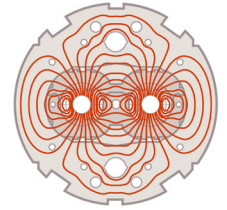


Incontri sulla Fisica delle Alte Energie

Torino, 15 Aprile 2004

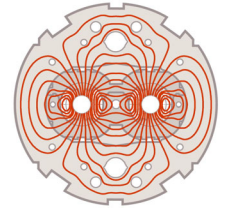


Large Hadron Collider: la macchina e le sue sfide

Lucio Rossi

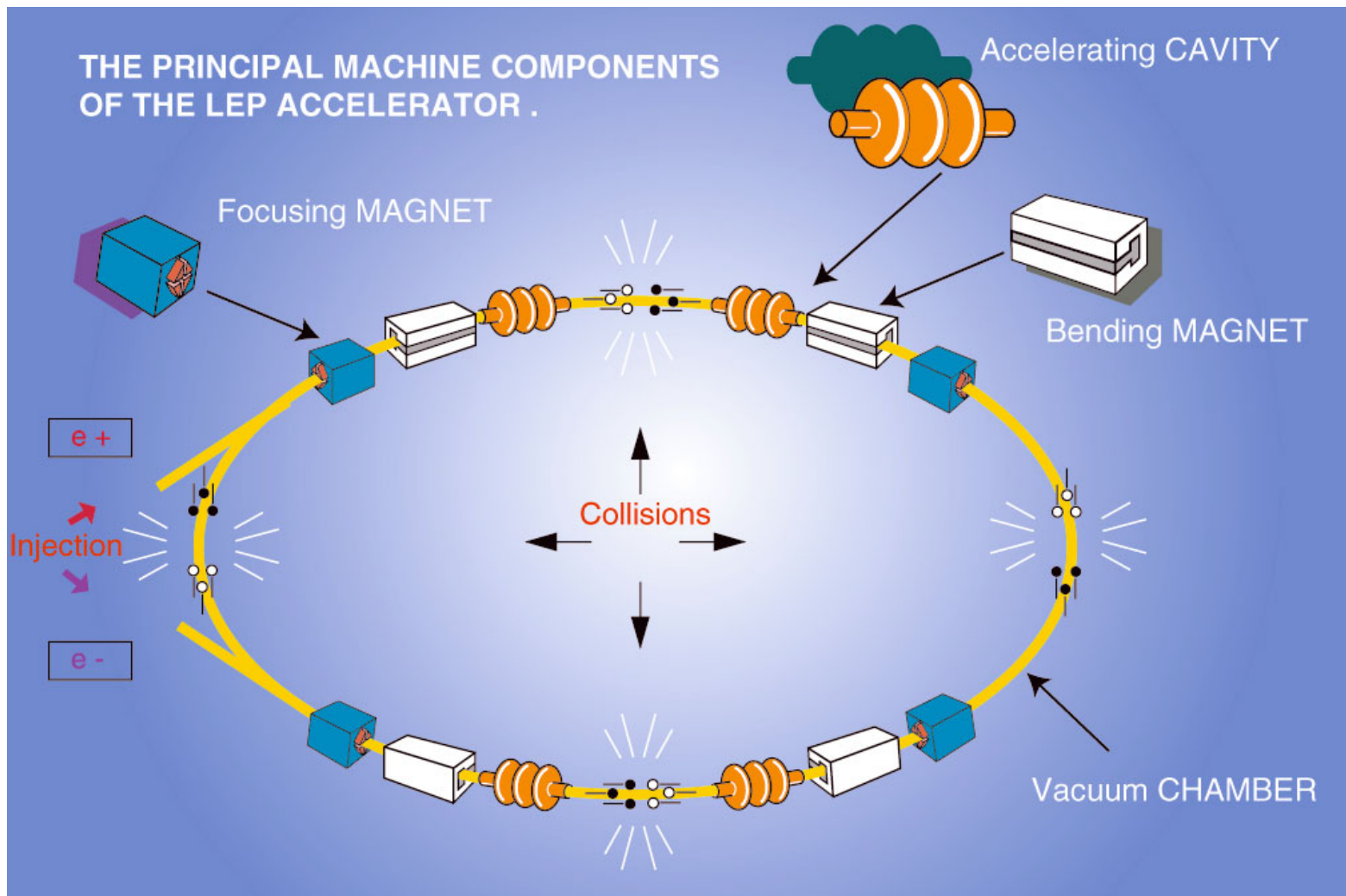
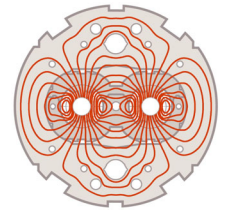
**CERN - Accelerator Technology Department
& Università degli Studi di Milano**

Indice



- **Magneti per acceleratori: caratteristiche e tipi**
- **Il cuore di LHC: i superconduttori**
- **La struttura meccanica dei magneti**
- **Le difficoltà: qualità di campo e allineamenti:**
- **Stato della produzione e risultati**
- **Installazione e Interconnessione: la prossima tappa**
- **Preparazione del fascio e linee di iniezione**
- **Criogenia e "electron cloud"**
- **Collimazione: la grande incognita**

Acceleratori circolari: magnet festival



$$E \approx 0.3 B R$$

(TeV, T, km)

LHC:

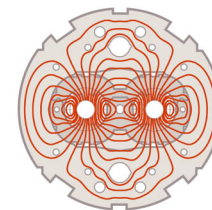
18 km MB

2.5 km MQ

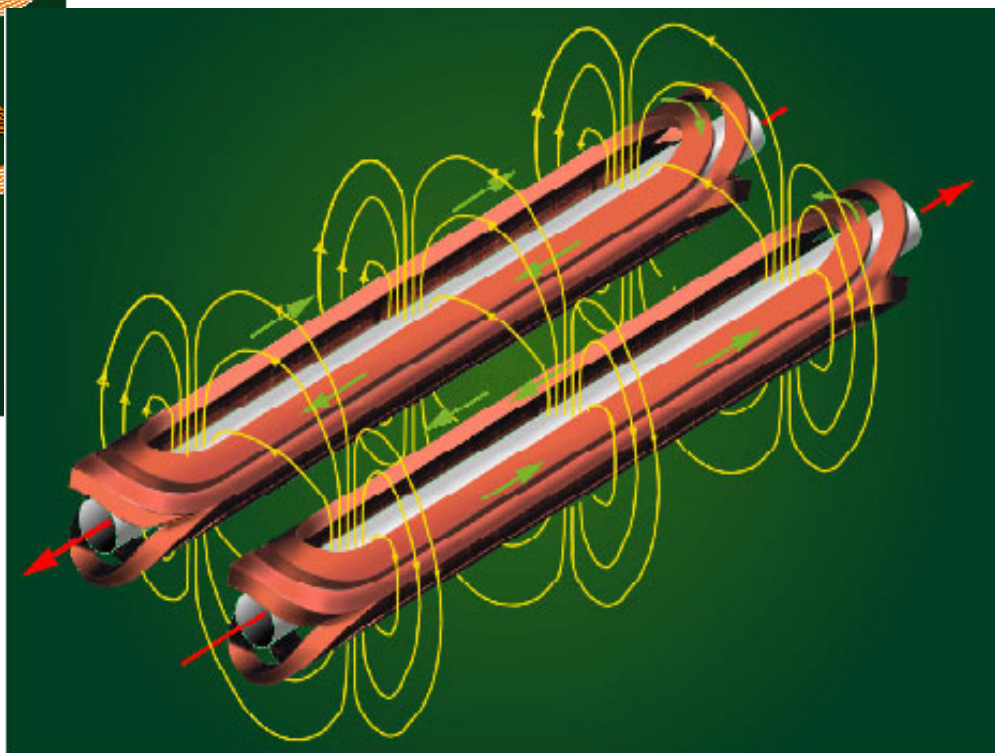
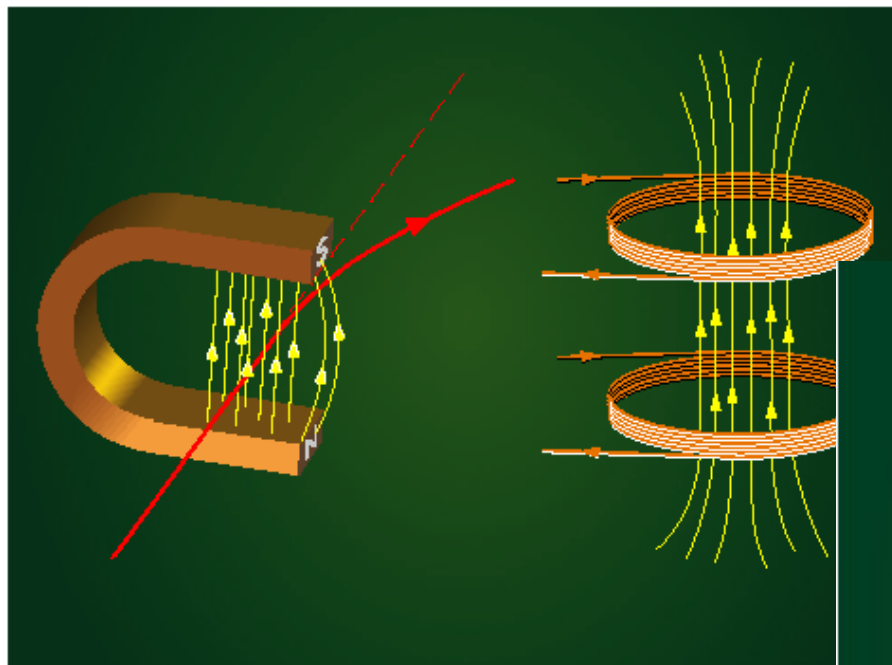
2 km di altri
Quads

**> 8000
magneti Sc!**

Magneti per acceleratori

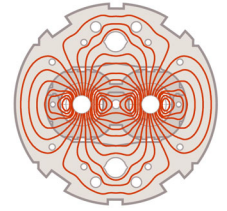


Bassa Energia : circa 10 acceleratori
(1 per medicina in costruzione)

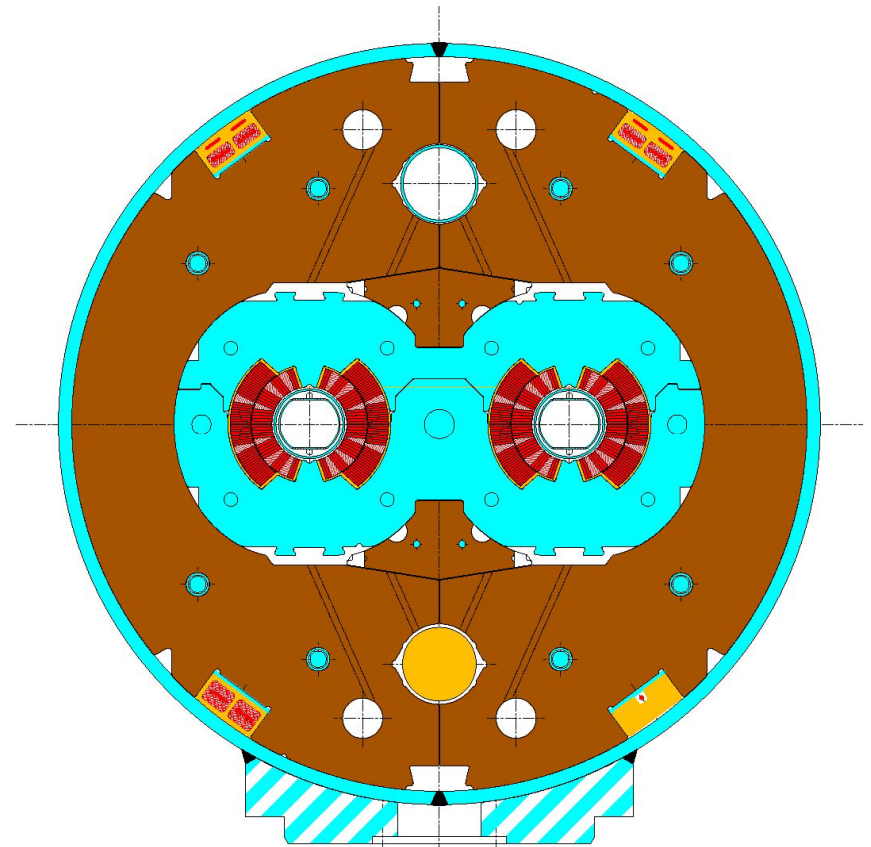
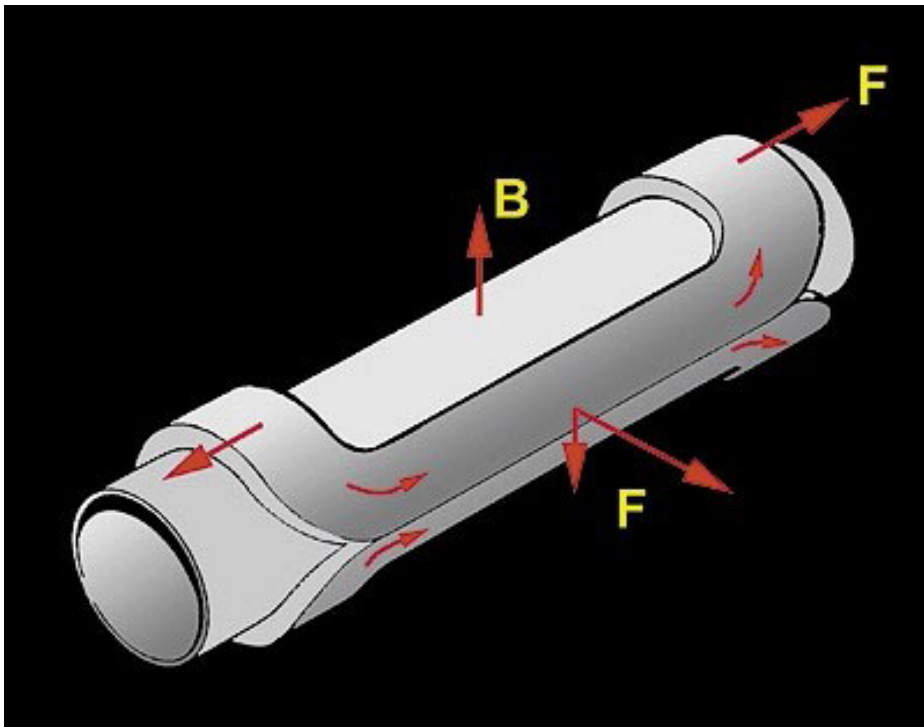


Per Alte Energie: 3 in
funzione, 1 in costruzione
LHC, 1 in progetto GSI

Dipoli: difficile geometria

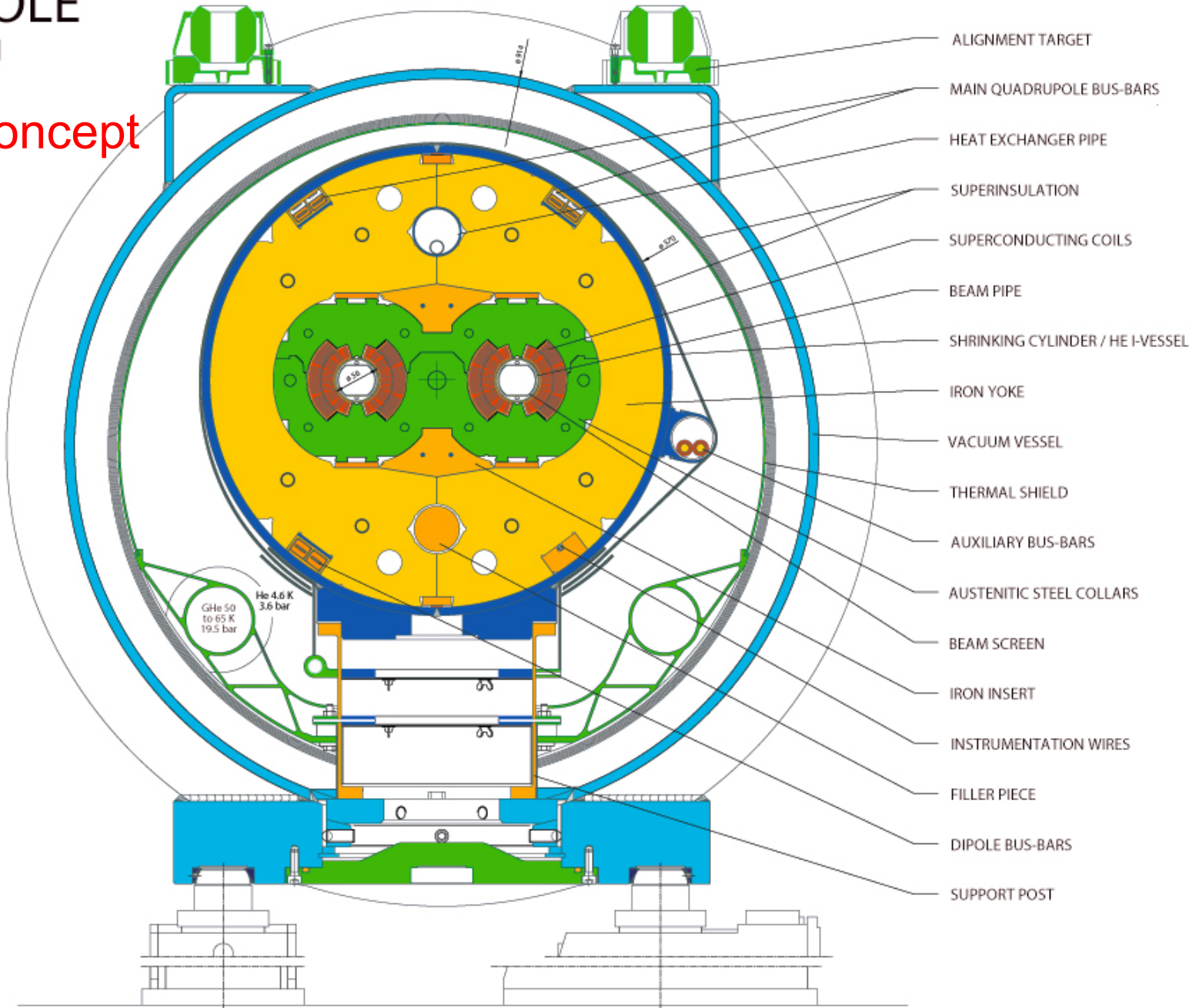


- Rispetto ad un solenoide la medesima Jd genera metà campo
- Non si può compensare con più spessore bobina $\Rightarrow J_{\text{overall}} \approx 500 \text{ A/mm}^2$!!!
- La configurazione non è autosostenentesi (come un solenoide)
- Campo B perfetto a 10 ppm

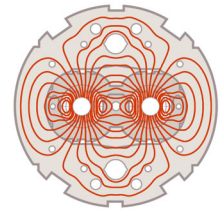
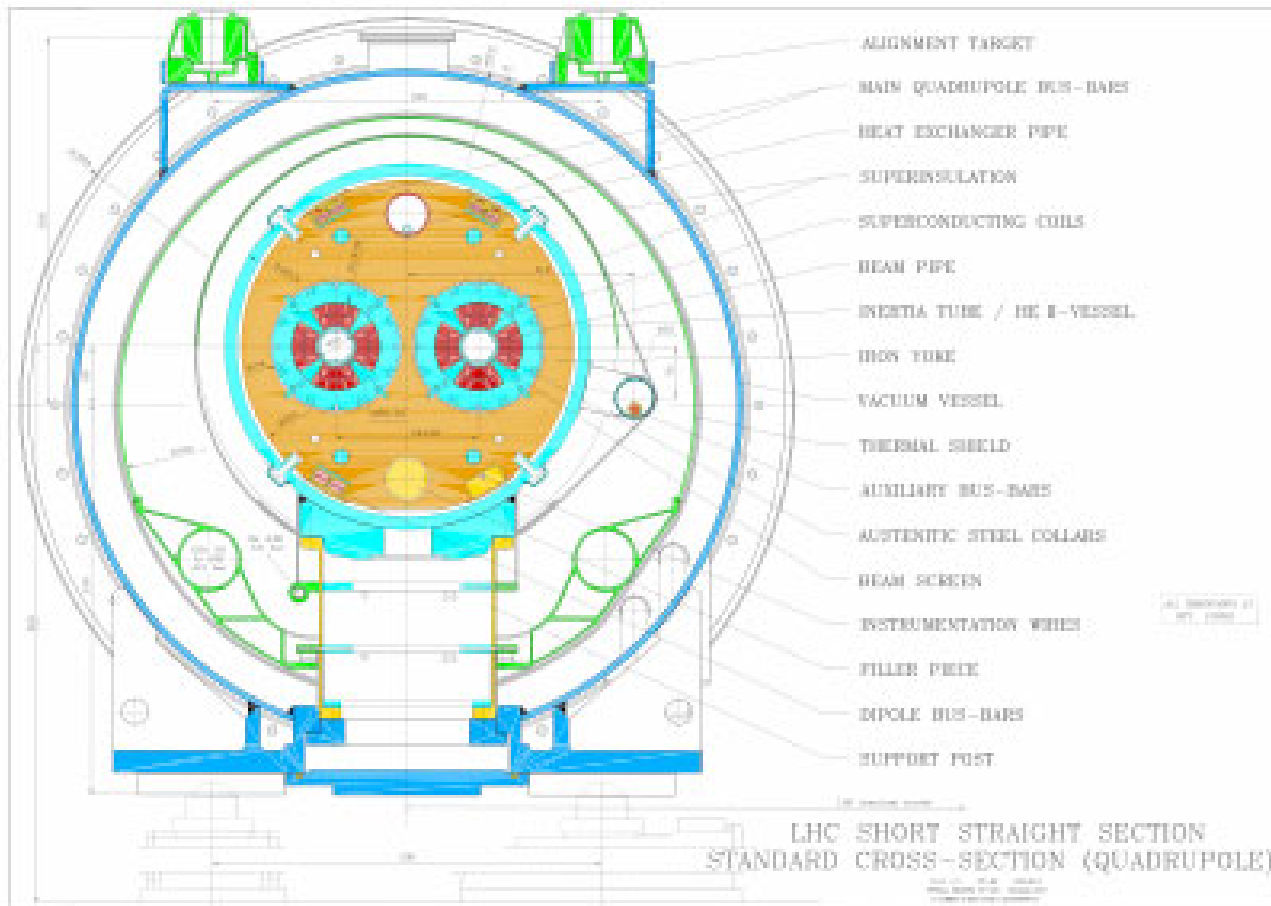


LHC DIPOLE CROSS SECTION

Twin Concept



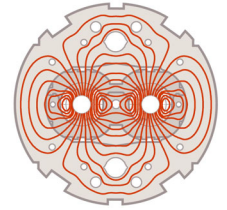
- ALIGNMENT TARGET
- MAIN QUADRUPOLE BUS-BARS
- HEAT EXCHANGER PIPE
- SUPERINSULATION
- SUPERCONDUCTING COILS
- BEAM PIPE
- SHRINKING CYLINDER / HE I-VESSEL
- IRON YOKE
- VACUUM VESSEL
- THERMAL SHIELD
- AUXILIARY BUS-BARS
- AUSTENITIC STEEL COLLARS
- BEAM SCREEN
- IRON INSERT
- INSTRUMENTATION WIRES
- FILLER PIECE
- DIPOLE BUS-BARS
- SUPPORT POST



MQ
Main
Quadrupoles
CERN-CEA

- Cavo in Cu-NbTi @ 1.9 K. $G_{op} = 223$ T/m
- forze e.m. tenute solo da collari only (il ferro serve per chiudere il flusso magnetico)
- Two-in-one concept (le due aperture sono disaccoppiate sia meccanicamente che magneticamente).
- 3.5 m di lunghezza, foro bobine 56 mm, magneti dritti, allineamenti dato dalla inerzia del tubo esterno. I correttori sono fissati sul tubo di inerzia

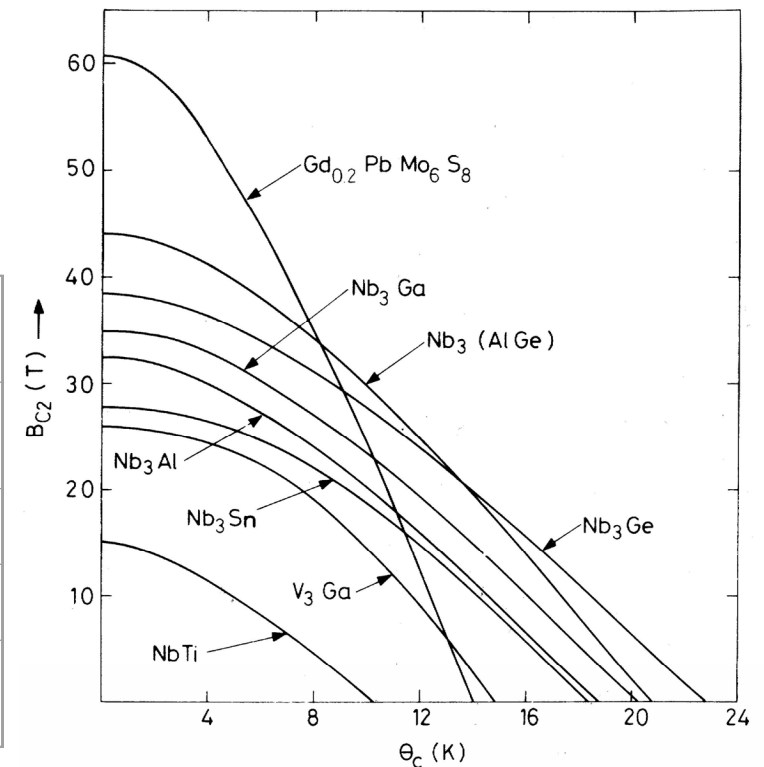
Practical Materials - $B_{c2}(T)$



Dalla fisica del materiale all'uso pratico:
il lungo cammino della selezione naturale

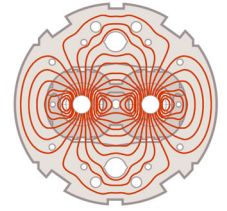
Iwasa table on the long route

<i>Criterion</i>	<i>Number</i>
Superconducting	~ 10,000
$T_c \cong 10$ K .and. $B_{c2} \cong 10$ T	~ 100
$J_c \cong 1$ GA/m ² @ $B > 5$ T	~ 10
Magnet-grade superconductor	~ 1



B_{c2} vs. T for practical materials
(from Wilson textbook)

I superconduttori non sono stabili !



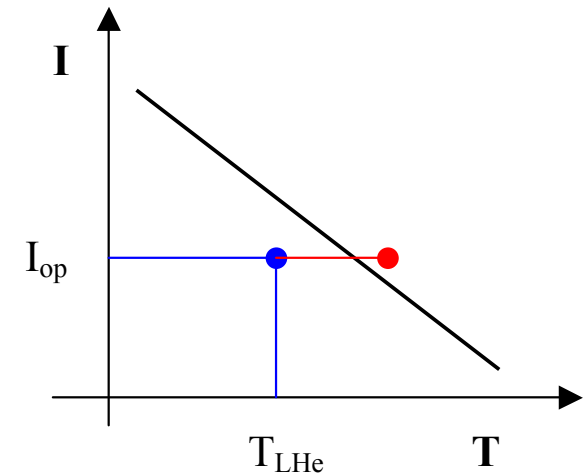
Piccoli ΔE di μJ possono riportare il materiale normale

A basse temperature ($T \ll T_{\text{Debye}}$) :

$C \propto T^3 \Rightarrow \Delta T = \Delta E / \gamma C$. Quindi anche piccoli ΔE
generano apprezzabili ΔT

\Rightarrow punto operativo oltre la superficie critica

\Rightarrow **QUENCH**



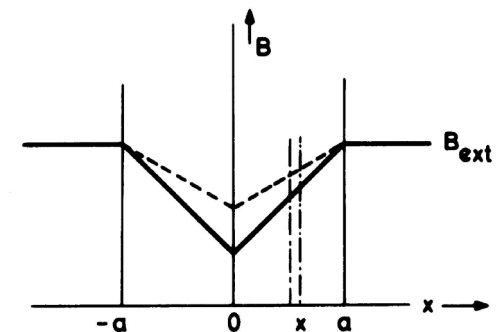
ΔE è generato da :

❑ **Movimenti dell'ordine di $1 \mu\text{m}$!!** $\Delta E / \text{Vol} = J B \delta \approx 10^9 \cdot 10 \cdot 10^{-6}$
 $= 10 \text{ kJ/m}^3$

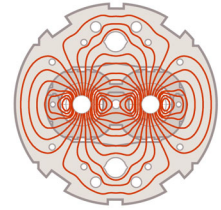
$\gamma C \approx 1\text{-}5 \text{ kJ/m}^3$ for NbTi and NbSn $\Rightarrow \Delta T \approx 2\text{-}10 \text{ K}$!

❑ **Cricche delle resine** (usate come isolanti e impregnanti)

❑ **Flux Jumping** : improvvise redistribuzioni del flusso magnetico nel materiale dovuto alla dipendenza di J_c da T e B .



Criteri di stabilità



Stabilità Elettrodinamica: contatto intimo con un buon conduttore:

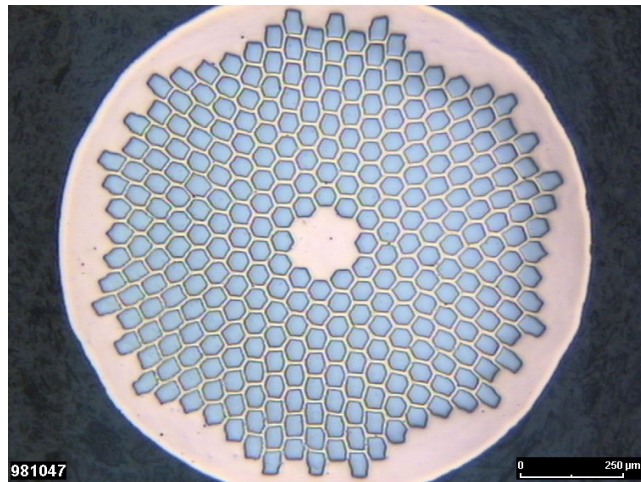
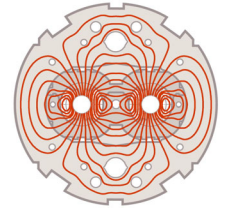
- percorso a bassa dissipazione nel momento in cui si sfora la superficie critica;
- meccanismo di smorzamento parziale dei flux jumps
- recupero veloce nella zona sotto la superficie critica (tramite ottimo conducibilità termica)

Stabilità Adiabatica o intrinseca: Se il Sc è sezionato in filamenti fini, il flux jumps avviene ma rilascia poca energia

$$\frac{\mu_0 J_c^2 a^2}{\gamma C (T_c - T_{op})} < 3$$

In pratica i filamenti devono essere meno di 100 μm in diam.

Fili e cavi

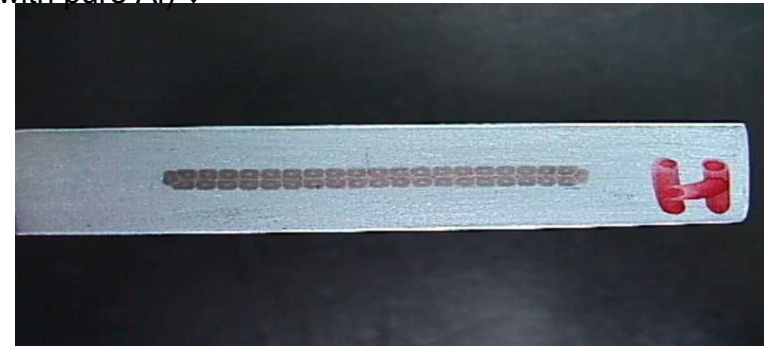
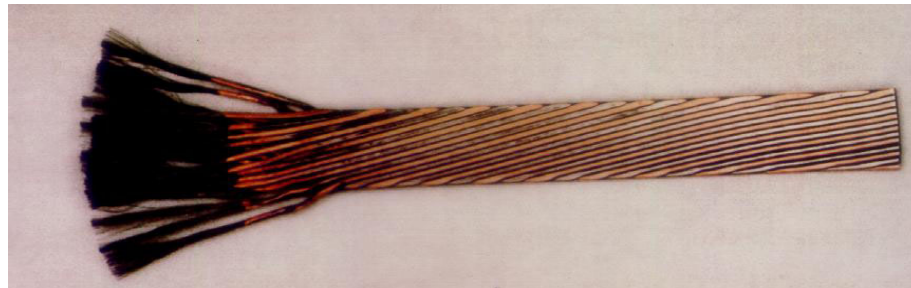
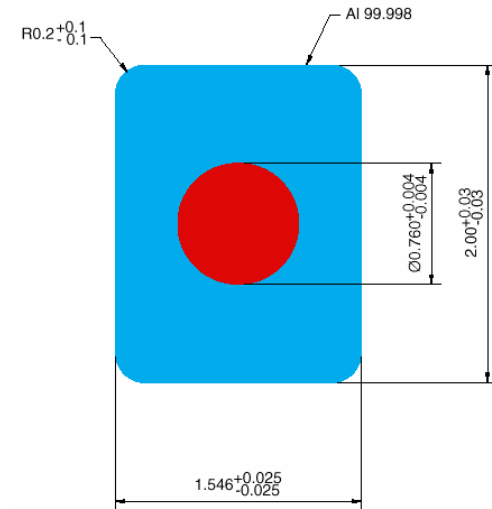


← Atlas Cu/NbTi wire

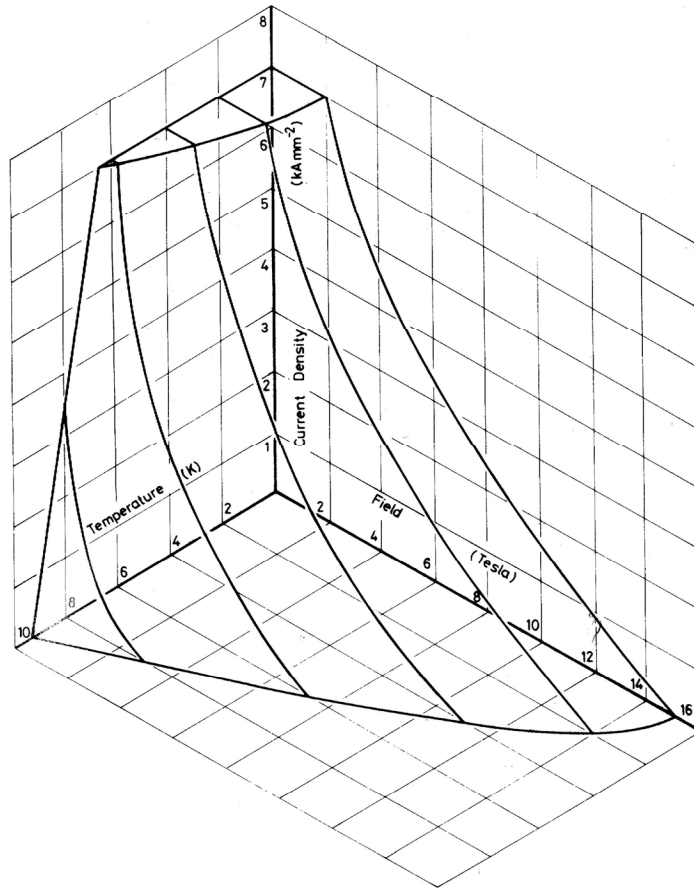
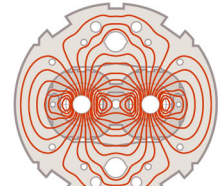
AMS-02 Cu/NbTi/Al →

**Rutherford cable for
↓ LHC dipole**

Atlas conductor (Rutherford
coextr. with pure Al) ↓

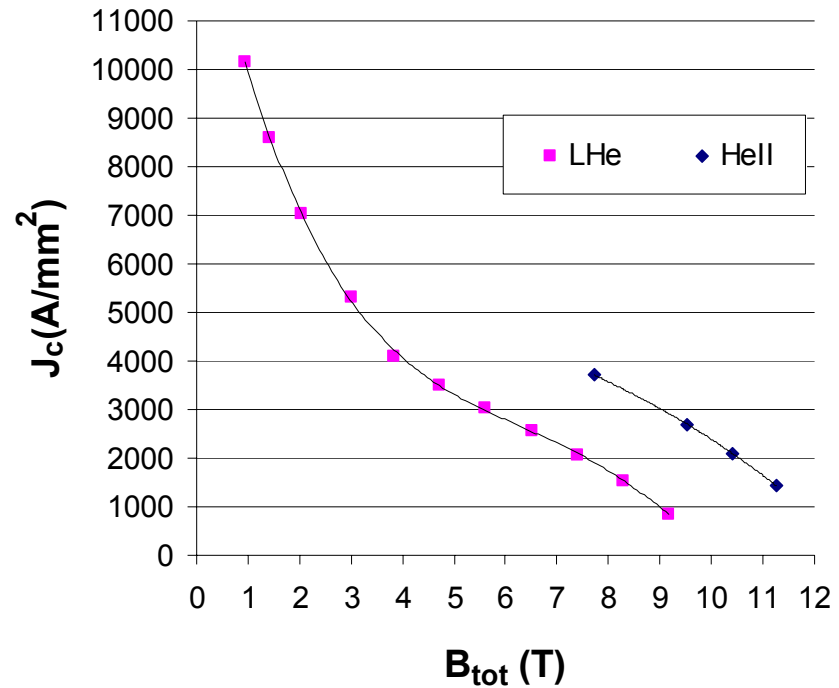


Niobio-Titanio



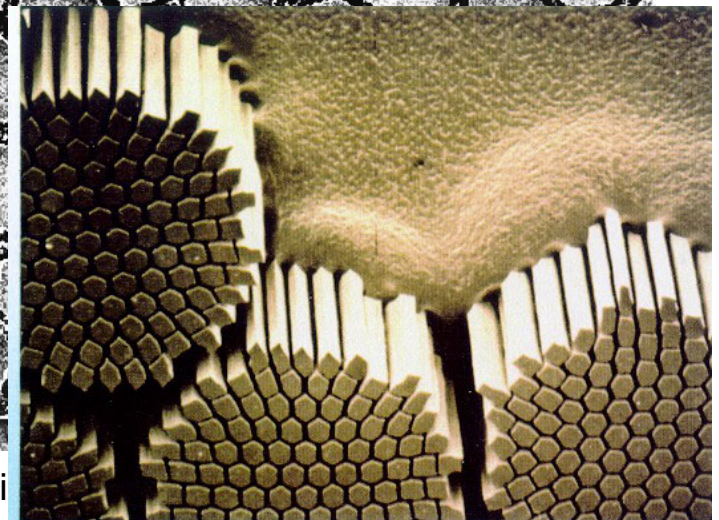
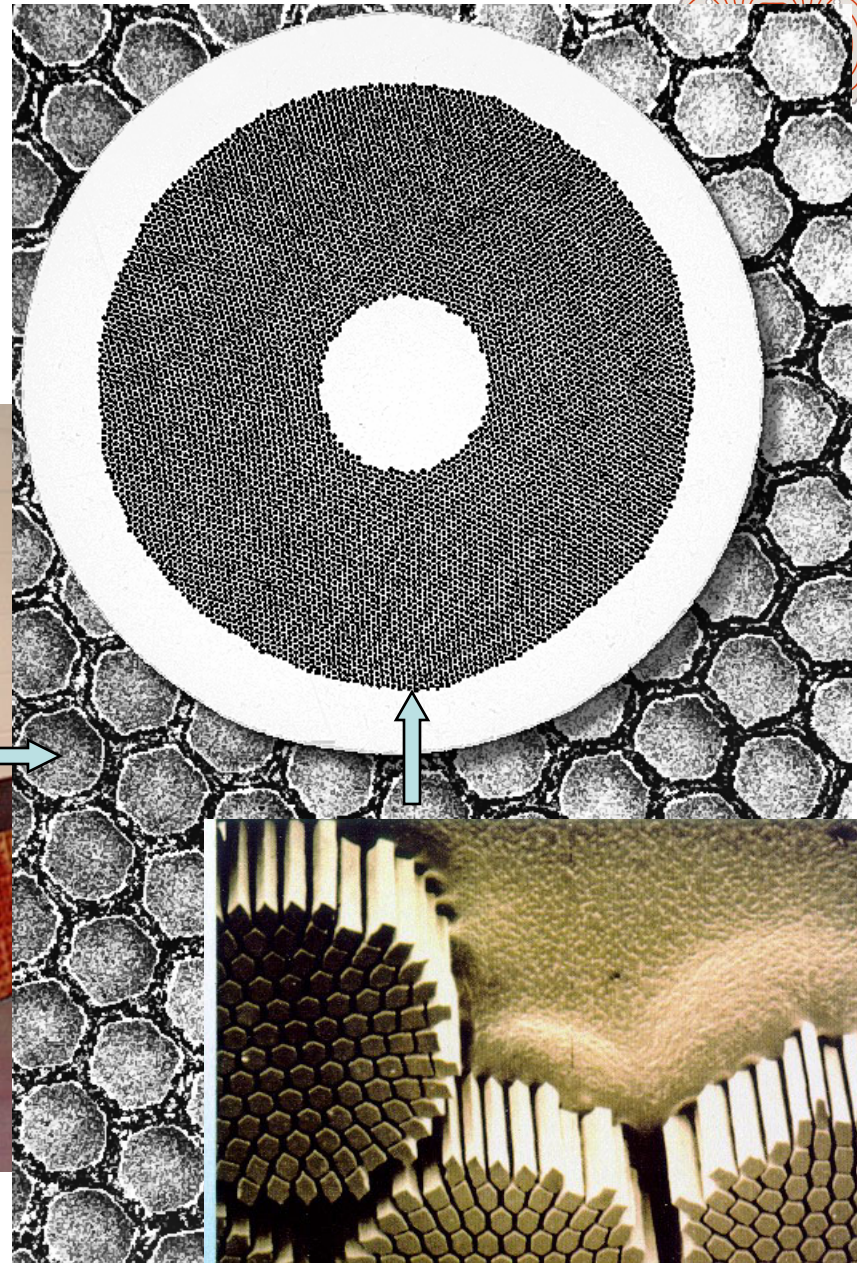
Critical surface of NbTi (from Wilson textbook)

Critical current density vs field measured on NbTi multiflamentary wire at 4.22 and 2.17 K



Critical current of best Cu/NbTi with typical 3 T field shift at superfluid helium (INFN-LASA lab, february 2000)

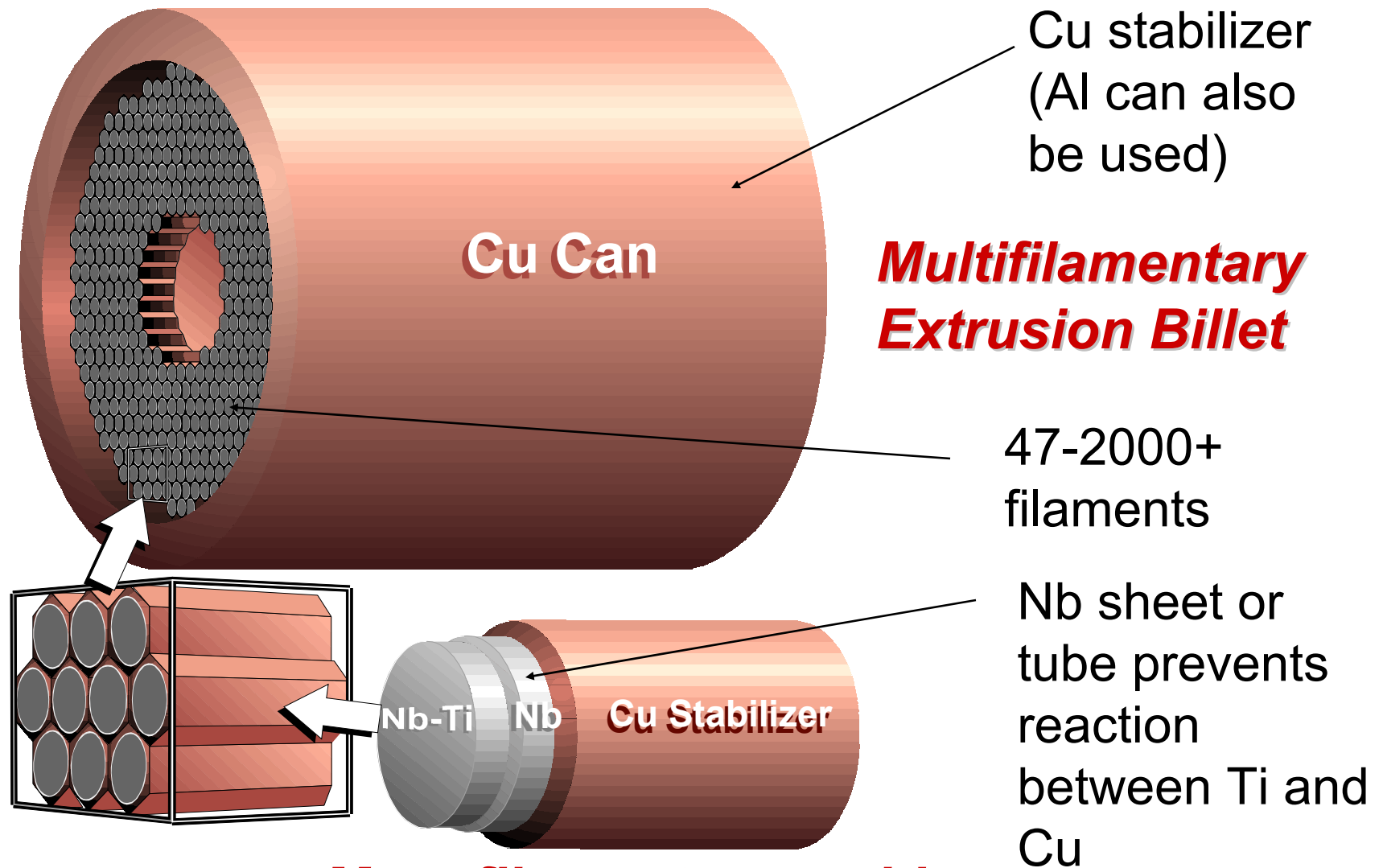
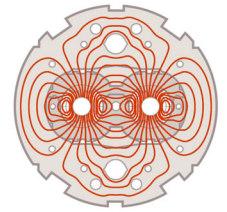
Fabbricazione Sc: 9 mesi dal materiale al filo



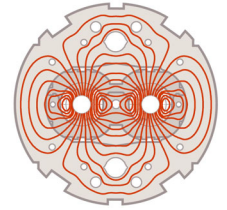
15 Aprile 2004

Lucio Rossi - LHC : la macchi

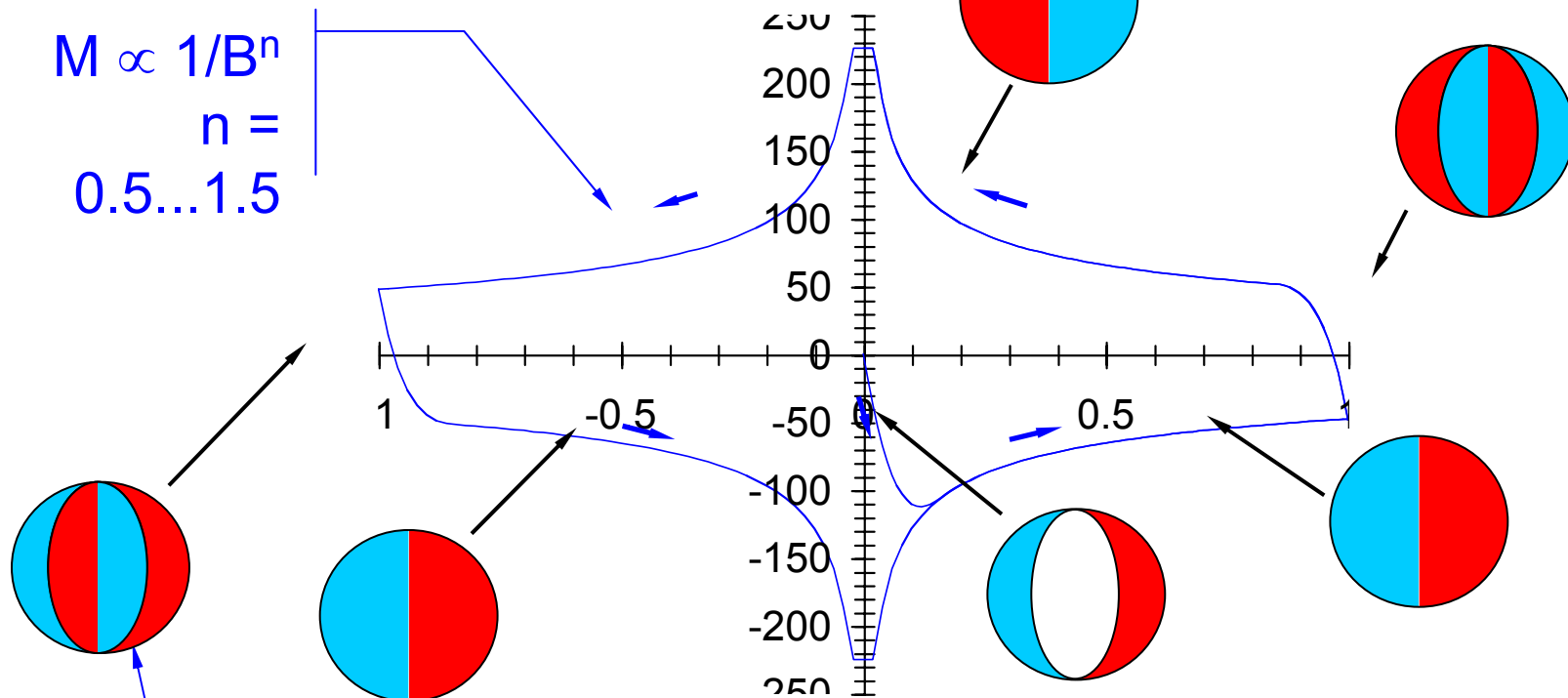
Nb-Ti Composite Overview



Magnetizzazione

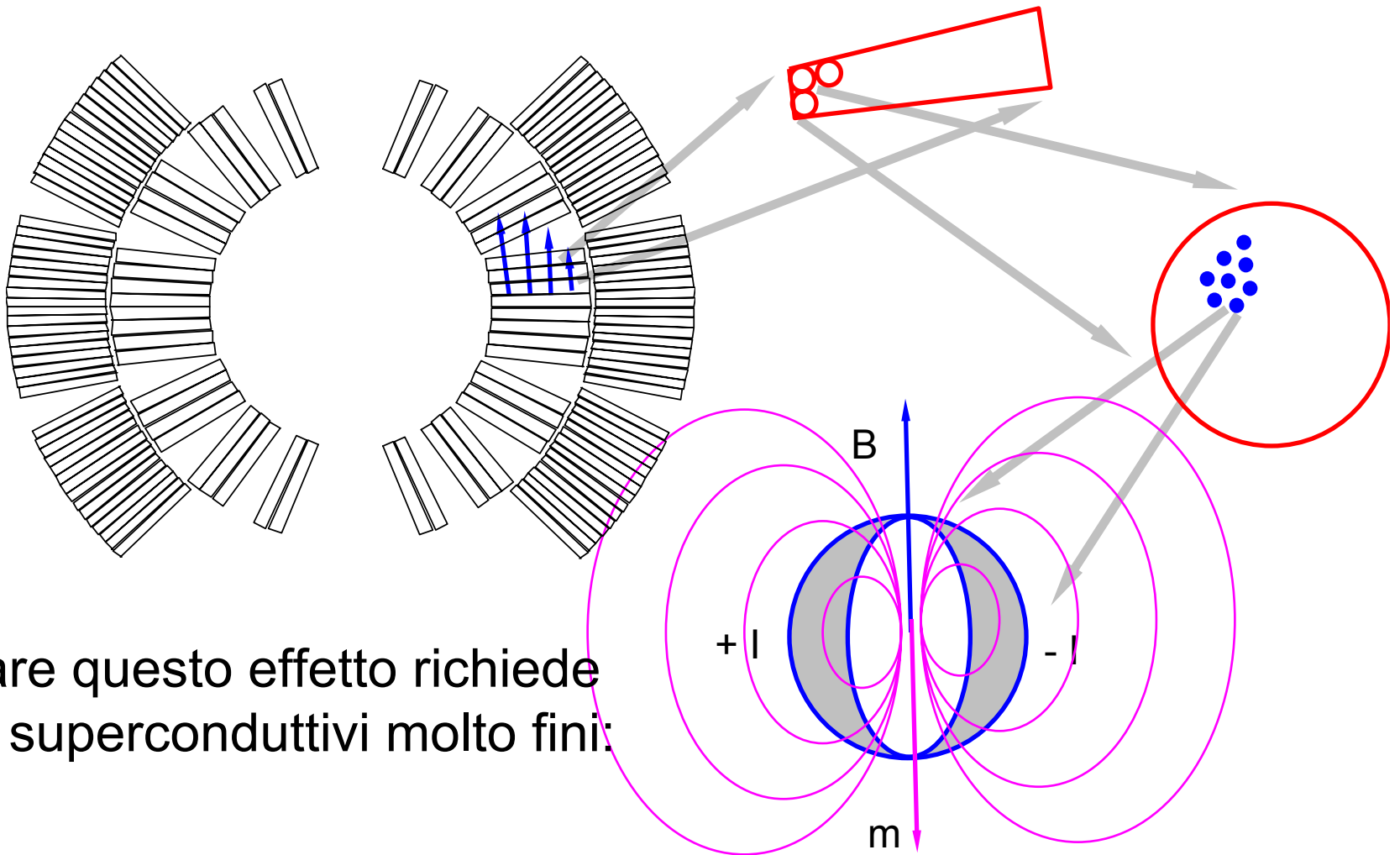
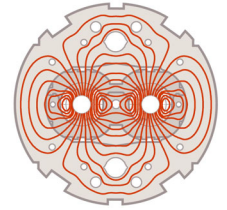


$$M \cong J_c D_{\text{eff}}$$



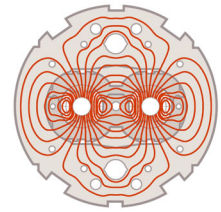
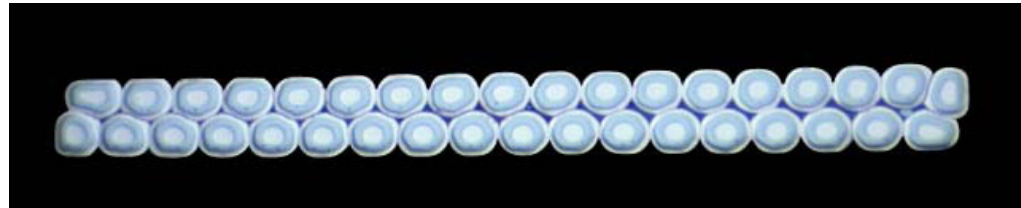
Strato di corrente superconduttiva che genera magnetizzazione (persistent currents)

I multipoli generati sono proporzionali a $1/B^n$
Se M è simmetrico allora sono presenti solo
multipoli ammessi



Controllare questo effetto richiede
filamenti superconduttivi molto fini:
 $6-7 \mu\text{m}$!

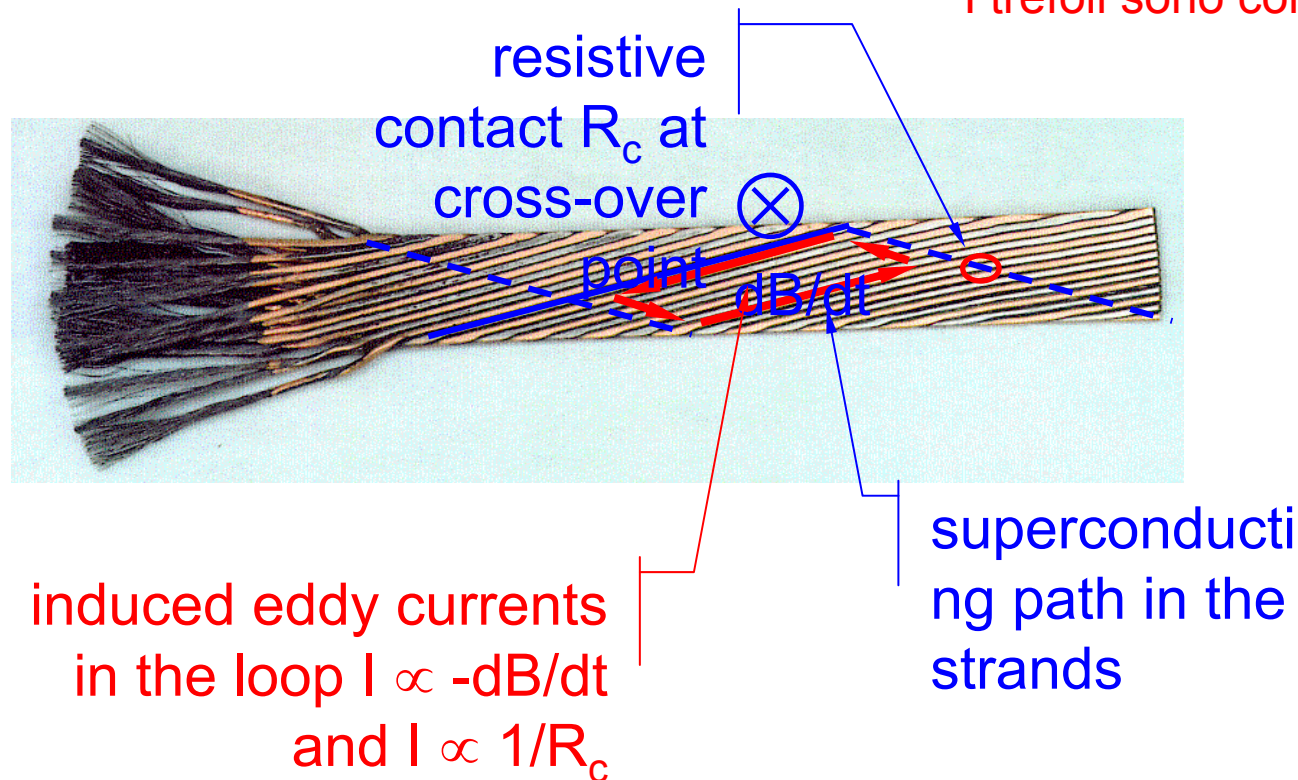
Cavi Rutherford



Correnti da 10-20 kA per la protezione

Grande packing factor : 90% !!

I trefoli sono completamente trasposti



Problemi:

Stabilità dei fili.

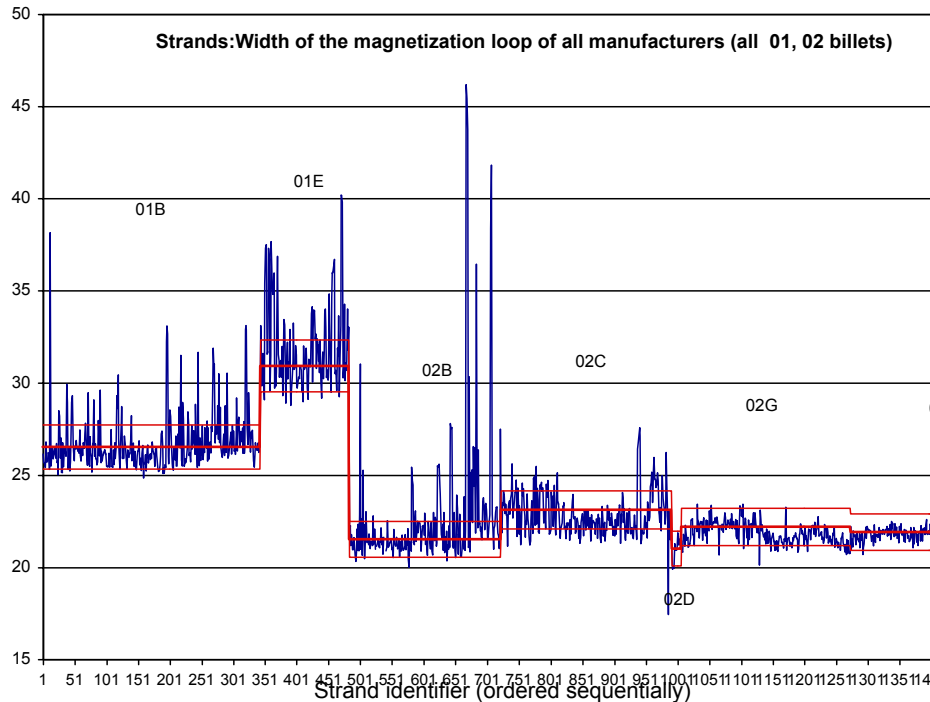
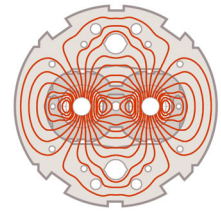
Soprattutto nelle testate

Problemi di qualità di superficie

Giunzioni

BICC

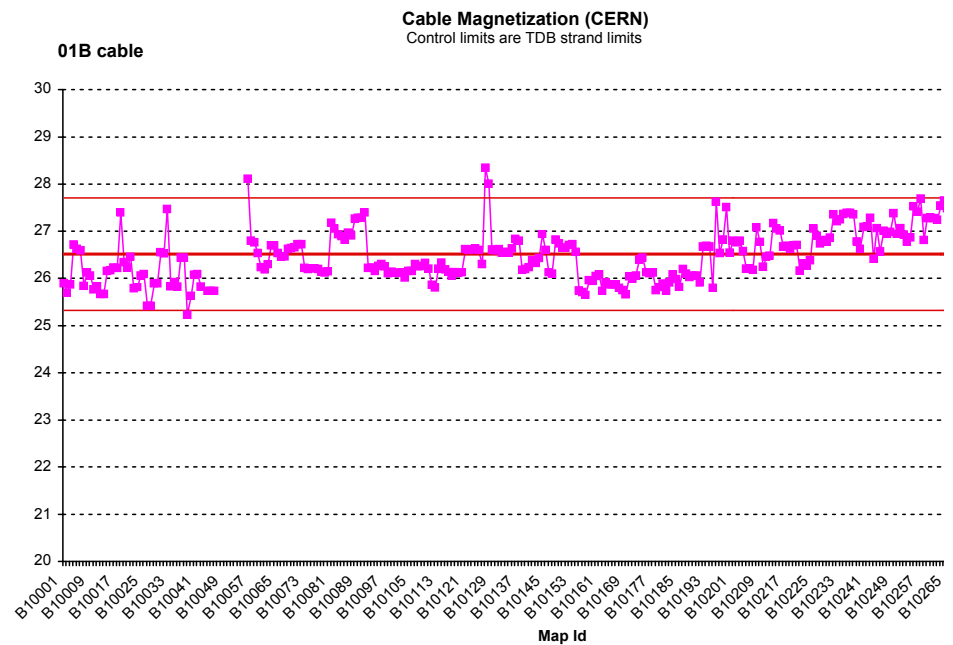
Magnetizzazione del Sc per LHC



Singoli fili



cavo



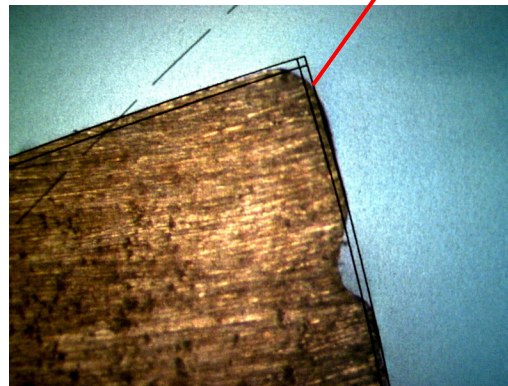
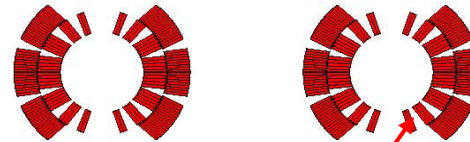
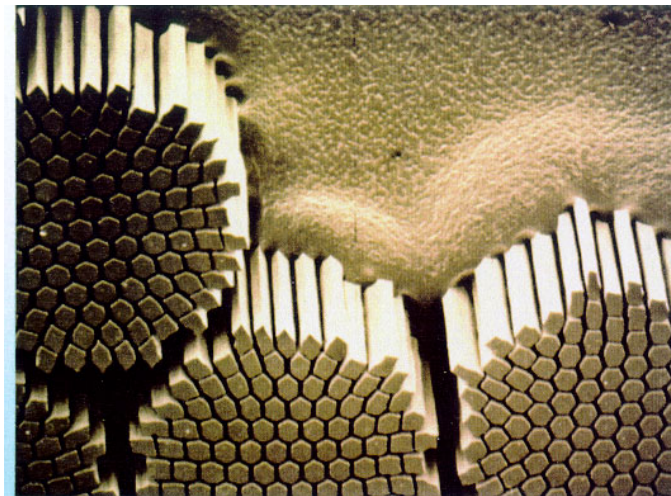
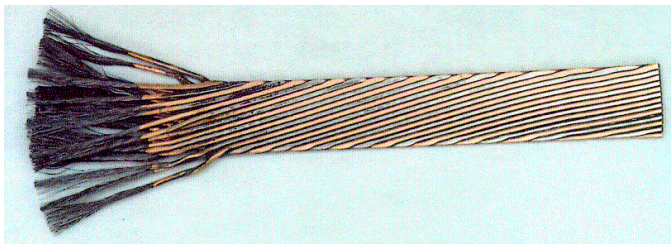
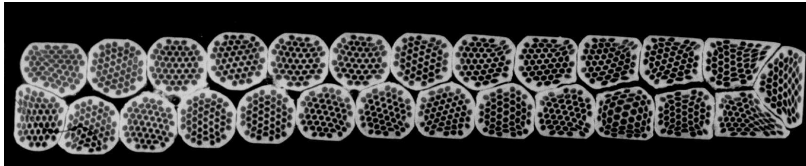
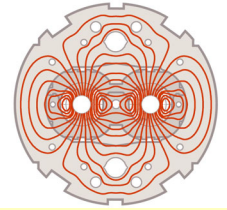
Courtesy of S. LeNaour

15 Aprile 2004

Lucio Rossi - LHC : la macchina

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Dipolo LHC : Lay-out del conduttore



Lucio Rossi - LHC : la macchina

Il cavo e gli **spacers** sono i principali componenti delle bobine.

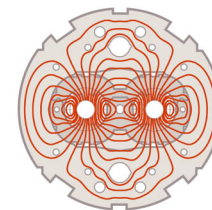
Controllo delle armoniche

Ottimizzazione del margine tra i blocchi

La configurazione deve essere stabile contro gli inevitabili errori di costruzione

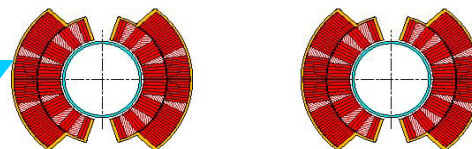
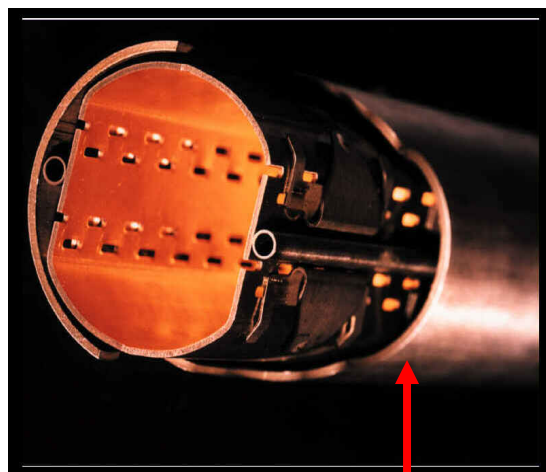
Praticamente non ci sono più quench nella zona dritta.

Dipolo LHC: il tubo freddo



Cold bore tube
Special Insulation
technique > 20 kV

Lo spazio tra bobine e il tubo freddo è di circa 0.5 mm sui 15 m di lunghezza.

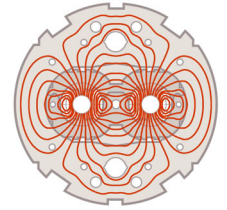


CBT

Finished Tube

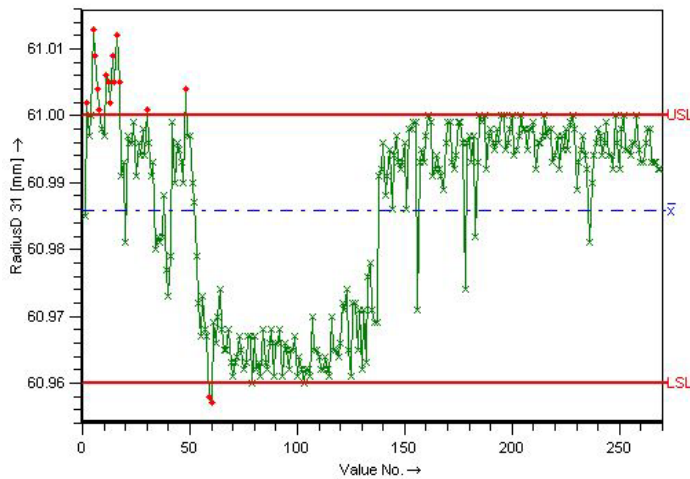
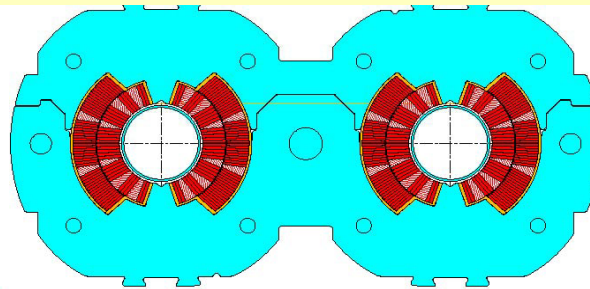
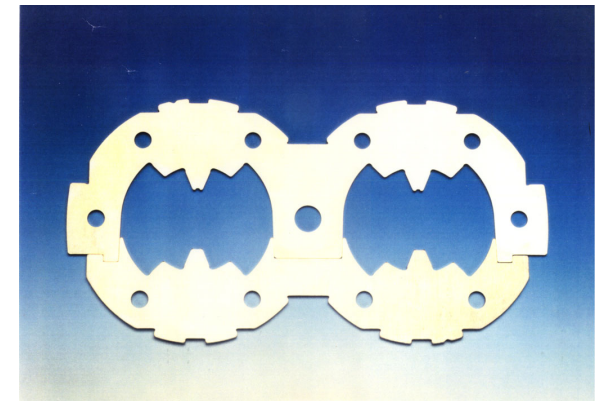
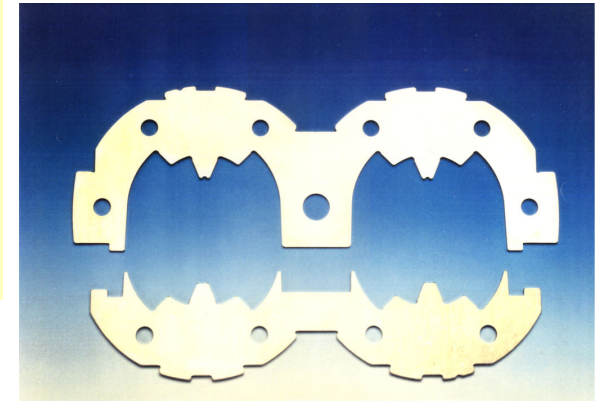


Dipoli LHC: I collari che danno la forma



Stampati per tranciatura fine da lamiere di speciale acciaio austenitico.

La accuratezza del profilo interno è di 20-30 μm ; messi con presse da 2500 ton/m

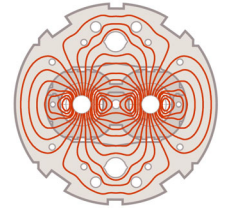


15 Aprile 2004

Lucio Rossi - LHC : la macchina

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Dipoli LHC: laminazioni del giogo magnetico

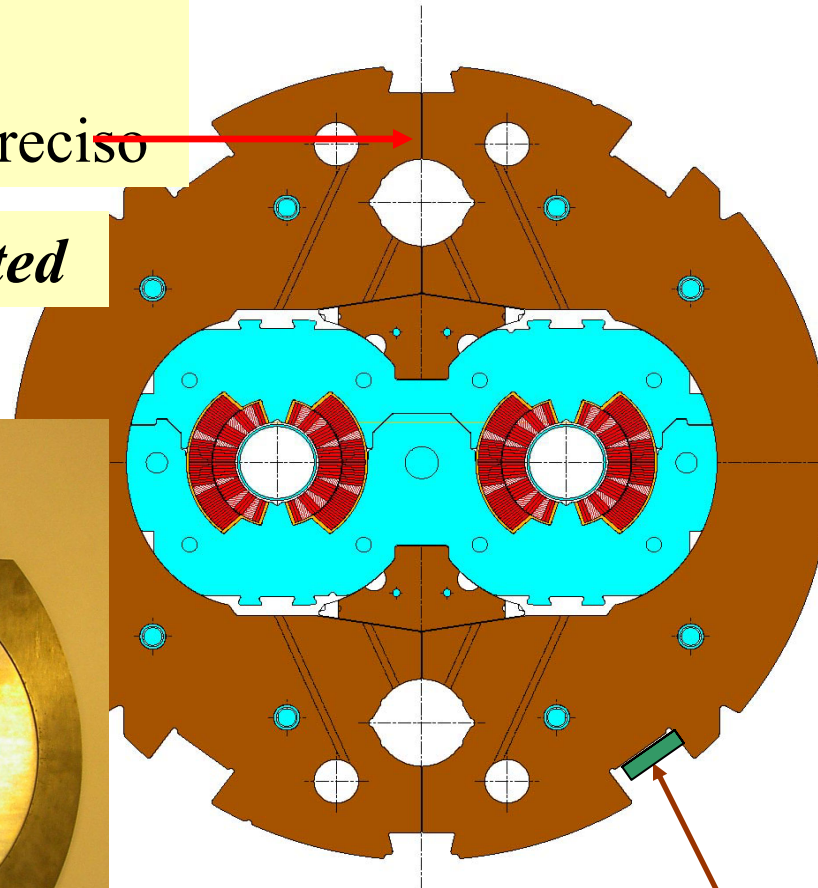
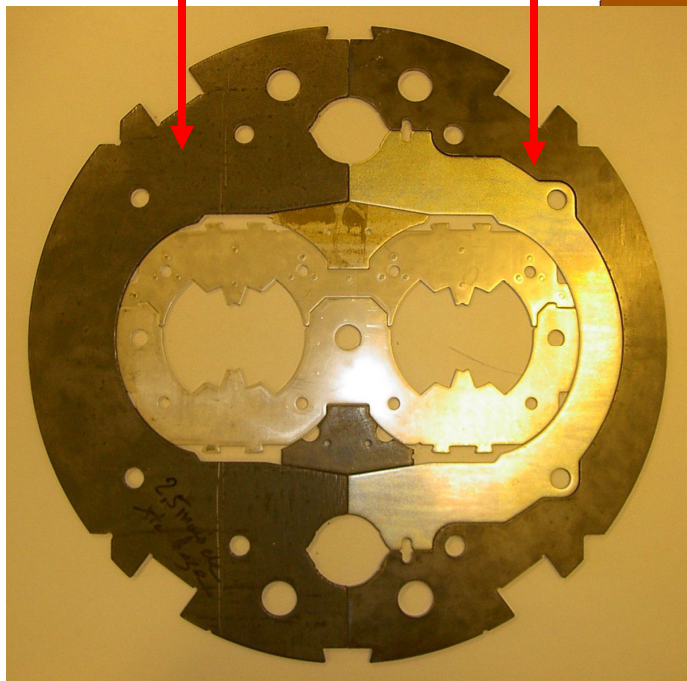


Speciale lega di ferro molto dolce: 50,000 tons

Gap verticale molto preciso

Regular

Nested



Temperature probe

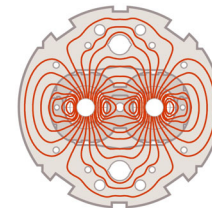
Funzioni :

Campo di fuga
+ 15% di campo
(con grosso vantaggio per la protezione)

La saturazione puo' dare problemi

Controllo della lunghezza magnetica

Dipole LHC: Cilindro di serraggio e supporti



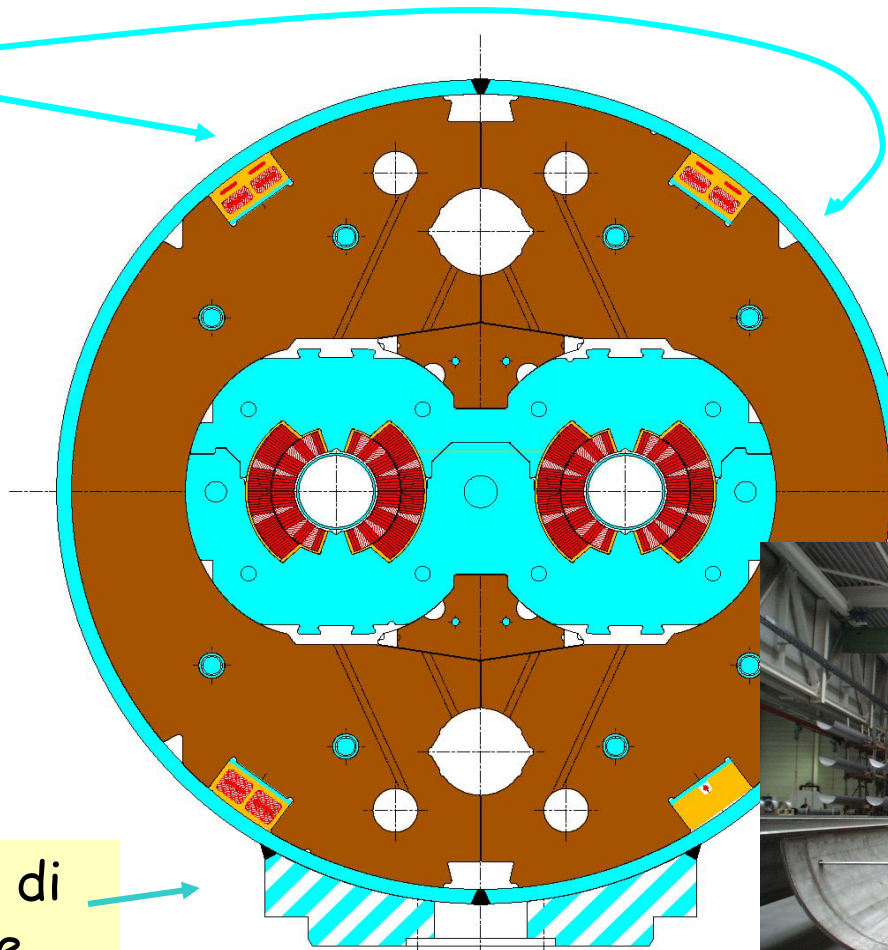
Due
semigusci
saldati sul
magnete
stesso

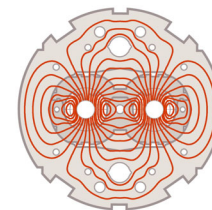
In assoluto
uno dei
componenti
piu' difficili

Supporto di
precisione

**Non un cilindro
consegnato in
tolleranza!**

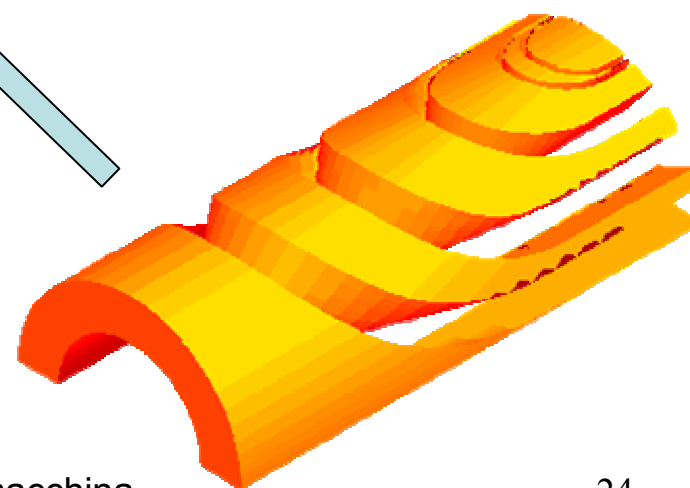
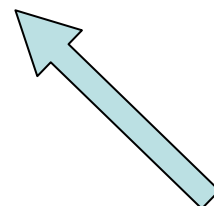
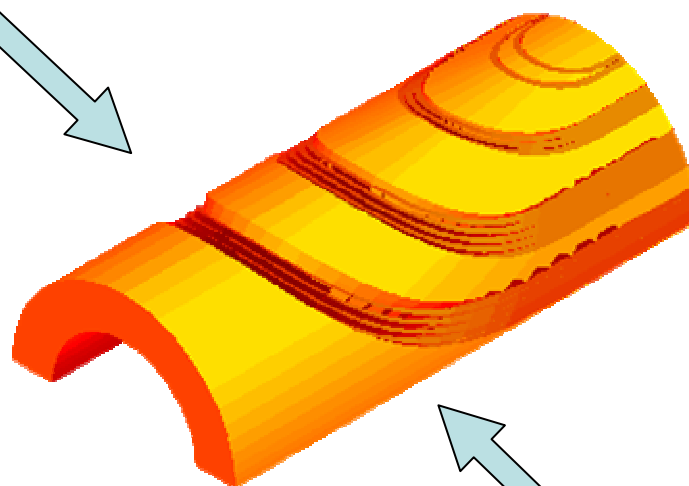
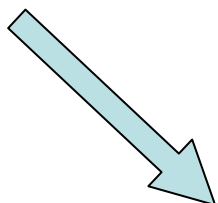
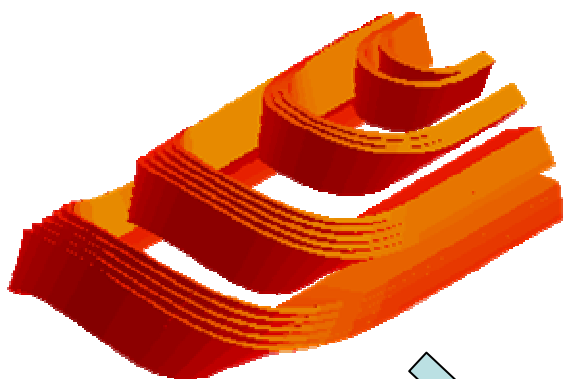
**Si tiene in
conto del
rilascio dopo
saldatura**





3D

Inner layer lyre side

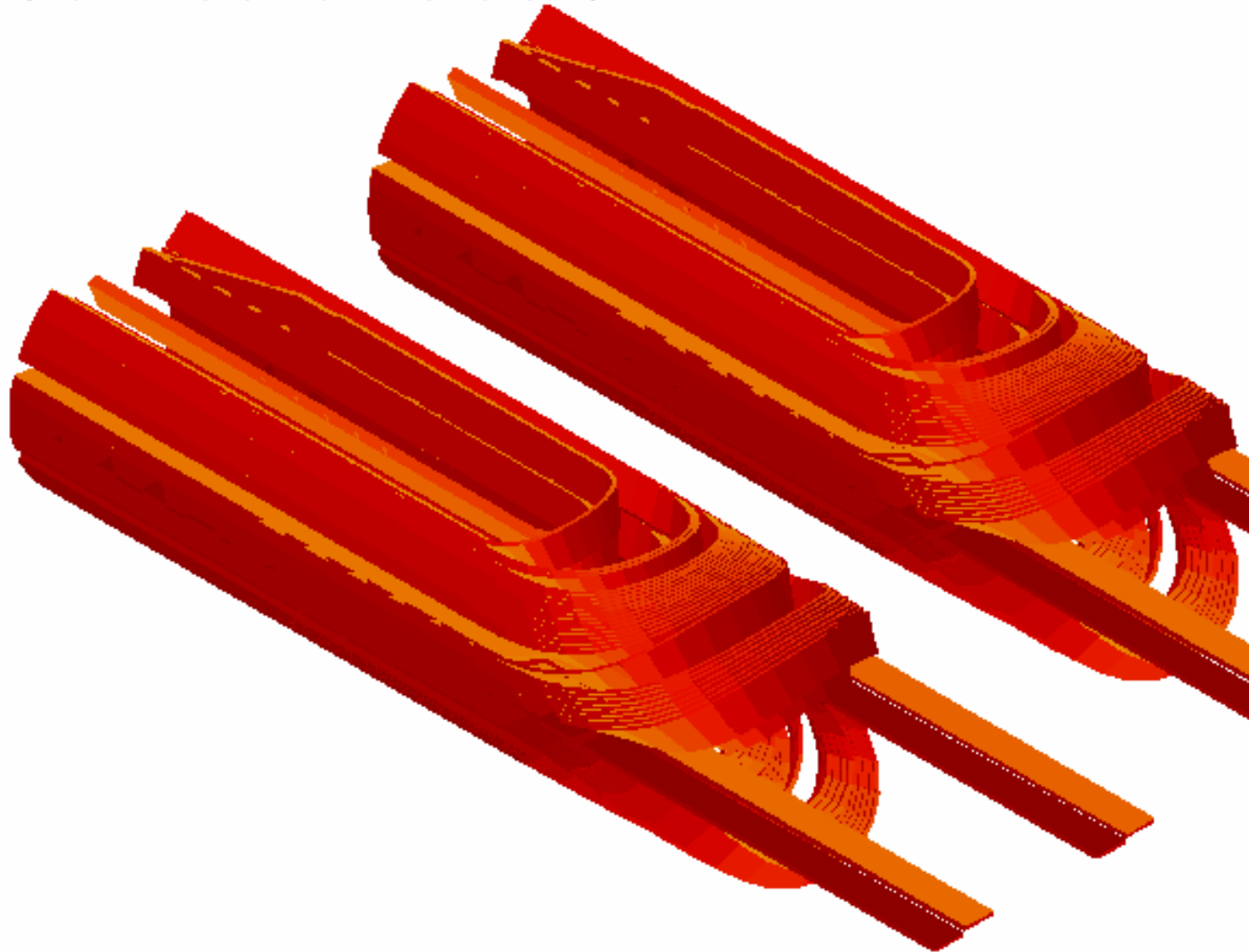
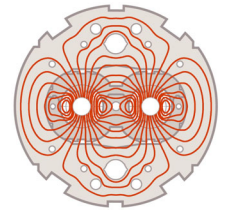


End Spacers: critici per Quench

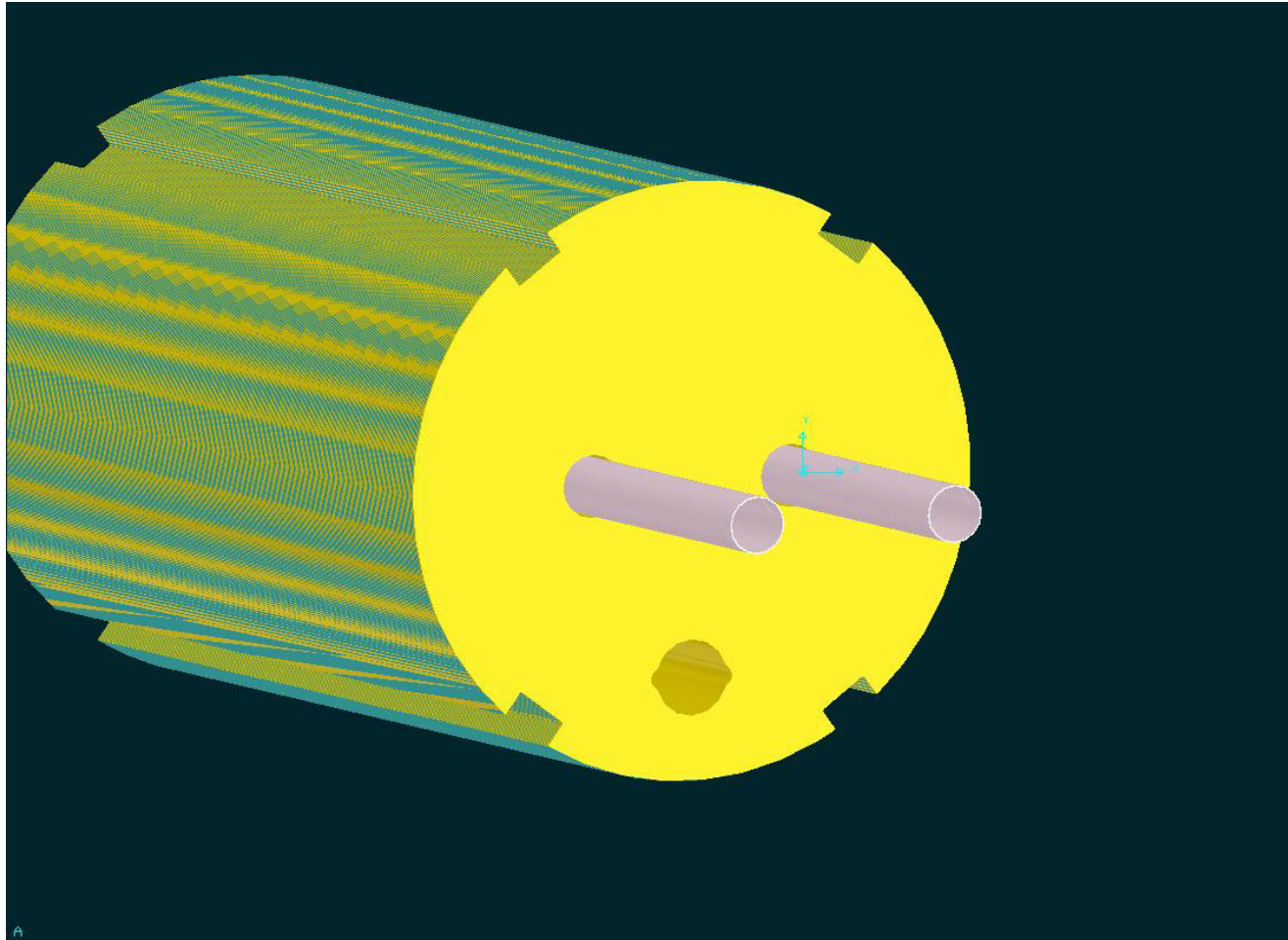
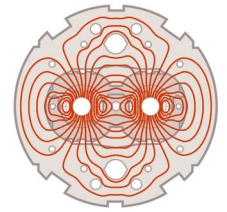
Il profilo deve adattarsi alla forma del cavo sulla curva

Il profilo è lavorato con speciali macchine a 5 assi

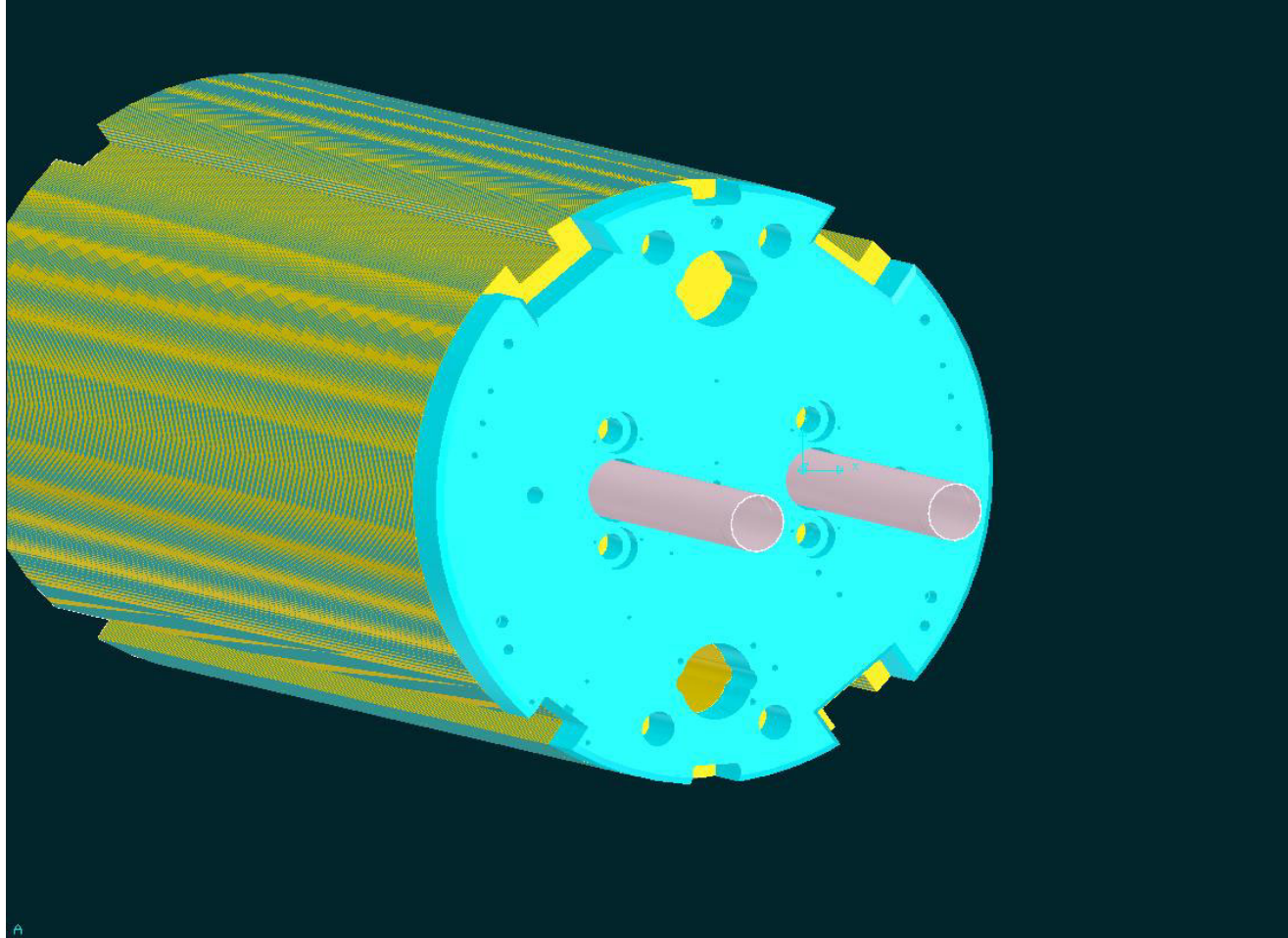
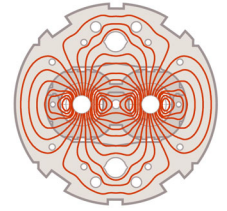
3D Connection side 3



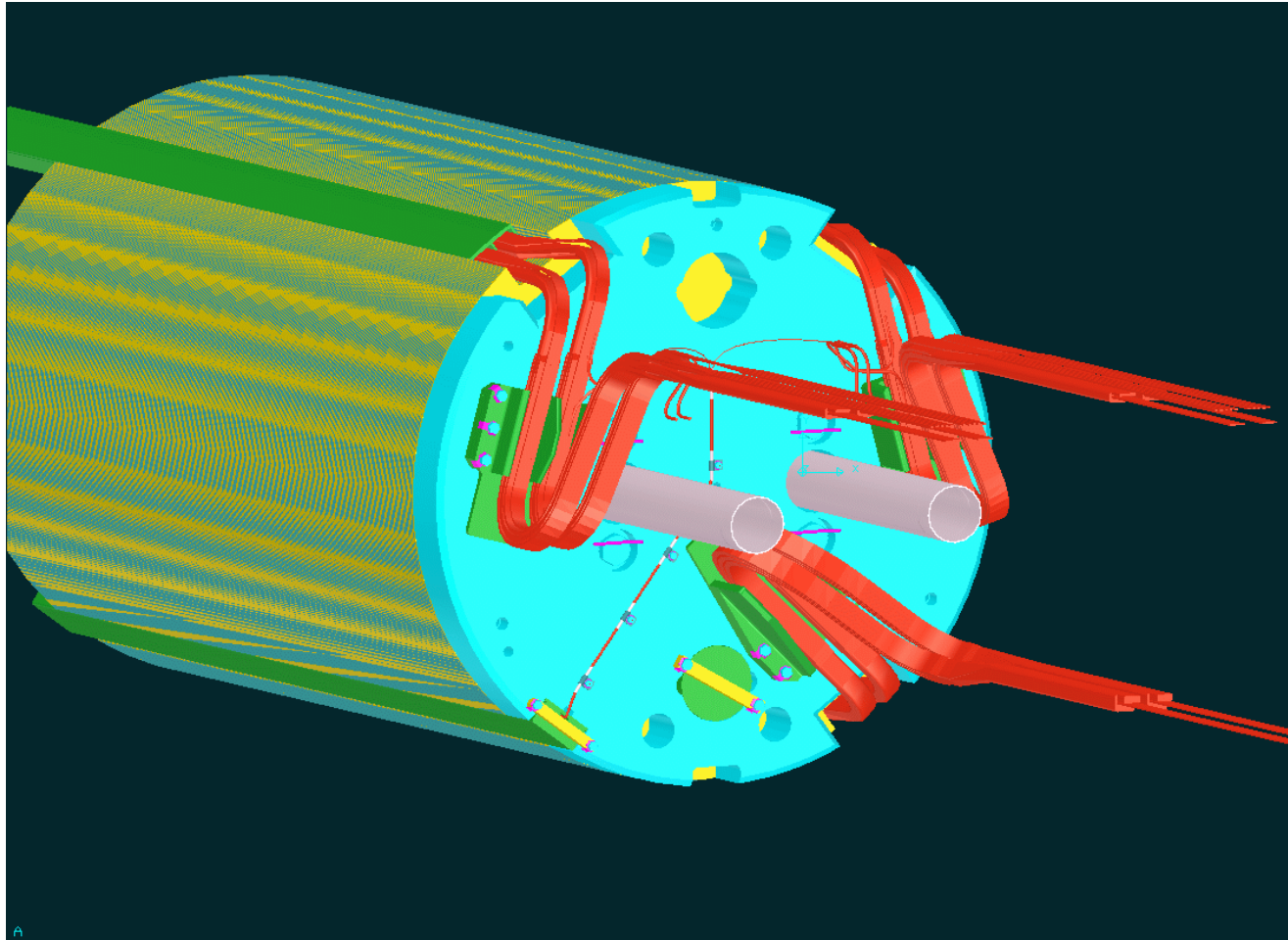
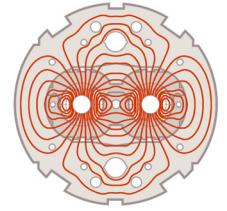
LHC MB - end part CBTs and Yoke



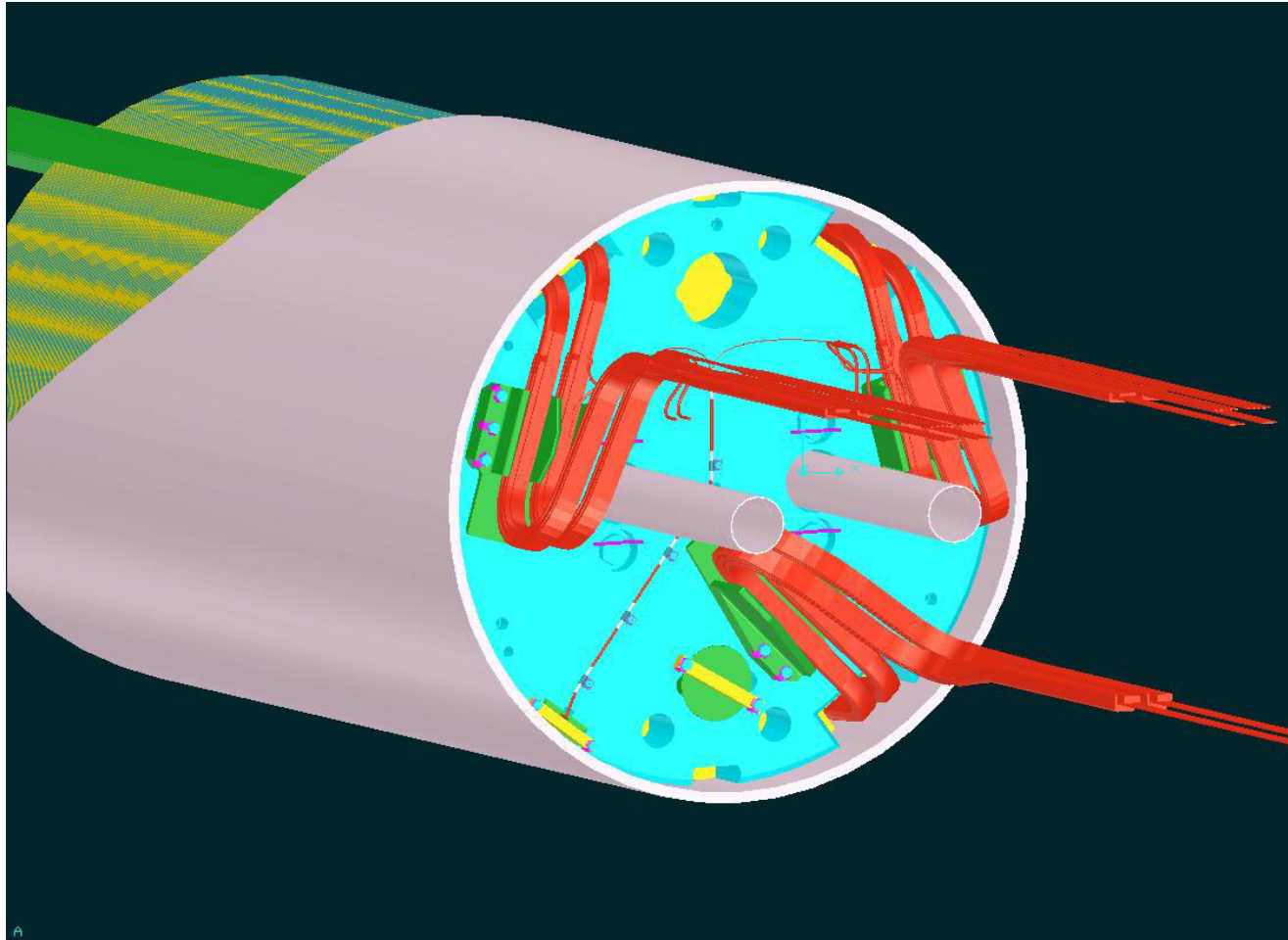
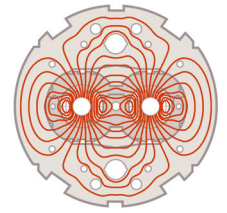
LHC MB -end part end plate



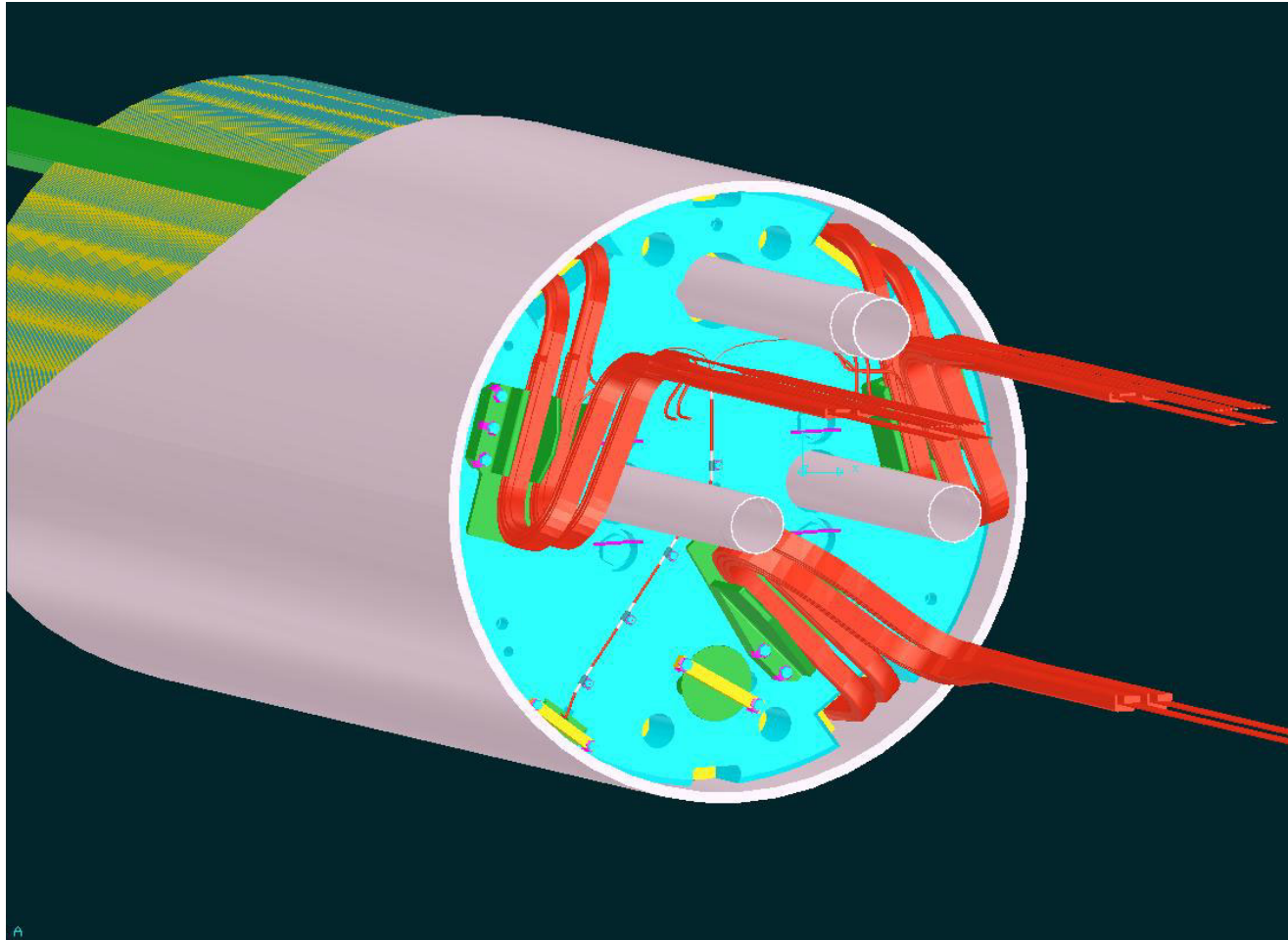
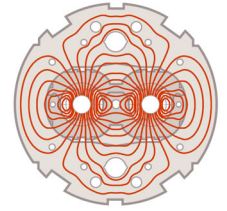
LHC MB-end part Bus Bars positioning



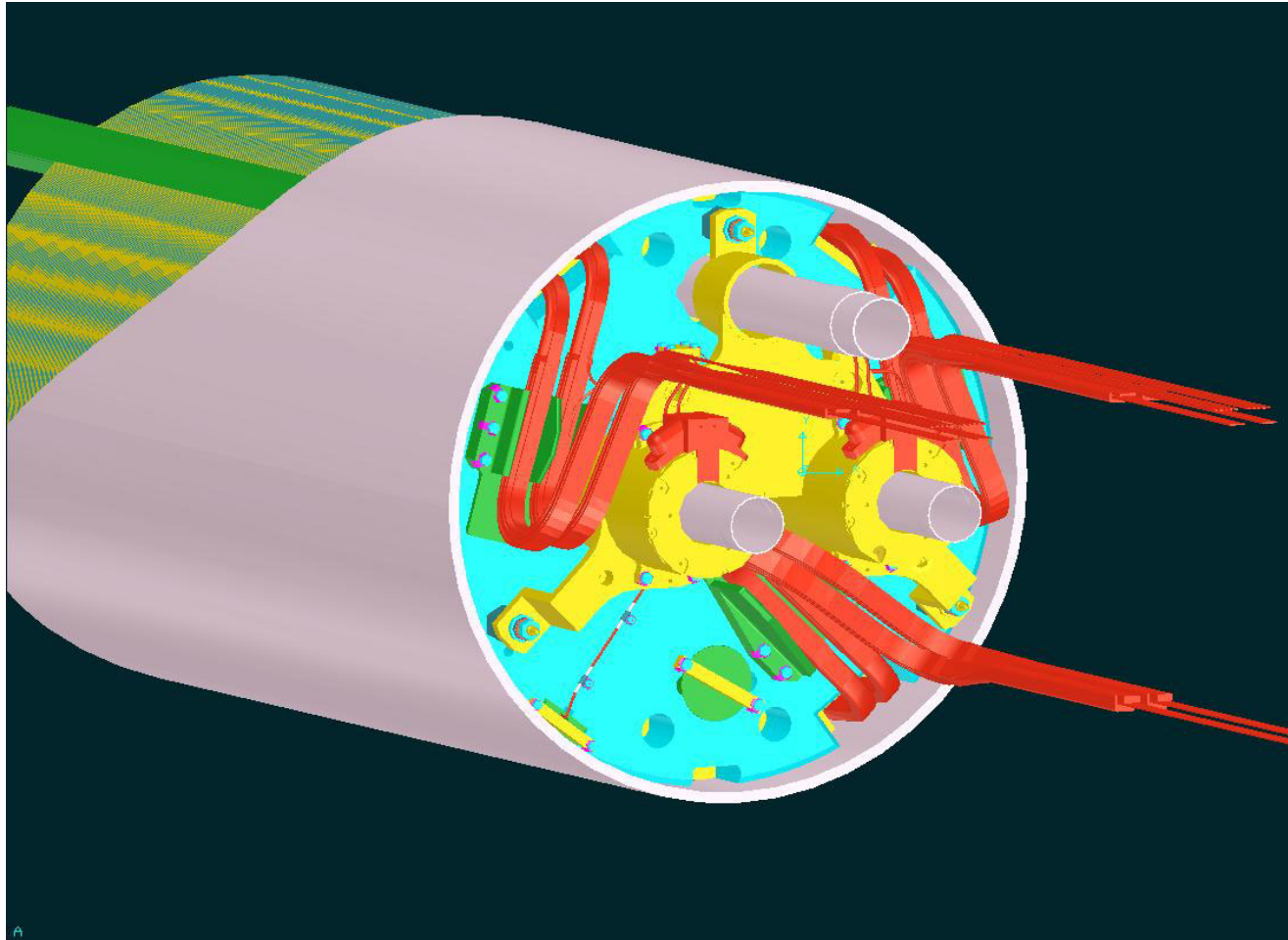
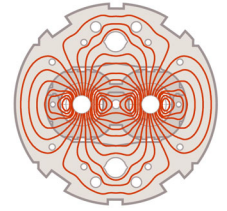
LHC MB -end part Shrinking cylinder



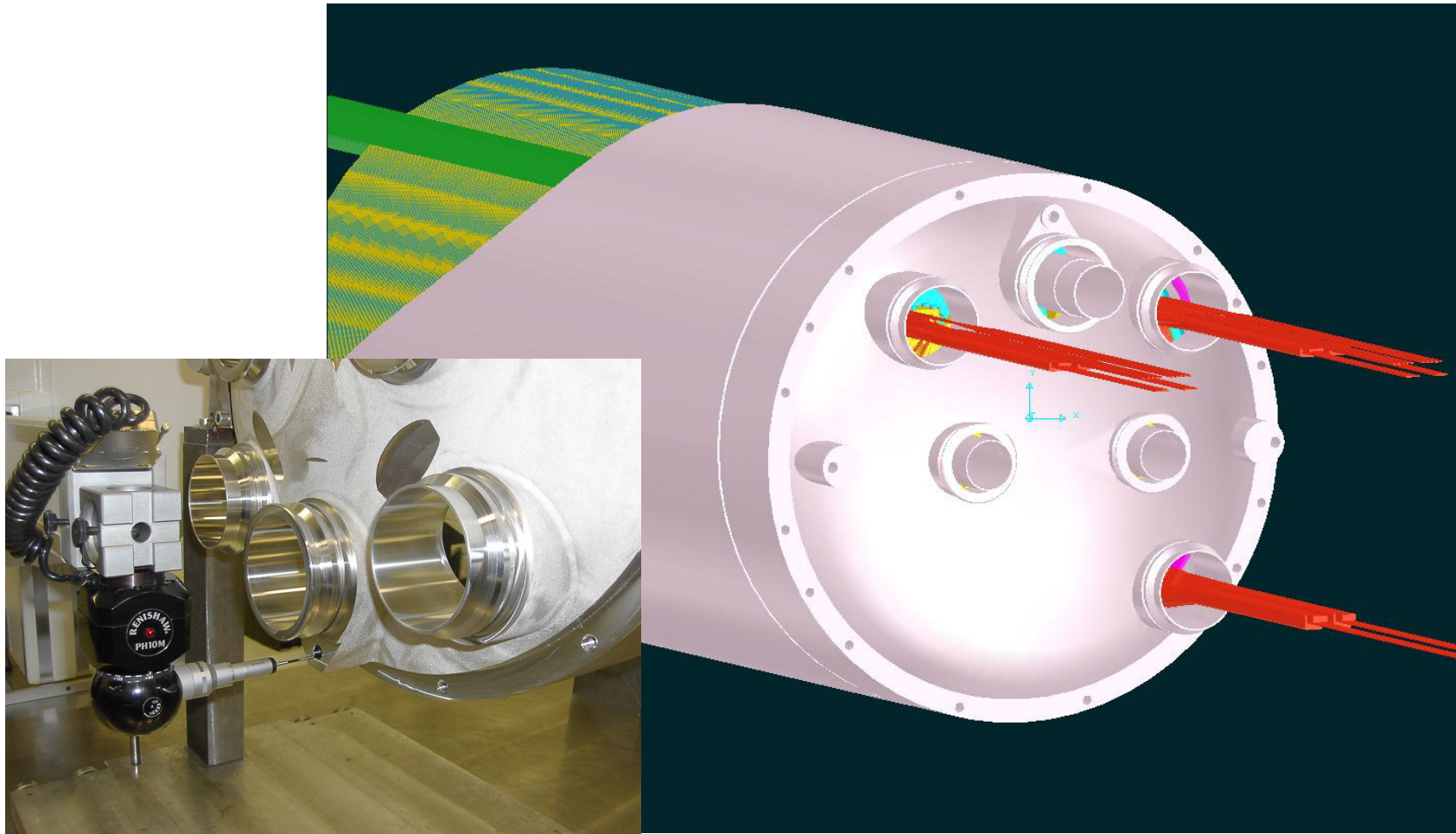
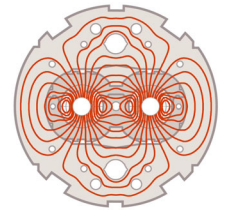
LHC Main Dipole -end part Cu HXT



LHC Main Dipole -end part Corrector Magnets (spool pieces)



LHC Main Dipole -end part End covers

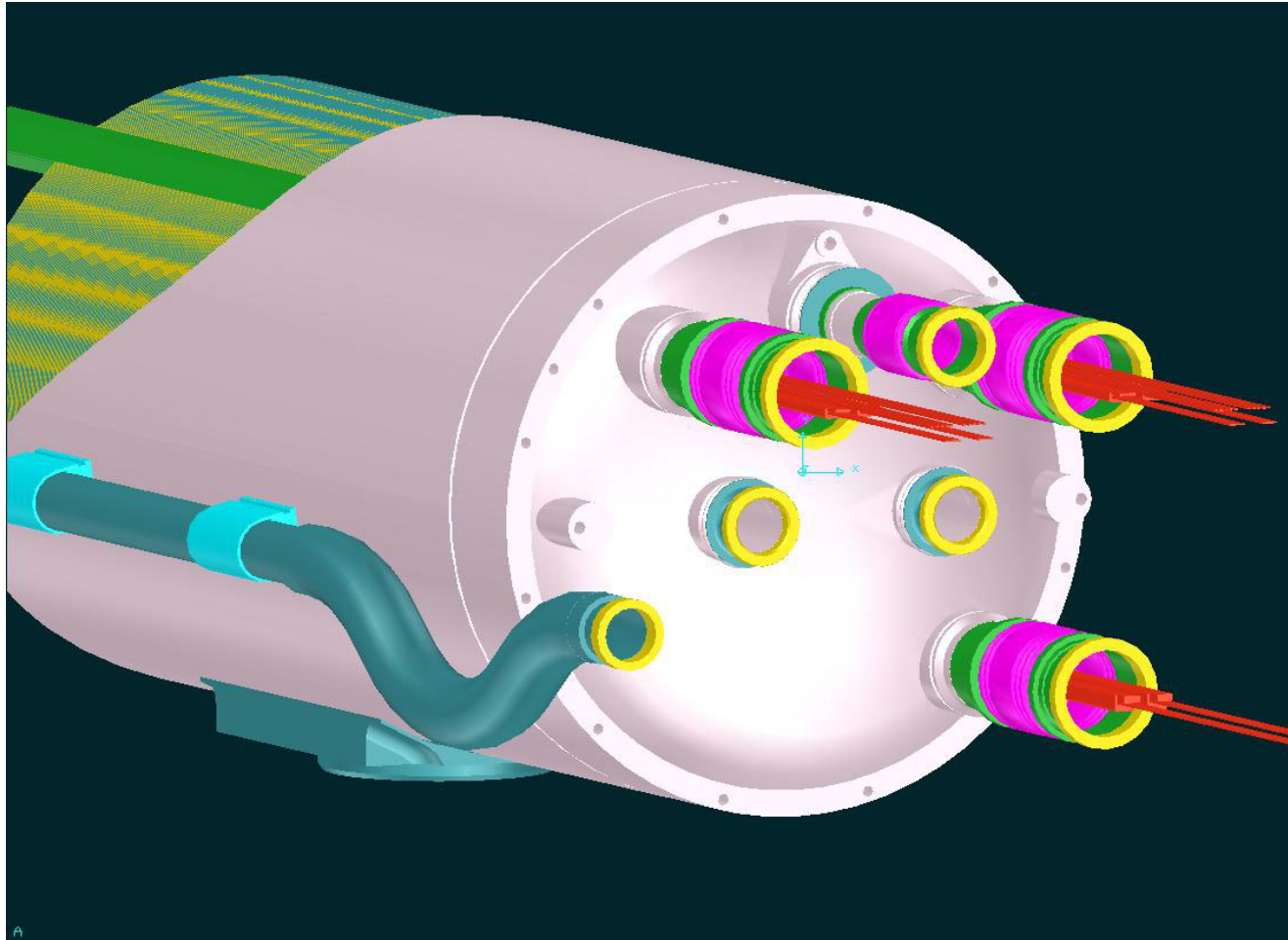
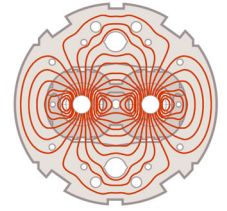


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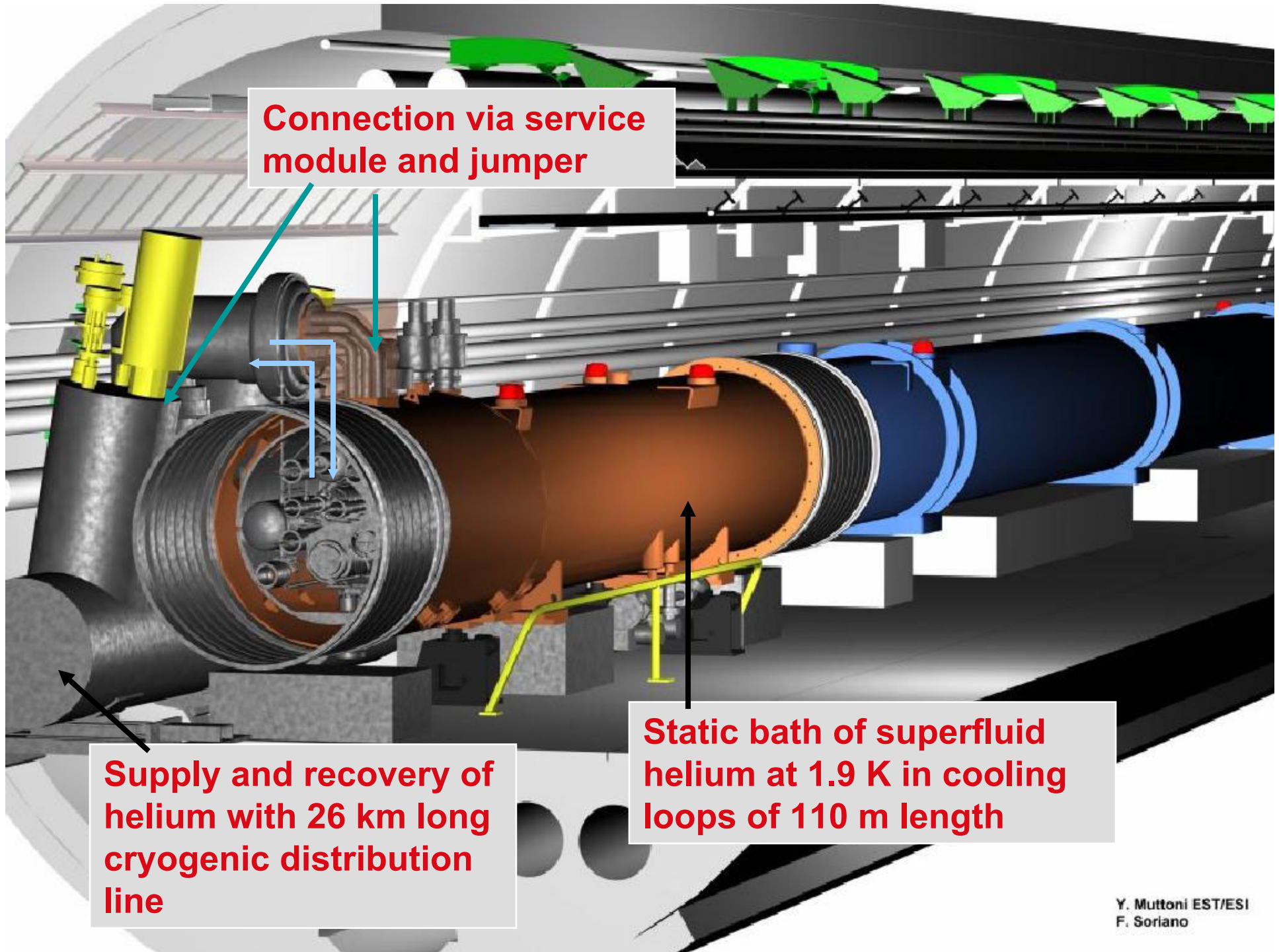
LHC Main Dipole -end part Bellows and N-line



Regular arc Magnets

392 main
quadrupoles +
2500 corrector
magnets

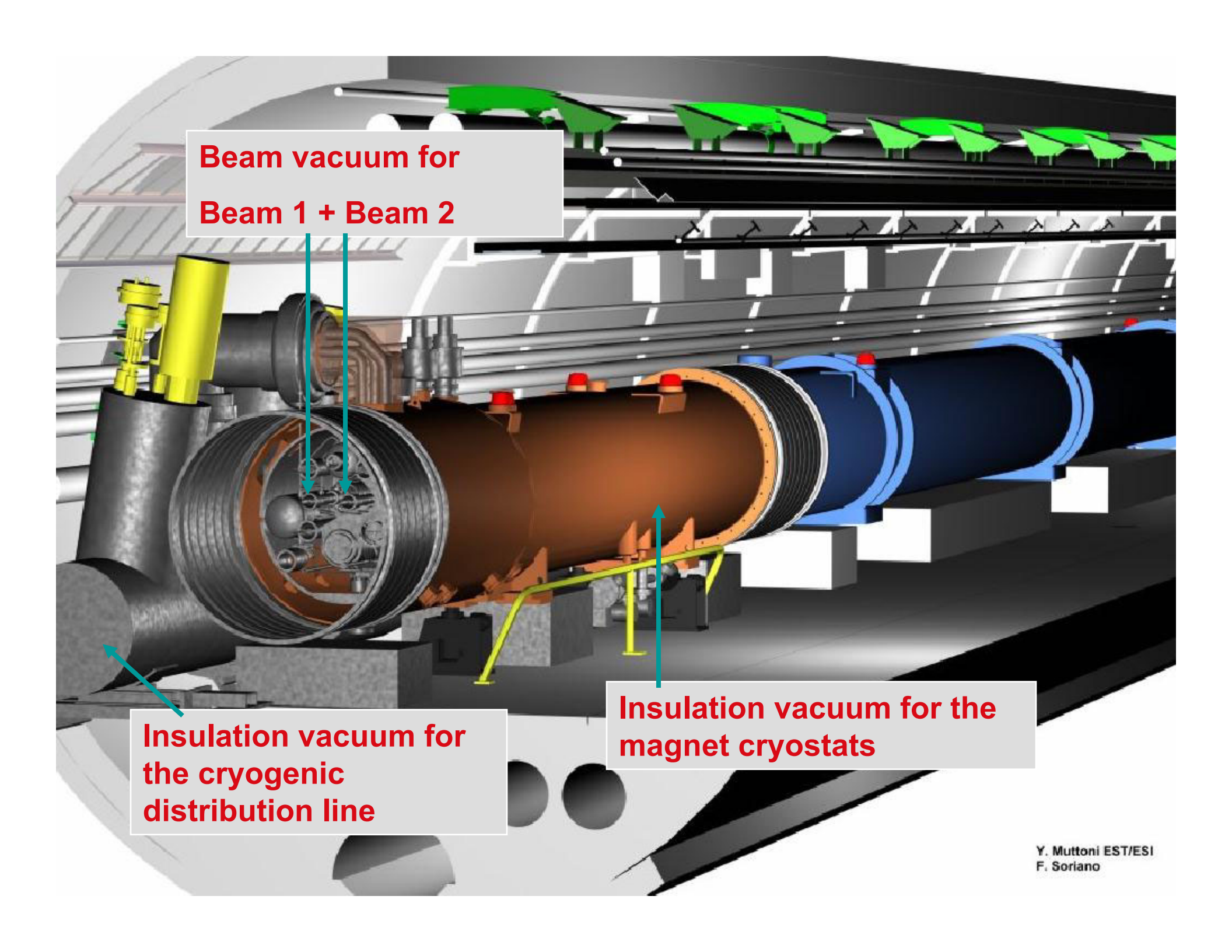
1232 main
dipoles +
3700
multipole
corrector
magnets



Connection via service module and jumper

Supply and recovery of helium with 26 km long cryogenic distribution line

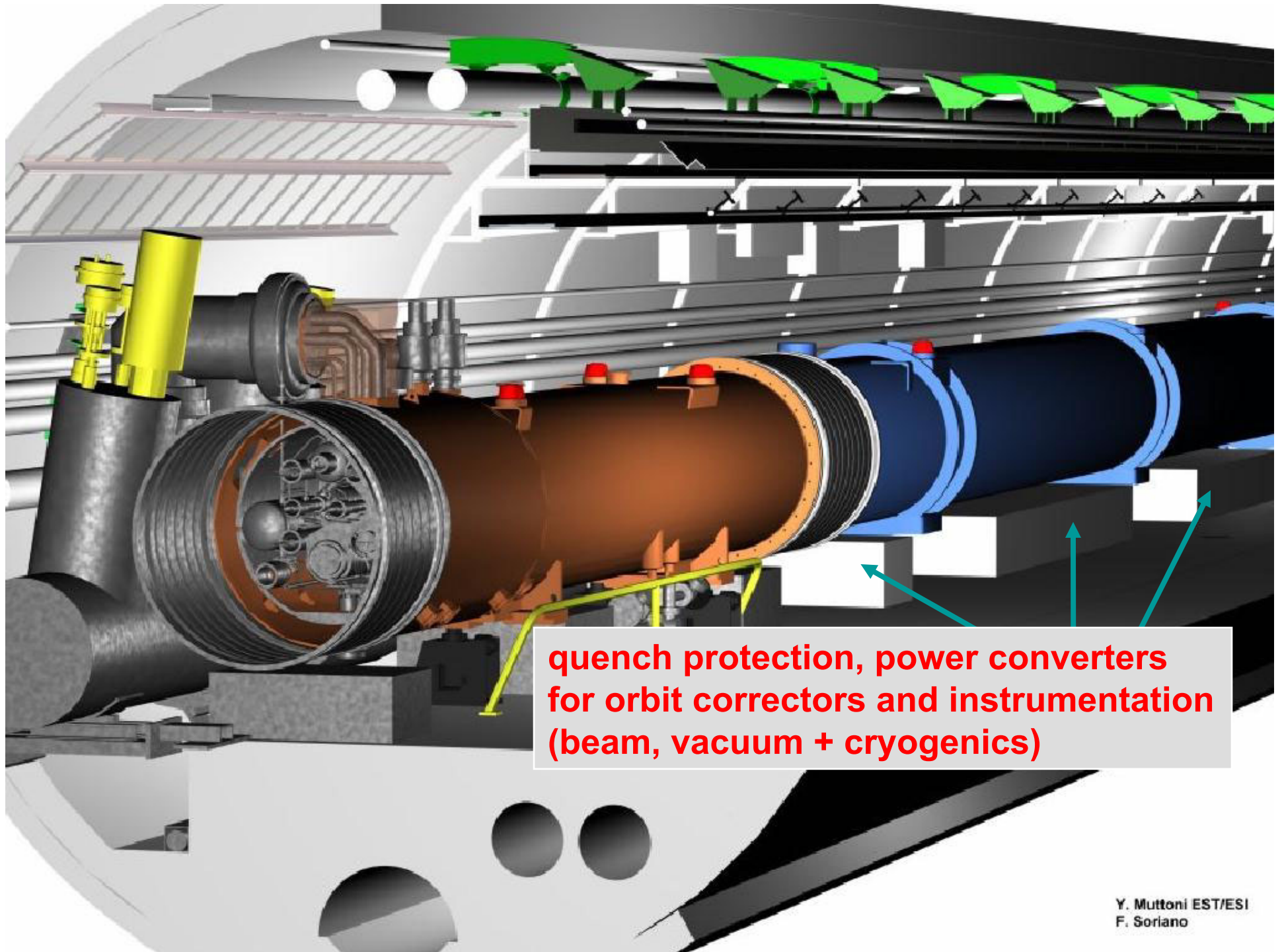
Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length



**Beam vacuum for
Beam 1 + Beam 2**

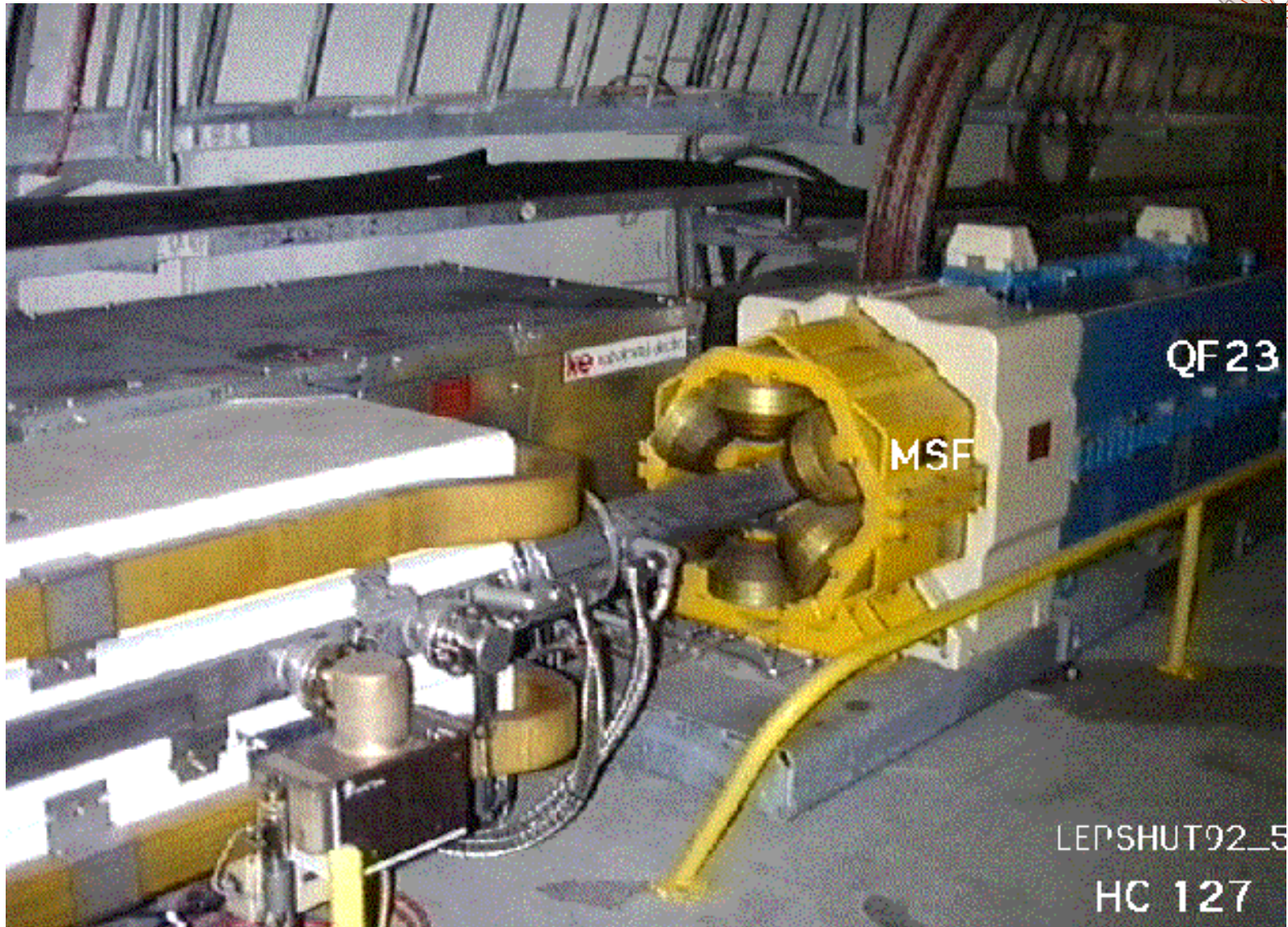
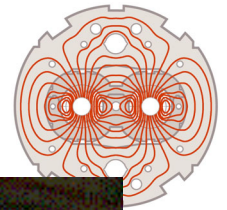
**Insulation vacuum for
the cryogenic
distribution line**

**Insulation vacuum for the
magnet cryostats**



**quench protection, power converters
for orbit correctors and instrumentation
(beam, vacuum + cryogenics)**

Interconnessione tra magneti: LEP

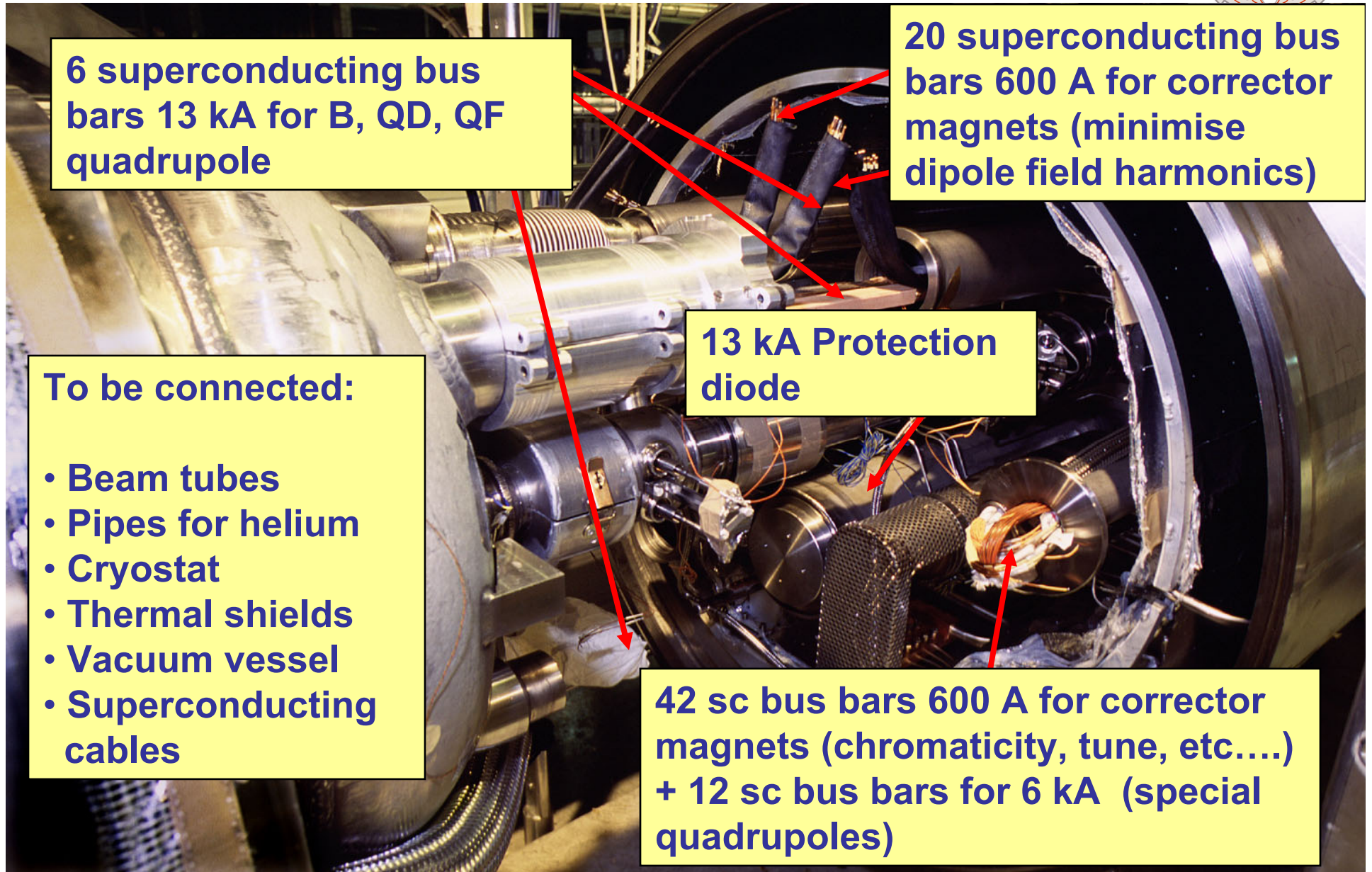
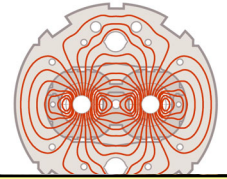


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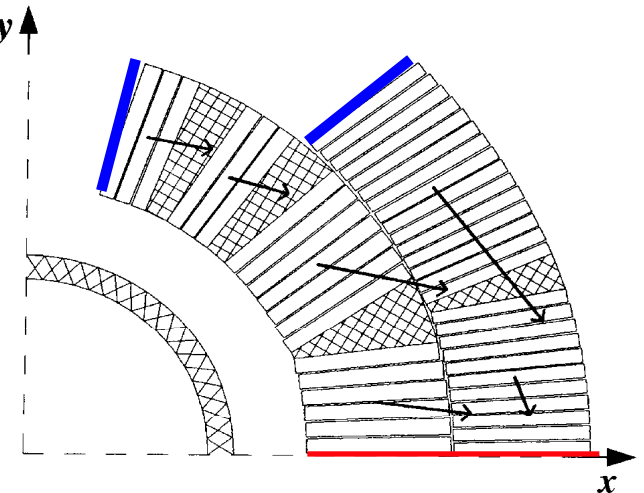
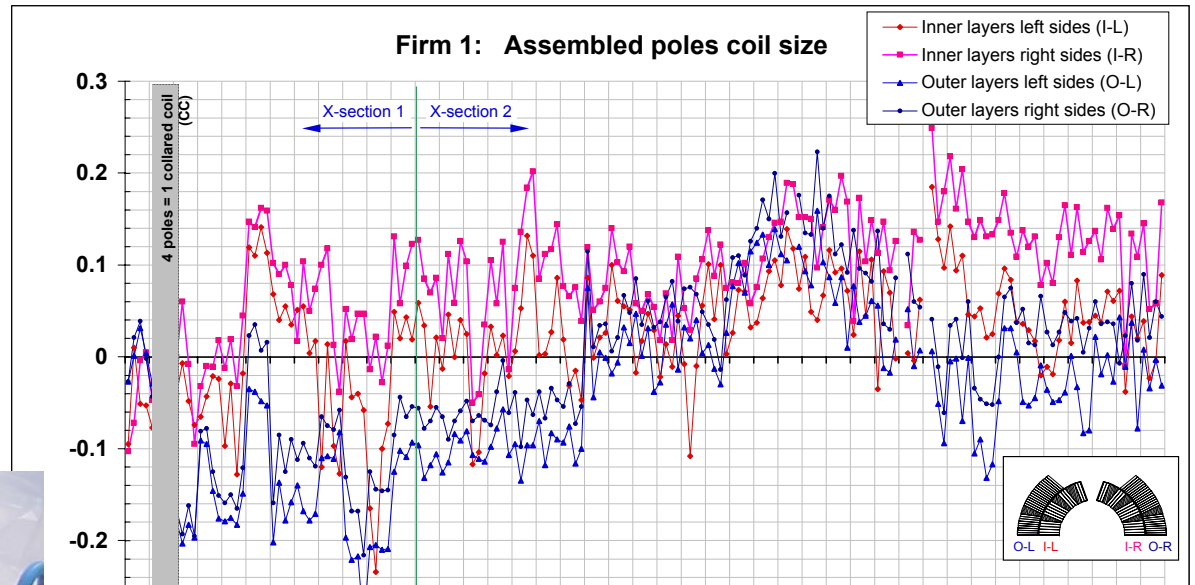
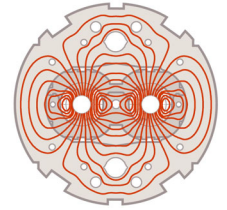
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Interconnessione in LHC tra magneti superconduttori

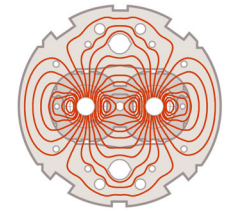


Processi critici Avvolgimenti-Polimerizzazione- formazione bobine

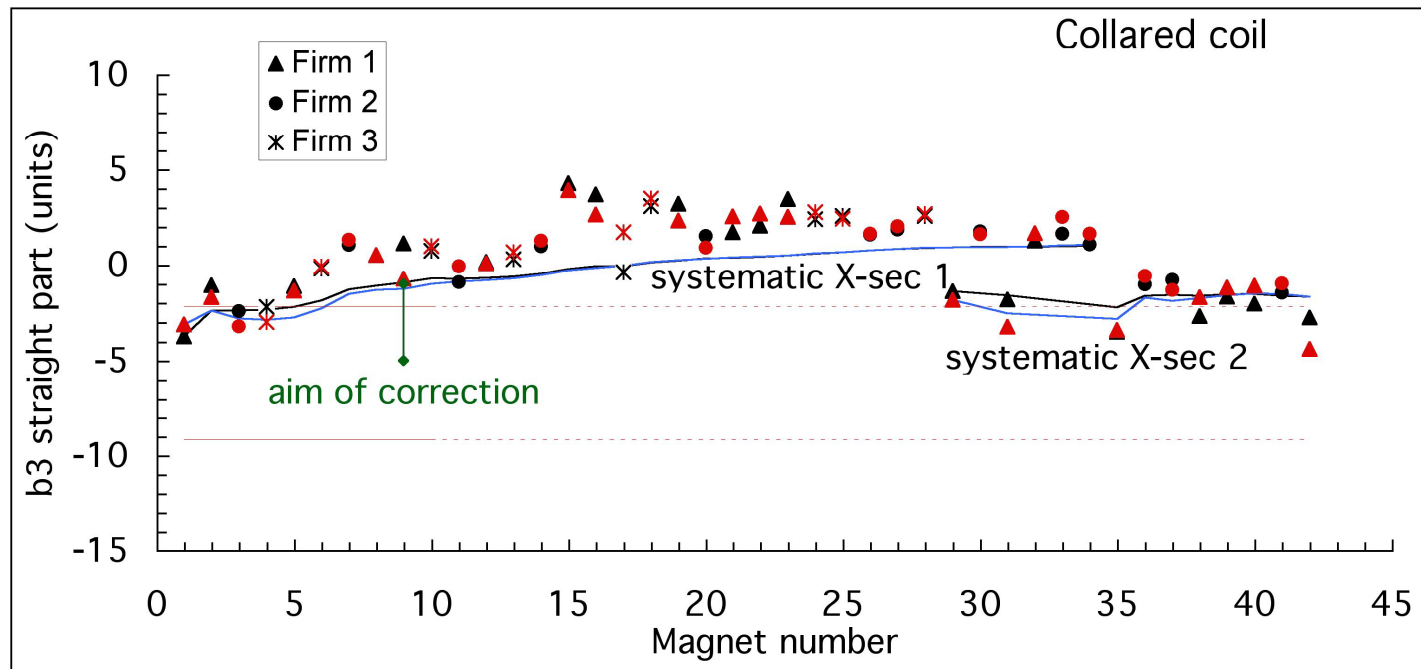


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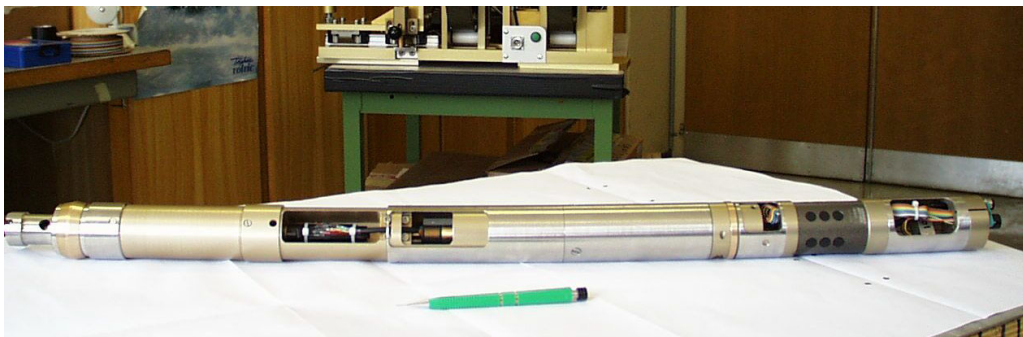
Lucio Rossi - LHC : la macchi



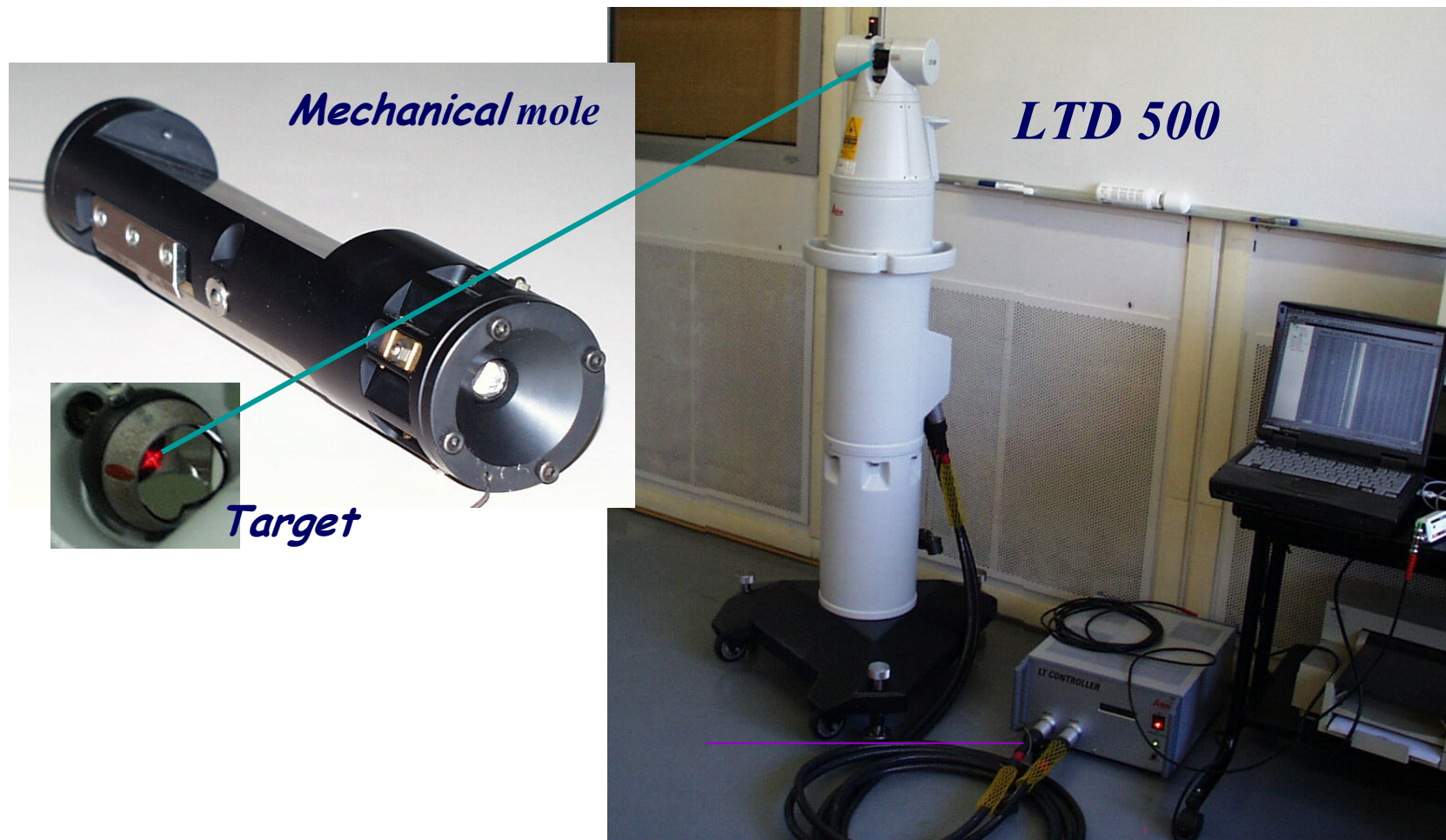
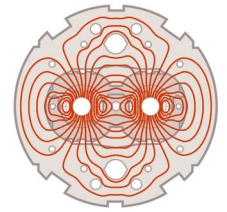
Controllo produzione per qualità di campo e check singoli errori per mezzo di misure magnetiche



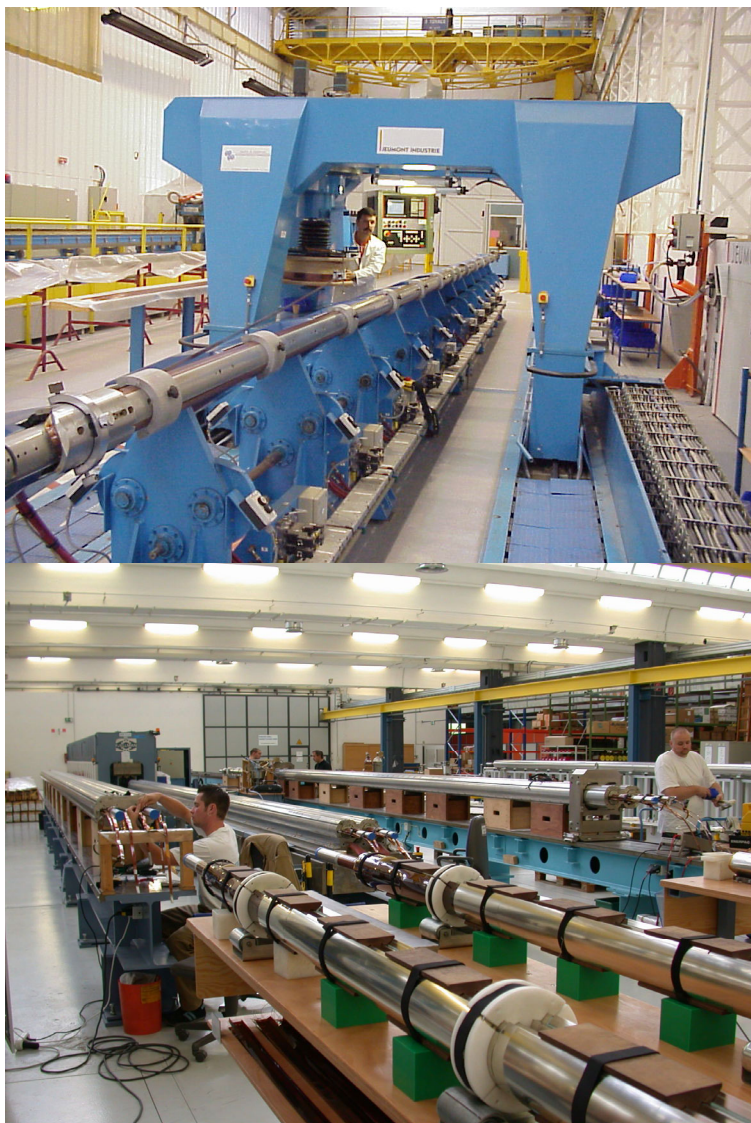
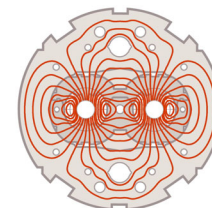
Ben 5 dipoli sono stati disassemblati per difetti costruttivi messi in luce da misure magnetiche



Misura della curvatura tramite delle talpe e di un tracciatore laser



Nelle Industrie -CC

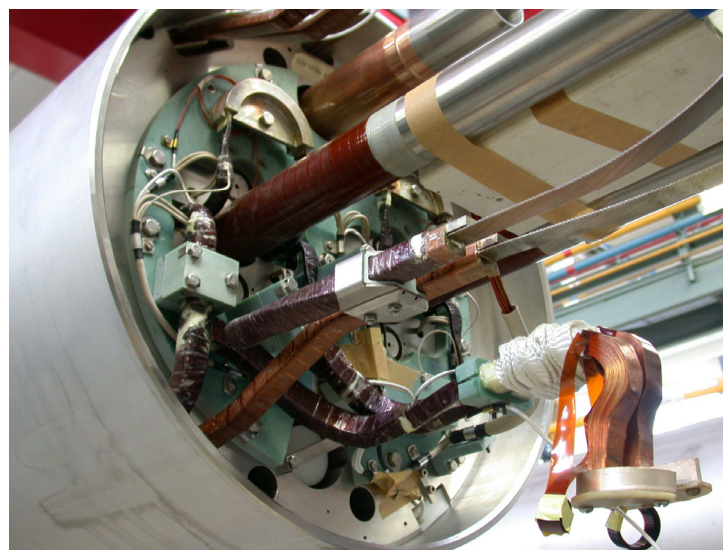
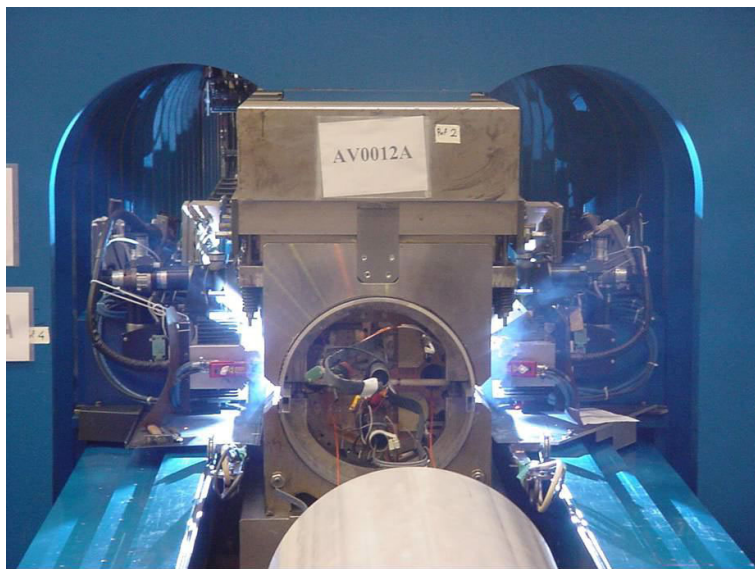
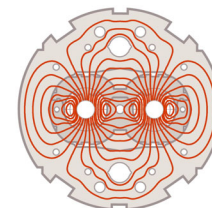


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Nelle Industrie -CM

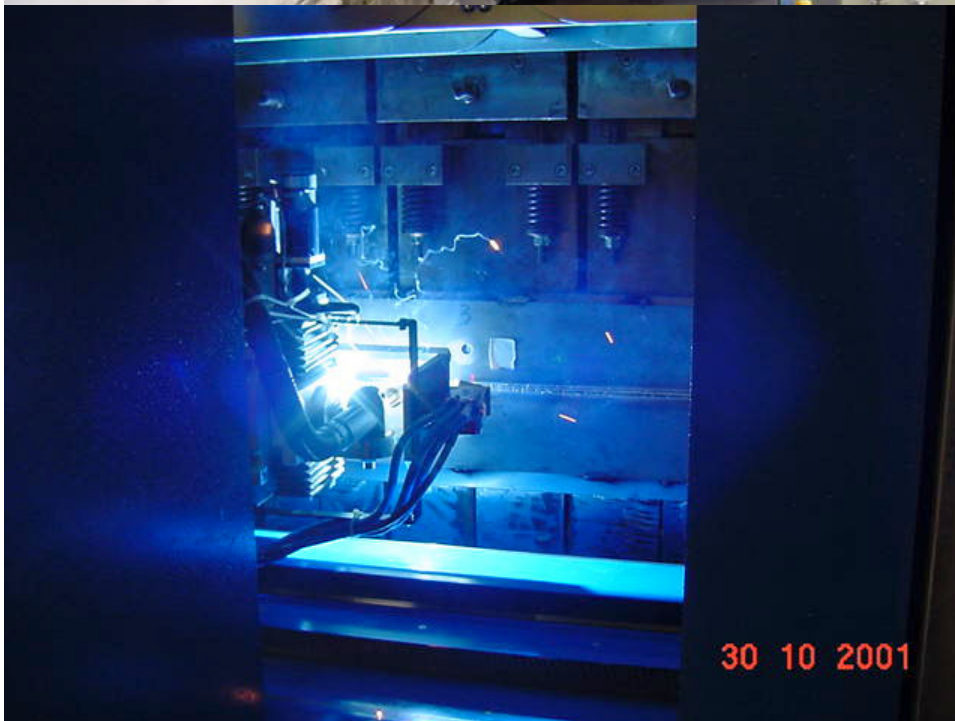
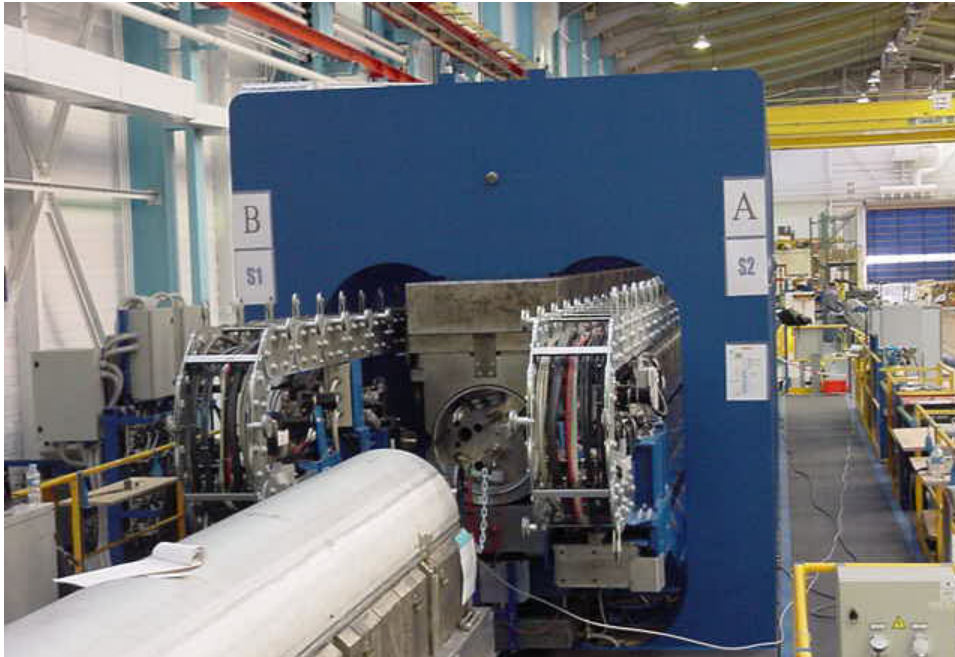
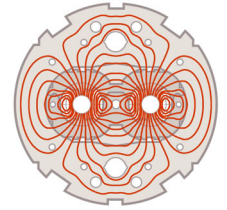


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La saldatura longitudinale



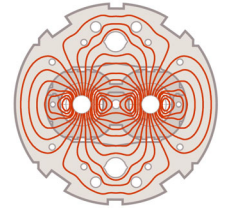
- **Sviluppata al CERN**
- **Presse installate nei CMAs**
- **Due cordoni saldati in sincronia**
- **Prima passata in STT: elevata qualità e controllo: una *PRIMA* mondiale in queste condizioni.**
- **Ora i problemi delle saldature è stato superato.**
- **Su ogni CM si fa la cercata di fughe a vuoto a 26 bar a livello di $2 \cdot 10^{-10}$ mbar-l-s⁻¹ !!!**

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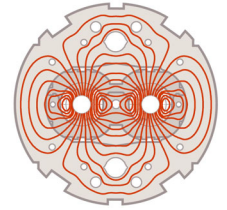
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Logistic and QA: Il lato oscuro della tecnologia!

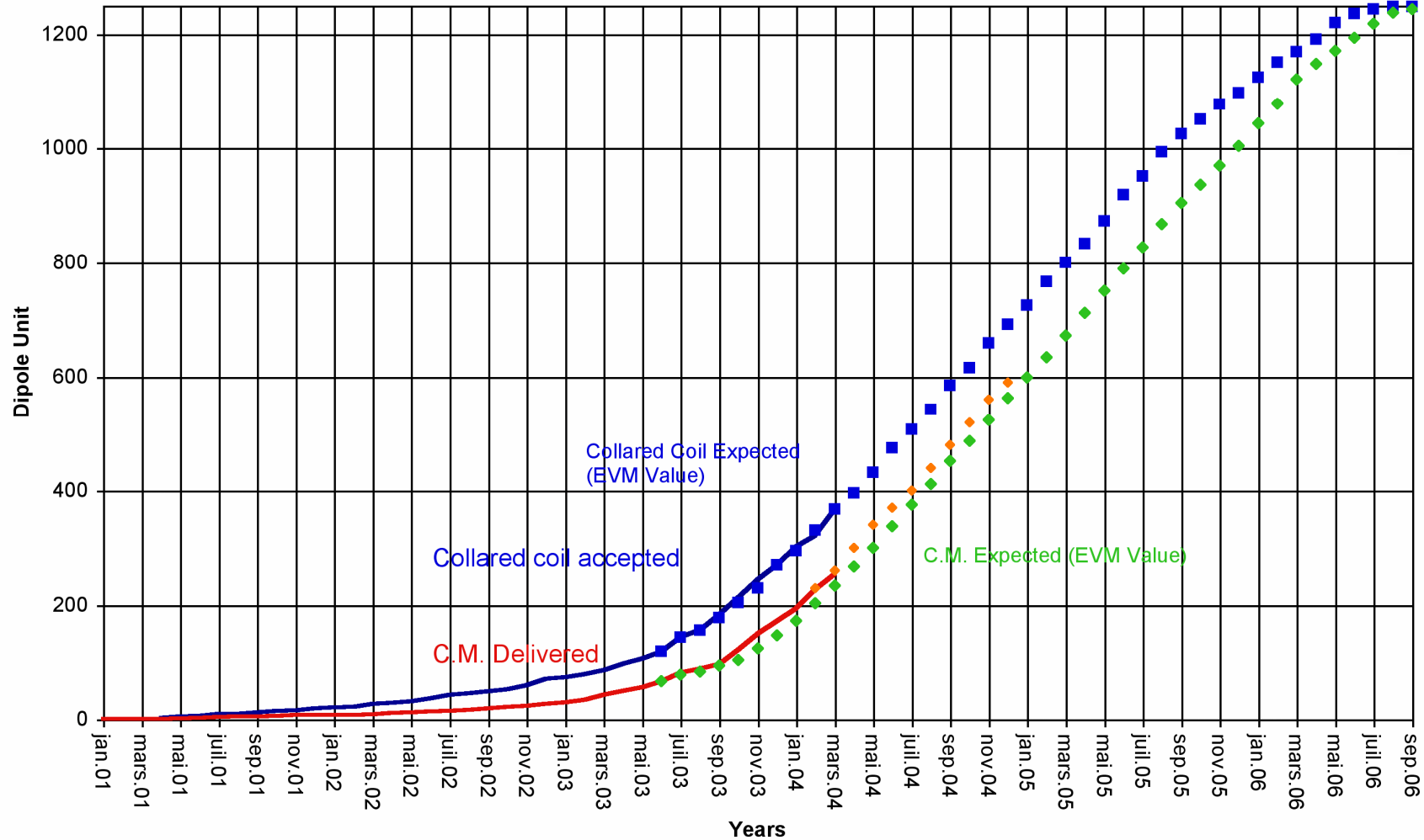


- 50,000 tons andranno nel tunnel
- 150,000 tons si muovono in Europe, in quattro anni.
~10000 TIR, \Rightarrow 10 TIR/giorno in media! \Rightarrow *Paperwork!*
- Pianificazione! Esempio acciaio al carbonio per il giogo
 - materiale primario (composto di 3 processi principali)
 - Passaggio al CERN,
 - Stoccaggio (in parte)
 - Dato in lastre per alcuni magneti al costruttore (MQ, MQM, MQY, MQT)
 - Dato in lastre ai tre stampatori per i dipoli
 - Le laminazioni passano al CERN (o in altre aree di stoccaggio e poi va ai 3 CMAs)
- QA : MTF Manufacturing Test Folder : 500 entrate per magnete!
Basato su ABS. Assicura la completa e permanente tracciabilità sia dei materiali che dei processi (contiene anche tutte le NC e i CoC dei componenti)

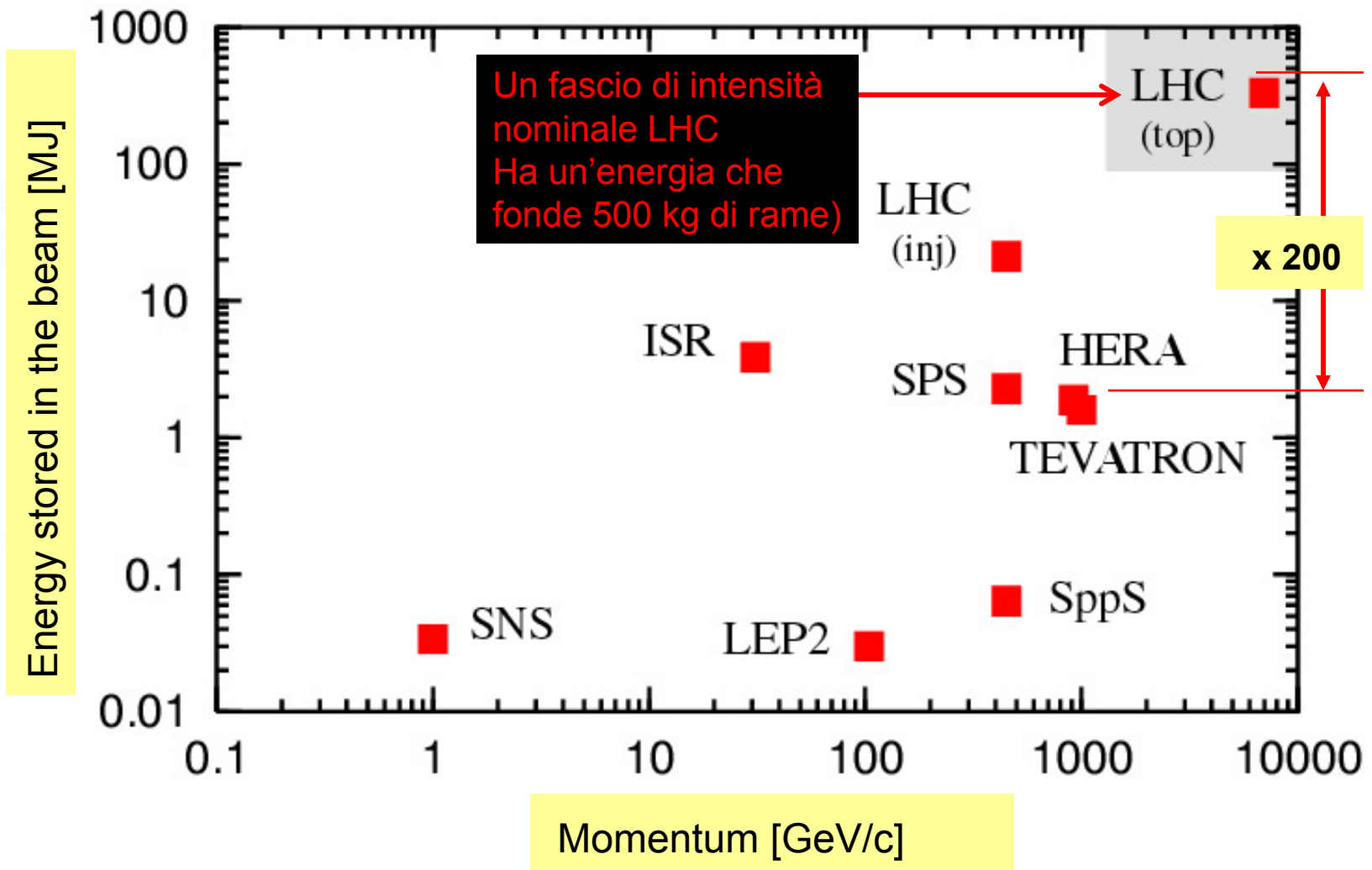
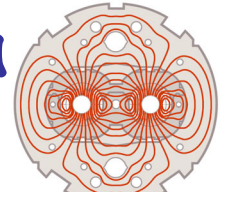
Diopoli: il planning



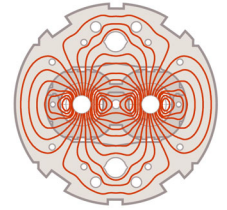
Total CC and C.M. Delivery Schedule (31 March 2004)



Una Sfida: energia immagazzinata nel fascio

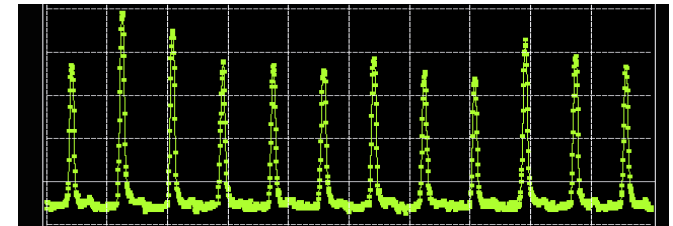
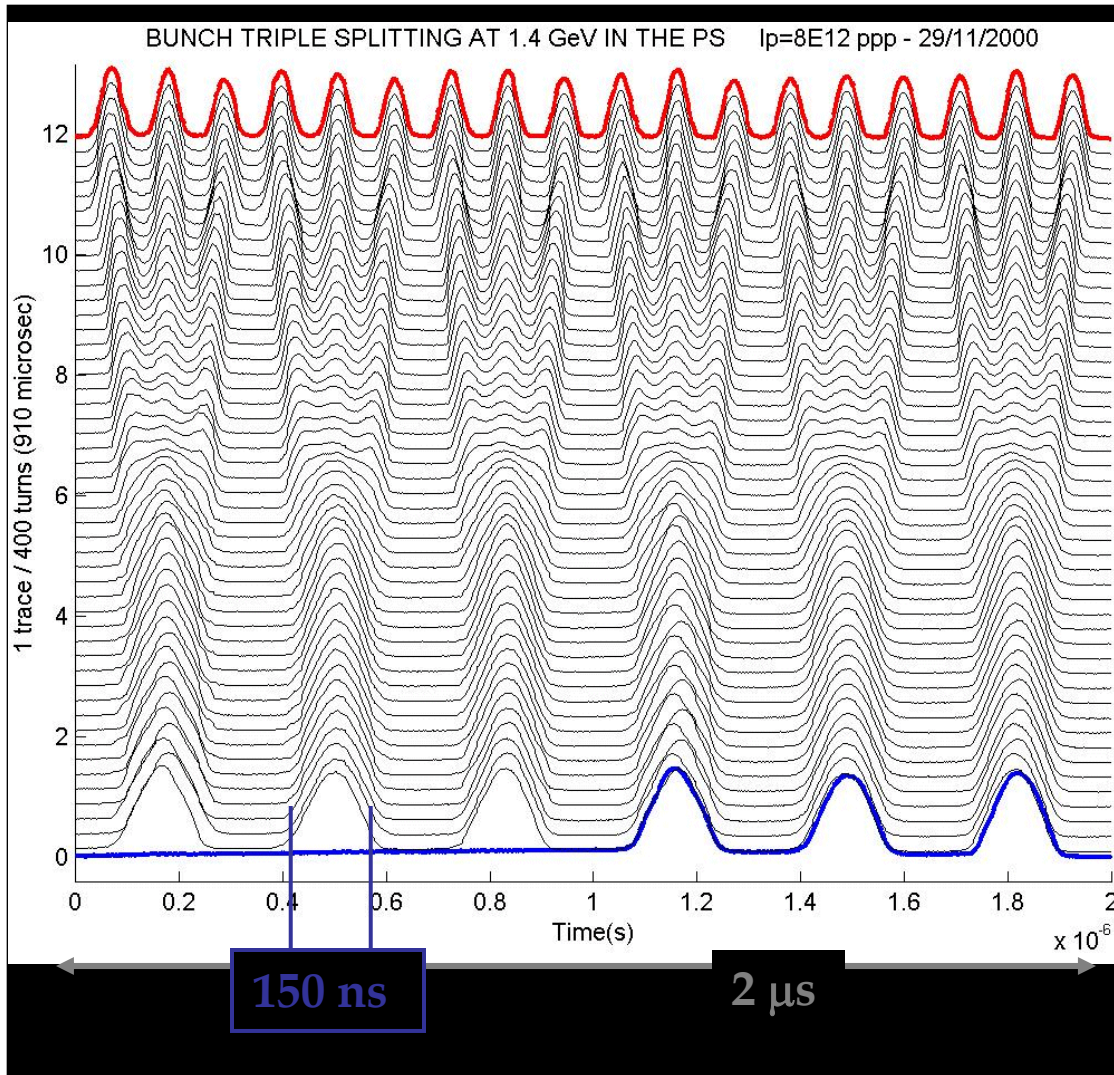
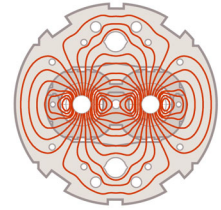


Sistema di iniezione

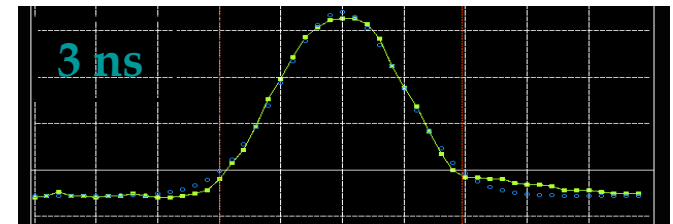


- Pre-iniettori: Linac, PS Booster and Proton Synchrotron iniettano fascio nell'SPS at 26 GeV
- L'SPS accelera il fascio da 26 GeV a 450 GeV
- Sia I pre-iniettori che l'SPS sono stati migliorati per le operazioni con i parametri di fascio nominali per LHC
- Già oggi, fasci con proprietà vicine alle richieste LHC sono stati accelerati.

Sistema di Iniezione: Bunch splitting nel PS

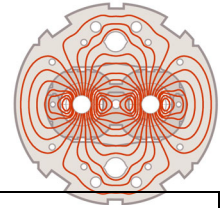


12 sui 72 bunches
dell'ultimo giro del PS
(30 ns/div)



zoom su un bunch
(1 ns/div).

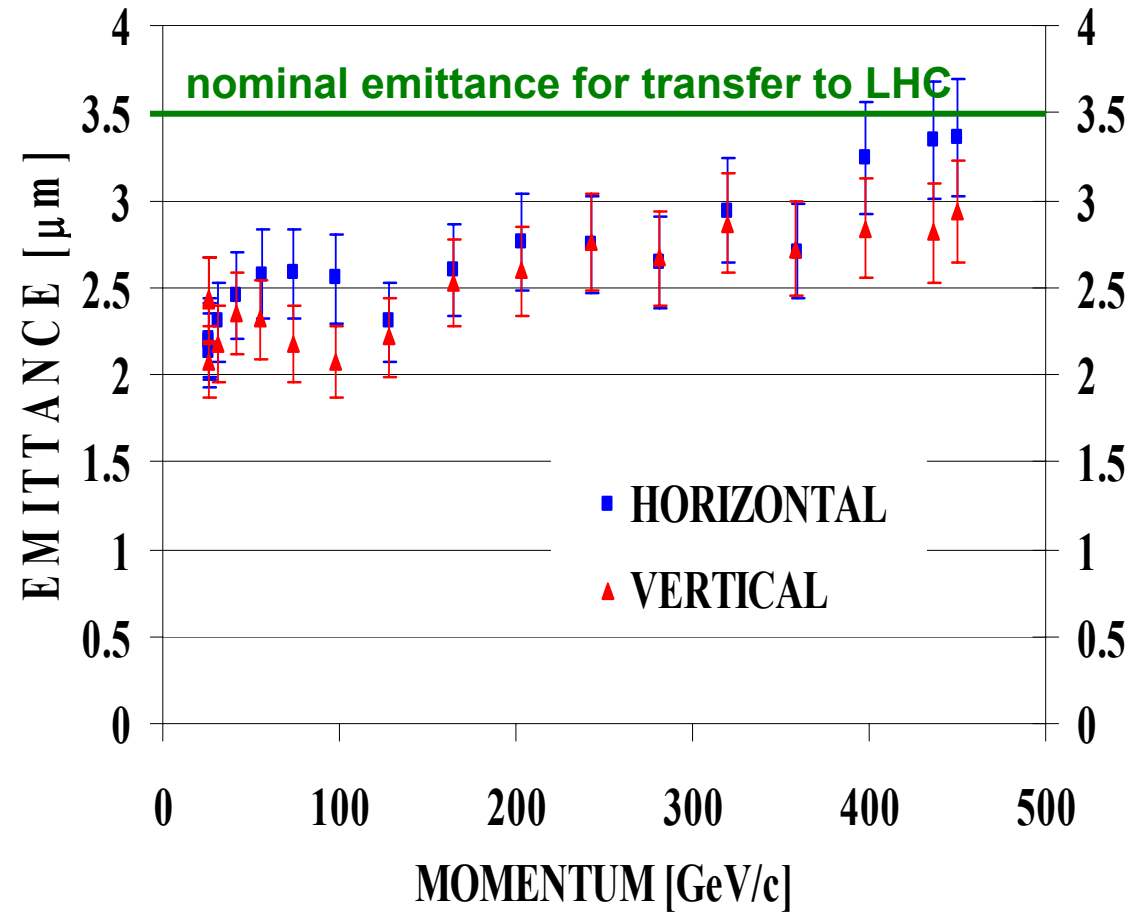
Sistema di Iniettori: Accelerazione nell' SPS



2001: emittance blowup
Durante la rampa,
causata dall'instabilità
indotta dall' electron
cloud (elettroni
accelerati e moltiplicati
a causa dell'elevata
intensità del fascio)
ma ancora sotto il
nominale di LHC a
corrente di fascio

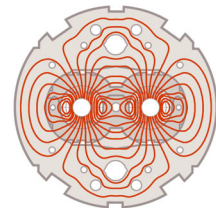
2002: beam scrubbing
Ha ridotto l'emissione
dei secondari => no
blow up durante il
plateau d' iniezione in
corso di studio

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Emittanza in funzione del momento durante il
run del 2001 (a corrente di fascio ridotta)

Linee di Transfer SPS - LHC



Due nuove linee di transfer dall' SPS to LHC sono in costruzione. Le linee sono basate su magneti resistivi. Ciascuna linea è lunga circa 2.8 km

Magneti TUTTI finiti,
fatti da BINP /
Novosibirsk

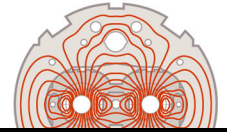
Commissioning prima
linea per il 2004



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Lucio Rossi - LHC la macchina **Magneti dipolari in stock per l'installazione** 52

Sistema da vuoto del fascio



Beam screen è inserito su quasi tutto l'anello

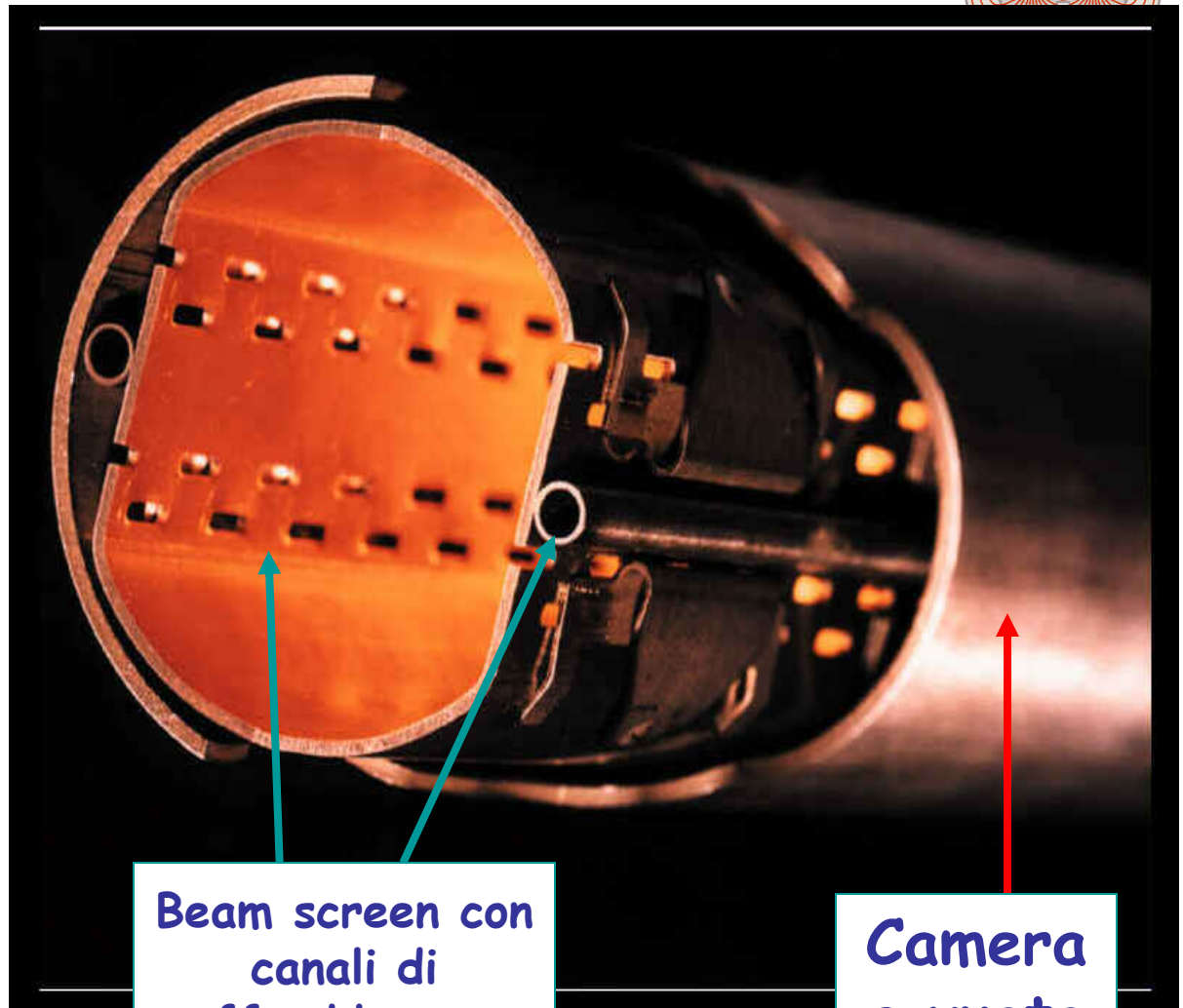
Assicura la stabilità del vuoto

Cattura a 5-20 K la radiazione di sincrotr.

Stabilità del fascio
=> Bassa impedenza:
Ricoperta da film di rame

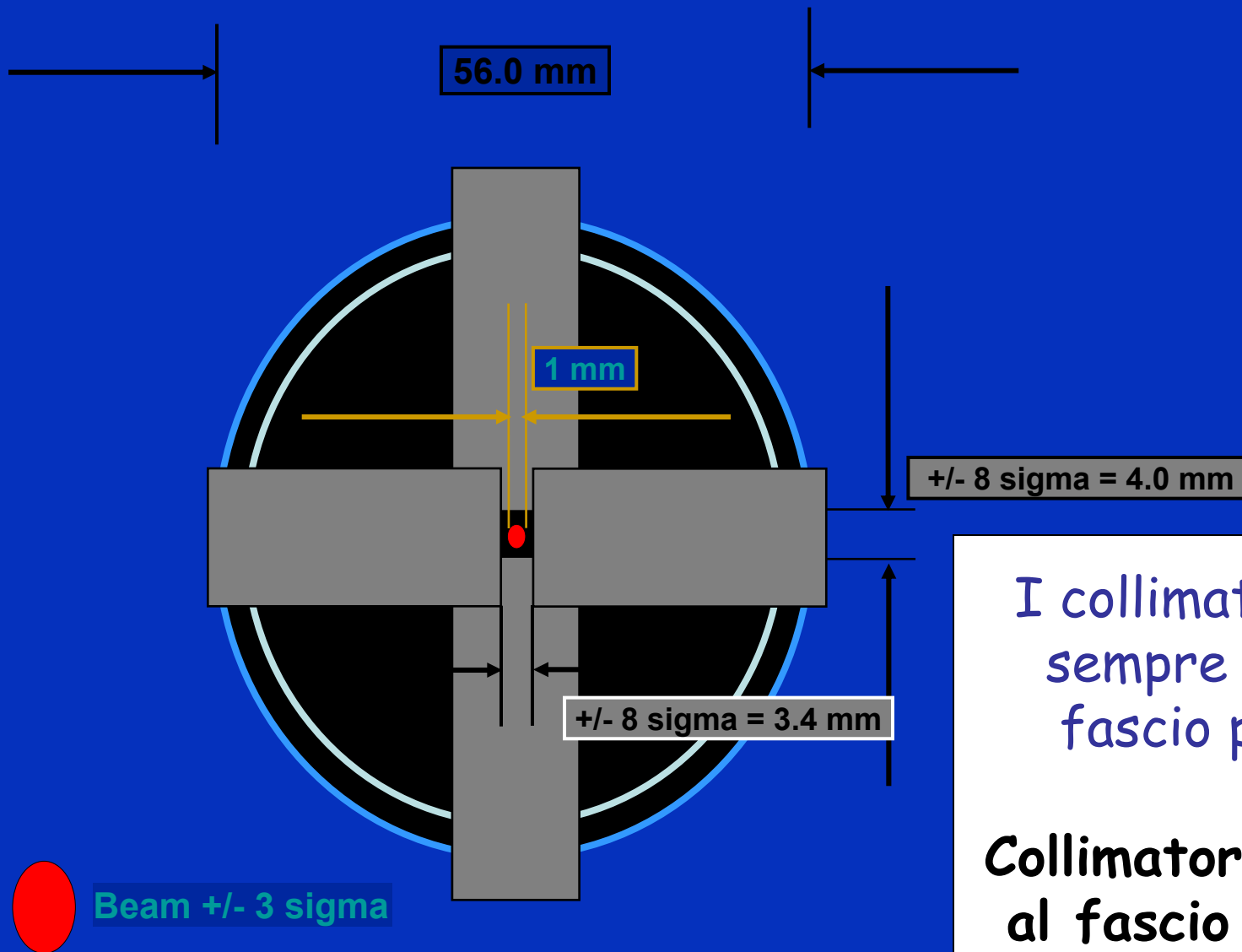
Effetti per contrastare l' Electron Cloud:
- Minimizzare la riflettività
- Beam scrubbing (come nel SPS)

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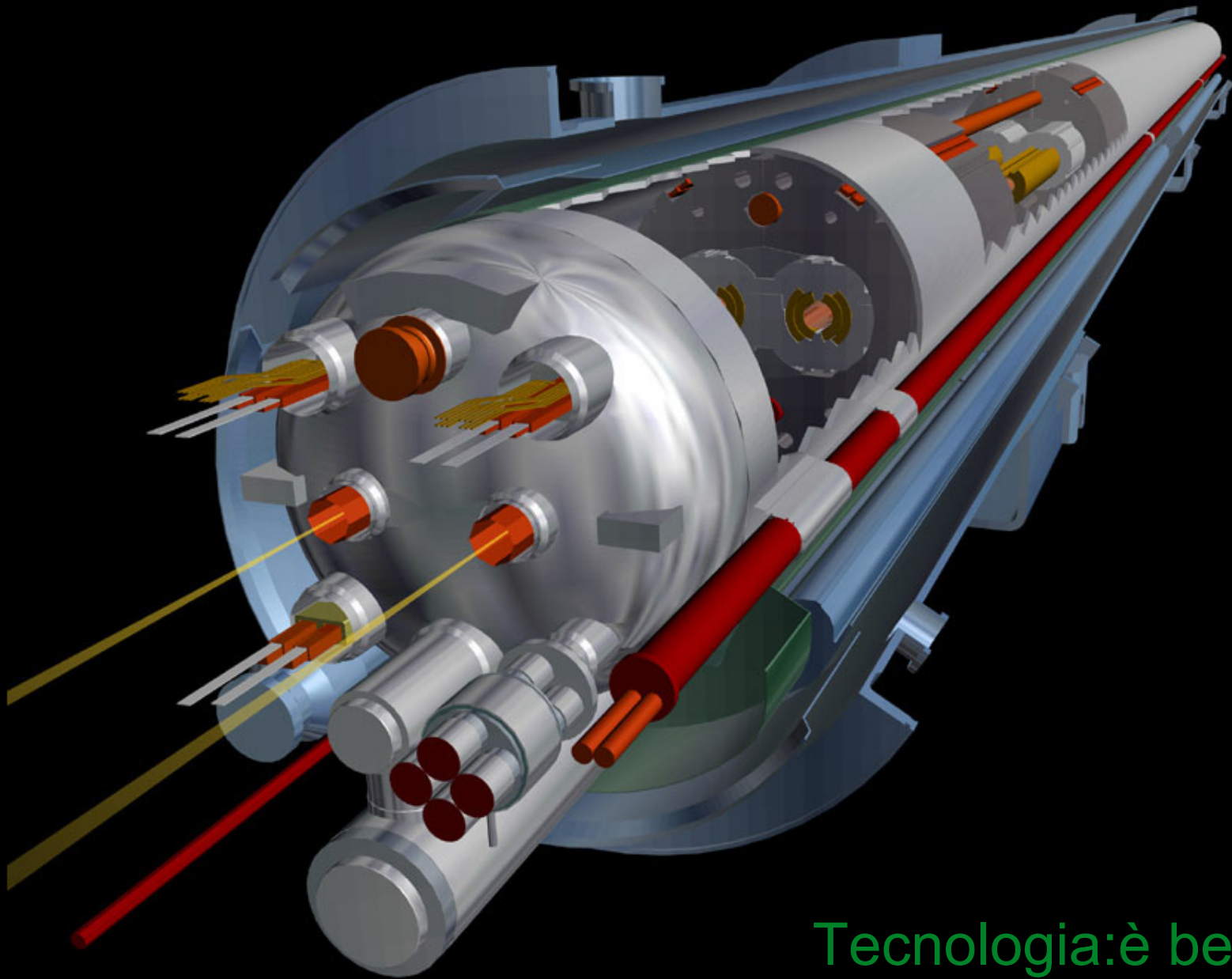
Beam screen con canali di raffreddamento e pumping slots

Camera a vuoto



I collimatori devono sempre toccare il fascio per primi!

Collimatori sono vicini al fascio durante la rampa



Tecnologia: è bella
quando è ben fatta!