(Long) Wide Aperture (High-Field) Superconducting Magnets

4th Patras Workshop,
DESY, 20.06.2008

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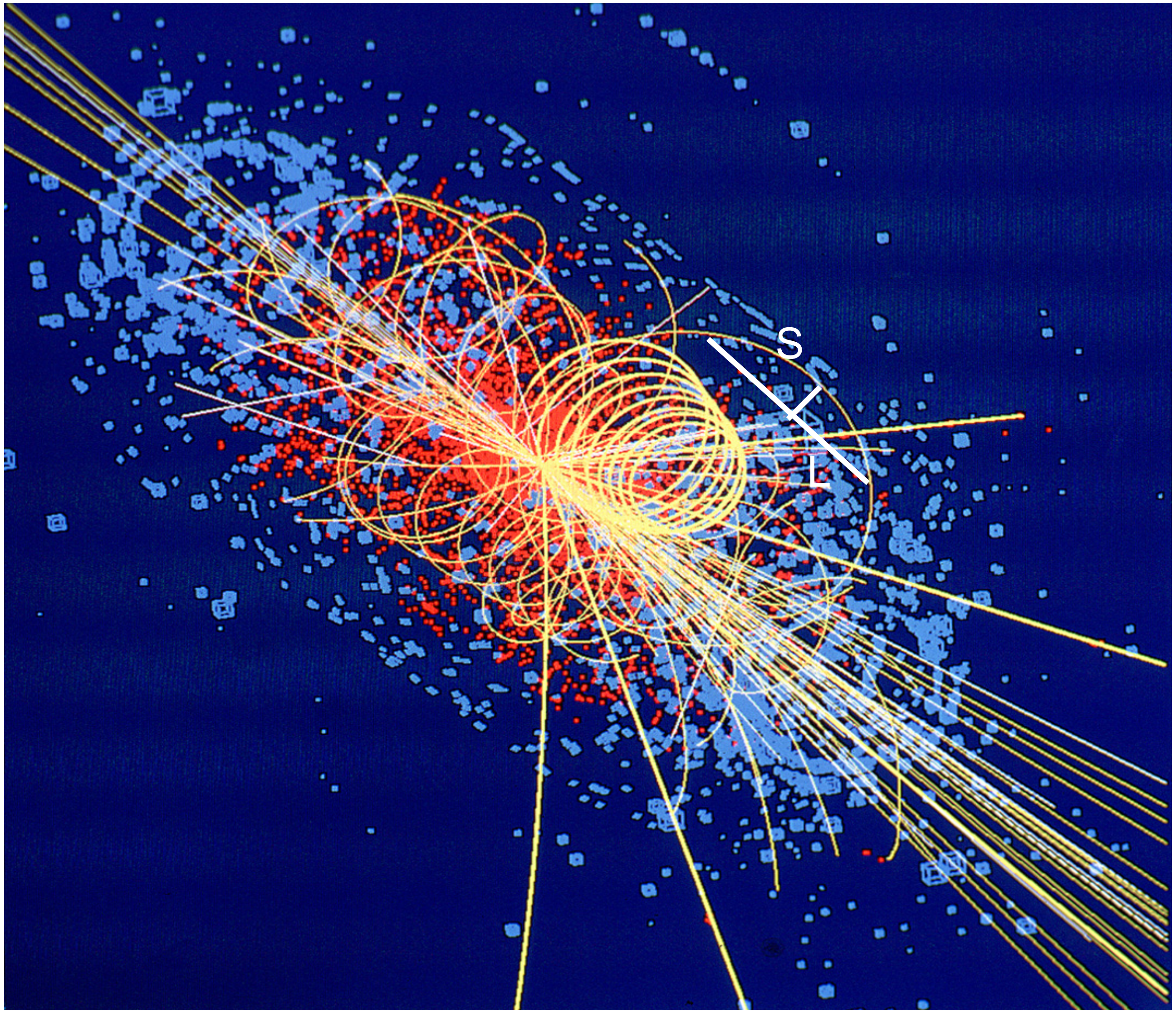
CERN, MEI-FP

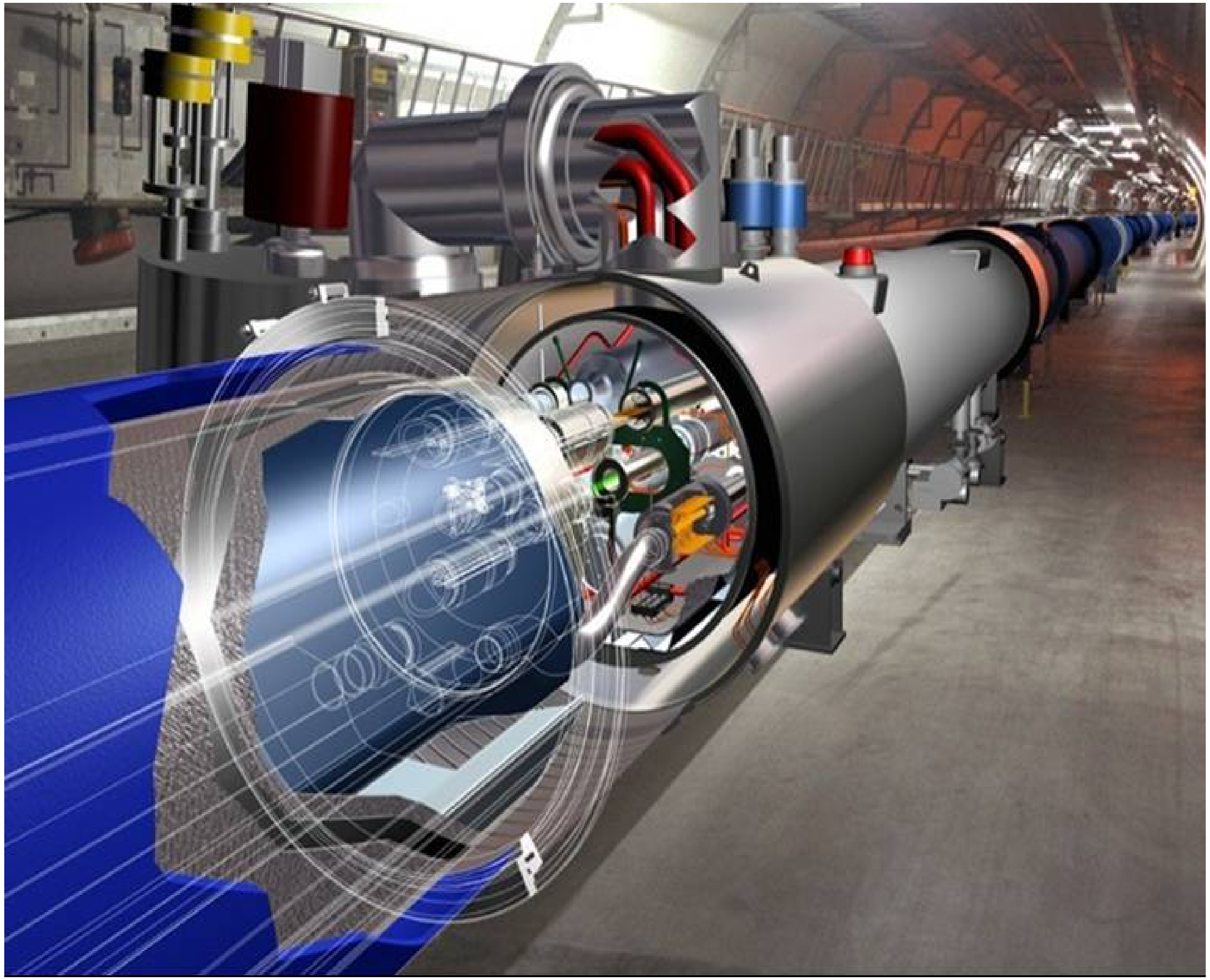
Higgs Event (Simulated)

$$S = R(1 - \cos\frac{\alpha}{2}) \approx \frac{R\alpha^2}{8} = \frac{QBL^2}{8p}$$



LHC in the LEP Tunnel (Maximum Energy)

$$\{p\}_{\mathrm{GeV/c}} \approx 0.3\{Q\}_e\{R\}_{\mathrm{m}}\{B_0\}_{\mathrm{T}}$$



CAST Experiment

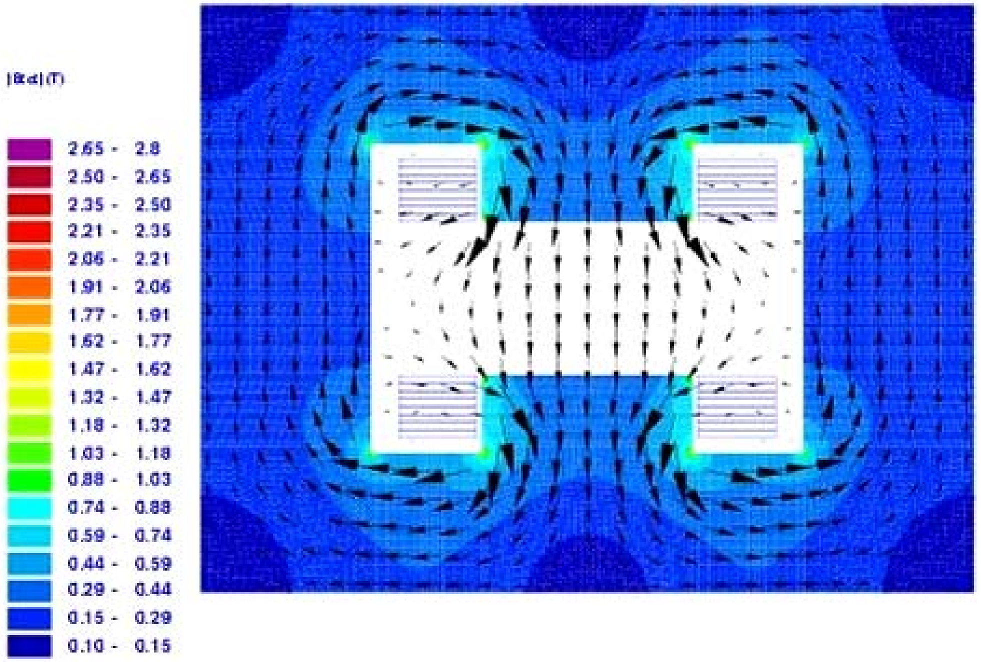
Conversion efficiency Q $(BL)^2$ Signal rate Q $(BL)^2A$

Magnetic length 9.26 m, Flux density 9 T, Aperture 50 mm, Coldbore 43-46 mm

Accelerator Magnet Requirements

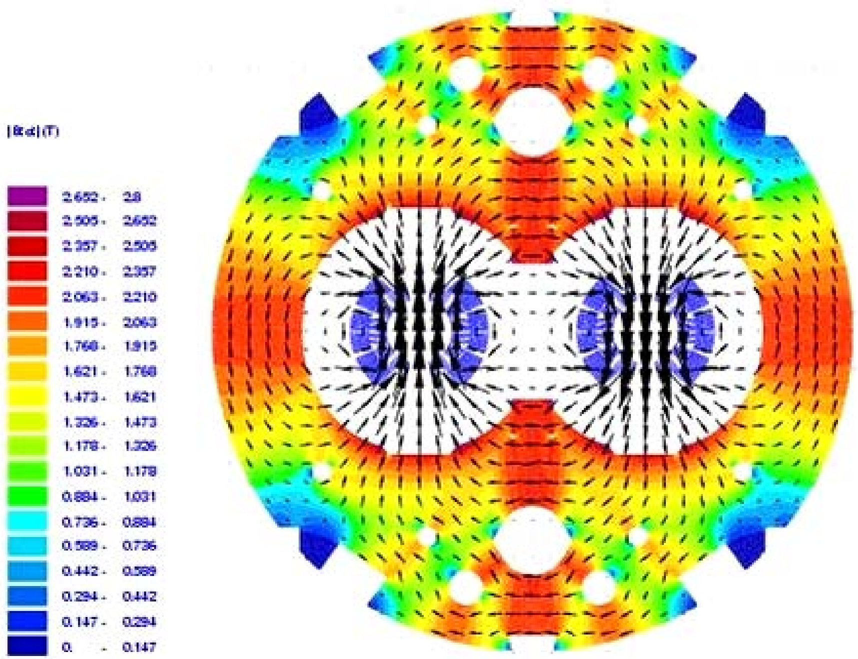
- ➔ Field quality
  - Filament magnetization
  - Saturation
- ➔ Ramp induced field errors
- ➔ Beam losses
- ➔ No training
- ➔ Series connection
  - Cold diodes
  - No energy extraction
- ➔ Sagitta
- ➔ Stationary
- ➔ Prototyping

- ➔ -
- ➔ -
- ➔ -
- ➔ -
- ➔ -
- ➔ Training is possible
- ➔ Single magnet
  - Power supply
  - Energy extraction possible
- ➔ Straight
- ➔ Moving
- ➔ No prototype work possible (except short model)



$N \cdot I = 24000$ A $\quad B_1 = 0.3$ T $\quad B_S = 0.065$ T $\quad$ Fill.fac. 0.98

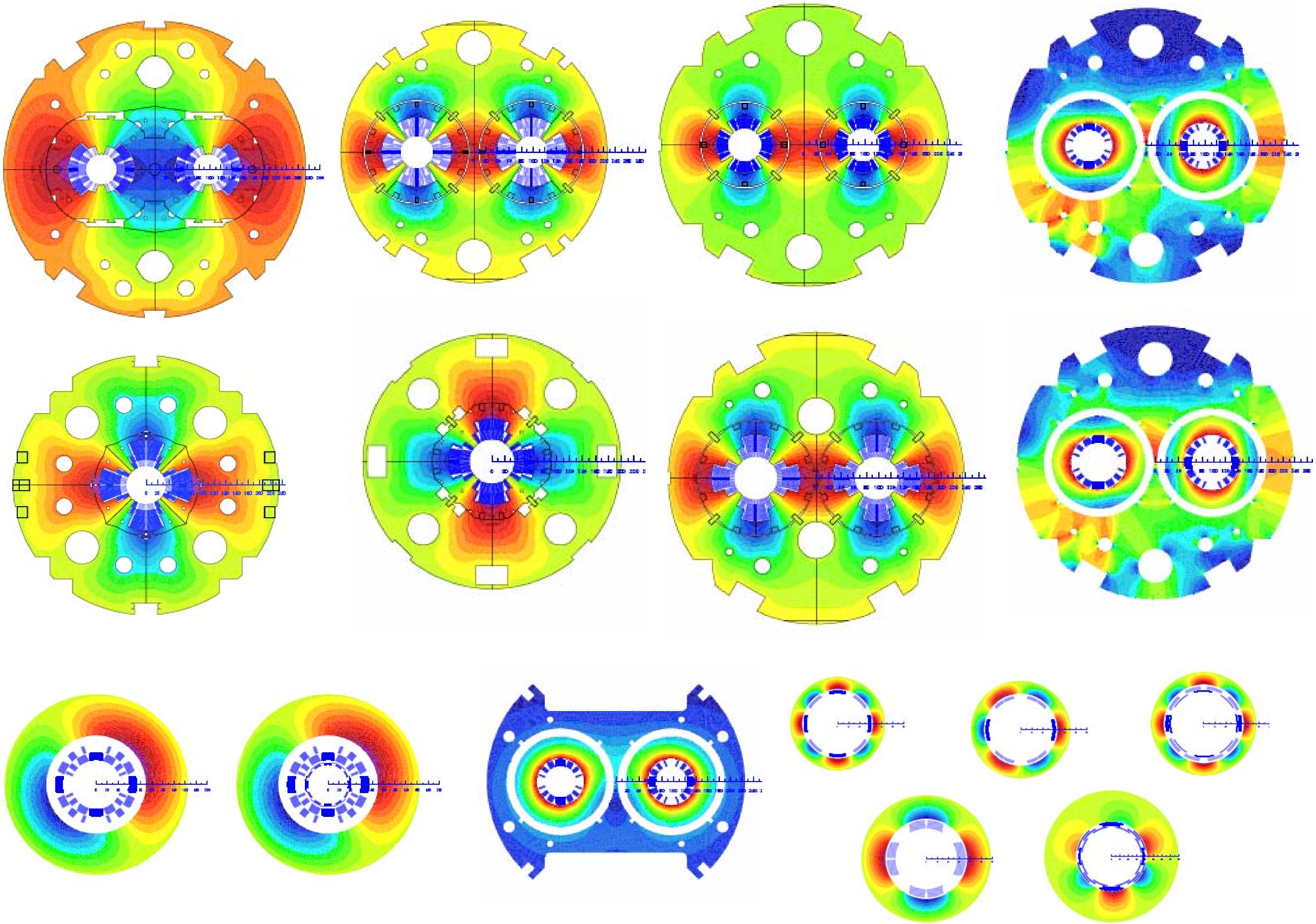
LHC Two-in-one Dipole (Coil Dominated)



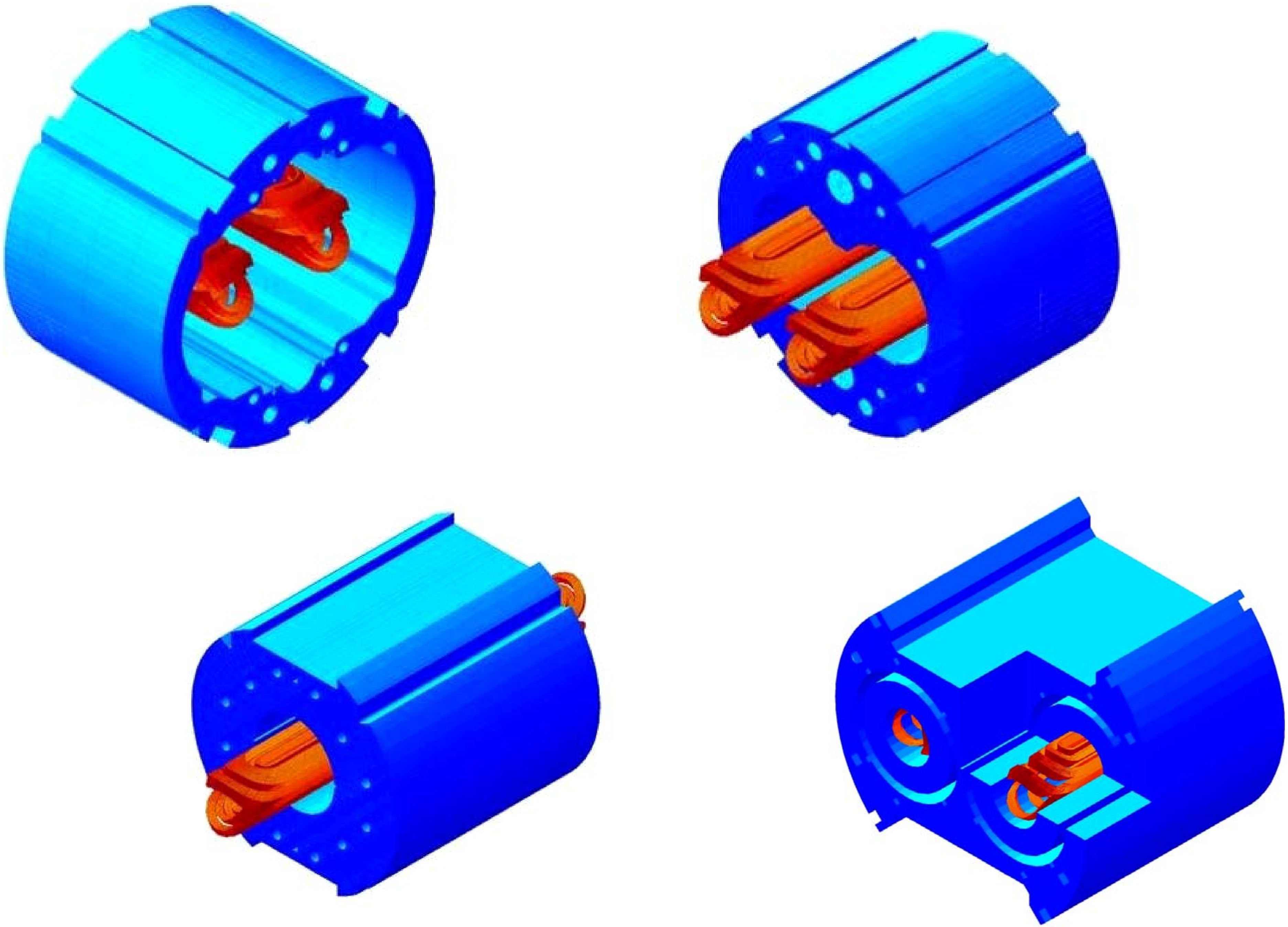
$N \cdot I = 2x944000$ A $B_1 = 8.32$ T $B_S = 7.44$ T

Operational field	8.3 T
Coil aperture	56 mm
Magnetic length	14.3 m
Operating current	11800 A
Stored energy	6.9 MJ

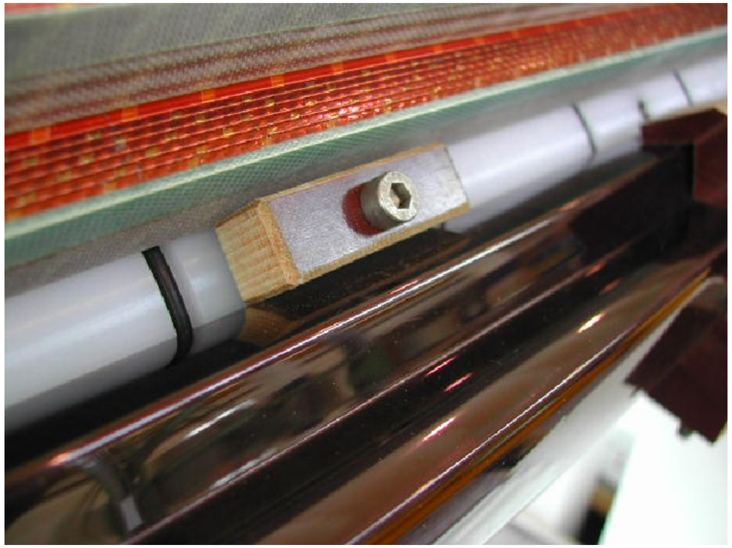
The LHC Magnet Zoo

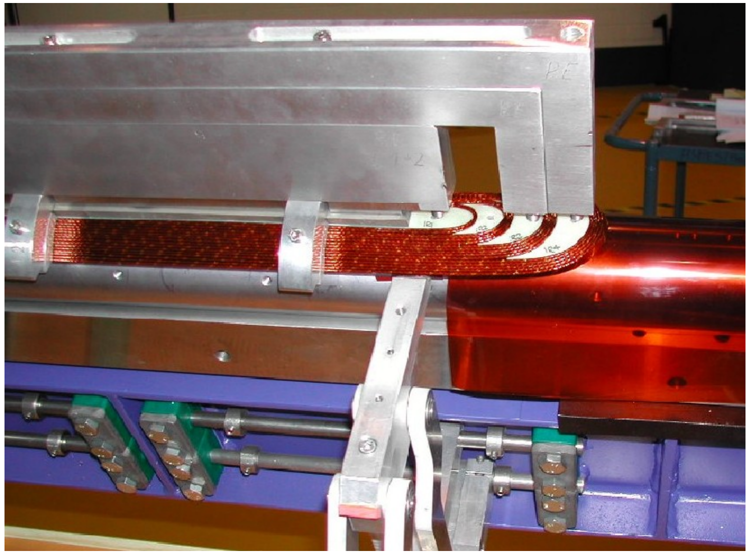


Magnet Extremities

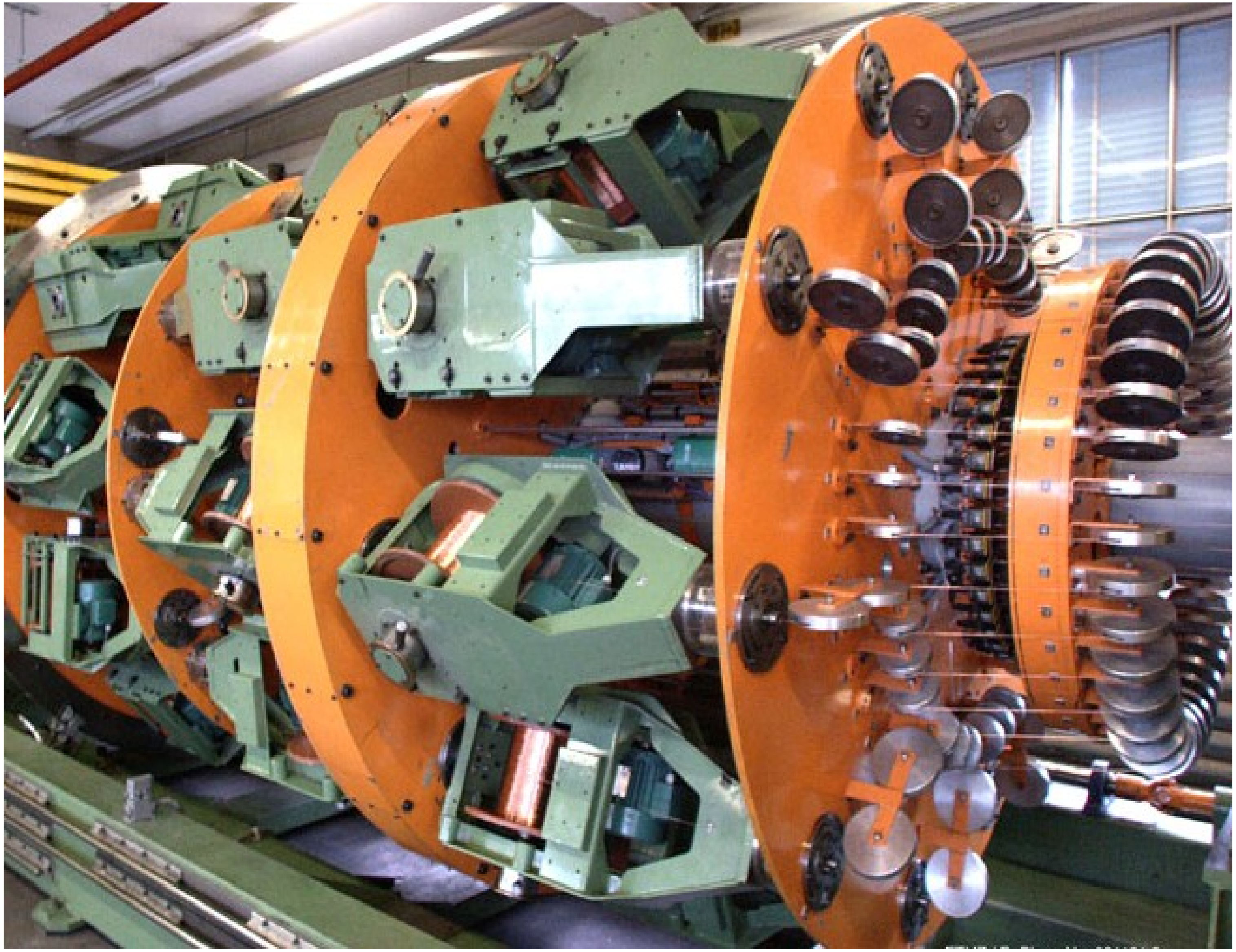


Coil Winding



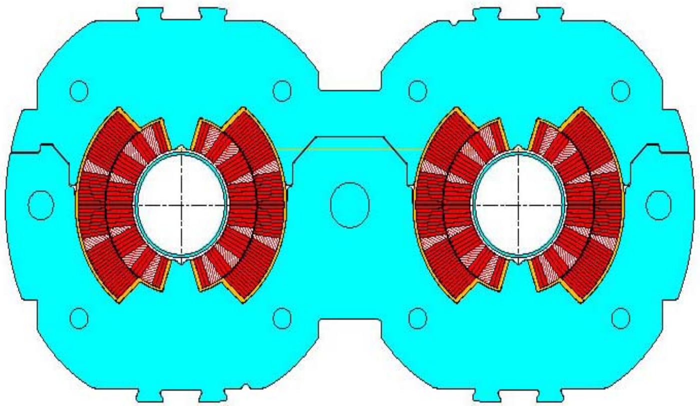


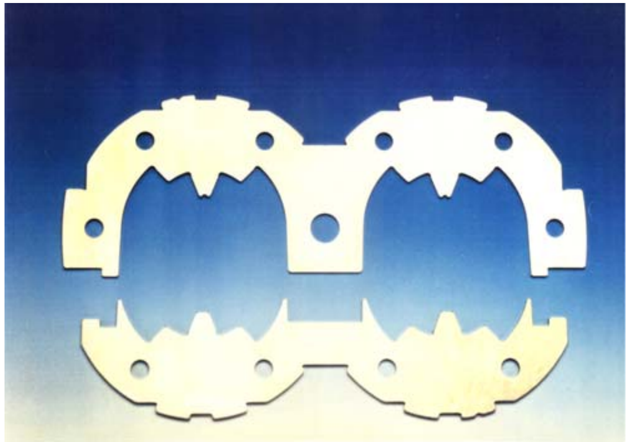
Cabling Machine for Rutherford Cables



Winding and Curing Tooling

Collaring Tooling





Collaring (an Alternative for Magnets > 16 m)

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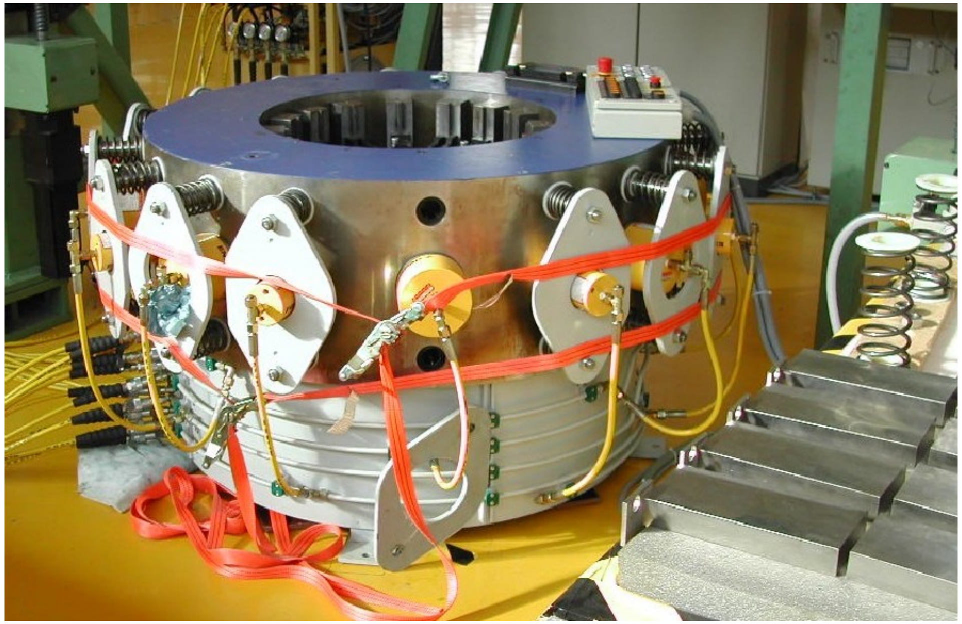
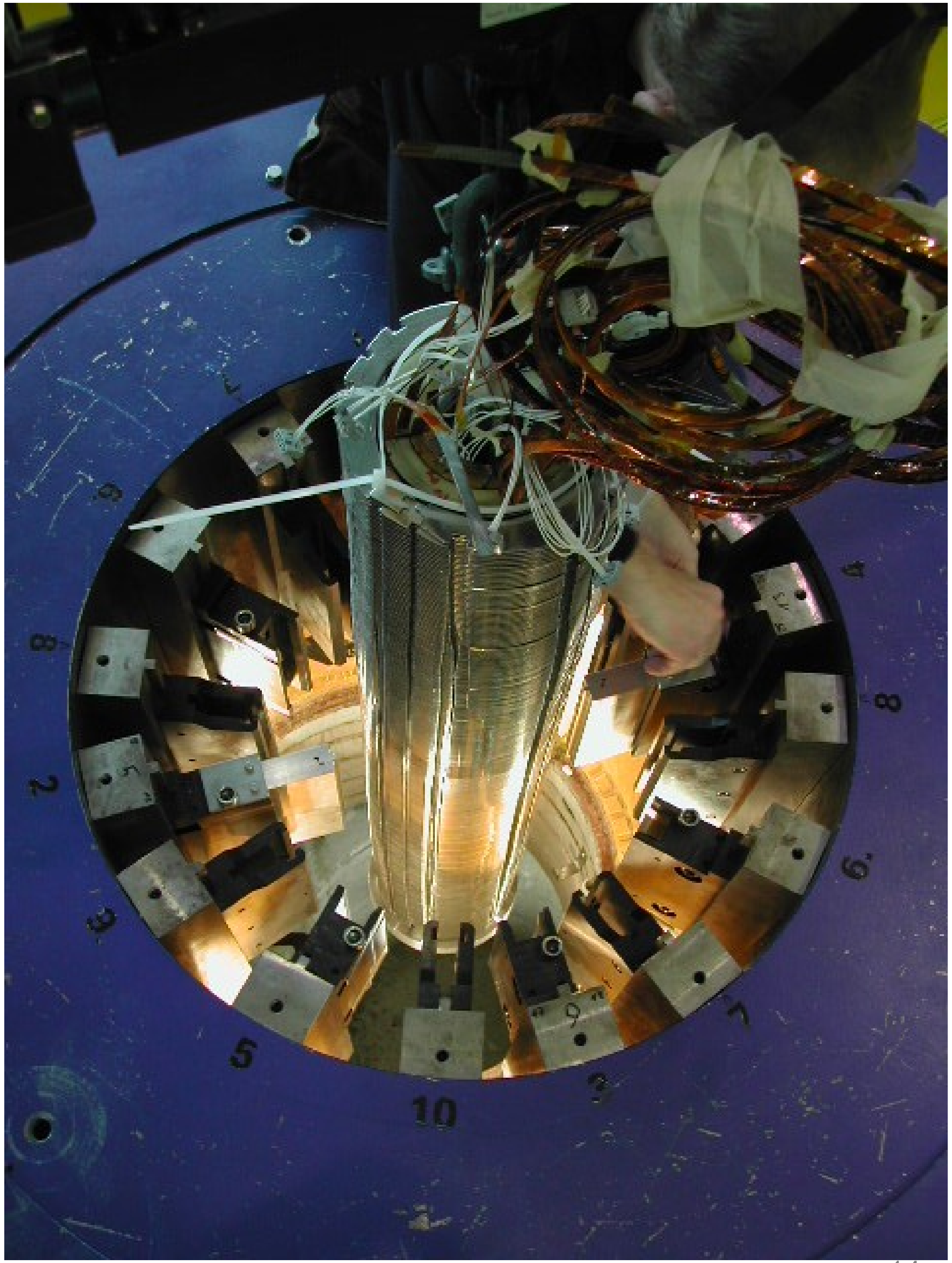
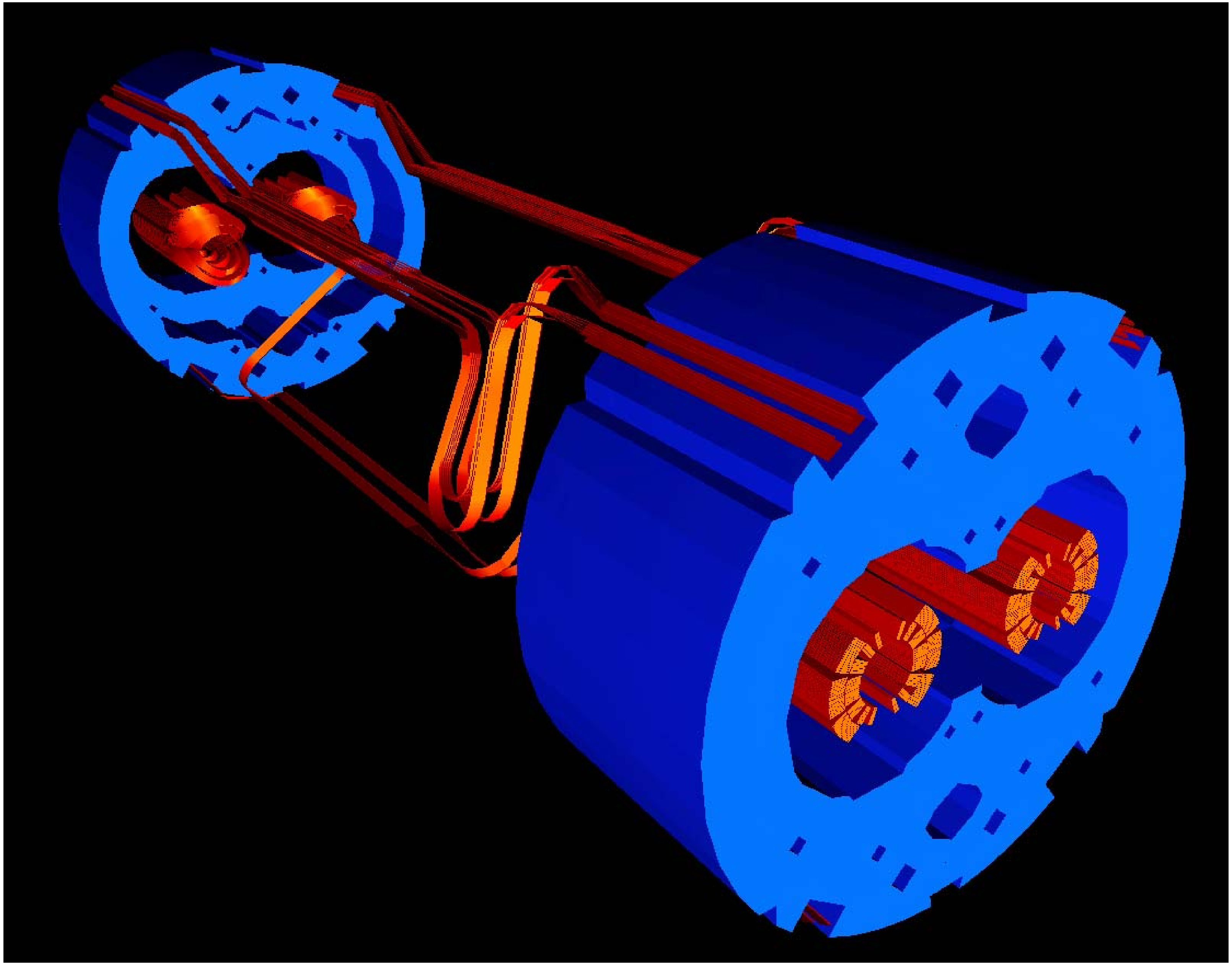
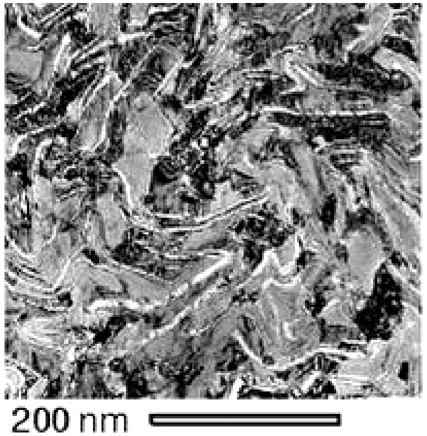




Virtual Reality Preview of Electrical Interconnection

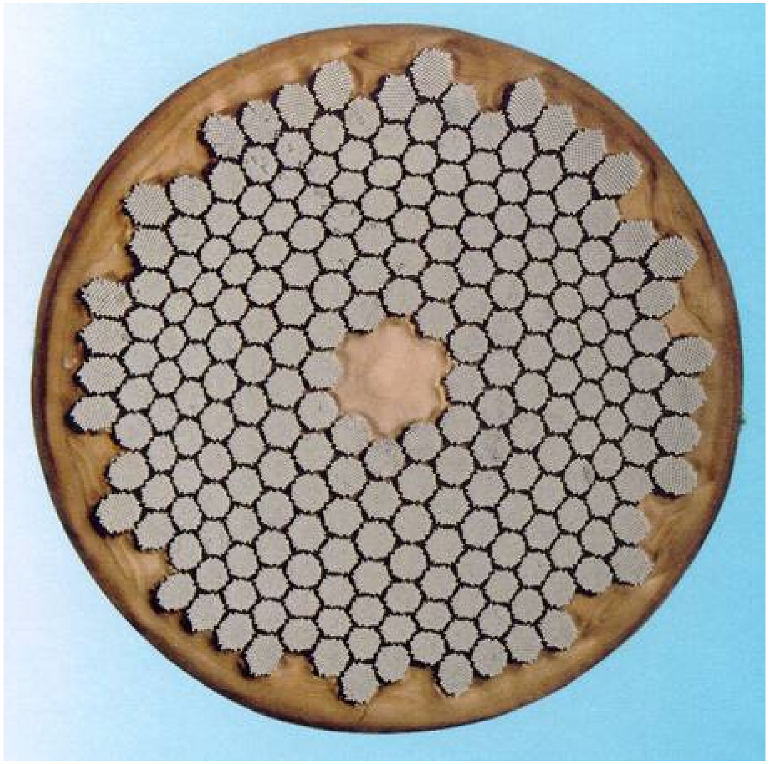


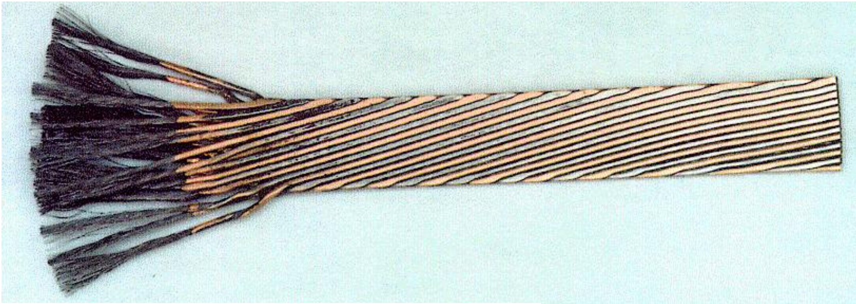
Rutherford Cable, Strand, NbTi Filament

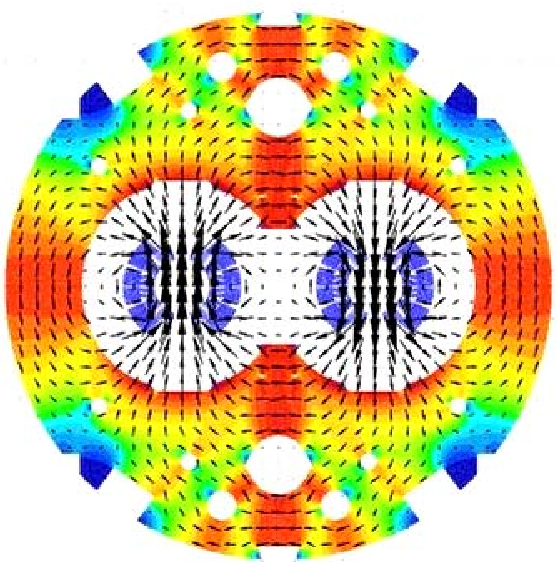


6 µm

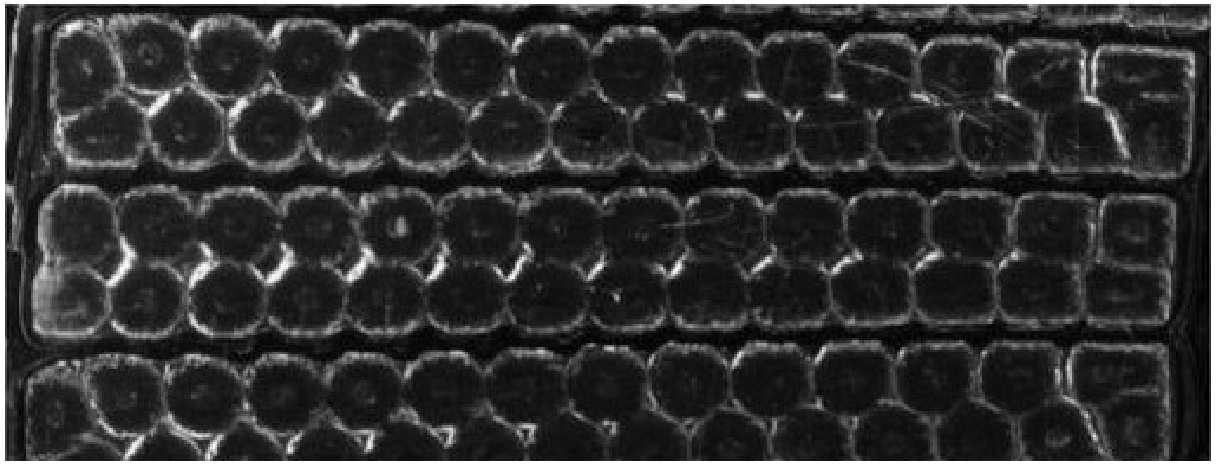
1 mm



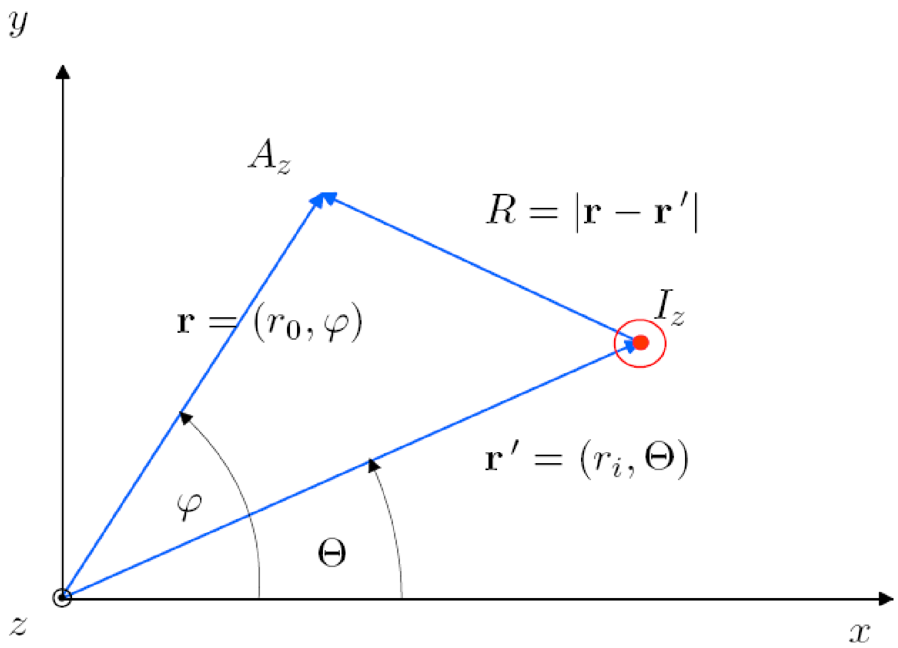




15 mm



The Field of a Line Current



$$B_n(r_0) = -\frac{\mu_0 I}{2\pi}\frac{r_0^{n-1}}{r_i^n}\cos n\Theta$$

$$A_n(r_0) = \frac{\mu_0 I}{2\pi}\frac{r_0^{n-1}}{r_i^n}\sin n\Theta$$

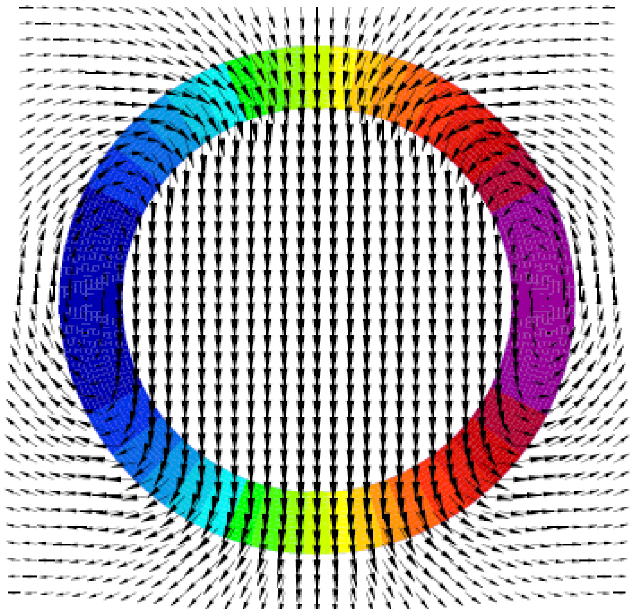
$$A_z(r_0,\varphi) = -\frac{\mu_0 I}{2\pi}\ln\left(\frac{r_i}{R_{\text{ref}}}\right) + \frac{\mu_0 I}{2\pi}\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r_0}{r_i}\right)^n \cos\left(n(\varphi-\Theta)\right), \qquad r_0 < r_i$$

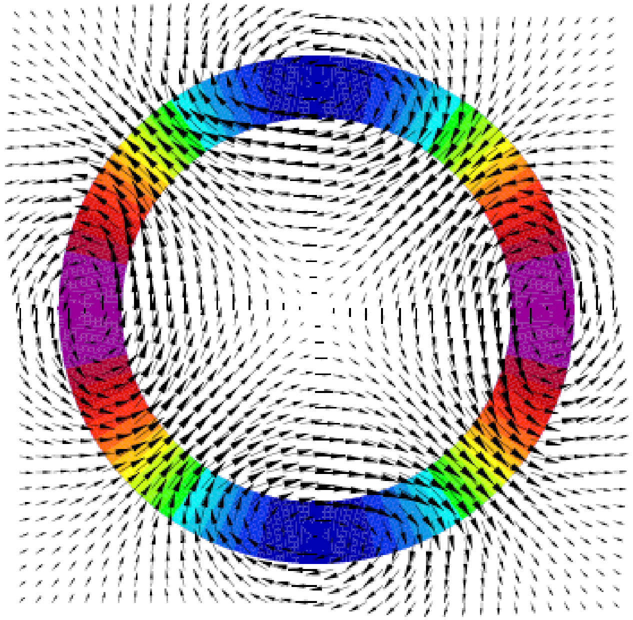
$$B_r(r_0,\varphi) = \frac{1}{r_0}\frac{\partial A_z}{\partial\varphi} = -\frac{\mu_0 I}{2\pi}\sum_{n=1}^{\infty}\left(\frac{r_0^{n-1}}{r_i^n}\right)\sin\left(n(\varphi-\Theta)\right)$$

$$= -\frac{\mu_0 I}{2\pi}\sum_{n=1}^{\infty}\left(\frac{r_0^{n-1}}{r_i^n}\right)(\sin n\varphi\,\cos n\Theta - \cos n\varphi\,\sin n\Theta), \qquad r_0 < r_i.$$

Ideal Current Distributions

$$B_n(r_0) = \int_{r_a}^{r_e} \int_0^{2\pi} -\frac{\mu_0 J_E r_0^{n-1}}{2\pi r^n} \cos m\Theta \cos n\Theta \, r d\Theta \, dr$$



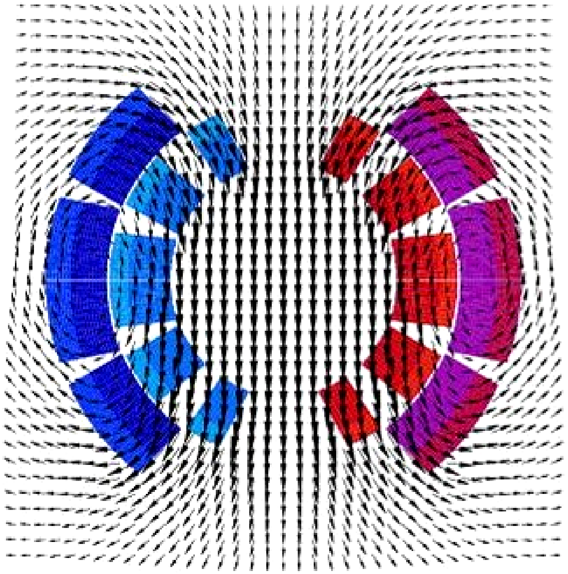


$$B_1(r_0) = -\frac{\mu_0 J_E}{2}(r_e - r_a)$$

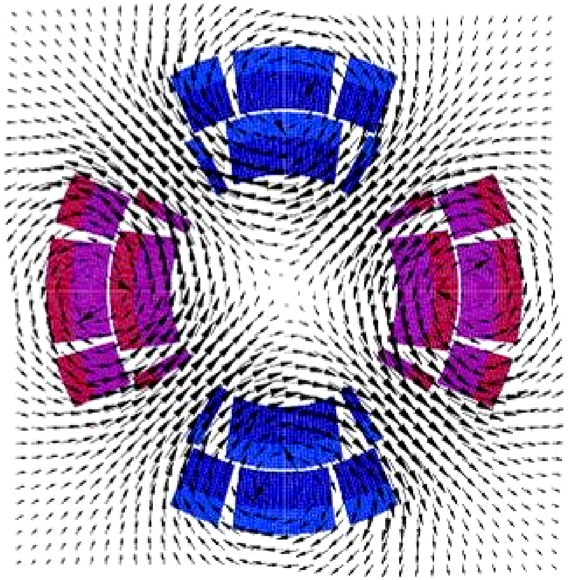
$$B_2(r_0) = -\frac{\mu_0 J_E r_0}{2} \ln\left(\frac{r_e}{r_a}\right)$$

Coil Block Approximation

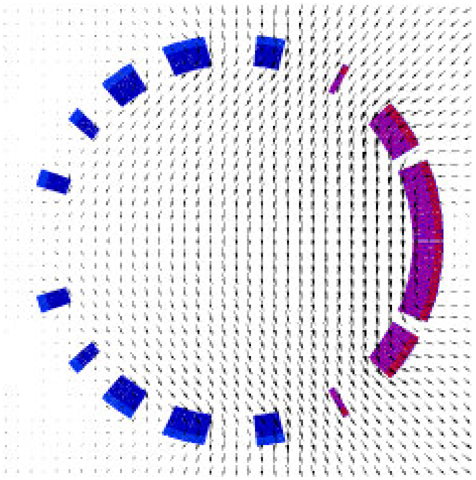
Dipole

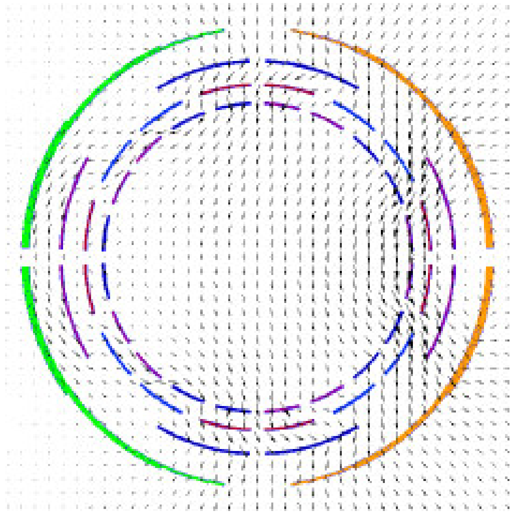


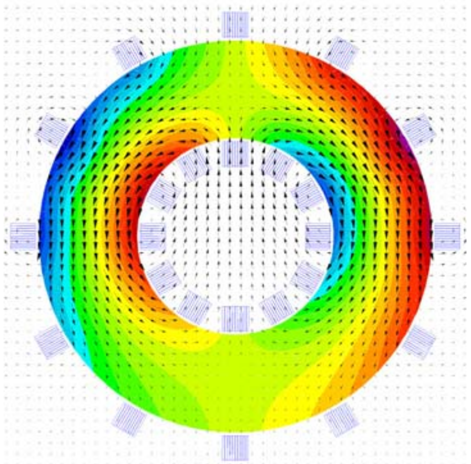
Quadrupole



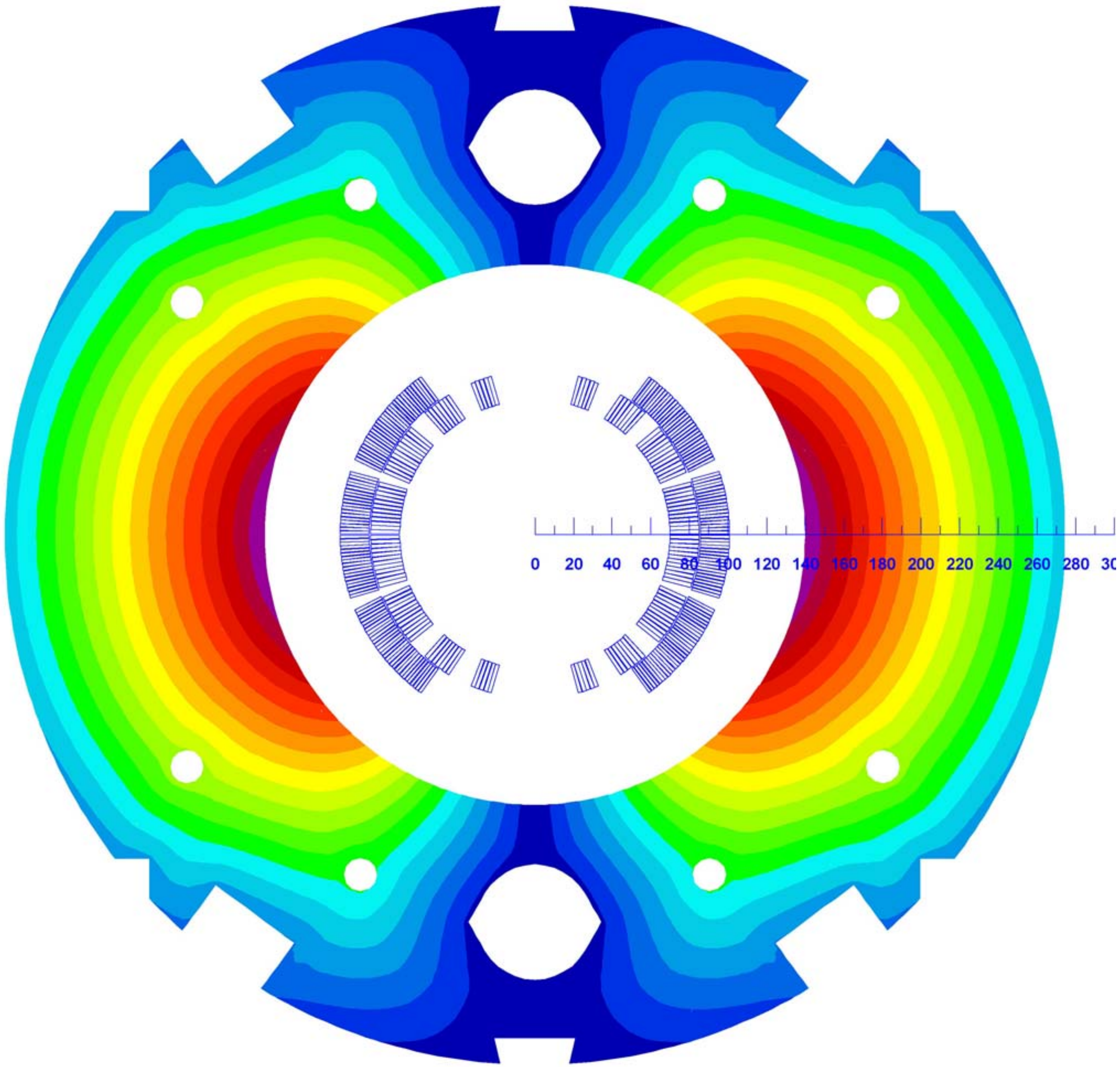
Combined Function Magnets





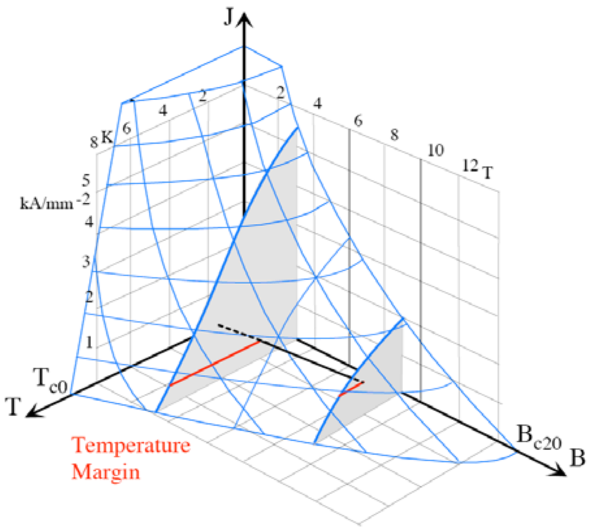


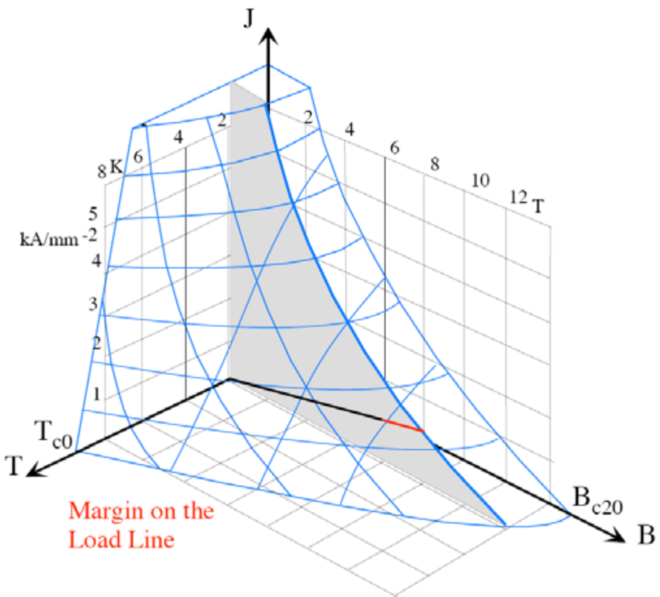
A Magnet based on LHC Technology

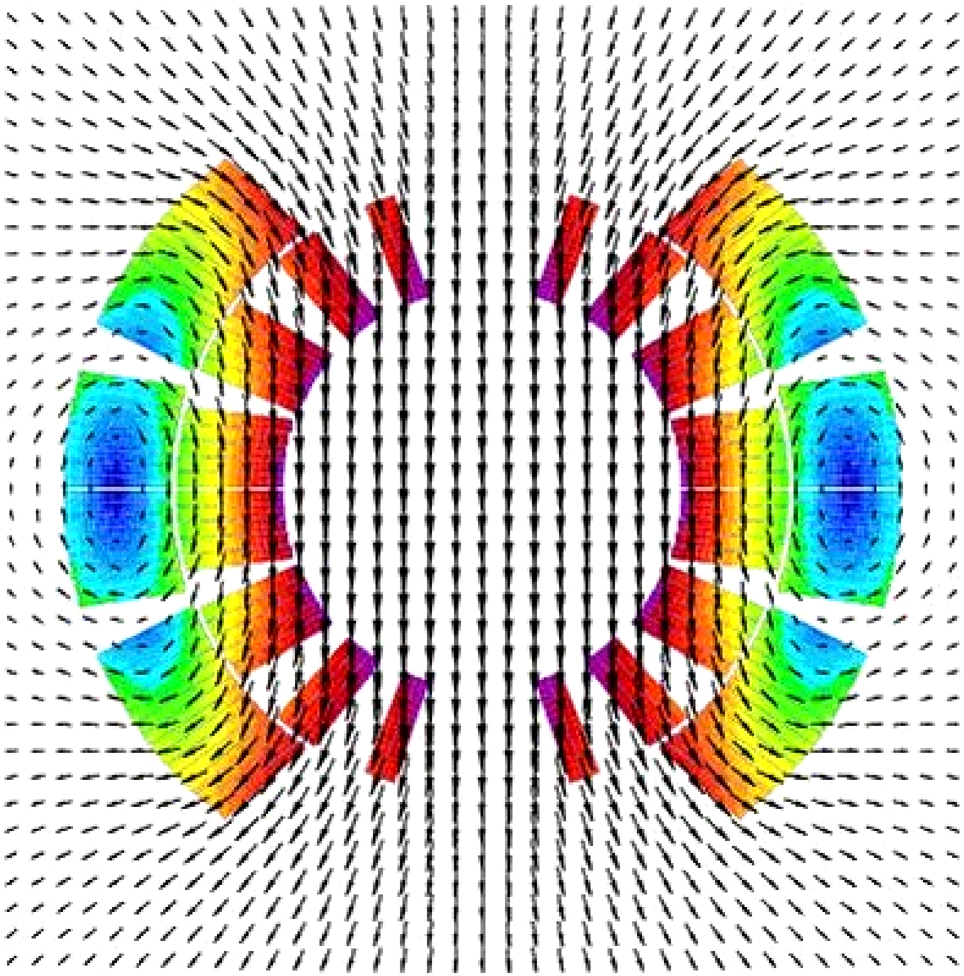


Flux density: 9 T
Length: 16 m
Aperture: 140 mm

Critical Surface of NbTi







$$B = \frac{\mu_0}{2} J_{\mathrm{E}}(r_{\mathrm{e}} - r_{\mathrm{a}}) = \frac{\mu_0}{2} \lambda_{\mathrm{tot}}\, J_{\mathrm{c}}\,(r_{\mathrm{e}} - r_{\mathrm{a}}) = \frac{\mu_0}{2} \lambda_{\mathrm{tot}}\, d\,(B_{\mathrm{c2}} - B)\,(r_{\mathrm{e}} - r_{\mathrm{a}})$$

Peter Lee's Plot of SC Critical Current Density

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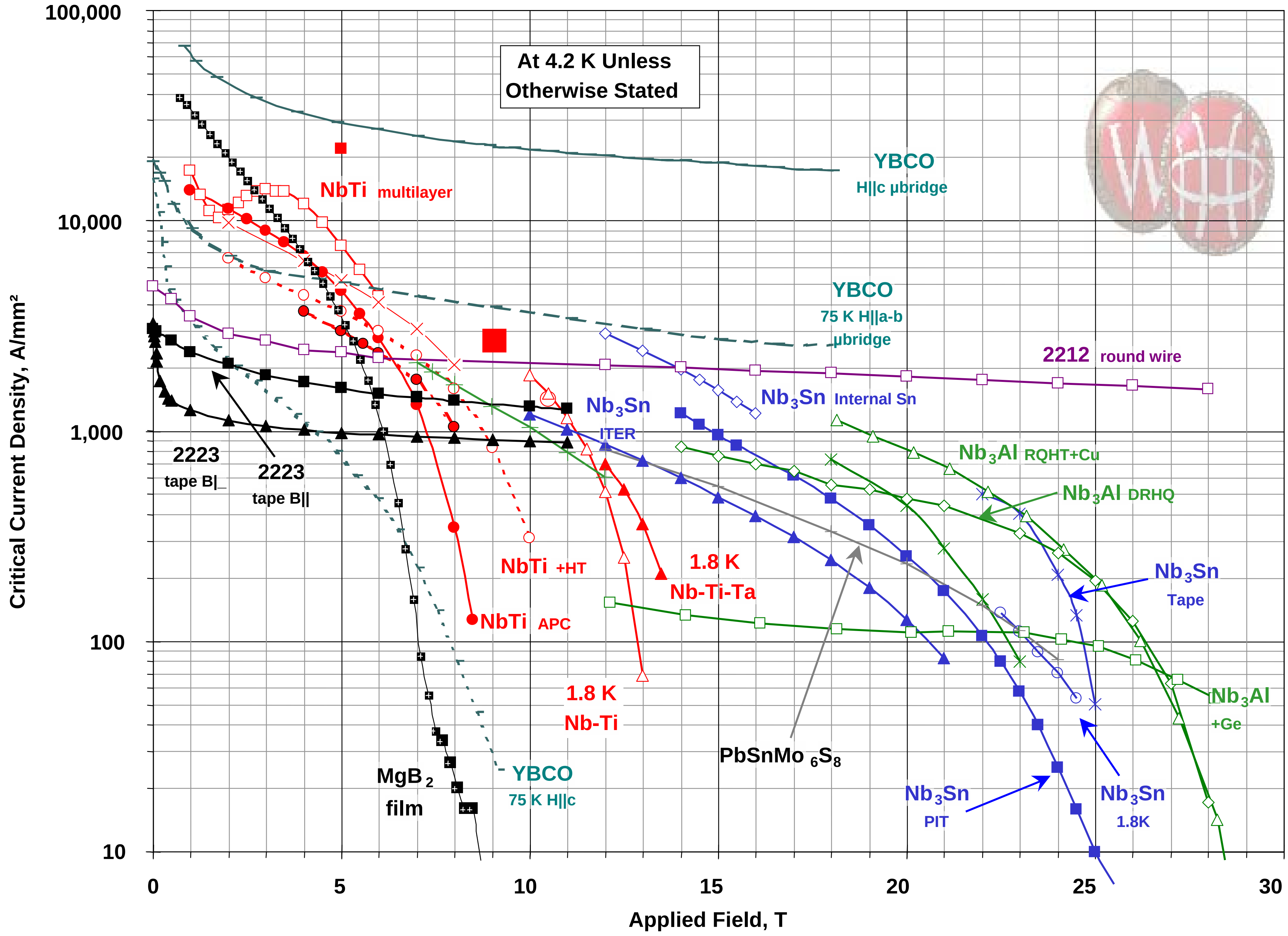
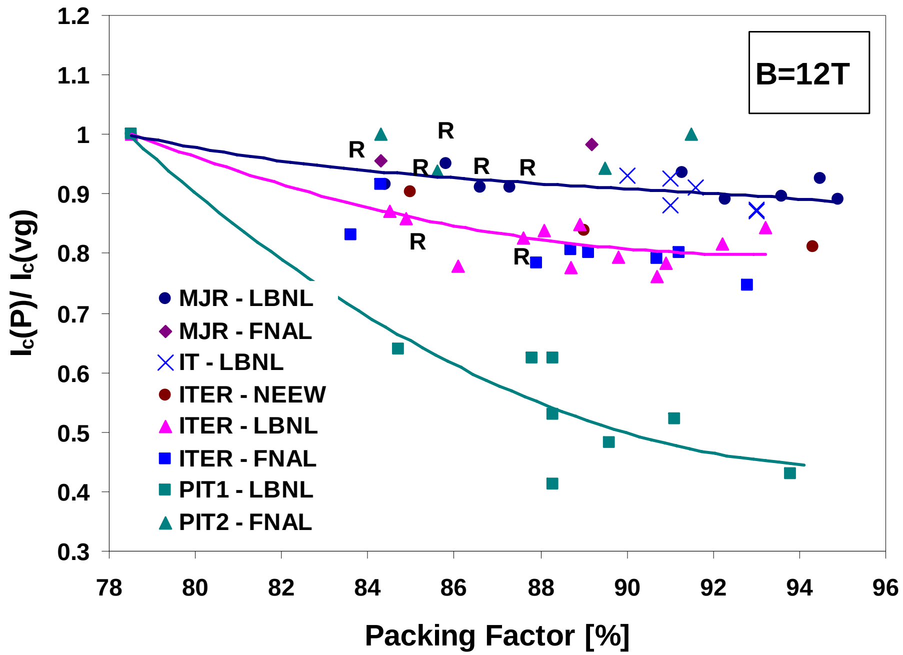
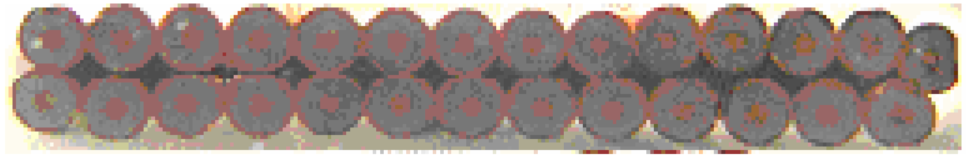
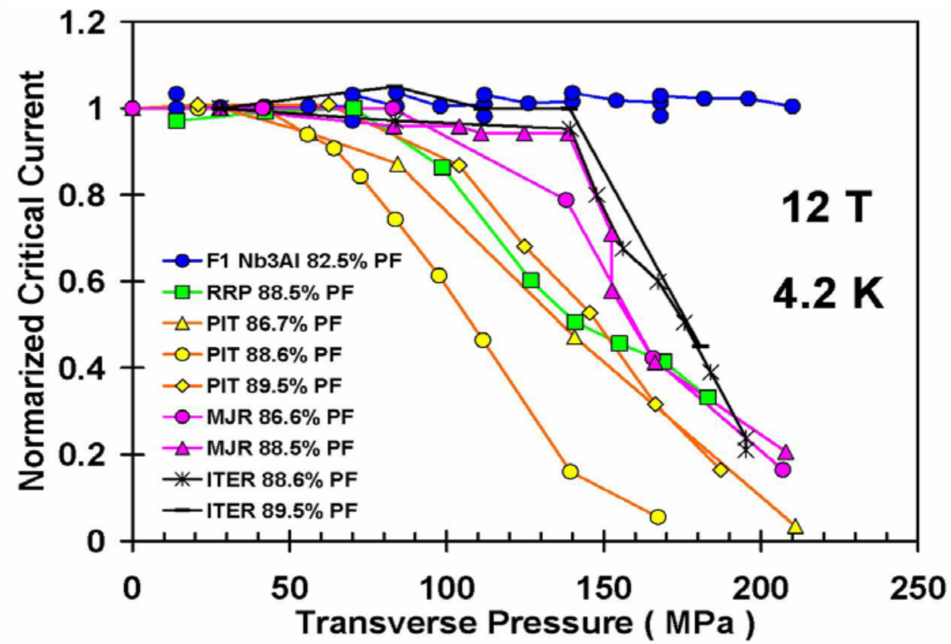


Nb_3Sn Rutherford Cable (Ref: P. Ferracin, Wamsdo Workshop 2008)





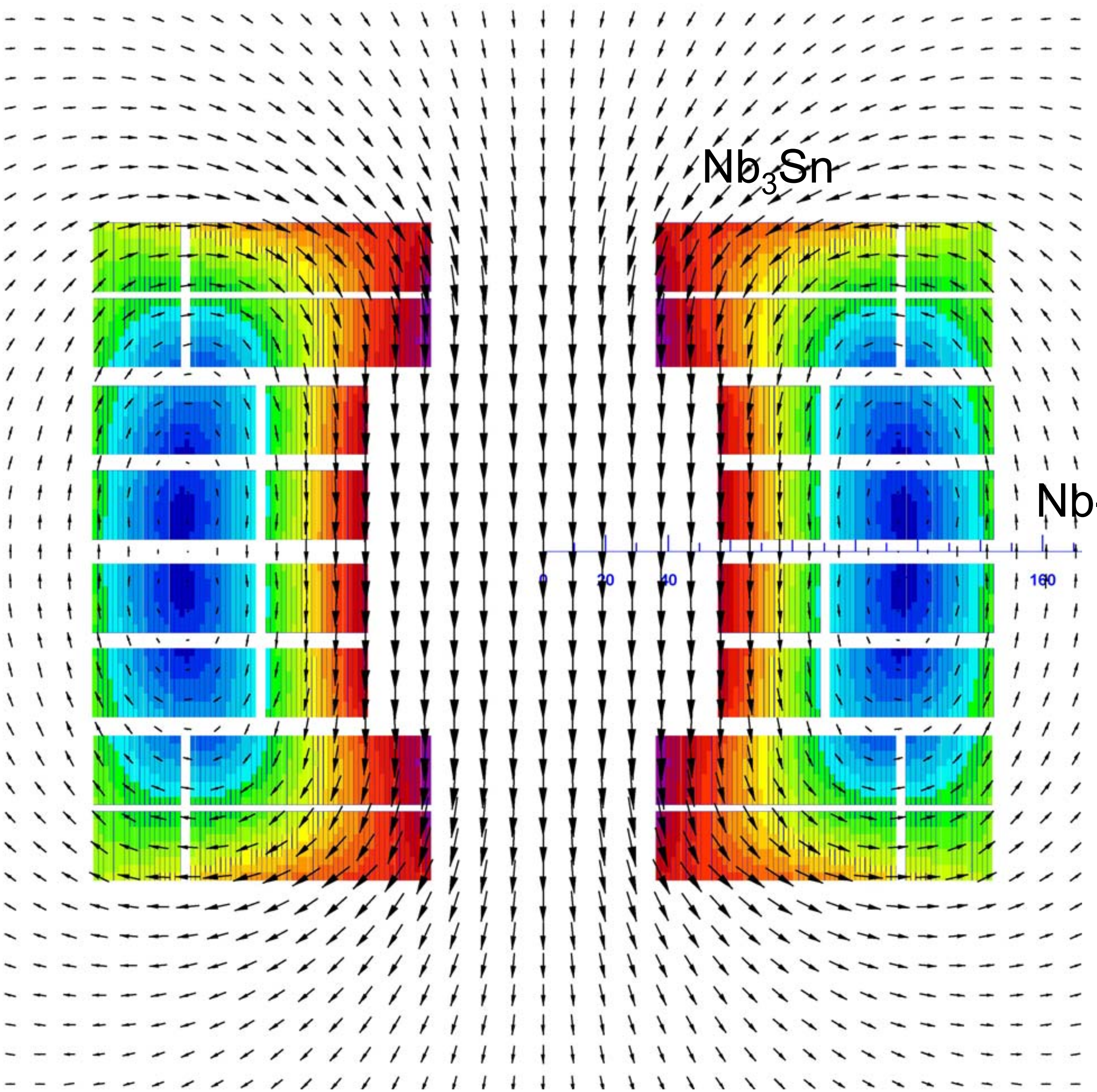
Power in Tube (PIT), Modified Jelly Roll (MJR) and Rod Restack Process (RRP) developed and studied at LBL.



- ➔ Ic and RRR degradation
- ➔ Low non-uniform interstrand contact resistance
- ➔ Bridle material
- ➔ High temperature insulation because of wind and react
- ➔ Epoxy impregnated coils

See also A. Godeke et al. and T. Collings (WAMSDO’2008).

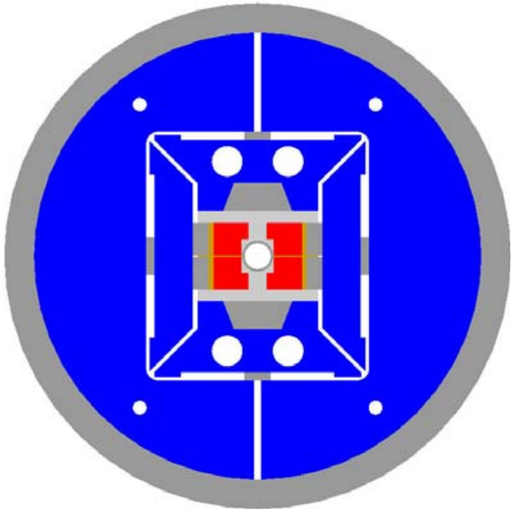
The (Realistic) Goal for 2013 (4 m, 13 T, 100 mm)



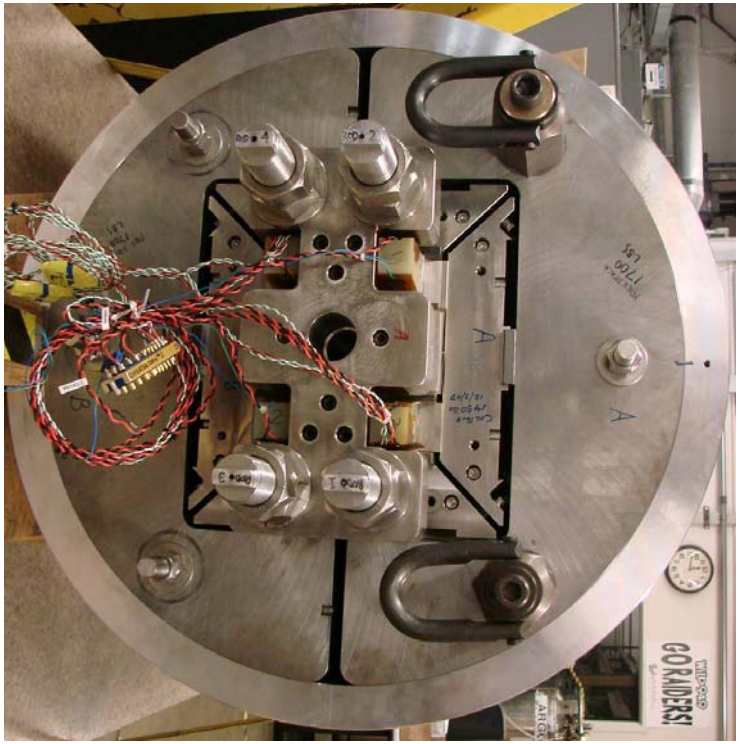
Stress management
Two materials
Two power supplies

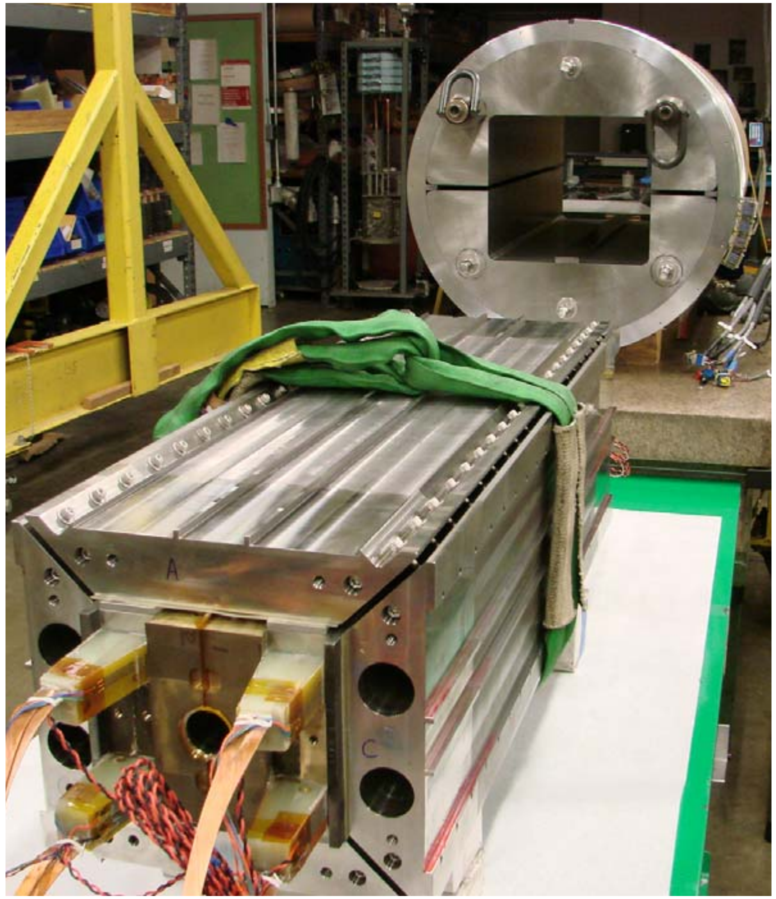
With interest and money
8 m, 13 T possible by
2016

HD2 Magent (Ref: P. Ferracin, Wamsdo 2008)



Reached 13.3 T after
18 Training Quenches

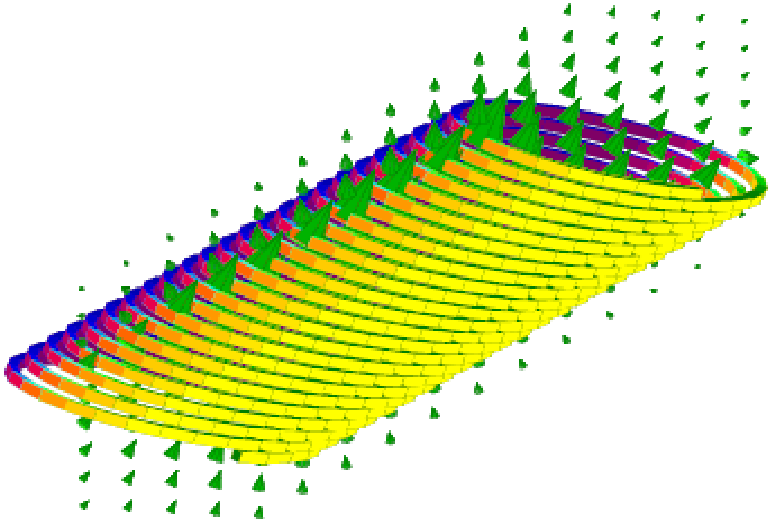


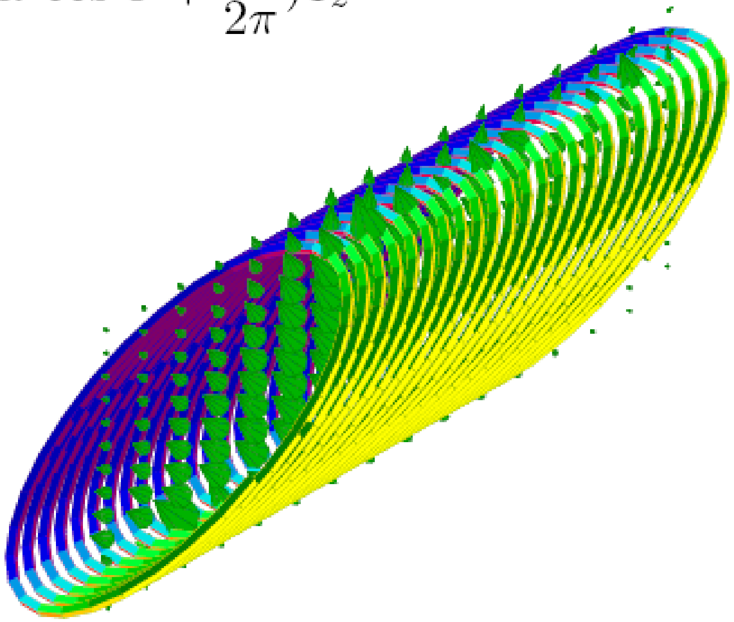


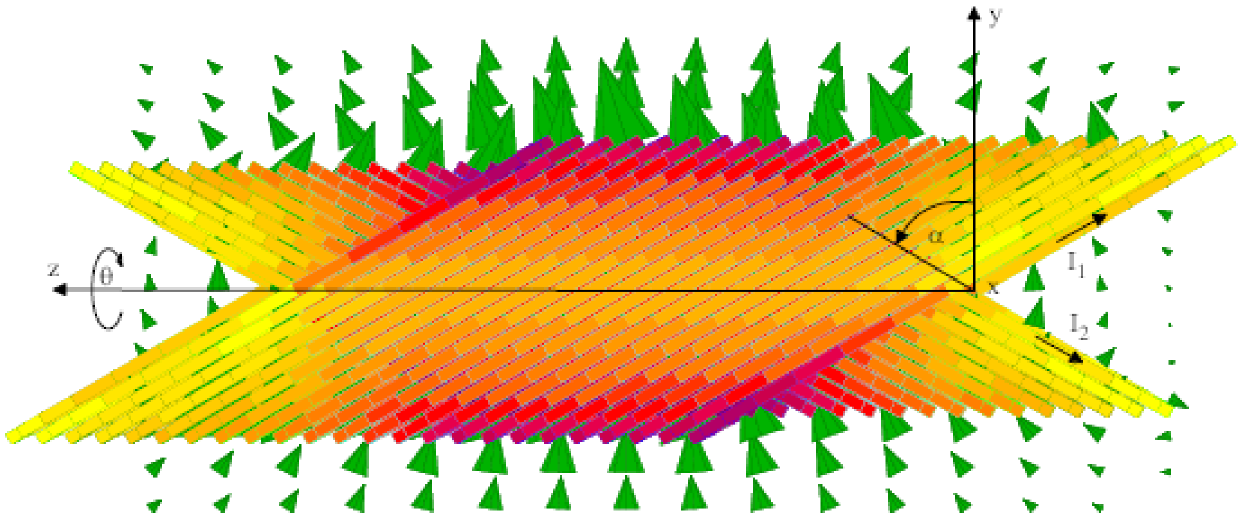
Double Helix Coil (HTC Insert for High Field Dipole)

$$\mathbf{r} = R_1 \cos\Theta \mathbf{e}_x + R_2 \sin\Theta \mathbf{e}_y + (R_2 \sin\Theta\ \tan\alpha + p\frac{\Theta}{2\pi})\mathbf{e}_z$$

$$\mathbf{v} = -R_1 \sin\Theta \mathbf{e}_x + R_2 \cos\Theta \mathbf{e}_y + (R_2 \tan\alpha\ \cos\Theta + \frac{p}{2\pi})\mathbf{e}_z$$



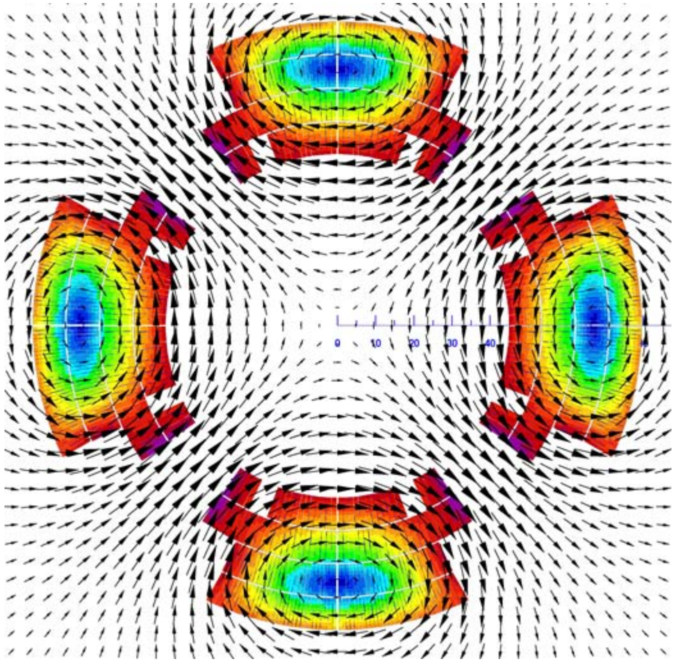


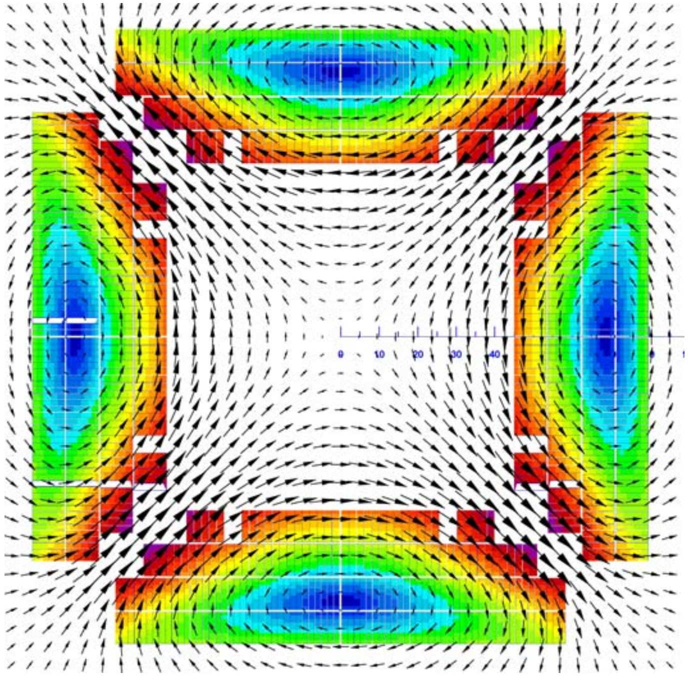


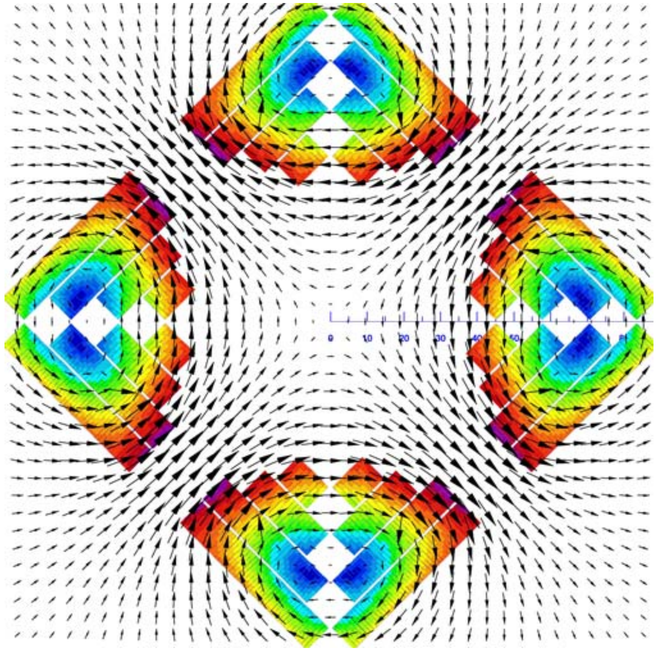
Alternative Layouts for Quadrupoles Nb_3Sn

Goal:

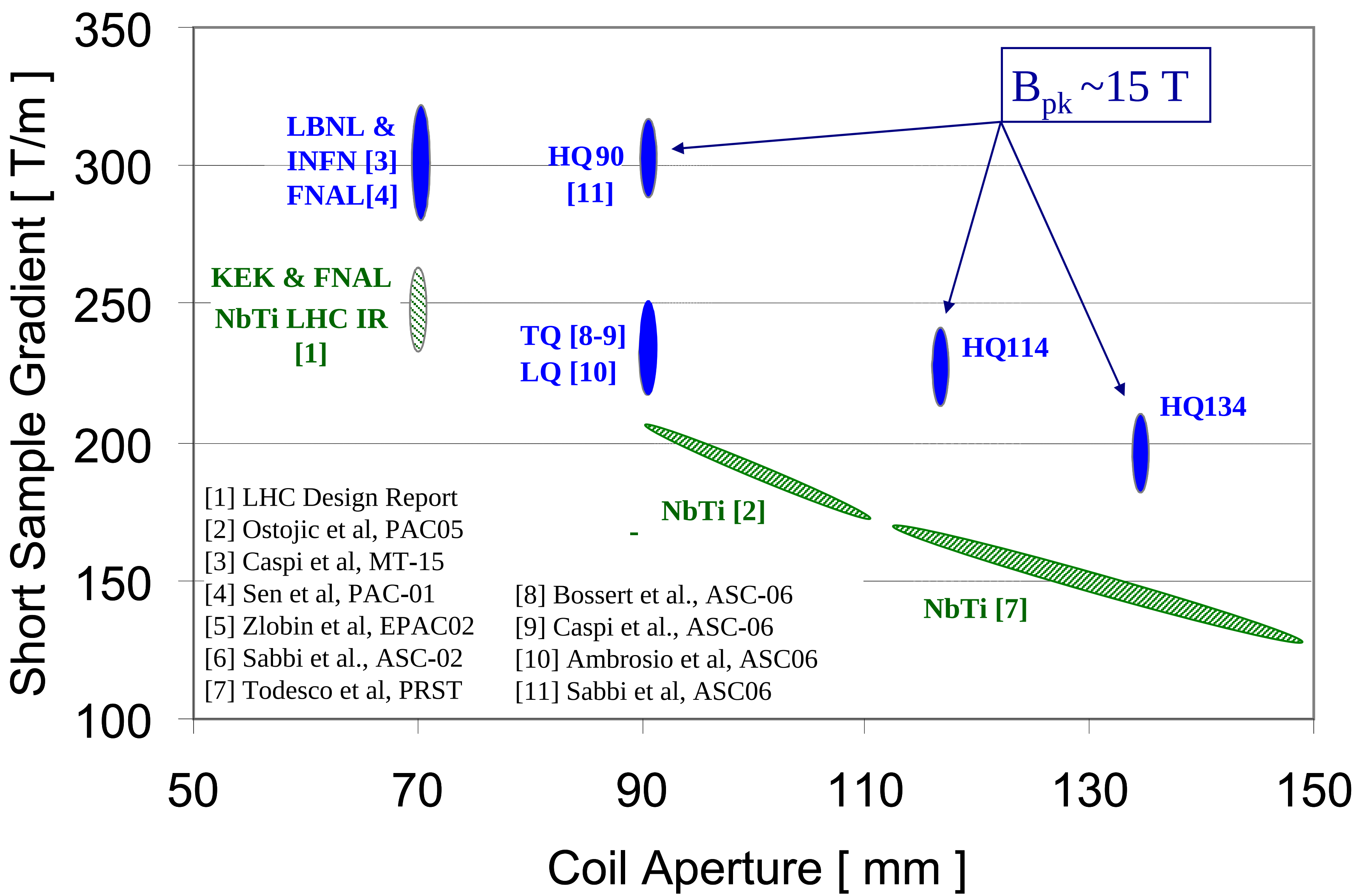
Aperture: 90 -120 mm
Gradient: 200 - 240 T/m







Quadrupole Design Space (Ref: G. Sabbi, Wamsdo 2008)



The Un-Feasible Domain

- Nb-Ti
  - L > 15 m
  - B > 10 T
  - A > 140 mm
  - < 2013 (resources)
  - < 2 MCHF

- Nb_3Sn
  - L > 8 m
  - B > 14 T
  - A > 140 mm
  - Cheap
  - < 2016

Projects to Hook-up with

- NED (Next European Dipole)
  - Nb_3Sn Conductor development with Power in Tube and Internal Tin diffusion technology
- US-LARP (LHC Accelerator Research Program, BNL, FNAL, LBNL, SLAC)
  - LHC-IR Quadrupoles for the next generation
    - LQ: 4 m, 90 mm, 220 T/m Quad in 2009
    - HQ: 1 m, 120 mm, 220 T/m Qaud in 2012
    - LR: 4 m, 12 T, Ractrack, no aperture
    - HD2: 1 m, 36 mm, 12 T (existing)
- EUCARD - CERN HFM (Coordinator G. de Rijk)
    - 1.5 m, 100 mm, 13 T Dipole for FRESCA, 2012
    - 4 m, 100 mm, 12 T Dipole, 2013
    - 4 m, 120 mm, 100 T/m Quad, 2013