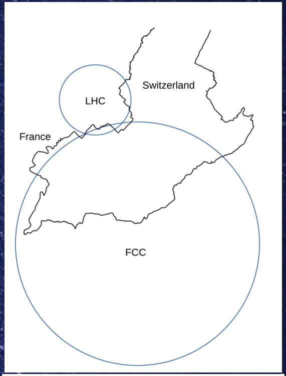
INFN ACCELERATORI GIORNATA ACCELERATORI

FUTURE CIRCULAR COLLIDER FCC

Manuela Boscolo



http://cern.ch/fcc

FUTURE CIRCULAR COLLIDER Innovation Study

INFN LNF

CERN

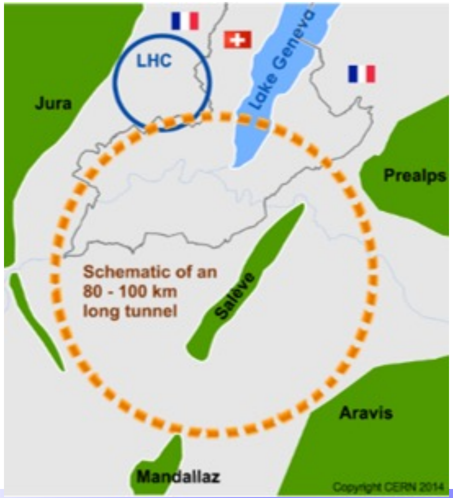
Outline

- FCC
- FCC-ee
- INFN involvement in the project
- First FCC-Italy workshop → areas for additional collaboration

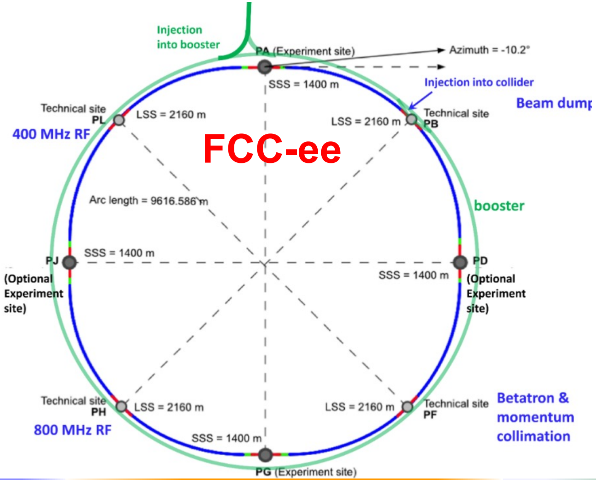
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive long-term program, maximizing physics opportunities

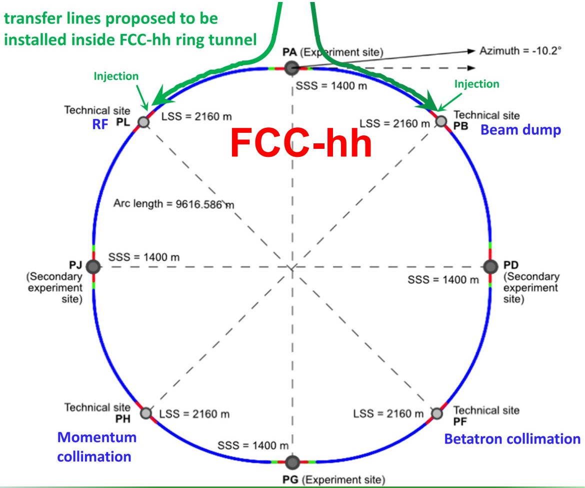
- Stage 1: **FCC-ee** (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities
- Stage 2: **FCC-hh** (~100 TeV) as natural continuation at energy frontier, with ion and eh options
- Complementary physics
- Common civil engineering and technical infrastructures
- Building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



2020 - 2040



2045 - 2060



2065 - 2090

Conceptual Design & input to ESPPU '19/20

FCC-Conceptual Design Reports (end 2018):

- **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) [Springer]**

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

EPJ is a merger and continuation of *Acta Physica Hungarica, Anales de Fisica, Czechoslovak Journal of Physics, Fizika A, Il Nuovo Cimento, Journal de Physique, Portugaliae Physica* and *Zeitschrift für Physik*. 25 European Physical Societies are represented in EPJ, including the DPG.

Summary documents input to EPPSU 2019/20

- **FCC-integral, FCC-ee, FCC-hh, HE-LHC**, at http://fcc-cdr.web.cern.ch/

FCC-hh

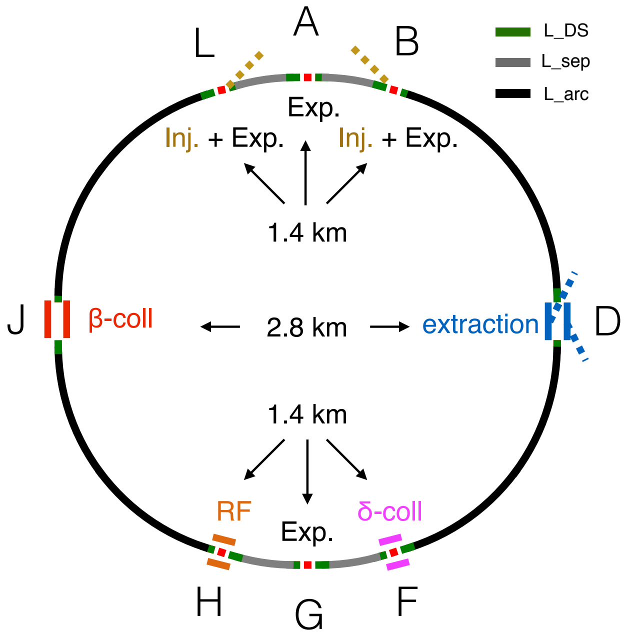
CDR parameters

	HL-LHC	FCC-hh
Cms energy [TeV]	14	100
Int. L., 2 det. [ab^{-1}]	6	30
Operation [years]	12	25
L [$10^{34}cm^{-2}s^{-1}$]	5	20-30
Circumference	26.7	97.75
Arc dipole field [T]	8	16
Bunch dist. [ns]	25	25
Backgr. events/bx	135	<1020
Bunch length [cm]	7.5	8
L* [m]	23	40

31 GHz of pp collisions

Pile-up 1000

4 THz of tracks



Two main IP's in A, G for both machines

Two High Luminosity IPs A/G

Two Lower Luminosity IPs L/B

Similar to layout at LHC

FCC-hh Key aspects funded by H2020-INFRADEV Design Study EUROCIRCOL

Strategic activity for the FCC CDR and cost review for the EPPSU in 2019

(2015-2019) 3 MEuro, INFN grant: 422 k€ INFN Scientific coordinator M. Boscolo

- WP3: **Experimental insertion region design** (M. Boscolo, LNF) 77 k€
  Impact of synchrotron radiation emitted by protons on detector and machine components and develop mitigation techniques (outcome study: only tens of W reach the central Be chamber, not an issue)

- WP4: **Cryogenic beam vacuum system** (R. Cimino, LNF) 208 k€
  SR power ~30W/m/beam in arcs, total 5 MW (LHC 7kW), 100 MW of cooling power
  → R&D planned at DAFNE (MoU)

- WP5: **High field magnet design** (S. Farinon, Ge) 137 k€
  The target field strengths to the order of 16 T require novel concepts and R&D studies
  → High field magnet program

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..”

→ launch of Future Circular Collider Feasibility Study in summer 2021

FCC Feasibility Study – coordination team and contact persons

EU Projects
NN

Collaboration building
Emmanuel Tsesmelis

Communications
Panagiotis Charitos, James Gillies

Study Support and Coordination
Study Leader: Michael Benedikt
Deputy Study Leader: Frank Zimmermann

Study Support Unit
IT: Sylvain Girod
Procurement: Adam Horridge
Quality control: NN
Resources: Sylvie Prodon
Scheduling, quality mangement: NN
Secretariat: Julie Hadre

Physics, Experiments and Detectors
Patrick Janot
Gavin Salam

- **Physics programme** – Matthew McCullough, Frank Simon
- **Detector concept** – Mogens Dam
- **Physics performance** – Patrizia Azzi, Emmanuel Perez
- **Software and computing** – Gerardo Ganis, Clément Helsens

Accelerators
Tor Raubenheimer
Frank Zimmermann

- **FCC-ee collider design** – Katsunobu Oide
- **FCC-hh design** – Massimo Giovannozzi
- **Technology R&D** – Roberto Losito
- **FCC-ee booster design** – Antoine Chancé
- **FCC-ee injector** – Paolo Craievich, Alexej Grudiev
- **FCC-ee energy calibration polarization** – Alain Blondel, Jorg Wenninger
- **FCC-ee MDI** – Manuela Boscolo, Mike Sullivan

Technical Infrastructures
Klaus Hanke

- **Integration** – Jean-Pierre Corso
- **Geodesy & survey** – Hélène Mainaud Durand
- **Electricity and energy management** – Jean-Paul Burnet
- **Cooling and ventilation** – Guillermo Peon
- **Cryogenics systems** – Laurent Delprat
- **Computing and controls infrastructure, communication and network** – Dirk Duellmann
- **Safety** – Thomas Otto
- **Operation, maintenance, availability, reliability** – Jesper Nielsen
- **Transport, installation concepts** – Cristiana Colloca

Host State processes and civil engineering
Timothy Watson

- **Administrative processes** – Friedemann Eder
- **Placement studies** – Johannes Gutleber, Volker Mertens
- **Environmental evaluation** – Johannes Gutleber
- **Tunnel, subsurface design** – John Osborne
- **Surface sites layout, access and building design**

Organisation and financing models
Paul Collier (interim)

- **Project organisation model**
- **Financing model** – Florian Sonnemann
- **Procurement strategy and rules**
- **In-kind contributions**
- **Operation model** – Paul Collier, Jorg Wenninger

Timeline of the FCC integrated programme

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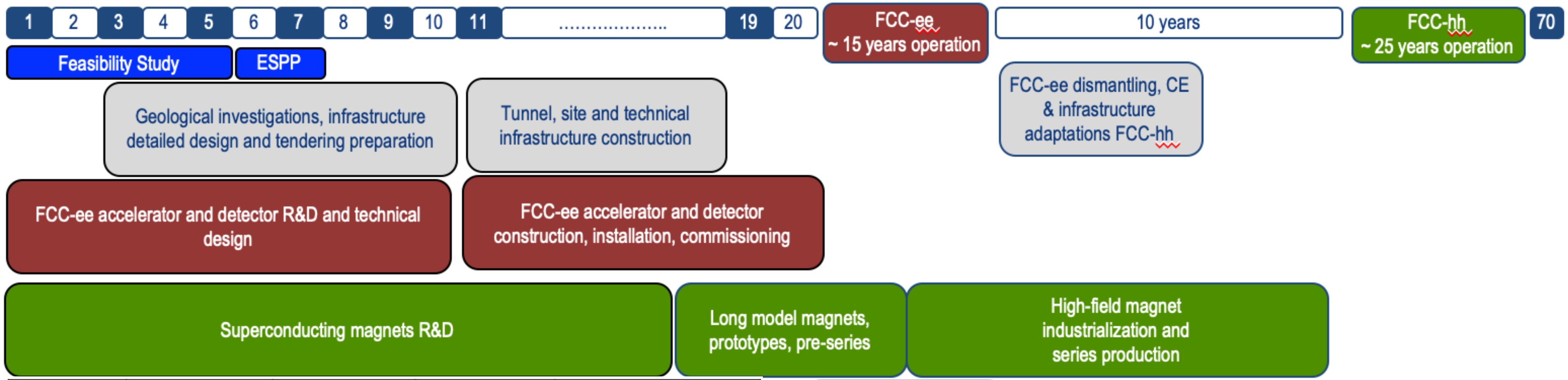
Technical schedule



	√s	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	230 x10^{34} 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

F. Gianotti

FCC Feasibility Study (2021-205): high-level objectives

FUTURE CIRCULAR COLLIDER

- demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- consolidation of the physics case and detector concepts for both colliders.

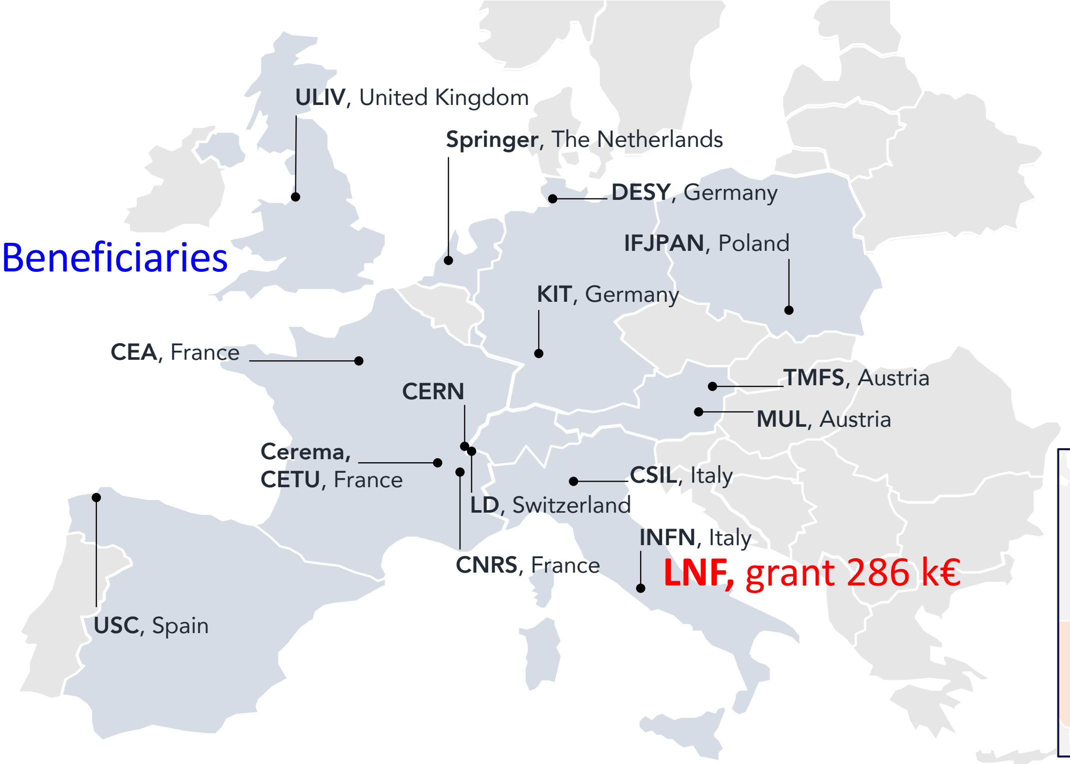
Results will be summarised in a Feasibility Study Report to be released at end 2025

F. Gianotti

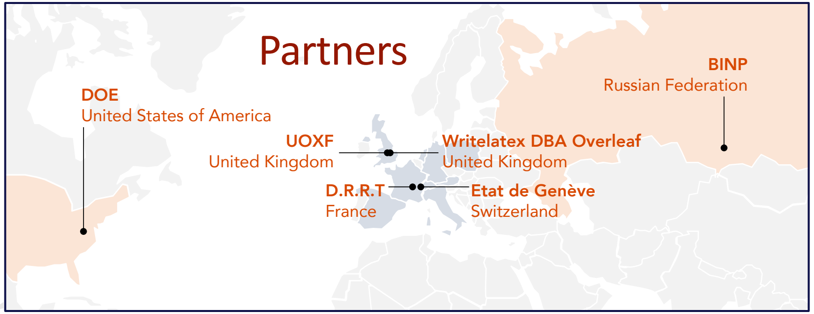
FCC Innovation Study (FCCIS) EU- H2020 Design Study 3 ME

Strategic activity for the FCC FS and cost update review for the next EPPSU in 2025/26

Beneficiaries



Topic	INFRADEV-01-2019-2020
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



Second Design Study on FCC focused on FCC-ee collider and tunnel feasibility (First INFRADEV was on FCC-hh, EuroCirCol)

FCCIS H2020-INFRADEV Design Study

INFN Scientific coordinator M.Boscolo

WP2: collider design (DESY) 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.

Task Interaction region and machine detector interface design

(lead: M. Boscolo, participants: CERN, CNRS, DESY partners BINP and UOXF)

Subtask: Analyse and mitigate **impedance and single-beam collective effects** in the collider rings (M. Migliorati, Roma1)

WP3: integrate Europe (CERN) Develop a feasible project scenario compatible with local – territorial constraints while guaranteeing the required physic performance.

WP4: impact & sustainability (CSIL, *Centro Studi Industria Leggera, Italy*) Develop the financial roadmap of the infrastructure project, including the analysis of socio-economic impacts.

WP5: leverage & engage(IFJ PAN) 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).

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 (or 4IPs) large horizontal crossing angle 30 mrad, **crab-waist** collision optics (FCC-hh 4 IPs)

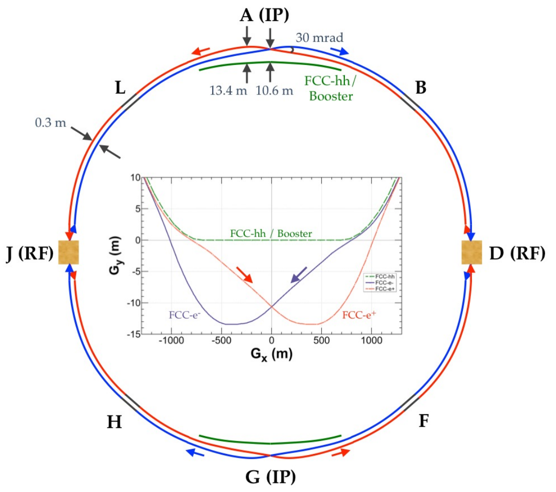
Synchrotron radiation power **50 MW/beam** at all beam energies

Top-up injection scheme for high luminosity Requires booster synchrotron in collider tunnel

"**Tapering**" of magnets along the ring to compensate the sawtooth effect

CDR

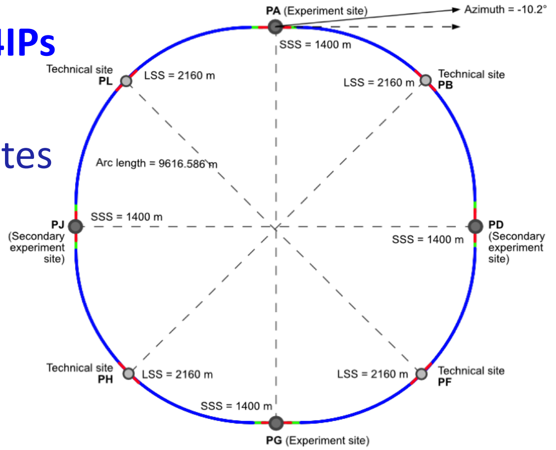
C=97 km



evolution 4IPs

C=91 km

8 surface sites



FCC-ee Interaction Region

Crab-waist scheme, based on two ingredients:
- concept of **nano-beam scheme** (vertical squeeze of the beam at IP and horizontal crossing angle increased, reducing the instantanous overlap area, allowing for a lower β_y*)
- **crab-waist sextupoles**

Smaller beams at IP → higher luminosity & higher backgrounds
(IP bkgs and beam losses in the final focus quads due to the very high β-function)

First Successful validation test performed at **DAFNE** (2008) link

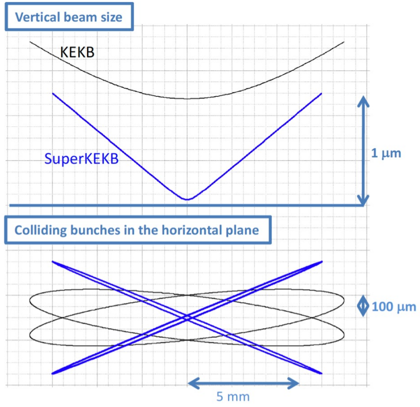


Figure 2: Schematic view of the nanobeam collision scheme.

https://arxiv.org/pdf/1809.01958.pdf

Squeezed beams at IP, tens of nm in σ_y* (vertical emittance ε_y =1 pm at 45.6 GeV)
This scheme, with the goal luminosity of 10^{36}cm^{-2}s^{-1} at 45 GeV sets the constraint to:
- L* (distance between IP and first quad)
- the strength of the final focus doublet
- the solenoidal detector field (e.g. $\varepsilon_y \propto B_z^{\,5}$)

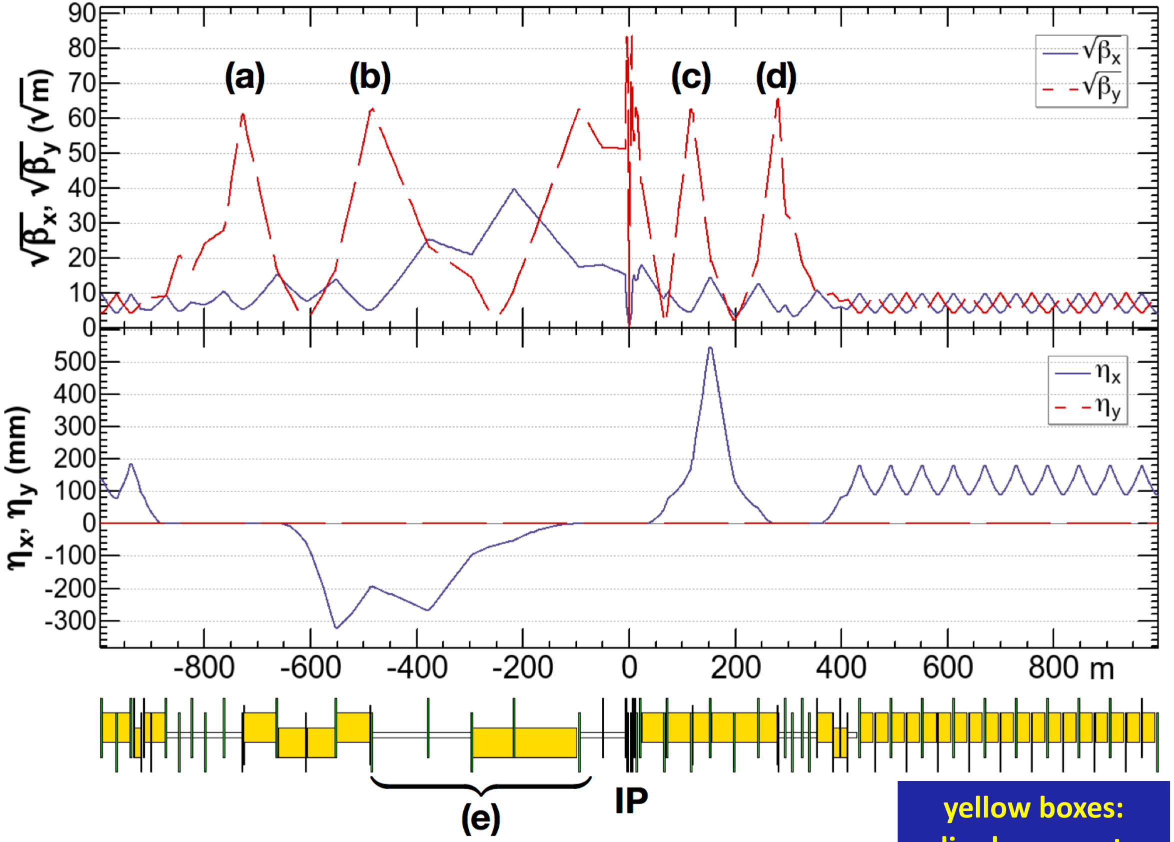
L*=2.2 m
B(detector) = 2 T

⬇

Tight and packed interaction region with first final focus quadrupole QC1 inside detector, different QC1 for each beam, and two anti-solenoids inside the detector, as well.

FCC-ee asymmetric crab-waist IR optics

ttbar 182.5 GeV



yellow boxes: dipole magnets

Novel asymmetric IR optics to suppress synchrotron radiation toward the IP, **$E_{critical}$ <100 keV from 450 m from IP (e) – lesson from LEP**

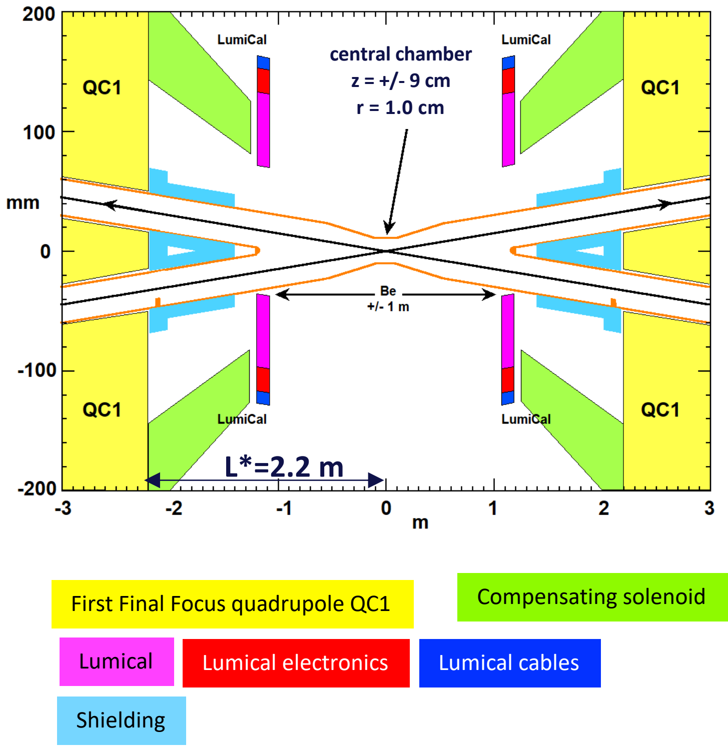
4 sextupoles (a – d) for local vertical chromaticity correction combined with crab waist, optimized for each working point **– novel "virtual crab waist", standard crab waist demonstrated at DAFNE**

K. Oide et al., Design of beam optics for the future circular collider e^+e^- collider rings, **Phys. Rev. Accel. Beams 19**, 111005 (2016).

Part of FCCIS (LNF) & partial funding CSN1 RD_FCC activity

FCC-ee Interaction Region

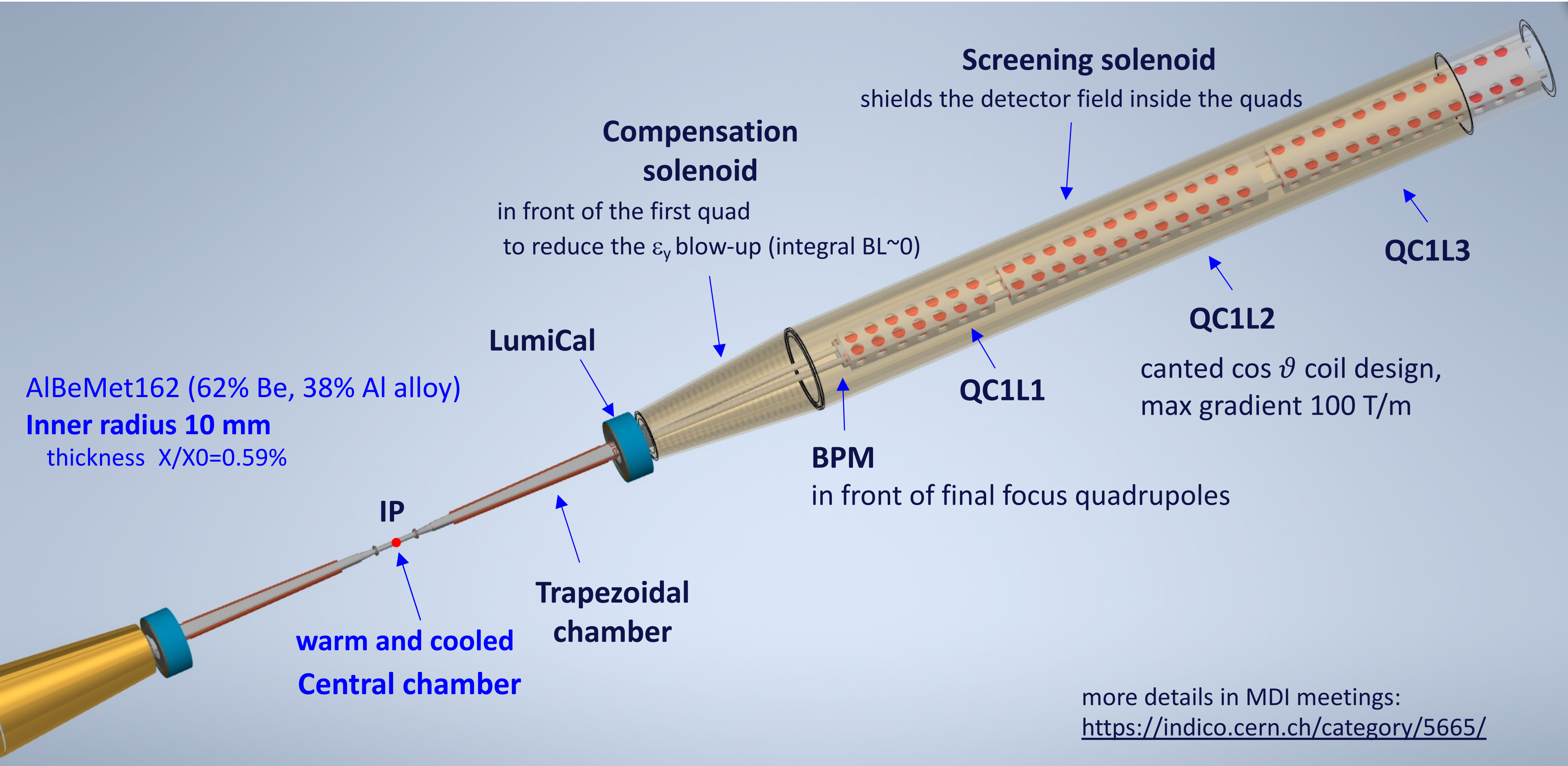
- **B(detector) = 2 T**
- **Flexible** design, one IR compatible for all beam energies
- **Compact** design: **QC1 and compensation solenoids inside detector** as a consequence of crab-waist scheme, nano-beams
- all elements required to be inside a cone of 100 mrad wrt beam axis
  - vibrations mitigation
  - alignment and monitoring system
  - feedback for beam orbit and luminosity
- **High intensity run @Z** (vacuum, residual gas, collective effects)
- **High energy run @ttbar**
- **Synchrotron radiation**
- **Beamstrahlung**
- **Luminosity detector** @Z: absolute meas. to $\mathbf{10^{-4}}$ (low angle Bhabha)



M. Boscolo et al. EPJ+ 2021

LNF coordinates the design of the Interaction Region and MDI and the engineering design of the IR

3D view of IR

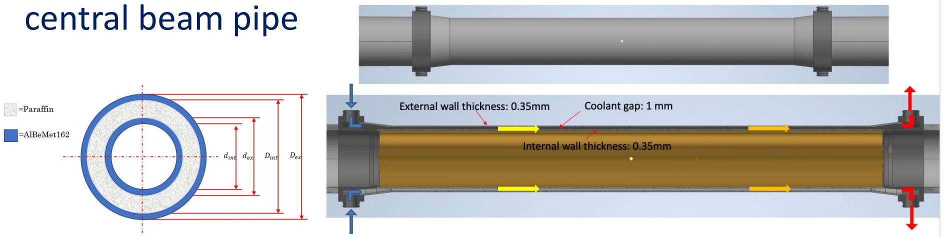


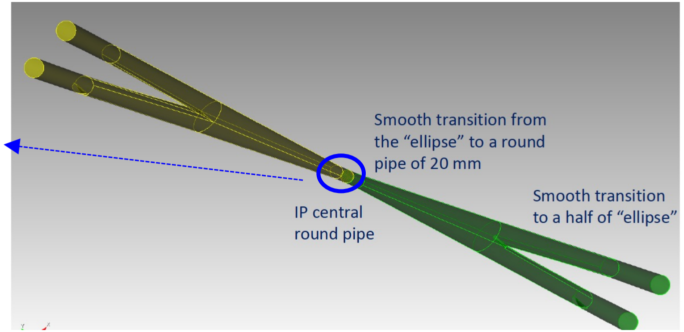
more details in MDI meetings:
https://indico.cern.ch/category/5665/

Low impedance central chamber

The double effect of smoothing the geometry and a smaller central pipe reduces the local heating power by a factor ten wrt the CDR design.

warm and cooled central beam pipe



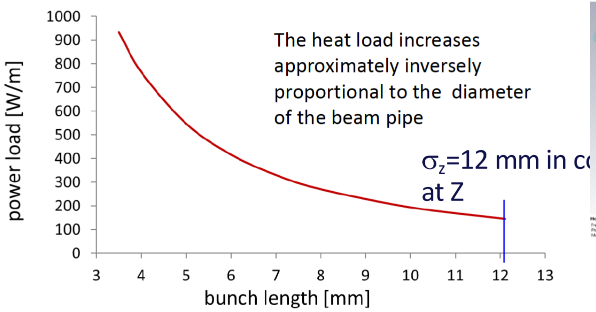


Inner radius 10 mm

Material	thickness
AlBeMet162 (62% Be and 38% Al alloy)	0.35 mm
Paraffin (PF200)	1 mm
AlBeMet162	0.3 mm
Au	5 µm

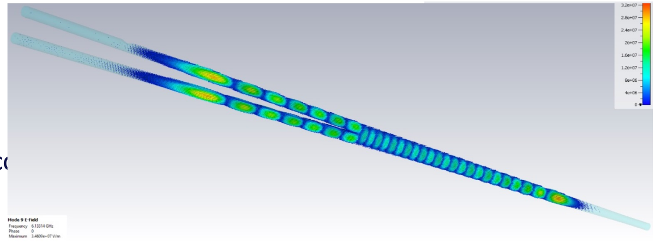
Thickness 1.7mm (X/X0=0.59%)

CDR: inner radius 15 mm for X/X0=0.47%



Heat load due to resistive wakefields vs bunch length for a r=1cm Be central beam pipe.

CST wake-field simulation (A. Novokhatski, SLAC)



Heating power is 260 W for the two beams, most of this power will travel out away from the IP

Collective effects

M. Migliorati (Sapienza & INFN-Roma1) leads the activity for FCC-ee
M. Zobov (LNF)

activity part of FCCIS
co-funded by CSN5 Arya activity

- Impedance budget evaluation in longitudinal and transverse planes:
  - CDR layout, 2IPs done
  - 4IPs present layout with optimization of beam parameters in progress.

    Refined collimators design (SuperKEKB geometry), increased number of bellows, RF baseline cavities 400 MHz
- Single beam collective effects in longitudinal plane: microwave instability

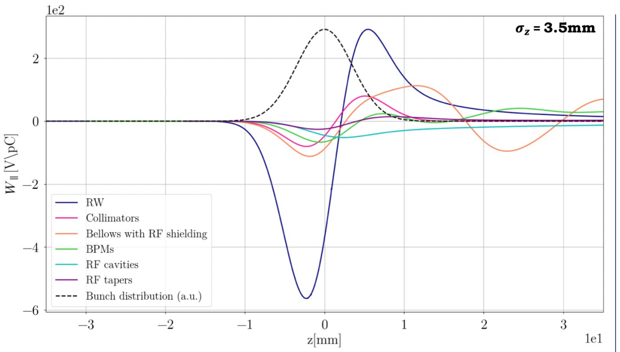
  can be cured with bb
- Single beam collective effects in transverse plane: transverse mode coupling instability (TMCI)

typically not cured in beam-beam collisions. Simulations give us an indication if we can expect problems with the transverse impedance.

- Beam-beam interaction including the longitudinal impedance
- Impedance and collective effects for the FCC-ee Booster (in collaboration with DESY)

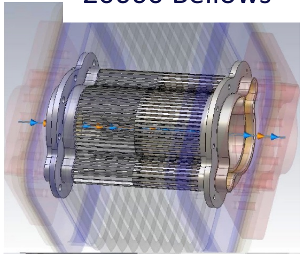
Impedance budget evaluation

Longitudinal impedance model (CDR)

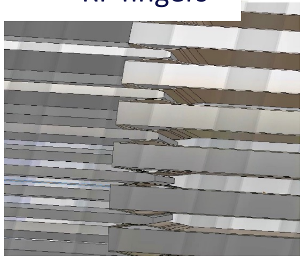


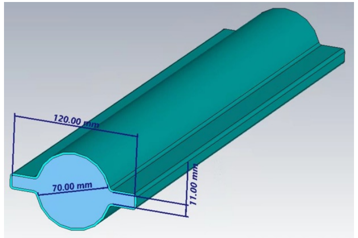
Component	Number	k_{loss}[V/pC]	P_{loss}[MW]
Resistive Wall (100nm)	97.75 km	210	7.95
Collimators	20	18.69	0.7
RF cavities	52	17.14	0.65
RF double tapers	13	24.71	0.93
BPMs	4000	40.11	1.5
Bellows	20 000 ~~8000~~	49.01	1.85
Total		**359.6**	**13.6** 3.7x smaller than 50 MW (SR)

20000 Bellows

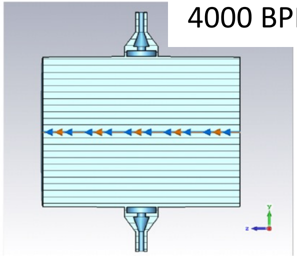


RF fingers

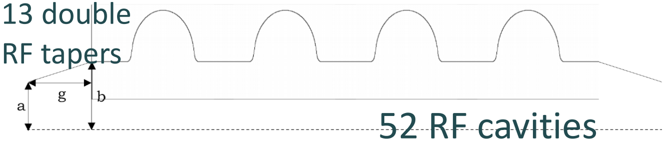




4000 BPM



13 double RF tapers



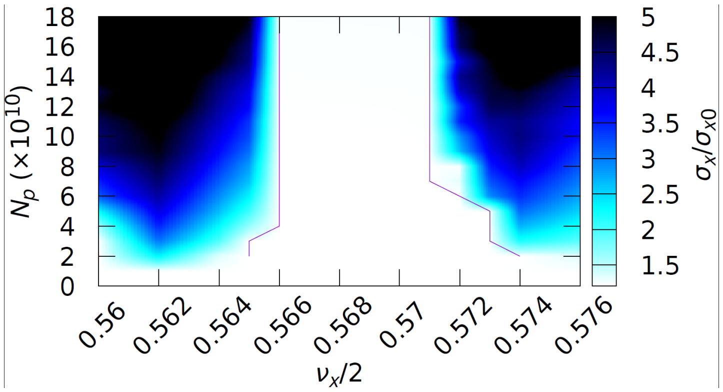
52 RF cavities

update with 4IPs layout and with new parameters table in progress

Horizontal beam size blow-up due to beam-beam interaction coupled to longitudinal impedance

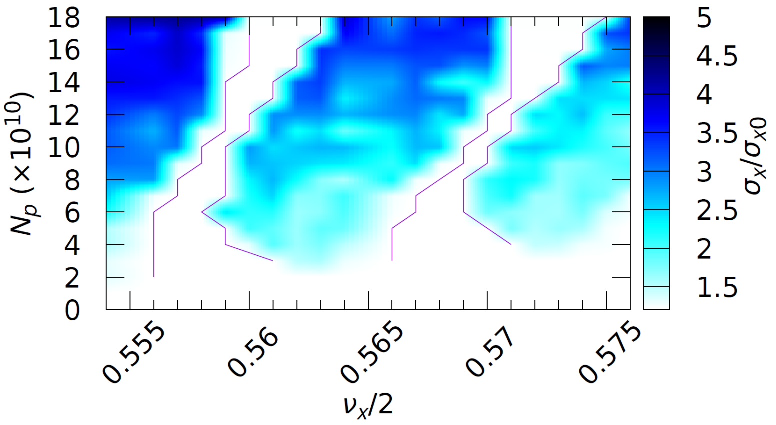
FCC-ee Z pole (CDR parameters)

Without longitudinal impedance



Blow-up of the horizontal beam size $\sigma x / \sigma x\ 0$ as a function of bunch intensity and the horizontal betatron tune without impedance

With longitudinal impedance



Blow-up of the horizontal beam size $\sigma x / \sigma x\ 0$ as a function of the bunch population and of the horizontal betatron tune by including the impedance

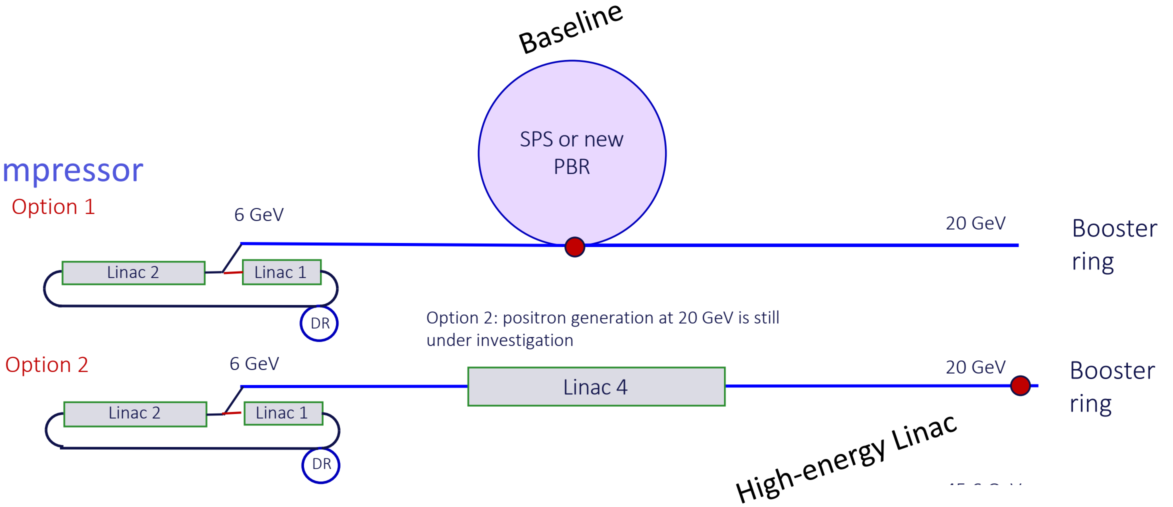
M.Migliorati, M.Zobov, et al. EPJ+ (2021) link

CHART: Founded in 2016 as umbrella organization for accelerator research and technology activities in Switzerland to support FCC via co-funded projects with CERN, PSI, ETHZ, EPFL and U Geneva. Dedicated CHART funding 10.5 MCHF for FCC FS

FCC-ee injector complex

Project in CHART: Collaboration between PSI and CERN with external partners: CNRS-IJCLab (Orsay), BINP (Novosibirsk), **INFN-LNF,** SuperKEKB (interested in the P^3 project) – **observer, INFN-Ferrara – radiation from crystal**

- e- gun
- Linac (two linacs in present scheme)
  - up to 6 GeV
  - positron production
- Damping ring @1.54 GeV
  - Bunch compressor and energy compressor
- Pre-booster ring up to 16 GeV
  - SPS (baseline)
  - Alternative design
- Main booster ring

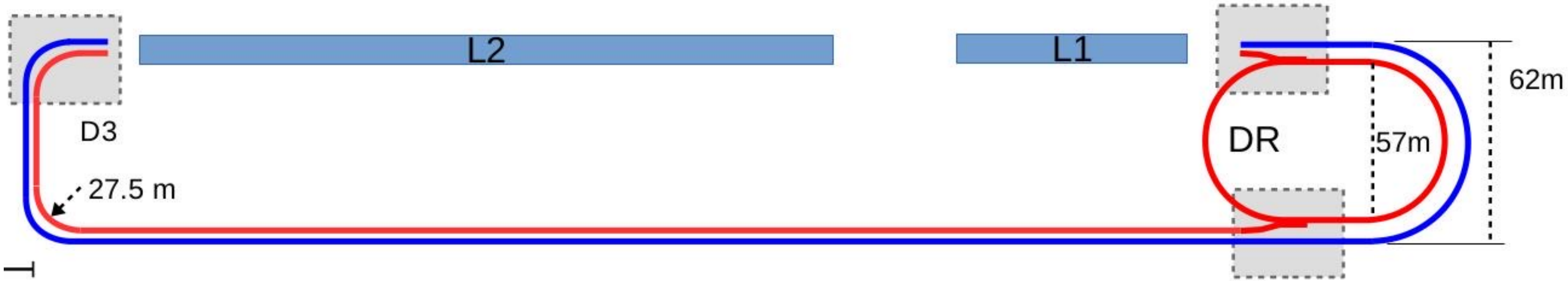


MAIN RINGS

- Transferred to the collider by accumulating current for the full filling or single injection for top-up
- **Interleaved** filling of e+/e- and **continuous top-up** (able to accommodate **bootstrapping**)
- Full filling below **20 min** for both species, but also able to accommodate bootstrapping
- Top-up target time, based on 3-5 % of current drop due to corresponding lifetime

C. Milardi (LNF) leads the activity WP4
A. De Santis (LNF)

FCC_ee Injector complex: transfer line and damping ring (WP4)



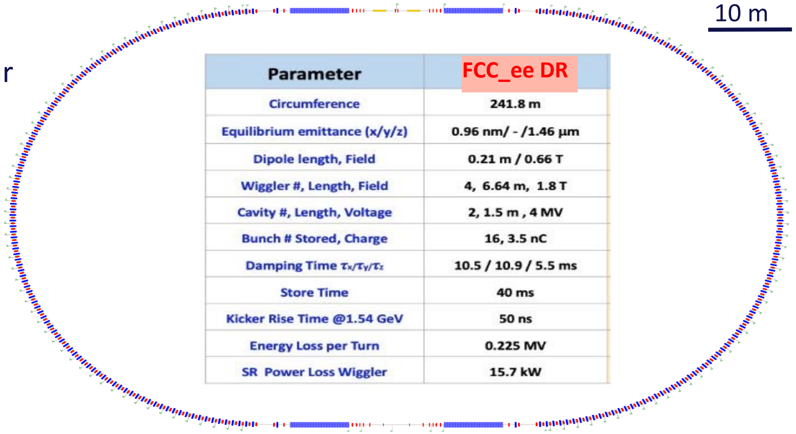
On Going Activities:

- Transfer line start-to-end simulation with PTC and Elegant for electrons
- Design of LINAC to DR for positron Transfer Line

Damping Ring (DR) studies rely on the initial layout provided by K. Oide and S. Ogur

Presently **DR design efforts** aim to:

- define injection and extraction line and equipment
- include a real RF section accounting for proper voltage requirements to optimize energy acceptance, power dissipation and energy consumption
- evaluate DR impedance budget
- define vacuum system
- define beam diagnostics
- study other collective effects such as: IBS, CSR, e-cloud



Parameter	FCC_ee DR
Circumference	241.8 m
Equilibrium emittance (x/y/z)	0.96 nm/ - /1.46 µm
Dipole length, Field	0.21 m / 0.66 T
Wiggler #, Length, Field	4, 6.64 m, 1.8 T
Cavity #, Length, Voltage	2, 1.5 m , 4 MV
Bunch # Stored, Charge	16, 3.5 nC
Damping Time $\tau_x/\tau_y/\tau_z$	10.5 / 10.9 / 5.5 ms
Store Time	40 ms
Kicker Rise Time @1.54 GeV	50 ns
Energy Loss per Turn	0.225 MV
SR Power Loss Wiggler	15.7 kW

PSI Positron Production (P³) project

Experiment to validate

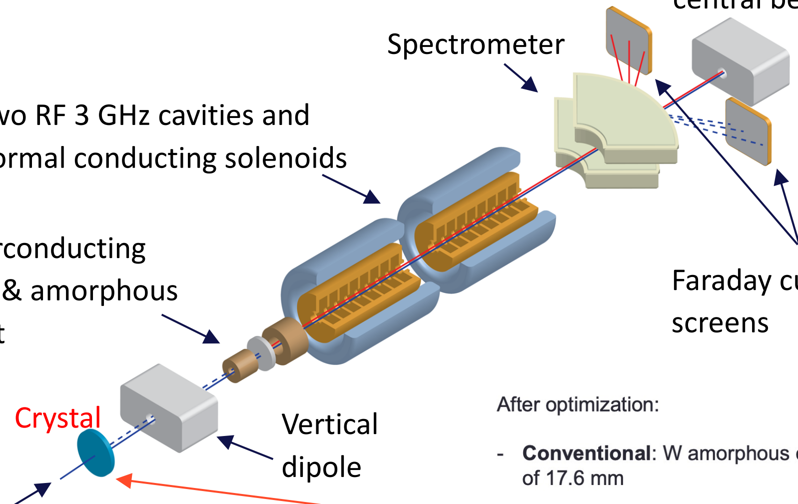
- **Positron Yield > 3** (simulation showed > 5) with conventional scheme (simulation vs measurement), Note: SuperKEKB has recently commissioned the upgraded injection system and has achieved a positron yield of 0.5 at 3.5 GeV (status of art of the positron source in operation)
- AMD: **SC Solenoid with HTS technology** including mech. and thermal (cryostat) concept, HTS technology for the solenoids around the RF structures

- **Phase 2: hybrid scheme with crystal**
  L. Bandiera (INFN-FE)

- decrease of the Peak Energy Deposition Density (2.5!) at the same production rate

scheme	conventional	hybrid[2]
target thickness [mm]	17.6	2 + 10
e^+ production rate $[N_{e^+}/N_{e^-}]$	14.4	15.1
target deposited energy $[\mathrm{GeV}/e^-]$	1.44	0.946
PEDD $[\mathrm{GeV}/\mathrm{mm}^3/e^-]$	0.0416	0.0156

arXiv:2203.07541



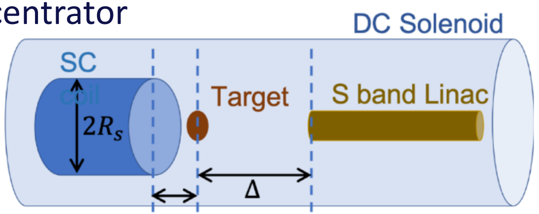
After optimization:

- **Conventional**: W amorphous converter of 17.6 mm
- **Hybrid**: W crystal of 2 mm + W amorphous converter of 10 mm

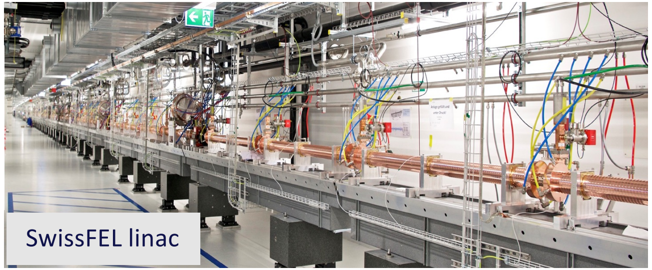
FCC key deliverables: prototypes by 2025

400 MHz SRF cryomodule,
with prototypes of multi-cell cavities
High-efficiency RF power sources

high-yield positron source
target with DC SC solenoid or flux concentrator

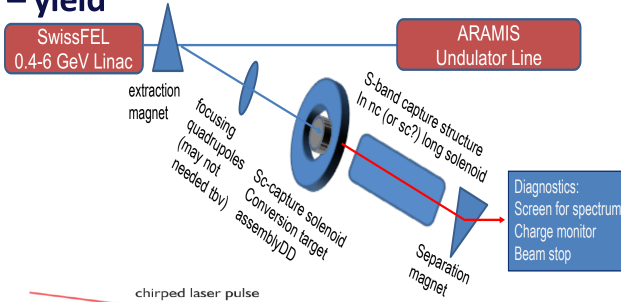


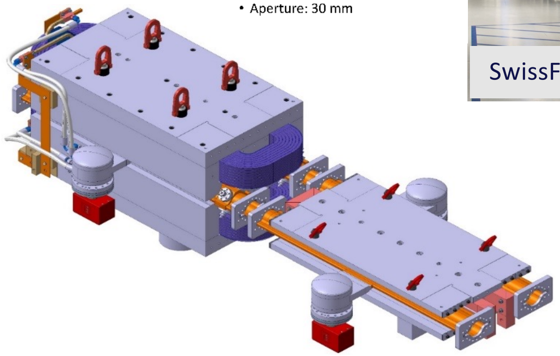
positron capture linac
large aperture S-band linac



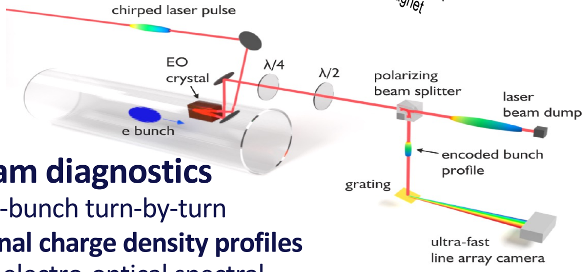
- Freq : 2.856 GHz
- 90 cells per structure
- Length: 3.254 m
- Distance between two TWs: 45 cm
- Gradient: 20 MV/m
- Aperture: 30 mm

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





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

RF system update with 4IPs layout

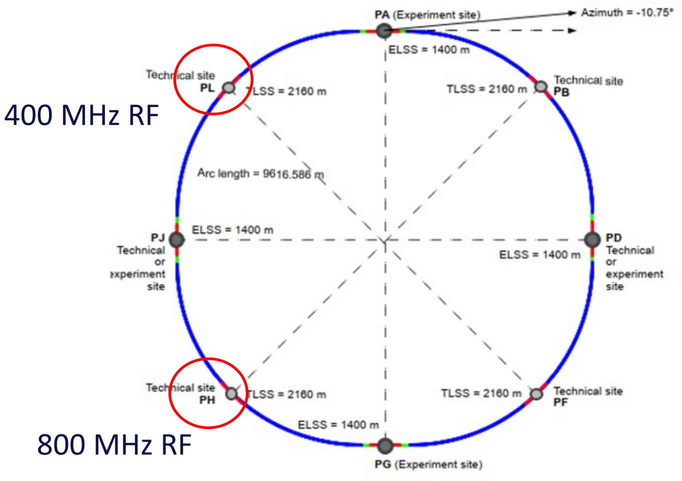
CDR baseline update:

- **Point L**: Z, W and ZH
  - 2 x 2.5 GV @ 400 MHz, 4.5 K
  - 1 x 2.5 GV @ 400 MHz, 4.5 K (booster)
- **Point H**: ttbar
  - + 6.7 GV @ 800 MHz, 2 K
  - + 9.2 GV @ 800 MHz, 2K (booster)
- Beam currents ~ CDR
- Increased charge per bunch
- Increased voltages for Z, W, ZH (~ + 20%)

1 RF point acceleration of e+ and e- in separate RF cavities (low gradient, high current) to eliminate uncertainties on E_{cm} due to beam energy losses (synchrotron radiation, beamstrahlung)

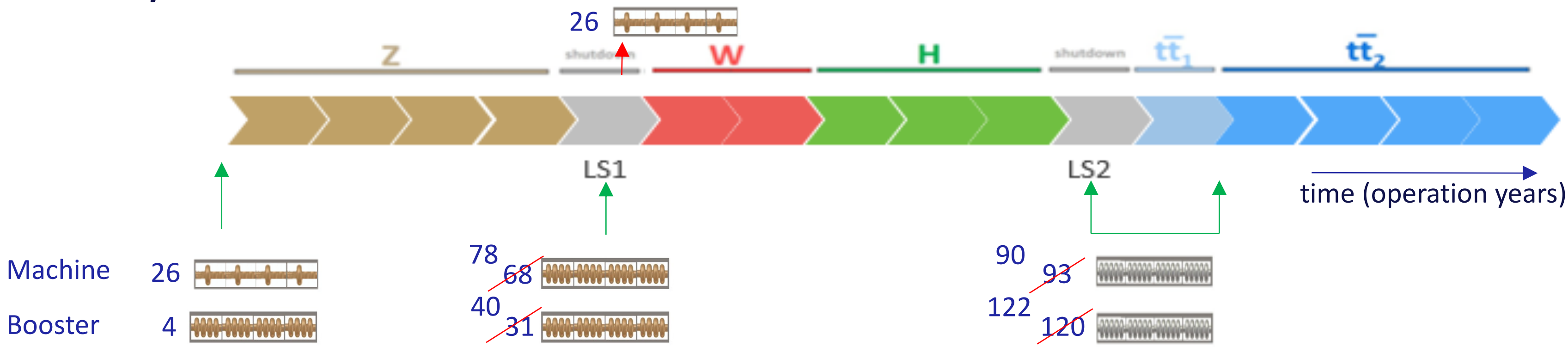
2 RF points at ttbar, e+ and e- acceleration in the same RF cavities (low current, high gradient)

Parameter	Z	W	H	ttbar
Beam Energy [GeV]	45.6	80	120	182.5
Beam current [mA]	~~1390~~ **1400**	~~147~~ **135**	~~29~~ **26.7**	~~5.4~~ **5**
Number of bunches	~~16640~~ **8800**	~~2000~~ **1120**	~~328~~ **336**	~~48~~ **42**
Beam RF voltage [MV]	~~100~~ **120**	~~750~~ **1000**	~~2000~~ **2500**	~~10930~~ **11670**
Runtime [year]	4	1	3	**4**



TIWG 29/09/2021

Updated 400 / 800 MHz scenario



- Designed for fixed synchrotron radiation power of 50 MW per beam
- Elliptical shape

R&D is necessary to reduce cost and increase reliability of the cavity production process and operation

- 400 MHz 1-cell cavities
- Nb/Cu, 4.5 K
- 104 cavities
- Eacc =5->6 MV/m
- 1 MW /cav
- 4 cav./cryom.
- Re-used for FCC-hh

- 800 MHz 5-cell cavities
- bulk Nb, 2 K
- 852 cavities
- Eacc=20 MV/m
- 200 kW/cav.
- 4 cav./cryom.

Italy has been involved since the birth of the idea of a e+e- circular collider in 2012 (LEP3-TLEP-FCC)

	2012	**TLEP workshops**
Snowmass	2013	14/Feb. 2013 LNF mini-Workshop: Higgs Factories LEP3 and TLEP, Physics opportunities
	2014	Oct '14 MoU INFN-FCC (CDR)
	2015	1st FCCWEEK15 Washington DC
	2016	2nd FCCWEEK16 Rome
	2017	FCC CDR
	2018	
	2019	
EPPSU	2020	
	2021	New MoU INFN-FCC (FS)
Snowmass	2022	
	2023	FCC FS
	2024	
	2025	
EPPSU	2026	

new collision scheme named **crab-waist allows to enhance luminosity: Italian contribution [Pantaleo Raimondi, LNF] opens the possibility for high luminosity e+e- circular collider**
(2006 for SuperB, validated at DAFNE in 2008)
All future e+e- colliders are based on this concept

CERN-OPEN-2011-047
20 January 2012
Version 2.9
arXiv:1112.2518v1 [hep-ex]

A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson

Alain Blondel[1], Frank Zimmermann[2]
[1]DPNC, University of Geneva, Switzerland; [2]CERN, Geneva, Switzerland

As well for FCC-hh

First FCC-Italy workshop 21-22 March 22

Strong interest by the President and the INFN Board to consolidate the Italian collaboration in FCC

04 APRILE 2022

IL PRIMO WORKSHOP ITALIANO SUL GRANDE ACCELERATORE DEL FUTURO

Si è recentemente tenuto a Roma il First FCC-Italy Workshop, il primo workshop italiano dedicato al progetto per il successore del Large Hadron Collider al CERN, il Future Circular Collider All'evento, organizzato dall'INFN, hanno partecipato 120 ricercatori e ricercatrici, e sono state presentate 15 relazioni.

Nell'ultimo documento sulla strategia europea per la fisica delle particel approvato dal Council del CERN nel giugno 2020, FCC è indicato come il progetto futuro di massima priorità: da qui è iniziato un vasto programm di studi di fattibilità, che costituirà un input importante per la prossima edizione dell'Update della Euroepan Strategy for Particle Physics.

Il progetto FCC prevede una nuova macchina acceleratrice molto più potente dell'attuale LHC, con una circonferenza di circa 91 km in un tunnel sotto il territorio francese e svizzero, in prossimità del CERN per sfruttarne le infrastrutture già esistenti. In una prima fase (FCC-ee il tunnel dovrebbe ospitare un collisore di elettroni e positroni di energia variabile da 90 a 365 GeV. Successivamente, questo verrebbe sostituito da un collisore di protoni (FCC-hh) con un'energia nel centro di massa di 100 TeV, quasi un ordine di grandezza superiore a quel di LHC. L'idea è di partire con FCC-ee e in parallelo proseguire il lavoro di R&D necessario per realizzare i dipoli di 16 T necessari a mantenere la traiettoria dei protoni di 50 TeV di energia all'interno dell'anello.

"Con FCC si lavora a una grande infrastruttura che garantirebbe all'Europa di mantenere la sua leadership nella ricerca in fisica delle alte energie: il progetto è dunque di importanza strategica nel panorama internazionale negli anni a venire", ha sottolineato Antonio Zoccoli, presidente dell'INFN, nel suo discorso di apertura in occasione del workshop. "L'INFN ha grandi potenzialità e può dare un contributo notevole alla sua realizzazione: in questa prospettiva è quindi importante identificare con chiarezza le principali attività dove investire, coalizzare le necessarie risorse umane e individuare possibili partner industriali".

https://home.infn.it/it/news-infn/news-comunita/4810-il-primo-workshop-italiano-sul-grande-acceleratore-del-futuro

https://agenda.infn.it/event/29752/

Agenda FCC-Italy workshop

21 March

Chair P. Campana	
Welcome – importance of FCC for the INFN scientific programme	**A. Zoccoli**
Summary Laboratory Directors Group (LDG) RoadMap	**F. Bossi**
The FCC feasibility study	**M. Benedikt**
The FCC-ee design	**F. Zimmermann**
Discussion	

Chair L. Rossi	
Technology opportunities in FCC-ee	**R. Losito**
FCC Accelerator activities: Italian involvement	**M. Boscolo**
Discussion	
New technology in SRF	**C. Pira**
SRF: INFN participation in large projects	**L. Monaco**
Italian activity in the High field magnet program for FCC-hh	**S. Farinon**

22 March

Chair C. Meroni	
FCC-ee Detector concepts	**F. Bedeschi**
FCC-ee: RD su Tracking	**P. Giacomelli**
FCC-ee: R&D Calorimetry for the IDEA detector	**R. Ferrari**
Discussion	
FCC-hh: Detector challenges	**M. D'Onofrio**
Discussion	

Chair R. Tenchini	
FCC physics: importance for HEP and challenges in theory and phenomenology	**F. Piccinini**
Physics and simulation studies	**P. Azzi**
Discussion and Outlook	

Opportunities for collaboration

In addition to well consolidated activities, in place with EU-fundings & MoUs

- Interaction Region design
- Collective effects
- Damping Ring and transfer lines

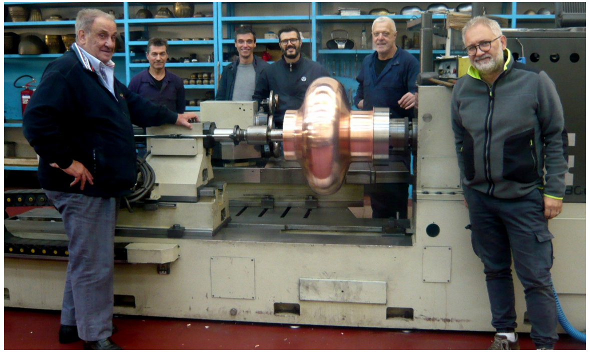
Other opportunities

- Prototyping/ Mock-up of FCC-ee Interaction Region components
- Detector activities on the Machine-Detector-Interface study (i.e. vertex, lumical) related to CSN1/ RD_FCC

reinforce and strengthen existing activity. Heart of the collider design, highly qualifying and visible

- FCC-ee IR magnets (interest expressed by INFN-Ge)
- FCC-ee magnets
- SRF

LNL SRF Activities



First 400 MHz seamless elliptical cavity prototype

Forming via spinning of seamless 400 MHz elliptical cavities Collab. Agreement with FCC (2015-2019)

The feasibility to produce a 400 MHz seamless cavity was demonstrated

Further developments are necessary to avoid cracks, increase geometry accuracy and internal surface quality

Surface Treatments by Plasma Electrolitic Polishing Funding CSN5 Samara

Nb_3Sn on Cu coatings 1.3 GHz prototype in 2025 Funding CSN5 Samara & iFAST

R. Losito
Courtesy J. Bauche

Opportunities for collaboration - Magnets

- **Development of large-scale manufacturing techniques for production of:**
  - Solid iron yokes
  - Laminated yokes
  - Extruded and coated copper and aluminum busbars
  - Impregnated coils

  Objectives:

  - Identification of suitable cost-effective techniques for high precision magnet yoke production with high repeatability (incl. automated processes for machining, measurements, assembly and welding)
  - Elaboration of a production plan with schedule and spending profile

- **Design and prototyping of sextupole magnet for the collider**

  Objectives:

  - Rework the design to match the updated specifications
  - Produce and measure a prototype magnet to validate the performance (field intensity and quality)

Other Opportunities

R. Losito

- The detailed design of FCC-ee is just at the beginning, many opportunities will appear in the next years
  - Beam Instrumentation
  - Dumps & Collimators
  - Injection/extraction
  - Mitigation of Radiation to Electronics
- Opportunities may exist as well in
  - Organization topics, e.g. quality & project management
  - Engineering support, e.g. creating and implementing a vision for the design and operation of a machine that will run in 20 years from now: Digital twins, remote control and maintenance, spare management etc…

Conclusion

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 in all domains.

Unique (might be the only one) opportunity for the community involved on high luminosity and high energy colliders!

Italian contribution well in place at the coordination and individual activity level, need to follow the acceleration of the project to secure full support, strongly needed for its success.

Additional material

Parameters

FUTURE CIRCULAR COLLIDER

$\beta_x^* = 10\,\text{cm}$ @Z

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.219
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	2.00 / 2.80
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	4.0 / 7.25
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.1
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.091 / 0.139
Luminosity / IP	[10^{34}/cm^{2}s]	182	19.4	7.26	1.24
Lifetime (q + BS)	[sec]	–		1065	5090
Lifetime (lum)	[sec]	1129	1070	596	752

[a] incl. hourglass.

$\beta_x^* = 15\,\text{cm}$ (Nov . 29)

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		9600	880	248	36
Bunch population	[10^{11}]	2.53	2.91	2.04	2.64
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	150 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.130	0.069 / 0.154	0.103 / 0.185	0.157 / 0.229
Bunch length (SR/BS) σ_z	[mm]	4.37 / 14.5	3.55 / 8.01	3.34 / 6.00	2.02 / 2.95
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	4.0 / 7.25
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Beam-beam ξ_x/ξ_y[a]		0.0040 / 0.152	0.011 / 0.125	0.014 / 0.131	0.096 / 0.151
Luminosity / IP	[10^{34}/cm^{2}s]	189	19.4	7.26	1.33
Lifetime (q + BS)	[sec]	–		1065	2405
Lifetime (lum)	[sec]	1089	1070	596	701

[a] incl. hourglass.

- By squeezing β_x^*, bunches/ring (bunch population), bunch length, energy spread also change. All affect the luminosity.
- $\xi_y \lesssim 0.14$ is set as a criterion (also set at $t\bar{t}$ this time).
- The betatron tunes are not yet chosen perfectly considering the instability.

FCC stage 1: infrastructure and FCC-ee project cost estimate and spending profile

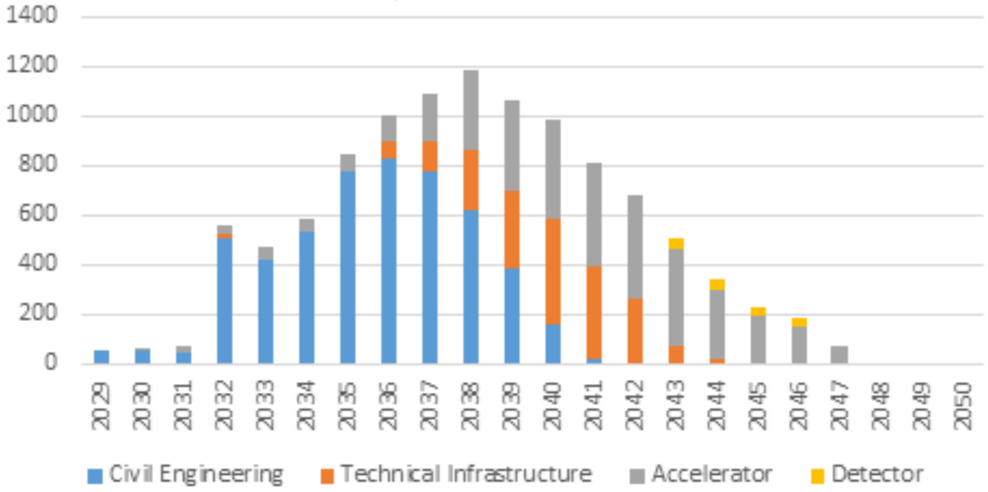
Construction cost estimate for FCC-ee

- Machine configurations for Z, W, H working points included
- Baseline configuration with 2 detectors
- CERN contribution to 2 experiments incl.

cost category	[MCHF]	%
civil engineering	5.400	50
technical infrastructure	2.000	18
accelerator	3.300	30
detector	200	2
total cost (2018 prices)	10.900	100

Spending profile for FCC-ee

- CE construction 2032 - 2040
- Technical infrastructure 2037 - 2043
- Accelerator and experiment 2032 – 2045
- Commissioning and operation start 2045 -2048.



Support from CERN Host States

8 Nov 2021: The **Préfet de la region Auvergne-Rhone-Alpes** was nominated by the **French Prime Minister Jean Castex** as "interlocuteur unique des autorités Swiss et du CERN" **to accompany CERN during the FCC Feasibility Study for all infrastructure related aspects, in concertation with Switzerland** and to ensure the compliance with all relevant rules. In particular, the Prime Minister asked the Préfet to establish, by the end of the year 2021, an organization diagram for the management of his mission, as well as a calendar identifying the actions to be taken in order to respond to CERN's requests, and to report regularly on the progress on the mission and make proposals to allow France to facilitate the execution of the feasibility study.

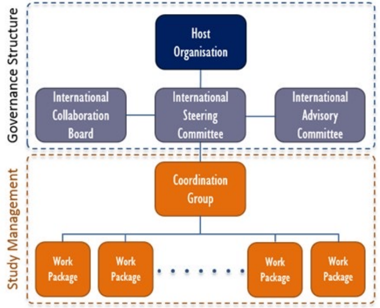
10 Dec 2021: The **Swiss Federal Council** announced that it will draw up a **federal sectoral plan** in order to clarify and facilitate the administrative procedures for spatial planning and **to improve planning security for all CERN projects, including the FCC** in the event of its implementation. The sectoral plan, which also responds to a request from the Republic and Canton of Geneva, will provide a framework for balancing the objectives of research policy, host-state policy and spatial planning policy.

Collaborations

- H2020-INFRADEV design study on:
  - FCC-hh: **EUROCIRCOL** 2015-2019
  - FCC-ee: **FCCIS** 2020-2024
- Other EU fundings where some FCC activities are included:
  - **EASITRAIN** 10/2017 – 09/2021
  - **I.FAST** (followed from ARIES)
- Other activities agreed with MoUs
  - Swiss Chart collaboration: Damping Ring & Transfer lines (LNF)
  - High field magnet program prototype 14 T dipole (but not part of the FCCFS)
  - Uni. Genova, Uni-Roma Tre, CNR-SPIN on High field superconducting materials

FCC Feasibility Study - organisational structure

- New structure very similar to the first phase of the FCC Study (2014-2020), leading to the Conceptual Design Report as input to the ESPPU.



- Classical structure common to CERN projects.

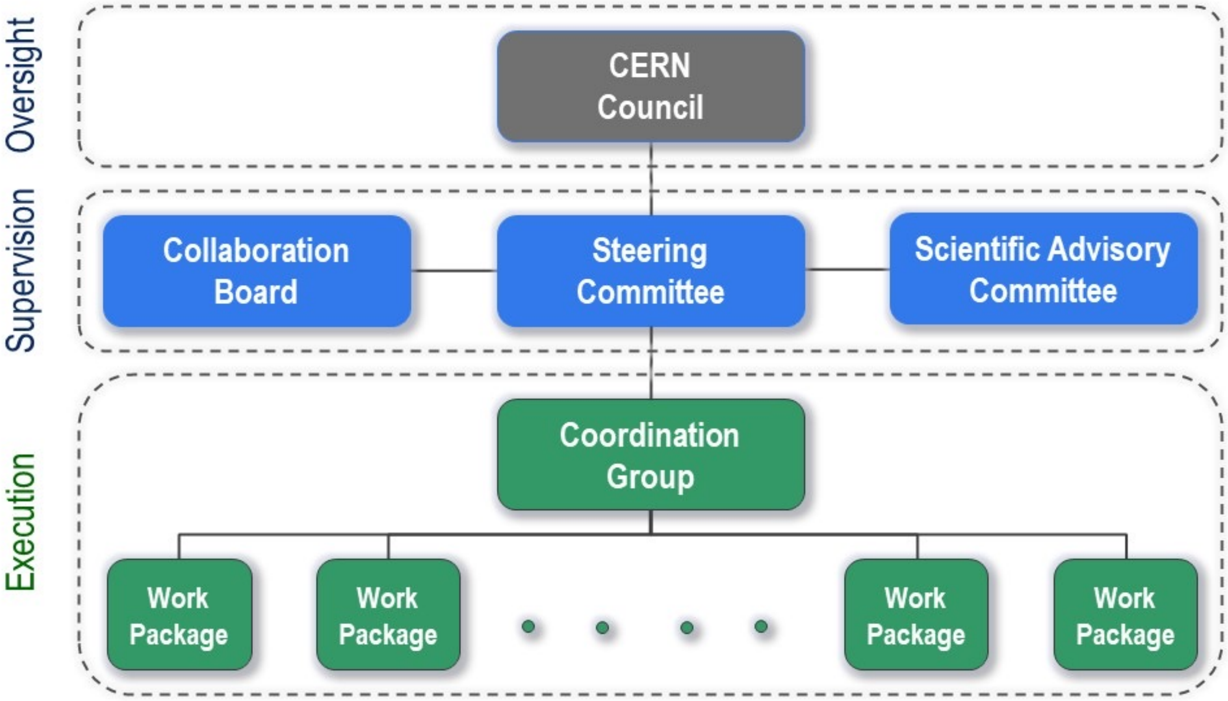
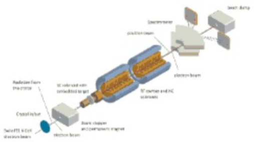


CHART – Switzerland

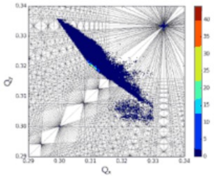
FUTURE CIRCULAR COLLIDER

Swiss Accelerator Research and Technology



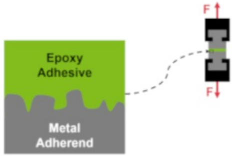
FCCee Injector

Design and positron production test program for FCC-ee Injector



FCChh Stability

Long term coherent stability and diffusion studies for the Future Circular Hadron Colliders



MagAM

Additive Manufacturing for Structural Components in Superconducting Coils

MagDev1

Superconducting Accelerator Magnet R&D

MagNum

Sustainable and Consistent Integrated Modelling of Superconducting Magnets

MagRes

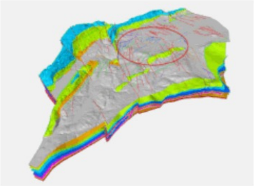
Development of optimized resin systems for SC magnet coil production

FCCee-Beam Dynamics Simulations

Accelerator design and simulation framework for FCC-ee: optics and collective effects

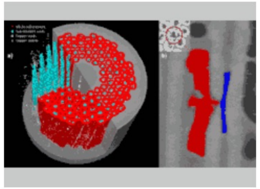
FCC Geodesy

Determination of a high-precision gravity field model for the FCC region and improvement of the Geodetic Reference Frames and the Geodetic Infrastructure



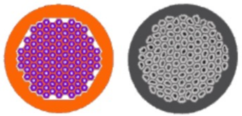
FCC Geology 3D Model

Development of a high-resolution 3D geological model and associated GIS-based subsurface data set for the FCC tunnelling work



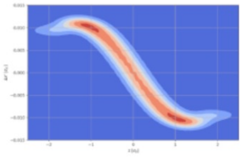
WireChar

Multiphysical characterization of Nb3Sn wires and of REBCO coated conductors



WireDev

Development of recipes and methods for the fabrication of Nb3Sn multifilamentary wires with enhanced current carrying capabilities



FCC / LHC-Lumi

Luminosity Precision Measurements for Hadron Colliders

Founded in 2016 as umbrella organization for accelerator research and technology activities in Switzerland to support FCC via co-funded projects with CERN, PSI, ETHZ, EPFL and U Geneva. Dedicated CHART funding 10.5 MCHF for FCC FS

FCC-ee figures of merit – cost & sustainability

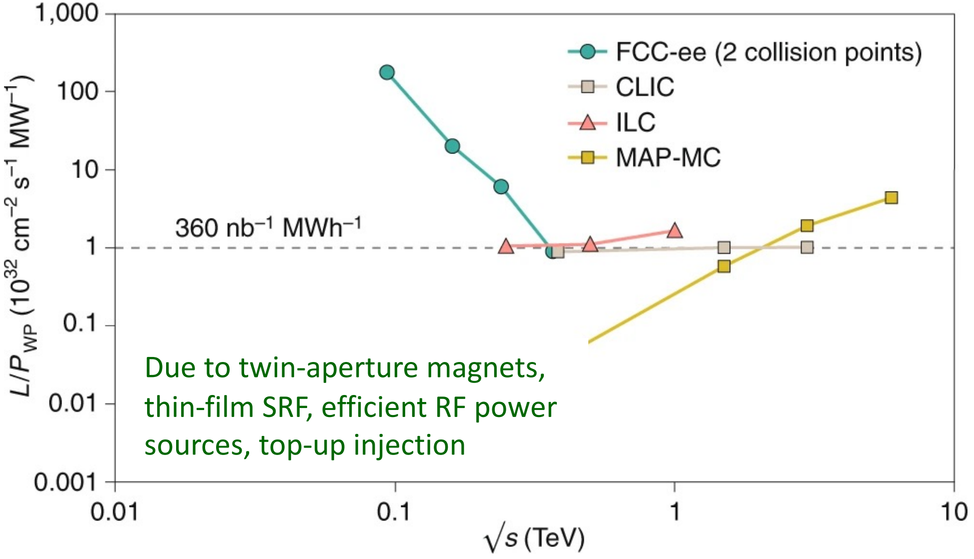
Luminosity vs. capital cost

- 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 5×10^{12} Z produced, the total investment cost corresponds to → 10 kCHF per 5×10^6 Z bosons

This is 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

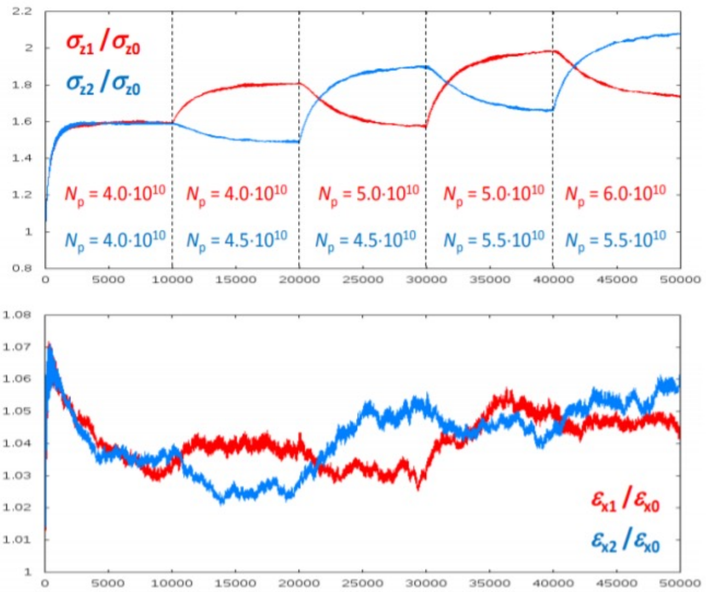


Highest lumi/power of all proposals
Electricity cost ~200 CHF per Higgs boson

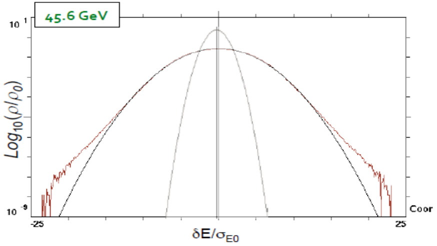
M. Benedikt, A. Blondel, P. Janot, et al., Nature Physics 16, 402-407 (2020), and European Strategy for Particle Physics Preparatory Group, Physics Briefing Book (CERN, 2019)

“bootstrapping” & top-up injection

injection from zero, alternating between beams to avoid beam-beam flip-flop effect



beam energy spectrum without/with beamstrahlung

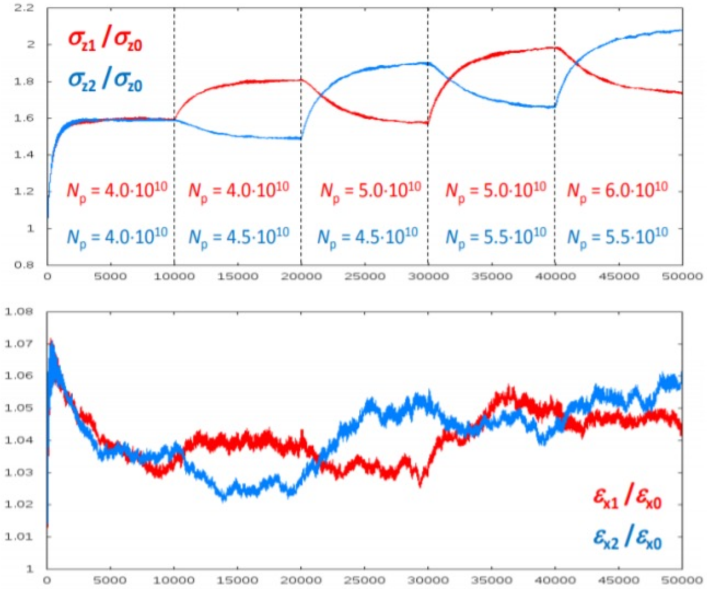


- **With the nominal bunch population required for high luminosity, σ_z increases ~3.5 times because of beamstrahlung**

- If we bring into collision so large currents with the “initial” σ_z (energy spread created only by SR), the beam-beam parameters will be far above the limits.
- The beams will be blown up and killed on the transverse aperture, before they are stabilized by the beamstrahlung.
- To avoid this, **we must gradually increase the bunch population during collision**, so we come to bootstrapping.

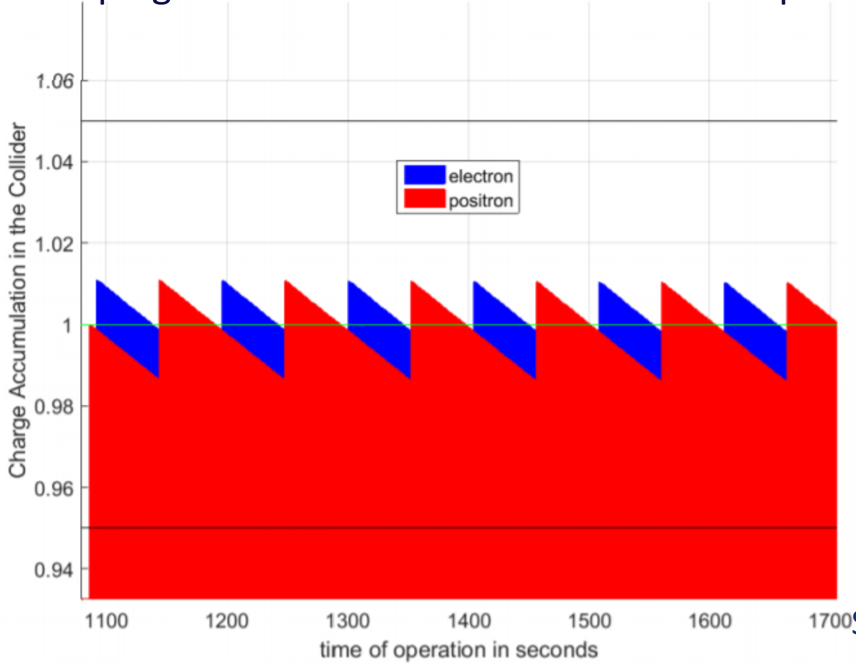
“bootstrapping” & top-up injection

injection from zero, alternating between beams to avoid beam-beam flip-flop effect



D. Shatilov

alternating replenishment of the two colliding beams, keeping beam currents stable within a few per cent



S. Ogur

average luminosity ~ peak luminosity

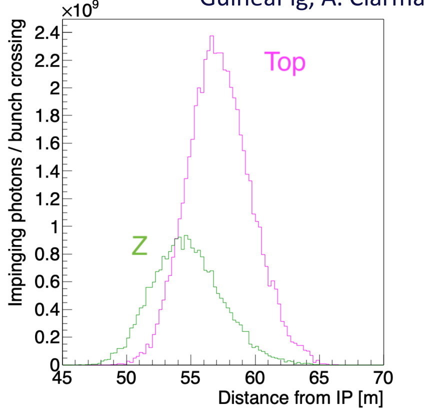
Beamstrahlung monitor for center-of-mass energy measurements

Radiation from the colliding beams is intense (380 kW over cm^2 section!)

Beam energy	Beamstrahlung Radiation power	<Eγ>
45.6 GeV	387 kW	2 MeV
182.5 GeV	89 kW	67 MeV

M. Boscolo et al : IPAC21 MDI

GuineaPig, A. Ciarma



potentially very precise monitoring of collision offsets in both x and y.

-- operations

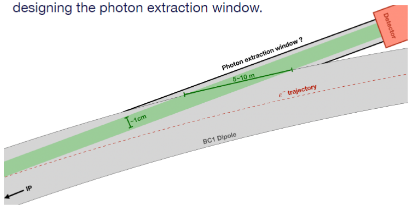
-- centre-of-mass energy control

-- basically un **instrumented beam dump**.

What detector system?

high rad situation akin to neutrino beam monitoring!

While the spot size is ~1x1cm², due to the very small impinging angle on the beam pipe wall (~1mrad) the region hit by the photons is **several meters long** on the longitudinal dimension, so this should be taken in consideration when designing the photon extraction window.

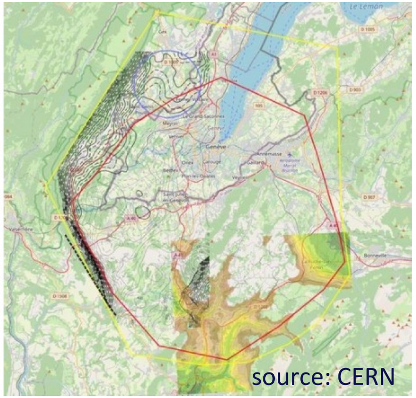


- The direction and intensity of the **beam-beam kick** are proportional to the offset between the beams.
- Because the radiation is produced collinear to the beams, it will carry the information of the offset.

Implementation studies

Accelerator design

- Scaling and adaptation of the CDR design (FCC-ee and FCC-hh) to the new layout.
- Integration with injector complex (LHC and/or SPS tunnels)
- Update of requirements on technical infrastructure for all surface points



source: CERN

Technical infrastructure

- Update of system parameters for all surface sites
- Scaling of CDR concepts to new parameters
- Verification of availability and connections to services

Civil engineering and associated activities

- Adaptation of CE project to 8-site layout, taking specific surface site location into account
  - Shaft depths < 300 m at experiment sites
  - Shaft depths < 400 m at technical sites
  - Stay below 50 m below lake bed

(example of some constraints)

- Update of construction concept (excavation methods, TBM lowering, etc.) and schedule

Construction of the FCC underground infrastructure would lead to about 9 million m^3 of **excavated materials**, mainly molasse. Study ongoing for its use.

Placements studies (ii)

J. Gutleber, V. Mertens

Target areas