **Different base maps** (flat, topography or satellite) and various additional layers (e.g. constraints maps) can be selected.

Results are output for **further processing**:

- **ArcGIS** for detailed territorial constraint and opportunity analysis
- **Geoportail** (France) and **SITG** (Switzerland) for topographic, land use, PLU/PDCOM and environmental compatibility checks
- Transfer to **documentation** and **data storage** environments

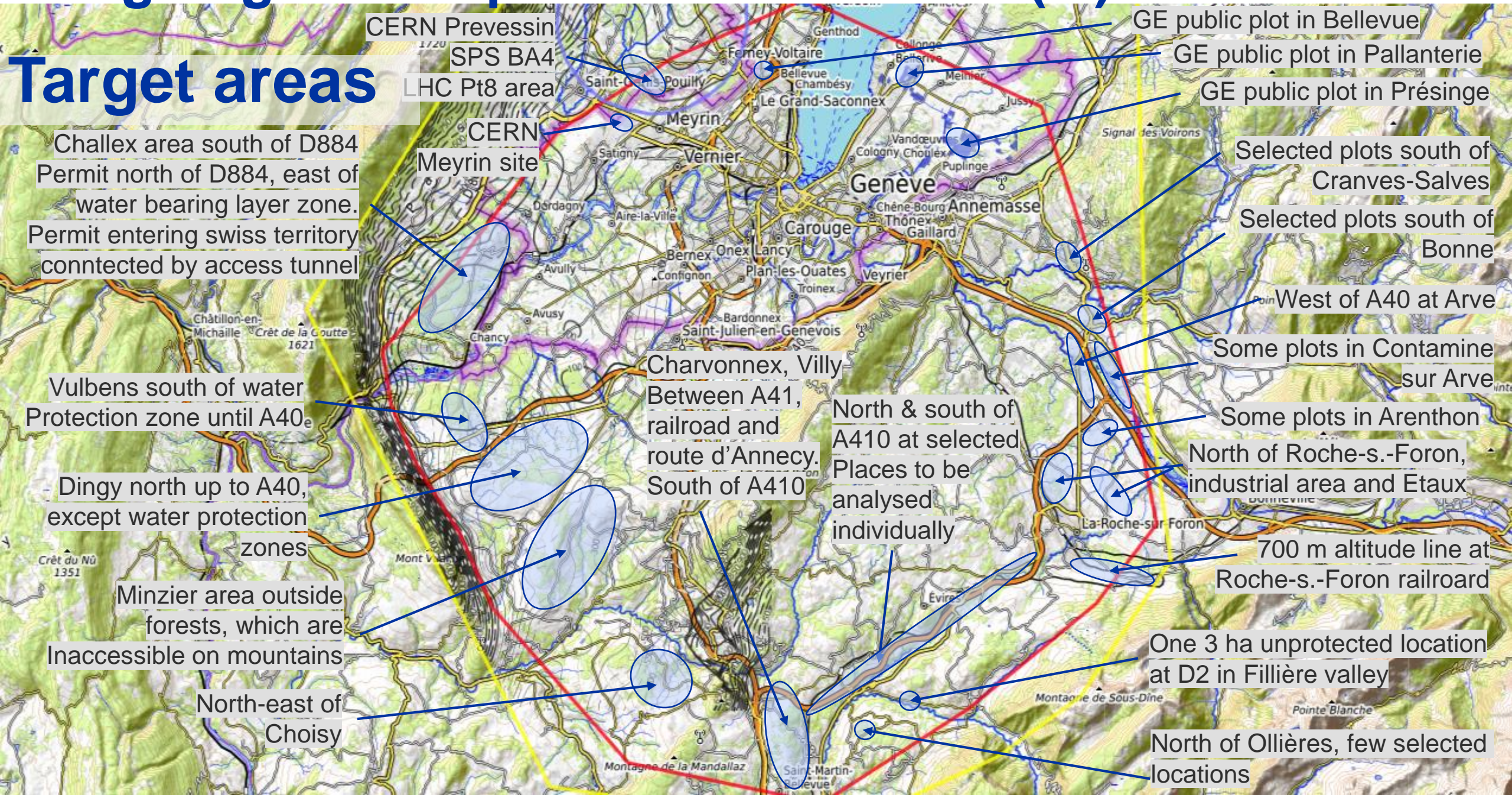
Ongoing work – placements studies (ii)

Constraints



Ongoing work – placements studies (iii)

Target areas



Recent FCC topical reviews, April – June 2021

FCC-ee Injector Review: 19 & 22 April, 2 June 2021; Reviewers: Deepa Angal-Kalinin (CI), Ralph Assmann (DESY), Günther Dissertori (ETHZ, Chair), Andrew Hutton (JLAB), Kazuro Furukawa (KEK), Marc Ross (SLAC), John Seeman (SLAC) ; **main recommendations:** adopt new layout (only one energy in linac, higher e+ prod. energy) ; concentrate on 2 bunch per pulse conservative scheme as recommended by review, with e+ target inspired by SLC's ; study linac extension

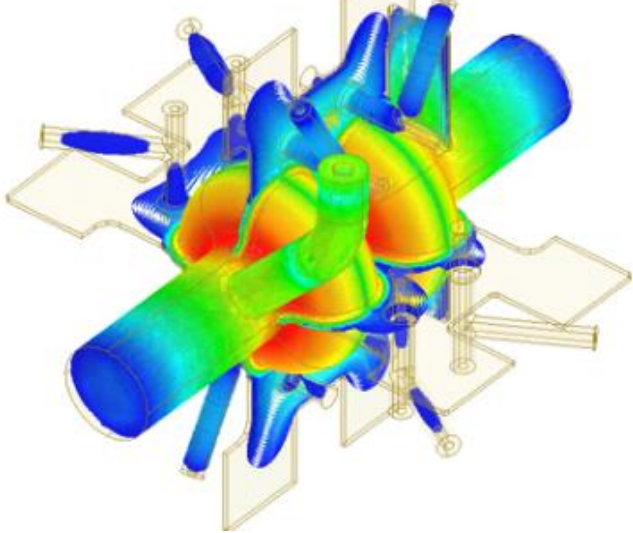
FCC-ee SRF Review: 20 & 22 April; Reviewers: Sergey Belomestnykh (FNAL), Ilan Ben-Zvi (BNL), Sébastien Bousson (IJCLab), Günther Dissertori (ETHZ, Chair), Philippe Lebrun (JUAS), Robert Rimmer (JLab), Marc Ross (SLAC), Akira Yamamoto (KEK) ; **main recommendations:** adopt new baseline RF frequency of 600 or 640 MHz (synergies with EIC, JLEIC, PIP-II, CEPC); explore heavily damped cavity concept with slotted waveguides as options for all energies

FCC Placement Review: 6 & 7 June 2021; Reviewers: Ralph Assmann (DESY, FCC IAC), Günther Dissertori (ETHZ, Chair FCC IAC), Gregor Herten (University Freiburg, FCC IAC), Giorgio Hofer (GEOCONSULT), Jean-François Hotellier (GADZ), Philippe Lebrun (JUAS, FCC IAC), Yung Loo (ARUP), Stephen Myers (ADAM SA), Franz Pacher (AMBERG), Andrew Parker (Cambridge, FCC IAC), Nedim Radoncic (AMBERG), Bernhard Stacherl (GEOCONSULT), Matt Sykes (ARUP), Tim Watson (ITER, FCC IAC); Observers: Vincent Delabrière (Canton Geneva), Anne Guillabert (Region Rhône-Alpes) ; **main recommendations:** define lowest-risk 8-Point option as new placement baseline ; leave open later choice between 2 and 4 IPs, reduced number of surface sites

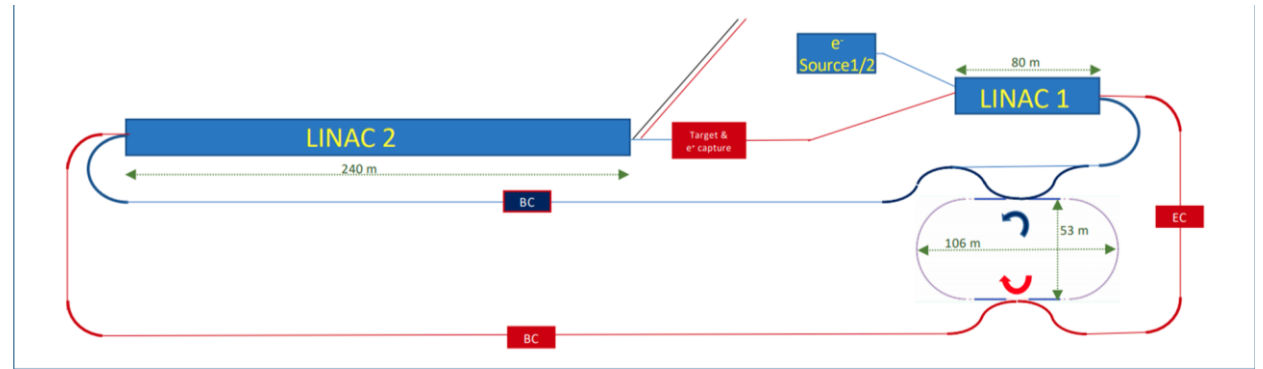


highlights from the topical reviews

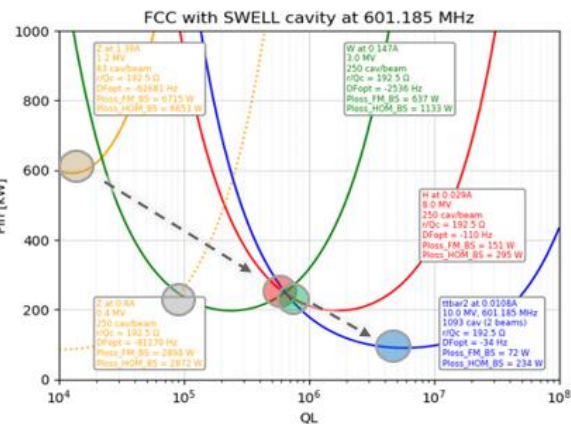
SRF: SWELL cavity:
one for all energies



FCC-ee injector:
conservative
approach,
optimized layout

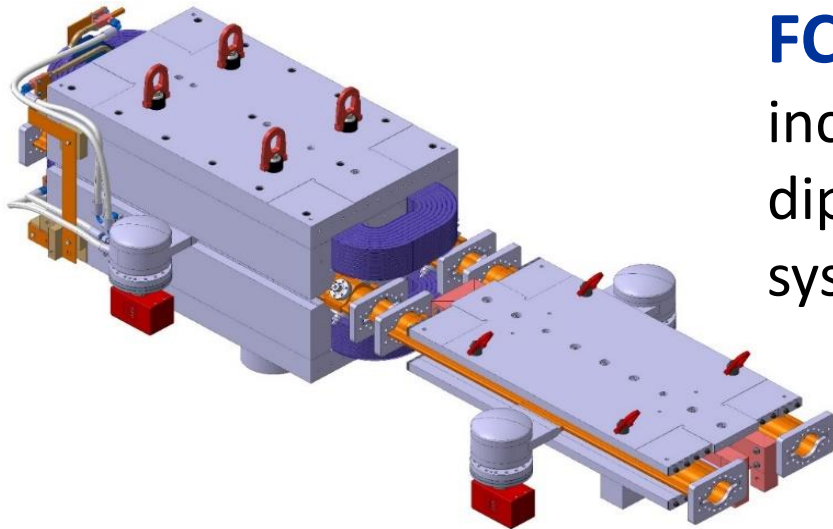


Placement:
minimizing the risk



SECTOR	RISK	FINAL RISK INDEX							Std. Dev.*
		17-0.8	19-0.3	21-0.3	31-0.4	35-0.6	37-0.3	38-0.1	
LAKE	Quaternary soft ground, water bearing	47	28	54	29	65	79	40	20
ARVE	Quaternary soft ground, water bearing	12	4	9	6	6	4	5	3
MANDALLAZ	Limestone, water bearing karsts	96	96	96	96	96	96	96	0
USSES	Quaternary soft ground, water bearing	7	7	5	3	1	2	2	2
VUACHE	Limestone, water bearing karsts	24	442	240	12	50	12	12	16
RHONE	Quaternary soft ground, water bearing	18	5	8	11	8	11	12	4
JURA	Limestone, water bearing karsts	100	672	864	100	100	100	100	0
TOTAL		304	1254	1276	257	326	303	267	29





FCC-ee complete arc half-cell mock up

including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces.

key beam diagnostics elements

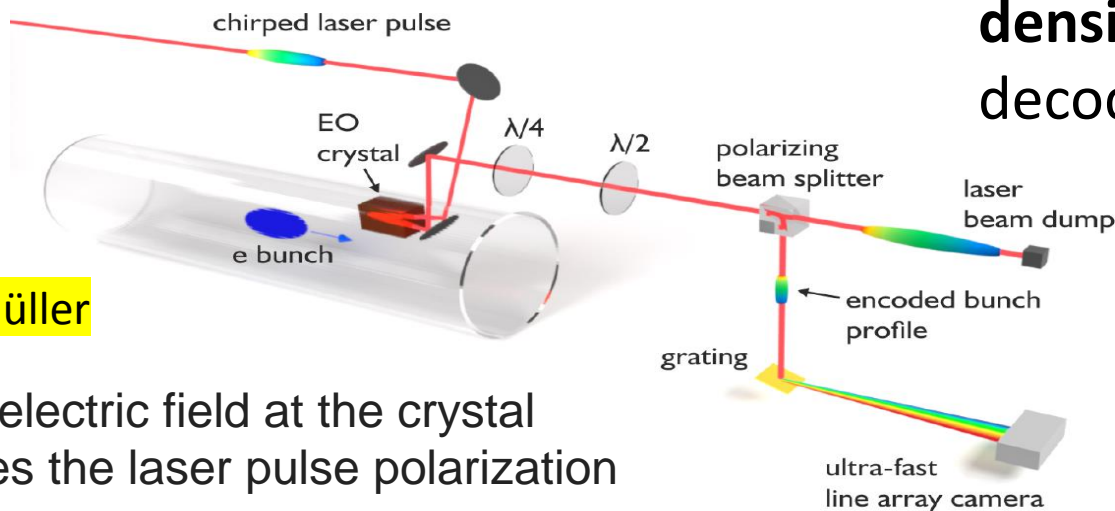
bunch-by-bunch turn-by-turn **longitudinal charge density profiles** based on electro-optical spectral decoding (beam tests at KIT/KARA) ;

ultra-low emittance measurement (X-ray interferometer tests at SuperKEKB, ALBA) ;

beam-loss monitors (IJCLab/KEK?) ;

beamstrahlung monitor (KEK);

polarimeter ; luminometer



A.-S. Müller

bunch electric field at the crystal changes the laser pulse polarization

FCC key deliverables: prototypes by 2025

**SRF cryomodule mock-up,
+ prototype multi-cell cavities
for FCC ZH operation
High-efficiency RF power sources**

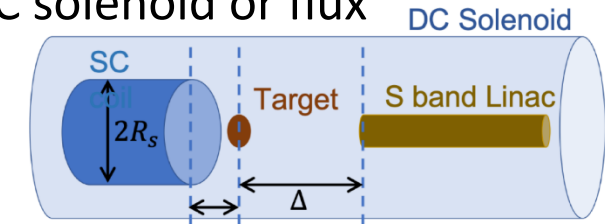
**positron capture linac
large aperture S-band linac**

- 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

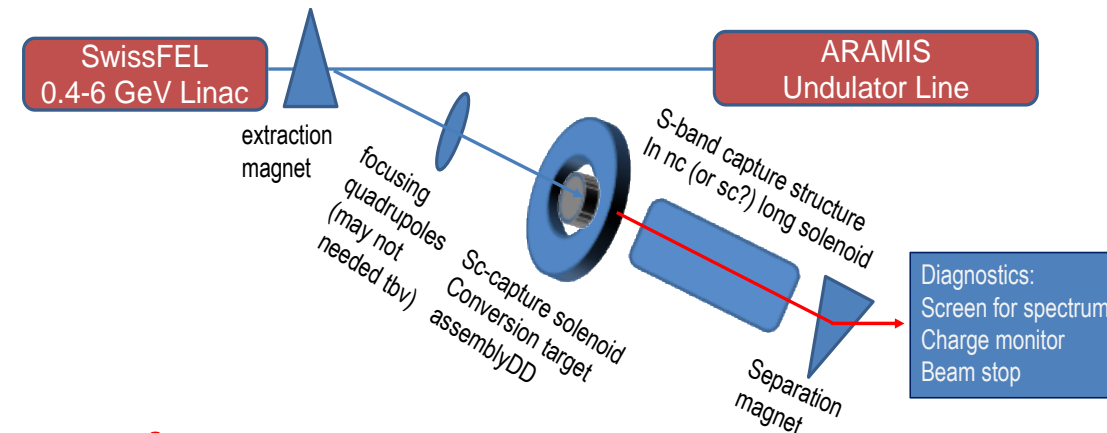


high-yield positron source

target with DC SC solenoid or flux concentrator



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

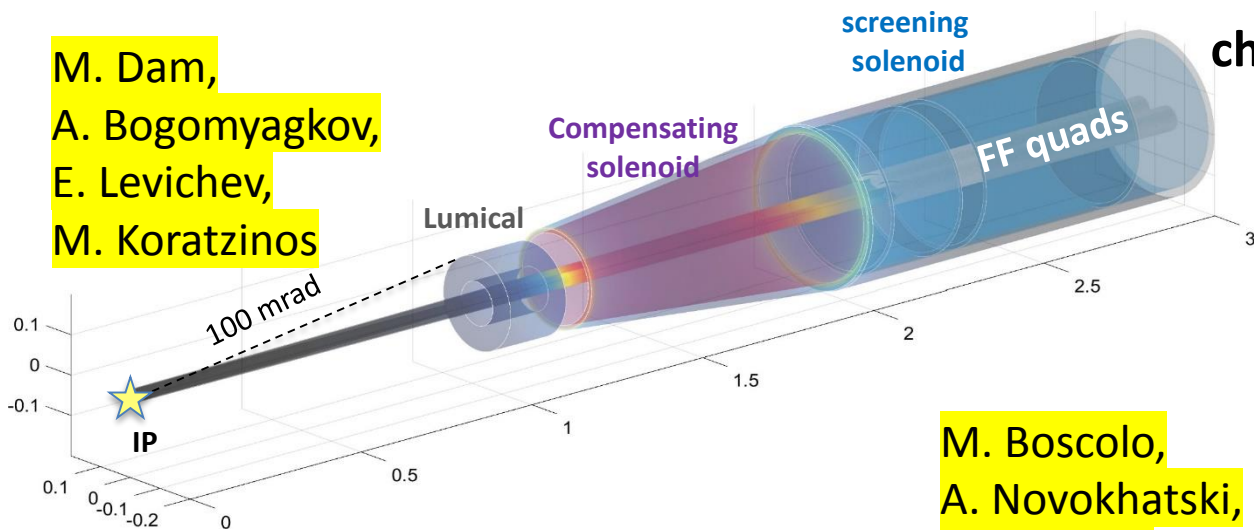


**strong support from Switzerland via CHART II program 2019 – 2024 for
FCC-ee injector, HFM, beam optics developments, geology and geodesy activities.**

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

FCC-ee Machine Detector Interface

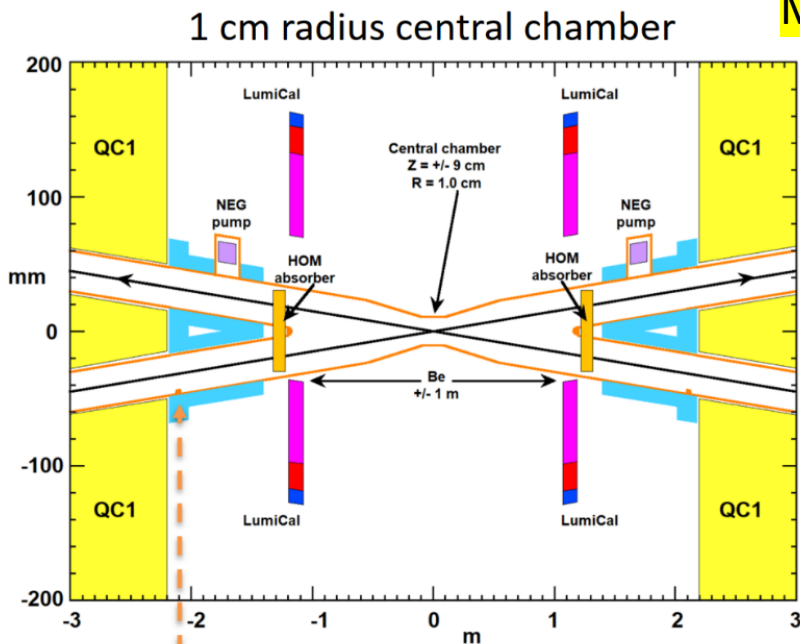
M. Dam,
A. Bogomyagkov,
E. Levichev,
M. Koratzinos



challenging integration:
2 T detector solenoid,
luminosity monitor
(Bhabha scattering),
compensation &
shielding solenoids

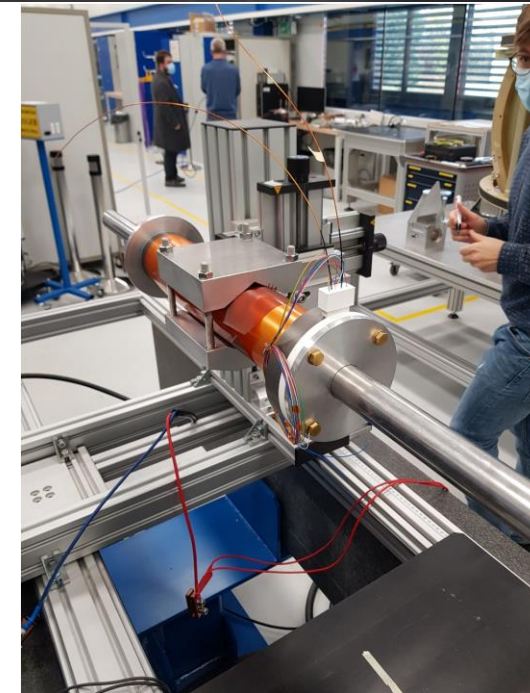


M. Boscolo,
A. Novokhatski,
M. Sullivan



**narrow
central
chamber**
with 1 cm
radius,
also avoids
trapped
modes

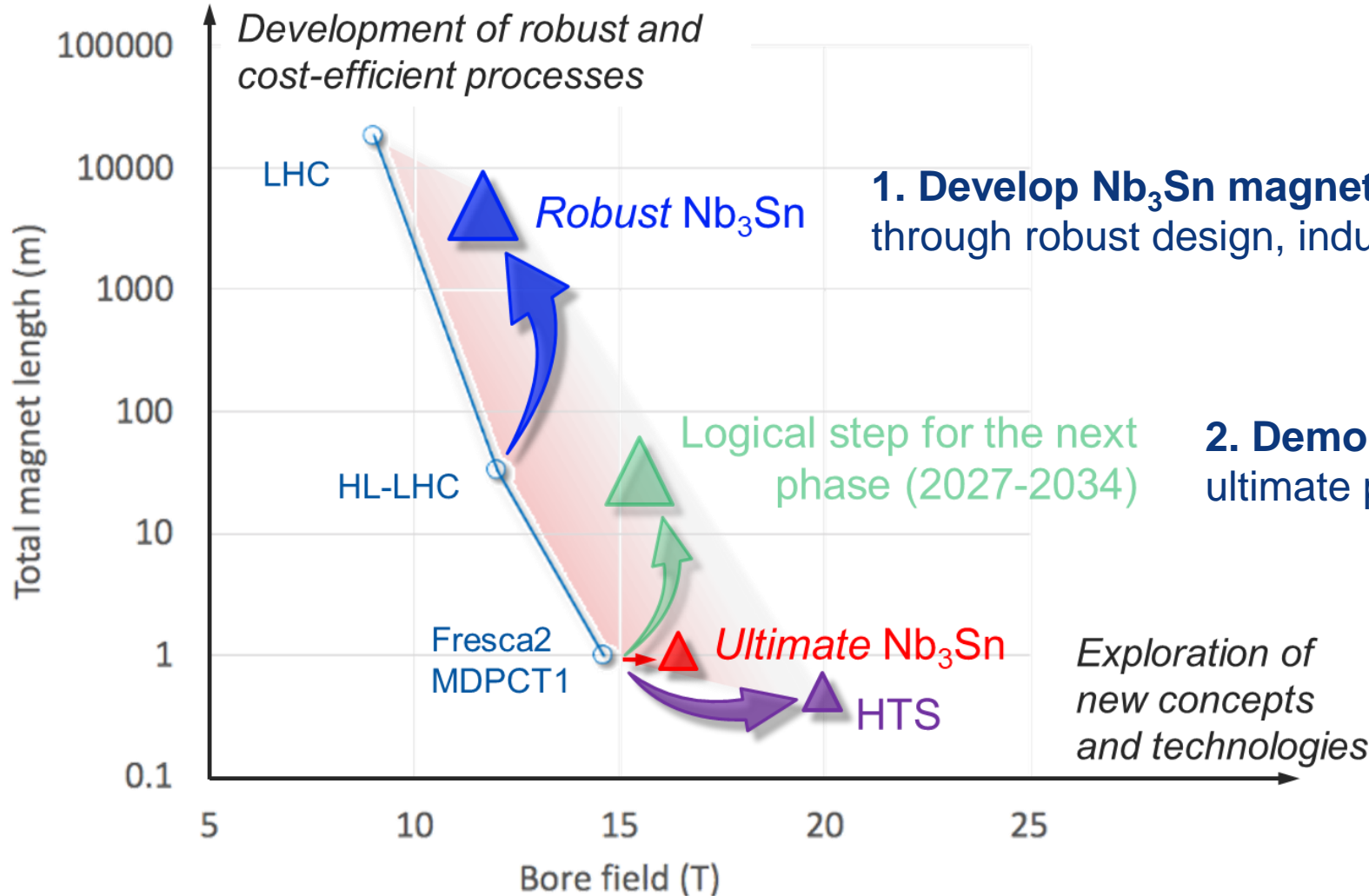
prototype Q1
canted cosine theta
with fringe field
correction,
using LHC SC cable
field measurement
at warm



M. Koratzinos

High Field Magnet program goals until 2027

L. Bottura



1. Develop Nb₃Sn magnets for collider-scale production, through robust design, industrial processes and cost reduction

2. Demonstrate Nb₃Sn full potential in terms of ultimate performance

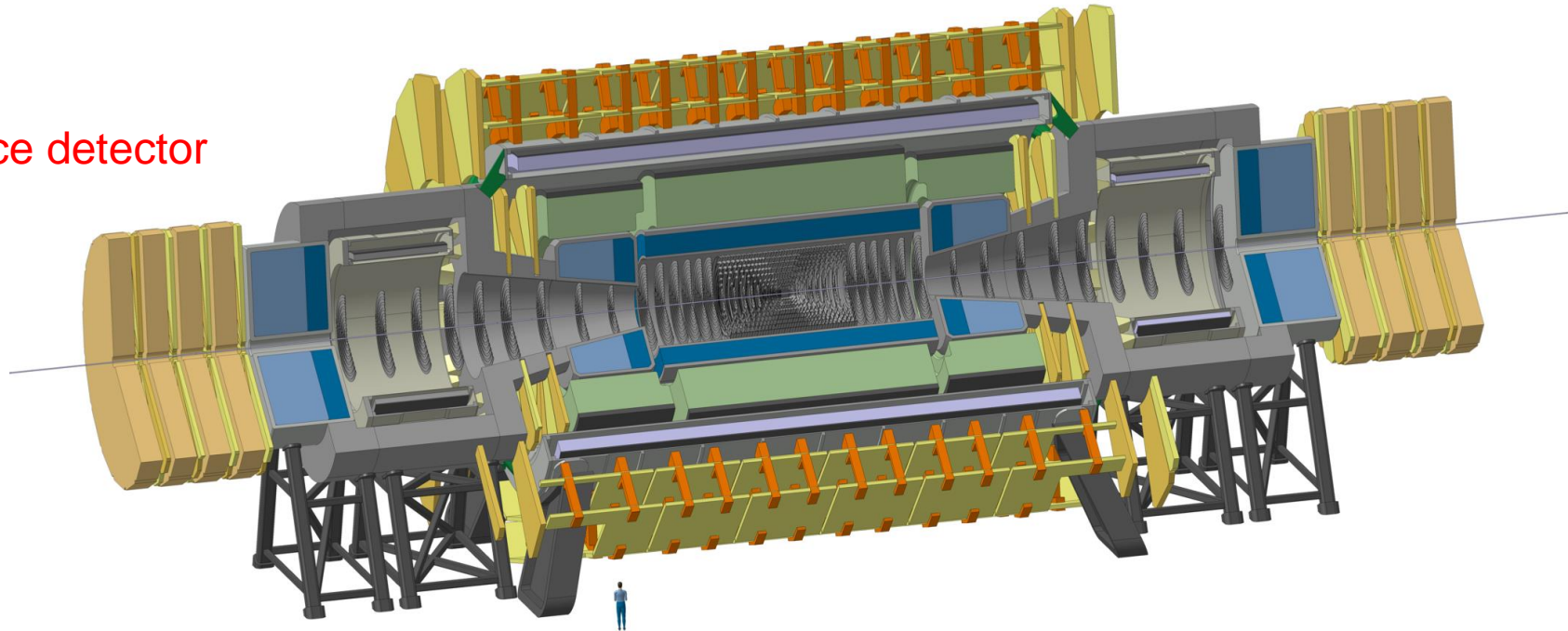
3. Provide a proof-of-principle for HTS magnet technology

Exploration of new concepts and technologies

Detector related roadmaps and programs

- **CERN – EP department R&D programme on Experimental Technologies**, initial 5-years period from 2020 onwards, covers detector hardware, electronics, software and detector magnets for new experiments and detector upgrades beyond LHC phase II.
- **ECFA development of a European Detector Roadmap**, to be presented at the EPS-HEPP conference in July 2021.

FCC-hh reference detector
from CDR



Summary

- The European Strategy Update 2019/20 issued **request for feasibility study of FCC integrated programme**, and suggested key technology R&D areas
- **The main activities of the FCC Feasibility Study are: concrete local/regional implementation scenario in collaboration with host state authorities**, accompanied by **machine optimization, physics studies and technology R&D**, performed **via global collaboration** and supported by **EC H2020 Design Study FCCIS**, to **prove feasibility by 2025/26**, in parallel **High Field Magnet program**
- Long term goal: **world-leading HEP infrastructure for 21st century** to push the particle-physics **precision and energy frontiers** far beyond present limits.
- **Success of FCC relies on strong global participation.**
- **I am wishing you an excellent week !**