FCC
ACCELERATORS & INFRASTRUCTURES TECHNICAL DESIGN

JP. Burnet, T. Raubenheimer, K. Hanke

FCC Week 2024

10/06/2024

We all dream of a new machine that allows us to increase our knowledge about universe

Focus on performance & luminosity

Let’s build it

Focus on safety, sustainability feasibility, and affordability

First, we need an accelerator technical design

Then we can design the technical infrastructures to host it

In fact, it is more an iterative process

FCC-ee Accelerators organisation

New Pilar

Accelerators FCC-ee F. Zimmermann, T. Raubenheimer

Accelerator Technical Design
JP. Burnet, T. Raubenheimer
- Beam transfer systems
- Beam instrumentations
- Beam Intercepting Devices
- Magnets, MDI
- Vacuum
- Power converters
- Radiation & shielding
- Radio Frequency
- Survey & alignment
- System engineering and interface management

- *Radiation WG*
- *MDI WG*
- *Arc cell mock-up WG*
- *Systems engineering and interface management*

Collider & Booster Design
F. Zimmermann, C. Carli
- Parameters
- Optics
- Beam dynamics
- OP parameter interface
- Operation concept incl. BBA
- Machine protection
- Polarisation & energy calibration
- Interfaces

- *Booster design WG*
- *EPOL WG*
- *Machine protection WG*

Transfer Lines Design
W. Bartmann
- Parameters
- Optics
- Beam dynamics
- OP parameter interface
- Operation concept incl. BBA
- Machine protection
- Interfaces

Injector 20GeV
P. Craievich, A. Grudiev
- e-/e+ sources
- Linacs
- Damping ring

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Accelerator Technical Design
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Accelerator Technical Design Coordination

- Guide the technical design of all accelerator components, based on input from accelerator design pillar
- Enable development of overall optimized integrated systems and solutions across technologies
- Assure the interfacing to and design optimization with technical infrastructure systems and accelerator design.
- Optimisation of investment/operation cost and performance
- Integration of eco-design and sustainability aspects (energy saving modus, etc.)

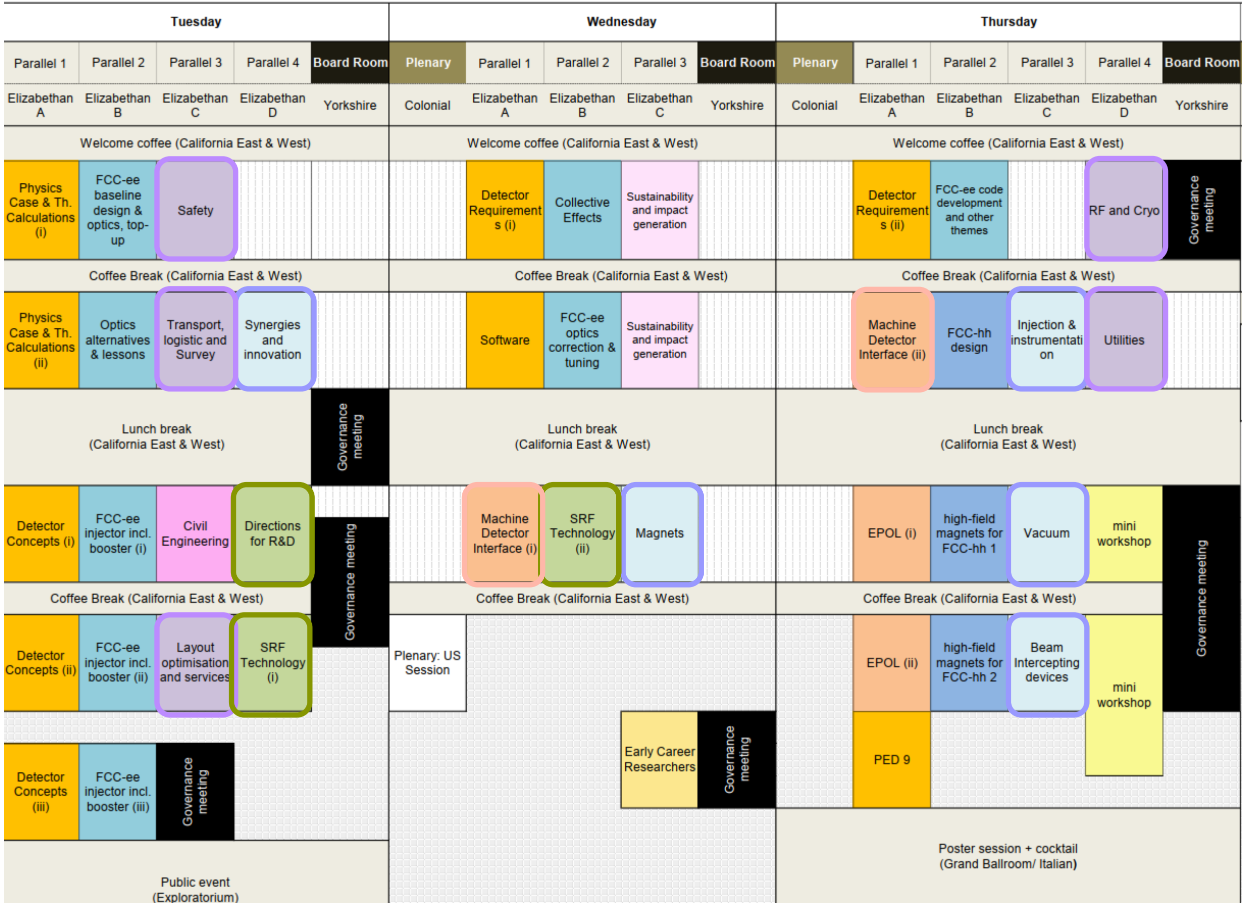
<u>ATDC kick-off meeting</u> 28.03.24

5 sessions on
Accelerator Technical Design

5 sessions on
Technical Infrastructures

3 sessions on SRF technology

2 sessions on MDI



Accelerator Technical Design

Technical infrastructures

SRF technology

MDI

FCC-ee Accelerators & Infrastructures Technical Design

Main objectives

➢ Safety	Develop safe concepts
➢ Sustainability	Reduce the environmental impact
➢ Feasibility	Identify challenges and propose solutions
➢ Affordability	Cost optimisation
➢ Performance	Reach physics objectives

Design focused on these criteria

FCC-ee Accelerators & Infrastructures Technical Design

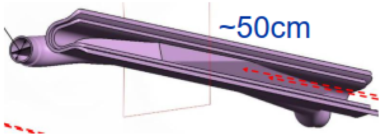
Some highlights since the Mid-term report

- Synchrotron radiation & ionizing doses & shielding
- Vacuum innovation
- Global optimisation tool
- Superconducting RF, R&D for energy performance
- HTS4 alternative
- Polarimeter
- Integration update
- Personnel transport
- Radioprotection
- Cooling

FCC-ee Collider arcs: Synchrotron Radiation Absorbers & ionizing dose

New Radiation and shielding Working Group, Anton Lechner (SY/STI), started 14 Feb. 2024

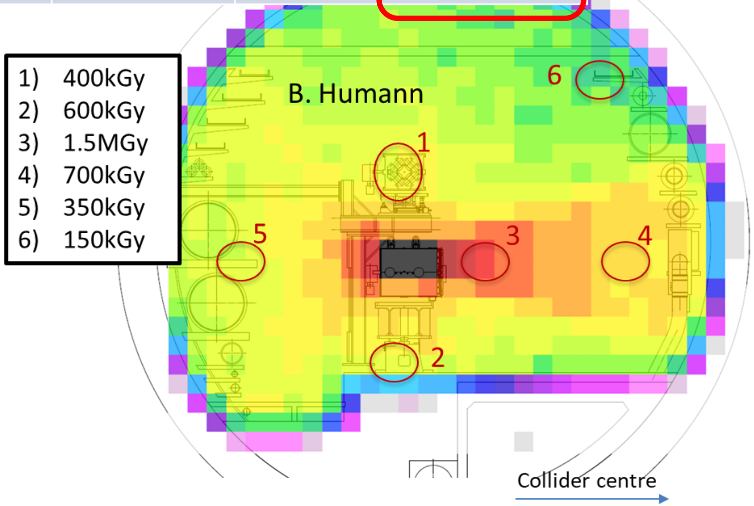
- **Discrete** photon absorbers (a la SuperKEKB), made of **copper-alloy**, are placed every few meters in the winglets of the vacuum chamber to intercept the primary SR fan (R. Kersevan et al., TE/VSC)



- **Need further measures, since the dose values are too high for different kinds of equipment**
- Possible measures include:
  - **Additional (local) absorbers on the outside of the vacuum chambers**
  - Choice of technologies (e.g. replace cables with wireless technologies where possible)
  - Radiation-hard design where unavoidable

	LEP (100GeV, 15A*h)	HL-LHC (per year)	FCC-ee (182.5GeV, 15A*h)
2)	2.25kGy	1.4Gy	600kGy
5)	50.3kGy		350kGy
6)	4.5kGy		150kGy

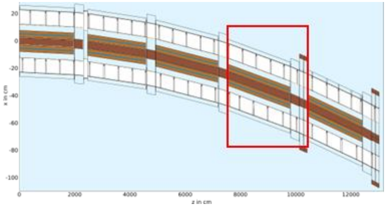
Per year @ttbar (w/o booster contribution)



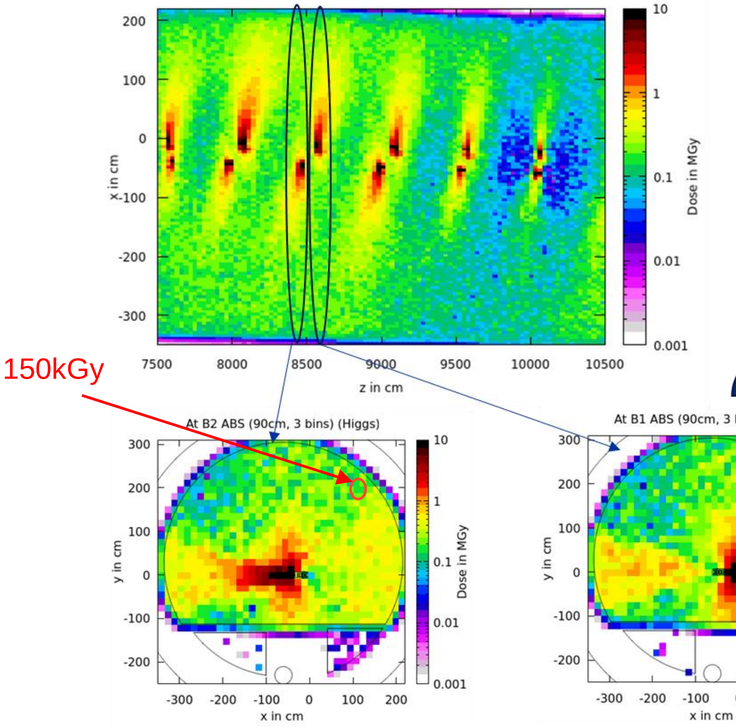
Feasibility

Dose levels in the tunnel without shielding

FLUKA simulations by Barbara Humann, dose in MGy



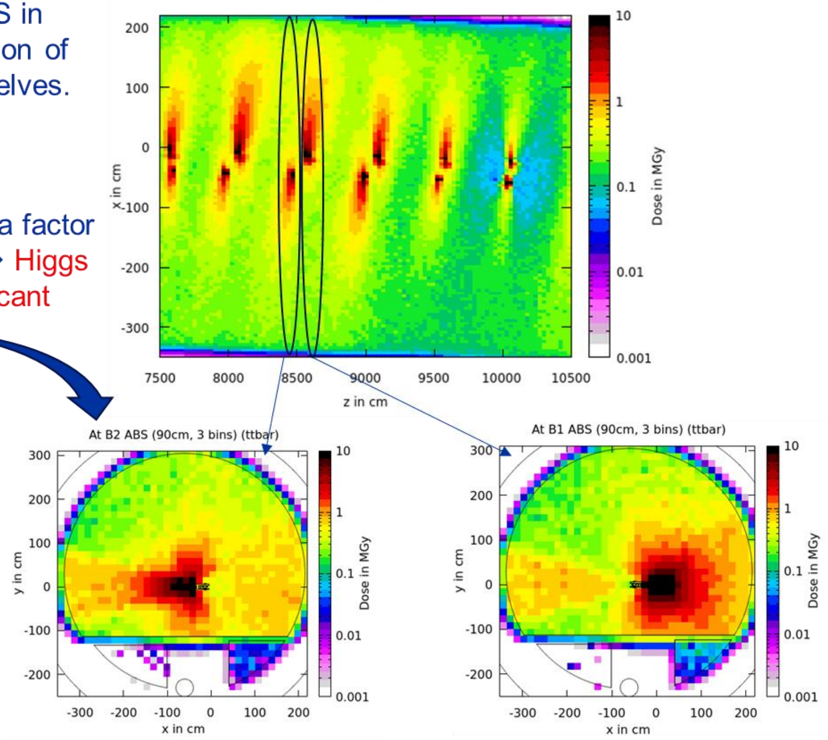
Higgs



Hot-spots due to ABS in the longitudinal position of the absorbers themselves.

Higgs to ttbar: up to a factor of three difference → Higgs contribution is significant

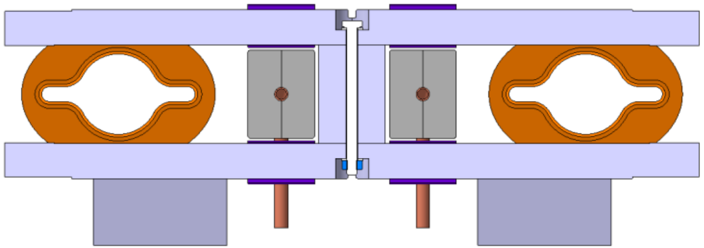
ttbar

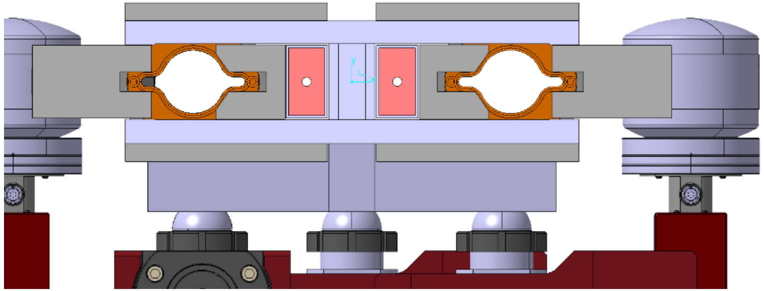


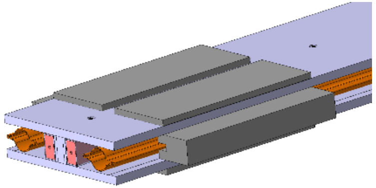
Lead shielding integration in magnets

60cm long lead shielding around each SR absorbers

+ 2300 kg / dipole
13ktons of lead in total





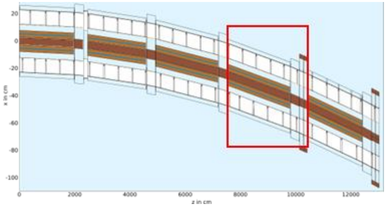


	Higgs	ttbar
MBs (w/o VC)	27.1kW	28.8kW
MB VC	3.4kW	4kW
MQs (w/o VC)	1.5kW	1.7kW
MQ VC	0.4kW	0.4kW
MSs (w/o VC)	0.01kW	0.04kW
MS VC	0.003kW	0.02kW
ABS (w/o VC) (~72%)	118.3kW	112.8kW
ABS VC	4.8kW	4.4kW
Tunnel (Air, Concrete)	8.7kW	12.3kW
TOTAL	**164.2kW**	**164.4kW**

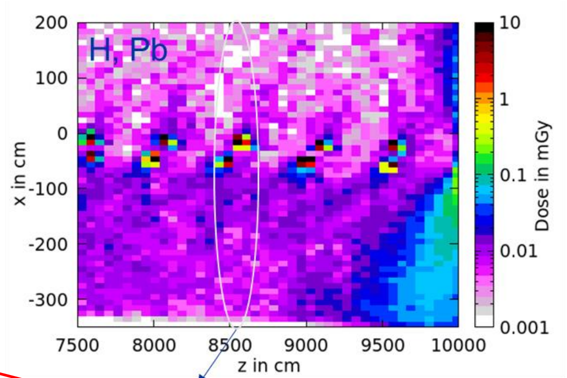
Operation mode — Shielding material

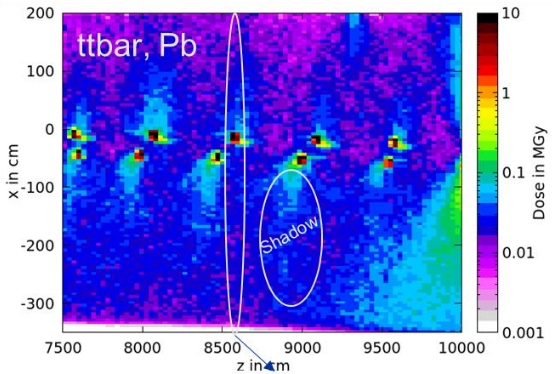
Component	H, Pb	ttbar, Pb	ttbar, W
Dipoles	6.8kW	7.7kW	5.3kW
Quadrupoles	1.4kW	1.6kW	1.6kW
Sextupoles	0.01kW	0.02kW	0.02kW
VC	7.9kW	8.4kW	7.8kW
SR Abs.	116kW	112kW	111kW
W Shield	---	---	36.1kW
Pb Shield[1]	31.2kW	32.7kW	---
Tunnel	1kW	1.8kW	1.3kW
Total	**164kW**	**164kW**	**164kW**

Dose levels in the tunnel with shielding

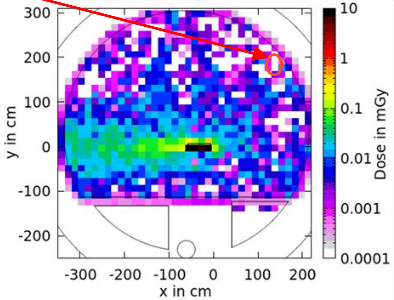


Simulations for Higgs and ttbar with Lead shielding



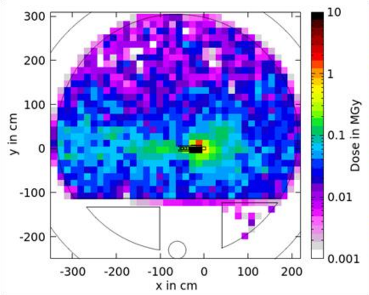


20kGy
ok for cables
Not for electronics



Higgs with Pb shielding:
Better statistics required to make precise estimation of the dose levels.
Looks promising, but shielding inevitable

NB: different scale for the dose levels

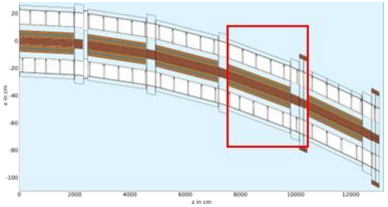


Ttbar with Pb shielding:
Similar dose levels in the tunnel environment for both shielding materials. Around **20kGy/year** in area of cable trays. A reduction down to 10kGy/year is targeted.

Solution must be found for the absorber shadows of B2.

Courtesy A. Lechner, B. Humann

R2E: radiation to electronics



order of magnitude levels and effects

Electronics in the tunnel need extra shielding

stochastic High-energy hadron fluence (cm^{-2} $year^{-1}$)	*cumulative* Total Ionizing Dose for 10 years (Gy)	Effects on Electronics
10^5	<<1	Possible SEE impact for commercial systems with MANY units and VERY demanding availability and reliability requirements
10^7	<1	SEE impact for systems with multiple units and demanding availability and reliability requirements
10^9	10	SEE mitigation (e.g. redundancy) at system level; cumulative effects can start to play a role
10^{11}	1 kGy	SEE mitigation (e.g. redundancy) at system level, very challenging TID level for COTS
10^{15}	10 MGy	Rad-hard by design ASICs

LHC R2E

Rubén García Alía | R2E perspectives for FCC-ee

Collider vacuum design

Courtesy R. Kersevan

Machine / optics design

- High Synchrotron Radiation (SR) photon flux generating **high photon-stimulated desorption** (PSD) gas load
- Rather **low specific conductance** of the vacuum chamber (dictated by the size of the quadrupole/sext opening)
- Requirement of **fast vacuum conditioning** so that a large integrated luminosity can be achieved
- Need for a vacuum system that **minimizes e-cloud** (e+ beam) and **ion-trapping** (e- beam) (to preserve the quality of the beam)

This leads to (Requirements):

- Efficient **removal of the 50 MW/beam** SR power load
- Vacuum surfaces (materials, thin-films, treatments) having a low PSD yield, **minimizing gas-beam interactions**
- **Efficient pumping**, both in cost and in performance
- **Minimization of the high-energy component of the Compton-scattered primary SR fan** (for energies W, H, T), as per FLUKA simulations/results

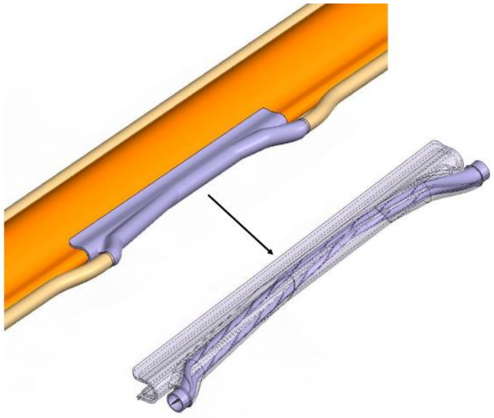
We can satisfy these requirements if we design a vacuum system based on:

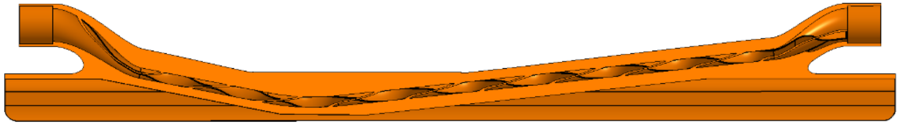
- **NEG-coating** (thin, ~200 nm, to reduce resistive-wall impedance contribution)
- Primary SR fans intercepted by **localized SR absorbers**, rather than a LEP-like configuration where the SR fans are distributed more or less uniformly along the external side of the vacuum chamber

Vacuum innovation

Courtesy C. Garion, M. Morrone

Synchrotron Radiation Absorber 3D printed



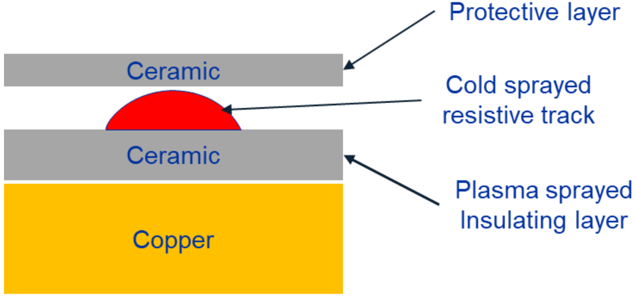


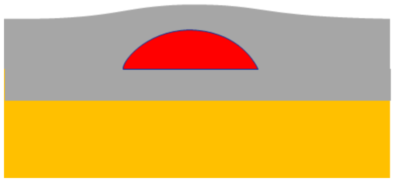
Laser Powder Bed Fusion (LPBF) has been selected as the method for the first prototype. This is the first copper 3D printed synchrotron radiation absorber.

Vacuum innovation

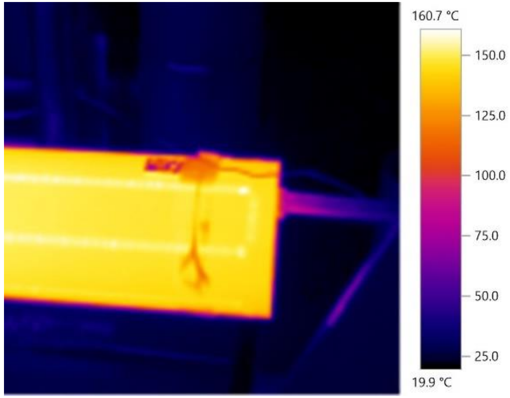
Courtesy C. Garion, M. Morrone

Rad-hard bake out system





OFE copper tube, 84 mm * 2 mm, 500 mm long
Al_2O_3-TiO_2 ceramic layer
Track in titanium, ~ 110 mm thick, 8 mm width
Distance between the tracks: ~30 mm

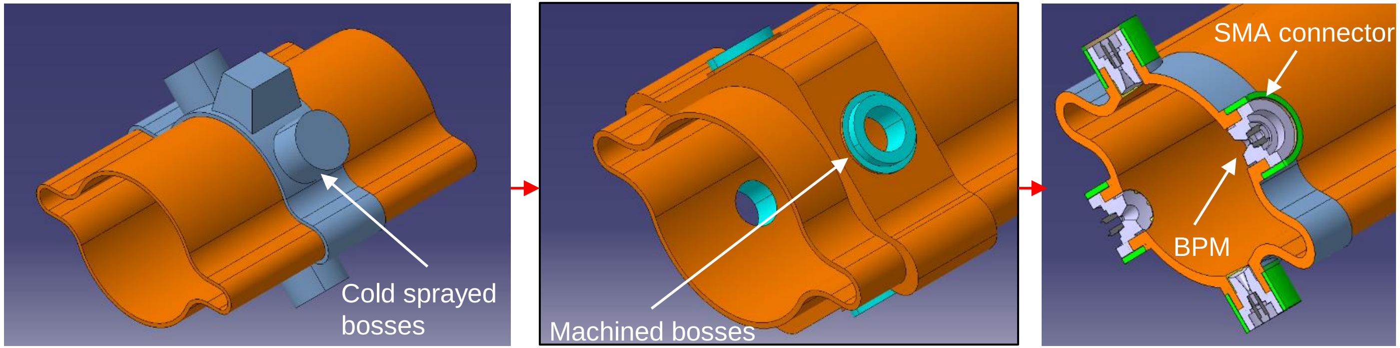


Bake out and NEG activation require a thermal cycle up to 230 °C +/- 20 °C.
To be added : Permanent rad-hard insulation (ceramic-based)

Vacuum innovation

Courtesy C. Garion, M. Morrone

Cold-spray for Beam Position Monitors (BPM)



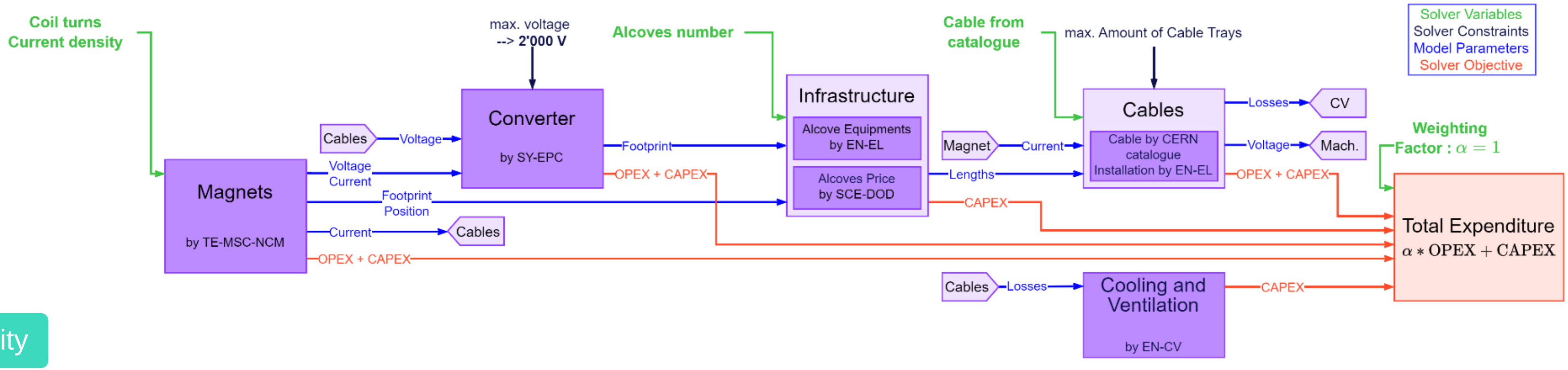
Global optimisation tool

Courtesy D. Aguglia, B. Wicki

The global model is composed of multiple interconnected sub-models, each intricately linked. Every sub-model is tailored to represent a distinct segment of the broader system.

The **Total Expenditure** is the **Sum** of the **Capital** and **Operational Expenditure** of each sub-models :

- ❑ **Magnets** **TE-MSC-NCM** with coil turns and current density.
- ❑ **Power Converters** **SY-EPC** with existing converters + adjustment to FCC's need.
- ❑ **Cables** + **Cable-Trays** **EN-EL** with CERN Catalogue.
- ❑ **Alcoves** **SCE-DO** with number and size of alcoves.
- ❑ **Electrical Equipment** **EN-EL** with number of alcoves (Equipment in Alcoves).
- ❑ **Cooling and Ventilation** **EN-CV** with cable's power losses in the arc.



Affordability

Global optimisation Solving for Best TOTEX

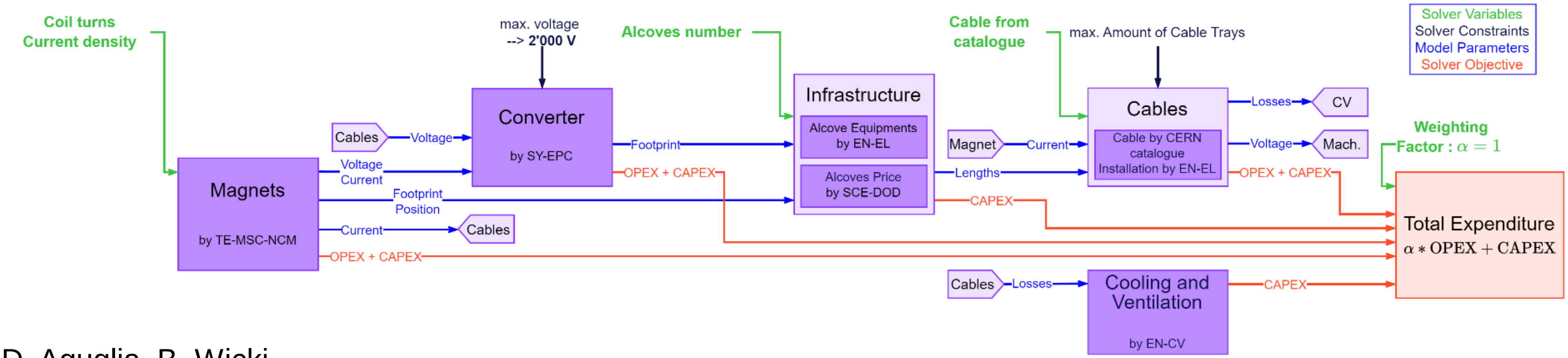
Following slides present optimised solutions, with varying constraints.
The objective being: reaching the **minimum Total Expenditure** while complying with constraints.

Solver's evolutionary optimisation algorithm identify the most likely optimal solution, meaning the best solution found within the given time frame.

Weighting Factor set to **1** so far, meaning that Operation and Capital Expenditure have the same weight when optimising.

OPEX calculated over 15 years of Operation

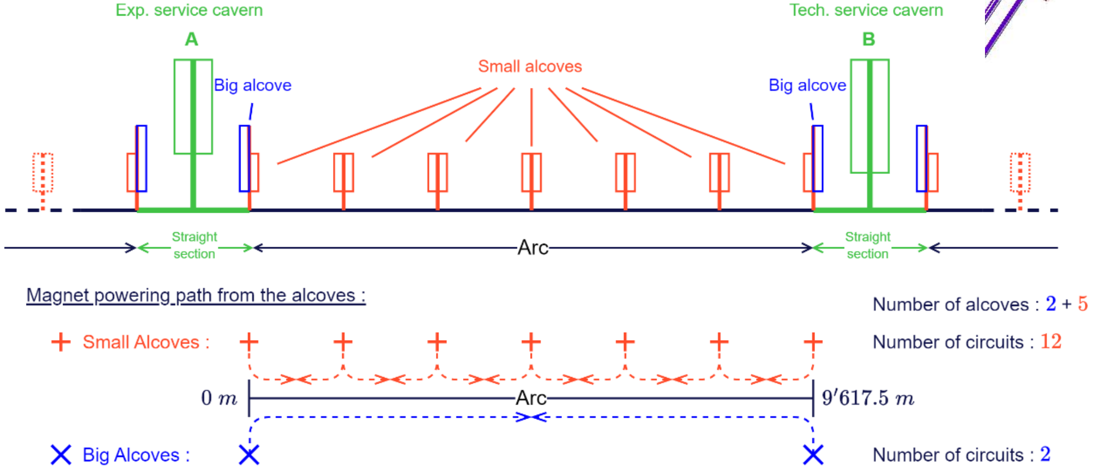
$$TOTEX = \alpha * OPEX + CAPEX, \alpha = 1$$



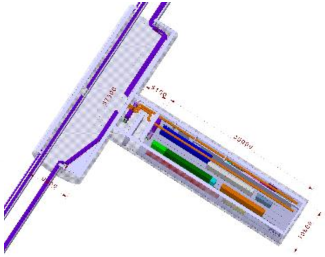
Courtesy D. Aguglia, B. Wicki

Global optimisation tool

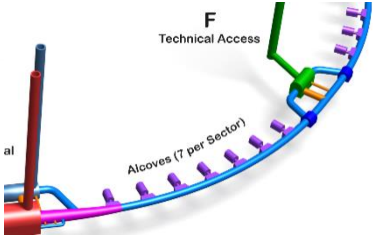
Arc's Small and Big Alcoves



Each alcoves power both side
Both ends of an arc houses a bigger alcove.
The big alcoves power the half of the arc.
The small alcoves power a section of the arc



	Magnets powering emplacement	Big Alcoves	Small Alcoves
Collider	Dipoles	X	
	Quadrupoles	X	
	Sextupoles		+
	Horizontal Correctors		+
	Vertical Correctors		+
	Skew Quadrupoles		+
Booster	Dipoles	X	
	Quadrupoles	X	
	Sextupoles	X	
	Horizontal Correctors		+
	Vertical Correctors		+
	Quadrupole Correctors		+



Circuits can be powered from :

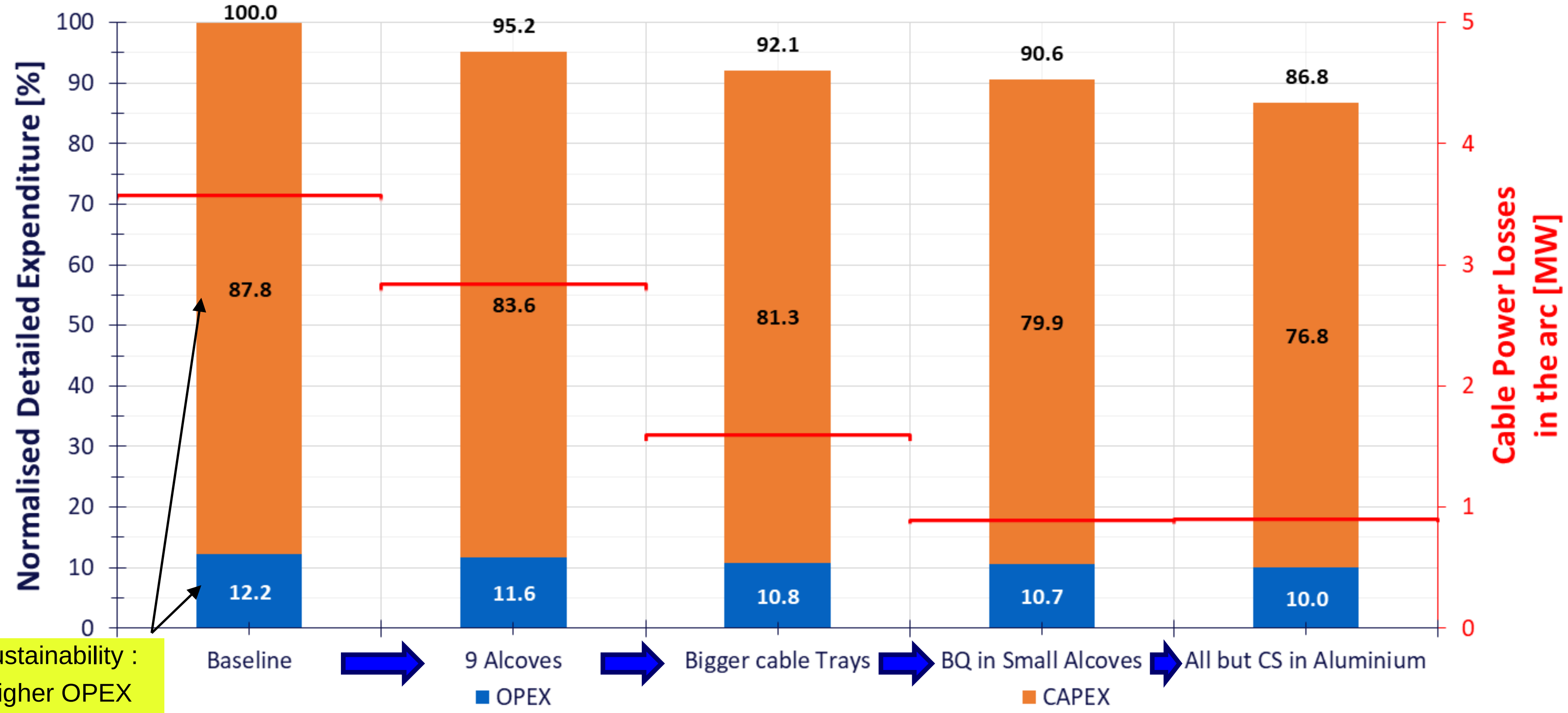
- ❑ Big Alcoves at the end of the arc
- ❑ Small Alcoves in the arc

Choosing the alcoves impacts greatly the expenditures.

Courtesy D. Aguglia, B. Wicki

Comparing all scenarios

Courtesy D. Aguglia, B. Wicki



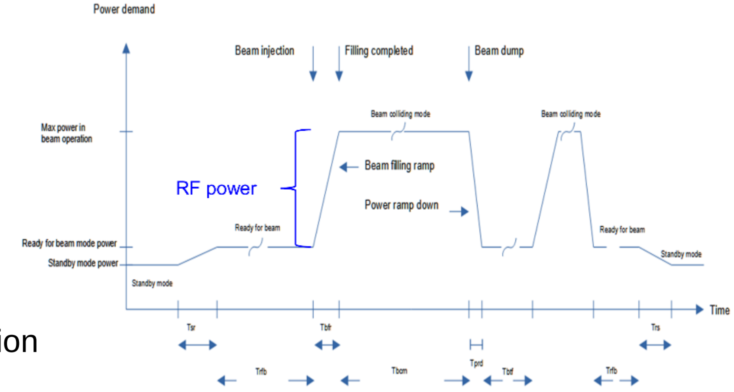
Sustainability :
Higher OPEX
Weighting factor ?

FCC-ee energy consumption per system

Balance of power

- RF systems represent 40% of the total energy consumption at Higgs
- Magnets are only significant at ttbar (5 years of operation)
- Cryogenic is also significant only at ttbar

- Operation of cooling and ventilation needs a smart energy consumption management (eco-mode, standby mode….)



120 GeV	Days	Hours	Power OP	DT with access	DT cycle	DT long	Power Com	Power MD	Power TS	Power Shutdown			
Days	365		139	16	16	14	30	20	10	120			
RF systems			148	0	0	0	74	22	0	0	559161.1	MWh	40%
Magnets			44	0	44	0	22	44	0	0	200604.5	MWh	14%
Cryo			13	13	13	13	13	13	13	3	83928	MWh	6%
CV			28	28	28	28	28	28	28	14	204960	MWh	15%
General services	365	8760	26	26	26	26	26	26	26	26	227760	MWh	16%
Exp + data center	365	8760	14	14	14	14	14	14	14	14	122640	MWh	9%
Power / period			273	81	125	81	177	147	81	34		MW	
Energy / Period			912027	31104	47997	27216	127580	70681	19440	163008	1399054	MWh	100%
			65.2%	2.2%	3.4%	1.9%	9.1%	5.1%	1.4%	11.7%	1399054	MWh	

Sustainability

FCC-ee R&D focus on energy performance

Superconducting RF as the main R&D program

- **High-efficiency Klystron**

  from efficiency at 50% (present technology) to 80% (multi-beam technology, CERN R&D program). This reduces the power demand from 233MW done to 146MW.

- **High Q0 cavity**

  reduce the cryogenic power from 48MW done to 35MW (US & CERN R&D to be launched).

- **High efficiency cryo compressor**

  reduce the cryogenic power from 35MW done to 26MW (industry R&D to be launched).

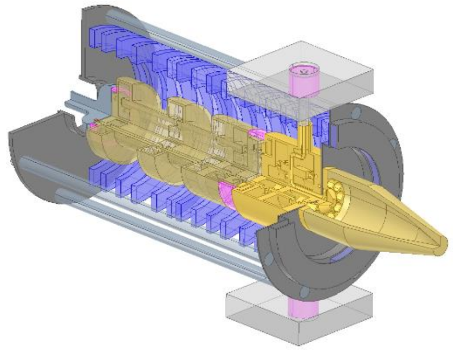
- **High efficiency high voltage power supply**

  from 90% (50hz technology) to 98% (multilevel technology, adaptation of new industrial product to our application).

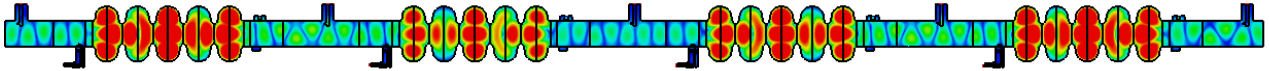
FCC-ee RF systems R&D

Courtesy F. Peauger, O. Brunner

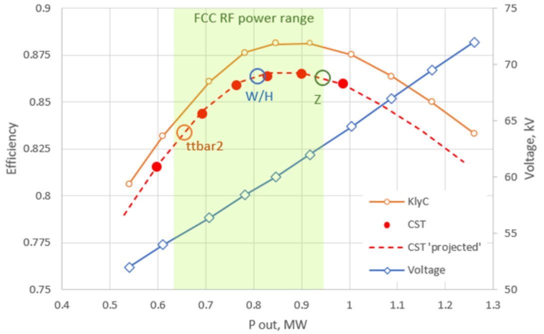
- **New SRF roadmap** proposed for an intense hardware R&D program in the next 5-10 years, oriented towards the improvements of **SRF surface resistance** and **RF power sources efficiency**.
- New **higher order mode damping schemes** of 400 and 800 MHz cavity strings designed.
- Full study of the **2-cell cavity option for Z** (to replace 1-cell cavities) finalized with some positive outcomes.
- Successfull **machining of two reference 400 MHz cavities** at CERN
- **First hydroformed cavities niobium coated** and tested at CERN/KEK



Conceptual design of the 1MW 400 MHz ultra-high efficiency klystron



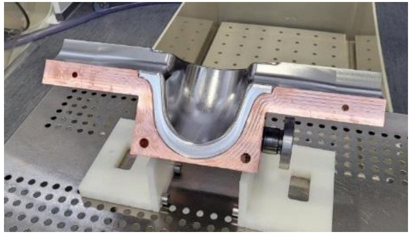
Example of 800 MHz cavity string with a higher order mode at 1.892 GHz being damped to Q = 1.5e4



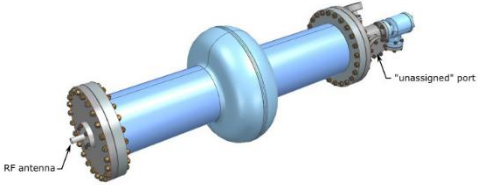
Feasibility

FCC-ee RF systems R&D

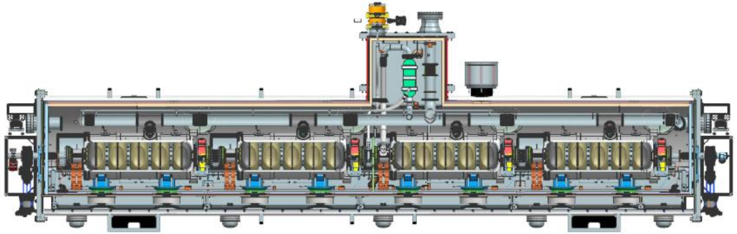
- Successfull **niobium coating** of the **1.3 GHz SWELL** cavity
- **R&D program on high Q0 / high gradient cavities** at 800 MHz started with FNAL.
- New strategy in discussion to explore **Nb3Sn material** where the main actors are CERN, FNAL, Cornell and Jlab. Nb3Sn material allows to operate 800 MHz cavities at 4.5 K instead of 2 K.
- **Experience from EIC-SRF system design**
- **Experience from LCLS-II cryomodule commissioning**
- Preliminary **mechanical design** of the **400 MHz and 800 MHz cryomodule** started.
- **Integration studies of the two RF straight sections** in point L and H on-going.



SWELL 1.3 GHz quadrant after niobium coating with HiPIMS



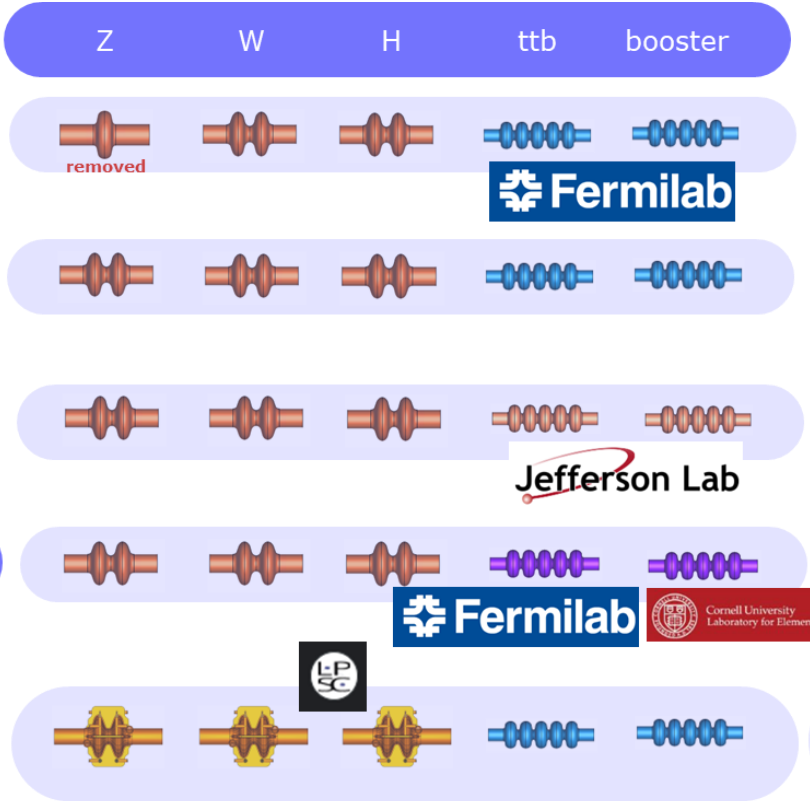
FCC 800 MHz 1-cell cavity for high Q0 R&D at FNAL



FCC 800 MHz cavities cryomodule preliminary design by FNAL (based on PIP II)

Courtesy F. Peauger, O. Brunner

Superconducting RF baseline & alternative options



	Comments
Baseline	Solid scheme with good margin for reliable operation Clear R&D paths identified (seamless copper cavities, HiPIMS coating, high Q0 bulk Nb cavities)
Z with 2-cell	Very attractive to optimize the cost and schedule The beam current at Z shall be reduced.
Full thin films	Very ambitious, allows for material cost savings Ideal to push even more the Nb/Cu technology
Full 4.5 K with A15 (Nb3Sn) materials	Extremely ambitious (?) for very high operational savings
SWELL	Innovative approach adapted to width variety of coatings No microphonics and LFD Reduced volume of helium

Sustainability

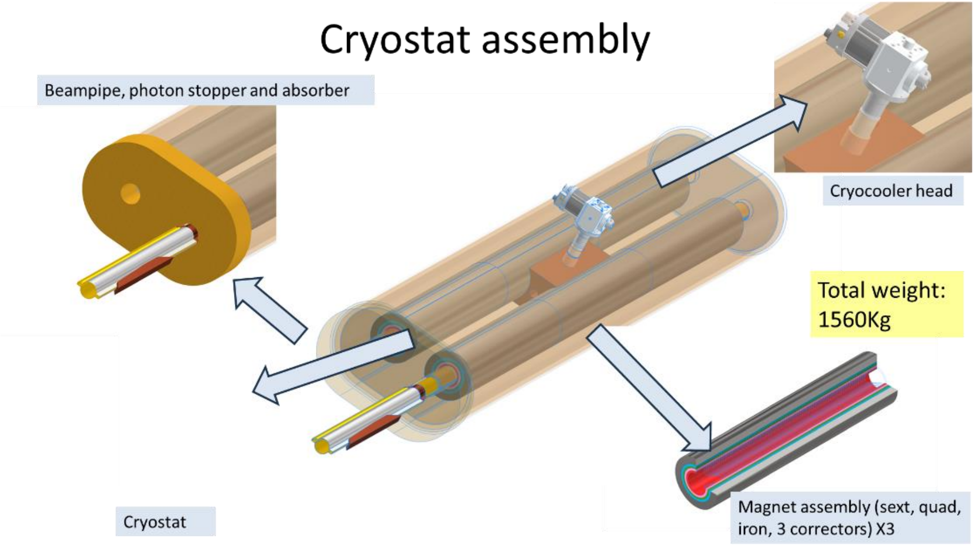
Courtesy F. Peauger, O. Brunner

Superconducting magnet alternative HTS4

Half cell length: 27.9 m

Courtesy M. Koratzinos

CHART
Swiss Accelerator Research and Technology



CCT demonstrator:
- Formers manufactured
- Quality control done
- HTS tape purchased

Sustainability

Production

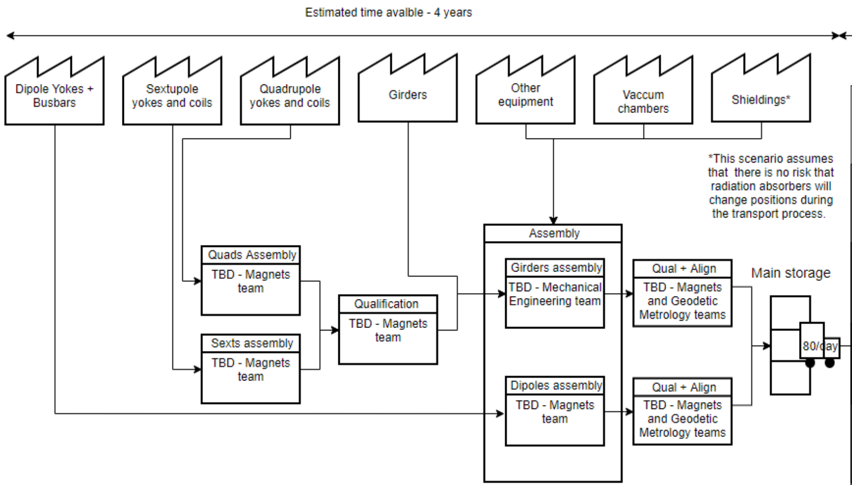
Study on Magnets Production and Installation for the FCC-ee Accelerator

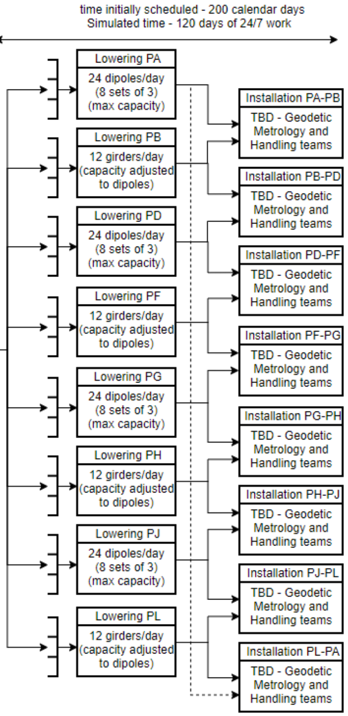
Courtesy M. Zielinski, J. Bauche

Study covers:
- Workforce
- Facilities
- Equipment
- Sequence of processes

Study outcome:
- Production operating model (what activities, where, by whom, when)
- Detailed input for the project scheduling
- Detailed input for the project budgeting

Ongoing consultations with:
- Magnets, Superconductors and Cryostats
- Handling Engineering
- Accelerator Coordination & Engineering
- Vacuum, Surfaces & Coatings
- Geodetic Metrology
- Mechanical and Materials Engineering



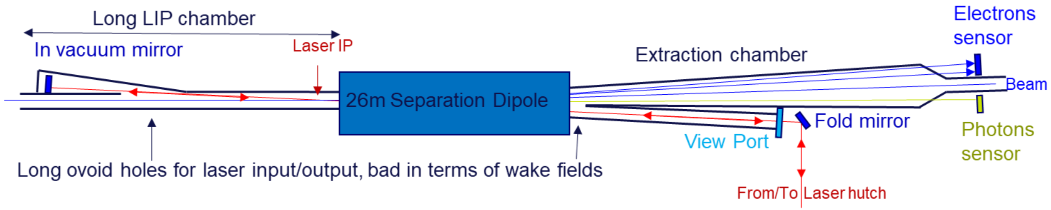


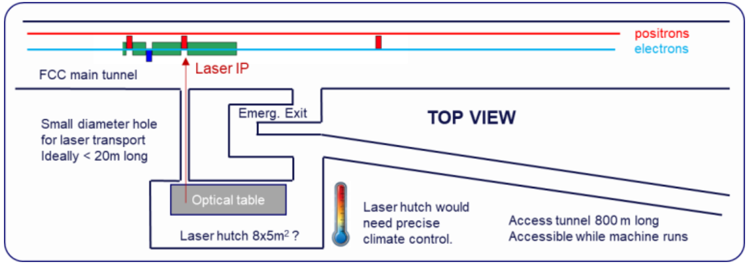
The study begins with magnets, as they present significant budgetary requirements and logistical challenges. In the future it will include other elements of the accelerator.

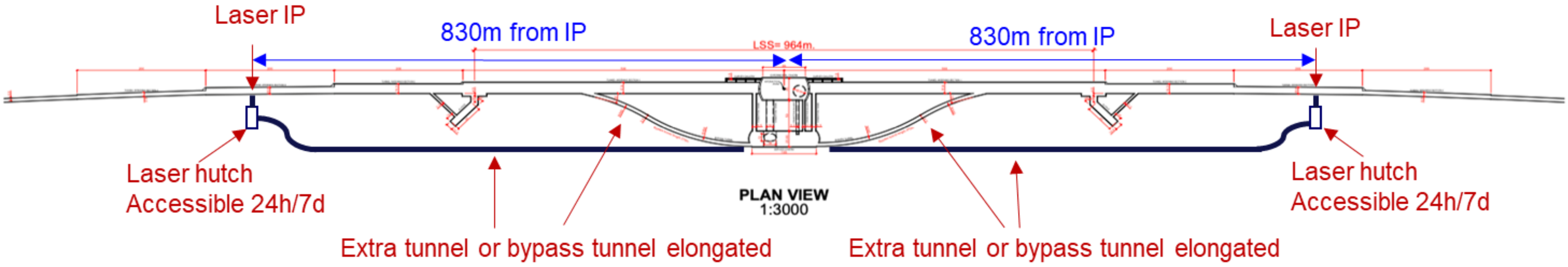
Feasibility

FCCee Polarimeters baseline in Experimental IP A

A single polarimeter per beam (2)
Option, four polarimeters per beam (8). Energy calibration done at each IP, to reduce systematic errors.
Need extra-long bypass tunnel to access Laser hutch all time. Alternative to manual tuning of Laser?







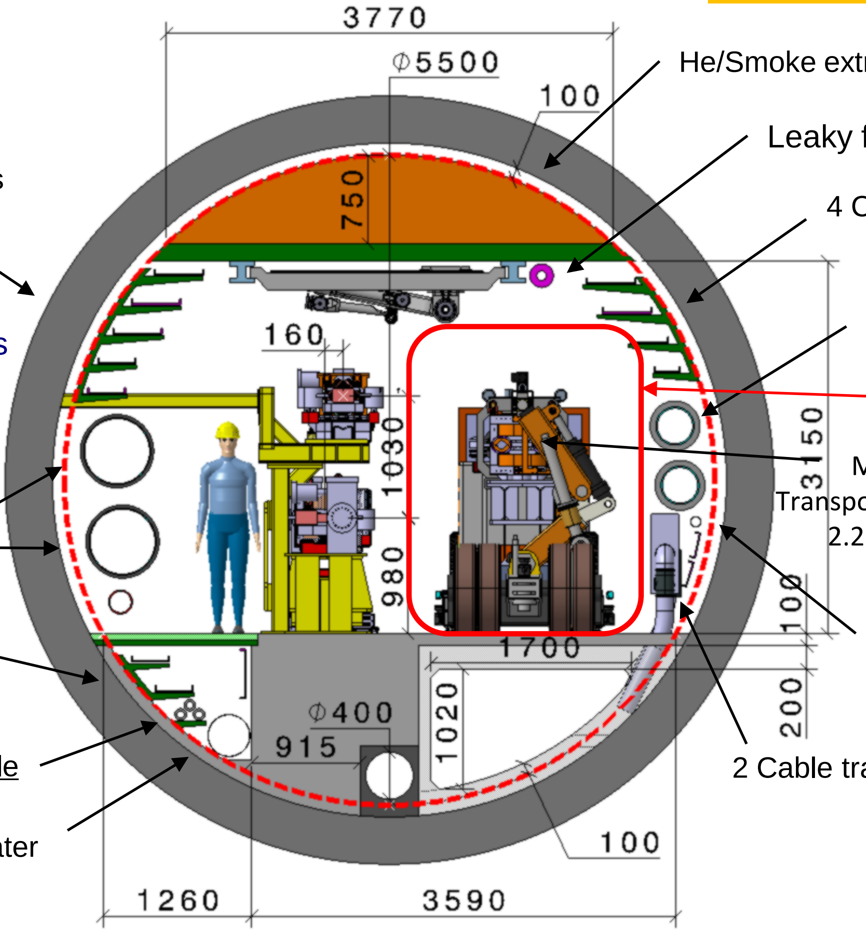
Courtesy R. Kieffer

New arc integration

Machine tunnel 5.5m in diameter

Courtesy F. Valchkova

Flat floor
2.2m*2.5m transport area
Cable trays, in ‘radiation safe area’
Central floor reinforced for FCC-hh magnets



in progress

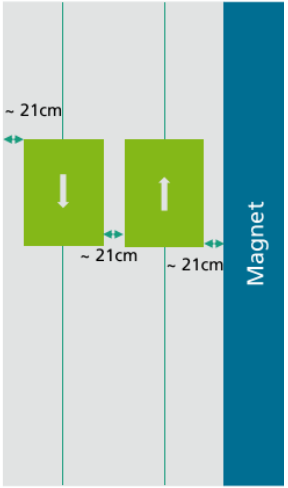
Feasibility

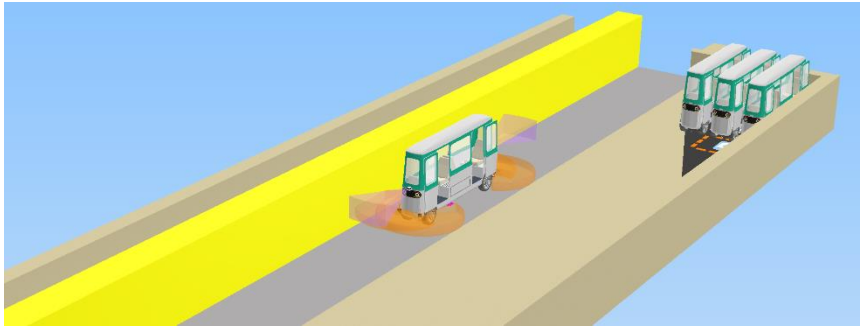
Collider Center

Personnel transport

Fraunhofer IML

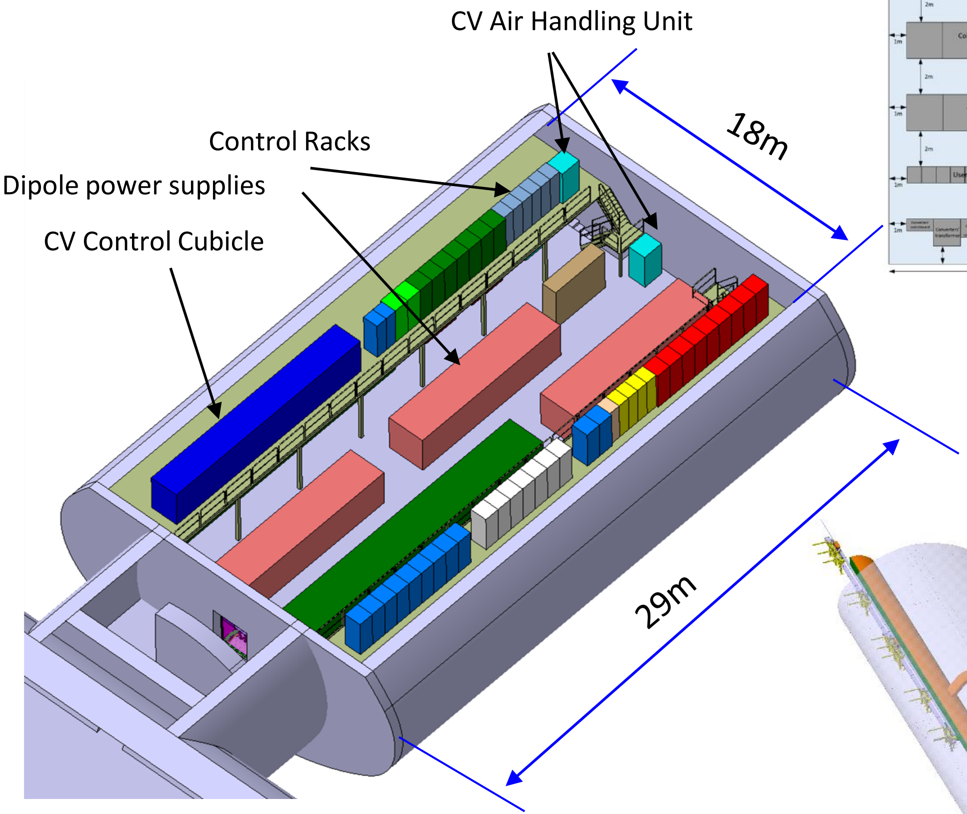
- Slim version of vehicle (80cm) to allow encountering traffic and bypassing
- Fully autonomous and symmetrical in both directions
- 4 seats and sliding doors for maximum comfort while using minimal space
- Driven by wheel hub motors with brakes
- Both axles are steerable 17°
- Maximum speed of vehicle is 30 km/h

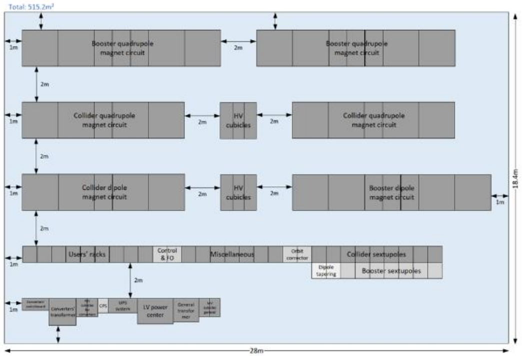


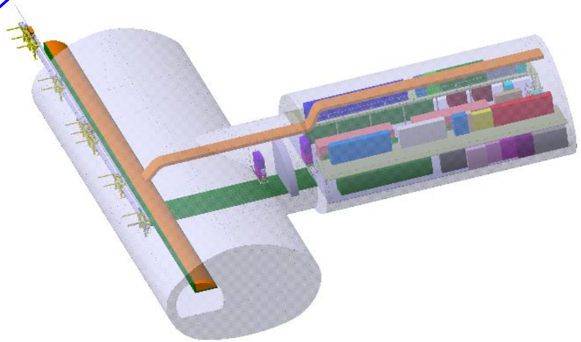


Safety

Integration: Big alcoves



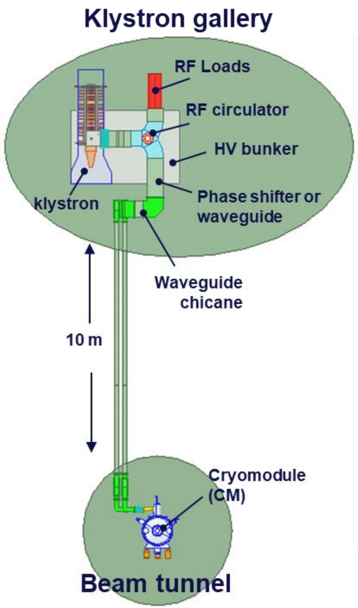


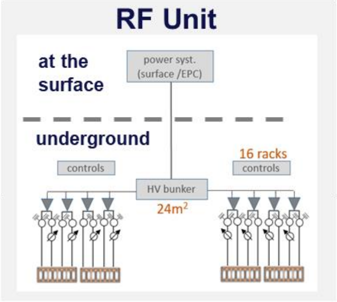


Blocks	Equipment	Number	Size	Required access at back and front?
Collider dipole magnet circuit		**1**		
	Power transformer	2	2m x 2m each	Yes
	Power converter	2	2m x 2m each	Yes
	Output + DCCT	1	1m x 2m	Yes
Collider quadrupole magnet circuit		**2**		
	Power transformer	2	2m x 2m each	Yes
	Power converter	2	2m x 2m each	Yes
	Output + DCCT	1	1m x 2m	Yes
Booster dipole magnet circuit		**1**		
	Power transformer	2	2m x 2m each	Yes
	Power converter	2	2m x 2m each	Yes
	ESS	2	1m x 2m each	Yes
	Output + DCCT	1	1m x 2m	Yes
Booster quadrupole magnet circuit		**2**		
	Power transformer	2	2m x 2m each	Yes
	Power converter	2	2m x 2m each	Yes
	ESS	2	1m x 2m each	Yes
	Output + DCCT	1	1m x 2m	Yes
HV cubicles	3 cubicles each	**2**	2m x 2m each	Yes
EL distribution				
	MV cubicles general	2	0.6m x 1m each	Yes
	300 kVA transformer general	1	1.3m x 1.4m	Yes
	LV power center	1	2m x 1.4m	Yes
	UPS system	1	1.6m x 0.8m	Yes
	CPS system	1	0.6m x 0.8m	Yes
	Control & optical fiber racks	2	0.6m x 0.8m each	Yes
	Users' racks	7	0.6m x 0.8m each	Yes
Other converters				
	MV cubicles for Power Converters	2	0.6m x 1m each	Yes
	400 kVA transformer for Power Converters	1	1.5m x 1.5m	Yes
	Power Converters' switchboard	1	1.5m x 0.65m	No
	Miscellaneous	7	0.8m x 0.9m each	Yes
	Orbit corrector	2	0.8m x 0.9m each	No
	Dipole tapering	2	0.8m x 0.9m each	No
	Booster sextupoles	7	0.8m x 0.9m each	No
	Collider sextupoles	9	0.8m x 0.9m each	No

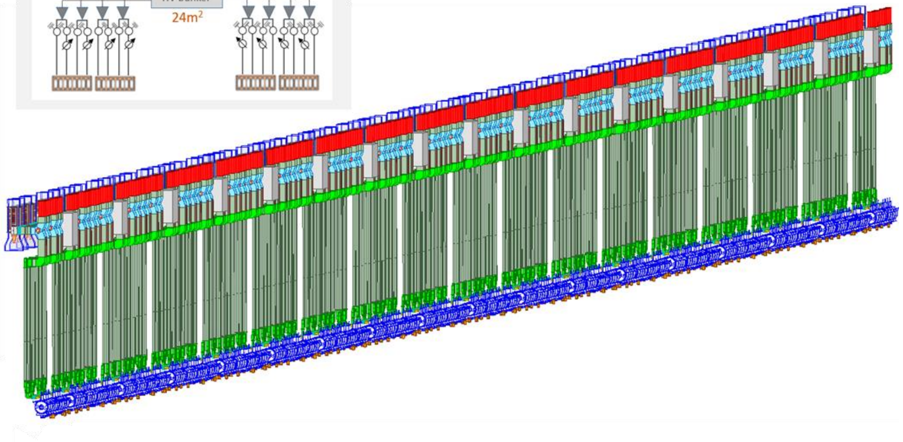
Feasibility

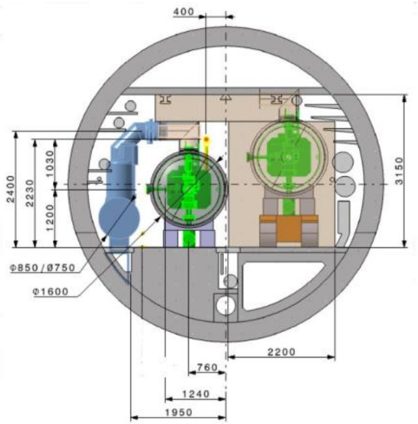
Integration: RF system configuration for Higgs factory



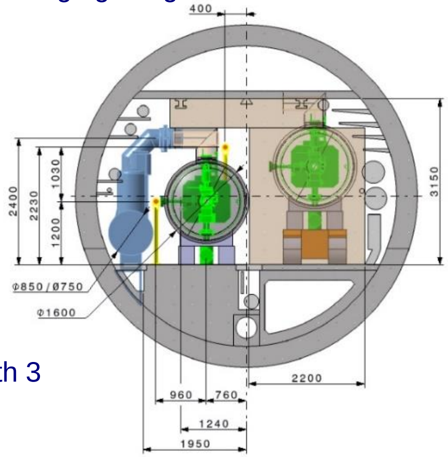


- 17 x RF Units = 900 m
- 66+2 cryomodules
- 272 cavities (4 cav/CM)





H-TT, challenging integration with 2 beam lines



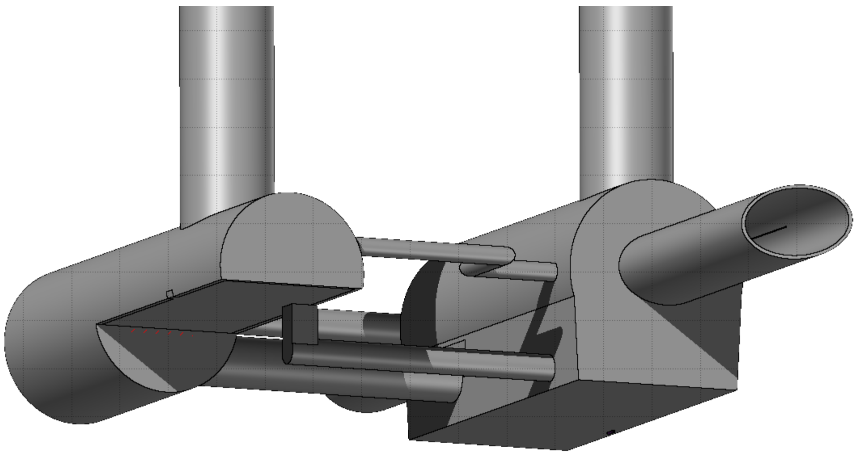
Z-W, even more challenging integration with 3 beam lines

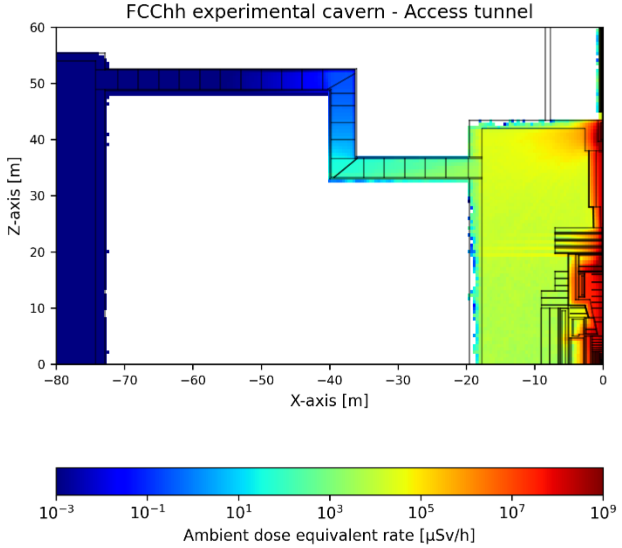
Courtesy V. Parma, F. Peauger

Integration: Radioprotection FLUKA simulations

Design of the infrastructure compatible with FCC-hh

Ambient dose equivalent rate scoring in the access tunnel





- ❑ The results shown in the plot illustrate **the ambient dose equivalent rate** resulting from pp collisions in the access tunnel, passing through a three-legged chicane of 20 meters, 20 meters, and 30 meters respectively.

Safety

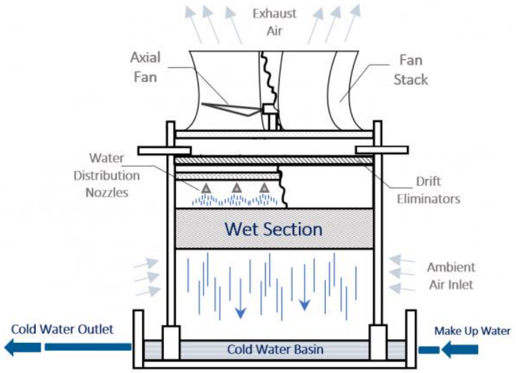
Courtesy Markus Widorski, Giacomo Lavezzari

Cooling towers

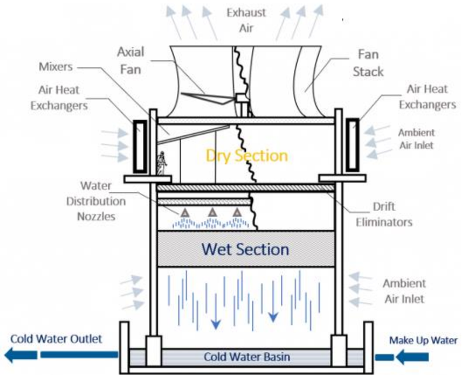
Consultant contract, HBI / AFRY

Technologies evaluation

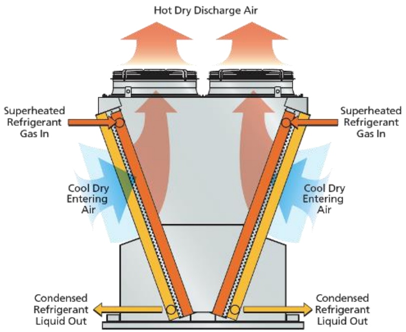
Classical tower



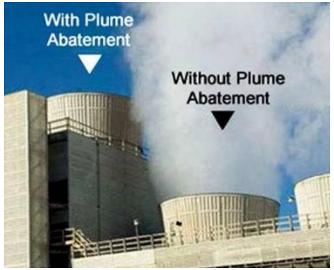
Classical tower with plume abatement



Dry cooling



- Visibility of plume
- High water consumption



- Plume invisible
- Approx. 10% water saving

- Approx. 80% water saving

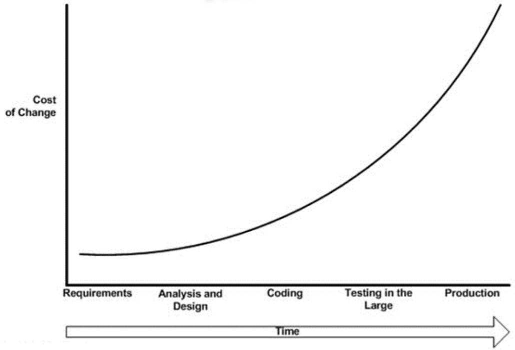
Courtesy G. Peon, I. Martin

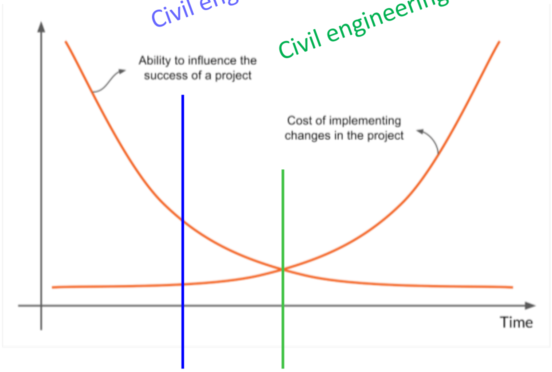
Sustainability

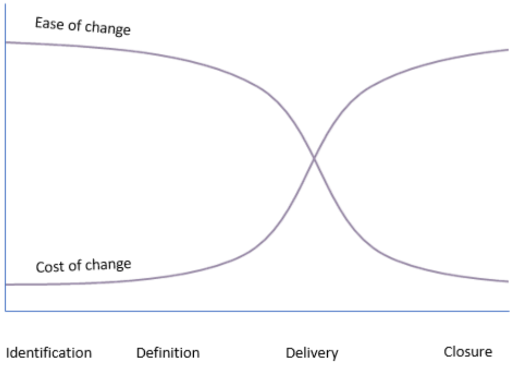
Toward a Pre-TDR for 2028

Engineering rule / Project management:
The cost of the design error and change increases exponentially

Recommendation from Cost Review Panel
Thomas Zurbuchen







Engineering to be started as soon as possible with the goal
to improve the cost estimate and to control the project budget & schedule

Summary

- Mid-term review 2023 didn't reveal showstoppers for accelerators and its infrastructures
- Still, there are some design challenges to work on
- Engineering works are to be started as soon as possible toward a pre-TDR for 2028
- Baseline, alternatives, and options to be clarified in the pre-TDR