Swiss Accelerator Research and Technology

PAUL SCHERRER INSTITUT

The FCCee-HTS4 project

M. Koratzinos

CHART workshop

11/10/2023

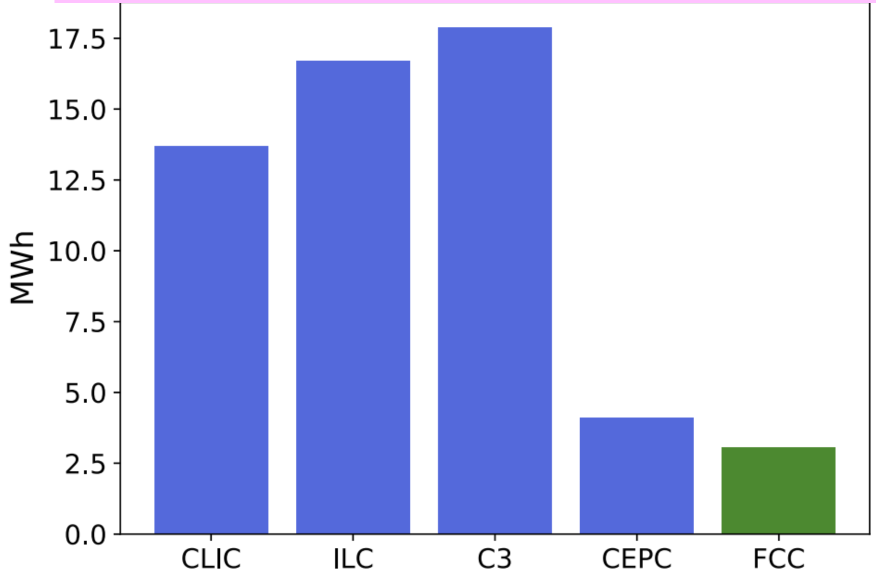
FUTURE CIRCULAR COLLIDER

This work is performed under the auspices and with support from the **Swiss Accelerator Research and Technology (CHART)** program (www.chart.ch).

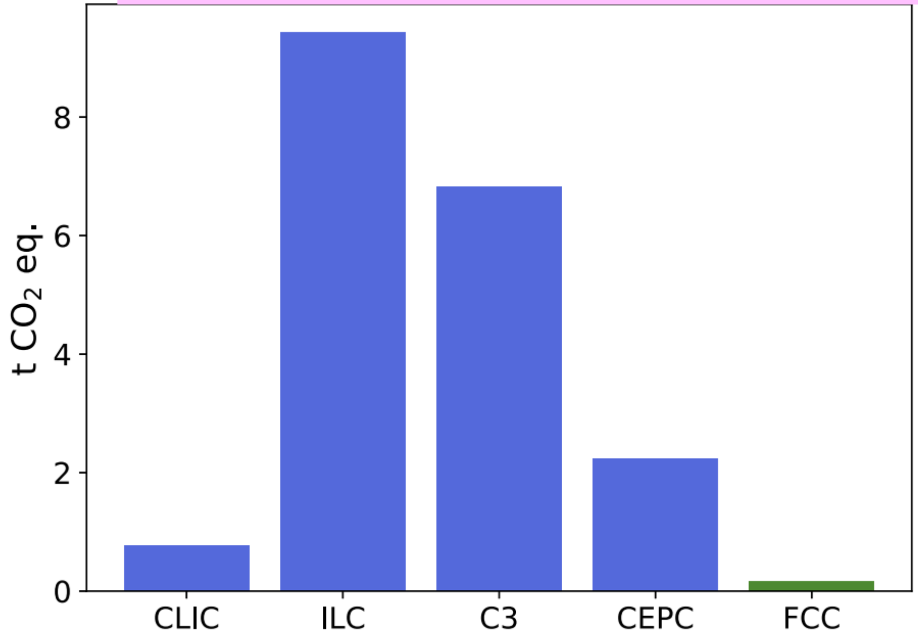
The big picture

- FCC-ee is the most energy-efficient accelerator proposed (and the one with the smallest CO2 footprint (see "the carbon footprint of proposed e+e- factories", Janot and Blondel, https://link.springer.com/article/10.1140/epjp/s13360-022-03319-w
- This is an attempt to make FCC-ee even more *sustainable* and at the same time increase *performance* by looking at the **main magnet systems** of FCC-ee
- We re also looking into increasing the *relevance* of FCC to *society* by adopting state-of-the-art technologies and trying to play a leading role in our respective fields

Energy consumption per Higgs produced



Carbon footprint per Higgs produced



FCC-ee: The power challenge

CDR: FCC-ee is a conventional (warm) accelerator, much like LEP (CERN, 1989-2002)

- The FCC-ee CDR has **2900** (20m-long) dipole, **2900** quadrupole and **4704** sextupole magnets, all normal conducting
- Every effort was made to have a "power saving" design for the quads (50% saving, but with some compromises)
- This power loss is dominated by the quadrupole and sextupole magnets.

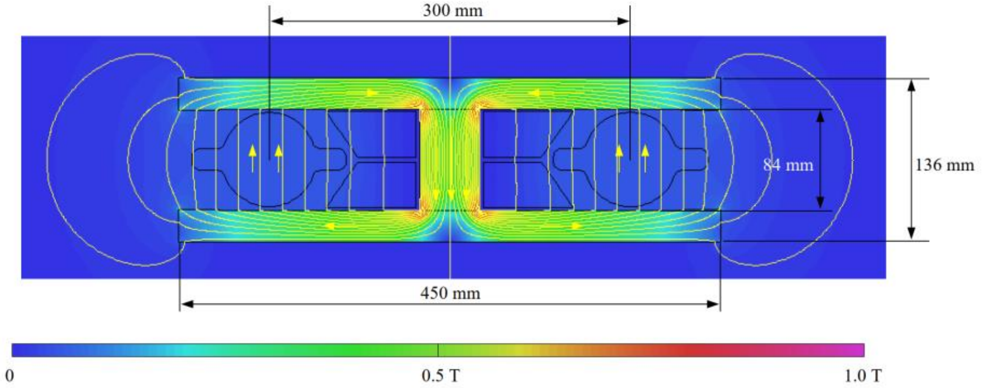


Figure 3.1: Cross-section of the main bending magnet; the flux density corresponds to 57 mT in the gap; the outline of vacuum chambers with side winglets is also shown.

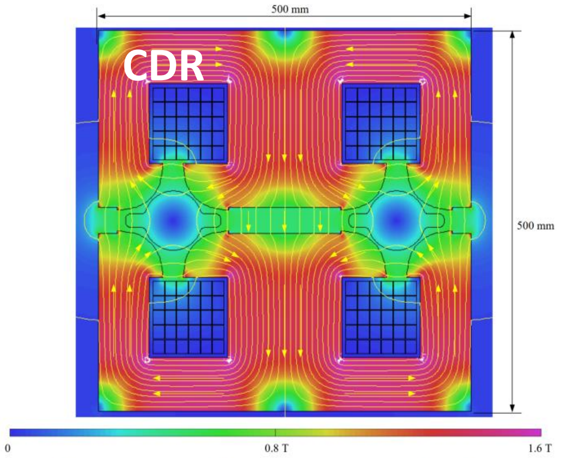


Figure 3.3: Cross-section of the FCC-ee main quadrupole, for a 10 T/m gradient.

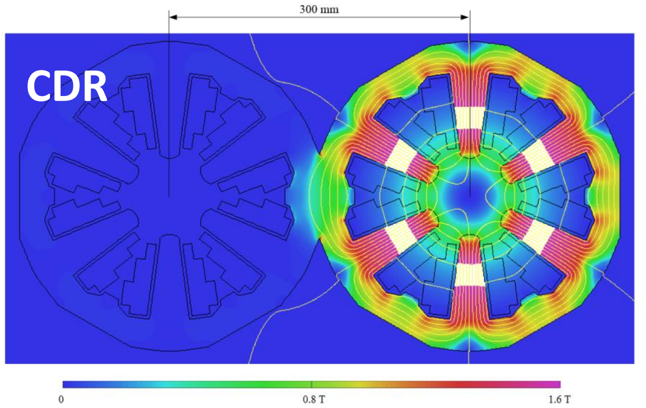


Figure 3.6: Cross-section of the FCC-ee main sextupole magnet. The position of the sextupole for the other beam is outlined on the left.

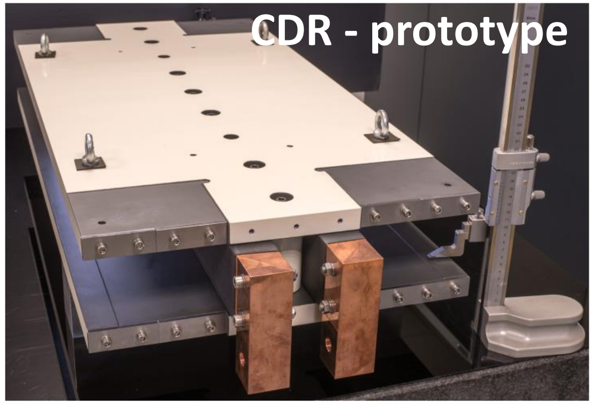


Figure 3.2: One of the ca. 1 m long model dipole magnets manufactured at CERN.

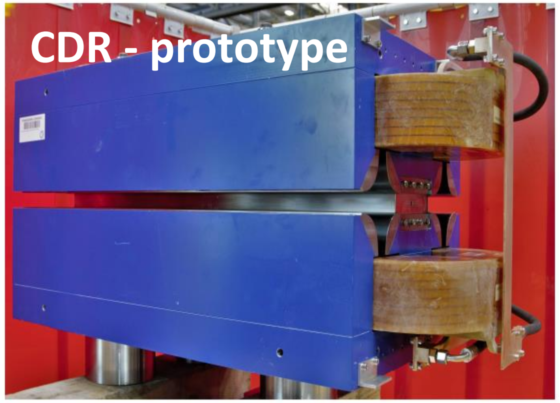


Figure 3.5: Picture of a 1 m long quadrupole prototype magnet for the FCC-ee.

(no prototype exists yet)

Big, heavy quads and sextupoles

Power consumption – collider main magnet systems

We pay twice for normal conducting magnets: one through ohmic losses, and again for removing the heat with our cooling and ventilation (CV) system.

Storage Ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
Magnet current	25%	44%	66%	100%
Power ratio	6%	19%	43%	100%
Dipoles (MW)	0.8	2.6	5.8	13.3
Quadrupoles (MW)	1.4	4.3	9.8	22.6
Sextupoles (MW)	1.3	3.9	8.9	20.5
Power cables (MW)	1.2	3.8	8.6	20
Total magnet losses	4.8	14.7	33.0	76.4
Power demand (MW)	5.6	17.2	38.6	89

CV needs to remove the heat of the storage and booster magnets (100MW at top), storage and booster RF (148 at top) and experiments (8MW). Total is 256MW
The share of storage ring magnets on CV is 35%, or **14MW**

Cooling and ventilation		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Pcv (MW)	all	33	34	36	40.2

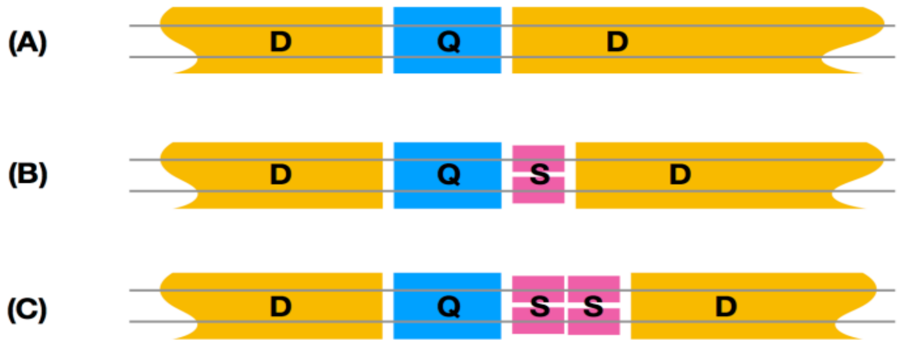
Total contribution of the collider ring magnets is therefore **~100MW** at the top, 76% of which comes from the quads and sextupoles

M. Koratzinos

FCC-ee: The power challenge

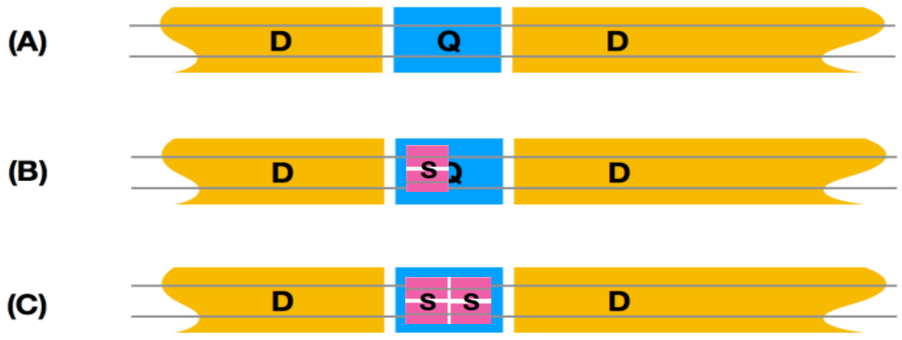
How can we improve in this design?
1/ Make the magnets superconducting. Then, energy is only spent cooling the magnets (zero Ohmic losses).
2/ Also, we can “nest” the magnets, so that they take less space
➔ This means that there is more space available for bending, so performance of the accelerator also increases.
➔ **Potential power reduction for these systems: ~90%**
➔ **2900 cryostats, 3.5m long each**

CDR



Half cell length: 27.9 m

This proposal



Other potential gains

Apart from the power consumption reduction, the gains of a nested system are:

- The packing factor increases by 7%, so, for the same luminosity, RF power can be reduced by 7%
- The higher packing factor also reduces the total voltage needed by the RF by 7%
- Total gain ~14% in the price of the RF system (which is O(1BnCHF). If the price of the magnet systems concerned is ~25% of the price of the total RF system, then ~40% of the cost of the cold SSSs is compensated by the reduction in the RF costs!
- We aim to produce the superconducting SSSs in the same price envelope as in the CDR.

- The optics design is much more flexible:
  - No requirement for fixed polarity electron/positron quadrupoles
  - Sextupoles available in all SSSs
  - Opens the path for 100% filling factor and tapering management (see next slide)

It should be made clear that this is a big change in the design of FCC-ee and many systems are affected, for instance photon stopper design, radiation environment in the tunnel, BPM design, girder design, optics, etc.

Can we do even better?

- Move the power supply inside the cryostat instead of the traditional cold magnet/warm power supply (FCCee-CPES project)
- This system can naturally be adapted to also have a nested dipole covering the entire length of the SSS (another potential gain of 7% in packing factor, reaching almost 100%).
- A nested dipole system (which will be individually powered) will also solve all our tapering needs (maximum dipole strength needed at the top is ~30%).
- The inclusion of a nested dipole system is not the baseline solution now, but it is useful to keep it in mind as a possible improvement (plus also an extra complication!).

The proposal

- A proposal was submitted and approved by the Swiss accelerator research and technology forum CHART in April 2022:

CHART

Swiss Accelerator Research and Technology

CHART Proposal Form

FULL TITLE	**FCC-ee High-Temperature-Superconducting Short Straight Section**
SHORT TITLE (max. 20 chars)	**FCCee HTS4**
Principal Investigator	**Dr. Michael Koratzinos**

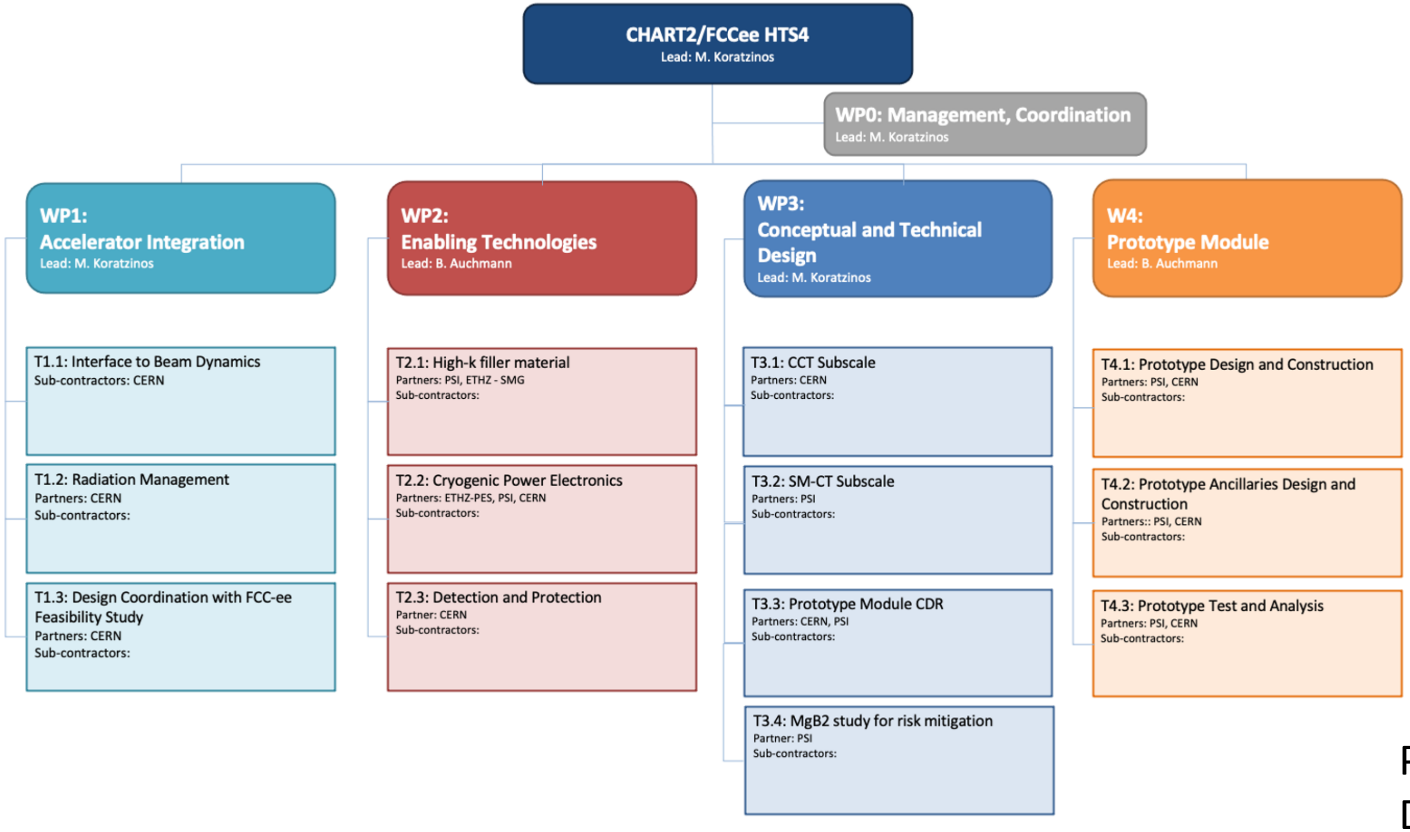
FCCee-HTS4 are: B. Auchmann, J. Kosse, V. Batsari, A. Thabuis,J. Schmidt (from 1 December 2023),M.K.

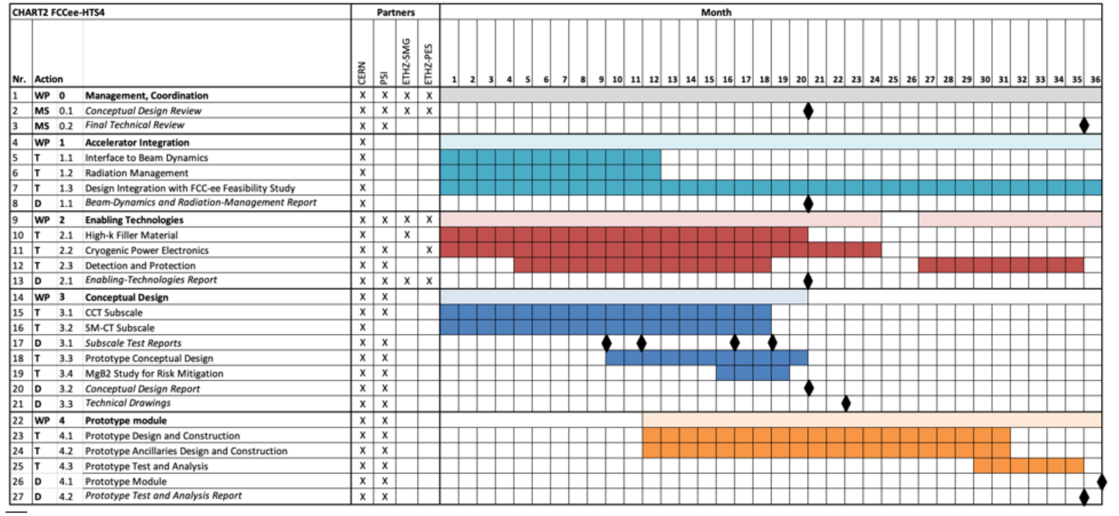
- (Our sister project, FCC-ee CPES, investigating the possibility of a cold power supply system, was also approved at the same session.)

FCCee-HTS4 in a nutshell

- Investigate the replacement of all FCC-ee short straight sections (SSSs) that contain arc quads, arc sextupoles and assorted correctors by superconducting ones.
- Nest the sextupoles and quadrupoles in the same unit.
- Use HTS conductors (ReBCO tapes)
- Operate at around 40K
- Investigate all integration issues
- Produce a ~1m prototype

The project





Project duration: 3 years (starting 1/7/2022)

Deliverables:

- Beam dynamics report
- Enabling technologies report
- One or more demonstrator hardware
- One prototype designed, manufactured and tested

SSS main parameters

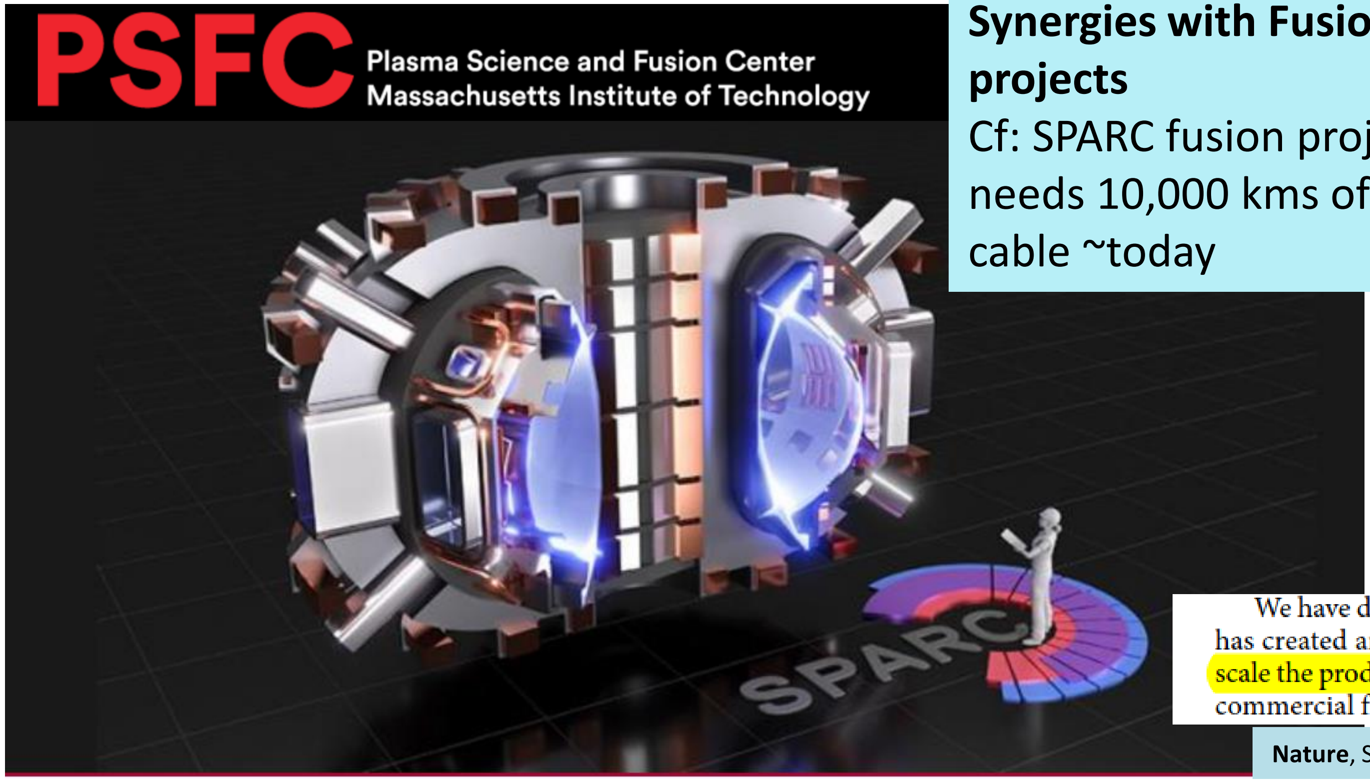
The FCC-ee optics design layout has the following specifications:

- Length of quads is 2.9m. Quads should not be shorter, due to SR issues
- Strength of quads is 11.84 T/m at tt.
- Length of sextupoles is 1.5m. Sextupoles can be made stronger and shorter at will.
- Strength of sextupoles is 812 T/m^2 at tt.
- Together with necessary gaps and with all services, the length of the SSS will be 3.5m

A question of cost

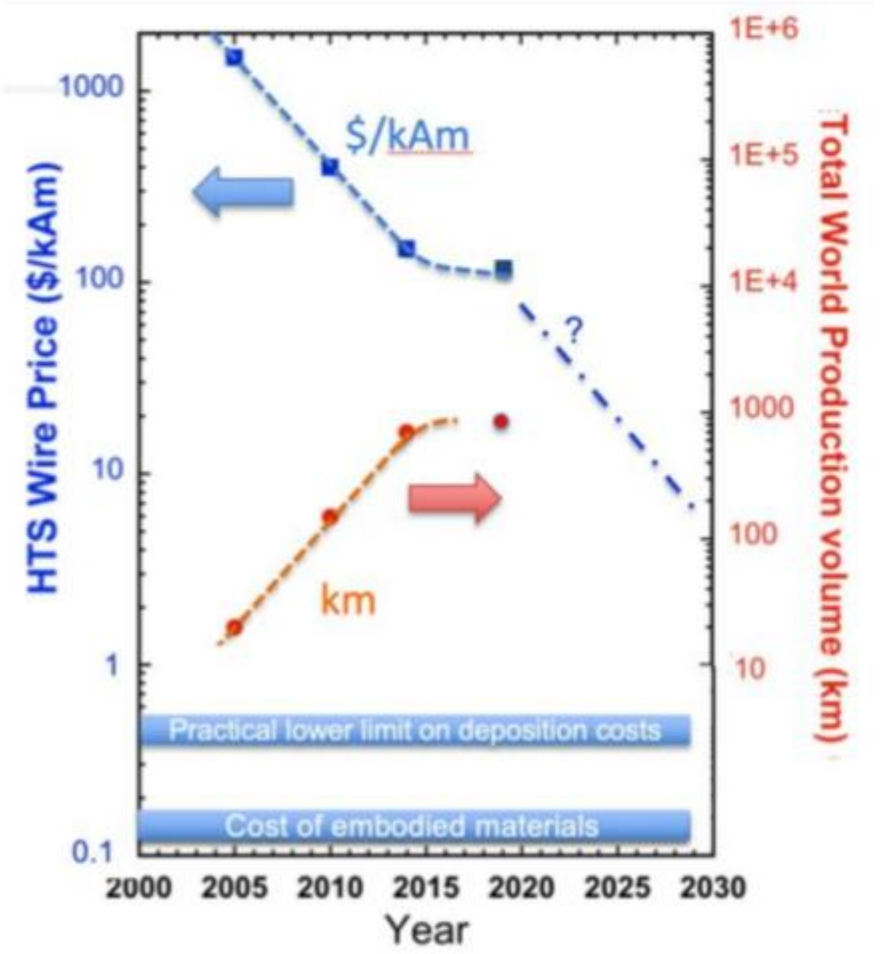
https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF7_AF0_Vladimir_Matias-251.pdf

- The cold SSS idea cannot cost more than the price of the normal conducting system. The major cost driver today is the HTS conductor
- For the above to be the case, we need a reduction in price of HTS tapes of about 3-4 compared to now in 20 years.
- We believe that the advent of fusion projects will help reduce the price of HTS by a factor 10 in 20 years, so we think we are competitive.



Synergies with Fusion projects

Cf: SPARC fusion project needs 10,000 kms of HTS cable ~today

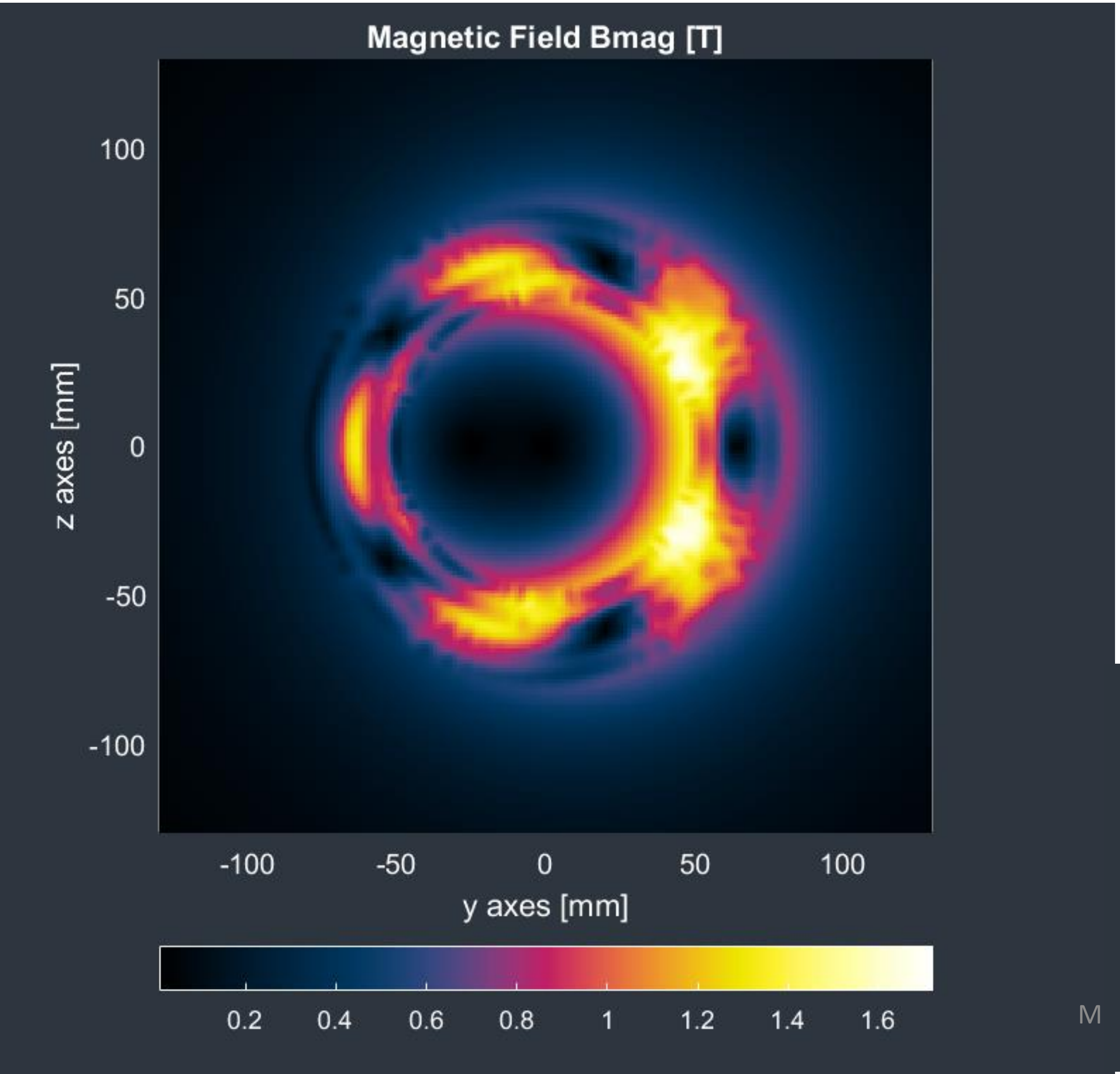


We have developed a product that satisfies specific performance requirements from the fusion industry, which has created an unprecedented demand on HTS wire. When this demand turns into orders, HTS industry will scale the production driving down the wire cost ultimately to tens of dollars per kiloAmpere-metre, at which level commercial fusion plants become economically feasible[18], as well as many other commercial HTS applications.

Nature, Scientific Reports | (2021) 11:2084 | https://doi.org/10.1038/s41598-021-81559-z

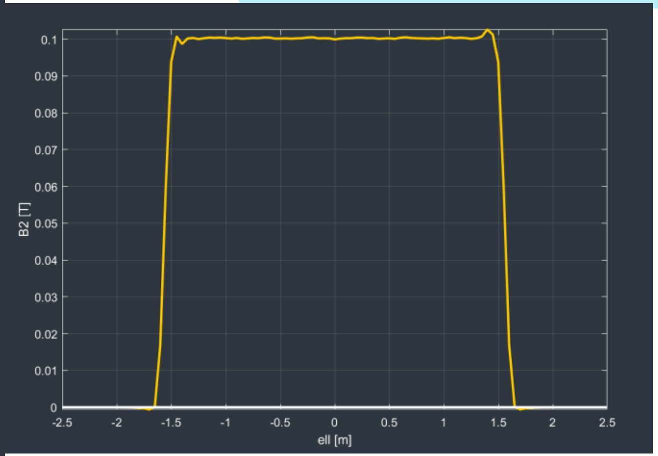
Quad and sextupole at full strength

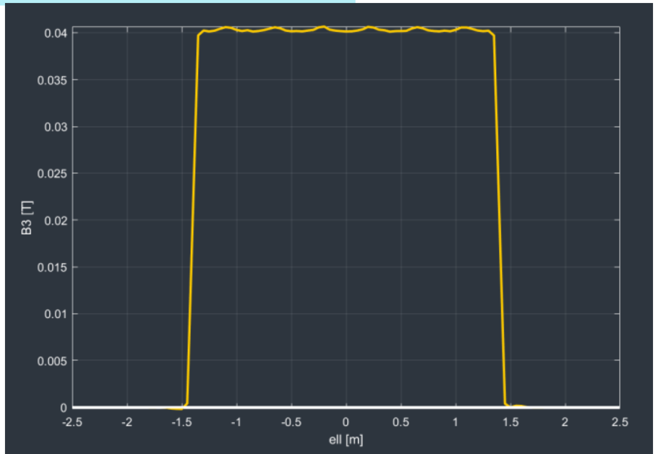
Magnetic analysis



- This is a low field application (1.7T max) gradients: 12T/m; 1000T/m^2
- There is no problem attaining the performance with today's HTS tapes

B2 @10mm: 0.1T; B3 @10mm: 0.04T





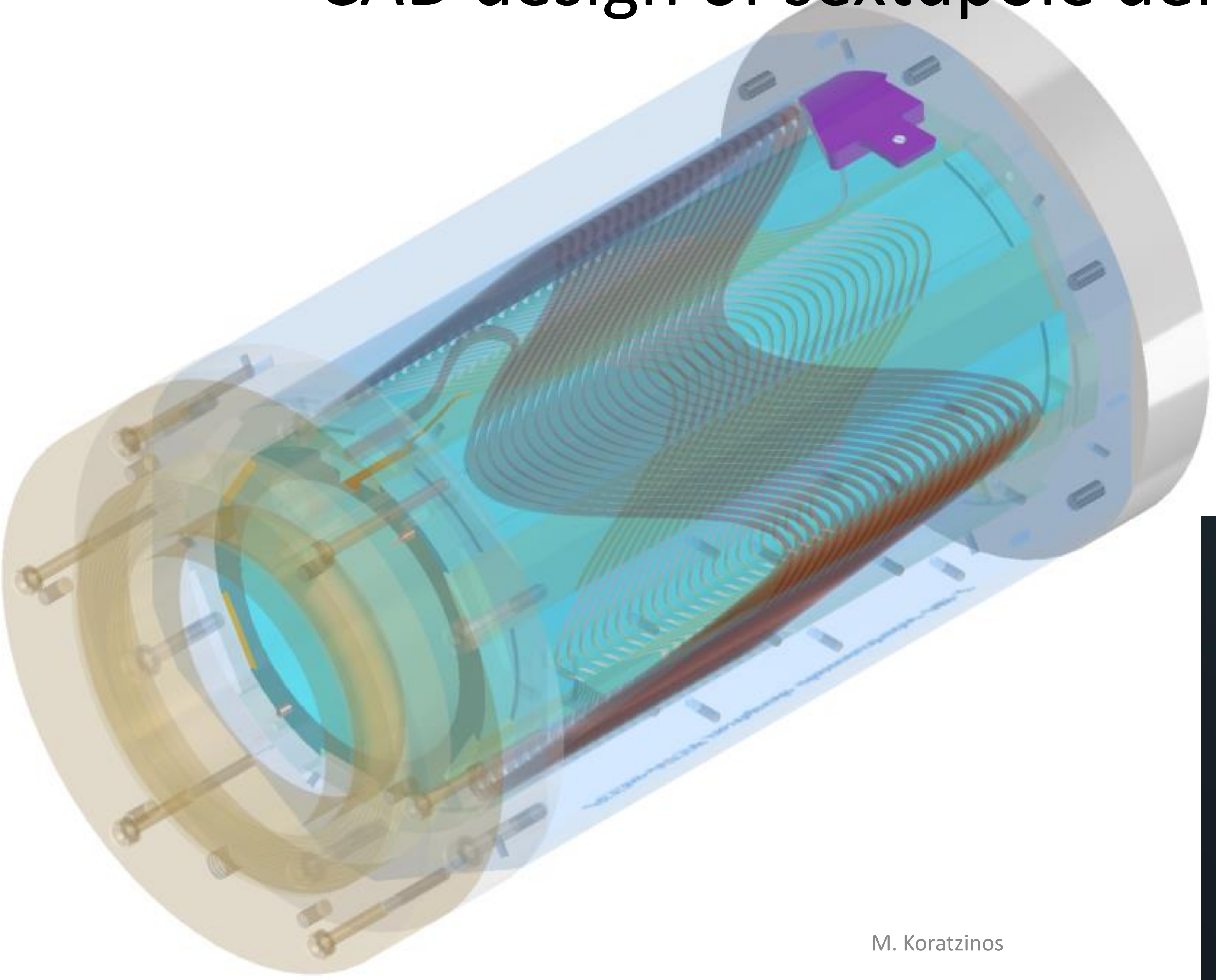
Demonstrator

- Since we are dealing with a new technology (quads and sextupoles using HTS conductor) one (or more) short-length demonstrators are needed to prove that our technology choices are correct.
- A sextupole demonstrator has been designed and is being manufactured
- The sextupole was chosen since in a nested (quad/sextupole) system, the higher order multipole goes closer to the beam pipe
- Progress:
  - Magnetic design finished using the RAT GUI from *Little Beast Engineering* (https://rat-gui.ch/)
  - CAD design finished
  - Material ordered
  - Waiting for manufacturing in the CERN main workshop

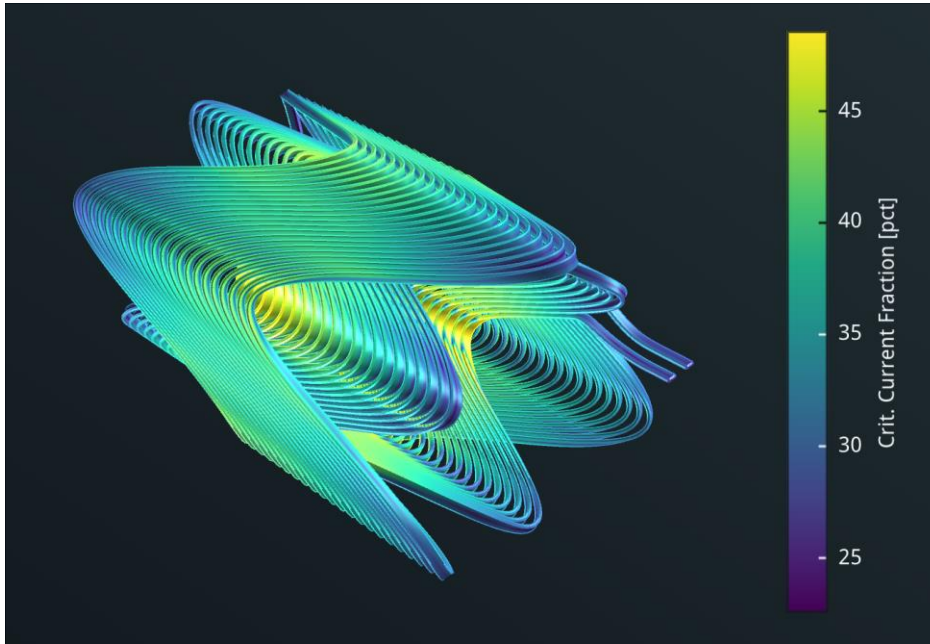
Demonstrator – choice of technology

- We have chosen a CCT magnet layout due to
  - Ease of construction
  - Good field quality
  - Quick design cycle
- Other approaches (i.e. standard cosine-theta) will also be pursued
- The use of HTS tape makes the design non-trivial compared to a round-conductor CCT, like the final focus prototype quadrupole already constructed and tested at warm.

CAD design of sextupole demonstrator



Specifications:
Aperture: 90mm
Current: 260A
Temperature: 40K
Field gradient: 1000T/m2
Max. field @conductor:1.5T
Crit. Current fraction: 49%
Temp. margin: 14K



Manufacturing

For the prototype stage, there are two main manufacturing techniques:

- Additive manufacturing (metal 3D printing)
  - Advantages: any geometry is realizable
  - Disadvantages: surface roughness, a lot of post-processing
- Subtractive manufacturing (CNC machine milling)
  - Advantages: mirror-like finish
  - Disadvantages: not all geometries realizable
  - Our choice for the first demonstrator
- We are actively looking at both techniques


Romain Gerard,
Numan Ghazali
(EN-MME-FW)

HTS4 in MT28

MT28-5POM03-05

Reliability engineering of cryocooler-based HTS magnets for FCC-ee

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*Paul Scherrer Institute (PSI) Villigen, Villigen, 5232, Switzerland
†European Center for Nuclear Research, 01631 Geneva, Switzerland

- We are proposing a large, distributed, cryogenic system.
- Availability of such a system is paramount.
- (a centralized cryogenic system will also be considered)

TABLE III

HTS4 TOTAL SYSTEM AVAILABILITY FOR 1-YEAR OPERATING PERIOD, WITH n COOLERS PER SSS OF WHICH AT LEAST k NEED TO BE OPERATIONAL. COLORS INDICATE CONFIGURATIONS WITH HIGH (GREEN), QUESTIONABLE (ORANGE) AND LOW (RED) RELIABILITY. MTTF OF EACH COOLER IS 10^7 HOURS, AND MTTR IS 1 MONTH.

		Working coolers k					
		1	2	3	4	5	6
Installed coolers n	1	0.8335					
	2	0.9998	0.7145				
	3	1.0000	0.9995	0.6253			
	4	1.0000	1.0000	0.9990	0.5558		
	5	1.0000	1.0000	1.0000	0.9983	0.5003	
	6	1.0000	1.0000	1.0000	1.0000	0.9975	0.4548

HTS4 in the news

Accelerating NEWS

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News › › Issue 44 › Topic: Future Circular Collider (FCC)

HTS4 project explores superconducting options for the FCC-ee

A new FCC-ee collaboration is another attempt to minimise energy consumption by replacing normal conducting sectors with high-temperature-superconducting ones, all within the same cost envelope.

5 JULY, 2023 | By Vasiliki Batsari (CERN), Bernhard Auchmann (PSI/CERN), Jaap Kosse (PSI) & Michael Koratzinos (PSI/CERN)

A new collaboration between CERN and PSI aims at replacing the normal conducting short straight sectors (SSS) of the FCC-ee main storage ring with high-temperature-superconducting

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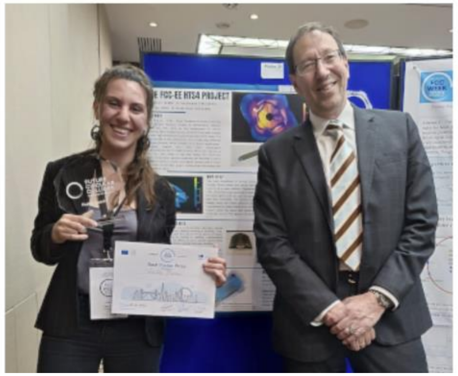
14. August 2023 - News

Best Poster Award at the FCC Week 2023



The FCC week, the traditional yearly get-together of the collaborators and proponents of the Future Circular Collider project of CERN, this year took place in London during the period of 5-9 June 2023. During that week, oral presentations and poster exhibitions presented progress and status for all aspects of the project, and notably CHART projects had a strong presence and impact. The poster session featured a collection of 28 posters, which were assessed by a scientific committee in terms of their quality, relevance, and appearance. Vasiliki (Vicky) Batsari was voted as the 'best poster award' winner by the committee, for her poster on the CHART project FCC-ee HTS4. The award also entailed an invitation to present the poster and the key points of the HTS4 project in a brief

Next presentation

Our sister project!: FCCee CPES (PES, ETHZ)

Power Electronic Systems Laboratory

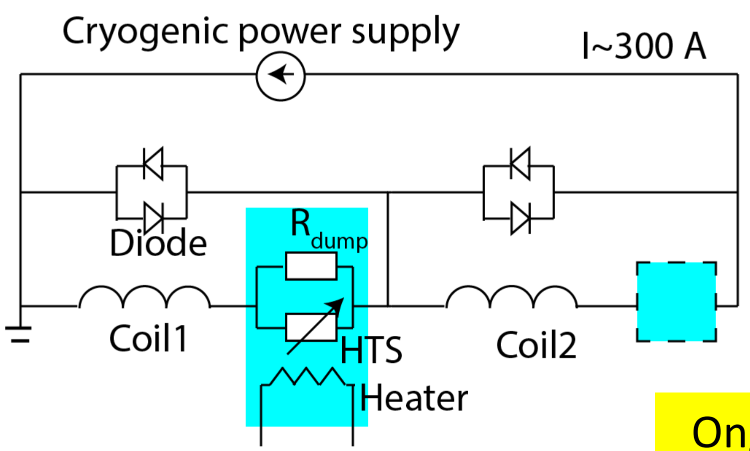
ETH zürich

CHART | FCCee CPES

Magnet protection

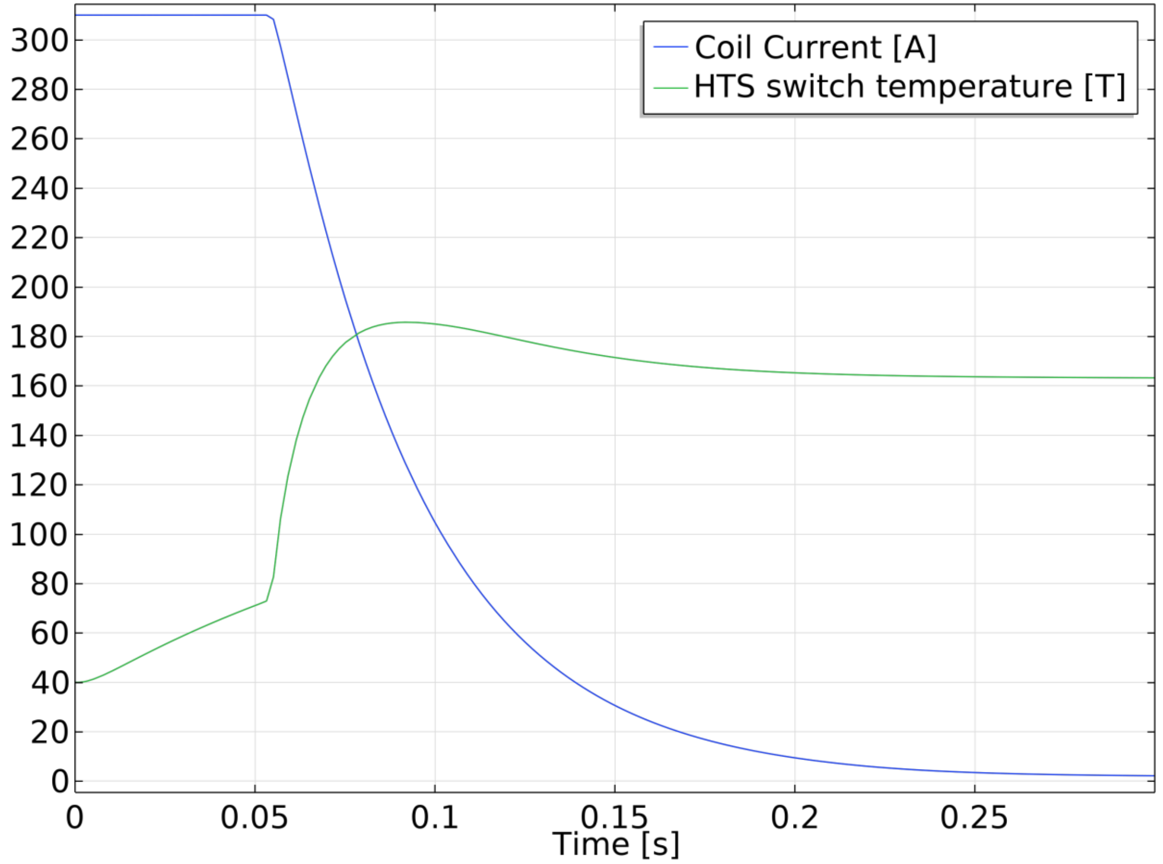
- If we use a cold power supply, the energy extraction system should also be cold
- But we do not want the switch to generate heat when idle

Energy extraction via HTS switch
- Heater activated
- Modular



J. Kosse

Ongoing work



Conclusions

- The idea of cold Short Straight Sections has substantial benefits in reducing power consumption and cost, while increasing the performance and flexibility of the accelerator.
- The FCCee-HTS4 project aims at demonstrating that this idea is feasible.
- Our sister project FCCee CPES goes a step further and aims to reduce cooling costs by developing a power supply that will operate at cryogenic temperatures.
- These projects will increase the sustainability credentials of FCC-ee as well as increase its performance.

THANK YOU