Swiss Accelerator Research and Technology

PAUL SCHERRER INSTITUT

IAS Program on High Energy Physics (HEP 2024)

SC Magnets for the FCCee Collider Ring

M. Koratzinos

Mini-workshop on Green Accelerator and Colliders

18/1/2024

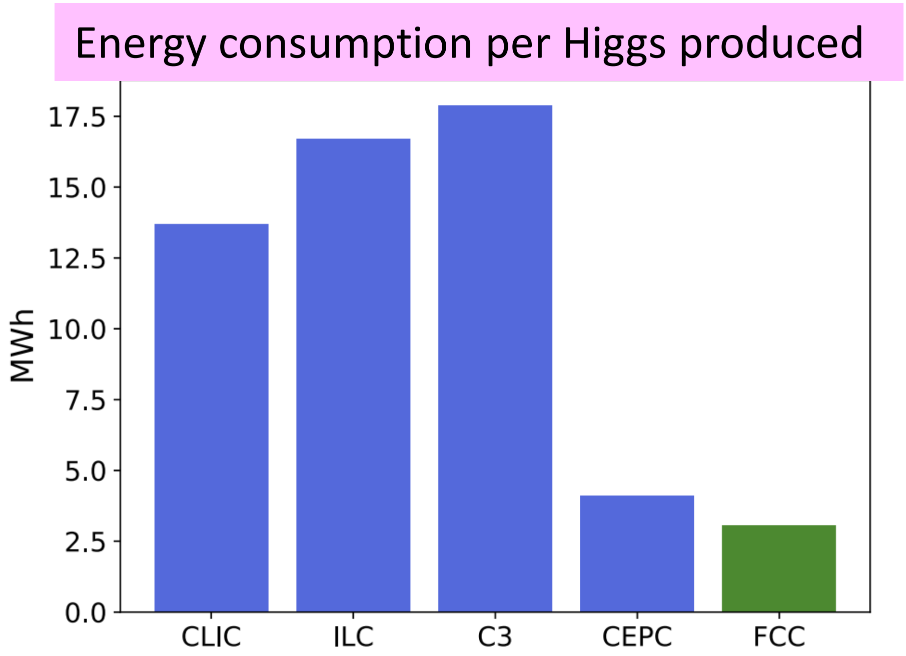
FUTURE CIRCULAR COLLIDER

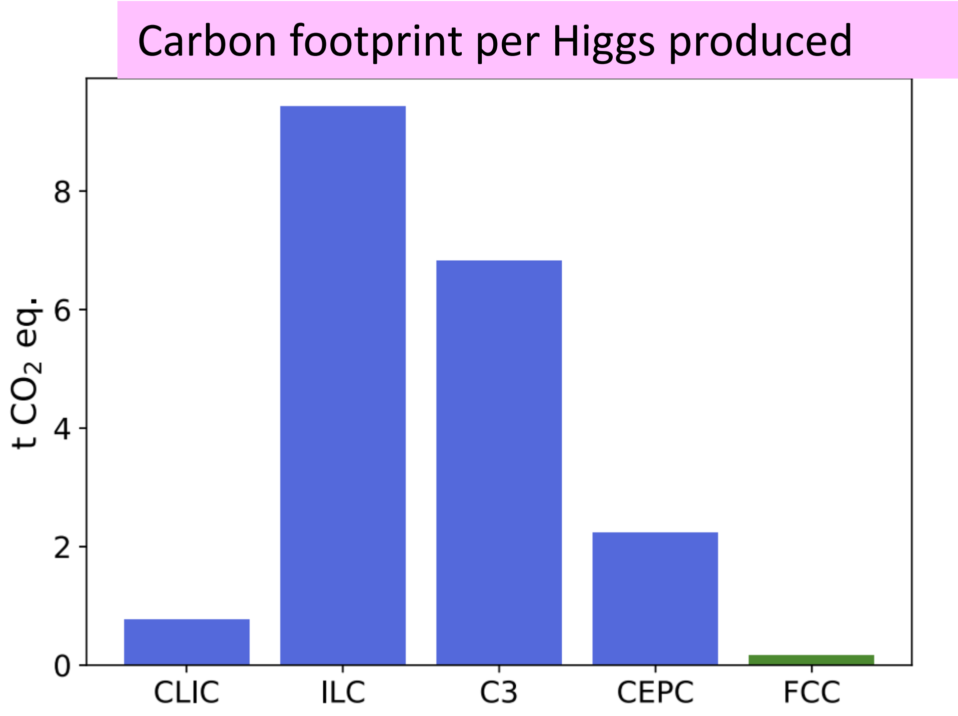
This work is performed under the auspices and with support from the **Swiss Accelerator Research and Technology (CHART)** program (www.chart.ch).

CERN

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
- But we do not stop here! I will present our work to make FCC-ee even more *sustainable* and at the same time increase *performance* by focusing on 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 demand of FCC at all energies

Main consumers: RF, magnets, CV (cooling and ventilation)

2023		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%
PRF EL (MW)	Storage	146	146	146	146
PRFb EL (MW)	Booster	2	2	2	2
Pcryo (MW)	Storage	1.2	11.5	11.5	27.6
Pcryo (MW)	Booster	0.35	0.80	1.50	7.40
Pcv (MW)	all	25	26	28	33
PEL magnets (MW)	Stroage	6	17	39	89
PEL magnets (MW)	Booster	1	3	5	11
Experiments (MW)	Pt A & G	10	10	10	10
Data centers (MW)	Pt A & G	4	4	4	4
General services (MW)		26	26	26	26
Power during beam operation (MW)		**222**	**247**	**273**	**357**

Comparison to the CEPC

Presented on 18/1/2024 from the 2023 TDR:

- Numbers are a bit more pessimistic, resulting in 25% more energy consumed.
- CV does not appear as a separate item
- But the magnet power consumption increases more than a factor 2 at the top!

Going from 30 to 50MW beam power increases efficiency per Higgs produced by 30%!

Table A3.15: Total facility power consumption in Higgs mode (50 MW/beam)

	System for Higgs (50 MW /beam)	Location and power Requirement (MW)						Total (MW)
		Collider	Booster	Linac	BTL	IR	Surface building	
1	RF Power Source	161.60	1.73	14.10				177.43
2	Cryogenic System	9.17	1.77			0.16		11.10
3	Vacuum System	5.40	4.20	0.60				10.20
4	Magnet System	42.16	8.46	2.15	4.89	0.30		57.96
5	Instrumentation	1.30	0.70	0.20				2.20
6	Radiation Protection	0.30		0.10				0.40
7	Control System	1.00	0.60	0.20				1.80
8	Experimental Devices					4.00		4.00
9	Utilities	46.40	3.80	2.50	0.60	1.20		54.50
10	General Services	7.20		0.30	0.20	0.20	12.00	19.90
	Total	274.53	21.26	20.15	5.69	5.86	12.00	339.49

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.

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

Jean-Paul Burnet (CERN) 2022

Arc magnets

- Power consumed at the top is ~76MW for the quadrupole and sextupole system and “only” ~24MW in the dipole system
- Quads and sextupoles reduce the packing factor
- Start from reducing power consumption/footprint to the quad/sext system (this presentation)
- …then move to the dipoles.

FCC-ee: baseline arc magnet system

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.

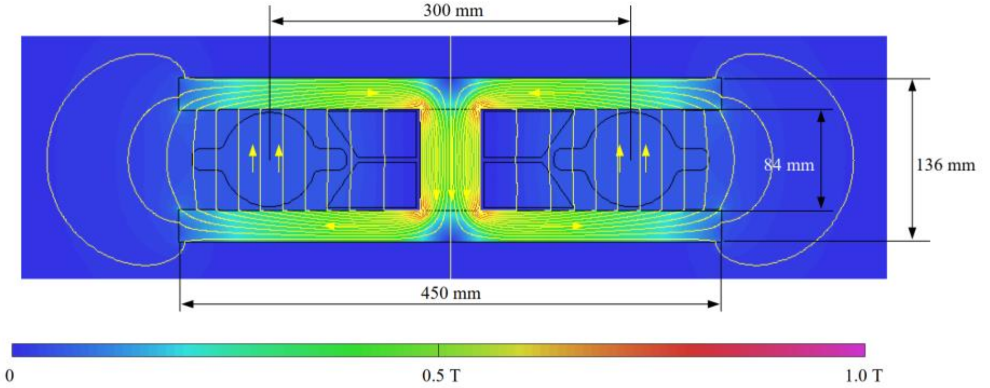


Figure 3.1: Cross-section of the main bending magnet; the flux density corresponds to 57 mT in the gap; the outline of vacuum chambers with side winglets is also shown.

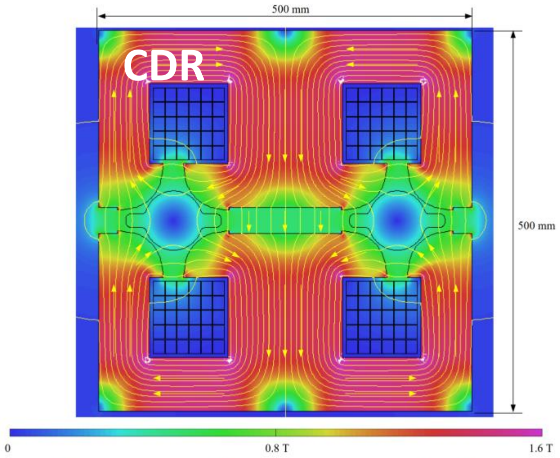


Figure 3.3: Cross-section of the FCC-ee main quadrupole, for a 10 T/m gradient.

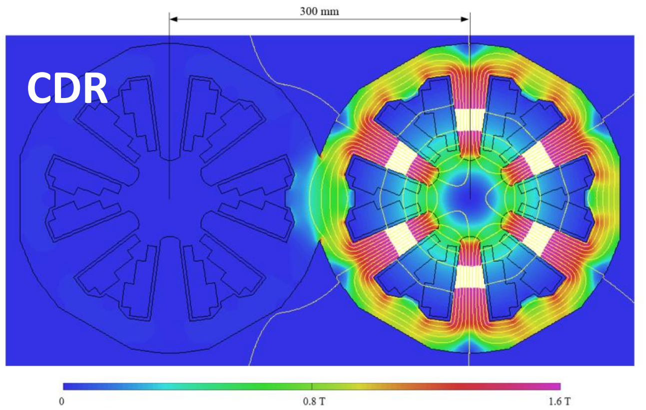


Figure 3.6: Cross-section of the FCC-ee main sextupole magnet. The position of the sextupole for the other beam is outlined on the left.

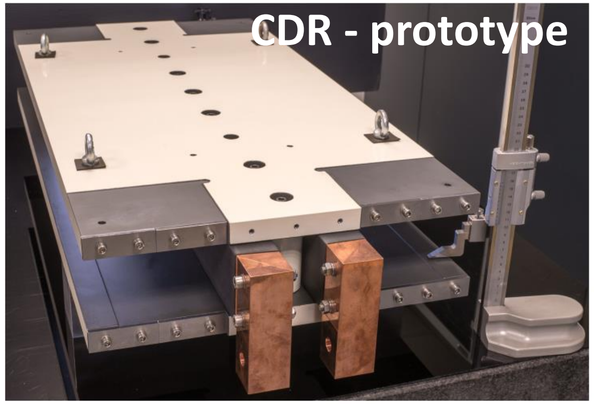


Figure 3.2: One of the ca. 1 m long model dipole magnets manufactured at CERN.

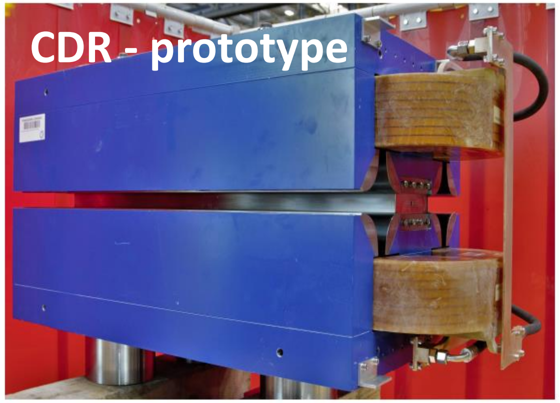


Figure 3.5: Picture of a 1 m long quadrupole prototype magnet for the FCC-ee.

(no prototype exists yet)

Big, heavy quads and sextupoles

FCC-ee: The cold SSS proposal

How can we improve in this design?

1/ Make the magnets superconducting. Then, energy is only spent cooling the magnets (zero Ohmic losses).

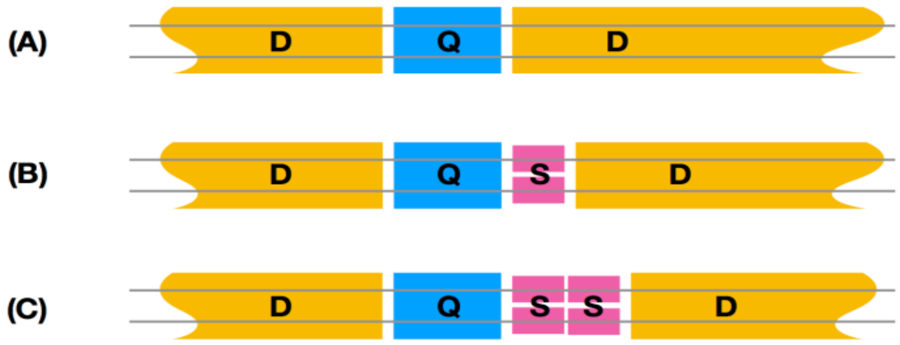
2/ Also, we can “nest” the magnets, so that they take less space

➔ This means that there is more space available for bending, so performance of the accelerator also increases.

➔ **Potential power reduction for these systems: ~90%**

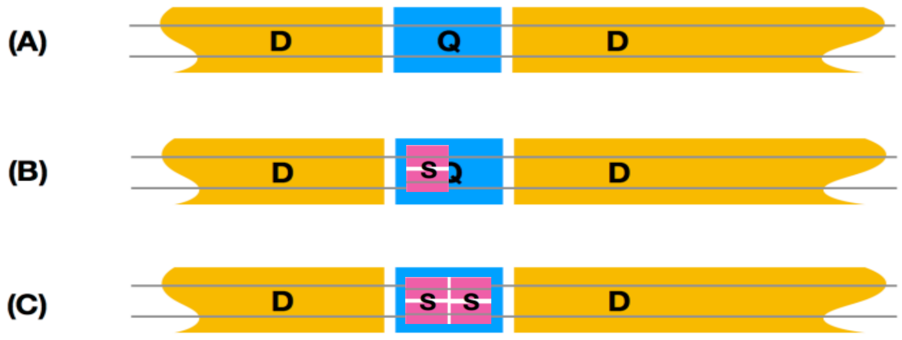
➔ **2900 cryostats, 3.5m long each**

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 alone!
- 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%).

FCCee-HTS4 project

- 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
- Funded by CHART

FCCee-HTS4 are: B. Auchmann, J. Kosse, J. Schmidt, V. Batsari, A. Thabuis, A. Habsburg, M.K.

Swiss Accelerator Research and Technology

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

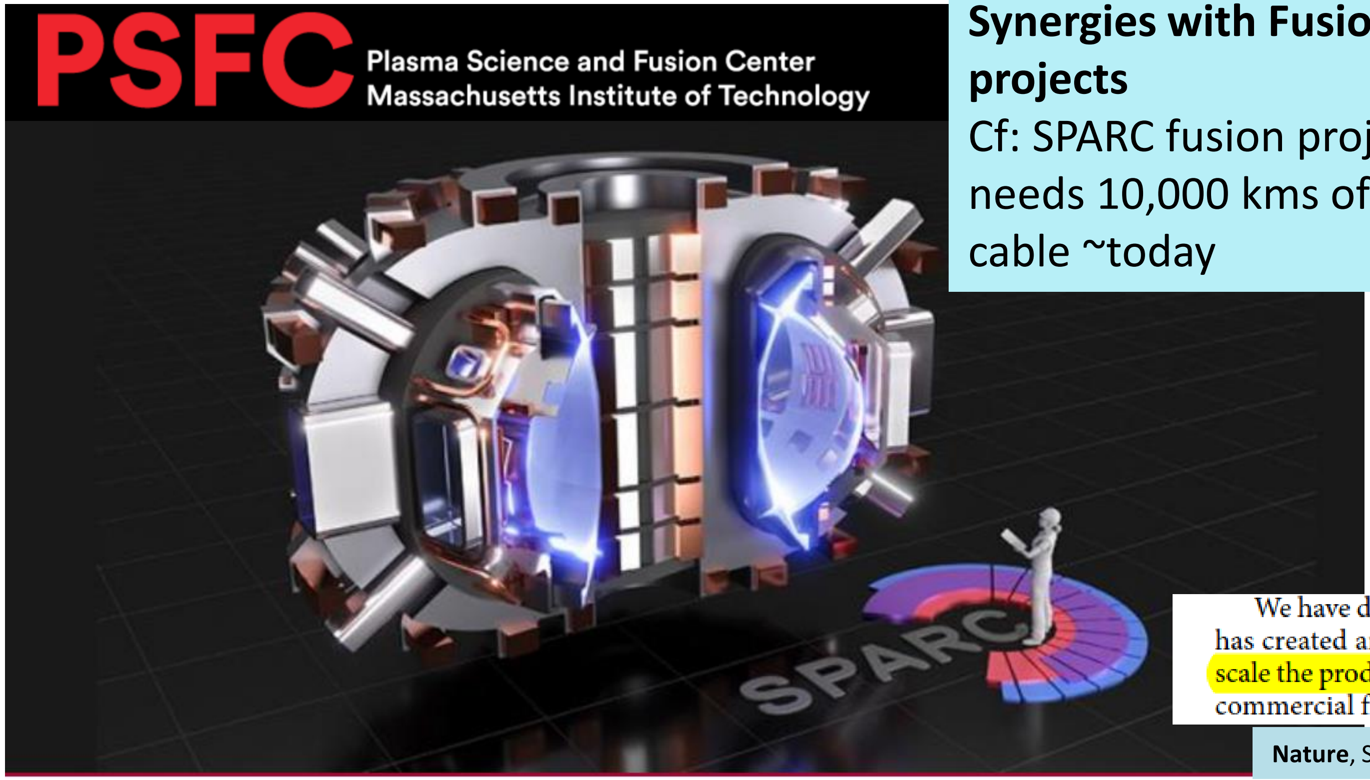
Choice of HTS as conductor (ReBCO tapes)

- ReBCO tapes are quickly becoming the industry standard, used by most Fusion (and other) projects
- The biggest disadvantage is the high cost (around 100$/kA/m).
- This cost is not due to the material cost of the tape (which is ~1$/kA/m)
- Neither is it due to the manufacturing process (which is also ~1$/kA/m)
- Expect for the cost to go down as demand increases

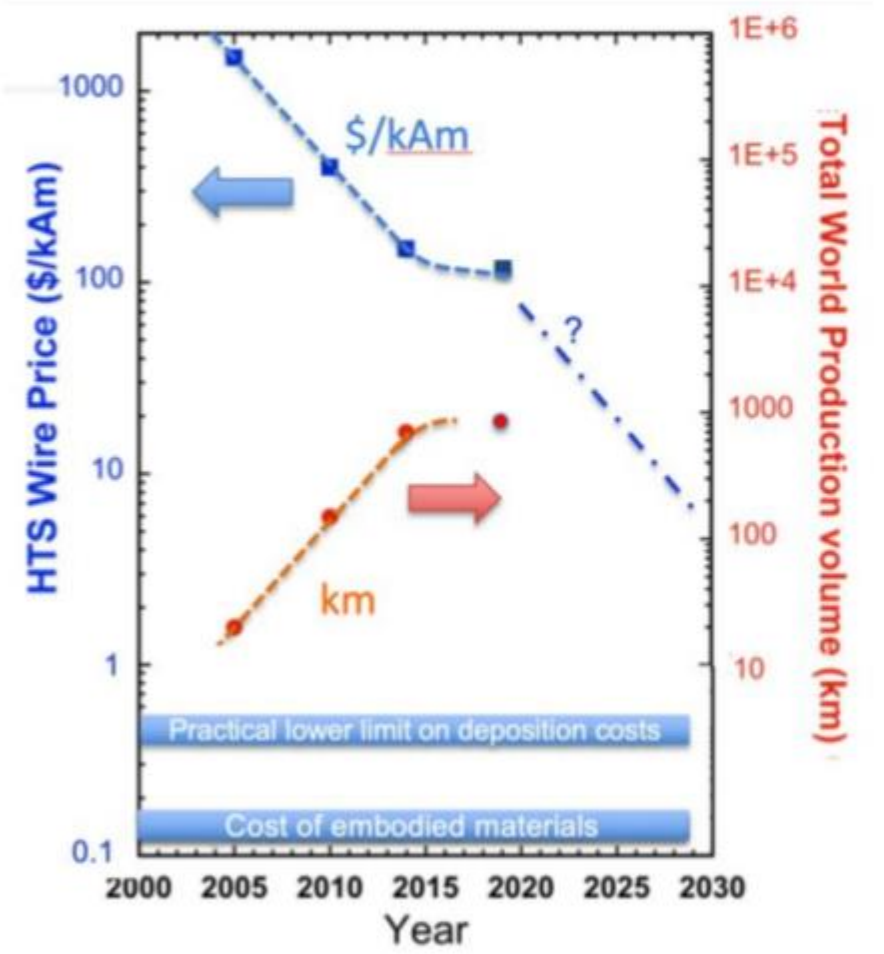
HTS cost

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

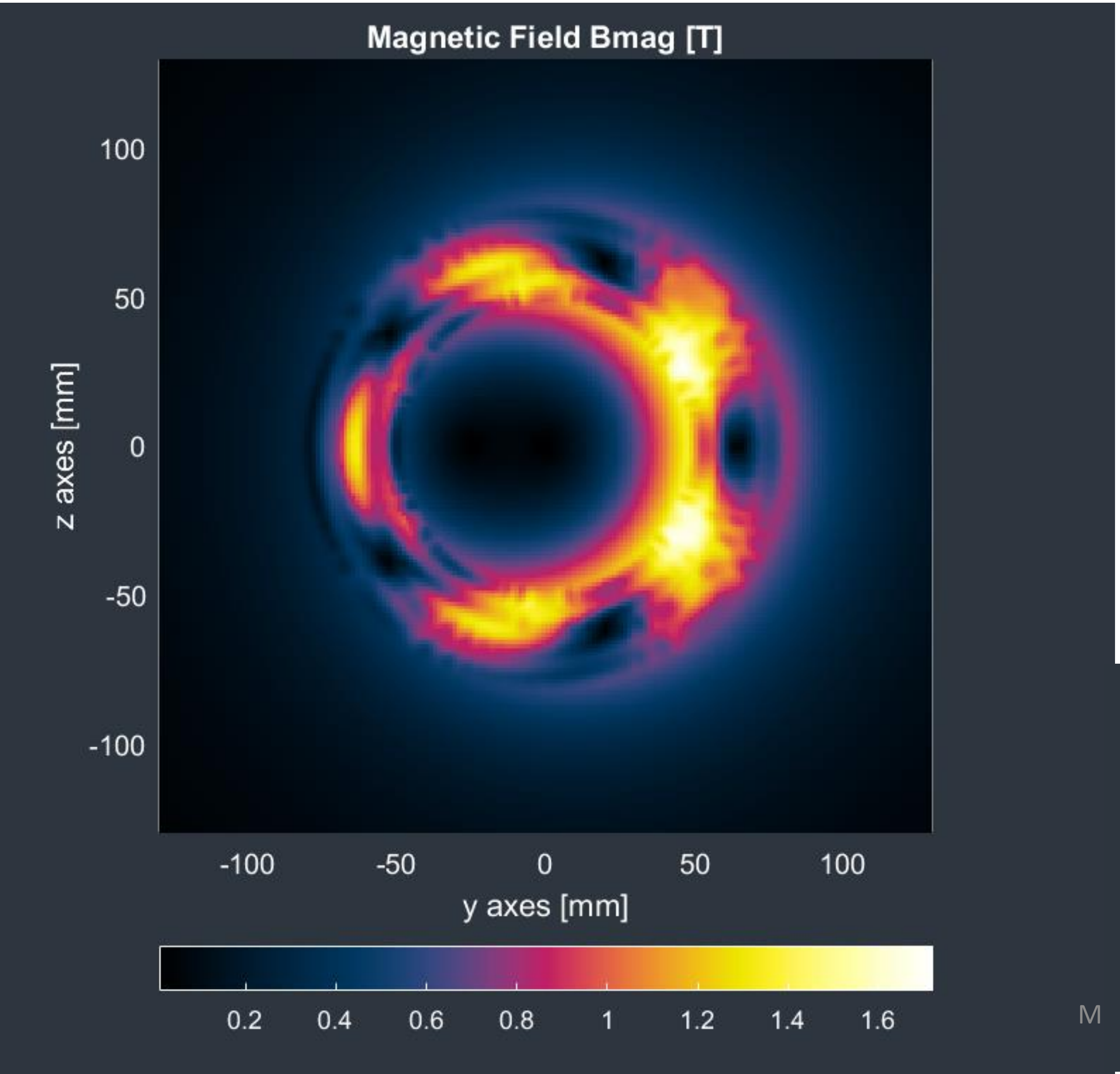


We have developed a product that satisfies specific performance requirements from the fusion industry, which has created an unprecedented demand on HTS wire. When this demand turns into orders, HTS industry will scale the production driving down the wire cost ultimately to tens of dollars per kiloAmpere-metre, 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

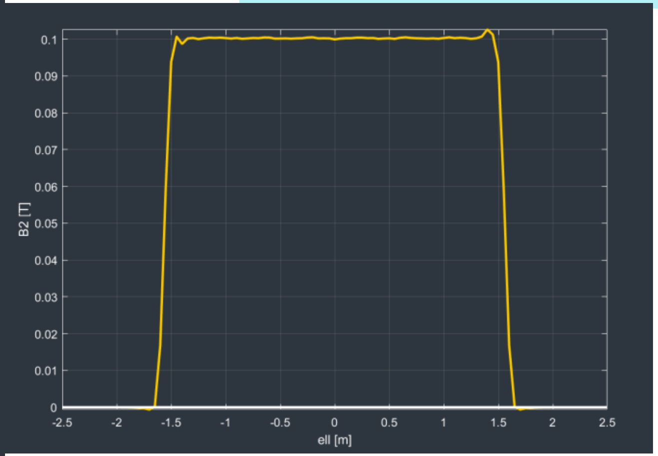
Magnetic analysis

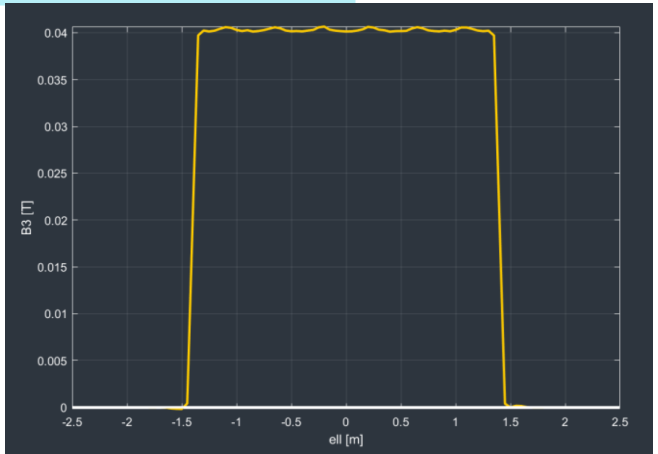
Quad and sextupole at full strength



- 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





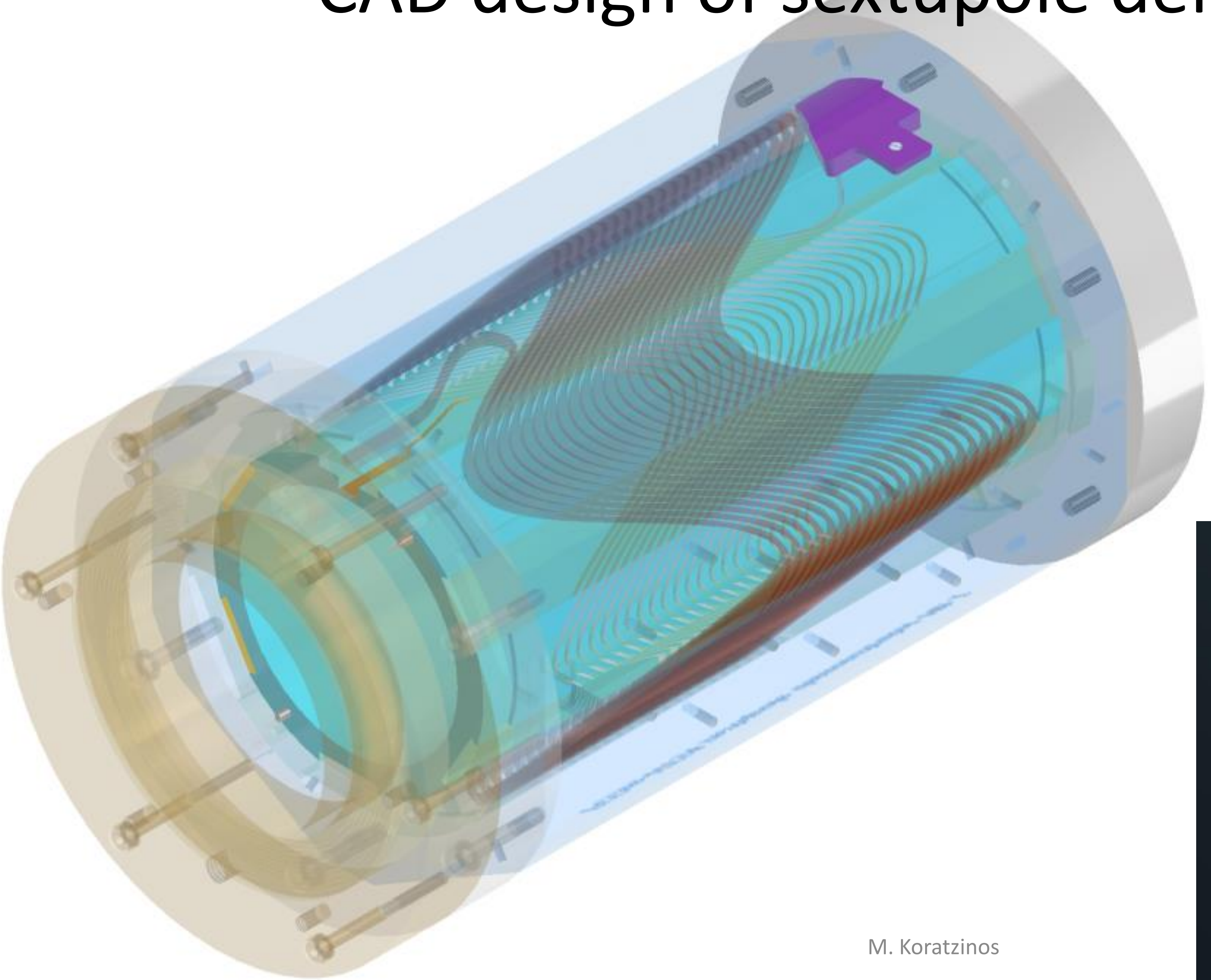
Demonstrator

- 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
  - Manufactured in the CERN main workshop

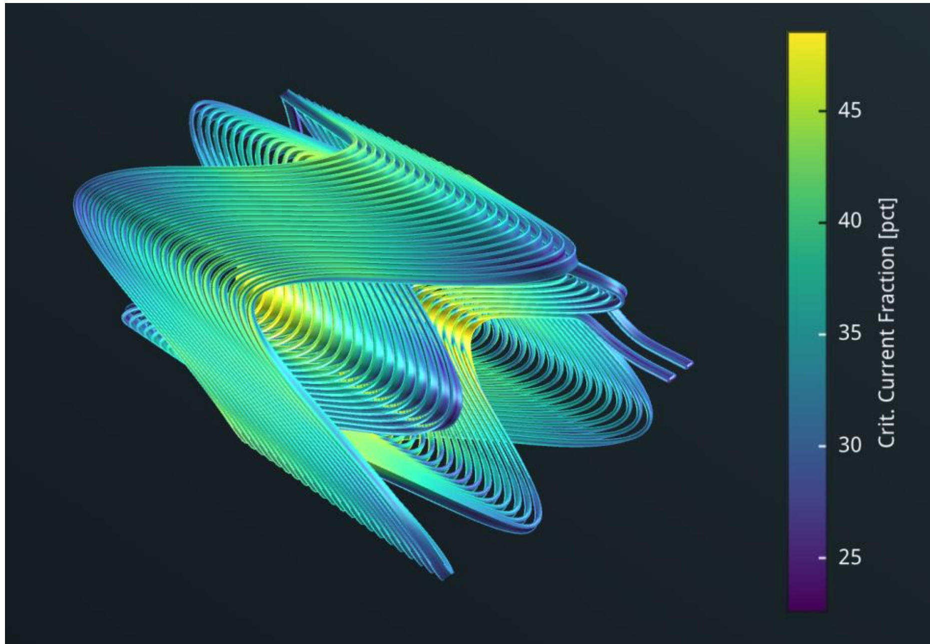
Demonstrator – choice of technology

- 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. Proprietary IP is used

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

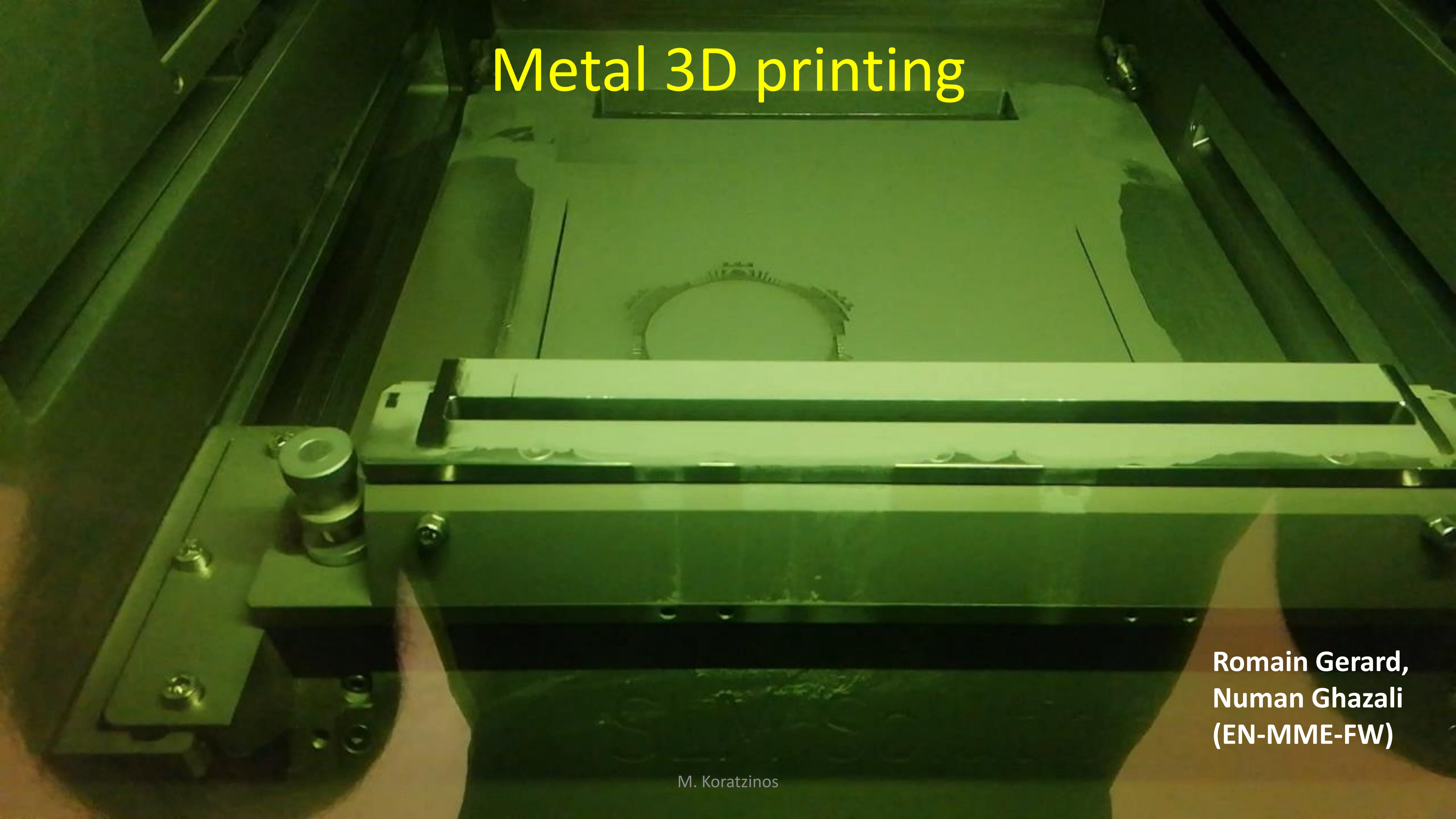


Manufacturing

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

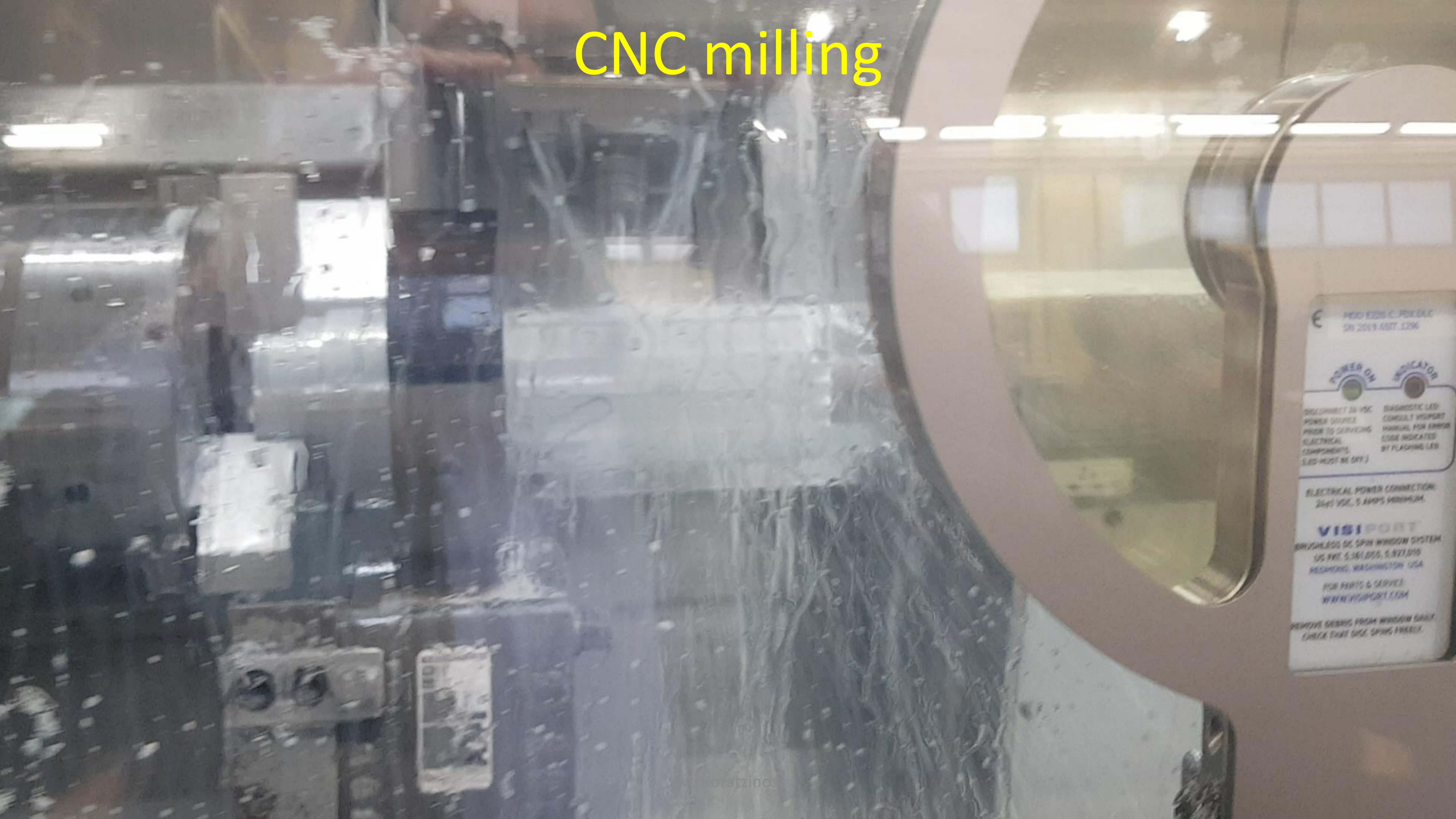
- Additive manufacturing (metal 3D printing)
  - Advantages: any geometry is realizable
  - Disadvantages: surface roughness, a lot of post-processing
- Subtractive manufacturing (CNC machine milling)
  - Advantages: mirror-like finish
  - Disadvantages: not all geometries realizable
  - Our choice for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

Metal 3D printing



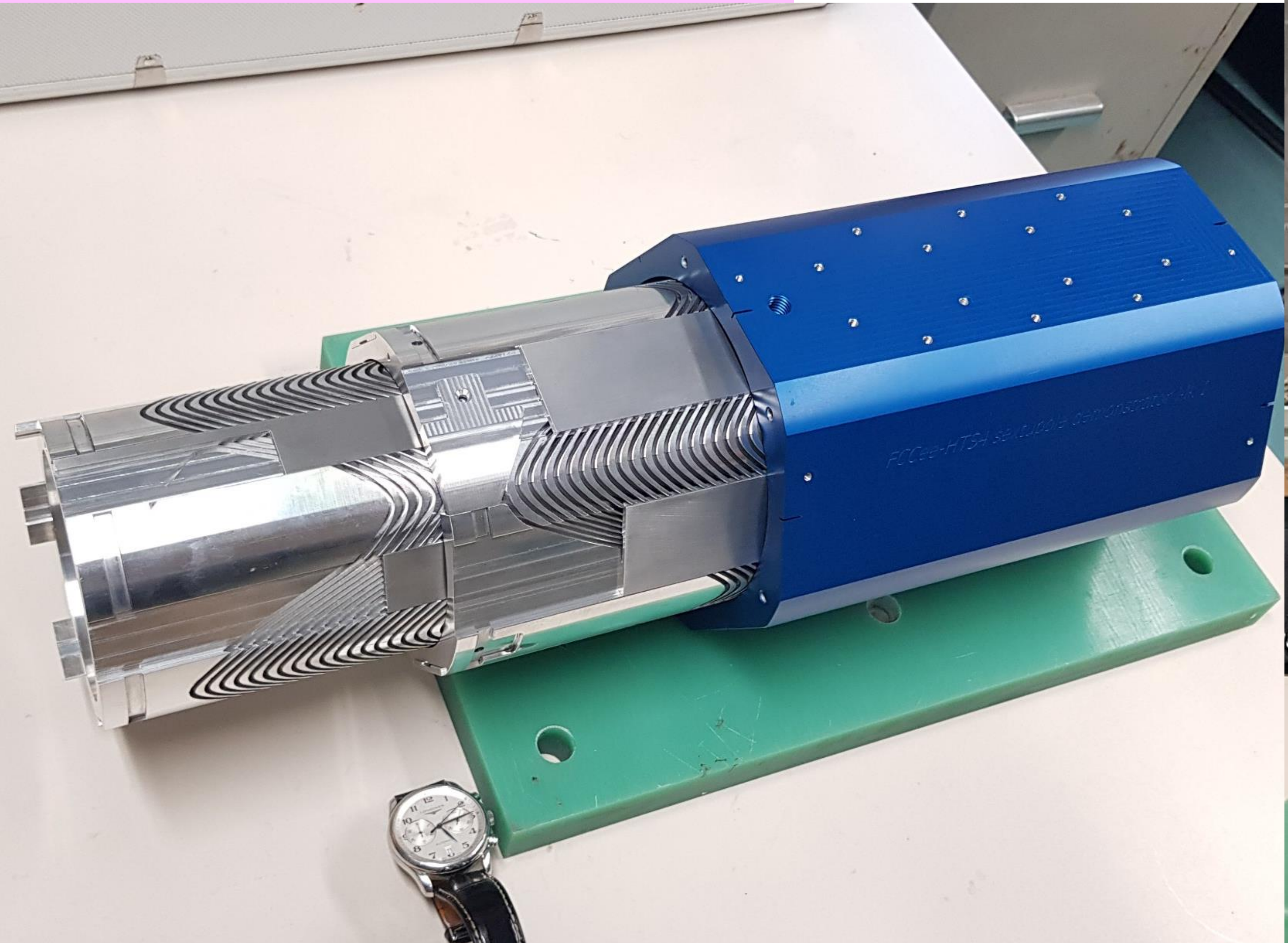
Romain Gerard,
Numan Ghazali
(EN-MME-FW)

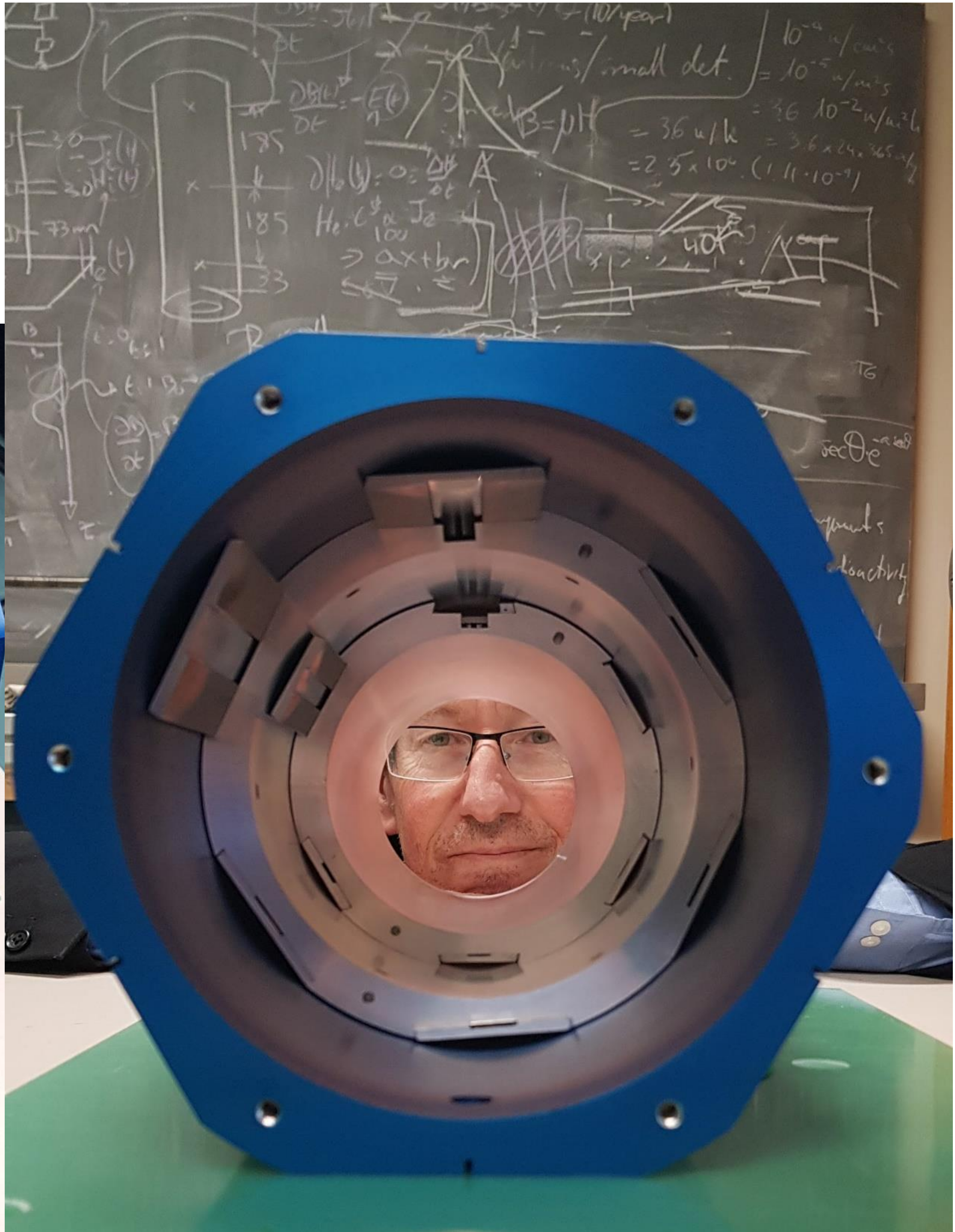
CNC milling



Demonstrator news

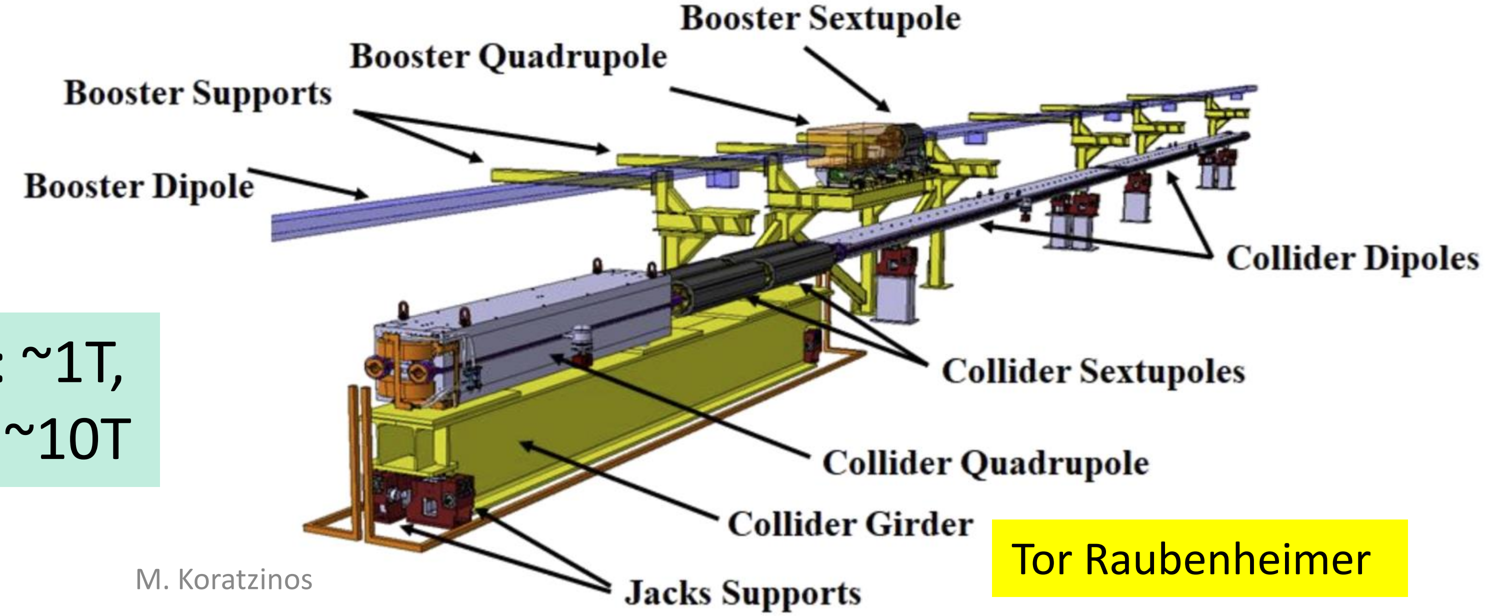
- Formers manufactured
- HTS tape purchased





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 new girder will be a very simple object – an SSS cryostat mechanical support



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

Tor Raubenheimer

HTS4 in MT28

MT28-5POM03-05

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

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†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.

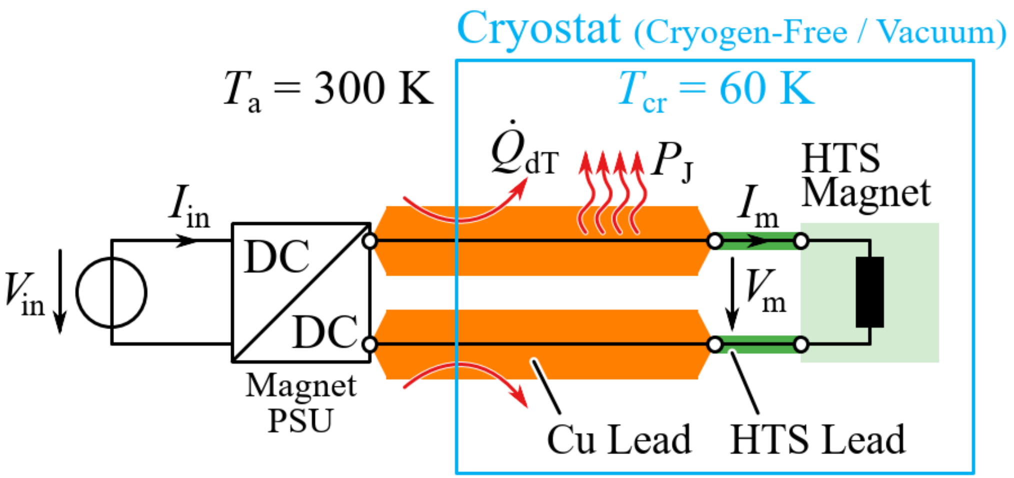
		Working coolers k					
		1	2	3	4	5	6
Installed coolers n	1	0.8335					
	2	0.9998	0.7145				
	3	1.0000	0.9995	0.6253			
	4	1.0000	1.0000	0.9990	0.5558		
	5	1.0000	1.0000	1.0000	0.9983	0.5003	
	6	1.0000	1.0000	1.0000	1.0000	0.9975	0.4548

Our sister project: The idea behind FCCee-CPES

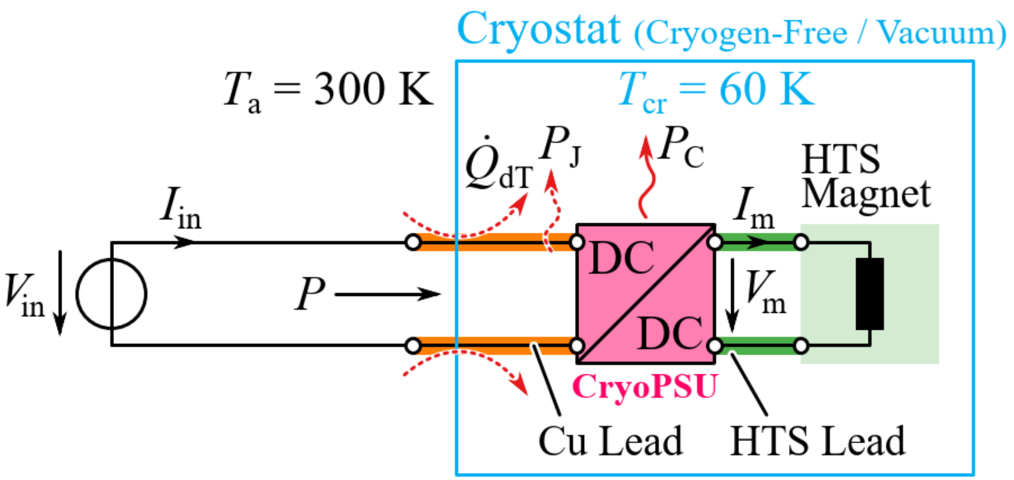
ETH zürich — PES Power Electronic Systems Laboratory

- 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 for the traditional approach.
- 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:



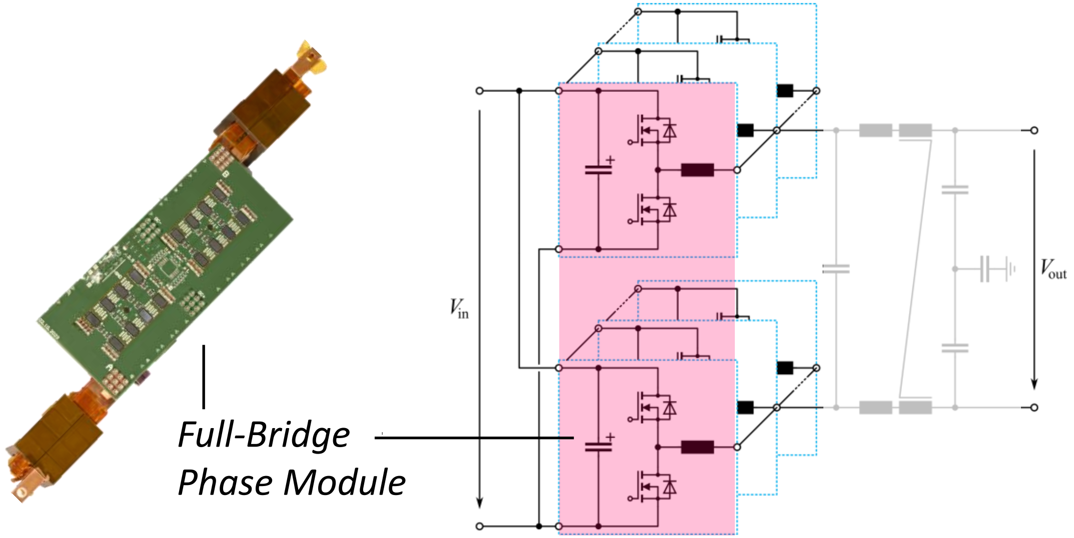
FCCee CPES (PES, ETHZ) Jonas Huber, Danqing Cao, Daifei Zhang

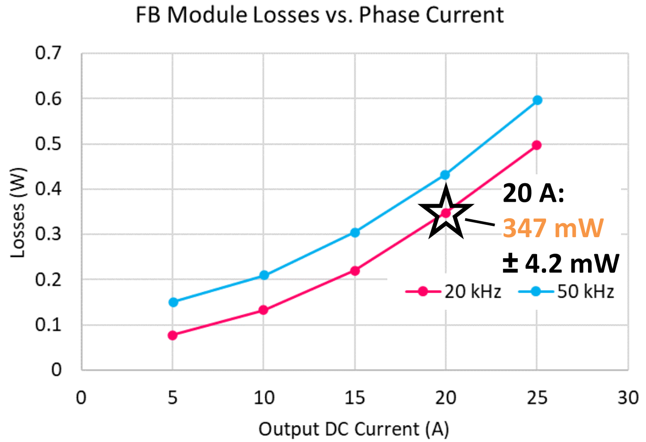
First prototype results

Very encouraging first prototype measurements: 4.5W of losses in a 250A system. Cf: the traditional approach has losses of 22.5W. This is a reduction of a factor 5

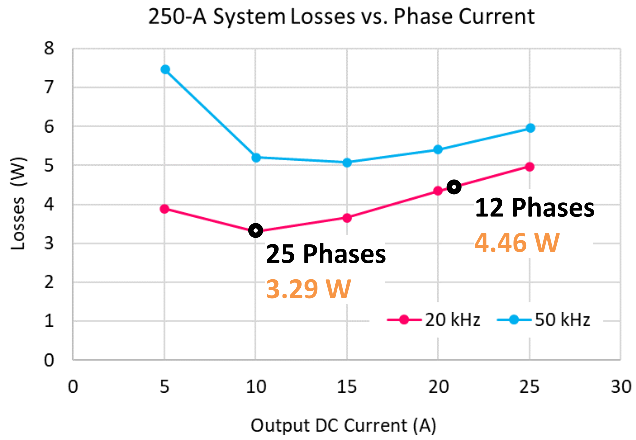
Feasibility of Cryogenic 250-A HTS Magnet PSU

- **Full-bridge phase module measured in LN_2 @ 77 K**
  - Including gate driver and phase inductor losses, 1 V dc input
  - 4 parallel EPC 2302 GaN transistors (100 V, 1.8 mΩ @ RT) per position
  - Optimizations of PCB losses, etc. ongoing





- **250-A system: 4.46 W ± 0.05 W**
  - Estimated based on 12 phase modules @ 21 A each
  - 6 W loss budget leaves 1.5 W for residual leak-in losses, EMI filter, and control electronics
  - Benchmark: 22 W leak-in losses for external (warm) PSU and 60 K cryostat temp.



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 using HTS ReBCO conductors.
- 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 – first results encouraging.
- These projects will increase the sustainability credentials of FCC-ee and increase its performance and relevance to society.

THANK YOU