The FCCee-HTS4 project

M. Koratzinos

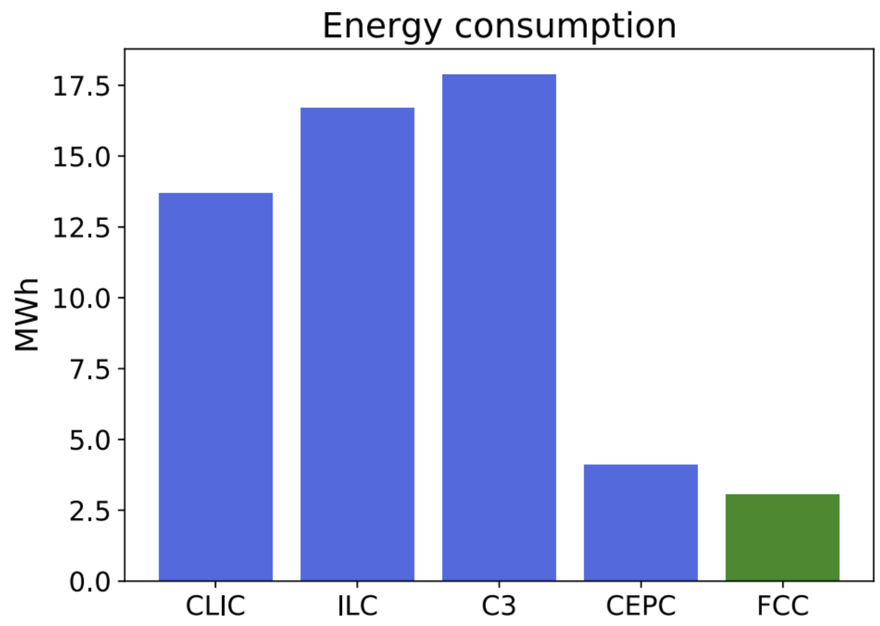
FCC week, London

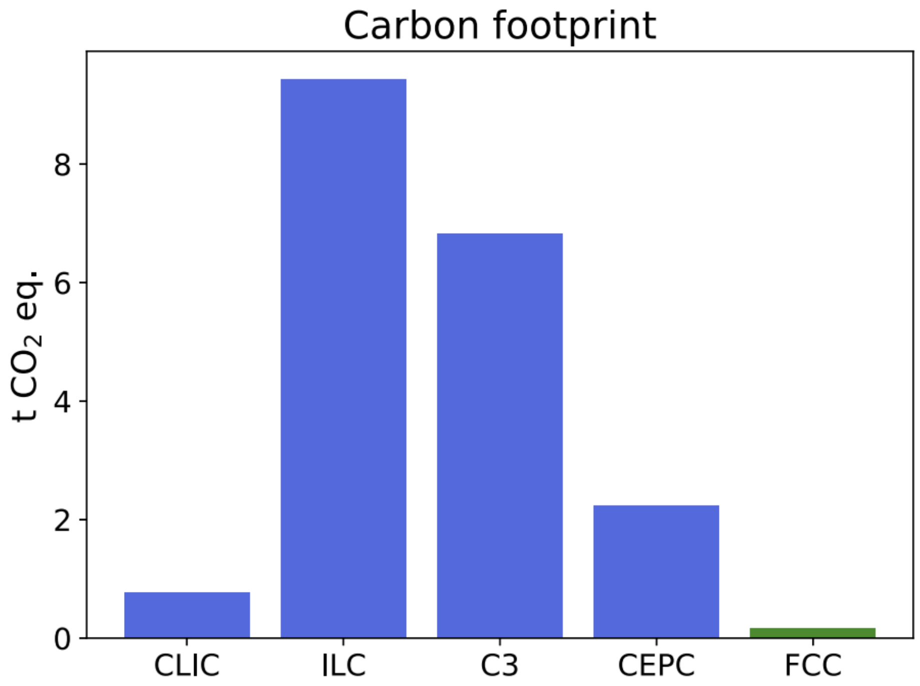
07/06/2023

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

Abstract

- 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





Power consumption – collider main magnet systems

See presentation of Jean-Paul Burnet (CERN) at FCC week 2022:

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

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**

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

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

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

FCC-ee: The power challenge

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

The situation at the Conceptual Design Report:

- 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.

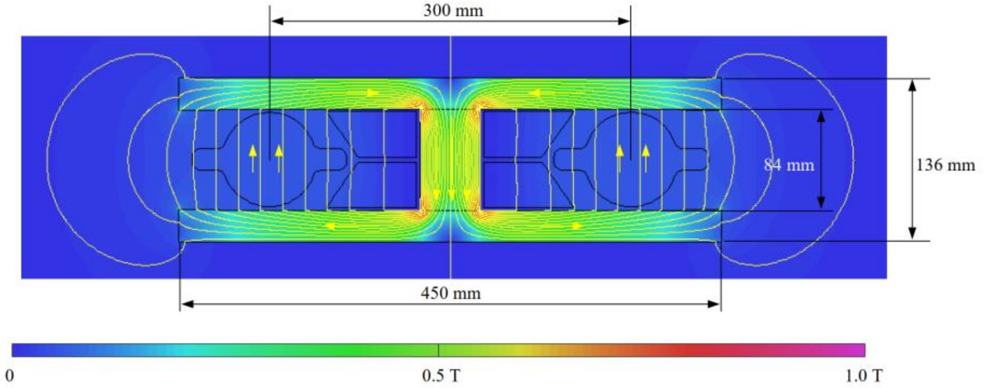


Figure 3.1: Cross-section of the main bending magnet; the flux density corresponds to 57 mT in the gap; the outline of vacuum chambers with side winglets is also shown.

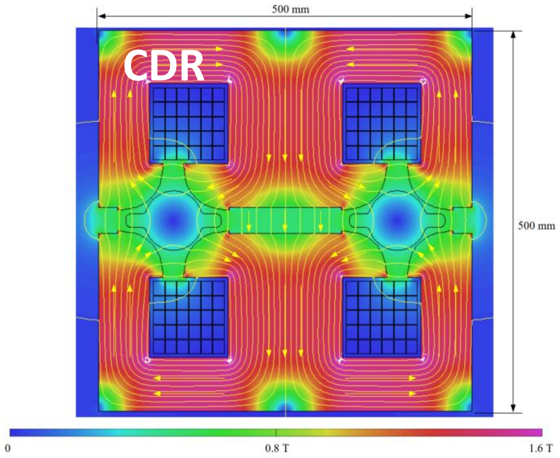


Figure 3.3: Cross-section of the FCC-ee main quadrupole, for a 10 T/m gradient.

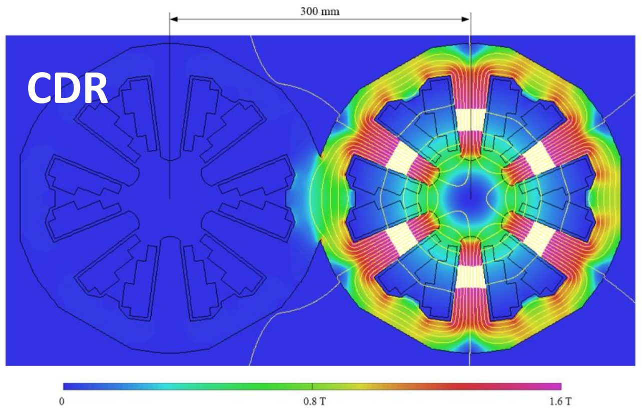


Figure 3.6: Cross-section of the FCC-ee main sextupole magnet. The position of the sextupole for the other beam is outlined on the left.

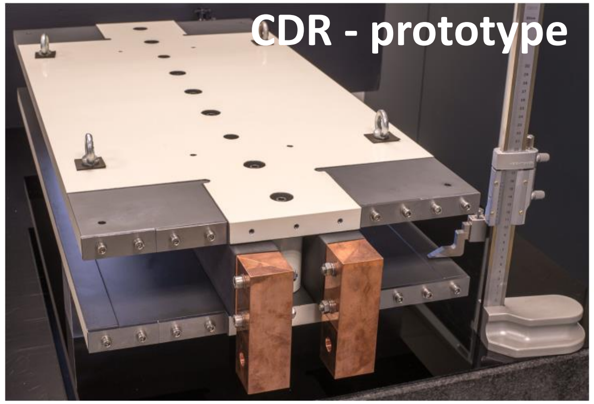


Figure 3.2: One of the ca. 1 m long model dipole magnets manufactured at CERN.

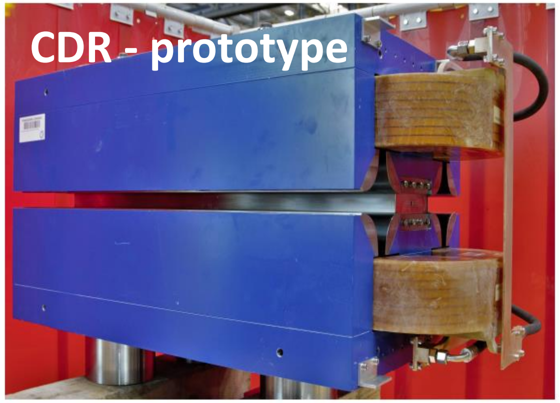


Figure 3.5: Picture of a 1 m long quadrupole prototype magnet for the FCC-ee.

(no prototype exists yet)

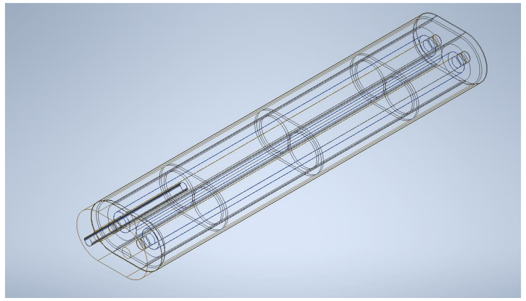
Big, heavy quads and sextupoles

FCC-ee: The power challenge

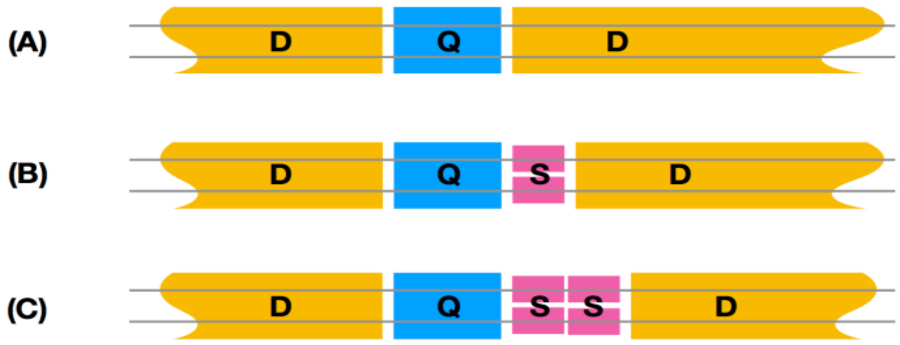
Can we do better?
Yes! Make the magnets superconducting. Then, energy is only spent cooling the magnets (zero Ohmic losses).
Also, we can “nest” the magnets, so that they take less space

- ➔ 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**

Many additional benefits: increase packing factor (and luminosity) by 7%, increase optics flexibility (next slide)

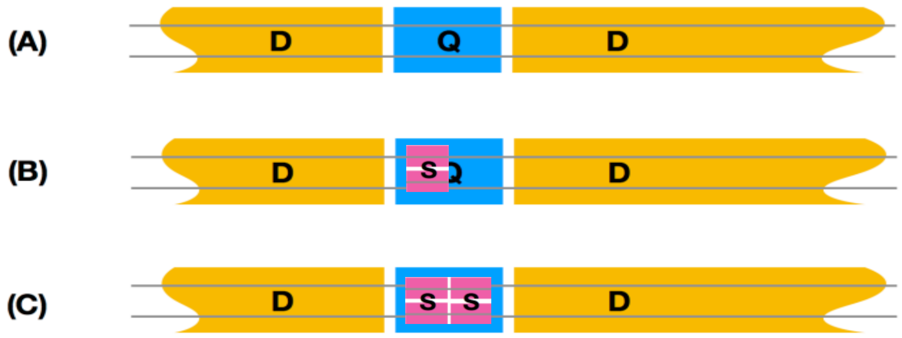


CDR



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 SSSs would come from 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, discussed later)
- 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**

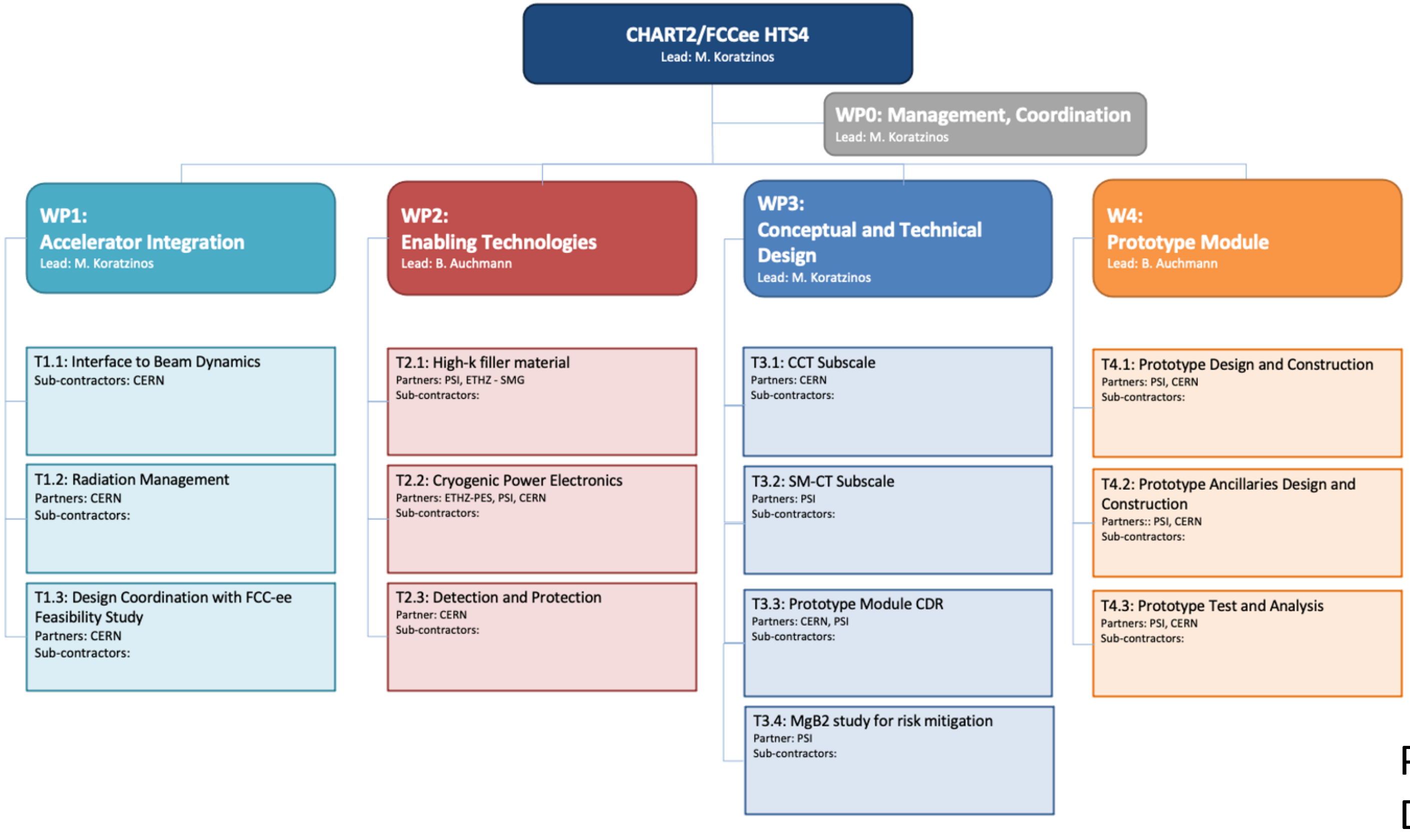
FCCee-HTS4 are: B. Auchmann, J. Kosse, V. Batsari, A. Thabuis (from 1/9/2023), M.K.

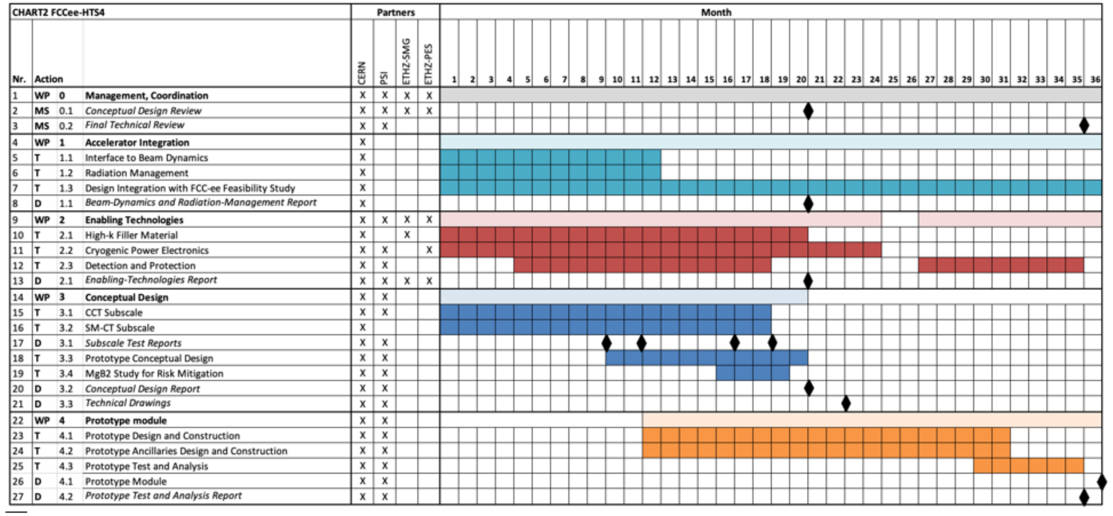
- Our sister project, FCC-ee CPES, investigating the possibility of a cold power supply system, was also approved at the same session.

FCCee-HTS4 in a nutshell

- Investigate the replacement of all FCCee 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
- (superconducting arc dipoles as well as a dipole component in the SSS to be used for tapering also, is beyond the scope of this phase of the project)

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 latest optics design layout has the following specifications:

- Length of quads is 2.9m (from 3.2m). Quads should not be shorter, due to SR issues
- Strength of quads is 11.84 T/m at tt (was 10T/m)
- 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

Choice of aperture

- First design choice is aperture: we have chosen a **90mm** aperture magnet.
- (inner diameter of the beampipe in the CDR is 70mm, with a lively debate if we should go to 60mm or not)
- What is important in our case is not only the beam pipe diameter, but also the position of the last photon stopper: photons that have just missed the photon stopper are at an angle of ~2.5mrad. As the distance of the last photon stopper to the end of the SSS is ~4m, the radius of the aperture needs to be ~10mm larger than the position of the stopper
- Strength of the sextupole (closest to the beam pipe): 1000T/m2 (specification is 812T/m2, but we have made the magnet can be made shorter)
- If there is a firm decision to go to 60mm beam pipe, we will reduce our aperture accordingly

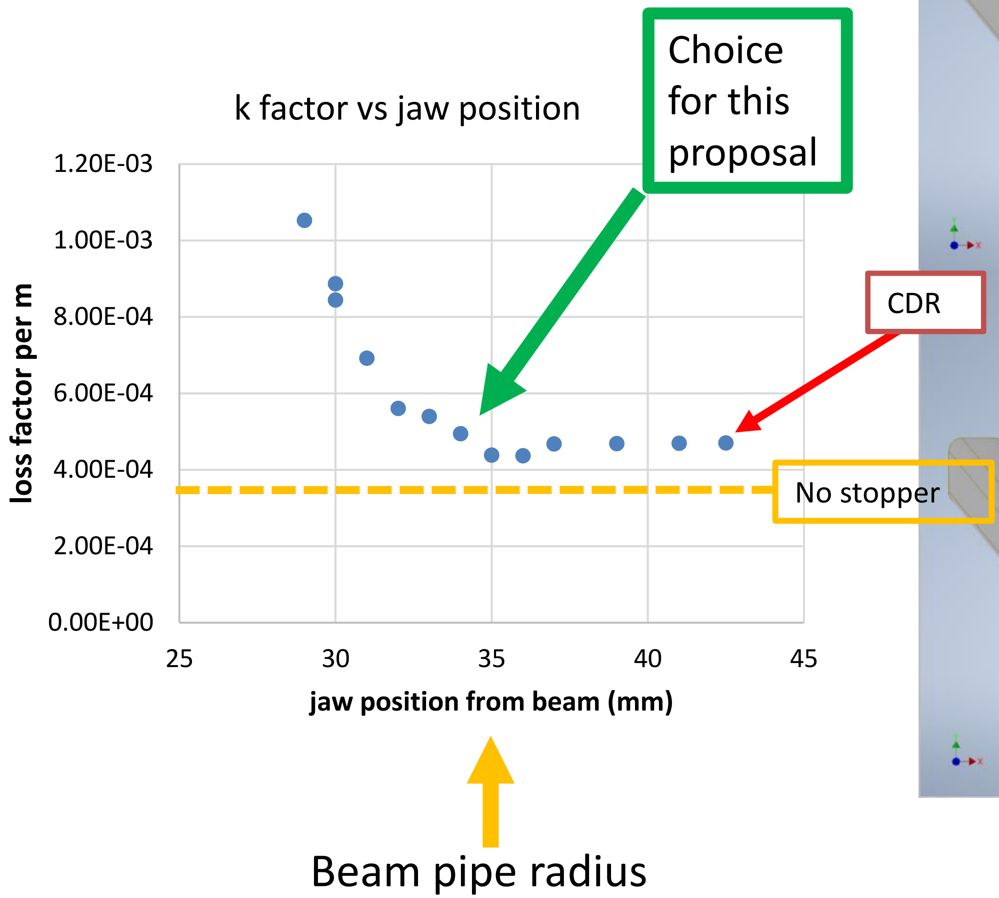
Photon stoppers, winglet, impedance

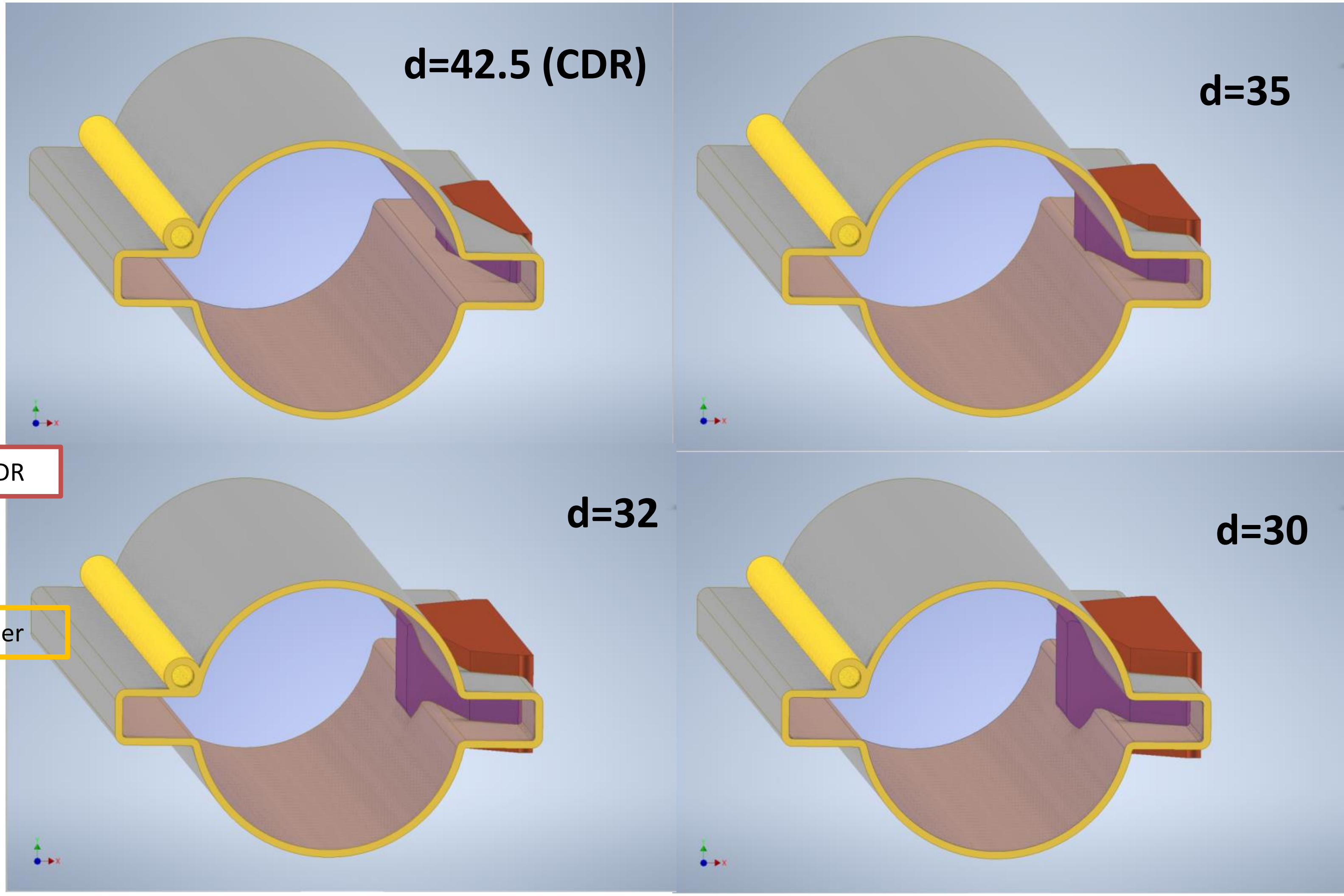
- How much would this idea increase the resistive wall impedance budget (and, therefore, wasted power) of the machine?
- Since space is at a premium, this idea accommodates much smaller winglets than the CDR design (110mm to 86mm) for the entire length of the SSS (3.5m)
- It also calls for photon stoppers that protrude more into the beam pipe than the CDR design
- A complete study using *CST studio suite 2020* was performed

Variable stopper sizes

We tried different stopper protrusions to see their effect on impedance

d is distance from the beam:

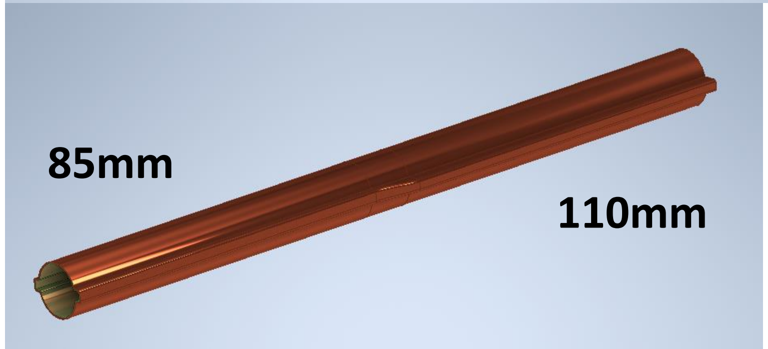


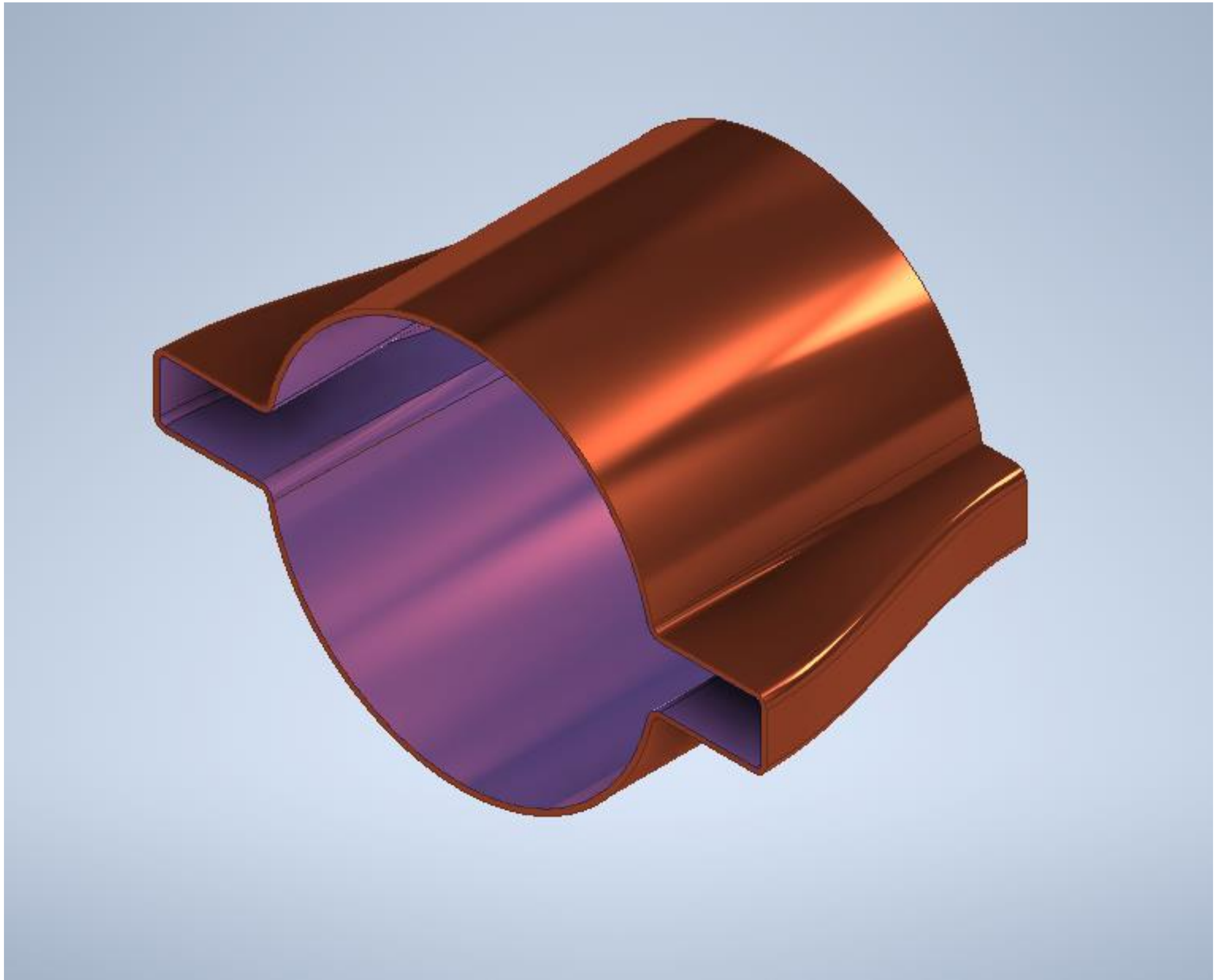


N. Nikolopoulos

Transitions

A smooth transition between a 110mm winglet to a 86mm winglet was developed





Results of impedance calculations

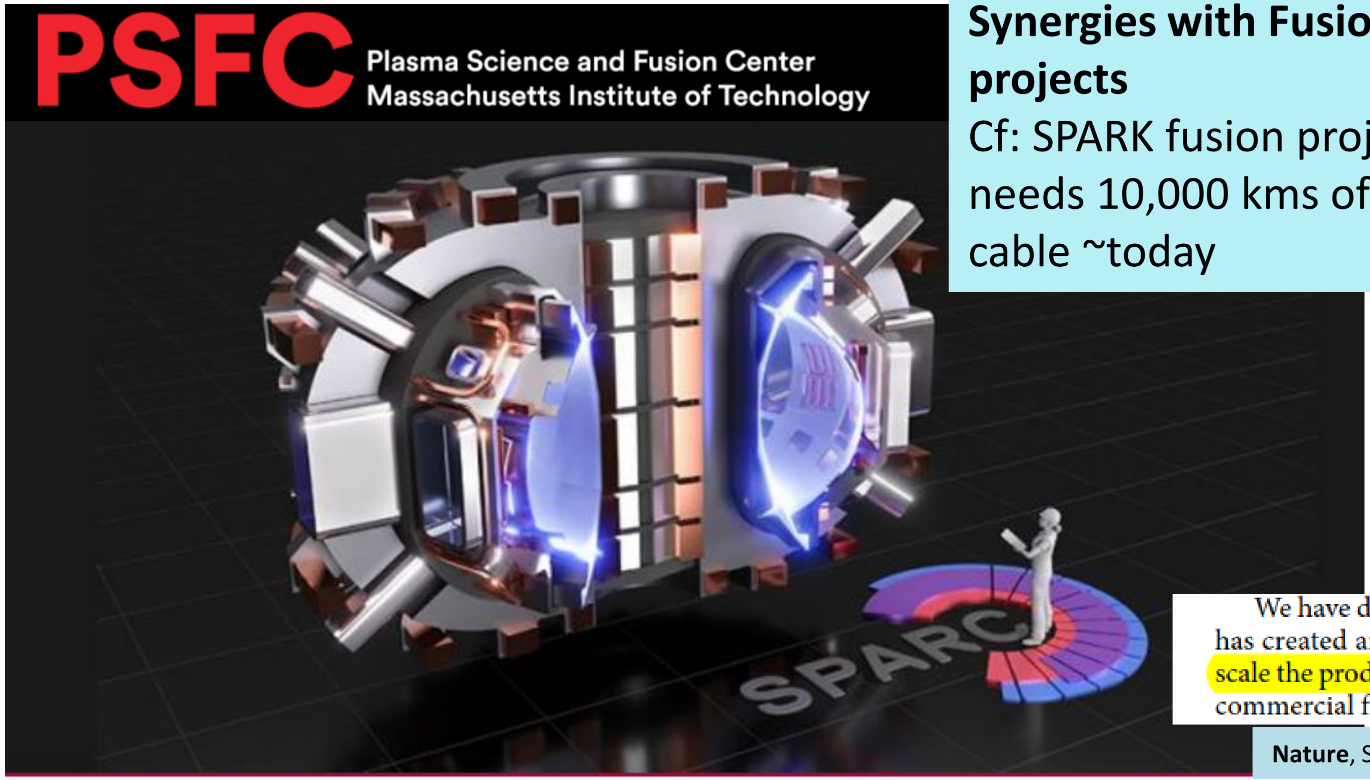
- A copper 35mm radius round pipe has a loss factor of 3.6×10^{-4} V/pC at the Z. This corresponds to a total power of 2.3MW for both beams
- A 35mm inner diameter pipe with winglets has a loss factor of 3.7×10^{-4} V/pC, close to the totally round case.
- Having a stopper as in the CDR increases the impedance of a 1m pipe to 4.7V/pC
- **Results indicate that the premium we need to pay in terms of power for this design is minimal (0.15MW on top of 2.73MW or 5%) even for a stopper @29mm from the beam**

	This proposal				CDR		
	k factor / m	no. of units (m)	k 100km ring	power two rings (MW)	k factor/m	power two rings (MW)	Premium (MW)
35mm pipe with winglet 110mm	3.67E-04	83250	30.55	2.31	3.67E-04	2.31	0.00
beam pipe with stopper @29mm	1.05E-03	2900	3.05	0.23	4.70E-04	0.10	0.13
transition 110mm to 86mm	4.40E-04	2900	1.28	0.10	3.67E-04	0.08	0.02
35mm SSS pipe with winglet 86mm	3.72E-04	5800	2.16	0.16	3.67E-04	0.16	0.00
transition 86mm to 110mm	4.04E-04	2900	1.17	0.09	3.67E-04	0.08	0.01
totals		**97750**		**2.89**		**2.73**	**0.15**

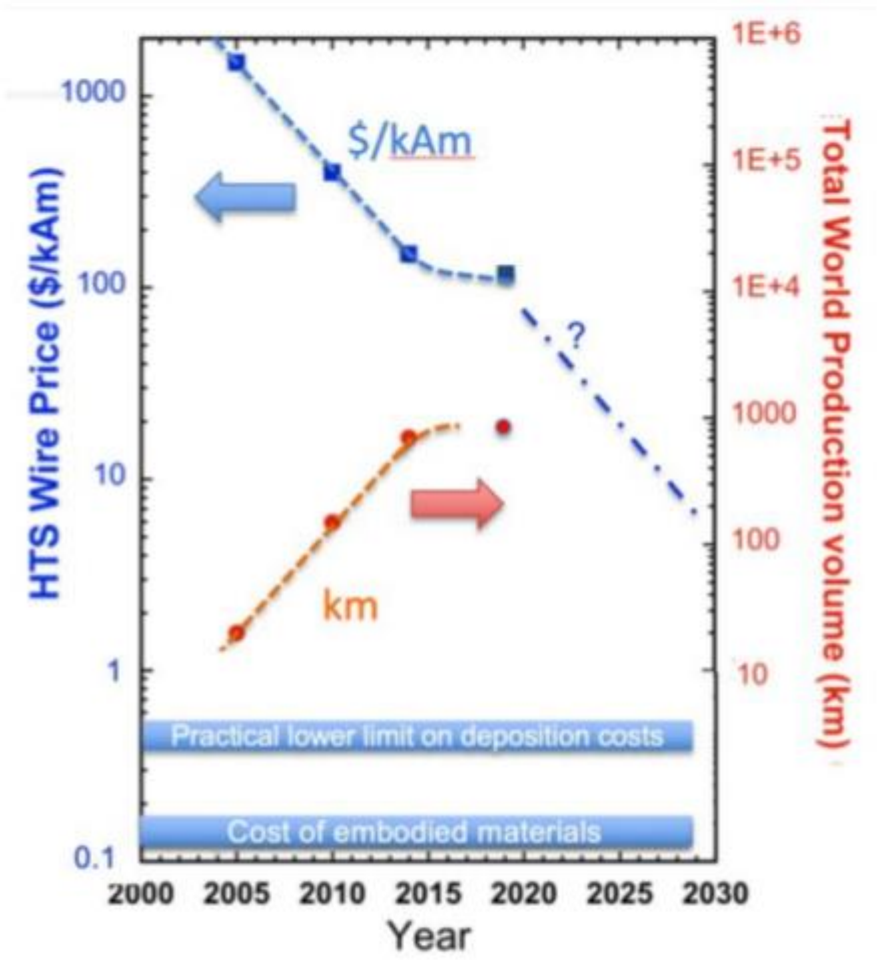
A question of cost

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 condutor
- 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: SPARK 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

Cooling the SSS

- The current design calls for individual dry cooling, using commercially available cryocoolers
- Questions to be answered:
  - Need to have adequate mean-time-between-failures
  - Need to consume as little as possible
  - Need to ensure operation in the harsh radiation environment of the tunnel
  - Are there any vibration issues?

Example cryocooler from SHI cryogenics

RD-125D 77K Cryocooler Series

Performance Specifications

Power Supply	50Hz	60 Hz
1st Stage Capacity	30 W @ 77 K	
Minimum Temperature[1]	<30 K	
Cooldown Time to 77 K[1]	<25 Minutes	
Weight	15.0 kg (33.1 lbs.)	
Dimensions (HxWxD)	345 x 140 x 301 mm (13.6 x 5.5 x 11.9 in.)	
Maintenance	10,000 Hours	
Regulatory Compliance	CE, UL, RoHS	

Standard Scope of Supply

- RD-125D Cold Head
- CNA-11 Compressor
- Helium Gas Lines – 7 m (23 ft.)
- Cold Head Cable – 3-6 m (10-20 ft.)
- Power Cable – 5 m (16.5 ft.)
- Tool Kit

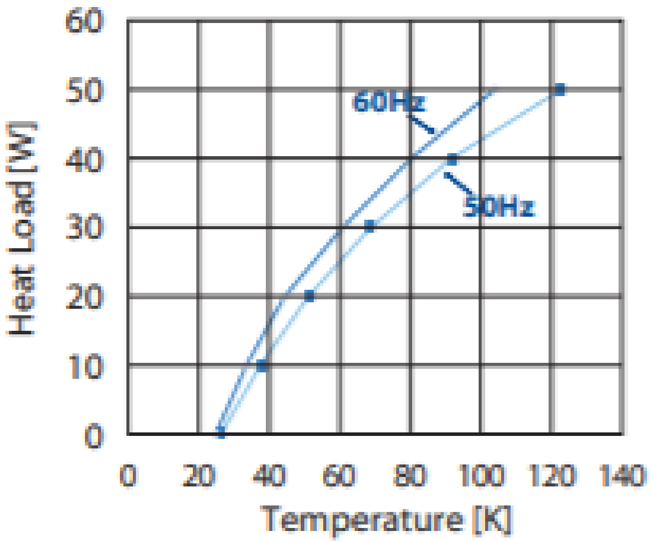
[1] *Lowest temperature and cooldown time are for reference only.*

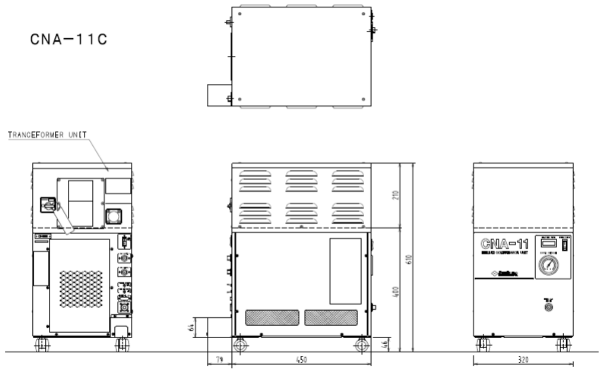
Power Consumption	Steady	Maximum	
50Hz	1.3 kW	1.4 kW	-- approx.
60Hz	1.4 kW	1.6 kW	-- approx.

Cooling capacity:
- 33W@77K,
- 12W@40K

Power consumption: 1.3kW,
Price today: 15.5k euros ready to cool

RD-125D Cold Head Capacity Map (50/60 Hz)
With CNA-11 Compressor and 7 m (23 ft.) Helium Gas Lines





COMPRESSOR UNIT

Size of unit is 320 X 450 X 610 mm

Power consumption of 2900 units:
4.1MW power or 20GWh per year
This is **~5% of the warm magnets consumption** at the top

Reliability

Cryocooler-based accelerator magnet operation: reliability and availability.

Jaap Kosse, Michael Koratzinos, Bernhard Auchmann

- We are estimating the mean time to failure (MTTF) given a mean time to repair (MTTR)
- Paper in preparation

MTTF of 10^7 hours means that the failure rate within a 30.000 h maintenance interval is 1.5% (this is a real life scenario of six MD-120 coldheads-which in the application of cryopumping all need to operate (k = n = 6) coupled to a TM-30 compressor.

TABLE IV

OTAL 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 BAD (RED) RELIABILITY. MTTF OF EACH COOLER IS 10^7 HOURS, AND MTTR IS 1 MONTH.

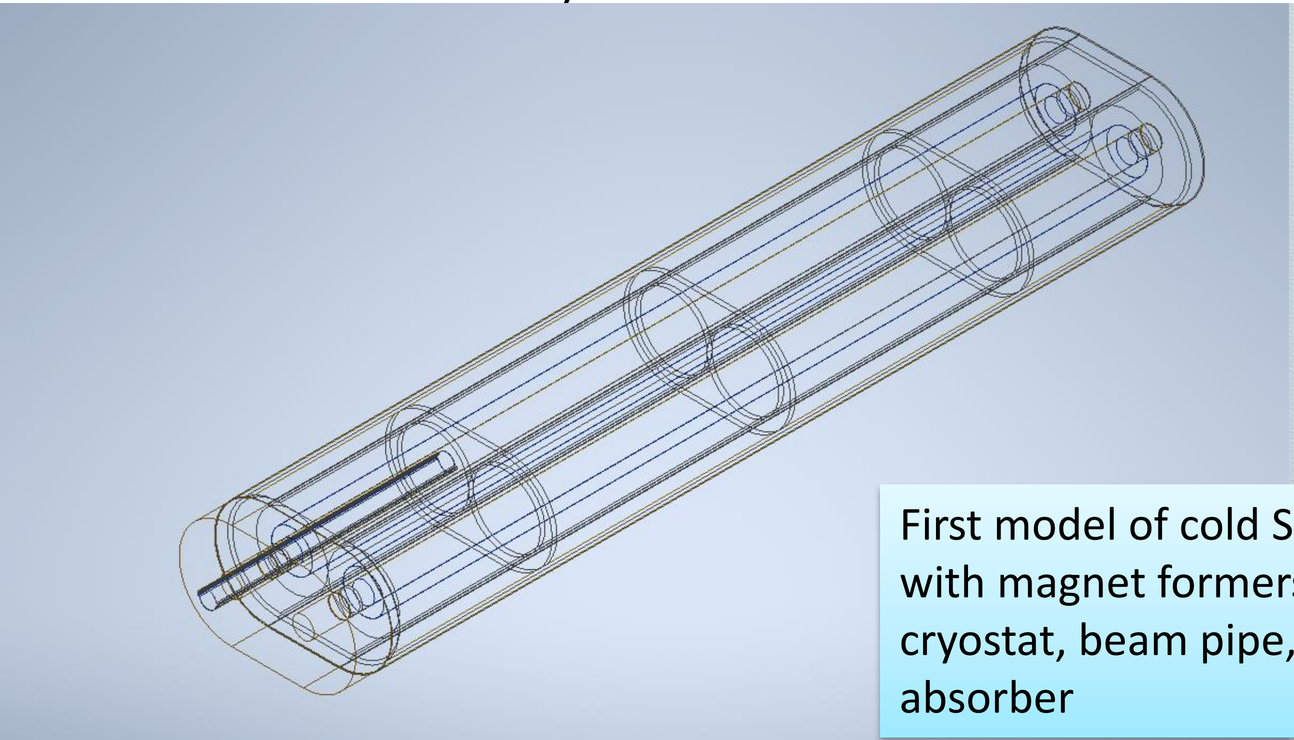
	Installed coolers n					
working coolers k	1	2	3	4	5	6
1	0.8335					
2	0.9998	0.7145				
3	1.0000	0.9995	0.6253			
4	1.0000	1.0000	0.9990	0.5558		
5	1.0000	1.0000	1.0000	0.9983	0.5003	
6	1.0000	1.0000	1.0000	1.0000	0.9975	0.4548

Jaap Kosse

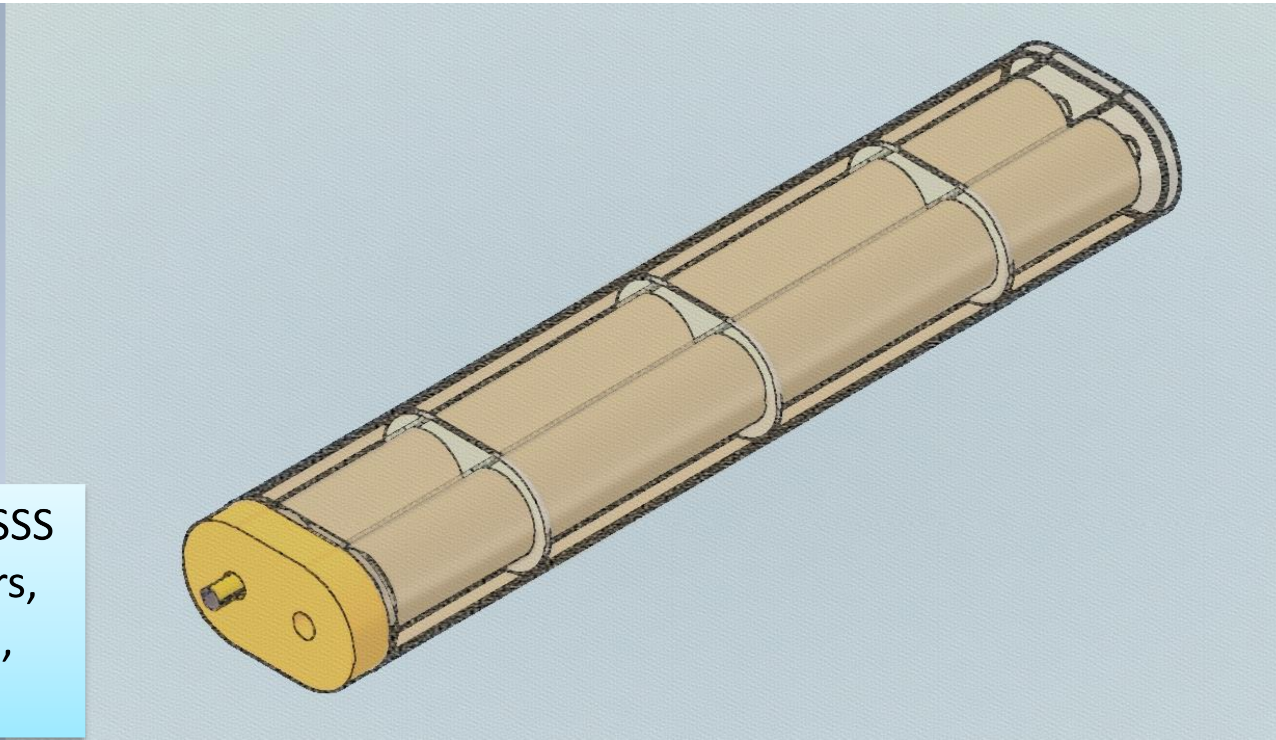
Heating budget

We need to pay attention to the following:

- Resistive wall heating due to the extra photon stoppers and different beam pipe design (not a problem – see slides before)
- Heat losses of the cryostat – radiation and conduction through supports (calculated to be ~12W)
- Cryostat heating due to debris from photon stoppers (calculated to be <2W)
- Conduction and ohmic heating of current leads – our sister project FCCee CPES aims at a value of ~10W)



First model of cold SSS with magnet formers, cryostat, beam pipe, absorber

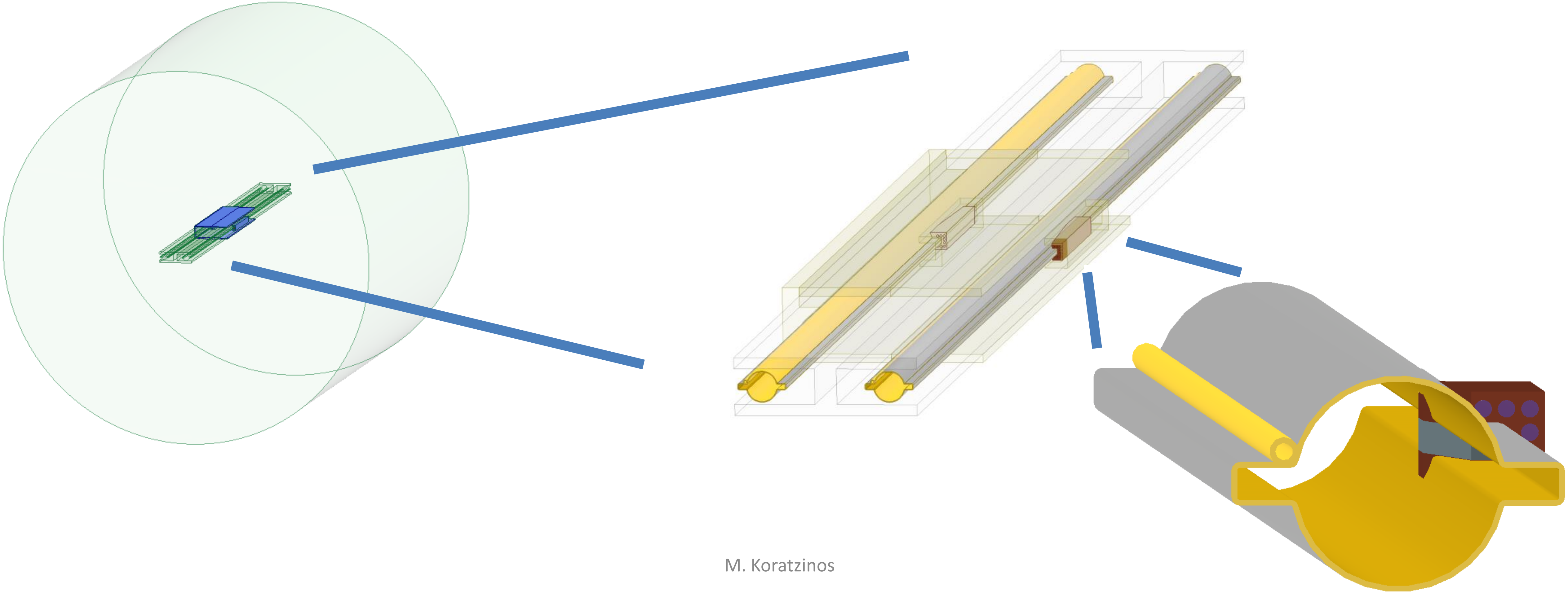


Radiation environment

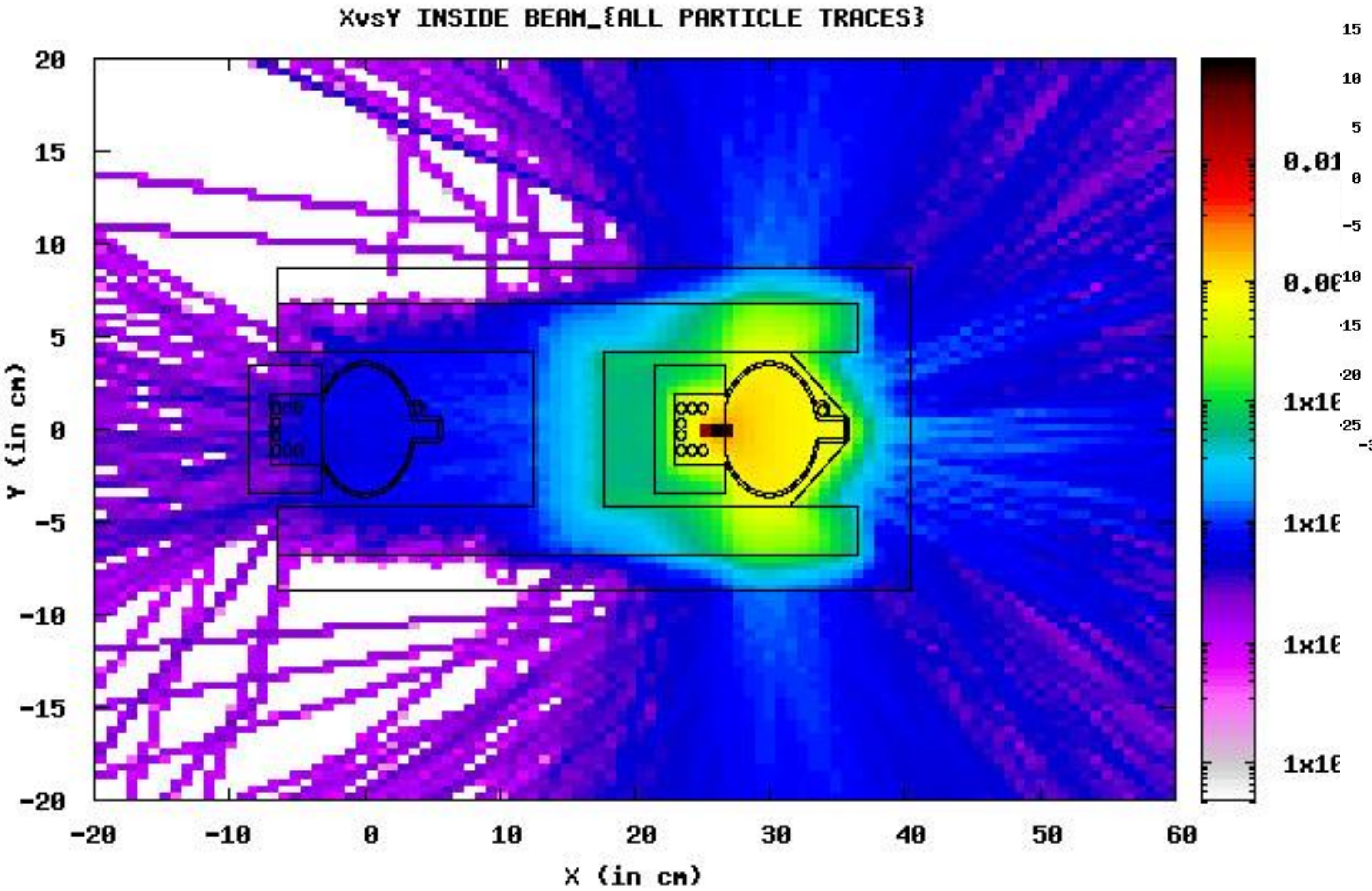
- The FCC-ee tunnel is a harsh radiation environment.
- We need to ensure that:
  - The cryostat is protected from radiation which will increase thermal loads
  - Any associated equipment with electronics (power supply, cryocoolers) will continue functioning for the lifetime of the accelerator.
- We have performed an exercise of including extra radiation shields around the photon stoppers in an attempt to see **how low we can push** the radiation reaching our cryostats and electronic equipment of the cryocoolers

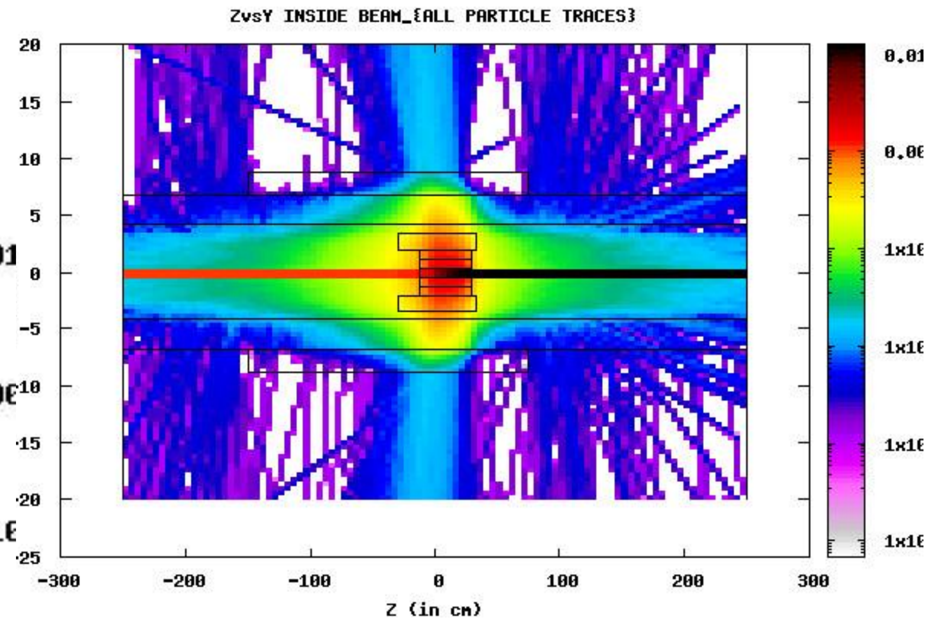
Radiation in the tunnel

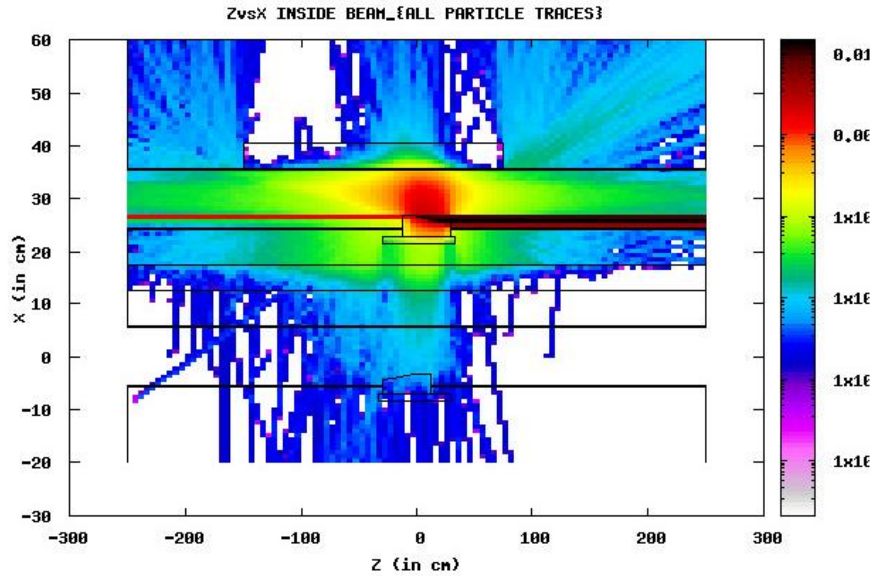
- See old presentation by N. Nikolopoulos https://indico.cern.ch/event/1113474/ in 2022
- A full system with tunnel, dipoles, beam pipe, photon absorbers, shields was simulated in FLUKA
- We have used tungsten for the extra shielding, which however can be replaced by lead of 1.5 times the thickness



FLUKA results, inside beam

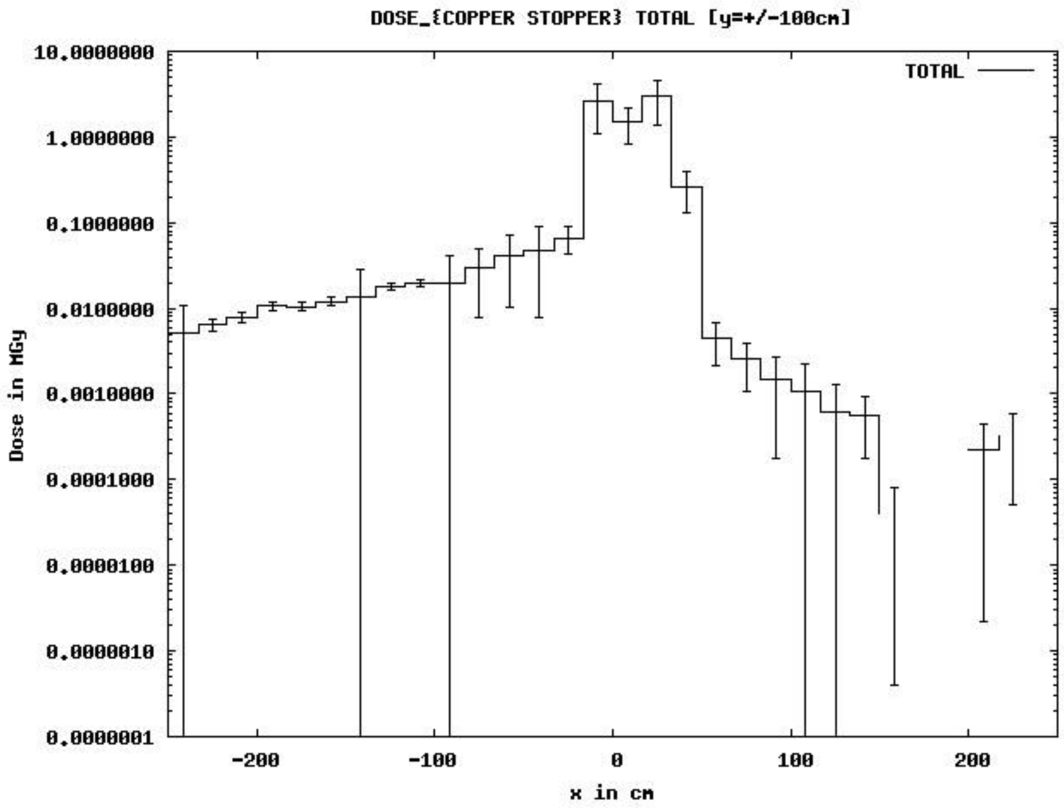


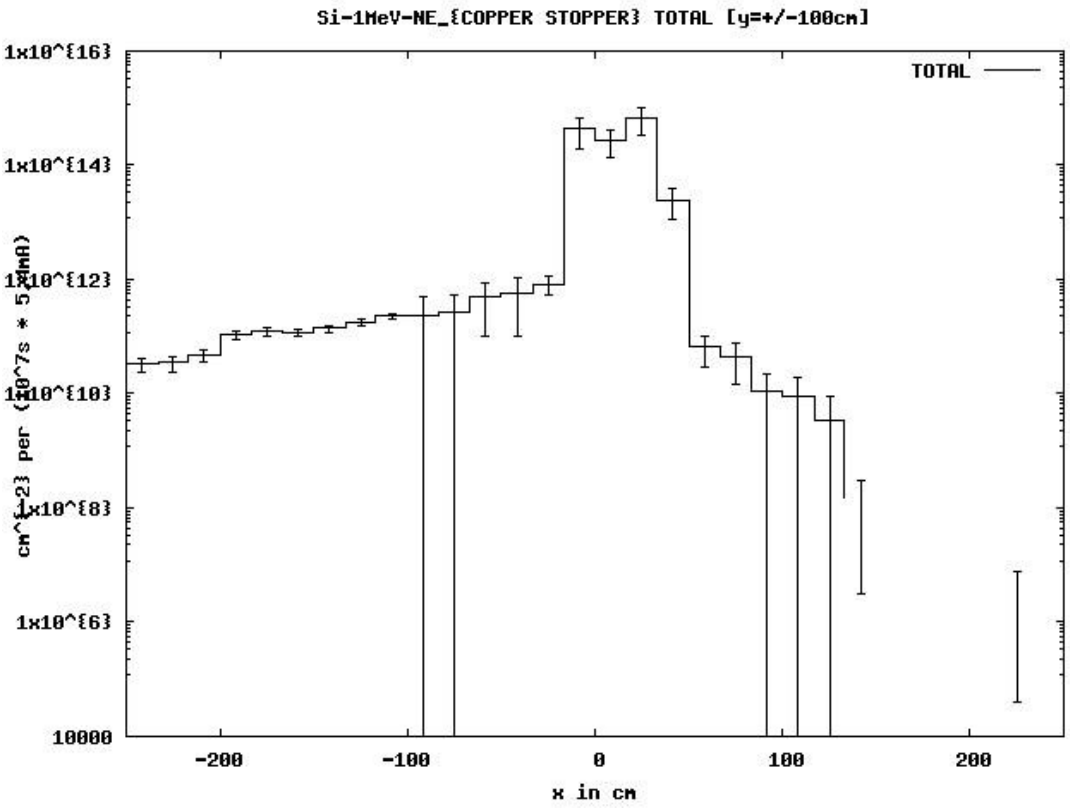




>99% of energy absorbed by various absorbers, beampipe or magnet

Both beams – dose and 1MeV n equiv. per year



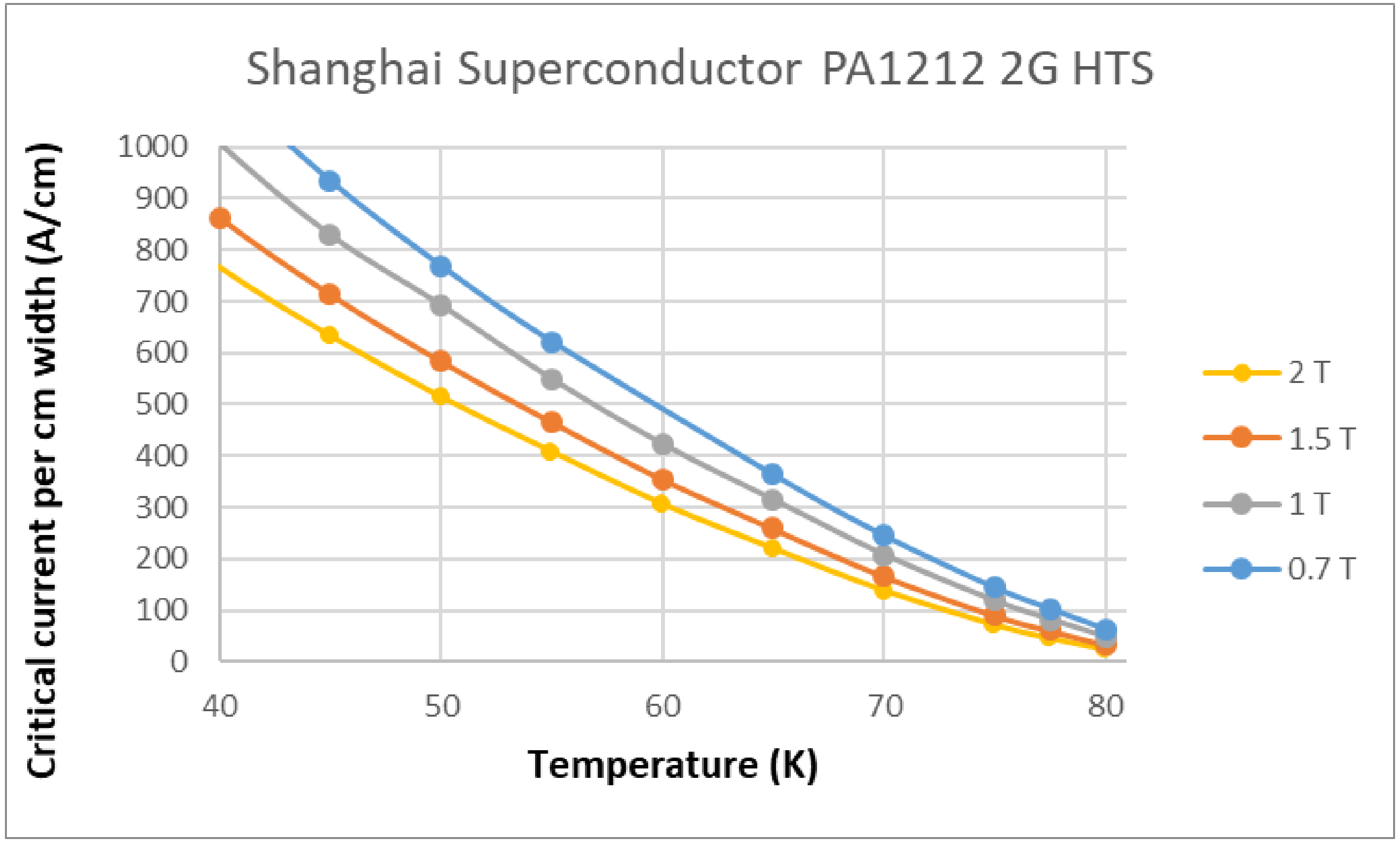


Dose: 1m from the beampipe, inside: ~600Gy
1m from the beampipe, outside: ~10kGy

1MeV n equiv.: 1m from the bp, inside: ~1E10
1m from the bp, outside: ~2E11

Doze can be **<1kGy per year 1m off the accelerator plane**. This analysis will be verified as design evolves

Choice of operating temperature



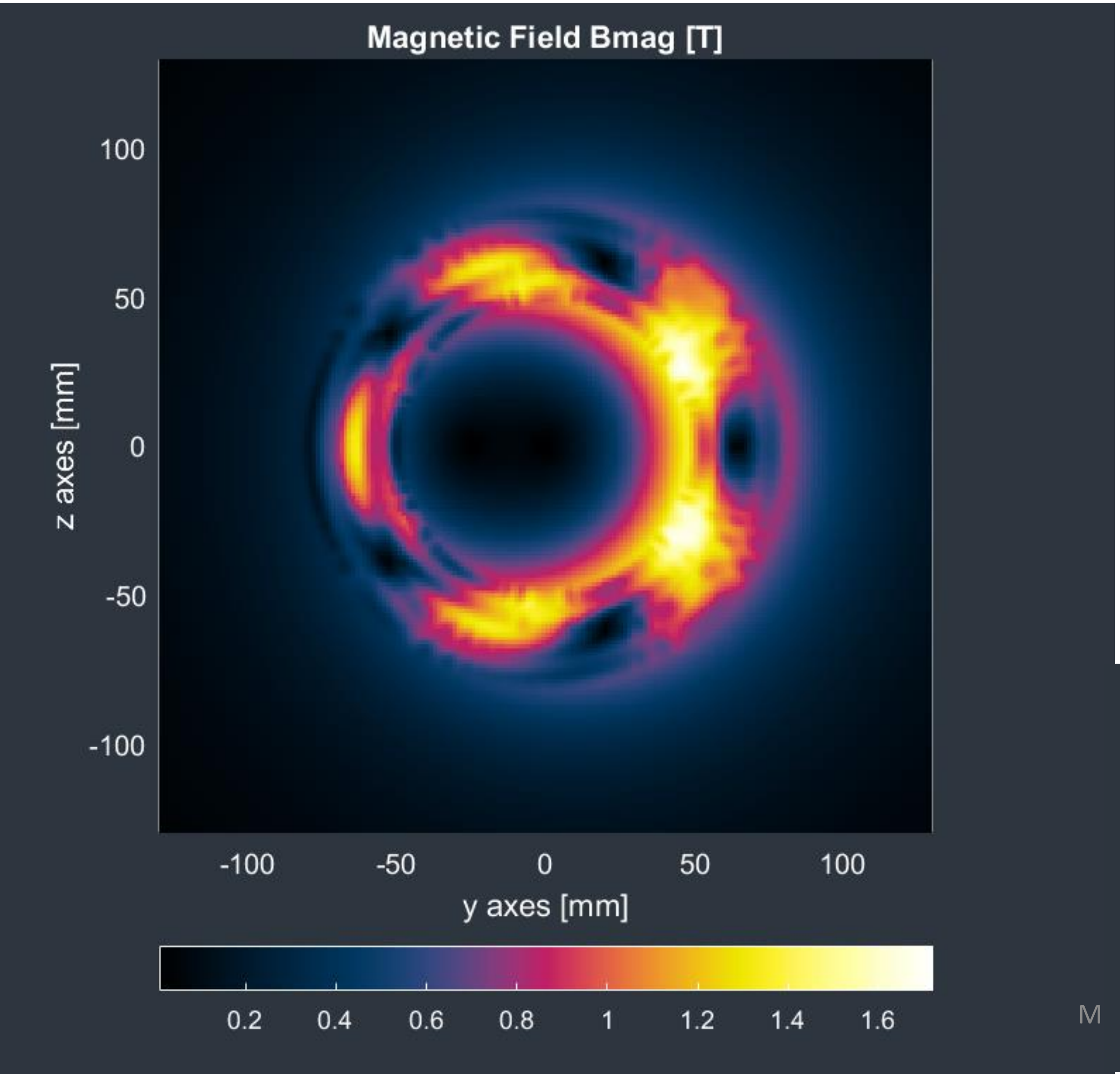
Above is typical ReBCO technology performance, all HTS companies will be considered (but difference in performance and price/performance is small.

- HTS performance at 40K compared to 77K differs by a factor ~10
- The cost of cryo cooling, only increases by a factor ~2
- Heat losses do not change significantly (due to the fourth power law of black body radiation)
- We aim to work at ~40K at the top energies
- Note that at 40K, materials still possess some heat capacity, so there will be no LHC-type quench problems

We are using 4mm ReBCO tape

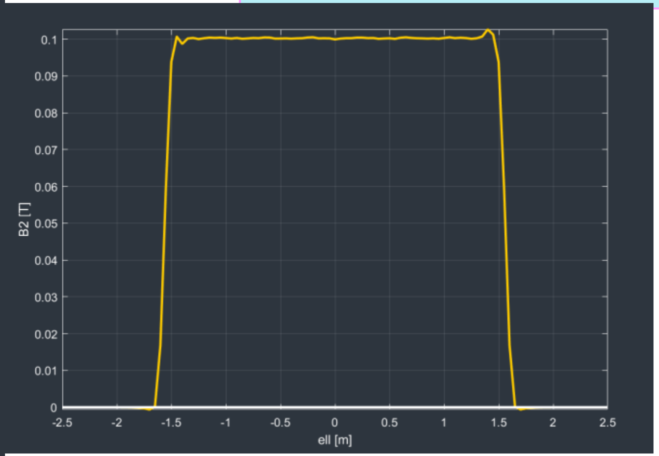
Quad and sextupole at full strength

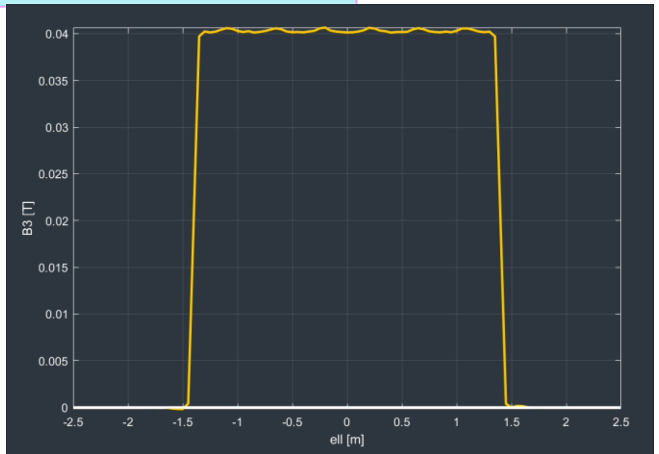
Magnetic analysis



- 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
- The question is only related to cost: the higher the performance, the lower the length of HTS tape needed, the lower the cost

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





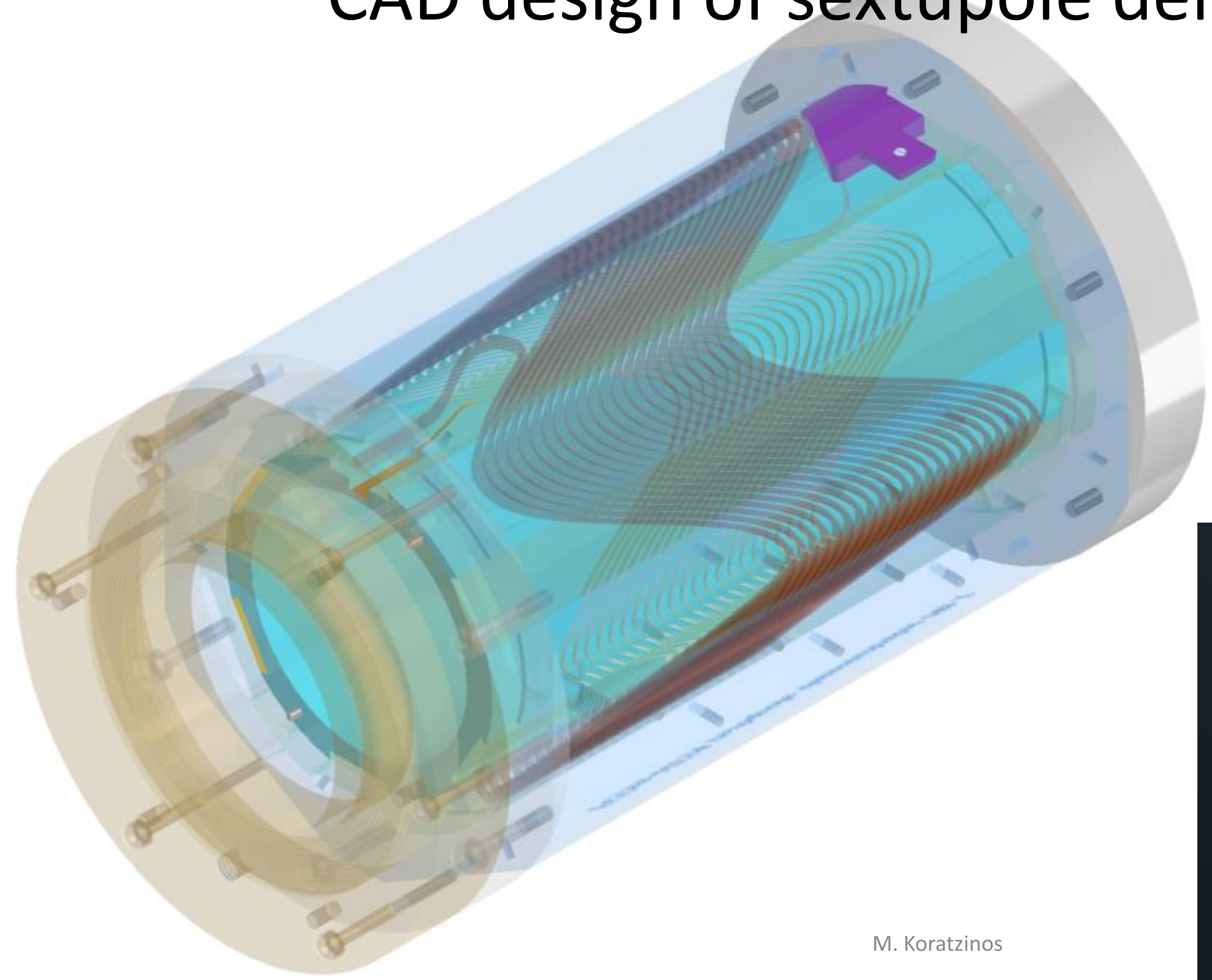
Demonstrator

- 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

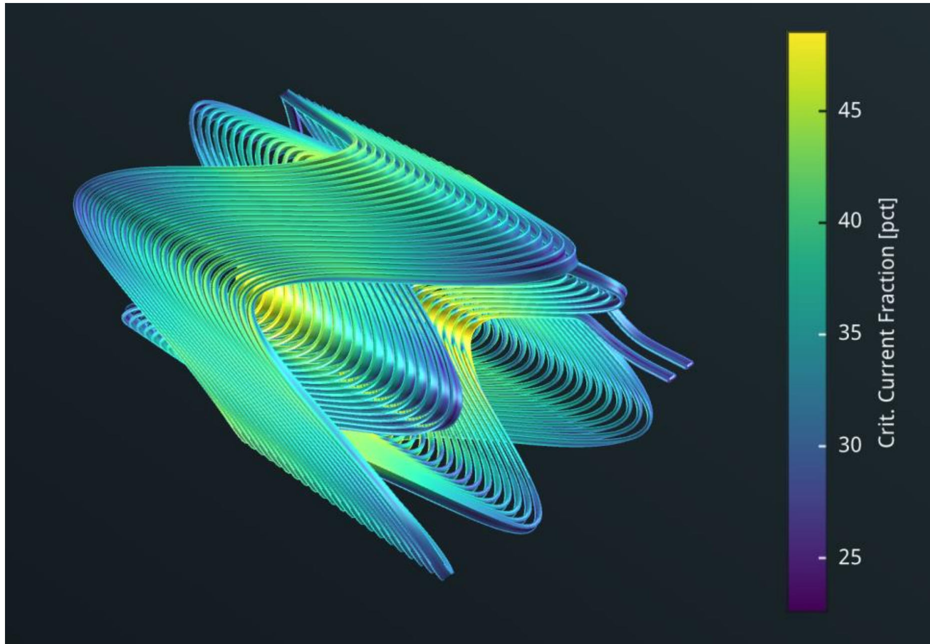
Demonstrator – choice of technology

- 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 considered
- 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



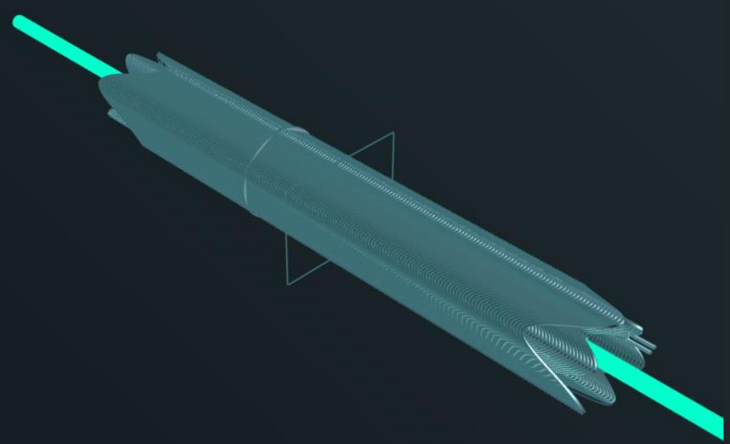
Specifications:
Aperture: 90mm
Current: 260A
Temperature: 40K
Field gradient: 1000T/m2
Max. field @conductor:1.5T
Crit. Current fraction: 49%
Temp. margin: 14K



Multipole errors - sextupole

A CCT magnet can very easily correct for multipole errors, which are in any case small.

B3dl corresponds to a strength of 1000T/m2



harmonics given at a reference radius of: 10.000 [mm]

Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	3.09e-06	0.76		B1	6.61e-07	0.16	
A2	5.21e-07	0.13		B2	3.43e-06	0.84	
A3	-1.87e-07	-0.05		B3	4.07e-02	10000.00	
A4	-1.34e-06	-0.33		B4	-1.29e-06	-0.32	
A5	2.29e-07	0.06		B5	1.16e-06	0.29	
A6	-1.13e-07	-0.03		B6	-4.26e-07	-0.10	
A7	6.49e-09	0.00		B7	1.63e-07	0.04	
A8	-7.44e-08	-0.02		B8	-8.21e-09	-0.00	
A9	1.57e-10	0.00		B9	2.96e-07	0.07	
A10	-7.32e-08	-0.02		B10	-4.42e-10	-0.00	

Manufacturing

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

- Additive manufacturing (metal 3D printing)
  - Advantages: any geometry is realizable
  - Disadvantages: surface roughness
- Subtractive manufacturing (CNC machine milling)
  - Advantages: mirror-like finish
  - Disadvantages: not all geometries realizable
- We are actively looking at both techniques


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

What about the arc dipoles?

- The dipoles are not part of the scope of FCCee-HTS4
- However, a very simple and elegant system of two HTS transmission lines can be envisaged: warm magnet, cold conductor (transmission line style)
- We can leave the rest of the design as is
- Need to investigate if conductor can be placed in the mid plane
- C.f.: maximum current is 1900 A

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

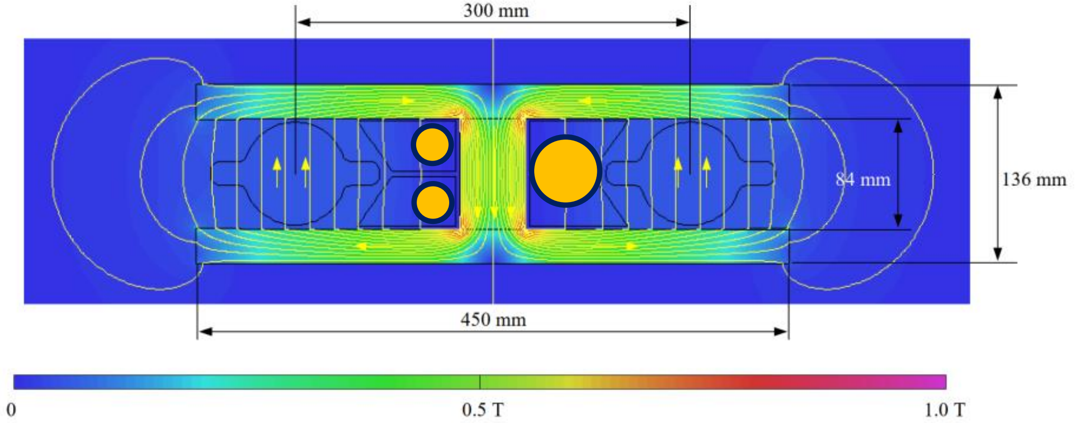
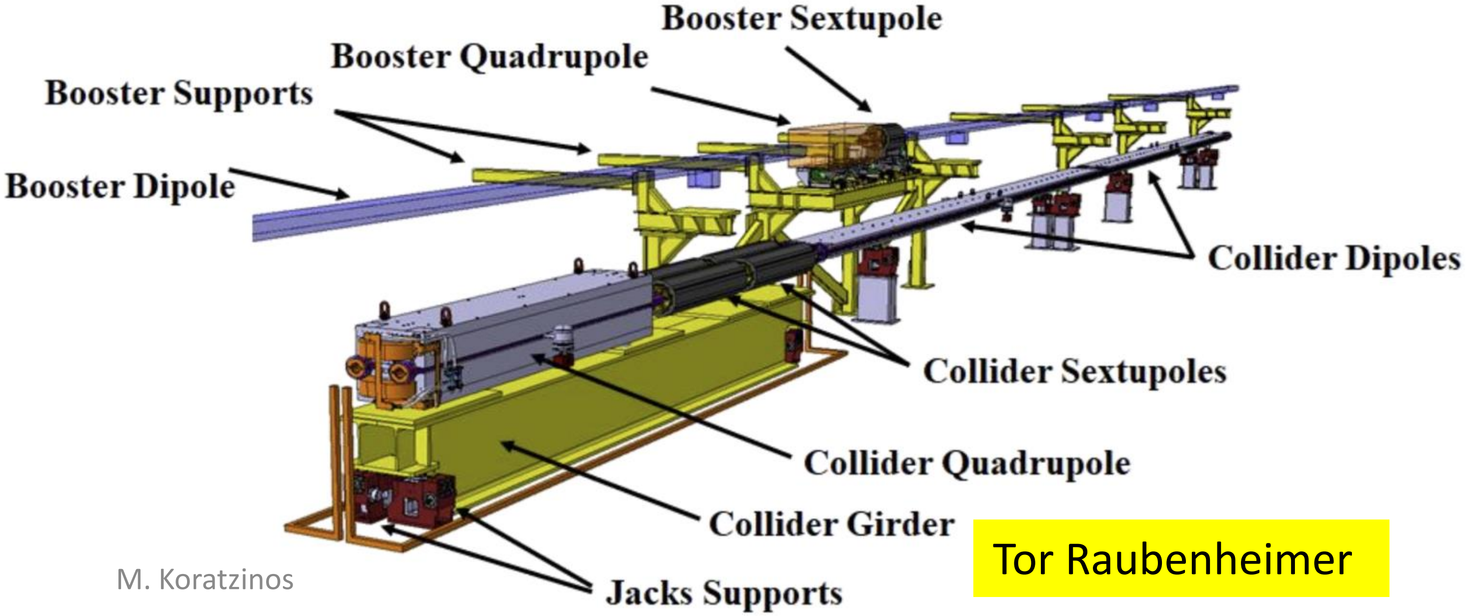


Figure 3.1: Cross-section of the main bending magnet; the flux density corresponds to 57 mT in the gap; the outline of vacuum chambers with side winglets is also shown.

The girder and alignment

- For the CDR, the quad and sextupole magnets will be mounted on a girder (in yellow, below), alignment presumably done before transportation to the tunnel.
- Then the girder, as a whole, will be aligned in situ.
- In the case of HTS4, the weight of the SSS is substantially reduced
- Having a much lighter and nested (therefore shorter) system would greatly reduce the cost of the girder and alignment uncertainties.
- The girder will be a very simple object – an SSS cryostat mechanical support



Tor Raubenheimer

Cold power supply

Our sister project: FCCee CPES (PES, ETHZ) Jonas Huber, Danqing Cao, Daifei Zhang

Power Electronic Systems Laboratory

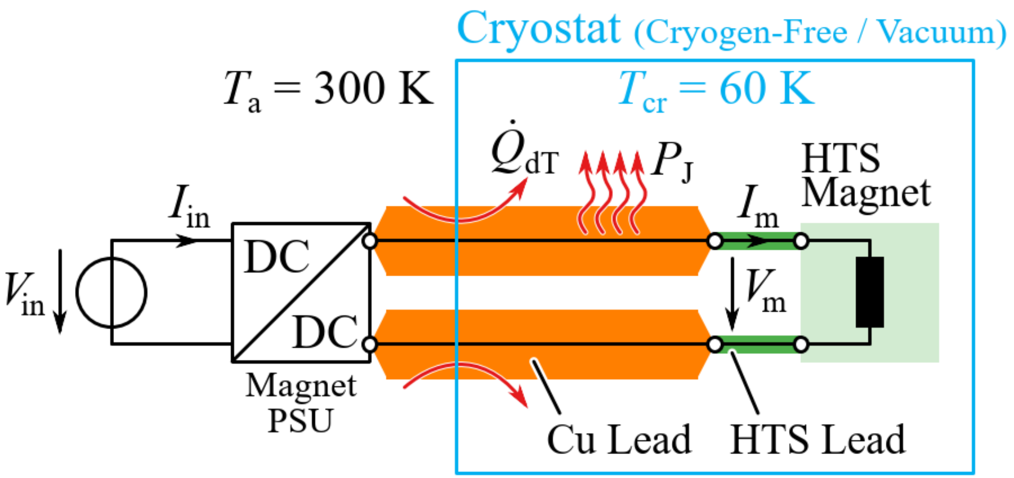
ETH zürich

CHART | FCCee CPES

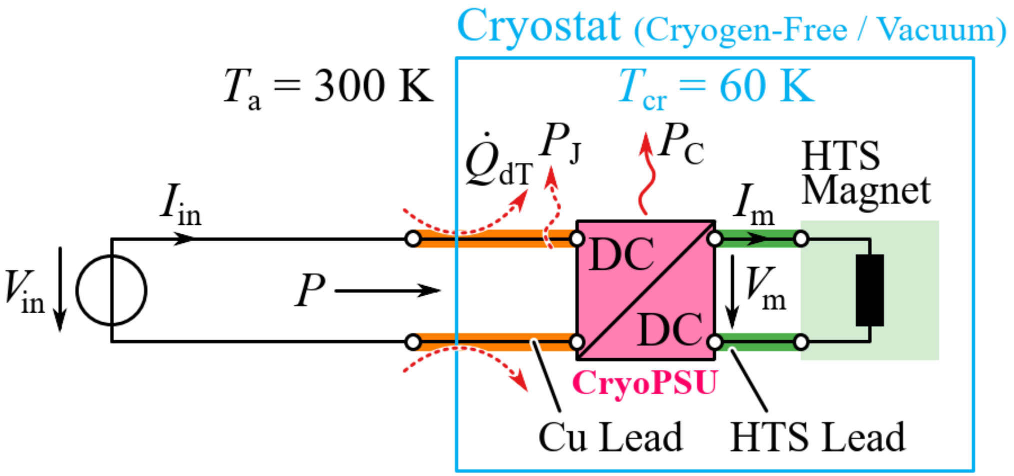
The idea behind FCCee-CPES

- Traditional systems have a heat loss due to the copper power supply leads of **~90W/kA** (two leads) see https://arxiv.org/abs/1501.07166.
- Although we have pushed the current down to 250A (at the expense of more coil windings), this still corresponds to a heat budget of **45W** for four current leads.
- By comparison, the heat load due to radiation and conduction through the feet of the cryostat are expected to be ~**12W**
- By moving the power supply inside the cryostat and operating it at 60-70K, we need only very thin wires to the outside word (this is a DC application with long charging times).
- the aim of the project is to decrease power consumption roughly **five-fold**.

Traditional system:



This proposal:



Conclusions

- The idea of cold Short Straight Sections has substantial electrical power reduction and cost benefits, 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 reduces 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 performance.

THANK YOU