# The FCCee-HTS4 project

**M. Koratzinos**

**FCC week, San Francisco**

**11/06/2024**

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

# Aim of this presentation and contents

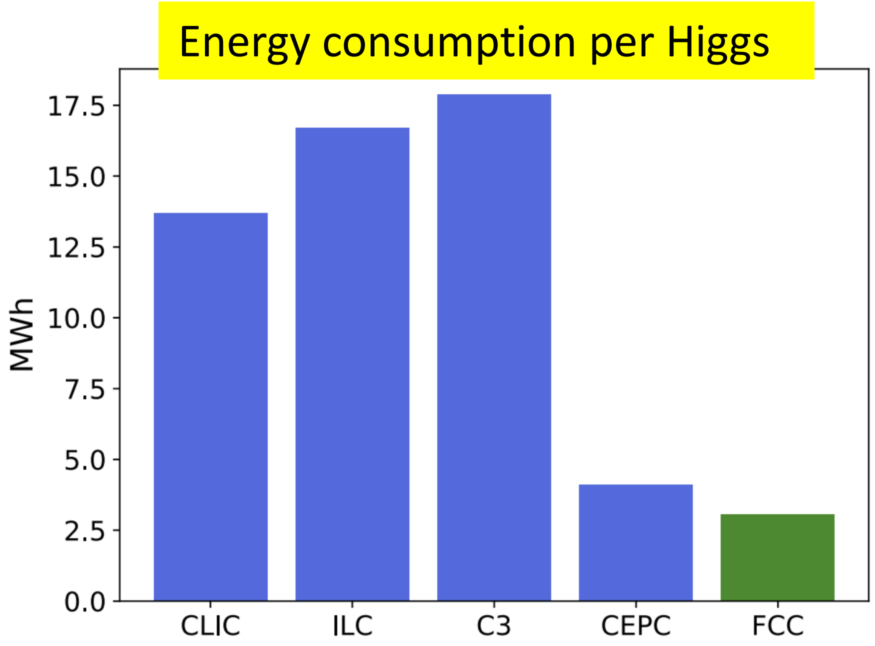
- HTS4 is a new project within FCC that aims at rather drastic changes to the baseline collider arc design.
- It has a number of important advantages, but also quite a few challenges.
- It is not part of the feasibility study
- I will introduce different aspects of the project including:
  - The general idea
  - HTS suitability and cost
  - Choice of aperture, winglet, impedance
  - Upgrade to a triple-nested system
  - Optics advantages
  - Conduction cooling
  - cryostat, girder, integration
  - Radiation environment
  - Demonstrators
  - Arc dipoles
  - FCCee-CPES

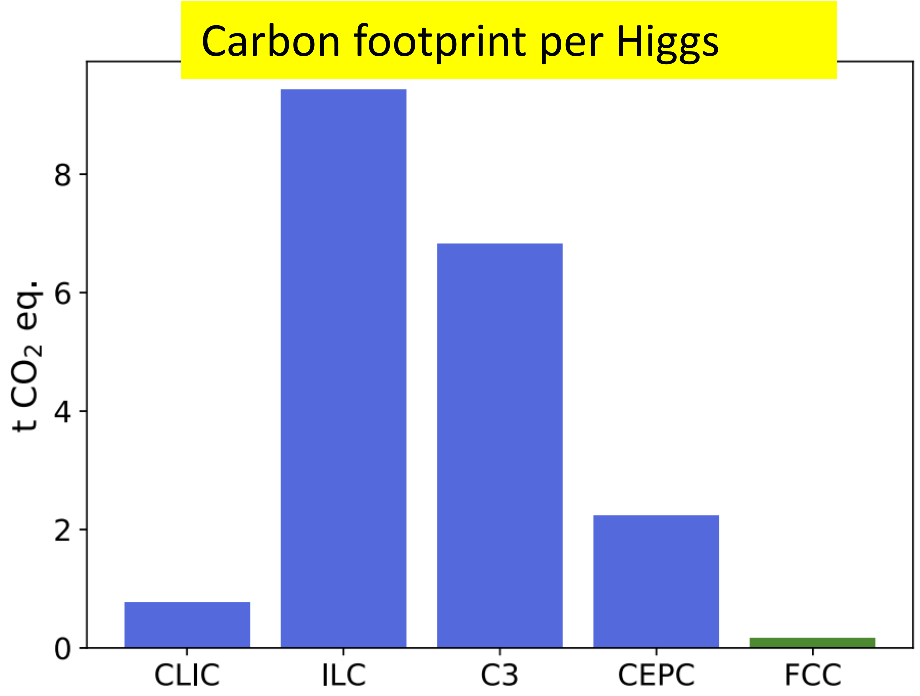
# Why?

- FCC is the best accelerator on the market today by a large margin
- All innovation in FCC-ee is in pushing optics and, in general, machine parameters to their 21st-century limit and, therefore, delivers unprecedented luminosity for physics.
- However, it uses old (and trusted) technology from the 20th century without advancing it considerably.
- Wouldn't it be nice to also push technology to its 21st century limits in certain areas (as long as we do not pay more?)

# Why? – sustainability

- 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

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

- At top energy ohmic losses are 89MW (2023) for the main arc magnet systems.
- The power share of CV is another ~14MW
- Total is **~100MW**
- Contribution of quads and sextupoles dominate this power (~75%)
- **A high temperature superconducting magnet system is projected to have a consumption of only ~10% of that**

F. Zimmermann yesterday:

J.-P. Burnet, J. Bauche, for GHC

| **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 |

| **nd ventilation** | | Z | W | H | TT |
|---|---|---|---|---|---|
| rgy (GeV) | | 45.6 | 80 | 120 | 182.5 |
| | all | 33 | 34 | 36 | 40.2 |

# A possibility emerges…

- Replace all arc quadrupoles and sextupoles, which in the baseline design are warm, with superconducting ones using HTS technology. Power everything individually.
- Immediate advantages:
  - Quads and sextupoles can be nested, resulting in an increased packing factor
  - Ohmic losses are zero and replaced by cryo system power consumption
  - Correctors will also be nested
  - A much lighter system (smaller girder, etc.)
  - No use of alcoves (for powering or cooling)
  - No need for increased intra-beam distance
  - No need for smaller vacuum chamber
  - A series of other advantages related to optics

Disadvantages:

- Cryogenic technology on a large scale - reliability
- HTS conductor is expensive
- Current ideas call for cryocoolers in the tunnel – radiation dose needs to be minimized.
- There are important integration issues: resistive wall impedance?

# The HTS4 project

- Financed under the auspices of CHART
- Started September 2022 for three years
- Collaboration between PSI and CERN
- HTS4 are:
  - B. Auchmann
  - J. Kosse
  - J. Schmidt
  - A. Thabuis
  - V. Batsari
  - O. Kuhlmann
  - A. Habsburg
  - M.K.

CHART
Swiss Accelerator Research and Technology

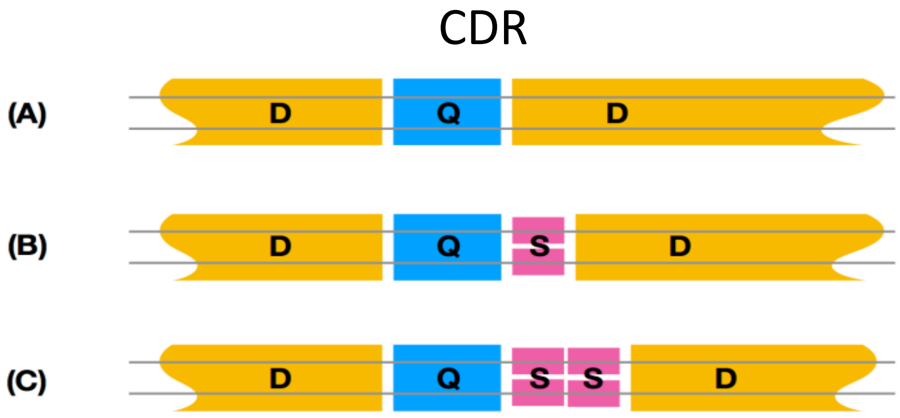
# SSS main parameters

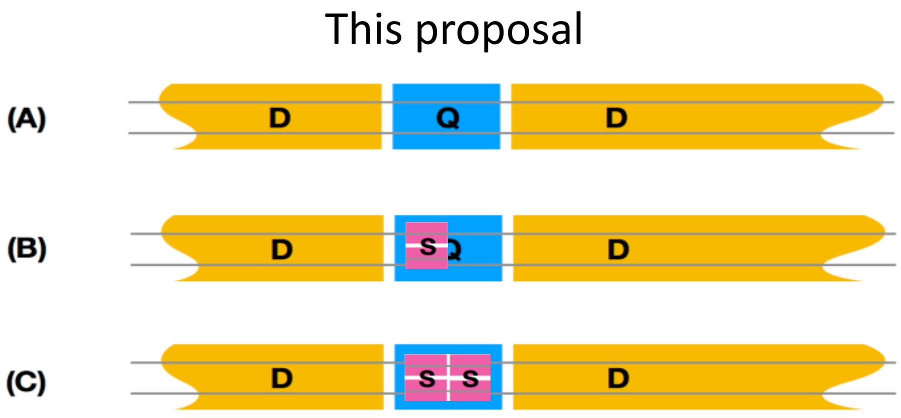
The latest optics design layout has the following specifications:

- 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

# PACKING FACTOR

# Improvement in packing factor




Half cell length: 27.9 m

- Three families of dipoles
- By nesting sextupoles and quads, only a single dipole size will be needed

Increase in packing factor: 6.8%

Warning: numbers are changing

| Lengths (m) | | | No. units | Lengths (m) | | |
|---|---|---|---|---|---|---|
| **CDR** | | | | **This proposal** | | |
| Dipole | quad | sext | units | dipole | quad | sext |
| **21.2** | **3.2** | **3.2** | **1152** | **24.4** | **3.2** | **-** |
| **22.7** | **3.2** | **1.5** | **492** | **24.4** | **3.2** | **-** |
| **24.4** | **3.2** | **0** | **1256** | **24.4** | **3.2** | **-** |
| **Tot. dipole length: 66237m** | | | | **Total dipole length: 70760m** | | |

# Advantages in packing factor, integration

- In this proposal, only one family of dipoles
- 7% increase in packing factor means:
  - ~7% increase in the number of bunches at all energies. This in turn means **~7% increase in luminosity (or one less year of running for the same physics potential)**

  **AND**

  - ~7% decrease of the energy loss per turn, so less RF voltage is needed at top energies. **This means ~7% less 800MHz RF cavities**
- If we also nest dipoles in the SSS the packing factor gain is 17% (see further)

# UPGRADE TO A TRIPLE-NESTED SYSTEM

# Possible upgrade – dipole component

Since we already have a quad-sextupole nested system, we can introduce also a dipole component

- Packing factor approaching the theoretical maximum
- Fervour of activity – three IPAC24 papers
- (this cannot be done easily in the baseline approach)

15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR10

**FIRST FCC-ee LATTICE DESIGNS WITH NESTED MAGNETS**

C. García-Jaimes*, T. Pieloni, L. van Riesen-Haupt, M. Seidel, EPFL-LPAP, Lausanne, Switzerland
R. Tomás, CERN, Geneva, Switzerland

15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR11

**PARAMETER SPACE FOR THE MAGNETIC DESIGN OF NESTED MAGNETS IN THE FCC-ee ARC CELL**

C. García-Jaimes*, T. Pieloni, L. van Riesen-Haupt, M. Seidel, EPFL-LPAP, Lausanne, Switzerland
J. Kosse, B. Auchmann, PSI, Villigen, Switzerland
R. Tomás, A. Thabuis, M. Koratzinos, CERN, Geneva, Switzerland

15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR12

**FIRST COMPARISON STUDIES IN DYNAMIC APERTURE FOR NESTED MAGNETS AND BASELINE LATTICE IN THE FCC-ee**

C. García-Jaimes*, T. Pieloni, L. van Riesen-Haupt, M. Seidel, EPFL-LPAP, Lausanne, Switzerland
R. Tomás, CERN, Geneva, Switzerland

- 17% increase in packing factor.
- This is huge and merits careful study

# OPTICS ADVANTAGES

# Optics advantages

A series of important optics advantages, all potentially increasing performance or decreasing risk:

- Possibility of adjacent quads are QD/QD and QF/QF (important if QF/QD lengths are different like in P. Raimondi's scheme
- Alignment problems are easier
- Magnetic axis shift is small (est. 3um)
- Correctors can be also nested (good for packing factor)
- Can easily correct the b3 components of the dipoles (which have very strict tolerances)
- Weight of the system is different (much lighter) so design of the girder is different and easier

F. Zimmermann yesterday:

LCC abandons twin quadrupoles

# Field quality

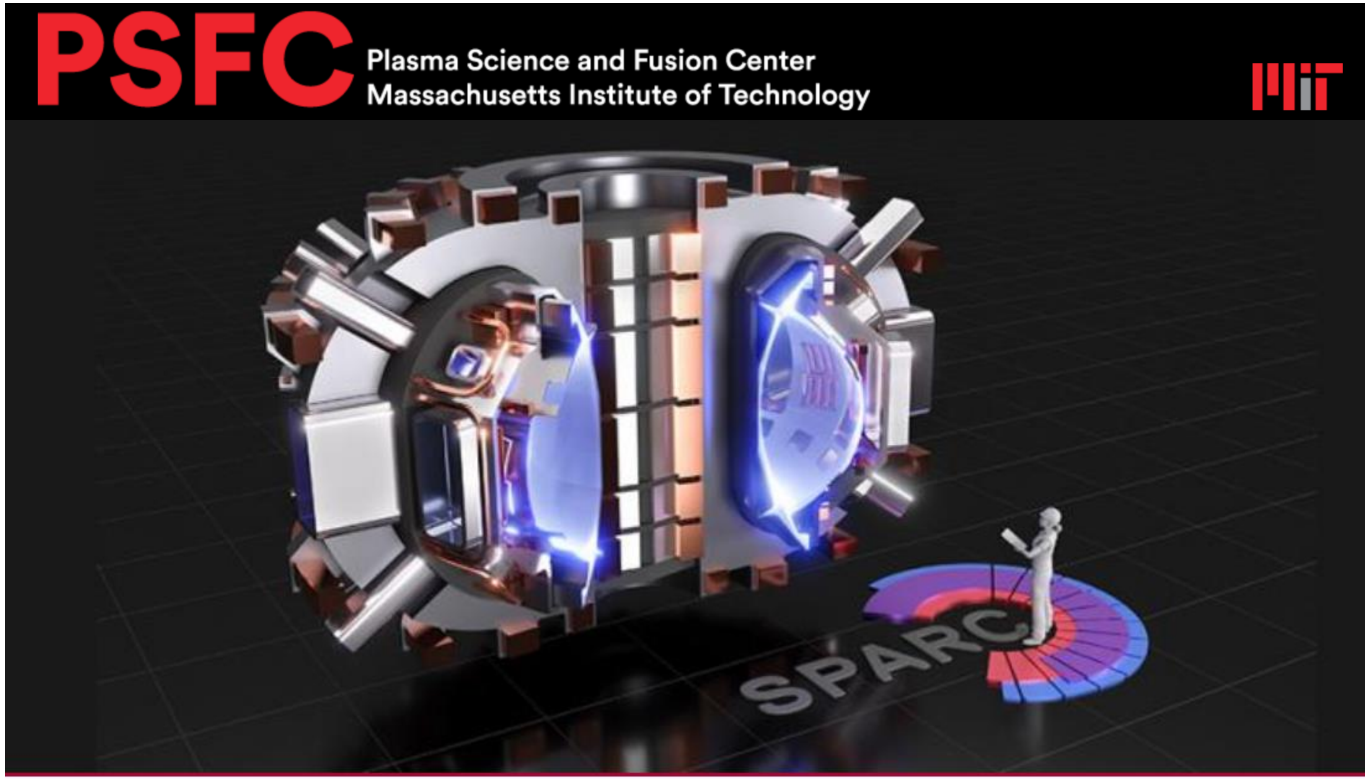
- Generally speaking, since S/C magnets do not rely on iron for field shaping, it is easier to get good field quality and linearity.
- A potential problem might be persistent currents in the HTS
- The HTS4 project studies both CCT and more conventional CT magnets.
- CCT field quality is expected to be below 1 unit of $10^4$ everywhere.

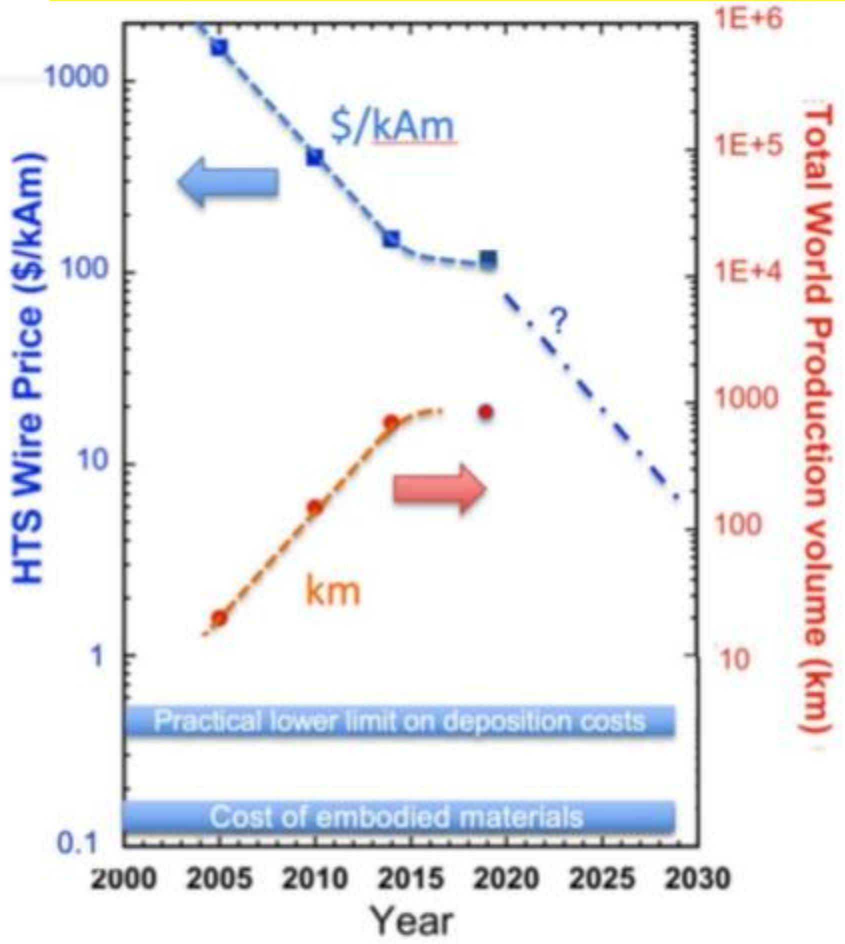
# HTS SUITABILITY, COST

# 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.



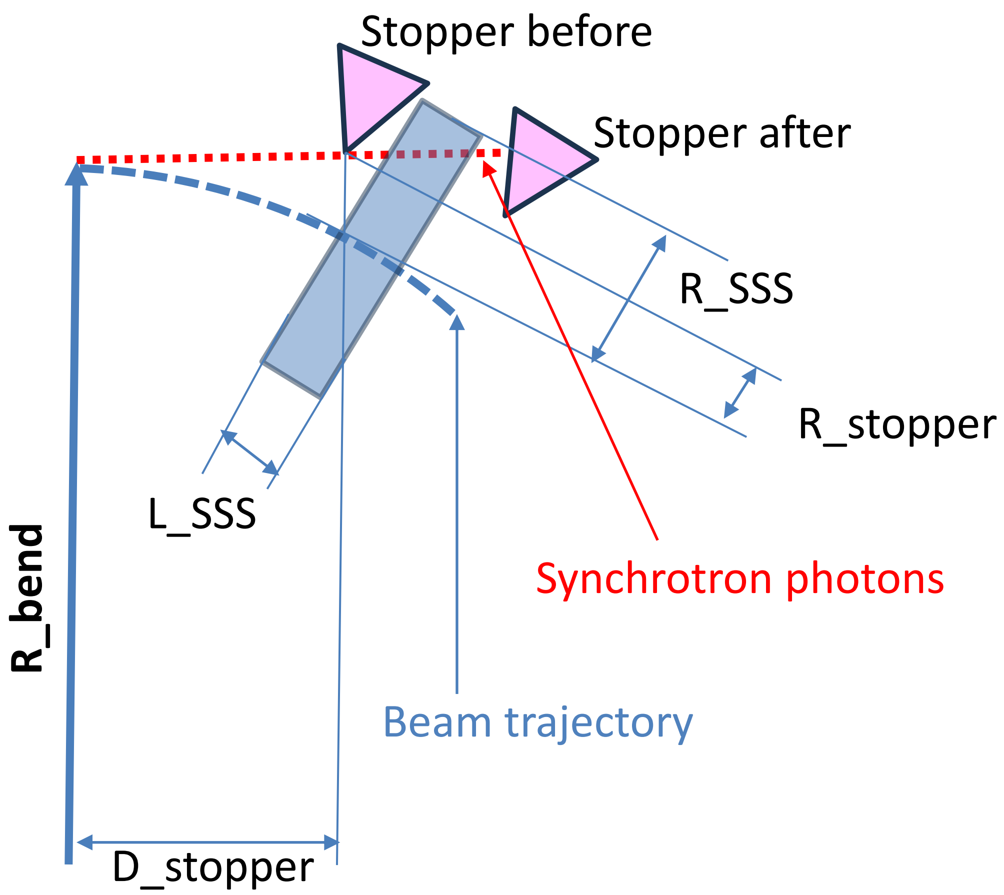




**Synergies with Fusion projects**
Cf: SPARC fusion project needs 10,000 kms of HTS cable ~today
FCC would need ~20,000kms

# CHOICE OF APERTURE, WIGNLET, IMPEDANCE

# 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 **84mm** for the SSS magnets
- Current design is **90mm**

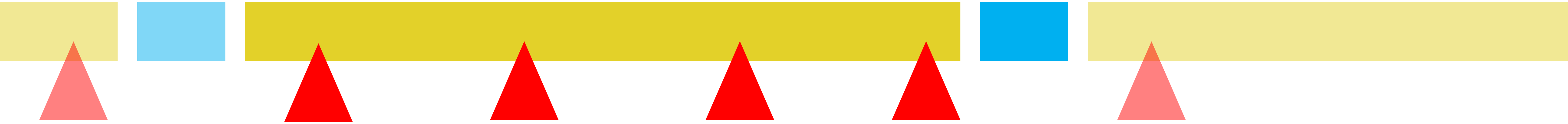



| R_bend (m) | beam pipe diam (m) | R_stopper (m) | D_stopper (m) | L_SSS (m) | R_SSS (m) |
|---|---|---|---|---|---|
| 10021 | 0.070 | 0.034 | 26.485 | 4.0 | **0.045** |
| 10021 | 0.060 | 0.029 | 24.521 | 4.0 | **0.039** |

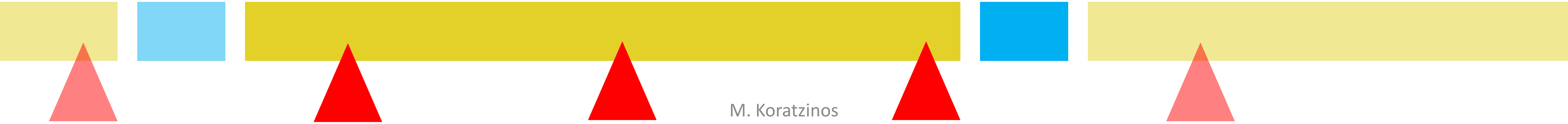
# Number of stoppers per FODO cell

- The half cell length of the new optics design is **26.1m**
- The length of nested quad-sextupole is ~3.2m
- The gap between dipole and SSS is ~0.3m
- Dipole length is therefore ~22.6m and constant
- Choice of three or four stoppers per dipole

First possibility: stopper at 3.5m, 10.5m, 17.5m, 22.5m. Distance between stoppers 7m,5m



Second possibility: stopper at 4m, 13m, 22m. Distance between stoppers 9m, 8m



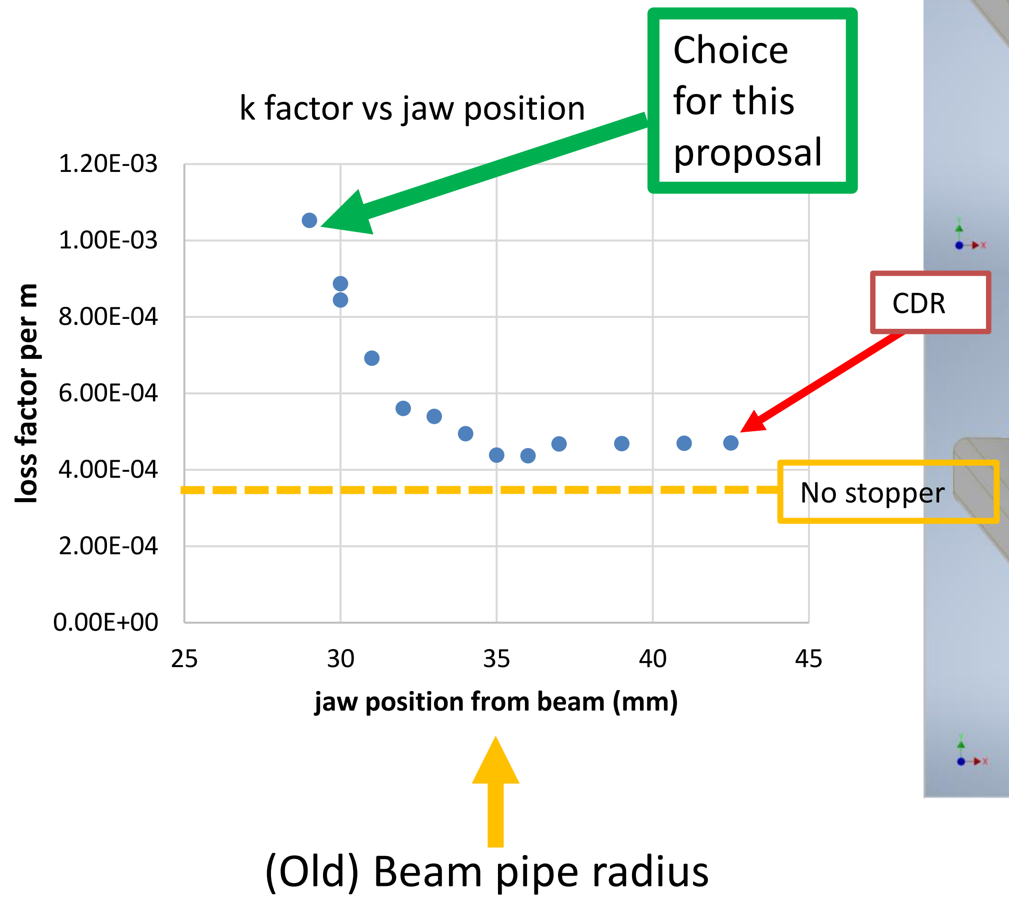
# Photon stoppers, winglet, impedance

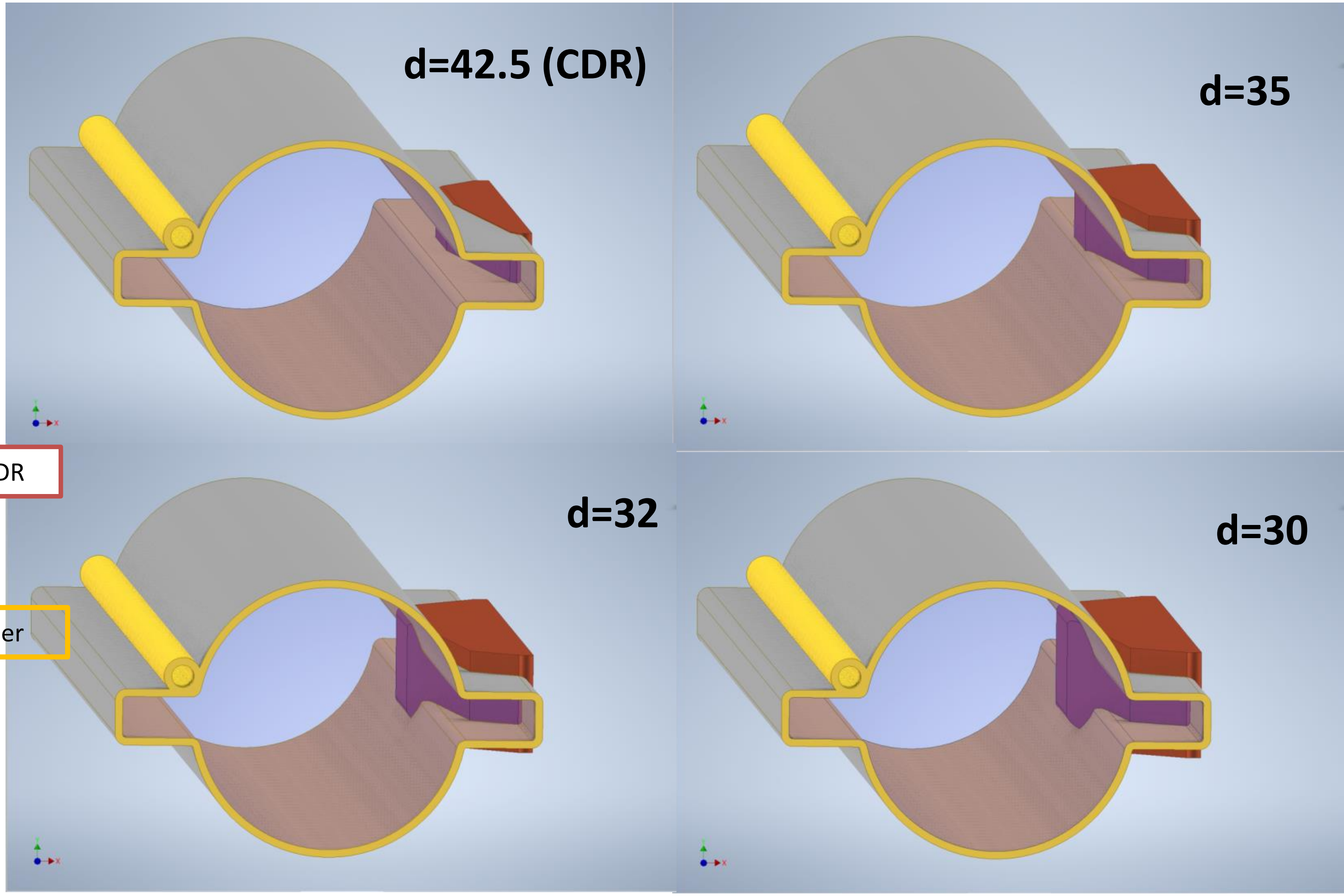
- How much would this idea increase the resistive wall impedance budget (and, therefore, wasted power) of the machine?
- Since space is at a premium, this idea accommodates much smaller winglets than the CDR design (110mm to 86mm) for the entire length of the SSS (3.5m)
- It also calls for photon stoppers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

# Variable stopper sizes

We tried different stopper protrusions to see their effect on impedance

**d** is distance from the beam:

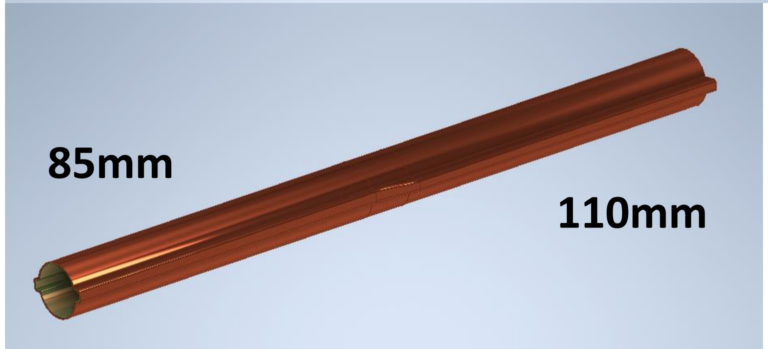


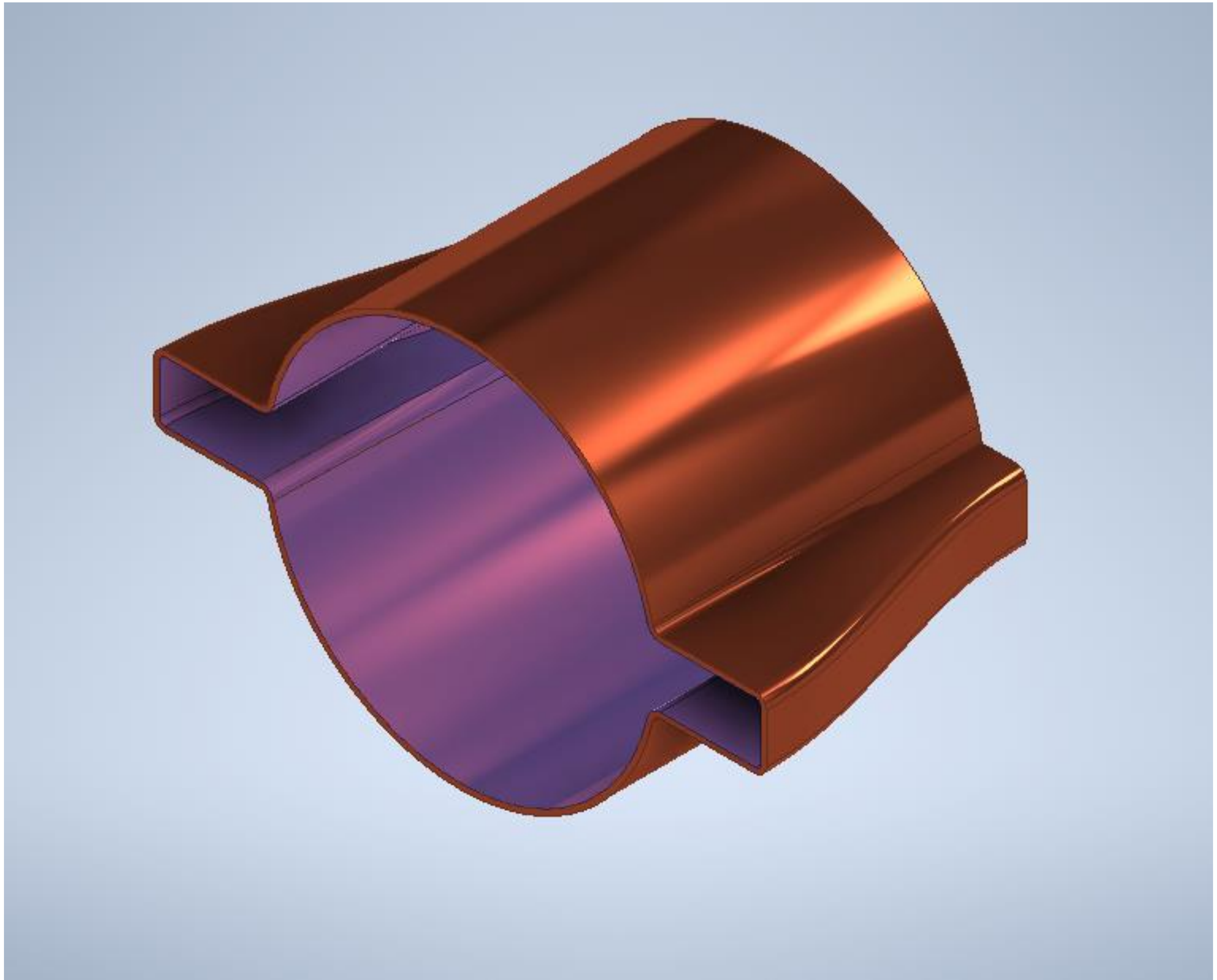




N. Nikolopoulos

# Transitions

A smooth transition between a 110mm winglet to a 86mm winglet was developed and its contribution to resistive wall impedance calculated and found acceptable

# CONDUCTION COOLING

# 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?
- **A centralized system should also be studied**

Cryocooler example: a popular choice: SHI RD-125

RD-125 Cooling capacity:
- 33W@77K,
- 12W@40K

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

## RD-125D 77K Cryocooler Series

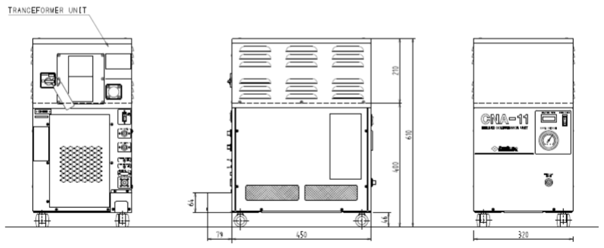
### Performance Specifications

| 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.*



COMPRESSOR UNIT

Size of unit is 320 X 450 X 610 mm

Power consumption of 2900 units: **4.1MW** power or 20GWh per year

# Reliability

MT28-5POM03-05

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

J. Kosse*, M. Koratzinos*†, B. Auchmann*†
*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)

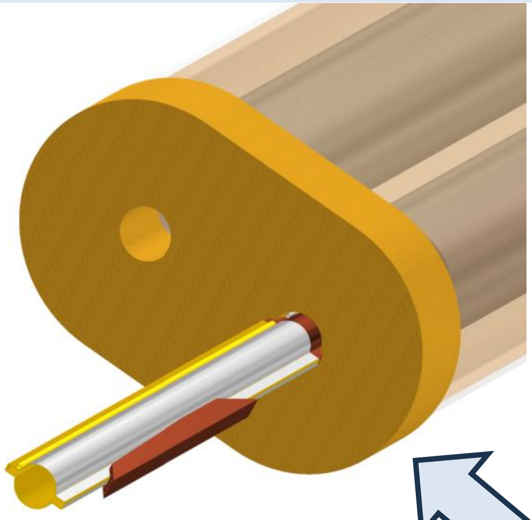
TABLE III
HTS4 TOTAL SYSTEM AVAILABILITY FOR 1-YEAR OPERATING PERIOD, WITH $n$ COOLERS PER SSS OF WHICH AT LEAST $k$ NEED TO BE OPERATIONAL. COLORS INDICATE CONFIGURATIONS WITH HIGH (GREEN), QUESTIONABLE (ORANGE) AND LOW (RED) RELIABILITY. MTTF OF EACH COOLER IS $10^7$ HOURS, AND MTTR IS 1 MONTH.

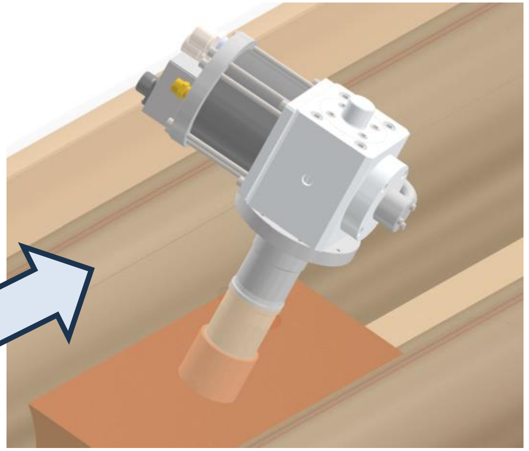
| Installed coolers $n$ | Working coolers $k$: 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 0.8335 | | | | | |
| 2 | 0.9998 | 0.7145 | | | | |
| 3 | 1.0000 | 0.9995 | 0.6253 | | | |
| 4 | 1.0000 | 1.0000 | 0.9990 | 0.5558 | | |
| 5 | 1.0000 | 1.0000 | 1.0000 | 0.9983 | 0.5003 | |
| 6 |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

# CRYOSTAT, GIRDER, INTEGRATION

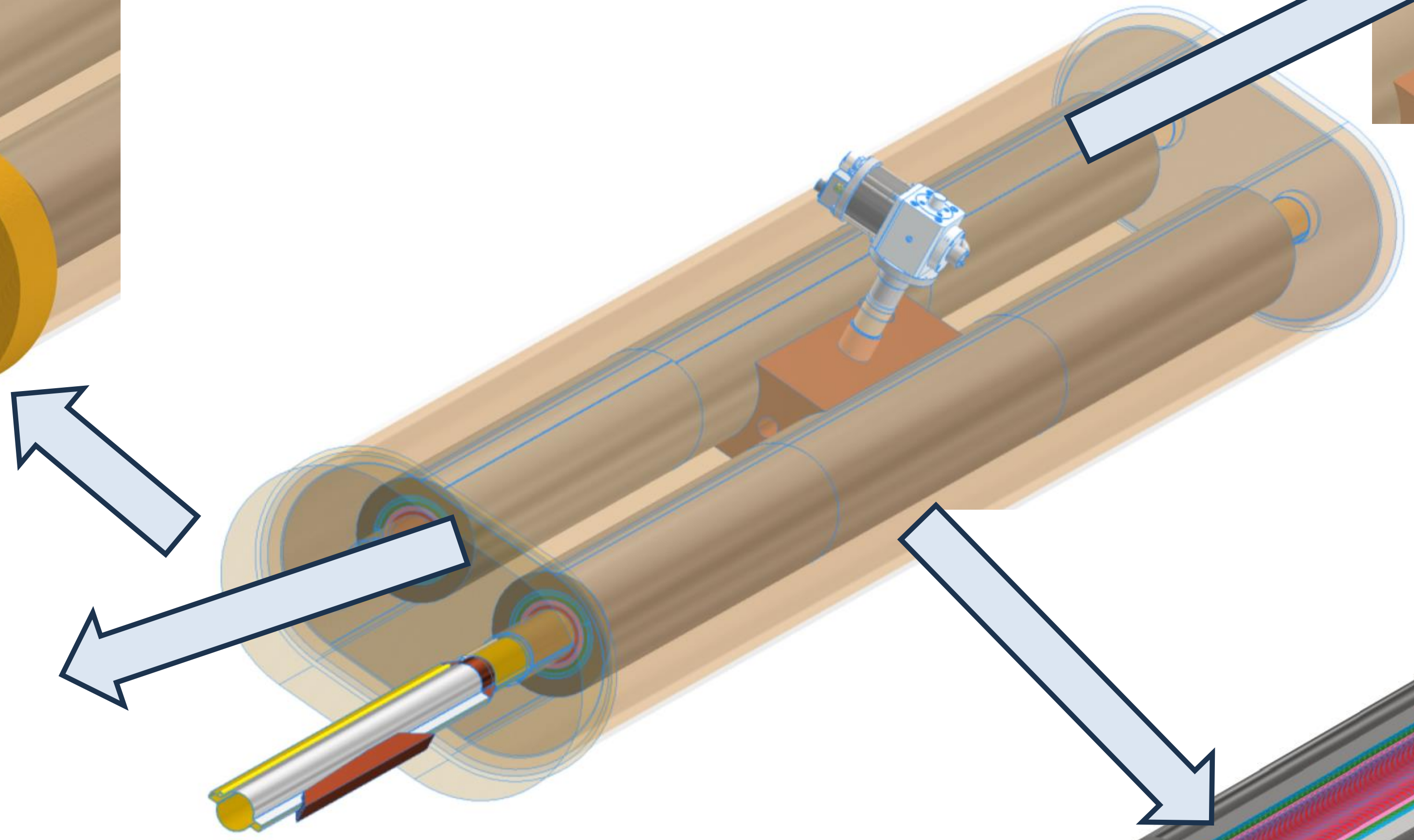
# Cryostat assembly

Beampipe, photon stopper and absorber

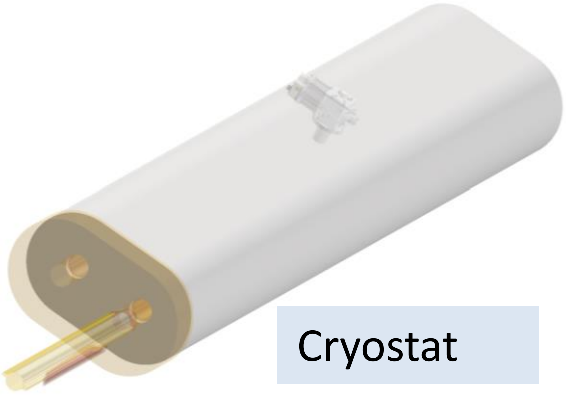




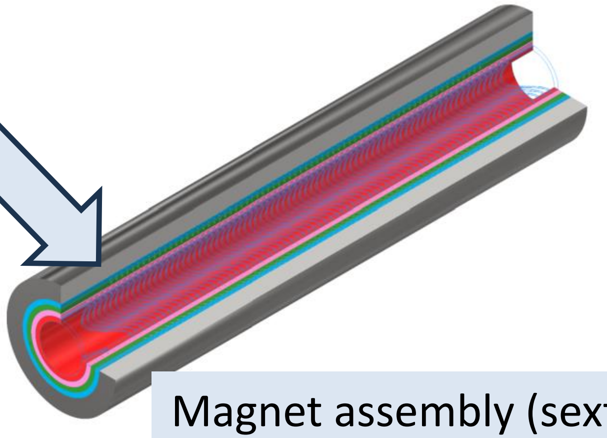
Cryocooler head



Total weight: 1560Kg



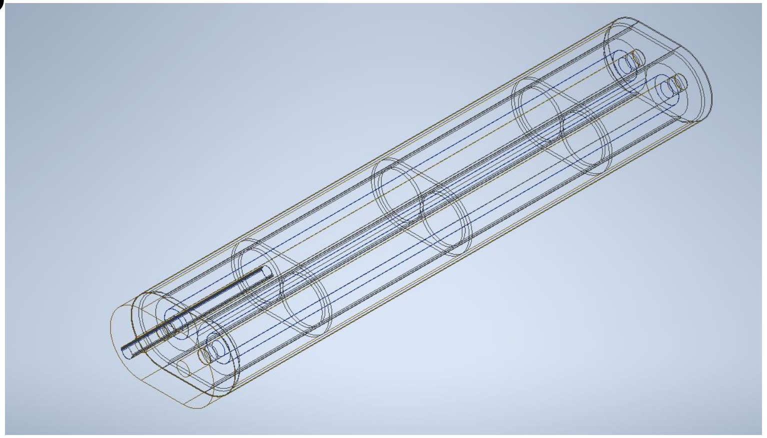
Cryostat

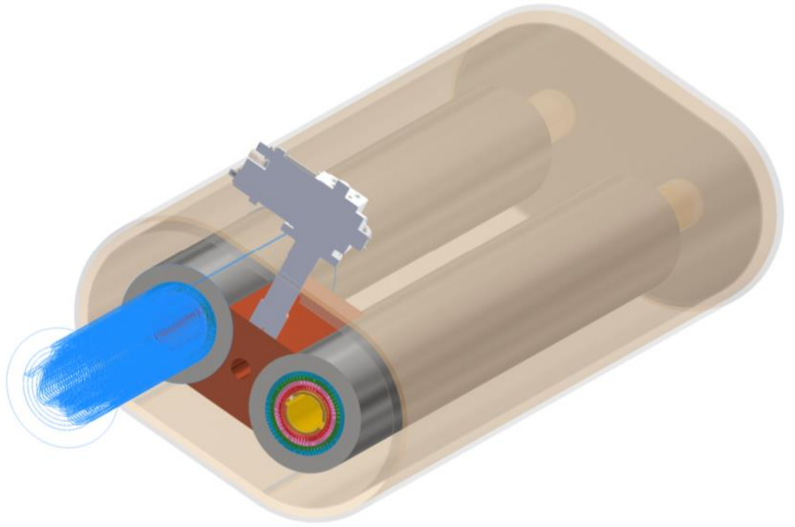


Magnet assembly (sext, quad, iron, 3 correctors) X3

# The cryostat - losses

- Operating temperature of HTS: ~40K (to be optimized)
- Operating temperature of power converters: ~70K (to be determined)
- Estimation of losses (extrapolating from the LHC main dipoles): **~11W** (4W conduction, 7W radiation). To be verified
- Losses due to current leads or internal power supplies) – **~12W**, see slides below





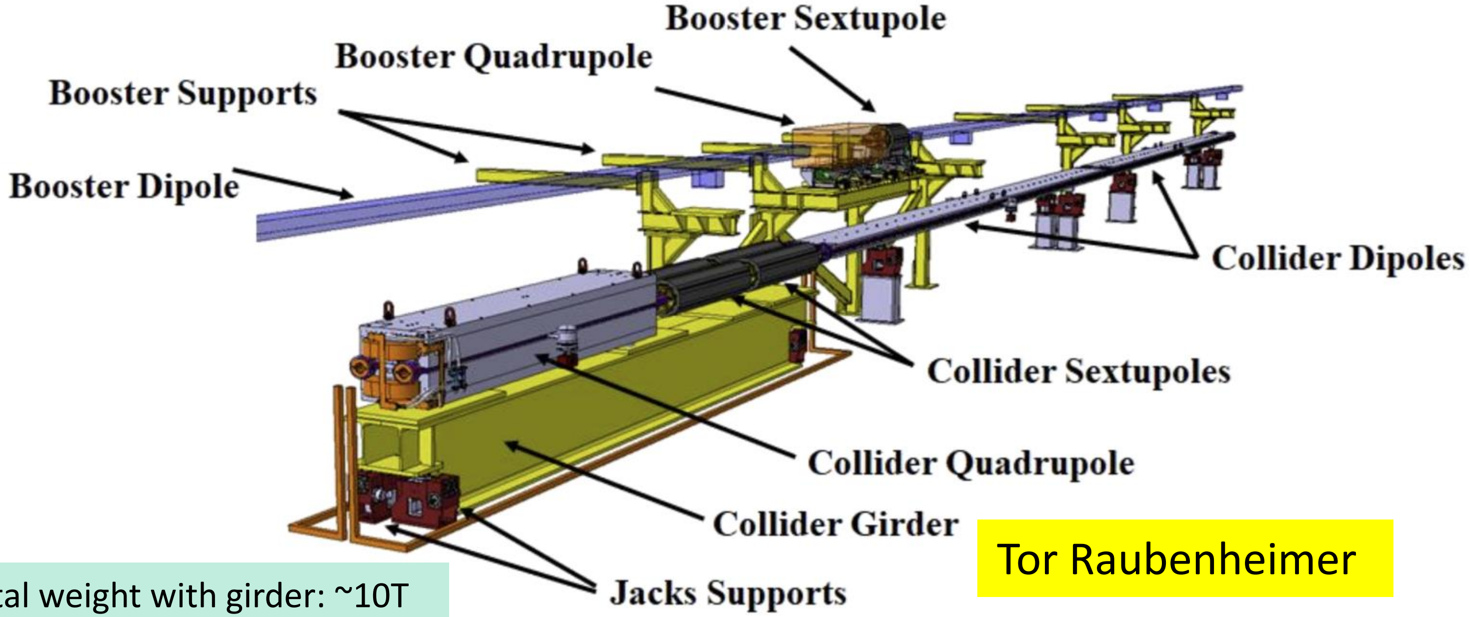
Inter-beam distance: 300mm (the old CDR value. New value: 350mm)

# 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

Weight of baseline solution:
Quadrupole (2.9m): 4400+820Kg
Sextupole (1.4m): 880+150Kg
Total weight from **5220kg to 7280kg**

Weight of this solution:
Magnets+iron+cryostat: **~1600kg**




Total weight with girder: ~10T

Tor Raubenheimer

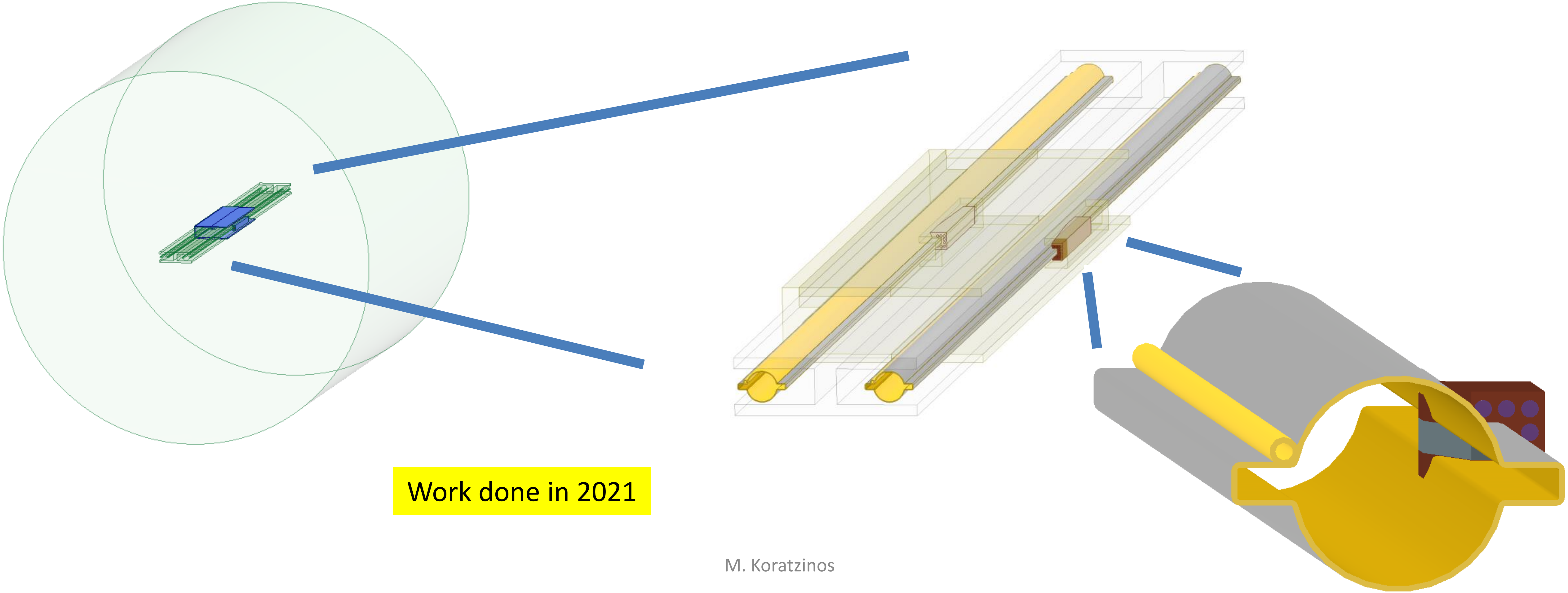
# RADIATION ENVIRONMENT

# 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

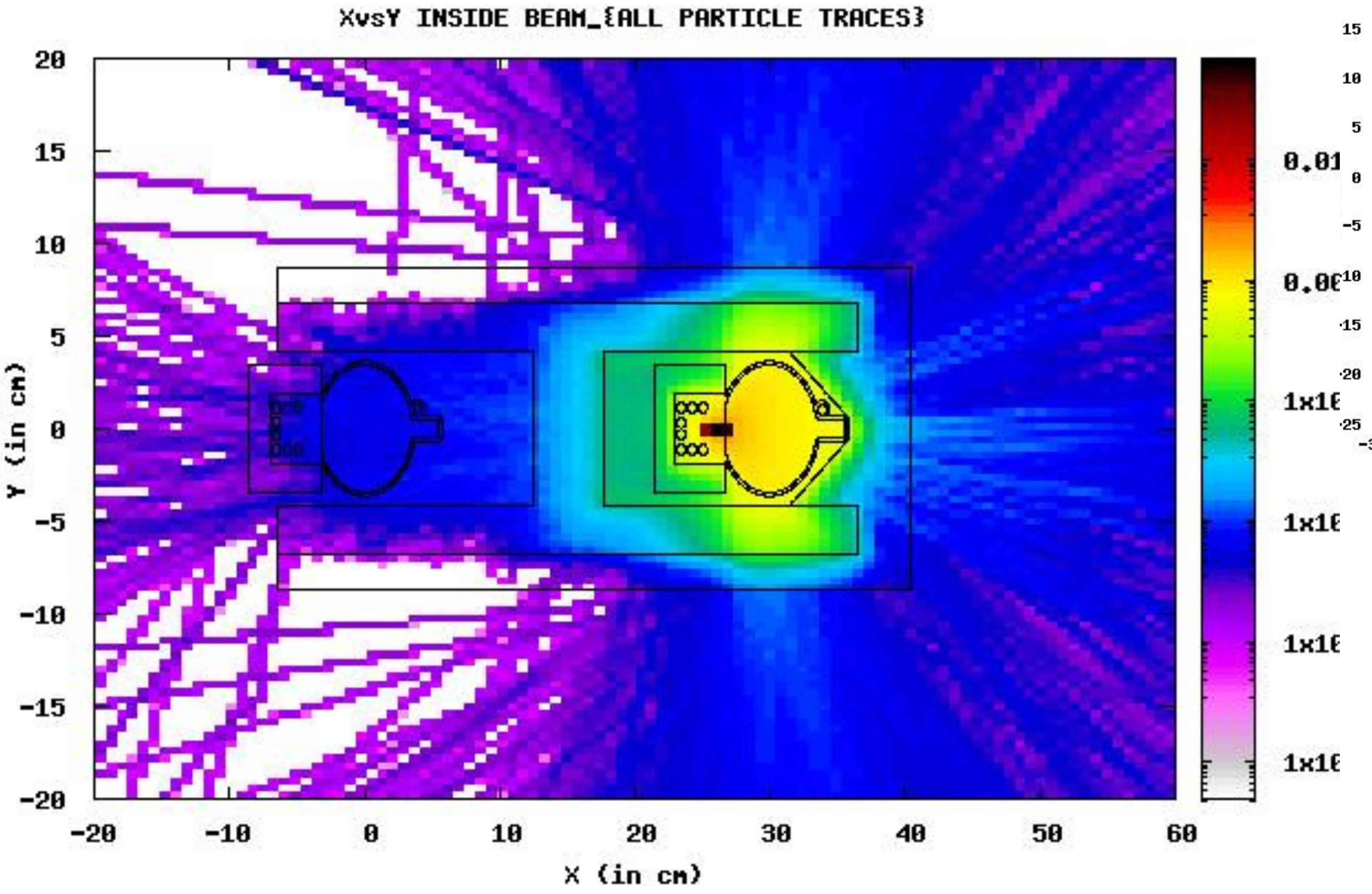
# Radiation in the tunnel

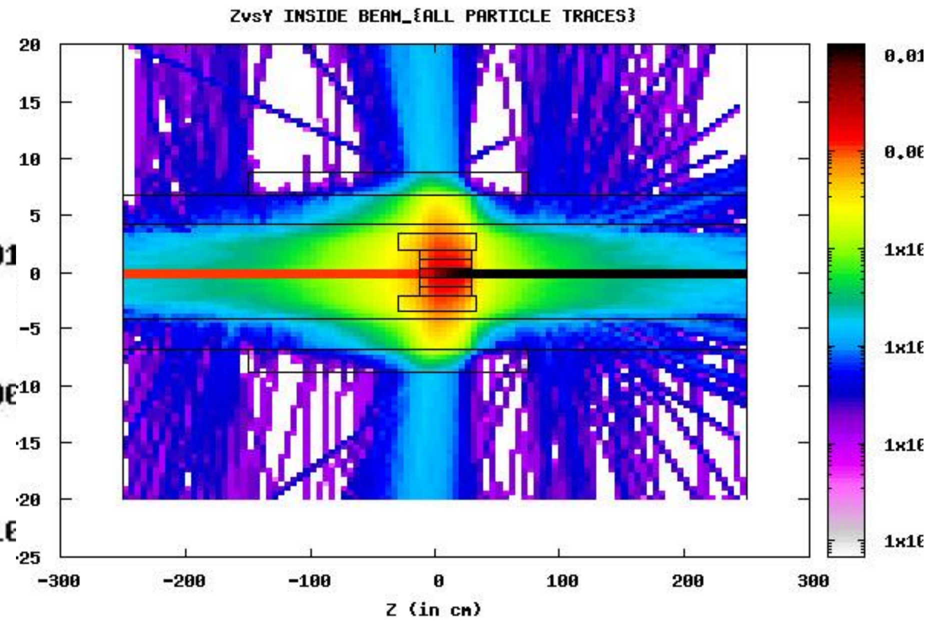
- See presentation by N. Nikolopoulos https://indico.cern.ch/event/1113474/ in 2022
- A full system with tunnel, dipoles, beam pipe, photon absorbers, shields was simulated in FLUKA
- (We have used tungsten for the extra shielding, which however can be replaced by lead of 1.5 times the thickness)

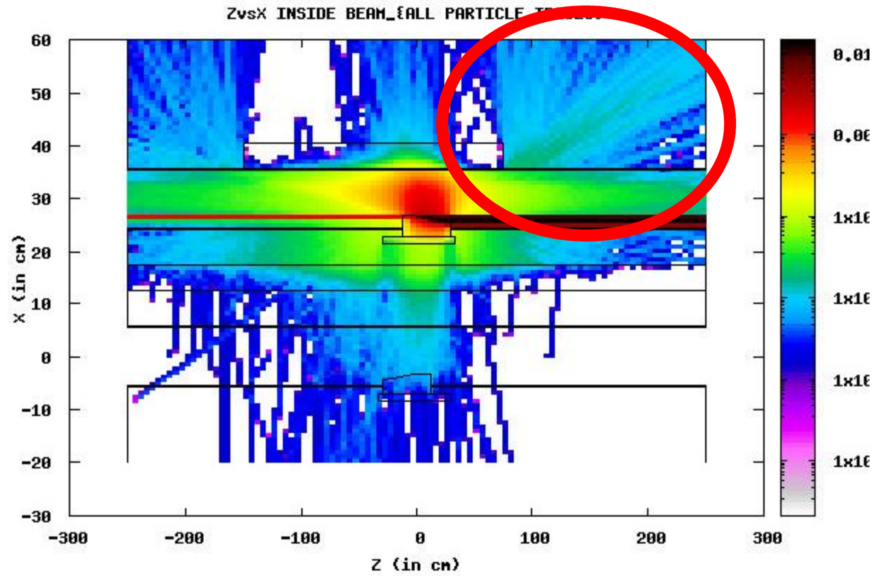


Work done in 2021

# FLUKA results, inside beam

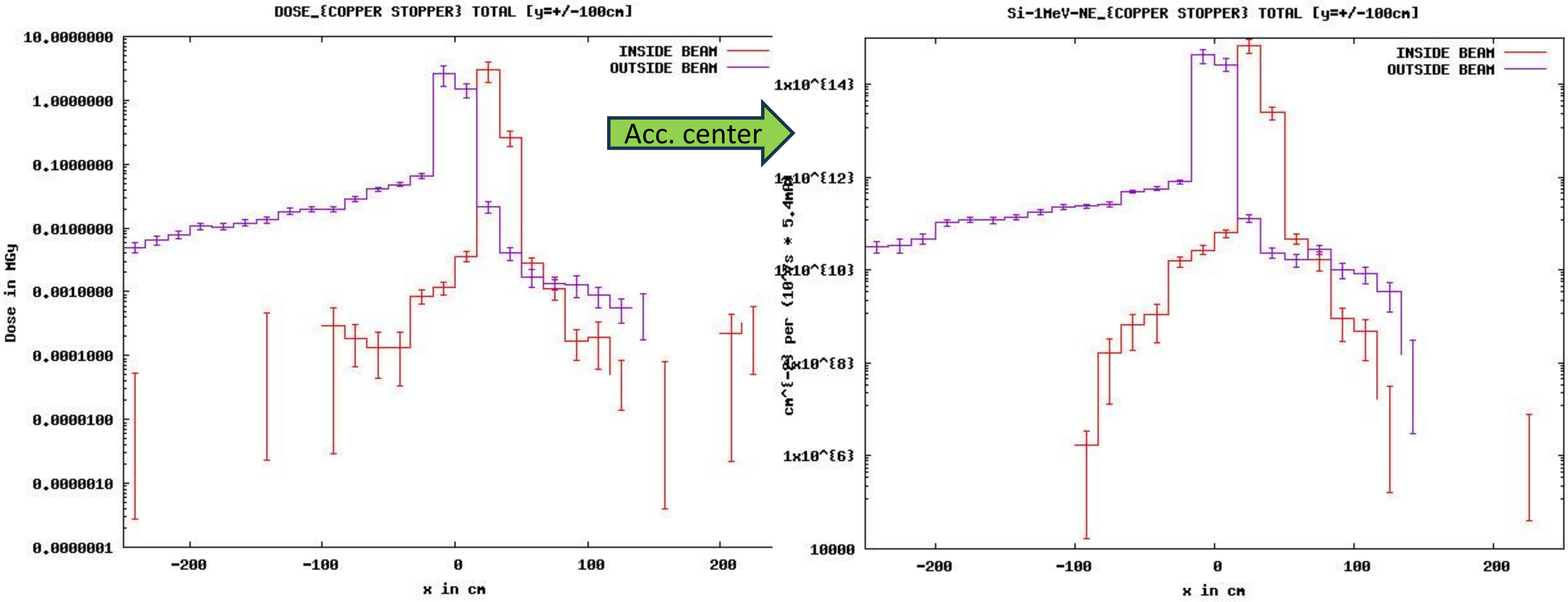



>99% of energy absorbed by various absorbers, beampipe or magnet

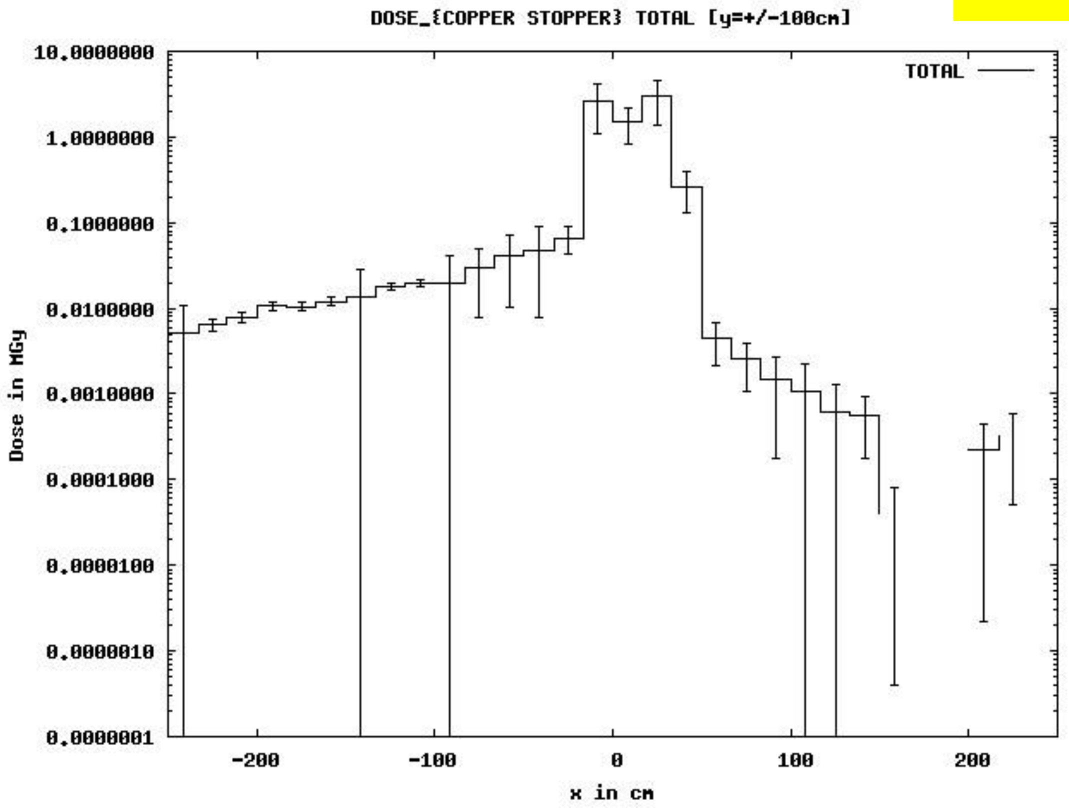
# FLUKA results – dose and 1MeV n equiv.

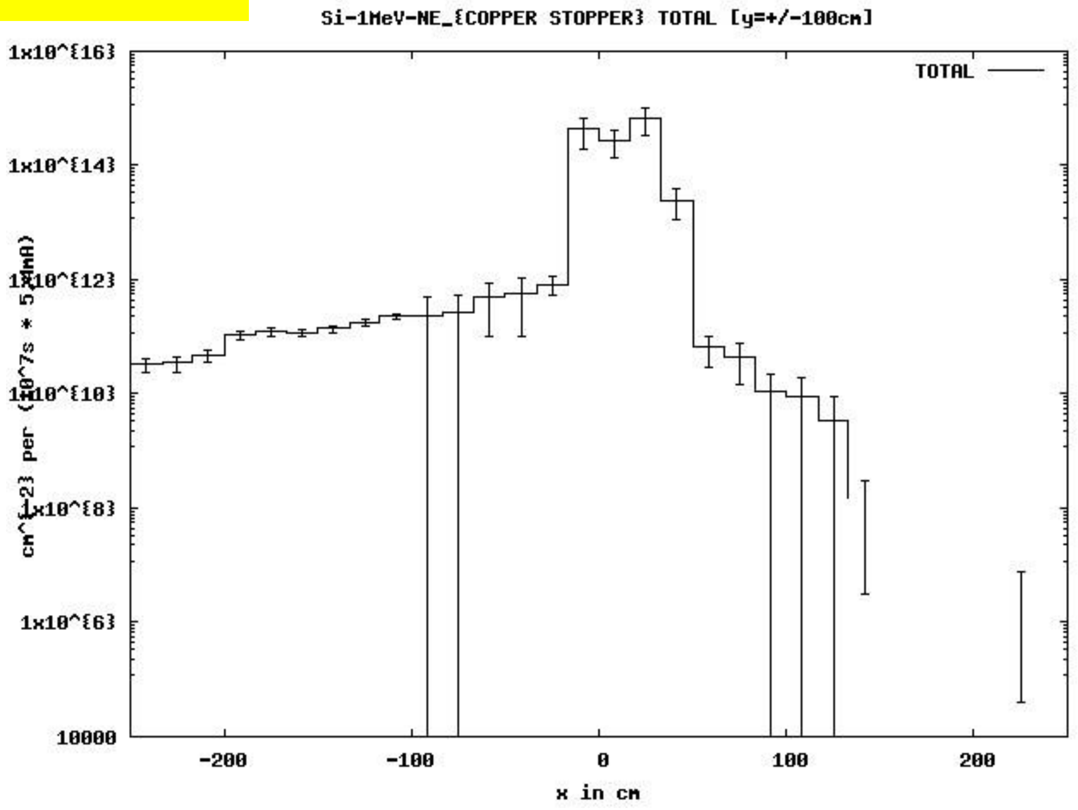



Here we look at the area **±1m vertically from the plane of the accelerator**. Positive X (x is the horizontal dimension) is towards the inside of the accelerator. The slice along Z (the direction of the beam) is ±2.5m. Each histogram bin is 166.6mm wide

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

Beam energy: 182.5GeV



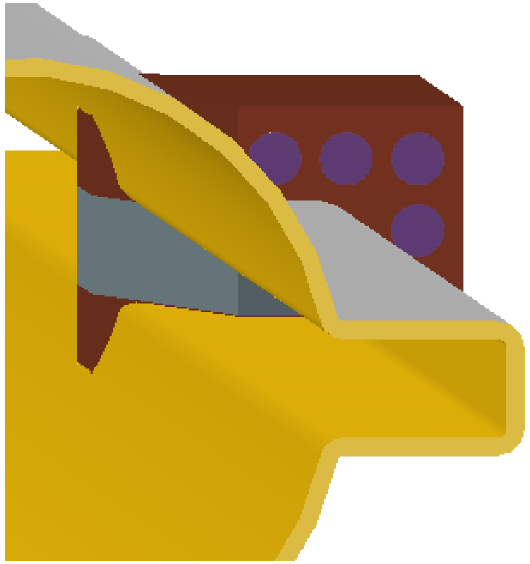

Dose: 1m from the beampipe, inside: ~600Gy
1m from the beampipe, outside: ~10kGy

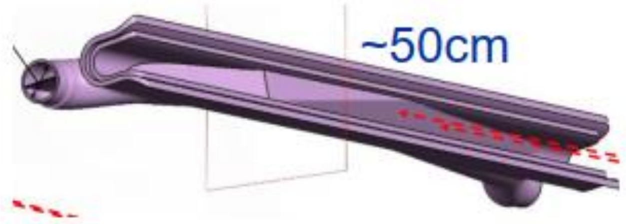
1MeV n equiv.: 1m from the bp, inside: ~1E10
1m from the bp, outside: ~2E11

Doze can be **<1kGy per year ±1m off the accelerator plane**. This analysis needs to be verified

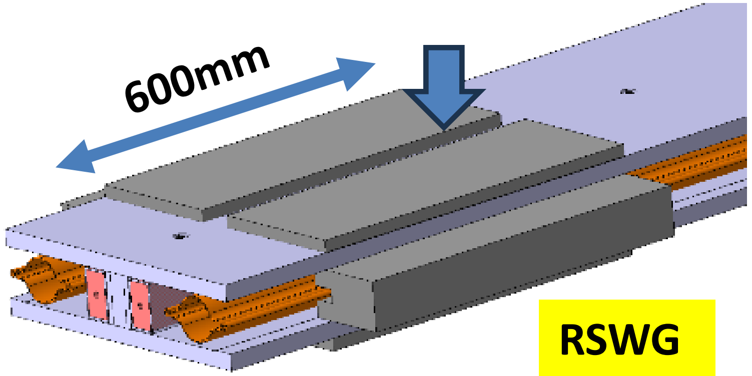
# Comparison with Radiation and shielding Working Group

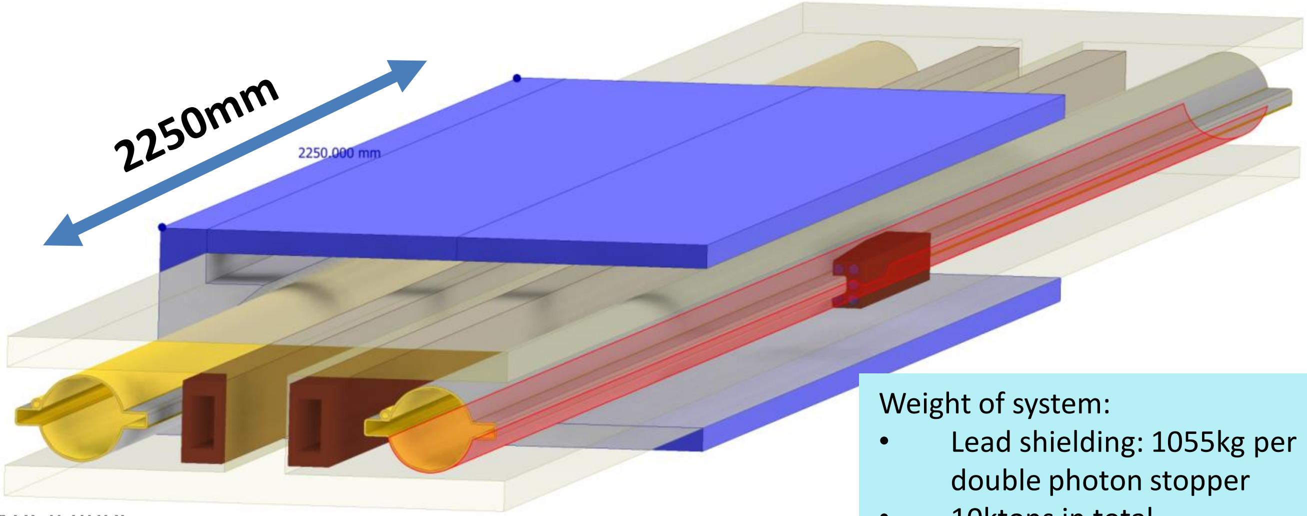
- Our estimate is a factor ~10 lower than recent work presented by the FCC radiation group.
- This could be due to the following differences:
  - We use a bigger photon stopper (extruded and not 3D printed), with Tungsten insert
  - We use more shielding – **length** is 2250mm and there is **no gap** between e+ and e-
  - Due to the extra length of the shielding, we would prefer having three instead of four stoppers per half cell






Weight of system:
- Lead shielding: 13ktons in total




Weight of system:
- Lead shielding: 1055kg per double photon stopper
- 10ktons in total
- Tungsten: 1.6kg

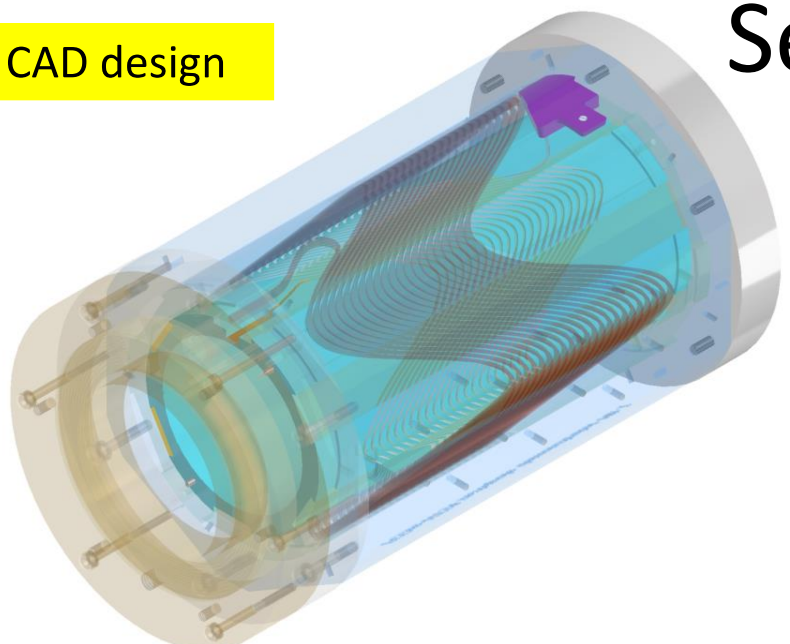
# DEMONSTRATORS

# Demonstrators

- 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.
- We are pursuing both CCT and more standard CT technologies
- We start from a sextupole demonstrator, since in a a nested (quad/sextupole) system, the higher order multipole goes closer to the beam pipe
- CCT demonstrator: advantages: Ease of construction, good field quality, quick design cycle. Disadvantages: HTS tape cannot be trivially wound around a cylindrical former
- Progress:
  - CCT: manufacturing done, quality control done, winding first layer done
  - CT demonstrator: investigation of partially insulated conductor technologies

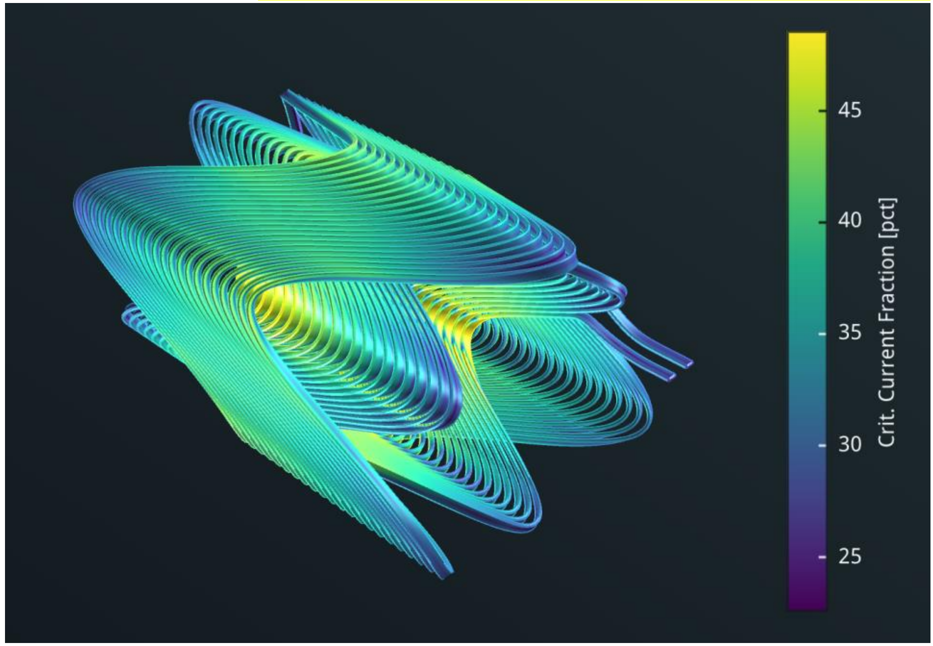
# Sextupole demonstrator

CAD design



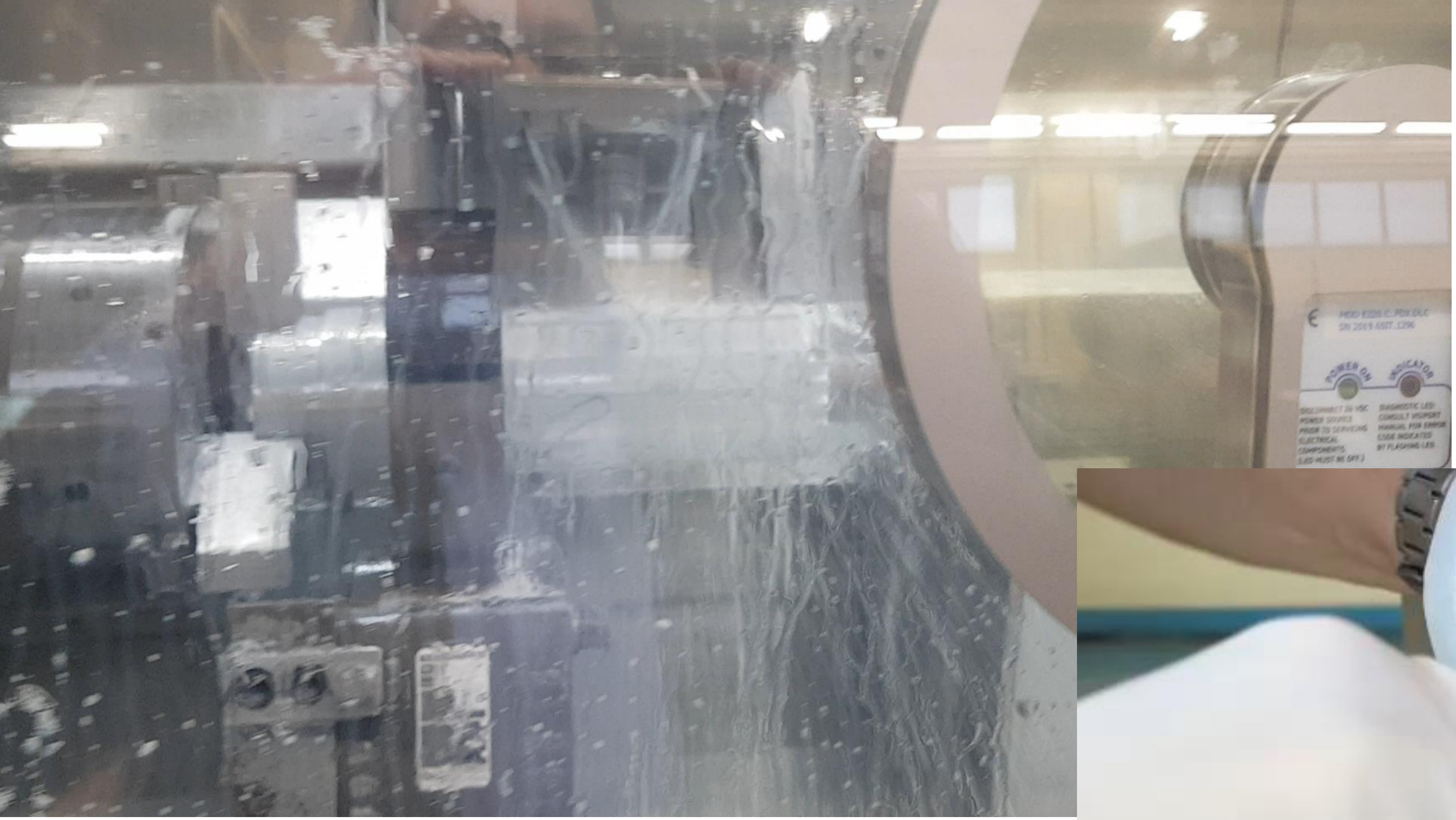
**Specifications**:
Type: CCT
Aperture: 90mm
Current: 260A
Temperature: 40K
Field gradient: 1000T/m2
Max. field @conductor:1.5T
Crit. Current fraction: 49%
Temp. margin: 14K

Critical current fraction at 40K




Aluminium formers

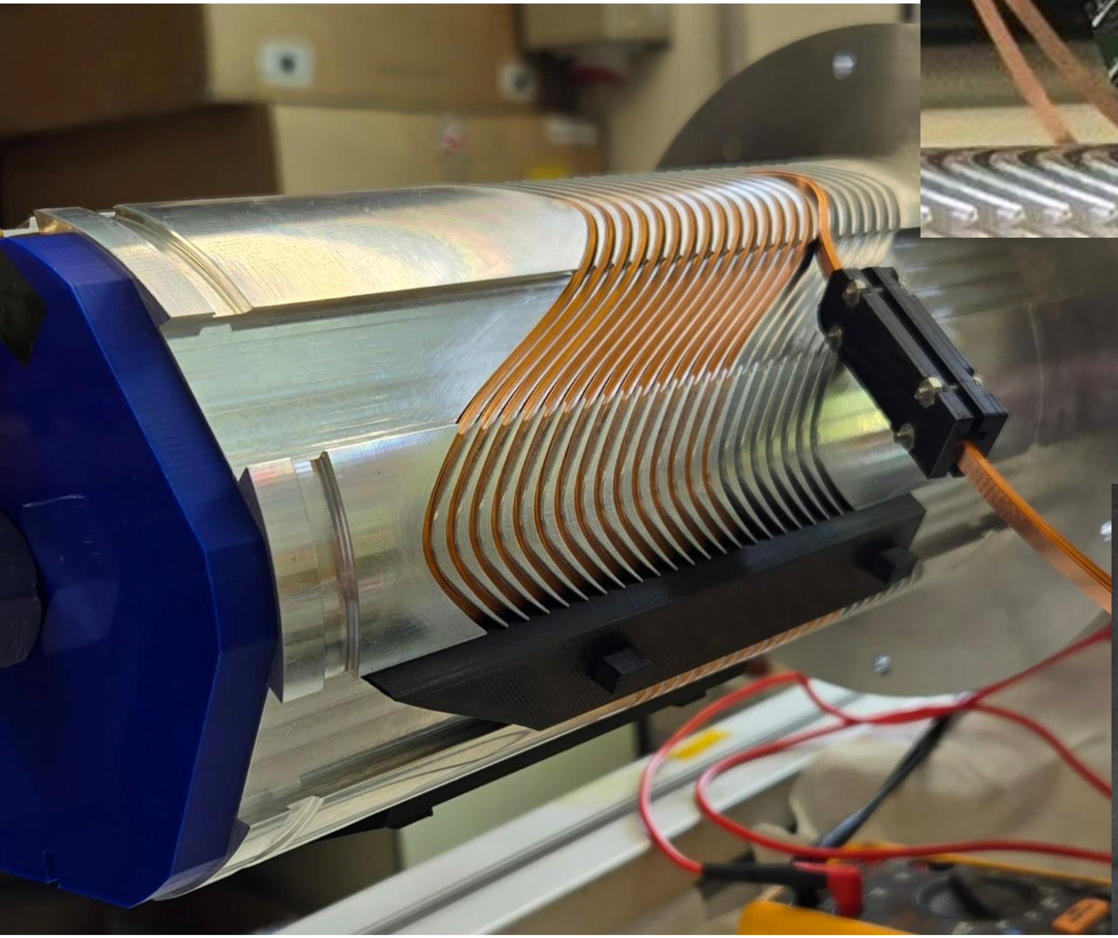
CT alternative

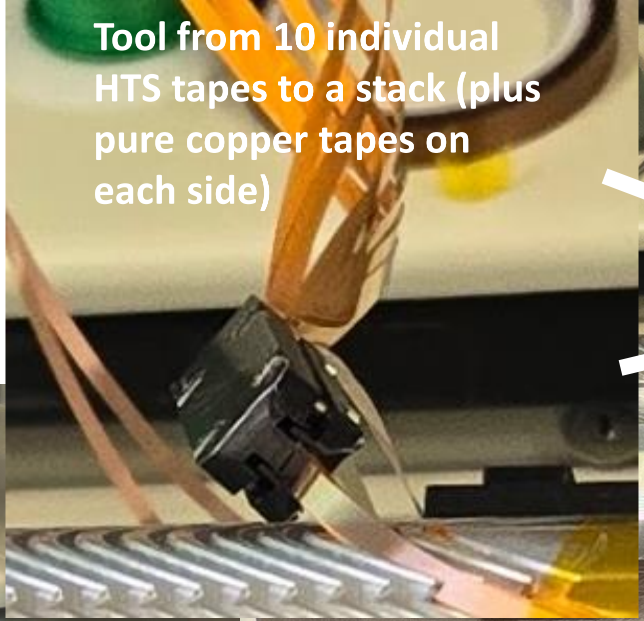


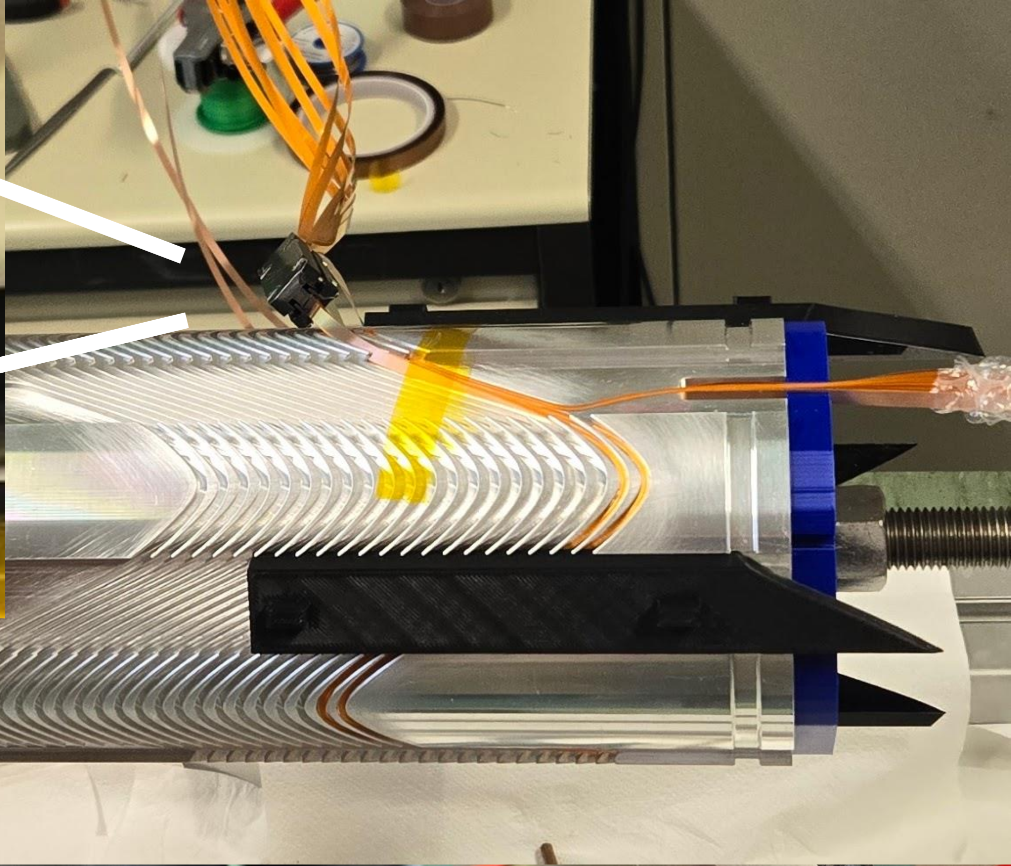
Manufacturing of aluminium formers

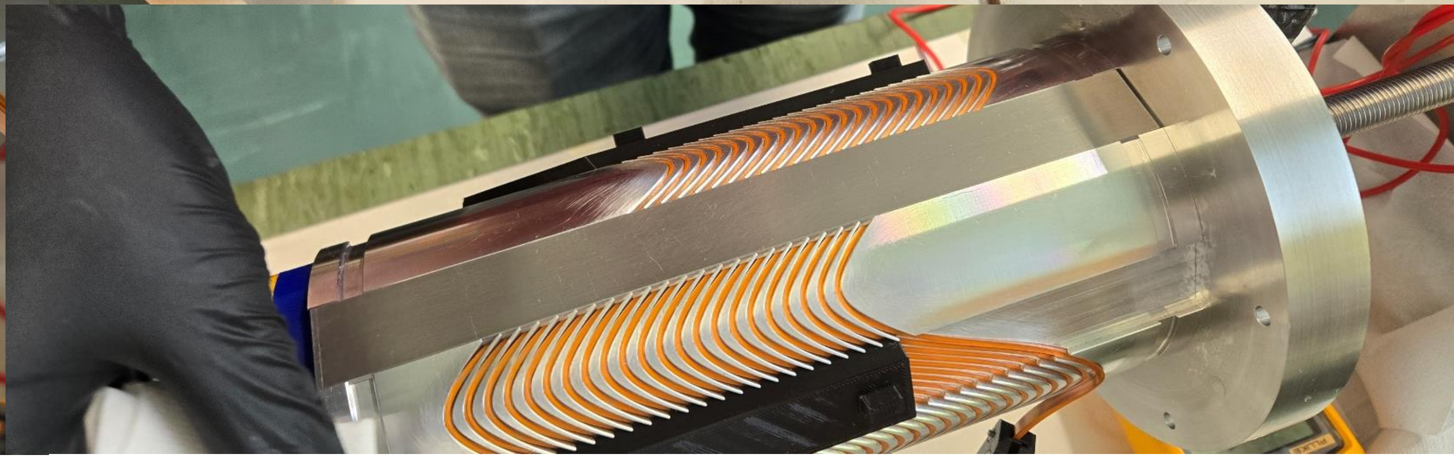
Winding of HTS tapes 7/6/2024

# Winding pictures

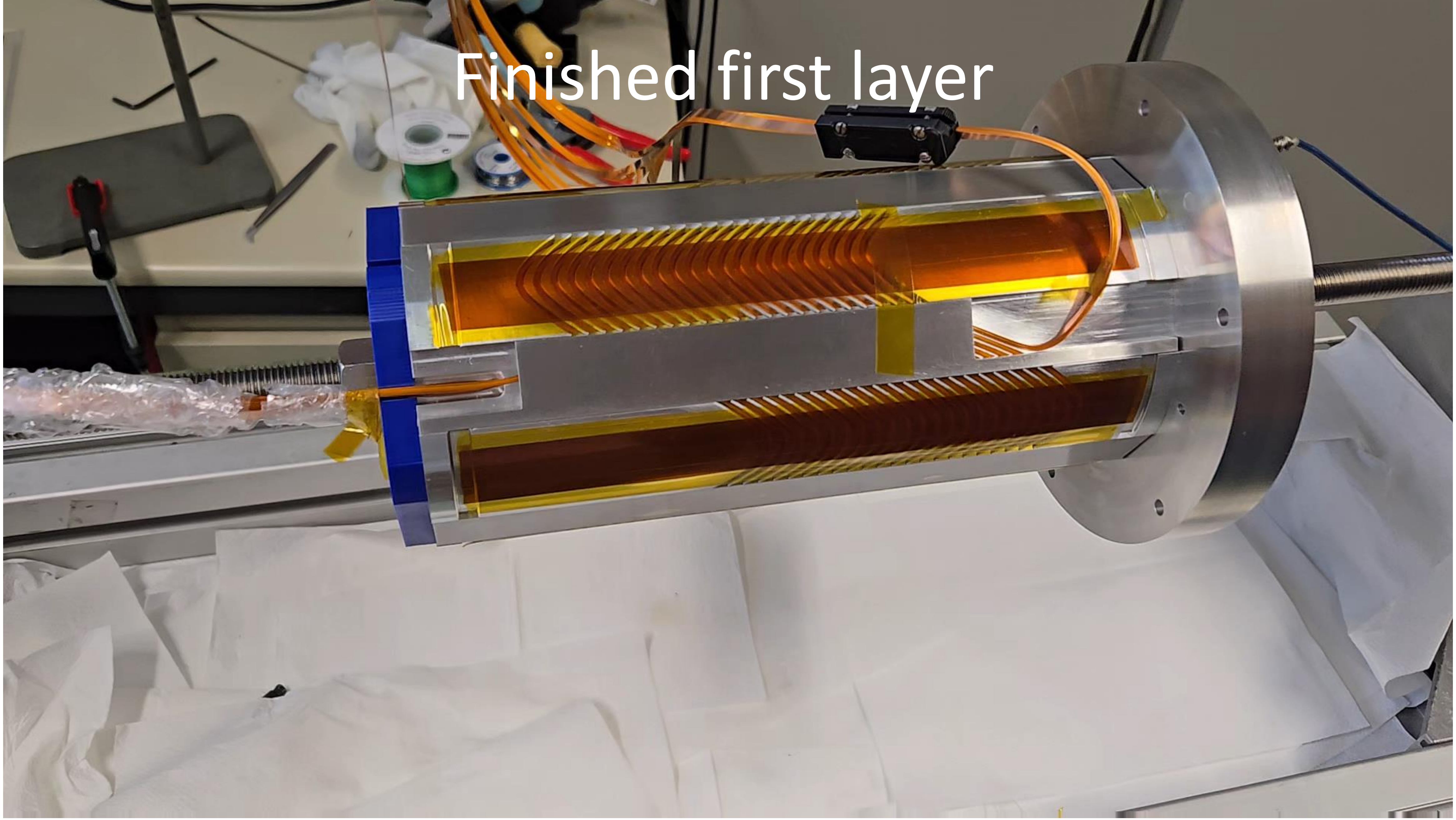






# Finished first layer



# ARC DIPOLES

# What about the arc dipoles?

- The dipoles are not part of the scope of FCCee-HTS4 (they are only responsible of ~25% of total power dissipation of the arc magnet systems)
- 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

NOT part of FCCee-HTS4

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

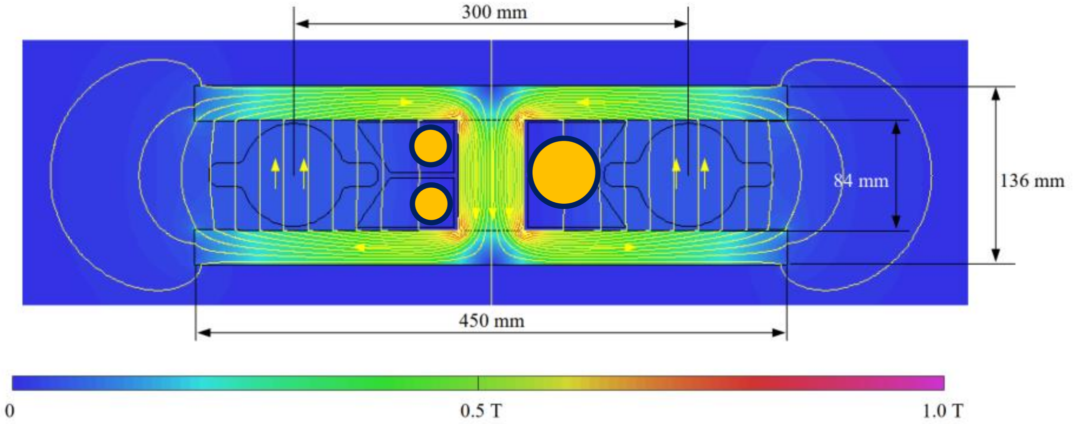



Figure 3.1: Cross-section of the main bending magnet; the flux density corresponds to 57 mT in the gap; the outline of vacuum chambers with side winglets is also shown.

# FCCEE-CPES

# Power converters

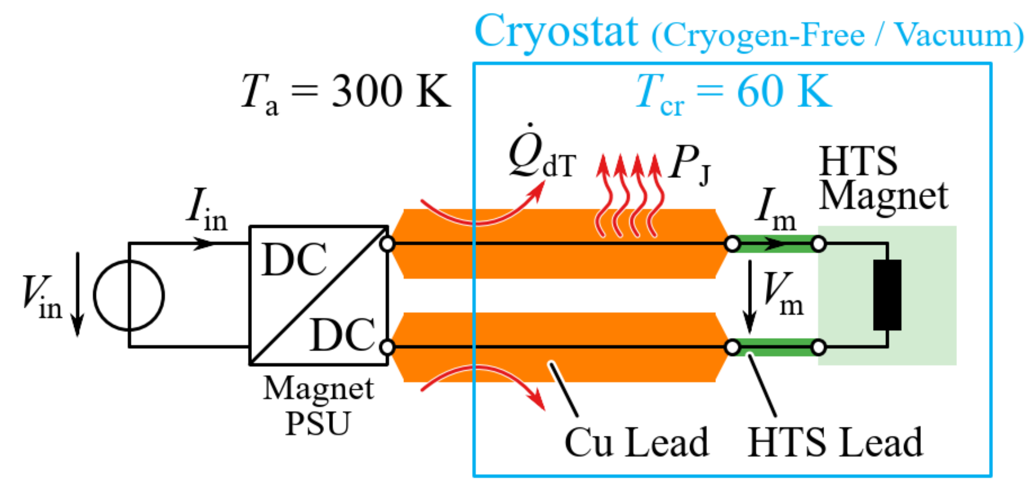
- We believe that individual power supplies for every component is the most performant solution.
- No need for a quadrupole trim, for instance.
- Allows for all polarities
- (in any case, baseline optics has a large number of sextupole families)

# Losses due to power supply leads

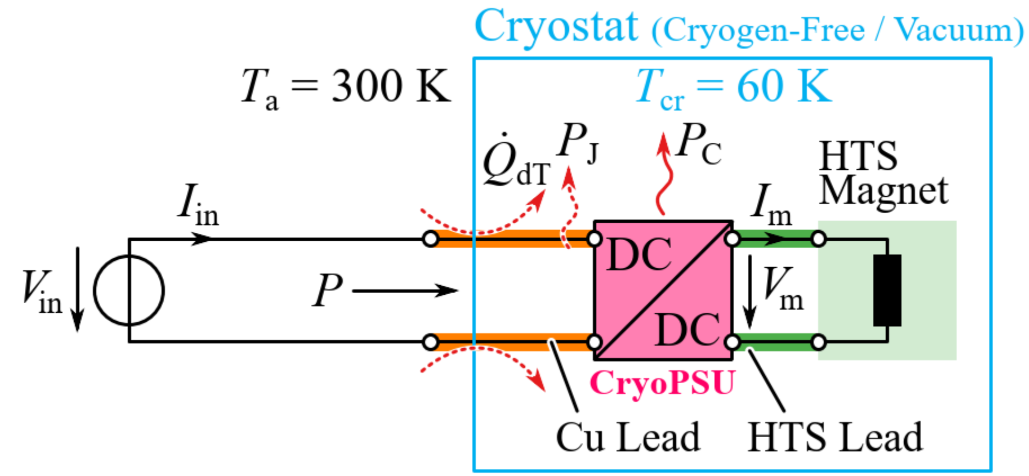
- The heat loss of a traditional system through the copper power supply leads follows the simple rule **~90W/kA** for two leads, see [https://arxiv.org/abs/1501.07166](https://arxiv.org/abs/1501.07166).
- Although we have pushed the current down to 250A (at the expense of more coil windings), this still 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**.

→ Our sister project, FCCee-CPES (PES, ETHZ) Jonas Huber, Danqing Cao, Daifei Zhang, Elias Bürgisser, Mücahid Akbas, Johann W. Kolar

**Traditional system:**

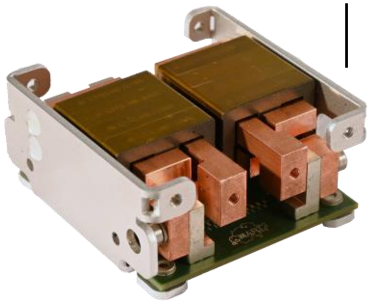


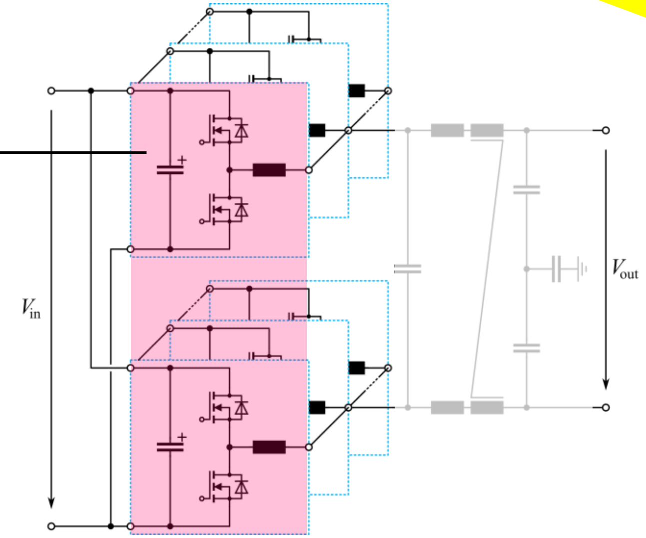

**This proposal:**



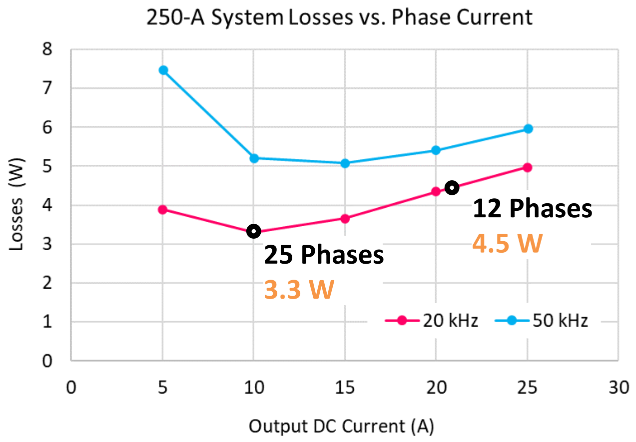
# CPES demonstrator

Full-bridge phase module losses measured in $LN_2$ @ 77 K

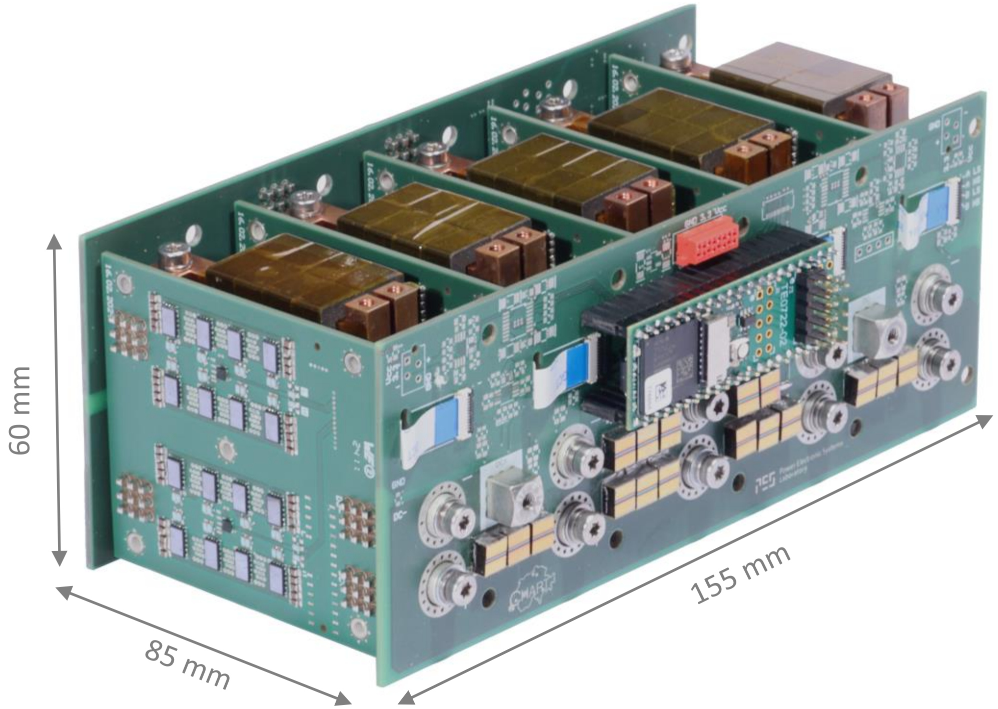



Modular system, can build redundancy for good availability




5-phase 100A demonstrator



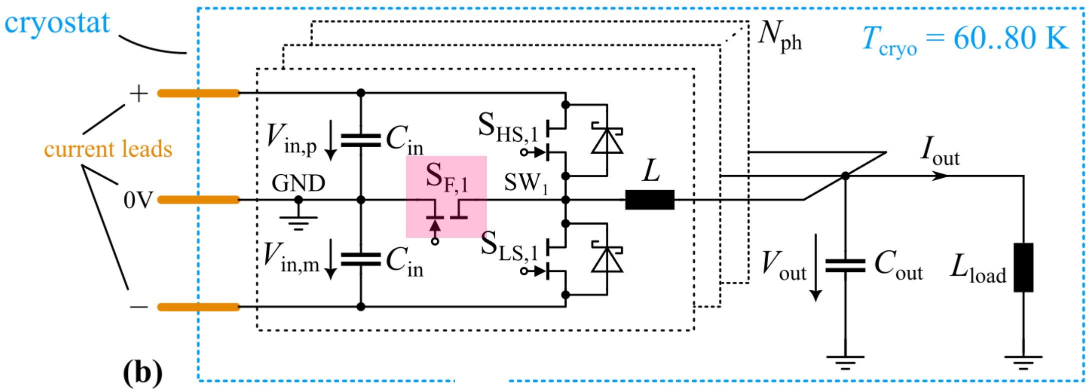

Extrapolation to a 250A system: 4.5W of losses (plus 1.5W for residual leak-in losses, EMI filter, and control electronics)

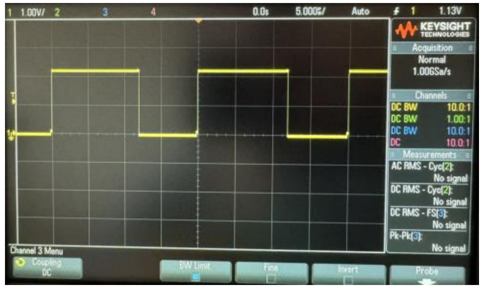
M. Koratzinos

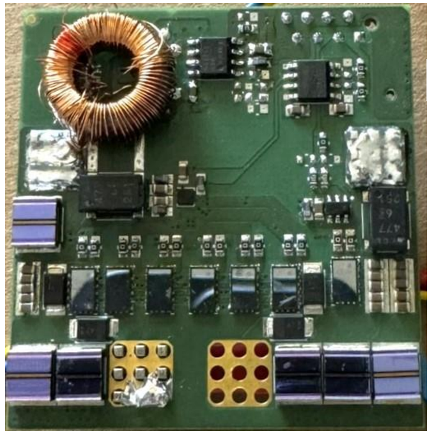
# Prospects for further reduction in power

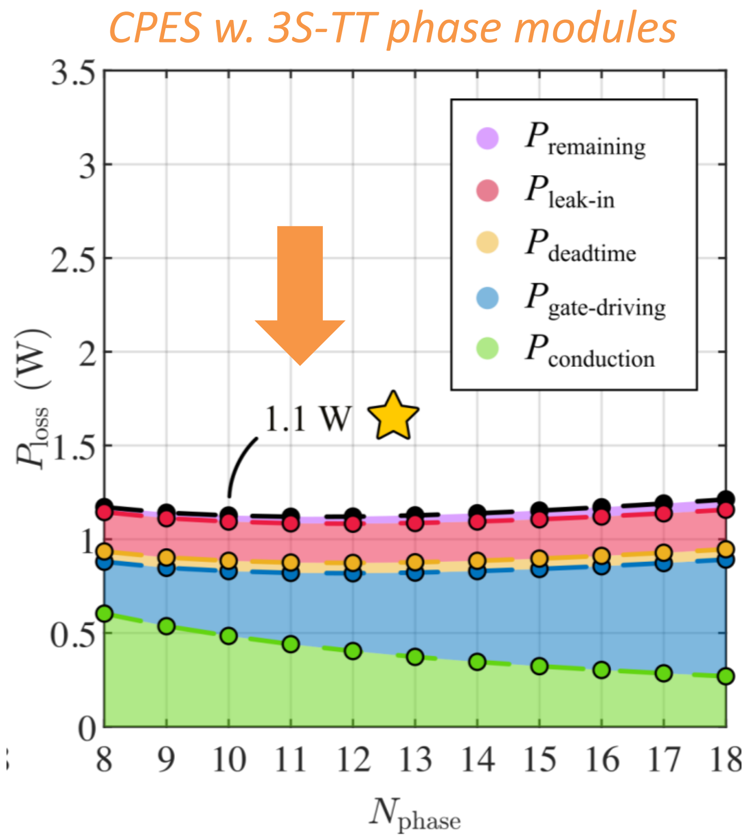
## New Three-Switch T-Type (3S-TT) Phase Modules

- Midpoint switch with single transistor enabled by functional symmetry of GaN HEMTs








Limited reverse blocking capability of a few volts sufficient for CPES / Commissioning & loss meas. ongoing
Only one switch in current path compared to two for full-bridge modules

Expected further system-level power-stage loss reduction by factor 2…3 (!)

M. Koratzinos

# FCCee-CPES summary

- For a traditional system with an external power supply, the losses for a 250A system would be 22W
- They were given the impossible task to reduce powering losses in a cryostat by a factor 4!
- FCCee-CPES are on the way of demonstrating losses of 6W or better
- Work is ongoing, but very encouraging results

# Conclusions

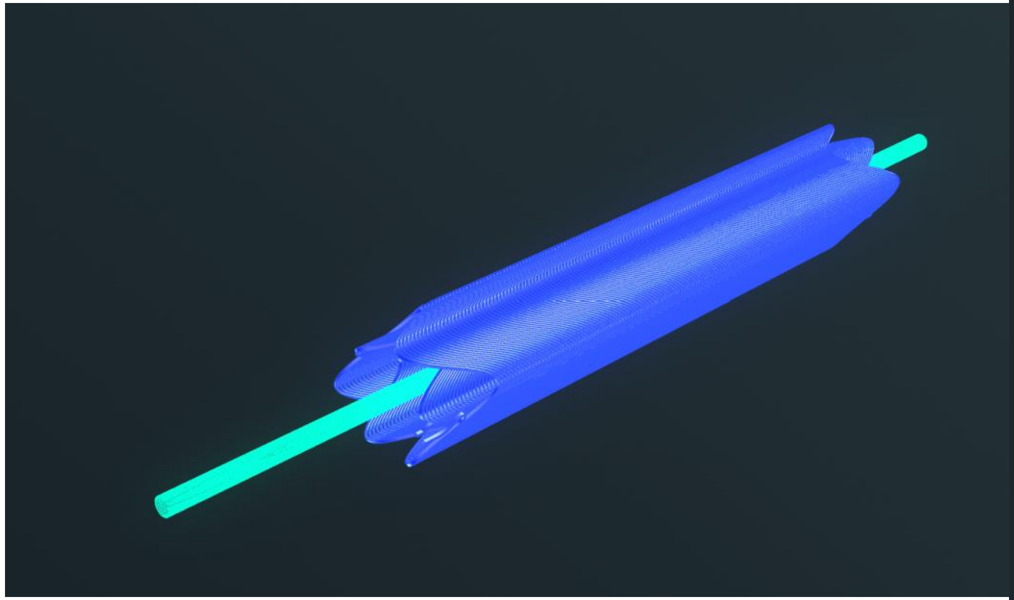
- The idea of cold Short Straight Sections has operational cost benefits, while increasing the performance and flexibility of the accelerator.
- The FCCee-HTS4 project aims at demonstrating that this idea is feasible.
- Our sister project FCCee-CPES goes a step further and reduces cooling costs by developing 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

# Extra slides

# Multipole errors - sextupole

- This is the design of the demonstrator but with full length. Current leads have not been optimized.
- Peak B3 corresponds to a strength of 1000T/m2.
- All higher multipoles less than 1 unit. There are 6-8 units of A1, A2 and B2 components that have not been optimized and in any case can be compensated by the nested magnets.

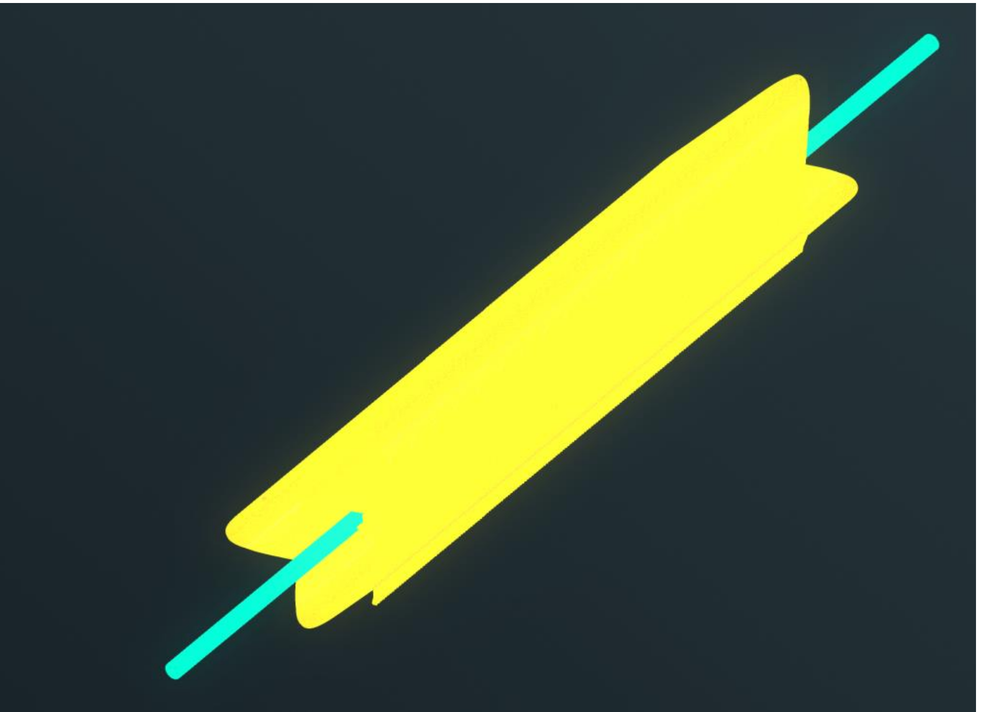


harmonics given at a reference radius of: 10.000 [mm]

| Order | An [T.m] | an | Normalized Shape | Order | Bn [T.m] | bn | Normalized Shape |
|---|---|---|---|---|---|---|---|
| A1 | 2.43e-05 | 6.88 | | B1 | 3.59e-08 | 0.01 | |
| A2 | -2.85e-05 | -8.08 | | B2 | -2.63e-05 | -7.45 | |
| A3 | 6.21e-06 | 1.76 | | B3 | 3.53e-02 | 10000.00 | |
| A4 | -9.75e-07 | -0.28 | | B4 | 1.01e-06 | 0.28 | |
| A5 | 2.08e-07 | 0.06 | | B5 | 1.31e-06 | 0.37 | |
| A6 | 1.61e-07 | 0.05 | | B6 | -3.53e-07 | -0.10 | |
| A7 | 5.48e-09 | 0.00 | | B7 | 5.20e-07 | 0.15 | |
| A8 | 1.93e-07 | 0.05 | | B8 | -4.37e-09 | -0.00 | |
| A9 | 8.05e-10 | 0.00 | | B9 | 5.45e-07 | 0.15 | |
| A10 | 1.94e-07 | 0.05 | | B10 | 4.73e-10 | 0.00 | |

# Multipole errors - quadrupole

- This is the design of the demonstrator but with full length. Current leads have not been optimized.
- Peak B2 corresponds to a strength of 12T/m.
- All higher multipoles less than 1 unit. There are 8 units of B1, due to the design of the current leads that can be optimized and, in any case, can be compensated by the dipole corrector.



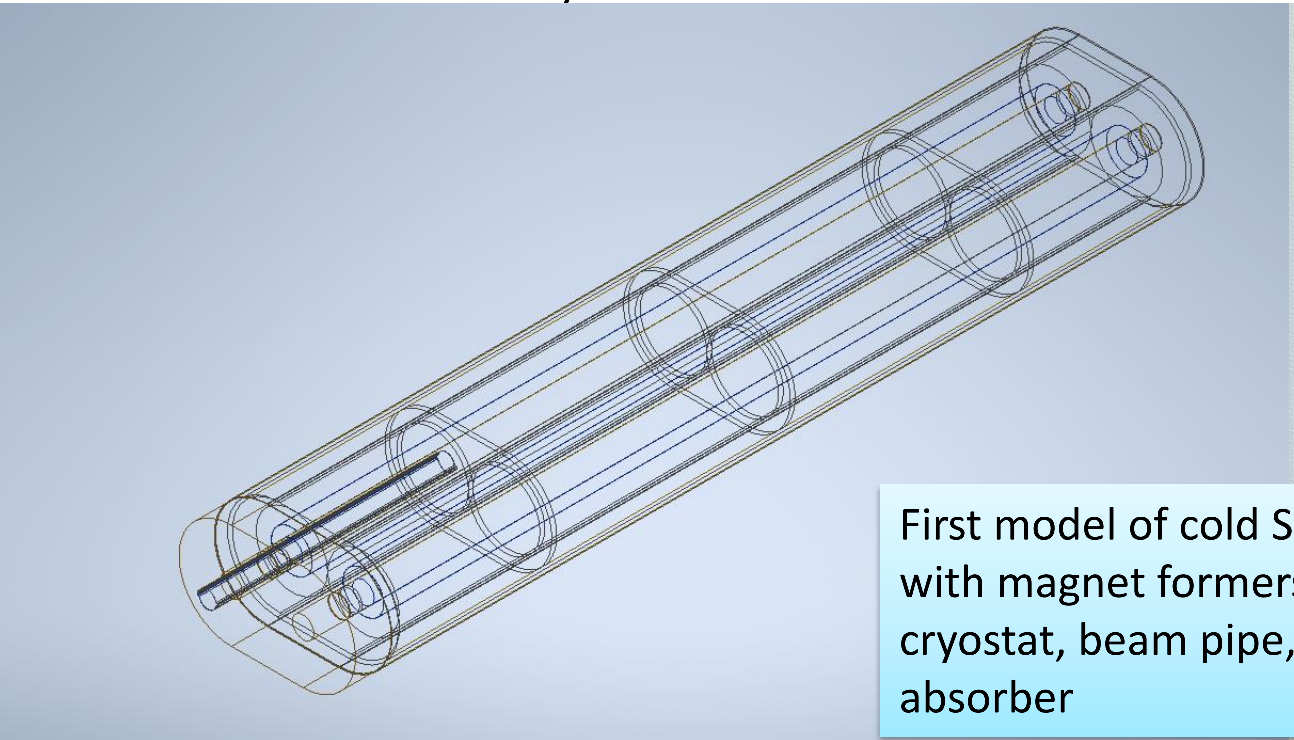
harmonics given at a reference radius of: 10.000 [mm]

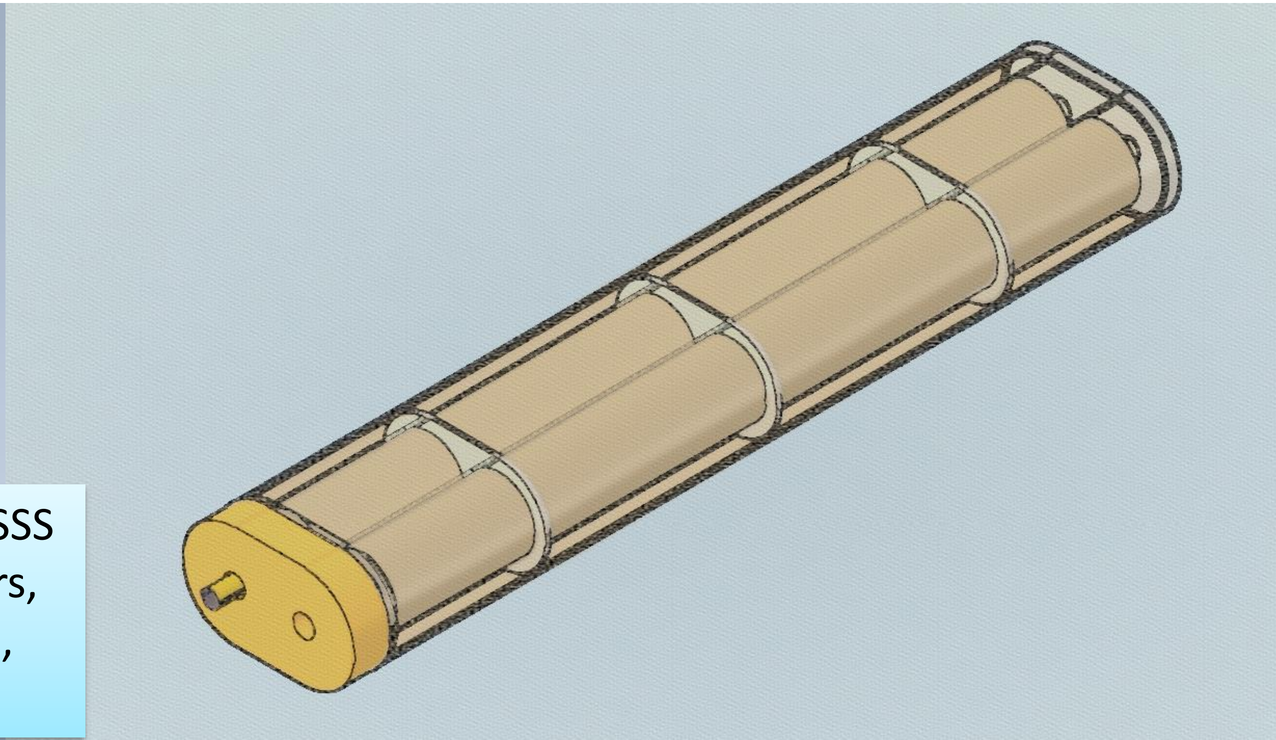
| Order | An [T.m] | an | Normalized Shape | Order | Bn [T.m] | bn | Normalized Shape |
|---|---|---|---|---|---|---|---|
| A1 | -6.58e-07 | -0.06 | | B1 | -7.99e-05 | -7.86 | |
| A2 | -7.08e-07 | -0.07 | | B2 | 1.02e-01 | 10000.00 | |
| A3 | 2.99e-07 | 0.03 | | B3 | -2.63e-06 | -0.26 | |
| A4 | -7.15e-08 | -0.01 | | B4 | 1.38e-06 | 0.14 | |
| A5 | 3.07e-08 | 0.00 | | B5 | -4.90e-08 | -0.00 | |
| A6 | -3.07e-09 | -0.00 | | B6 | 9.50e-07 | 0.09 | |
| A7 | 1.55e-08 | 0.00 | | B7 | -1.69e-08 | -0.00 | |
| A8 | -1.70e-10 | -0.00 | | B8 | 4.31e-10 | 0.00 | |
| A9 | 1.56e-08 | 0.00 | | B9 | 1.50e-08 | 0.00 | |
| A10 | -2.34e-10 | -0.00 | | B10 | 3.94e-08 | 0.00 | |

# Heating budget

We need to pay attention to the following:

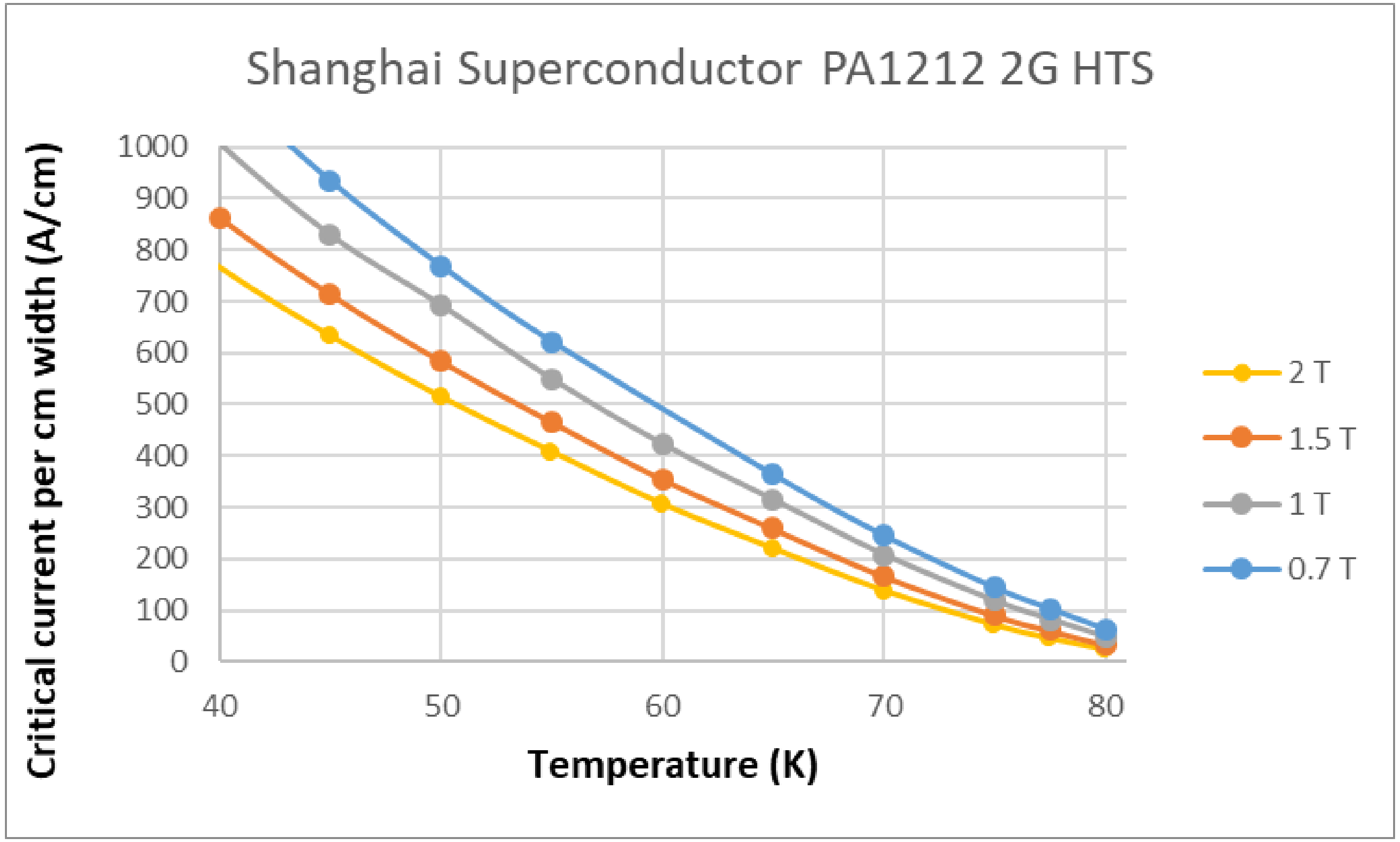
- Resistive wall heating due to the extra photon stoppers and different beam pipe design (not a problem – see slides before)
- Heat losses of the cryostat – radiation and conduction through supports (calculated to be ~12W)
- Cryostat heating due to debris from photon stoppers (calculated to be <2W)
- 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

# Choice of operating temperature

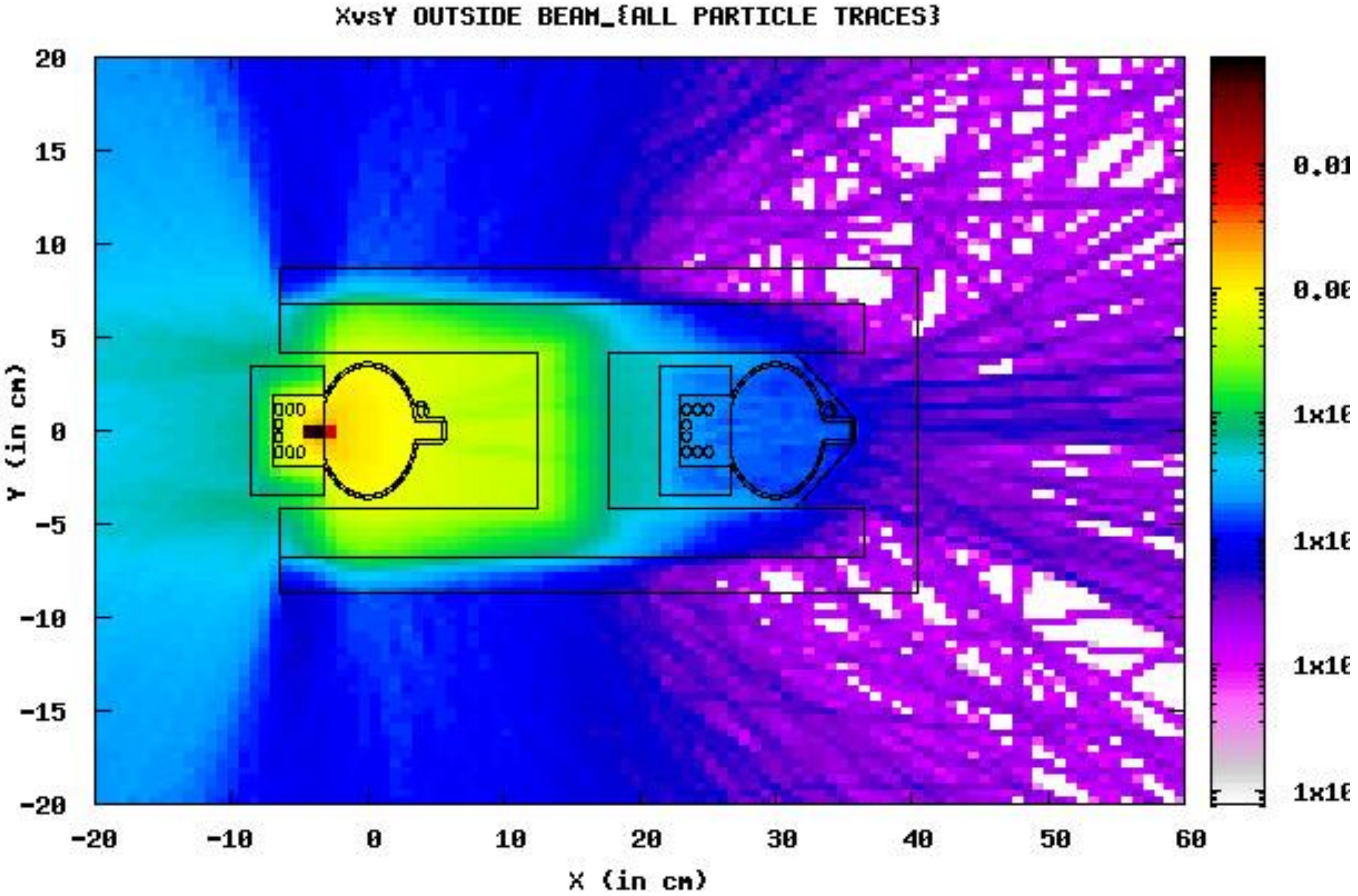


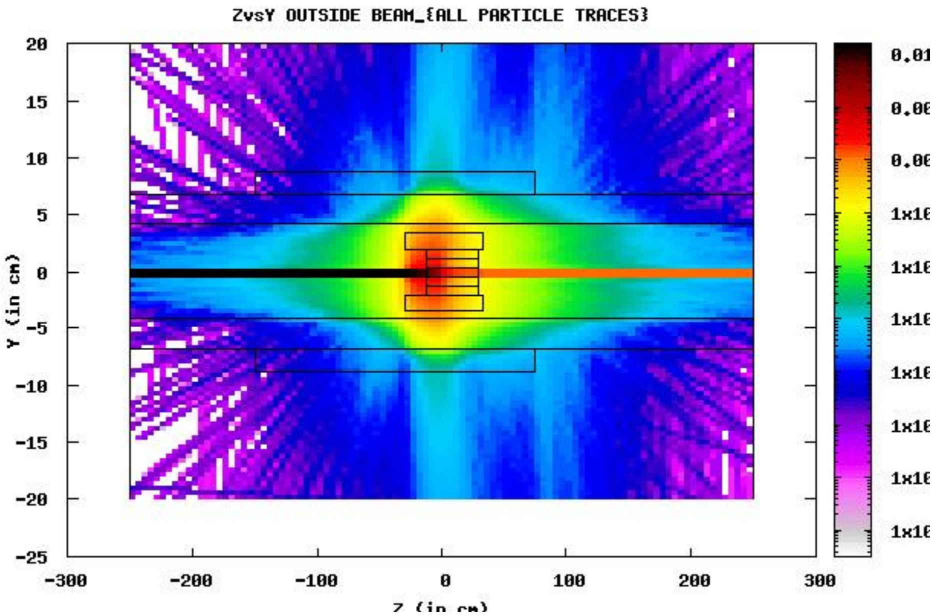

Above is typical ReBCO technology performance, all HTS companies will be considered (but difference in performance and price/performance is small.

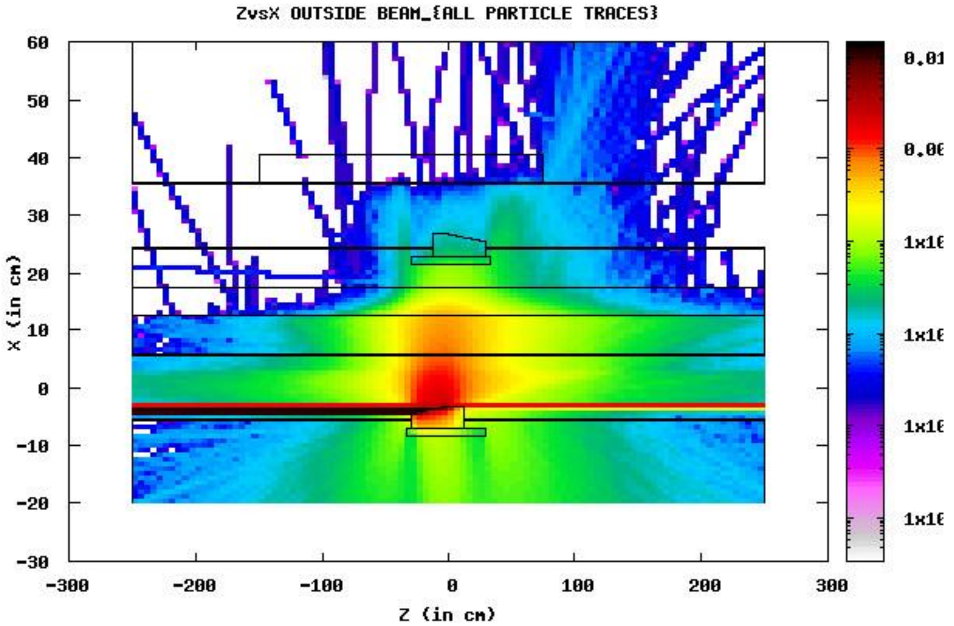
- HTS performance at 40K compared to 77K differs by a factor ~10
- The cost of cryo cooling, only increases by a factor ~2
- Heat losses do not change significantly (due to the fourth power law of black body radiation)
- We aim to work at ~40K at the top energies
- Note that at 40K, materials still possess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

We are using 4mm ReBCO tape

# FLUKA results, outside beam



# FLUKA results, inside beam

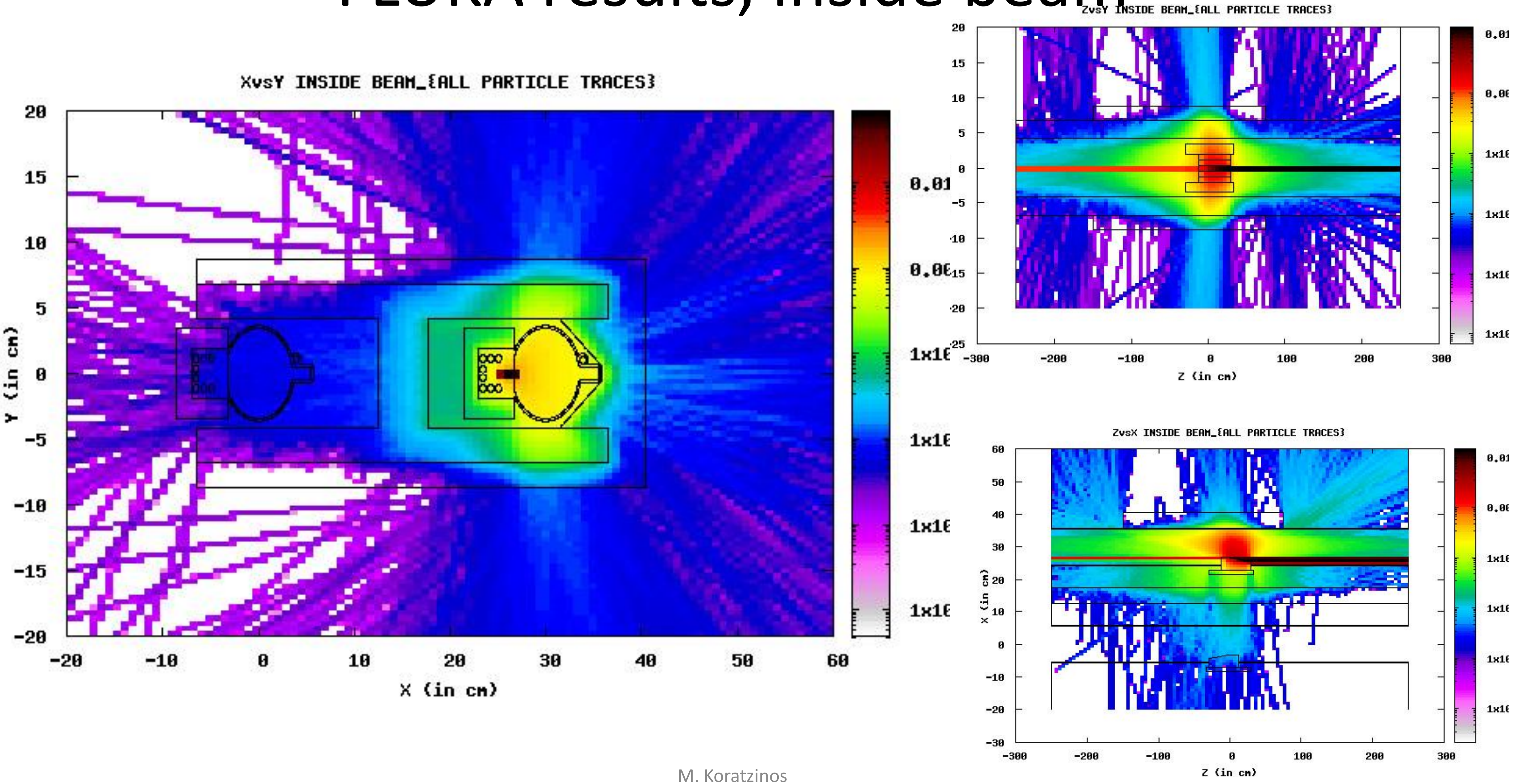


CHART | FCCee CPES

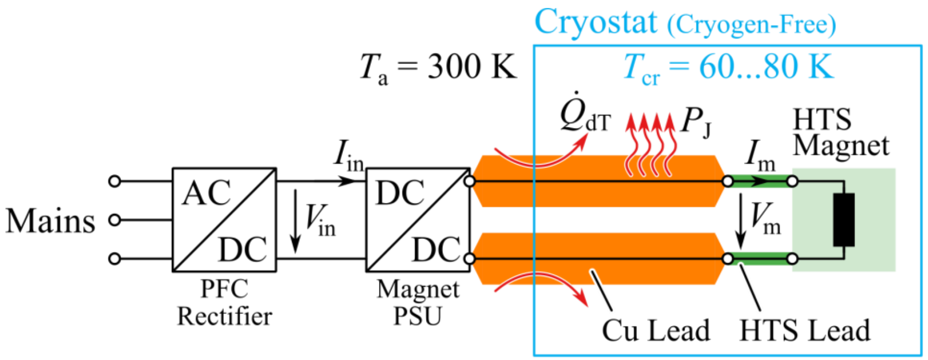
# Slides for FCCee Week

Daifei Zhang, Elias Bürgisser, Mücahid Akbas, Johann W. Kolar, and Jonas Huber
Power Electronic Systems Laboratory, ETH Zürich

June 8, 2024

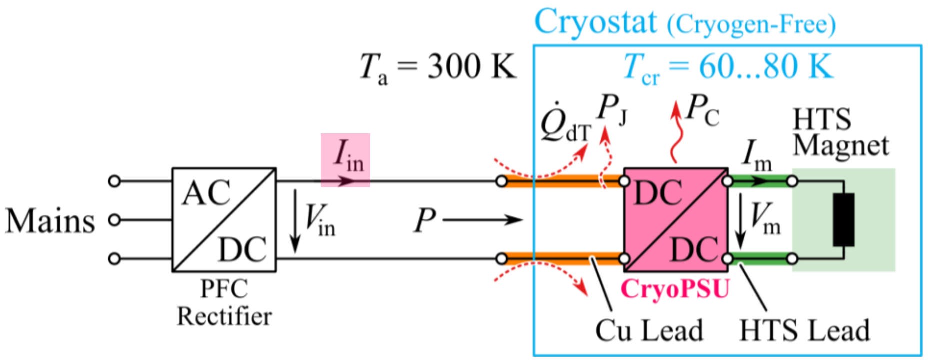
# 250-A Cryogenic Power Electronic Supply (CPES) Concept

■ **Conventional: Power supply unit (PSU) at room-temperature**




- **Minimum leak-in losses: 21 W**
  (250 A, 300 K to 60 K, opt. *L*/*A* leads)

■ **CPES: DC-DC step-down converter *inside* of the cryostat with $V_{in}$ >> $V_m$ and $I_{in}$ << $I_m$**



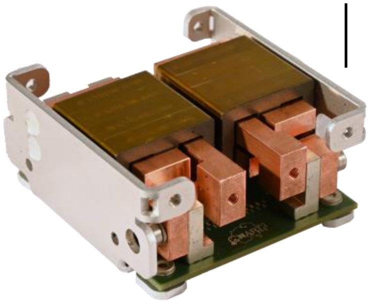

- **Target total losses: 5...6 W (!)**
  (Leak-in plus converter losses)

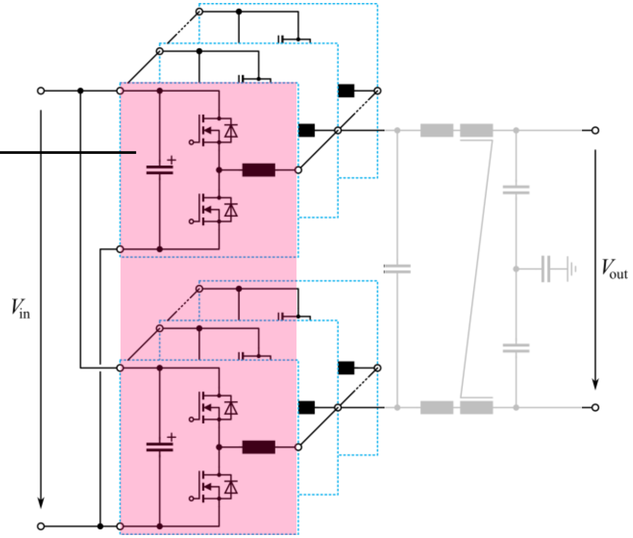
- Extracting 1 W of losses requires about 20 W of cryocooler power (60 K to 300 K) [1] → Ultra-low losses!

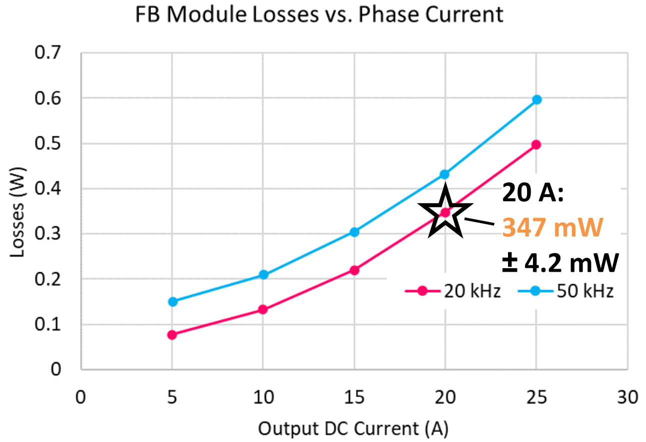

[1] S. Büttner and M. März, "Profitability of low-temperature power electronics and potential applications," *Cryogenics*, vol. 121, p. 103392, Jan. 2022.

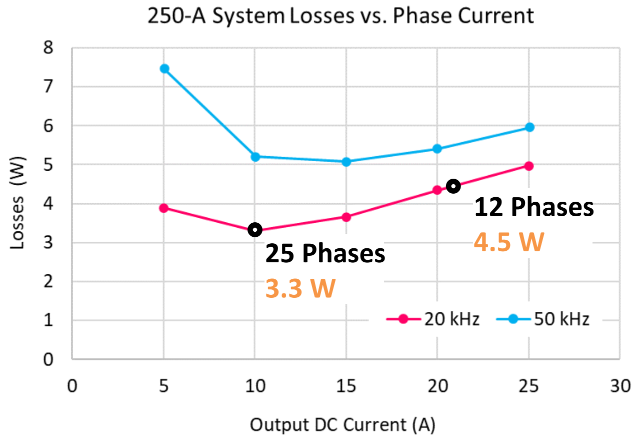
# CPES Demonstrator (1)

- **Full-bridge phase module losses 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



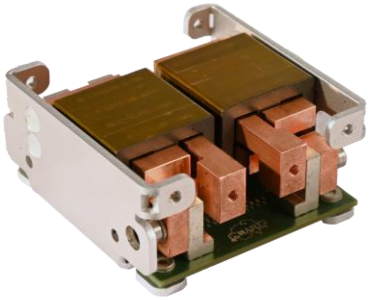



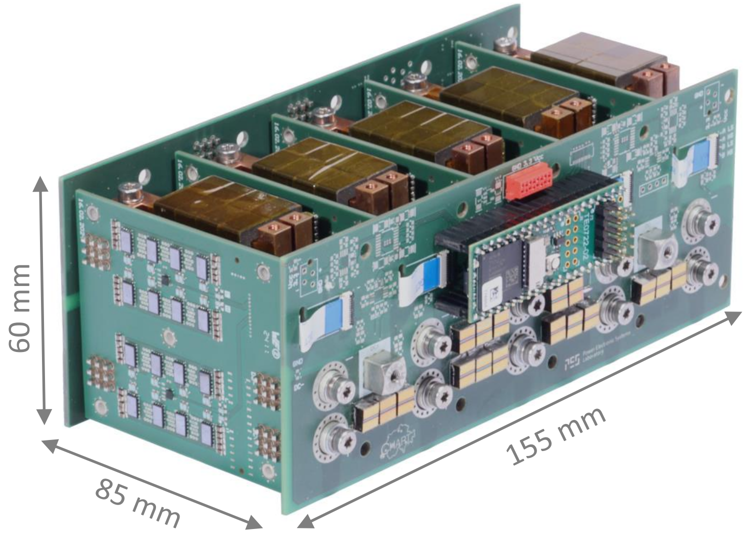




- **250-A system: 4.5 W of losses expected**
  - Estimated based on 12 phase modules @ 21 A each
  - 6 W loss budget leaves 1.5 W for residual leak-in losses, EMI filter, and control electronics
  - Benchmark: 21 W leak-in losses for external (warm) PSU and 60 K cryostat temp.

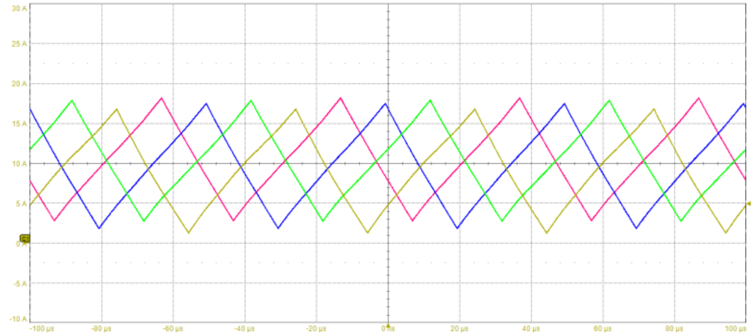
# CPES Demonstrator (2)

- **5-Phase / 100-A demonstrator**
  - Full system (incl. analog & digital sensing/control electronics) tested in $LN_2$ @ 77 K
  - Commissioning of new lossless phase-current balancing

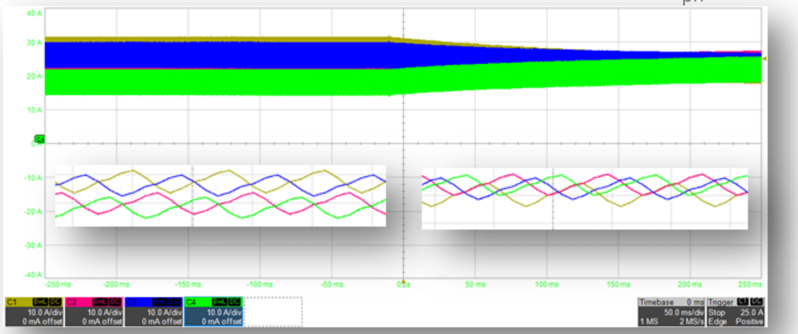





*Exemplary interleaved phase currents ($N_{ph}$ = 4)*



*Exemplary phase current balancing test ($N_{ph}$ = 4)*

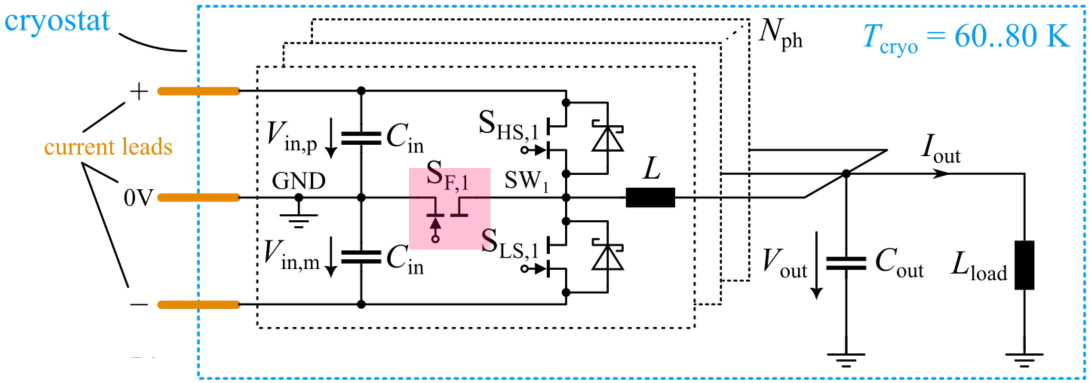


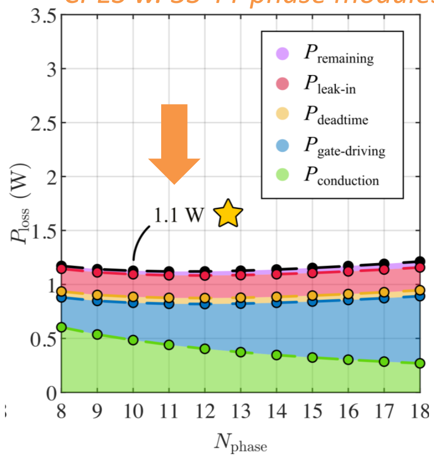
- **Auxiliary power losses**
  - Control FPGA (Xilinx Zynq): 1 W
  - Gate drivers (20 kHz, 5 modules): 300 mW (60 mW per module)

- **Next: System loss characterization and *T* < 77 K**

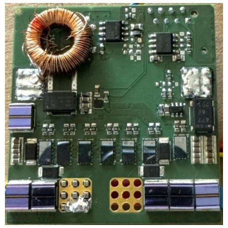
# Outlook: New Three-Switch T-Type (3S-TT) Phase Modules

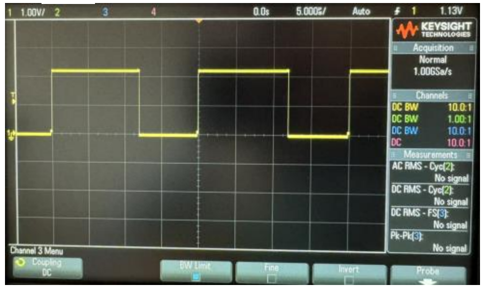
- **Midpoint switch with single transistor enabled by functional symmetry of GaN HEMTs**




- Limited reverse blocking capability of a few volts sufficient for CPES / Commissioning & loss meas. ongoing
- Only one switch in current path compared to two for full-bridge modules






- **Expected further system-level power-stage loss reduction by factor 2…3 (!)**