"Advances and perspectives on compact, low consumption magnets for future accelerators"

Michele MODENA - CERN

in cooperation with:

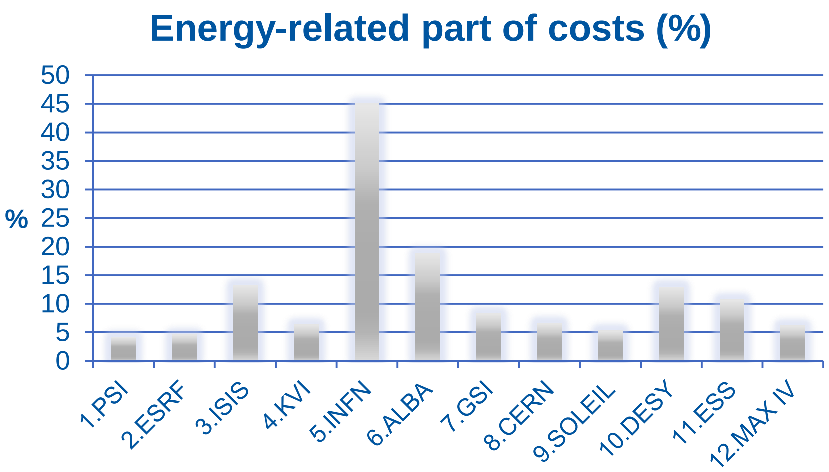
MOTIVATION 1

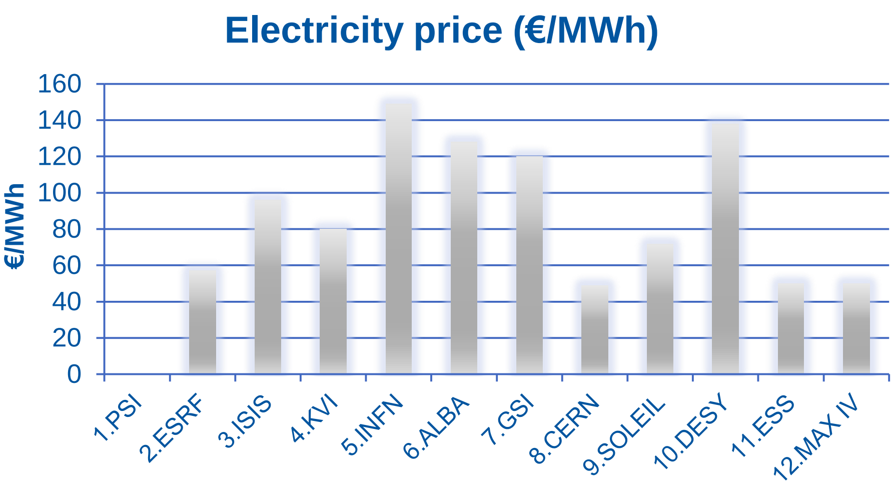
"*Saving costs*" *(evidently…)*

- A **mandatory aspect** to be addressed and study for **any new project** One of the major reasons in several **upgrade & revamping** projects (ex. injectors, transfer lines, booster, etc.)

Boundary conditions:

- Price of electricity in the short-mid term "will not decrease"
- This problem interest all major European and Western Laboratories.





(Courtesy of F. Bordry, CERN)

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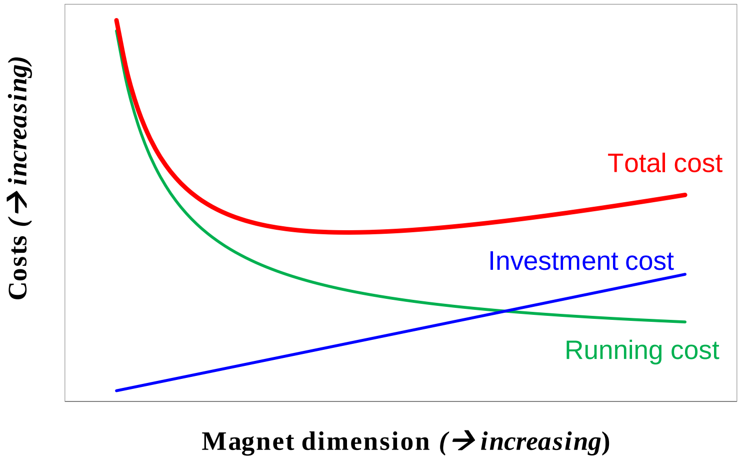
MOTIVATION 1

"Saving costs" plays on two major aspects:

- The INVESTMENT costs (proportional to: size of magnets, technologies, size of needed services, etc.)
- The RUNNING costs (proportional to: power consumption, operating mode, etc.)
- Both aspects deserve a deep analysis especially looking at the possibility offered by ***new technologies and new designs***.
- Sometimes the two aspects are pulling in opposite directions (ex. the impact of current density in NC coils) → *optimization*



Costs building-up for a Normal-conducting (NC) magnet

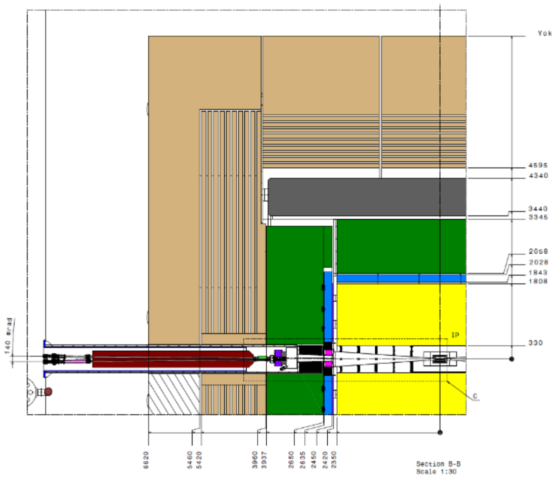
MOTIVATION 2

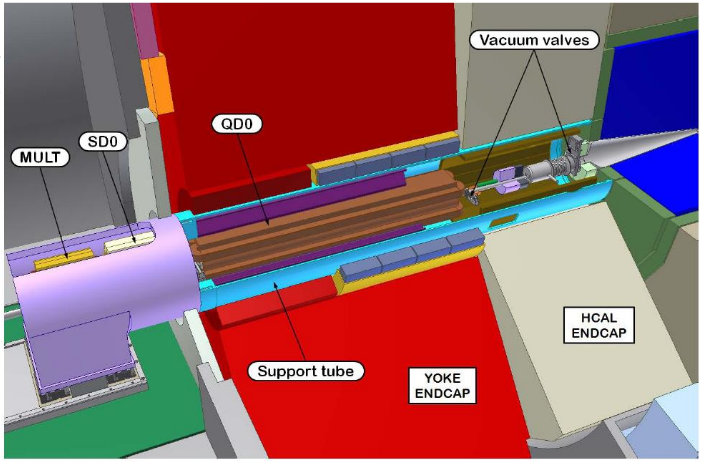
“Saving space” *(or fit the just available…)*

Examples:

Final Focus systems for Future Linear Colliders Projects (ILC, CLIC)

ILD Dimensions





Upgrades of existing machines *(respecting the existing spaces).*

(Courtesy: G. Le Bec, ESRF)

Example: ***ESRF Upgrade Phase II:***

- *New storage ring for reduced horiz. emittance*
- *Increased number of magnets*
- *Same insertion devices source points*
- *Reduced longitudinal space*
- *Reduced power consumption*

DISCLAIMER

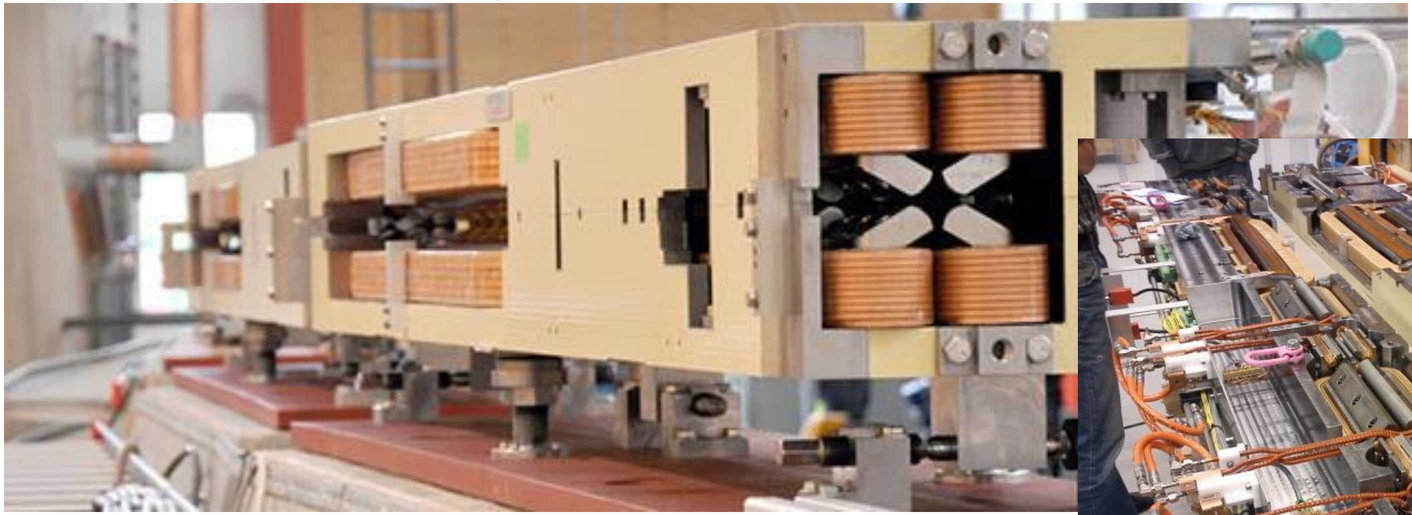
- *It would be quite ambitious to cover in 20 minutes a so wide subject!*
- *As a personal point of view I present few examples of "energy efficiency" in magnet design projects on-going and in R&D phases. Some information for "Reference (past) projects" are also reported.*
- *A recent WS on "Compact and Low Consumption Magnet Design for Future Linear and Circular Colliders" (CERN, Nov. 2014) that I was pleased to chair, provided some sources for all this (→ I am debtor toward several speakers for material !)*
- *Full presentations of that WS could be a starting reference for further details:* ***https://indico.cern.ch/event/321880/***

Saving paths for magnets design

- ***NORMAL-CONDUCTING (NC) magnets:*** *(state-of-the-art still improving with new ideas, layouts, etc.)*
- ***PERMANENT MAGNETS (PM):*** *(domain showing an impressive number of new development; very interesting perspectives)*
- ***HYBRID (PM + NC) design:*** *(idem as P.M)*
- ***PULSED magnets:*** *(also showing new developments mainly joined with Power Supplies Energy Recovery technologies development)*
- ***SUPER-FERRIC design:*** *(the "low magnetic field range", the one covered in this talk, is a domain with a lot of project on-going and with sure future developments).*

NORMAL-CONDUCTING:

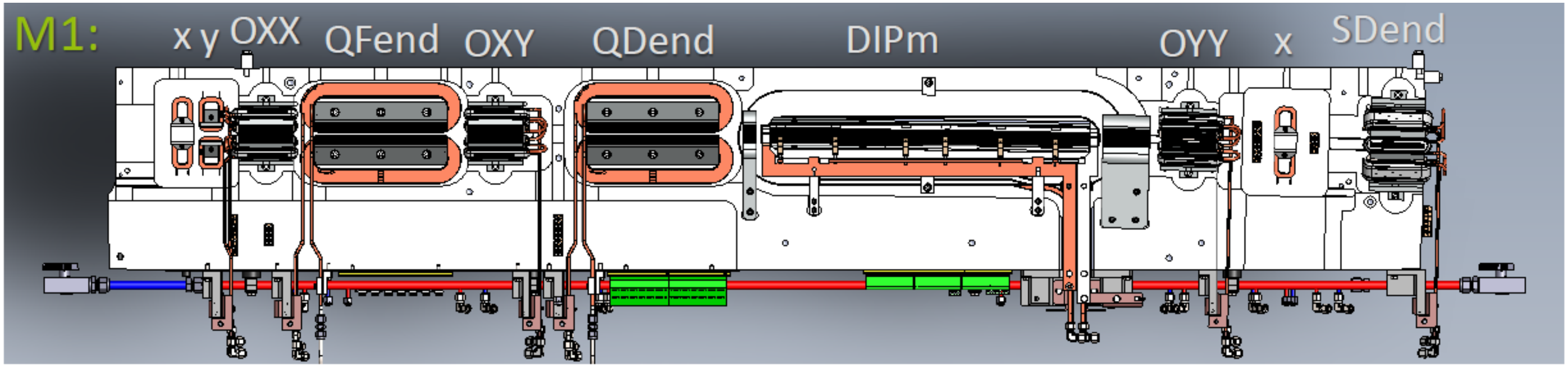
- MAX IV at MAX-Lab in Lund, Sweden, is a new synchrotron radiation facility under commissioning since this year:
- The main 3 GeV ring contains 140 “integrated magnet block units”. Each unit contains several consecutive magnet elements: dipole, 4-poles, 6-poles and 8-poles.
- Each block unit consists in two monolithic half-yokes with length: 2.3÷3.4 m and machining precision: ±20 μm
- (In the same way, the smaller 1.5 GeV ring contains 12 similar integrated magnet block units).

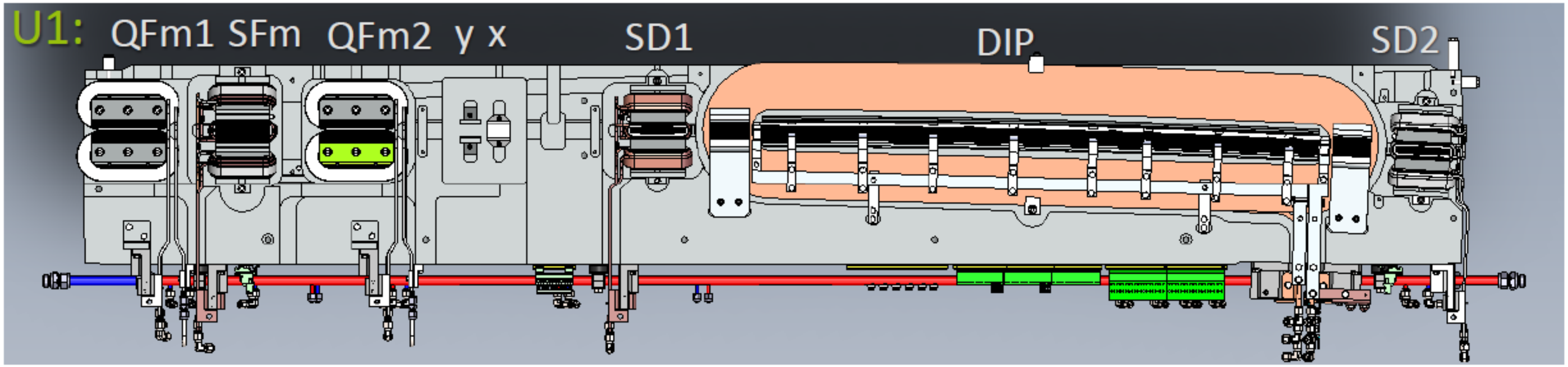


(Courtesy: M. Johansson , MAX Lab)

NORMAL-CONDUCTING:

- Magnets aperture (25 mm); value carefully chosen to optimize:
- minimum length of each magnetic element and their interaction (→ field quality),
- B at pole-tip to stay very far from saturation, (→ reduced power consumption; the full magnets-ring consumption is 339 kW (!)





(Courtesy: M. Johansson , MAX Lab)

NORMAL-CONDUCTING:

- The KEY points:
  - *The "integrated magnet block units" choice was done mainly for:*
    - *Vibration stability.*
    - *Ease of installation.*
    - *The magnet block being an alignment concept which is totally outsourced to industry.*

- The CRITICAL aspects:
  - *Meeting the ±20 μm mechanical tolerances.*
  - *Performing Hall mapping with the same level of positioning accuracy.*
  - *Solving rotating coil measurements access while also meeting specified accuracy.*
  - *And doing all this with required production rate*

(Courtesy: M. Johansson , MAX Lab)

PERMANENT MAGNETS:

Main PROS and CONS aspects for Permanent Magnet design:

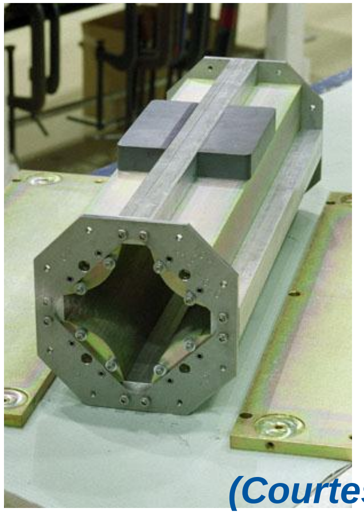
***PROS*:**
- *More compact for small aperture magnets*
- *No power consumption*
- *No coil heads/fringing field*
- *Big saving in space/weight*
- *High reliability, no monitoring for failure detection needed*

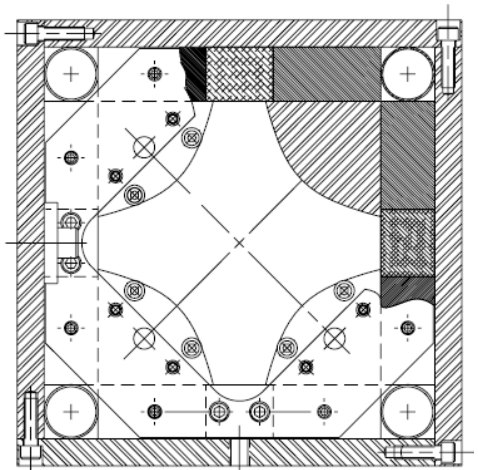
***CONS*:**
- *Risk of radiation damage ($\rightarrow$ Sm_2Co_{17})*
- *ΔT ($\rightarrow$ can be compensated)*
- *Mech. complexity, (especially when wide tunability required).*
- *Safety aspects for workers*

- The best "large scale" example is the Fermilab Recycler Ring *(built in 1997…not so young!):*

344 Focusing and Defocusing Dipoles + 50 Quadrupoles (tunable) based on Type 8 Strontium Ferrite with Ni-Fe alloys strips for temperature compensation.

- *Dipole length of 3÷4.5 m, Quads: 0.6 m.*



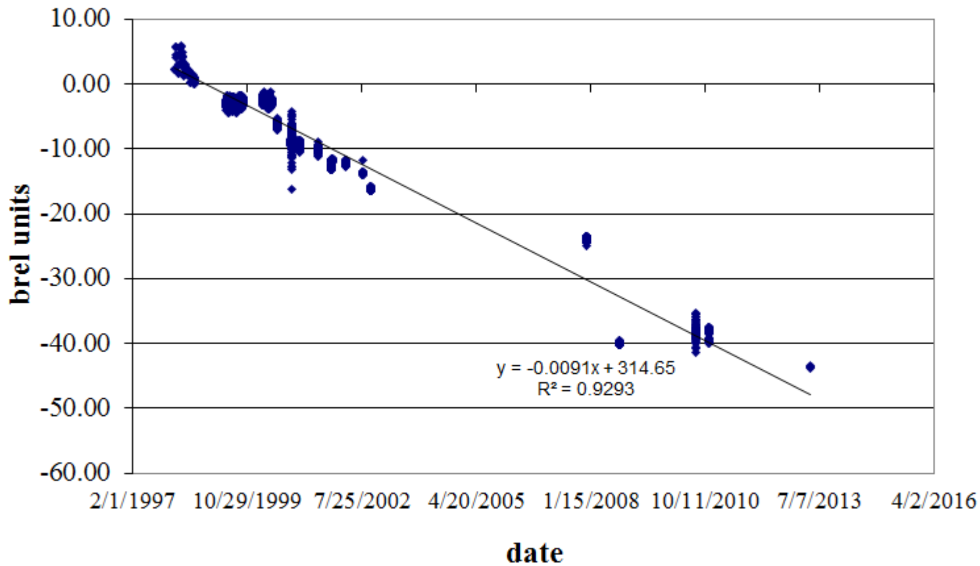


(Courtesy: V. Kashikhin, Fermilab)

PERMANENT MAGNETS:

- The construction of the Recycler ring has allowed to study and get realistic perspectives for “full accelerator size” PM blocks industrial production (in this case “Type 8” Strontium Ferrite).
- About 70’000 blocks of an ad-hoc standard shape (6x4x1 inches) were procured with the consequent follow-up of critical aspects like: production, tolerances, QA, transportation, storage, measurements, manipulation and stability issues.

- The overall magnet strength stability measured on ~ 15 years was of ~3 units/year decrease.



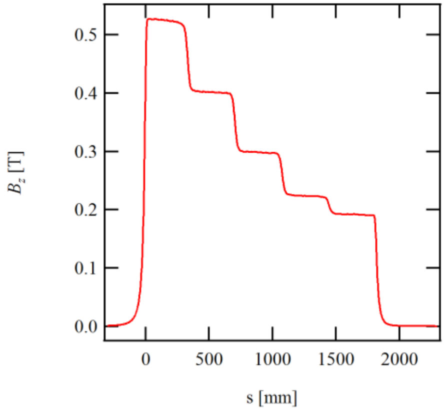
(Courtesy: V. Kashikhin, Fermilab)

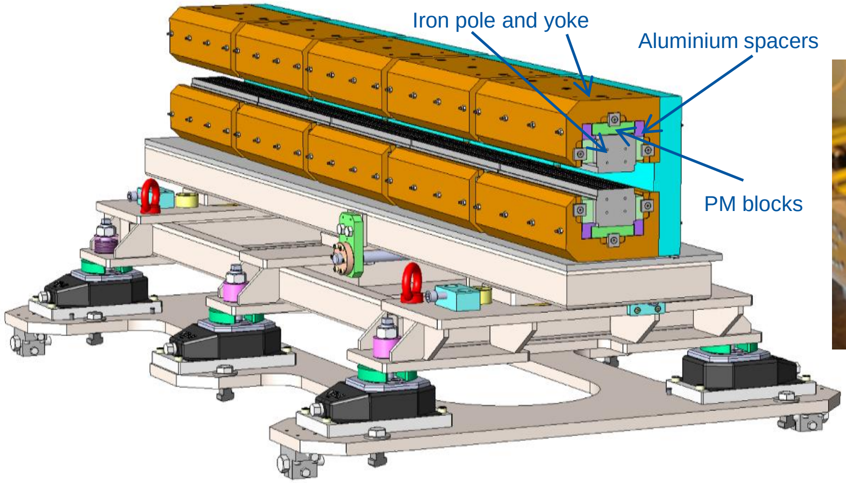
PERMANENT MAGNETS:

Several Labs are working on innovative designs. Few examples:

- **ESRF Upgrade Phase II:**

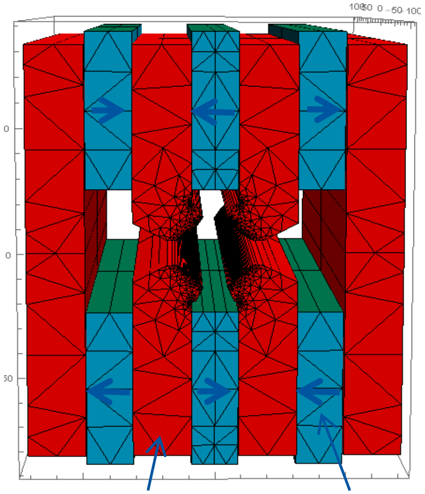
- Dipole with Longitudinal Gradient for emittance reduction:





- PM quadrupole prototype (G= 82 T/m):

- 36 NdFeB blocks + ARMCO steel
- PM blocks far from e^- beam
- Large space for X-rays port
- Total mass 45 kg
- Quick and easy assembly
- Hybrid version (for tuning) under study



(Courtesy: J. Chavanne, G. Le Bec , P. N'gotta, ESRF)

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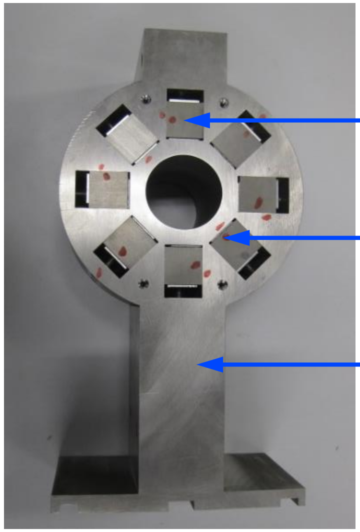
PERMANENT MAGNETS:

CERN recent experience:

- LINAC4 "iron-free" quadrupoles:

(14 units, G: 11-16T/m, different for each quad)

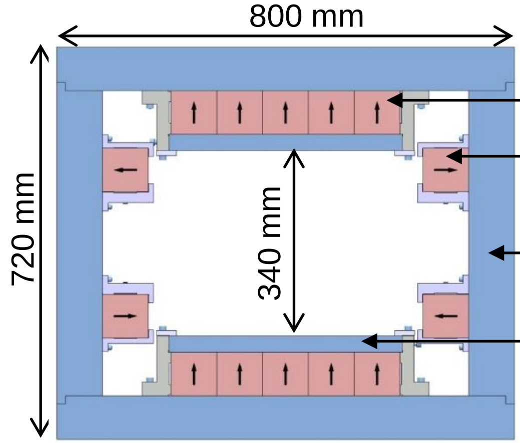


Permanent magnet block (Sm2Co17)

Non magnetic shims (austenitic steel 316LN)

Non magnetic yoke (austenitic steel 316LN)

- "n-Tof" dipole: (0.25 T; 168 PM blocks !)



PM block Sm_2Co_{17}, as a flux generator

PM block to improve field quality

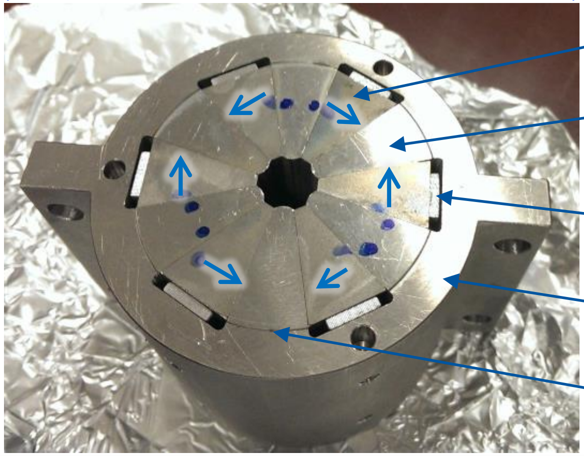
Return yoke low-carbon steel

Pole tip to smooth in PM block magnetization direction

- ASACUSA sextupoles (two units installed INSIDE the high vacuum spectroscopy beam line, G= 114480 T/m^2)

98 mm

72 mm



PM block Sm_2Co_{17}, as a flux generator.

Pole Fe-Co, to canalize magnetic flux and assure field quality.

Shim 316LN non magnetic austenitic steel but possibility to insert iron shims to adjust the sextupole field.

External yoke Titanium T40, non magnetic to hold the poles together and guaranty the geometry.

Vacuum brazing Gapasil filler.

(Courtesy: P. Thonet, CERN)

PERMANENT MAGNETS:

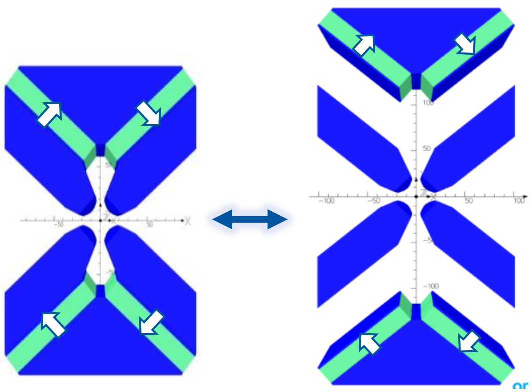
- **ZEPTO (Zero-Power Tunable Optics) Prototypes at Daresbury Laboratory :**

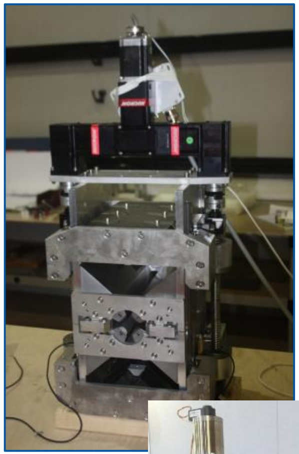
Target is an energy efficient design for the 41’400 Drive Beam quadrupoles for CLIC 3 TeV Project. The innovative idea is a “fully mechanic tunable PM quads” design. Saving would be impressive (EM version total power consumption from 8 -17 MW)

2 prototypes built to cover the full gradient range required in the very limited space available:

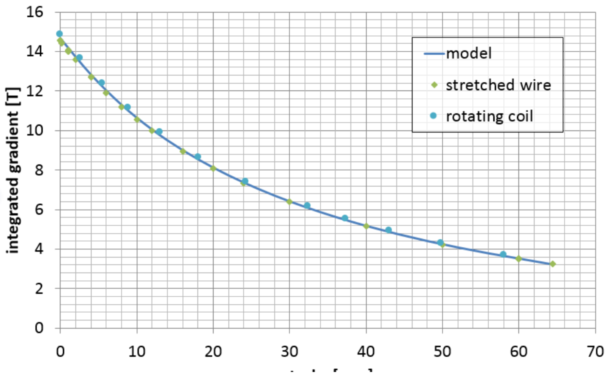
(15 ÷60.4 T/m ; 3.5 ÷ 43.4 T/m in a 390 x390 x 270 mm space)

- *ZEPTO-Q1: high strength:*

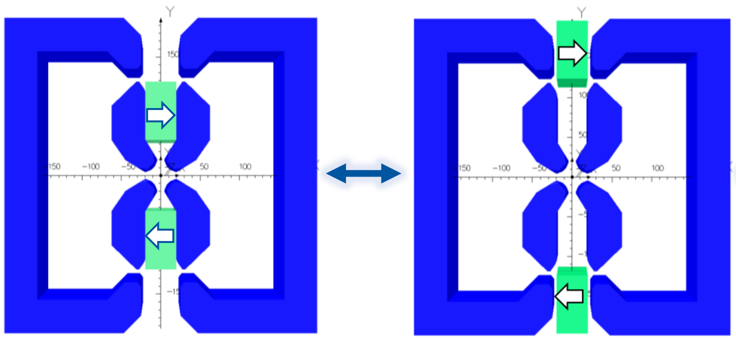




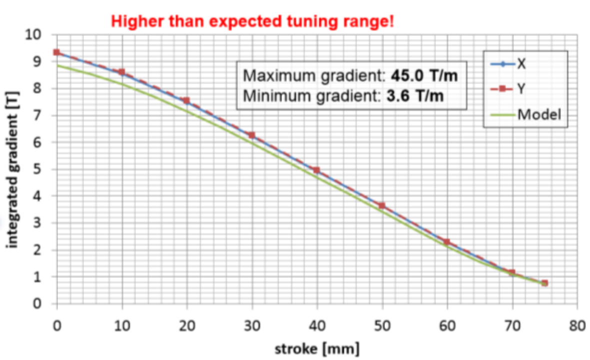
Measured Integrated Gradient



- *ZEPTO-Q2: low strength:*



Measured Integrated Gradient

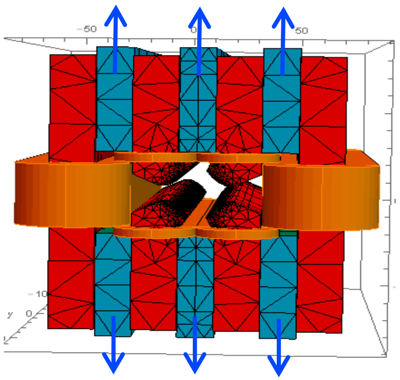


(Courtesy: B.Shepherd, STFC, UK)

HYBRID (PM + NC) MAGNETS:

- ## ESRF Upgrade Phase II:

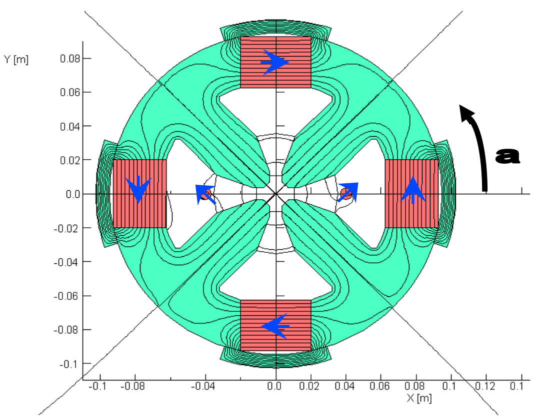
- The already shown PM prototype is under development for an hybrid concept:

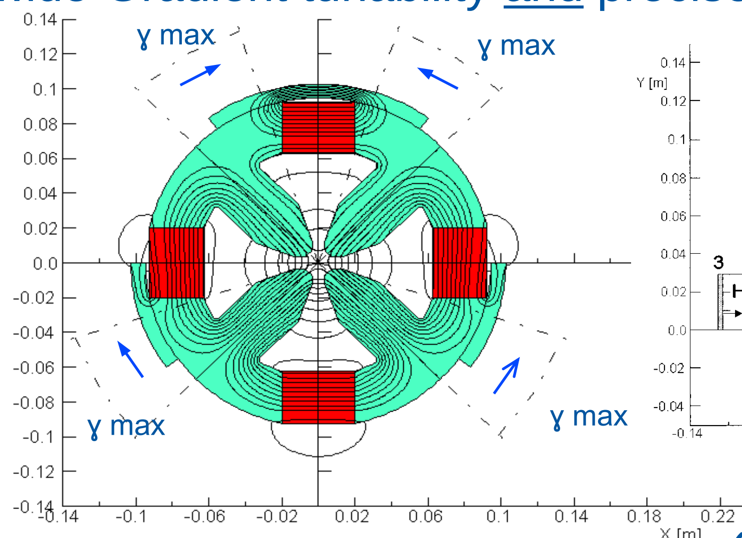


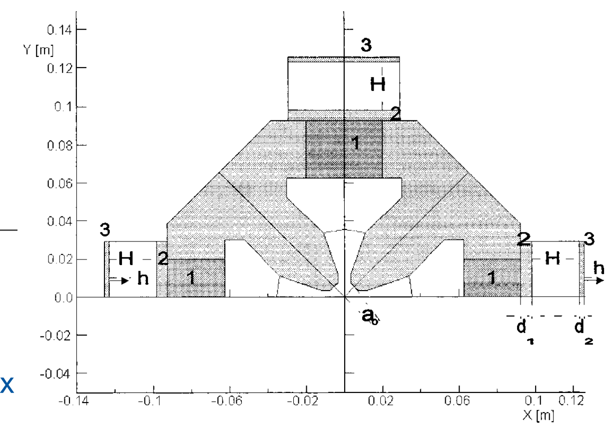
Advantages:
- Very strong gradients & compactness
- Simple field correction
- Easy assembly
- Wide tunability

- ## DESY experience in hybrid quadrupoles R&D:

- Innovative solutions for wide Gradient tunability and precise magnetic center adjustment:







(Courtesy: B. Krause, DESY)

HYBRID (PM + NC) MAGNETS:

- **CERN experience in CLIC 3 TeV R&D**

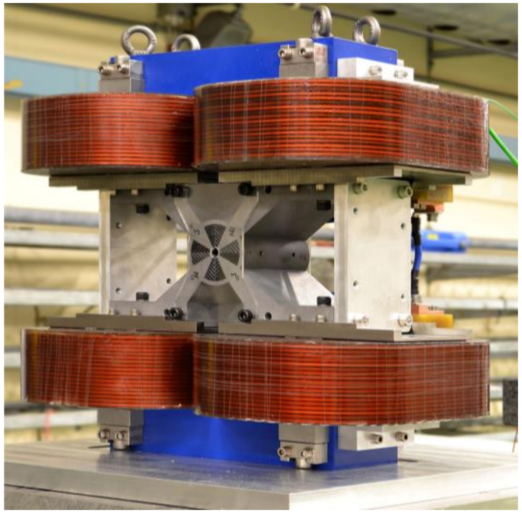
A new conceptual design was necessary for the QD0 quad of the FF system due to:

- Extremely high Gradient required: ~ 575 T/m for an open bore of ~ 8.5 mm
- Compactness: magnet inside the Detector Solenoid
- Integration: magnet layout shall be compatible with the post collision vacuum pipe presence.
- Tunability: ≥ 20%
- Rigidity and no-vibrations: since quad will be equipped with an active nano-stabilization system
- Alignment budget: 10 µm

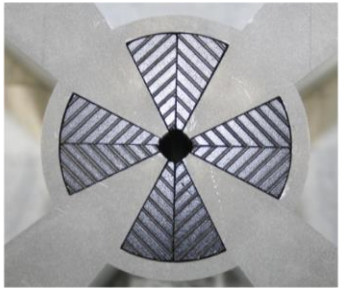
The high gradient, compactness and tunability requirements would suggest a Super-conducting design (as in the case of ILC), but this would be not compatible with stability (for nano-stabilization) and alignment requirements.

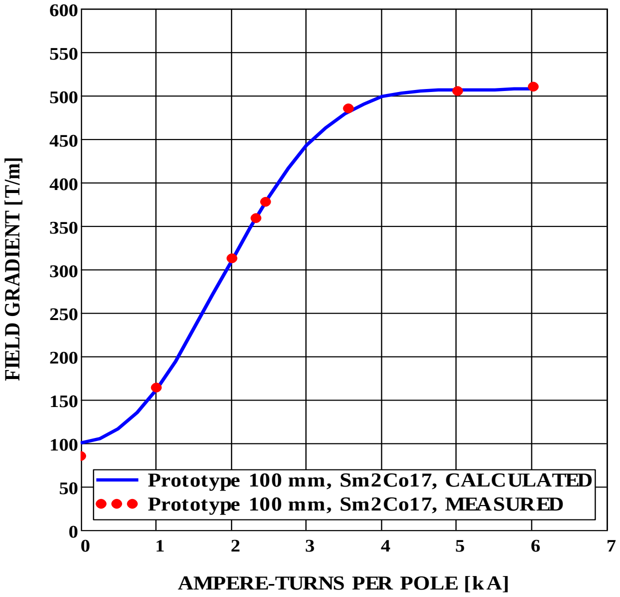
For this reason an innovative hybrid (PM & air-cooled coils) design was finally developed. A short prototype was successfully built and tested.

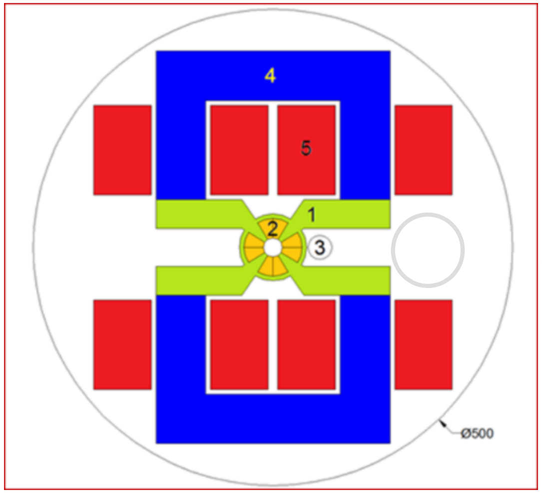
HYBRID (PM + NC) MAGNETS:

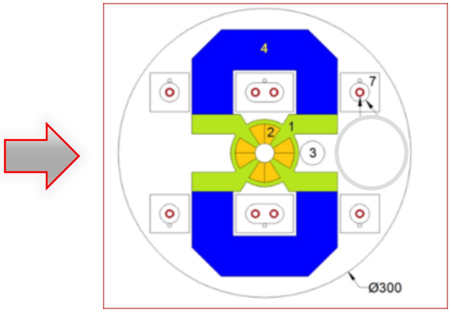


Hybrid QD0 and
measurements details

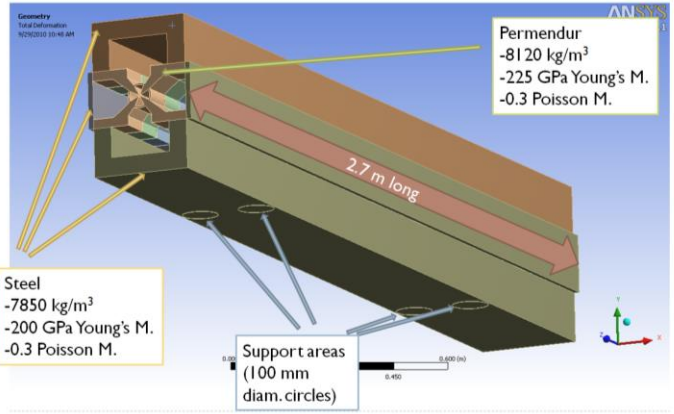








a possible
Super-ferric evolution



The full-size assembly concept

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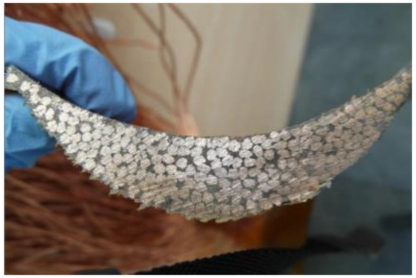
PULSED magnets:

- **GSI R&D on High Current Pulsed magnets for transport and final focussing of bunched beams (SIS18)**



Conductors and poles:

- *Insulated copper wires (Ø 0.355 mm) strand*
- *Cos 2θ cross-section*
- *Winding of one single conductor*
- *Symmetric ends (as much as possible)*
- *Energy efficient and relaxed tech. services needs*

	Conventional Quad	**Pulsed Quad (1 Hz)**
Gradient	10 T/m	15.4 T/m
Length	1 m	0.65 m
GxL	10 T	10 T
Aperture r	0.065 m	0.056 m
Peak I	270 A	77 kA
Peak V		4.7 kV
Stored E	5.5 kJ (in the magnet gap)	5 kJ (in capacitor)
Power	18 kW	5 kW (0.8*)

** with Energy Recovery circuit*

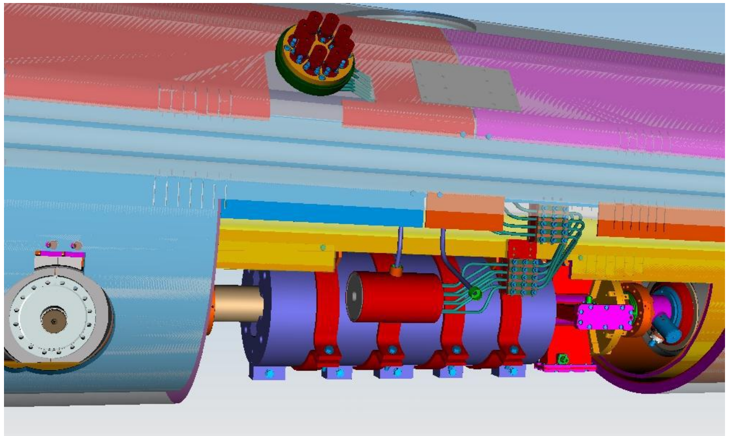
Coil, winding details and 3D-model

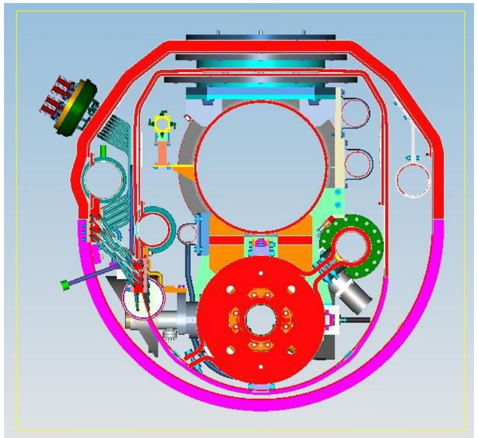
(Courtesy: P. Spiller, C. Tenholt, GSI)

SUPER-FERRIC design:

SC magnets *can provide* *energy efficient* *solutions for* *low field* *magnets especially when the cryogenic capability are available as required by other systems (ex. by RF system, or by high-field magnets).*

- A good example of that is the **ILC Main Linac Quadrupole**: a NbTi “Cold Super-ferric” magnet, with conduction cooling and including SC stabilization coils (working in persistent mode during normal operation). Magnets (560 units for the all ILC) are installed in the ILC cryomodule between SCRF cavities.





Peak Gradient	54 T/m
Required tunability	-20 %
Aperture	78 mm
Magnetic length	660 mm
Peak I	100 A
Dip. corr.	0.075 Tm
Magn. axis stability	5 µm
Max axis offset	0.3 mm
Total length	800 mm
Units	560

- Magnet was fully tested and measured at KEK and FNAL.
- An “Integrated Magnet System Scheme” (i.e. powering the quad in persistent current mode) is under study.
- This would provide major savings in hardware (ex. factor 10 reduction in PS and current leads units, in quench detection systems, etc.). For the actual coils design (with 5 splices with R< 10nΩ) the current decay would be 0.02%/day (tau ~ 12 years).

(Courtesy: V. Kashikhin, Fermilab; A. Yamamoto, KEK)

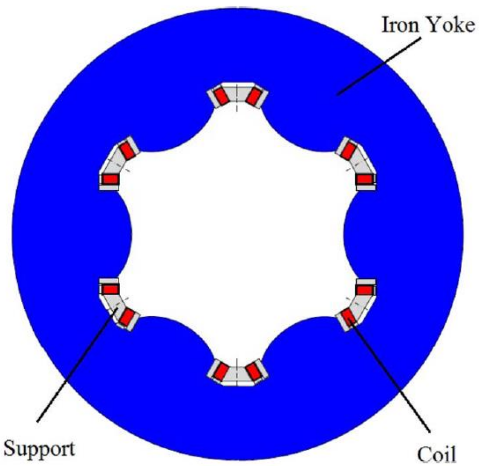
SUPER-FERRIC design:

Another example: **"Hi-Lumi LHC"** (the High Luminosity Large Hadron Collider project), that will increase the peak luminosity of LHC of a factor 10.

- In the FF region 36 corrector magnets are needed. They will be subject to intense radiation rates (~ 26 MGy expected for magnet lifetime).The retained magnet choice is for Nb-Ti Super-ferric designs now under development.

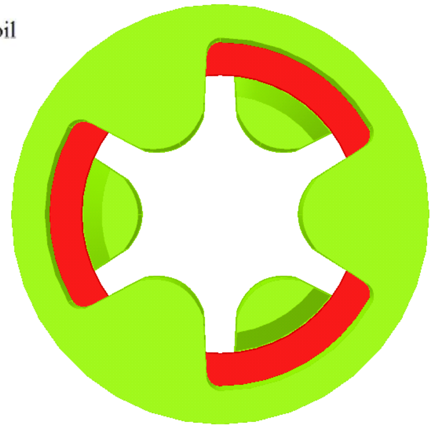
Magnet Order	n	Integrated strength at r = 50 mm (T·m)	Magnetic Length (m)	Field modulus at r = 50 mm (T)	Coil Peak Field (T)	Stored Energy (kJ)	Operating current (A)	No turns per coil
Quadrupole	2	1.000	0.807	1.239	2.97	24.6	182	320
Sextupole	3	0.063	0.111	0.569	2.33	1.3	132	214
Octupole	4	0.046	0.087	0.530	2.41	1.4	120	344
Decapole	5	0.025	0.095	0.264	2.34	1.4	139	256
Dodecapole†	6	0.086	0.430	0.200	2.04	4.3	167	154
Dodecapole§	6	0.017	0.089	0.191	2.01	0.9	163	172

† normal; § skew.



Sextupole corrector magnet cross section.

- During the R&D phase, alternative and more innovative design like the **Round Coils Super-ferric Magnet** (RCSM) were investigated. This solution was finally not retained, but due to its extremely interesting features and advantages, a prototype with **MgB_2** coils will be built in the aegis of a CERN-INFN collaboration agreement.



(Courtesy: G. Volpini, INFN; V. Kashikhin, Fermilab)

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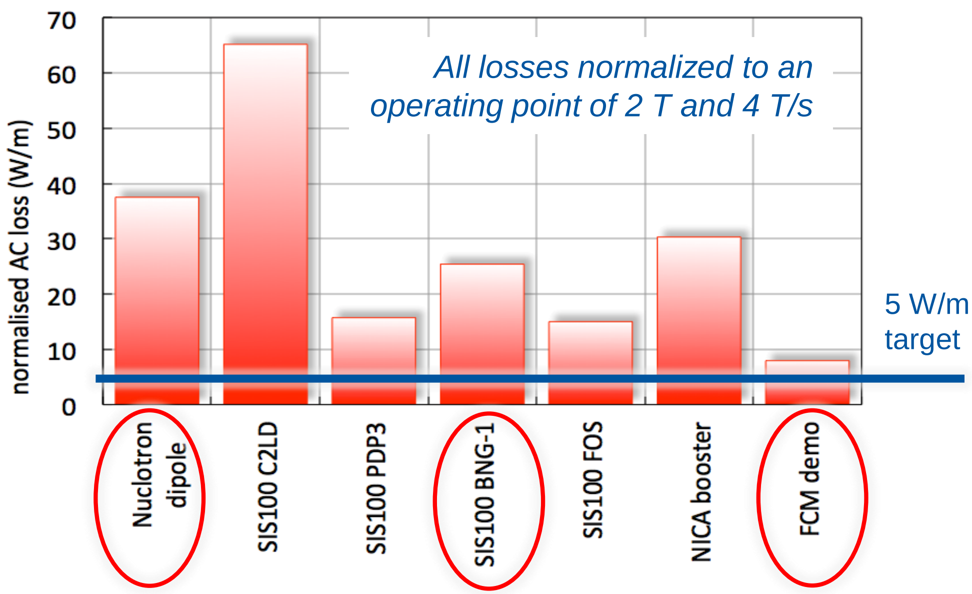
SUPER-FERRIC design:

SC vs. NC trade-off:

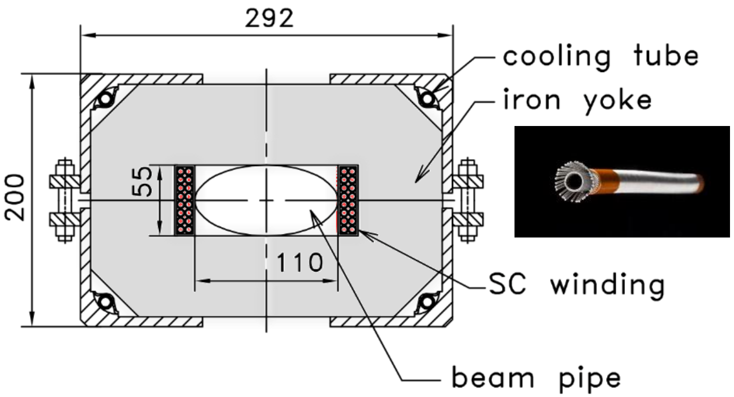
- Considering a "test case" with : B=2 T, h= 60 mm, J= 5 A/mm^2, a SC design will be competitive vs. a NC one if wall-plug power would be < ~4 kW/m.
- For FCM (Fast Cycled Magnet) operation, hysteresis losses must be also be take into account: *For a SC design they are proportional to ΔB (ex. hysteresis loss in filaments) or to dB/dt and ΔB (ex. coupling loss in strands and cables, losses in iron yokes).*
- A FCM-SC magnet with loss per units < 5 W/m will be competitive.
  Higher would be the cryogenic working temperature, more competitive it will be…



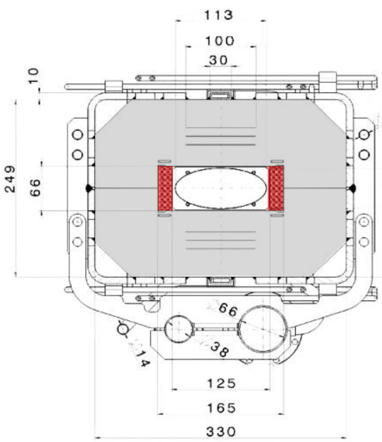
(Courtesy: L. Bottura, CERN)

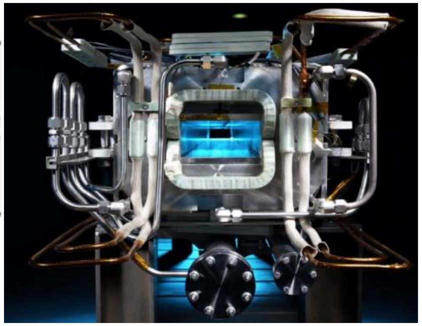
SUPER-FERRIC design:

- **FCM experience with Nuclotron (1992) at JINR, Dubna:**
  - Built from 1987 to 1992
  - Designed for acceleration of heavy ion beams, up to ^{238}U
  - Dipole magnets with NbTi hollow conductor designed for 2 T, 4T/s, 1 Hz repetition rate. Achieved 2 T at ≈ 0.2 Hz in operation



- **FCM experience at GSI-SIS 100:**
  - Synchrotron for the acceleration of intense $^{238}U^{28+}$ beams up to 2.7 GeV/u and p^+ beams up to 29 GeV
  - Fast pulsed dipoles, 2 T, 4 T/s (i.e. 1 Hz repetition rate) based on an improved Nuclotron concept
  - Several prototypes tested, now under construction





Cross section of first industrial prototype

Pre-series full-scale dipole

(Courtesy: L. Bottura, CERN)

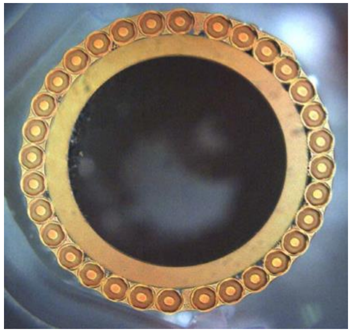
SUPER-FERRIC design:

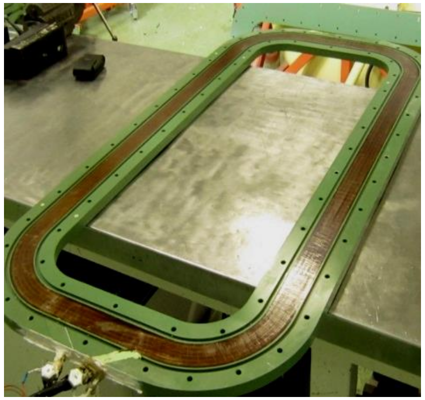
FCM R&D experience at CERN:

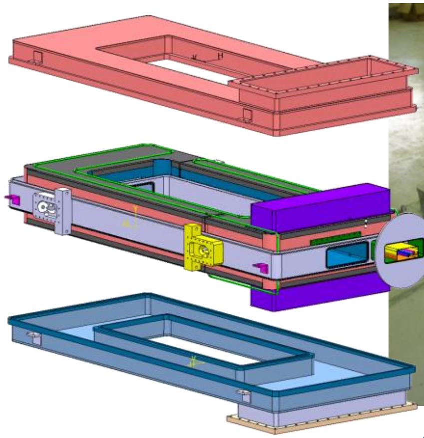
In the frame of CERN-PS2 upgrade study, CERN built and test a Super-ferric FCM dipole based on NbTi coils operated at 4.5 K and with working parameters suitable for the PS2 operation (dipole field strength: 1.8 T, ramp rate: ± 1.5 T/s, cycle: 2.4 s). Such design implemented on the PS2 layout (200 Dipoles) would bring very interesting cost figures:

	“PS2” Full power consumption (MW)	**Operating cost** ***(on 40 Chf/MWh base)***	**Investment cost (MChf)**
NC	14.6	3.8 MChf/y	60.5 MChf
Super-Ferric	7.6	2.2 MChf/y	66.7 MChf

(NOTE: a “classical” SC design was also evaluated but it was not competitive due to the low operating field (1.8 T), high AC losses (5-8 W/m) with consequent high cost for the cryogenic plant (15 kW needed).







(Courtesy: L. Bottura, CERN)

SUPER-FERRIC design:

- **FCM R&D future plans:**

We consider that a Super-ferric FCM magnet working at 77 K with a simplified cryogenic system (ex. cryocooler) would be a demonstrator improving the Technology Readiness Level toward HTS magnets future applications for multiple domains (ex. medical imagery and diagnostic devices, energy transport, energy storage, magnetic separation, etc.).

"**NEEDS**" (***N**ovel **E**nergy **E**fficient **D**esign of **S**uperconducting magnets*) is a very recent application to a Horizon 2020 "FET-Open" call *(…answer expected for beginning 2016)*

CERN and CEA, plus other 4 University and Industrial Partners, propose a R&D plan for:

- Innovative HTS tapes (ReBCO) and cables optimized for fast-cycled operations design and fabrication.
- Design and fabrication of an innovative HTS coils working at LN2 temperature (77 K) with a CPHP (Cryogenic Pulsating Heat Pipes) cooling system directly integrated inside the coil assembly.
- Construction and fully test at CERN premises, of a demonstrator magnet (with two different coils solutions) to validate the successful implementation of the new solution.

THANK YOU for the attention