Les Journées Thématiques AFF-CCS au CERN
Cryogénie et Supraconductivité pour le LHC et ses détecteurs

Organisées par l'Association Française du Froid
Commission de Cryogénie et de Supraconductivité

Superconducting Magnet Projects and R&D at CERN

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Background

- **Reference document: *White Paper*** (*Scientific Activities and Budget Estimates for 2007 and Provisional Projections for the Years 2008-2010 and Perspectives for Long-Term*, ADMDOC/fc-9997, 5 October 2006)
  - » Update to "*The European Strategy for Particle Physics*" (CERN/2685), presented to the Special Restricted CERN Council Session in Lisbon (July 2006)
  - » Overview of LHC and non-LHC funded activities in the period 2006-2010
  - » **Further activities**
    - First Theme: "*highest priority programme to fully exploit the physics potential of the LHC*"
      - **A new LHC IR using NbTi material**
    - Second theme: "*high priority* […] *to eliminate the concern about reliability of LHC operation*"
    - Third theme: "advanced accelerator and detector R&D programme to prepare for an LHC upgrade in luminosity"
      - First component:
        - > **High field superconducting magnets, based on Nb_3Sn to be used for the interaction regions (IR) at higher LHC luminosity**
        - > **R&D on pulsed field magnet for a […] superconducting version of PS**

Outline

- **A new IR for the LHC**
- **High Field (Superconducting) Magnets**
- **Fast Cycled (Superconducting) Magnets**
- **Other *high-tech* projects**
- **Conclusions**

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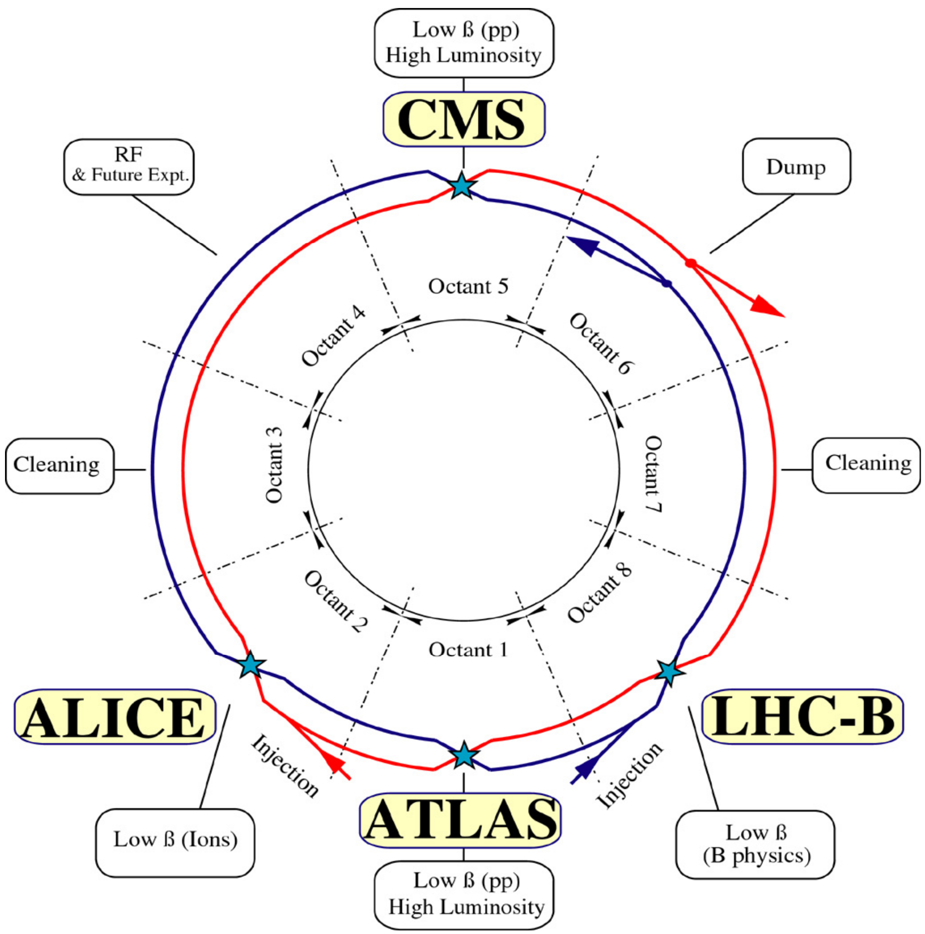
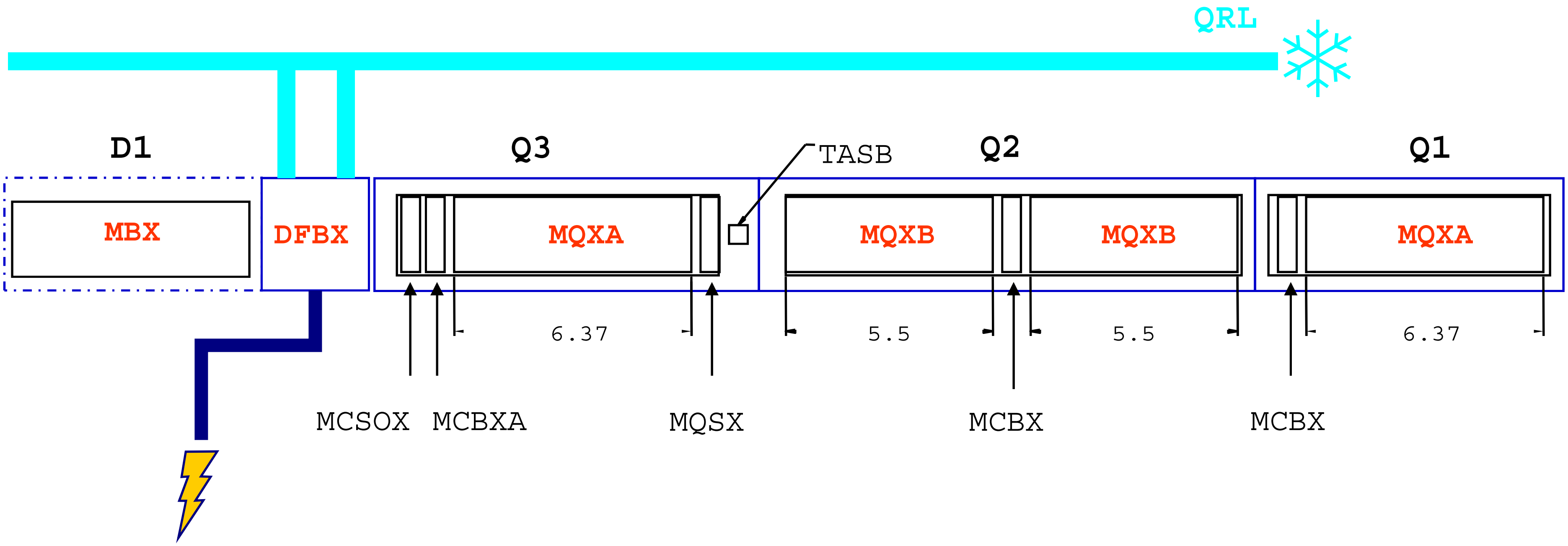
LHC Insertions

- **Experimental insertions in points**
  - » 1 (ATLAS),
  - » 2 (ALICE),
  - » 5 (CMS), and
  - » 8 (LHC-B)

  contain *low-beta quadrupole* triplets
- **In total, eight triplets are installed in the LHC**



The LHC low-β triplet

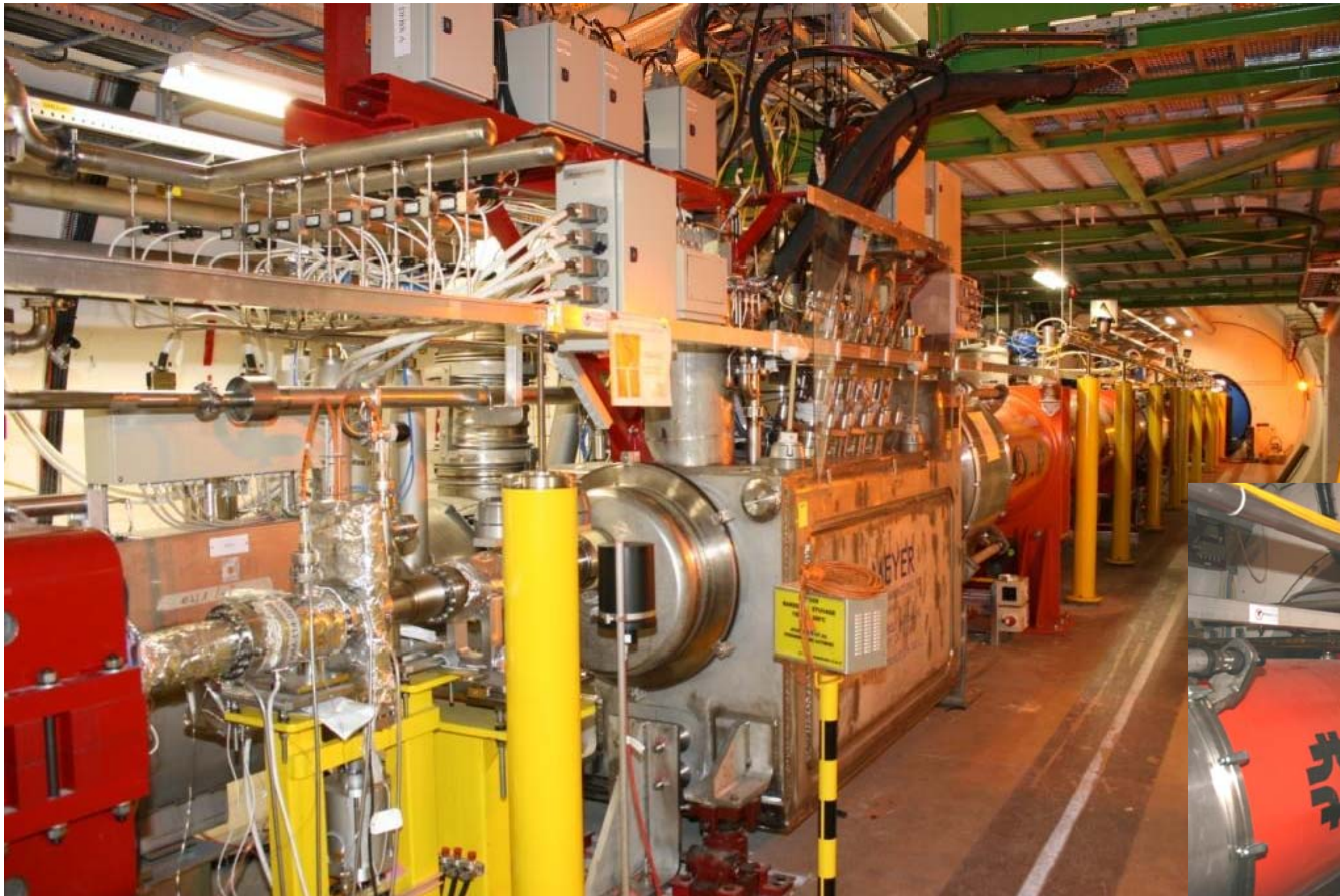


IR 1 and 5, D1 is a normal conducting dipole.

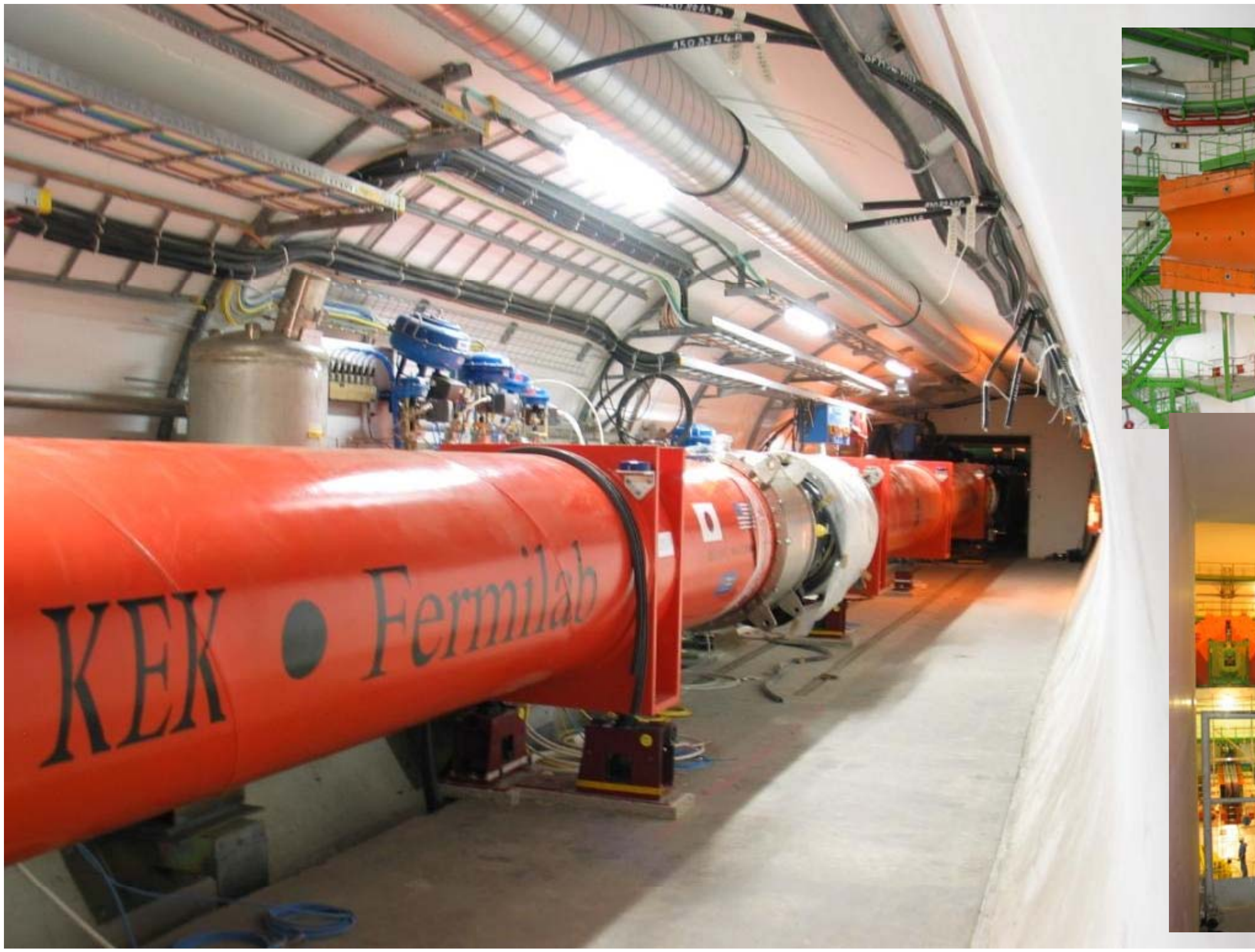
Triplets were designed and built by a collaboration of five laboratories: BNL, CERN, Fermilab, KEK, LBNL.

Low-β triplet – full view

Low-β triplet in IP1



Low-β triplet in IP5



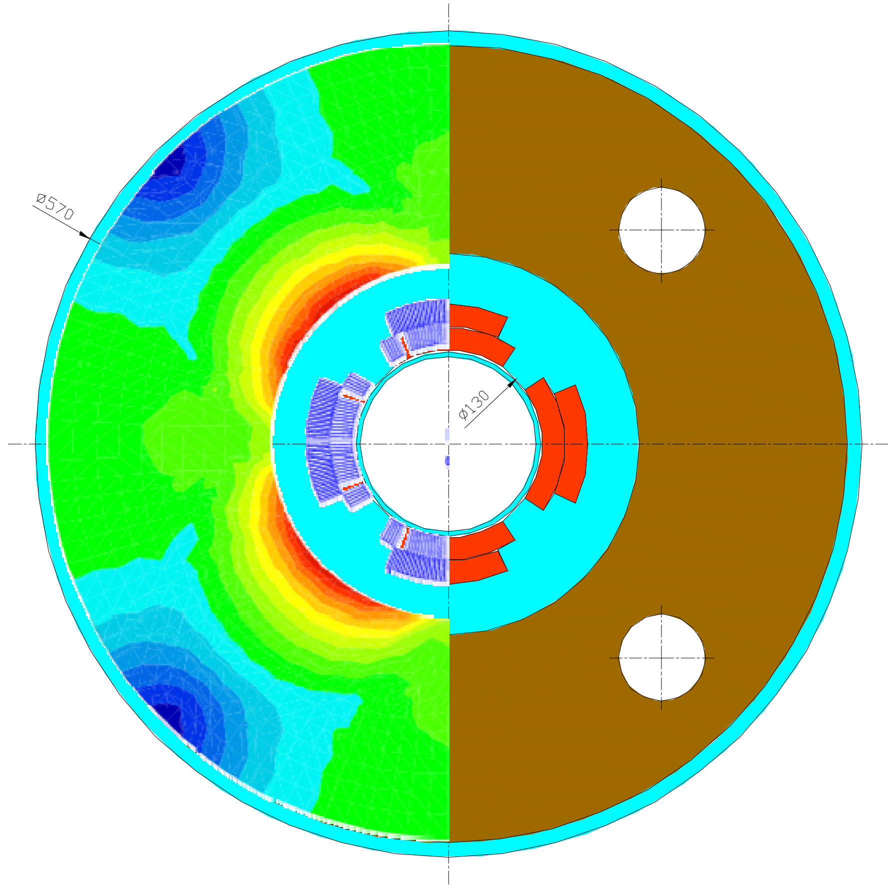
LHC IR Upgrade - Phase I

- **Goal and scope of the upgrade:**
  - » Enable focusing of the beams to **β*=0.25** m in IP1 and IP5, and reliable operation of the LHC at **2 10^{34} $cm^{-2}s^{-1}$** on the horizon of the physics run in 2013.
  - » Scope :
    - Upgrade of ATLAS and CMS interaction regions. The interfaces between the LHC and the experiments remain unchanged at ± 19 m.
    - **Replace the present triplets with wide aperture quadrupoles based on the LHC dipole cables (Nb-Ti) cooled at 1.9 K.**
    - Upgrade the D1 separation dipole, TAS and other beam-line equipment so as to be compatible with the inner triplet aperture.
    - The cooling capacity of the cryogenic system and other main infrastructure elements remain unchanged.
    - Modifications of other insertion magnets (e.g. D2-Q4) and introduction of other equipment in the IR to the extent of available resources.

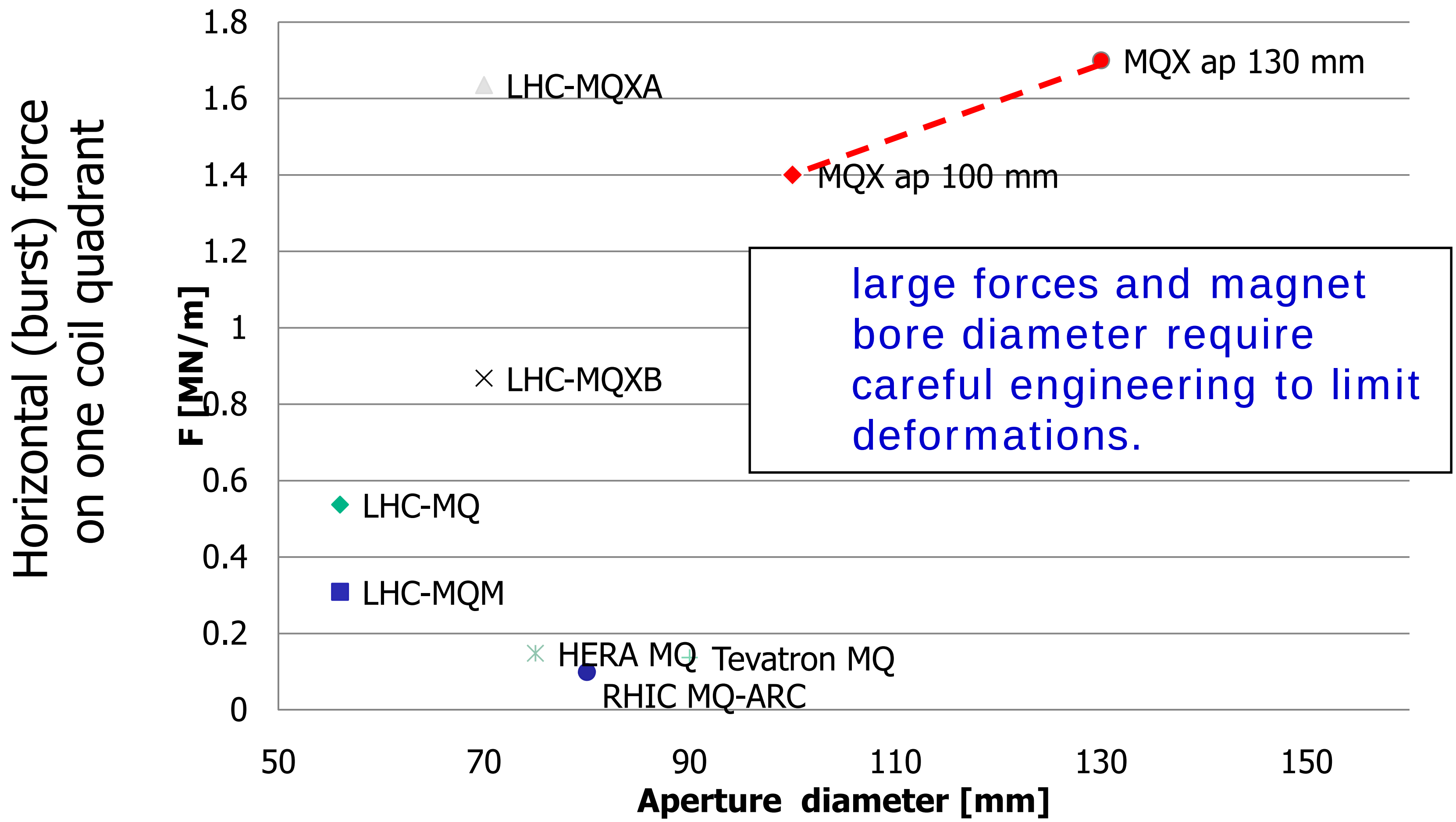
Courtesy of E. Todesco and F. Borgnolutti

Preliminary parameter set

Magnet aperture	≈ 110 mm … 130 mm
Gradient	**110 T/m … 130 T/m**
Length	Q1=Q3: 9m … 11m Q2a=Q2b: 7m … 9 m
Working point	≈ 80 % of I_{quench}
SC Cable	**LHC cable**

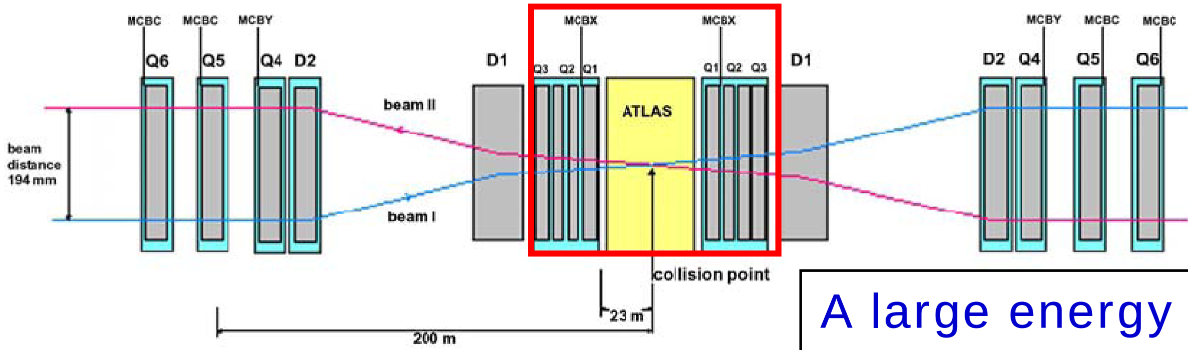


Issues: Horizontal force vs. aperture

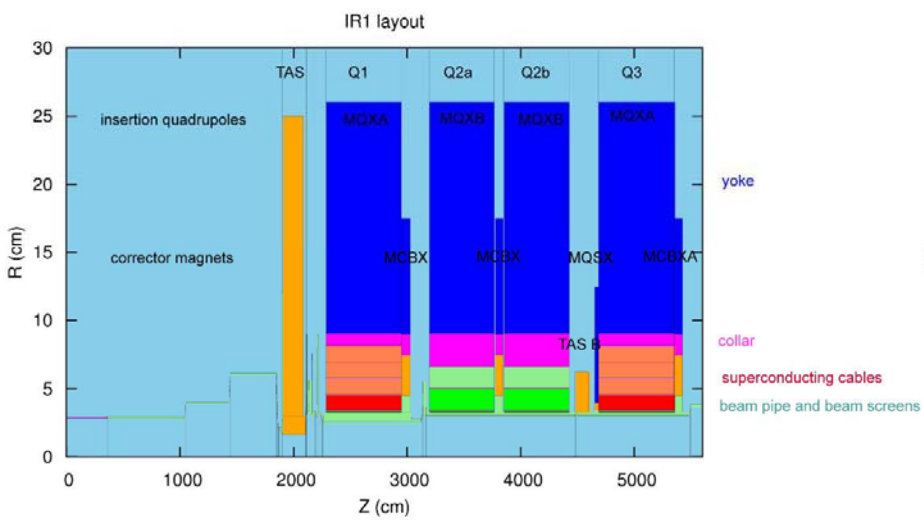


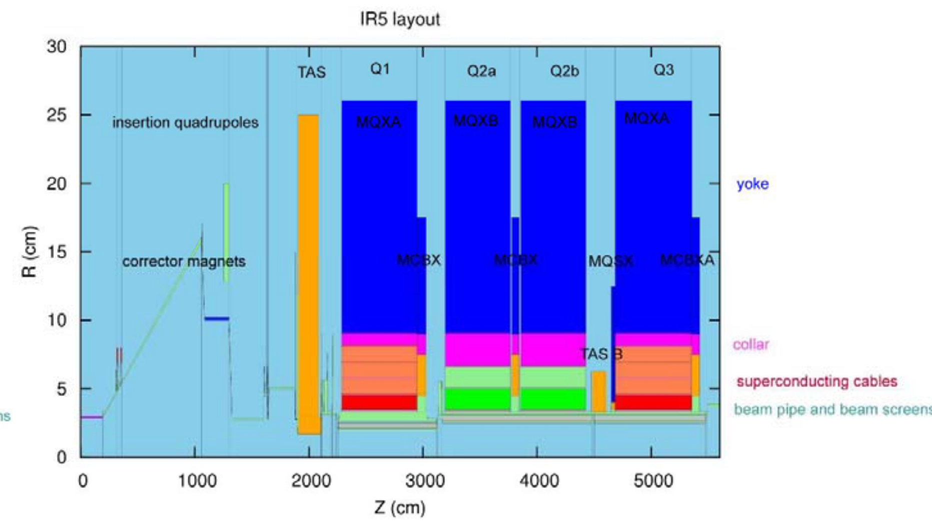
Courtesy of C. Hoa

Issues: Energy deposition - Model

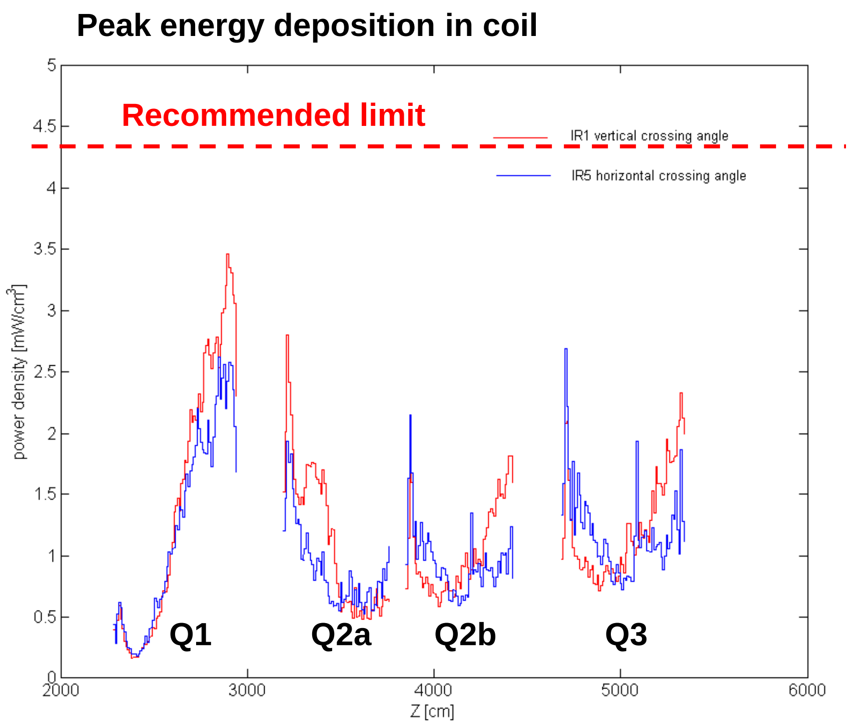


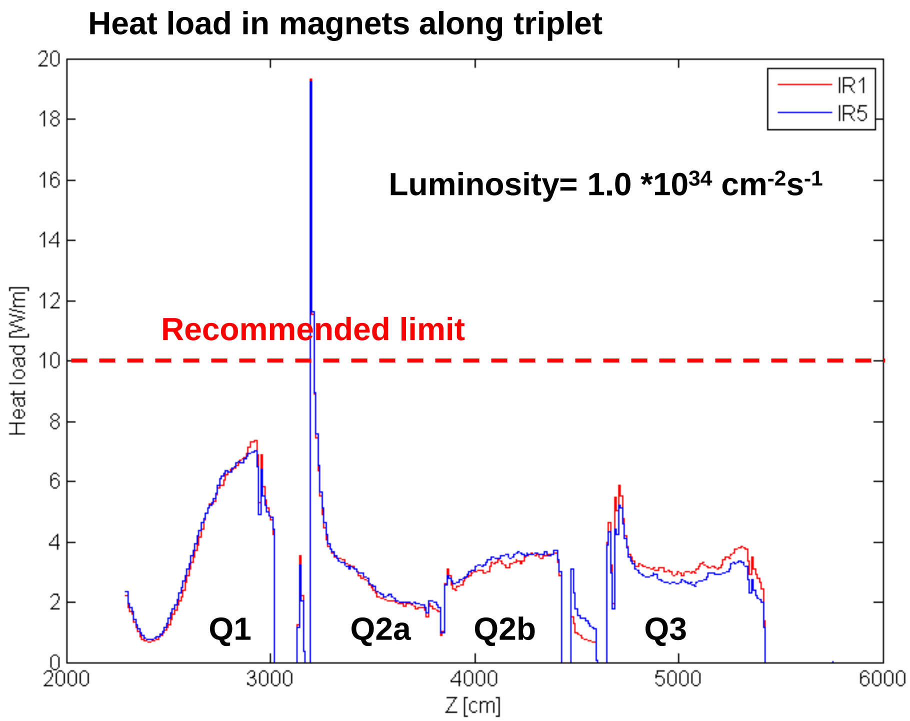
A large energy is deposited in the vicinity of the IR





Issues: Energy deposition - Today





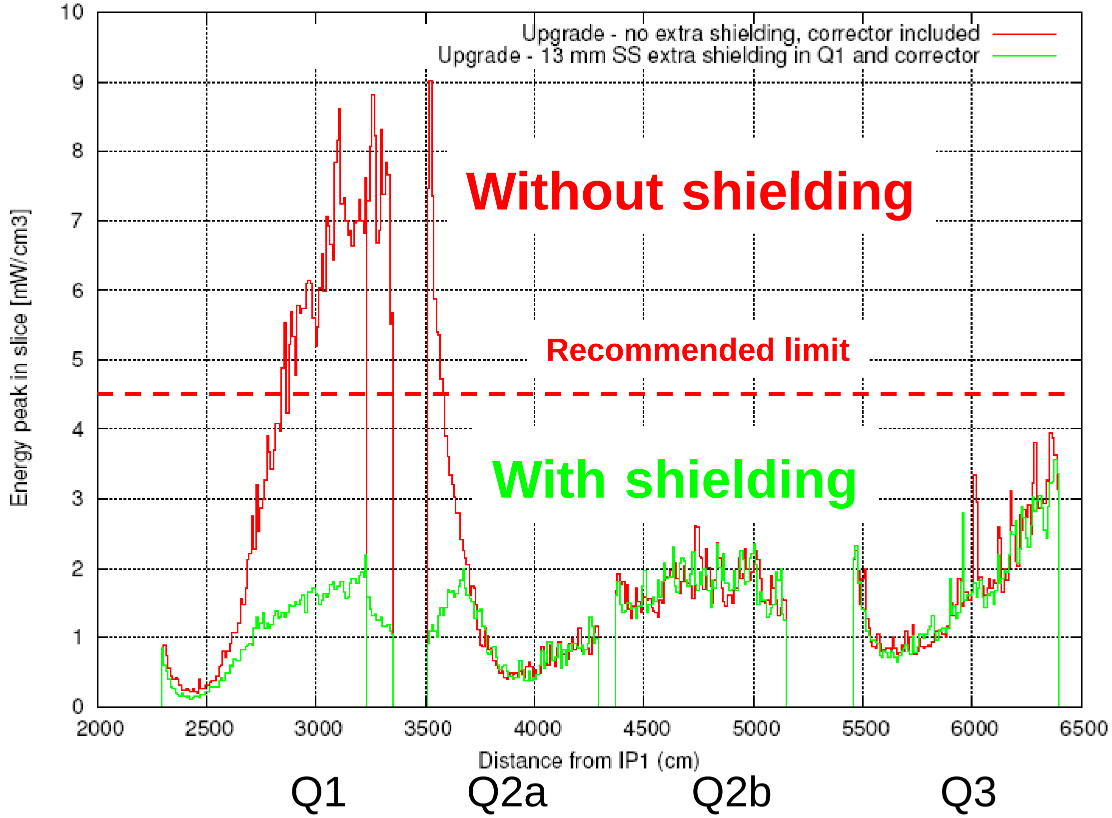
Total in magnet: 28.6W 23.5W 23.5W 25.8W

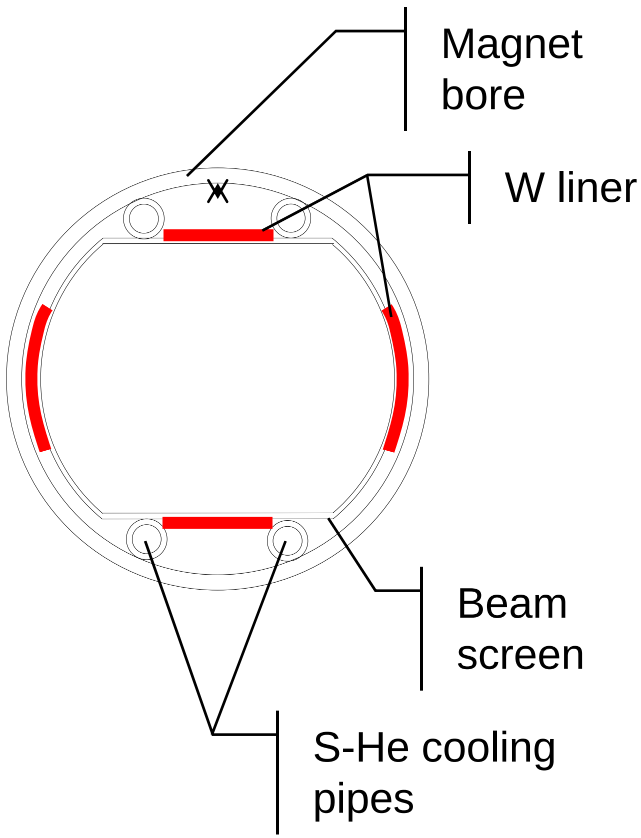
Liner in Q1 and MCBX of thickness 6.5 mm (stainless steel)
Length of triplet 31 m
Magnet apertures 70 mm
Half crossing angle 142.5 mrad

Courtesy of E. Wildner, F. Cerutti, M. Mauri, A. Mereghetti

Issues: Energy deposition - New IR

Peak energy deposition in each longitudinal bin

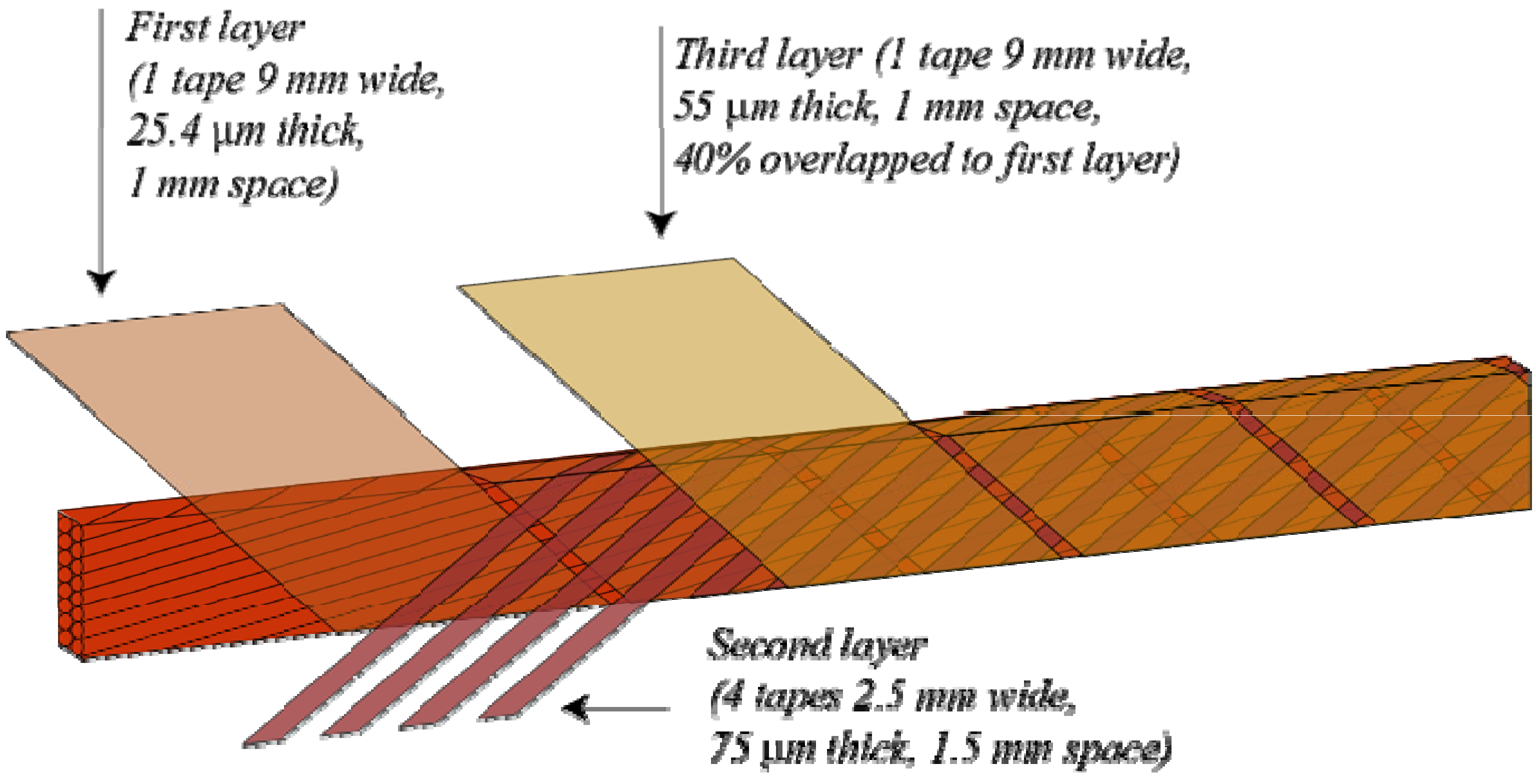




Courtesy of D. Tommasini

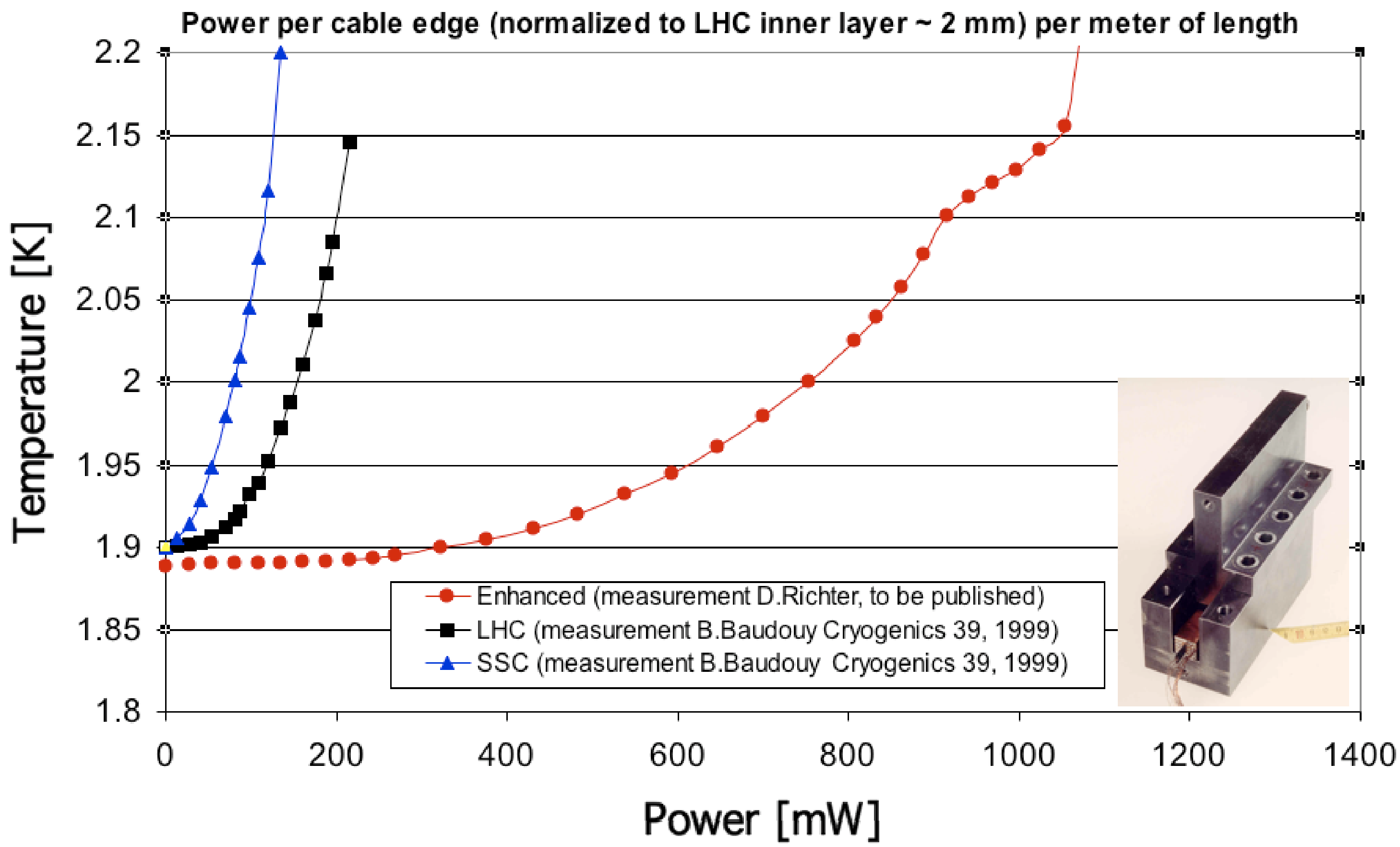
Issues: Energy removal from the cables

Enhanced (porous) insulation technique

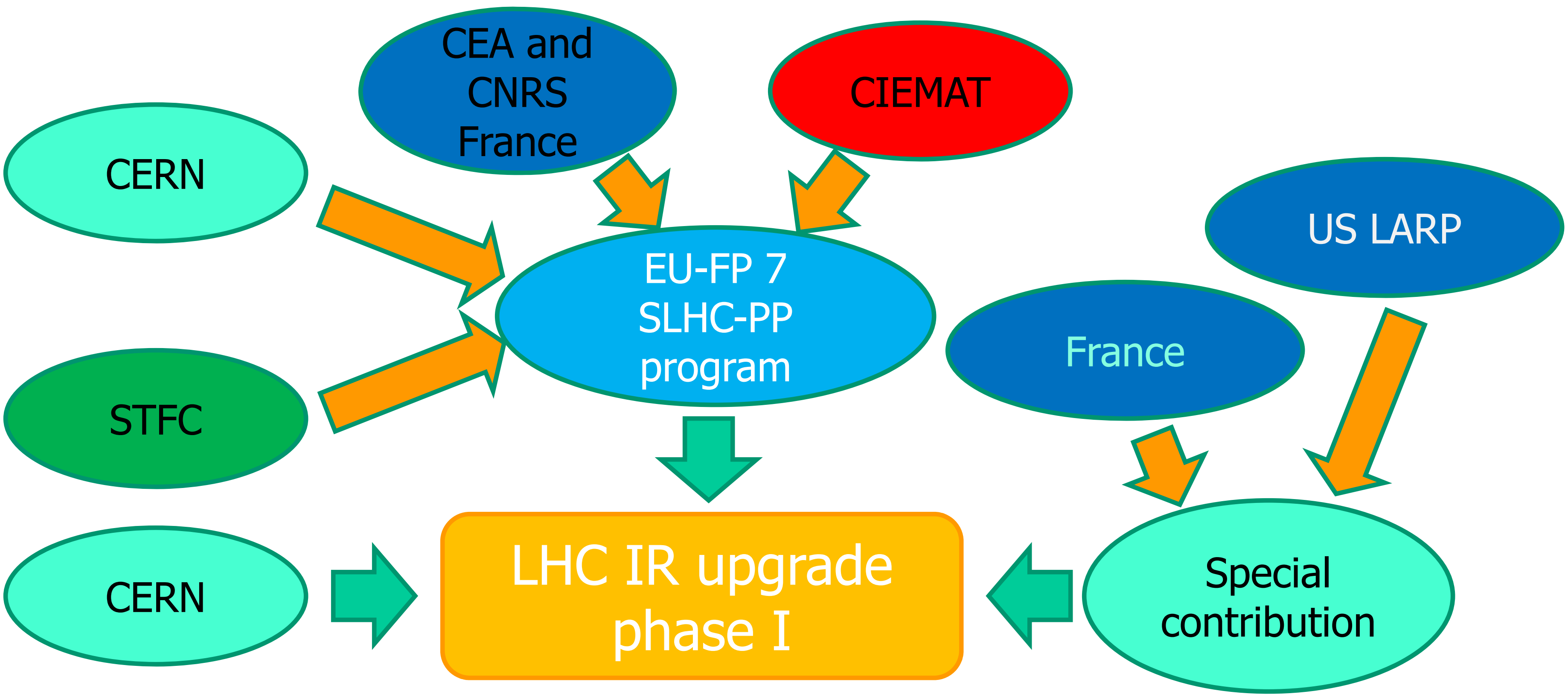


Courtesy of D. Richter

First results from heat transfer tests



A joint R&D and construction effort



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CERN High Field Magnet program

- **Need for HFM program**
  - » LHC luminosity upgrade: ***high field* low beta quadrupole magnets**
    - A gradient increase brings a luminosity upgrade by a factor 1.4
    - Larger (allowable) coil field permits wider apertures, needed to increase the beam currents
  - » Special magnets in LHC at high radiation zones (cleaning insertions, dispersion suppressors, etc.). Presently posing limits
  - » New machines: muon collider and neutrino factories
  - » LHC-FEF horizon: we have a tunnel with the proper infrastructure, the Farthest Energy Frontier (30-40 TeV c.o.m.) will be on the table after 2017
- **The conductor: Nb_3Sn (possibly HTS)**
  - » **B_{C20} ≈ 28…30 T** (vs. 14.5 T of Nb-Ti)
  - » **T_{C0} ≈ 18 K** (vs. 9 K of Nb-Ti)
  - » Brittle material (ε_{irr} ≈ 0.1…0.3 %), J_C debgades with strain (factor 0.5 at ε ≈ -0.6 %)
  - » Requires a **high temperature reaction** for the Nb_3Sn formation: magnet technology needs demonstration
- **A vigorous R&D program needed for this technology to be ready for the LHC phase II upgrade in 2017**

HFM R&D chapters

- **Conductor**
  - » continuous development program, aim:
    - $J_C \approx$ 3000 A/mm2,
    - D_{fil} < 50 μm mm
    - Flux-jump stable (RRR)
    - stress sensitivity compatible with cabling and winding technology
- **Enabling technologies**
  - » design choices (cos(θ) vs. block coil, collars vs. shell)
  - » Insulation, thermal effects, radiation hardness, mechanical tests
  - » Subscale models (racetrack coil tests)
  - » High temp superconductor: prospect insert coils to go up to 20 T
- **Models**
  - » Dipole model (2010-2011)
    - 13 T bore
    - 100 mm aperture
    - 1.5 m length
  - » Quadrupole model (2012)
    - > 150 T/m
    - 130 mm aperture
    - 1 m length
  - » Corrector model (> 2012)
- **Prototype magnet**
  - » 4 m long prototype 2012-2013

Pre-HFM: CARE / NED JRA

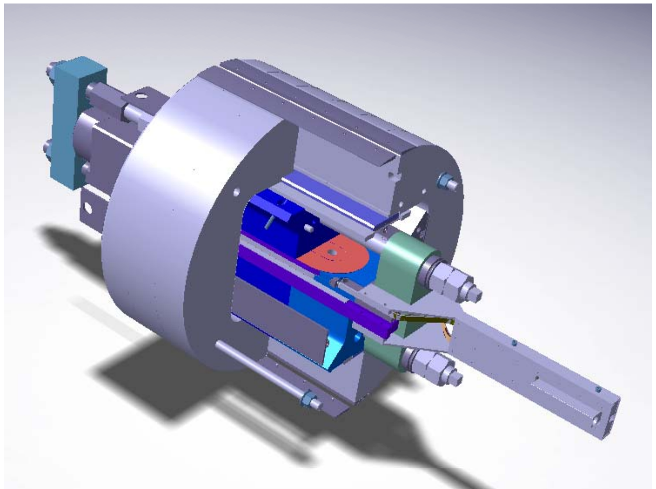
- **In 2003 (EU peer review), the scope of the NED program was re-focussed on Nb_3Sn conductor and insulation development**
- **The NED JRA consists of four Work Packages and one Working Group**
  - » 1 Management & Communication (M&C),
  - » 2 Thermal Studies and Quench Protection (TSQP),
  - » **3 Conductor Development (CD),**
  - » 4 Insulation Development and Implementation (IDI),
  - » 5 Magnet Design and Optimization (MDO) Working Group.
- **It involves 7 institutes (8 laboratories)**
- **Budget: ≈2 M€; EU grant: 979 k€ (over ≈ 3 years)**

The CERN HFM program will provide the continuity needed for the transfer of the technology developed for NED

Transition from NED to HFM

- **CCLRC/RAL, CEA and CERN have agreed to manufacture and test a series of LBNL-type Short Model Coils (formally outside CARE/NED JRA) wound from NED-sub-cables so as to investigate**
  - » cable and insulation performances in real coil environment,
  - » design limits for transverse and longitudinal loads.

- **Status:**
  - » Coil design completed
  - » Cold mass design being finalized
  - » Winding tests with dummy in progress by RAL-CERN team (interactions with LBNL)
  - » Waiting for Nb3Sn strand from NED. First magnet foreseen to be tested in Sept-Oct at CERN

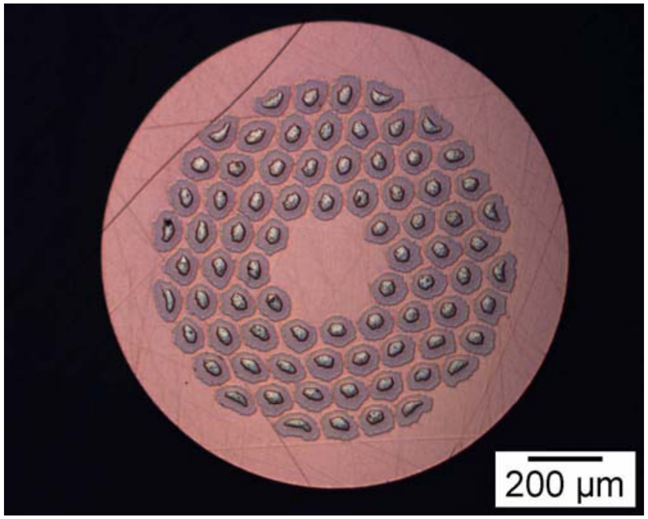


Courtesy of P. Ferracin

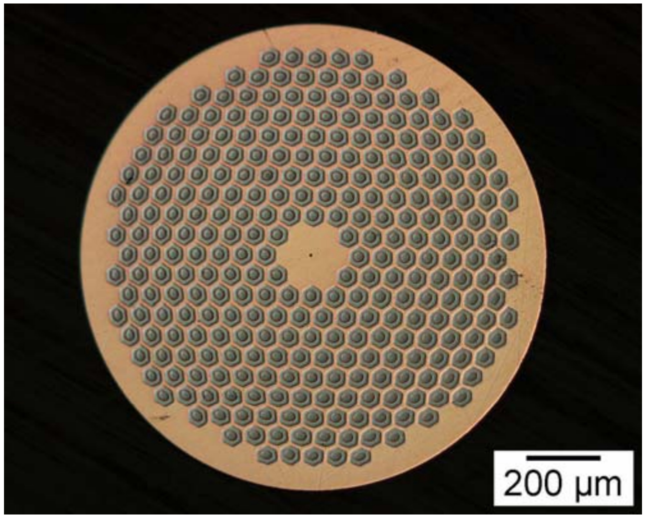
Courtesy of A. Devred

Nb_3Sn conductor development (NED-CD)

- **Wire development at ALSTOM and SMI achieved great progress in the past 3 years**
- **Thorough characterizations at CEA, CERN, INFN-Genova, INFN-Milan, and Twente University.**



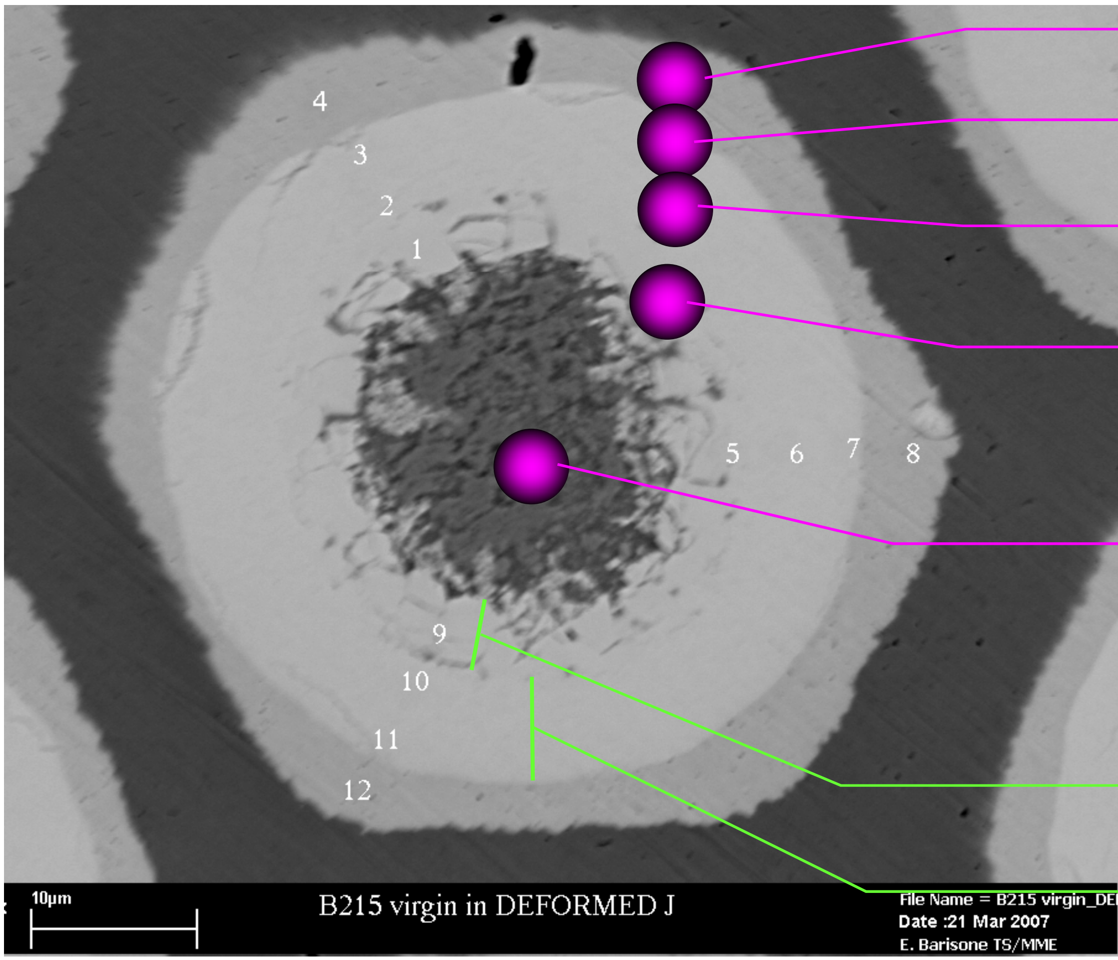
Alstom/NED (workability studies)
1.25 mm; 78 x 85 µm sub-element
920 A (~1950 A/mm²) @4.2 K & 12T



SMI/NED (near final design)
1.26 mm; 288 x 50 µm tube
1400 A (~2500 A/mm²) @4.2 K & 12T

Courtesy of G. Arnau, E. Barisone

Stoichiometry is in the detail...



Values in at%
Balance is Nb

Ta 4.5 ±0.2

Sn 24.1 ±0.5
Ta 3.7 ±0.2

Sn 24.1 ±0.6
Ta 3.5 ±0.2

Sn 26.3 ±0.3
Ta 1.9 ±0.2

Sn 3.6 ±0.5
Nb 30.2 ±6.8
Ta 0.3 ±0.1
Cu 65.9 ±6.4

< 4.4 µm

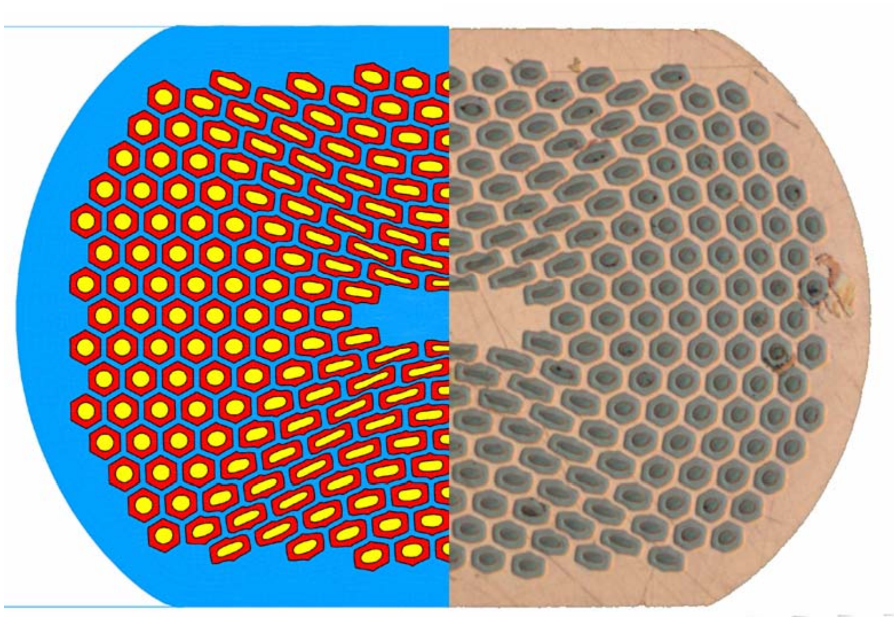
7.0 ÷ 8.3 µm

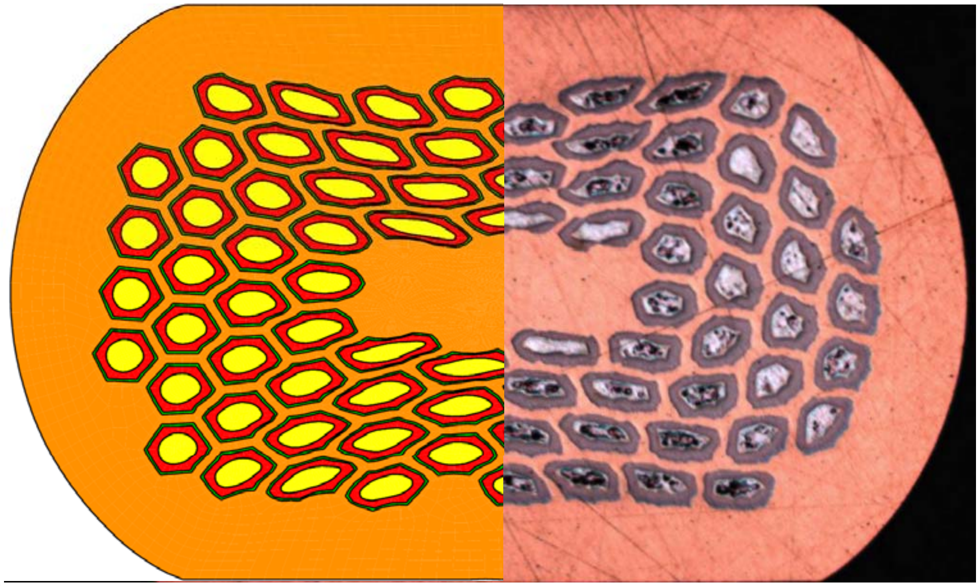
Courtesy of S. Farinon

Cabling deformation studies

PIT wire

Internal Sn wire



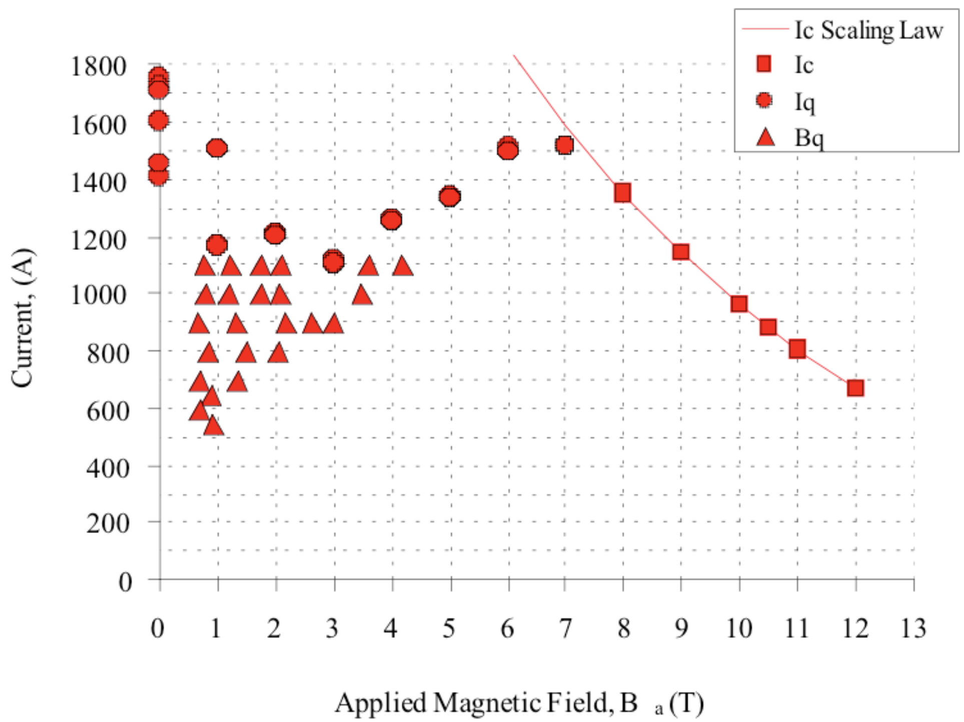


Courtesy of B. Bordini

Stability of High-Jc Nb_3Sn wires

- The high J_C of Nb3Sn wires, coupled with large D_{eff} , has drawn attention to the problem of **flux jumps**
- Flux jumps are magneto-thermal instabilities, that can quench the superconductor and severely limit the strand performance

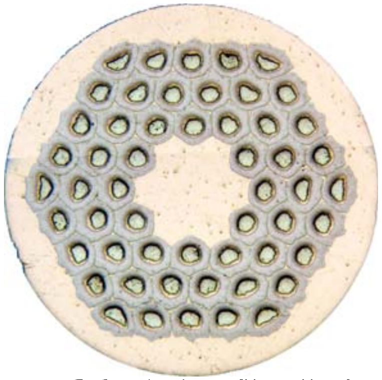
Strand diam. [mm]	*Strand type*	*J_c @ 4.2 K-12 T [A/mm²]*	*B_{c2} @ 4.2 K [T]*	*D_{eff} [μm]*	*RRR*
0.8	RRP 54/61	2602	24.54	80	8



Courtesy of B. Bordini

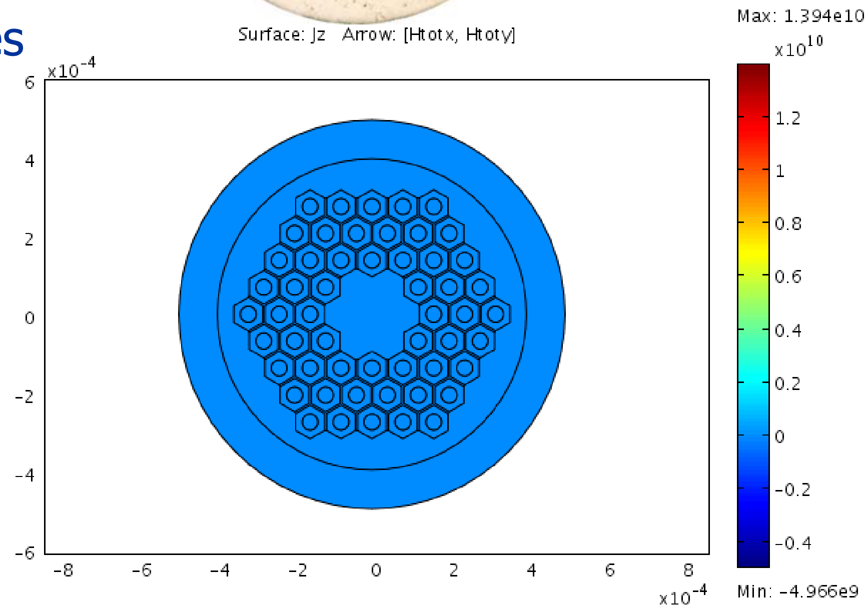
Modeling Magneto-Thermal Instabilities

- At CERN a semi-analytical model was developed [1] to calculate the minimum quench current of superconducting strand affected by magneto-thermal instabilities
- At present we are developing a Finite Element Model to study more in details magneto-thermal instabilities in SC wires



0.8 mm RRP Nb_3Sn strand

[1] B. Bordini, E. Barzi, S. Feher, L.Rossi, A.V. Zlobin, "Self-Field Effects in Magneto-Thermal Instabilities for Nb-Sn Strands", to be published in IEEE Trans. Appl. Supercond. 2008



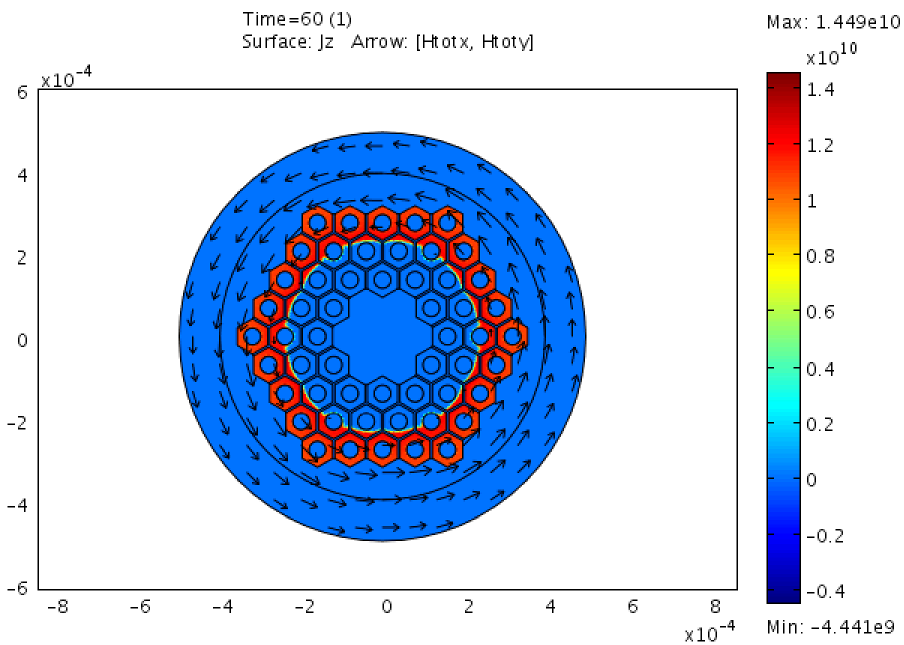
Distribution of the transport current while increasing the current from 0 to 1200 A in a fixed applied field, B_a=6T

Courtesy of B. Bordini

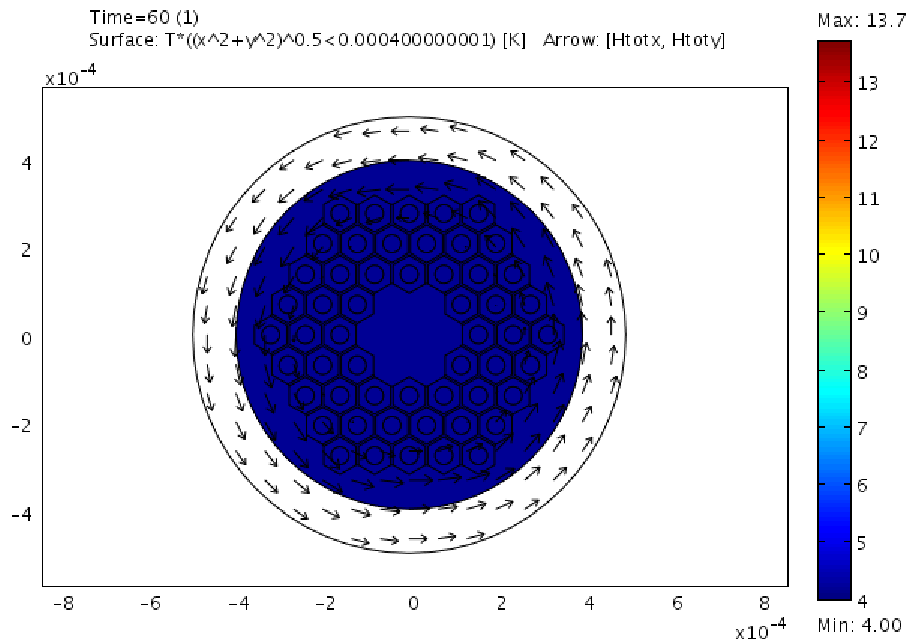
Simulation of Self-Field Instability

B_a=6 T , I=1200 A , T_i=4.2 K

Transport Current distribution



Temperature distribution



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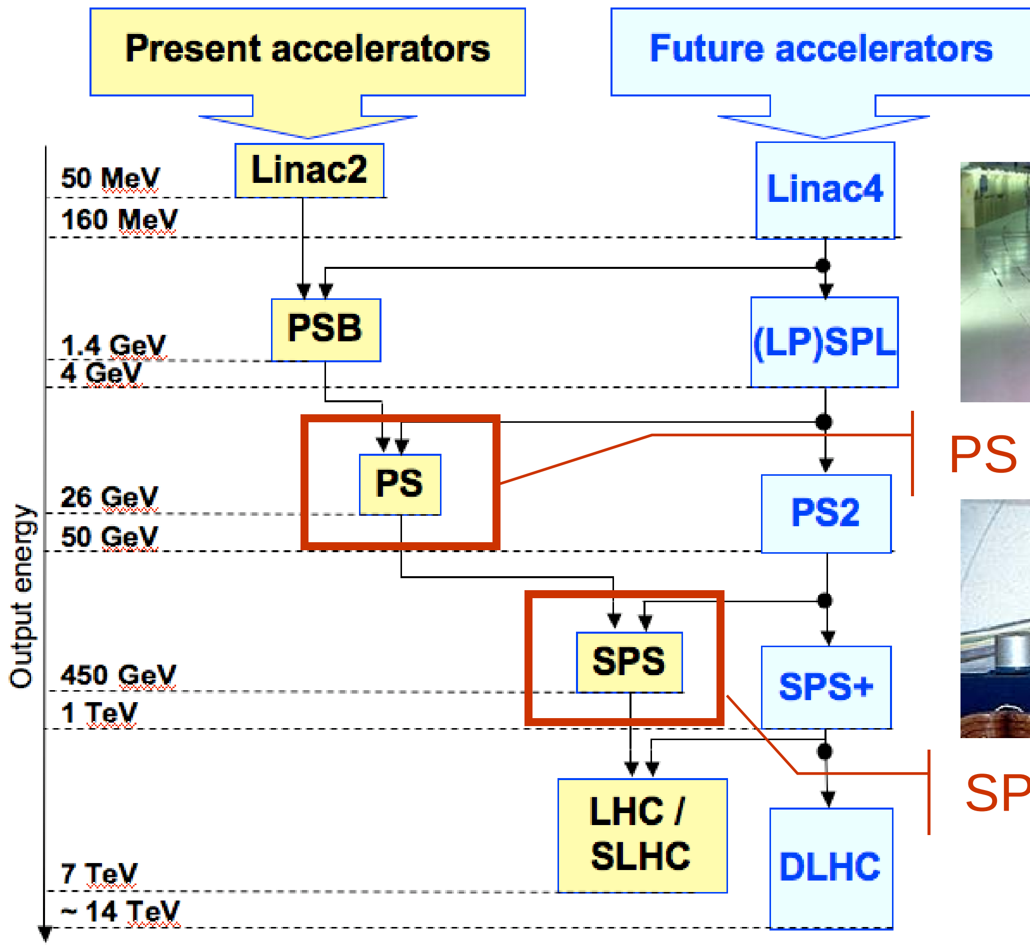
The LHC Accelerator Chain



PS was built in 1959

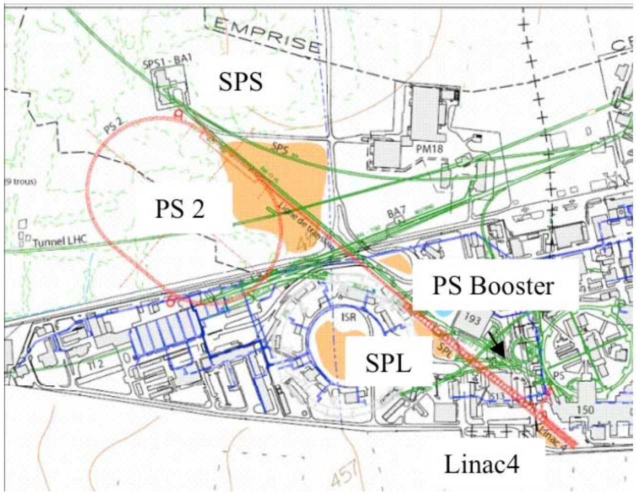
SPS was commissioned in 1976

A New PS: Magnet Requirements

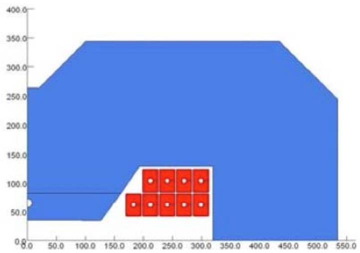
Modest requirements

- **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

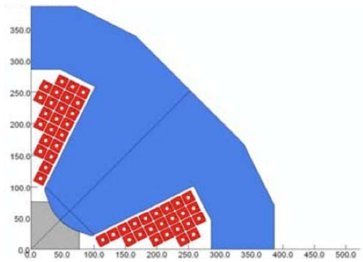
The location of the new PS2



dipole

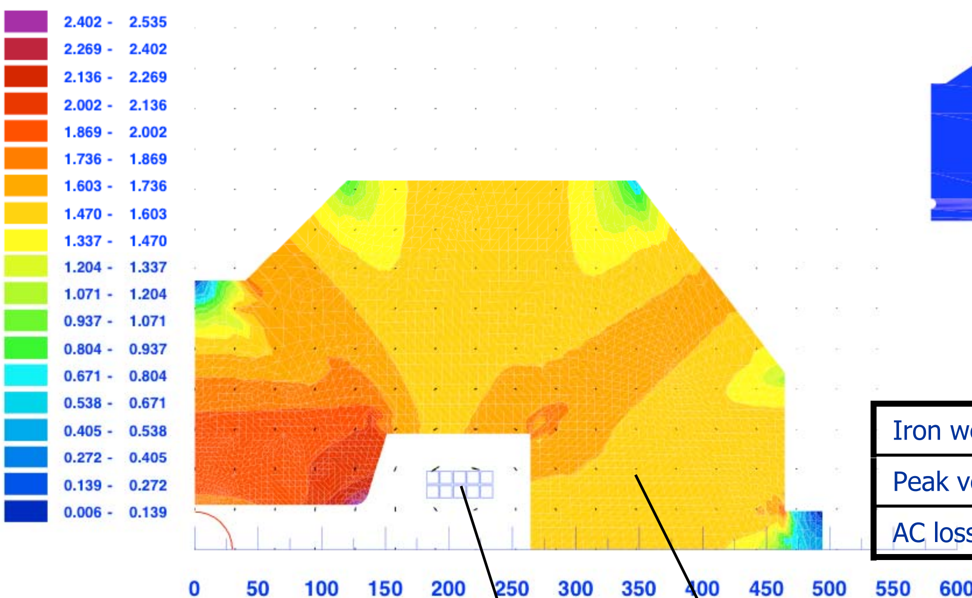


quadrupole



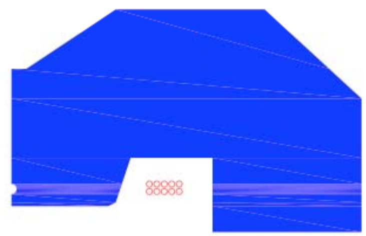
Design by courtesy of D. Tommasini and M. Karppinen

Superconducting Electromagnets for PS2



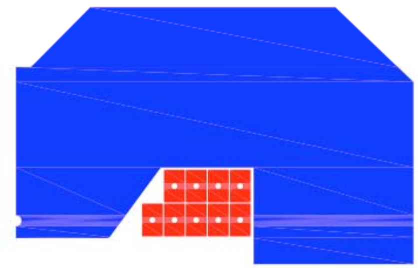
Warm iron

Cryostated superconducting coil



super conducting

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



normal conducting

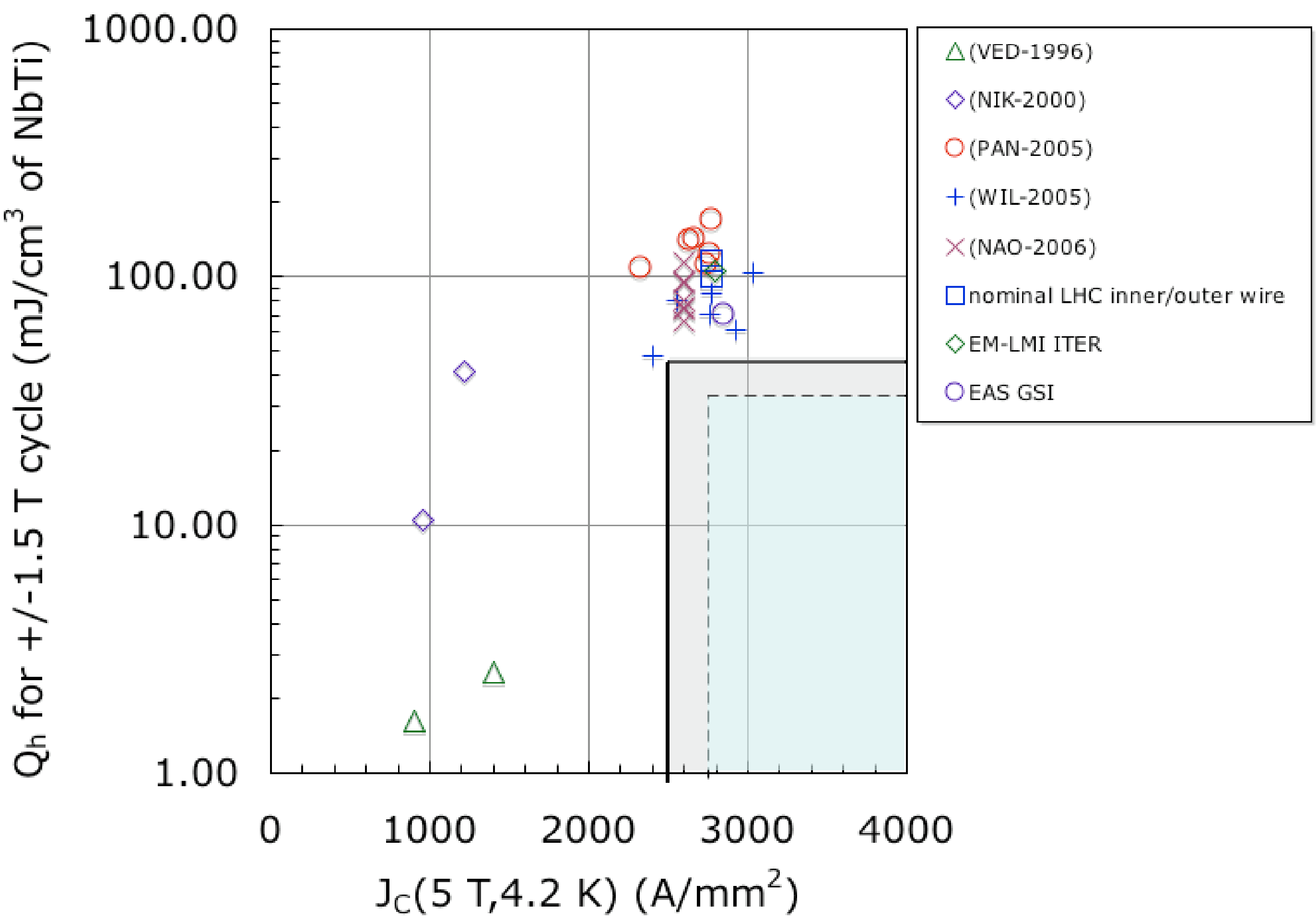
Iron weight [tons]	15
Peak voltage [V]	41
Resistive power [W]	27000

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

FCM 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)
    - Strand and cable R&D (relevant to both PS2 and SPS+)
      - $J_c > 2500$ A/mm²
      - $D_{eff} < 3$ µm (Q_h for a 1.5 T bi-polar cycle < 45 mJ/cm³ of Nb-Ti)
      - $\tau < 1$ ms
      - $R_c > 10$ mΩ, $R_a > 100$ µΩ
    - 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*

Critical R&D: Low-loss Nb-Ti Wire



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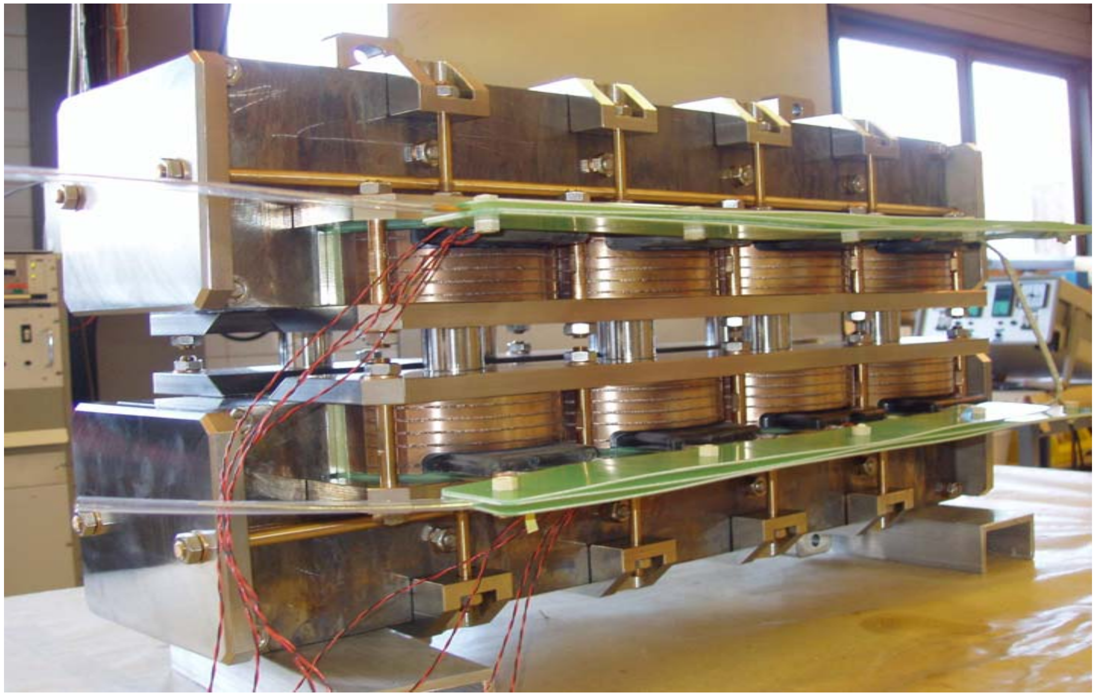
Courtesy of R. Maccaferri

An Undulator for SR Diagnostic in LHC

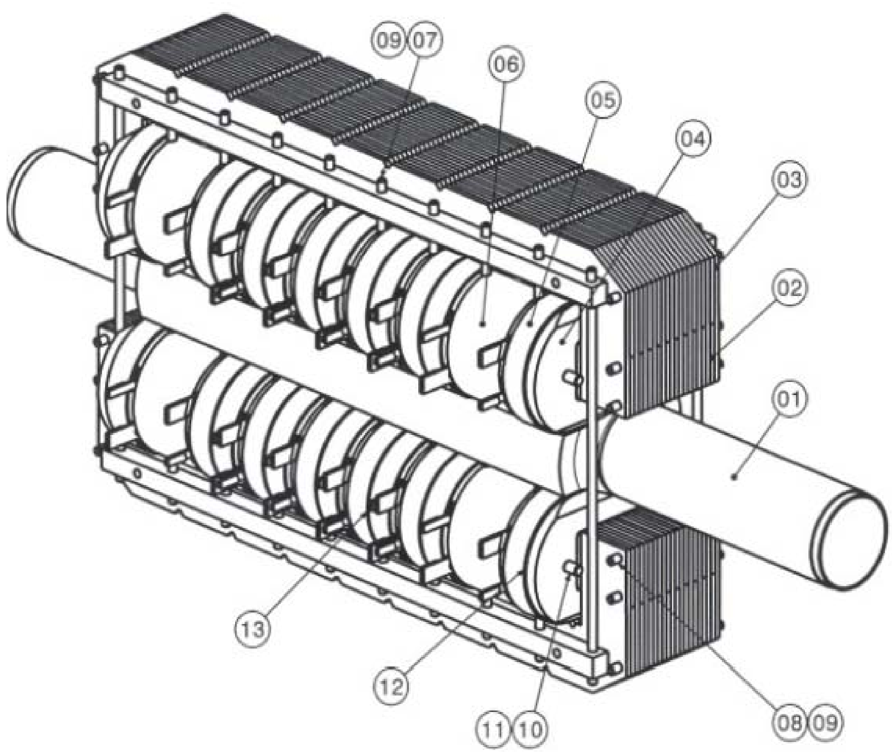
Period length	280 mm
Number of periods	2
Iron yoke length	704 mm
Pole gap	60 mm
Beam pipe HxV	70 x 58 mm
B_{max}	5 T
Homogeneity at +/- 10 mm	0.25 %
Inductance	1.5 H
E	150 kJ
Strand size	1.53 x 0.67 mm
Cu:NbTi	1.63
Operating temperature	4.2 K
Operating current	450 A
Operating fraction of I_C	73 %
B_{peak} / B_{max}	0.83
Hot spot temperature	80 K



Courtesy of R. Maccaferri

An SR Dual period undulator

Aim: LHC Pb ions and p^+ beam diagnostic

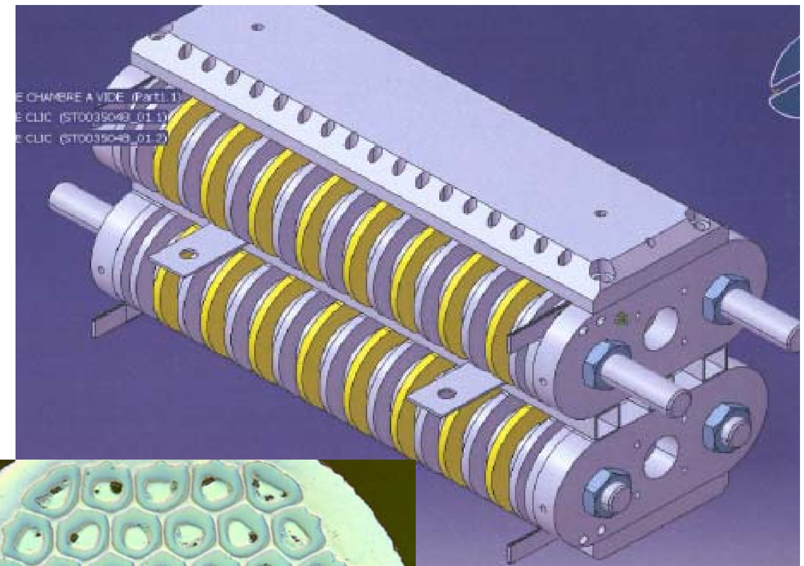


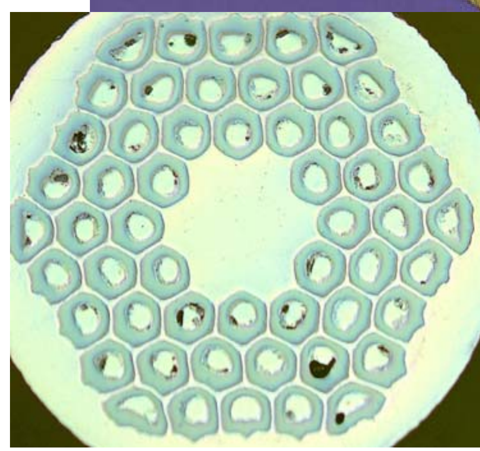
Period length (mm)	280	140
Number of periods	2	2
Iron yoke length (mm)	704	704
Pole gap (mm)	60	60
Peak field (T)	7	9
Gap field (T)	5	4.2
Operating Current (A)	500	600
Stored energy (kJ)	150	60
Strand Type (OST)	Nb_3Sn RRP	
Diameter (mm)	0.8	
Jc (A/mm^2, 4.2 K, 12 T)	3000	
Inter-turn insulation	S2-Glass +Al_2O_3	

Courtesy of R. Maccaferri

Wiggler for the CLIC SR damping rings

Number of periods	8
Period:	40 mm
Pole gap	20 mm
Main Field	3.5 T
Peak Field	8 T
Op current	1200 A
Inter-turn insulation	S2-Glass+Al_2O_3
Strand Type (OST)	Nb3Sn RRP
Diameter	0.8 mm
Jc	3000 A/mm^2





Outline

- A new IR for the LHC
- High Field (Superconducting) Magnets
- Fast Cycled (Superconducting) Magnets
- Other *high-tech* projects
- **Conclusions**

A *managerial* view

- **IR upgrade - Phase I**
  - » 2008-2013: ≈ 50 MCHF + ≈ 100 FTEy
- **HFM**
  - » 2008-2011: 9 MCHF + 44 FTEy
  - » 2012-2013: 12 MCHF + 45 FTEy
- **FCM**
  - » 2008-2009: 1.5 MCHF + 7 FTEy
- **Total engagement, over the coming 6 years:**

≈ 70 MCHF + 200 FTEy

Conclusions

- **This is a significant R&D in applied superconductivity !**
- **Very relevant to foster technology development in EU industry**
  - » Material R&D
  - » Magnet R&D
- **Mandatory to maintain the experimental capability within (and without !) Europe**

Backup slides

There Are More Things in Heaven and Earth, Horatio…

New IR - The emerging concept

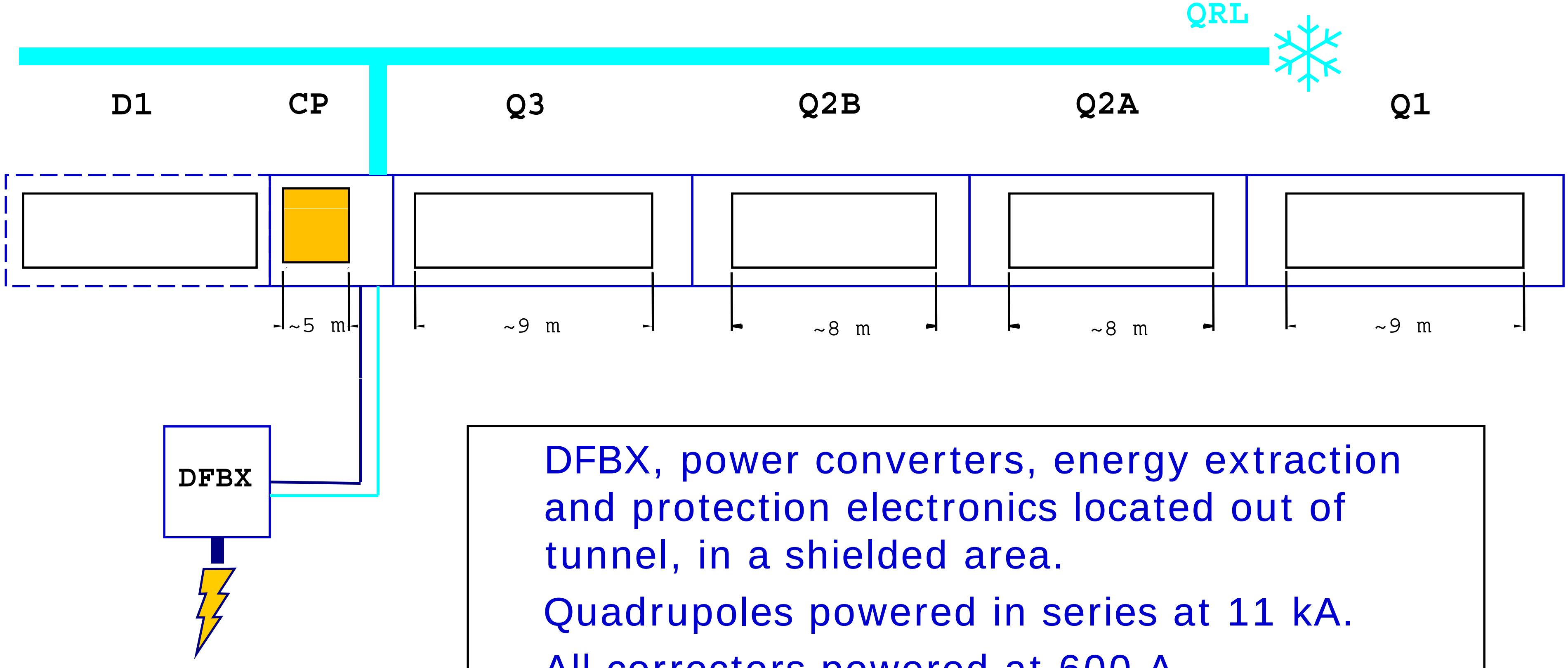
- **Triplet:**
  - » Composed of **four cryo-quadrupoles** of similar length (~ 8 m).
  - » Cold bore+beam-screen engineered as **magnet protection elements**, BS cooled at 40-60 K.
  - » Interconnections (He-pipes, PIM and BS) identical in IR1 and IR5.
  - » All **correctors lumped in a separate cryo-unit** located in between D1 and Q3.

- **Powering**
  - » Each magnet protected separately. Energy extraction included in the main circuit.
  - » Delicate equipment in shielded areas. **DFBX** linked to the triplet through a **link (HTS or LTS)**.

- **Matching Section**
  - » D2, Q4 and Q5 moved by about 15 m towards the arc to improve the flexibility of the insertion.

- **Low-beta quadrupoles**
  - » The ultimate parameters: $\beta^*=0.25$ m, $n_1=7$, using definitions for nominal LHC. This leads to a beam-stay-clear of ~95 mm and **coil ID of ~110 mm**.
  - » Magnet aperture and length to take into account optimal use of existing cable.

New IR - The emerging layout



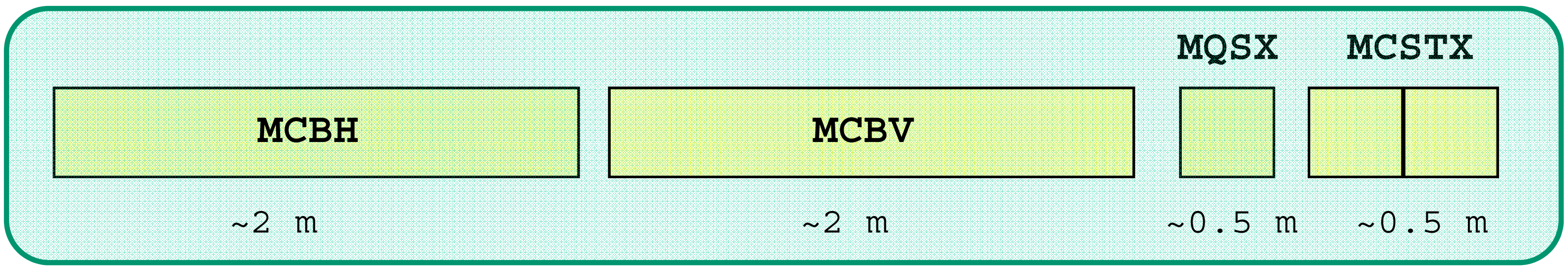
DFBX, power converters, energy extraction and protection electronics located out of tunnel, in a shielded area.

Quadrupoles powered in series at 11 kA.

All correctors powered at 600 A.

New IR - A corrector cryo-unit (CP)

CP: a cold mass containing all correctors



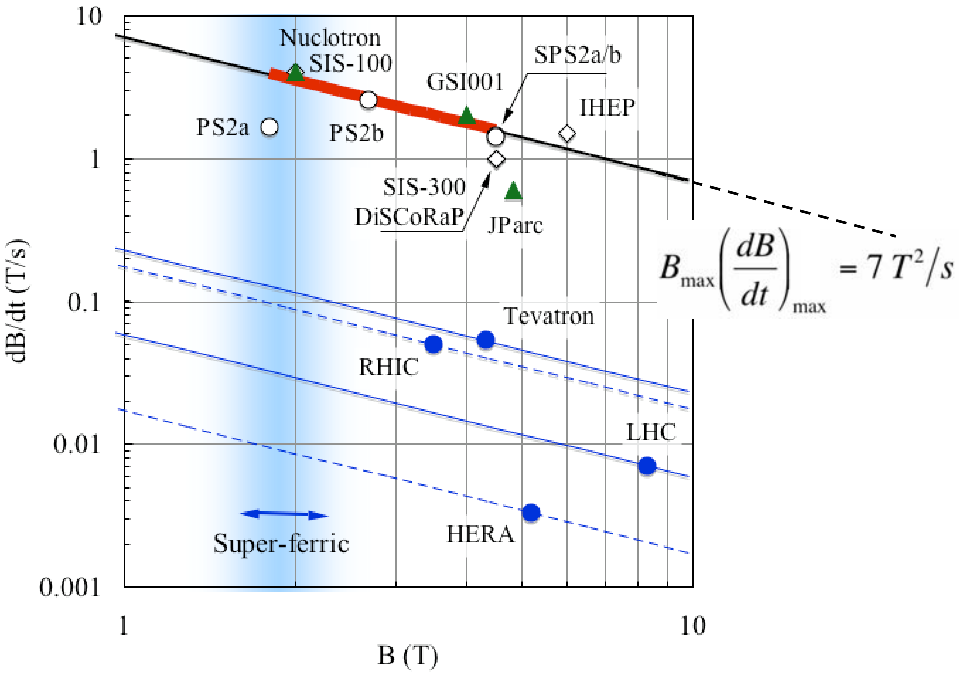
	Current	Integrated strength (field)	Aperture (identical to quads)
MCBX	**+/- 600A**	**~ 6 Tm/ (~3 T)**	**110-130mm**
MQSX	**+/- 600A**	**~ 20 T (~40 T/m)**	**110-130mm**
MCSX	**+/- 100A**	**~ 0.01 Tm (~0.05T@17mm)**	**110-130mm**

A Broader View to the R&D on FCM

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

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

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

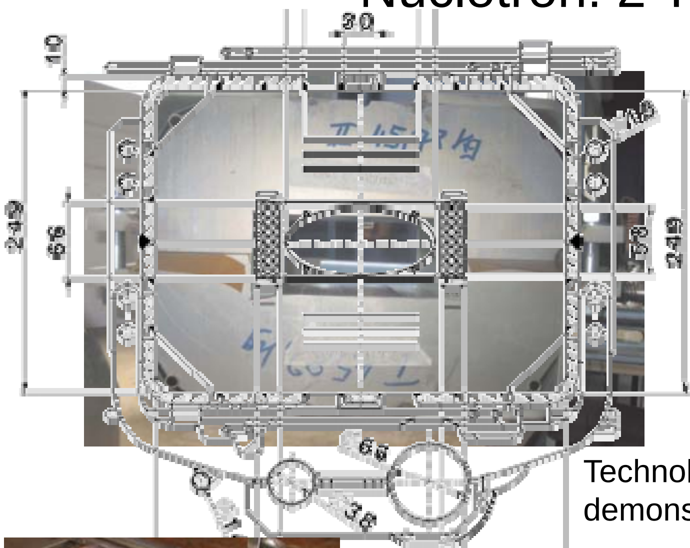


- **The present developments aim at a target of Π ≈ 7 T²/s independently of the magnet details. This appears to be today the upper limit of economical feasibility**

Courtesy of G. Moritz, GSI

The FAIR Program at GSI

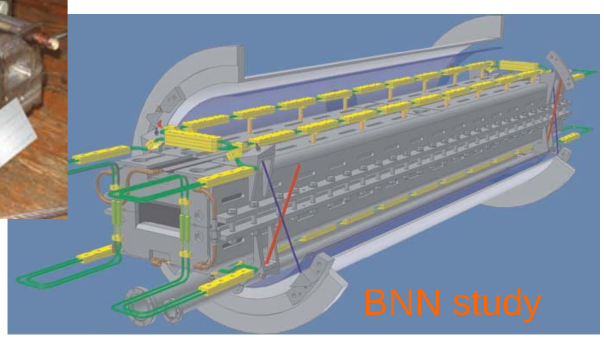
Nuclotron: 2 T at 4 T/s



Coil pack model

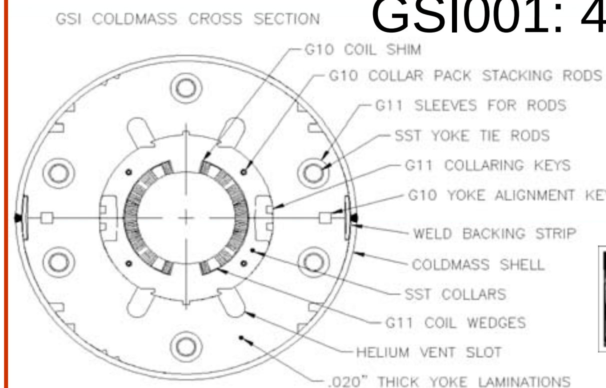
Technology demonstration

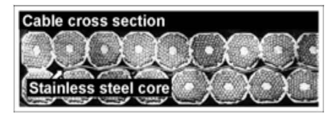
Slitted yoke end



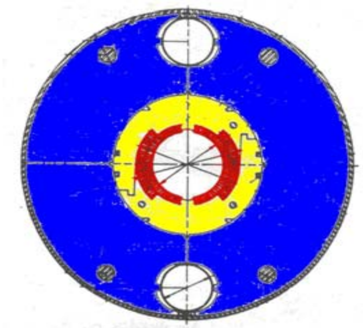
SIS-100

GSI001: 4 T at 1 T/s





of a model of a curved, 4.5 T, 1 T/s dipole for SIS-300



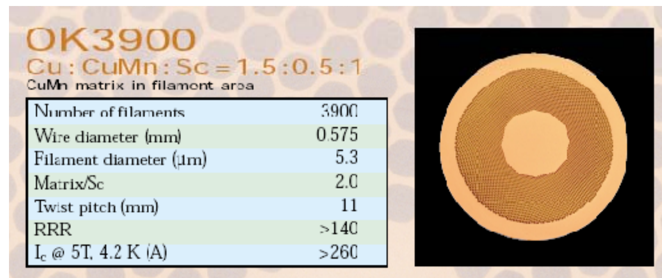
Conceptual and technical design study GSI-IHEP on a modification of the UNK dipole design (5 T, 0.11 T/s) to the SIS-300 (6 T, 1 T/s)

SIS-300

Courtesy of P. Fabbricatore, INFN

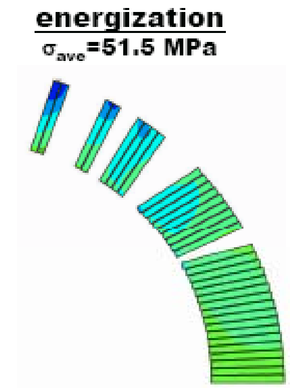
The FAIR Program at INFN

- **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)

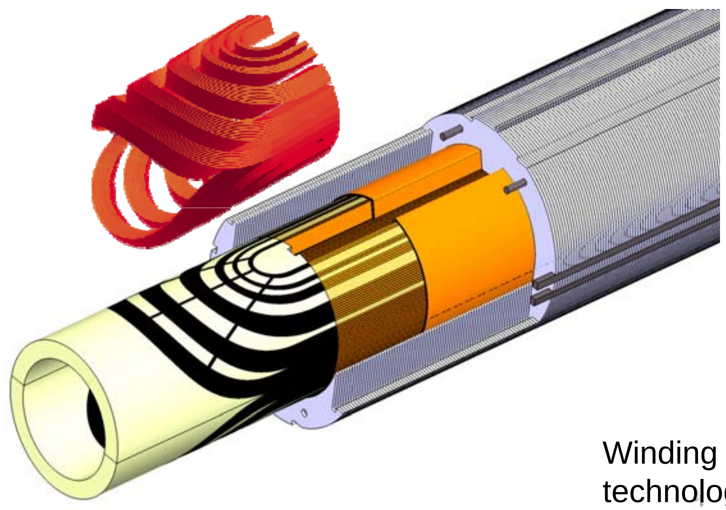


Number of filaments	3900
Wire diameter (mm)	0.575
Filament diameter (µm)	5.3
Matrix/Sc	2.0
Twist pitch (mm)	11
RRR	>140
I_c @ 5T, 4.2 K (A)	>260

Wire R&D



X-section optimization and magnet analysis



Winding optimization and technology demonstration

FCM Magnet Design 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