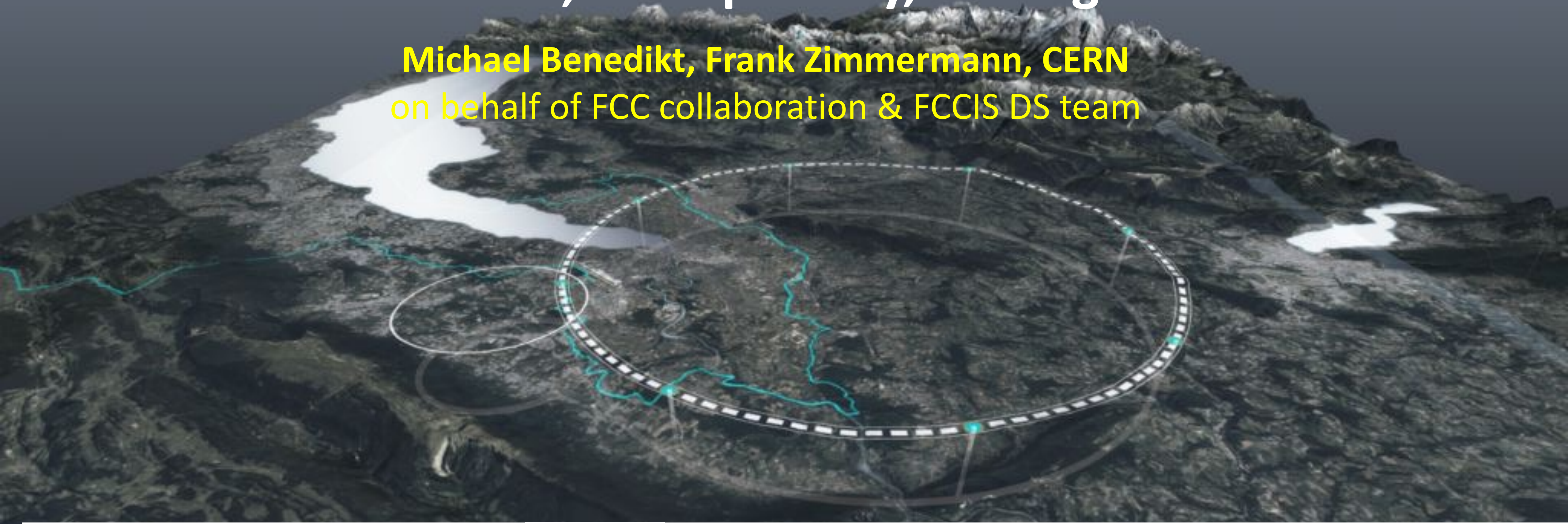
FCC Feasibility Study Status

EPS-HEP’23, ECFA plenary, 24 August 2023

Michael Benedikt, Frank Zimmermann, CERN
on behalf of FCC collaboration & FCCIS DS team



http://cern.ch/fcc

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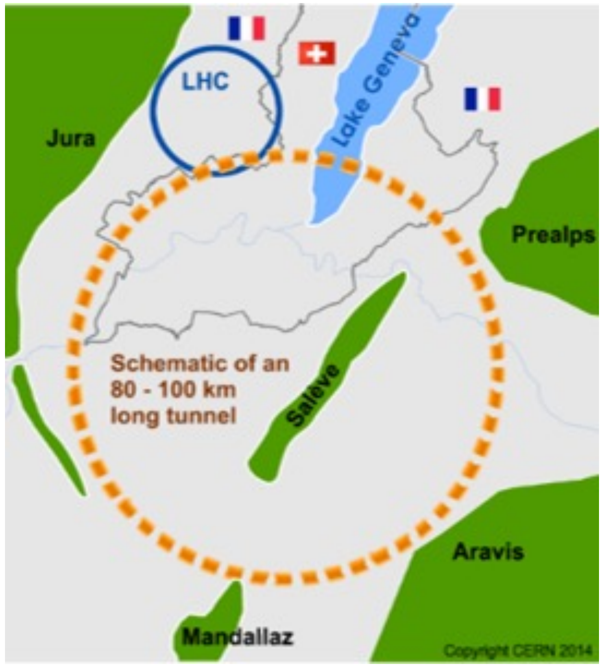
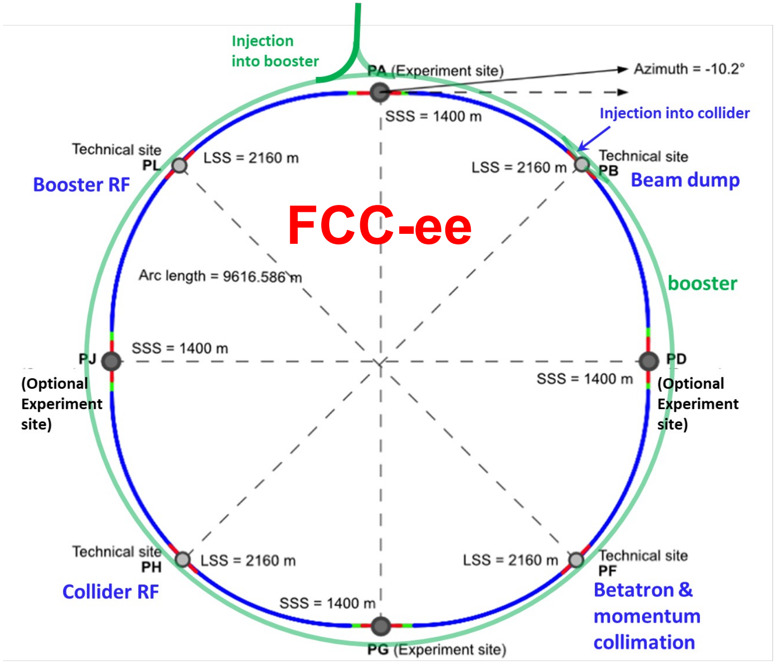
photo: J. Wenninger

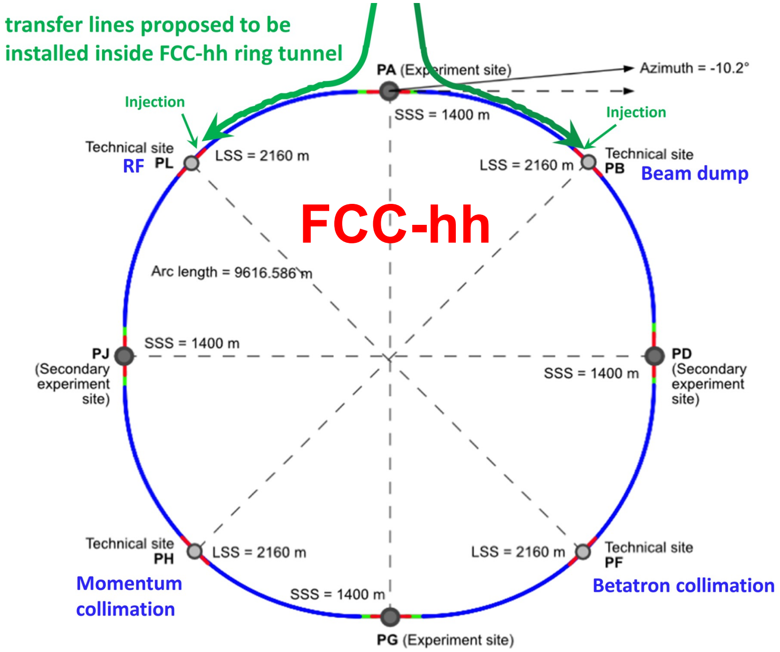
FCC integrated program

comprehensive long-term program maximizing physics opportunities

- **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**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- 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 a few years of the end of HL-LHC



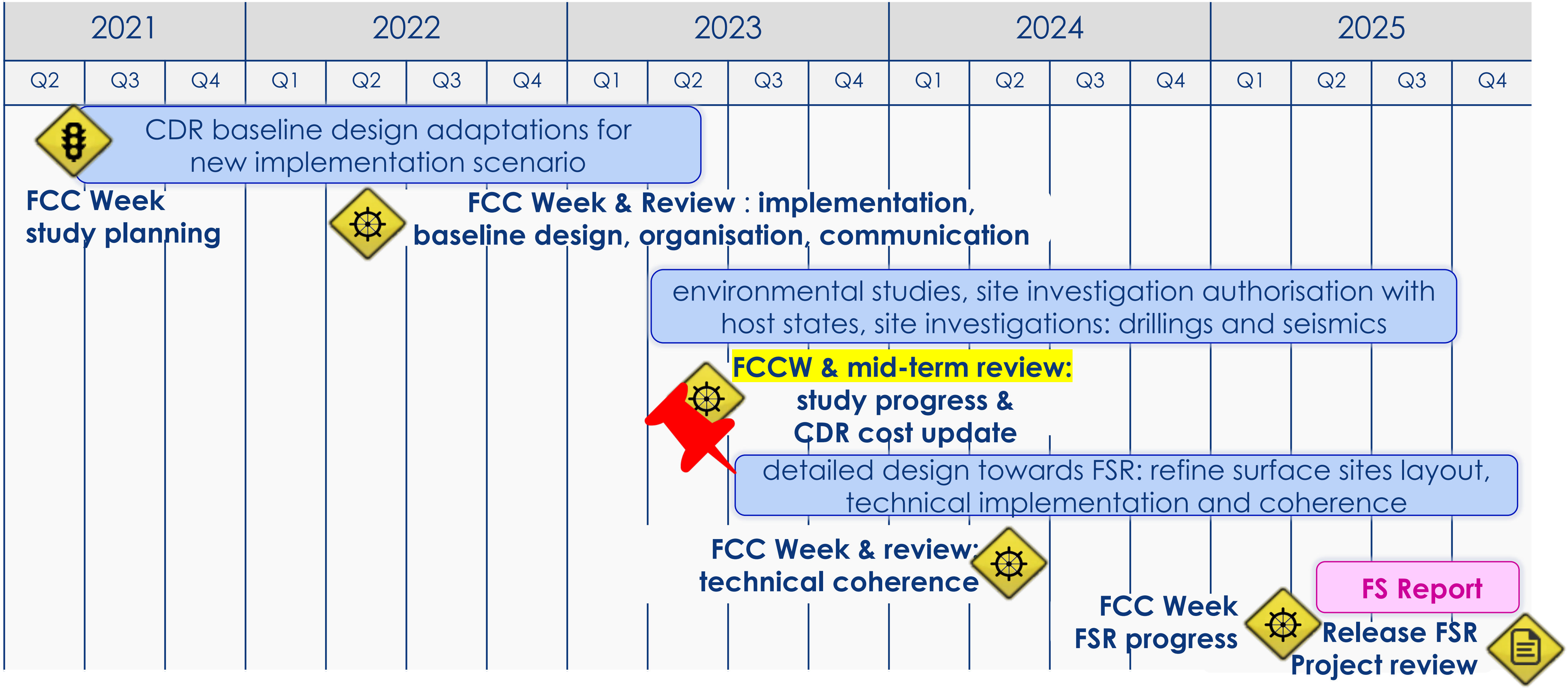




2020 - 2040 | **2045 - 2063** | **2070 - 2095**

FUTURE CIRCULAR COLLIDER

Feasibility Study Timeline and main activities/milestones



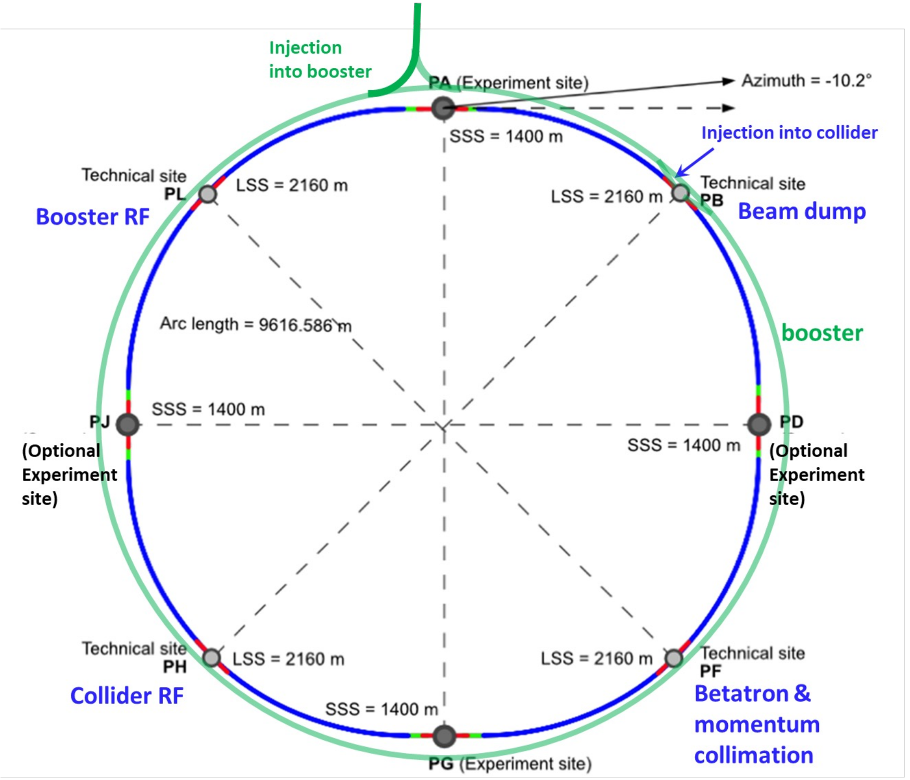
Optimized placement and layout for feasibility study

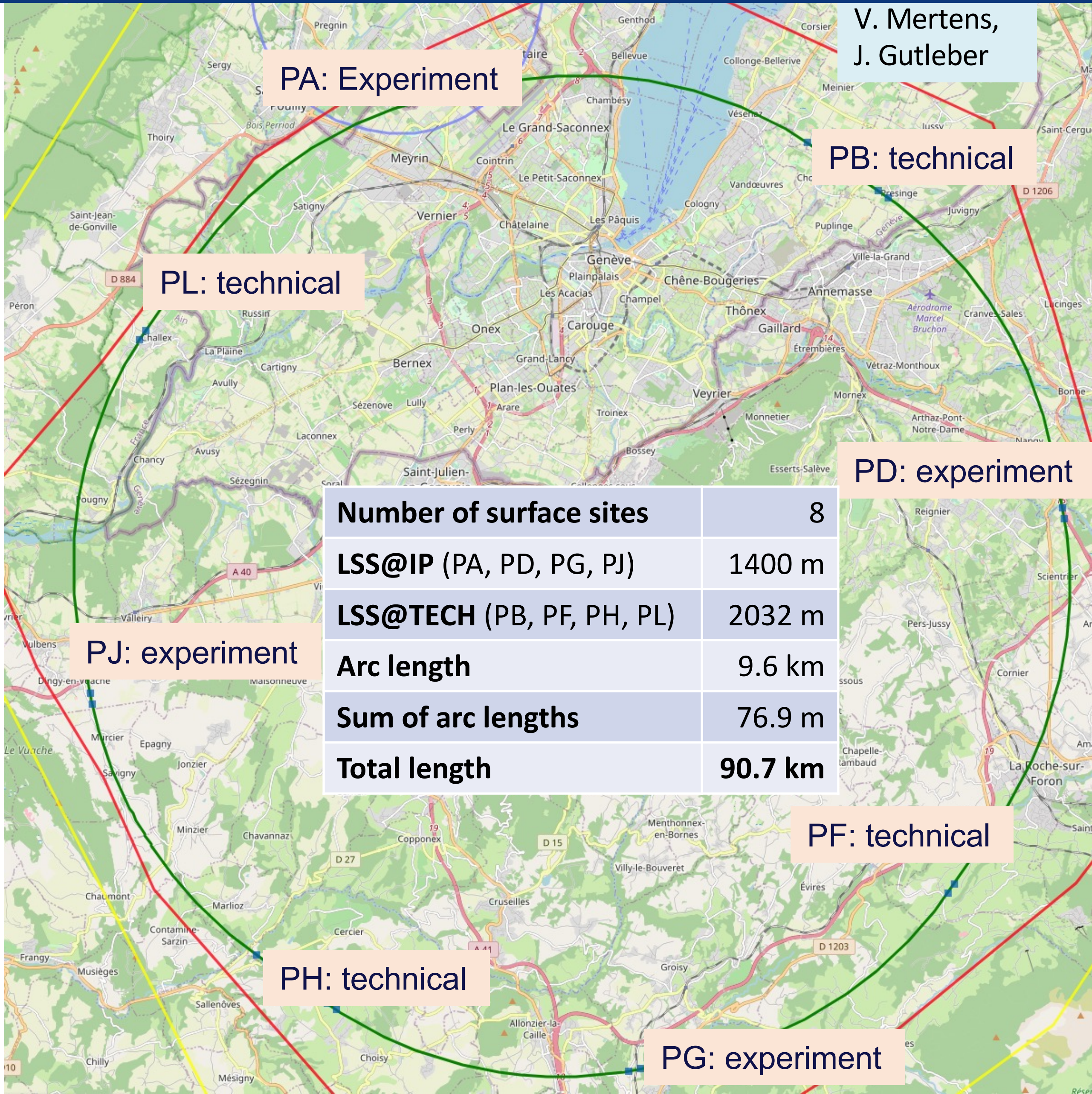
FUTURE CIRCULAR COLLIDER

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“Avoid-reduce -compensate” principle of EU and French regulations

Overall lLowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement

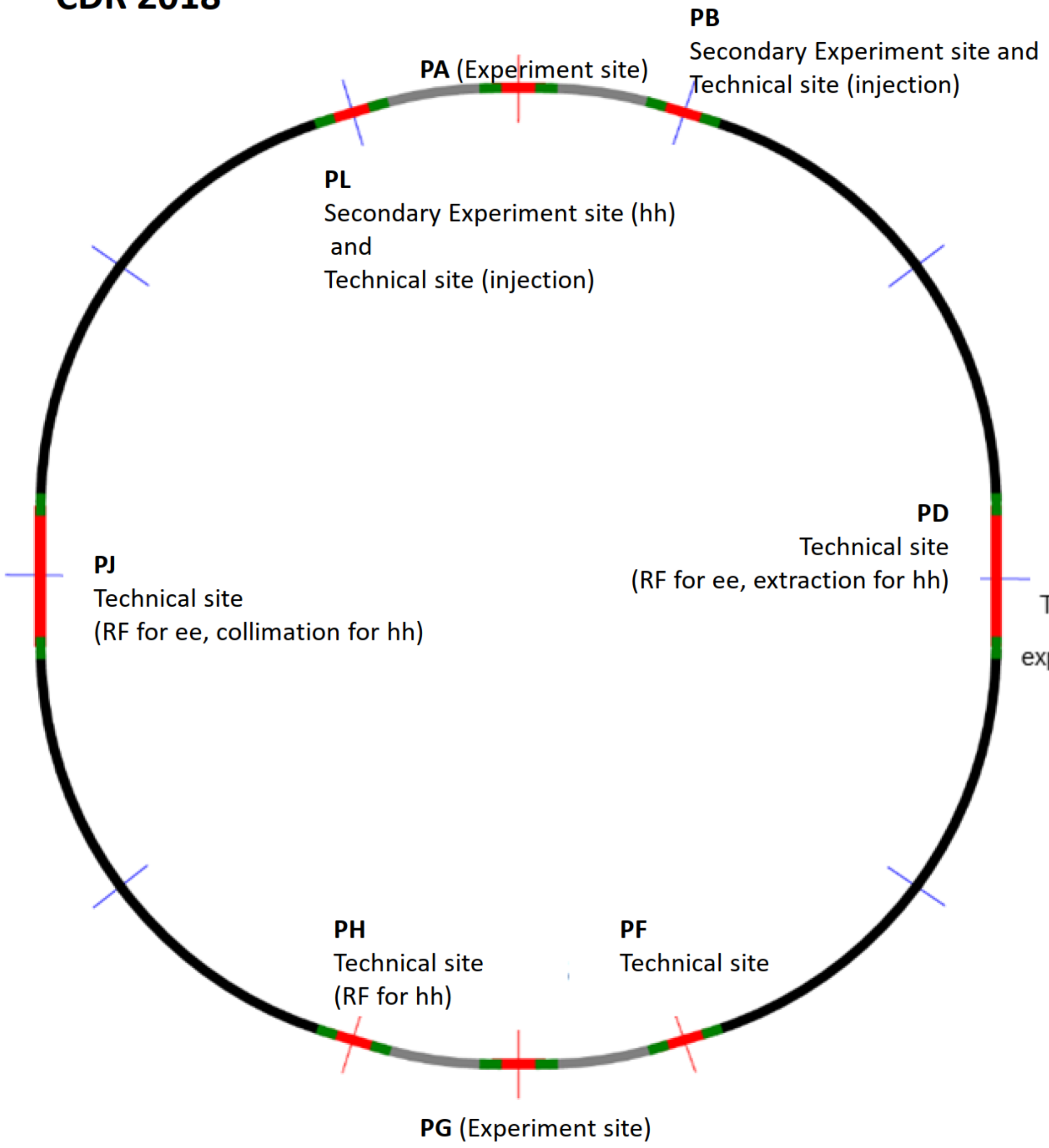




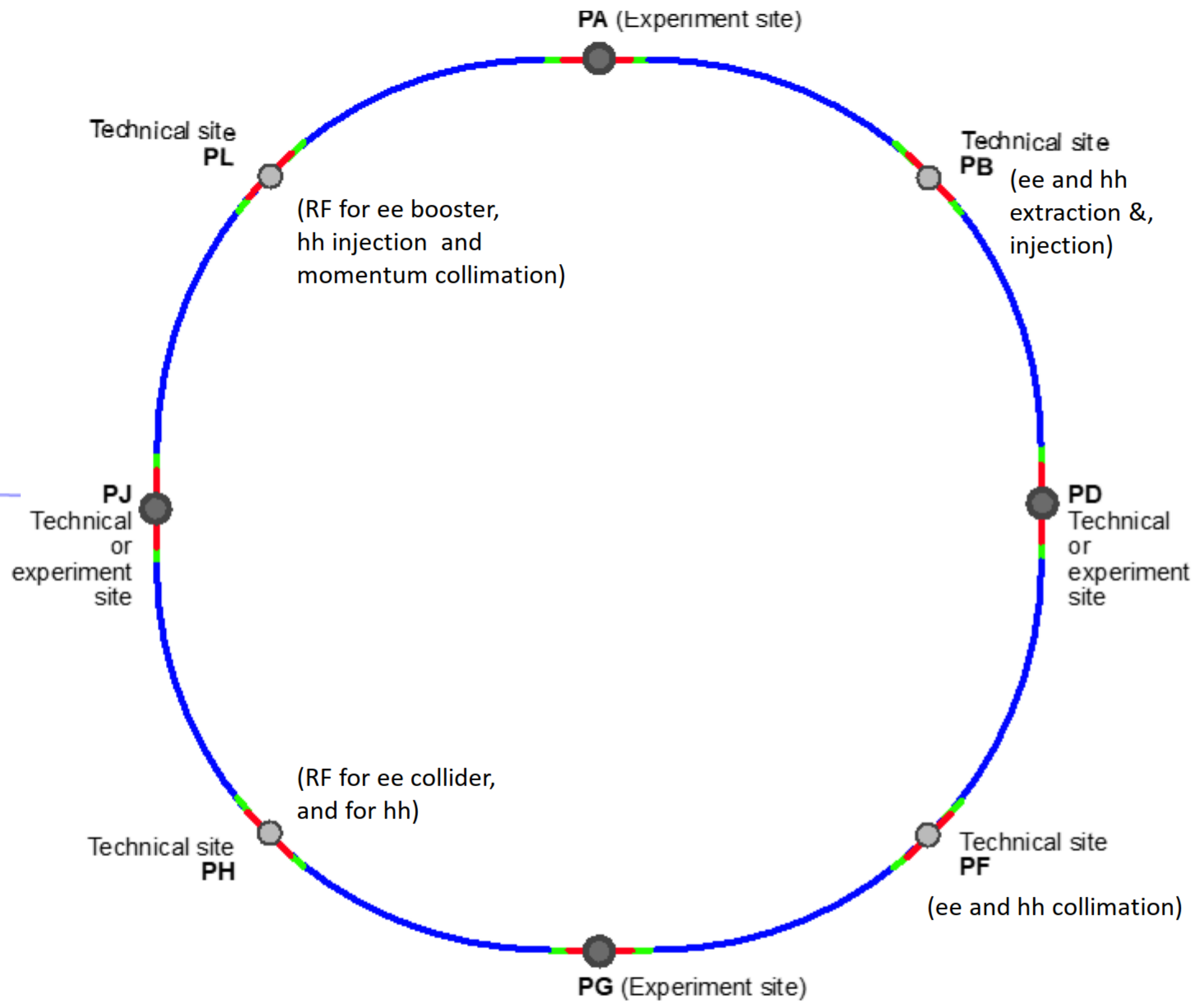
Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

Revised layout and geometry

CDR 2018



"Optimised" Midterm 2023



K. Oide, M. Hofer, et al.

FUTURE CIRCULAR COLLIDER

Main geometrical parameters

Main changes

- **# access points** reduced from 12 to 8
- facilitating placement and reducing the overall surface area required
- **circumference has shrunk** from 97.75 km to 90.657 km
- new layout with **4-fold superperiodicity**, enabling FCC-ee operation with either **2 or 4 collision points**
- **hadron collider** RF system now **shares** a **klystron gallery tunnel with lepton collider**
- new circumference matched to both LHC and the SPS tunnels, corresponding to 400 MHz harmonic ratios of h_{FCC}/h_{LHC}=1010/297 & h_{FCC}/h_{SPS}=1010/77, **allowing for hadron beam injection from either the LHC or from a new superconducting SPS**, with bunch spacings of 2.5, 5.0, 7.5, 10, 12.5, 15, 20, and 25 ns

Parameter	unit	2018 CDR [1]	2023 Optimised
Total circumference	km	97.75	90.657
Total arc length	km	83.75	76.93
Arc bending radius	km	13.33	12.24
Arc lengths (and number)	km	8.869 (8), 3.2 (4)	9.617 (8)
Number of surface sites	—	12	8
Number of straights	—	8	8
Length (and number) of straights	km	1.4 (6), 2.8 (2)	1.4 (4), 2.031 (4)
superperiodicity	—	2	4

progress with implementation baseline PA31 90.7 km

Meetings with municipalities concerned in France (31) and Switzerland (10)

PA – Ferney Voltaire (FR) – site experimental

PB – Présinge/Choulex (CH) – site technique

PD – Nangy (FR) – site experimental

PF – Roche sur Foron/Etaux (FR) – site technique

PG – Charvonnex/Groisy (FR) – site experimental

PH – Cercier (FR) – site technique

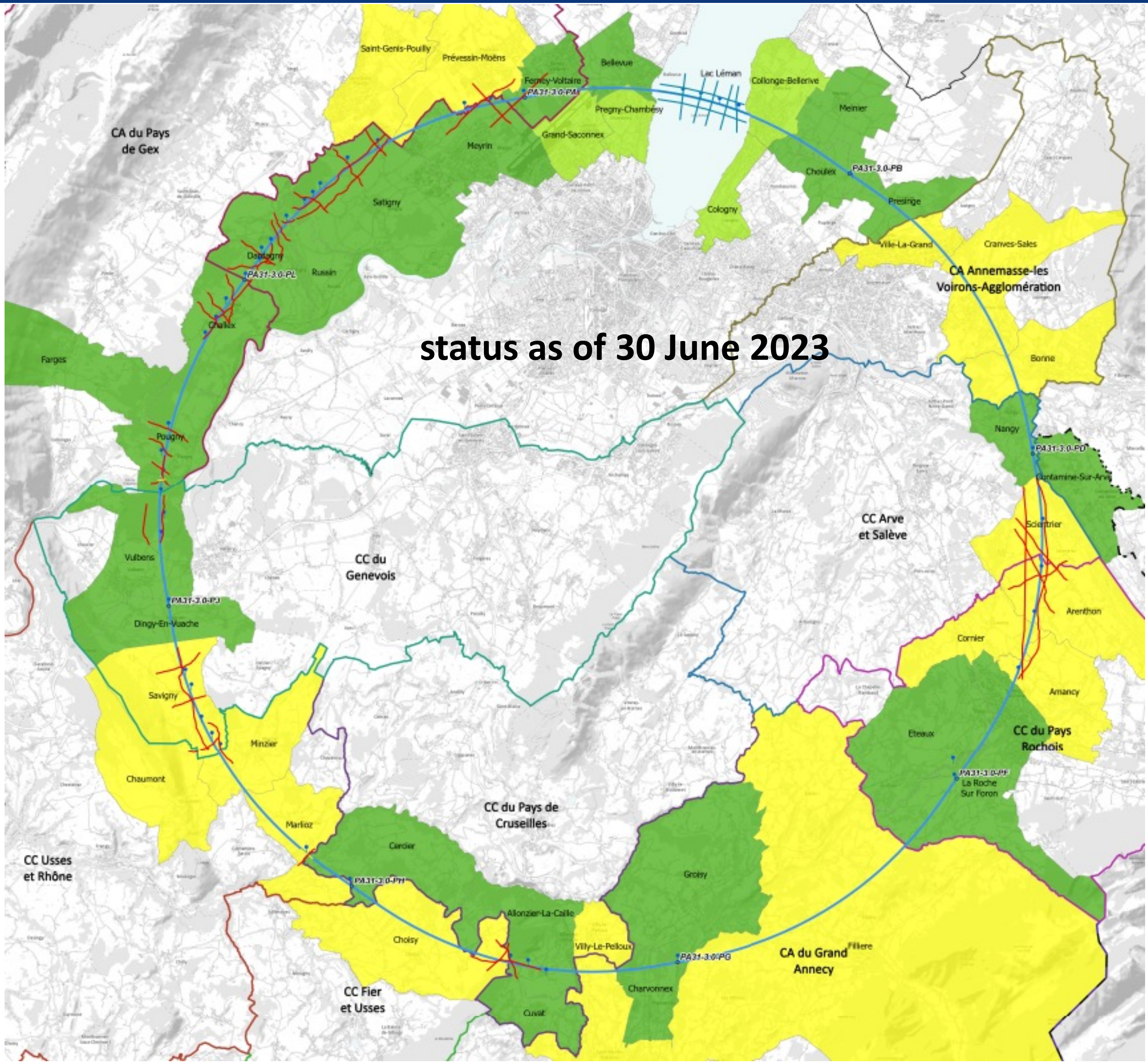
PJ – Vulbens/Dingy en Vuache (FR) site experimental

PL – Challex (FR) – site technique

Rencontrée individuellement

Rendez-vous proposé / programmé

Rencontre collective



Environmental studies and preparation of geological investigations (drillings and seismics) ongoing since February 2023

Communication aspects

FUTURE CIRCULAR COLLIDER

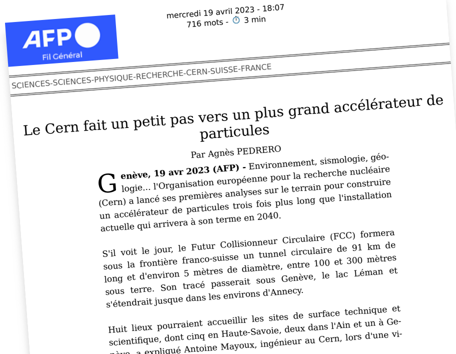
- **CERN press release in February 2023 to inform about FS and organisation**
- **Prepared with France and Switzerland « groupe de dialogue territoriale »**


Information presse CERN

L'étude de faisabilité d'un éventuel FCC démarre sur le terrain

- **Press visit at CERN for local medias in April 2023**

- 11 journalistes
- **90 press clippings**
- 31 countries


AFP Fil Général

mercredi 19 avril 2023 - 18:07

716 mots - 3 min

SCIENCES-SCIENCES-PHYSIQUE-RECHERCHE-CERN-SUISSE-FRANCE

Le Cern fait un petit pas vers un plus grand accélérateur de particules

Par Agnès PEDRERO

Genève, 19 avr 2023 (AFP) - Environnement, sismologie, géologie... l'Organisation européenne pour la recherche nucléaire (Cern) a lancé ses premières analyses sur le terrain pour construire un accélérateur de particules trois fois plus long que l'installation actuelle qui arrivera à son terme en 2040.

S'il voit le jour, le Futur Collisionneur Circulaire (FCC) formera sous la frontière franco-suisse un tunnel circulaire de 91 km de long et d'environ 5 mètres de diamètre, entre 100 et 300 mètres sous terre. Son tracé passerait sous Genève, et le lac Léman et s'étendrait jusque dans les environs d'Annecy.

Huit lieux pourraient accueillir les sites de surface technique et scientifique, dont cinq en Haute-Savoie, deux dans l'Ain et un à Genève, a expliqué Antoine Mayoux, ingénieur au Cern, lors d'une vi-

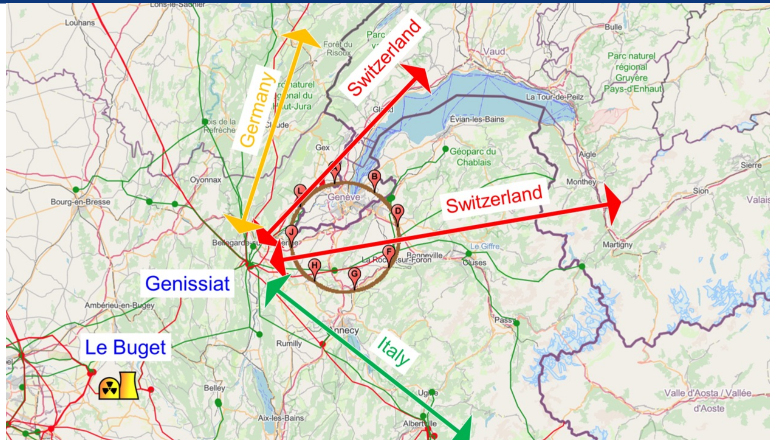

LE DAUPHINÉ LIBÉRÉ

GENÈVE | ET LA SUISSE VOISINE

Avec l'accélérateur de 91 km, le Cern veut garder le leadership de l'Europe

Connections to electrical grid infrastructure

Updated FCC-ee energy consumption	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Max. power during beam operation (MW)	**222**	**247**	**273**	**357**
Average power / year (MW)	122	138	152	202
Total yearly consumption (TWh)	**1.07**	**1.21**	**1.33**	**1.77**

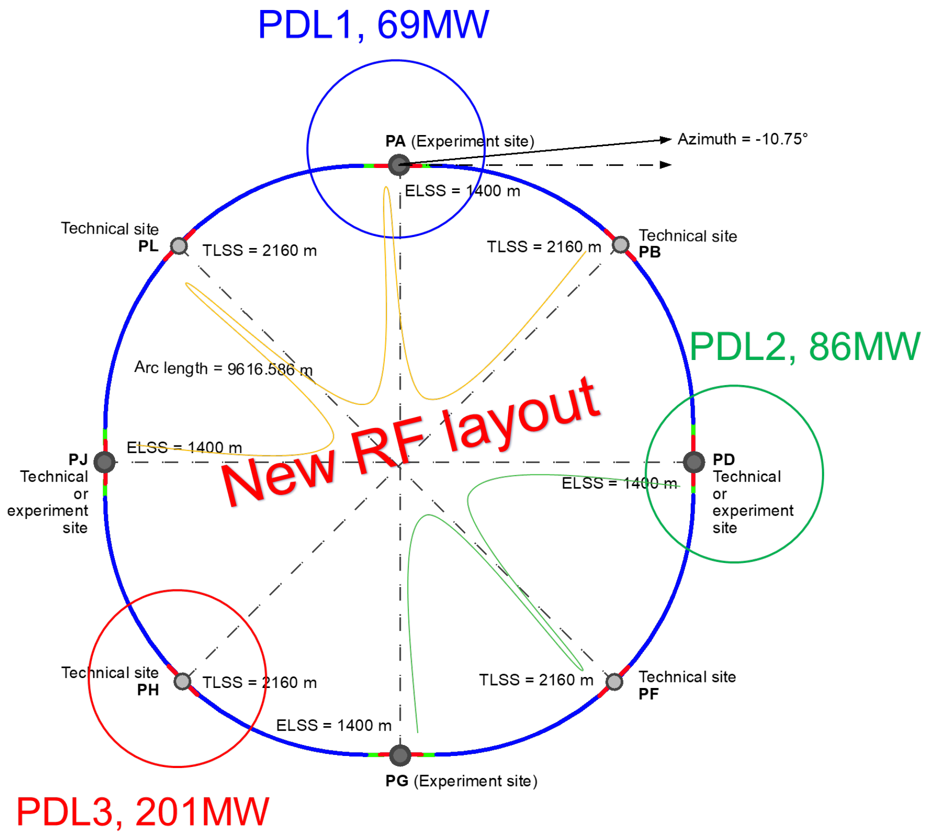


Powering concept and max power load by sub-stations:

The loads could be charged on three sub-stations (optimally connected to existing regional HV grid):

- **Point D with a new sub-station** covering PB – PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF
- **Point A with existing CERN station** covering PB – PL – PJ

- **Connection concept was studied and confirmed by RTE (French electrical grid operator)**
- **Requested loads have no significant impact on grid**
- **Powering concept and power rating of the three sub-stations compatible with FCC-hh**



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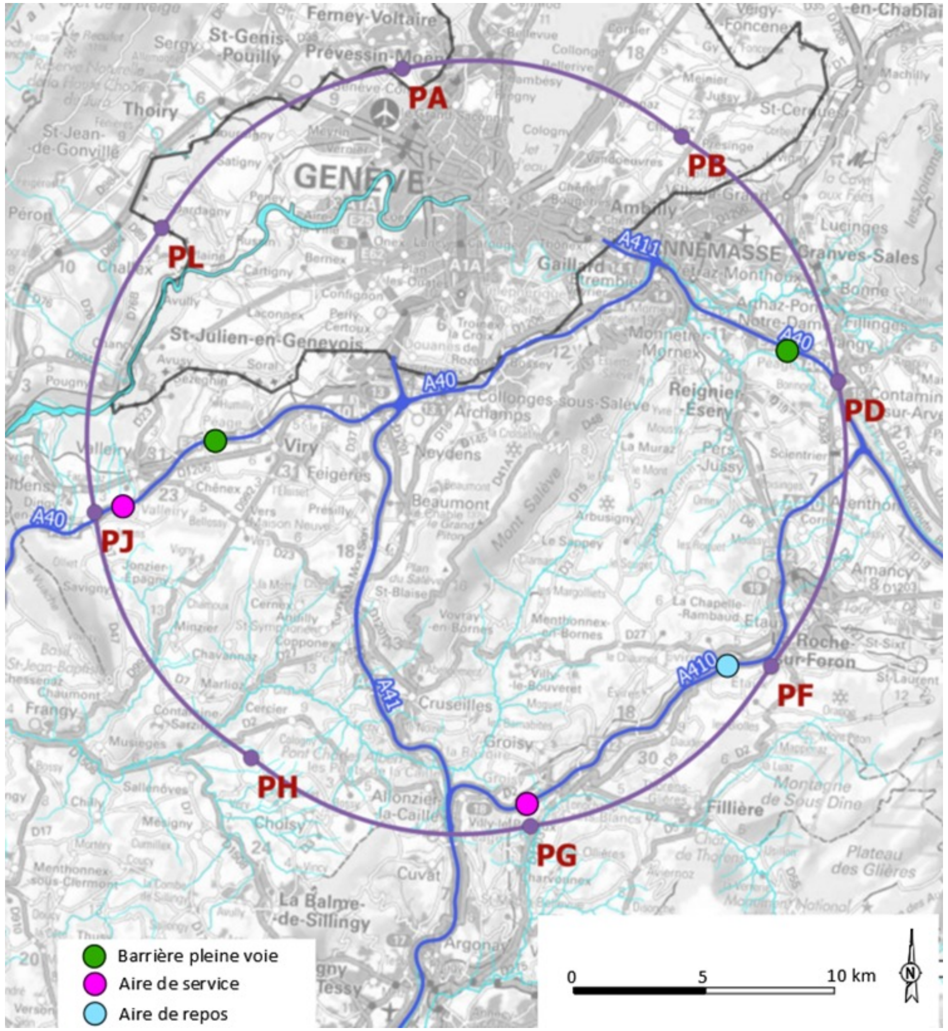
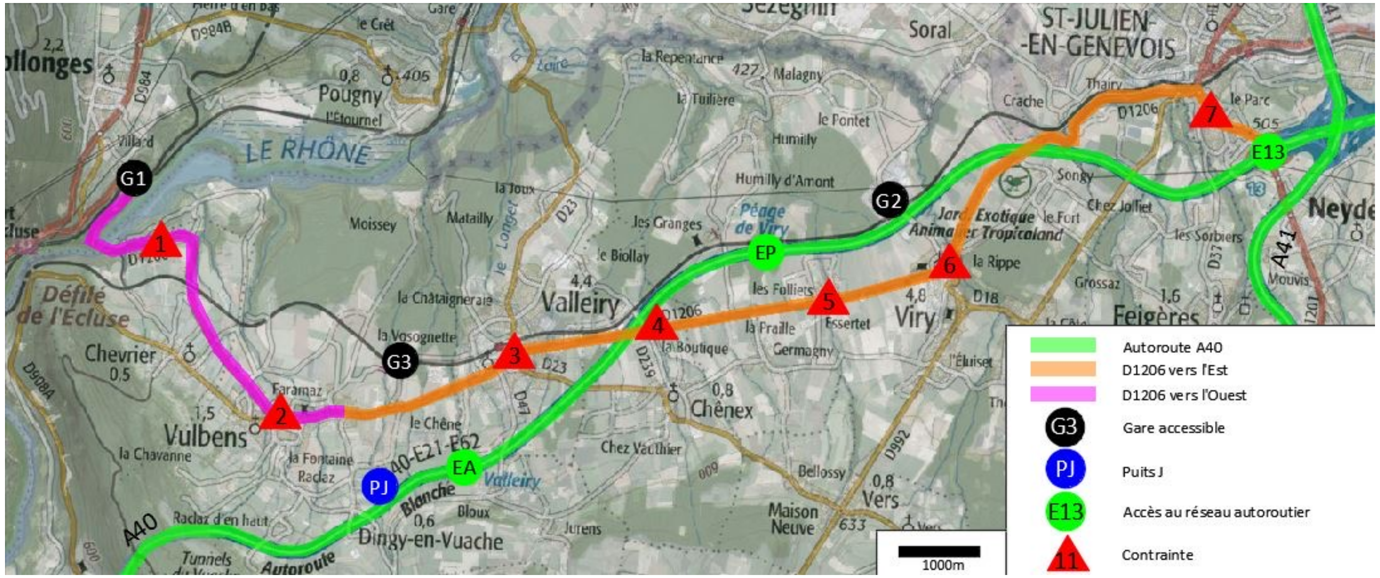
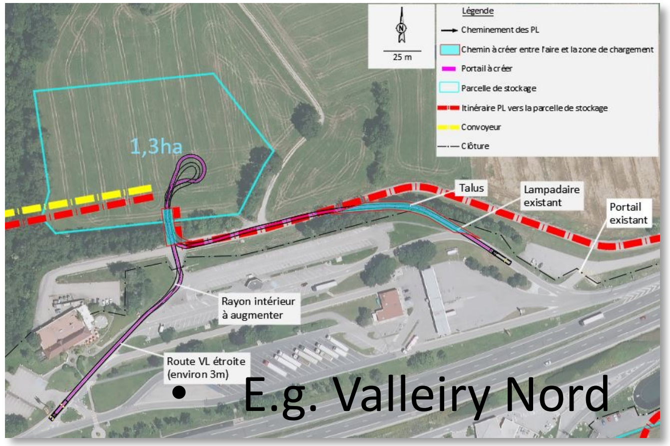
Connections to transport infrastructure

- Road accesses identified and documented for all 8 surface sites
- Four possible highway connections defined (materials transport)
- Total amount of new roads required < 4 km (at departmental road level)





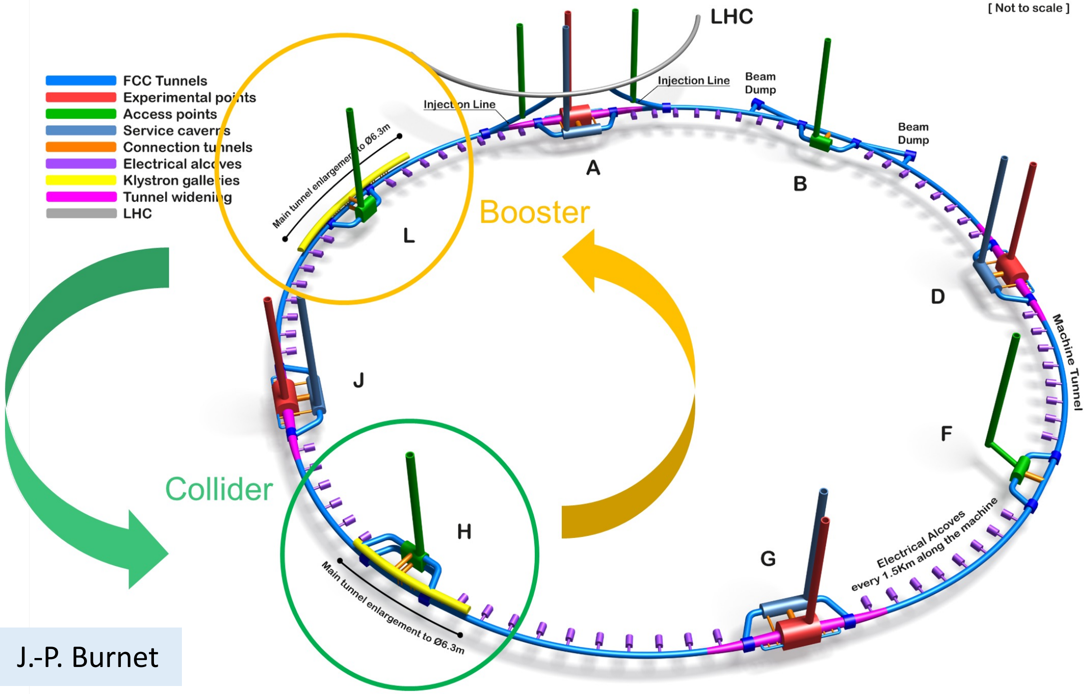


- E.g. Valleiry Nord

Detailed road access scenarios & highway access creation study **carried out by Cerema, including regulatory requirements in France**

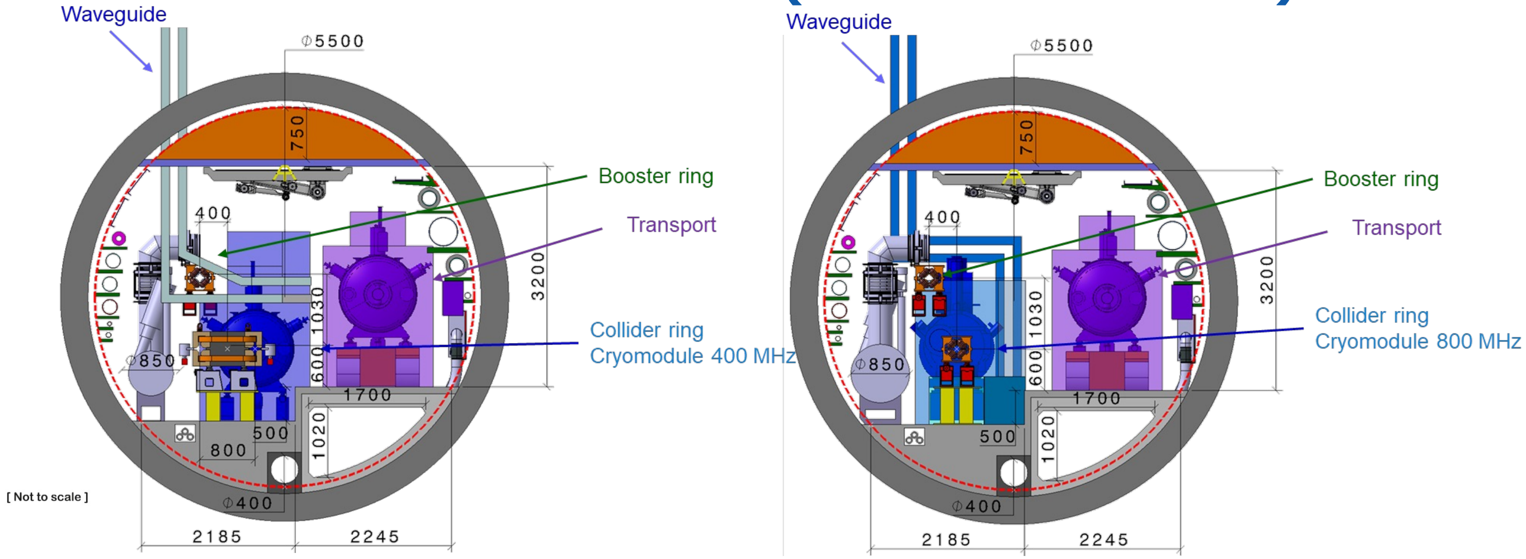
modified FCC-ee RF layout

- RF for collider and booster in separate straight sections H and L.
- fully separated technical infrastructure systems (cryogenics)
- collider RF (highest power demand) in point H with optimum connection to existing 400 kV grid line and better suited surface site

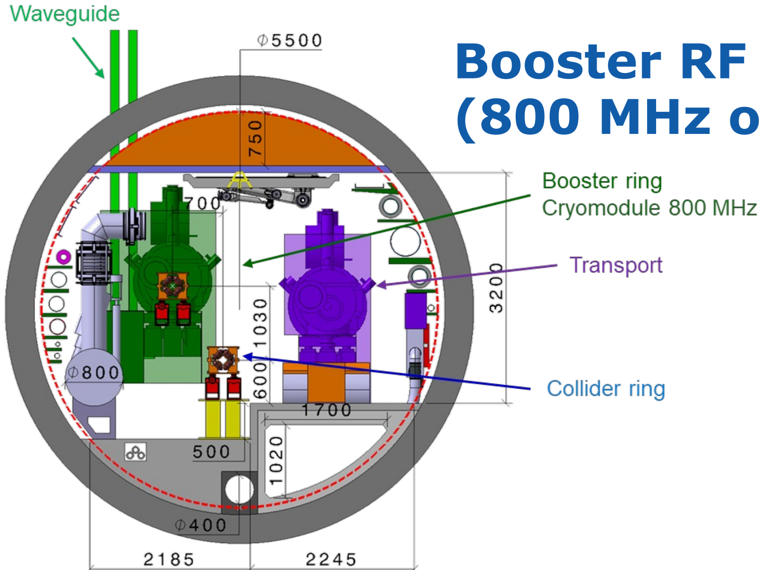


J.-P. Burnet

Collider RF - Point H (400 and 800 MHz)



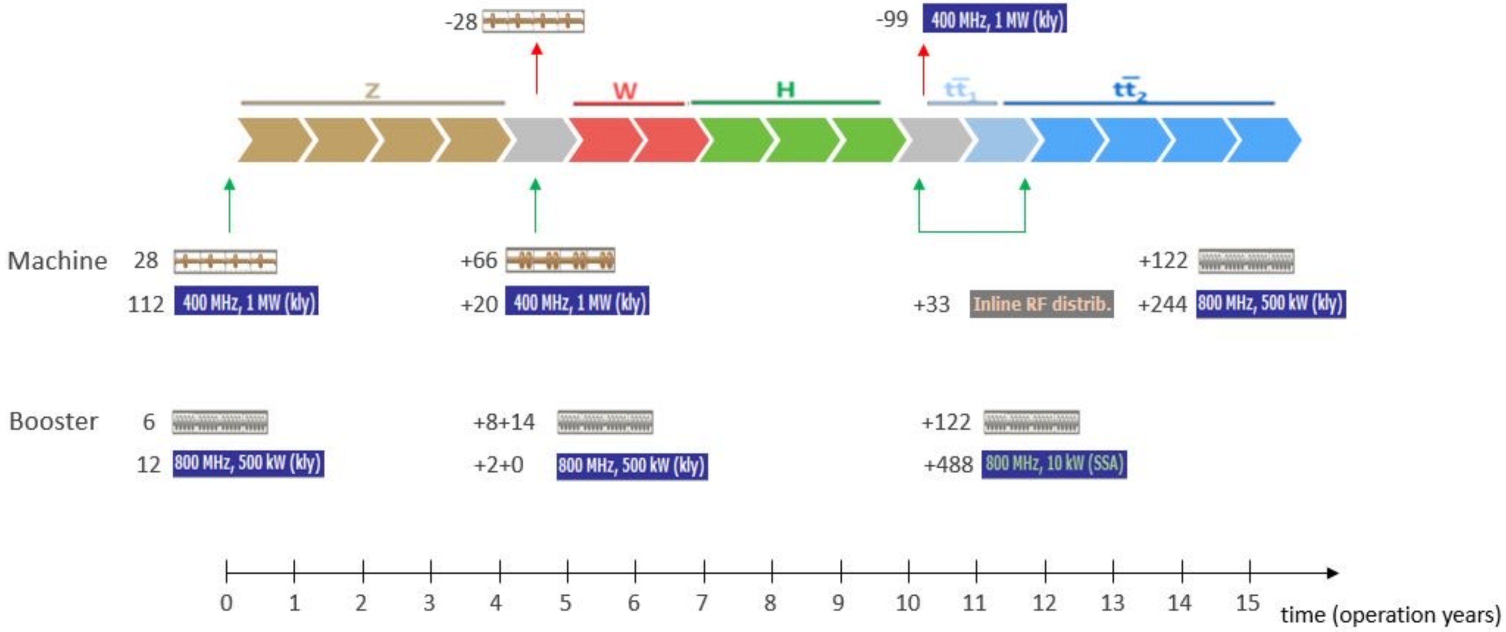
Booster RF - Point L (800 MHz only)

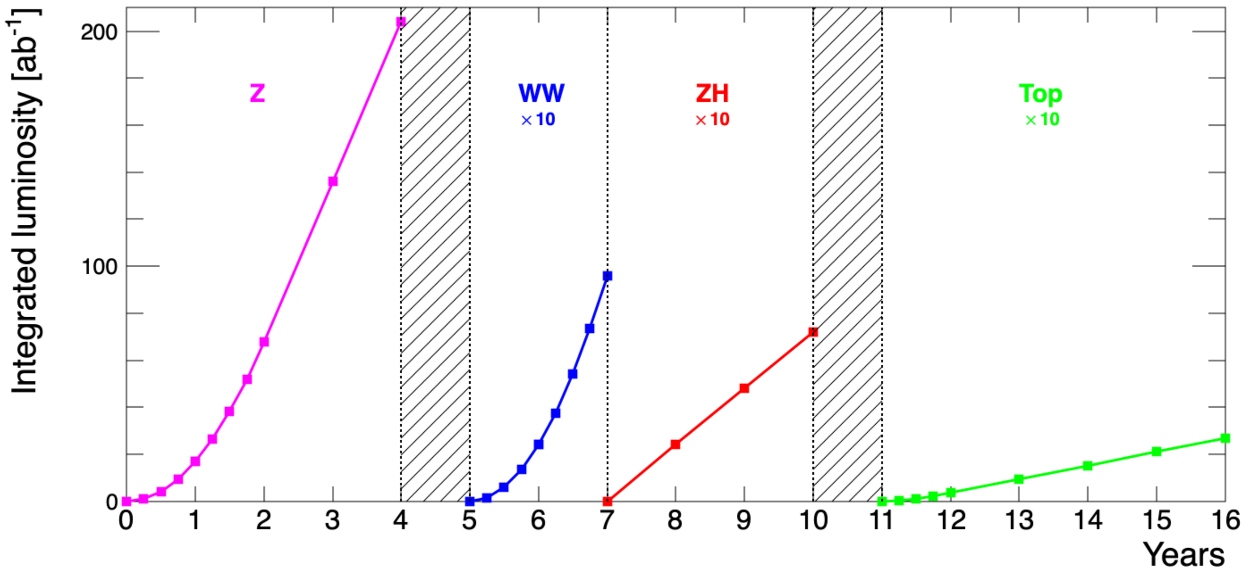


F. Valchkova, F. Peauger

baseline operational sequence starting from Z

O. Brunner, F. Peauger

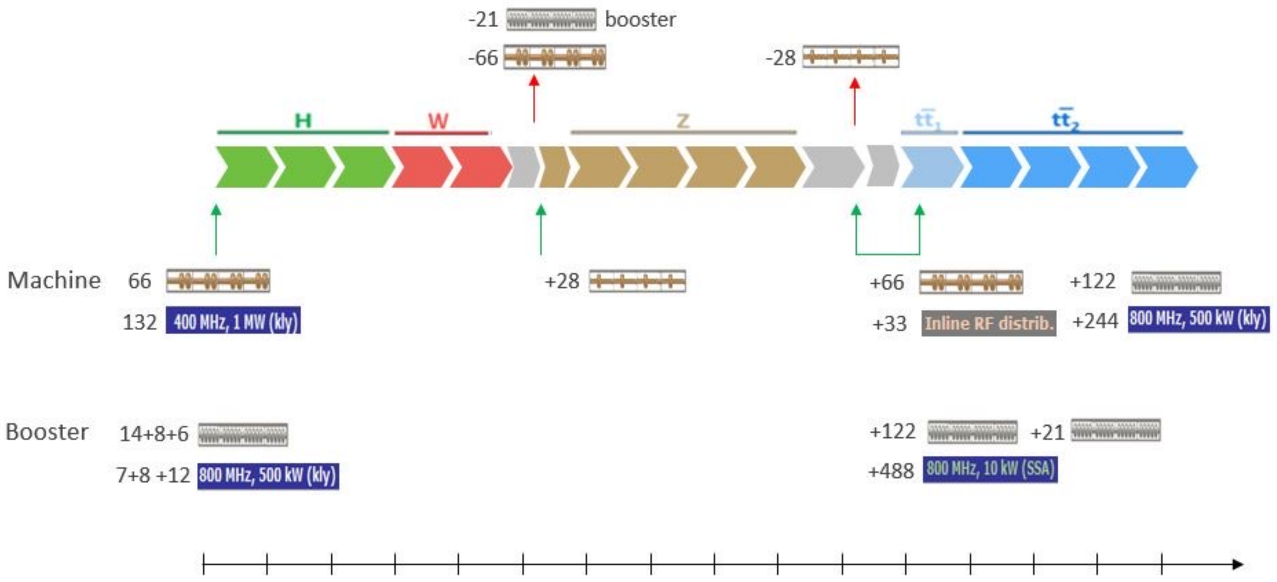


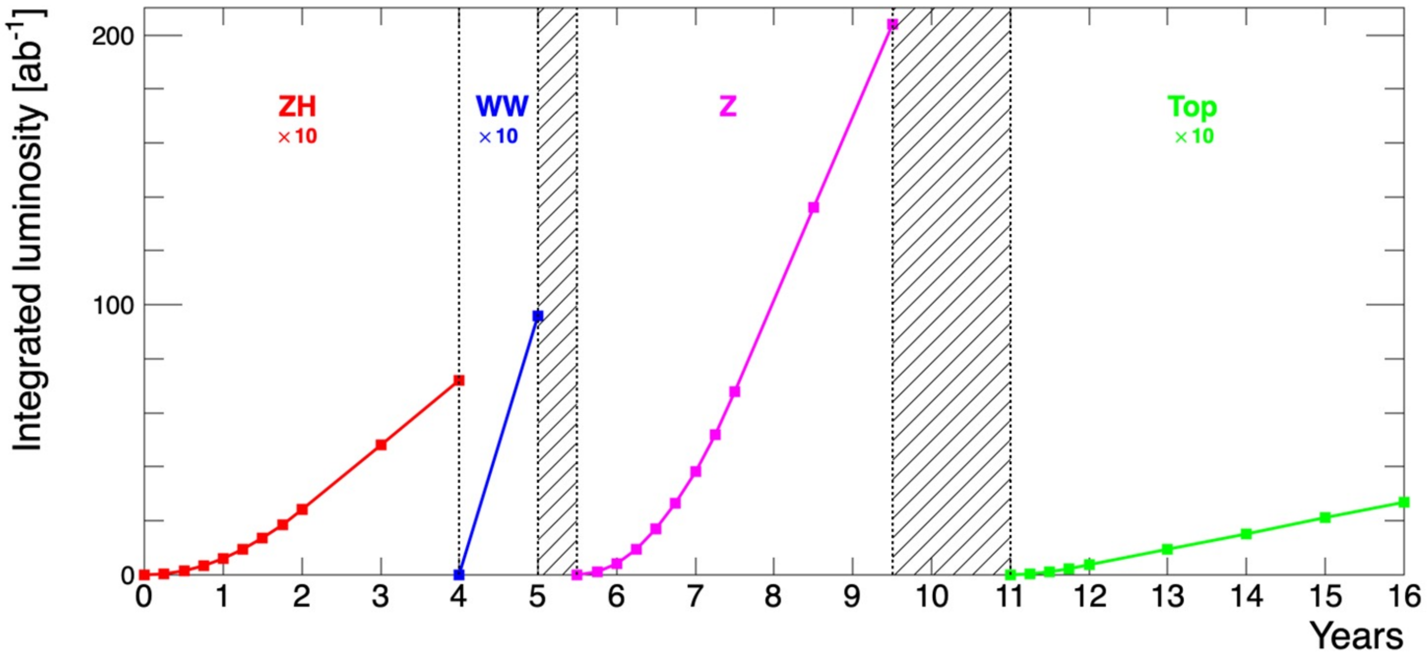


P. Janot

alternative operational sequence starting from ZH

O. Brunner, F. Peauger





P. Janot

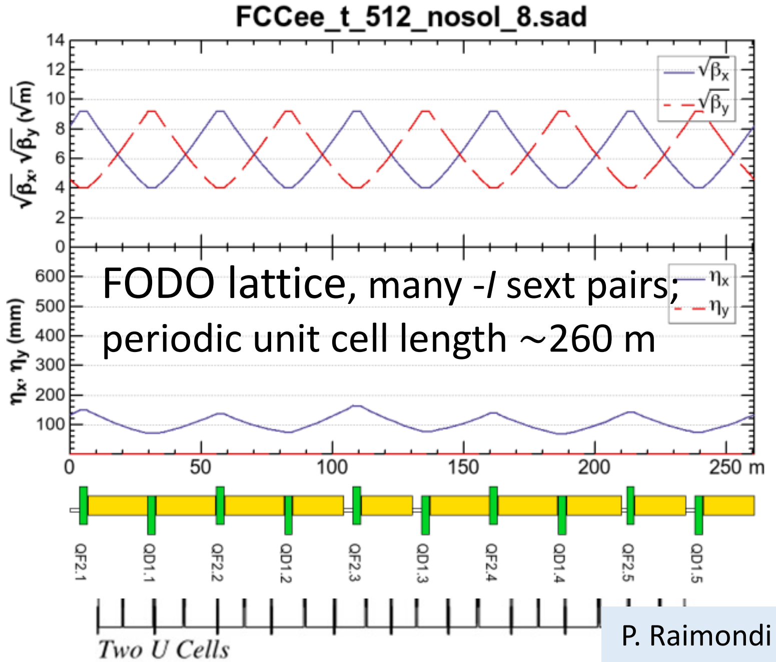
FCC-ee optics baseline & further evolution(s)

FUTURE CIRCULAR COLLIDER

regular arc

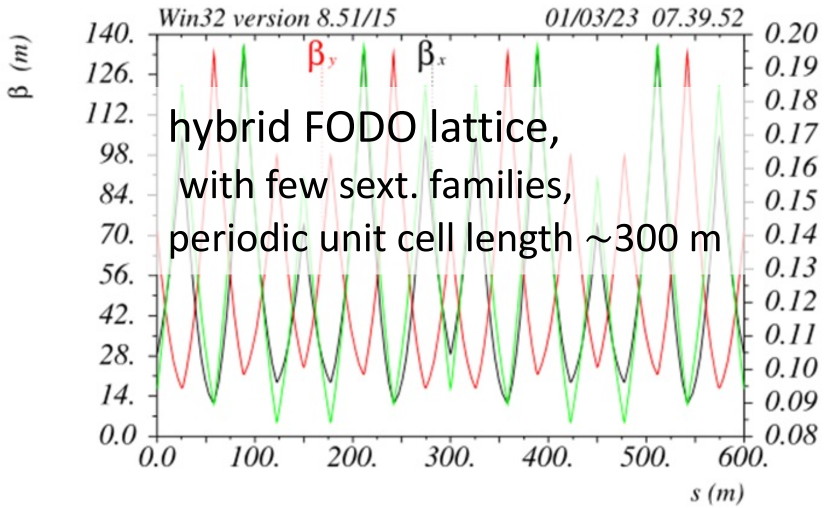
K. Oide

Short 90/90: $t\bar{t}$, Zh



FODO lattice, many -*I* sext pairs;
periodic unit cell length ~260 m

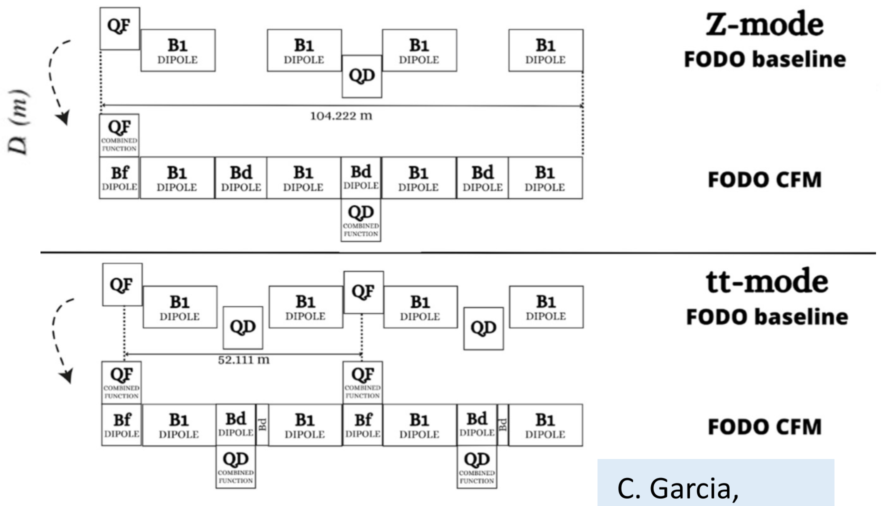
P. Raimondi



hybrid FODO lattice,
with few sext. families,
periodic unit cell length ~300 m

optimisation goals:

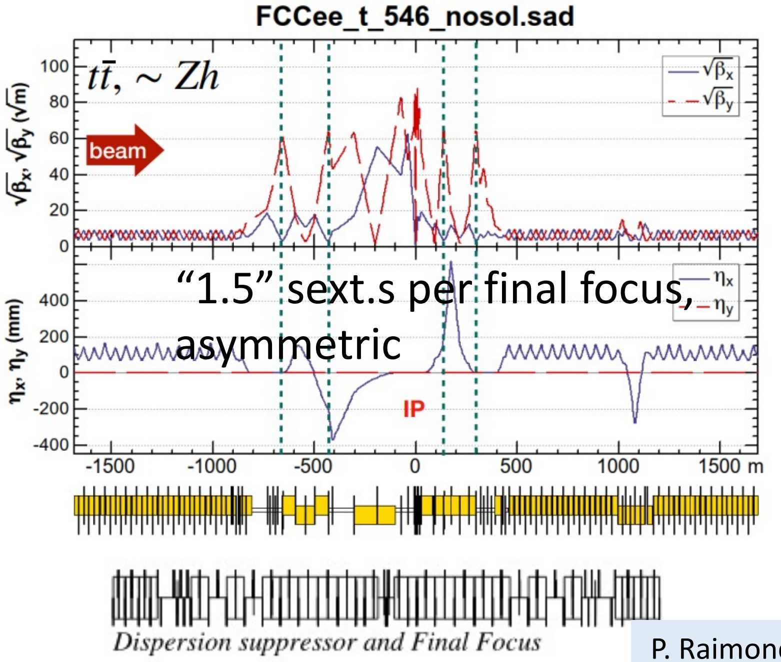
- reduced power consumption
- lower SR energy loss
- increased momentum acceptance
- relaxed tolerances
- larger dynamic aperture
- simplified powering schemes



C. Garcia,
R. Tomas, et al.

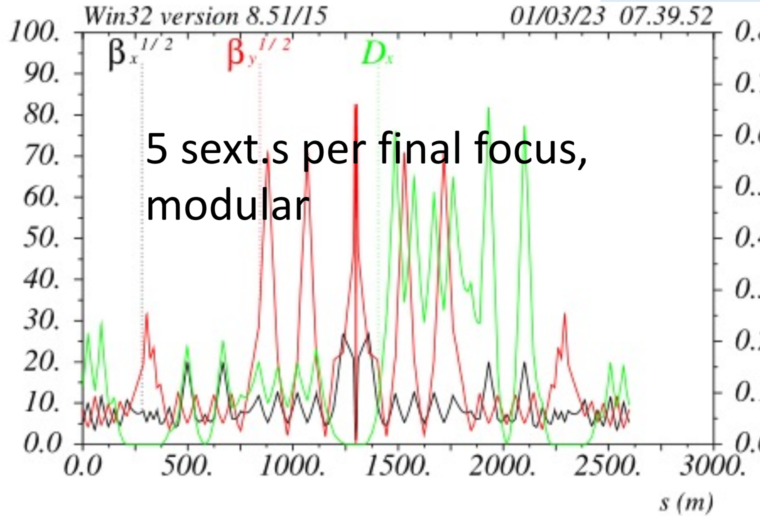
interaction region

K. Oide



"1.5" sext.s per final focus,
asymmetric

P. Raimondi



5 sext.s per final focus,
modular

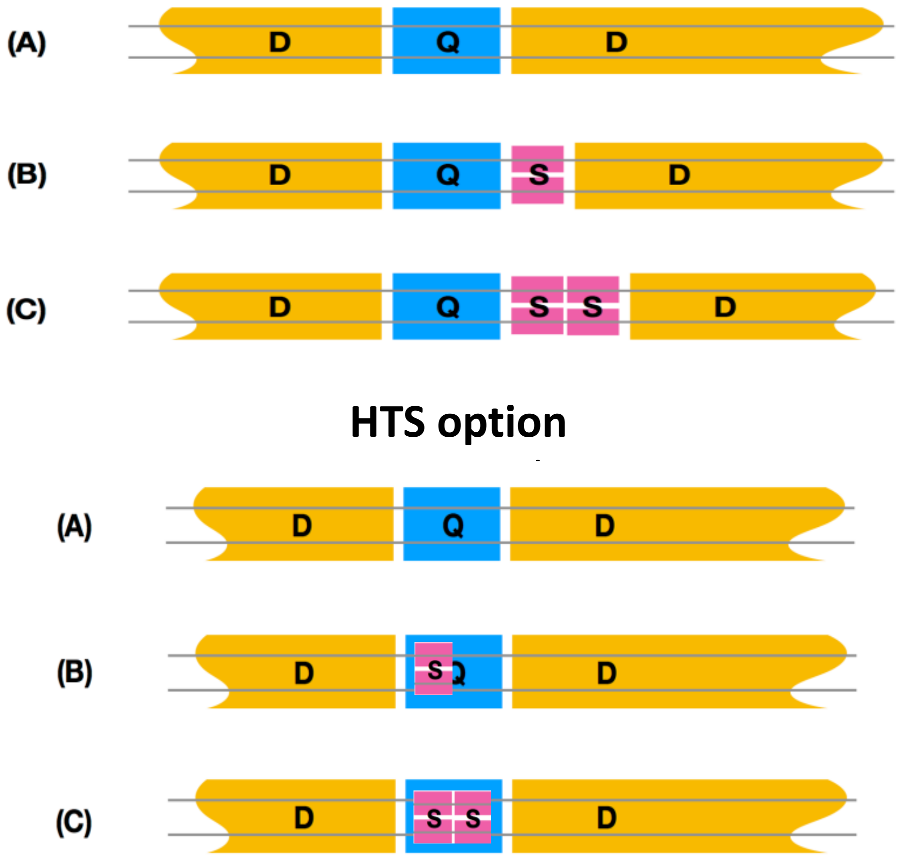
FUTURE CIRCULAR COLLIDER

R&D on HTS option for FCC-ee arc quads and sextupoles

CDR: 2900 quads & 4700 sextupoles

- Normal conducting, ~50 MW @ ttbar
- 3 different types of short straight sections

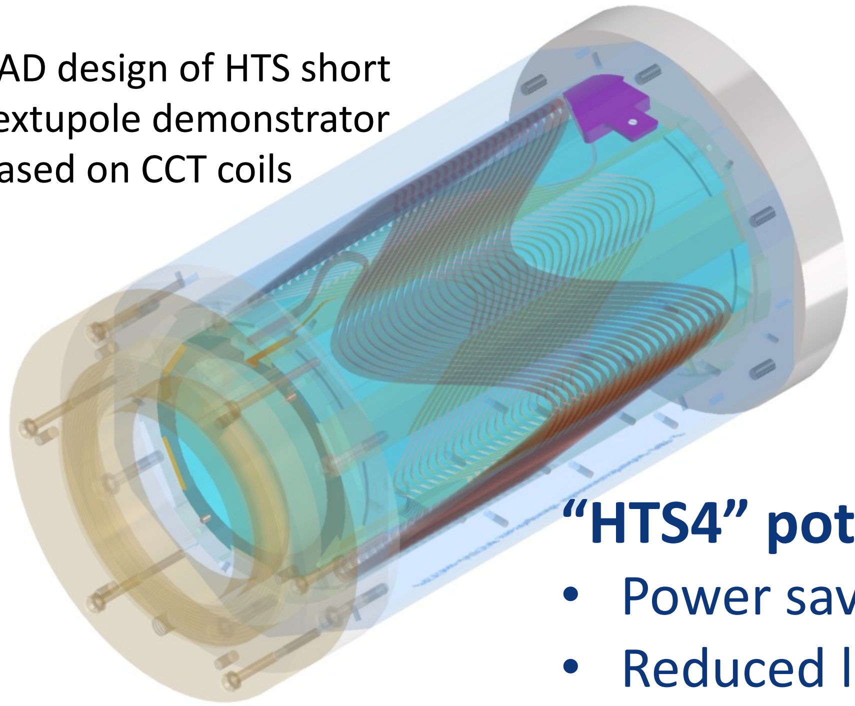
CDR arc lattice

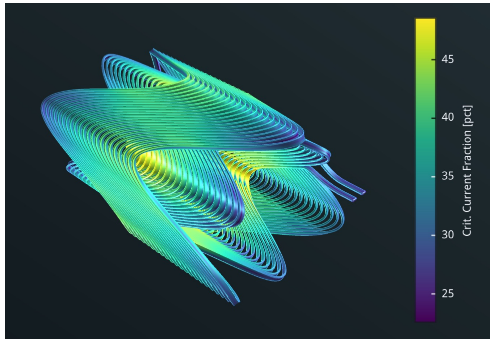


"HTS4" project within CHART collaboration

- Nested SC sextupole and quadrupole.
- HTS conductors operating at around 40K.
- Cryo-cooler supplied cryostat
- Produce a ~1m prototype by 2026

CAD design of HTS short sextupole demonstrator based on CCT coils





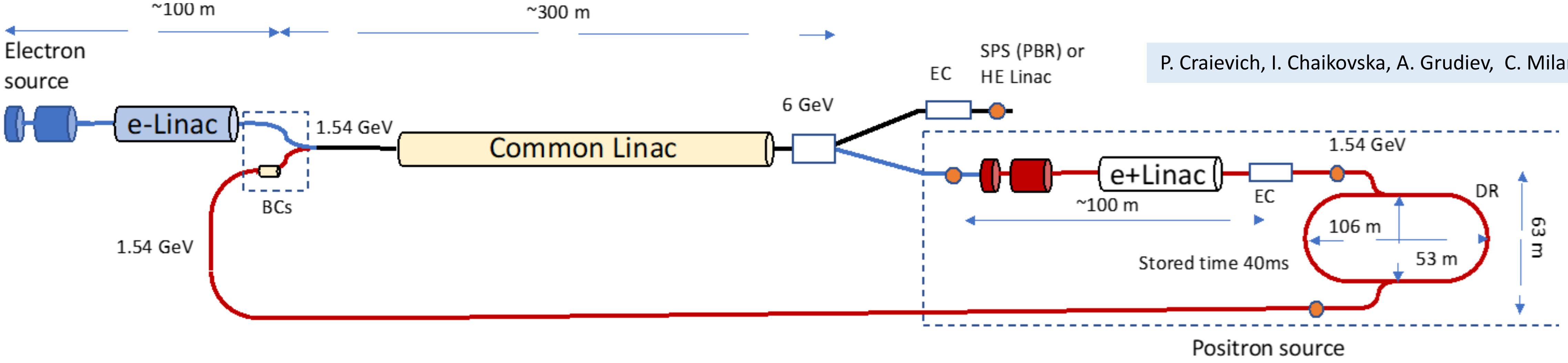
M. Koratzinos, B. Auchmann

"HTS4" potential

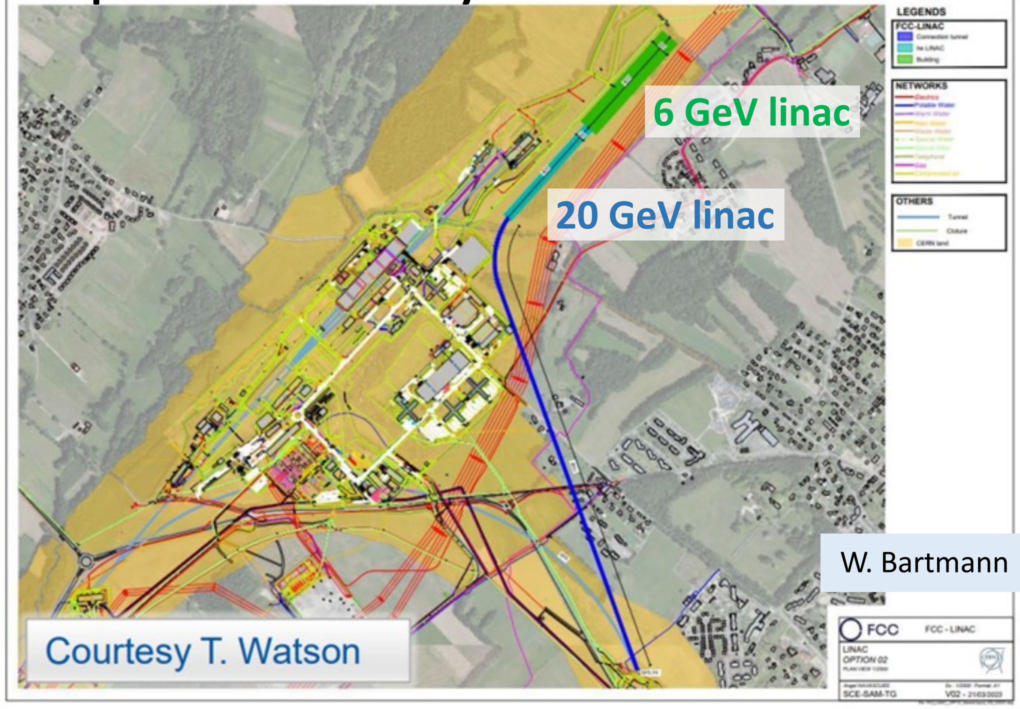
- Power saving
- Reduced length and increased dipole filling factor
- Optics flexibility

new FCC-ee injector layout & implementation

P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al



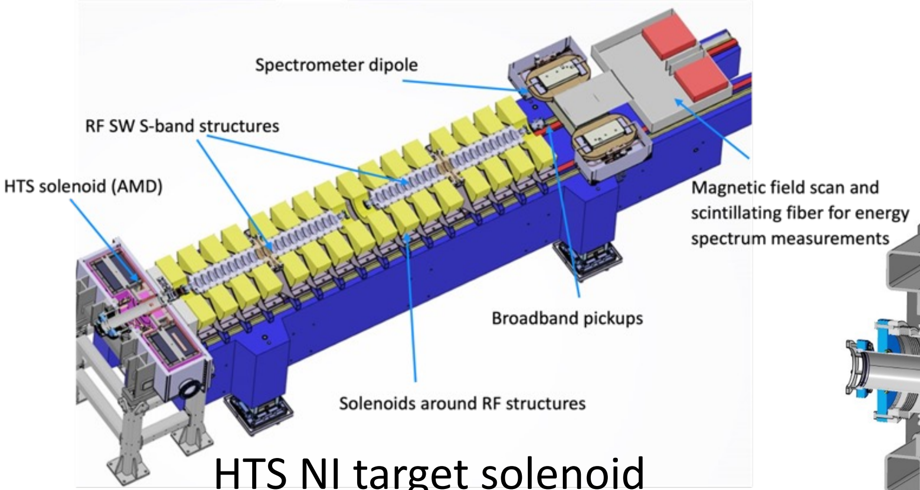
implementation study on Prevessin site

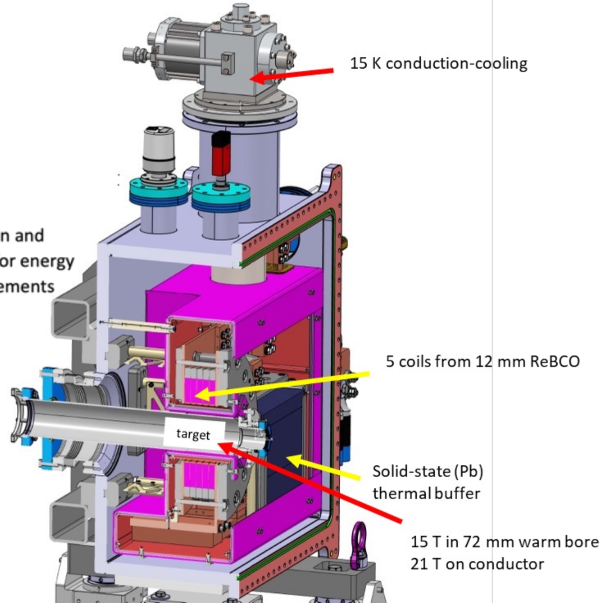


W. Bartmann

Courtesy T. Watson

"Positron production experiment" at PSI's SwissFEL, beam tests from 2025/26





HTS NI target solenoid

J. Kosse, T. Michlmayr, H. Rodrigues

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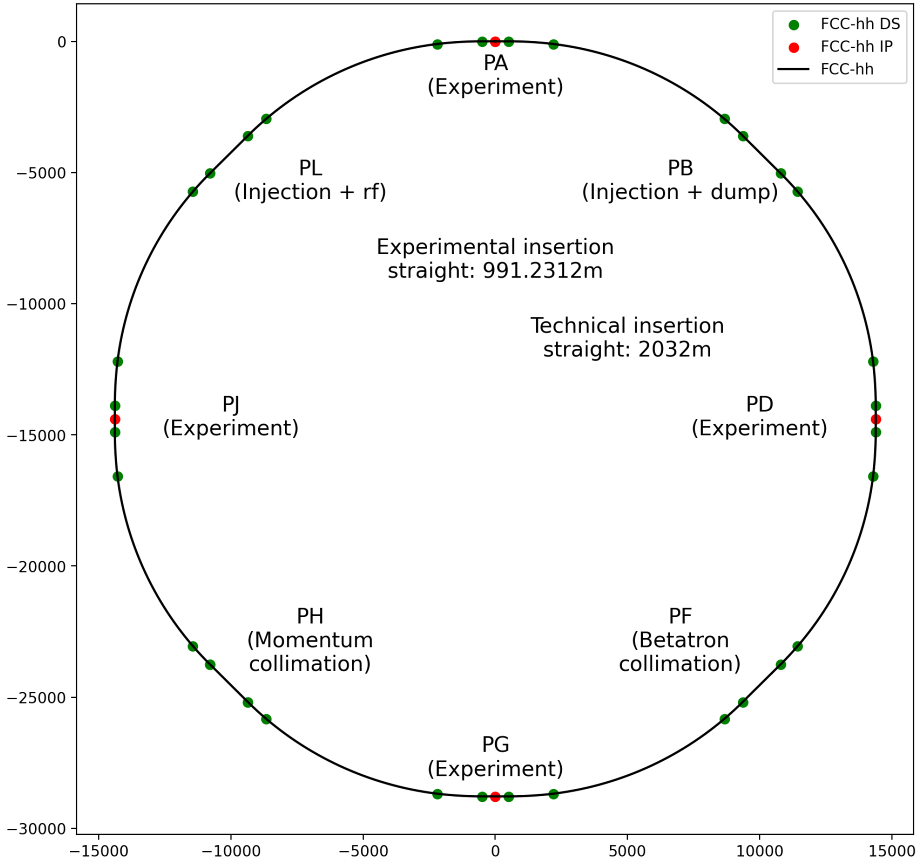
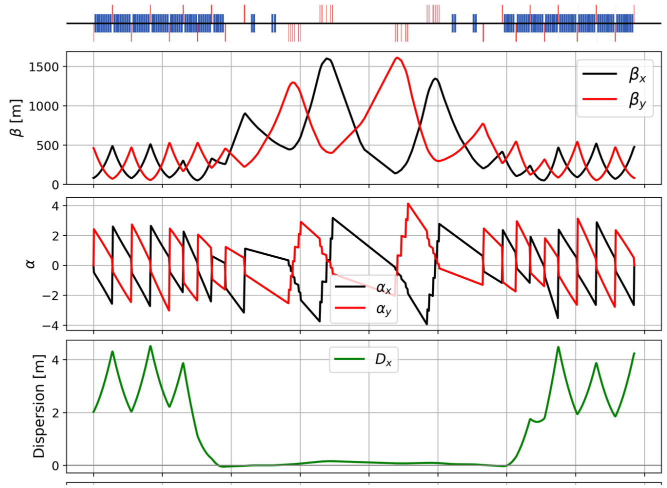
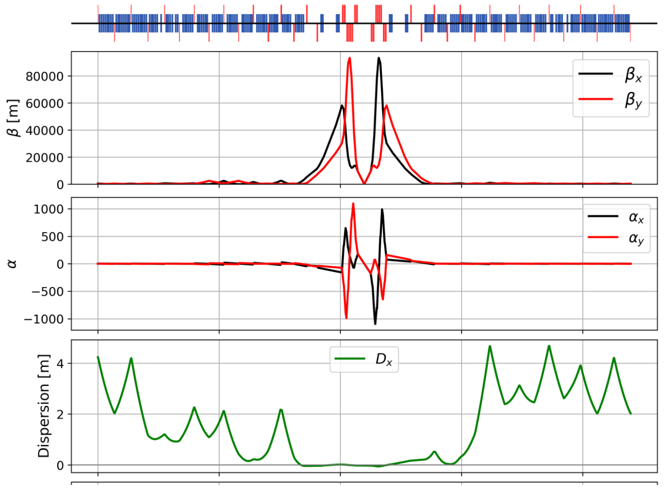
FCC-hh layout, optics work, geom. integration



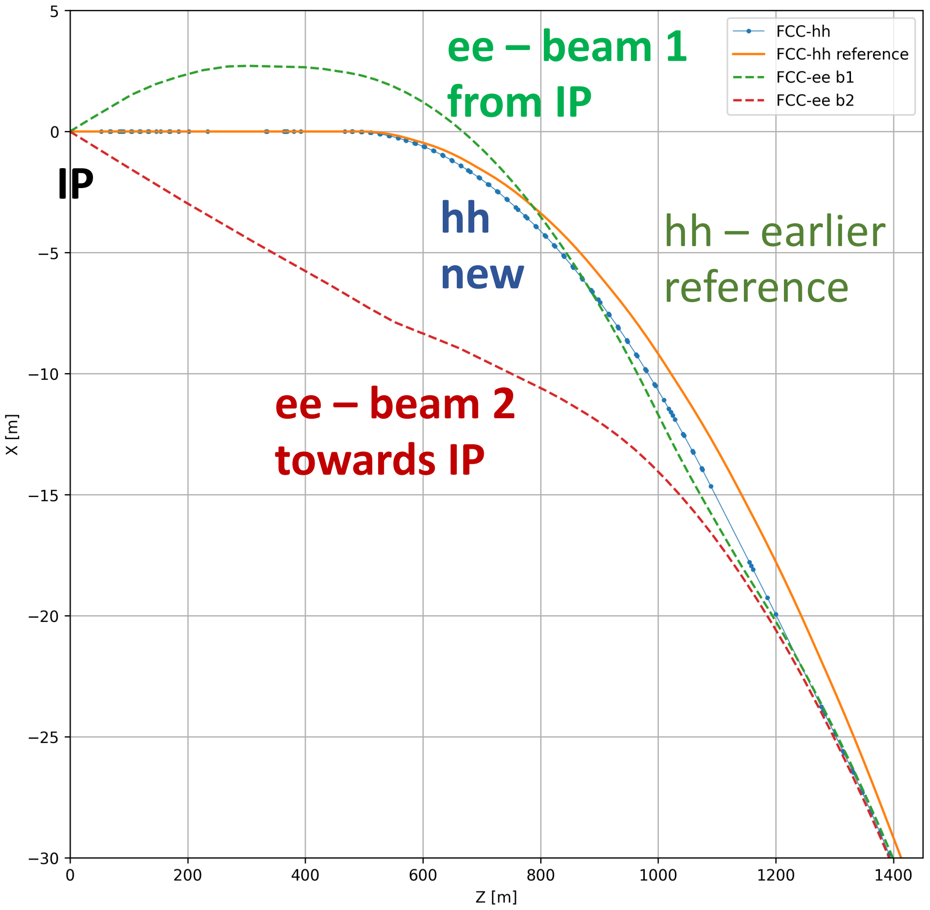
betatron collimation straight



experimental straight



3 - beam footprint at interaction point



- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)
- move hh IPs on top of ee IP to optimise tunnel and cavern widths.

M. Giovannozzi, T. Risselada, G. Perez Segurana, M. Hofer, K. Oide

FUTURE CIRCULAR COLLIDER

FCC-ee: main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity $[10^{11}]$	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP $[10^{34}\ cm^{-2}s^{-1}]$	140	20	5.0	1.25
total integrated luminosity / IP / year $[ab^{-1}/yr]$	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5×10^{12} Z LEP x 10^5	2 years $> 10^8$ WW LEP x 10^4	3 years 2×10^6 H	5 years 2×10^6 tt pairs

currently assessing technical feasibility of changing operation sequences (e.g. starting at ZH energy)

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

FUTURE CIRCULAR COLLIDER

FCC-hh: main machine parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

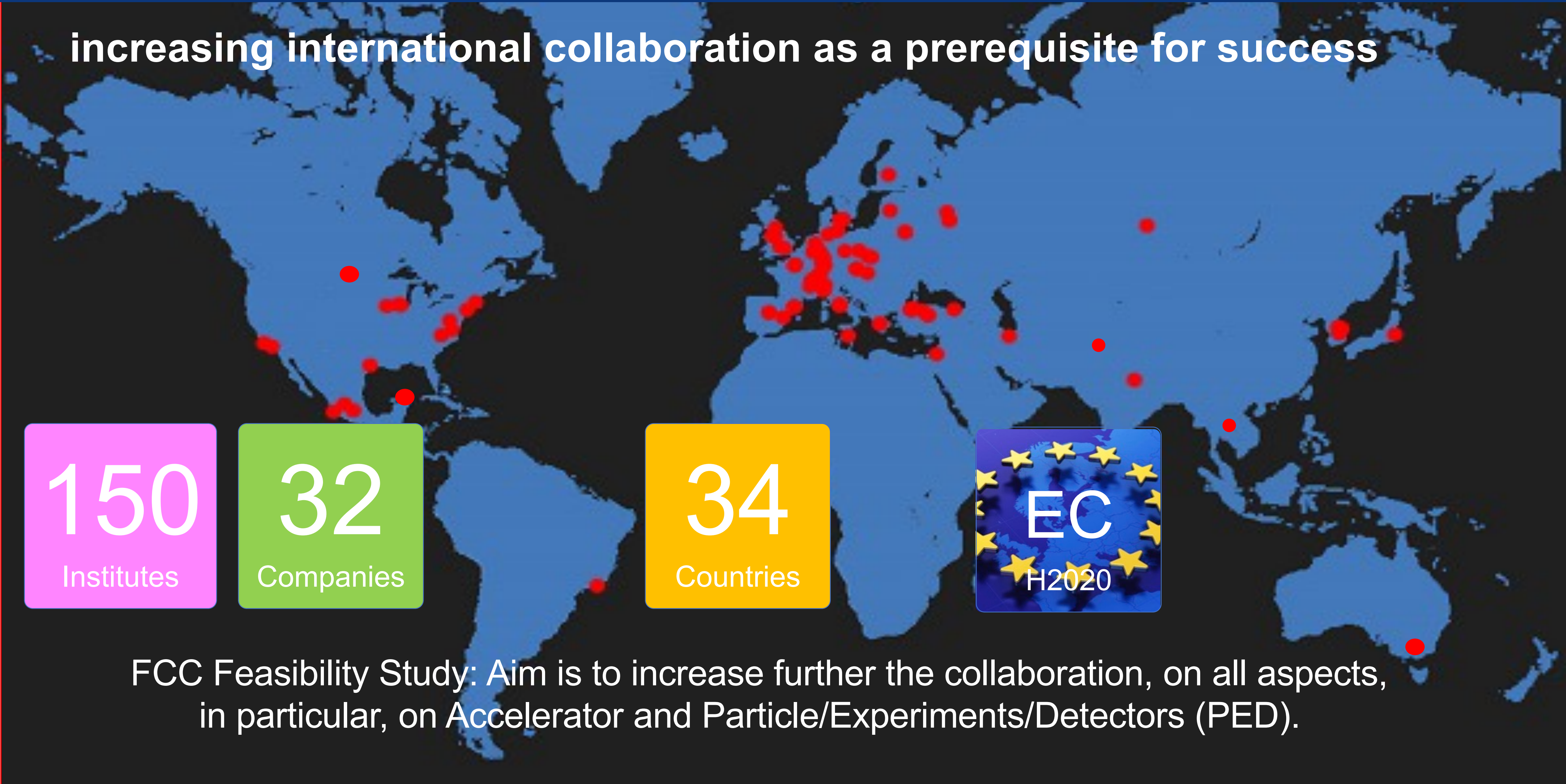
Formidable physics reach, including:

- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- ❑ Final word about WIMP dark matter

F. Gianotti

Status of FCC global collaboration

increasing international collaboration as a prerequisite for success



FCC Feasibility Study: Aim is to increase further the collaboration, on all aspects, in particular, on Accelerator and Particle/Experiments/Detectors (PED).

FUTURE
CIRCULAR
COLLIDER

FCC Week 2023
London

473 participants

362 in person and
111 remote

Courtesy P. Charitos

FCC Feasibility Study – status summary

The first half of the FCC Feasibility Study will soon be completed with the mid-term review

Topics addressed: **Infrastructure & placement, Technical Infrastructure, Accelerator design FCC-ee and FCC-hh, Physics, experiments, detectors, Organisation and financing, Environmental impact, socio-economic impact**

- End October 2023: Review committee reports available to Scientific Policy Committee and Finance Committee
- 20 – 22 November 2023: SPC and FC review meetings on mid-term review
- 2 February 2024: CERN Council meeting on mid-term review

Focus so far: identifying best placement & layout and adapting entire project to new placement

- 3D underground civil engineering model, siting study for implementation of FCC-ee pre-injector on CERN Prevessin site
- FCC-ee 4 IP variant, significant effort in FCC-ee lattice design with two complete optics solutions, major progress towards full performance simulations including beam-beam, impedance etc.
- FCC-ee SRF configuration and layout further optimized.
- FCC powering concept defined in cooperation with French network operator RTE.

Fruitful collaboration between all scientific & technical actors and in close cooperation with the host state services concerned; at departmental/cantonal and local level. Direct exchange with communes concerned by surface sites. Environmental studies ongoing.