Fast Cycled superconducting Magnets (FCM) for PS2

WAMSDO, May 23rd, 2008

Presented by L. Bottura

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Outline

- Motivation
- Superconducting magnet design
- R&D target and issues
- Medium term plan
- Conclusions and perspectives

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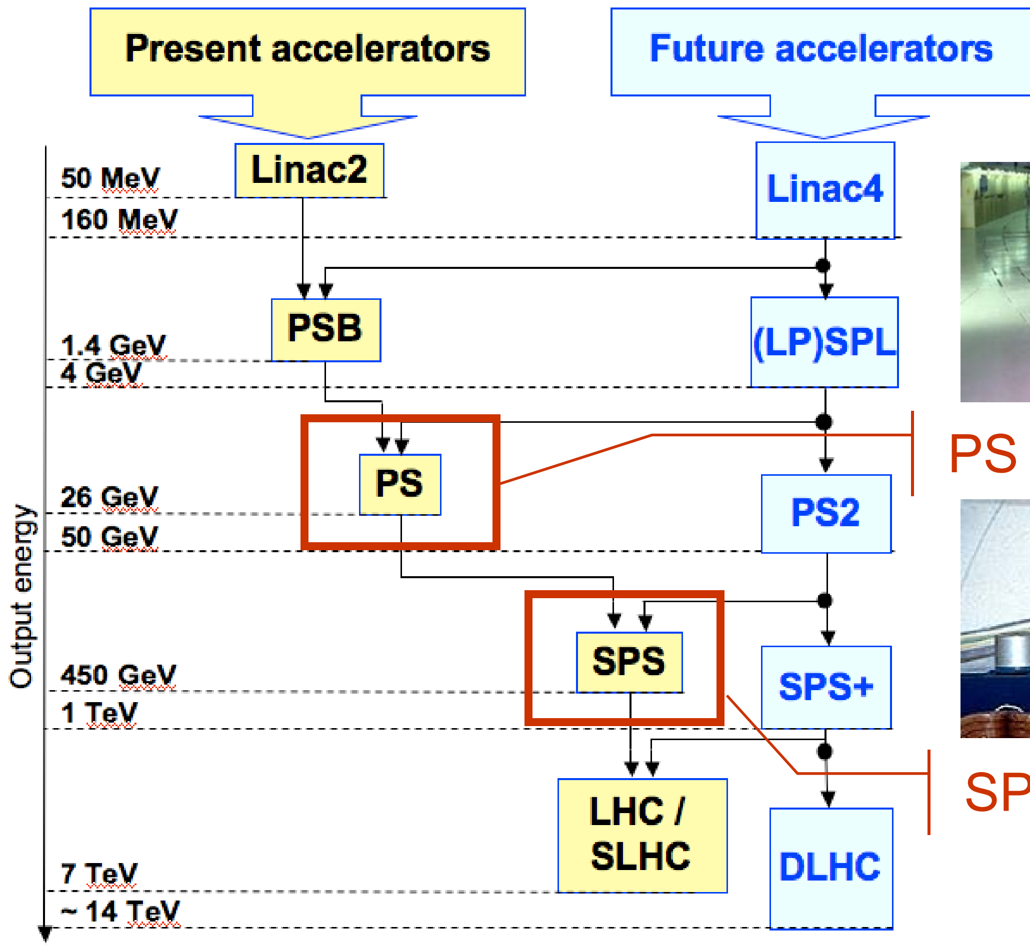
Courtesy of R. Garoby, CERN

The LHC Accelerator Chain



PS was built in 1959

SPS was commissioned in 1976

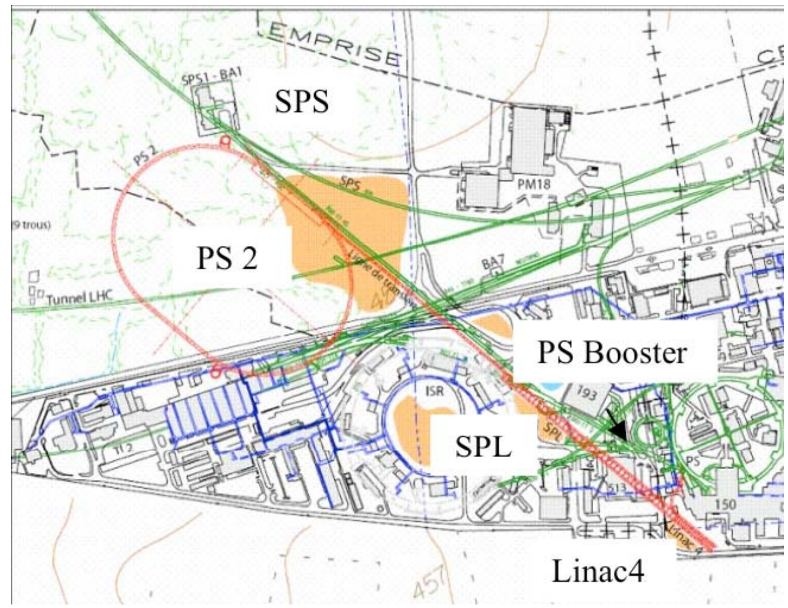
Magnet design by courtesy of Th. Zickler, CERN

PS2: Magnet Requirements

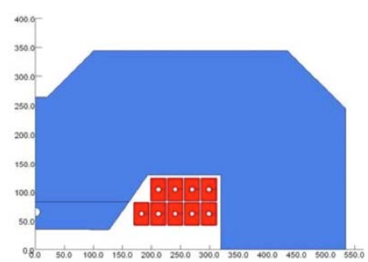
- PS2 will be an accelerator with a length of ≈ 1.3 km
  - Injection at 3.5 GeV
  - Extraction at 50 GeV
  - 200 dipoles
    - Nominal field: 1.8 T
    - Ramp-rate: 1.5 T/s
    - Magnet mass: ≈15 tons
  - 120 quadrupoles
    - Nominal gradient 16 T/m
    - Ramp-rate: 13 T/ms
    - Magnet mass: ≈4.5 tons
- Average electric power ≈ 15 MW
  - The magnets require ≈ 7.5 MW, i.e. about 50 % of the total consumption

Modest requirements

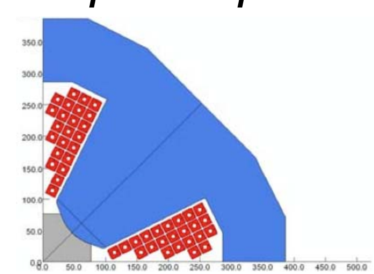
The location of the new PS2



dipole



quadrupole



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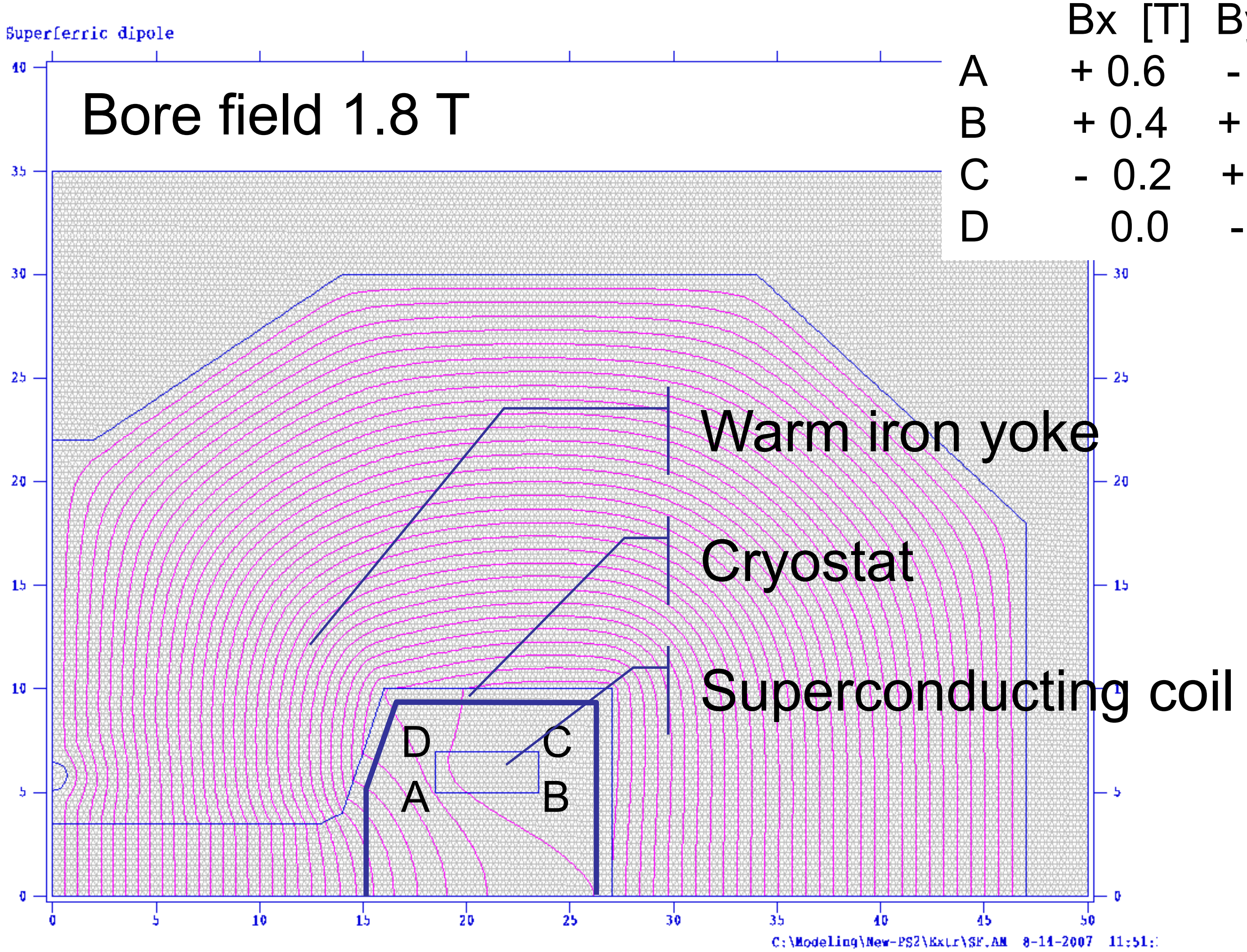
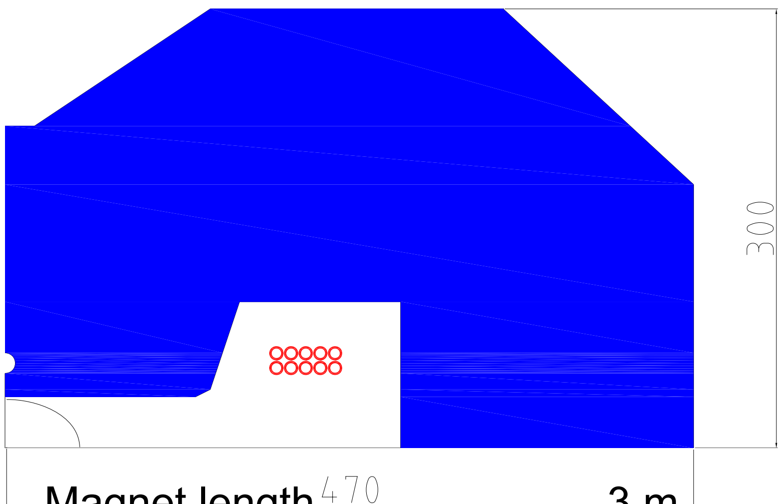
Design by courtesy of D. Tommasini and M. Karppinen, CERN

Iron Dominated SC Dipole

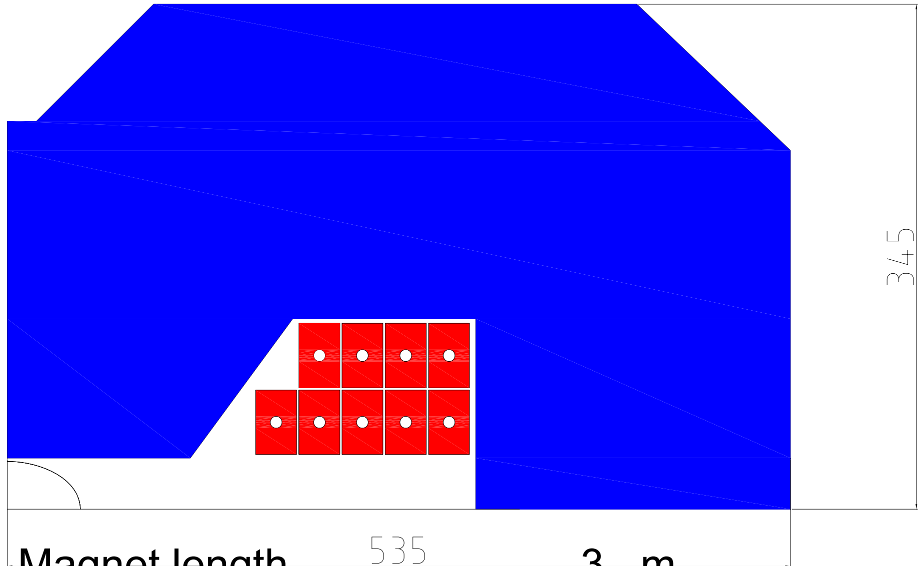


	Bx [T]	By [T]	Bmod [T]
A	+ 0.6	- 0.8	1.0
B	+ 0.4	+ 0.2	0.4
C	- 0.2	+ 0.2	0.3
D	0.0	- 0.7	0.7

Comparison of Dipole Designs



Magnet length	3 m
Number of magnets	200
Iron weight	**10 tons**
Peak current @ 1.8 T	5300 A
Current rise rate	4830 A/s
Number of turns	2x10
Inductance	7 mH
Peak voltage	34 V

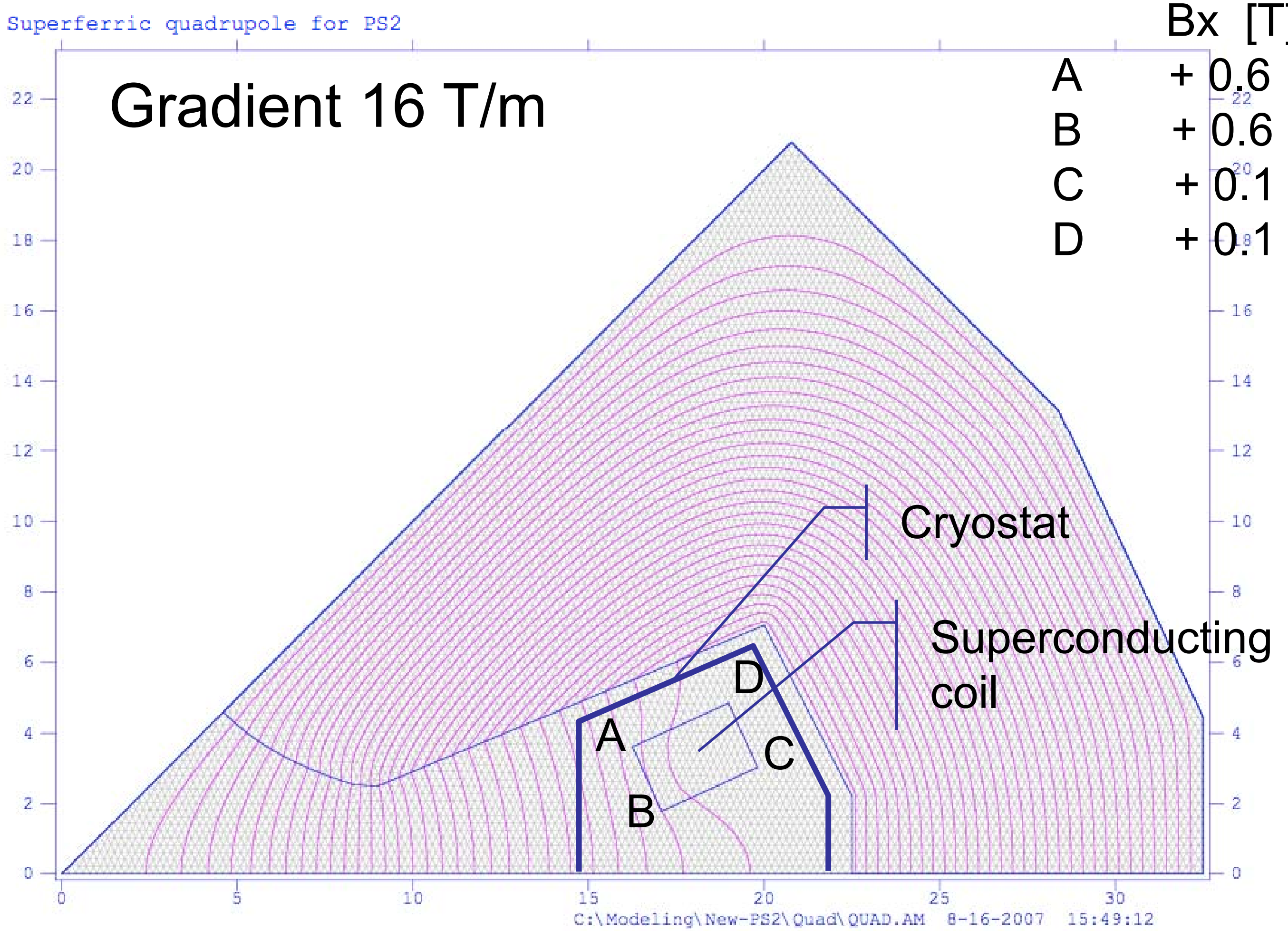


Magnet length	3 m
Number of magnets	200
Iron weight	**15 tons**
Peak current @ 1.8 T	5775 A
Current rise rate	5260 A/s
Number of turns	2x9
Inductance	6 mH
Resistance	1.7 mΩ
RMS Current	3990 A
Power consumption	27 kW
Peak voltage	41 V

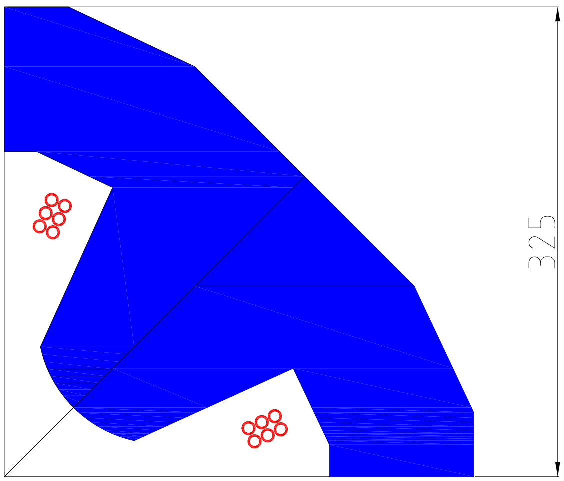
Design by courtesy of D. Tommasini, CERN

Iron Dominated SC Quadrupole

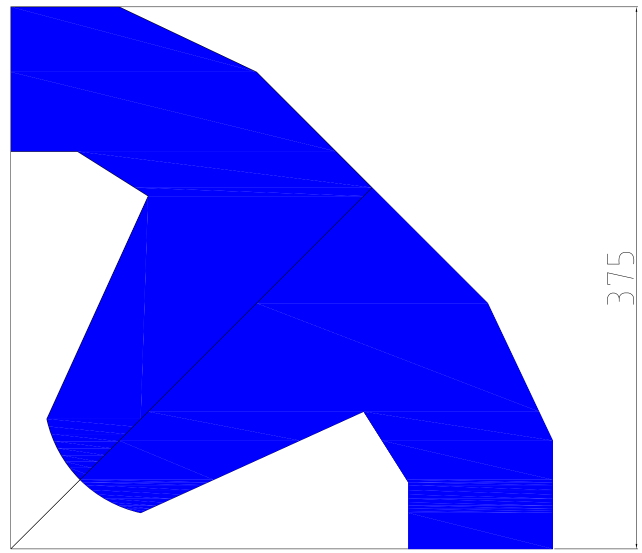
	Bx [T]	By [T]	Bmod [T]
A	+ 0.6	0.0	0.6
B	+ 0.6	0.0	0.6
C	+ 0.1	0.0	0.1
D	+ 0.1	0.0	0.1



Comparison of quad designs



Magnet length	1.75 m	
Number of magnets	120	
Iron weight	**2.8**	**tons**
Peak current @ 16 T/m	4600	A
Current rise rate	3830	A/s
Number of turns	4x6	
Inductance	**2.2**	**mH**
Peak voltage	**8**	**V**



Magnet length	1.75 m	
Number of magnets	120	
Iron weight	**4.4**	**tons**
Peak current @ 16 T/m	1200	A
Current rise rate	1000	A/s
Number of turns	4x23	
Inductance	**35**	**mH**
Resistance	26.7	mΩ
RMS Current	830	A
Power consumption	18	kW
Peak voltage	**67**	**V**

Cost of NC PS2 by courtesy of M. Benedikt

Cost comparison - investment

- NC magnets
  - Dipoles: 30 MCHF
  - Quadrupoles: 9 MCHF
  - Testing: 1 MCHF
  - Auxiliaries: 1.5 MCHF
- Power converters
  - Total: 19.3 MCHF
- Cooling and ventilation
  - Total: 1.1 MCHF
- **Total cost: 61.9 MCHF**

- SC magnets
  - Dipoles: 21.3 MCHF
  - Quadrupoles: 6.6 MCHF
  - Testing: 3.2 MCHF
  - Auxiliaries: 4 MCHF
- Cryogenics
  - Plant + lines: 13.5 MCHF
  - Building: 3.1 MCHF[1]
- Power converters
  - Total: 15 MCHF
- Cooling and ventilation
  - Total: 1.1 MCHF[2]
- **Total cost: 67.8 MCHF**

[1] Scaled to 1/2 of estimate for the 15 kW plant

[2] Assume the same as for NC magnets, benefiting from lower power requirement

Installed power of NC PS2 by courtesy of M. Benedikt

Power requirements

Electrical consumption	**NC**	**SC**
Main Magnets	7.5 MW	0 MW
RF	2 MW	2 MW
Other systems	3 MW	3 MW
Cryoplant	0 MW	1.3 MW
Water cooling station	1.2 MW	0.4 MW
Ventilation	0.5 MW	0.5 MW
Climatisation	0.4 MW	0.4 MW
Total consumption	***14.6 MW***	***7.6 MW***

Cost of NC PS2 by courtesy of M. Benedikt

Cost comparison - operation

- NC magnets
  - Energy: 14.6 MW * 6000 hrs/yr
  - Energy cost[1]: 3.8 MCHF/yr
- Total cost: 3.8 MCHF/yr

- SC magnets
  - Energy: 7.6 MW * 6000 hrs/y
  - Energy cost[1]: 1.9 MCHF/yr
  - Cryo maintenance: 0.3 MCHF/yr
- Total cost: 2.2 MCHF/yr

bottom line

Estimated ≈ 7 MW saving, half of the ≈ 15 MW projected power consumption of the PS2 complex, which corresponds to 1.6 MCHF/yr at the present cost of electricity

[1] Assuming 40 CHF/MWh

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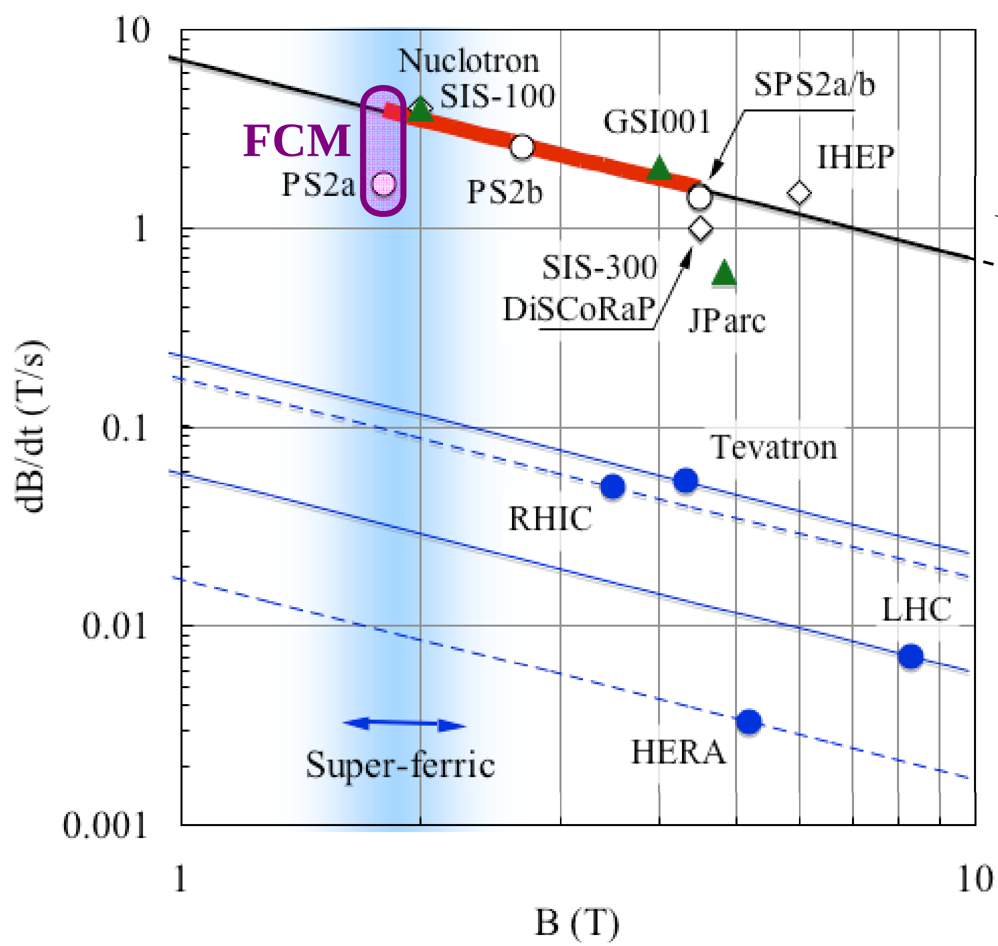
A Broader Perspective



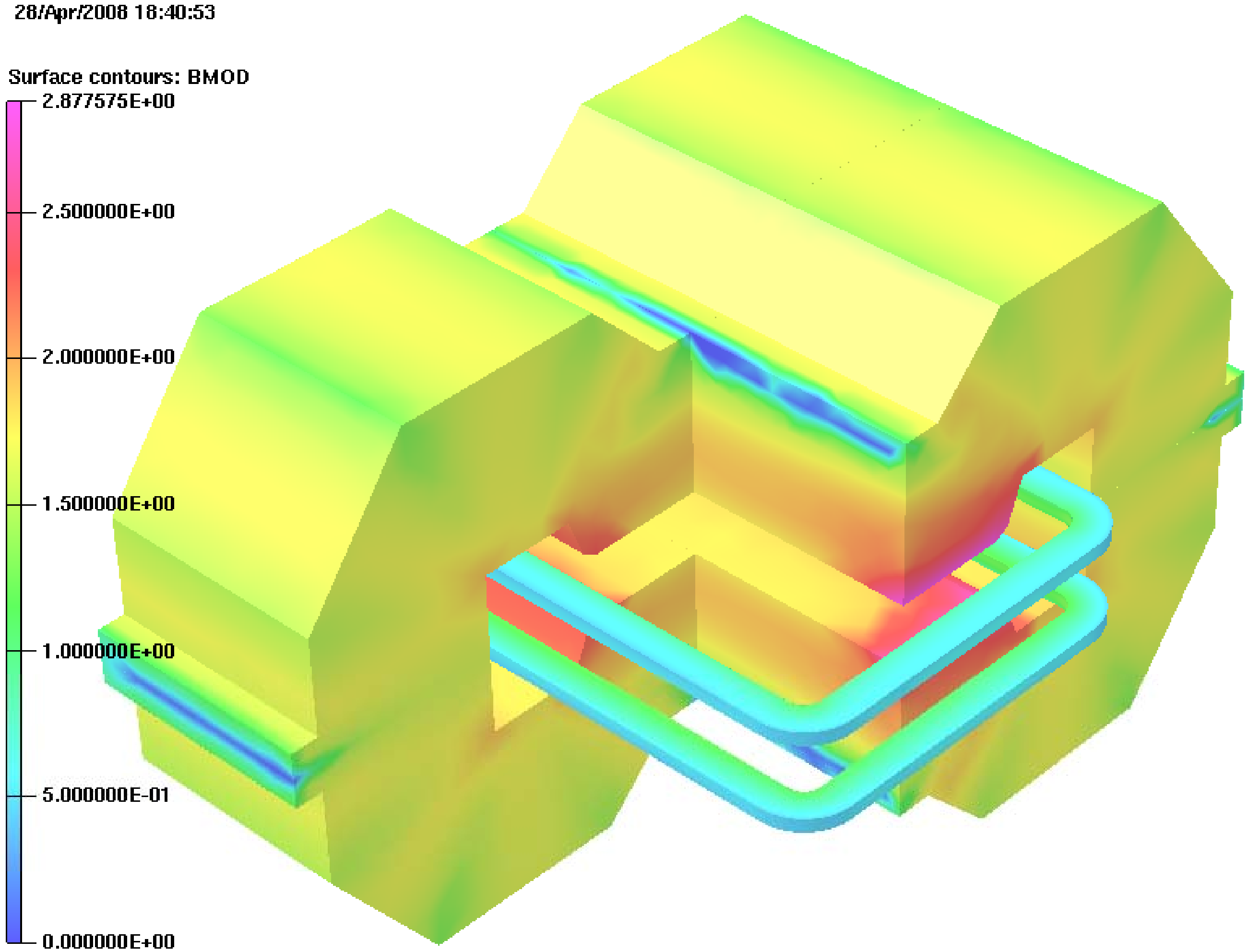
$\Pi = B_{max} \times (dB/dt)_{max} = 7\ T^2/s$

FCM R&D Objectives

- Build and test a demonstrator that:
  - **Achieves PS2 nominal conditions** (B=1.8 T, dB/dt = 1.5 T/s) and the Π=7 T^2/s target (B=1.8 T, dB/dt ≈ 4 T/s)
  - Demonstrates the **low-loss properties of the SC magnet option** (1 W/m of magnet for the PS2 nominal conditions)
    - Address strand and cable R&D issues, relevant to both PS2 and SPS+
    - Prototype of the of **coil, cryostat, supports** relevant for a PS2
  - Various other **side results**, such as a demonstration of the *cooling scheme*, *quench detection* and *protection*, ramped *field quality* and its *measurement*

Design by courtesy of M. Karppinen, CERN

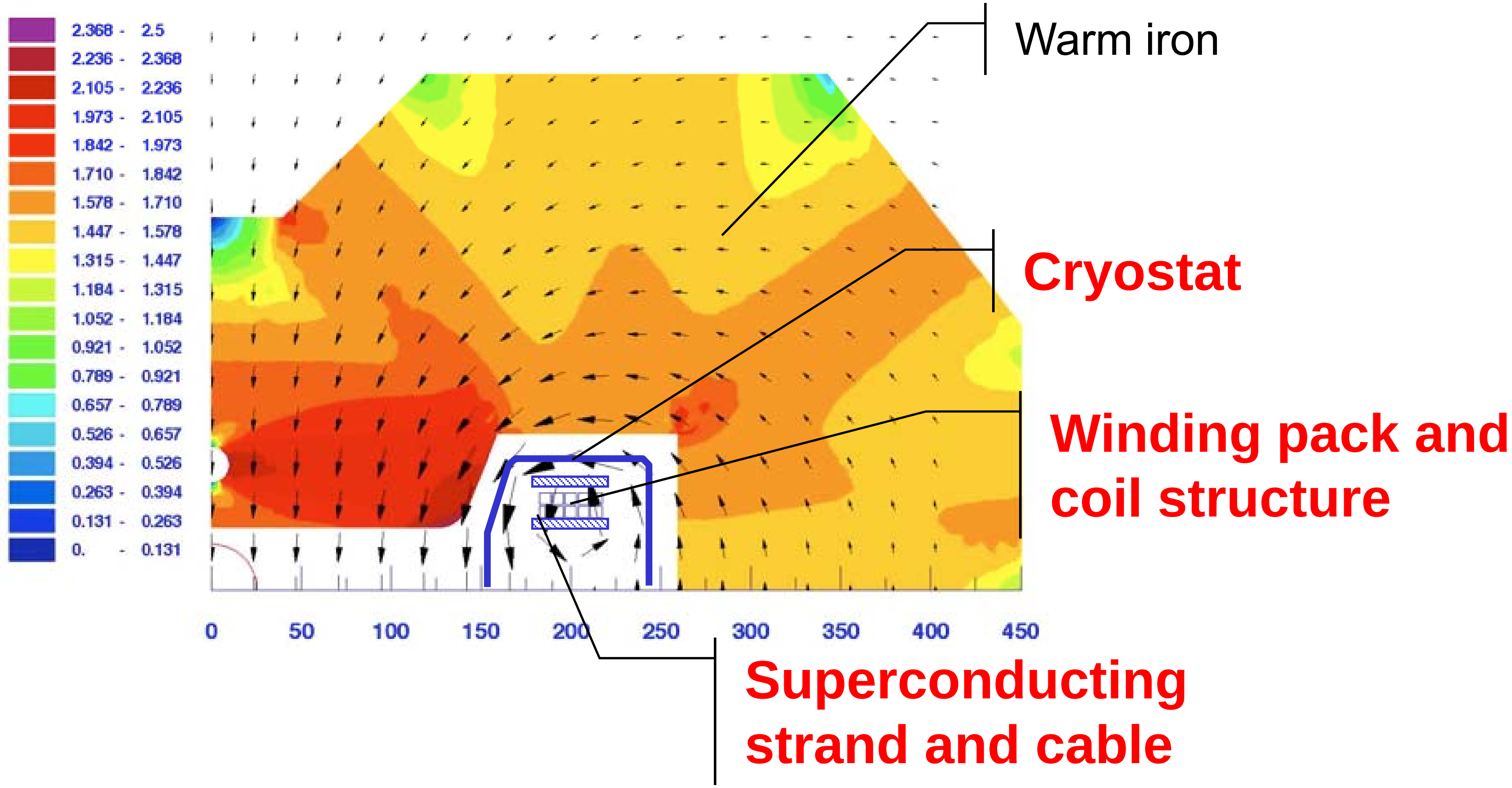
First Step: Short Dipole Model



Vector Fields
software for electromagnetic design

Design by courtesy of M. Karppinen, CERN

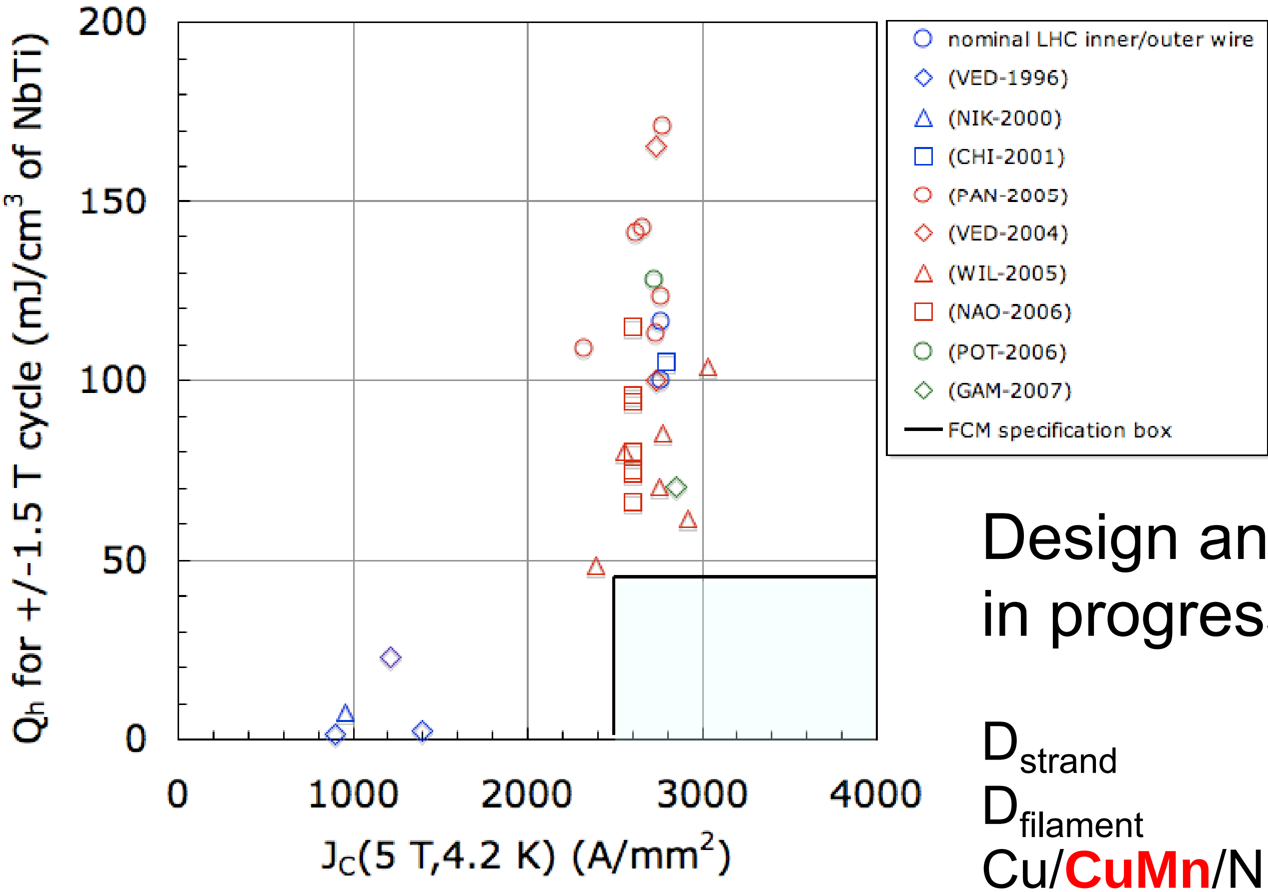
Critical Issues Identified to Date



Superconducting Strand and Cable

- NbTi strand, *modest* critical current
  - I_c > 460 A @ 4.2 K and 2 T
  - J_c > 2500 A/mm^2 @ 4.2 K and 5 T (below LHC standard)
- ***Low-loss*** **strand and cable**
  - D_{eff} < 3 μm (≈ 3…4 μm achieved on LHC strands)
    - **45 mJ/cm^3 of NbTi for a +/- 1.5 T cycle**
  - strand τ < 1 ms (≈ 0.1 ms achieved with resistive barriers on previous productions)
    - **9.5 mJ/cm^3 of NbTi for a +/- 1.5 T cycle at 1 T/s**
  - Cable nτ < 2 ms (corresponds to Ra ≈ 100 μΩ and Rc ≈ 10 mΩ)
    - **9.5 mJ/cm^3 of NbTi for a +/- 1.5 T cycle at 1 T/s**
- Force-flow cooled cable
  - Stability advantage, robust against perturbations, for reliable operation, small He inventory, good voltage insulation properties, *classical* winding techniques

Nb-Ti Wire: Low Hysteresis Loss

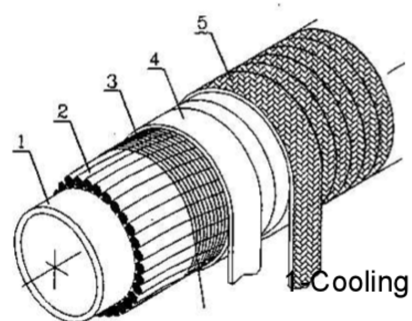


Design and prototyping work in progress on a strand with:

D_{strand}	0.6 mm
$D_{filament}$	≈ 2.5 μm
Cu/**CuMn**/NbTi	≈ 1.8 / ≈ 0.4 / 1

Force-Flow Cooled Cables

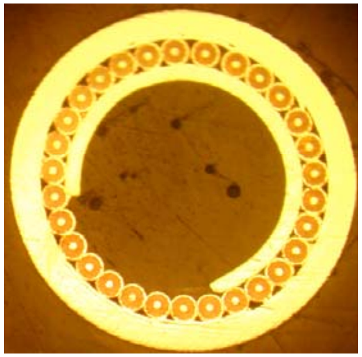
- Low current (5…7 kA)
- The first short models will be based on existing cables. A cable re-design is in progress
  - Larger hydraulic diameter for cooling efficiency
  - Co-wound copper strands for protection
  - Reduction of AC loss, depending on present status



Nuclotron

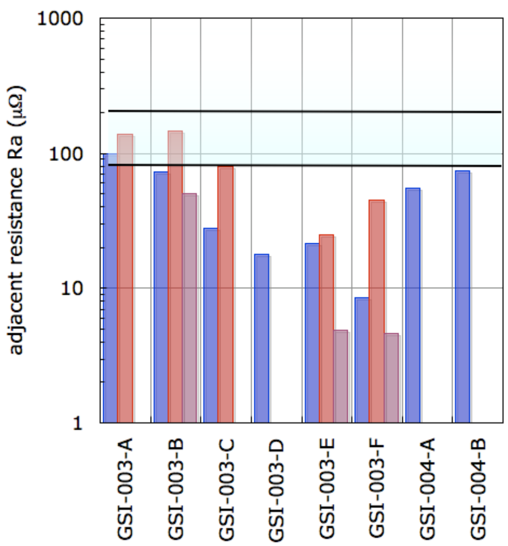
1- Cooling tube
2- Sc. strands
3- Nichrome wire
4- Kapton tape
5 Glassfiber tape

Internally cooled cable Prototype from VNIIKP

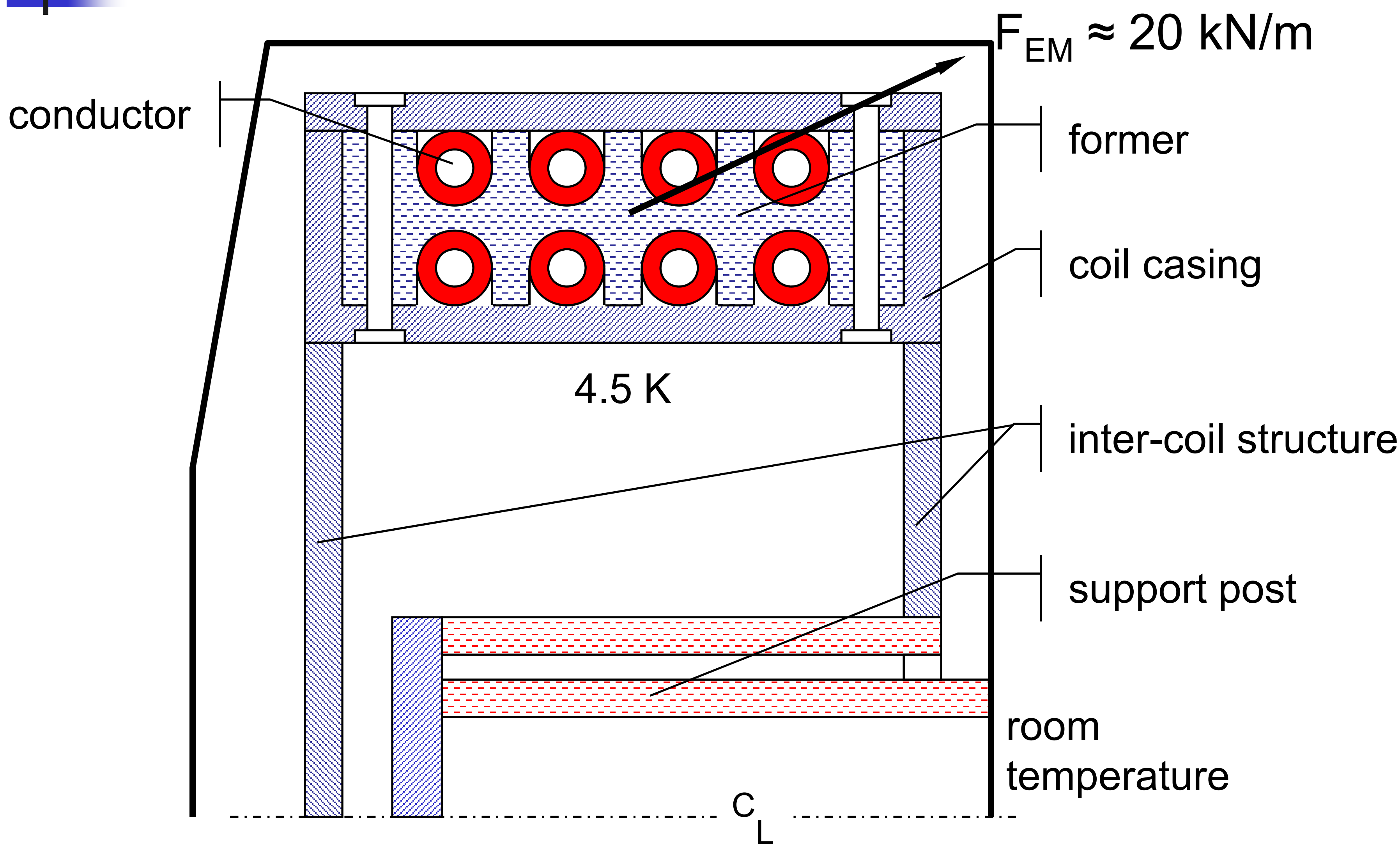


$$P \approx \frac{2}{\pi}\frac{ND^2L_p}{R_a}\left(\frac{dB}{dt}\right)^2$$

$R_a \approx 75 \ldots 200\ \mu\Omega$



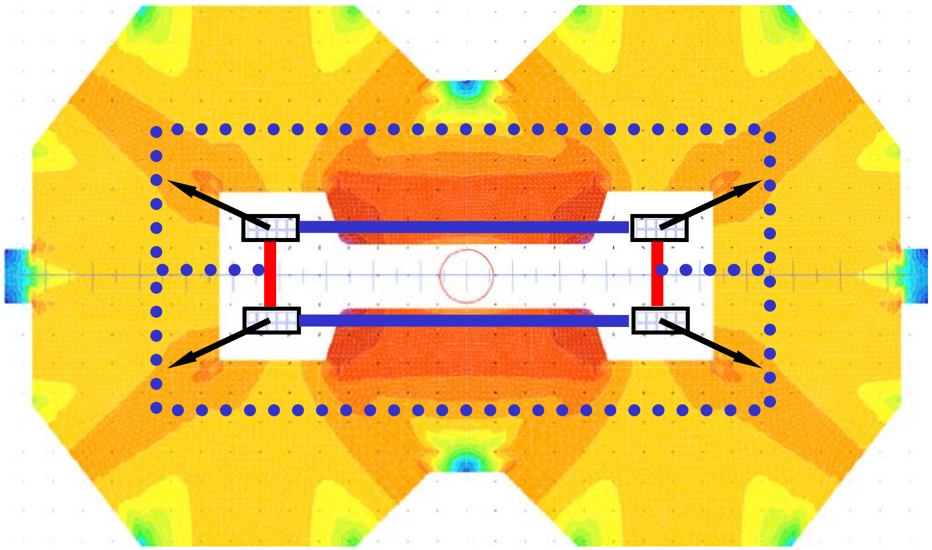
Coil Winding & Support Concept



Design calculations and ideas by G. Kirby and M. Karppinen, CERN

Coil Support Structure

Vertical load path: 0.8 tons/m

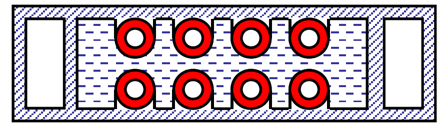


Horizontal load path: 1.6 tons/m

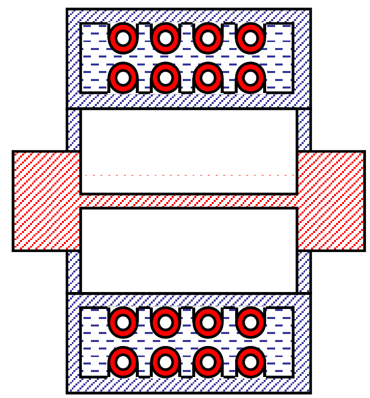
Through posts to the iron

Composites and fibers to avoid eddy currents

Make the coil self-supporting…



Stiffened coil



77 K structure

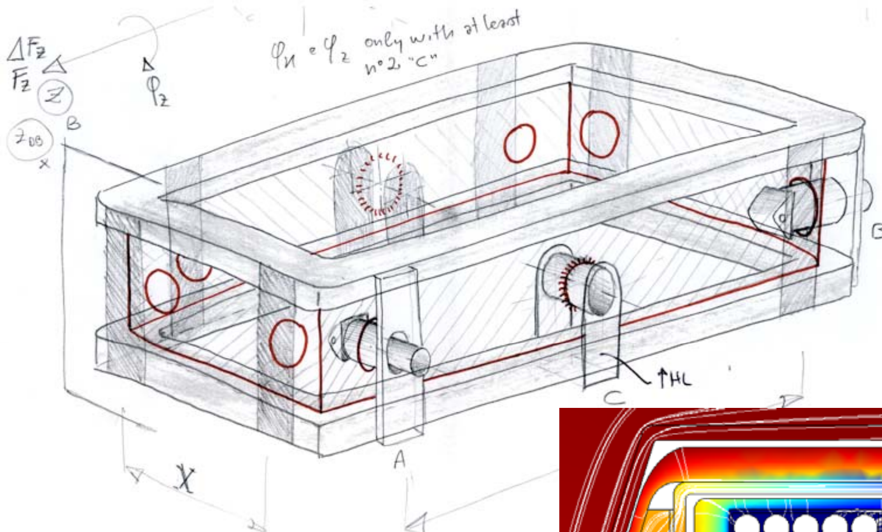
Horizontal straps and *toblerone* iron

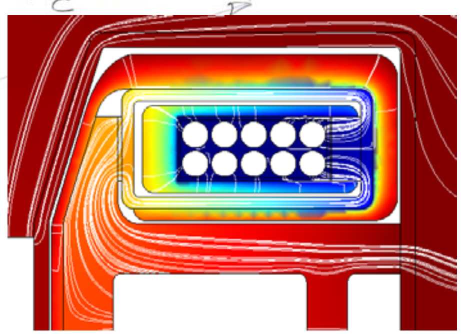
Design by courtesy of C. Maglioni and V. Parma, CERN

Cryostat and Supports

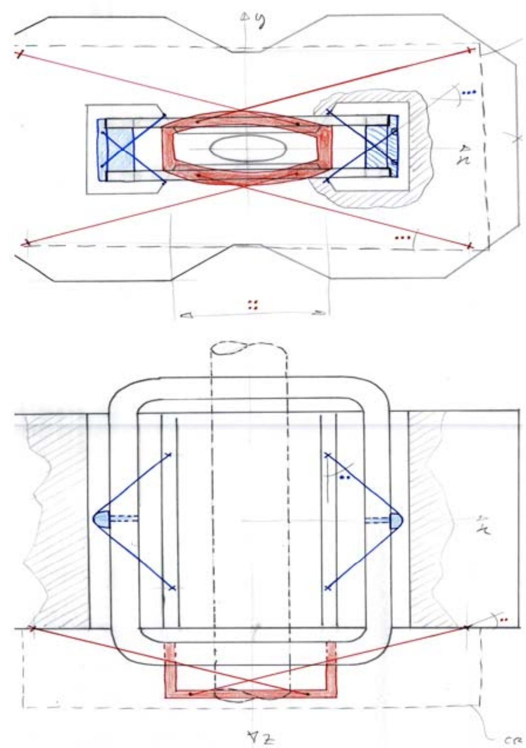
- Conflicting requirements of mechanical rigidity vs. low heat input

Support feet





Tensioned rods or straps



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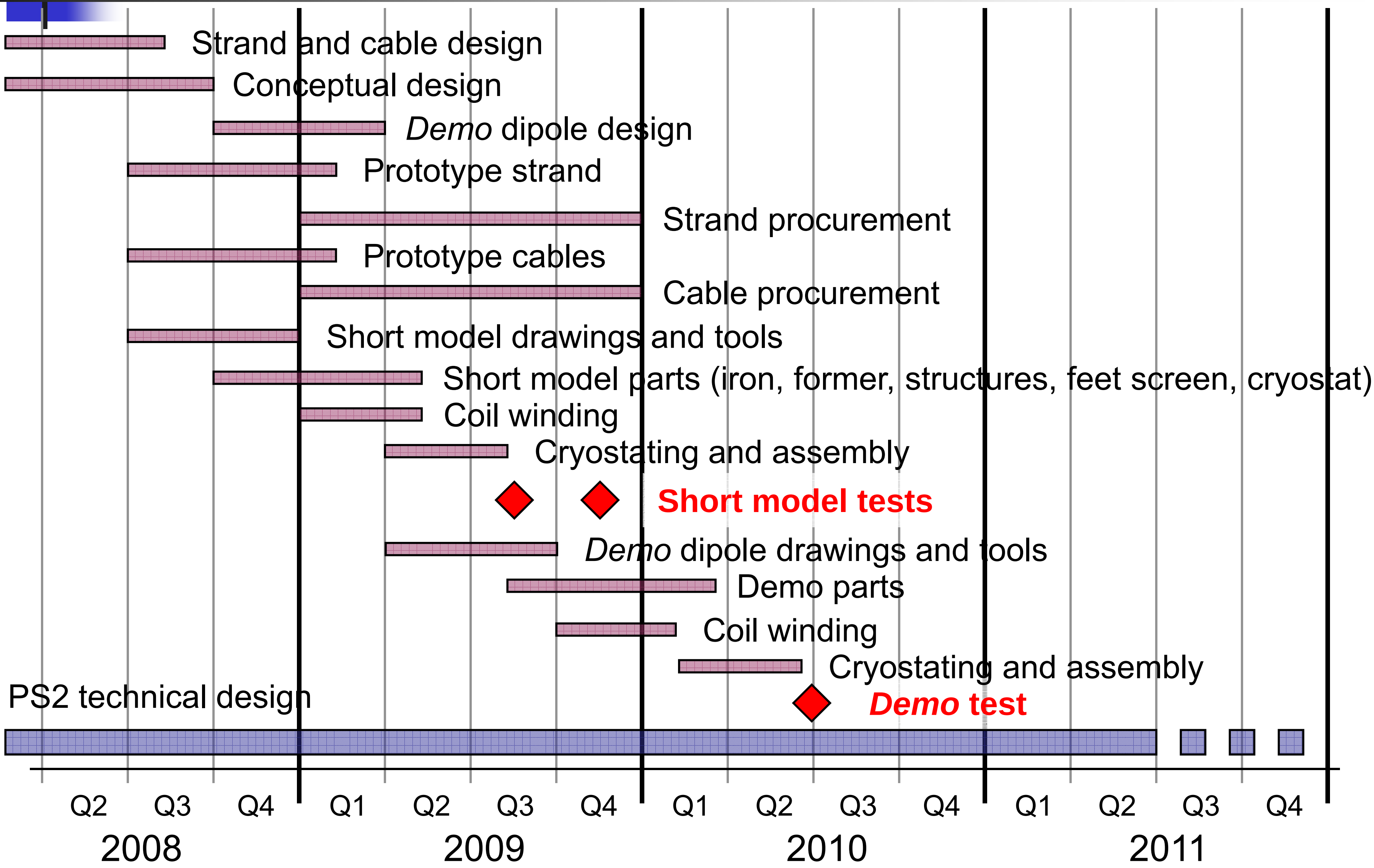
Plan for FCM R&D



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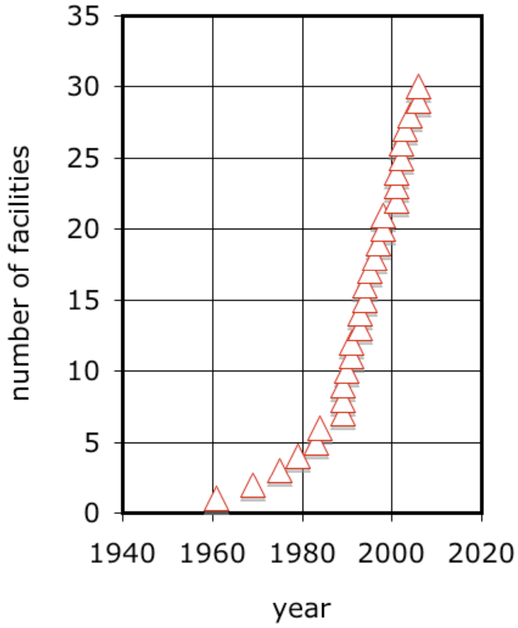
Conclusions and perspectives

- This is a challenging bet: we are trying to displace normal conducting magnet technology from its *proprietary domain*.
- We have to prove that our SC alternative is:
  - Equally reliable
  - Equally robust
  - More efficient


CNAO Carbon Therapy Center (Pavia, I)

The rise of *hadron therapy* synchrotrons



This is a worthy effort, not only for tl
Beauty of Science !

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- Additional information

Assumptions for cost analysis

- SC magnet construction:
  - Iron yoke (warm): 6.6 CHF/kg
  - Superconducting coil: 250 CHF/kg
  - Cryostat: 25 kCHF/magnet
  - Magnet testing: 10 kCHF/magnet
- SC auxiliaries:
  - Quench detection & protection: 1 MCHF total
  - Current leads and bus-bars: 3 MCHF total
- Power converters costs are taken identical to previous analysis
- Cooling and ventilation costs are assumed equal for NC and SC because of the reduced SC power requirement
- Buildings cost for cryogenic plant are assumed to be reduced for the lower installed power
- Operation:
  - Cryogenic operation is run by CERN (as power converters)
  - Electricity is quoted at 40 CHF/MWh

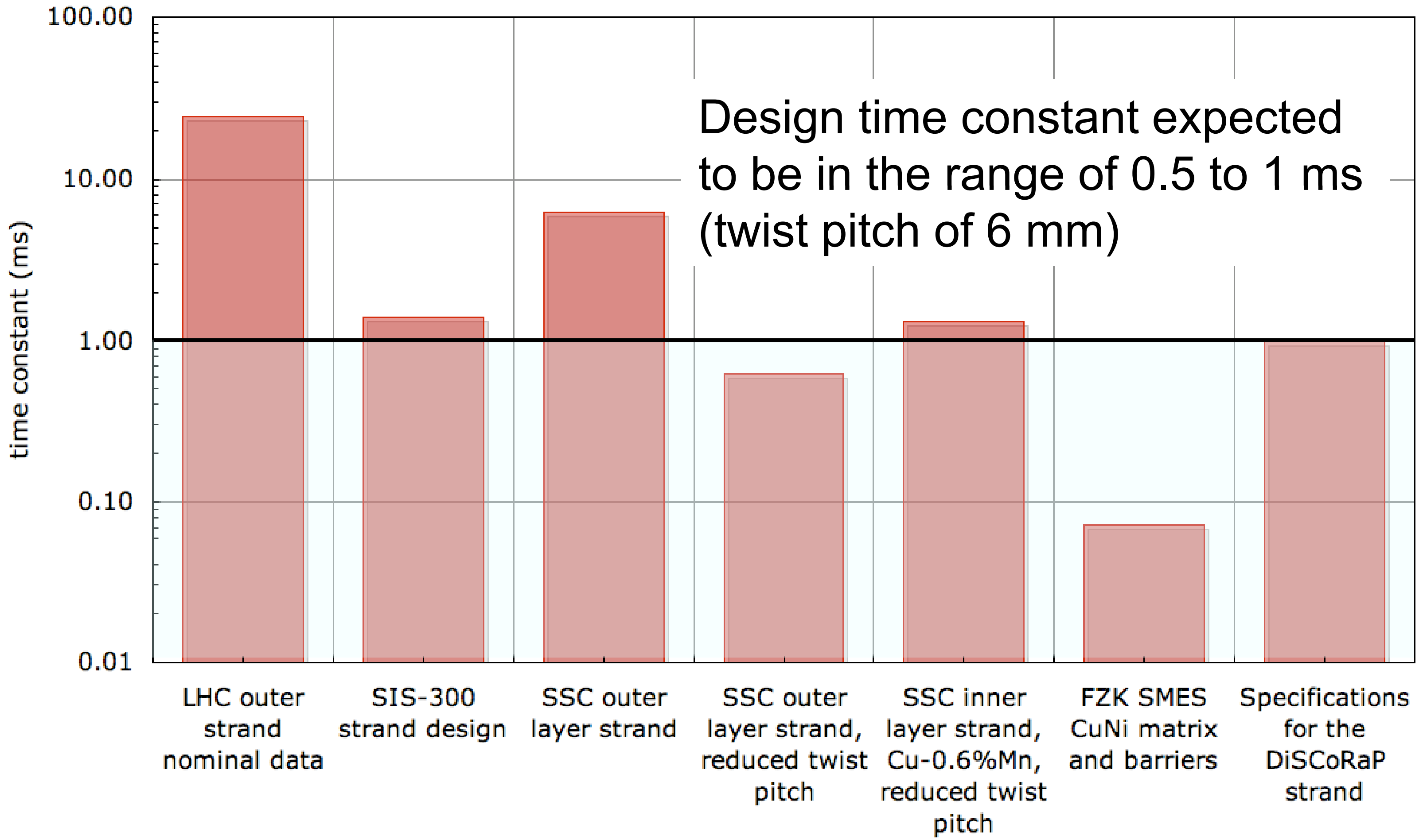
Is HTS an option ?

- The use of HTS materials would affect:
  - Construction cost
    - Coil more expensive, cryostat simpler, smaller cryogenic installation (at best liquid nitrogen)
  - Operation
    - A larger margin to improve robustness
    - The cryogenic load can be removed at higher operating temperature, which requires lower installed power
  - Changes in the cost estimates for the SC PS2:
    - Investment cost reduced by 5 … 10 MCHF
    - Installed power reduced by 1 MW
    - Operation cost reduced by 0.25 MCHF/year

Marginal gain with respect to previous figures (10 %)

could be beneficial for the overall reliability

Nb-Ti Wire: Moderate Coupling



Magnet Projects and Related R&D