HTS magnets for the Short Straight Sections – Part 2

M. Koratzinos

FCCIS 2023 WP2 Workshop

14/11/2023

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

Swiss Accelerator Research and Technology

You have just heard…

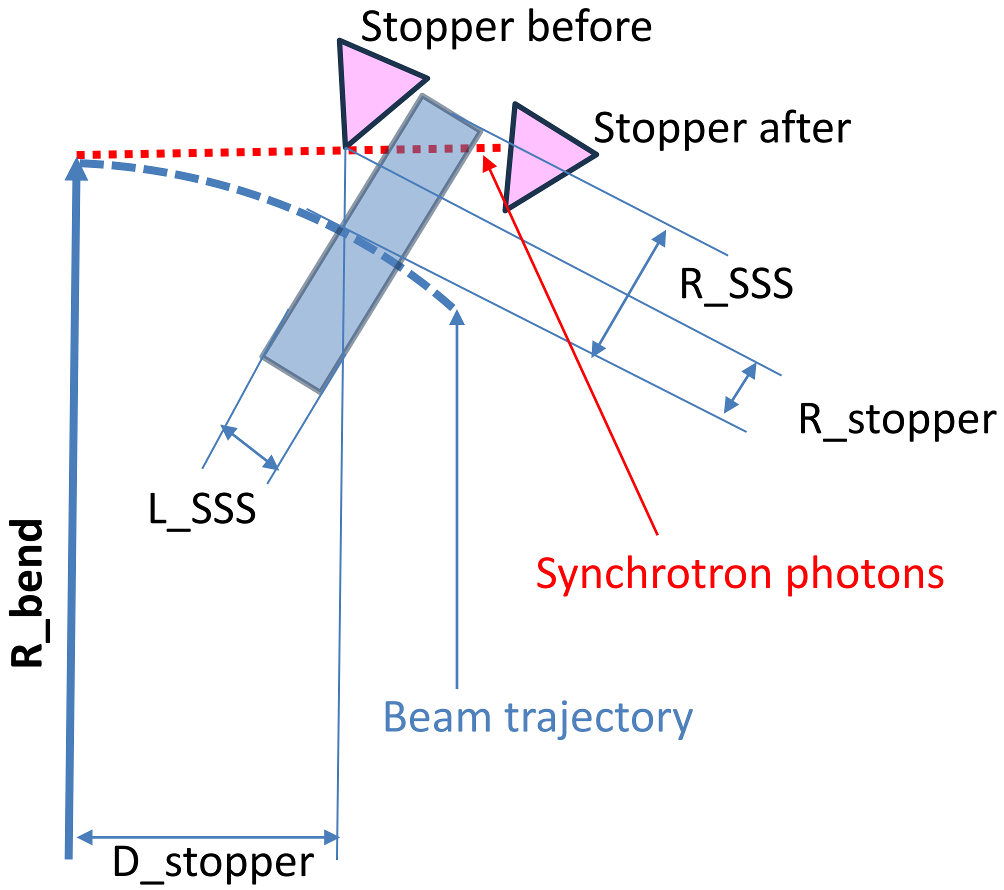
- The big picture
- why we do it
- What is HTS4

You will now hear…

- Individual points of interest in this project

Choice of aperture

- Radius of beam pipe of the SSS should be such that photons from the last stopper do not touch it
- For a beam pipe diameter of 60mm, for a 4m length of SSS we need a minimum inner radius beampipe of 39mm
- This allows an aperture diameter of **82mm** for the SSS magnets
- Current design is **90mm**
- If we do not nest sextupoles and quadrupoles the SSS will be longer (7m) and the minimum inner radius of the beampipe 46mm ➔ aperture would have to be **96mm**



R_bend (m)	beam pipe diam (m)	R_stopper (m)	D_stopper (m)	L_SSS (m)	R_SSS (m)
10021	0.070	0.034	26.485	4.0	**0.045**
10021	0.070	0.034	26.485	7.0	0.048
10021	0.060	0.029	24.521	4.0	**0.039**
10021	0.060	0.029	24.521	7.0	0.046

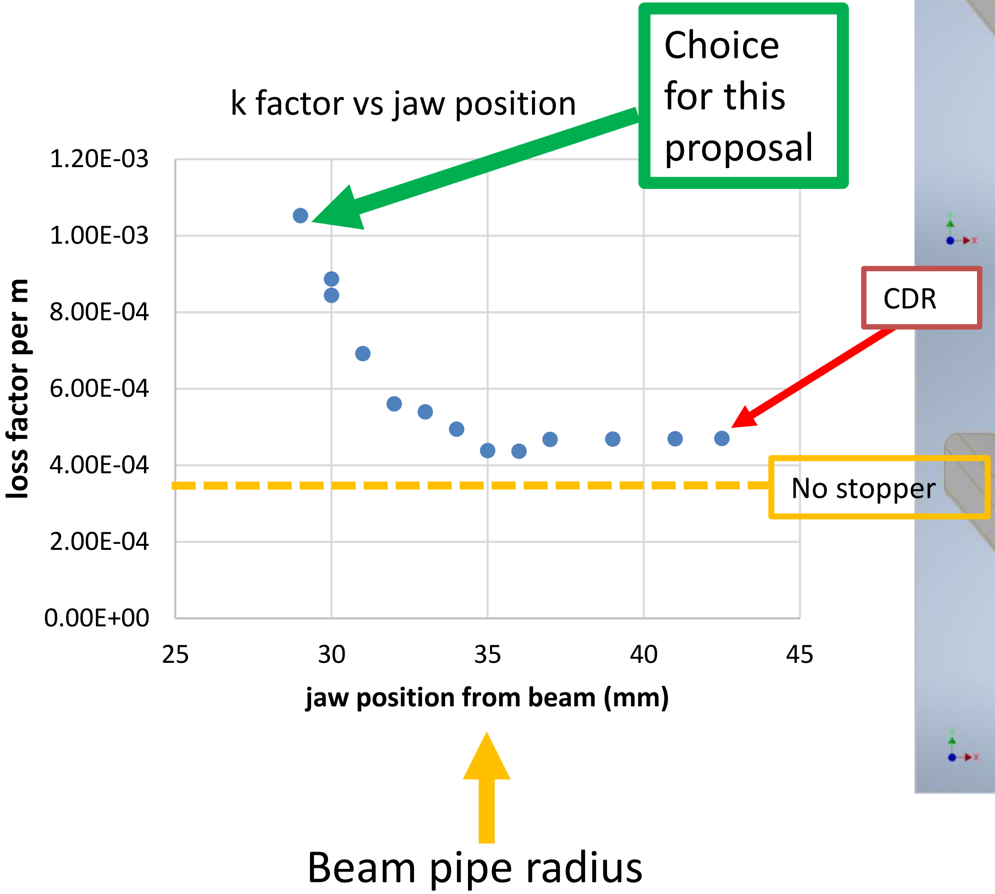
Photon stoppers, winglet, impedance

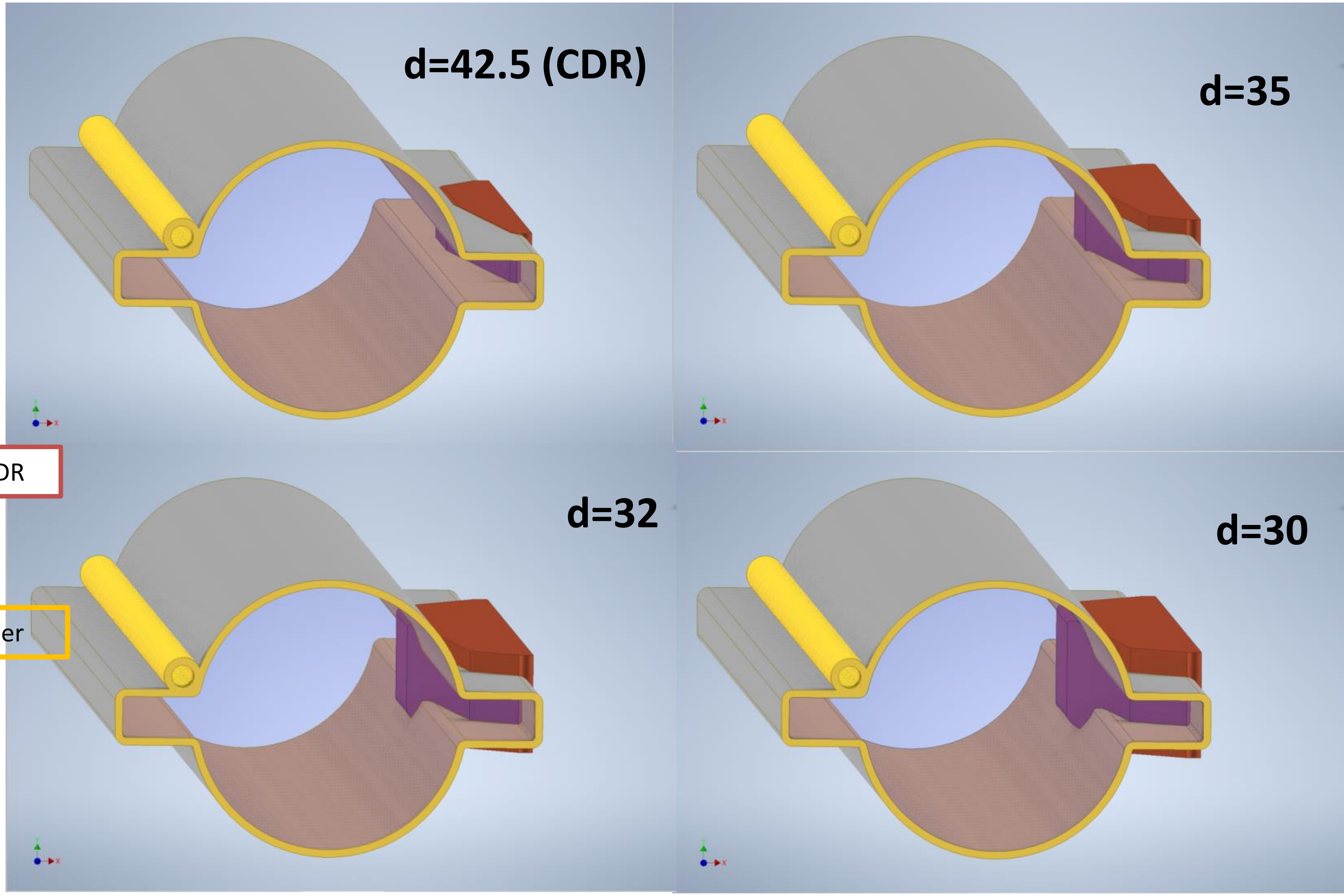
- How much would this idea increase the resistive wall impedance budget (and, therefore, wasted power) of the machine?
- Since space is at a premium, this idea accommodates much smaller winglets than the CDR design (110mm to 86mm) for the entire length of the SSS (3.5m)
- It also calls for photon stoppers 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:

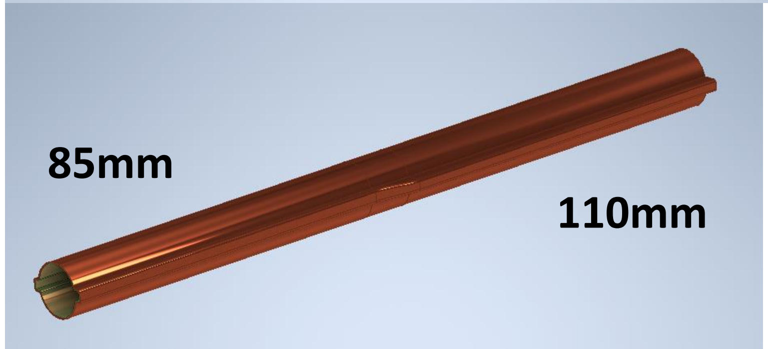


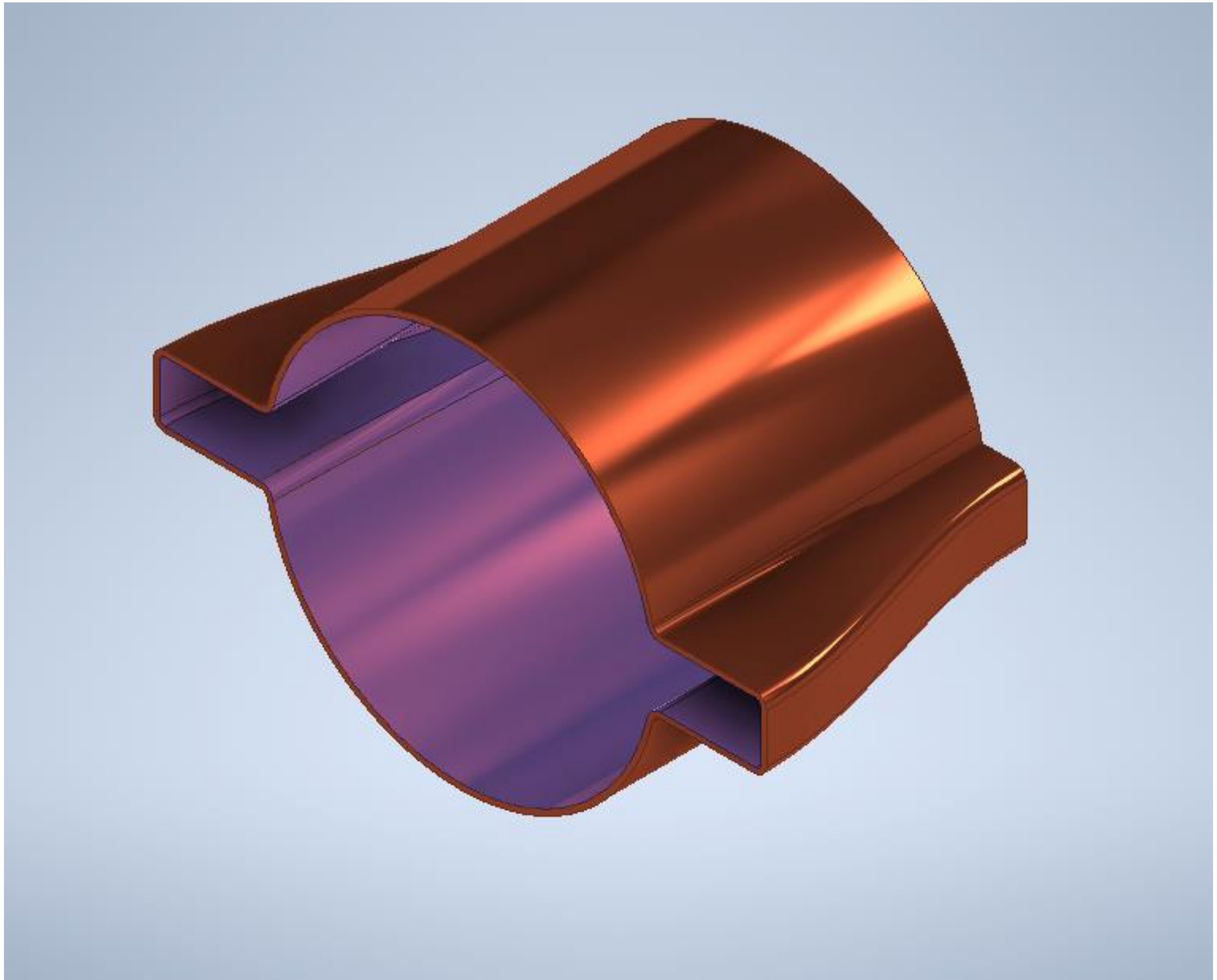


N. Nikolopoulos

Transitions

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





Results of impedance calculations

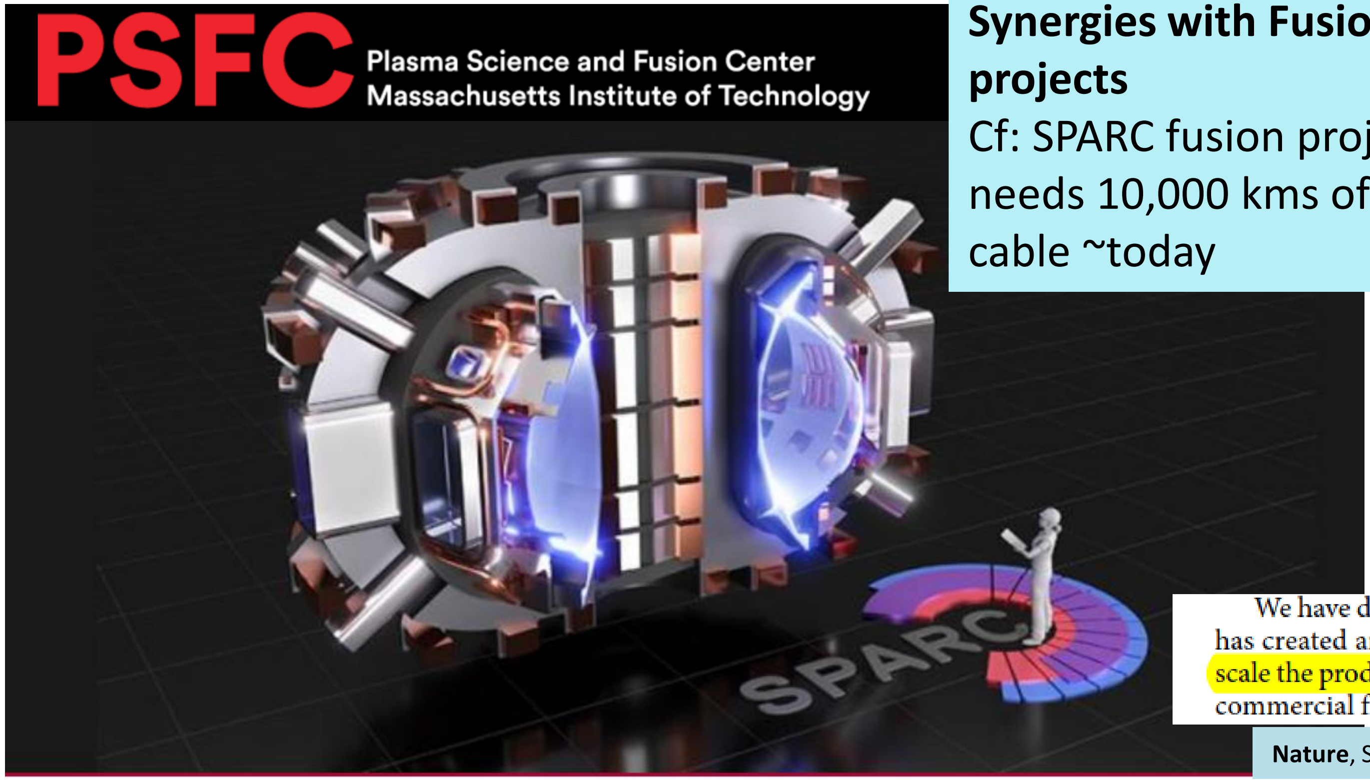
- A copper 35mm radius round pipe has a loss factor of 3.6×10^{-4} V/pC at the Z. This corresponds to a total power of 2.3MW for both beams
- A 35mm inner diameter pipe with winglets has a loss factor of 3.7×10^{-4} V/pC, close to the totally round case.
- Having a stopper as in the CDR increases the 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

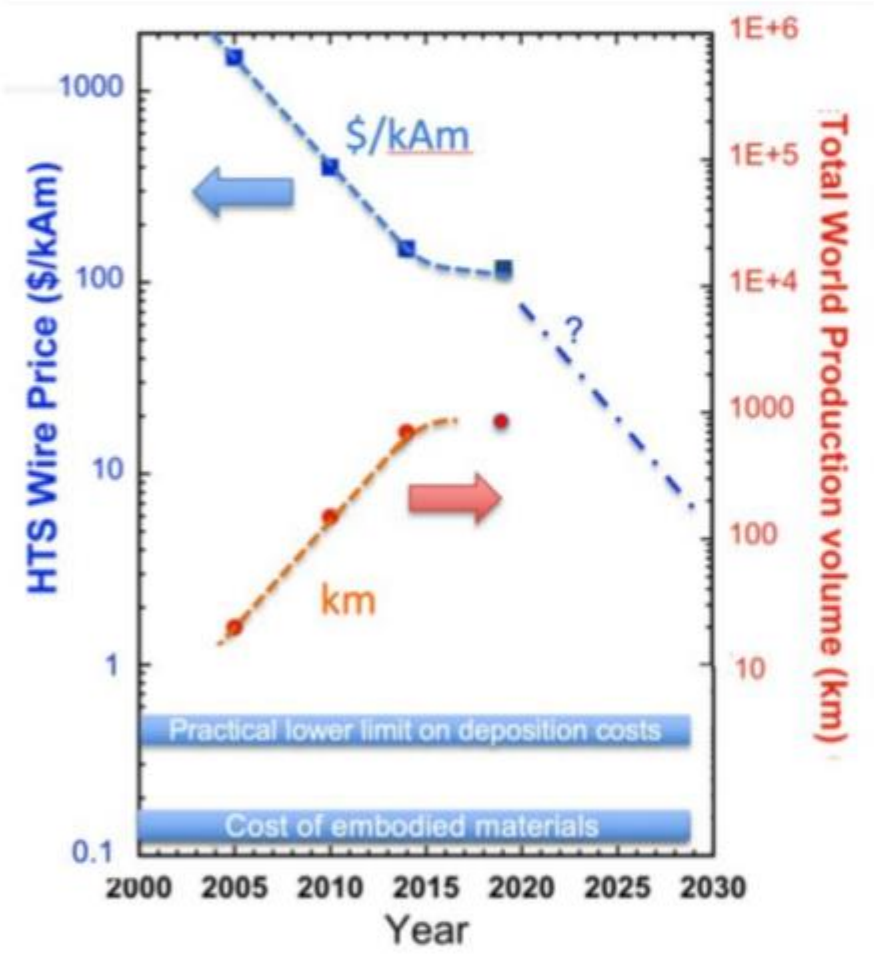
https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF7_AF0_Vladimir_Matias-251.pdf

- The cold SSS idea cannot cost more than the price of the normal conducting system. The major cost driver today is the HTS 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

Cooling the SSS

- The current design calls for individual conduction 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.*

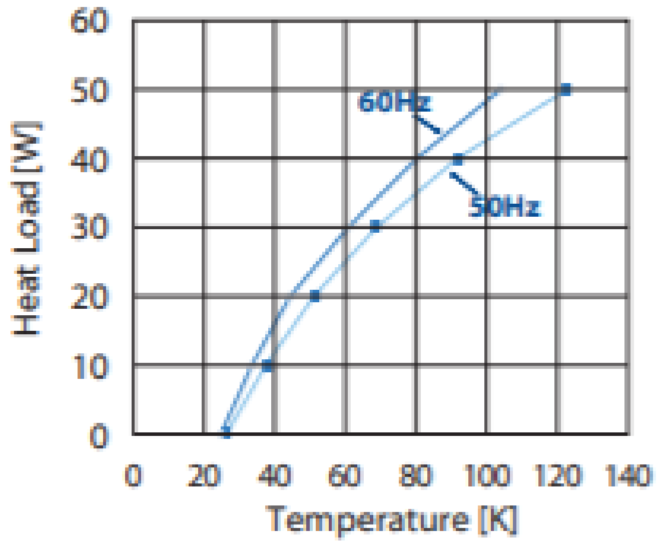
Power Consumption	Steady	Maximum	
50Hz	1.3 kW	1.4 kW	-- approx.
60Hz	1.4 kW	1.6 kW	-- approx.

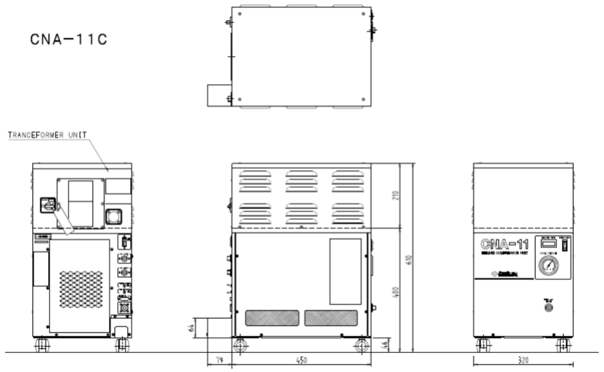
Cooling capacity:
- 33W@77K,
- 12W@40K

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

MT28-5POM03-05

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

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- 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.

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

Alternative – QRL line

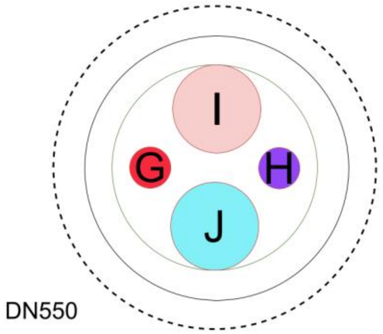
- We should investigate the efficiency and cost of a centralized system, just like the LHC, with a cryogenic distribution line (QRL)
- FCC-hh will certainly need a QRL, so it is a question of early investment
- FCC-ee will also need a large cryogenic plant at each IP, to take care of the two Final Focus cryostats, expected to have a heat load of 100W@1.9K each – there might be some synergies here

We are engaging the cryo people at CERN

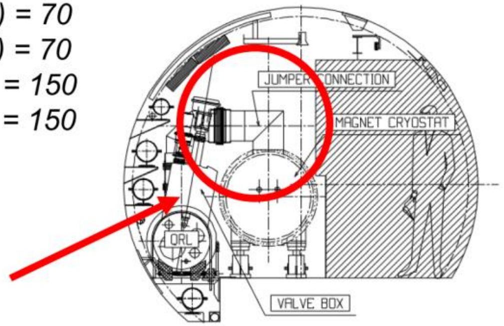
Distribution – Integration

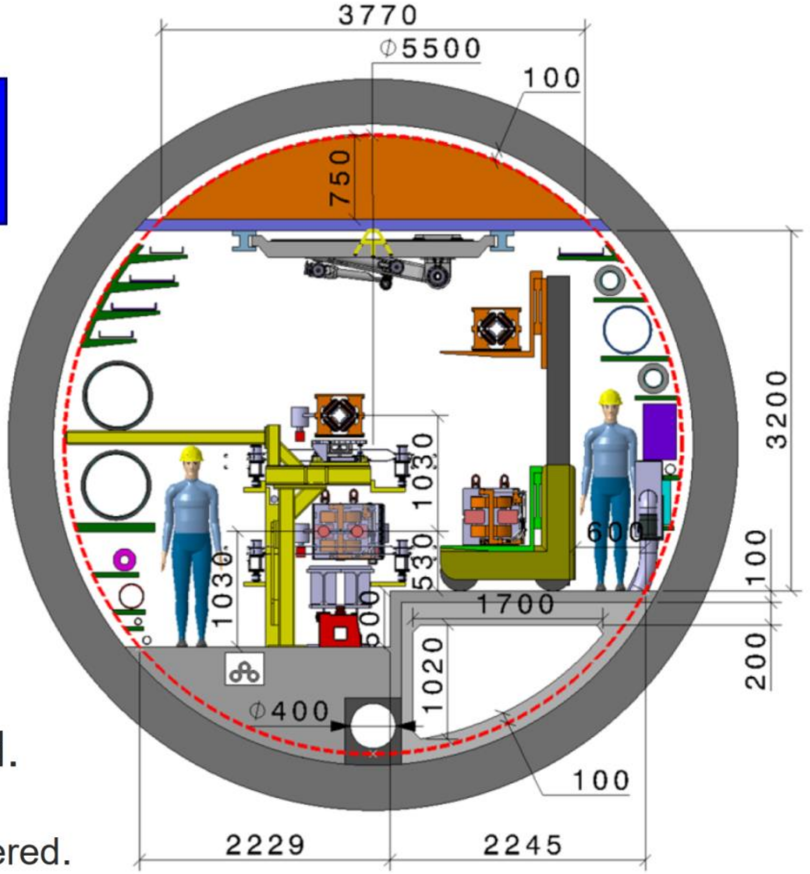
- DN550
- 40 K circuit – lines G and H
- 80 K circuit – lines I and J

DN could be optimized with a more refined assessment of the heat loads / innovative ideas like the usage of Ne-He.



G (supply 40K) = 70
H (return 40 K) = 70
I (supply 80 K) = 150
J (return 80 K) = 150





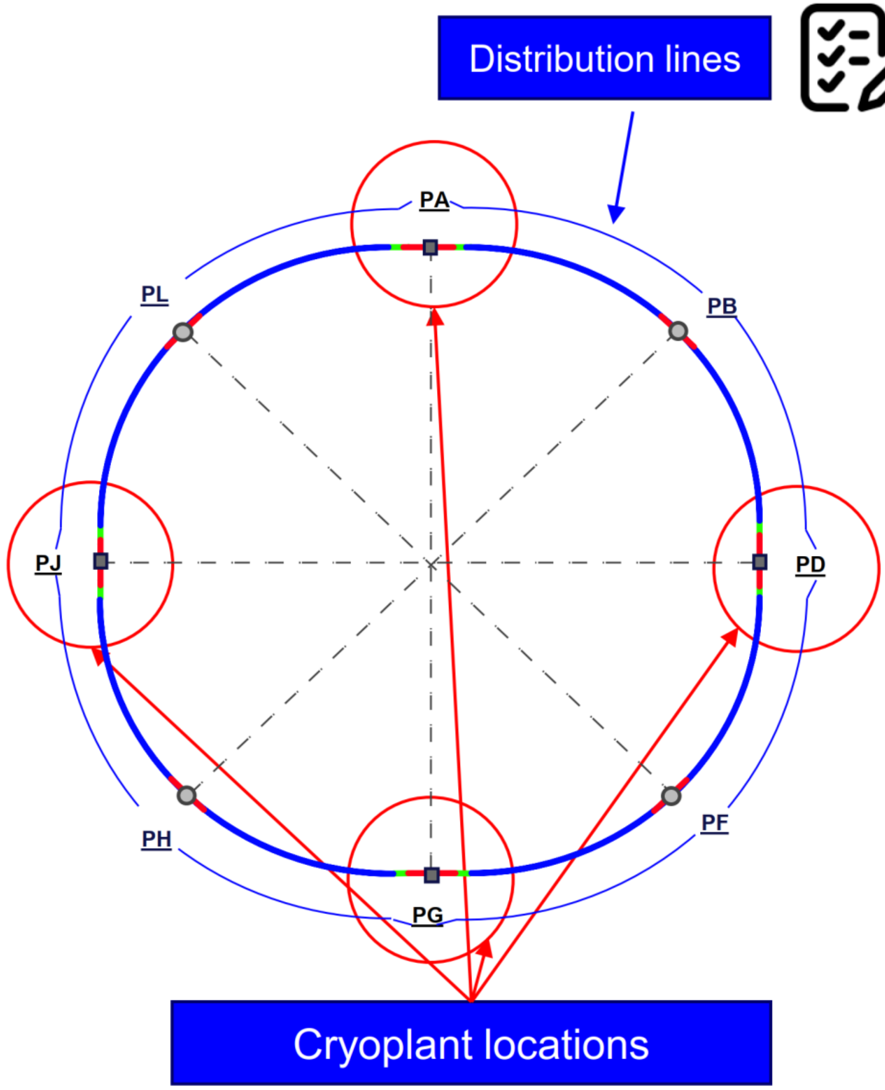
- Service module and jumper size need to be considered.
  - One service module per magnet or 363 per sector (**x10 LHC**)
  - No optimization made so far – LHC-like service modules are considered.
- Integration in the arc can be complicated. To be confirmed with integration team.

One of the options of the arc cross-section
F. Valchkova-Georgieva

Their conclusions

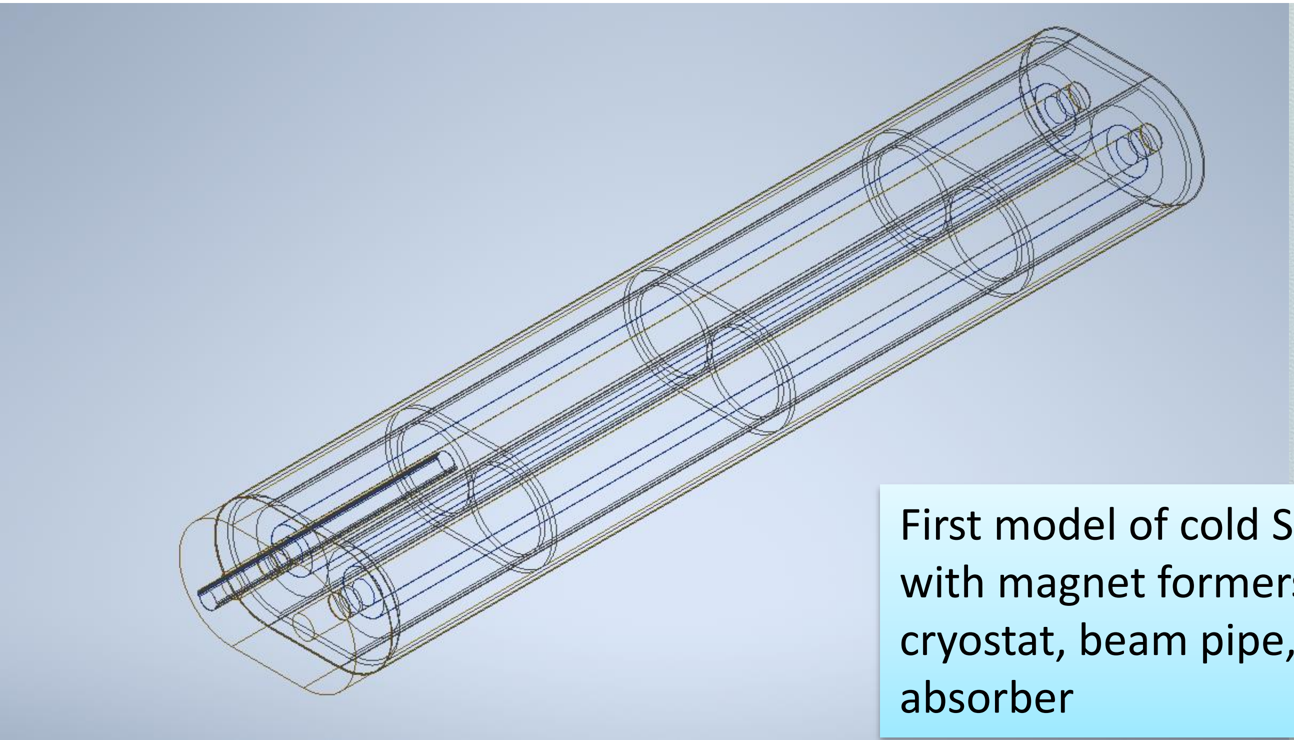
Conclusions

- 4 cryoplants of 5.3 kW @ 4.5 Keq needed to cover the HTS4 loads.
- The cryoplants need to be located at points PA, PD, PG and PJ to avoid the busy RF points PL and PH.
- Electrical consumption of the cryogenic system for HTS4 is limited to 5 MWe.
- Preliminary distribution line size of DN550.
- Each magnet requires its own set of valves and interconnections (service modules) to the distribution line.
  - Amount of service modules needed makes the project cost prohibitive.
  - The exergetic efficiency is also very poor because of this.
  - A point-wise cooling along the arcs does not seem to be a viable approach.

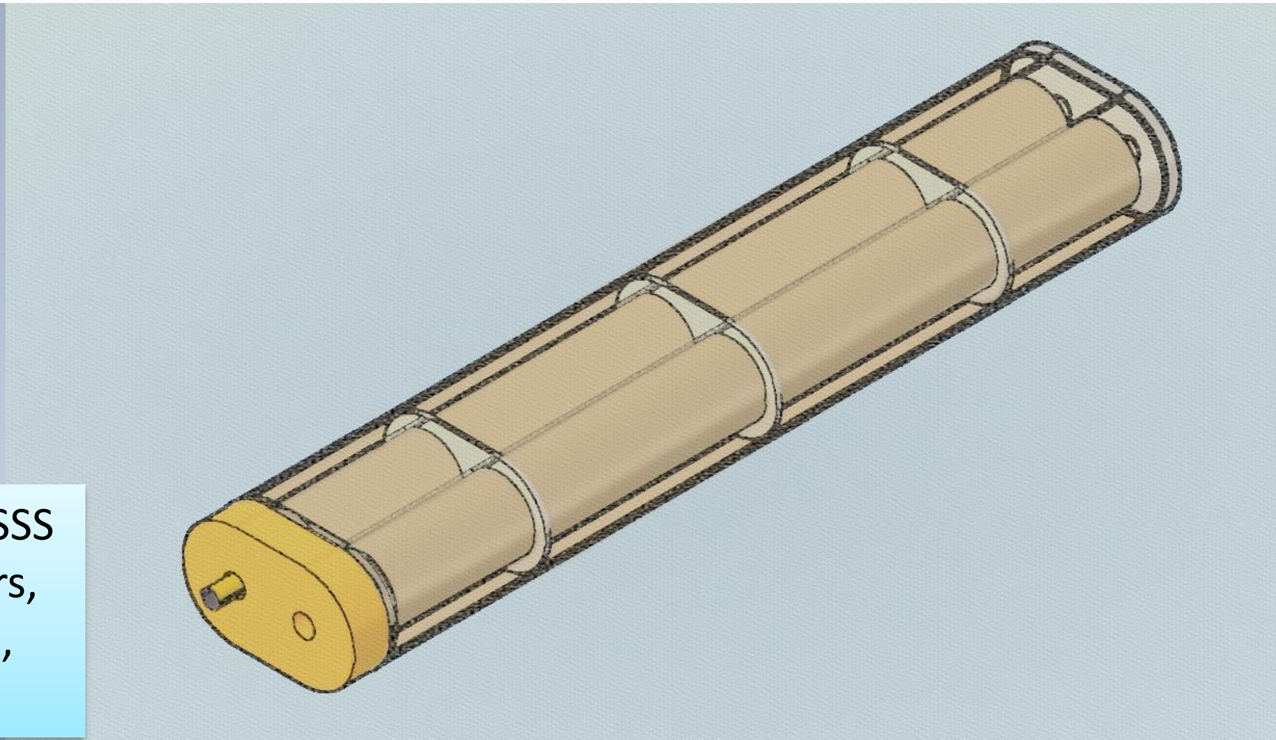


Heating budget

- 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

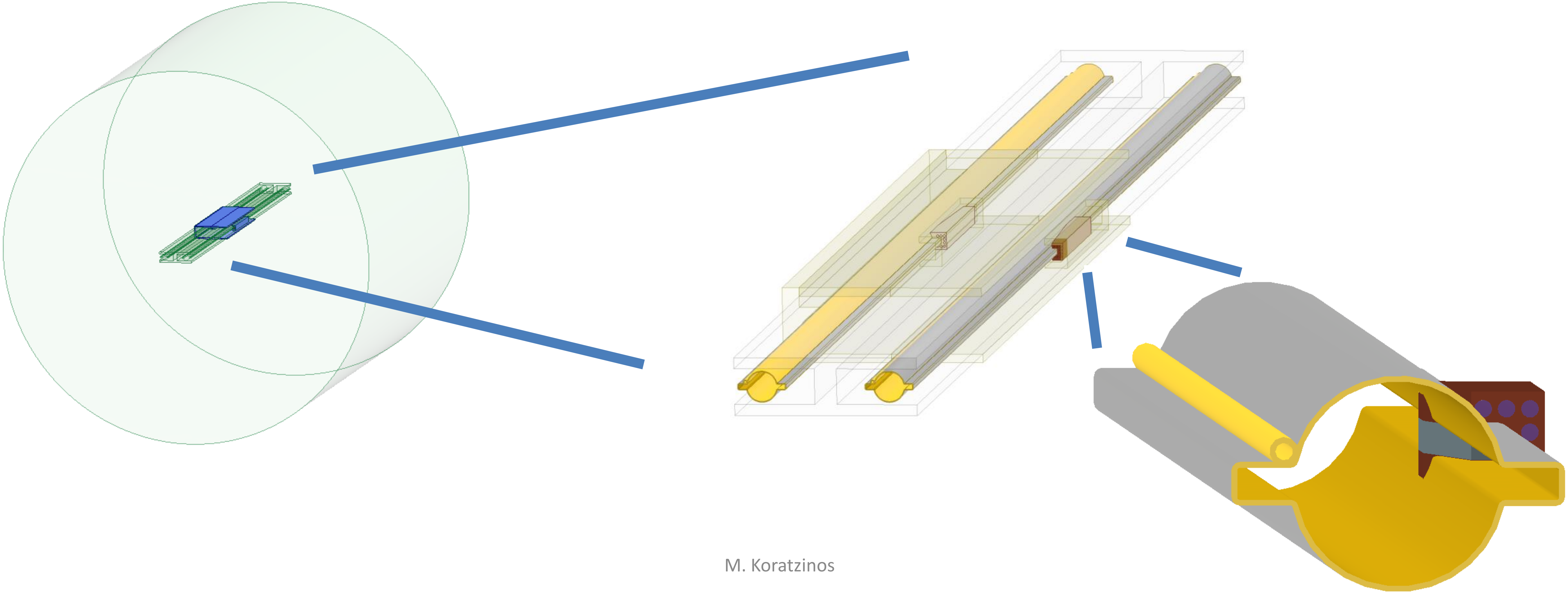


Radiation environment

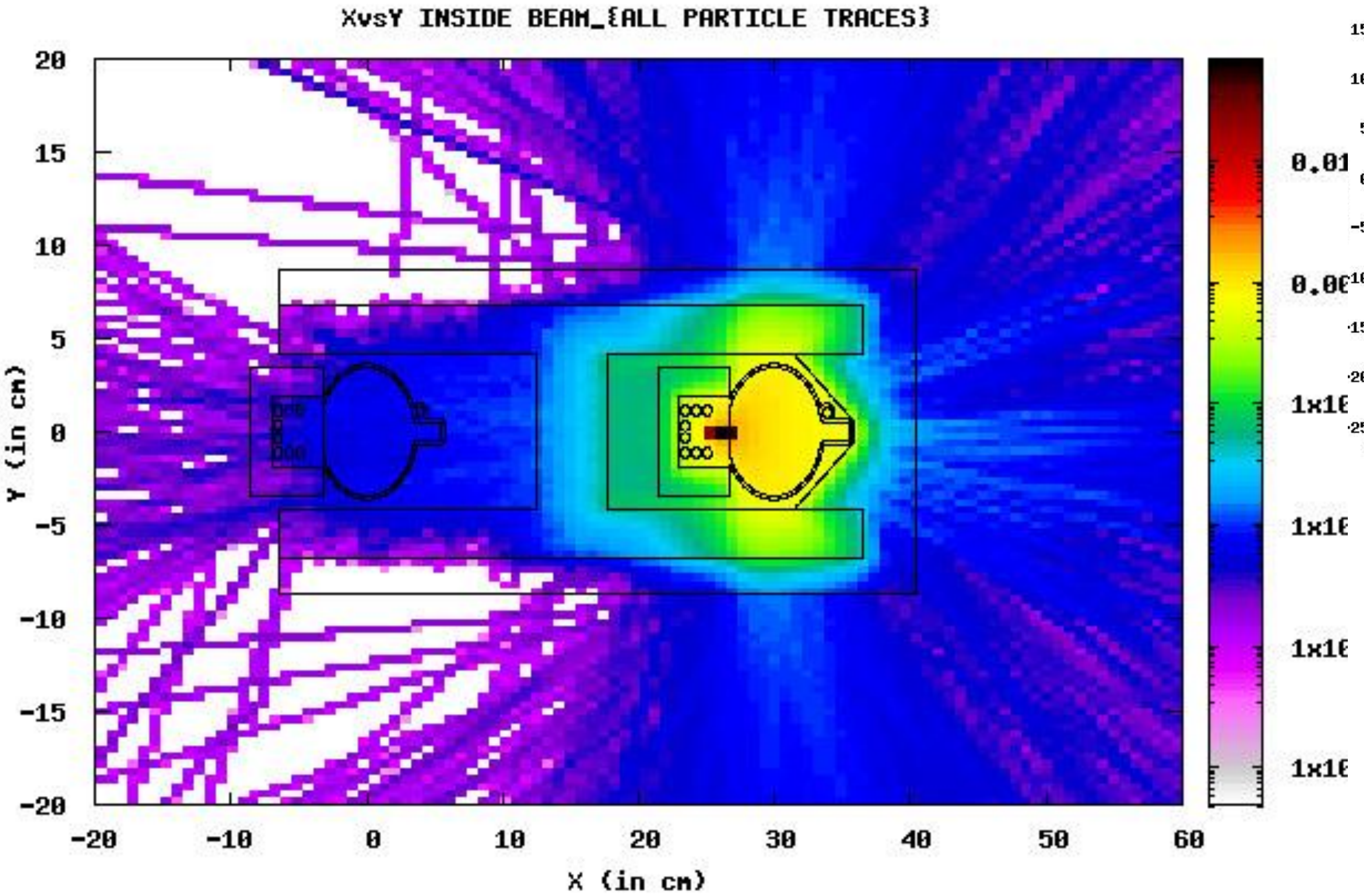
- The FCC-ee tunnel is a harsh radiation environment.
- We need to ensure that:
  - The cryostat is protected from radiation which will increase thermal loads
  - Any associated equipment with electronics (power supply, cryocoolers) will continue functioning for the lifetime of the accelerator.
- We 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

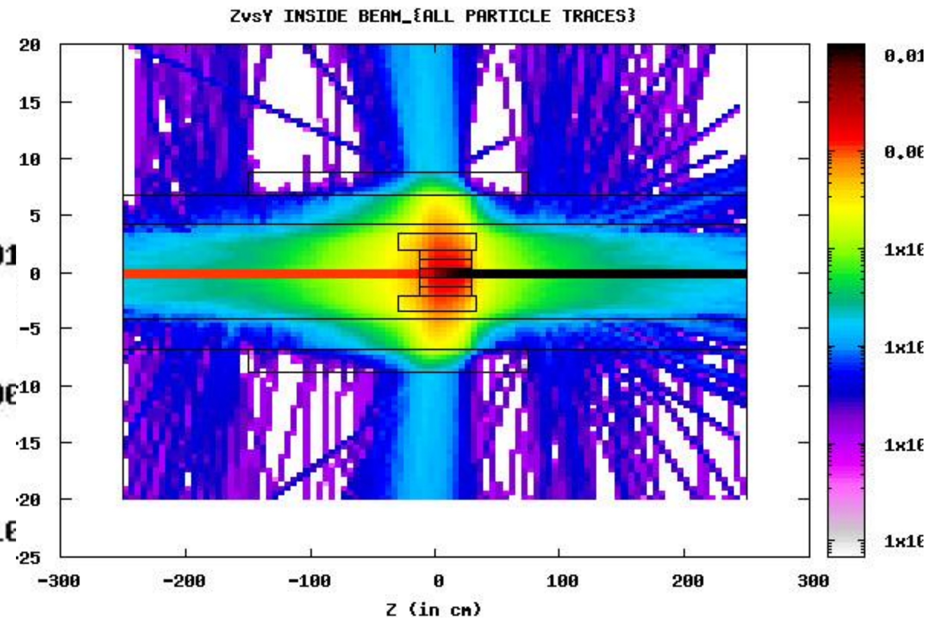
Radiation in the tunnel

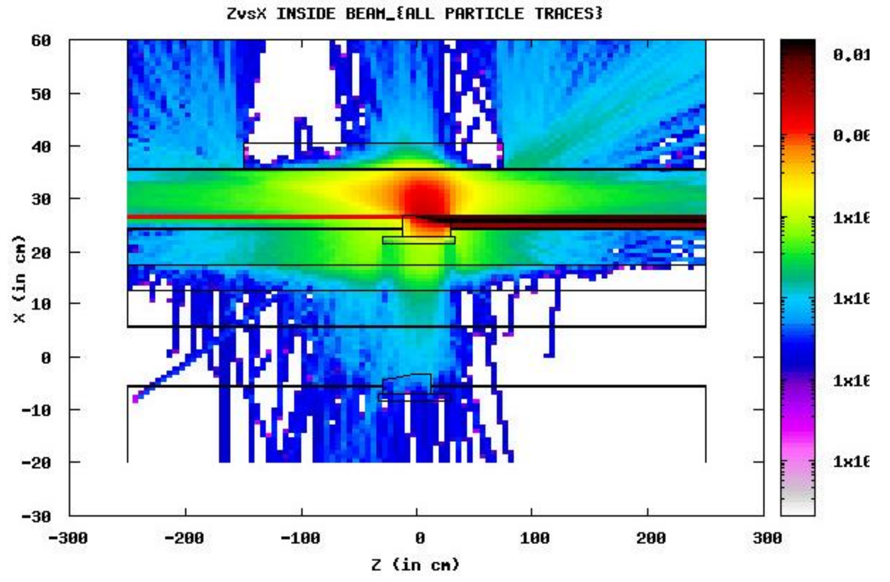
- See presentation by N. Nikolopoulos https://indico.cern.ch/event/1113474/ in 2022
- A full system with tunnel, dipoles, beam pipe, photon absorbers, shields was simulated in FLUKA
- We have used tungsten for the extra shielding, which however can be replaced by lead of 1.5 times the thickness



FLUKA results, inside beam



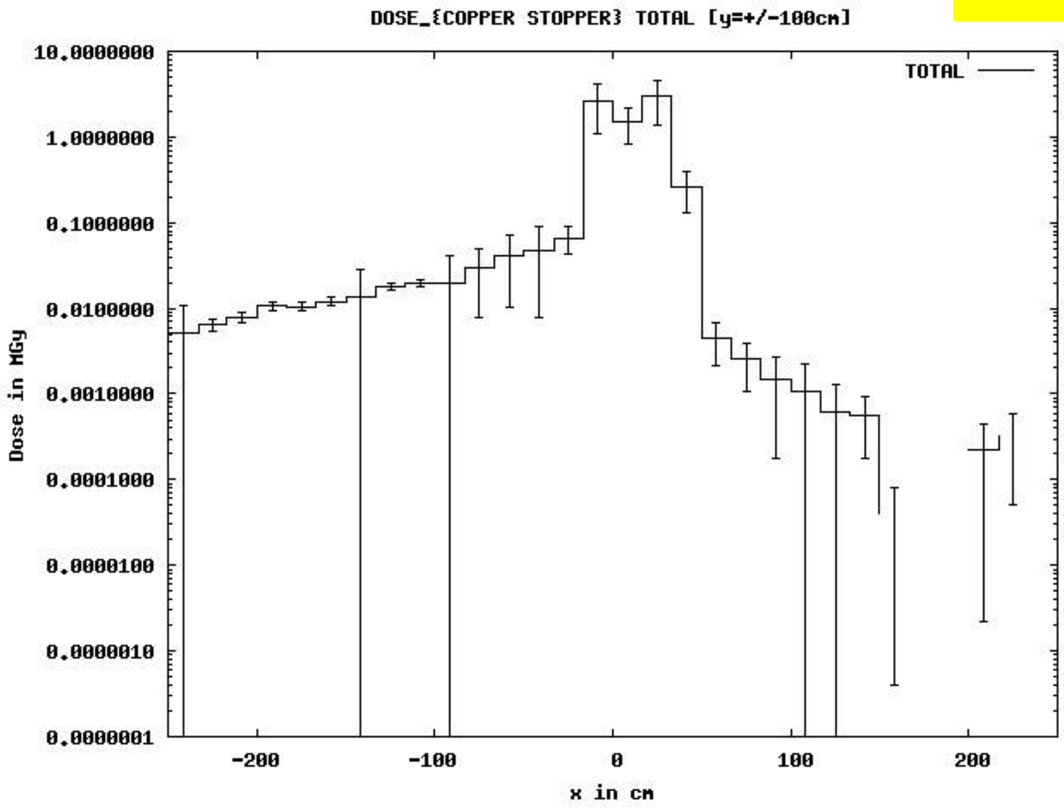


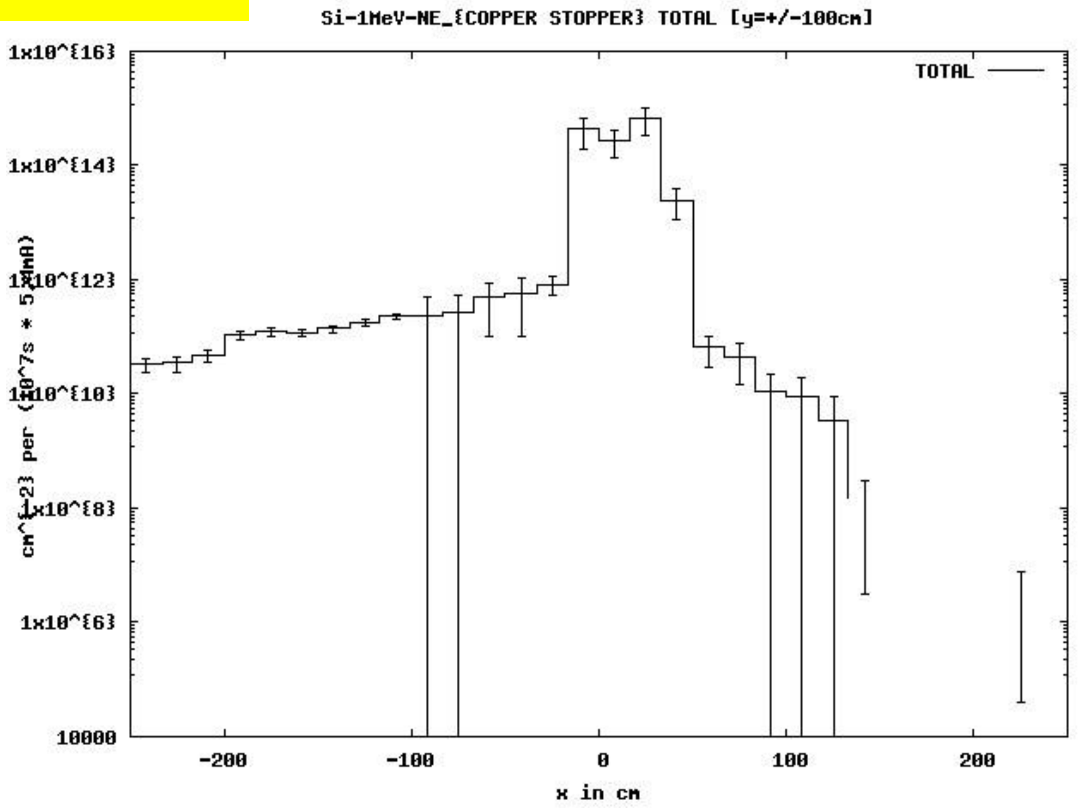


>99% of energy absorbed by various absorbers, beampipe or magnet

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

Beam energy: 182.5GeV





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

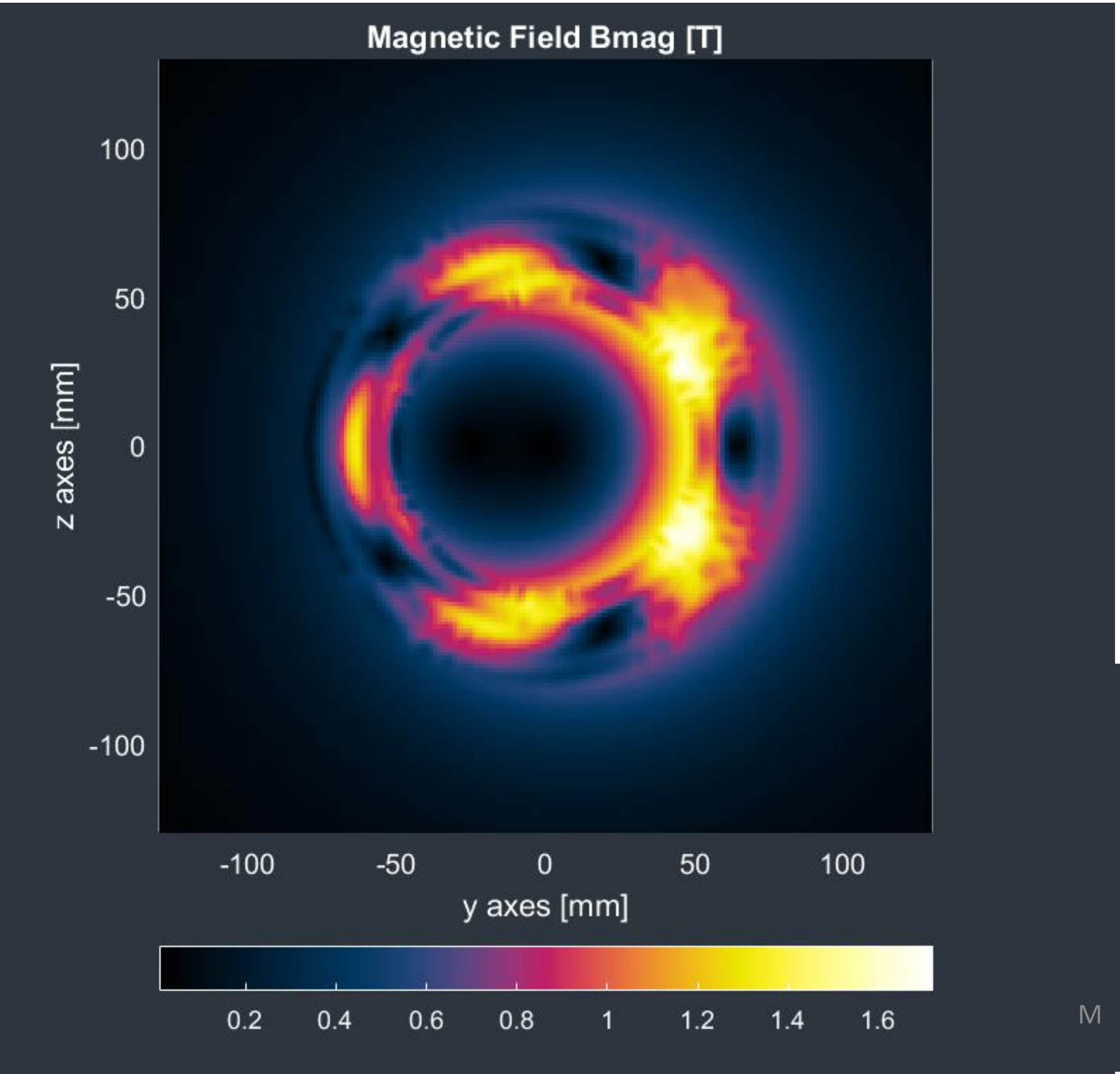
Doze can be **<1kGy per year 1m off the accelerator plane**. This analysis will be verified as design evolves

Radiation levels in the tunnel

- We have performed a FLUKA study with extra shielding around photon stoppers
- .stp files are available.
  - Total weight of lead shields 1055Kg per double stopper
  - Total cost using lead: ~2000USD per double stopper
- Results are that the yearly dose of less than 1kGy per year (1m inside of the collider, in a region of +-1m from the vertical level of the collider
- These results need to be fine-tuned for cost, integration, etc.
- These results need to be verified by the FCC FLUKA team

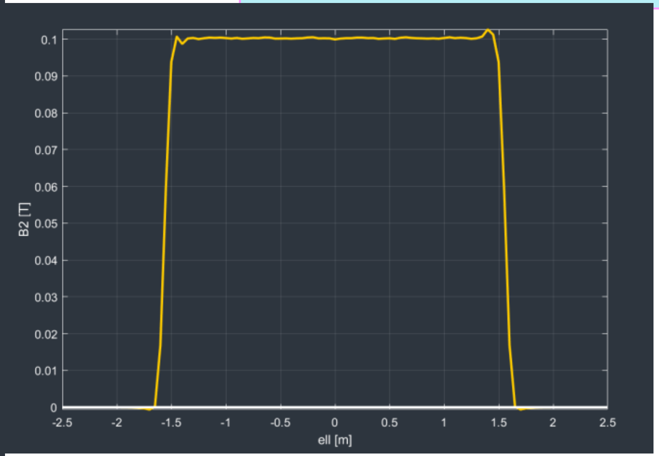
Quad and sextupole at full strength

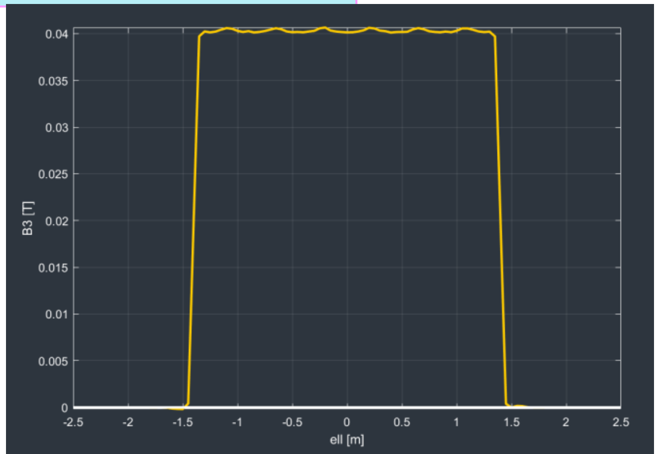
Magnetic design



- 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





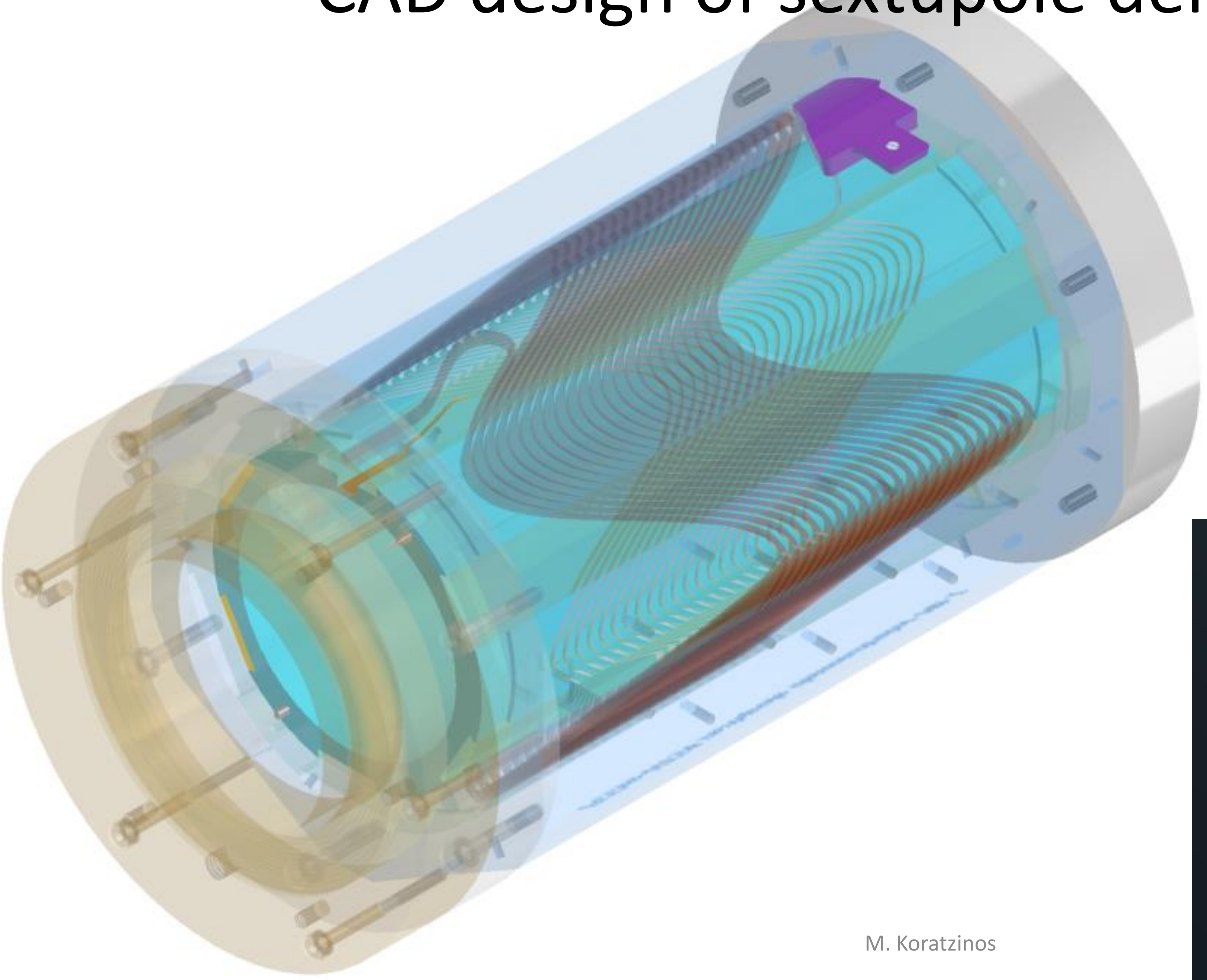
Demonstrator

- 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

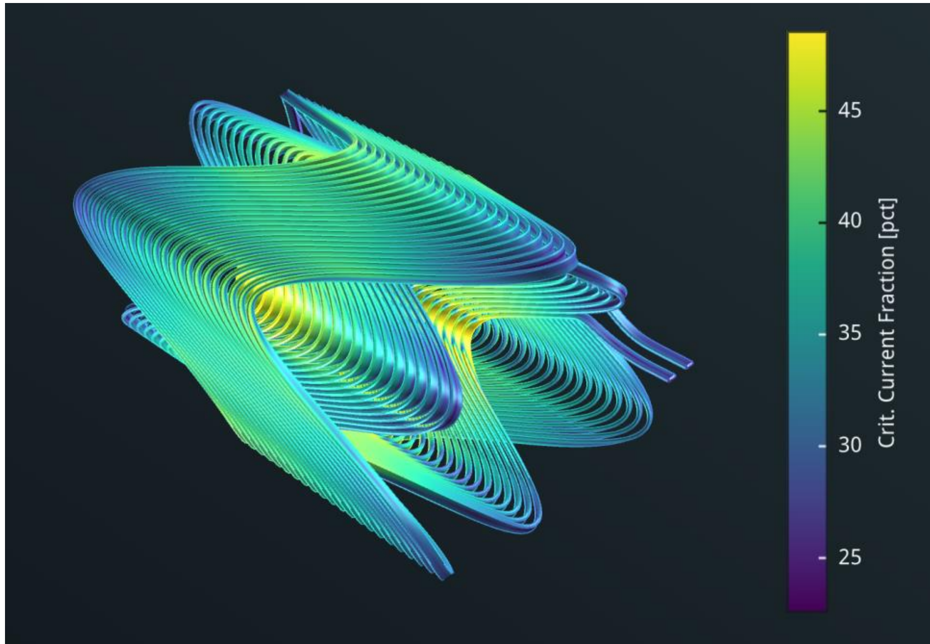
Demonstrator – choice of technology

- 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



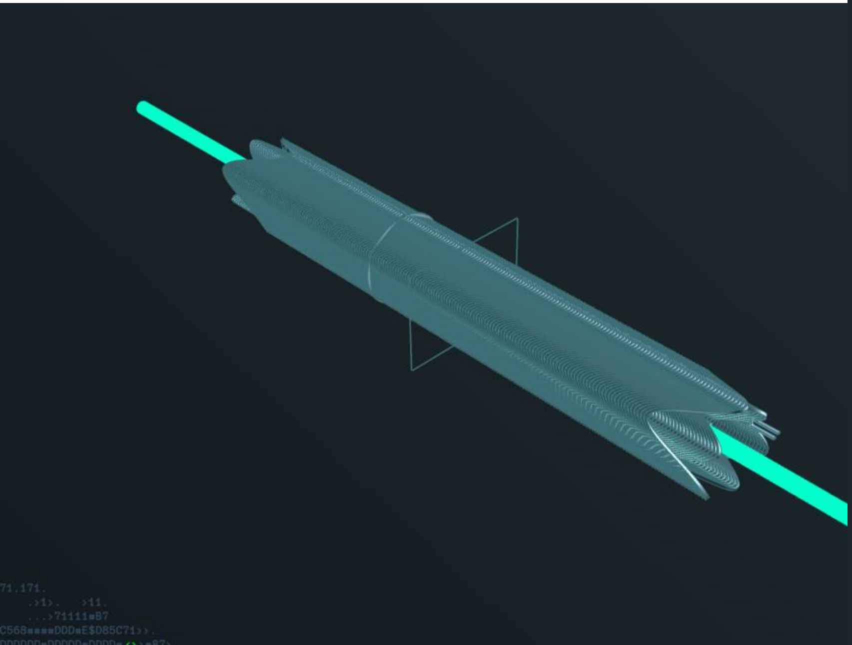
Specifications:
Aperture: 90mm
Current: 260A
Temperature: 40K
Field gradient: 1000T/m2
Max. field @conductor:1.5T
Crit. Current fraction: 49%
Temp. margin: 14K



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]

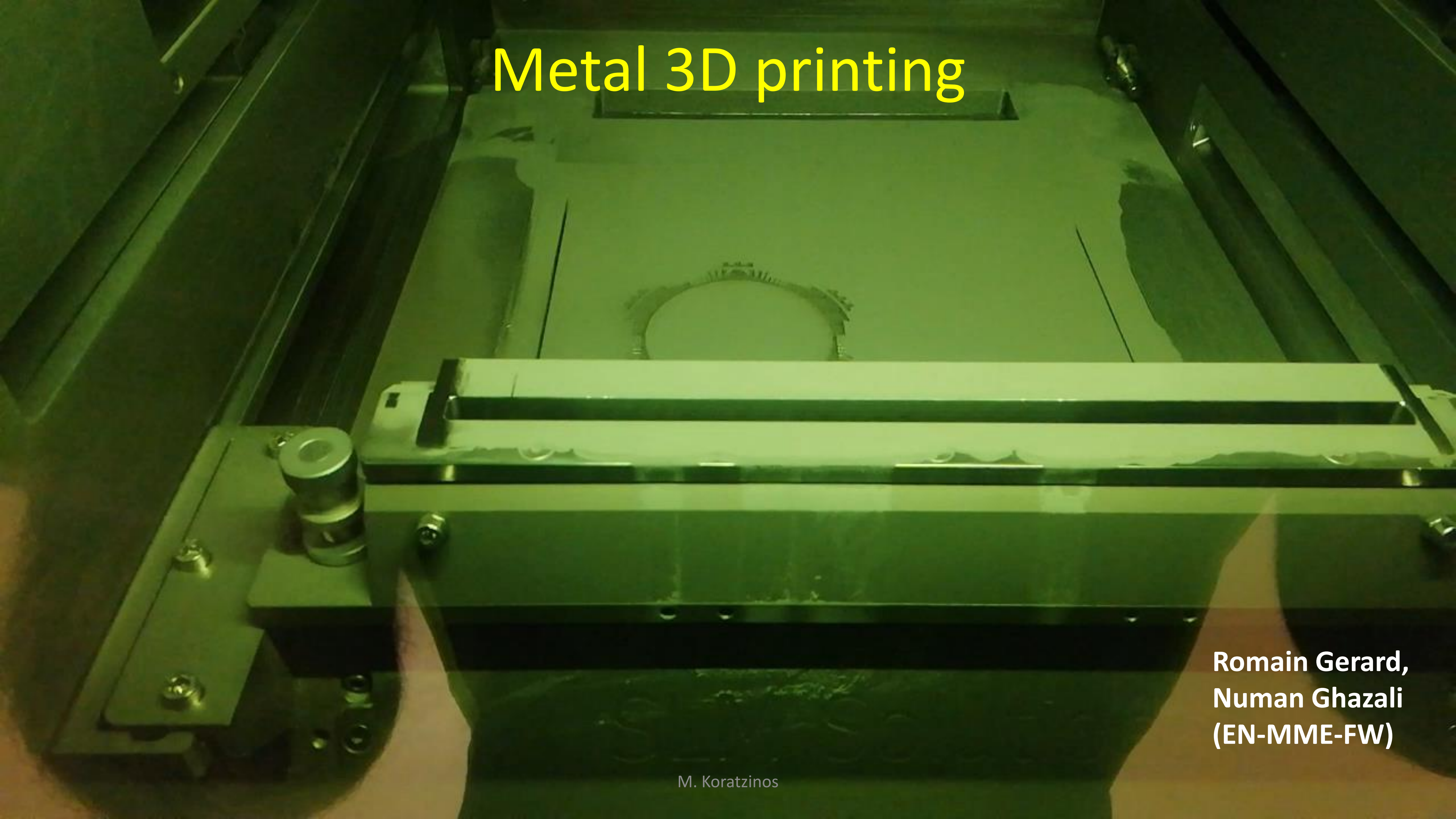
Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	3.09e-06	0.76		B1	6.61e-07	0.16	
A2	5.21e-07	0.13		B2	3.43e-06	0.84	
A3	-1.87e-07	-0.05		B3	4.07e-02	10000.00	
A4	-1.34e-06	-0.33		B4	-1.29e-06	-0.32	
A5	2.29e-07	0.06		B5	1.16e-06	0.29	
A6	-1.13e-07	-0.03		B6	-4.26e-07	-0.10	
A7	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:

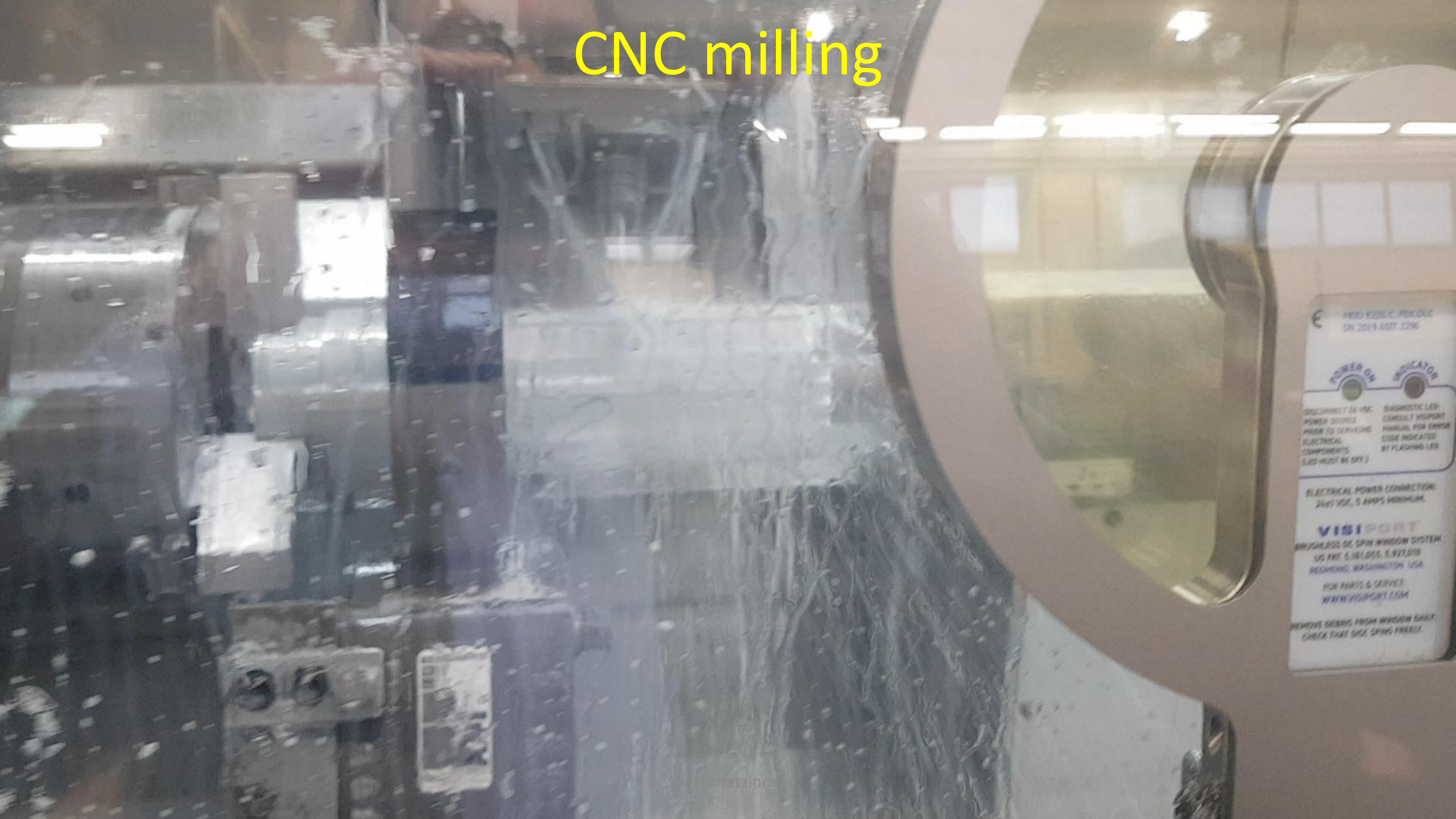
- Additive manufacturing (metal 3D printing)
  - Advantages: any geometry is realizable
  - Disadvantages: surface roughness
- Subtractive manufacturing (CNC machine milling)
  - Advantages: mirror-like finish
  - Disadvantages: not all geometries realizable
- We are actively looking at both techniques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

Metal 3D printing



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

CNC milling

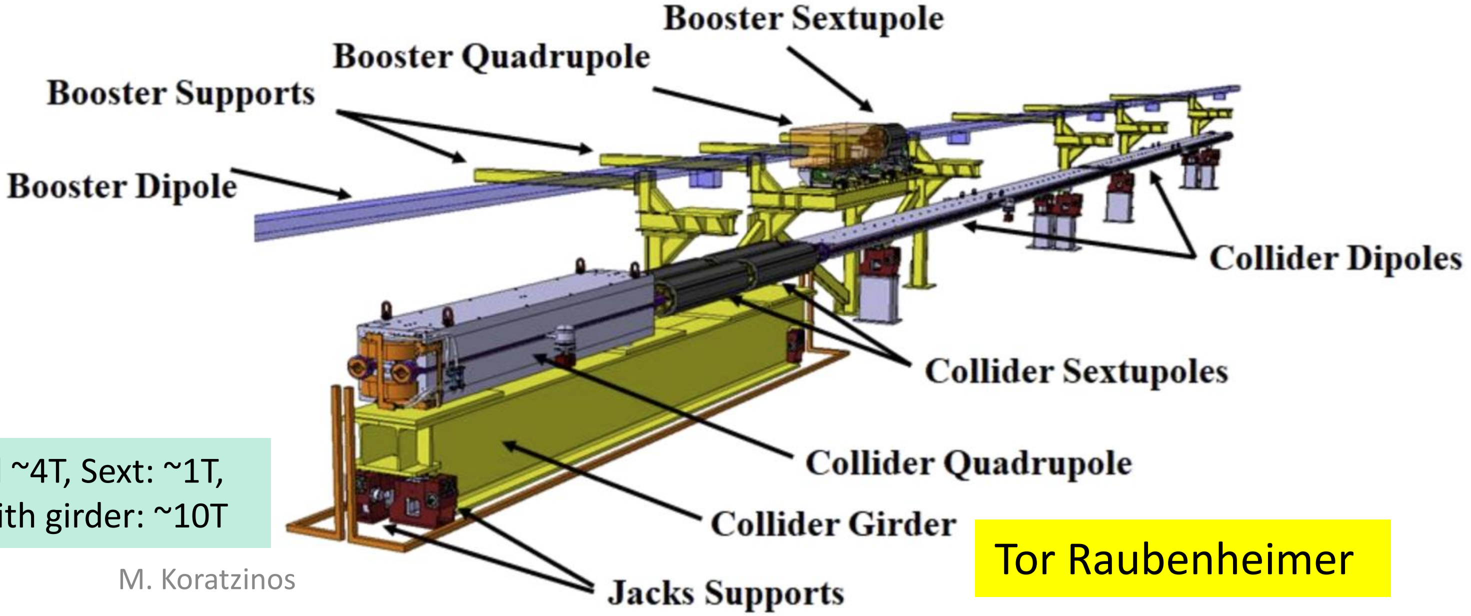


Demonstrator news

- Formers manufactured
- HTS tape purchased

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



Weights: Quad ~4T, Sext: ~1T, total weight with girder: ~10T

Tor Raubenheimer

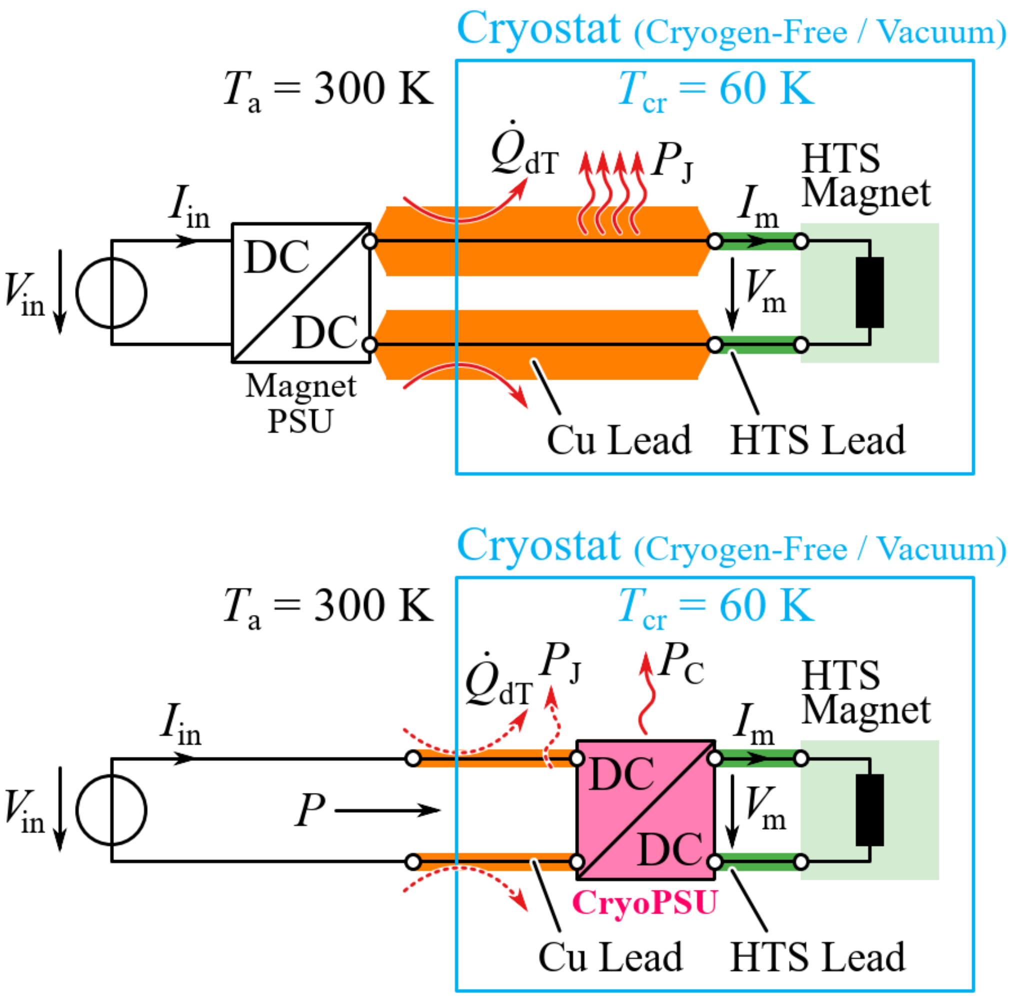
Our sister project: The idea behind FCCee-CPES

- 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**.

ETH zürich — Power Electronic Systems Laboratory

Traditional system:

This proposal:



FCCee CPES (PES, ETHZ) Jonas Huber, Danqing Cao, Daifei Zhang

Correctors

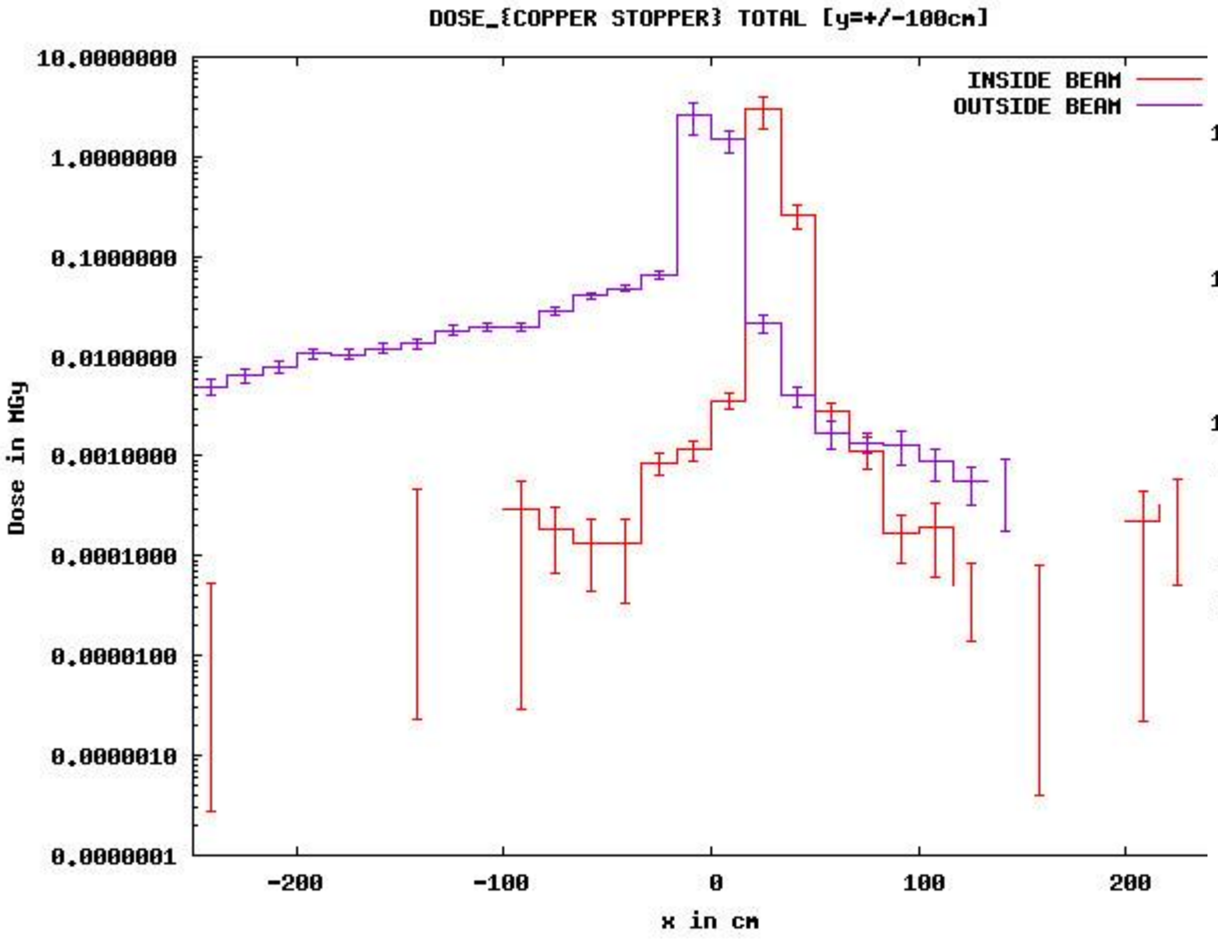
- All units (for e+ and e-) are individually powered, necessary for tapering, and magnetically isolated.
- Horiz. nnd vertical dipole correctors plus skew quads will be included in the SSS
- We do not suffer field quality problems from this.

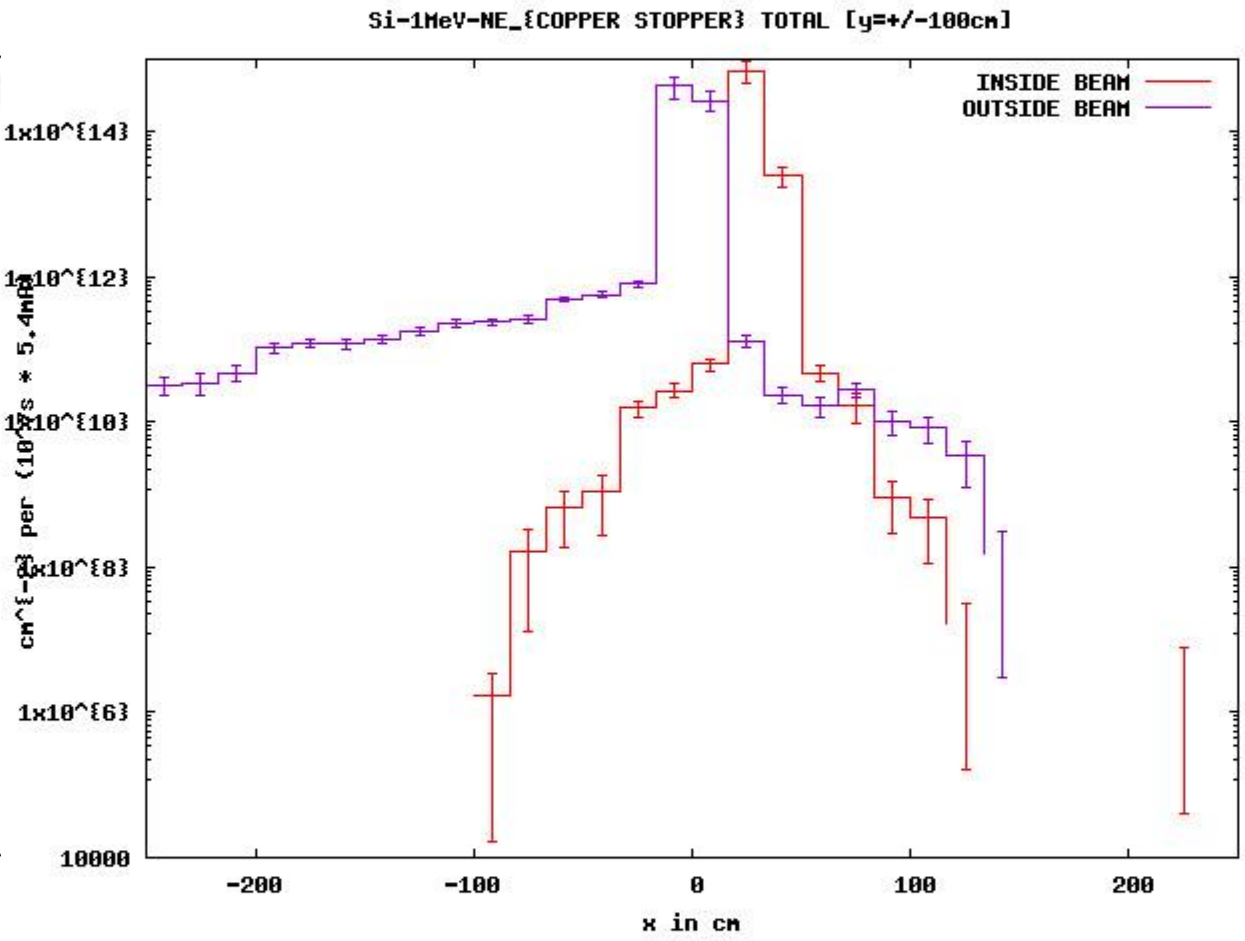
Conclusions

- 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

FLUKA results – dose and 1MeV n equiv.

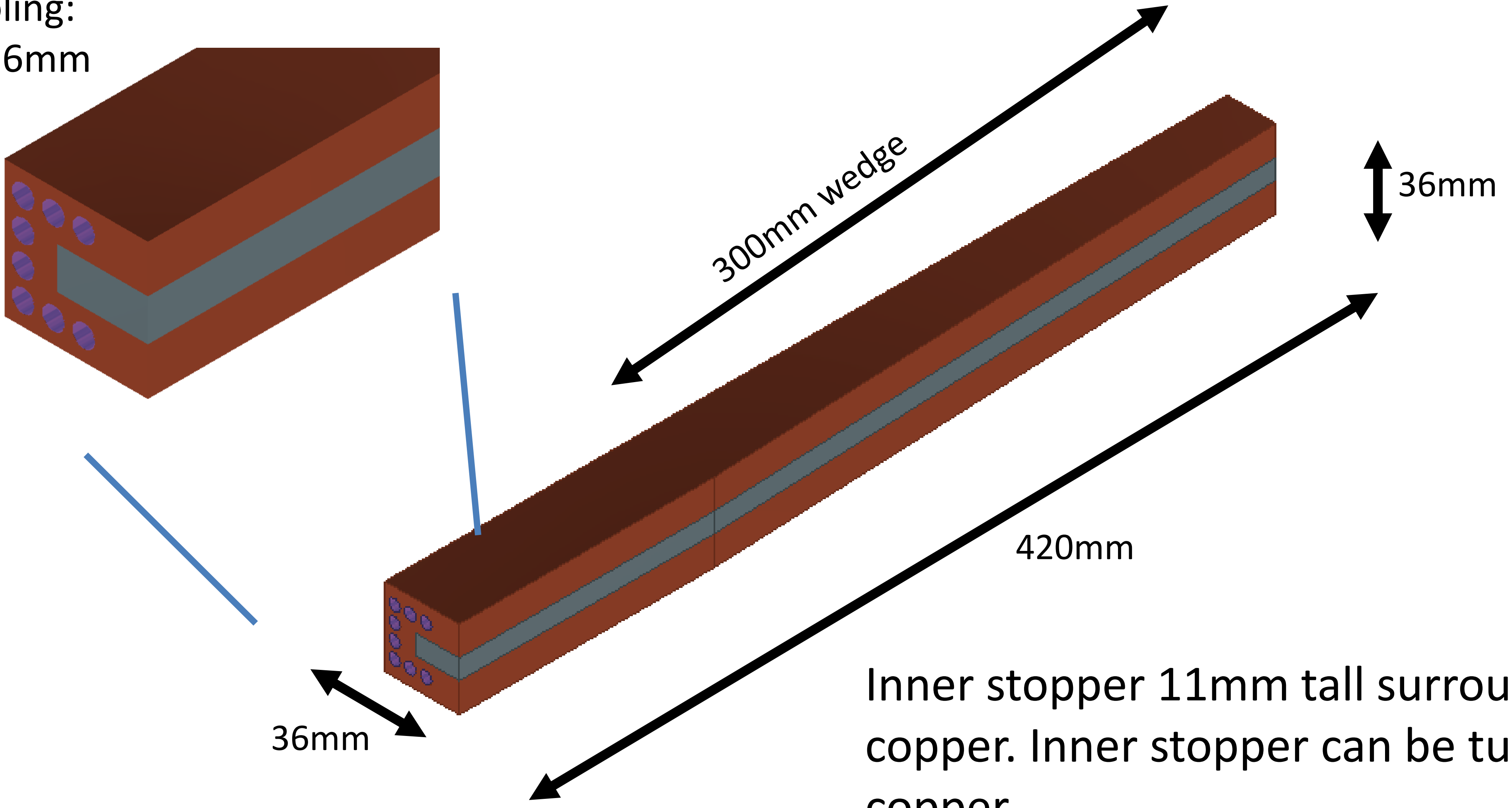




Here we look at the area ±1m vertically from the plane of the accelerator. Positive X (x is the horizontal dimension) is towards the inside of the accelerator. The slice along Z (the direction of the beam) is ±2.5m. Each histogram bin is 166.6mm wide

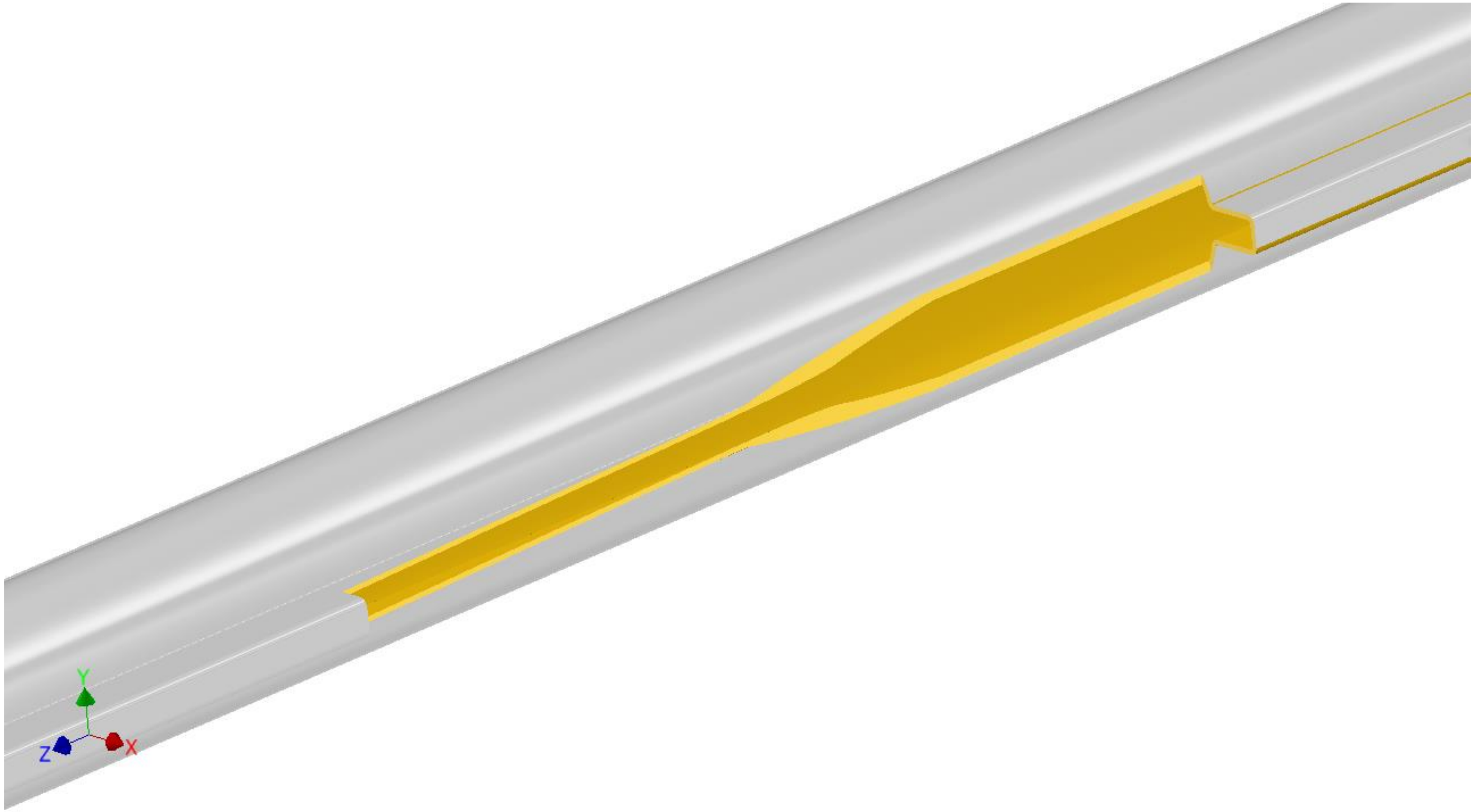
Proposed absorber

Water cooling:
8 holes of 6mm
diameter

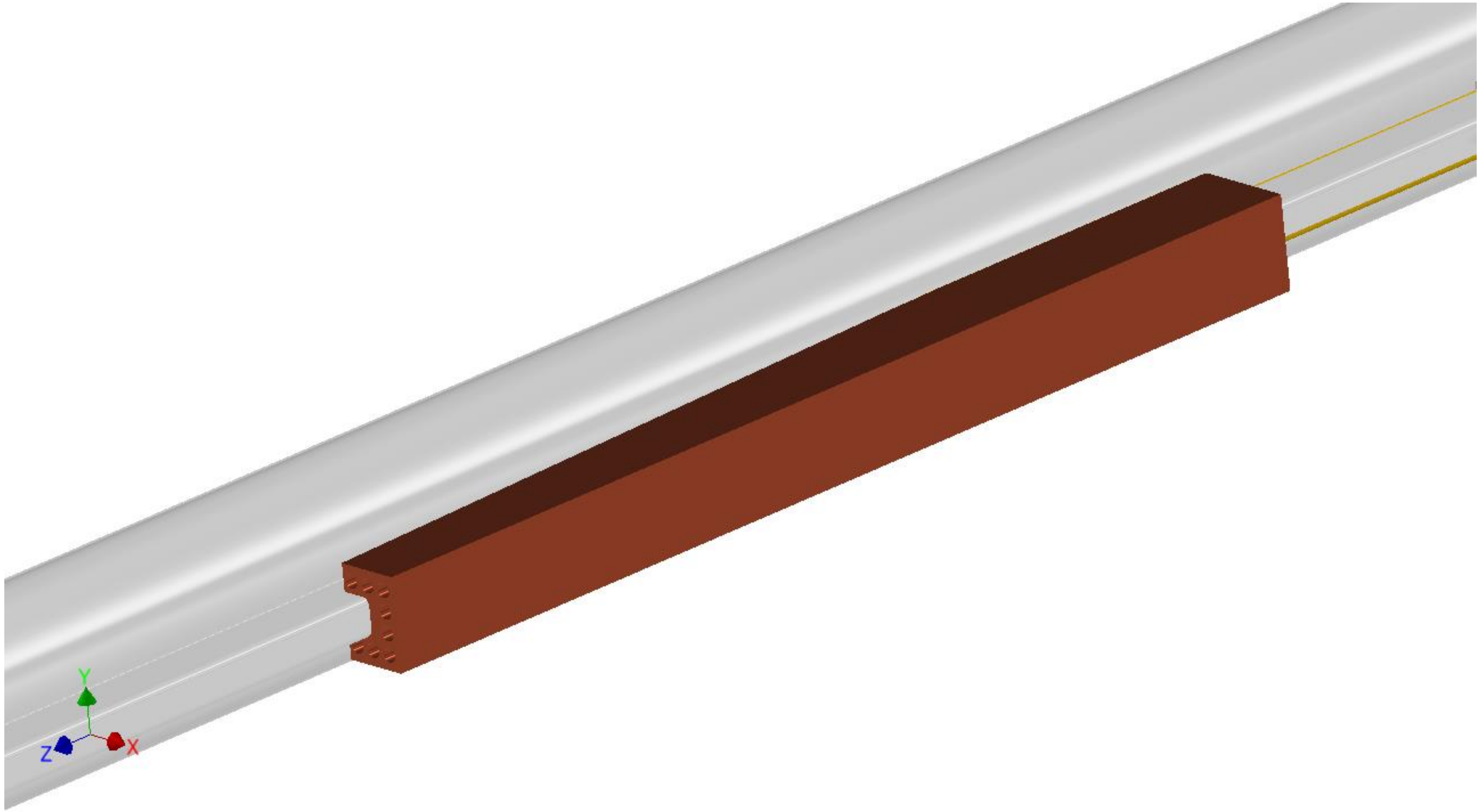


Inner stopper 11mm tall surrounded by copper. Inner stopper can be tungsten or copper

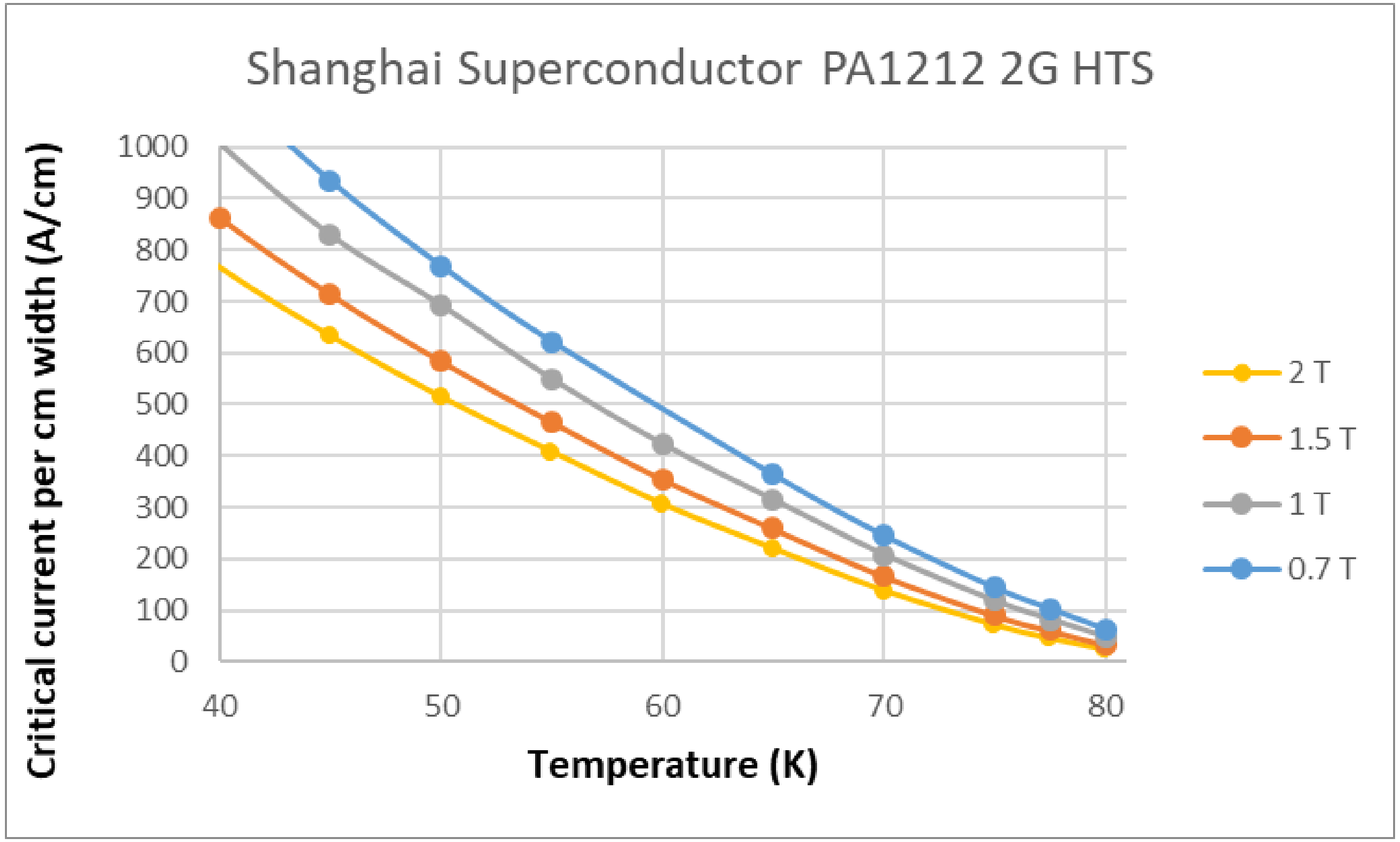
Beam pipe cut and ready to accept stopper



Stopper in place



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 increases 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

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.

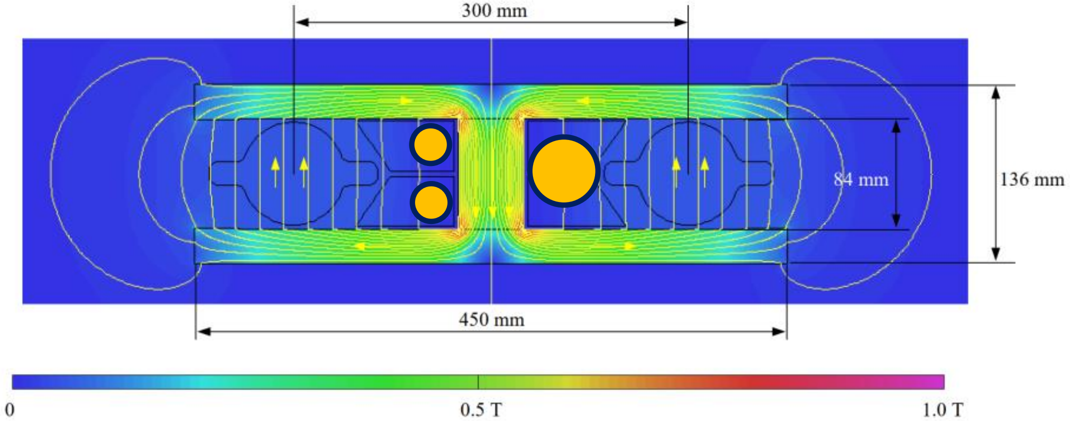


Figure 3.1: Cross-section of the main bending magnet; the flux density corresponds to 57 mT in the gap; the outline of vacuum chambers with side winglets is also shown.