Fast Cycled Superconducting Magnets

Prepared by L. Bottura

thanks to the work of (among others): C. Maglioni, G. Kirby, L. Oberli, T. Renaglia, D. Richter, D. Tommasini

CARE-HHH Workshop 2008

Scenarios for the LHC Upgrade and FAIR

Chavannes, 24.-25. November 2008

Outline

- Why fast cycled **superconducting** magnets ?
  - $FC_{SC}M$'s for the *medium field* range
  - $FC_{SC}M$'s for the *low field* range
  - $FC_{SC}M$'s R&D in perspective
- A summary of running projects
  - FAIR
    - DISCORAP
  - $FC_{SC}M$ @ CERN
  - Other projects and opportunities
- Conclusions and perspectives

Why $FC_{SC}M$'s ? - 1/2

- B >> 2 T
  - Superconductivity is the **enabling technology** in this range of field
  - The key issue is the **performance** (B_{max} at dB/dt_{max}) affected by:
    - Margins (T_{CS}, J_C) and current distribution
    - Magnitude of the heat loads (AC loss)
    - Heat removal capability (heat transfer, cryogenics)

Why $FC_{SC}M$'s ? - 2/2

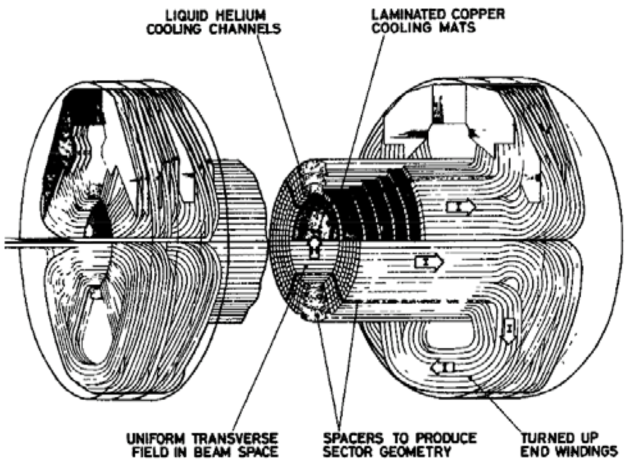
- $B \le 2$ T
  - In this range of field superconductivity can provide **higher efficiency**
  - The key issue is the **energy efficiency** of the system, including cryogenics (MWh) depending on:
    - Magnitude of the heat loads (AC loss and nuclear heating from beam loss)
    - Efficiency of the cryogenics operation (operating temperature and pressure, coolant flow)

FC$_{SC}$M archeology

'AC3' – A PROTOTYPE SUPERCONDUCTING SYNCHROTRON MAGN

M N Wilson, R B Hopes, R V Stovold, G E Gallagher-Da
R Tolcher, J V Lawler, J Brown, V W Edwards

Rutherford Laboratory, Didcot, Berks., U.K.



AC3: 4 T, 1 s

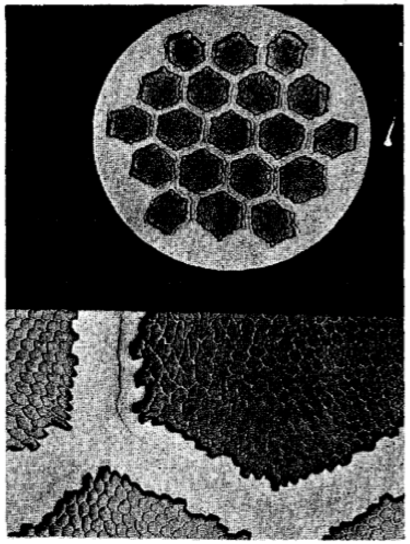


Fig. 5: Cross section of a NbTi-CuNi-Cu composite (7600 filaments)(RHEL-IMI)

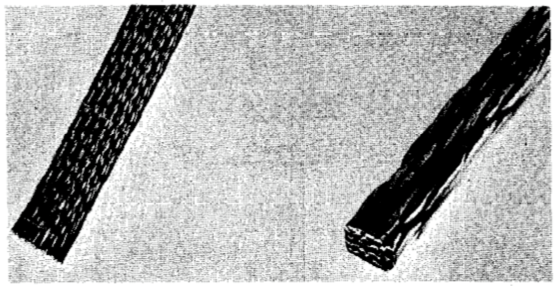


Fig. 6: Fully insulated braid with 26 strands for 1000 A(VAC) and cable with 25 strands, for 5000 A(IMI).

PULSED SUPERCONDUCTING MAGNETS

H. Brechna, M.A. Green,
IEKP, Kernforschungszentrum Karlsruhe

D2/D3: 4.5 T, ≈ 5 s

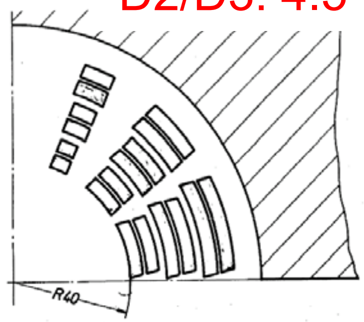


Fig. 1a: Dipole configuration (IEKP)

AC5: 4.5 T, ≈ 1.5 s

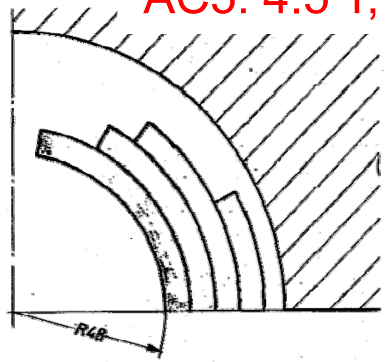


Fig. 1b: Dipole configuration (RHEL)

ALEC: 5.5 T, ≈ 5 s

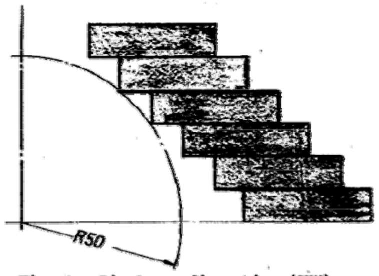
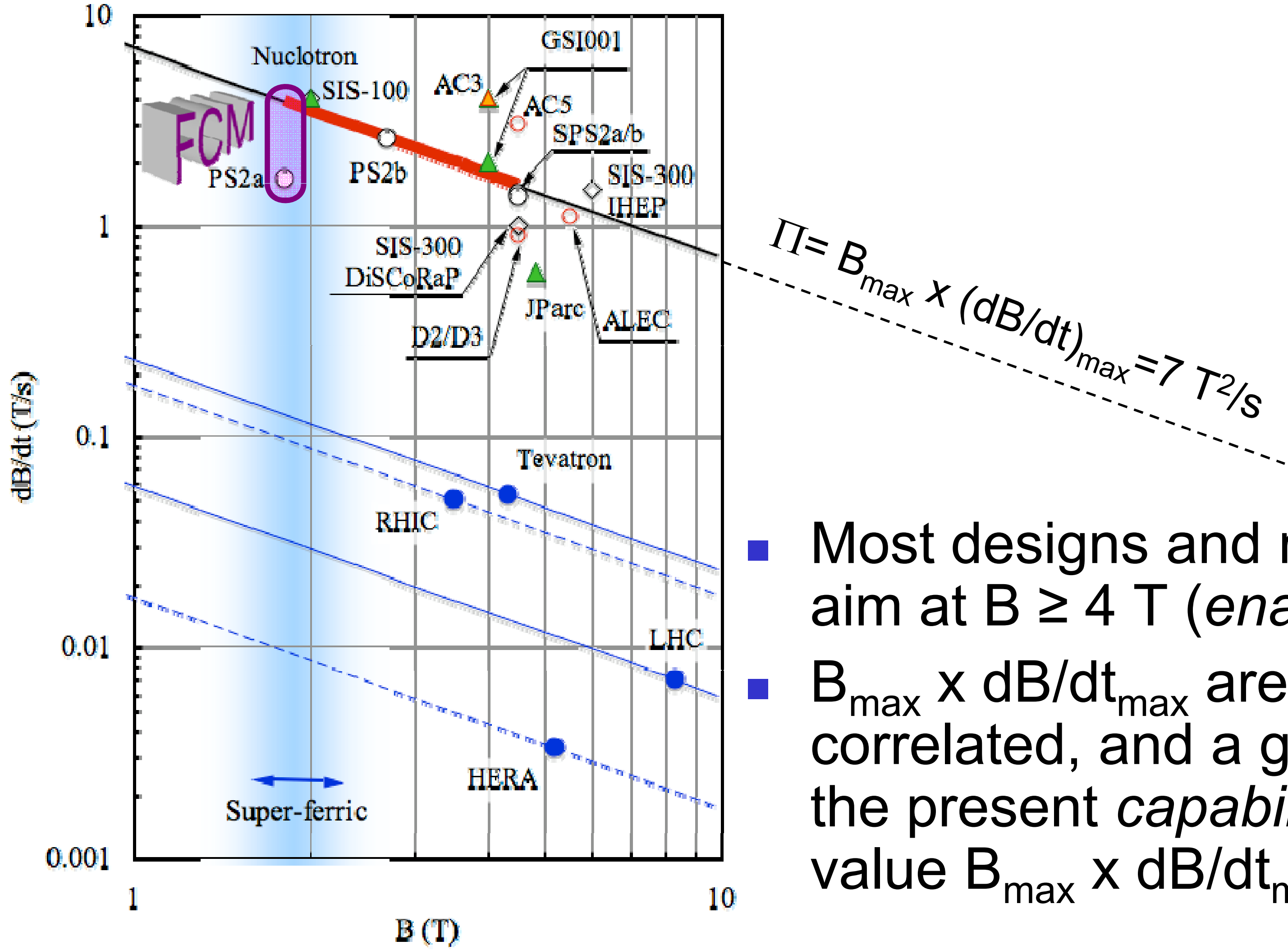


Fig. 1c: Dipole configuration (CEN)

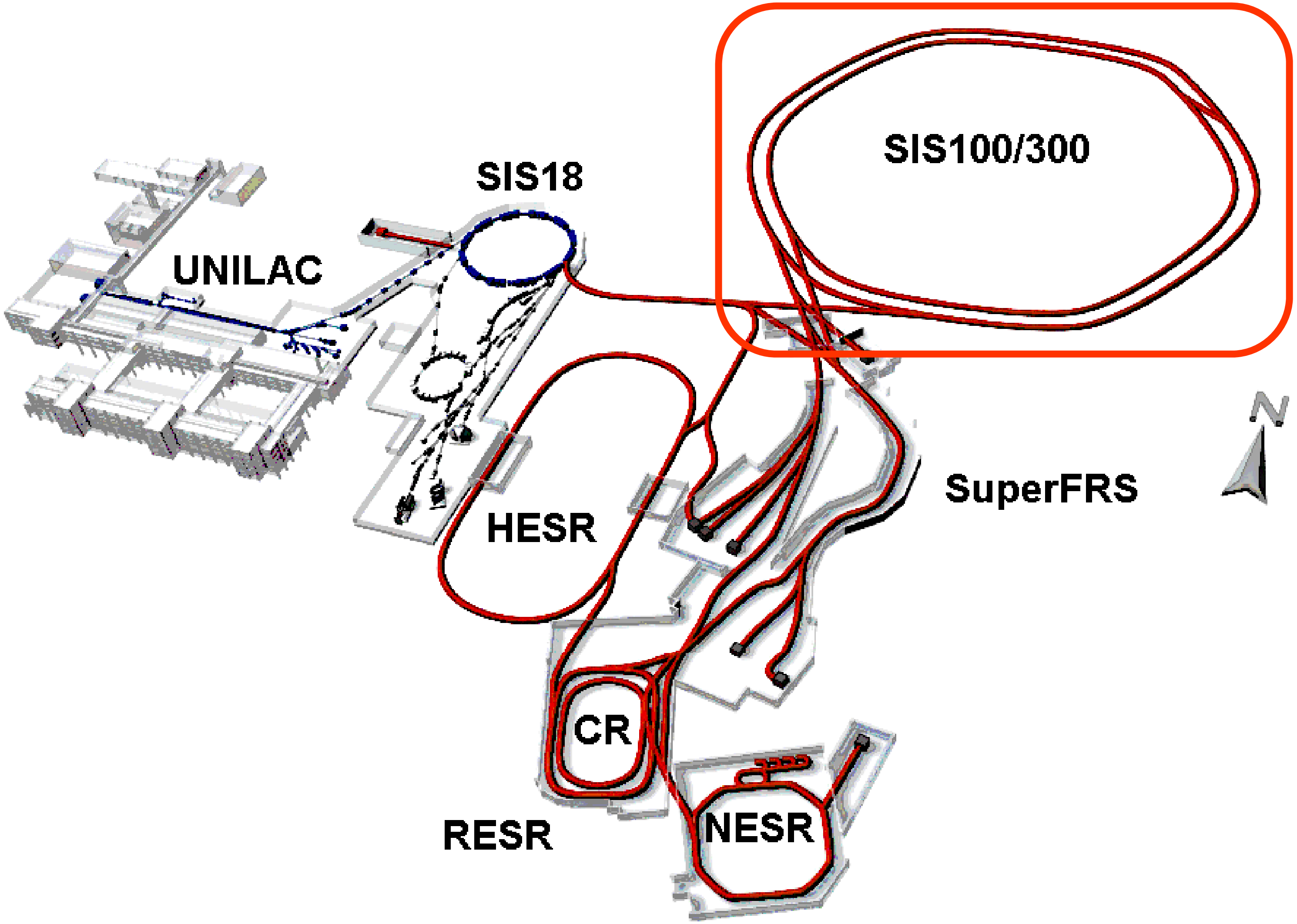
Proceedings of 1972 Appl. Sup. Conf., Annapolis (USA), **1972**

A perspective for $FC_{SC}M$'s



- Most designs and models aim at B ≥ 4 T (*enablers*)
- B_{max} x dB/dt_{max} are correlated, and a good bet of the present *capability* is a value B_{max} x dB/dt_{max} ≈ 7 T^2/s

$FC_{SC}M$'s in the FAIR complex



FAIR FC$_{SC}$M specifications

SIS-100 magnets

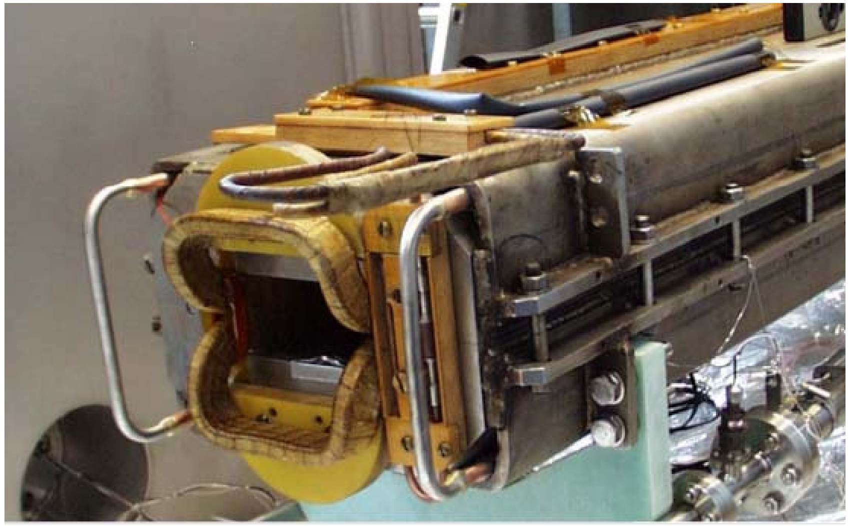
Magnet family	Number of magnets (-)	Curvature radius (m)	Aperture h x v (mm x mm)	Magnetic length (m)	B_{max} G_{max} (T / T/m)	dB/dt_{ma} dG/dt_{ma} (T/s / T/m/s)
dipole	108	52.6	115 x 60	3.062	**1.9**	4
quadrupole	168	straight	136 x 65	1.3	27.0	57

SIS-300 magnets

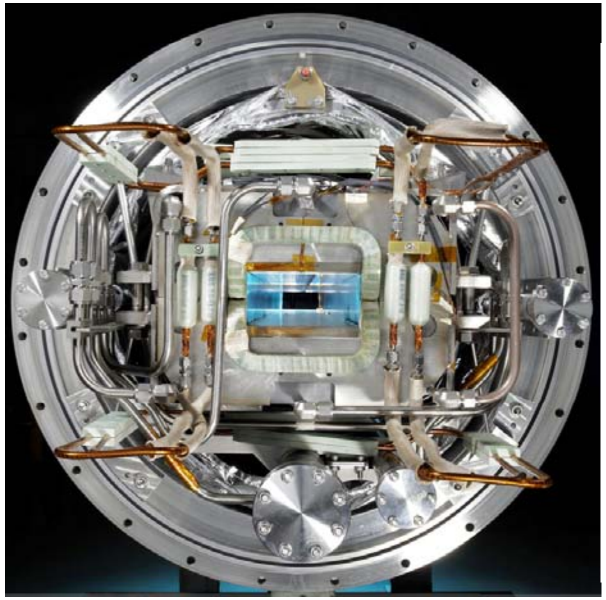
Magnet family	Number of magnets (-)	Curvature radius (m)	Aperture diameter (mm)	Magnetic length (m)	B_{max} G_{max} (T / T/m)	dB/dt_{ma} dG/dt_{ma} (T/s / T/m/s)
dipole	48/12	66.7	86	7.757/3.879	**4.5**	1
quadrupole	84	straight	105	1.0	45	10

Both features of SC magnets are pursued:
energy efficiency for SIS-100, technology enabling for SIS-300

FAIR SIS-100



4KDP6a model SIS-100 dipole from JINR recently tested at GSI



Prototype straight SIS-100 dipole manufactured by BNN

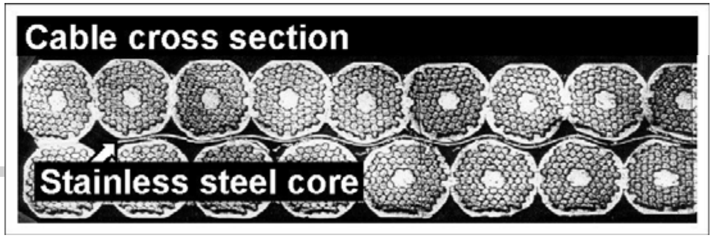
1.9 T, 4 T/s achieved for single pulse trains

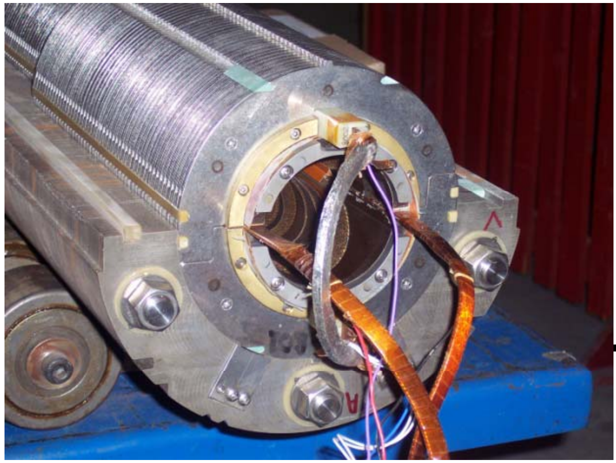
Cooling (flow, temperature) marginal for continuous operation

AC loss 8 to 16 W/m_{magnet} (target 13 W/m_{magnet})

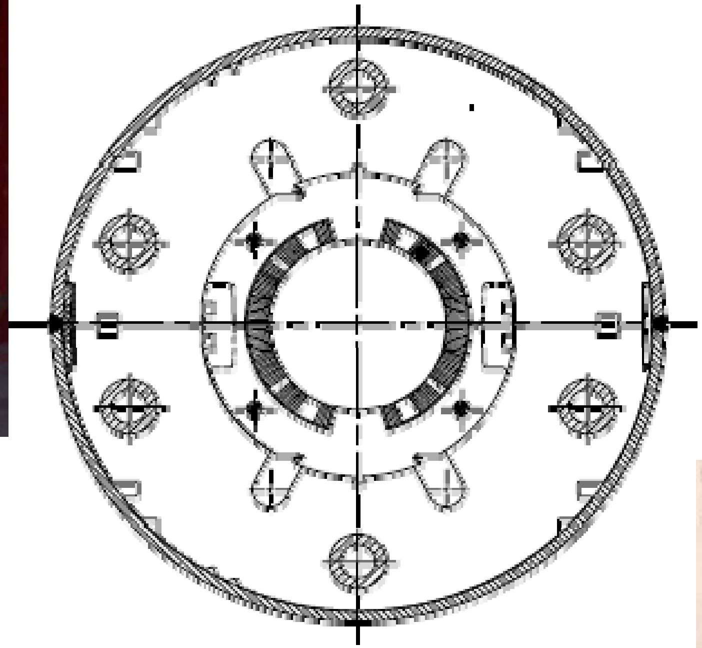
Test of industrial prototype *imminent*

(FAIR SIS-200)



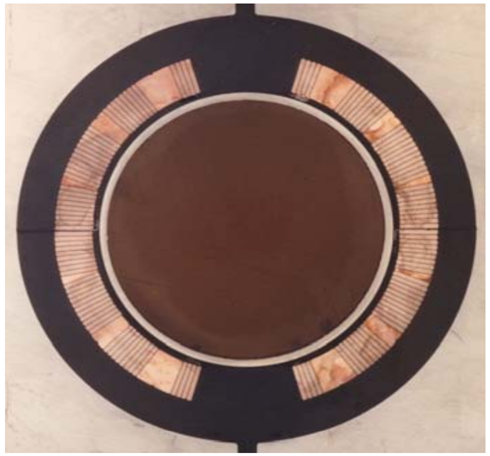


SS collars
Si steel yoke



GSI001 model from BNL

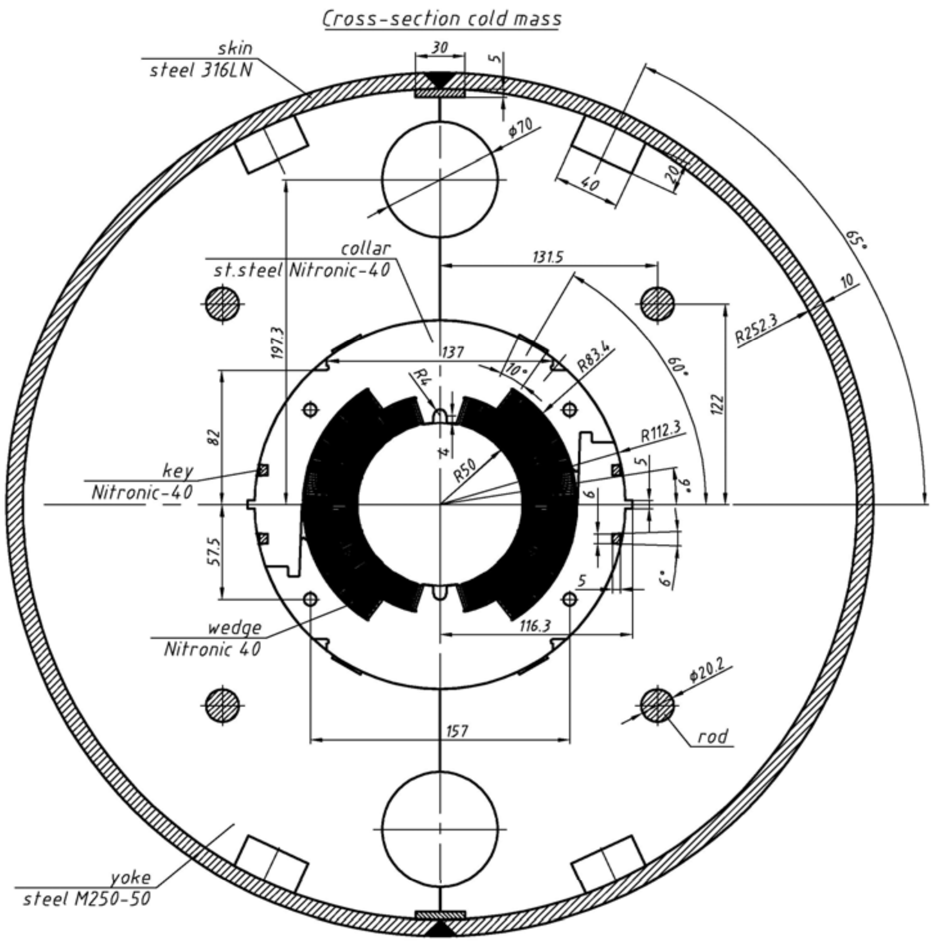
perforated insulation



1-layer coil design
G11 spacers

4 T, 4 T/s 3 cycles
4 T, 2 T/s 500 cycles
AC loss ≈ 20 W/m_{magnet}

FAIR SIS-300 - IHEP model



IHEP/GSI R&D

Central field: 6 T

Ramp rate: 1 T/s

Length: 1 m

Inner coil diameter: 100 mm

Two layers (IL: 4 blocks, OL: 3 blocks)

Cooling: supercritical helium

Ra of about 200 μΩ

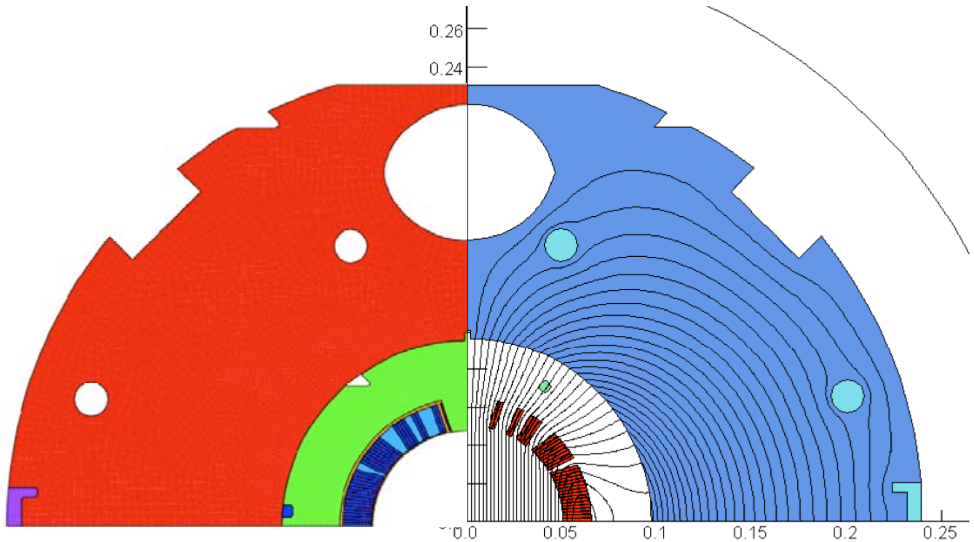
Model for the end of 2008

FAIR SIS-300 - DISCORAP

INFN R&D

Mixed matrix strand (Cu/Cu-Mn)
J_C = 2700 A/mm^2
D_{fil} = 3.5 … 2.5 μm
36 strands cable, 15 mm width
Stainless steel core

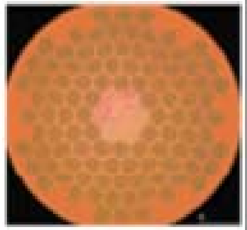
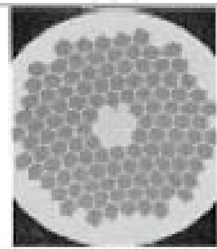
Central field: 4.5 T
Ramp rate: 1 T/s
Length: 3.9 m
Inner coil diameter: 100 mm
One layer (5 blocks)
Cooling: supercritical helium



Model for the end of 2010

Wait for the next talk…

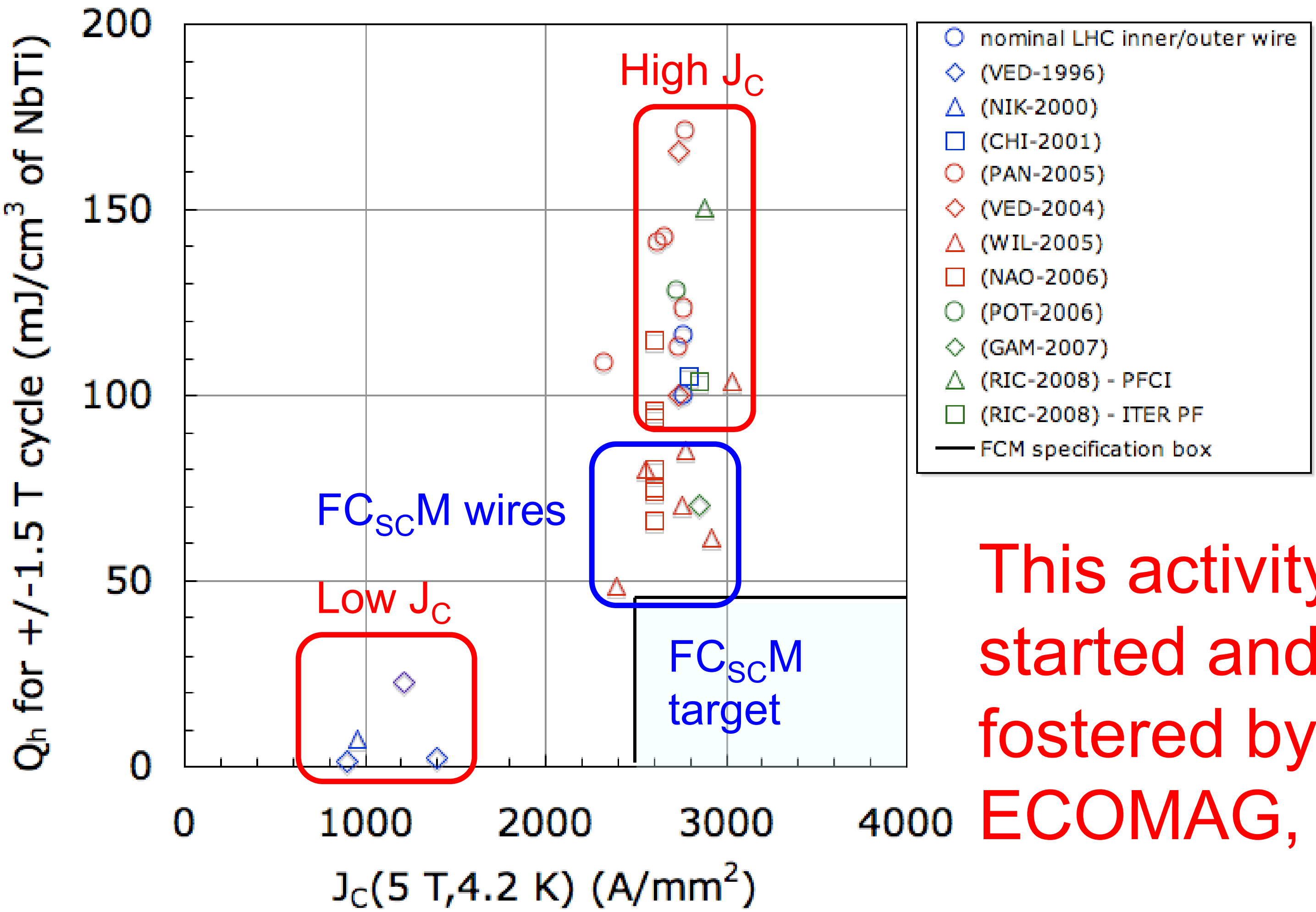
GSI R&D on superconductors…

Manufacturer	OST	EAS	EAS	EAS	EAS	IGC
Billet	91-0-80122A-05	2A212	3N7	K2001T4	G2001T6	B944-2
Project	RHIC					SSC
						
Architecture	Single stacked	Double stacked	Single stacked	Double stacked	Double stacked	Triple extruded Double stacked
Filaments (-)	3580	8670	6264	12300	12300	22686
J_C (A/mm^2)	3029	2558	2922	2759	2773	2397
Matrix:NbTi (-)	2.25:1	1.65:1	1.25:1	2.21:1	2.21:1	1.7:1
D_{fil} (μm)	5.71	3.4	3.4	3.4	4.3	2.6
D_{eff} (μm)	5.71	5.2	3.5	4.25	5.1	3.35
RRR	198			173	166	102

A summary of recent R&D on new NbTi material for low-loss and high J_C strands

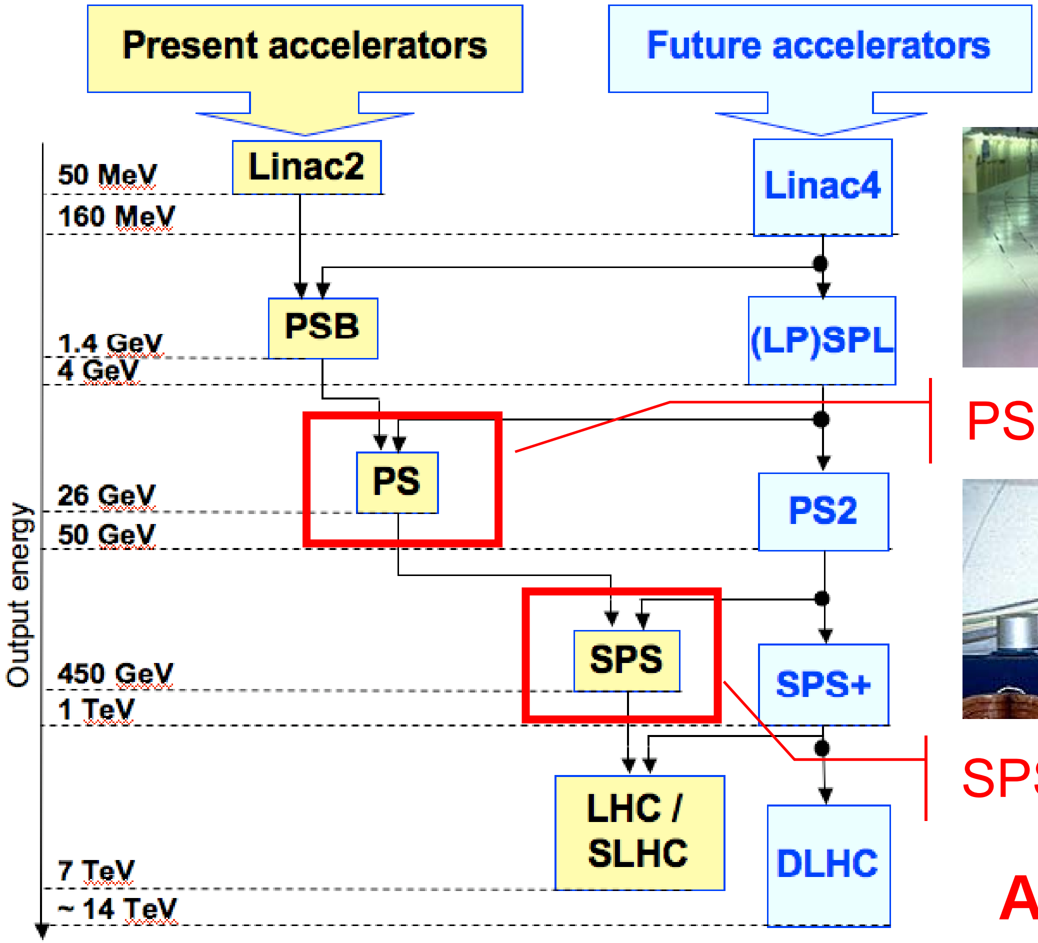
Summary by courtesy of H. Mueller (GSI) and M. Wilson (Consultant)

… and a broader picture



This activity was started and fostered by ECOMAG, 2005

Upgrade path for the CERN accelerator complex



PS was built in 1959

SPS was commissioned in 1976

A PS re-haul is *imminent*

SPS is some 15 years away

Courtesy of R. Garoby, CERN

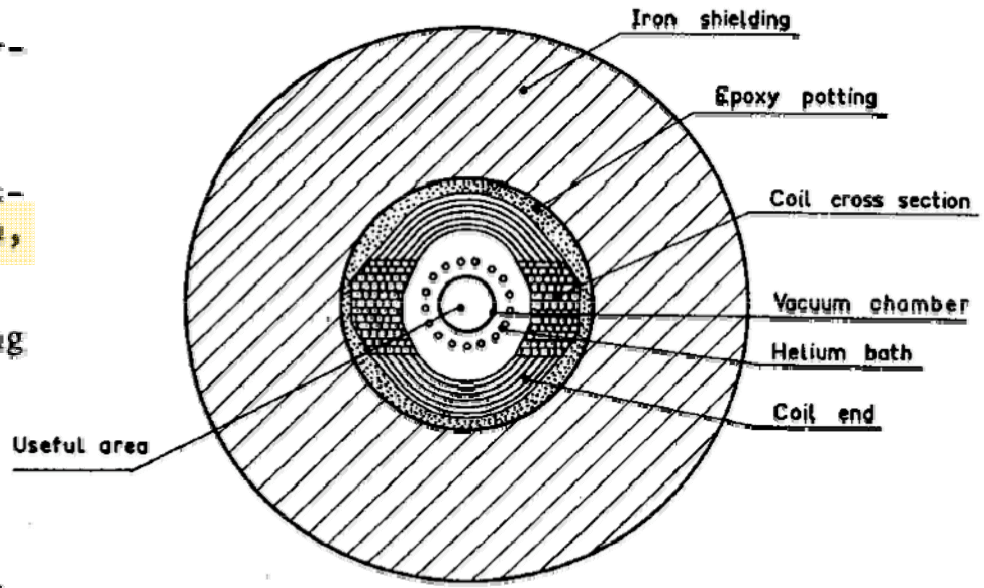
A curiosity on SPS…

CONSEQUENCES OF REPLACING CONVENTIONAL MAGNETS BY SUPERCONDUCTING MAGNETS IN AN EXISTING SYNCHROTRON.

G. BRONCA, G. NEYRET, J. PARAIN, J. PEROT
Département du Synchrotron Saturne
CEN/SACLAY (France).

Abstract

In order to increase the energy of an existing synchrotron it is possible to replace conventional magnets by super-conducting magnets operating at higher magnetic field. With niobium-titanium superconducting materials the sensible limit of the maximum field is 6 to 8 teslas. For the present CERN II synchrotron, a central field of 6 T will allow us to reach 1200 GeV, including straight sections to accommodate multipole correcting magnets. Main ring superconducting magnets with the same aperture as conventional magnets will allow us to use all existing equipment, such as the radio frequency system, the power supply and the control system. With these changes, a longer cycle duration is required; for the 1200 GeV synchrotron a cycle of about 80 seconds has been chosen.



Magnet design by courtesy of Th. Zickler, CERN

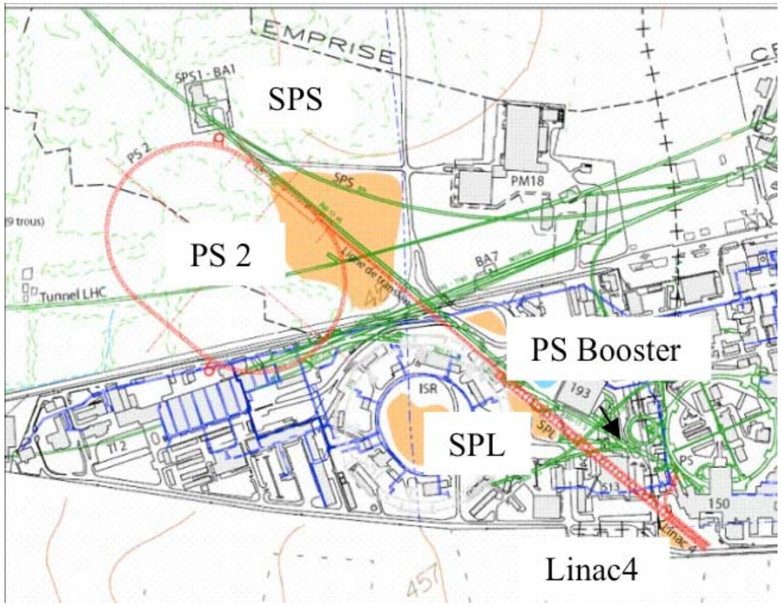
PS2: Magnet Requirements

- 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

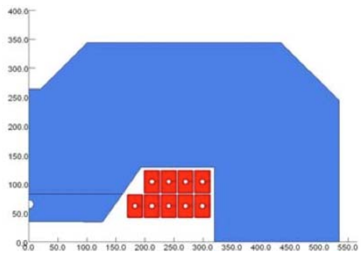
Modest requirements

- Average electric power ≈ 15 MW
  - The magnets require ≈ 7.5 MW, i.e. about 50 % of the total consumption

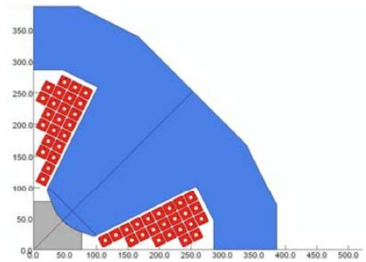
The location of the new PS2



dipole



quadrupole



Cost of NC PS2 by courtesy of M. Benedikt, CERN

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(1)
  - 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(2)
- Power converters
  - Total: 15 MCHF
- Cooling and ventilation
  - Total: 1.1 MCHF(3)
- **Total cost: 67.8 MCHF**

(1) Cost estimates for the SC option as documented in EDMS 871183.v3

(2) Scaled to 1/2 of estimate for the 15 kW plant

(3) Assume the same as for NC magnets, benefiting from lower power requirement

Installed power of NC PS2 by courtesy of M. Benedikt, CERN

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***

Power estimates for the SC option as documented in EDMS 871183.v3

Cost of NC PS2 by courtesy of M. Benedikt, CERN

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

A window of opportunity

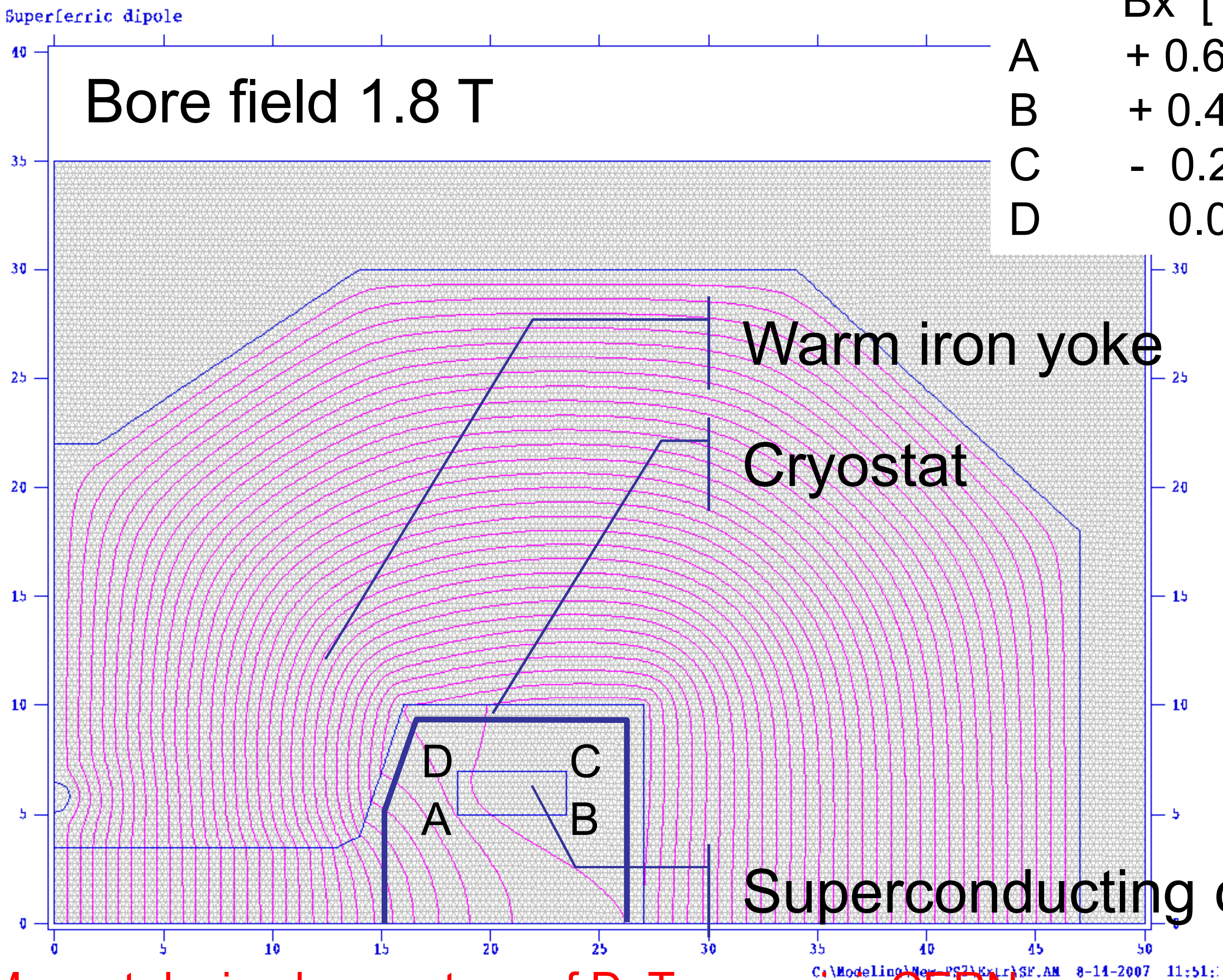
- A $FC_{SC}M$ solution for PS2 could bring:
  - Lower installed electric power (7.6 MW, available today)
  - Lower operation costs, especially in the long run
  - *Politically interesting*, in the perspective of an increase of efficiency for the CERN accelerator complex
- We have started since 2007 an R&D, with limited scope, leveraging on companion R&D programs, to:
  - Develop the conceptual design to an engineering demonstration of the feasibility of the innovative ideas
  - Explore the performance limits (B_{max}, dB/dt_{max}, AC loss)
  - Assess reliability and robustness of a $FC_{SC}M$ for PS2

FCM targets

- Produce and test a representative dipole model for PS2, test its limits up to $\Pi \approx 7\ T^2/s$
  - Spec: $B_{nom} \approx 1.8$ T at $dB/dt_{nom} \approx 1.5$ T/s triangular cycle
    - Target: $B_{nom} \approx 1.8$ T at $dB/dt_{max} \approx 4$ T/s
  - Spec: $Q_{AC} < 5\ W/m_{magnet}$ average over a triangular cycle (2.4 s)
    - Target: $Q_{AC} < 1\ W/m_{magnet}$
  - Spec: Good field region ($\approx 10^{-4}$ homogeneity):
    - Injection (3.5 GeV): ±42 mm x ±30 mm
    - Extraction (50 GeV): ±42 mm x ±14 mm
- With this choice:
  - The R&D complements the on-going work for FAIR at GSI and INFN
  - This R&D is scalable "*also possibly for an SPS2+ in the future*" (quoted from White Paper)

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



Lower field
Higher margin
Lower loss
Coil *hidden*

Magnet design by courtesy of D. Tommasini, CERN

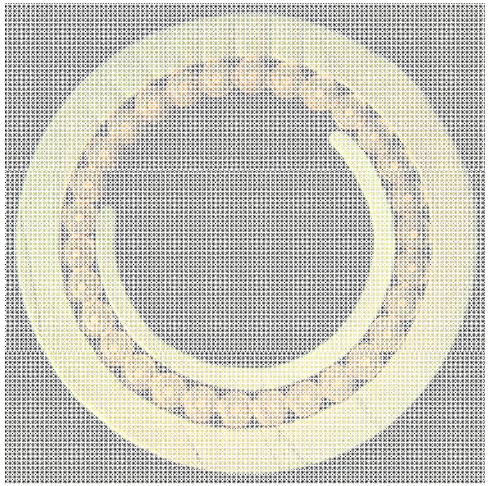
FCM - conductor

- Strand specifications
  - D_{strand} = 0.6 (mm)
  - Matrix:Nb-Ti = 2.15 (-)
  - $J_C \geq 2500$ (A/mm^2)
  - Q_h (+/-1.5 T) ≤ 45 (mJ/cm$^3_{NbTi}$)
  - Q_c (+/-1.5 T, 1 T/s) ≤ 9.5 (mJ/cm$^3_{strand}$)
- Conductor design
  - 34 strands around 5 x 6 mm pipe
  - Nichrome wrap
  - Glass tape insulation

On-going procurement at ALSTOM (+BNN)

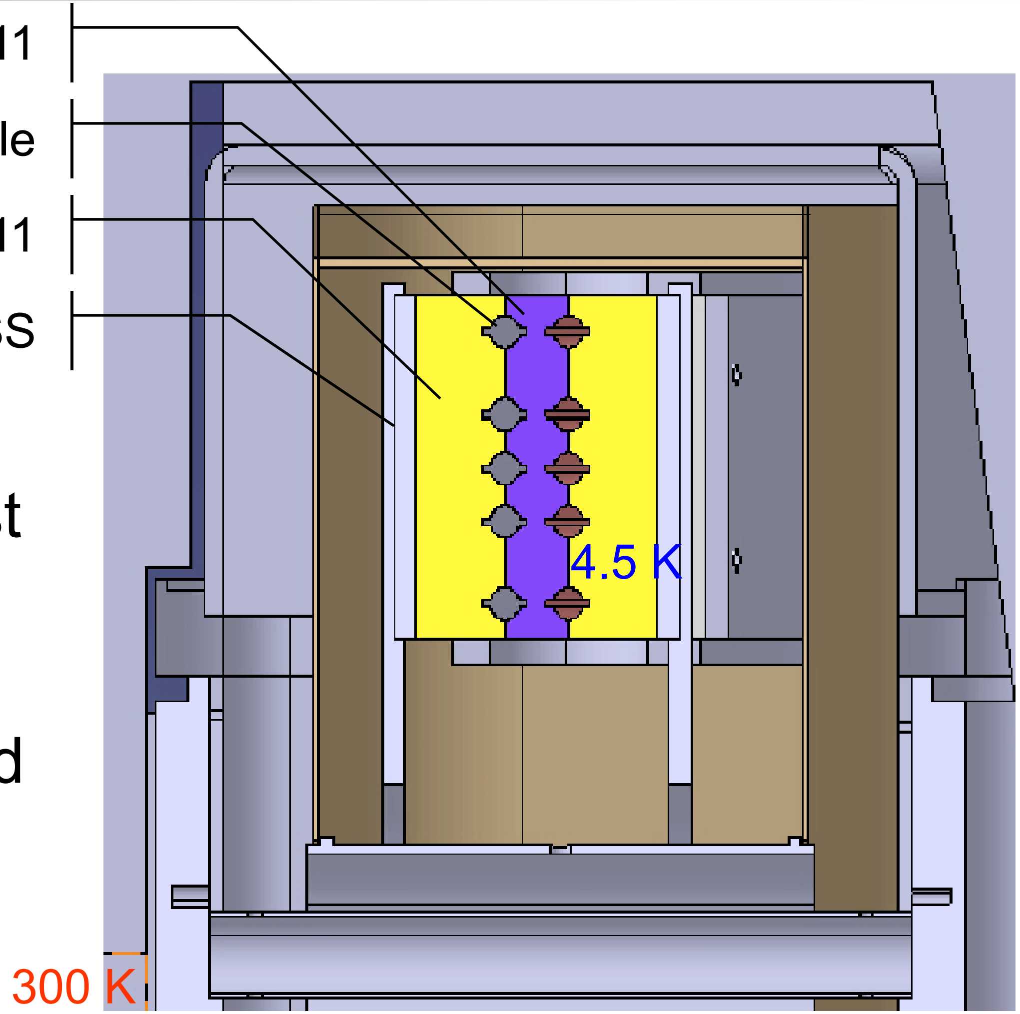
Baseline design

Option design

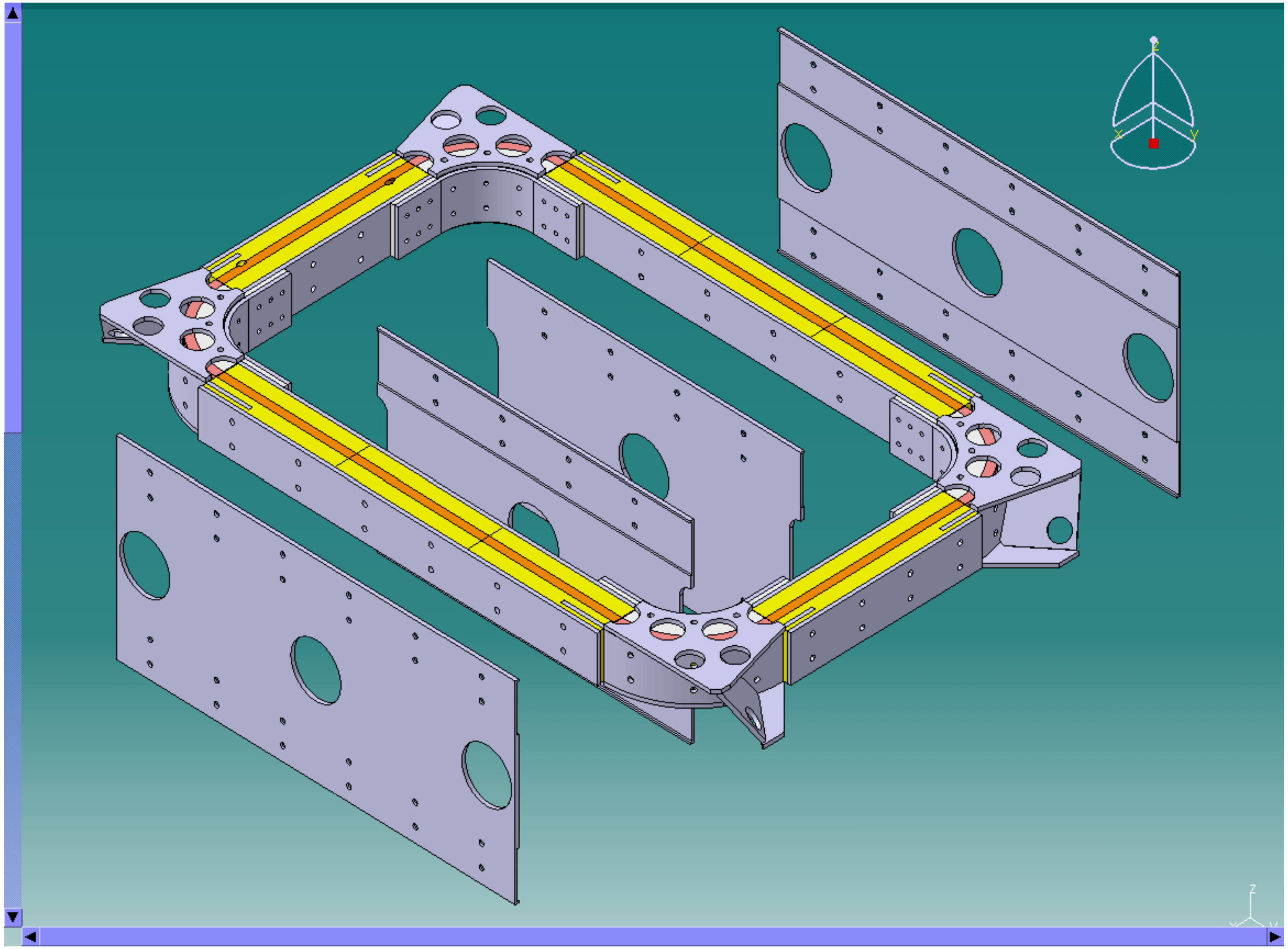


FCM - winding

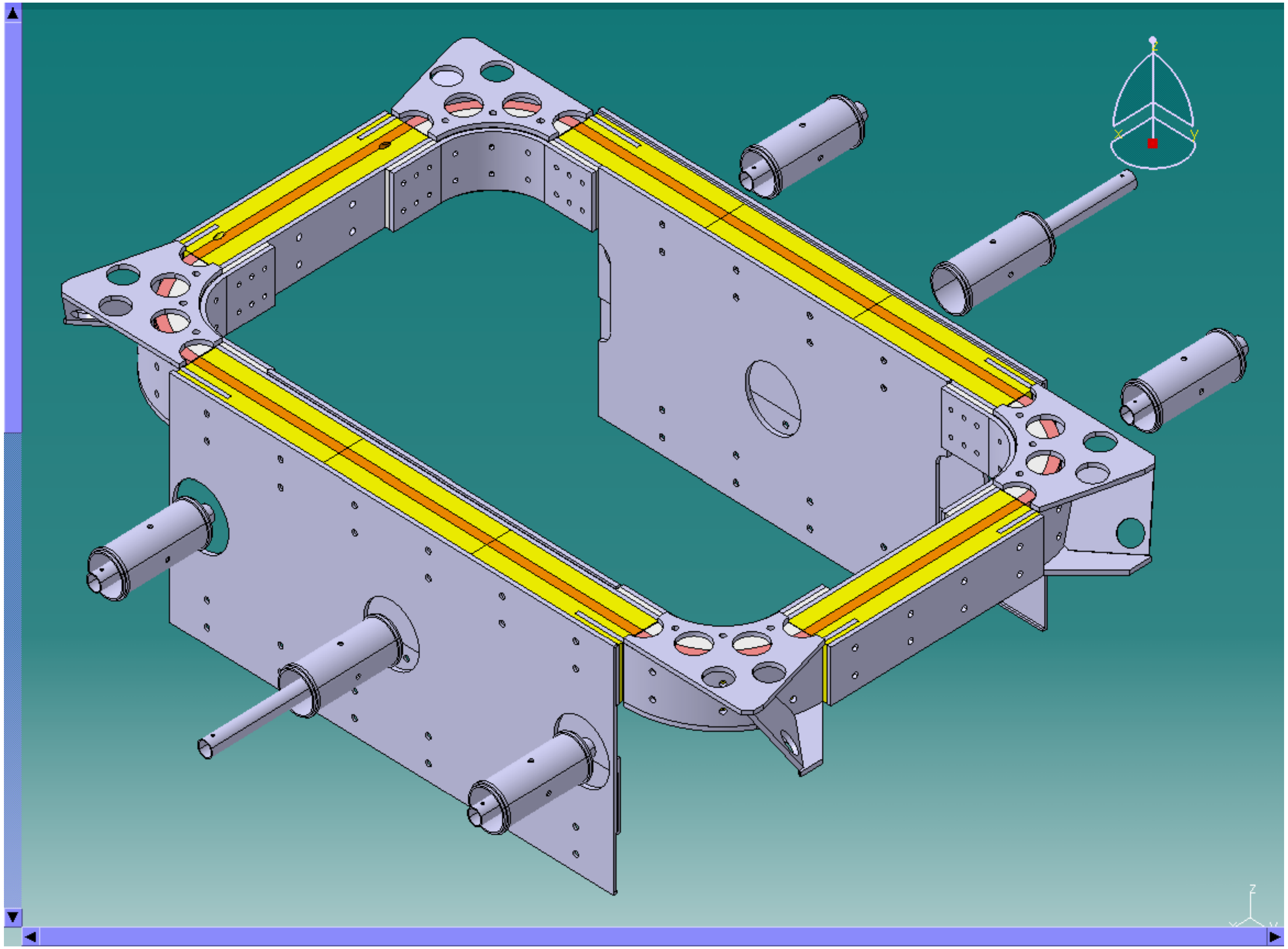
- Composite coil
  - Steel-G11-steel sandwich
  - Vacuum impregnated
  - Self-supporting against electromagnetic loads (cold feet optional)
  - Tie-rods for gravity and out-of-symmetry loads



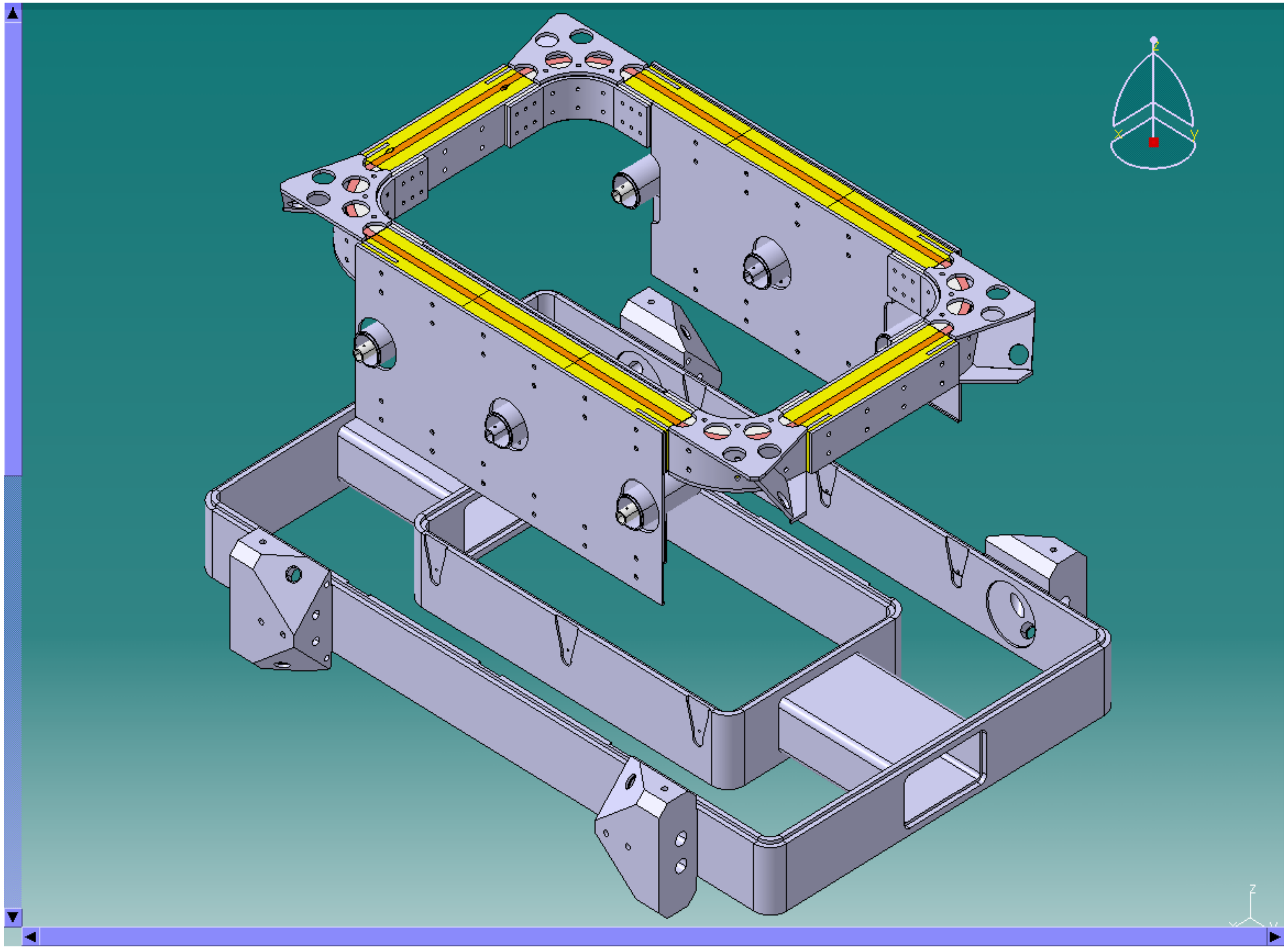
Magnet assembly - 1/12



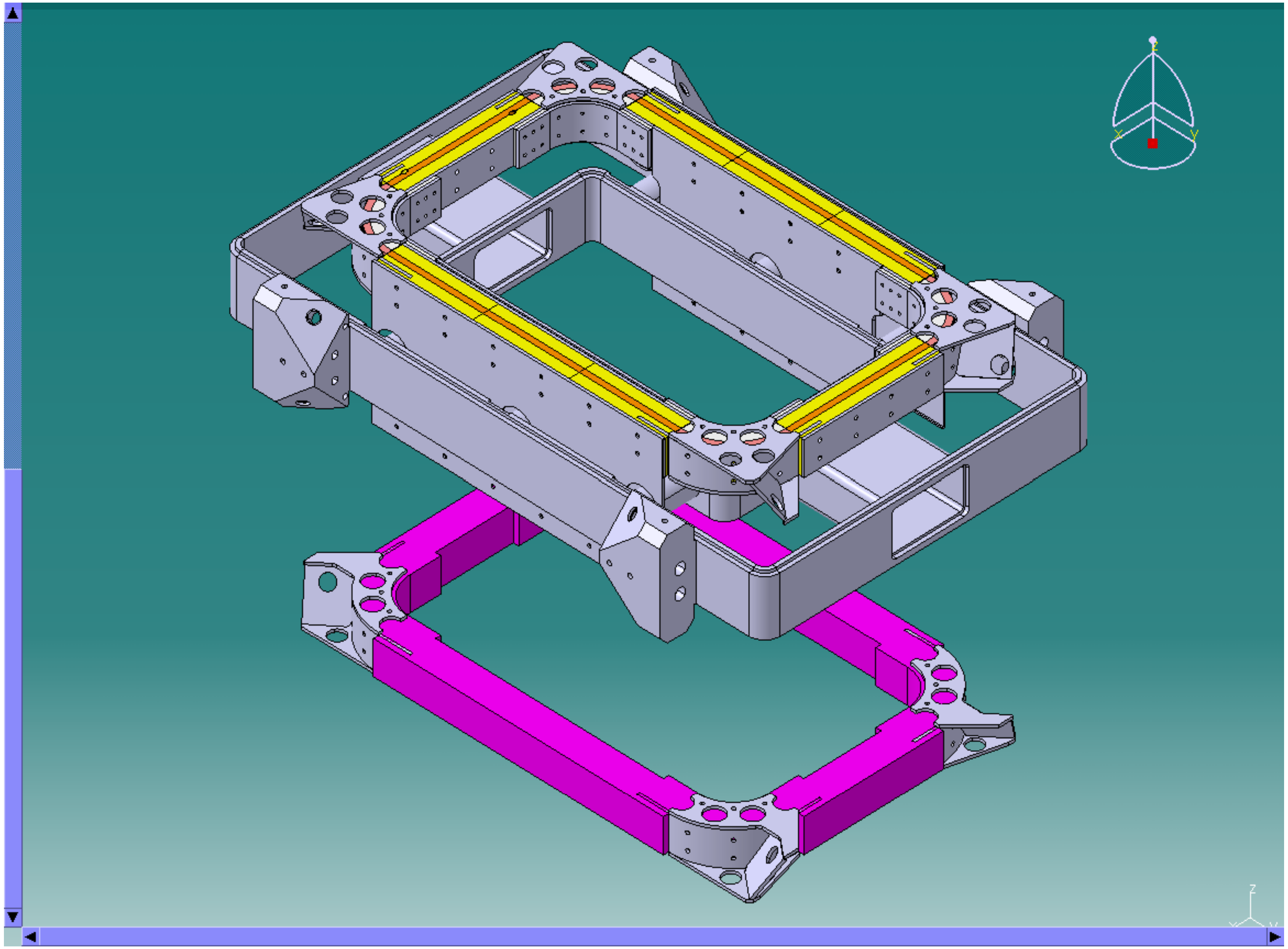
Magnet assembly - 2/12



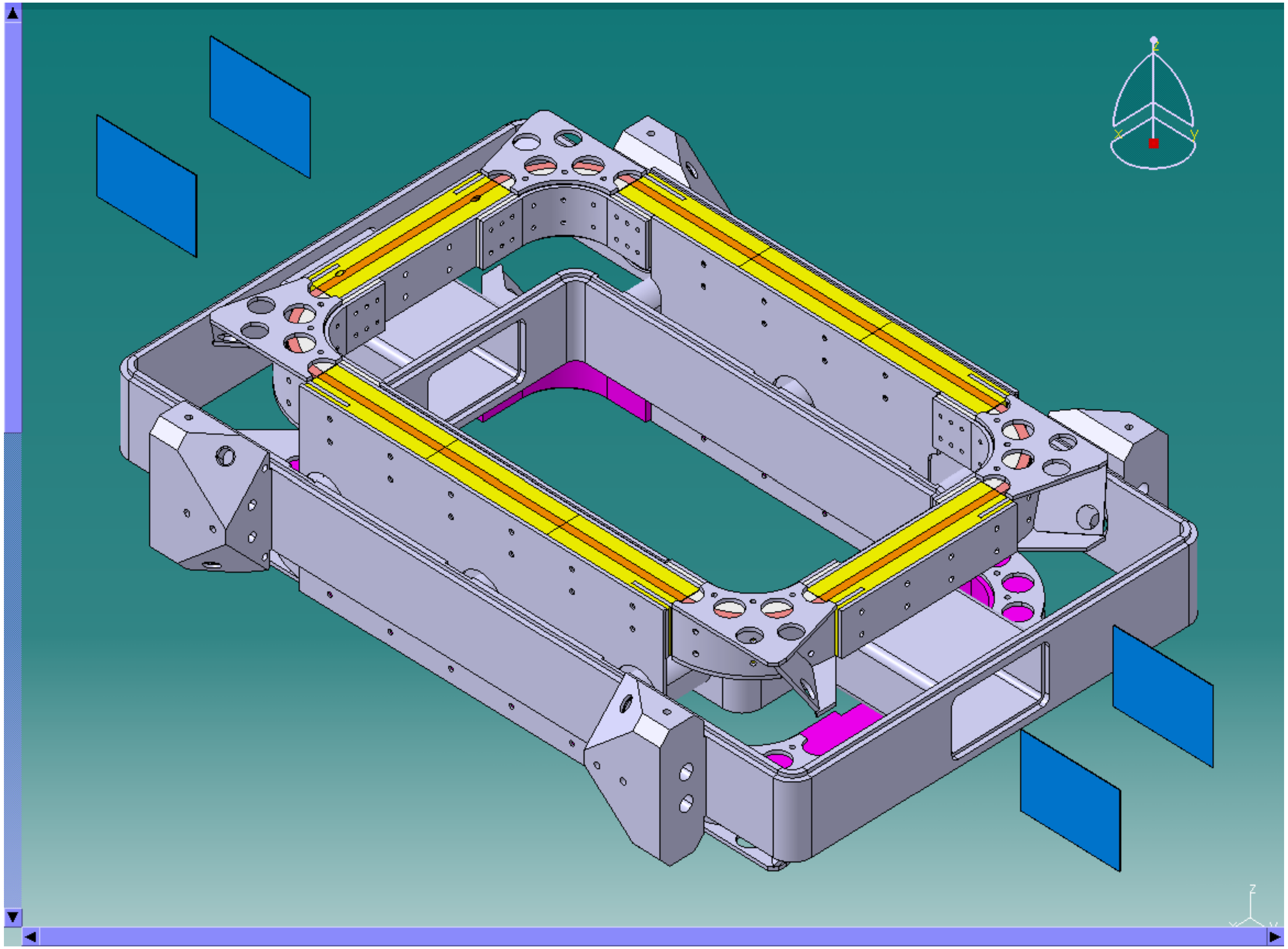
Magnet assembly - 3/12



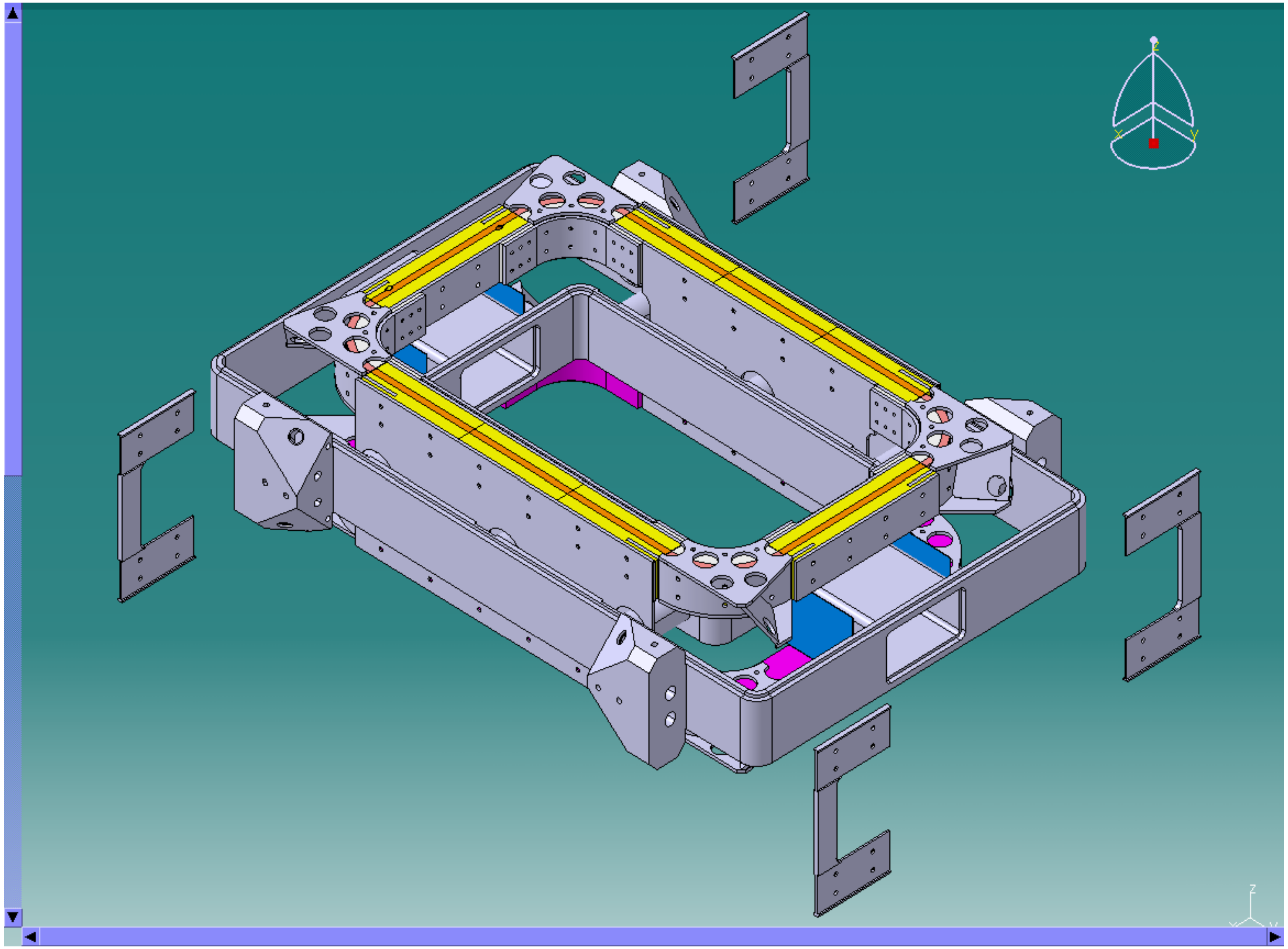
Magnet assembly - 4/12



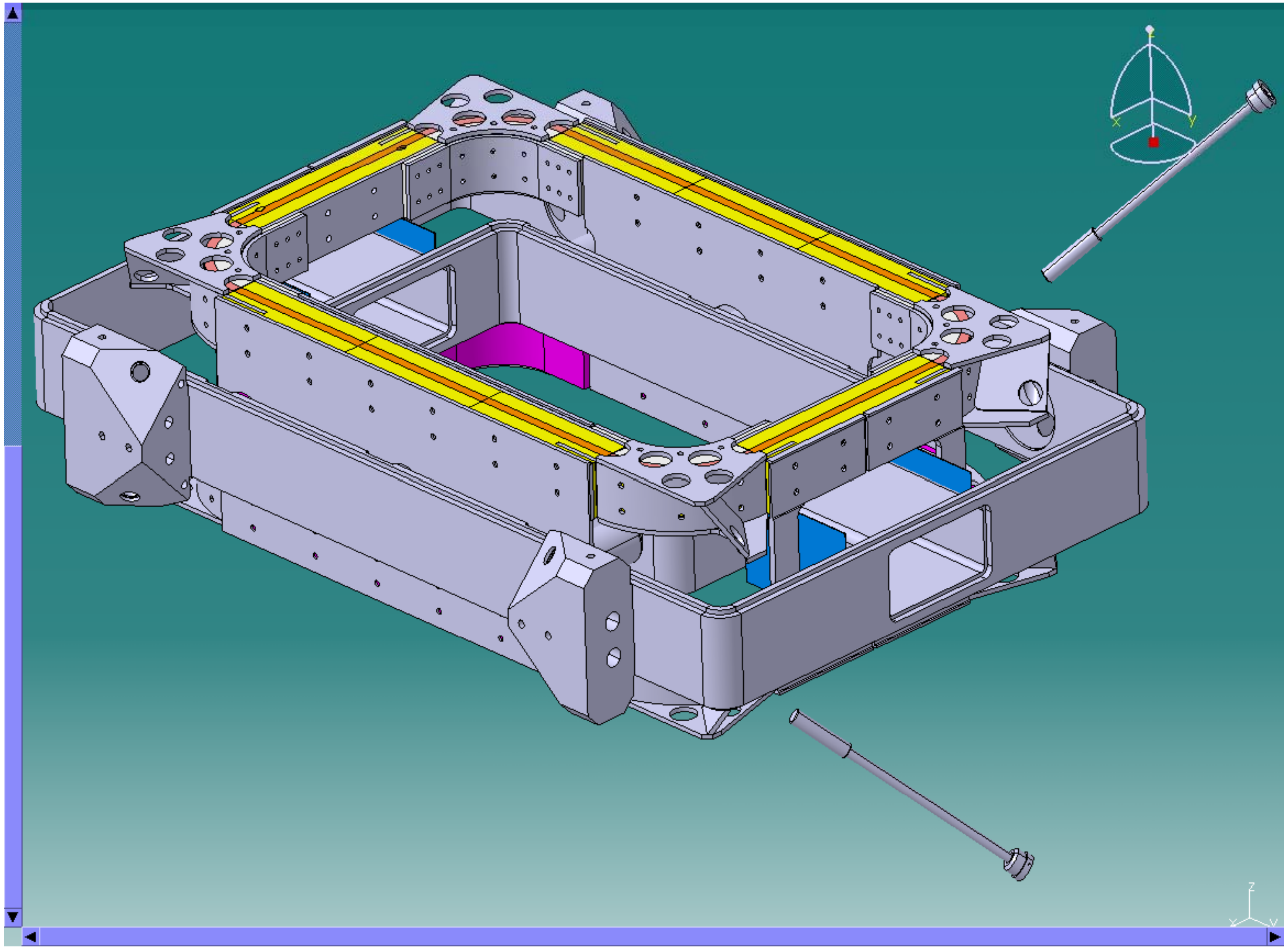
Magnet assembly - 5/12



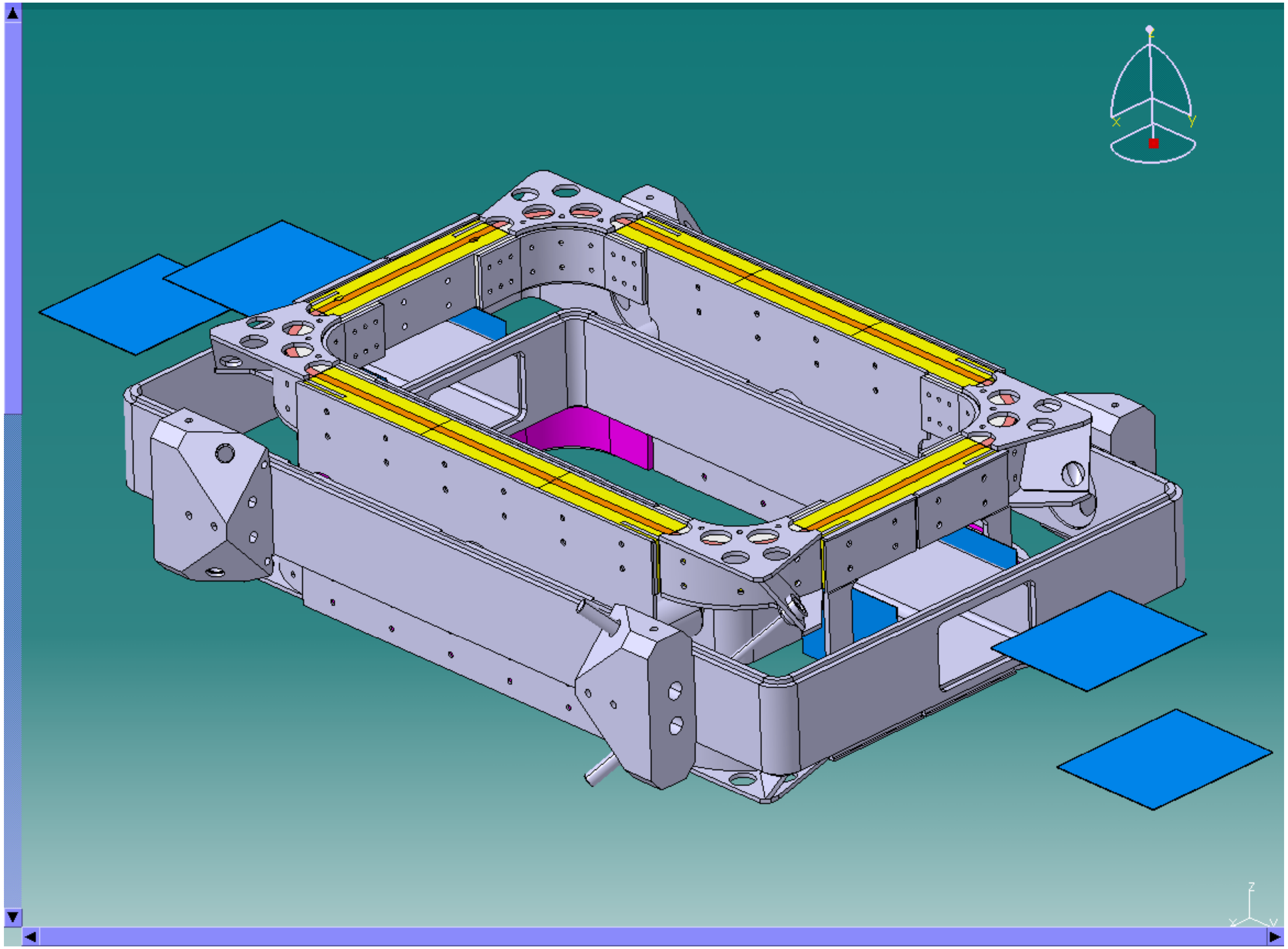
Magnet assembly - 6/12



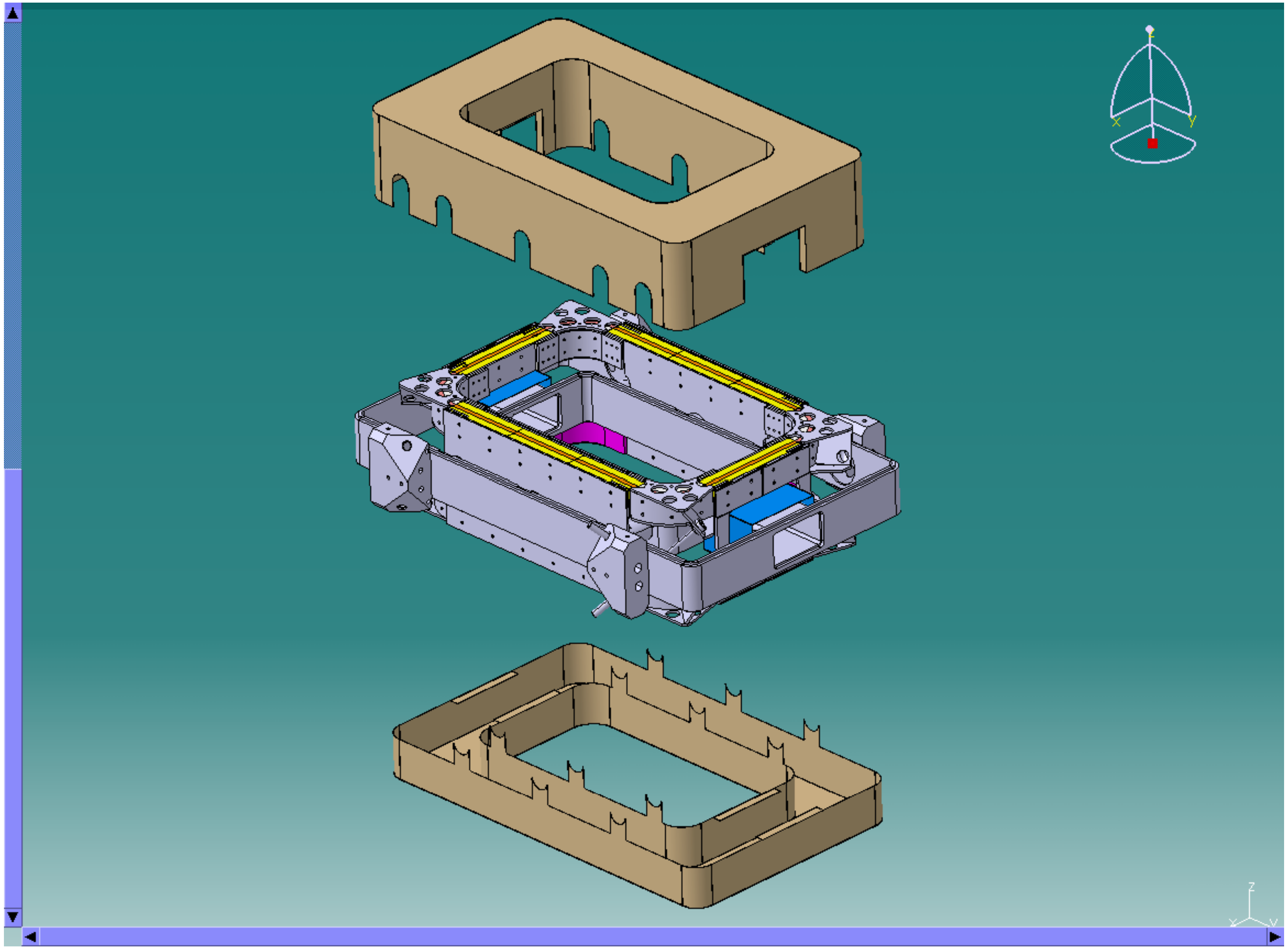
Magnet assembly - 7/12



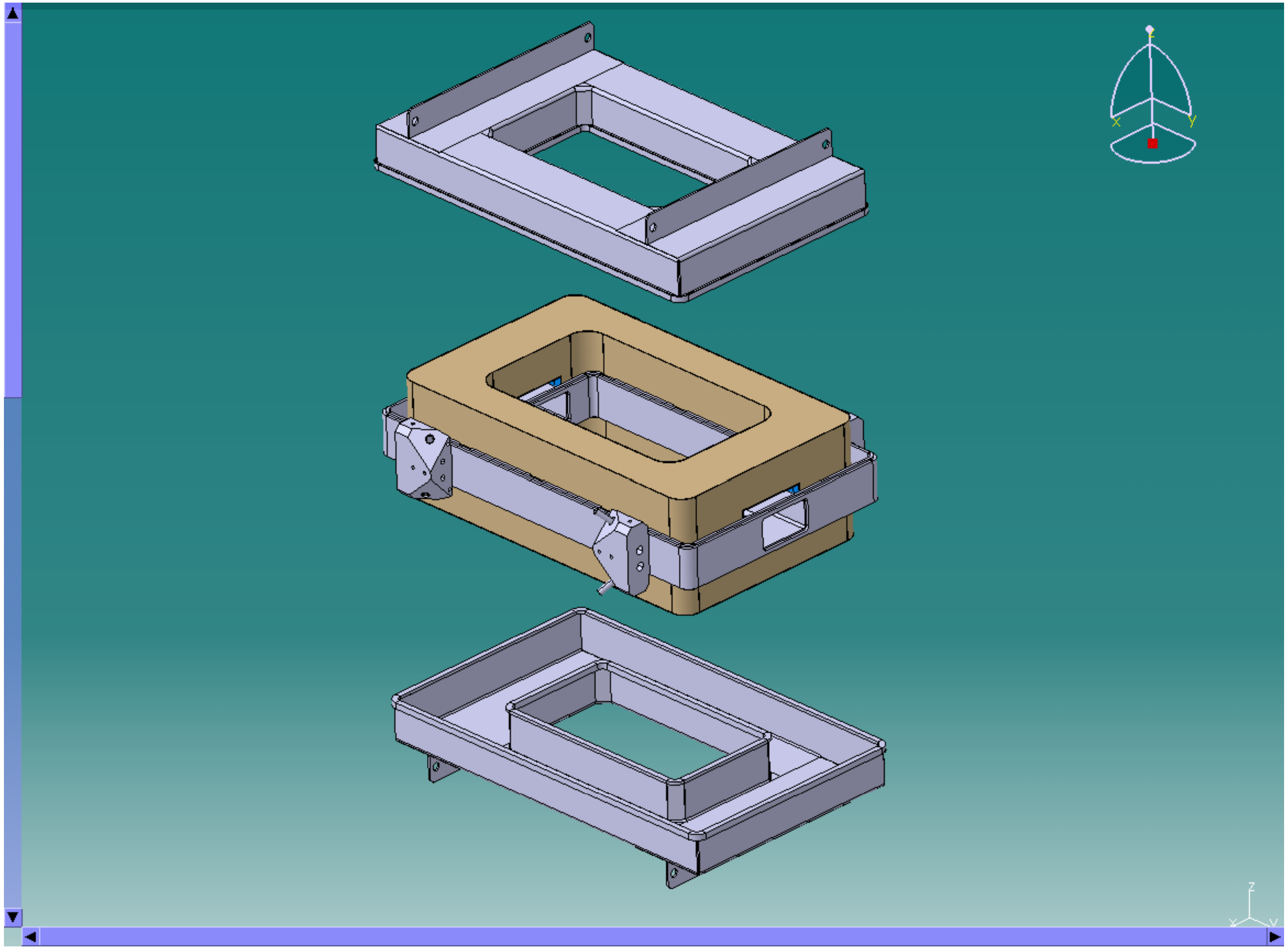
Magnet assembly - 8/12



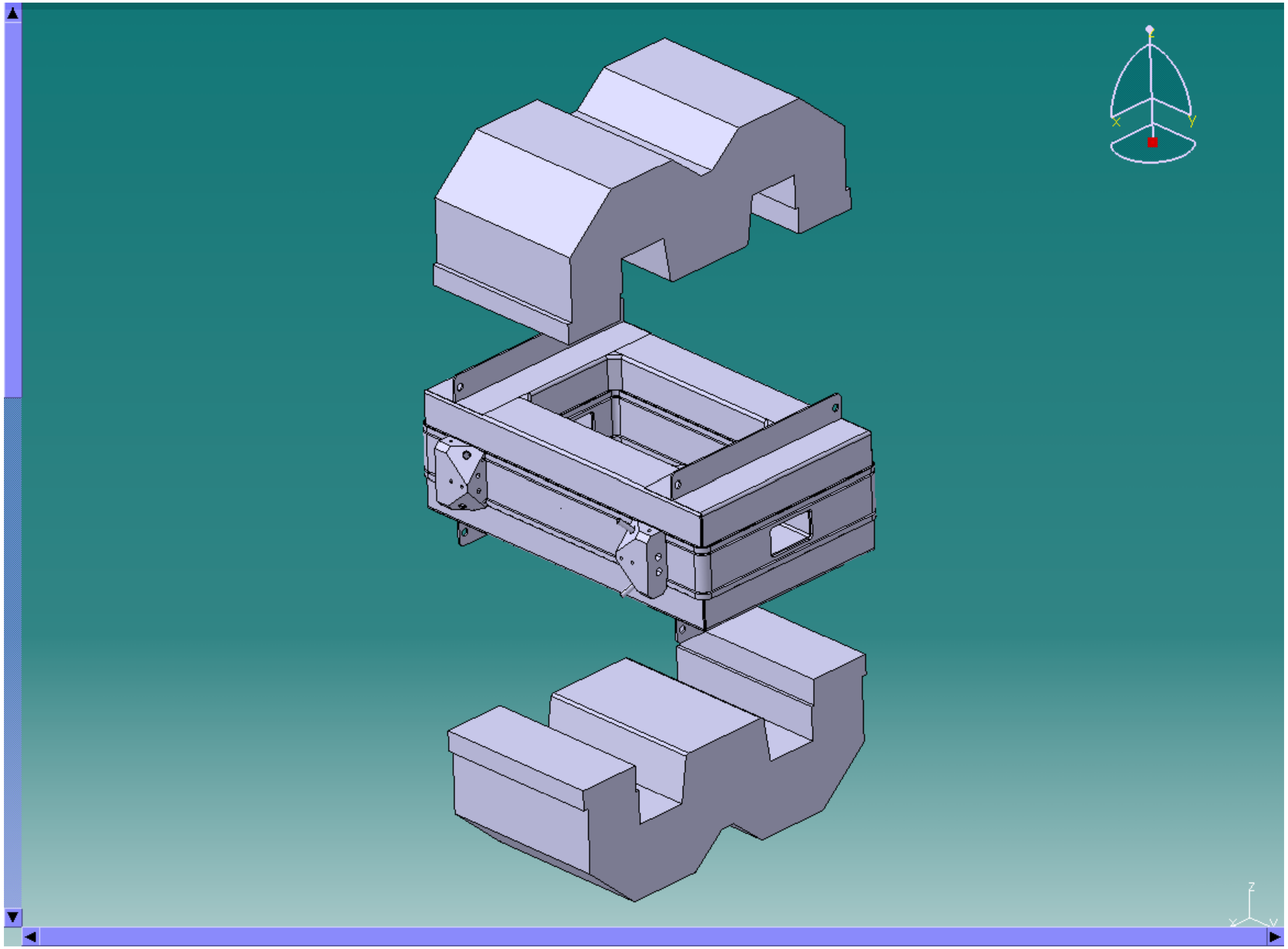
Magnet assembly - 9/12



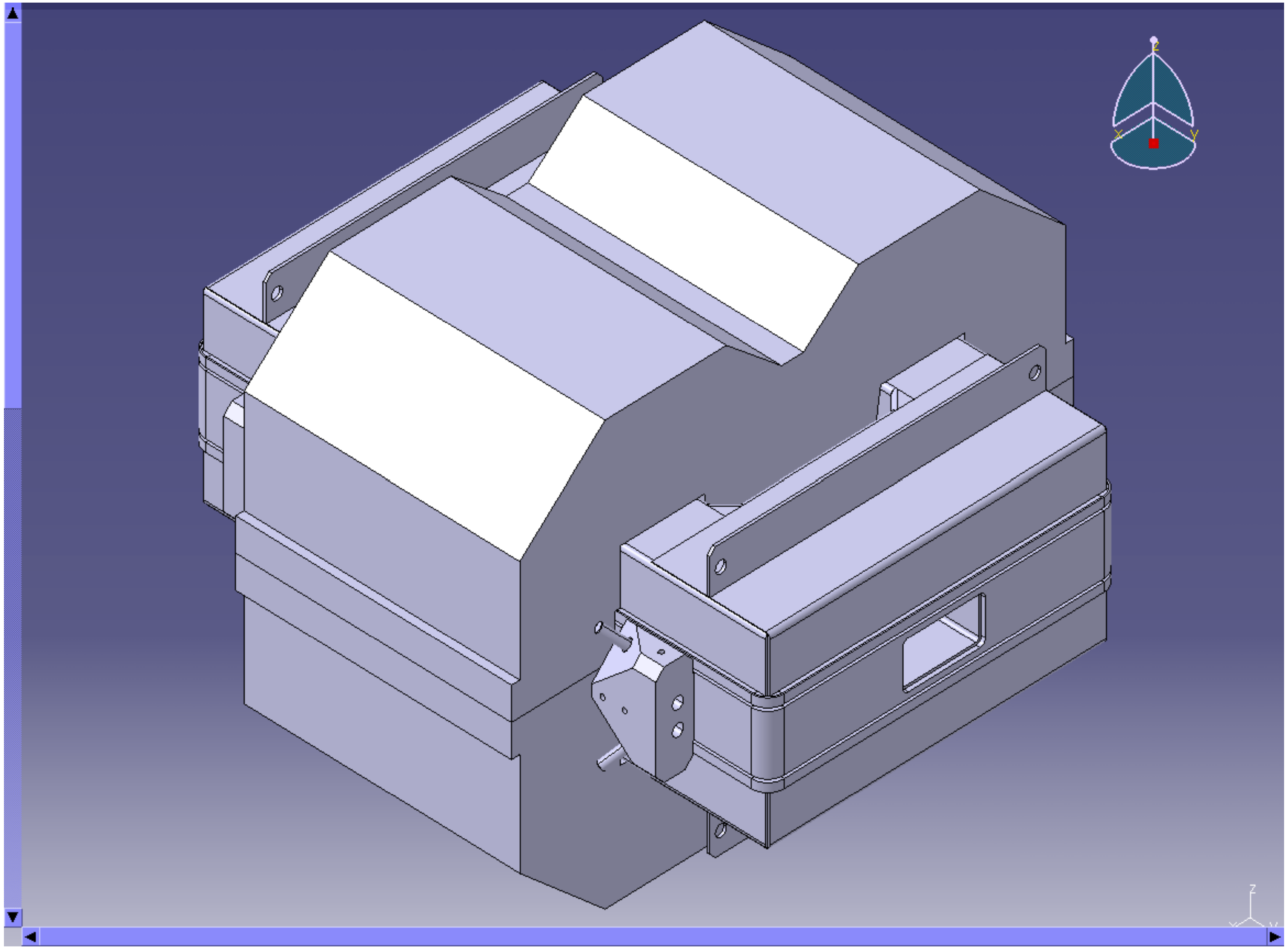
Magnet assembly - 10/12



Magnet assembly - 11/12

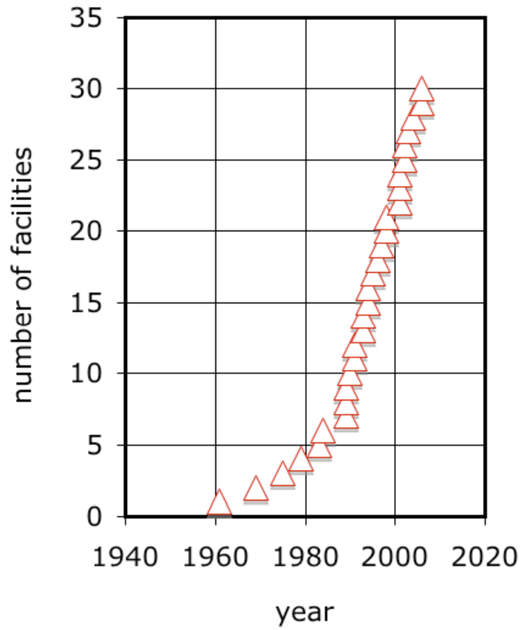


Magnet assembly - 12/12



Other projects and opportunities

- The use of HTS would make an ***enormous*** difference in terms of ease of use and reliability
  - See the work of H. Piekarz, FNAL
- Hadron therapy is a rising specialty of accelerators with an ***enormous*** impact on society
  - $FC_{SC}M$ are considered for compact machines and gantries



Conclusions

- Fast cycled superconducting magnets are a mandatory direction of technology R&D to exploit the domain of medium field accelerators (2…6 T)
- A targeted R&D (e.g. FCM) profiting from the above work may displace resistive conductor technology from the low field domain, achieving better efficiency
- HTS (high current cables) would be the holy grail to achieve premium efficiency and robustness - not necessarily cost-effective
- CARE HHH has offered an optimal and unique opportunity to coordinate and share the R&D on this topic

Additional material

Assumptions for PS2 cost

- 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

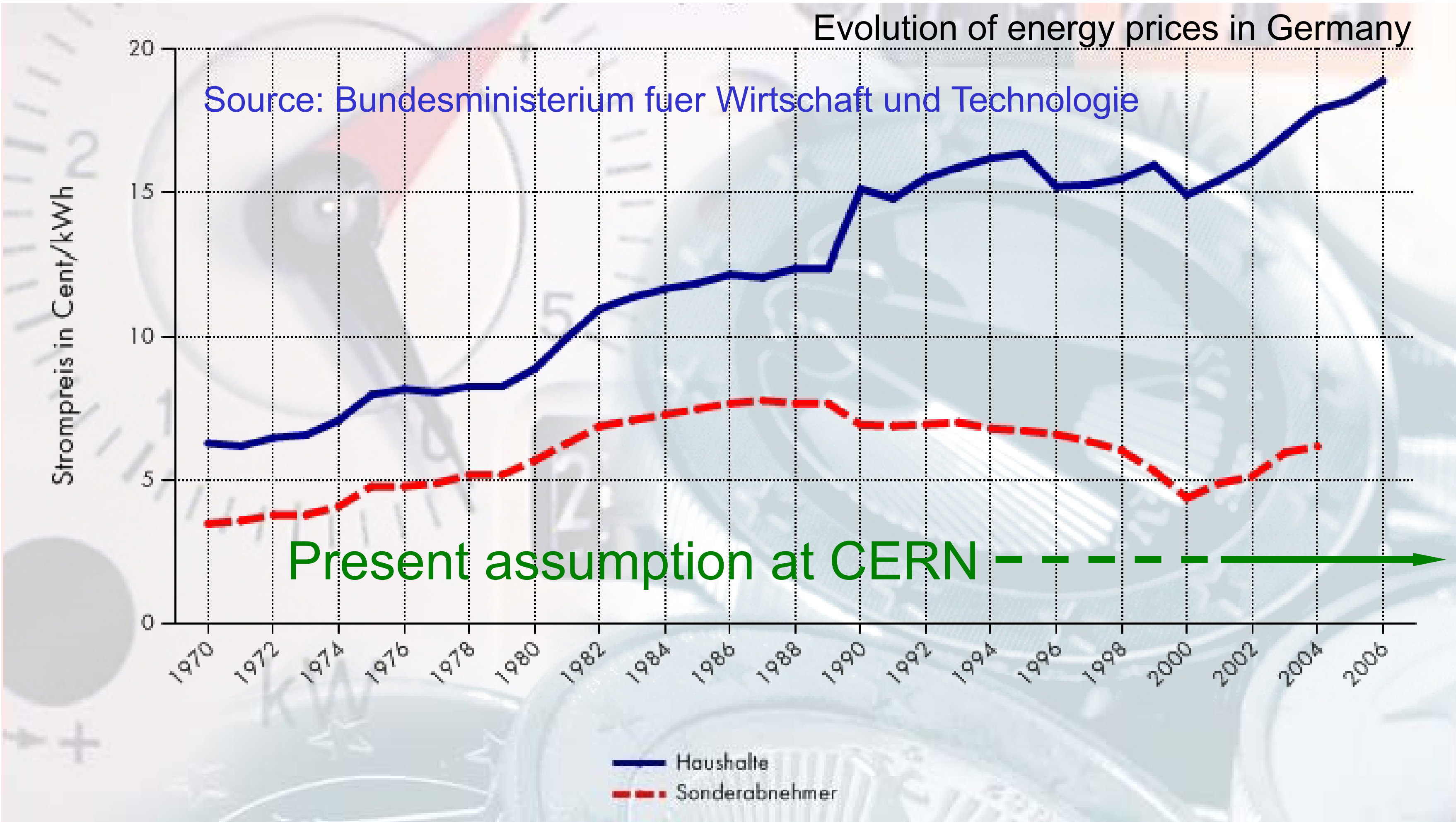
Is HTS a cost-effective option ?

- 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

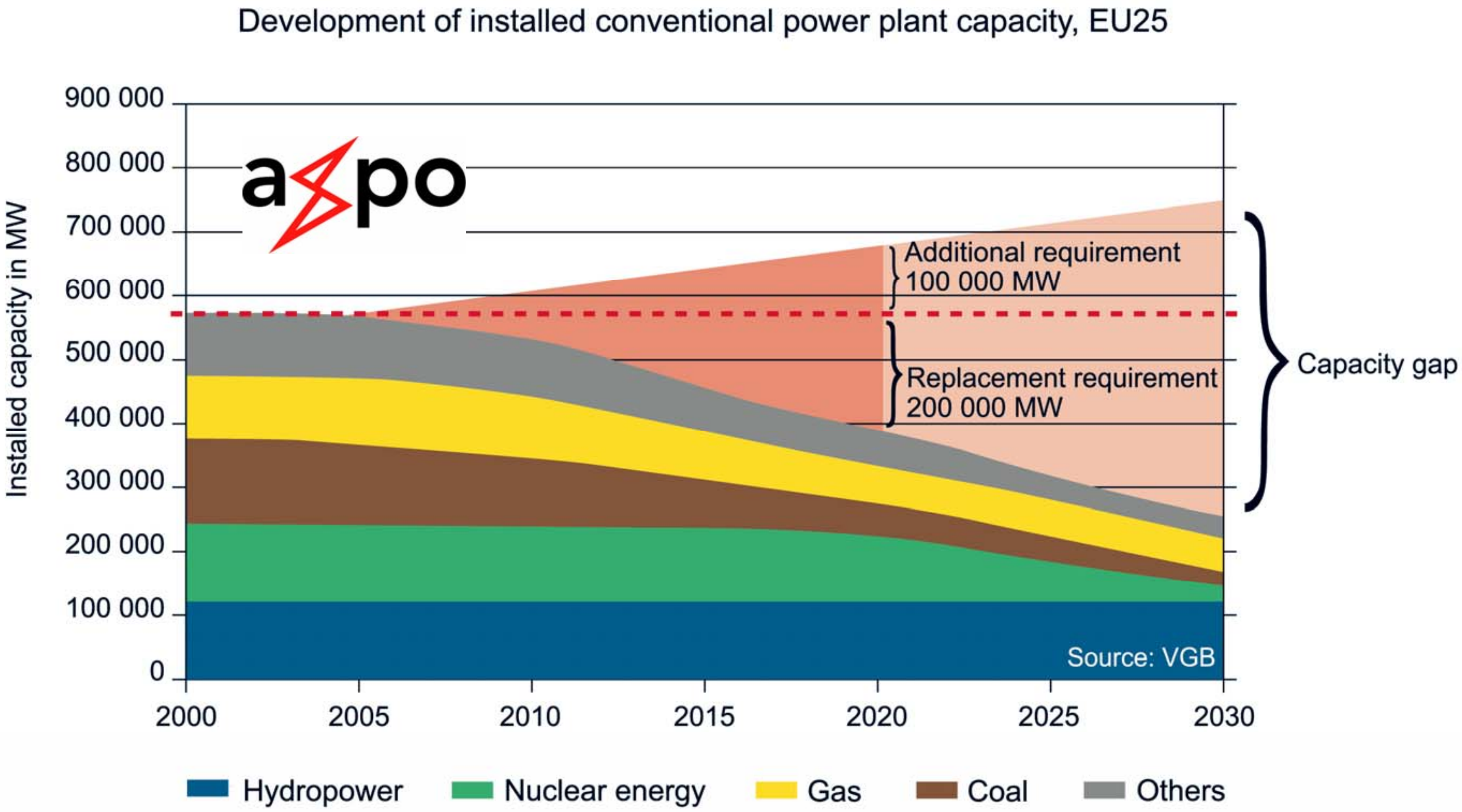
Marginal gain with respect to previous figures (10 %)

could be beneficial for the overall reliability

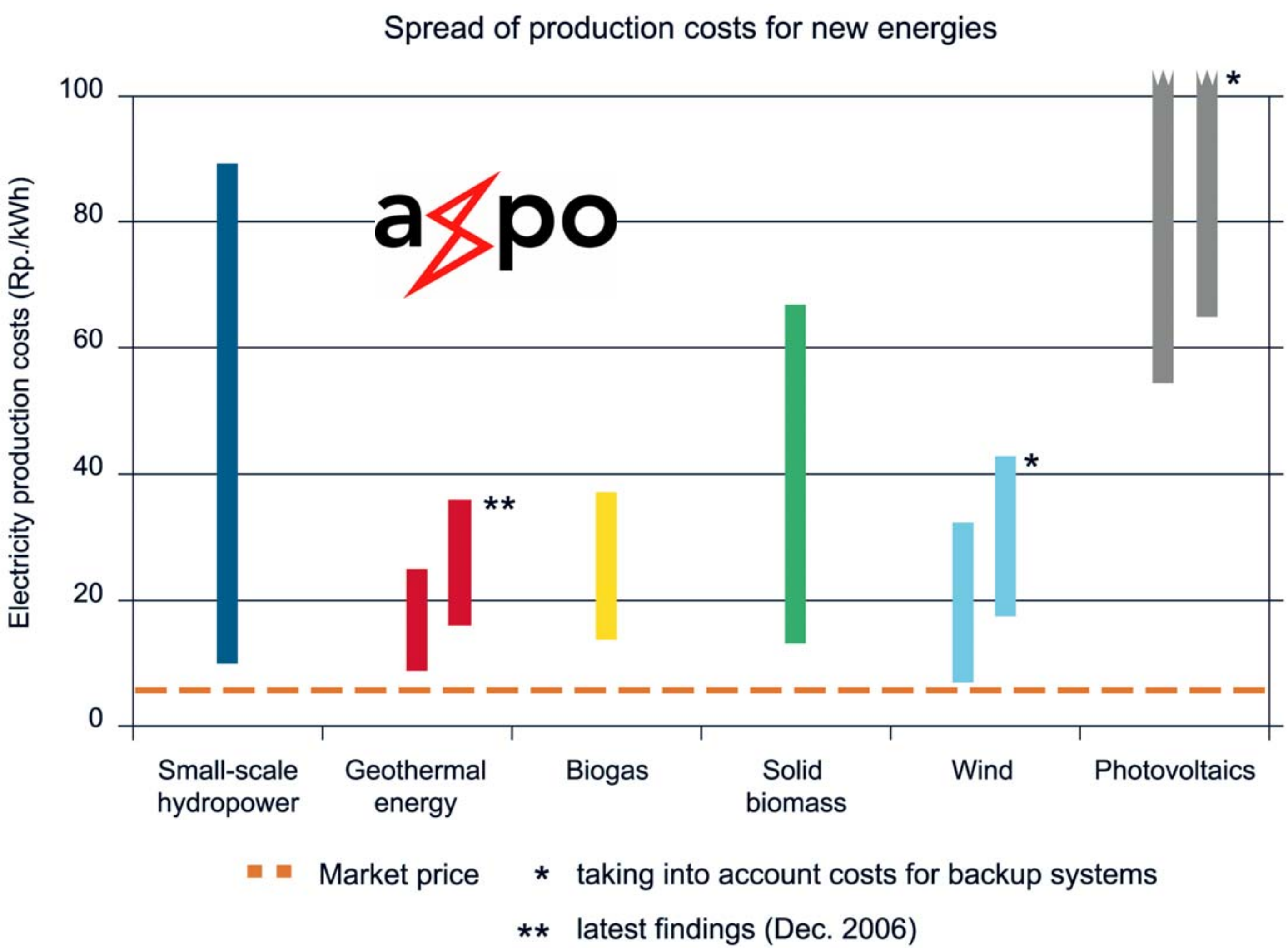
Prices of electricity



Availability of electricity



Price of new energies



15 years from now

UCTE System Adequacy Forecast 2007-2020

… Generation adequacy decreases over the period 2010-2015 in scenario A, **the remaining capacity reaching the level of ARM [Adequacy Reference Margin] by 2014** (+ or -

asures consideration).

p System Adequacy

Ratings for Swiss Electricity Suppliers Remain Stable

… However, high electricity prices and **continuing strong demand** for electric power should support the market […] The operating environment will grow harsher over the next few years as the Swiss electricity market is opened up, and an expected **future supply shortfall** will require higher capital expenditure by the electricity companies. Consequently, there isn't really any scope for the credit ratings to improve.

CS Press Release, Zurich, November 28, 2006

On a time span of ~ 15 years, we will need to increase efficiency, and reduce consumption, to run **reliably** and **economically** our facilities