HTS4

Towards an energy-efficient FCC-ee

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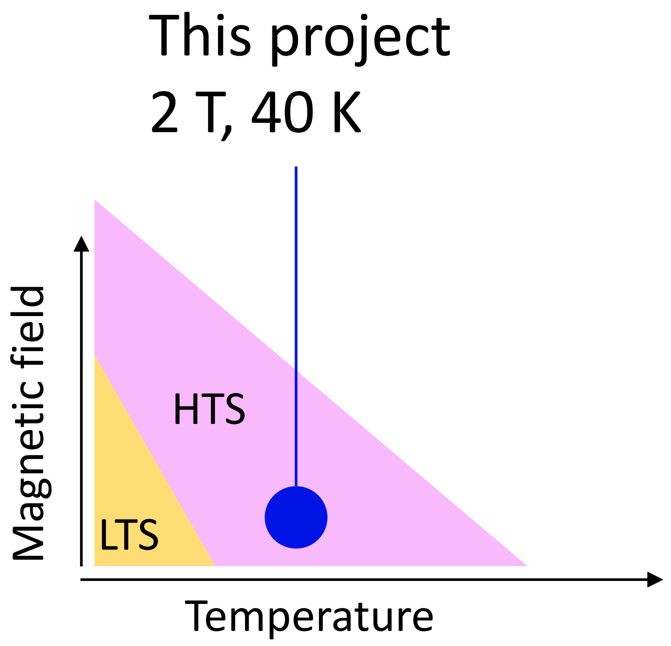
Contents

- HTS4 project goals
- Hardware demonstrators
- Cryogenic cooling & operating temperature
- Powering

High temperature superconductors (HTS)

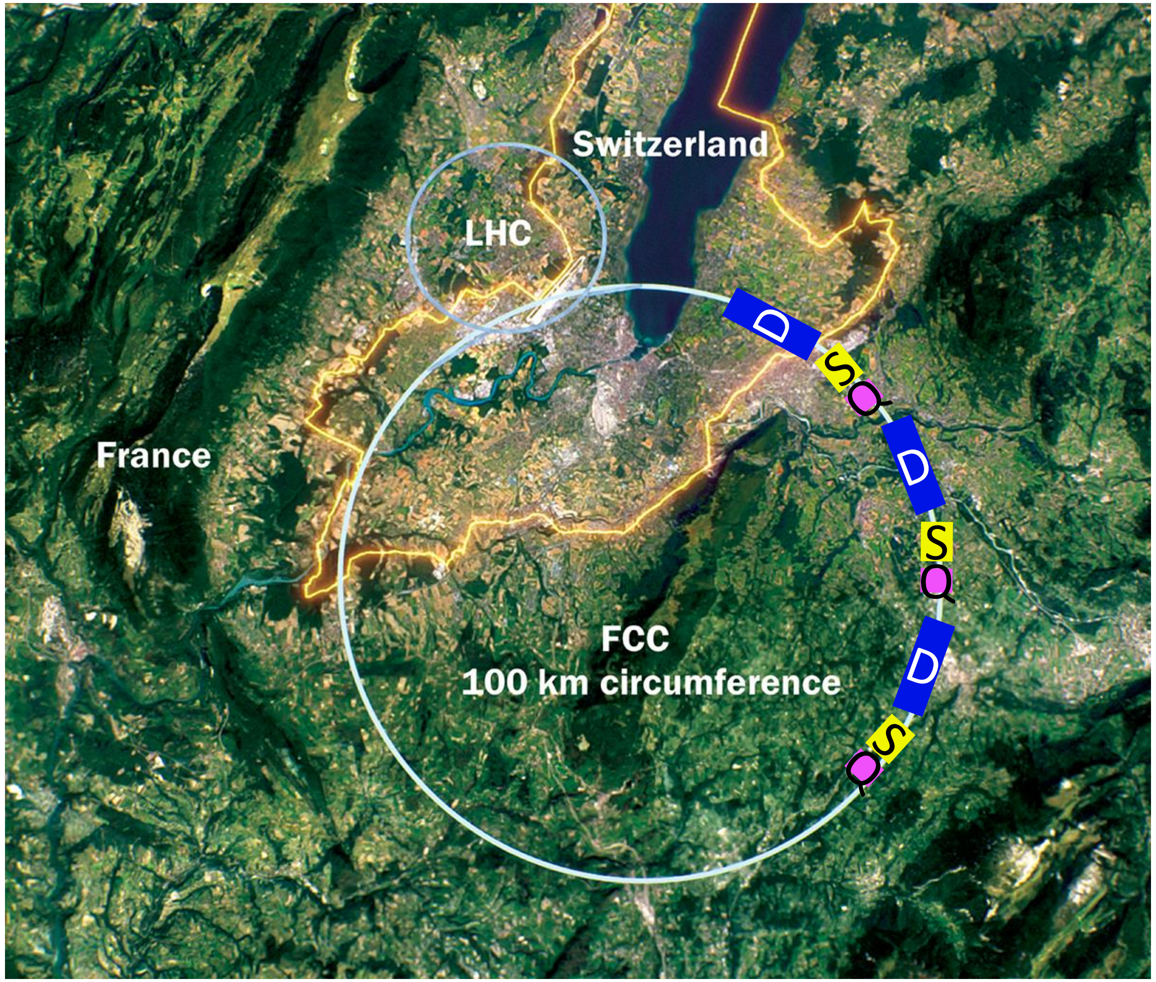
- Superconducting devices *can**
  - Provide otherwise not achievable functionality
  - Increase availibility
  - Make operation more energy efficient
- HTS compared to LTS opens up the design space, both in terms of field and temperature



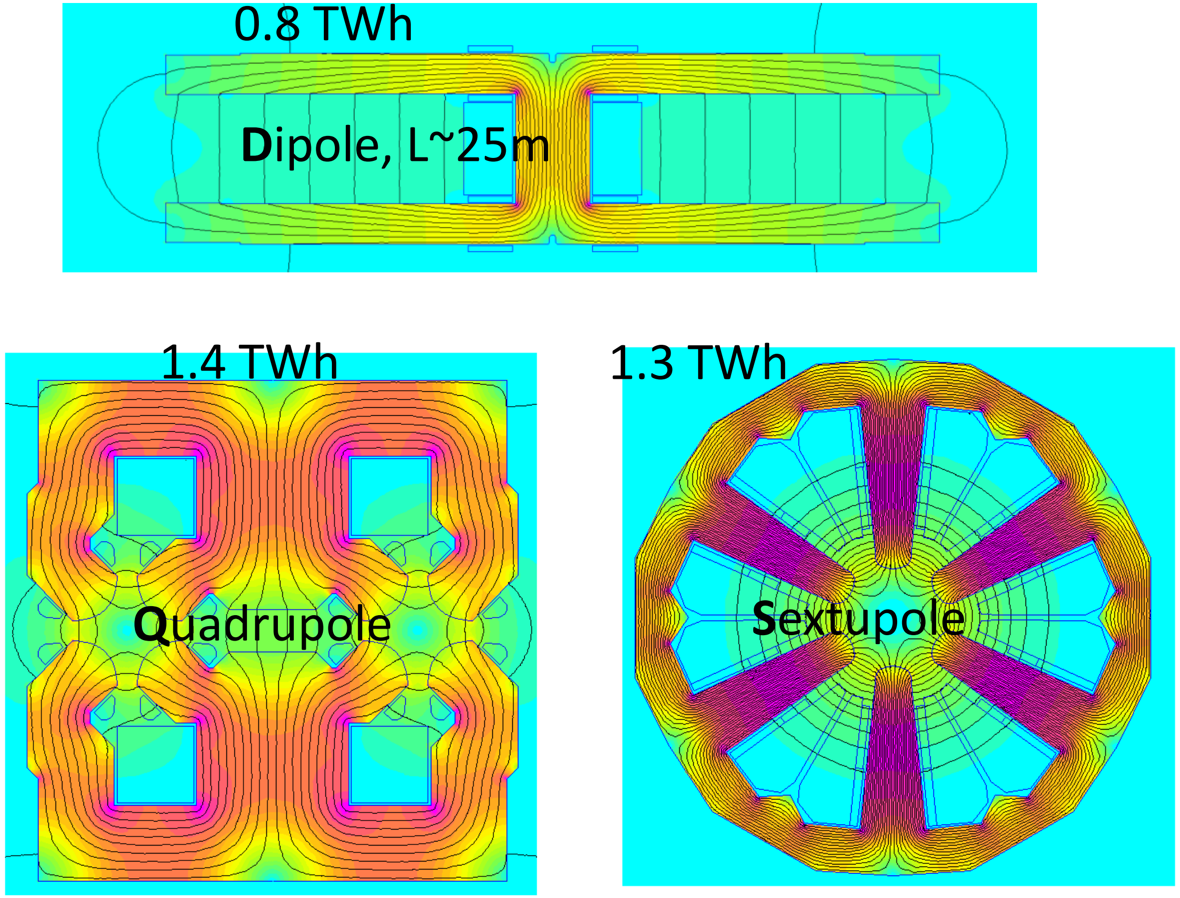
*Not always…

FCC-ee conceptual design

90-100 km ring with normal-conducting magnets



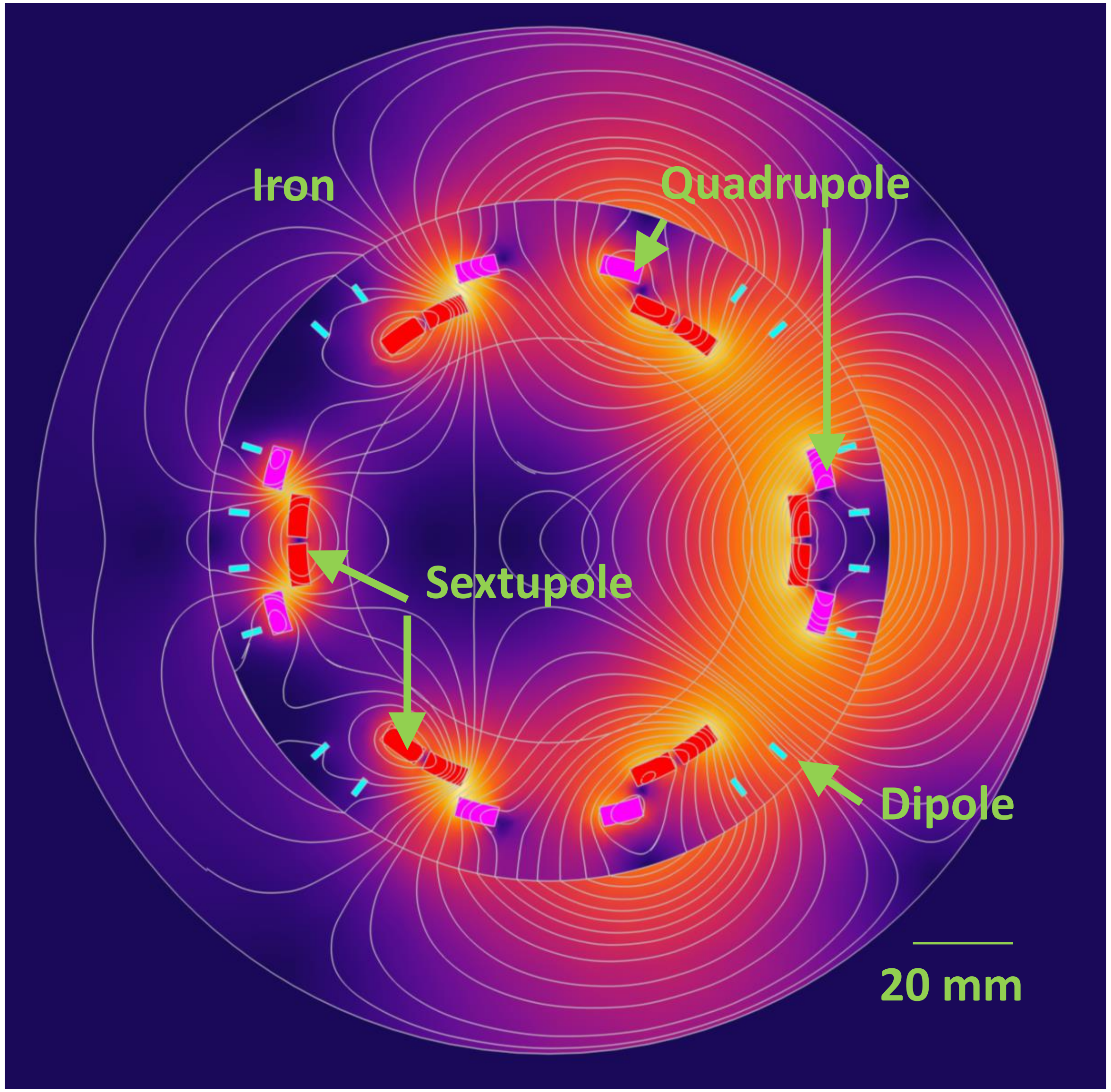
Synchrotron radiation loss → 11.9 TWh



Q+S=*short straight section (SSS), L~3-6 m*

Jeremie Bauche, CERN, FCC week 2024

Proposal: HTS nested dip+sext+quad
HTS short straight section: HTS4



- Save 2.8 TWh on joule heating in S+Q
  Save 2 TWh on SR radiation
  Pay ~ 1 TWh for cryocooling

~20% reduction
of total FCC-ee consumption

- Gain optics flexibility

- Cost competitive (?)

Three related CHART projects

FCC-ee beam dynamics, EPFL

FCC-ee HTS short straight sections (HTS4), CERN/PSI

FCC-ee cryogenic power converter (CPES), ETHZ

Swiss Accelerator
Research and
Technology

Requirements

- 2900 SSS, double aperture,

spaced ~ 30 m from each other along 90 km tunnel

Optics requirements

dipole, sextupole, quadrupole independent

→

Combined function won’t work

Can’t rely on iron

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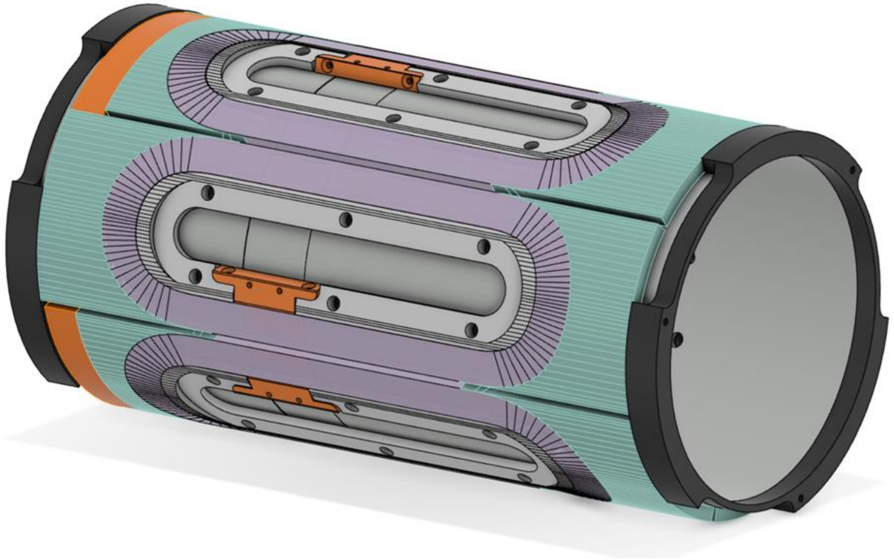
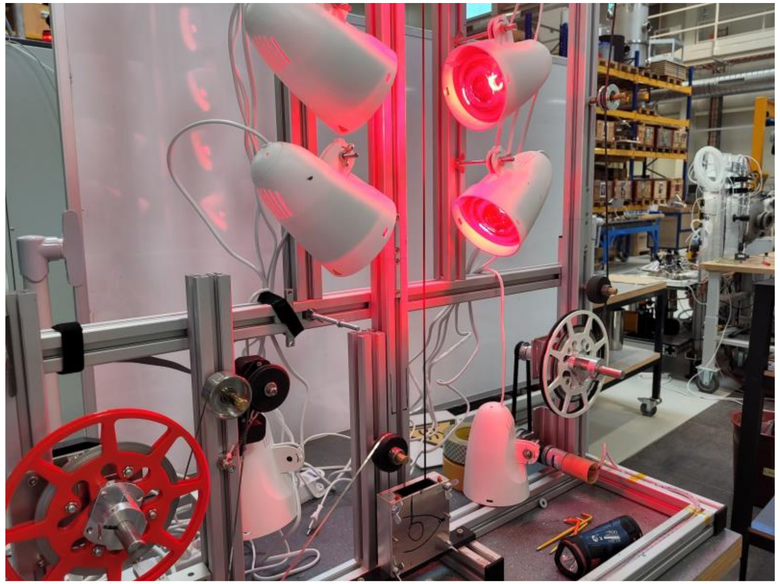
HTS4 hardware plans (1)

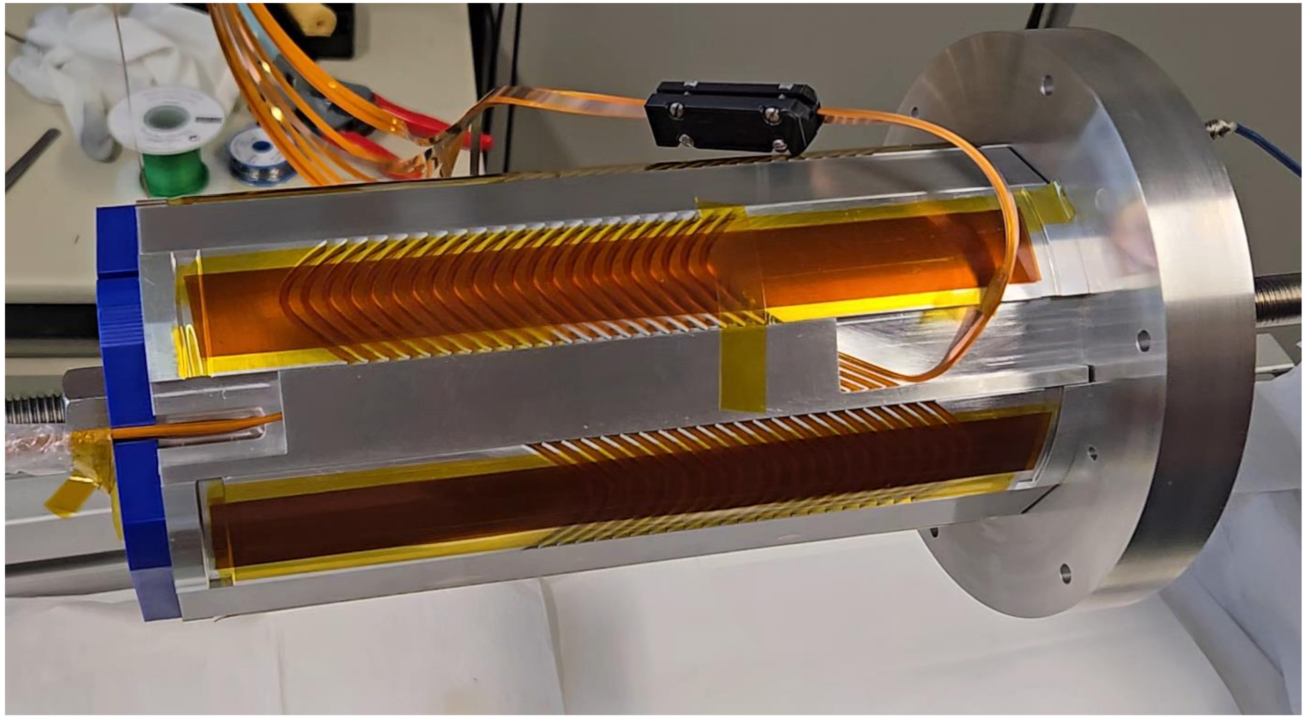
- Sextupole demonstrator, cosine-theta type
- **Self-bonding coating**
  - Allows coil curing after winding. Polyvinylbutyral with silver powder and graphite powder.
  - Coating provides partial-insulation with **controlled resistance**, targeting $100\ \mathrm{m\Omega \cdot cm^2}$

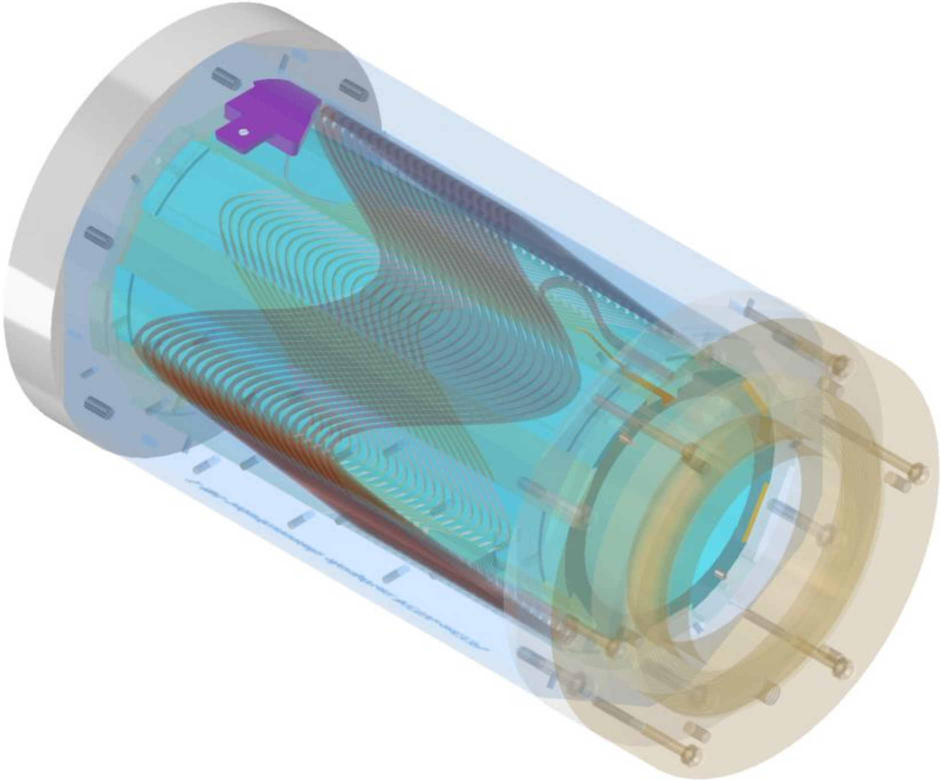




HTS4 hardware plans (2)

- Sextupole demonstrator, canted-cosine-theta type
- Insulated conductor
- Wax impregnated





HTS4 hardware plans (3)

- 1-m prototype
  - Technology choices to be based on lessons from the 2 demonstrators

Contents

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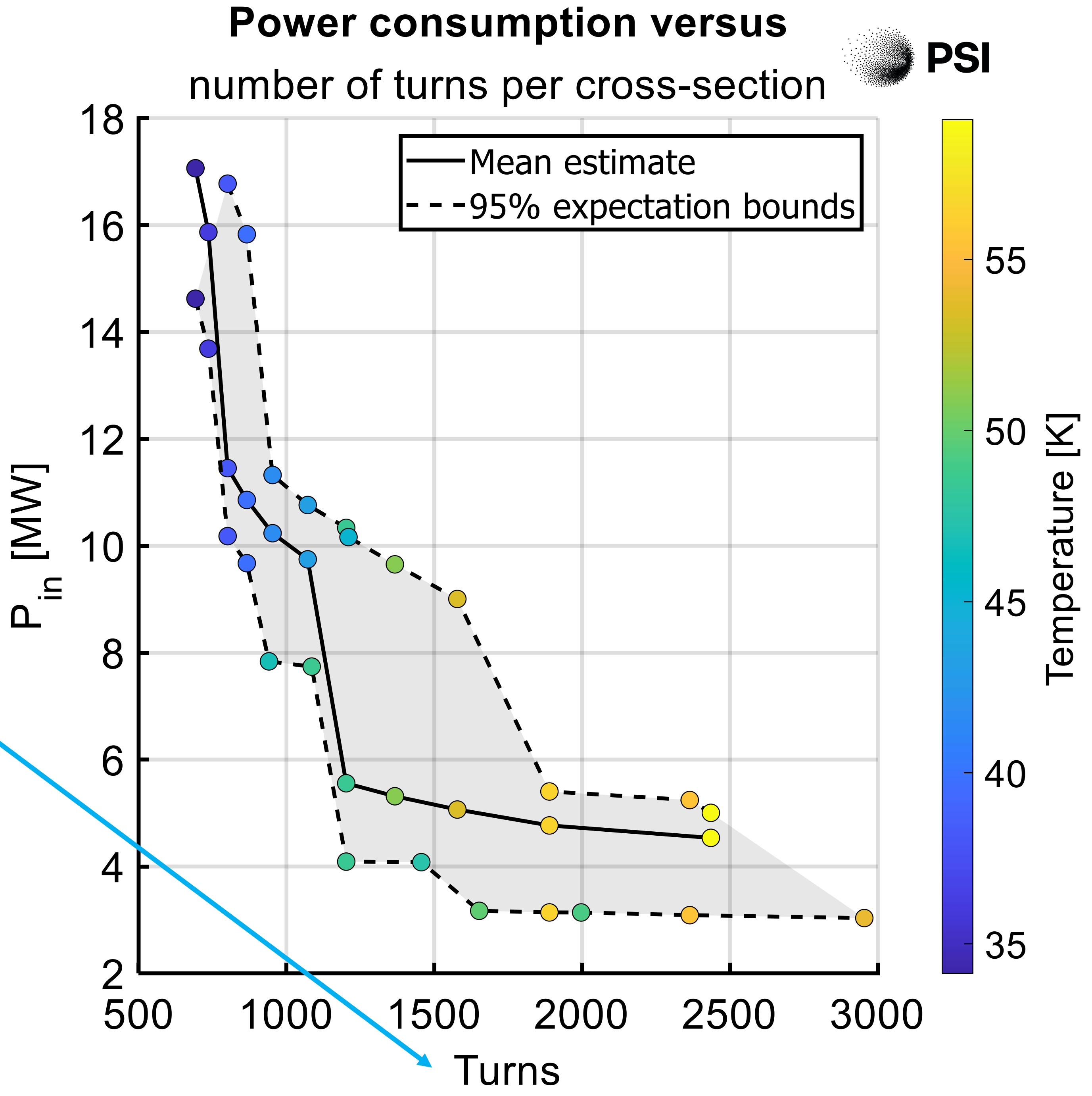
The **optimum operating temperature** depends on the price of

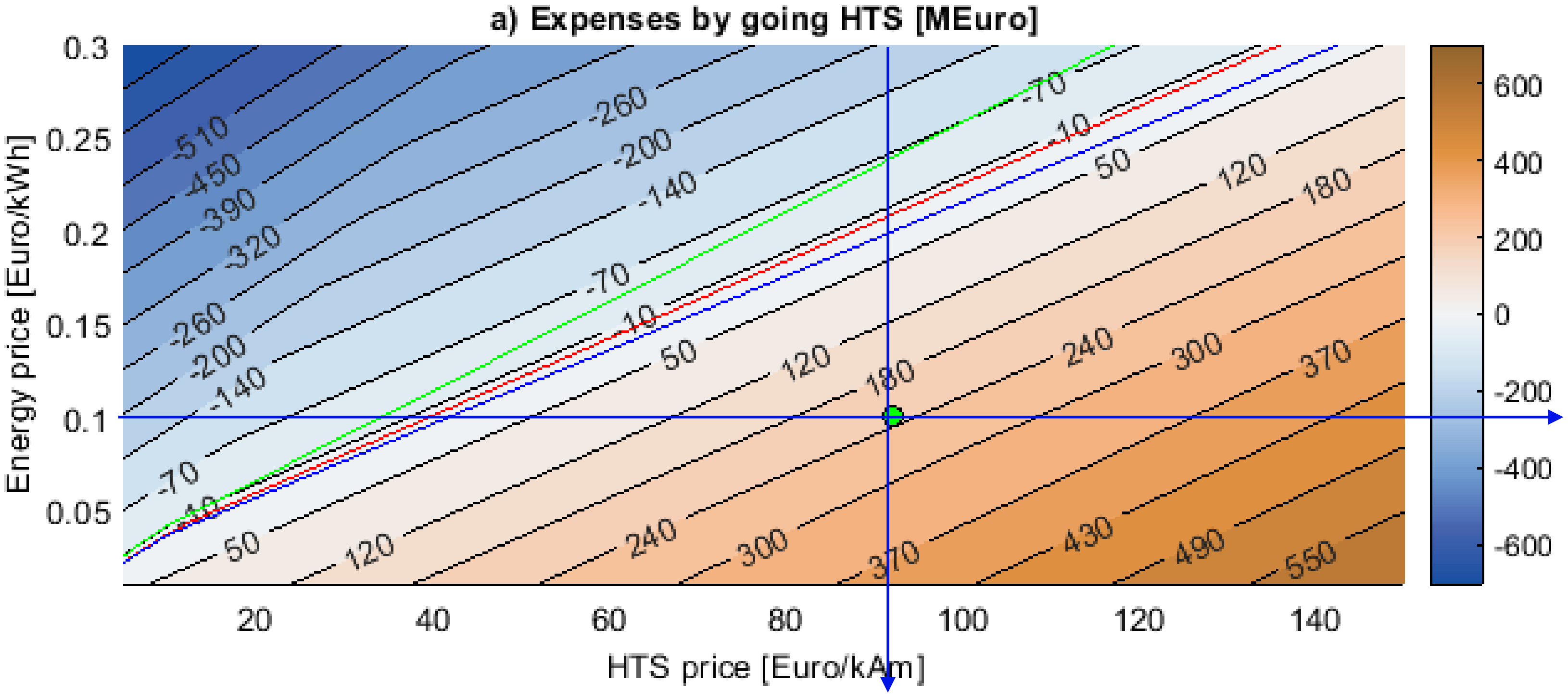
- electricity
- HTS conductor

The sweet spot is around **40 K** across a wide range of costs



HTS vs NC option

$$\Delta \text{costs} = \Delta \text{costs}_{\text{electricty}} + \Delta \text{costs}_{\text{capital}}$$



2023 estimate for CERN

2024 estimate

Cryocooler-based HTS SSS more expensive than room-temp option
… for now

*RF hardware saving not taken into account

Cooling

Route 1) Centralized cooling plant with distribution line

+Thermal switch to connect to each SSS

Route 2) Individual cooling of each magnet

Unknown: radiation aspects

Cryocooler based option

Individual cooling of each magnets, via high-reliability single-stage coolers+redundancy

Variable frequency operation

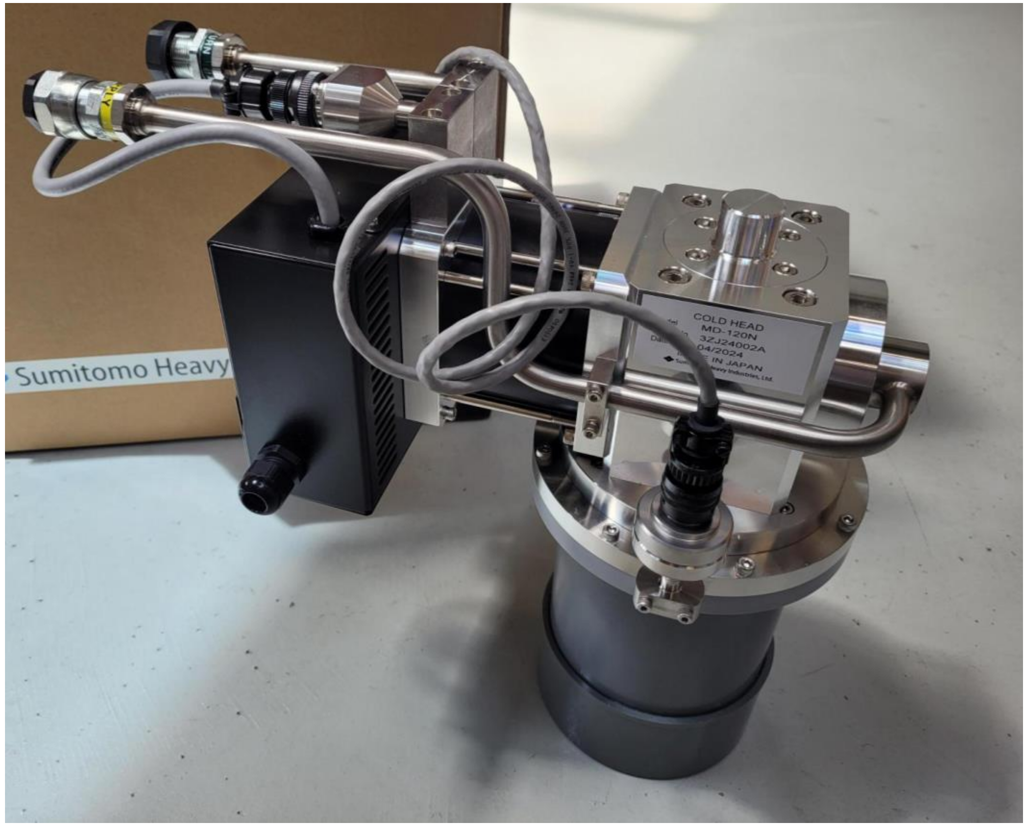
Cooling system (2900 magnets, 8700 coldheads)

Reliability	(1 year)	0.9939
Availability	(1 year)	0.9995

In-tunnel maintenance 300 FTE-days/year

Unknown: radiation aspects

10.1109/TASC.2023.3346847



Alternative: cryogenic distribution line

Contents

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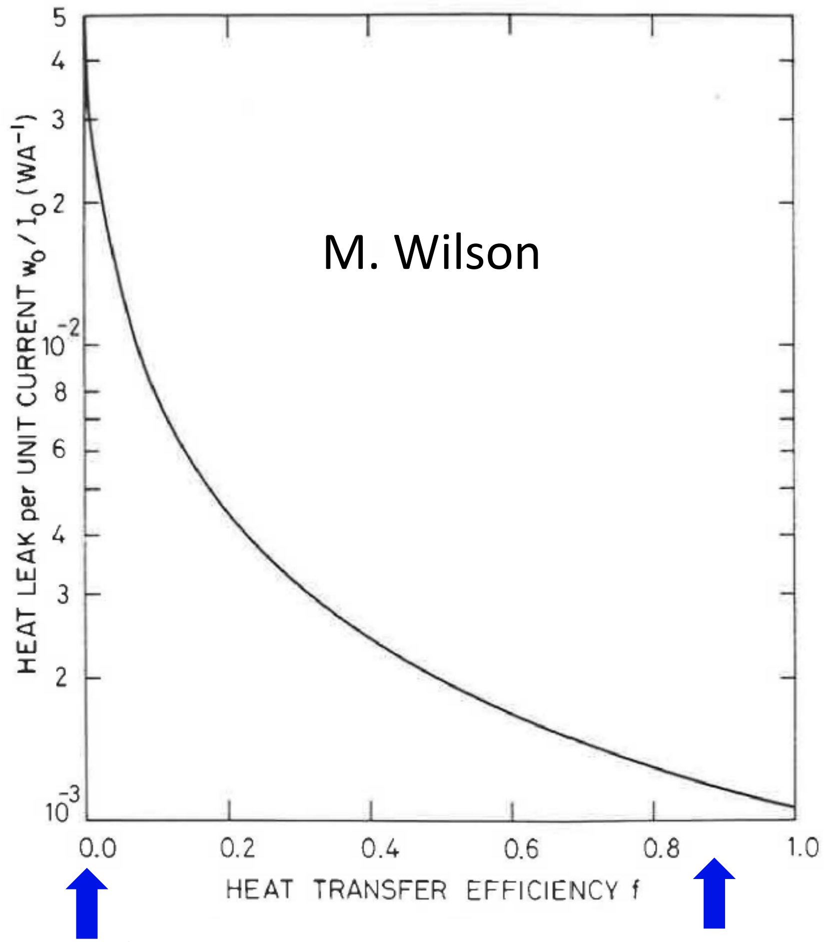
Current leads

High current conduction-cooled leads result in a big heat load

E.g. 2 kA leads in PSI test stand need dedicated cryocooler (7 kW power draw)



M. Wilson

Conduction-cooled

Gas-cooled

Cryogenic Power Electronic System

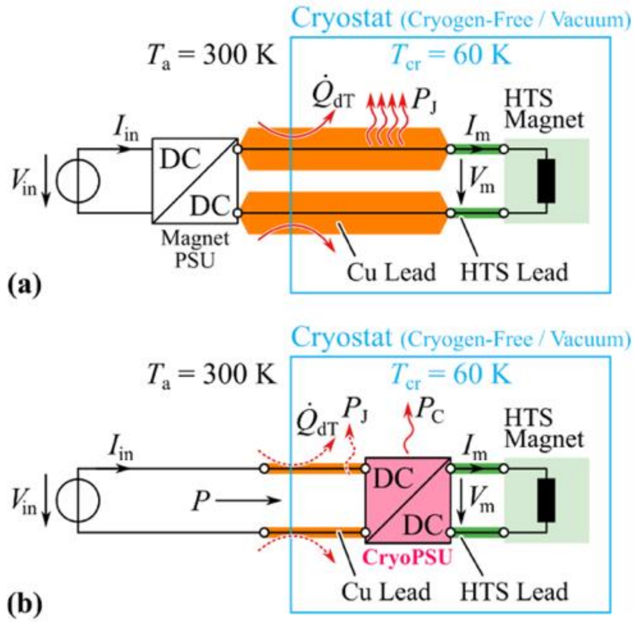
Swiss Accelerator
Research and
Technology

In support of FCCee HTS4, CPES develops a cryogenic power supply which, in its first iteration, may reduce heat load to cold source by 70%.

First 5-phase 100-A demonstrator successfully tested in LN2.

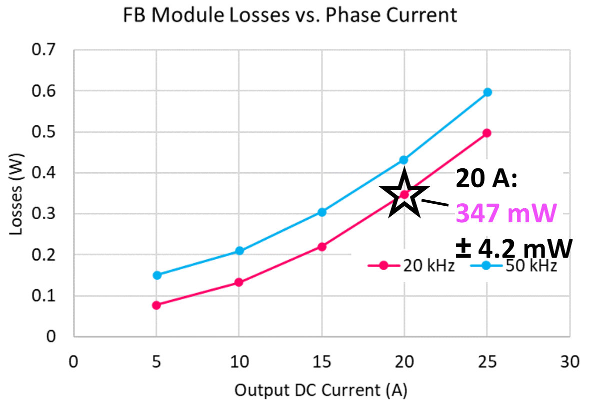
Next steps:

- low-temperature testing
- Reliability engineering
- Scale-up of I_{op}



Societal Impact:

Interest by Airbus in CPES collaboration.



Follow-up projects should tackle:

Availability + Maintainability = Dependability and

Radiation hardness for FCC-ee

and scaling to higher currents (10-20 kA range) for HFM

Courtesy J. Huber, D. Zang. ETHZ

Conclusions

Moving from room-temp to HTS magnets can reduce FCC-ee power consumption significantly (~20%)

Demonstrators are under constructions

Cryocooler-based HTS short straight sections might be cost-effective in the future

But radiation might be a show-stopper

Cryogenic dc/dc convertor might make conduction-cooled systems much more energy efficient

Distributed cooling line is under investigation

Requirements

- 2900 SSS, double aperture,

spaced ~ 30 m from each other along 90 km tunnel

Optics requirements ⇒ Combined function won’t work

dipole, sextupole, quadrupole independent ⇒ Individual power supply (=6x) OR shared+trim

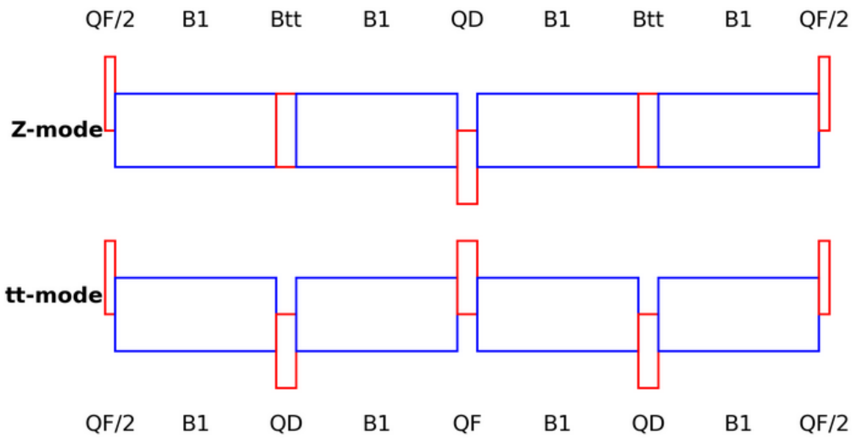
Synchrotron radiation intercepted at discrete locations ⇒ Make the magnet as short as possible

Longer magnet→longer distance between stoppers→larger bore

Quadrupole can not be shorter than 2.9 m

Dipole filling factor as high as possible ⇒ Dipole, quadrupole, sextupole share the same axial space (nested)

Requirements



Via EPFL (Leon Van Riesen-Haupt , Cristobal Garcia)

Z

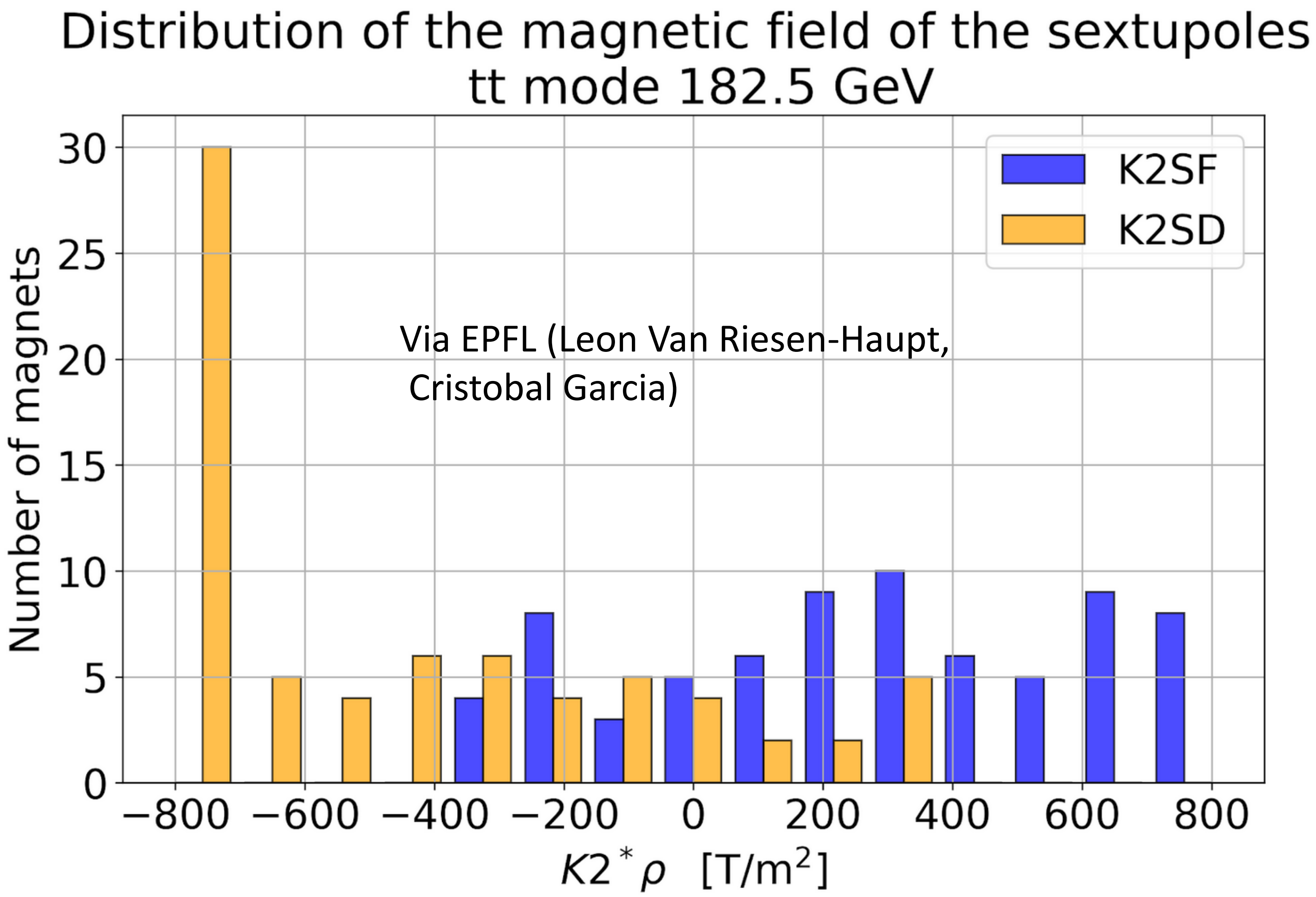
Element	Magnetic component		Baseline Fields		CFMs	
	Dipole	Quad	Dipole [T]	Quad [T/m]	Dipole [T]	Quad [T/m]
Mian Dipoles	B1	- - -	0.0152	- - -	0.0125	- - -
Quad F	Bf	QF	- - -	1.449	0.0067	1.449
Quad D	B1	QD	- - -	-1.449	0.0125	-1.449

$t\bar{t}$

Element	Magnetic component		Baseline Fields		CFMs	
	Dipole	Quad	Dipole [T]	Quad [T/m]	Dipole [T]	Quad [T/m]
Mian Dipoles	B1	- - -	0.0612	- - -	0.0503	- - -
Quad F	Bf	QF	- - -	11.860	0.0271	11.860
Quad D	B1	QD	- - -	-11.860	0.0503	-11.860

Dipole x 4
Quad x 8

How about the sextupole?



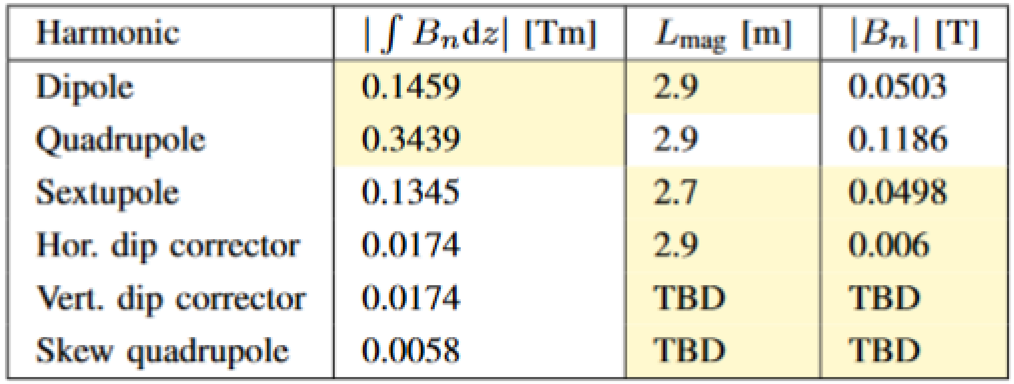
Via EPFL (Leon Van Riesen-Haupt, Cristobal Garcia)

Many different sextupole strengths

Configurations with less families NOT actively studied

Requirements

Via EPFL/CERN



Harmonic	$\lvert\int B_n \mathrm{d}z\rvert$ [Tm]	L_{mag} [m]	$\lvert B_n\rvert$ [T]
Dipole	0.1459	2.9	0.0503
Quadrupole	0.3439	2.9	0.1186
Sextupole	0.1345	2.7	0.0498
Hor. dip corrector	0.0174	2.9	0.006
Vert. dip corrector	0.0174	TBD	TBD
Skew quadrupole	0.0058	TBD	TBD

Quadrupole can not be made shorter (quadrupole synchrotron radiation)

→bad news for short but powerful independent harmonics

State of art

When CFMs are introduced into the lattice, the Damping Partition change due to the **introduction of a dipolar component** in the quadrupoles.

The problem comes from the radiation integral I4, that depends on the sign of K1.

$$I_2 = \oint \frac{1}{\rho^2} ds \, , \qquad I_4 = \oint \frac{D_x}{\rho} \left(2\, k_1 + \frac{1}{\rho^2} \right) ds \, ,$$

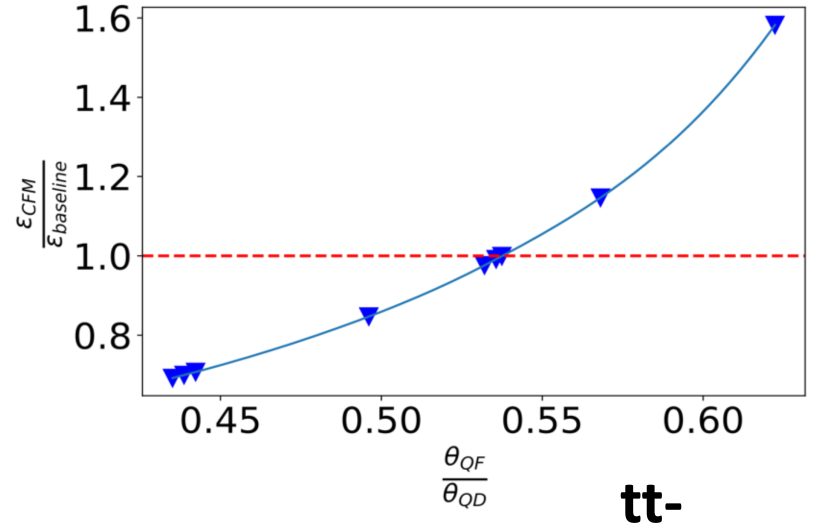
$$I_5 = \oint \frac{\mathcal{H}(s)}{|\rho^3|} ds \, , \qquad J_u = 1 - \frac{I_4}{I_2} \, ,$$

$$\epsilon_u = C_q \frac{\gamma^2}{J_u} \frac{I_{5u}}{I_2} \, , \qquad \tau_u = \frac{2E}{J_u U_0} T_0 \, ,$$

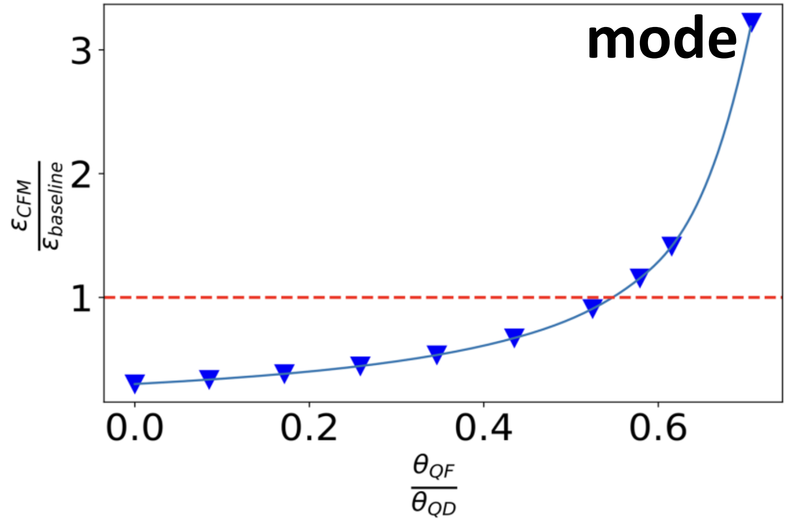
We studied different ratios of bending angles in QF and QD CFMs

→ The ratio of fields (or bending angles) must be 0.53 to achieve the nominal emittance.

Z-mode



tt-mode



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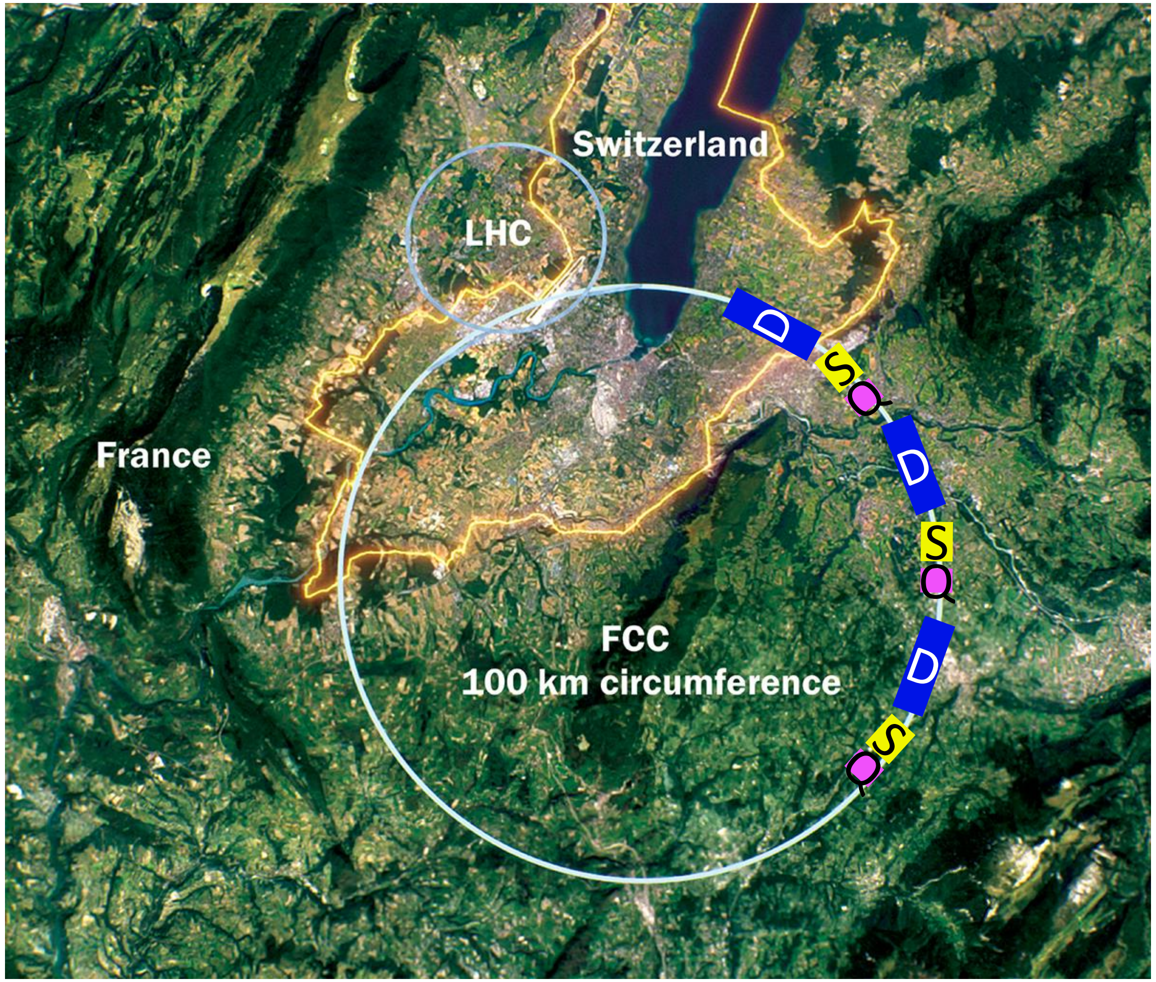
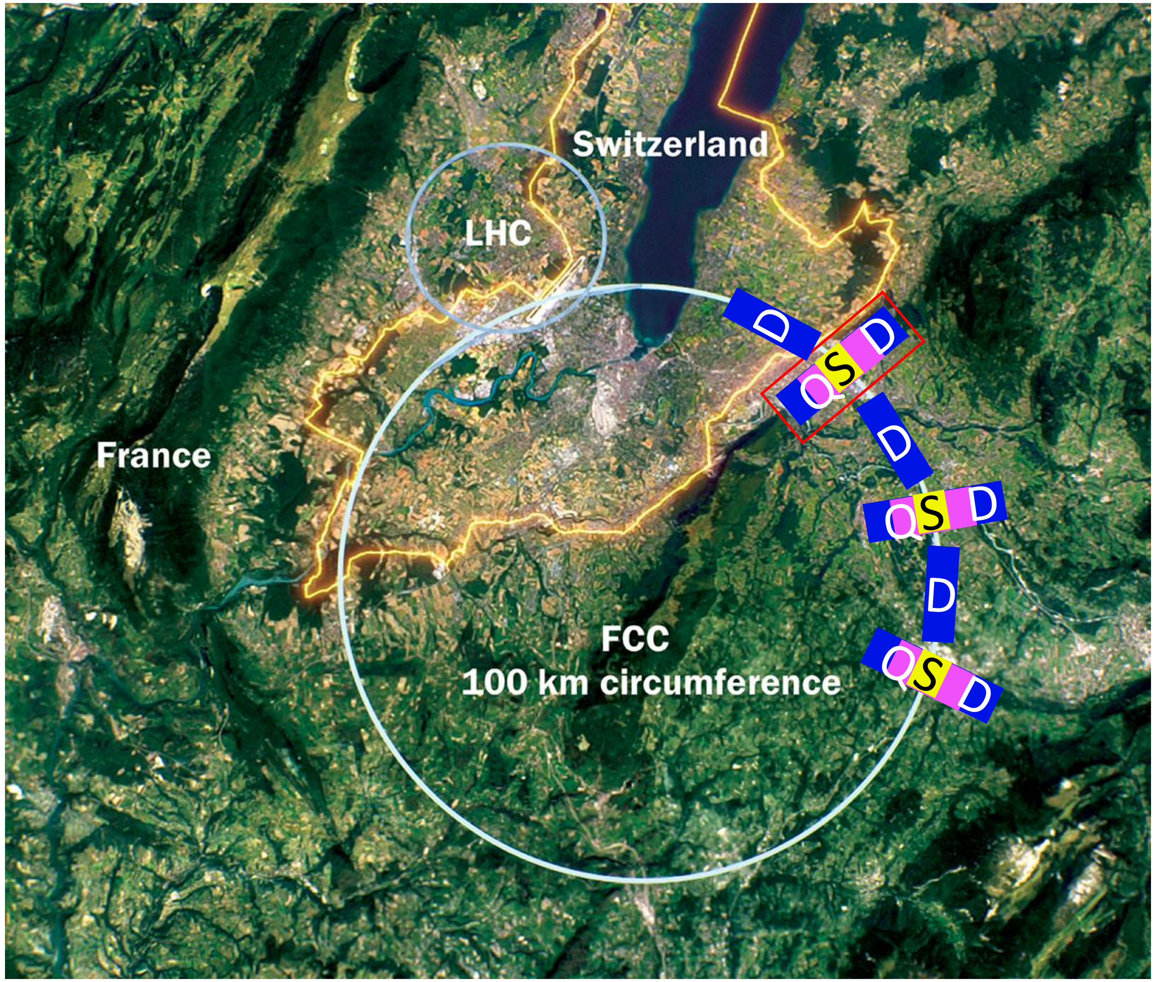
HTS short straight section: HTS4



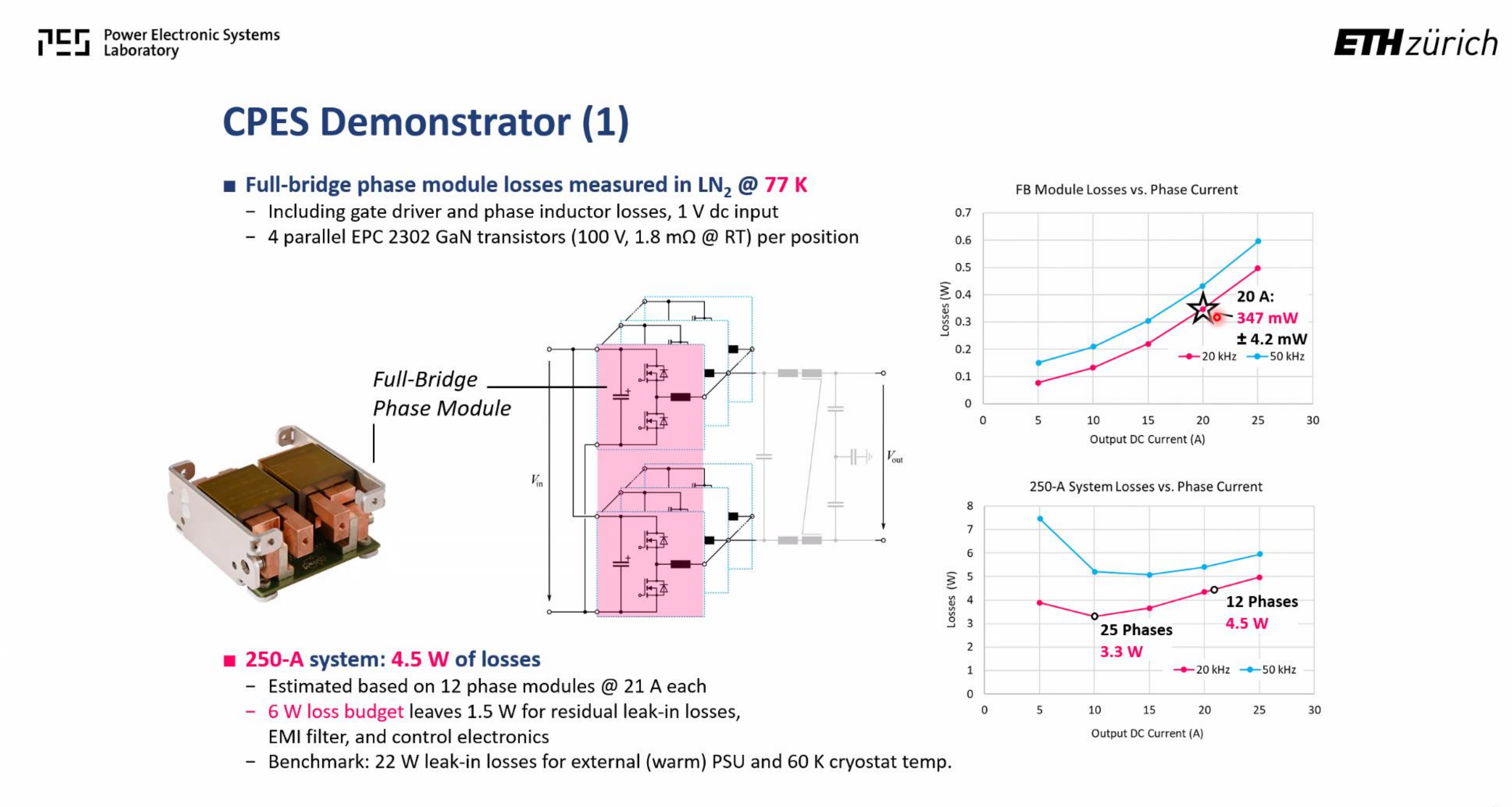


Save 2.8 TWh on joule heating in S+Q
Save 2 TWh on SR radiation
Pay ~ 1 TWh for cryocooling

~20% reduction
of total FCC-ee consumption

Cryogenic dc/dc convertor

5-10x more efficient than high-current leads



Power Electronic Systems Laboratory

ETH zürich

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**
  - 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.

Unknown: radiation aspects

Jonas Huber et al, ETHZ

CHART project FCC-ee cryogenic power converter (CPES), ETHZ