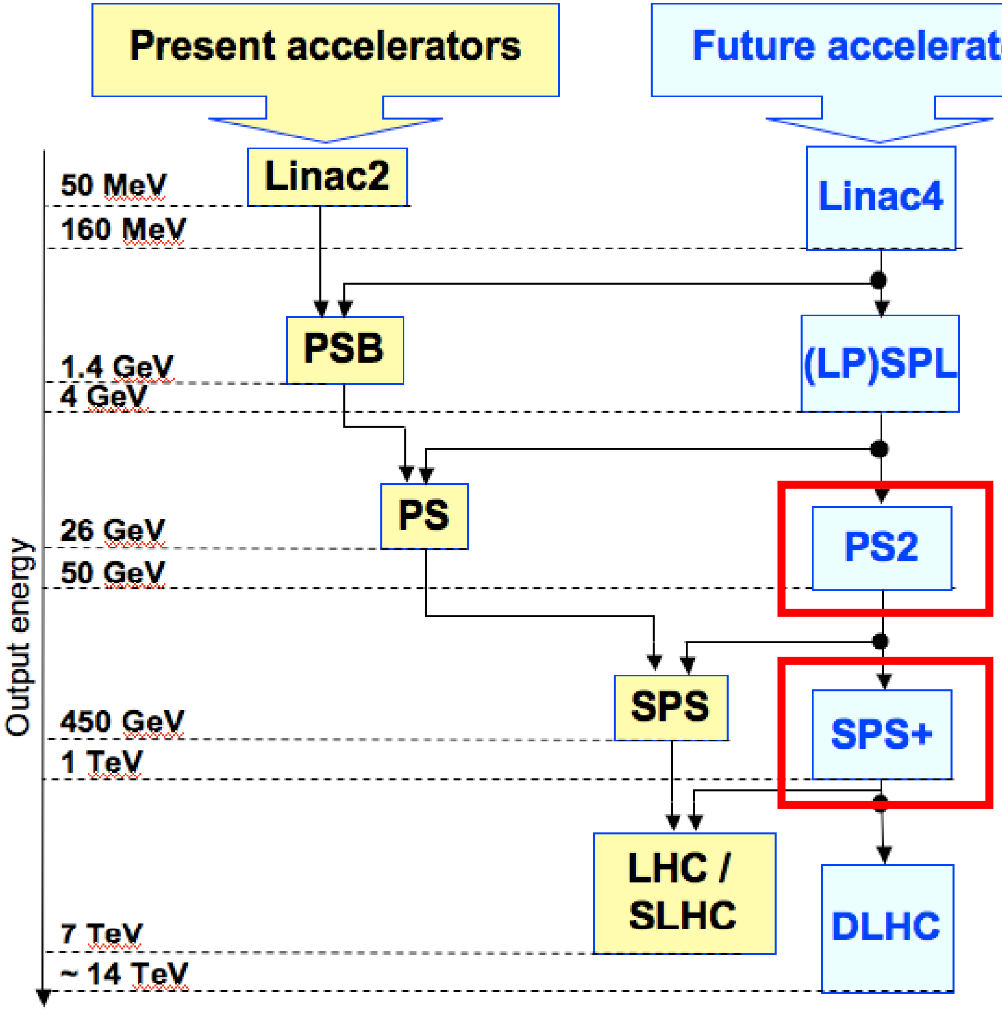
Superconducting Magnets for the Upgrade of the LHC Injectors

L. Bottura

CARE-HHH-APD BEAM'07
October 5th, 2007

Courtesy of R. Garoby

The path for the LHC upgrade



A digression on PS2

Focus on SPS+

Outline

- Requirements for the SPS+ (and PS2) magnets
- SPS+ magnet design study
  - Outstanding issues
  - Scaling of relevant quantities such as magnet volume, material weight (cost), voltage, stored energy and AC loss
- A look over the fence (other EU R&D)
- A look beyond the hill (15 years from now)
- What we should do (R&D plan)

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Magnet design parameters as from ECOMAG-05 and LUMI-06

	PS2+a	PS2+b	SPS+a	SPS+b
Injection energy [GeV]	4	4	**50**	75
Extraction energy [GeV]	**50**	75	**1000**	1000
Injection field [T]	0.144	0.144	**0.225**	0.337
Maximum field [T]	1.8	2.7	**4.5**	4.5
Maximum ramp-rate [T/s]	1.6	2.5	1.43	1.39
Ramp time [s]	1.1	1.1	3	3
Dipole magnetic length [m]	3	3	6	6
Number of dipoles [-]	200	200	750	750
Number of cycles [Mcycles]	60	60	1	1

PS2 reference

The choice of energy in PS2 makes the nominal SPS+ **very difficult** (**low injection field, field swing by a factor 20**)

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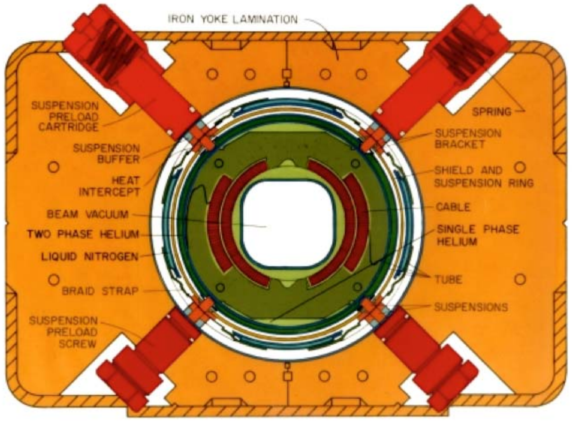
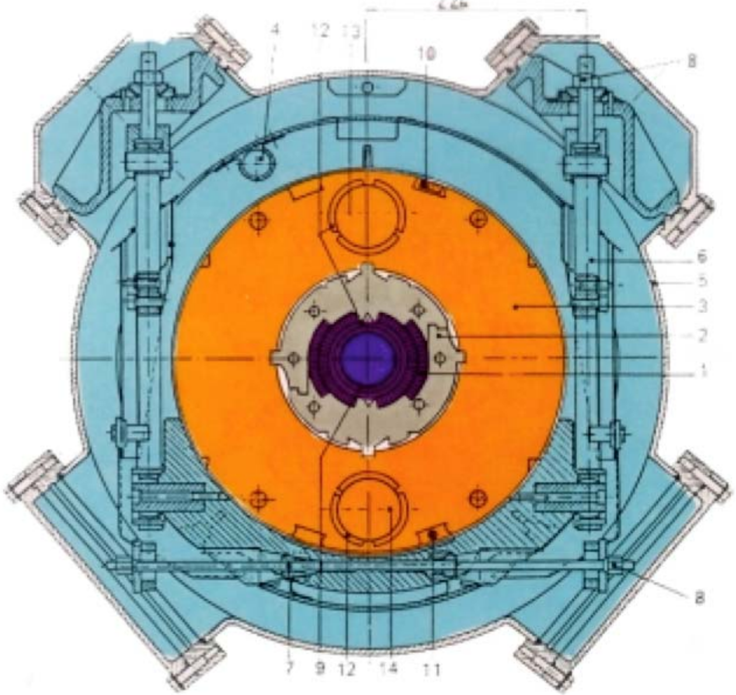
Which magnet design ?

Tevatron



B_{peak} = 4 T
$B_{injection}$ = 0.66 T
dB/dt ≈ 50 mT/s
D_{coil} ≈ 75 mm

HERA

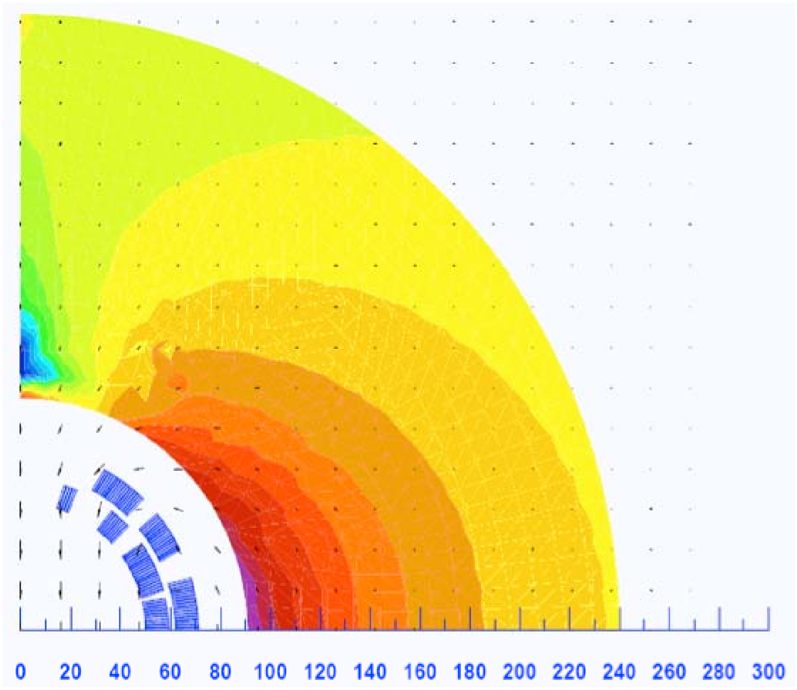


B_{peak} = 5.2 T
$B_{injection}$ = 0.23 T
dB/dt ≈ 3 mT/s
D_{coil} ≈ 75 mm

A (rather arbitrary) baseline magnet design

- In the 4…5 T range the only practical magnet option is based on coils wound with superconducting cables
- The most efficient design is a cos(θ) coil

Nominal dipole field [T]	4.5
Coil inner diameter [mm]	100
Nominal current [A]	3200
Operating temperature [K]	**4.5**
Length [m]	6
Mass [tons]	**7.6**
Stored energy [kJ]	700
Inductance [mH]	140
Ramp voltage (inductive) [V]	**150**
Average AC loss (coil + yoke) [W]	**19+15**



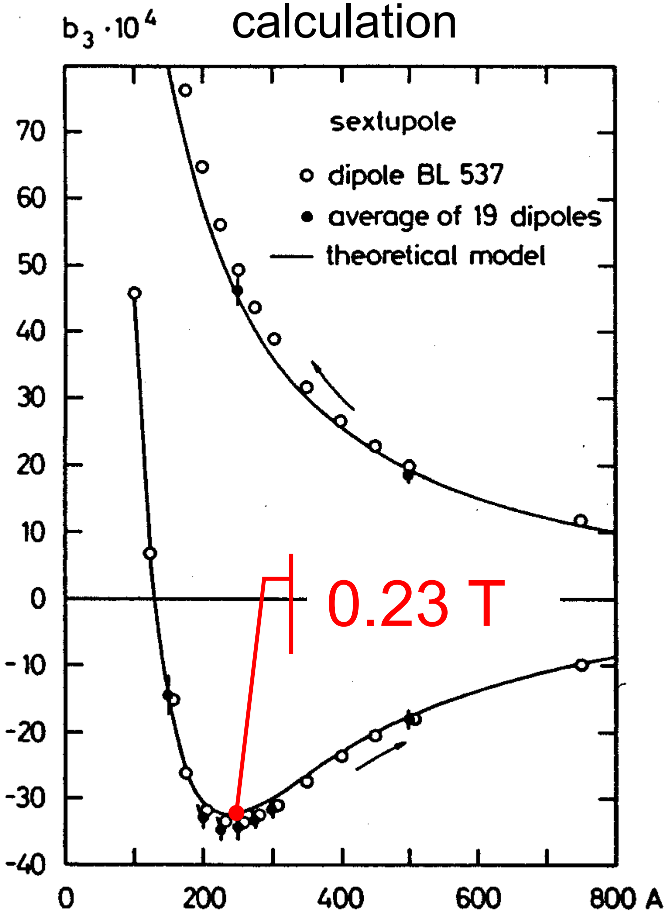
Sample SPS+ magnet design
by courtesy of G. Kirby, CERN
AC loss calculation by A. Verweij, CERN

Magnet design, manufacturing and operation issues

- **AC loss** in the coil (and iron)
- **Radiation dose** and **heat deposition** caused by beam loss during acceleration
- **Cooling** of the cable and heat removal from the magnet
- **Quench detection** and **protection** under high-voltage ramped conditions
- **Field quality** in ramped conditions (design, manufacturing and measurement)
- **Fatigue** at large number of cycles

The issue of the field swing

Measured sextupole in HERA dipoles vs. calculation



Proc. of MT-11, pp. 147-152, **1990**.

- HERA dipoles:
  - Injection field: 0.23 (T)
  - Nominal field: 5.2 (T)
  - Field swing: 23 (-)
  - Measured field errors at injection:
    - $b_1^{PC} \approx 50$ units
    - $b_3^{PC} = 36$ units @ 25 mm
- For comparison, LHC dipoles:
  - Injection field: 0.54 (T)
  - Nominal field: 8.3 (T)
  - Field swing: 15 (-)

An increase of injection field will make the LHC *easier*, but SPS+ will become the *most critical* ring in the chain

General magnet design scaling

- Coil volume

$$V_{coil} \approx B_{max}^{1.3}\ D_{coil}$$

- Iron yoke volume

$$V_{yoke} \approx B_{max}\ D_{coil}$$

- Magnet weight

$$W_{magnet} \approx \boxed{B_{max}^{1.5}\ D_{coil}}$$

cost proportional to magnet size, grows more than linearly with bore field

- Magnetic energy

$$E_{Magnetic} \approx B_{max}^{2}\ D_{coil}$$

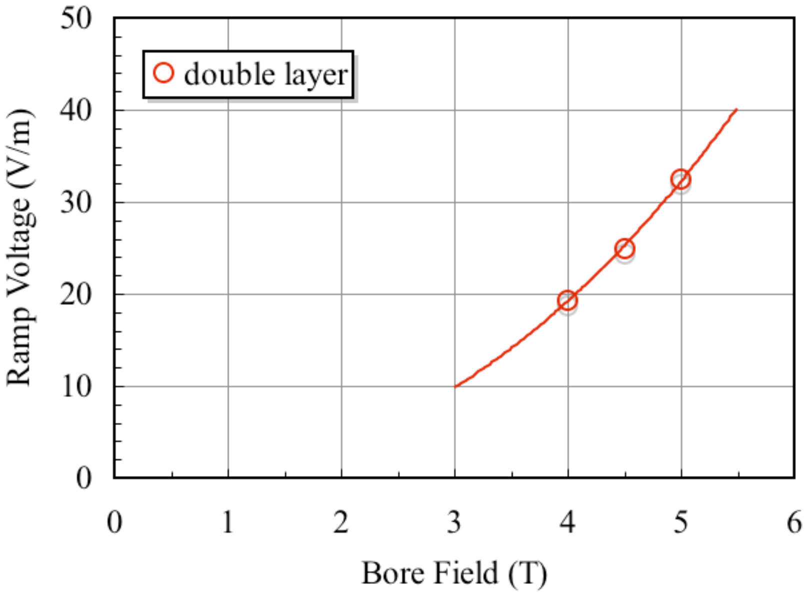
- Ramp voltage

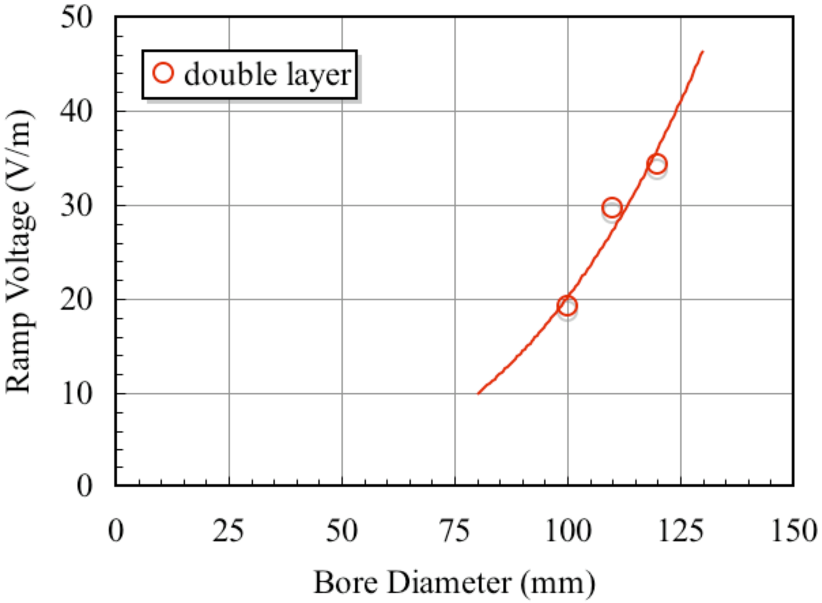
$$V_{ramp} \approx 1/t_{ramp}\ \boxed{B_{max}^{2}\ D_{coil}^{2}}$$

strong dependence !

Coil voltages and protection

- Integrated ramp voltages for SPS+ are in the range of 120 kV (750 dipoles, 6 m length)
  - Requires **partitioning of the circuit** in sectors to use standard technologies (below 20 kV)
  - **Quench detection** is an issue (0.1 V signal in 200 V) and requires compensation of inductive voltage at the level of 0.1 %
  - **Quench protection** has to be demonstrated in fast-ramped, high current density accelerator magnets





Lessons and recipes - 1

- Even in the 4…5 T range, choose sparingly bore field and magnet aperture. Each extra Gauss and mm is costly (magnet volume and weight) and makes operation and protection more difficult (ramp voltage, stored energy)
- Iterate early with beam specifications for bore field and magnet aperture

AC loss scaling with magnet design parameters

- Loss in the superconducting coil
  - Hysteresis in the superconducting filaments:

$$P_M \approx \underset{\text{strand}}{\boxed{D_{fil}\, J_c}}\ \underset{\text{magnet design}}{\boxed{V_{coil} \log (B_{max})}}\ \boxed{1/t_{ramp}}\ \text{operation}$$

  - Coupling (eddy) currents in superconducting strands and cables:

$$P_C \approx \underset{\text{cable}}{\boxed{w\, f(N,R_a,R_c)}}\ \underset{\text{magnet design}}{\boxed{V_{coil}\, B_{max}^2}}\ \boxed{1/t_{ramp}}\ \text{operation}$$

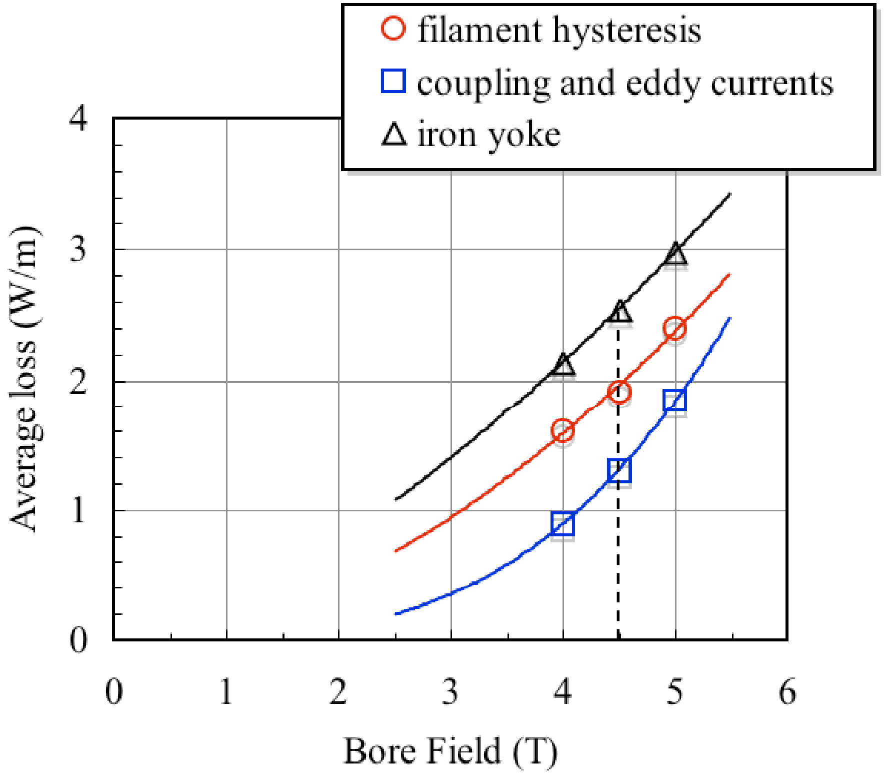
- Loss in (optimised) iron

$$P_{yoke} \approx \underset{\text{magnet design}}{\boxed{V_{yoke}}}\ \boxed{1/t_{ramp}}\ \text{operation}$$

V_{coil} and V_{yoke} depend on B_{max} and D_{coil}

AC loss values for the baseline SPS+ dipole design

- Average AC loss (dynamic load) during a 12 s cycle: 5.7 W/m @ 4.2 K
    - This represents a large cryogenic load: 34 kW @ 4.2 K
    - Large installation, the size of 2 LHC refrigerators, and would require 8.5 MW of electric and cooling power
    - Only marginally acceptable percentage (15 %) of the power presently needed to run the SPS (the total value quoted is 60 MW)
- A further reduction of AC loss is required: R&D on strand, cable and iron yoke



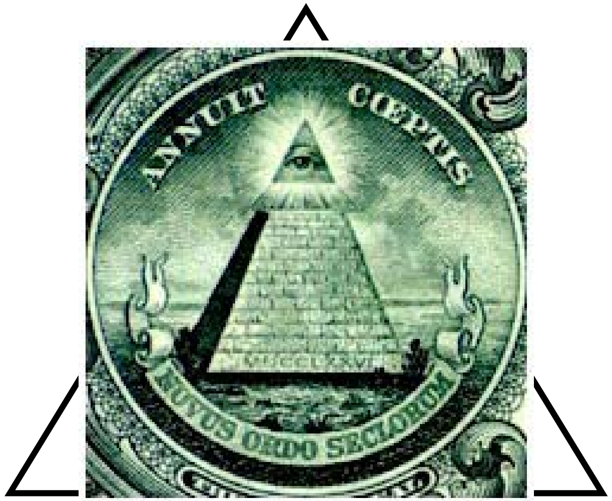
AC loss is **strongly dependent** on **magnet bore field and aperture** as well as the details of the cross section

Lessons and recipes - 2

- Minimize AC loss, compatibly with protection, stability (transient heat balance) and current distribution

The **tri-lemma** of the optimum pulsed superconducting cable design

(courtesy of P. Bruzzone)



Current Distribution

Heat Balance

AC Loss

… and cost !

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On-going European R&D on fast-ramped superconducting magnets

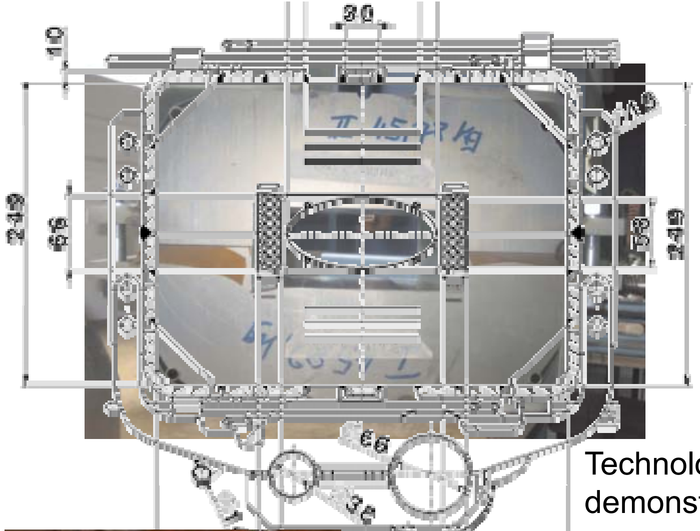
- FAIR at GSI (Darmstadt, D)
  - SIS-100 (2 T, 4 T/s, Superferric, Nuclotron magnets)
  - SIS-300 (4.5 T, 1 T/s, cos-theta magnets)
  - Total R&D cost estimated at 15 MEUR (**M = 24 MCHF**), no data for P
- DiSCoRap at INFN (Milano, Genova, Frascati,I)
  - R&D on a 5…6 T, 1…1.5 T/s dipole for SIS-300
  - MoU covers the R&D work, the financial envelope is estimated at 4.7 MEUR (**M = 7.5 MCHF**), with **P = 30 FTE**

Seen from here, the grass in the garden of the neighbors seems much greener

Courtesy of G. Moritz, GSI

The GSI program

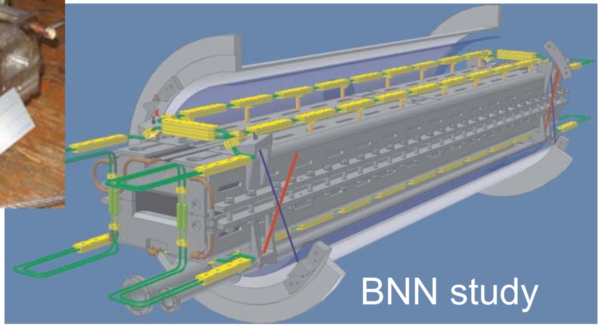
Nuclotron: 2 T at 4 T/s



Coil pack model

Technology demonstration

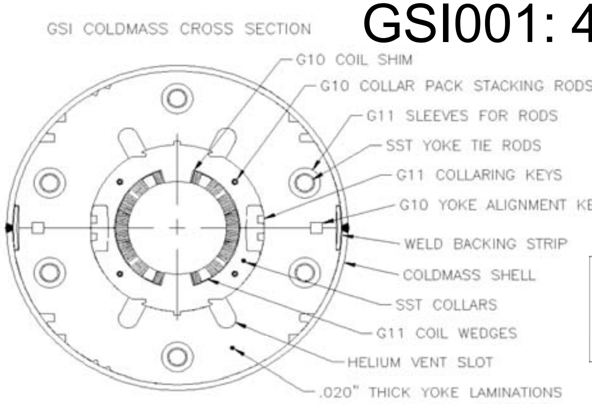
Slitted yoke end

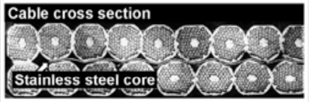


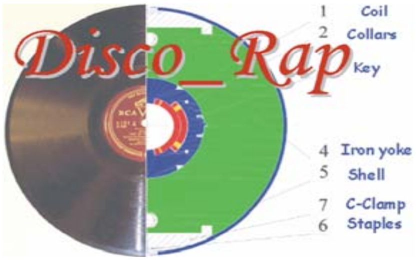
BNN study

SIS-100

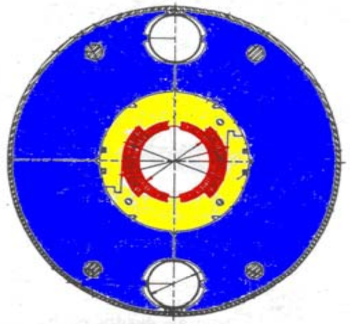
GSI001: 4 T at 1 T/s







INFN design and fabrication of a model of a curved, 4.5 T, 1 T/s dipole for SIS-300



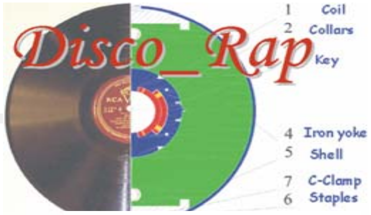
Conceptual and technical design study GSI-IHEP on a modification of the UNK dipole design (5 T, 0.11 T/s) to the SIS-300 (6 T, 1 T/s)

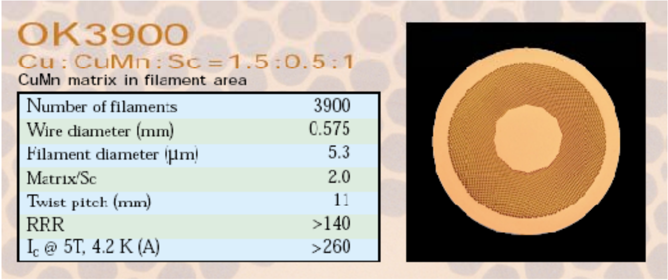
SIS-300

Courtesy of P. Fabbricatore, INFN

The INFN program

- Crucial R&D addressed
  - AC loss: reduce wire and cable loss (material, conductor, winding optimization)
  - Winding technology for 114 mm sagitta over 7.8 m length
  - Fatigue at 10^6 cycles (design optimization and material qualification)




OK3900

Cu : CuMn : Sc = 1.5 : 0.5 : 1

CuMn matrix in filament area

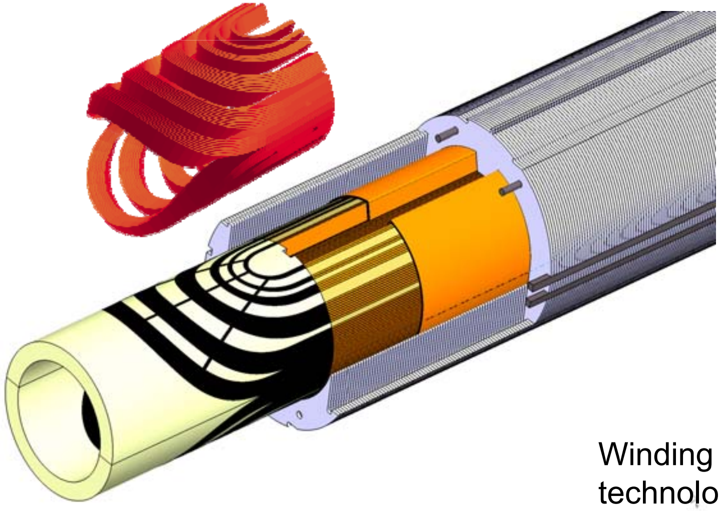
Number of filaments	3900
Wire diameter (mm)	0.575
Filament diameter (μm)	5.3
Matrix/Sc	2.0
Twist pitch (mm)	11
RRR	>140
I_c @ 5T, 4.2 K (A)	>260

Wire R&D

energization

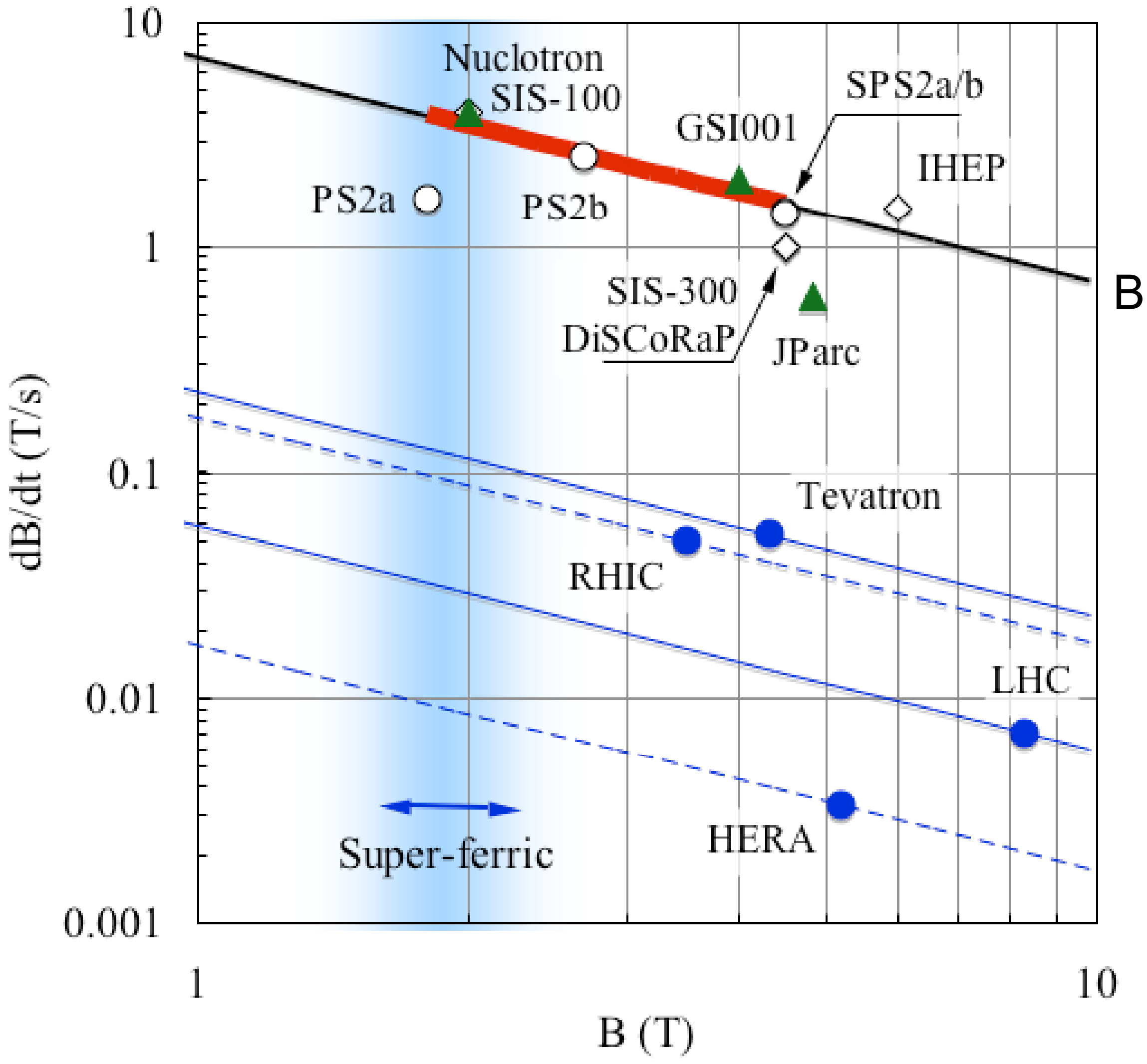
σ_{ave}=51.5 MPa

X-section optimization and magnet analysis



Winding optimization and technology demonstration

A broader perspective



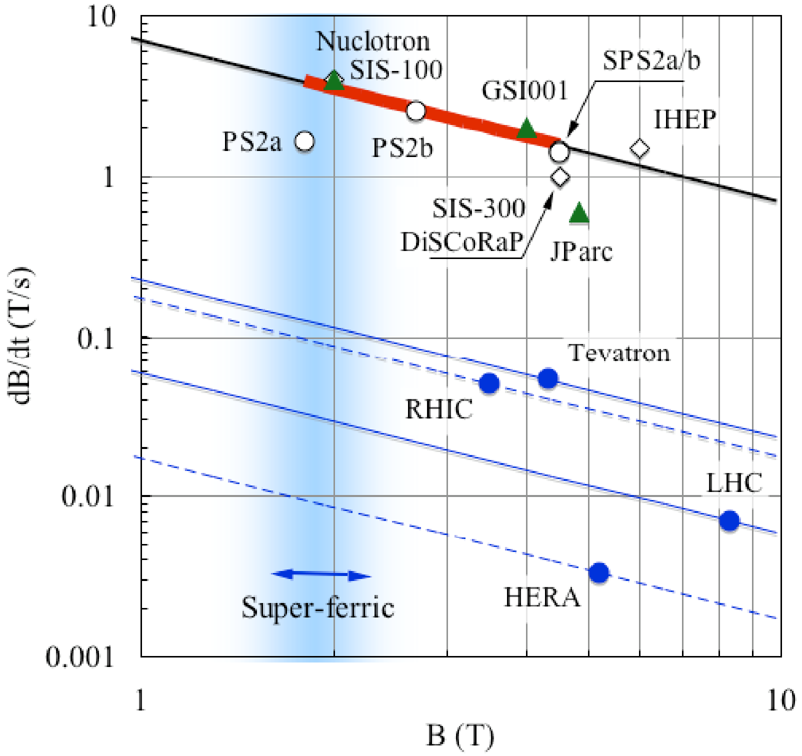
$B_{max} \times (dB/dt)_{max} = 7\ T^2/s$

Comments - 1

- The power per unit volume delivered to (and recovered from) the magnet is proportional to:

$$\Pi \approx B_{max} \text{ x } (dB/dt)_{max}$$

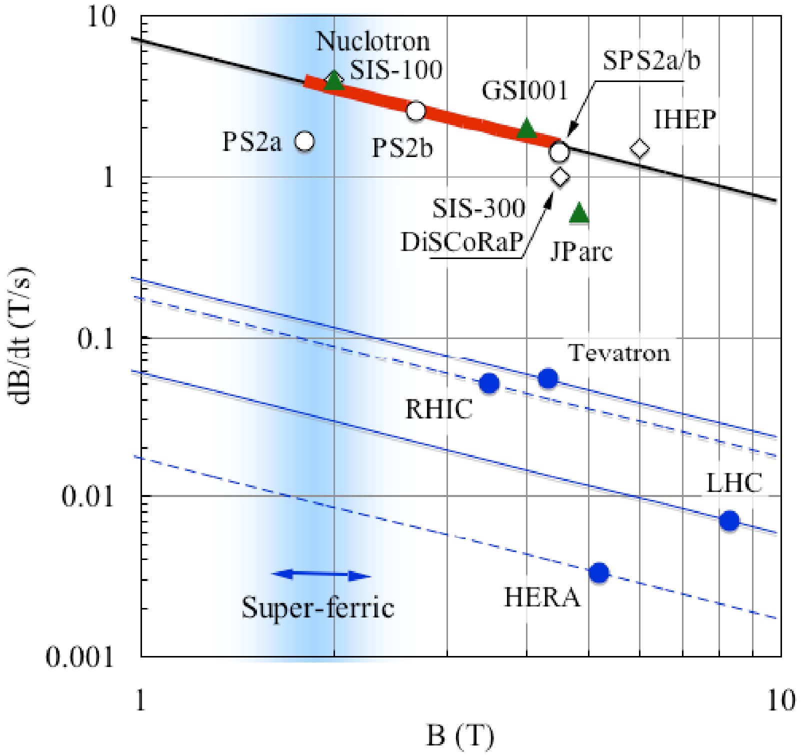
- An increasing value of Π is associated with increasing AC loss and voltages, two of the main issues in fast ramped magnets



- **Present developments aim at a target of $\Pi \approx 7$ T^2/s**, independently of the magnet details. This appears to be today the upper limit of technology plus practical feasibility

Comments - 2

- Magnets of equal *difficulty* can be realised taking as objective Π ≈ constant
- *It so happens* that PS2+b **has the same** Π as SPS+
  - PS2+b:
    - B_{max}=2.7 T, $(dB/dt)_{max}$=2.5 T/s
  - SPS+a:
    - B_{max}=4.5 T, $(dB/dt)_{max}$=1.4 T/s



- A technology demonstrator with B_{max}=2.7 T, $(dB/dt)_{max}$=2.5 T/s would provide the proof of principle for **both** a superconducting SPS **and a** superconducting option for PS2

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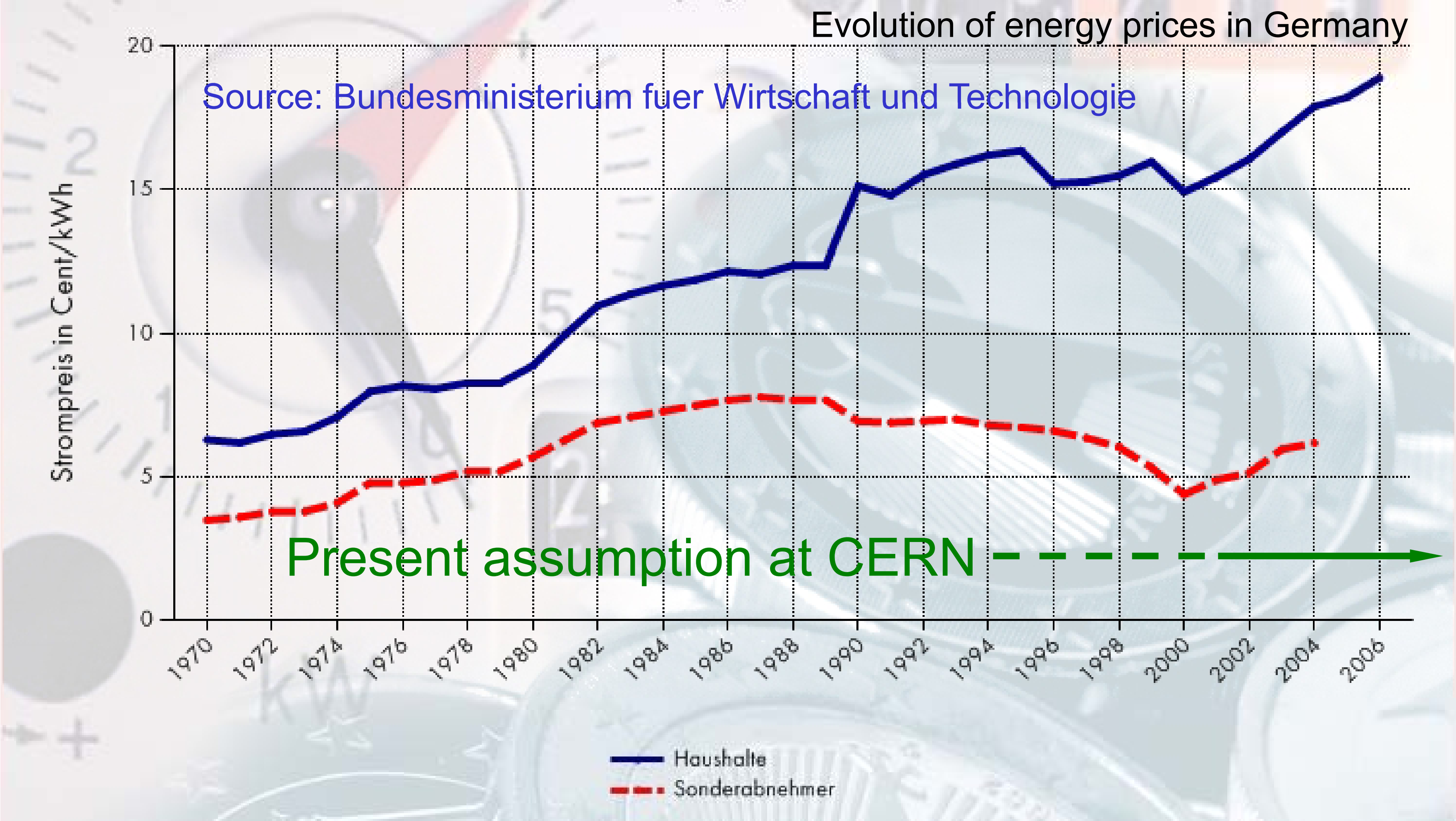
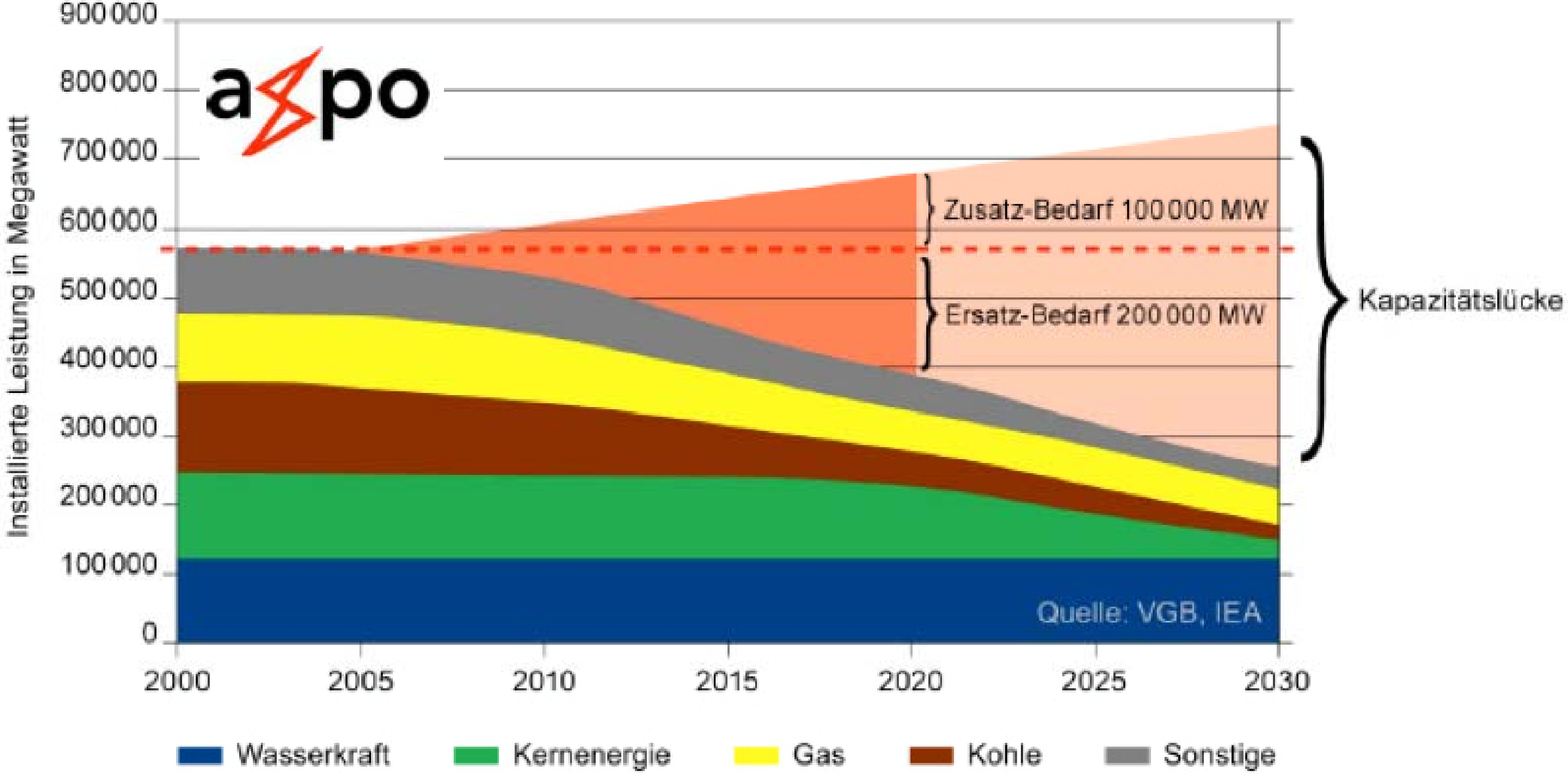
Prices of electricity

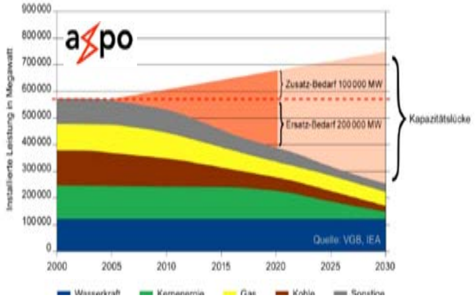


Availability of electricity



Quelle: VGB, IEA

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 - one year depending on DSM measures consideration).

up System Adequacy

Ratings for Swiss Electricity Suppliers Remain Stable

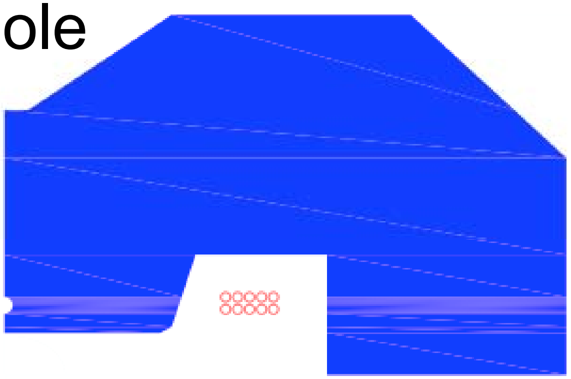
… However, high electricity prices and **continuing strong demand** for electric power should support the market […] The operating environment will grow harsher over the next few years as the Swiss electricity market is opened up, and an expected **future supply shortfall** will require higher capital 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

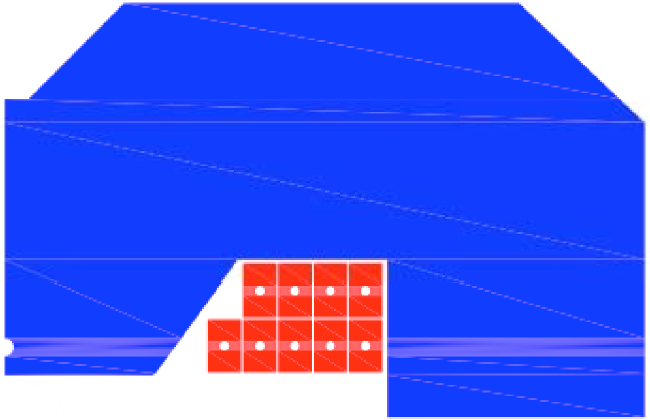
On a time span of ~ 15 years, we will need to increase efficiency, and reduce consumption, to run **reliably** and **economically** our facilities

A (f)lower-power option for PS2

Super-conducting iron-dominated PS2 dipole



Normal-conducting PS2 dipole



Iron weight [tons]	10
Peak voltage [V]	34
Average AC loss power [W]	1.3

Iron weight [tons]	15
Peak voltage [V]	41
Resistive power [W]	27000

L. Bottura, R. Maccaferri, C. Maglioni, V. Parma, L. Rossi, G. de Rijk, W. Scandale, Conceptual Design of Superferric Magnets for PS2, EDMS 871183

Potential for saving 7 MW of the 15 MW estimated total power consumption of PS2 complex

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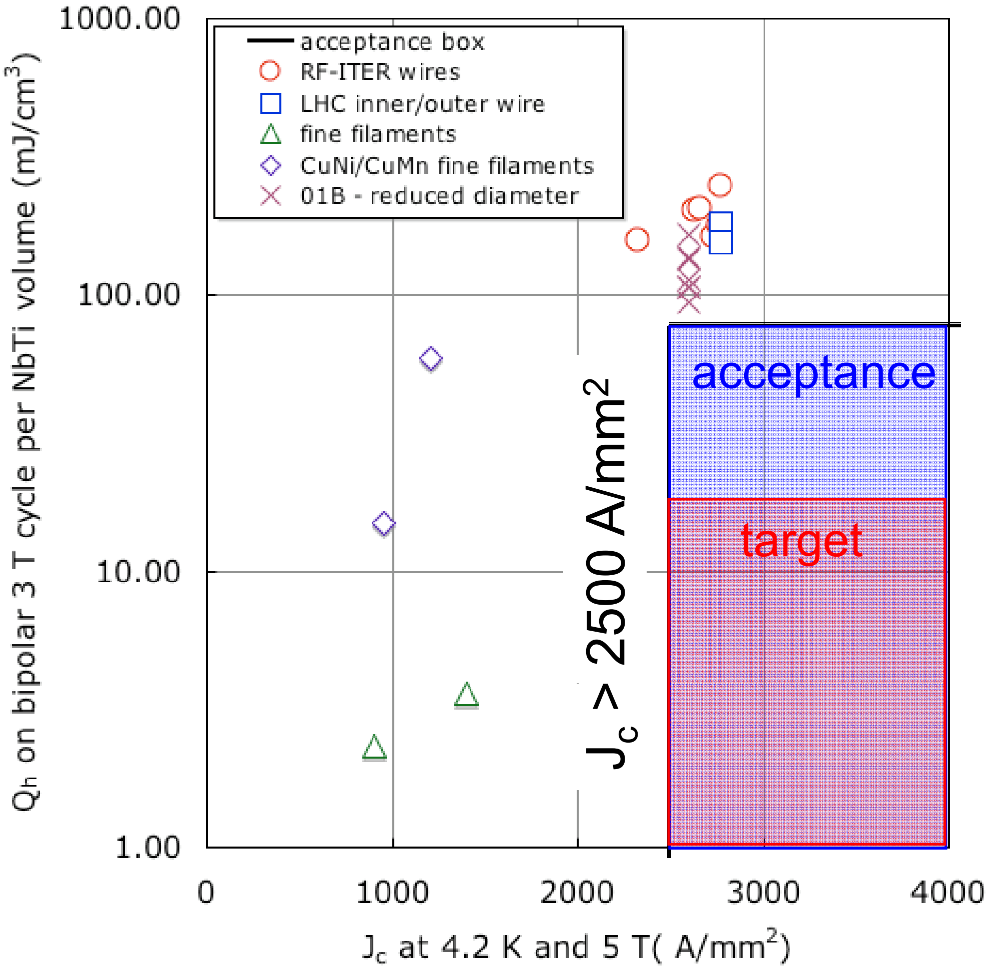
Strand and cable R&D

- Design, develop and procure NbTi wire with
    - Jc > 2500 A/mm^2
    - $D_{eff} < 3\ \mu m$, corresponding to Q_h for a 3 T bi-polar cycle < 80 mJ/cm^3 of NbTi
    - $\tau < 1$ ms
- Design and produce a cable for pulsed operation
    - R_c and R_a targets are 10 mΩ and 100 $\mu\Omega$ respectively. Examine surface coating options vs. central core for cable production
    - Choose and test a cable insulation scheme for heat removal
    - *Develop the joint technology for pulsed operation (AC loss and current distribution)*

These R&D targets are consistent and complementary to the programs at GSI and INFN

NbTi wire R&D targets



$D_{eff} < 3$ µm

$D_{eff} < 2$ µm

ITER-like specification box:
$J_c(4.2$ K, 5 T$) > 2500$ A/mm^2
$Q_h(+/- 3$ T$) < 80$ mJ/cm^3 NbTi

In addition, specify coupling loss time constant to less than 1 ms

Beyond strand and cable

- We need a technology demonstrator to adress:
  - Design and material properties for a low-loss structure (iron yoke, coil components such as spacers, collars, keys, …)
  - *Heat transfer from cable/coil and heat removal from magnet*
  - *Quench detection and magnet protection scheme*
  - *Fatigue at large number of cycles*
  - *(Radiation hardness)*
- In addition, there is a need for R&D in the field of instrumentation and testing:
  - *Strand and cable AC loss measurement facilities*
  - Field and AC loss measurements on model/prototype magnet

Activities at GSI and INFN are relevant, but cannot substitute specific R&D based on specific needs and boundary conditions at CERN

Conclusions

- There is consensus in the community of experts that **all issues** specific to fast-ramped superconducting magnets **can be addressed and solved** by
  - Adapted design solutions: phenomena are well known, engineering tools exist
  - Material R&D: within reach
- Focus should be put on a technology demonstration magnet, that proves **low-loss, robust and reliable** performance
  - Purchase wire
  - Produce cable
  - Wind coils
  - Test magnet models
- This technology would provide valuable **input and potential savings for PS2** that **cannot be discarded**

Specifications for the Technology Demonstrator

- Target: produce and test a representative dipole model, $\Pi \approx 7\ T^2/s$
  - $B_{max} \approx 2.7$ T (minimum 1.8 T)
  - $dB/dt_{max} \approx 2.5$ T/s (B_{min} to B_{max} in 1 s) (minimum 1.5 T/s)
  - $Q_{AC} < 5$ W/m average over 2.4 s cycle
  - 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
  - *R&D is scalable "also possibly for an SPS2+ in the future" (quoted from White Paper)*

R&D success criteria

- **Magnet performance**: achieve stable operating conditions (nominal field, nominal ramp-rate) cycling over long times (> 12 hours);
- **Low loss**: achieve AC loss below 5 W/m of magnet;
- **Robustness**: operate stably in sequences of rapidly varying cycles, exceeding in short sequences (typically 10 cycles) the nominal performance by 20 % of the maximum field and 50 % of the nominal ramp-rate;
- **Reliability**: achieve a low rate of fake quench detection (< 10^{-6}) and sustain accelerated life tests (TBD) to simulate the expected fatigue over 20 years operation.