SUMMARY OF ACCELERATORS TECHNICAL DESIGN AND SRF TECHNOLOGIES

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FCC Week 2025

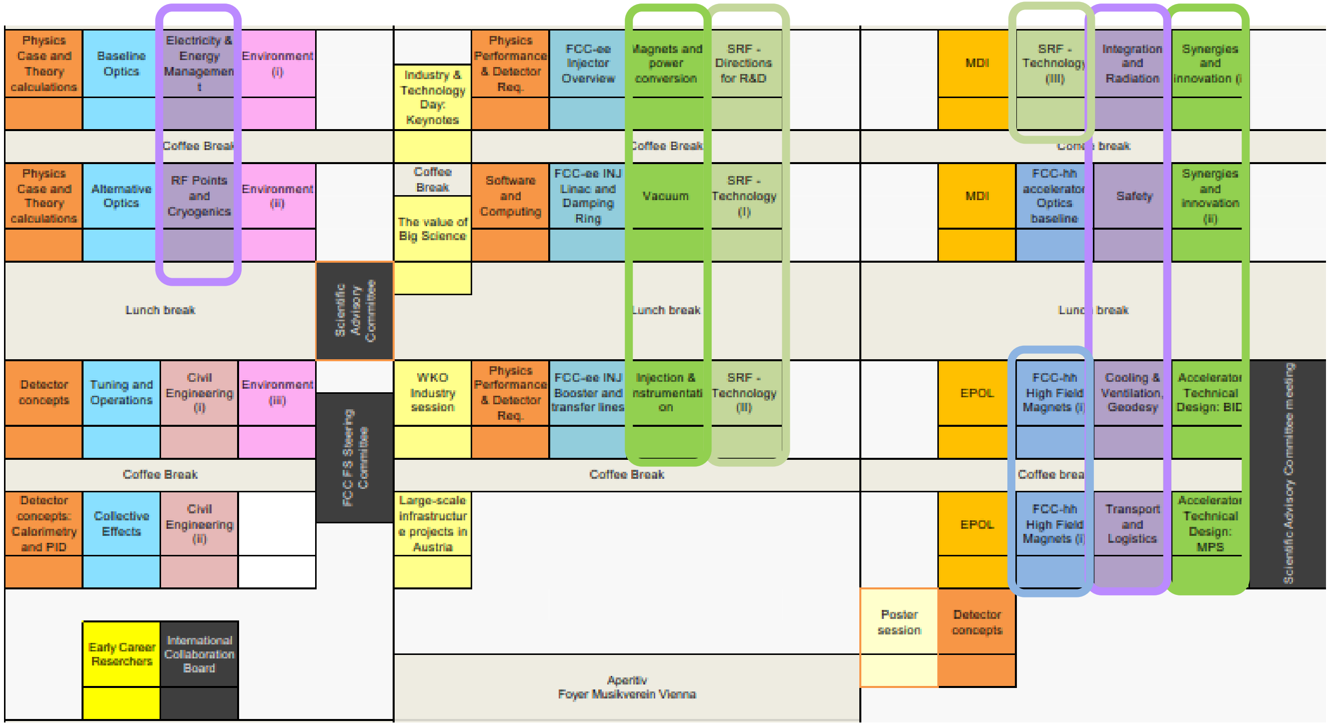
22/05/2025

7 sessions on
Accelerator Technical Design

6 sessions on
Technical Infrastructures

4 sessions on SRF technology

2 sessions on High field magnets



Accelerator Technical Design

Technical infrastructures

SRF technology

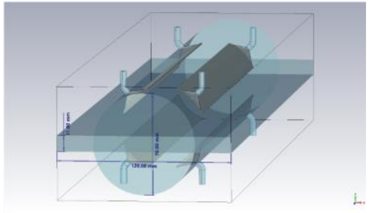
High Field magnets

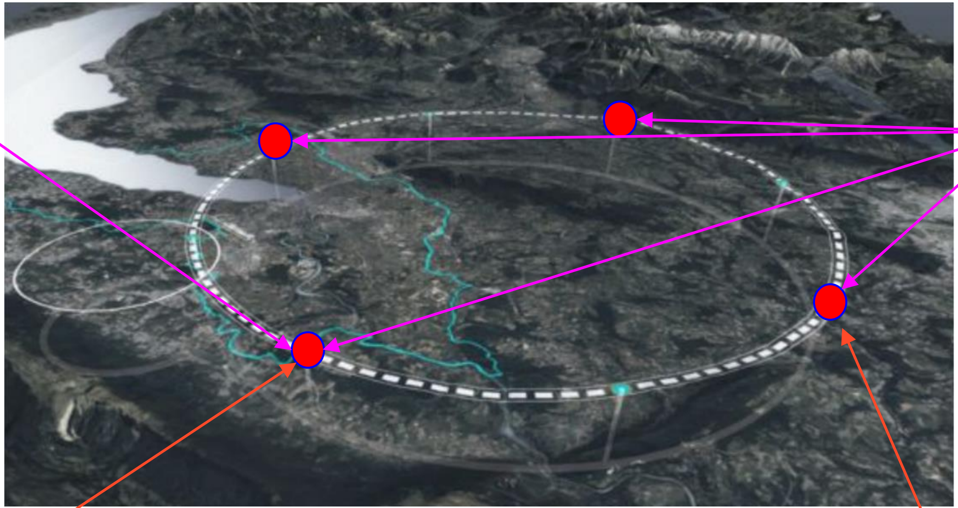
Superconducting Radiofrequency Sessions : Directions for R&D, I, II, III

22 presentations → 7 slides…

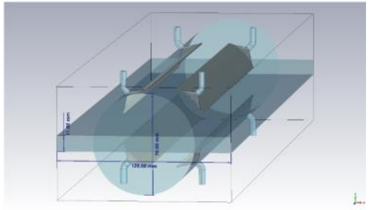
FCC-ee RF systems

Booster transverse feedback system





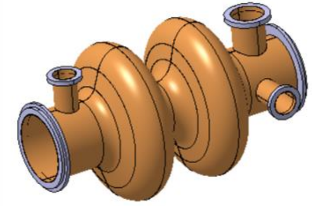
Collider transverse feedback system & depolarizer



Booster RF system

Collider RF system

Z-WW-ZH



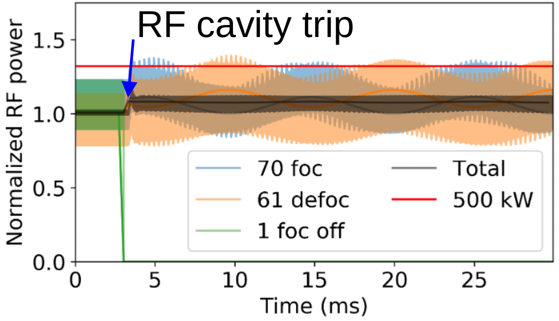
+

ttbar

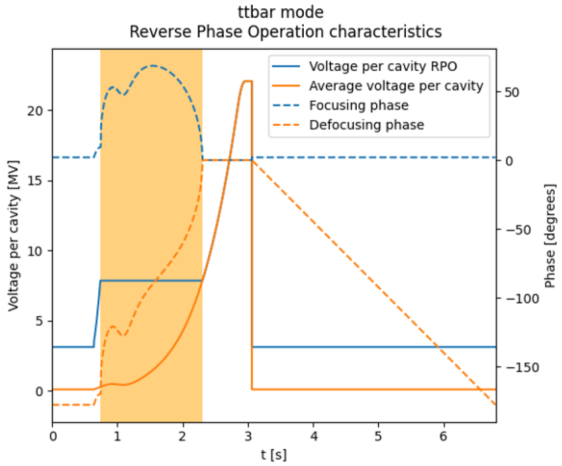
FCC-ee RF systems

2-cell 400 MHz RF system for Z-WW-ZH

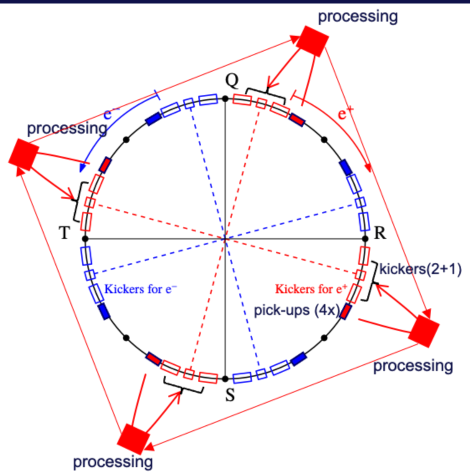
- Feasibility of Reverse Operation Mode (RPO) is confirmed
- Remaining challenge is preserving beam in case of RF system failures



800 MHz RF system for ttbar collider and booster



- Momentum and voltage programs are designed for all energies
- Optimisations of wigglers required for beam stability is ongoing

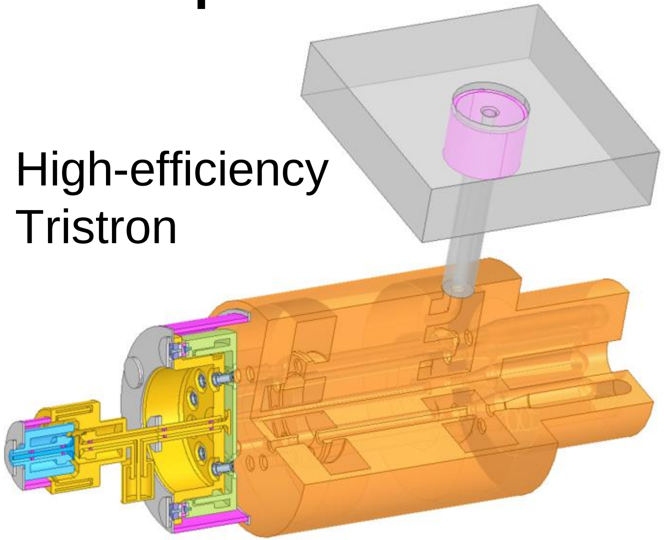


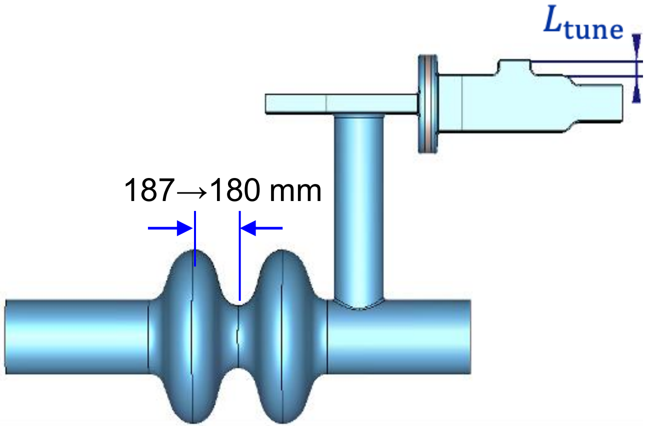
Transverse feedback systems (combined with depolarizer)

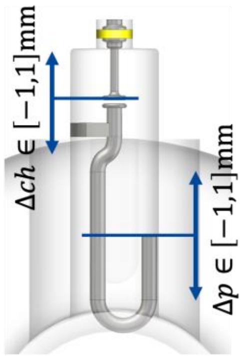
- First design is developed and space is allocated
- Impedance contribution and 5 ns bunch spacing capability to be addressed

RF power source, coupler, and cavity designs

High-efficiency Tristron







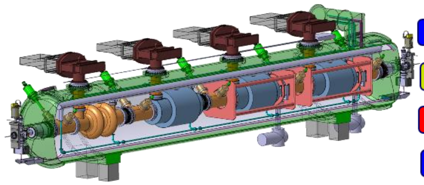
Hook-Type HOM Coupler

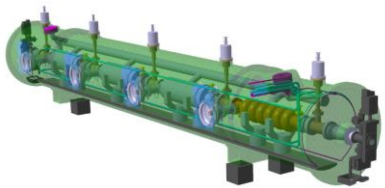
- Significant progress towards demonstrator in ~2028-2029
- RF power modulations impose challenging HV supply requirements

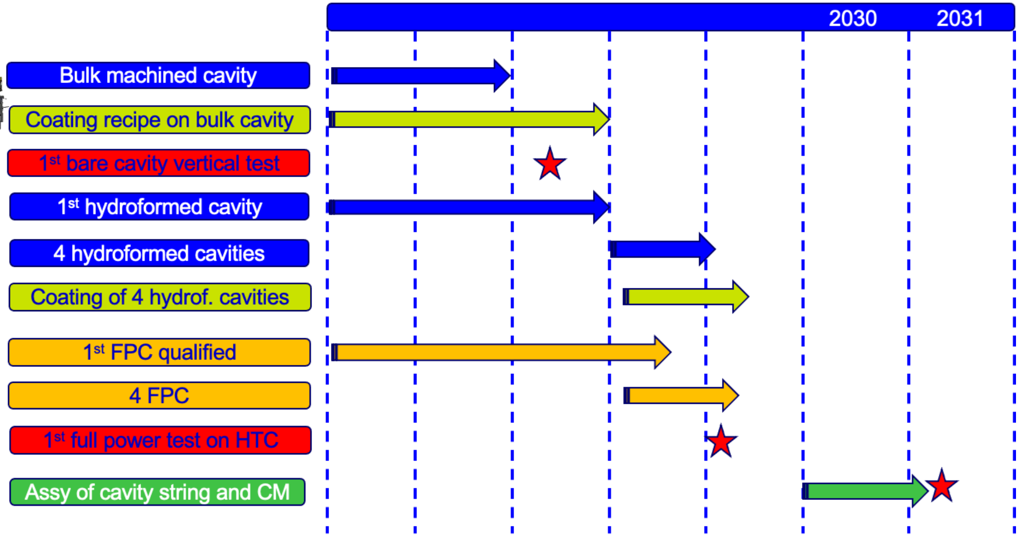
- Cavity shape optimization for 0-mode suppression & FPC capability to adjust quality factor for ttbar mode
- 800 MHz cavity HOMs are critical for booster at 20 GeV

- Performance of HOM damping is almost unaffected by geometry perturbation, except for a transverse mode of 2-cell cavities

Cryomodule development





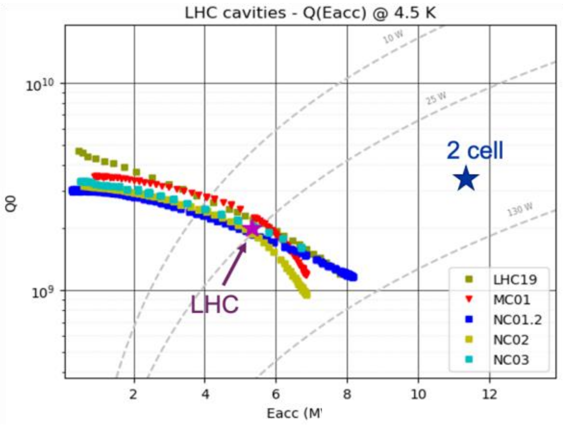


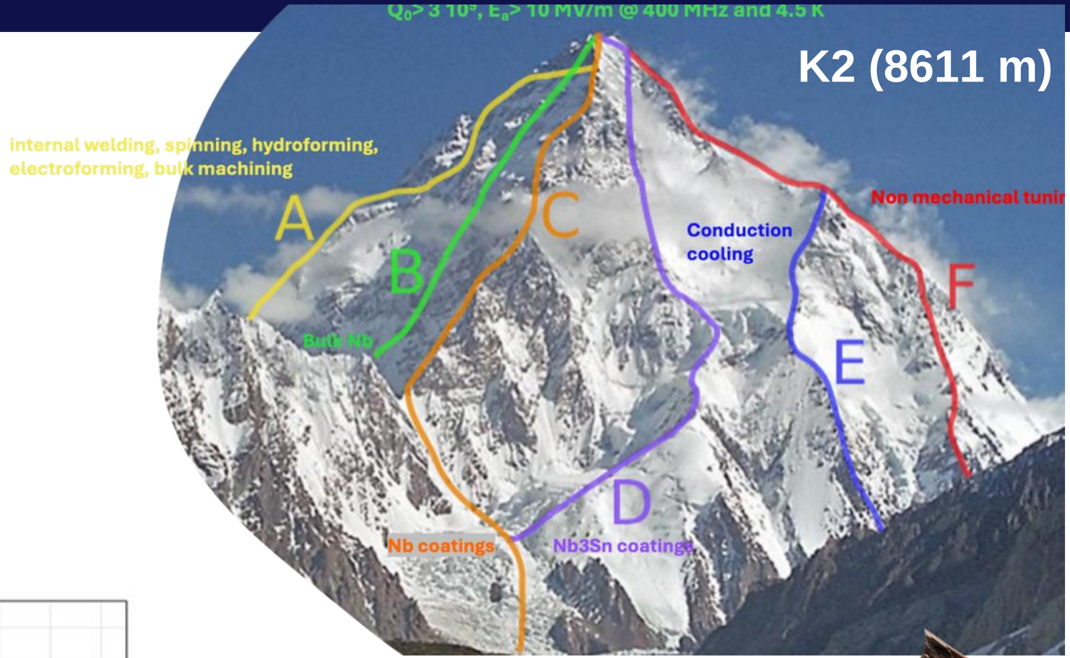
Important progress in design and definition of specifications for various systems
→ Clear path towards 400 MHz demonstrator

Dry cavity cooling → R&D for drastic reduction of He content (30-50x)

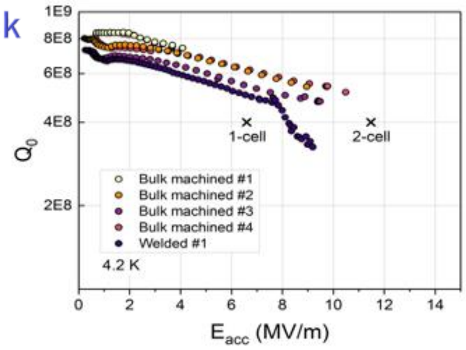
V. Parma K. Canderan K. McGee T. Koettig

R&D 400 MHz





1.3 GHz Ellipt. Monoblock



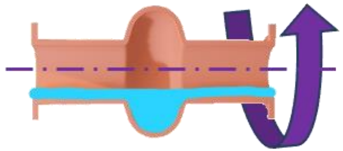
Plasma Electrolytic Polishing is a possible Game Changer

Scaling to **400 MHz is challenging**

Explore different set-ups

Half immersion + rotation

Jet-PEP

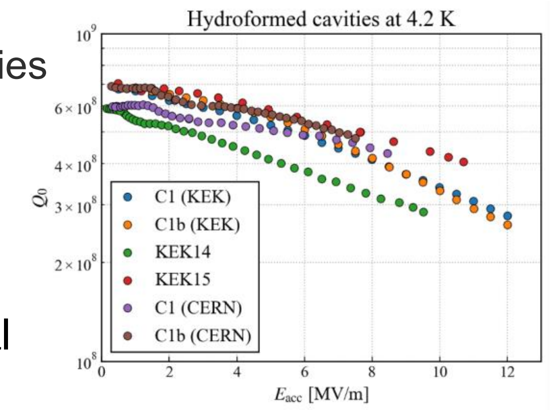


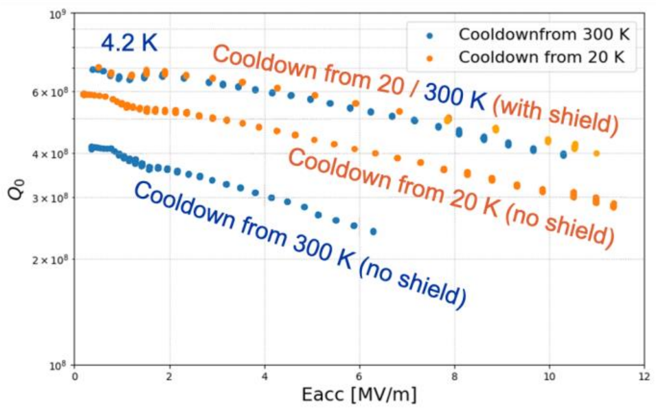
Surface preparation and quality of coating are crucial

Recent results at 1.3 GHz

Hydroformed cavities

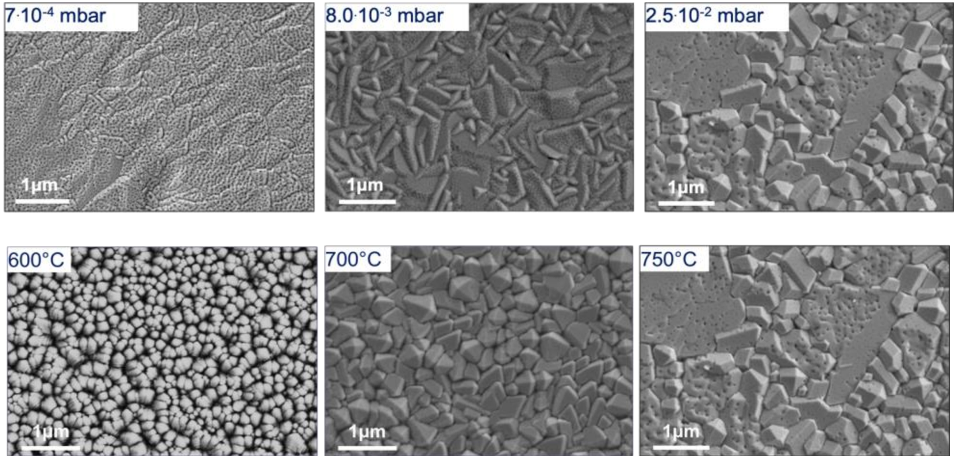
→ Mitigation of thermoelectric currents is crucial





High Power Impulse Magnetron Sputtering (HiPIMS)

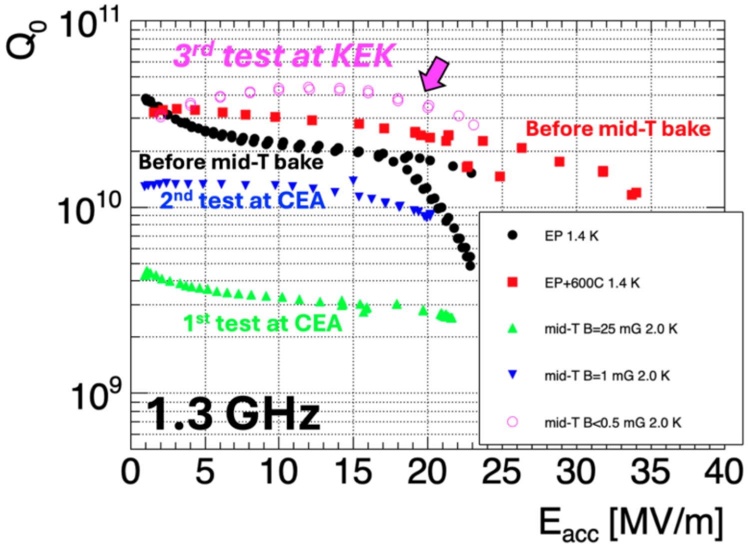
Coating pressure & temperature dependency

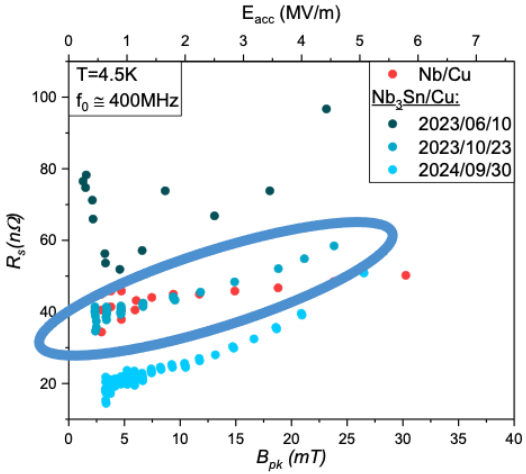


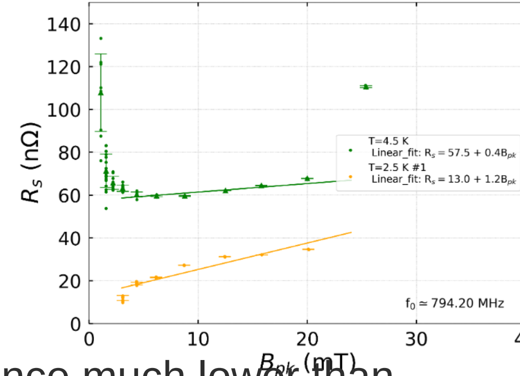
R&D 800 MHz

Frequency	Technology	T operation	Qo	Ep (MV/m)	Bp (mT)	Ea (MV/m)
1.3 GHz	Nb/Cu	2 K	10^{10}	50	106.5	25
400 MHz	Nb/Cu	4.5 K	$3.3\ 10^{9}$	26	69.3	13
800 MHz	Nb3Sn/Cu	4.5 K	10^{10}	50	100	20
800 MHz	Bulk Nb	2 K	$3\ 10^{10}$	50.8	108	25
800 MHz	Nb/Cu	2 K	$2\ 10^{10}$	50.8	108	25

1st mid-T baked cavity
treated at IJCLab







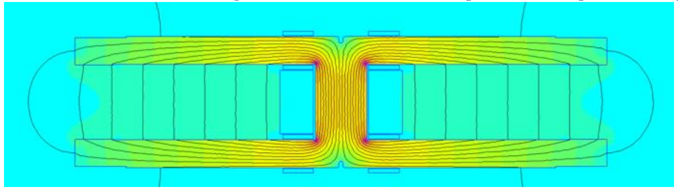
Cavities become factor 5 more sensitive to the residual magnetic field

800 MHz surface resistance much lower than could be extrapolated !

Accelerators Technical Design Sessions: 1 - 3
Magnets, Vacuum, Injection & instrumentation

Collider magnets, GHC and LCC optics

Extensive study of the GHC dipoles, quadrupoles and sextupoles



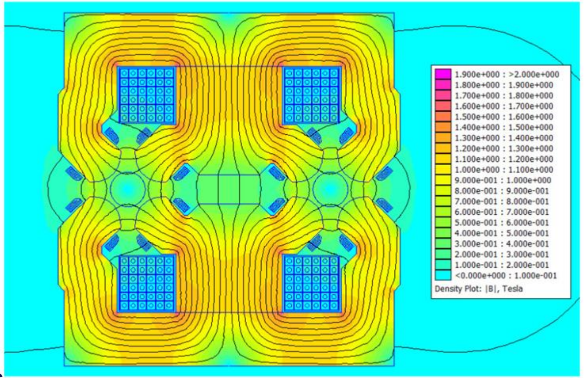


Fig. 3.2: Field map in the quadrupole cross-section at $t\bar{t}$ operation.

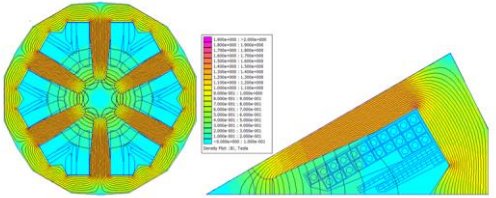


Fig. 3.3: Left: Field map in the sextupole cross-section at $t\bar{t}$ operation (peak field). Right: Detailed view of a half-sextant. The conceptual positioning of the conductor has been generated from parametric modelling for checking integration feasibility. It will be optimised for industrial production during the pre-TDR phase.

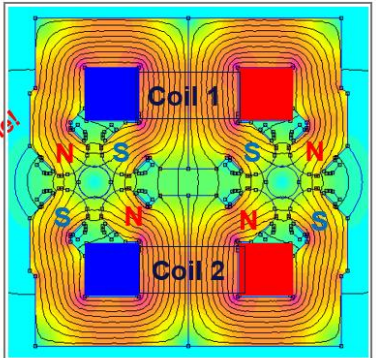
Studying implementation of tapering and addition of correctors: H and V dipole and skew quadrupole

Design is developing next level of detail with 3D effects, impact of harmonics induced by tuning and excitation

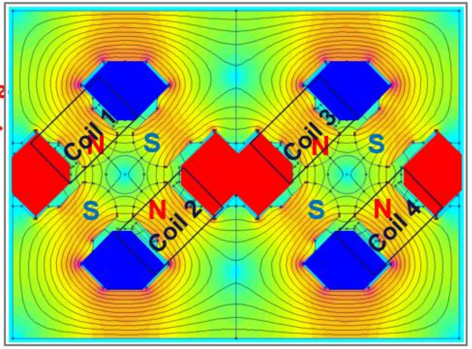
Starting to look at magnets for the LCC optics.

QF and QD have different strengths and can be configured as QD/QD or QD/QF.
Studying integrated magnet as well as dual magnets.

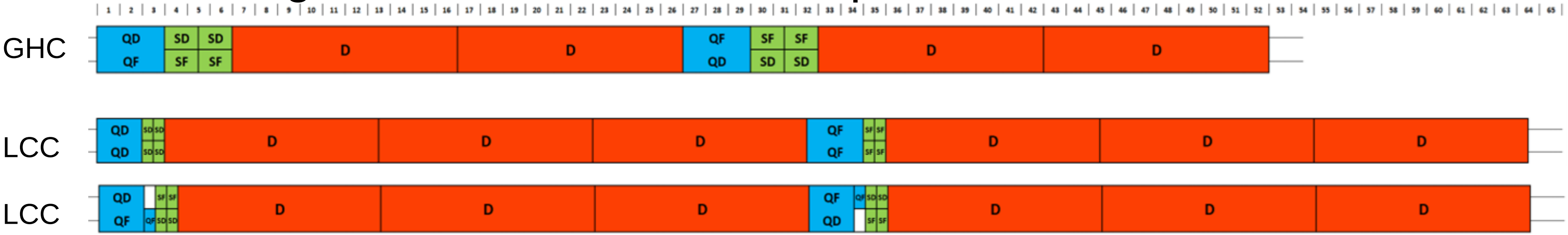
Fixed polarity, NOT configurable!



Configurable polarity!



Collider magnets, LCC versus GHC optics

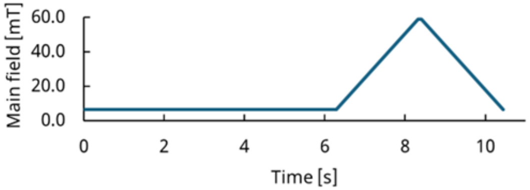


More dipole units, but **fewer SSS magnets with weaker sextupoles**

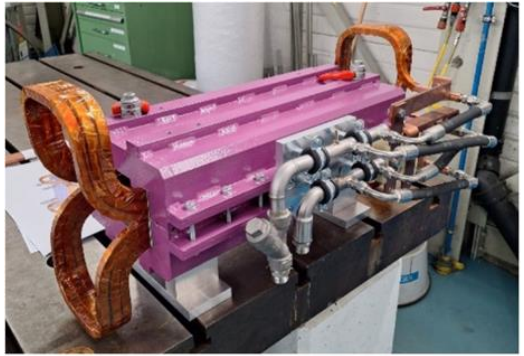
Dipole are much cheaper to produce than the SSS magnets, Potential savings -30% with LCC, same power consumption

Booster magnets

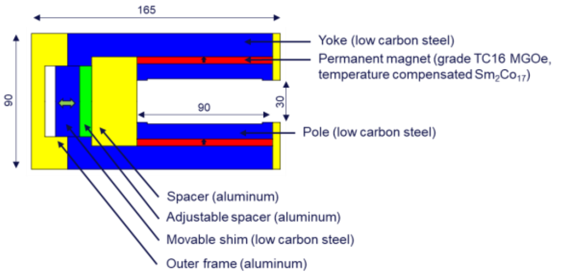
Demonstration of the feasibility of low-field cycled dipole, active development to further refine design

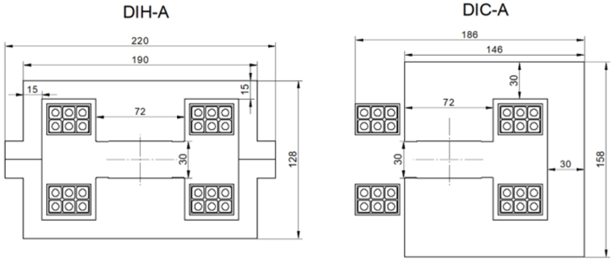


	Dipole
Total number in lattice…	6146
…of which in arcs	5536
Aperture [mm]	
Length [m]	11
Max strength†, arcs ($t\bar{t}$ extraction)	58.9 mT
Min strength†, arc (injection, 20 GeV)	6.5 mT



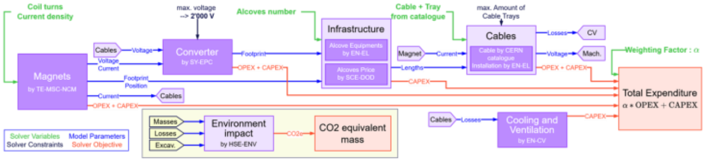
Transfer line magnets, permanent magnet or electromagnet?

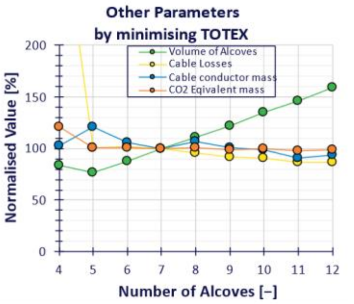


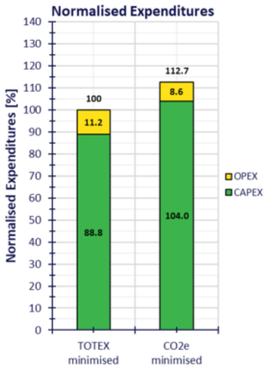


Feasibility: Both technologies Permanent Magnets (PM) and Electromagnets (EM) are technically feasible
Capital costs: in total the EM option is by factor ~1.5 more expensive than the PM
EM have been chosen as the baseline technology due to the higher operational flexibility for the FCC and any science programme beyond the FCC.

Magnet's circuits and system optimisation update





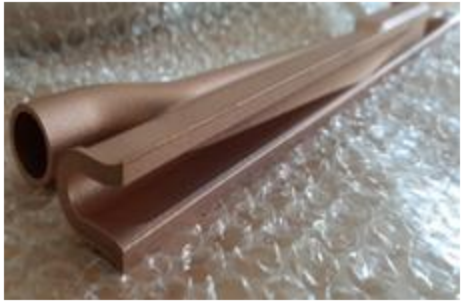


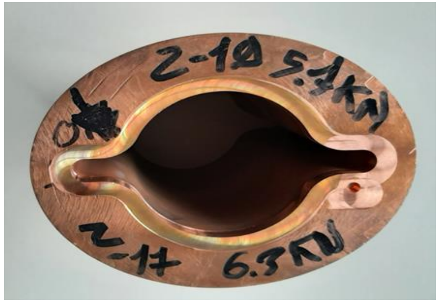
With the optimisation tool, an environmentally friendlier FCC can be achieved

- by prioritising the operation expenditure with the OPEX weighting factor
- or by minimising the CO2 equivalent mass instead of the total expenditure.

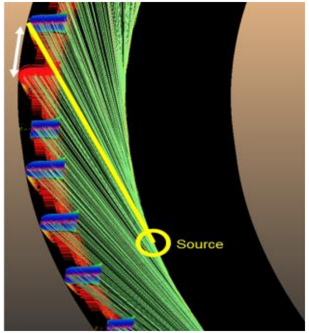
Update of FCC-ee vacuum system development

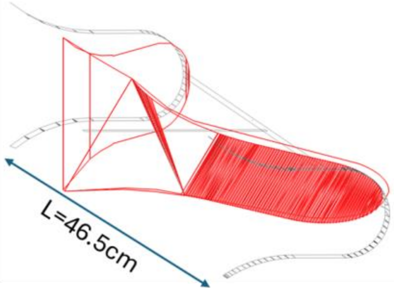
- Vacuum design well advanced
- Many prototypes under construction
- Validation of new technologies for vacuum systems

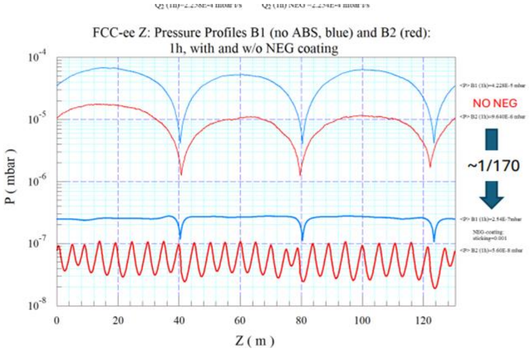





Synchrotron radiation management and pressure profiles



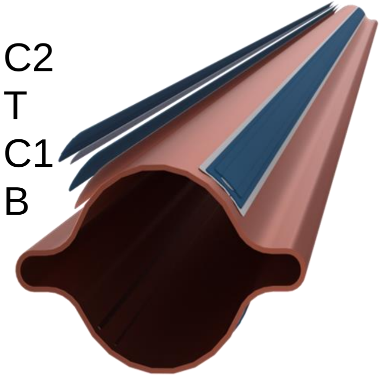




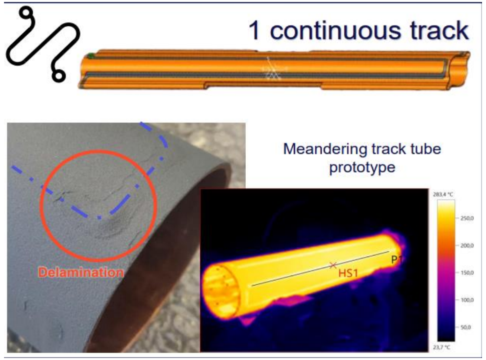
- Regular spacing analysis on photon absorber
- Static and dynamic pressure studies
- NEG coating effects beneficial to reach desired pressure levels

Additive Manufacturing Strategies for the Bake-Out System

C2
T
C1
B



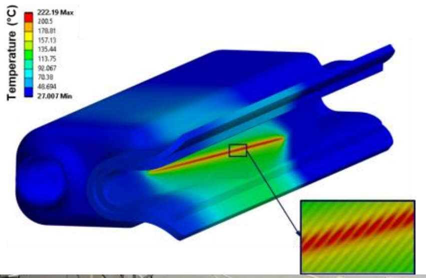
Layer	Function	Material	
Substrate		Cu-OFS	
B	Mediation	NiCr20	
C1	Electrical Insulation	Alumina -Titania 87/13	Spinel 72/28
T	Heating	Ti grade 4	
C2	Protection	Alumina -Titania 87/13	Spinel 72/28

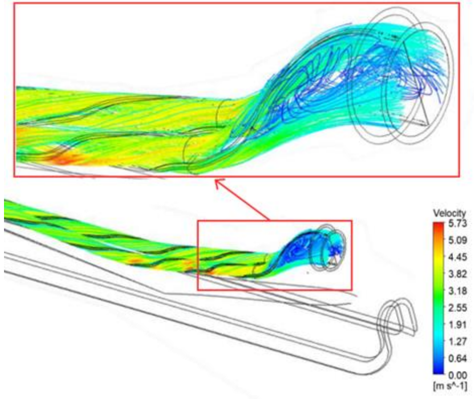


- Heating tracks integrated in the chamber to bake-out the chamber for NEG activation
- Promising experimental result: 250 degC reached

Thermo-mechanical and CFD simulations for SRA

- Design of the photon absorber being optimised
- Fluid Thermo-Dynamics Simulations introduced
- Experimental validation





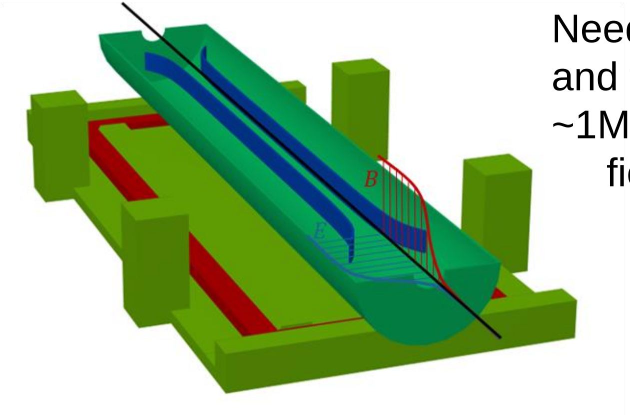
Thermo-mechanical results (considering measured material properties) :

- Maximum temperature: **184°C**
- Maximum Von Misses Stress: **360 MPa** (Safety Factor of **1.4**) (highly localized)

Electromagnetic Separators

E and B Fields
Must be matched everywhere to avoid synchrotron radiation production

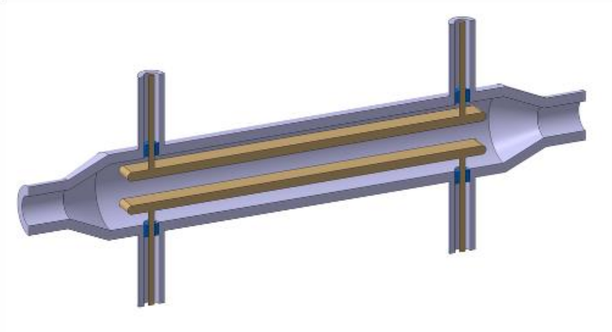
→ Fields matching error to be minimised by design



basic representation of the EMS toplogy

Needed for Zh and t-tbar.
~1MV/m electric field

Kickers systems



	Damping ring	Booster injection	Booster extraction	Booster Dump	Collider injection	Collider dump
Magnet topology	Stripline	Stripline	Lumped inductance	Lumped inductance	Lumped inductance	Lumped inductance
Generator topology	Inductive adder	Inductive adder	Marx generator	LBDS-like generator	Marx generator	LBDS-like generator
Element under vacuum	Yes	Yes	No	No	No	No
Elements / Systems	2/4	1/2	14/2	9/2	6/2	9/2
Novel technology	Yes	Yes	Yes	No	Yes	No
R&D required/ Prototyping required/ Conventional technology	R&D - prototype required	R&D - prototype required	R&D - prototype Required	Prototype required	R&D - prototype required	Prototype required

Many different rise times, pulse lengths, and repetition rates ranging from individual bunches, damping ring trains, to main ring injection, e.g. <25ns / 80 ns at 100 Hz to 600 ns / 300 us at 0.3 Hz

Beam Instrumentation Systems

Large number of beam instrumentation systems will be required. No show-stoppers expect but lots of work: Current, Position, Losses, Trans. and long. Profiles, Polarisation, Luminosity

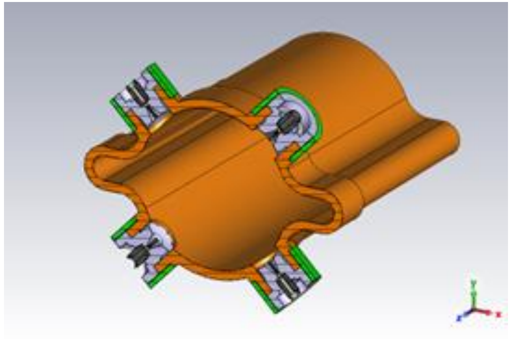
Focusing on:

- Devices related to machine protection
- Devices requiring a substantial R&D phase with large impact on performance
- Devices involving very large quantities with large impact on cost

Need updated requirements, especially for challenging systems, e.g. IR BPMs and bunch-to-bunch needs

Arc Beam Position Monitors

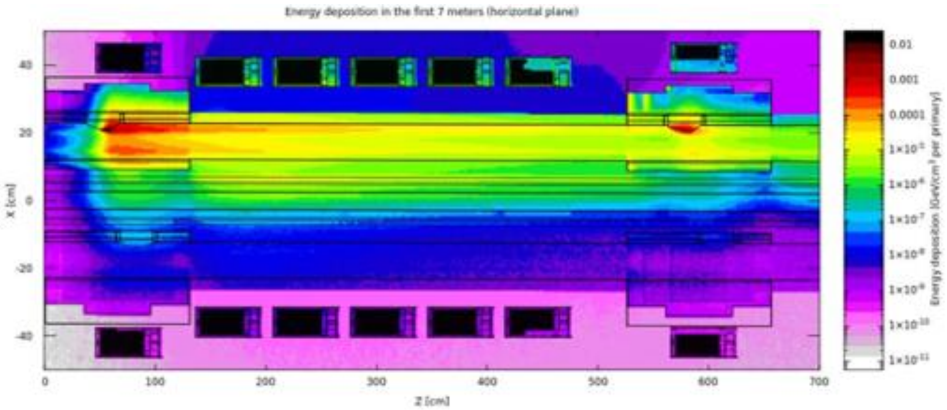
Concept developed for low-impedance button BPM system which integrates with the vacuum system; will design a cost-efficient bunch-by-bunch and turn-by-turn data acquisition system



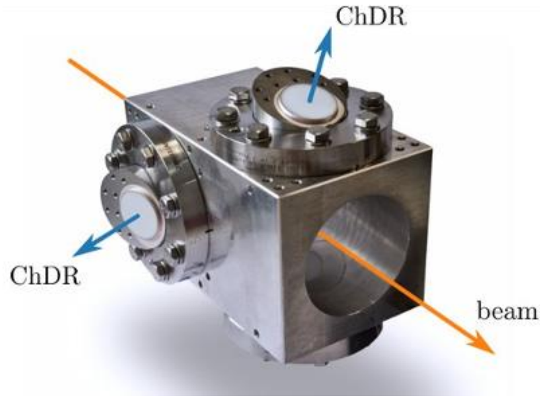
Beam Loss Monitors

MC simulations to develop a BLM system :

- Identifying losses from main rings vs booster
- Insensitive or weakly sensitive to Sync. Rad.



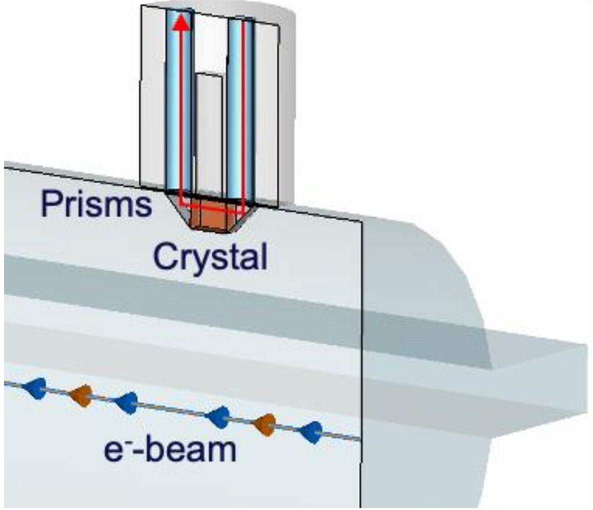
Longitudinal profile measurement



Non-invasive techniques:

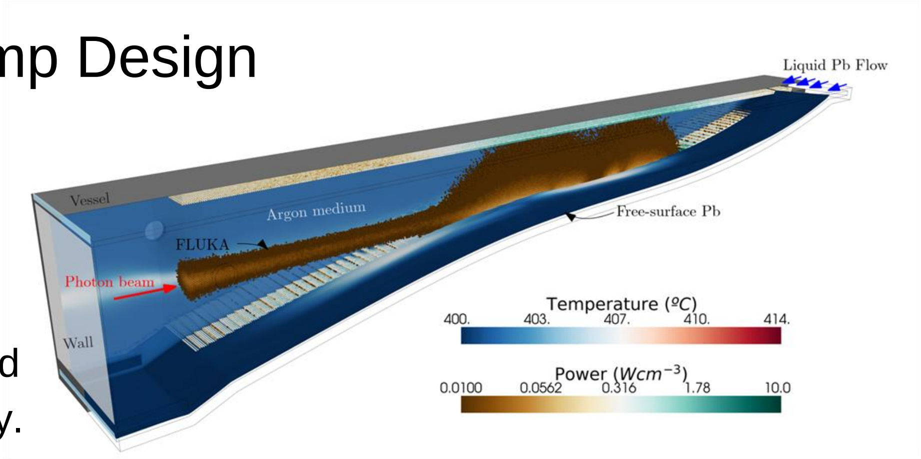
Cherenkov Diffraction Radiation: emitted when a charged particle passes in the vicinity of the dielectric medium.

EOSD: Electro optical spectral decoding of a chirped laser pulse.



Accelerators Technical Design Session 6 - 7 :
Beam Intercepting Devices, Machine Protection, and Availability

Status of the Beamstrahlung Dump Design



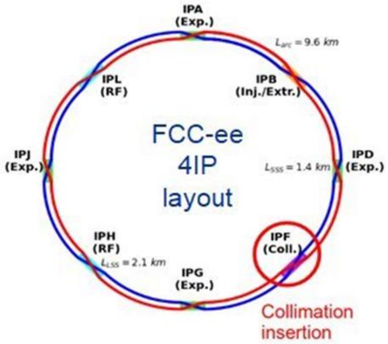
Beamstrahlung dump needs to absorb up to ~500 kW from each beam at each IP.

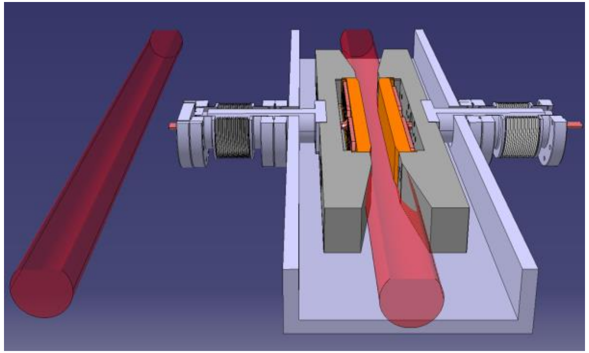
- Present concept is to use liquid lead with ~300 kg/s flow. Working on detailed optimization and integration. Aiming to build 1:2 prototype to verify concepts and stability.

Preliminary design of FCCee collimators

Collimator systems will be critical for IR background control and Machine Protection

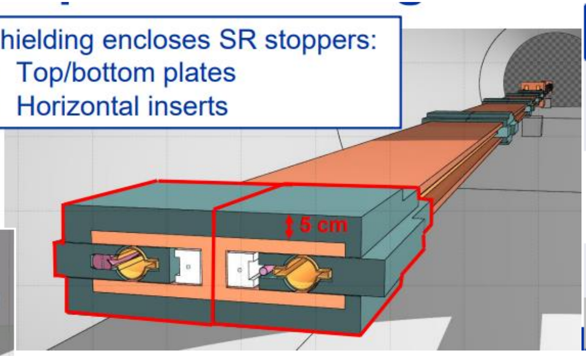
- Many open questions.
- Plan to reuse some of the LHC/HL-LHC and SuperKEKB experience but new challenges.



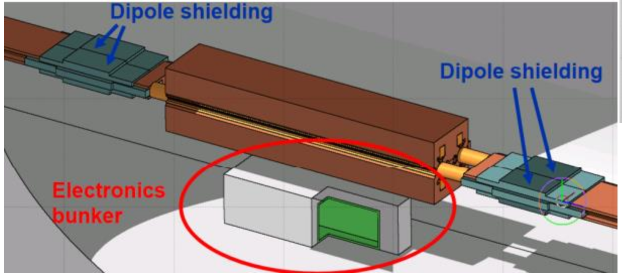


Strategy for mitigating radiation to equipment in FCC-ee

Radiation to equipment is a significant concern for FCC-ee:
➢ Mainly due to synchrotron radiation and from beam losses

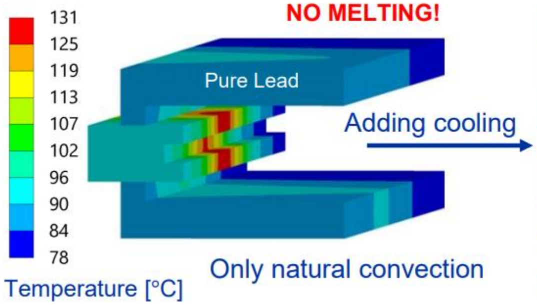


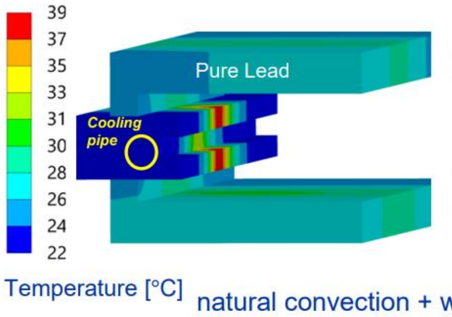
Shielding material for full ring (arcs)	
Shielding weight per stopper	400 kg
Photon stoppers per 20 m dipole	10 (5 per beam)
# dipoles	2840
Total weight	11360 tons

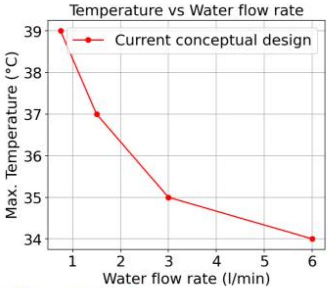


The arc shielding concepts elaborated in the FSR (dipole shielding + electro bunker) provide a first basis for managing radiation in FCC-ee

Preliminary technical design for the FCC-ee dipole shielding







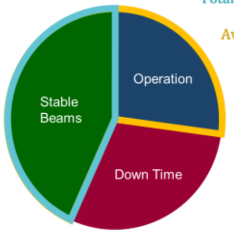
- Cooling needed for the external shielding is recommended
- The conceptual design results in low beam-induced stresses.

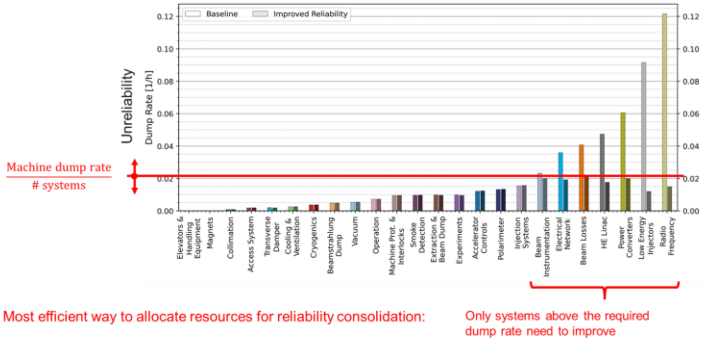
Availability, Efficiency and Integrated Luminosity

Success in FCC requires machine-wide improvement in reliability compared to LHC

$$\text{Efficiency } E = \frac{\text{Stable Beams time}}{\text{Total physics time}}$$

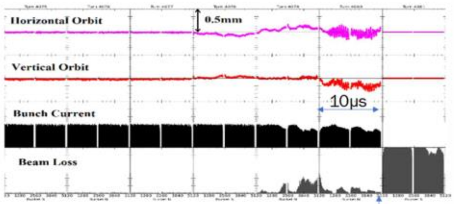
$$\text{Availability } A = \frac{\text{Up time}}{\text{Total physics time}}$$





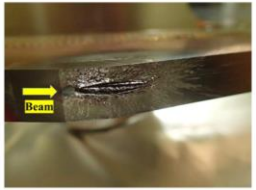
FCCee Machine Protection Considerations

Beam signal measured by
Beam Oscillation Recorder(BOR) & Bunch Current Monitor(BCM)

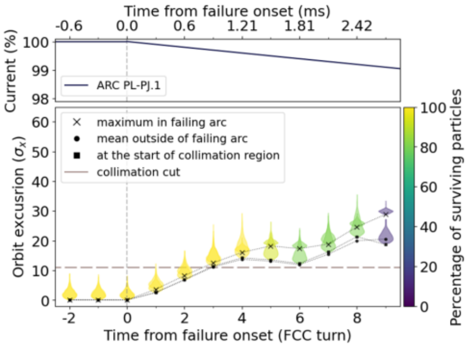


- The beams are dangerous, very bright
- The environment is hostile with a lot of synchrotron radiation
- Several failure modes with a time scale of a few turns have been identified
- The inherent delay of dumping a beam is four turns•A full inventory of failures needs to be made

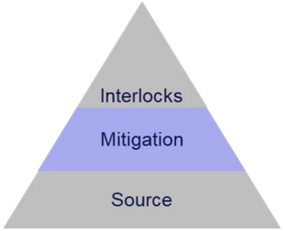
Sudden Beam Losses as seen at SuperKEKb



Effects and criticality of powering failure in the FCC-ee main dipoles



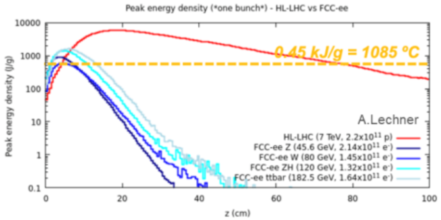
11σ orbit excursion	
Inside "failing half-arc	3 turns
Outside "failing half-arc"	3 turns
Particles losses	
Start of loss	Turn 5
Time to lose all particles	5 turns
Beam blow up	
Limited blow up during the failure	



Add element with larger inductance-to-resistance ratio in the circuit ⇒ feasibility to be discuss with the system experts
Slows down the failure dynamics

Very critical failure requiring mitigation and hardware interlocks

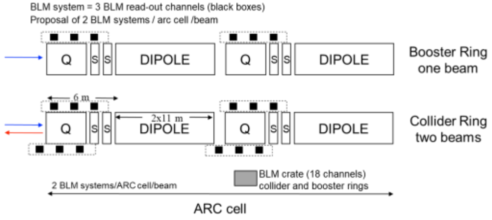
Beam loss monitoring system for FCCee



Detect beam losses fast enough to protect accelerator components and trigger a beam extraction for machine protection.

Provide regular measurements of the amount and location of beam losses for machine optimization and performance

First specifications for the ARC BLM is that it should be able to detect:at least 0.01% of this type of losses iUp to 10 times this damage limit

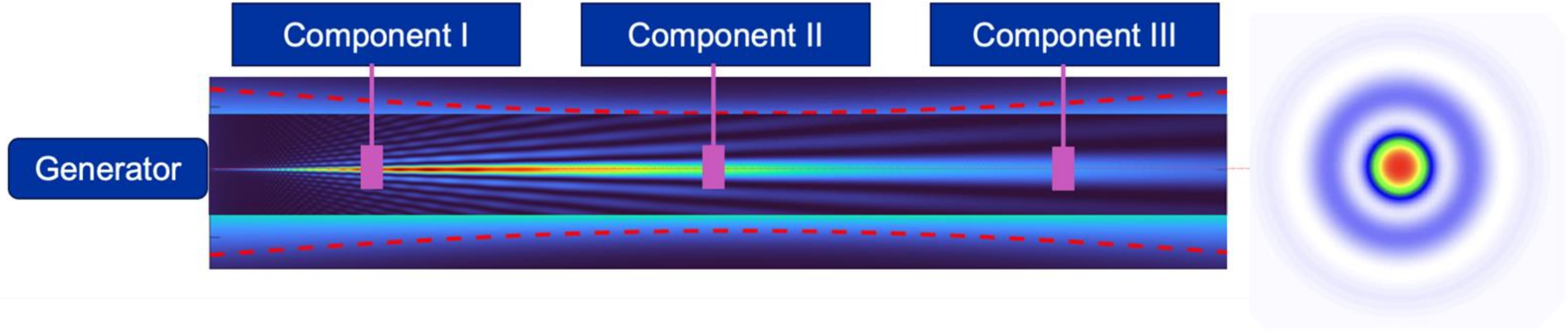


Challenges

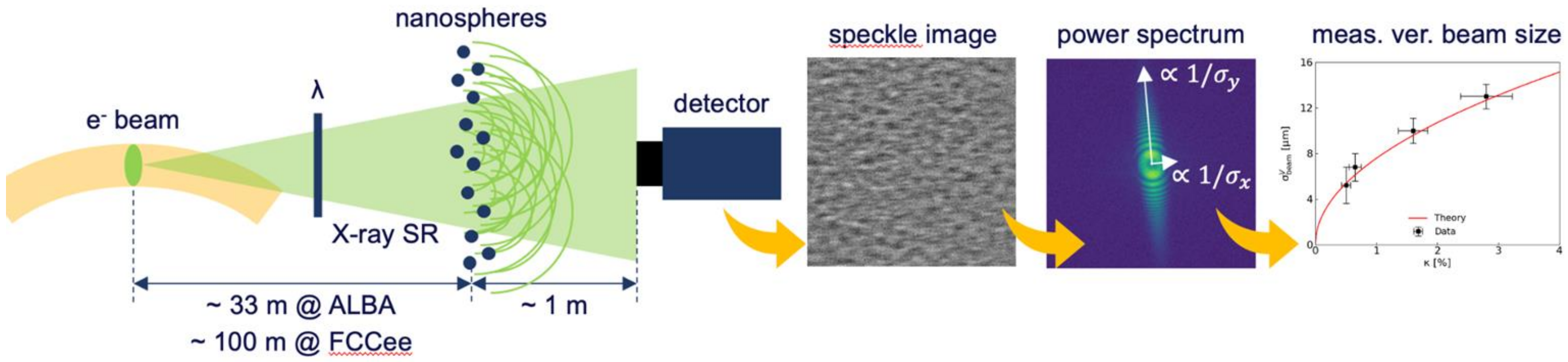
- Synchrotron radiation to electronics and detector
- Signal to background levels
- Huge number of monitors: availability and reliability of the system, production, etc.
- Very small vertical beam size

Accelerators Technical Design Sessions: 4 - 5
Synergies and innovation

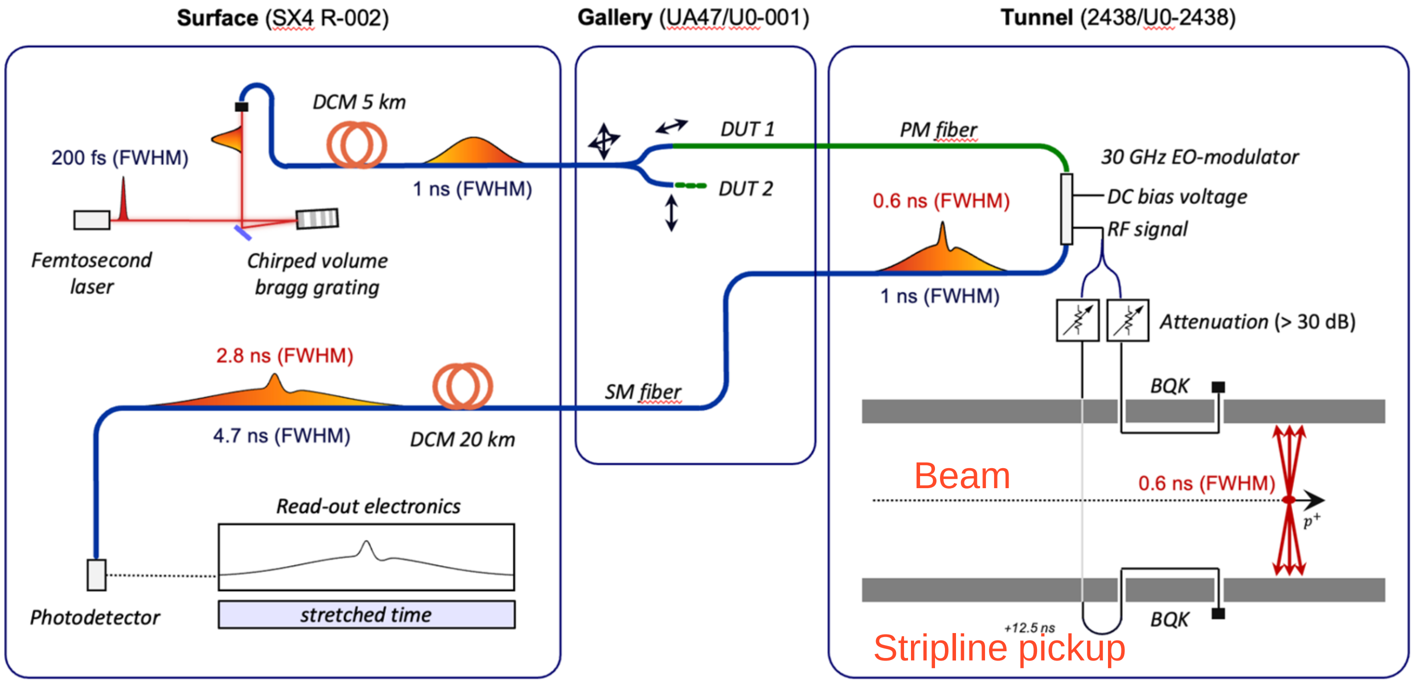
Alignment system based on a Structured Laser Beam under vacuum



Heterodyne Near Field Speckles beam size monitor



Fast readout system for beam signal digitalisation in the FCC era



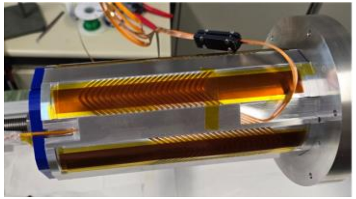
Encode and stretch an EMG pulse from a pickup into a chirped laser pulse to allow digitisation: **up to 50Ghz bandwidth !**

HTS4 development

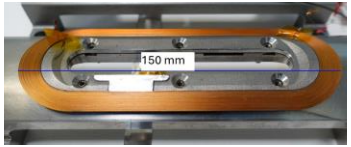
HTS4 program developing HTS-based magnets for SSS – integrated dipole, quadrupole, sextupole

- Reduce SR with integrated dipole
- Reduce electrical power for quad / sextupole

Studying options for cryocoolers and centralized cryogenic system as well as powering options



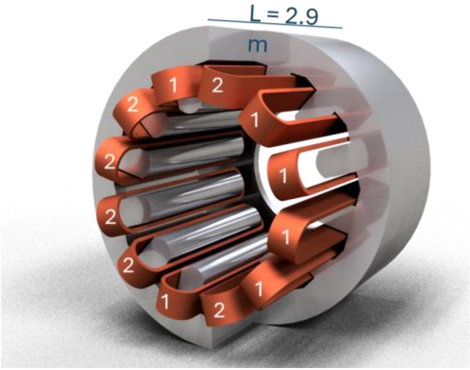
Two short sextupole test at PSI: CCT and Racetrack CT



A flat racetrack HTS design for the lattice combined function MQ/MS

Another approach for the SSS magnets is to use a superferric HTS-based magnet

Open questions include: power supply configuration, field quality and impact on adjacent beam, and coil fabrication; ESMA project @ LASA plans address the latter.



R&D of autonomous production line for CEPC magnets

Unfortunately, the talk was not able to be given.

CEPC has been actively developing quasi-autonomous manufacturing techniques for the number of magnets that will be required.

IP Feedback Tolerances & new modelling of SuperKEKB in Xsuite

IP Feedback is critical to maintaining luminosity with nm-scale beams

- Beam-Beam deflection for the vertical plane
- Dithering for the horizontal plane

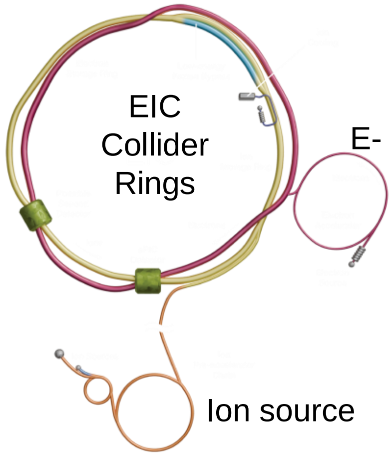
Similar approach to SuperKEKB Design

SuperKEKB model ported to XSuite providing new opportunity to model and understand performance and derive lessons for FCC-ee

Parameter	Z	WW	ZH	tt
σ_x [μm]	8.84	21.8	13.1	39.9
σ_y^{BS} [nm]	36.5	46.9	37.4	50.6
σ_z^{BS} [mm]	15.5	5.41	4.70	2.17

Synergies with Electron Ion Collider

Synergies with Electron Ion Collider



The Electron Ion Collider at BNL will have a high current electron storage ring with many similar challenges:

- High current electron beam (nearly 2e11 with 10 ns spacing)
- Different energy set points (5, 10, 18 GeV)
- High gradient SRF with Reverse Phase Operation
- On energy injection
- Beam collimation with high energy density beams
- Complicated IR with compact SC magnets
- High resolution diagnostics and beam feedback
- Polarized electrons
- S-band injector linac

- Commissioning mid-2030's

NSLS-II, EIC & FCC-ee beam parameters

	NSLS-II	EIC	FCC-ee-Z
Beam energy [GeV]	3	10 (18)	45.6 (80)
Bunch population [10^{11}]	0.08	1.7	2.1
Bunch spacing [ns]	2	10	25
Rms bunch length [mm]	4.5 - 9	10	3.5 from SR 15 incl. BS
Beam current [A]	0.5	2.5 (0.27)	1.39
RF frequency [MHz]	500	591 or 394	400
SR power / beam /meter [W/m]	900	7000	600
Critical photon energy [keV]	2.4	9 (54)	19 (100)

Summary

Great sessions with lots progress

Engagement at CERN and with collaborators is increasing

R&D timelines are clear; all reasonable for construction start in 2030’s

Ready to begin pre-TDR stage once component specifications are clarified

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Thank you all!