“Compact and low-consumption accelerator magnets”

Michele MODENA - CERN

DISCLAIMER

- *Quite ambitious to cover in 20 minutes a so wide subject!*
- *As a personal point of view I present few examples of "**energy efficiency**" and "**compactness**" in magnet design projects on-going and in R&D phases. Some past "reference projects" are also reminded*
- ***https://indico.cern.ch/event/321880/*** **:**

  a WS on "Compact and Low Consumption Magnet Design for Future Linear and Circular Colliders" (CERN, Nov. 2014) could provided reference and details (→ I am debtor toward several speakers for material)

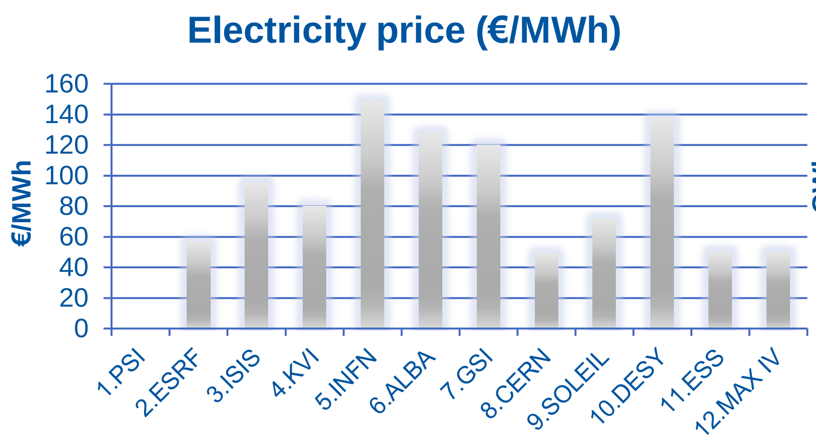
A FIRST MOTIVATION for Compactness

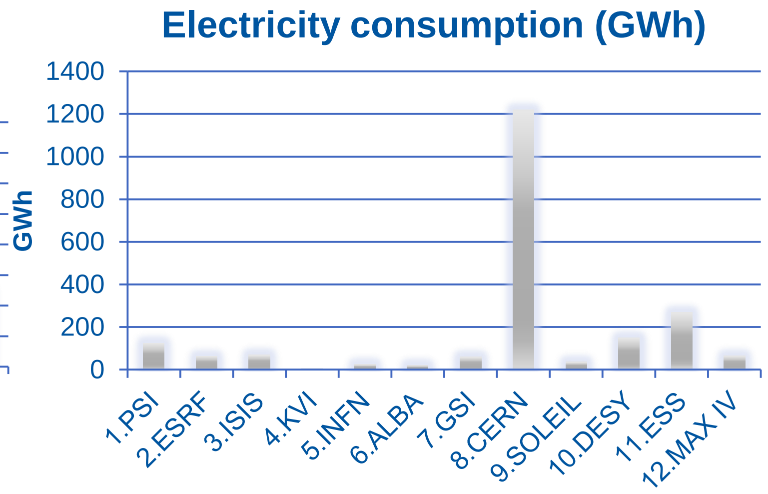
"*Saving costs*"

- A **mandatory aspect** to be addressed and study for **any new project**
- And today also for **any upgrade & revamping** project (injectors, transfer lines, booster, synchrotron radiation facilities, etc.)

Boundary conditions:

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





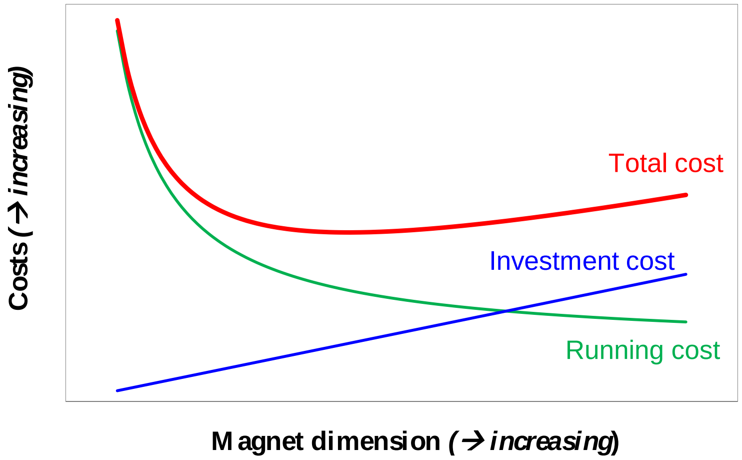
(Courtesy of F. Bordry, CERN)

A FIRST MOTIVATION for Compactness

"Saving costs" plays on two major aspects:

- The **INVESTMENT** (Capital) cost: proportional to magnets size, technologies, technical services size, etc.
- The **OPERATION** (Running) cost: proportional to power consumption, operating mode, etc.
- In some cases the two aspects are pulling in opposite directions (ex. the impact of current density in NC coils) → *optimization*

- Both aspects deserve a deep analysis especially looking at the possibility offered today by ***new technologies and new designs***.



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

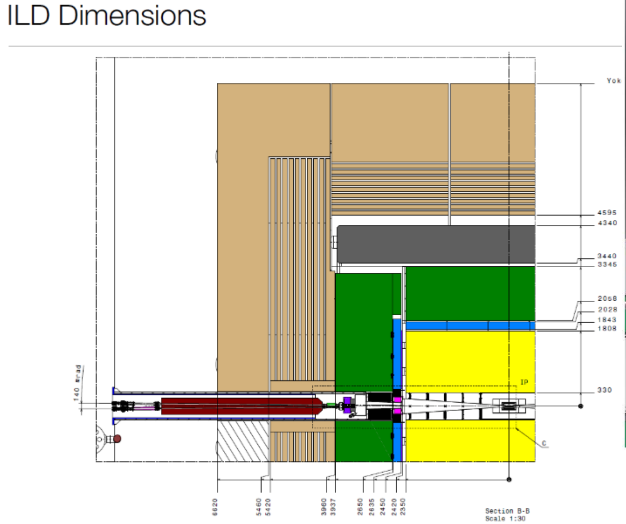
A SECOND MOTIVATION for Compactness

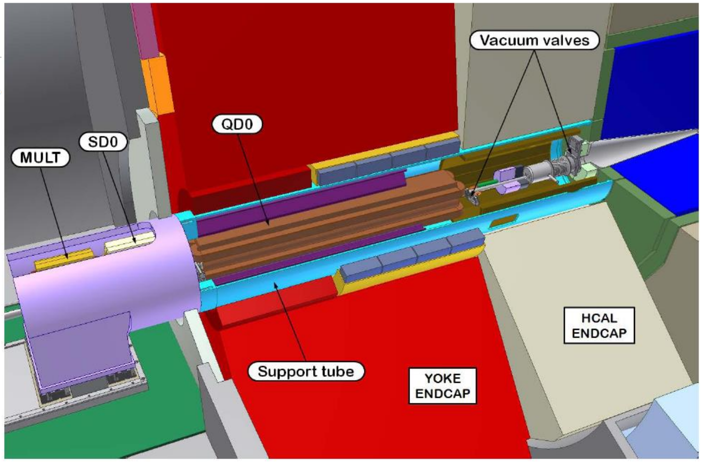
International Workshop on Future Linear Colliders LCWS2015

"Saving space" *(or fit the just available…)*

Examples:

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





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

(Courtesy: G. Le Bec, ESRF)

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

A new storage ring with reduced horiz. emittance

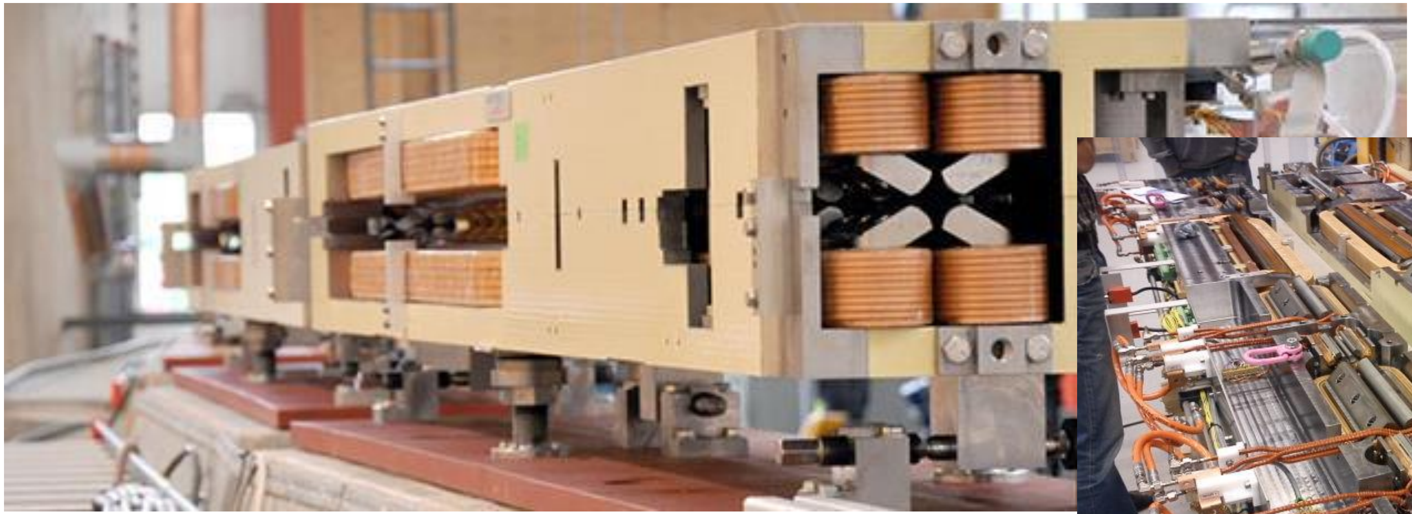
- *Increased number of magnets*
- *Same insertion devices source points*
- *Reduced longitudinal space*
- *Reduced power consumption*

Magnets design paths

- ***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:

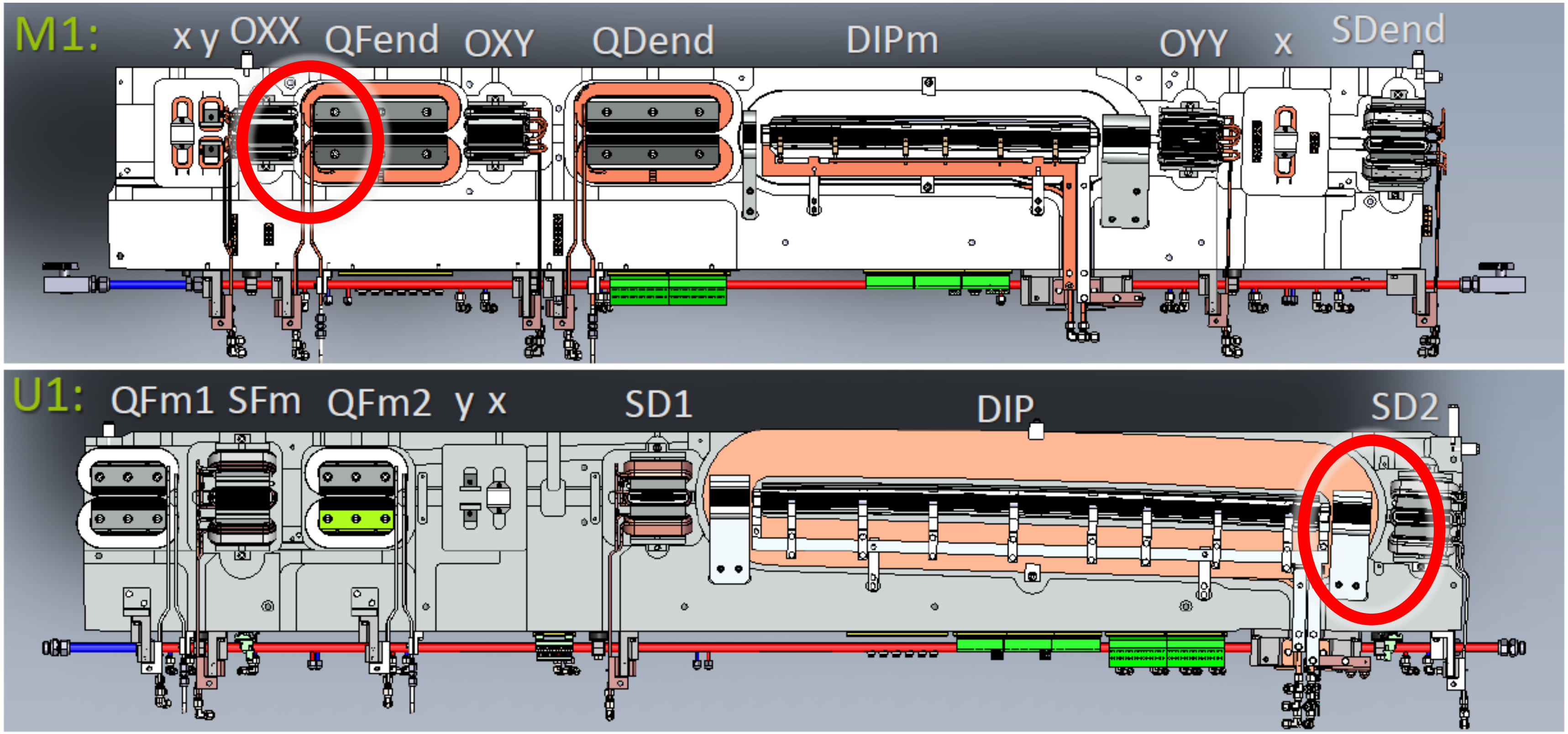
- **MAX IV at MAX-Lab** in Lund, Sweden, is a new synchrotron radiation facility under commissioning since this Summer:
- The main 3 GeV ring contains <u>140 “integrated magnet block-units</u>”. Each unit contains several consecutive magnet elements: dipole, 4-poles, 6-poles and 8-poles.
- The smaller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



(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 far from saturation, (→ reduced power consumption; the full magnets-ring consumption is 339 kW (!)



(Courtesy: M. Johansson , MAX Lab)

NORMAL-CONDUCTING:

- MAX IV choice key points:

  - The "integrated magnet block units" choice was done mainly for:

  - *Compactness*
  - *Energy Efficiency*
  - *Vibration stability.*
  - *Ease of installation.*
  - *The majority of the alignment difficulties are "built-in" in the block-units (outsourced to industry).*

- 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.*
  - *All this respecting the required production rates*

(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*

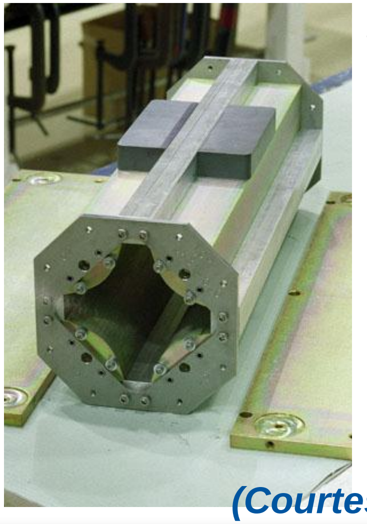
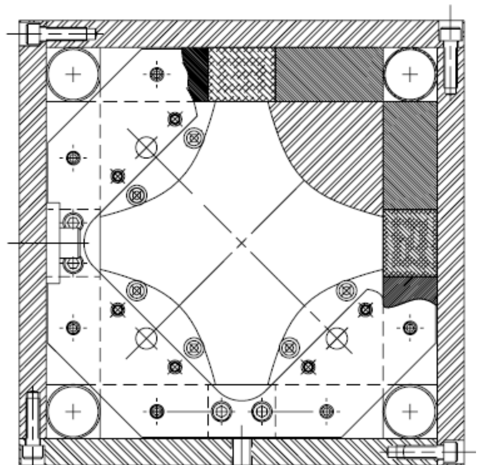
***CONS**:*
- *Risk of radiation damage (→ Sm_2Co_{17})*
- *ΔT (→ can be compensated)*
- *If wide tunability required, mechanical complexity increases*
- *Safety aspects for workers*

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

***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.*

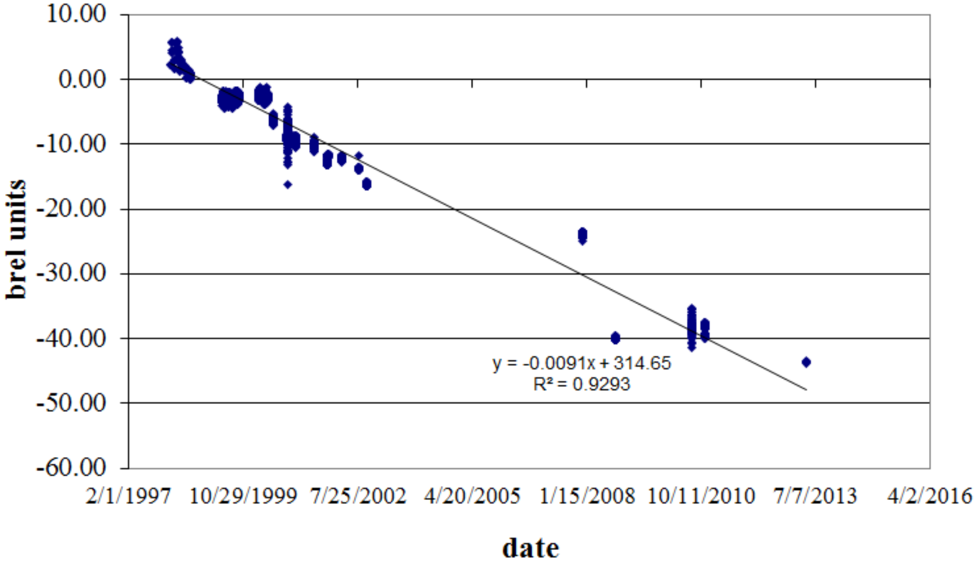


(Courtesy: V. Kashikhin, Fermilab)

PERMANENT MAGNETS:

- The construction of the Recycler ring has allowed to study and get realistic perspectives for "full accelerator size" PM blocks industrial production
- About 70'000 blocks of an ad-hoc standard shape (6x4x1 inches) were procured with the consequent follow-up of critical aspects like: production uniformity and tolerances, QA, transportation and storage (under controlled temperature), measurements, manipulation and stability issues.
- The overall magnet strength stability measured on ~ 15 years was of ~3 units/year decrease.



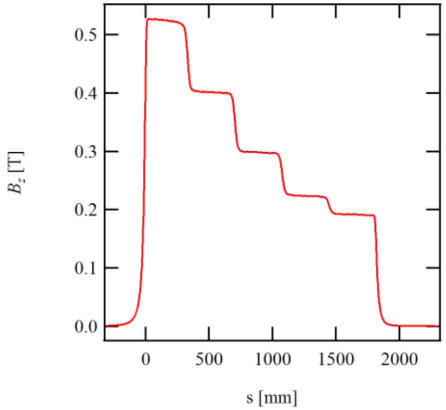
(Courtesy: V. Kashikhin, Fermilab)

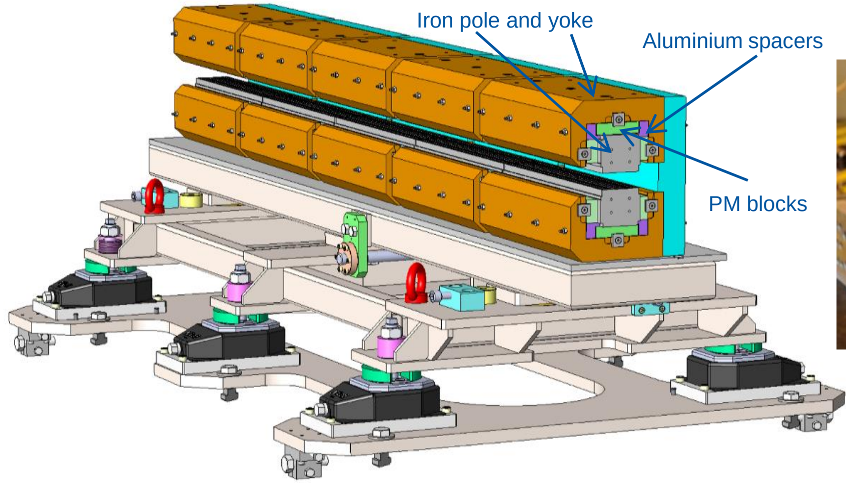
PERMANENT MAGNETS:

Several Labs are working on innovative designs. Few examples:

- **ESRF Upgrade Phase-II (**or **EBS: E**xtremely **B**rilliant **S**ource)

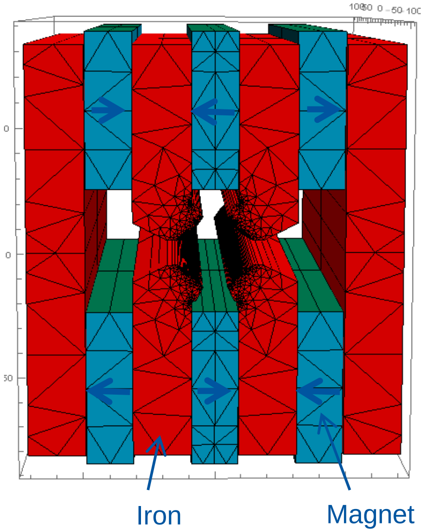
  - Dipole with Longitudinal Gradient for emittance reduction:





  - 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

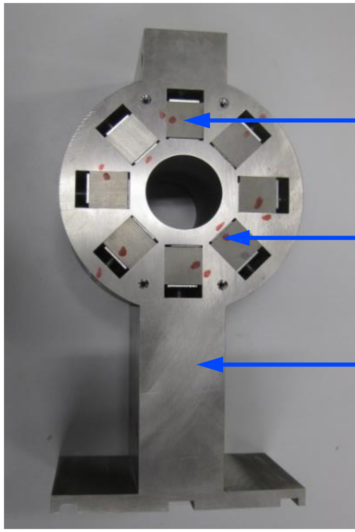


(Courtesy: J. Chavanne, G. Le Bec , P. N'gotta, ESRF)

PERMANENT MAGNETS:

- **CERN recent experience:**

- ***LINAC4*** *"iron-free" quadrupoles:*



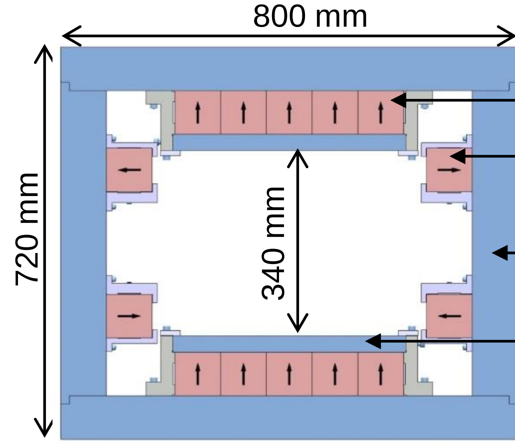
(14 units, G: 11-16T/m, different for each quad)

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 !)*



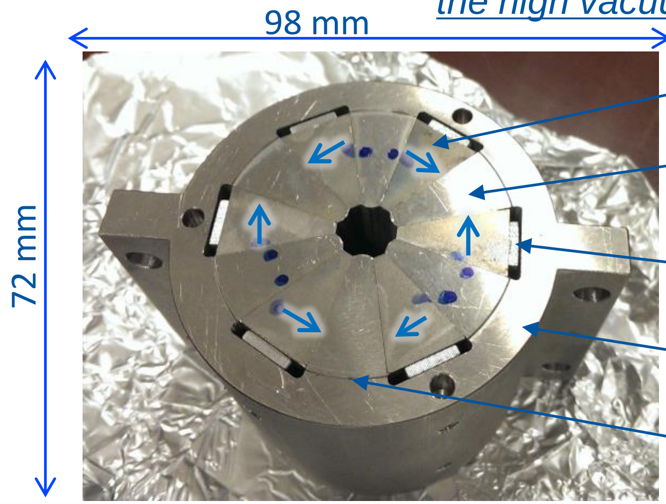
PM block Sm_2Co_{17}, as a flux generator

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/m²)*



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:

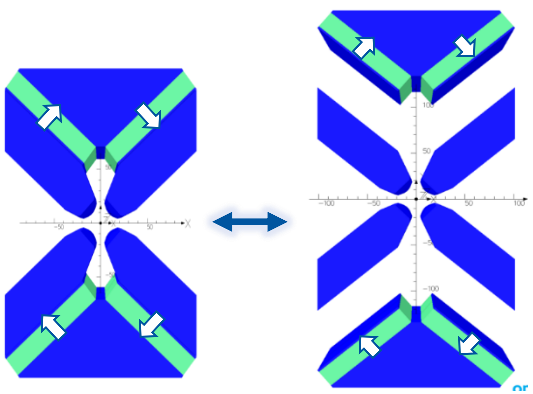
- **ZEPTO** (Zero-Power Tunable Optics) Prototypes at **Daresbury Laboratory:**

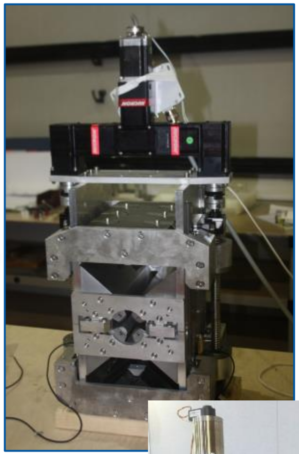
An energy efficient proposal design for the 41’400 Drive Beam quadrupoles for CLIC 3 TeV Project. The innovative idea is a “fully mechanic tunable PM quads” design. Saving would be impressive (EM version total power consumption up to 17 MW)

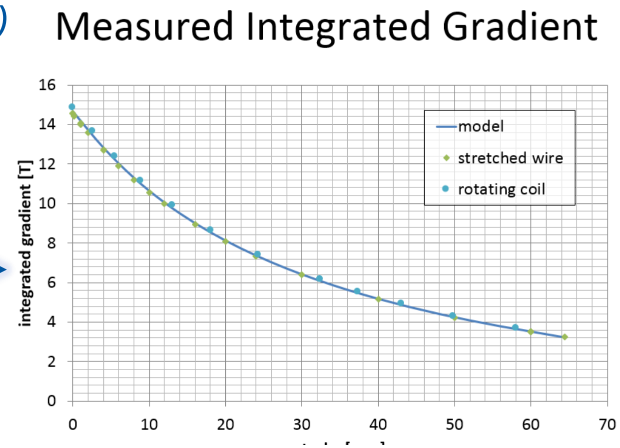
2 prototypes built to cover the full gradient range required in the very limited space available:

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

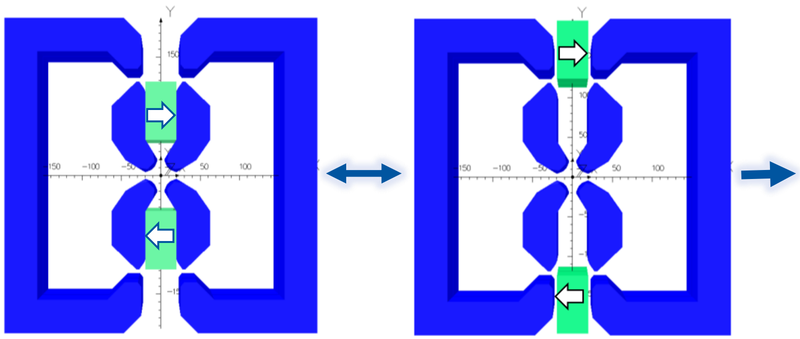
- *ZEPTO-Q1: high strength:*

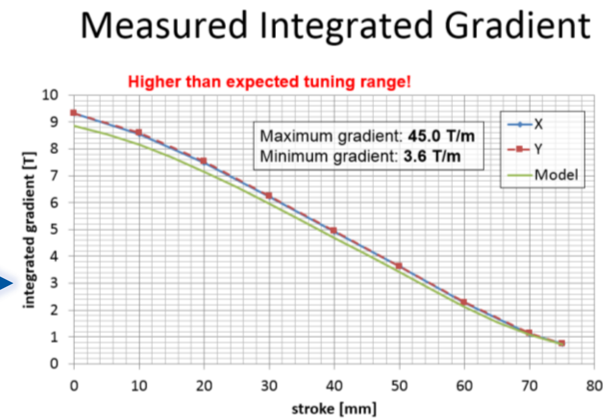






- *ZEPTO-Q2: low strength:*



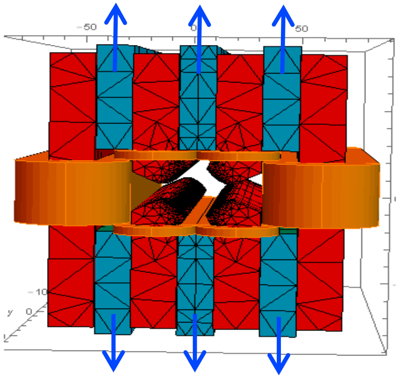


(Courtesy: B.Shepherd, STFC, UK)

HYBRID (PM + NC) MAGNETS:

ESRF Upgrade Phase II:

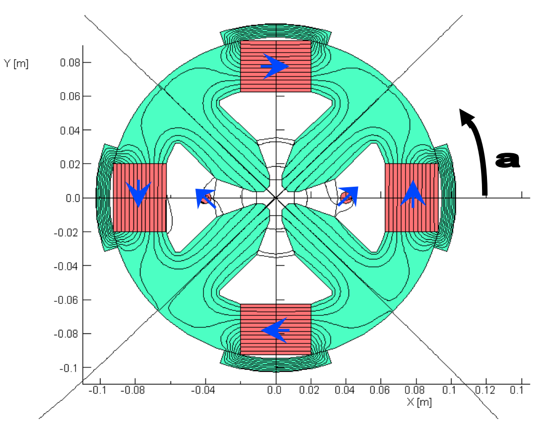
- The already shown PM prototype is under development for an hybrid concept:

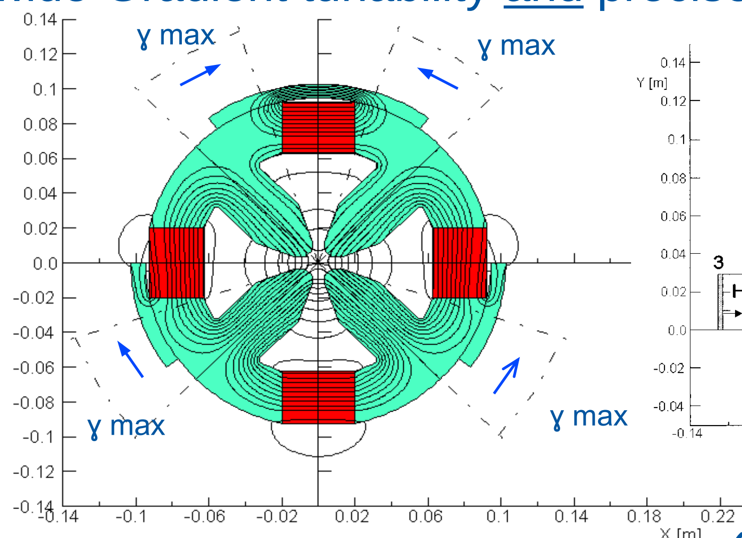


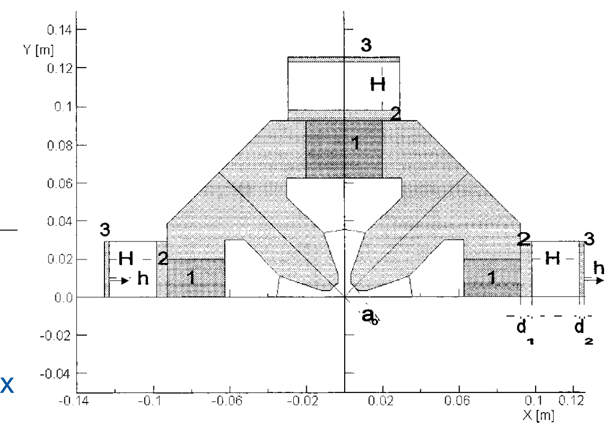
- Wide tunability
- Strong gradients & compactness
- Simple field correction
- Easy assembly

DESY experience in hybrid quadrupoles R&D:

- Innovative solutions for wide Gradient tunability <u>and</u> precise magnetic center adjustment:







(Courtesy: B. Krause, DESY)

HYBRID (PM + NC) MAGNETS:

- **CERN experience with CLIC 3 TeV R&D:**

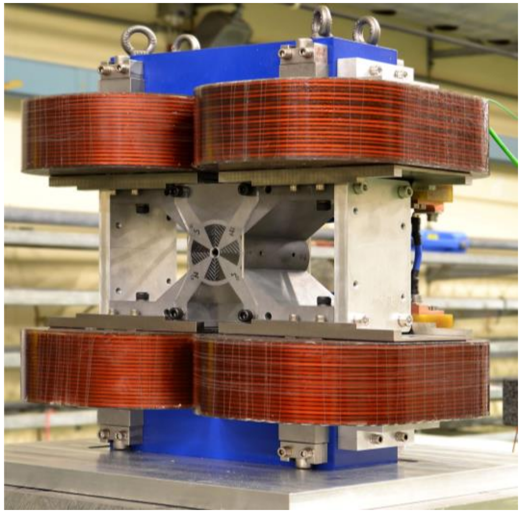
Very challenging requirements for the QD0 quad of the FF system:

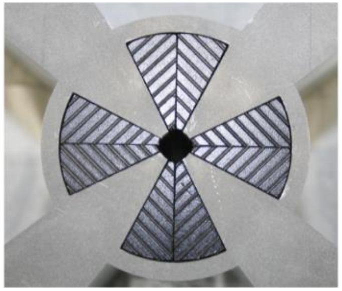
- Extremely high Gradient required: ~ 575 T/m for an open bore of ~ 8.5 mm
- Compactness: magnet inside the Detector Solenoid
- Integration: magnet layout shall be compatible with the post collision vacuum pipe presence.
- Tunability: ≥ 20%
- Rigidity and no-vibrations: since quad will be equipped with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

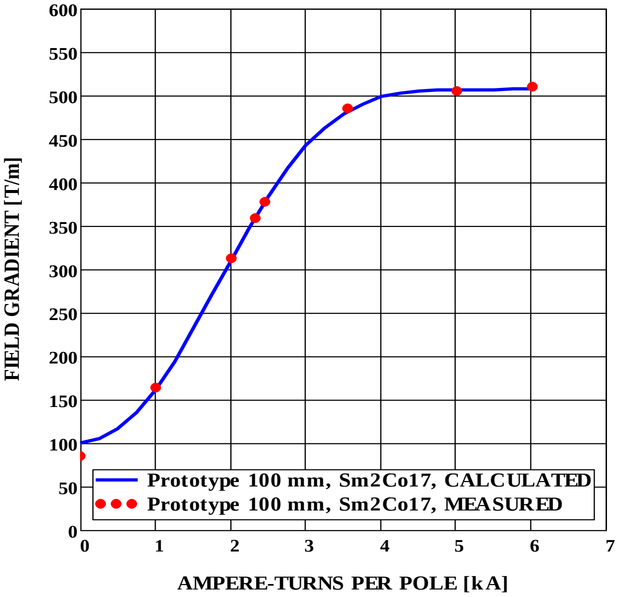
The high gradient, compactness and tunability requirements would suggest a Super-conducting design (as in the case of ILC), but this would be extremely difficult to do it compatible with stability (for nano-stabilization) and alignment requirements.

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

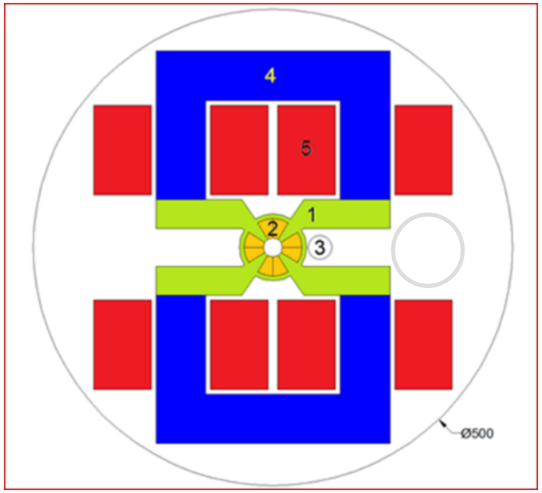
HYBRID (PM + NC) MAGNETS:

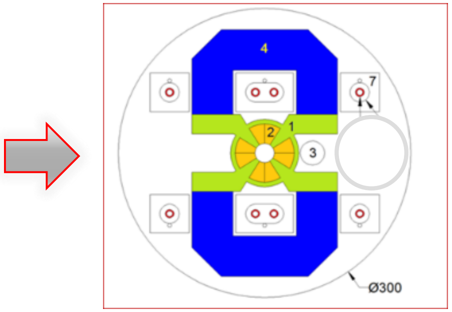




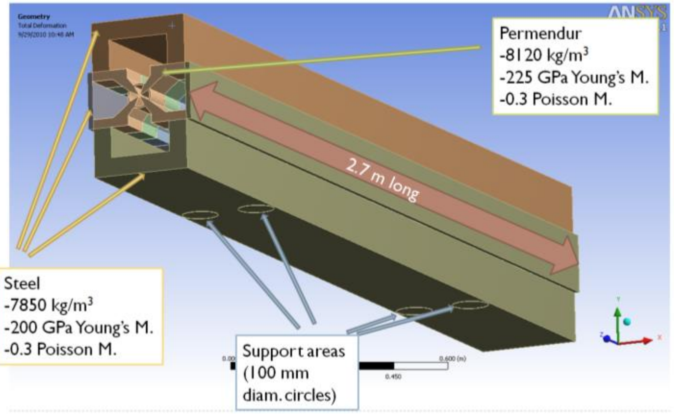


Hybrid QD0 and measurements details





a possible Super-ferric evolution



The full-size assembly concept

PULSED magnets:

- **GSI R&D on High Current Pulsed magnets for transport and final focusing 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*

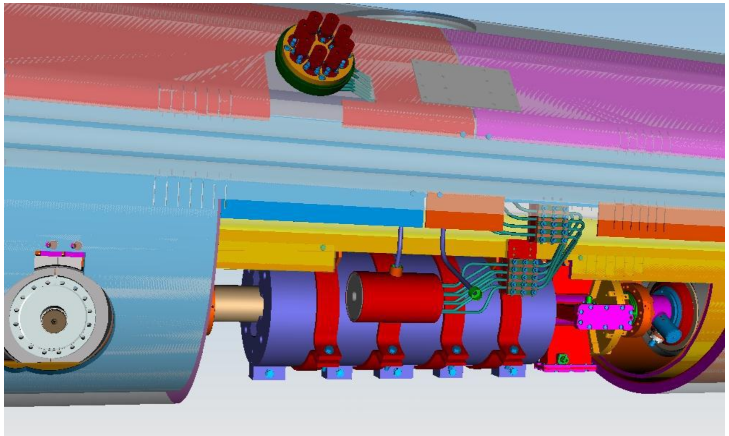
Coil, winding details and 3D-model

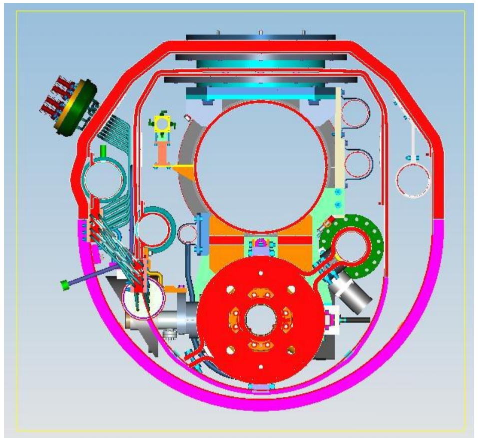
(Courtesy: P. Spiller, C. Tenholt, GSI)

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

- Prototypes fully tested and measured at KEK and FNAL, and now installed in the Cryomodules prototypes.
- An "Integrated Magnet System Scheme" (i.e. powering the quad in persistent current mode) is also 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)

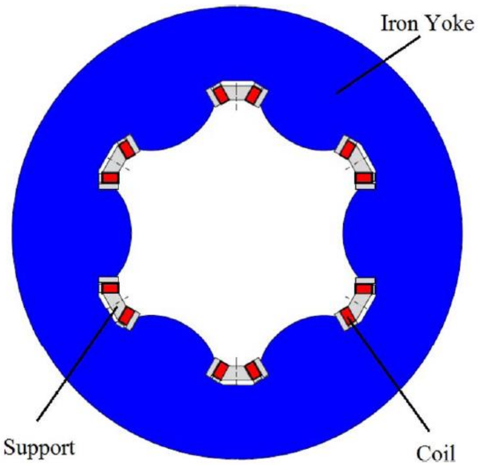
SUPER-FERRIC design:

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 exposed to intense radiation rates (~ 26 MGy expected for magnet lifetime).The retained magnet choice is for NbTi Super-ferric designs now under development.

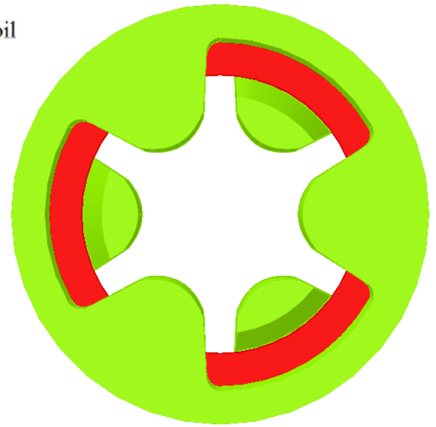
Magnet Order	n	Integrated strength at r = 50 mm	Magnetic Length	Field modulus at r = 50 mm	Coil Peak Field	Stored Energy	Operating current	No turns per coil
		T·m	m	T	T	kJ	A	
Quadrupole	2	1.000	0.807	1.239	2.97	24.6	182	320
Sextupole	3	0.063	0.111	0.569	2.33	1.3	132	214
Octupole	4	0.046	0.087	0.530	2.41	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.

- <u>Alternative and more innovative design</u> like the **Round Coils Super-ferric Magnet** (RCSM) were investigated during the R&D phase. 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.

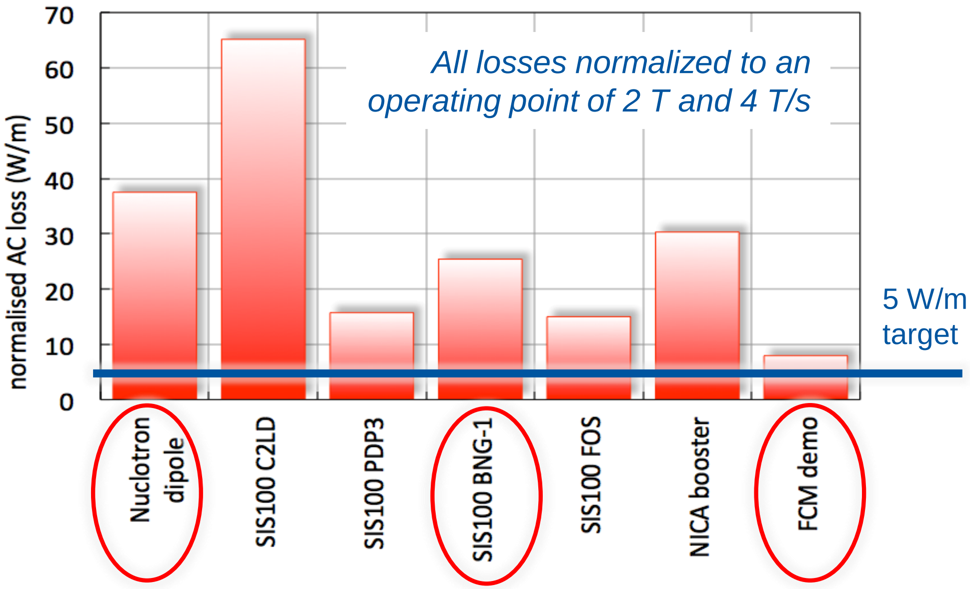


(Courtesy: G. Volpini, INFN; V. Kashikhin, Fermilab)

SUPER-FERRIC design:

SC vs. NC trade-off:

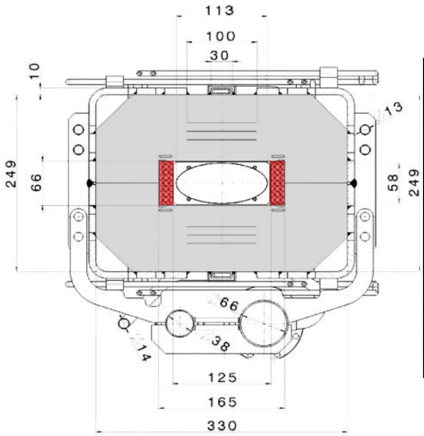
- Considering a "test case" with : B=2 T, h= 60 mm, J= 5 A/mm^2, a SC design will be competitive vs. a NC one if wall-plug power would be < ~4 kW/m.
- For <u>FCM</u> (Fast Cycled Magnet) operation hysteresis losses must also be take into account: *For a SC design they are proportional to ΔB (ex. hysteresis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

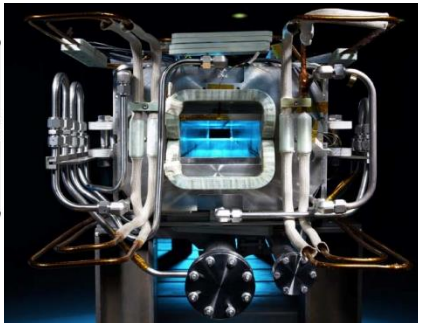


(Courtesy: L. Bottura, CERN)

SUPER-FERRIC design:

- **FCM experience 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

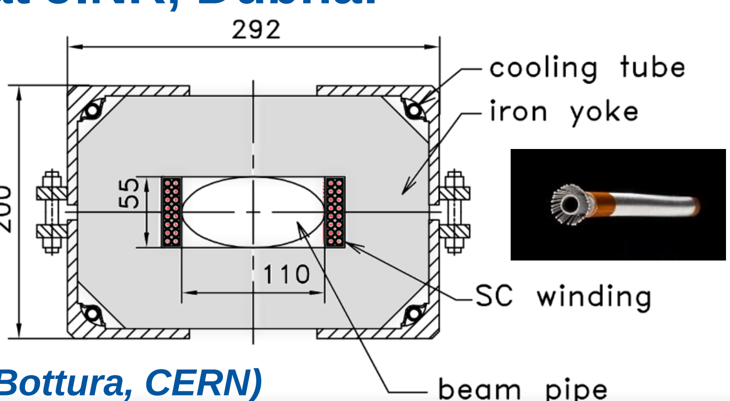




Cross section of first industrial prototype

Pre-series full-scale dipole

- **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



(Courtesy: L. Bottura, CERN)

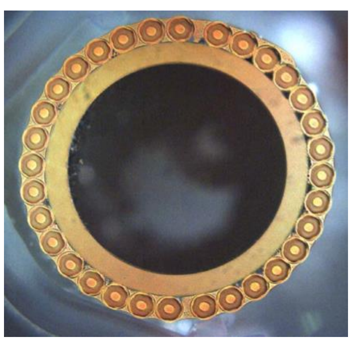
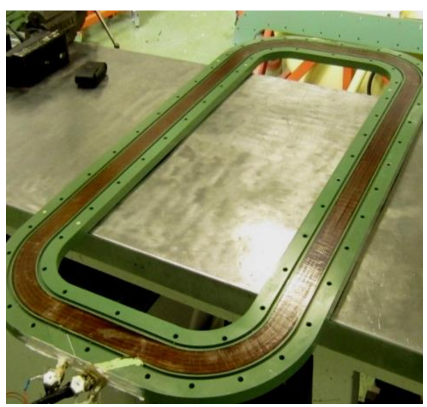
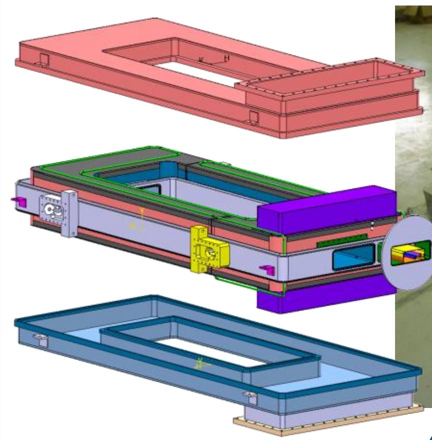
SUPER-FERRIC design:

• 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 to very interesting costs figure:

	"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:**

A Super-ferric FCM magnet working at LN2 (77K) 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*): a very recent application to a Horizon 2020 "FET-Open" call :

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

- Design and fabrication of innovative HTS tapes (ReBCO) and cables optimized for fast-cycled operations.
- Design and fabrication of innovative HTS coils working at LN2 temperature with a CPHP (Cryogenic Pulsating Heat Pipes) cooling system 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 innovative solutions.

THANK YOU for the attention