CERN Accelerator School

Bruges , Belgium June 16-25 , 2009

MAGNETS

Solenoids

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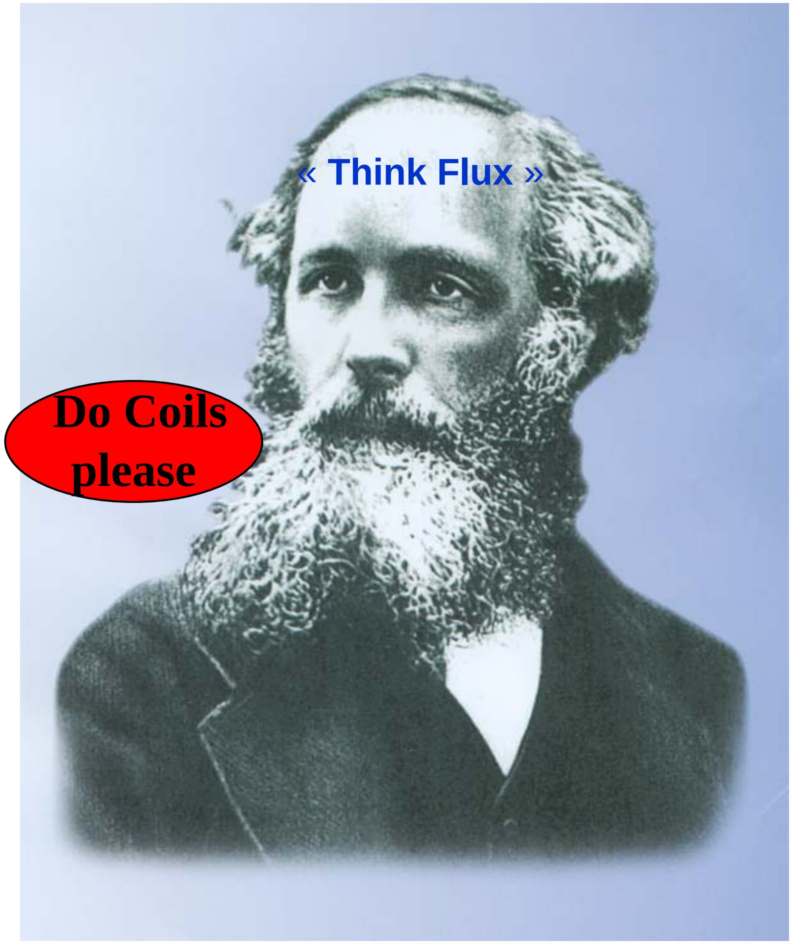
A few things that I know about solenoids....

- Flux tubes
- Formulas
- Homogeneity
- Bitter Magnet
- Solenoid lense
- CMS
- Iseult

Maxwell equations : think Flux



James Clerk MAXWELL

- The phenomenons are perfectly known.
- All the day we obey to Maxwell equations to create magnetic field.
- The representation of flux tubes is a very powerful method.
- Flux is going from North to south

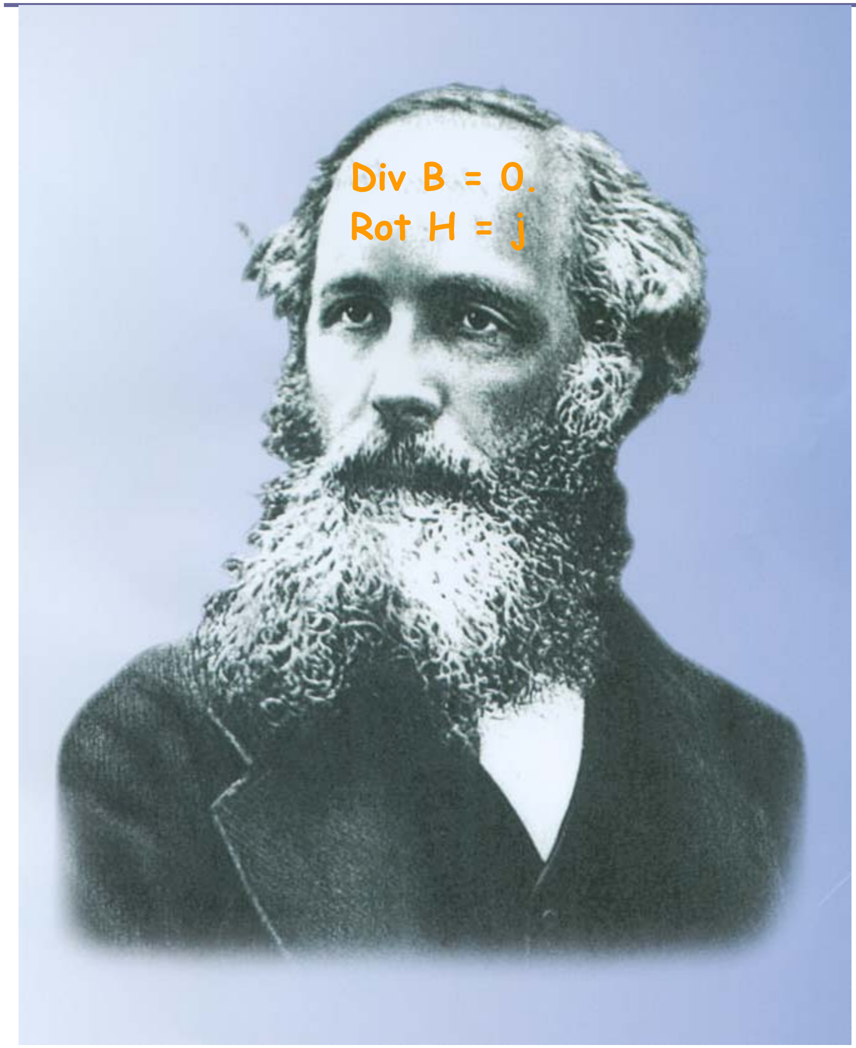
Discussion 3.6: "Double-Pancake" vs. "Layer-Wound"

Of the two magnet winding techniques, one is commonly known as "double-pancake" or simply "pancake," and the other as "layer-wound." A double-pancake coil is generally wound with flat conductor, e.g., tape, and sometimes with "large" square- or rectangular-cross-sectioned conductor, e.g., CIC. Each is wound with a

Fig. 3.23 Pictorial view of a double-pancake coil, with the top and bottom pancakes separated axially for clarity. The pancakes in this drawing are wound with a tape conductor. Points A and B indicate the ends of a continuous conductor, with Point C marking the approximate midpoint.

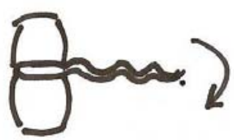
Courtesy of Pr Y.Iwasa

Maxwell's equations for magneto-statics

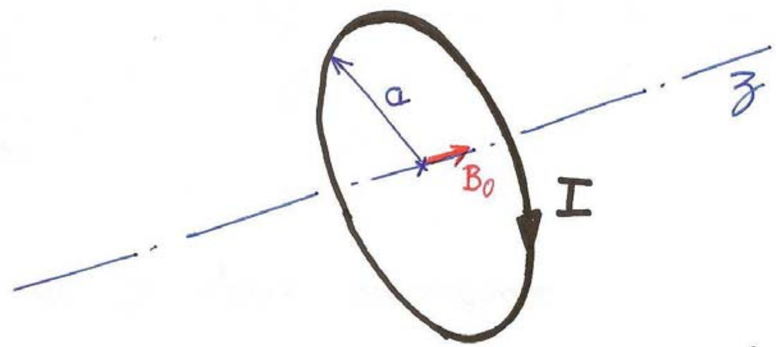


- Maxwell's equations have been solved by different methods.
- The precision request is in the range of **10-6**
- Sophisticated computer codes have been developed on a large scale due for RMN & MRI industry
- These codes need 3D analytical representation of the field and "double precision"

The Ring Coil



Center Field of a ring coil of radius a



$$B_0 = \mu_0 \frac{I}{2a} \qquad \mu_0 = 4\pi . 10^{-7}$$

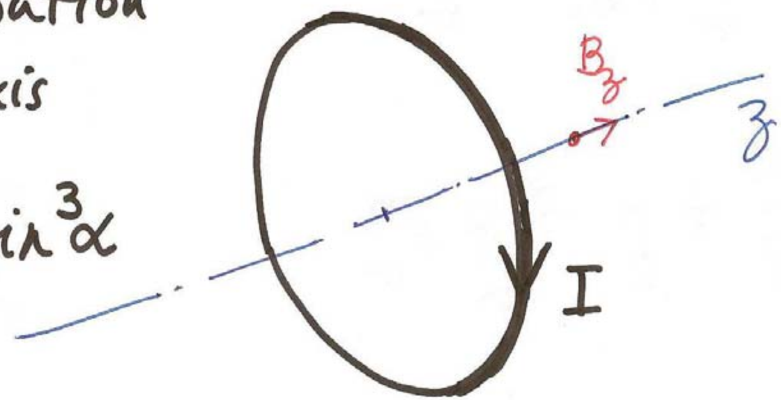
2a = diameter

I	B	2a
1A	1mT	1.25mm
200A	0.8mT	300mm

Ring Coil

Field Distribution along the axis

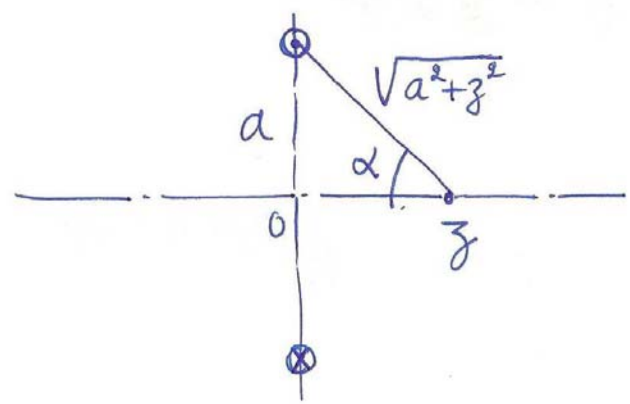
$$B_z(z) = B_0 \sin^3\alpha$$



$z = a$

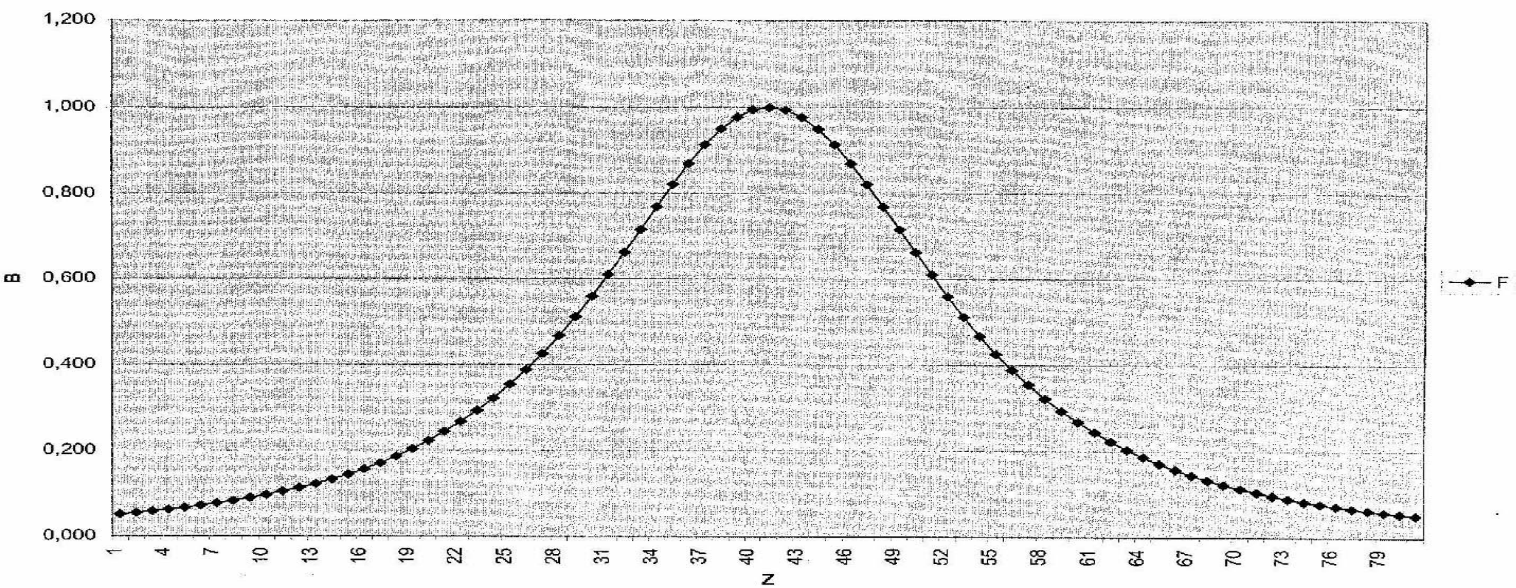
$\alpha = \frac{\pi}{4}$

$B_z(a)$ # $0.35\, B_0$



Field distribution of a ring coil along axis

Champ d'une spire circulaire



APPLICATION du théorème d'Ampère

$$\int H\, dl = NI$$

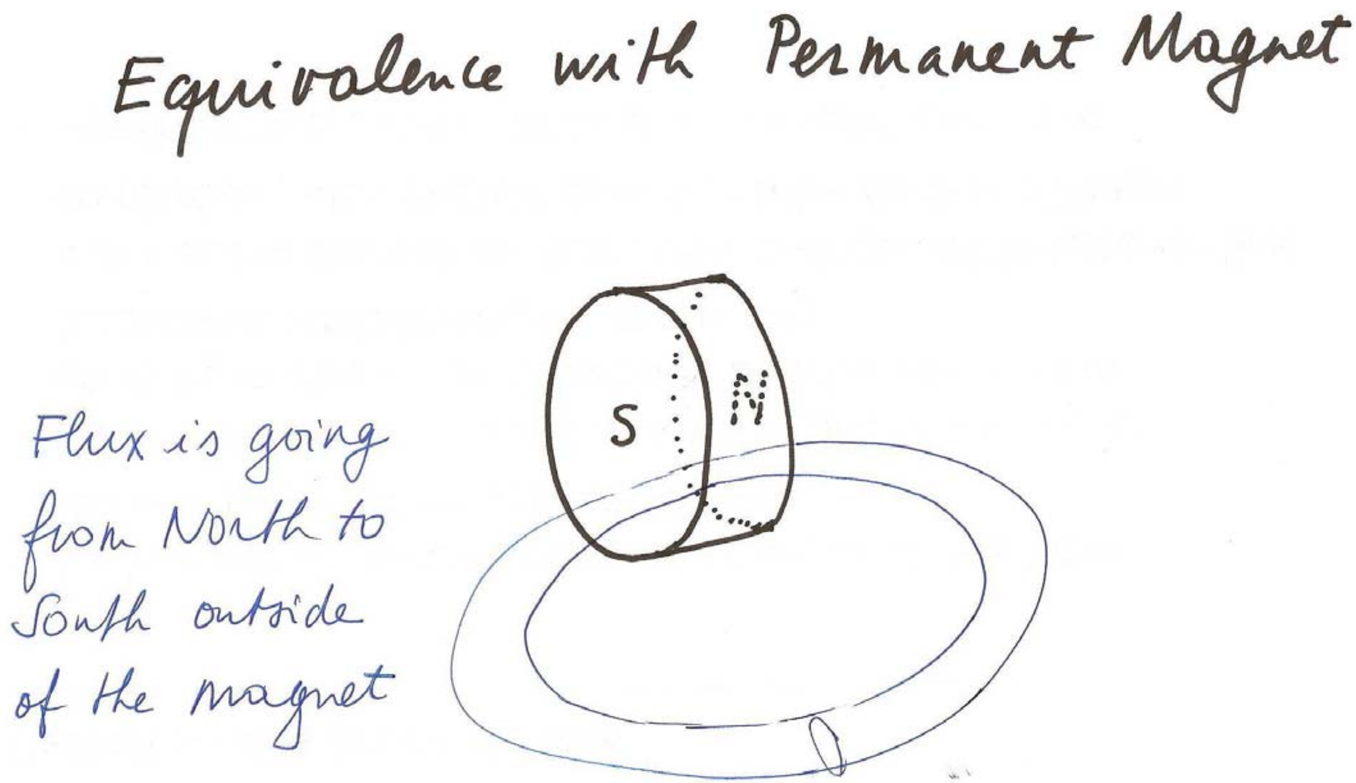
$$\int_{-\infty}^{+\infty} B_z\, dz = \mu_0 NI$$

Equivalent length : 2*a

Inflexion at a/2

Long distance effect

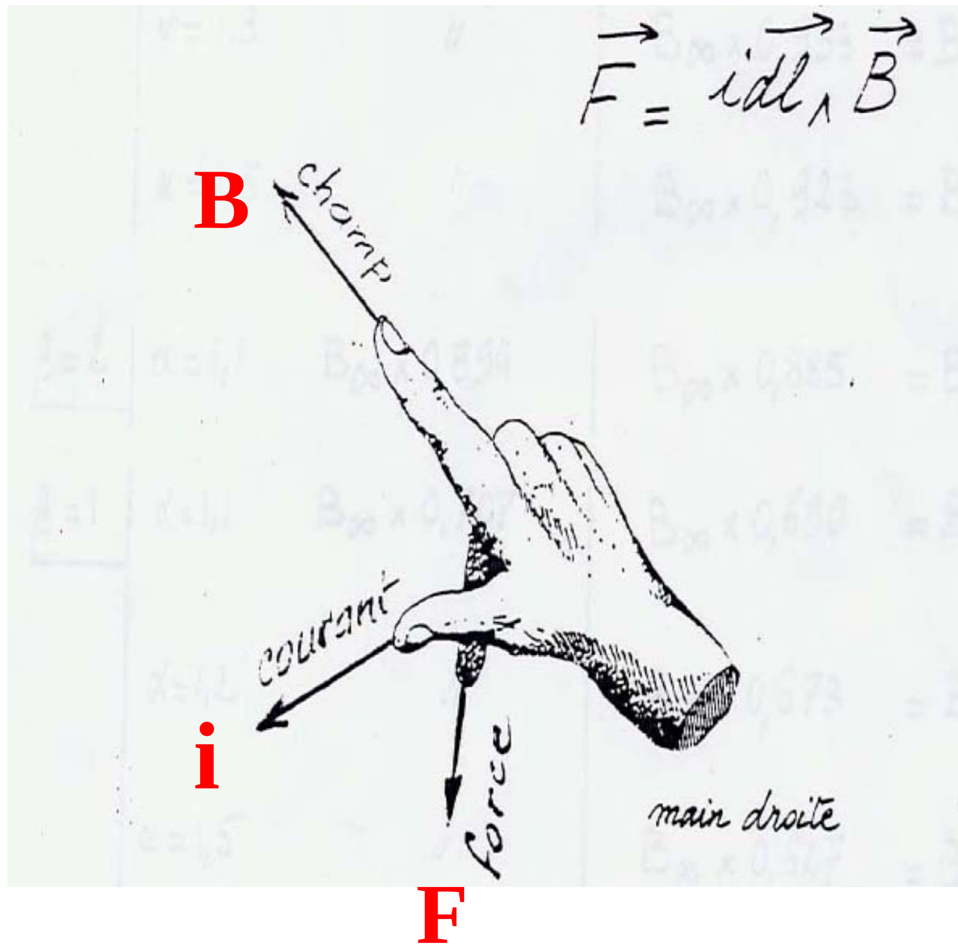
Ring Coil



Equivalence with Permanent Magnet
Flux is going from North to South outside of the magnet
S
N

Laplace’s theorem: the 3 fingers of the right hand

$$F = BiL$$

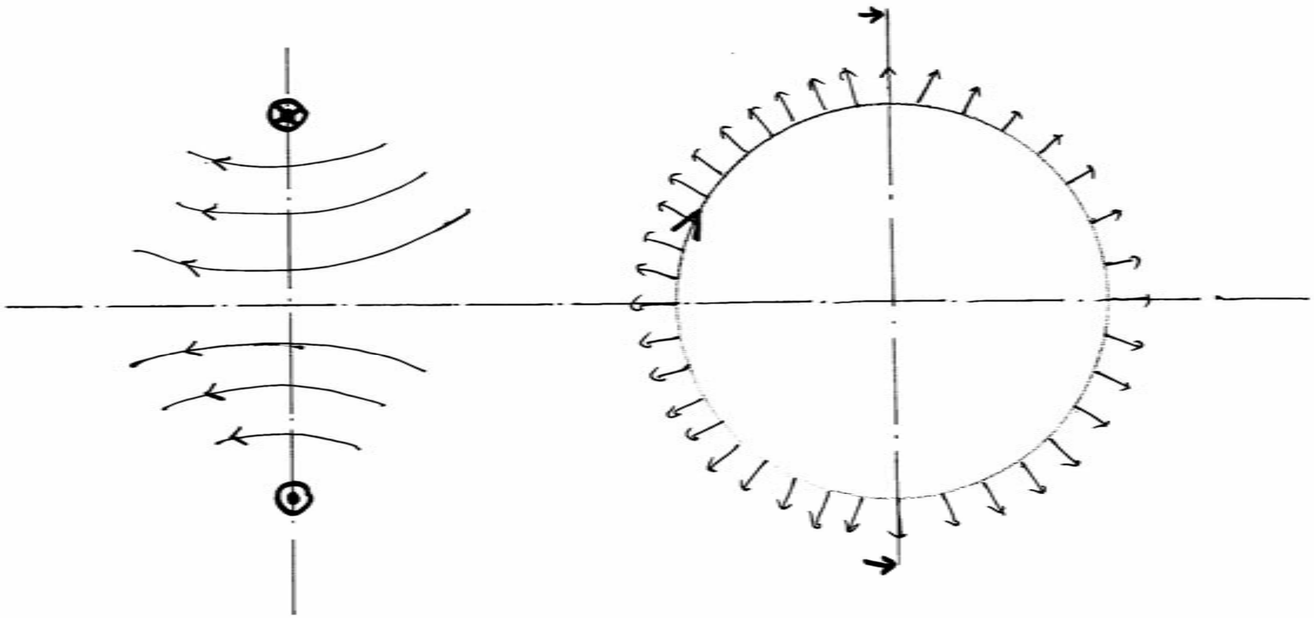


« Hoop stress »

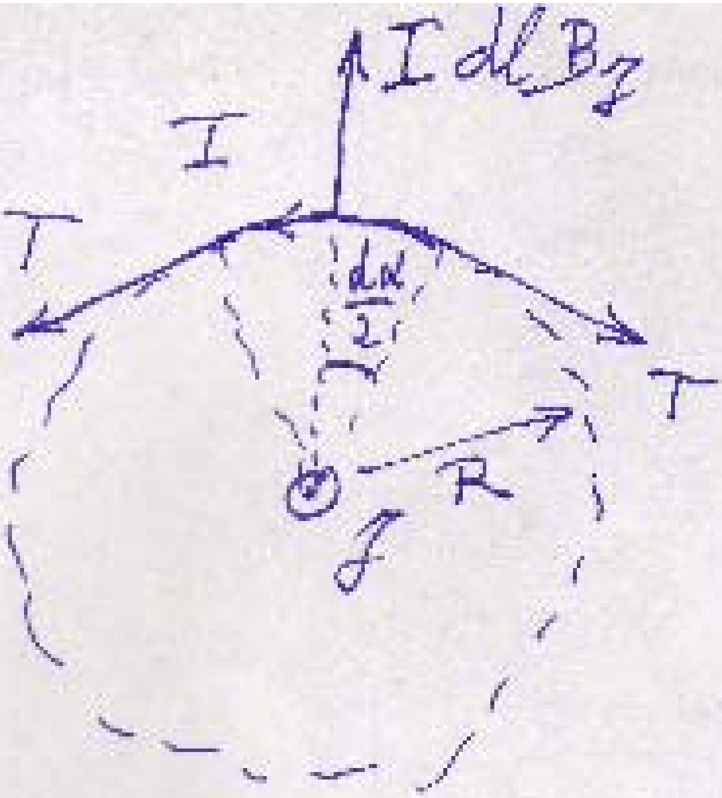
Forces sur les conducteurs

$$d\vec{F} = I\,\vec{dl} \wedge \vec{B}$$

cas de la spire circulaire



Hoop stress in the ring coil (manuscript of Pr Guy Aubert)



$$I\,dl\,B_z = 2T \sin\frac{d\alpha}{2}$$

$$dl = R\,d\alpha$$

$$T = I R B_z$$

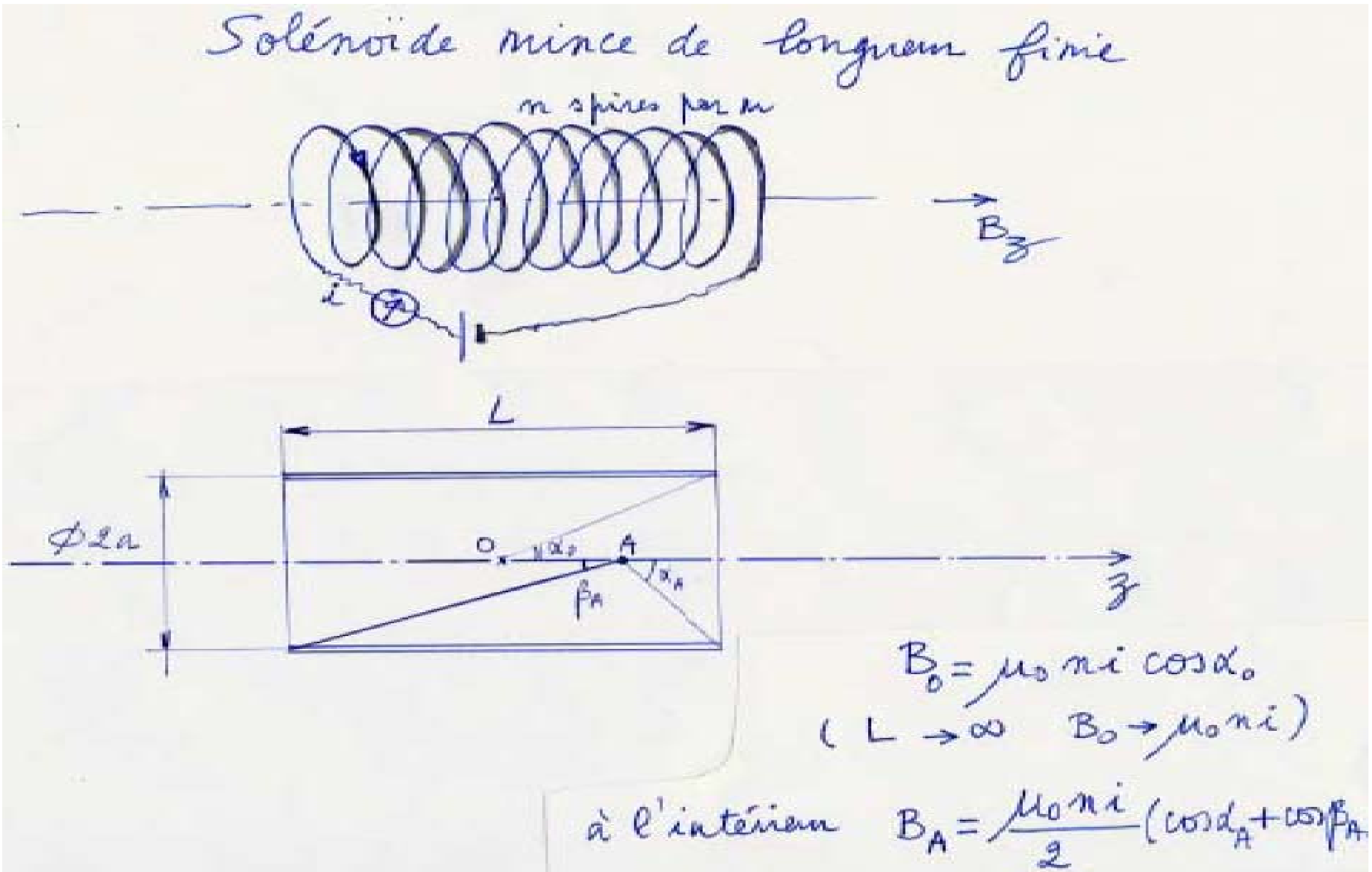
Stress=J*B*R

(MPa)=(A/mm2)*Tesla*m

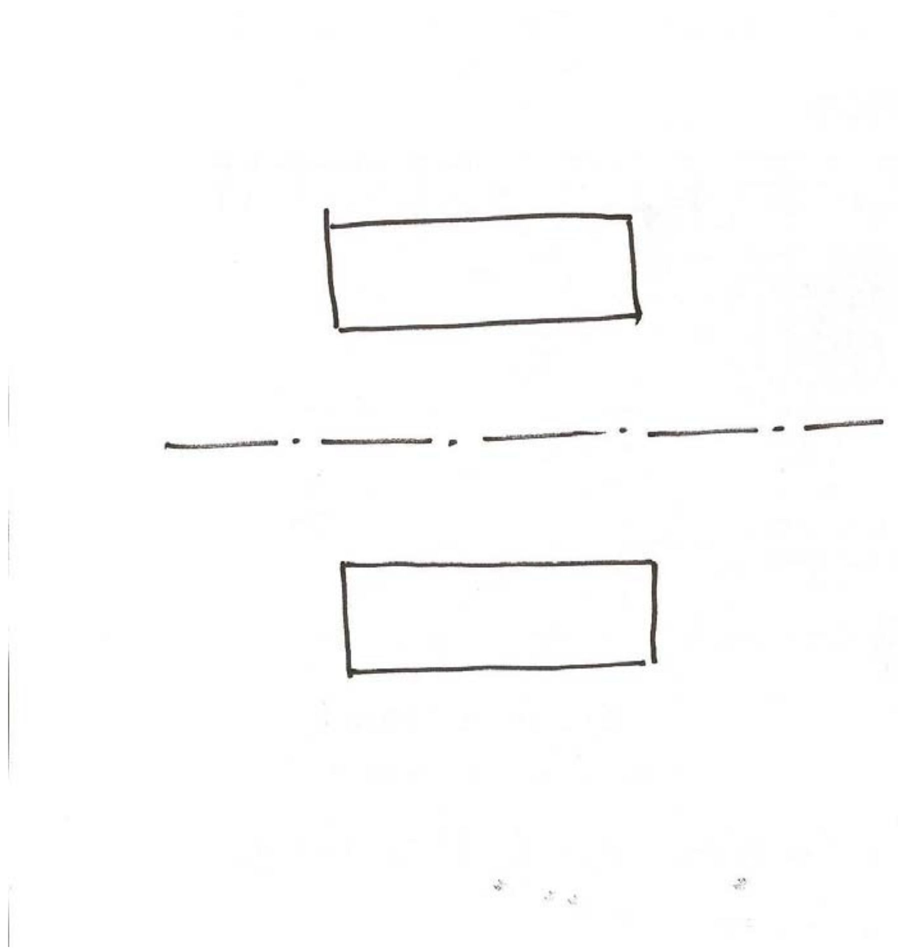
100 MPa=100A/mm2*2T*0.5m

The radial force is trying to extend the radius of the ring coil and it is equilibrated by the tension force. The approximation is valid for a turn on itself and slightly pessimistic in solid coils

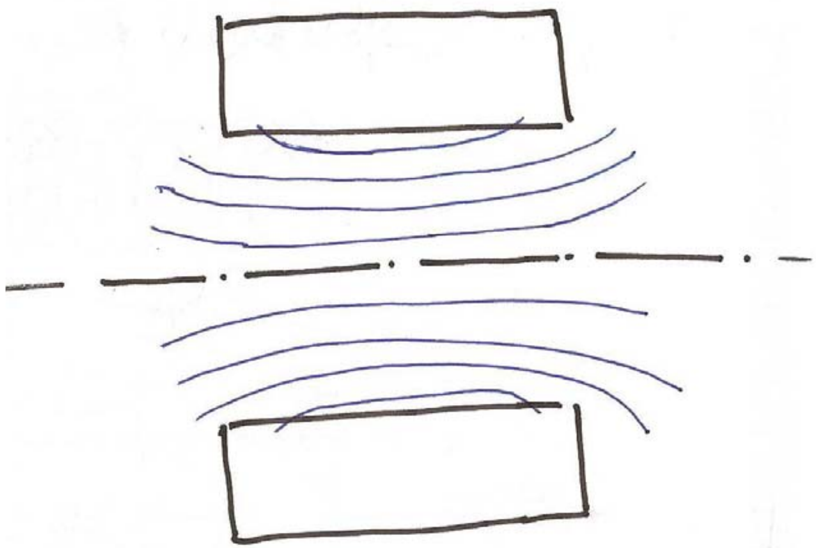
Field of a thin solenoid of finite length



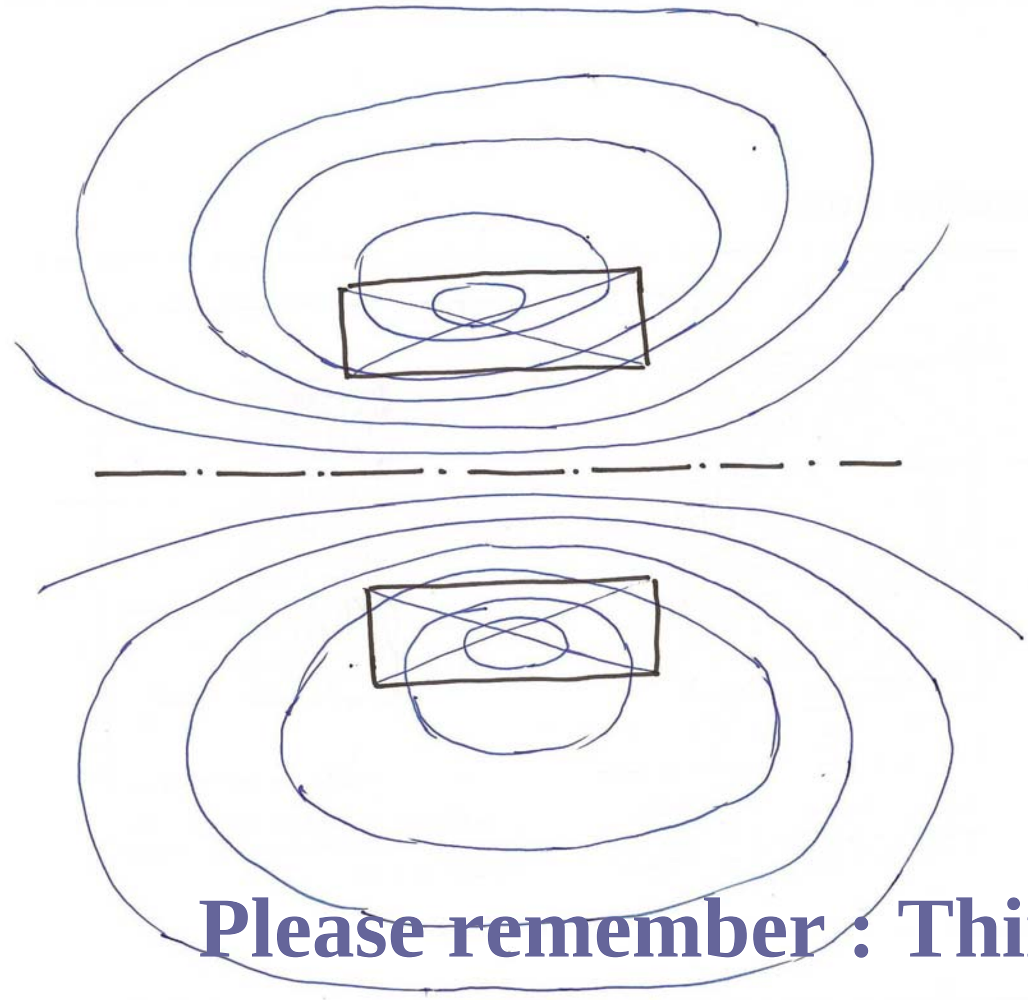
Plotting the flux lines of a thick air core solenoid
Flux tubes step1



Plotting the flux lines of an air core solenoid
Flux tubes step2



Plotting the flux lines of an air core solenoid
Flux tubes step3



Please remember : Think FLUX

Plotting the flux lines of an air core solenoid

- In the middle , field is homogeneous , flux lines are parallel
- In the ends , field is roughly half , flux tubes should be twice larger
- Near the axis , flux tubes are going very far to close on them selves
- Close to the coil , flux is turning , creating a longitudinal compression,
- Near the median plane, part of the flux is returning inside the coil around a zero field point.
- The inner part of the coil is suffering an expanding effort
- The outer part of the coil is suffering a radial compression
- The total force is an expanding effort.

Thick solenoid

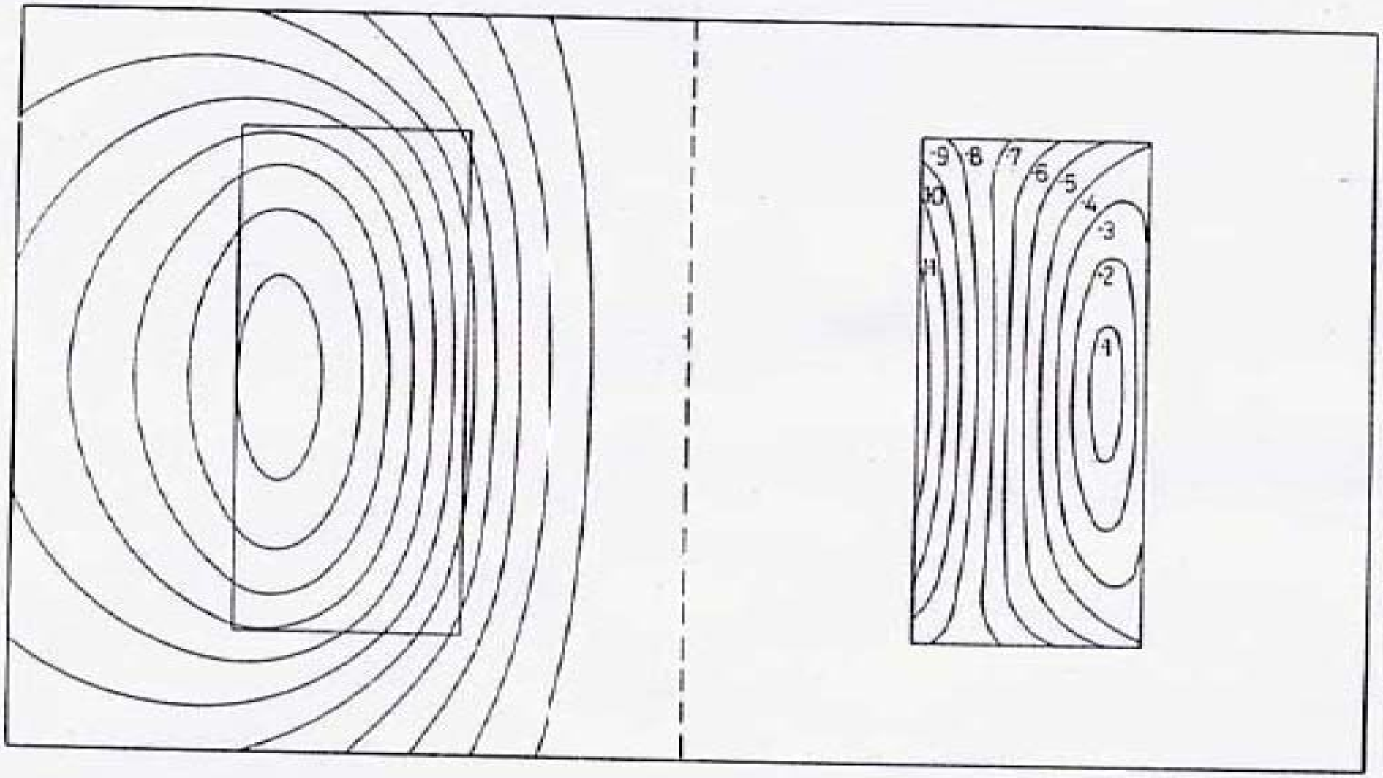


Fig. 3.6. Computer plot of the field in a simple solenoid showing, on the left hand, magnetic lines of force and, on the right hand contours of constant field intensity |**B**| relative to the central field B_0 (C. W. Trowbridge, Rutherford Laboratory, private communication).

La compréhension des forces est primordiale

42 MAGNETIC FORCES AND STRESSES

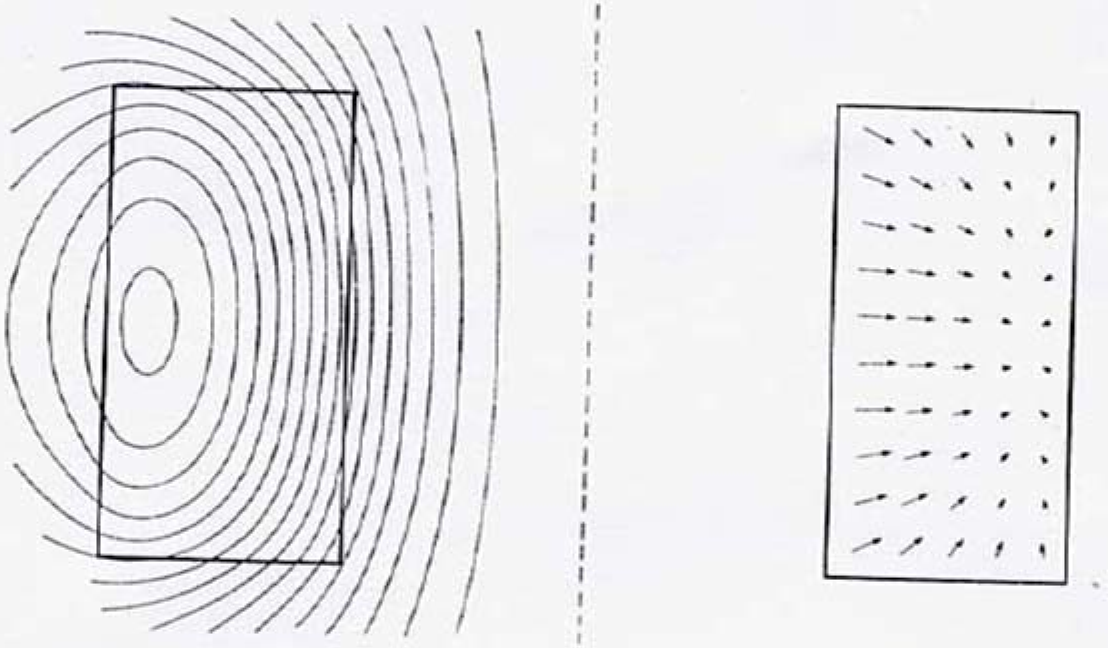


Fig. 4.1. Computer plot for a solenoid showing, on the left-hand side, magnetic lines of force and, on the right, vectors of electromagnetic force per unit volume, represented in amplitude and direction by length and angle of arrows (C. W. Trowbridge, Rutherford Laboratory, private communication).

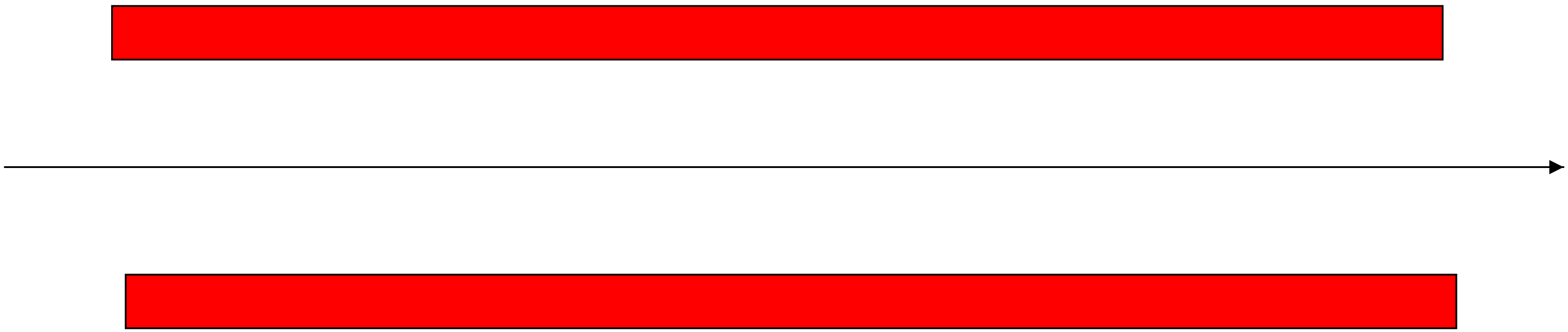
Thick solenoid

- Field formulas for thick solenoids are complicated
- Peak field
- Lehmann Point
- Internal magnetic forces
- Magnetostatic pressure is equivalent to stored energy density : B*B/2*Muo

Field	Magnetic pressure
1.6Tesla	1MPa
4Tesla	6.25 MPa

Discussion on homogeneity SMC magnet parameters

- 2 M Ampere turns per meter are creating around 2.57 T



If a finite solenoid of 300mm in diameter
Is only 2 meters long the field drop at 0.1m is already:

Ampere's Theorem

- Please remember:

Current	Field	Length
1A	1mT	1.25 mm

It applies to infinite solenoids

800*2500 = 2M Ampere turns i.e. for 500 Amps 4000 turns per meter	2.57 Tesla Factor 2500	1m Factor 800

Even a long thin solenoid is not homogeneous.....

- B0= MU0*nI*cos(Alpha0)
- B1= MU0*nI*(cosAlpha1+cosAlpha2)

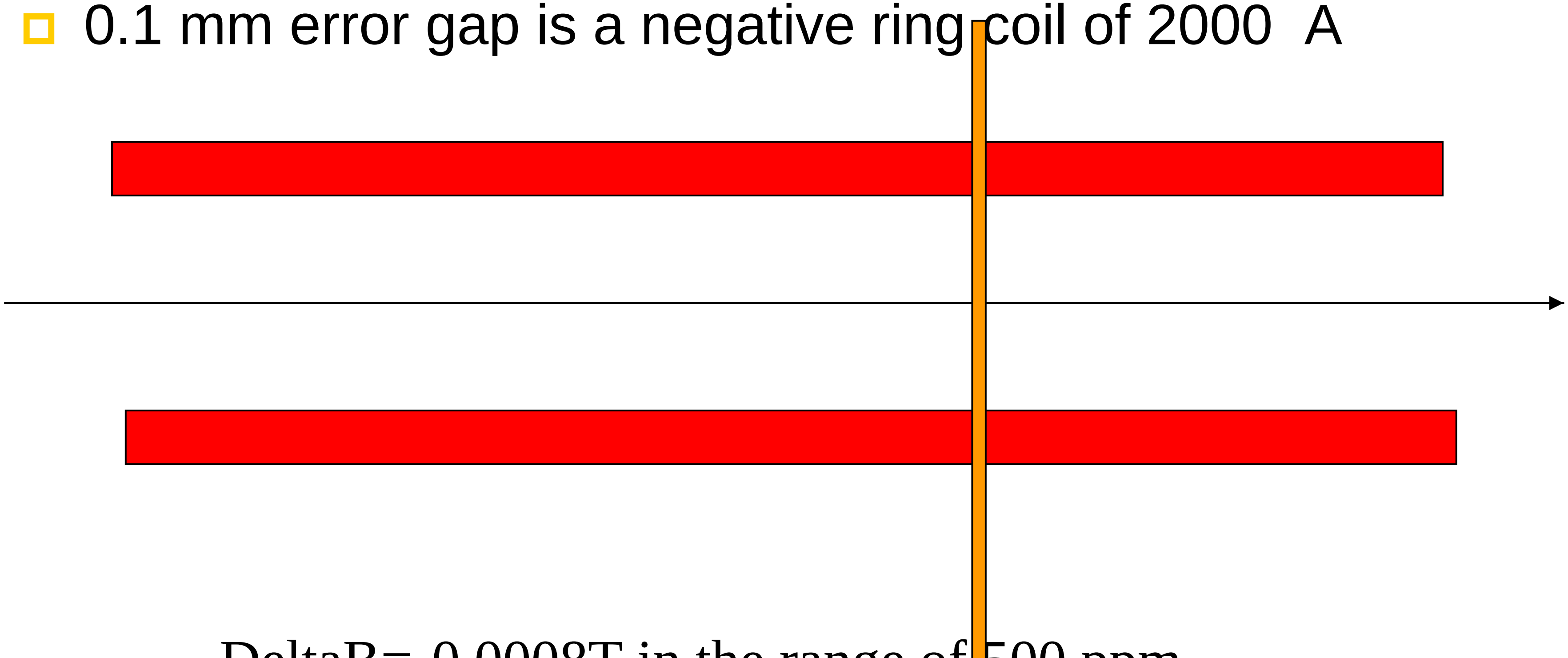
ALPHA0=8,530 degrés B0=0,9941 Tesla
At z= 0,100m
ALPHA1=9,462 degrés ALPHA2= 7,765 degrés

B1=0,98861205

DeltaB/B0=0,005607= 5 10-3

Long solenoid with small error gap in the winding

- 0.1 mm error gap is a negative ring coil of 2000 A

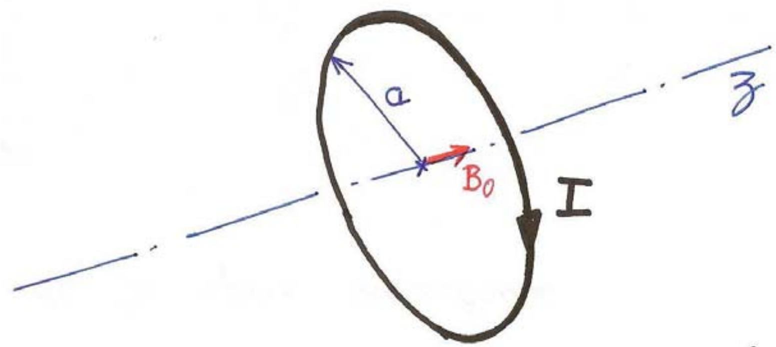


DeltaB=-0.0008T in the range of 500 ppm

If you need a magnet with 25 ppm , it is huge

The Ring Coil

Center Field of a ring coil of radius a



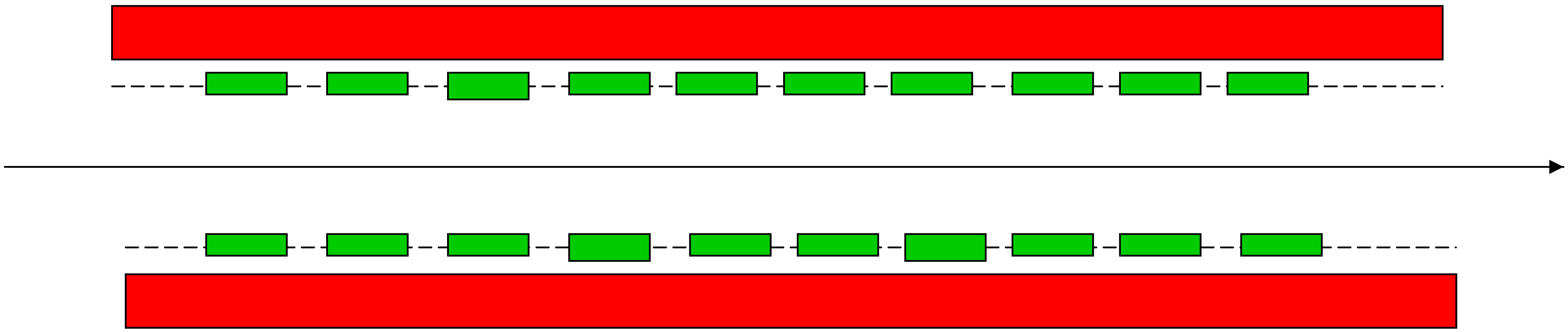
$$B_0 = \mu_0 \frac{I}{2a} \qquad \mu_0 = 4\pi . 10^{-7}$$

(2a: diameter)

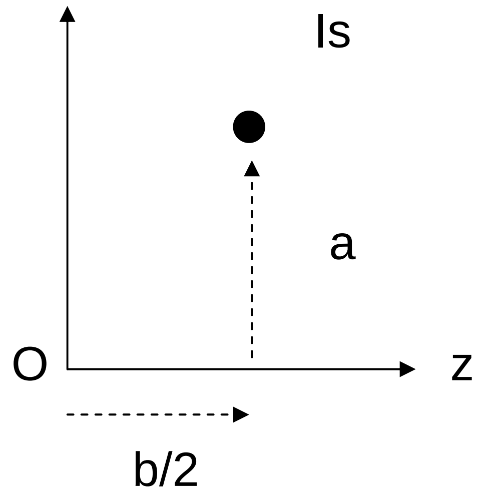
I	B	2a
1A	1mT	1.25mm
200A	0.8mT	300mm

Long solenoid with errors in the winding

- It is impossible to realise the winding of a long solenoid without a lot of distributed errors in the range of 0.1mm

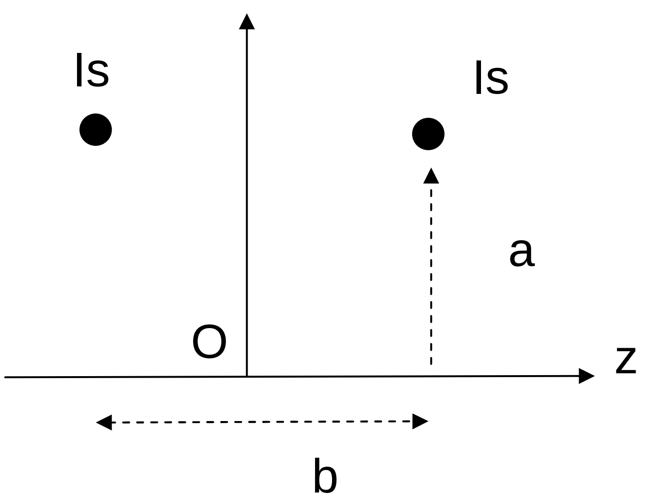


The error results in a superposition of ring coil curves randomly distributed .It must be corrected by a family of longitudinal trim coils indepedantly supplied.They will also compensate for the natural drop



B in a point z of the axis created by a ring coil of radius a situated in b z=b/2 and with current I

$$Bz(z) = \frac{\mu 0\ Is^2\ a^2}{2\left(a^2 + \left(z - \frac{b}{2}\right)^2\right)}$$



For two rings

$$Bz(z) = 0.5\ \mu 0\ Is^2\ a^2 \left(\frac{1}{a^2 + \left(z - \frac{b}{2}\right)^2} + \frac{1}{a^2 + \left(z + \frac{b}{2}\right)^2} \right)$$

For two ring coils

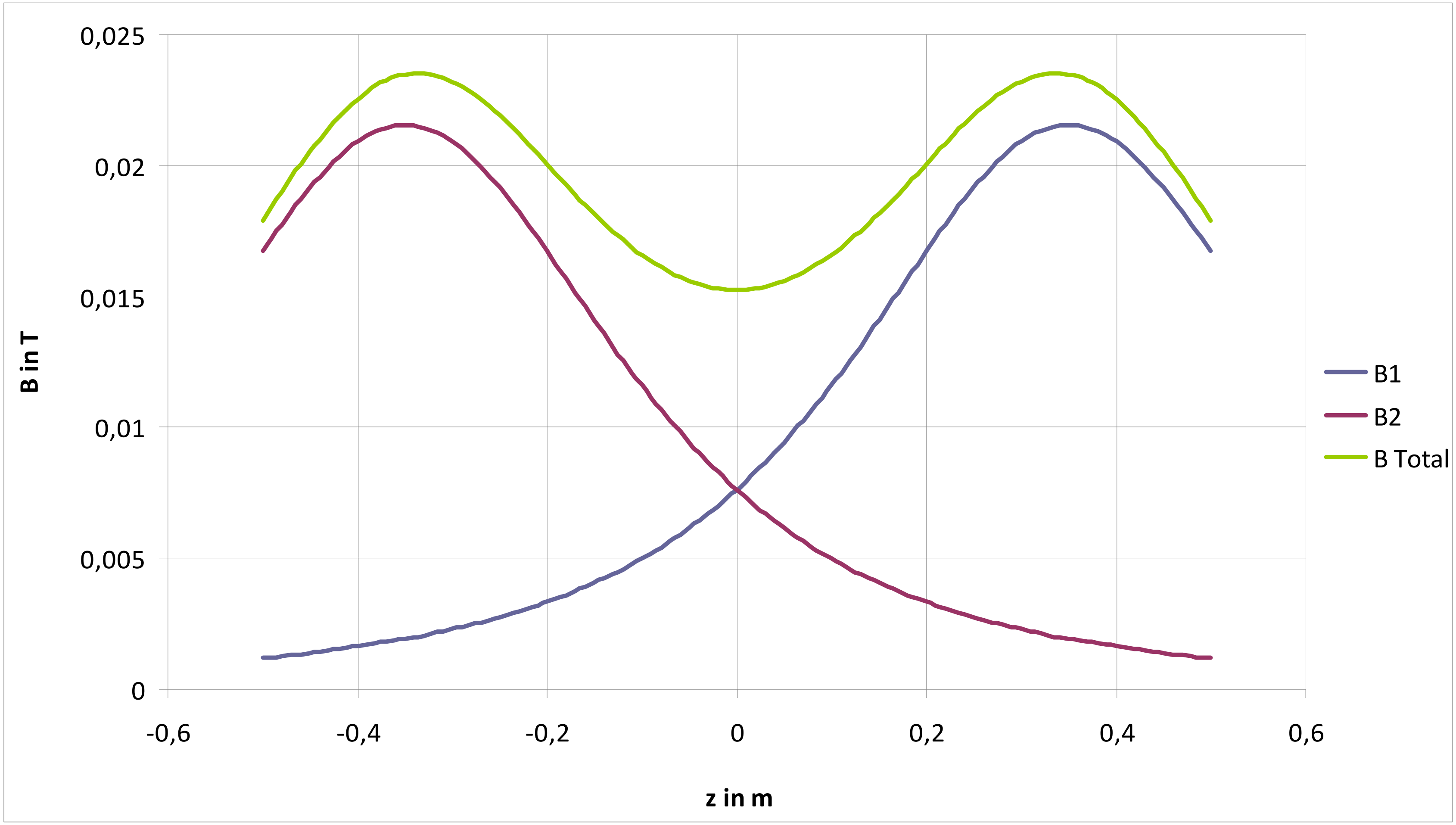
$$\frac{d^2Bz}{dz^2} = \frac{3\,\mu 0\, Is^2\, a^2\,(b^2 - a^2)}{\left(a^2 + \frac{b^2}{4}\right)^{\left(\frac{7}{2}\right)}}$$

$$\frac{d^4Bz}{dz^4} = \frac{45\,\mu 0\, Is^2\, a^2\,(8\,a^4 - 24\,a^2\,b^2 + 4\,b^4)}{8\left(a^2 + \frac{b^2}{4}\right)^{\left(\frac{11}{2}\right)}}$$

$\frac{d^2Bz}{dz^2} = 0$ conduit à $a = b$ (position de Helmholtz)

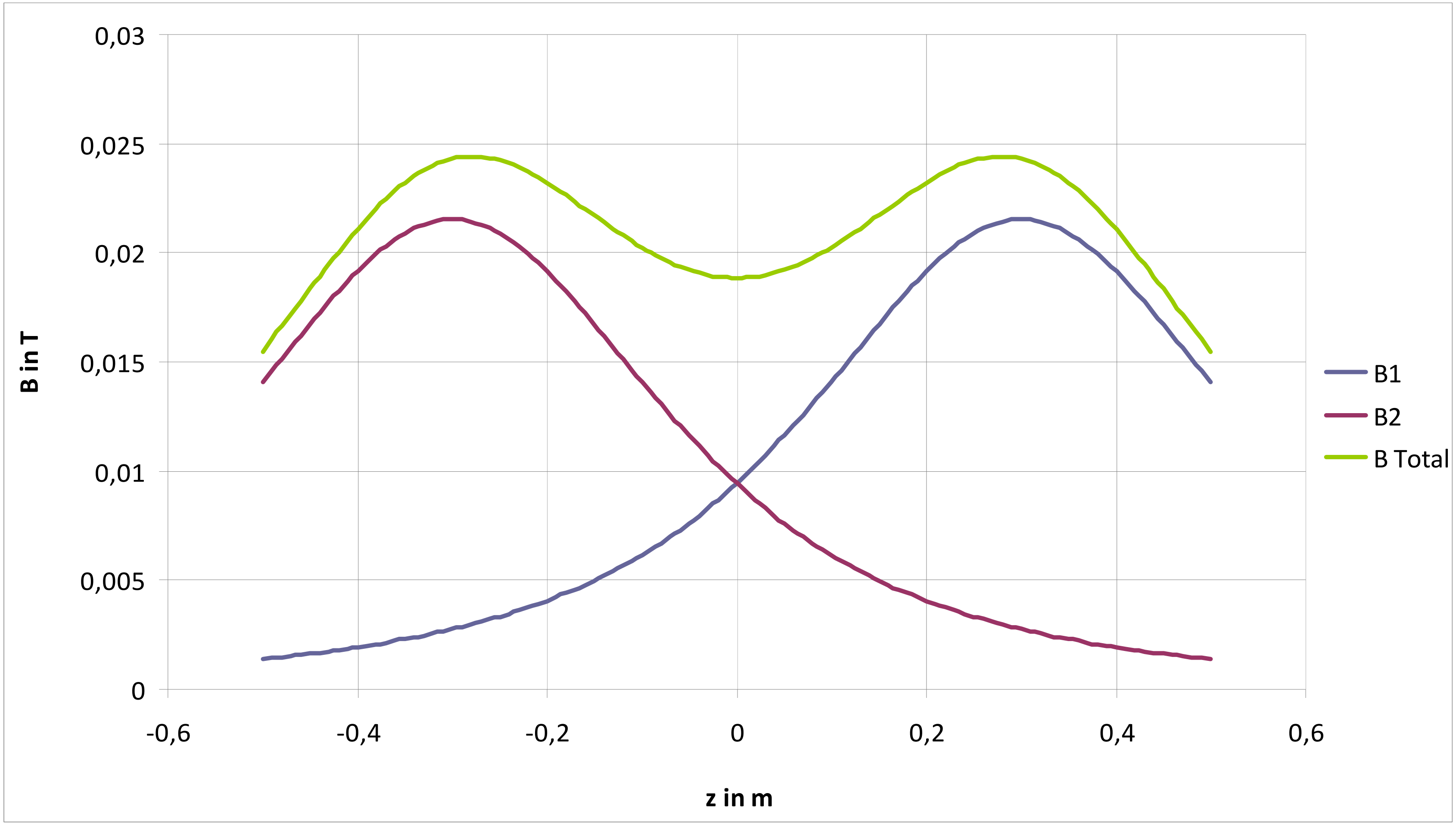
a=0,350 2b=0,700

Ordre 2: 2 Helmholtz coils (12000A)

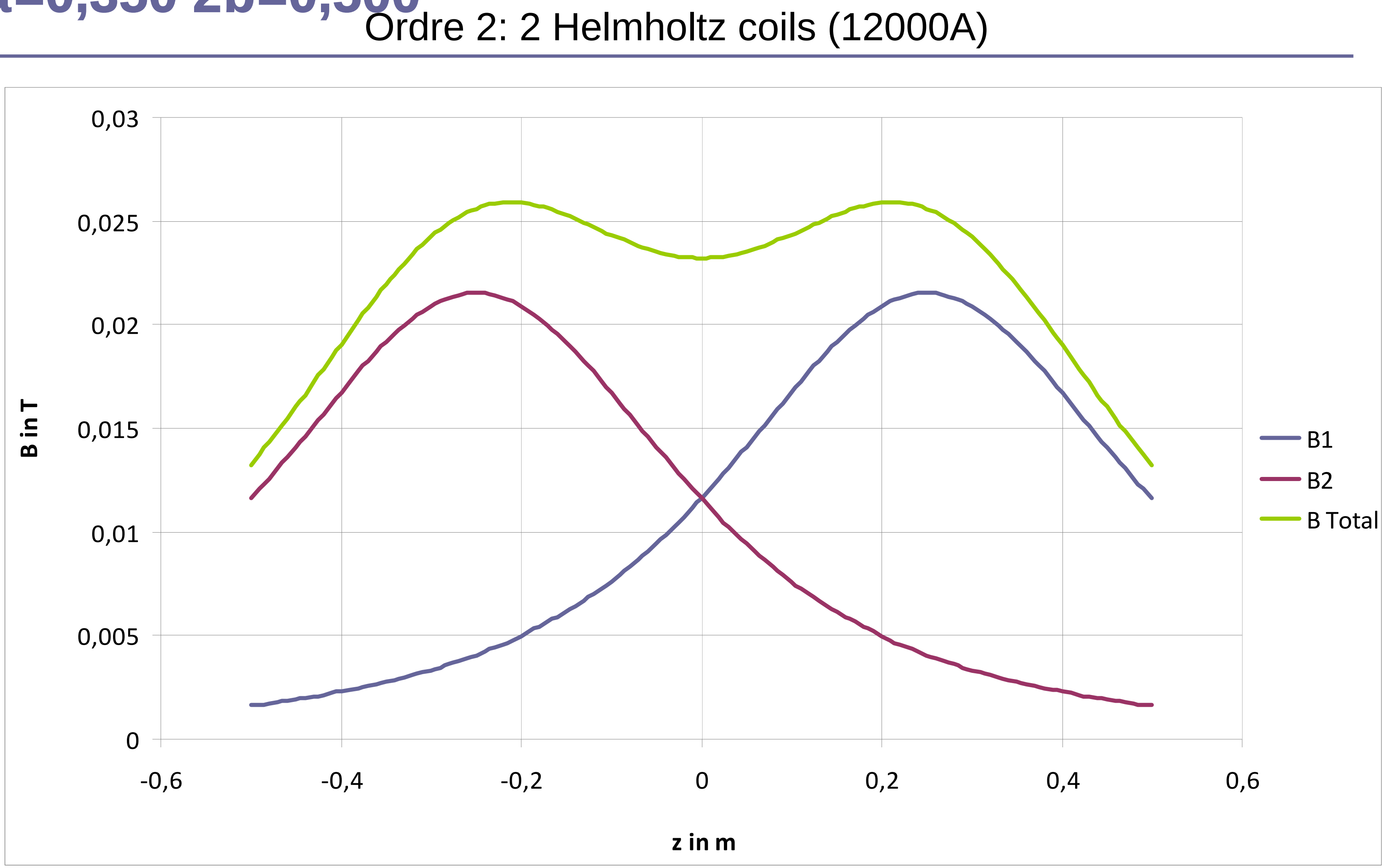


a=0,350 2b=0,600

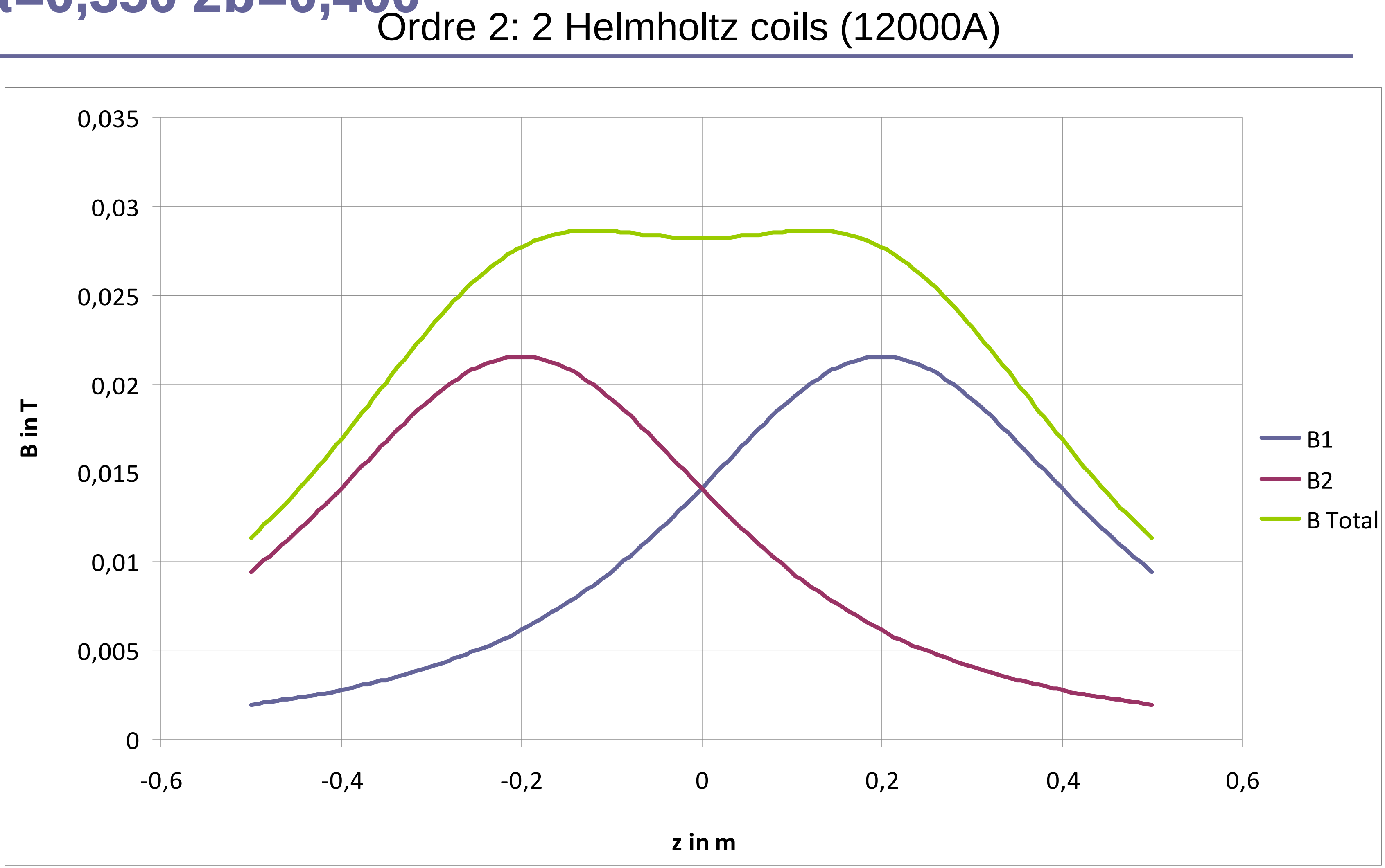
Ordre 2: 2 Helmholtz coils (12000A)



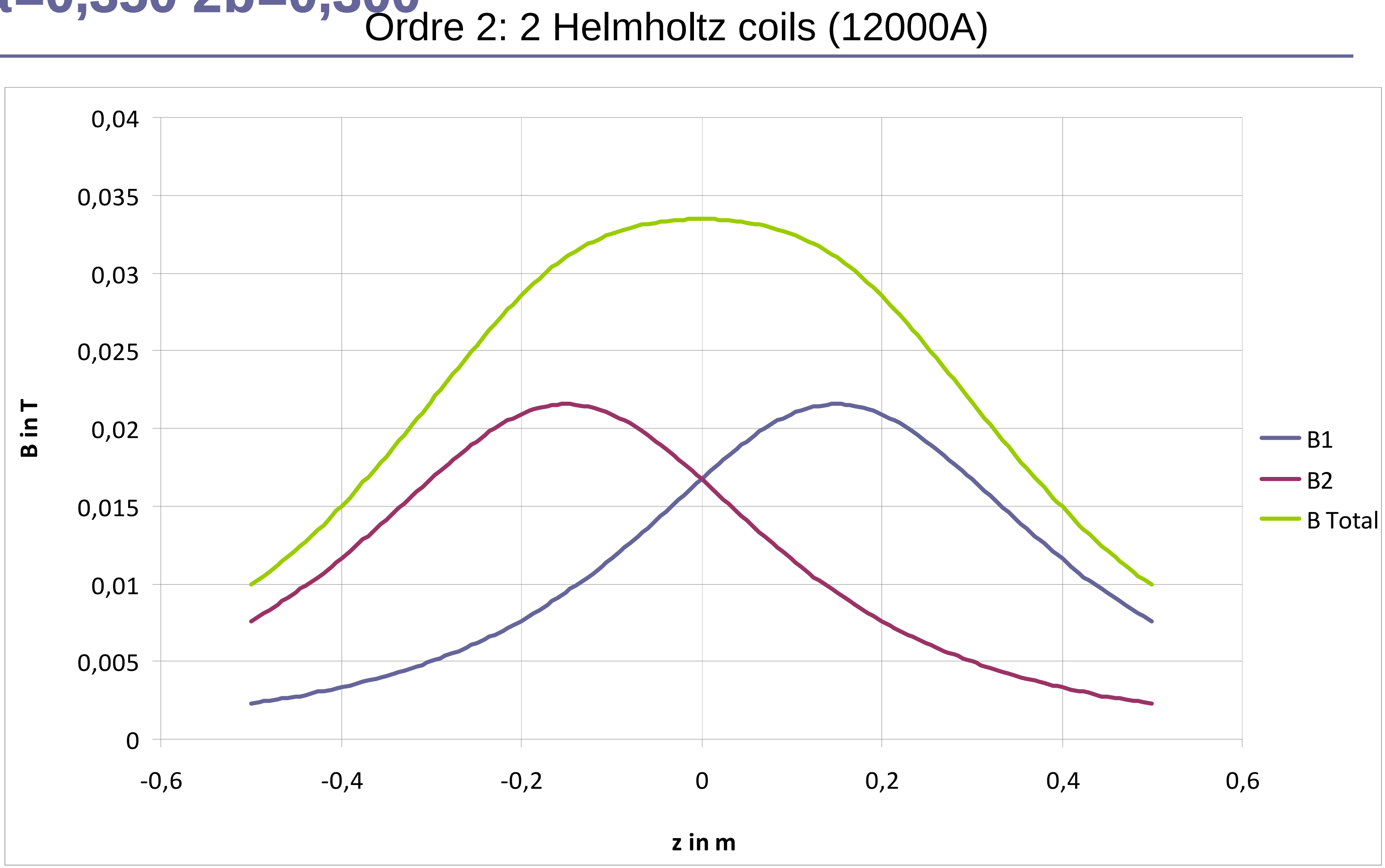
a=0,350 2b=0,500



a=0,350 2b=0,400

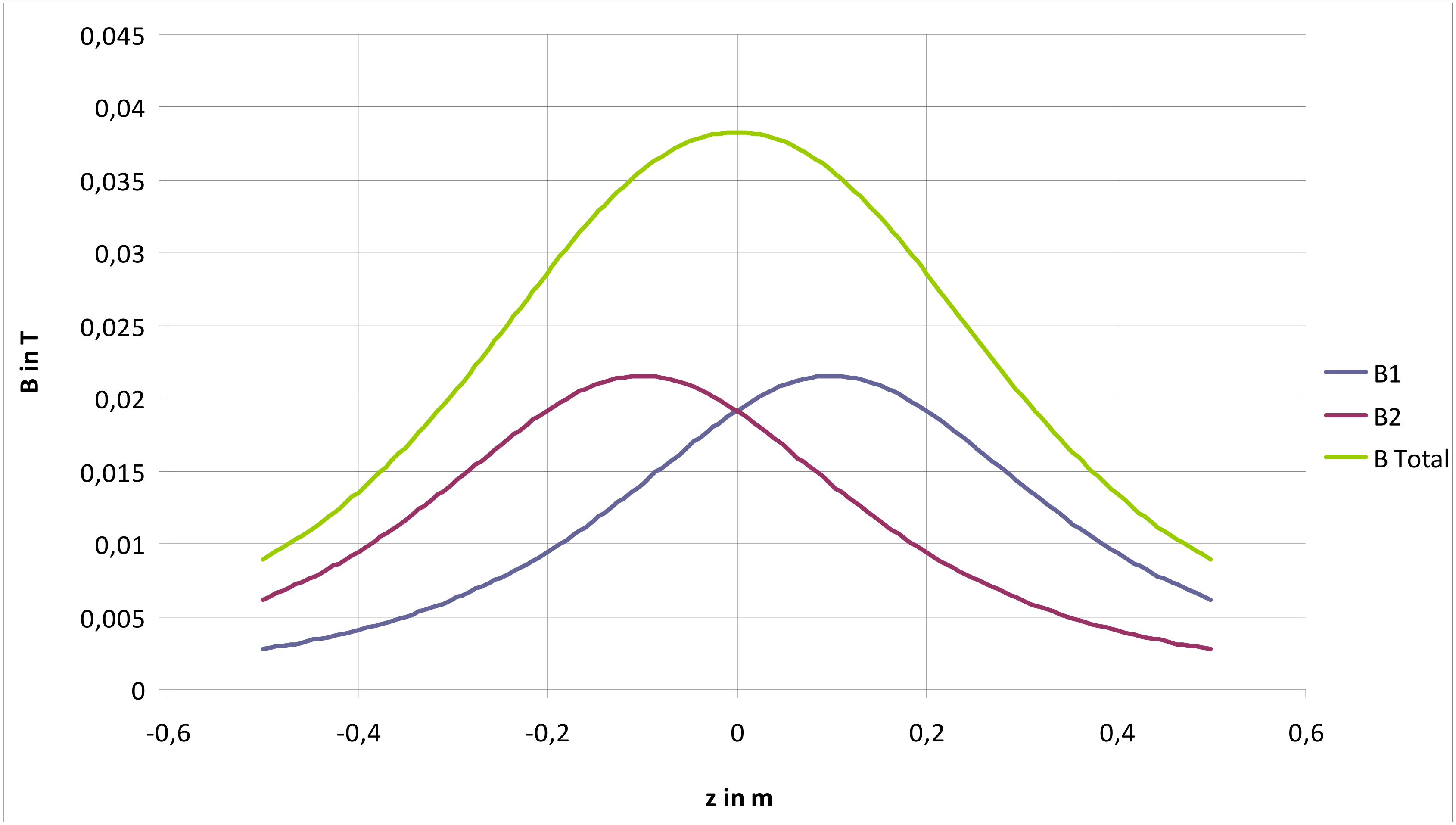


a=0,350 2b=0,300

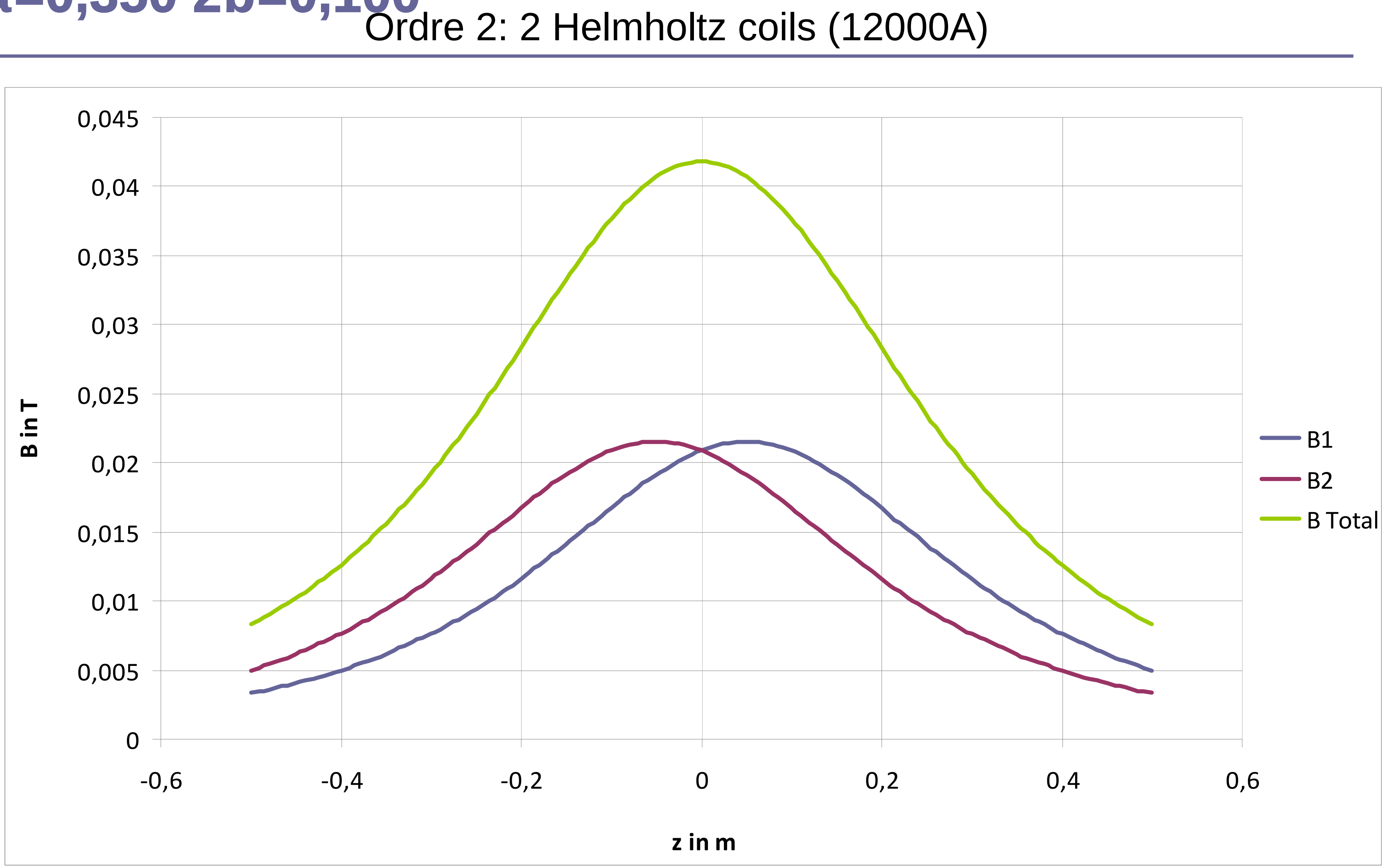


a=0,350 2b=0,200

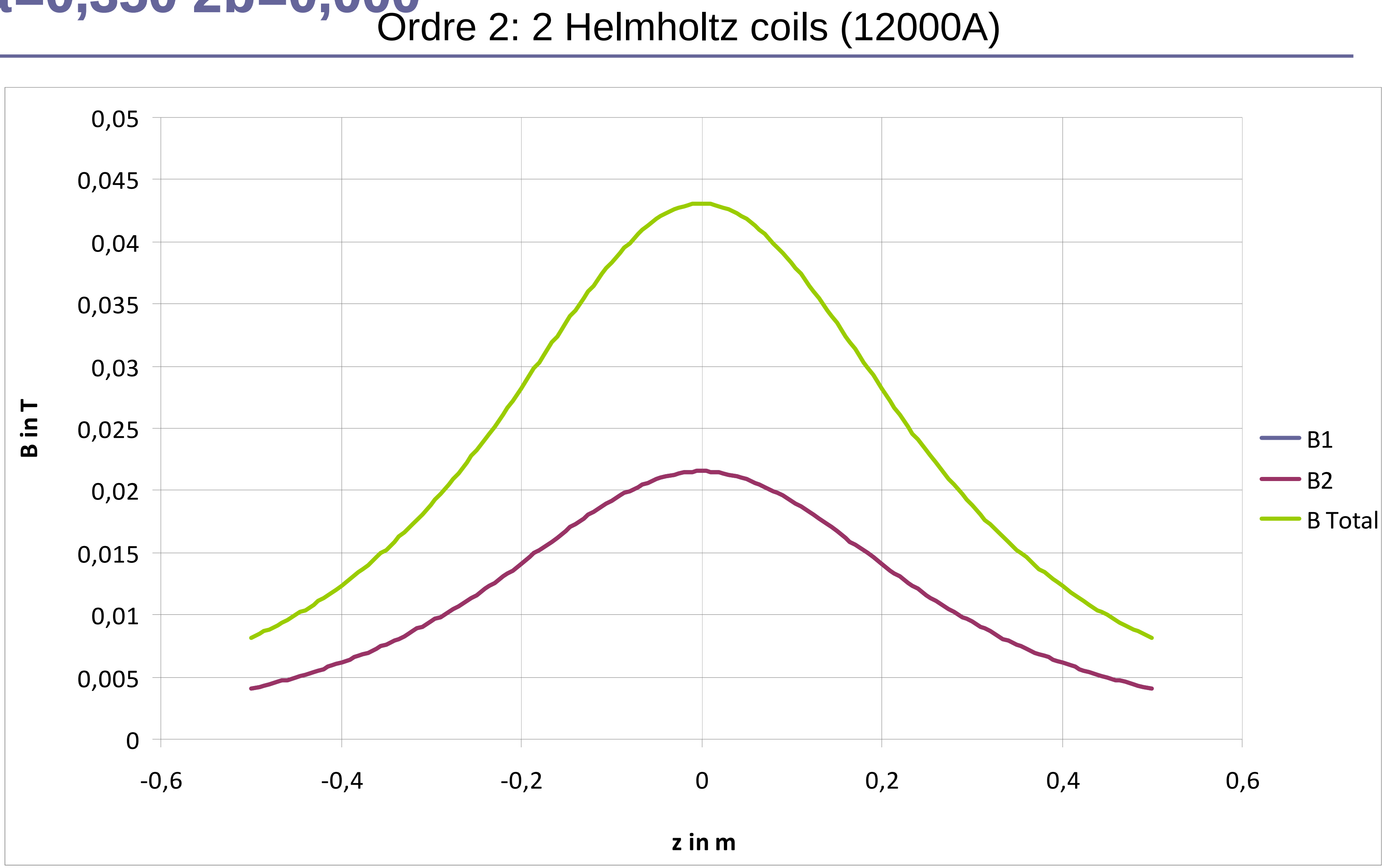
Ordre 2: 2 Helmholtz coils (12000A)



a=0,350 2b=0,100

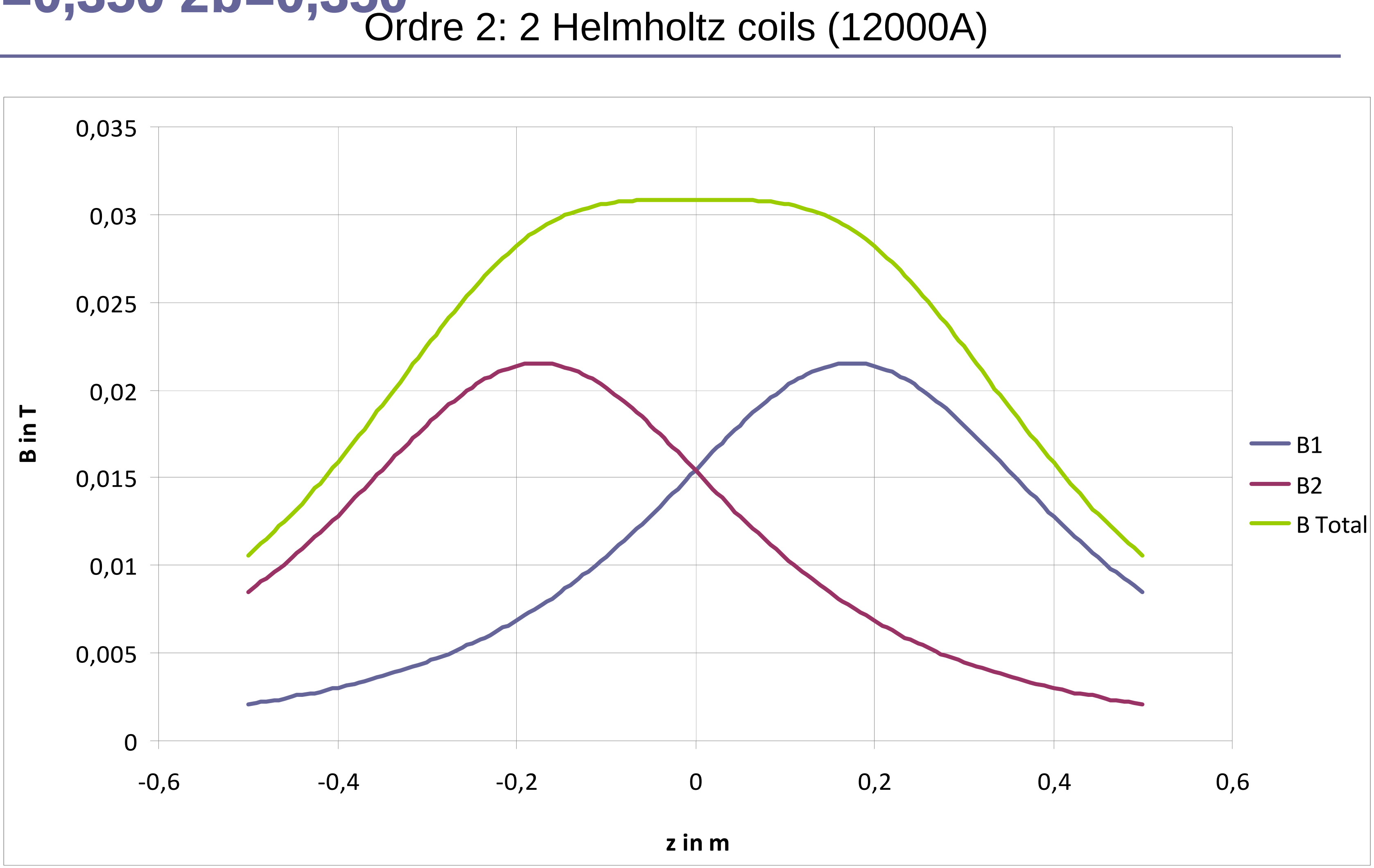


a=0,350 2b=0,000

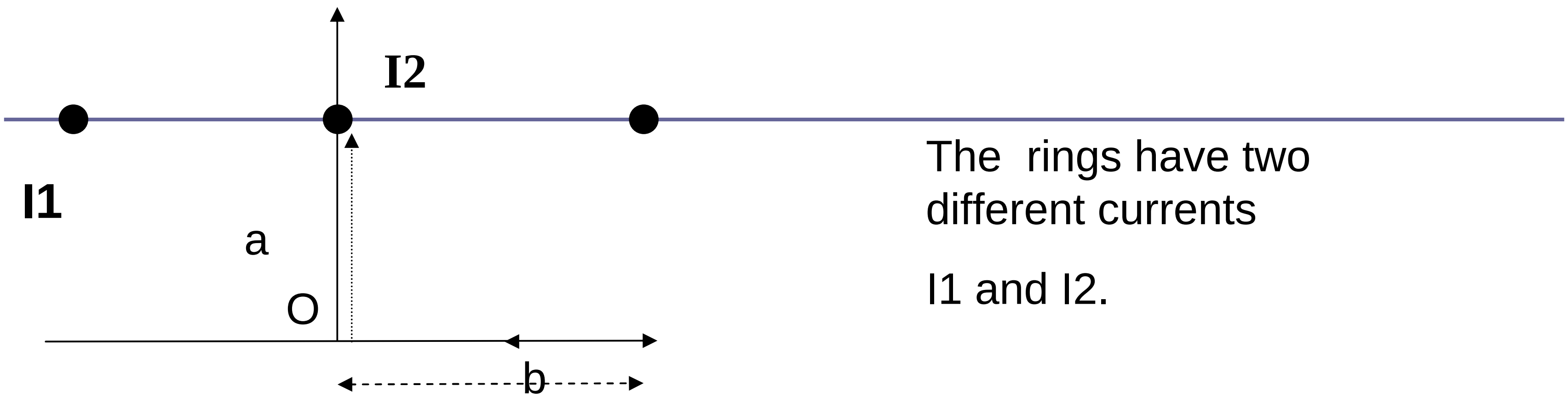


1000ppm in +-65mm

a=0,350 2b=0,350



Optimisation with 3 symetric ring coils



The rings have two different currents

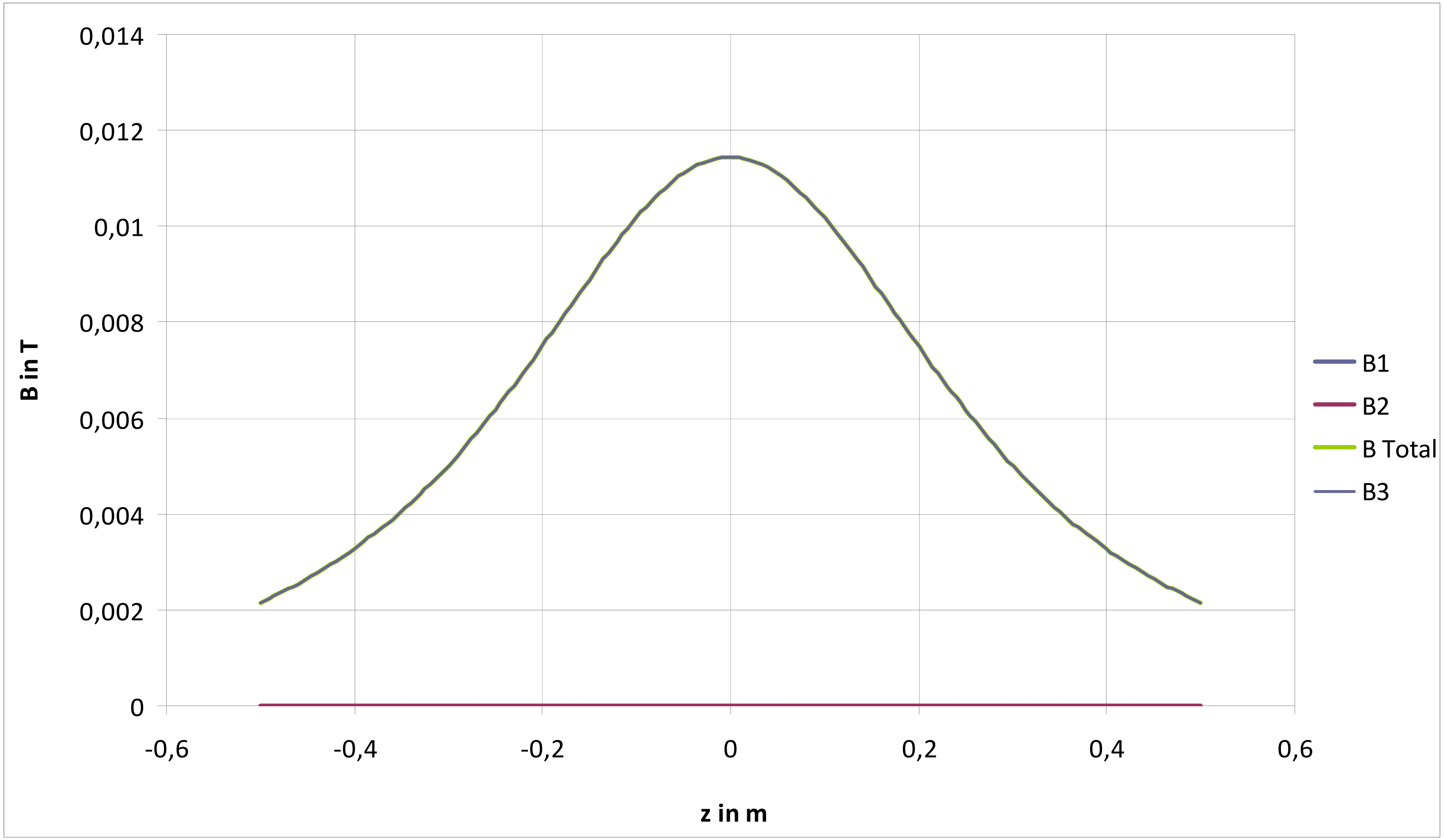
I1 and I2.

We look for:

$$\frac{d^2Bz}{dz^2} = 0 \quad \text{and} \quad \frac{d^4Bz}{dz^4} = 0$$

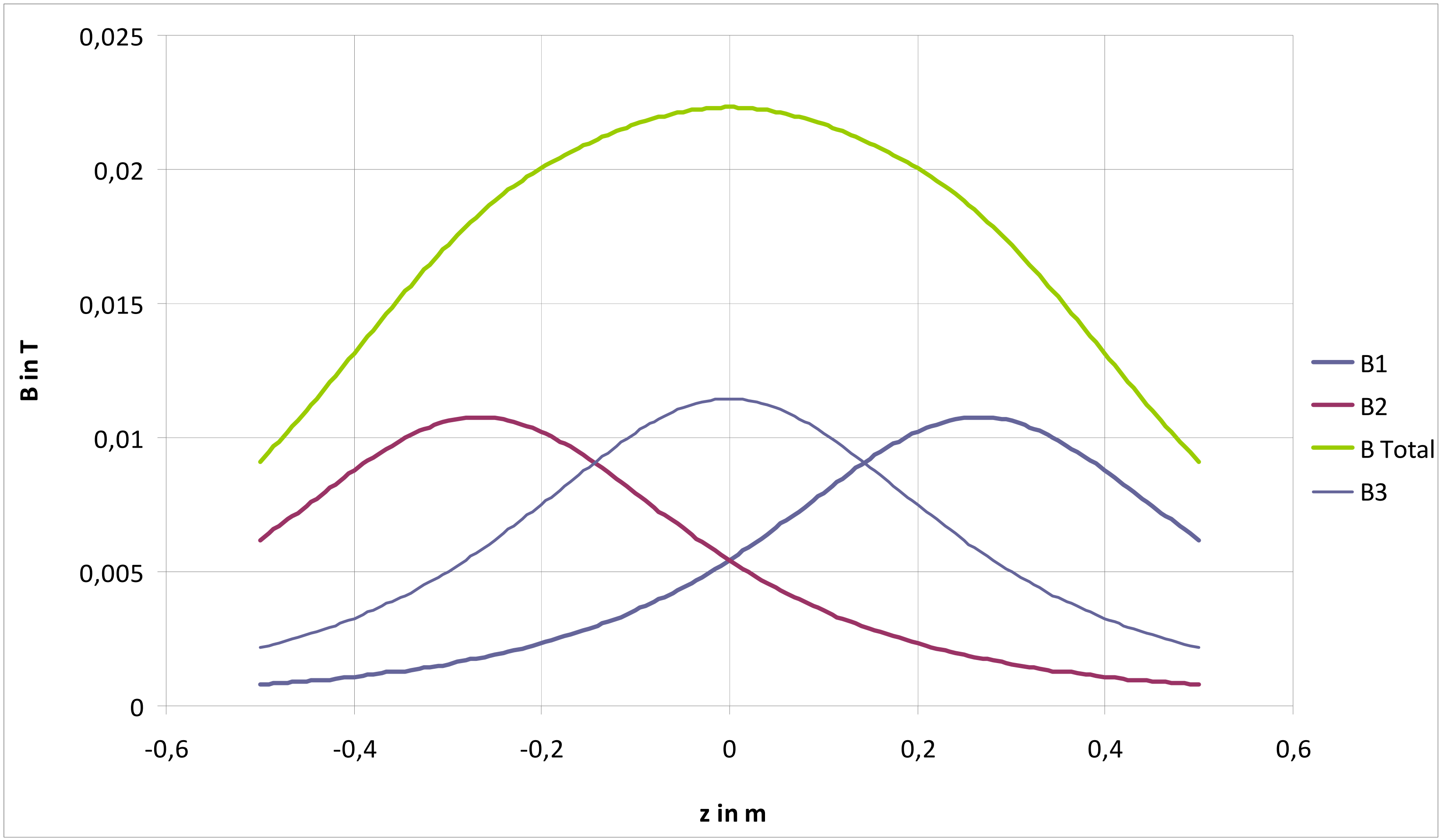
I1=0A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



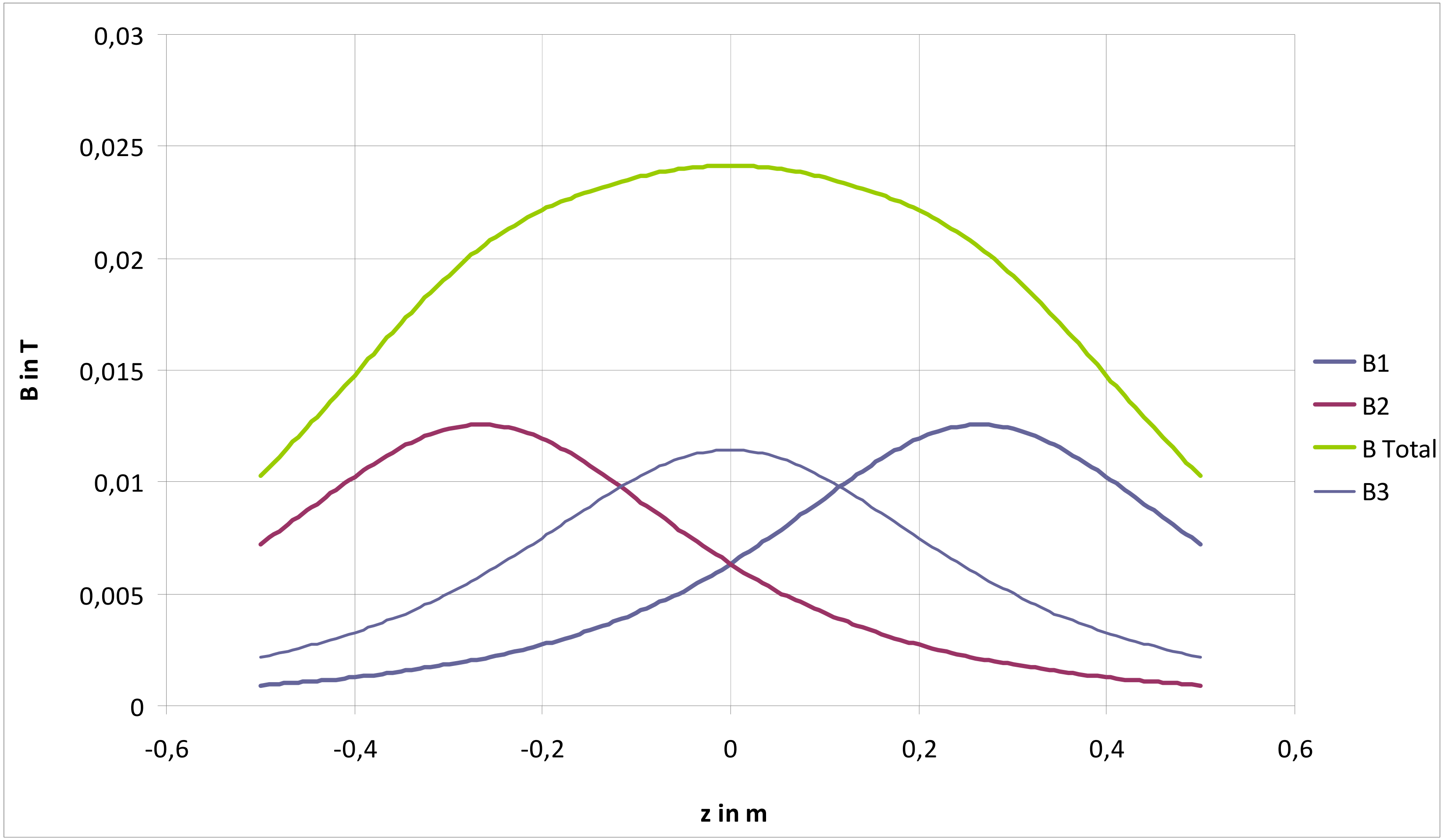
I1=6000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



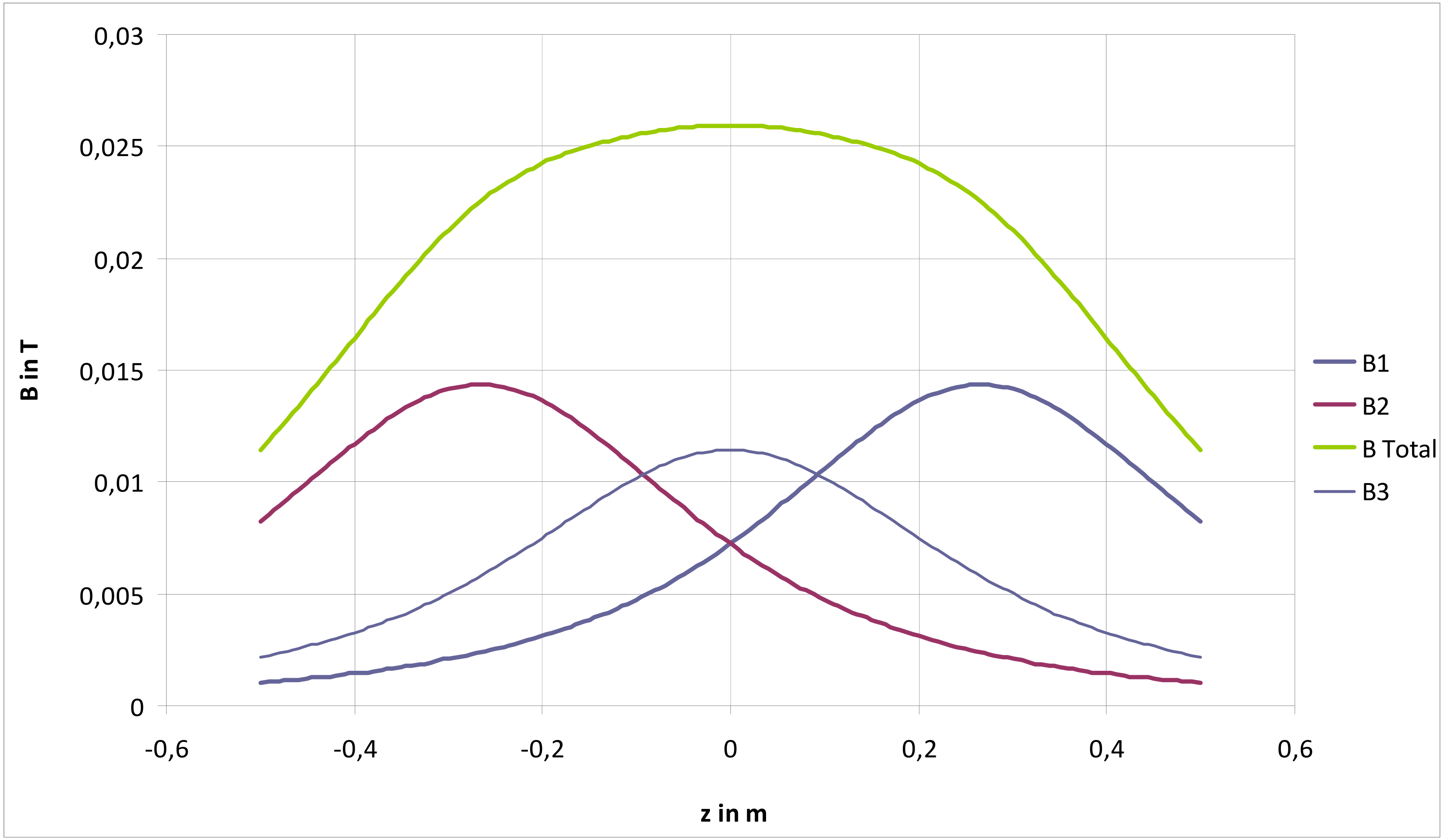
I1=7000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



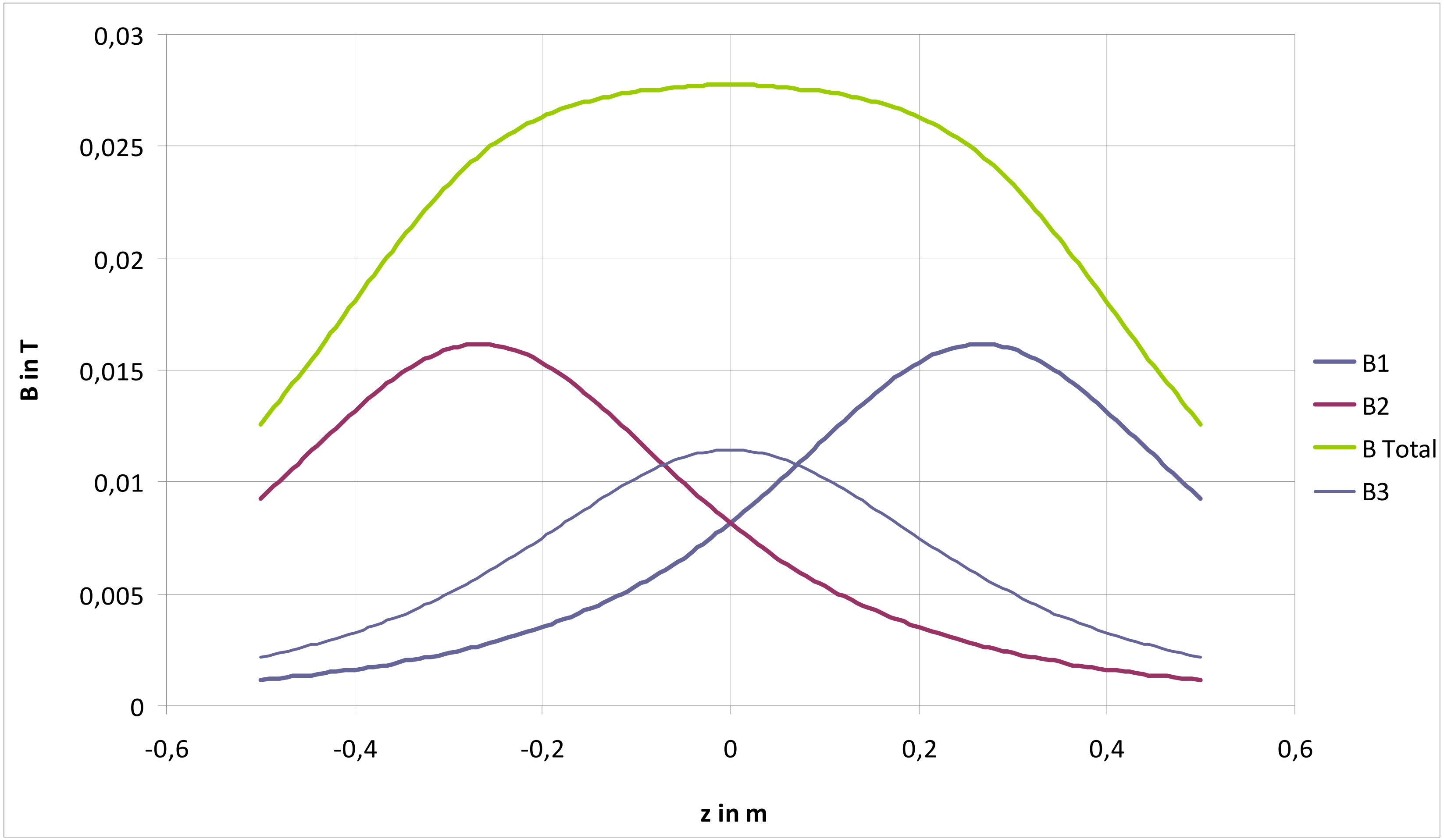
I1=8000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



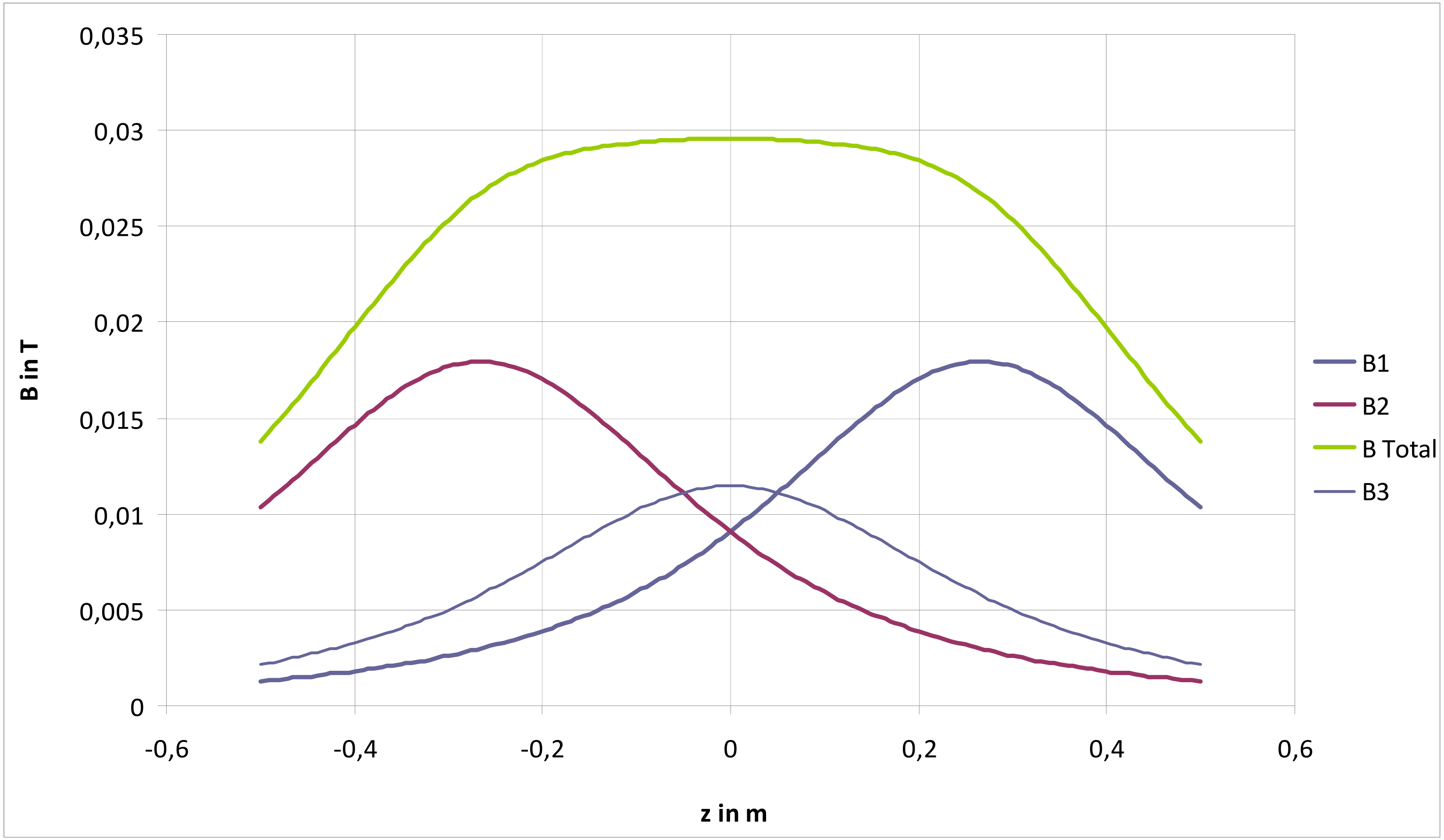
I1=9000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



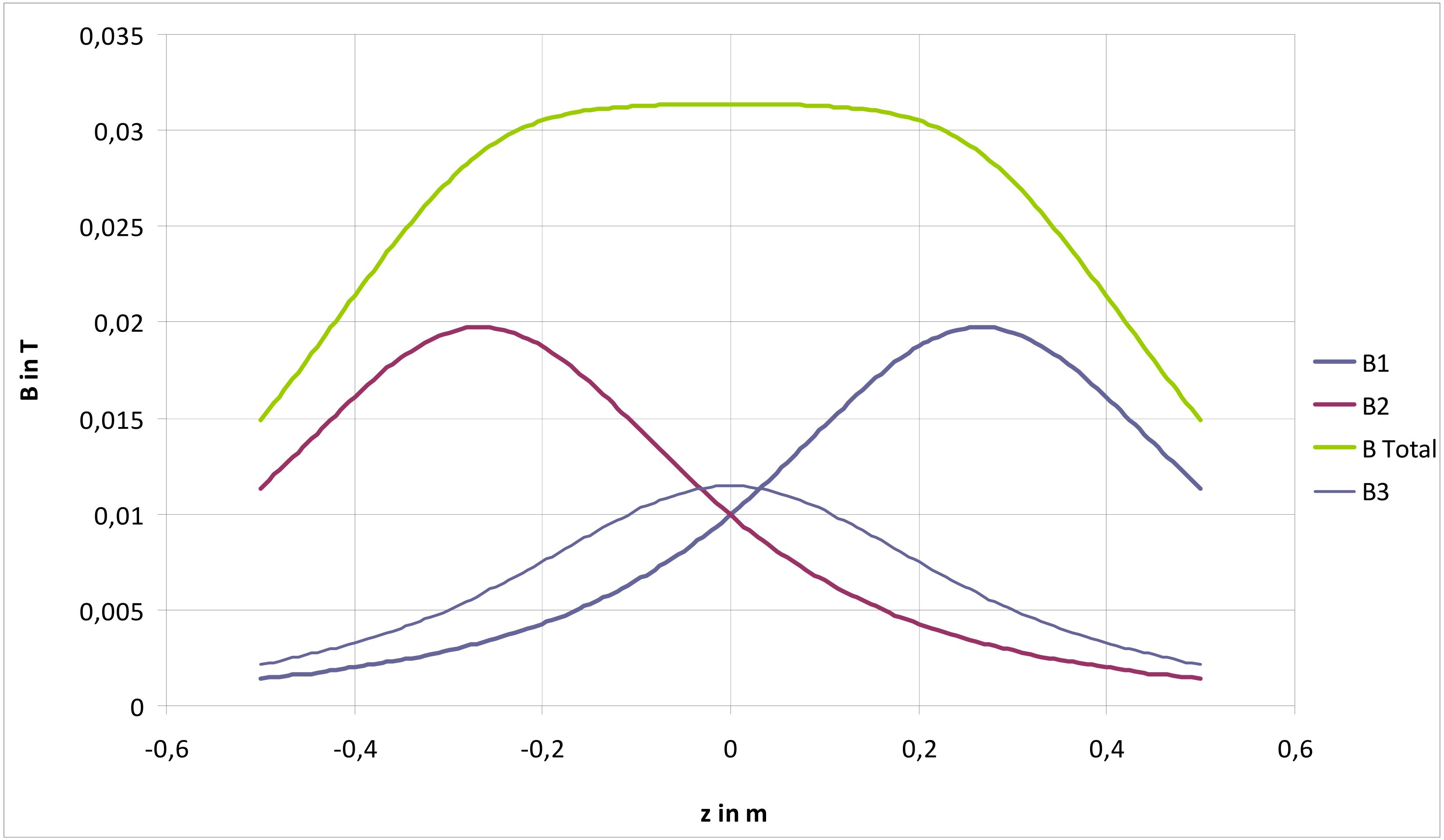
I1=10000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



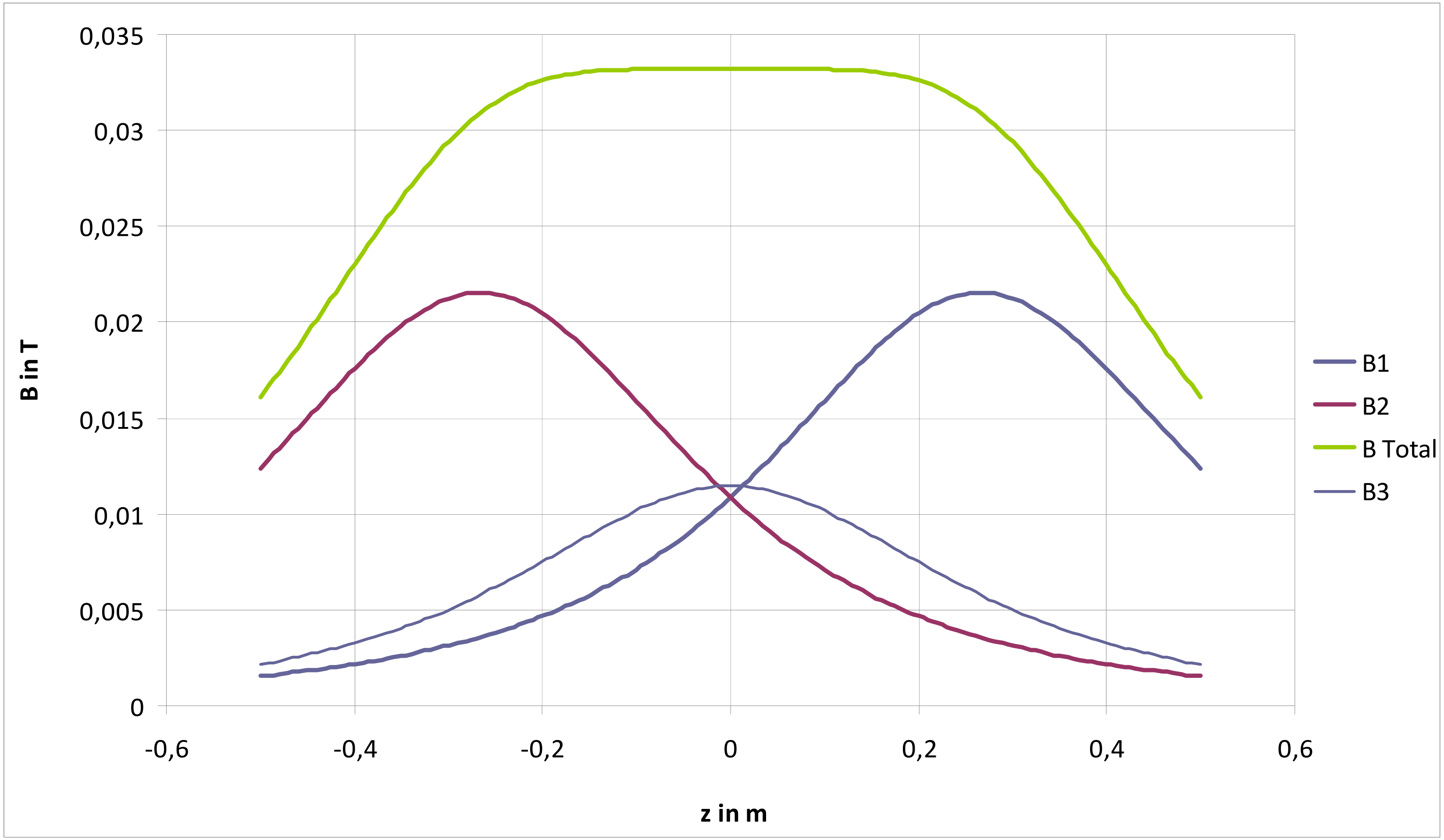
I1=11000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



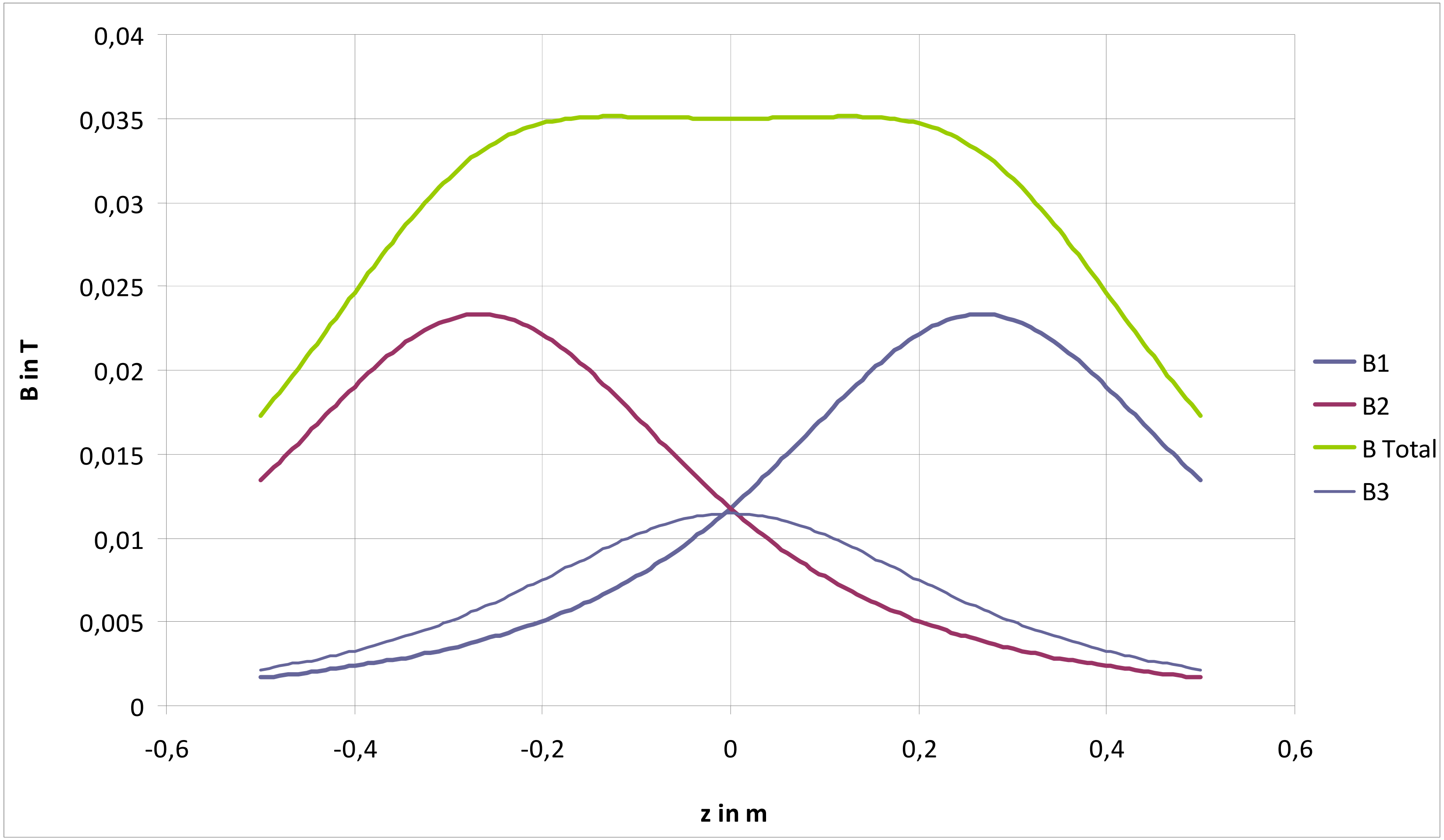
I1=12000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



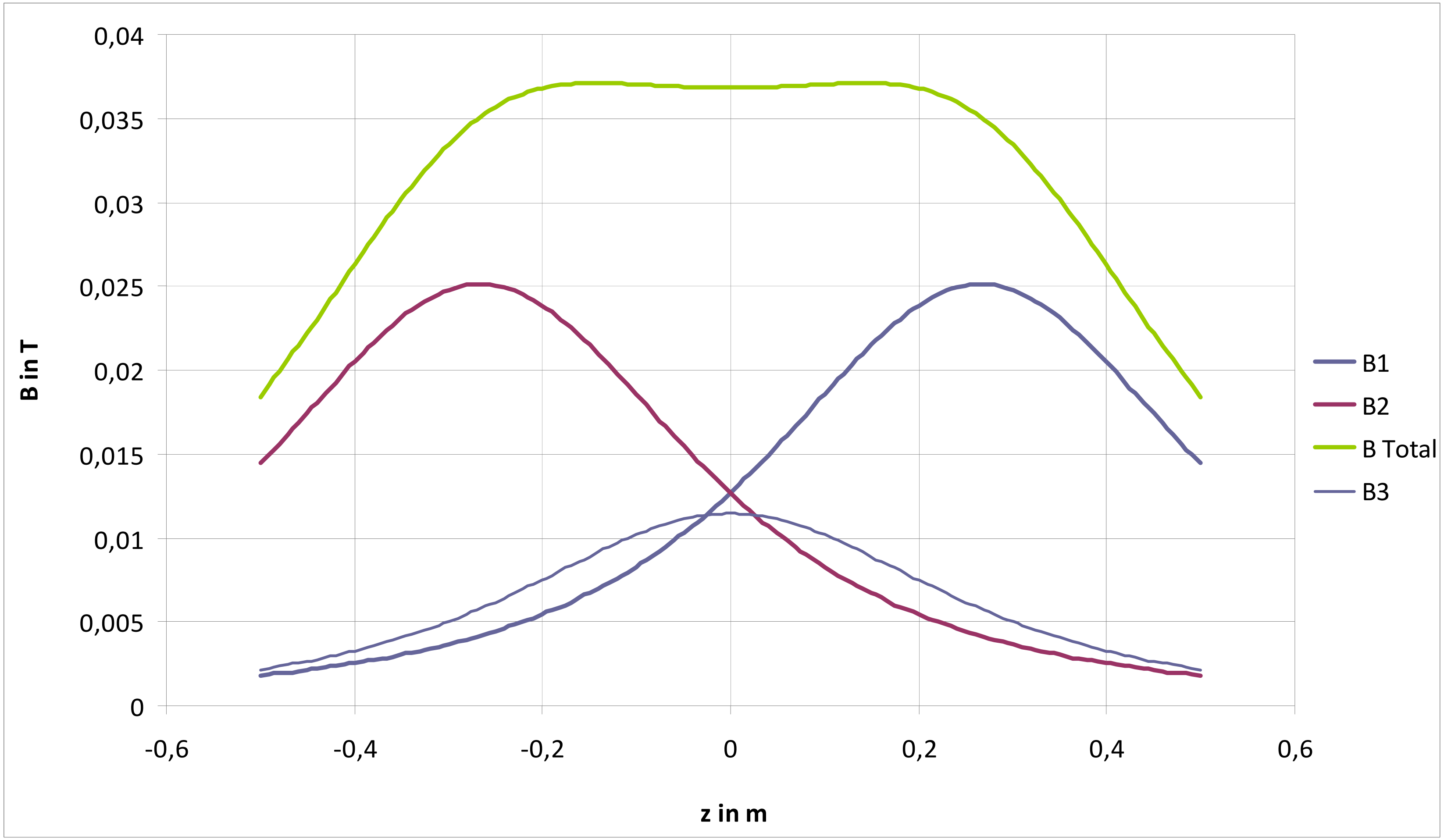
I1=13000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



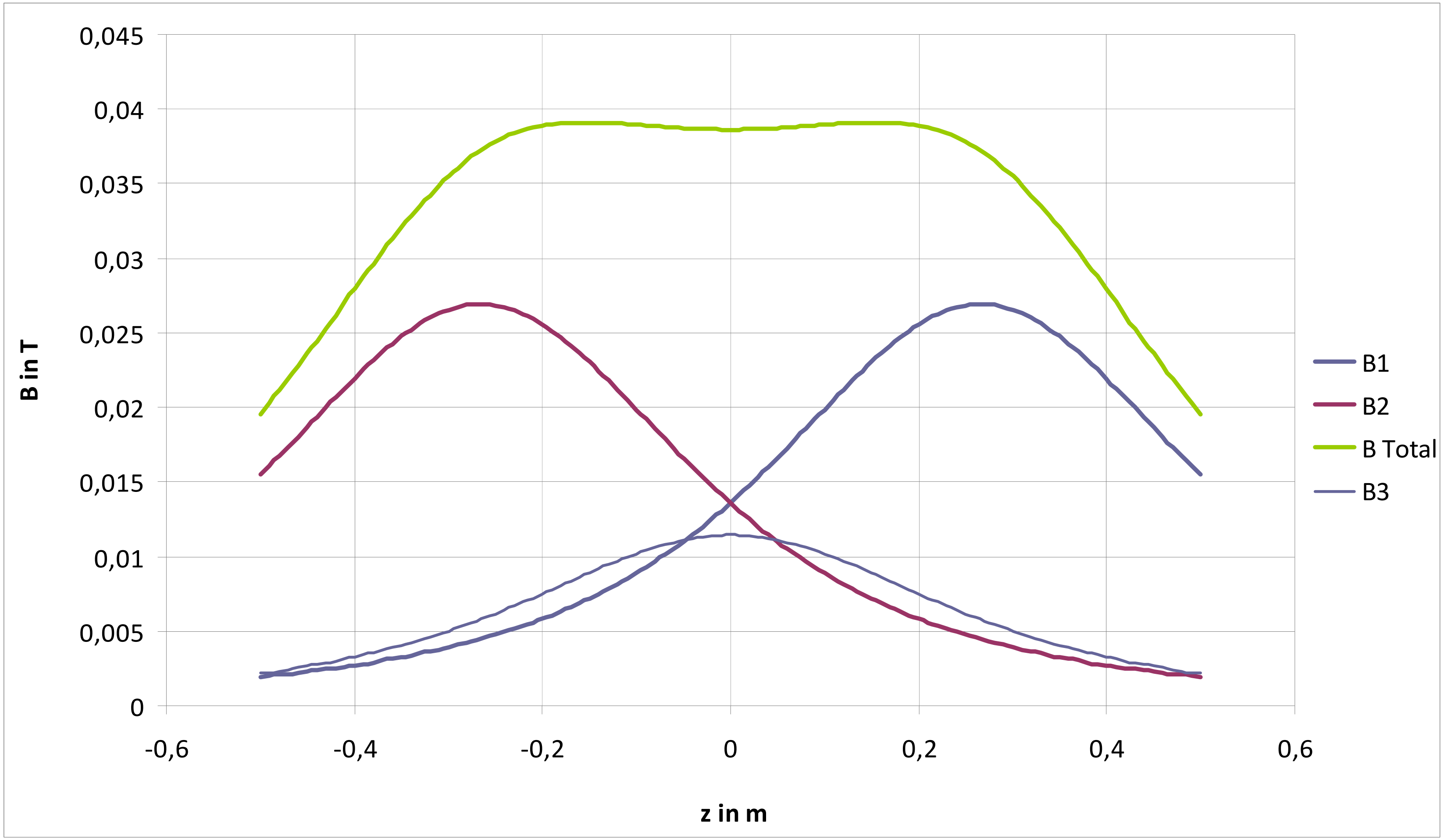
I1=14000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



I1=15000A I2=6377A

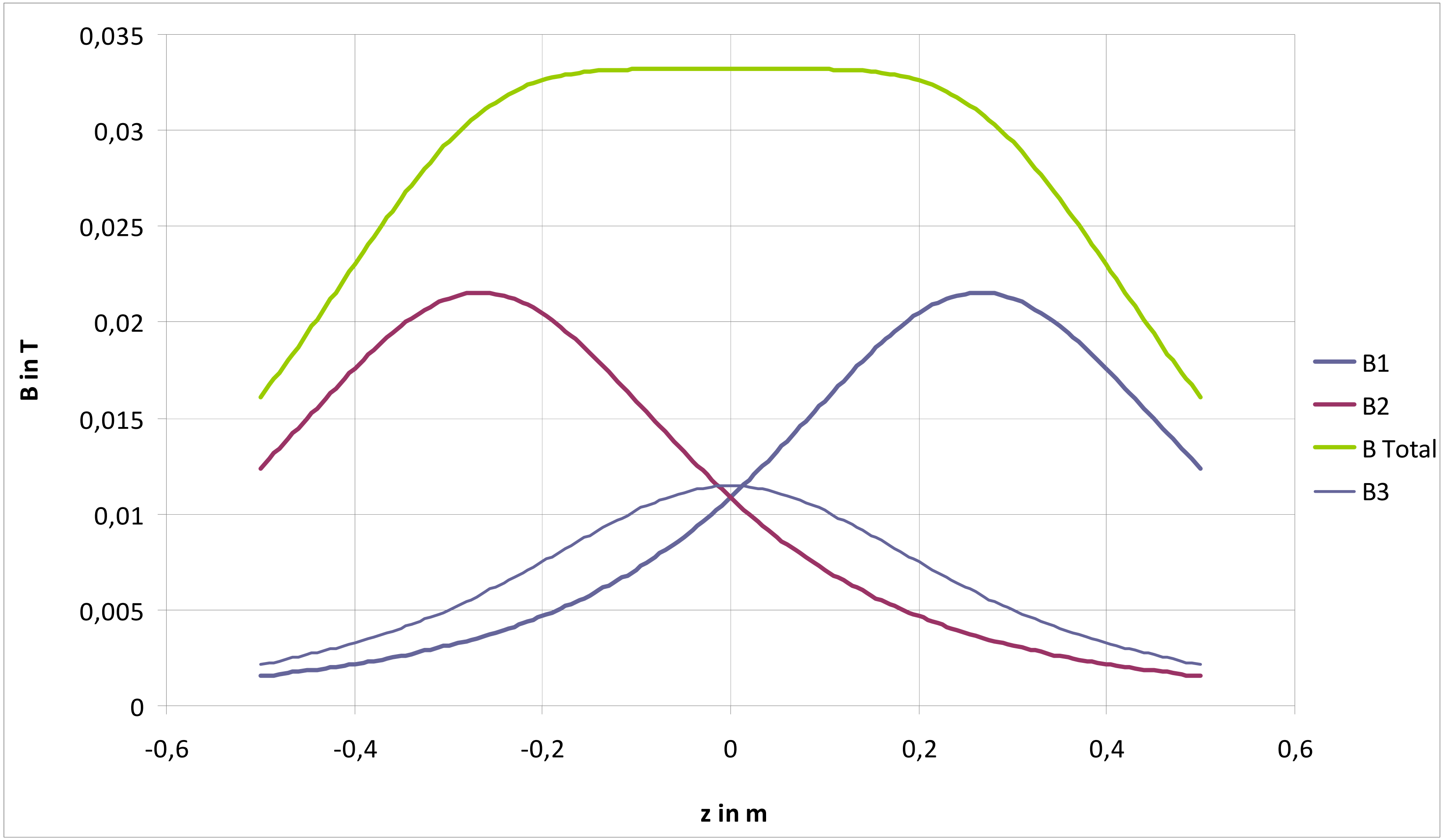
Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



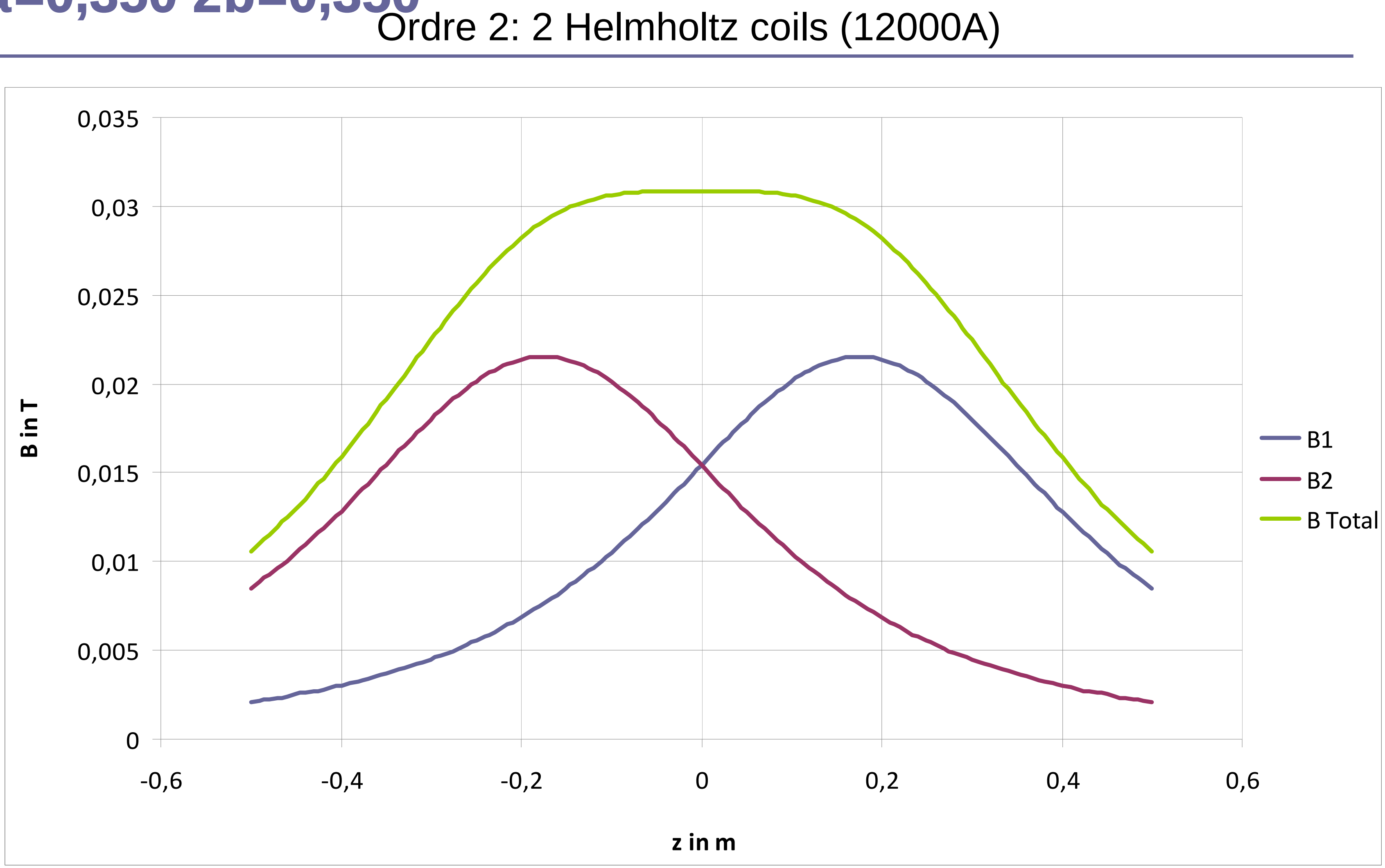
1000 ppm in +-115mm

I1=12000A I2=6377A

Ordre 4: two symetric coils (2b=0.532) I1 & one central coil I2



a=0,350 2b=0,350



How to increase the field

My Magnets (Part 2 of 3 Parts)

—Passage from Francis Bitter's *Magnets: The Education of a Physicist*

. . . By using a variable-size wire in the construction of a coil, I found it possible to increase the magnetic field at the center by a factor of just 1.52 over the best design for a coil with a uniform winding. Therefore, by going into all kinds of practical complications, one could improve the performance of coils only one and a half times or a little more. However, this now was settled; there was no use worrying about it any more. In the end these calculations did show me a practical way of improving the performance of coils by an appreciable amount.

Courtesy of Pr Y.Iwasa

Bitter Magnet

Bitter's design employed a conductor in the form of a stack of annular plates, each with a slit and separated by a thin sheet of insulation except over a sector. The slit allows the bare sector to pressure-contact the next plate's bare sector, enabling the current to commutate from one plate to the next in a quasi-helical path as it flows from one end of the stack to the other. Each "Bitter" plate is punched with hundreds of cooling holes. To generate a high field, tens of thousands of amperes of current are pushed through the electrically resistive stack, consuming megawatts of electrical power, which heat the stack. This heat is removed by water forced through the cooling holes at high velocity, $\sim 20\,\mathrm{m/s}$. A silhouette of two nested "Florida-Bitter" plates, developed in the 1990s at the National High Magnetic Field Laboratory (NHMFL), is shown in Fig. 3.18 [3.9]. A radial slit in each plate is clearly visible. Also note that each water passage hole is not circular as in Bitter's plates; the elongated—in the direction of current—shape was first developed by Weggel at M.I.T. in the 1970s. The outer plate of the set here is 148 mm in diameter; plate sizes have been more than 400 mm in diameter. The sixteen large holes are for axially clamping the plates with tie rods. A key feature of the Bitter magnet construction is that it is modular, consisting of many similar plates. Plate thickness, mechanical properties, and electrical properties can be tailored to the axial position to optimize magnet performance.

Courtesy of Pr Y.Iwasa

NHMFL Bitter Magnet

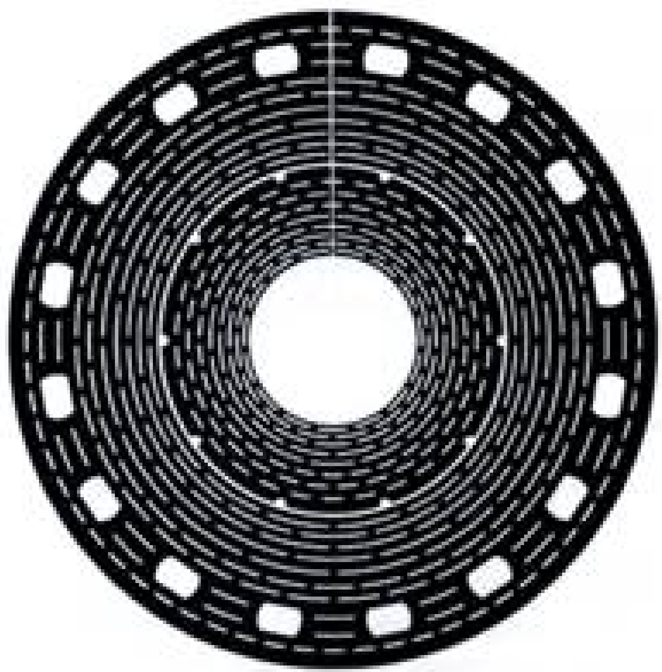


Fig. 3.18 Silhouette of two nested "Florida-Bitter" plates, with an outer plate of 140 mm in diameter, in "water" magnets at the National High Magnetic Field Laboratory [3.9].

Courtesy of Pr Y.Iwasa

NHMFL 45 T Hybrid Magnet

Figure 3.22 shows a cross-sectional view of the "water" magnet, SCM, and some auxiliary components of the 45-T hybrid magnet at the NHMFL [3.31]. The water magnet has four nested coils; it generates a center field of 31 T at 24 MW. The SCM, consisting of three coils, A, B, and C, operated at 1.8 K, initially generated 14 T but now operates at 11 T [3.30]; the water magnet has been redesigned to contribute 34 T at 30 MW. The system includes a superfluid helium supply cryostat, to which the SCM cryostat is connected by a pipe, shown truncated at the right, middle of the figure.

Courtesy of Pr Y.Iwasa

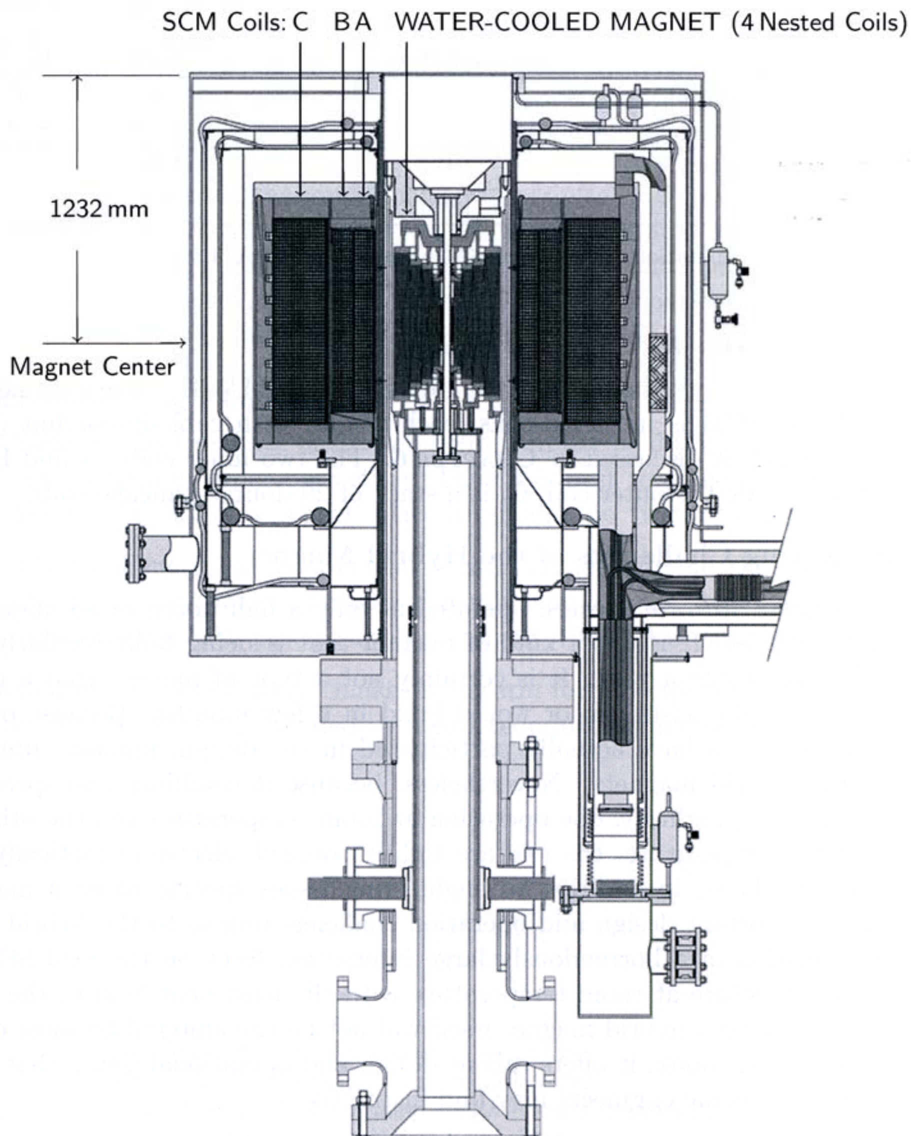
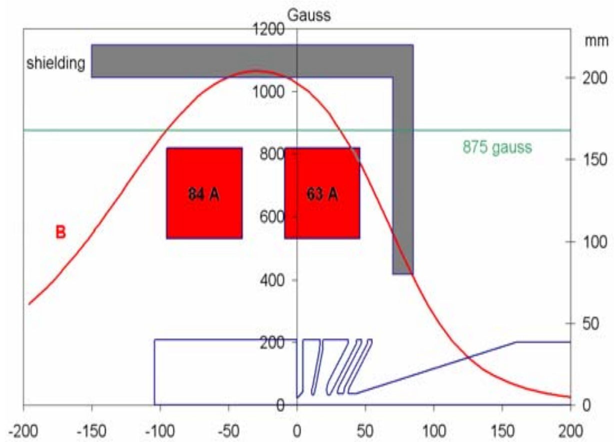
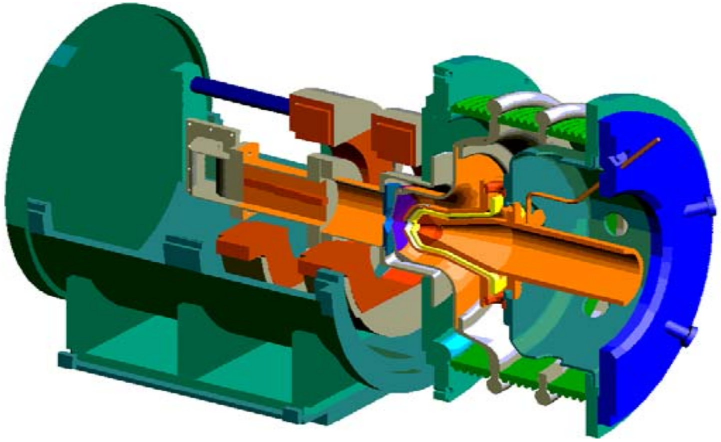


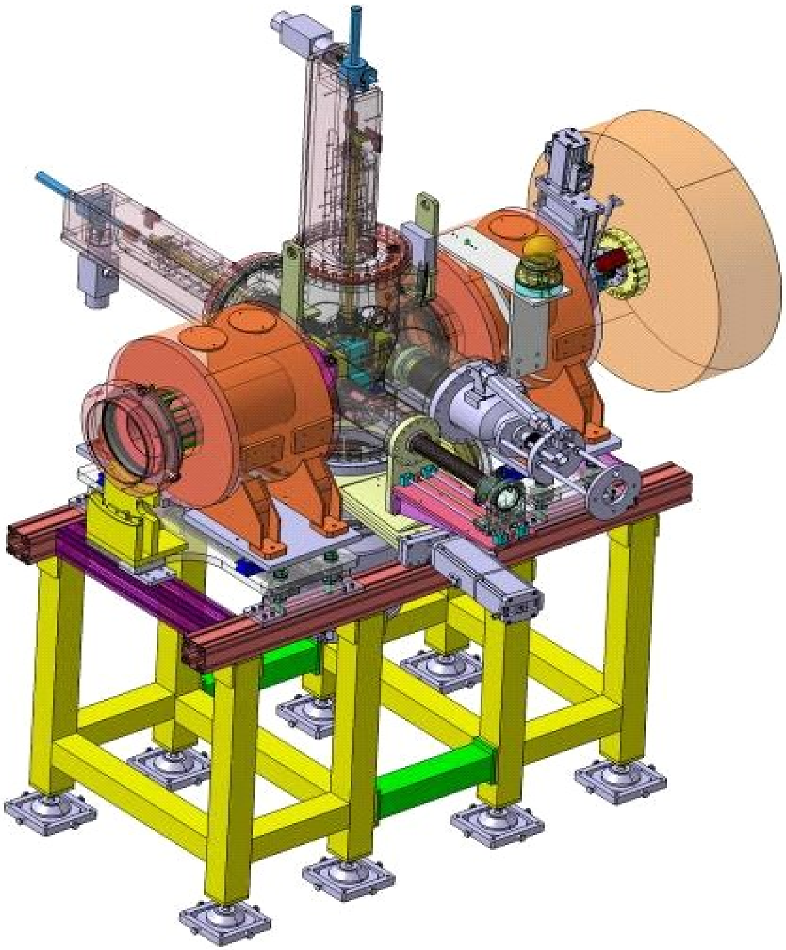
Fig. 3.22 Cross sectional view of the 45-T hybrid magnet at NHMFL [3.31].

Courtesy of Pr Y.Iwasa

Solenoid Lens for Ion Beam source & LEBT



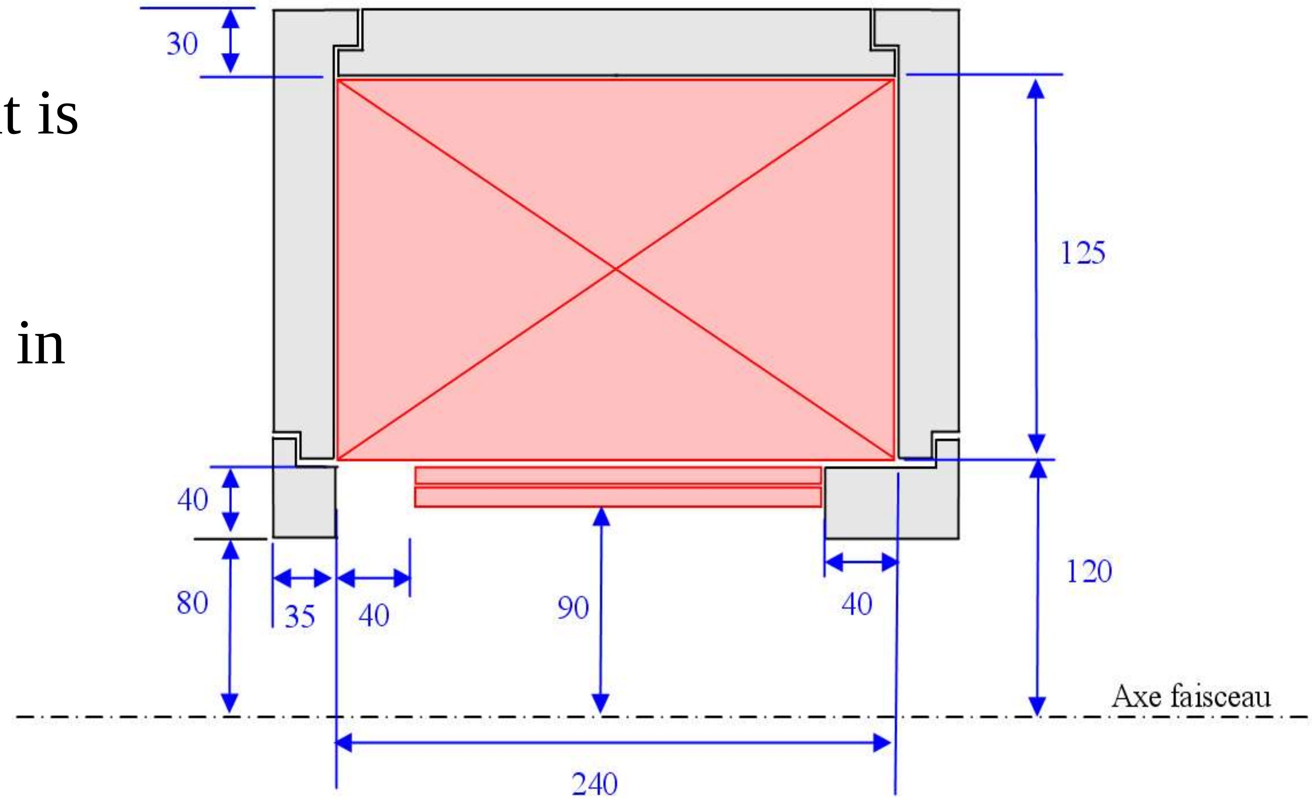




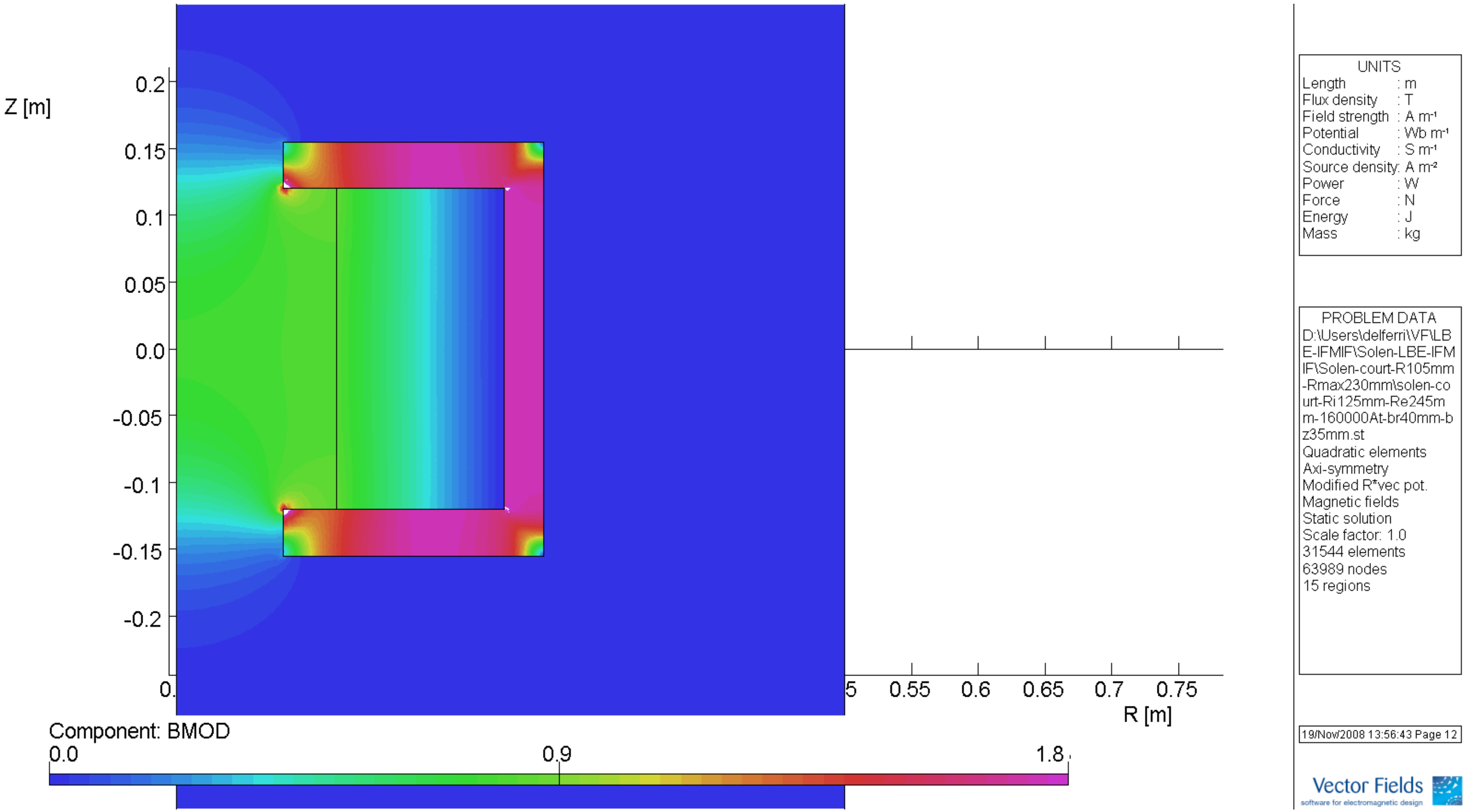
1A	1mT	1.25mm
1A 160000At	1mT 0,800T	240 Factor 200

Coil parameters

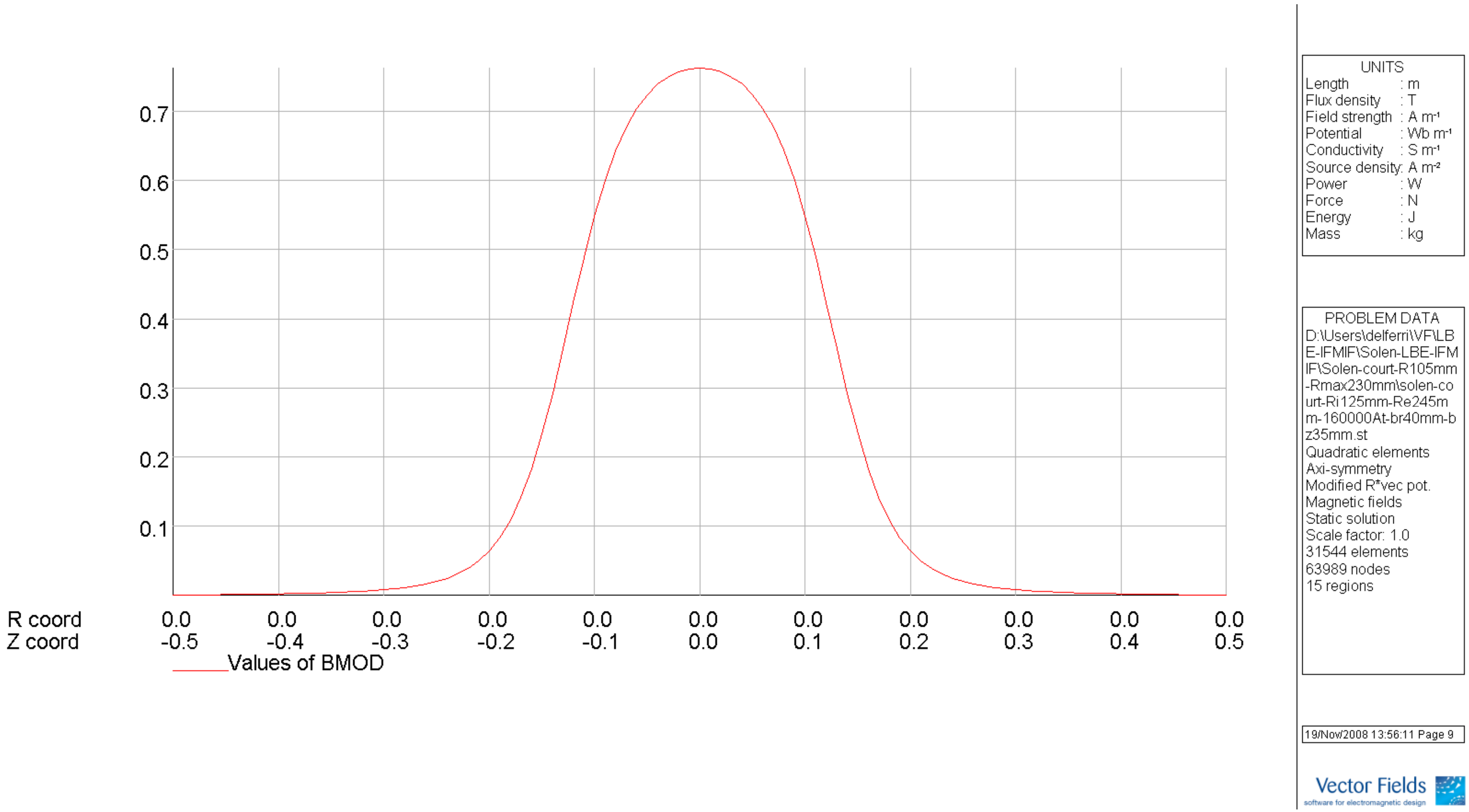
The magnetic circuit is saturated
Jeng=10 A/mm2
An electrical Power in the range of 15kW is necessary

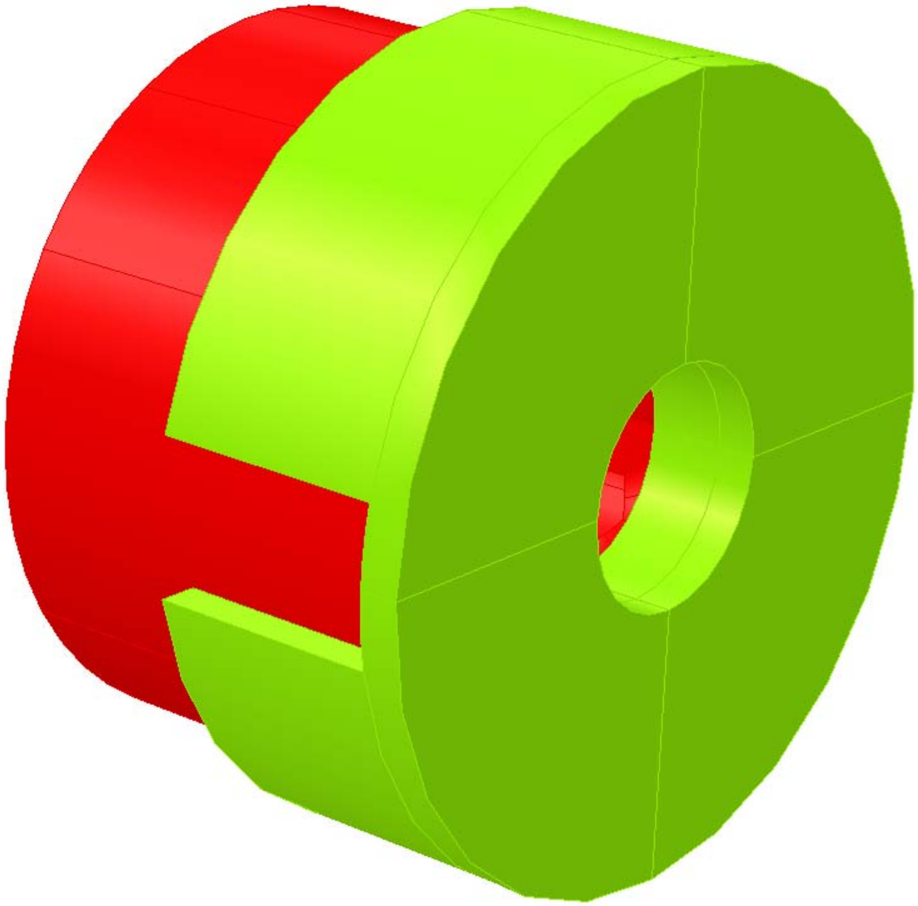


Field level computed by TOSCA

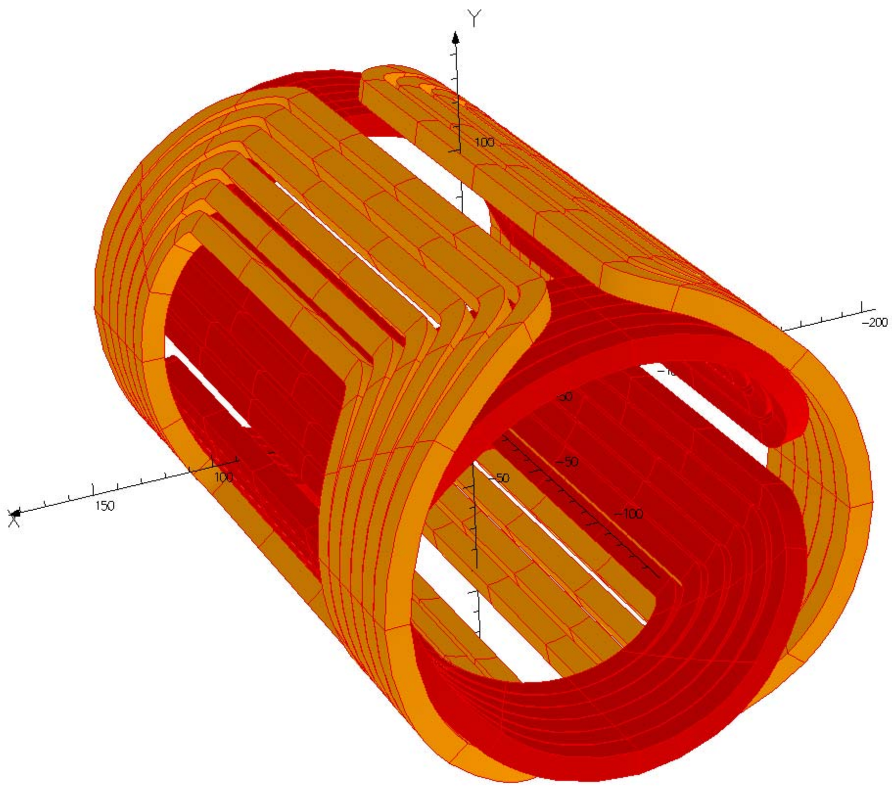


Field curve of a magnetic lense

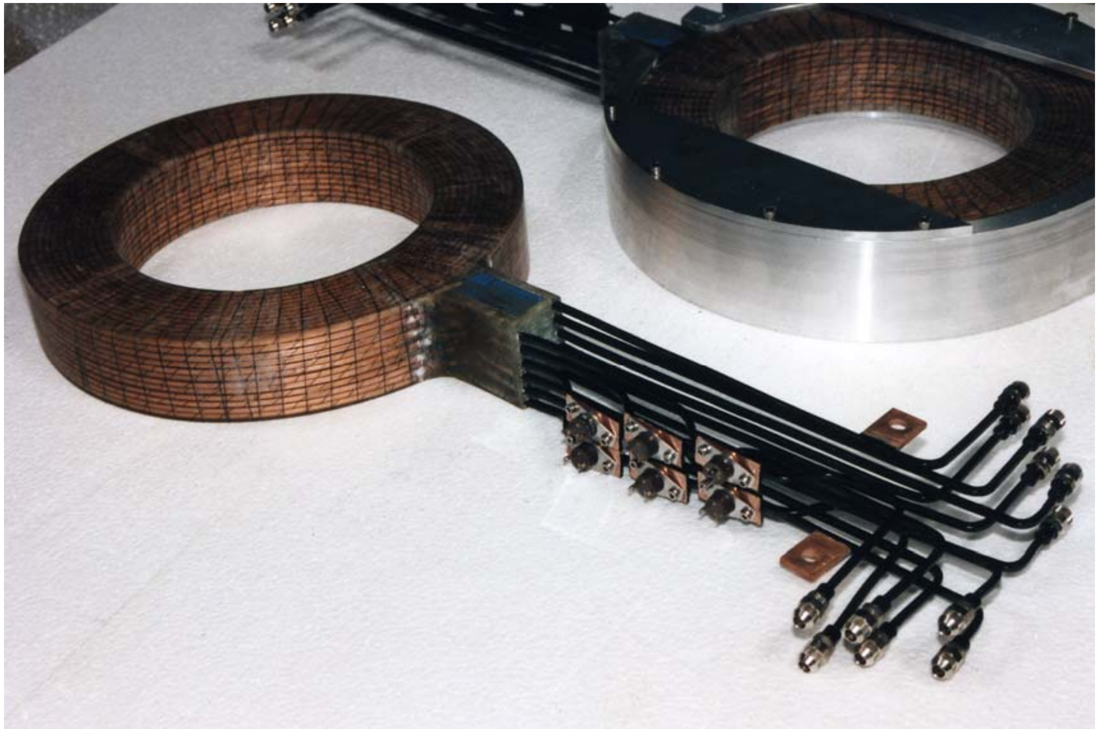




Steering coils are installed inside the solenoid to save space.



View of the coils: due to high power , the connections are space consuming.

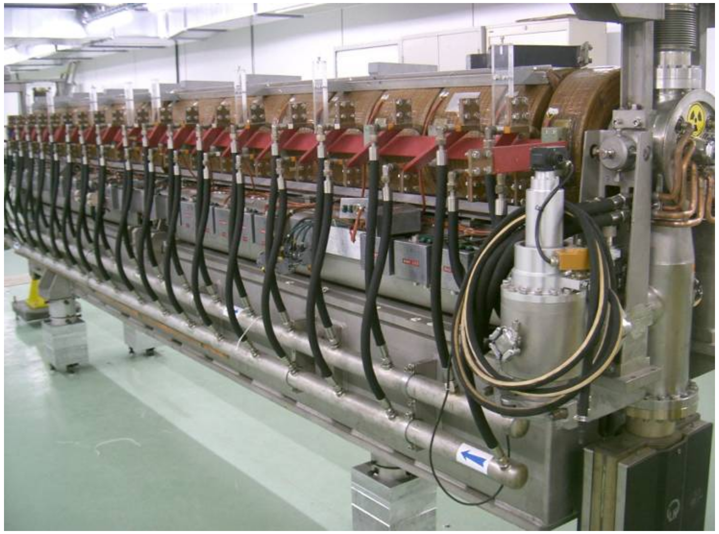


In accelerators solenoids are used
For focusing in the low energy sections:
Electron guns
CLIC-CTF3 Probe beam LINAC

Structure 3 GHz nue

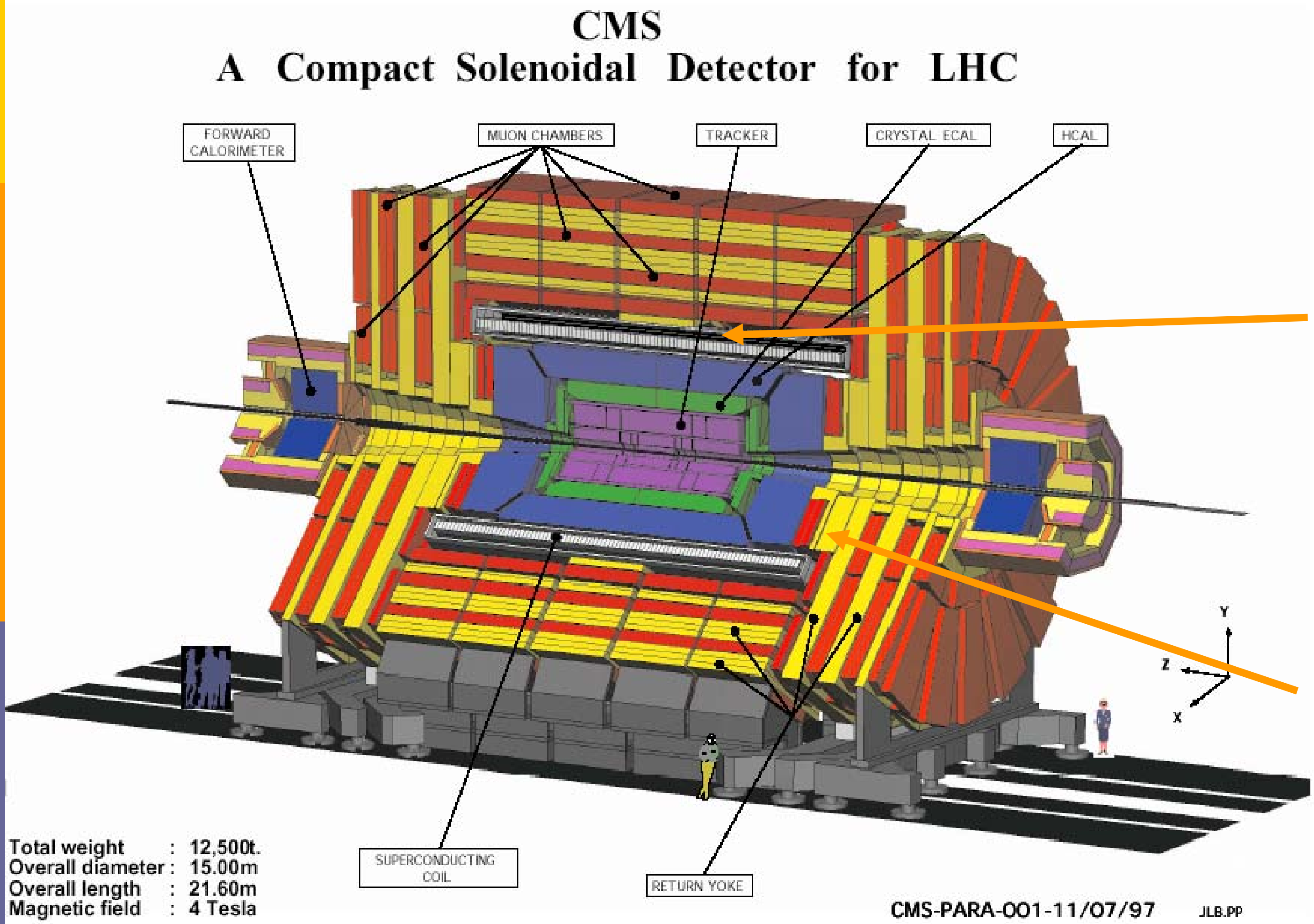
Califes: vue upstream

Structure 3 GHz avec solénoïdes



Vue downstream

Let's stay at CERN: CMS (Compact Muon Solenoid)



Design compact

Basé sur un solenoïde SC

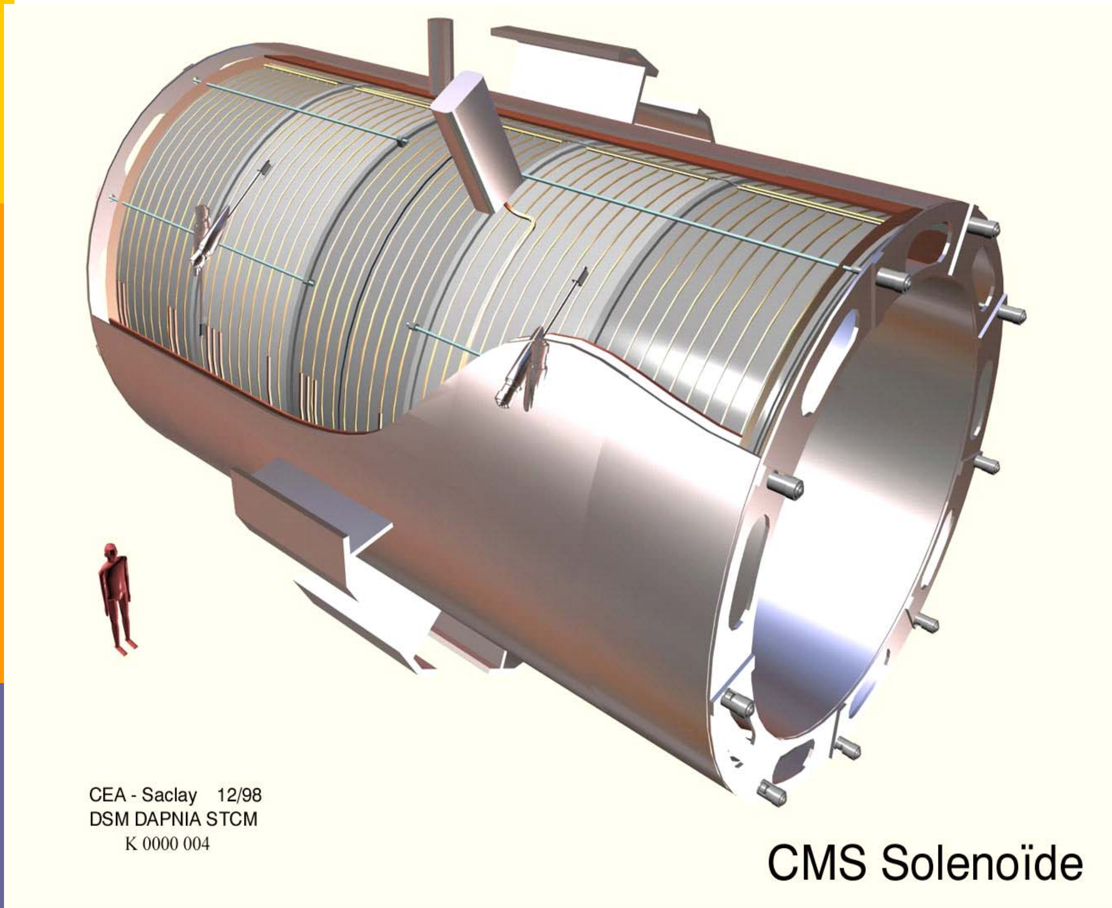
6 m de diamètre

13 m de long

Champ élevé 4T

+ culasse en fer doux

Du Virtuel au Réel : 1998-2006



Champ central : 4 T

Courant nominal : 20 kA

Energie stockée : 2,6 GJ

Masse froide

Longueur : 12,5 m

Diamètre interne : 6 m

Poids : 220 t

A few challenges of the CMS Magnet CMS

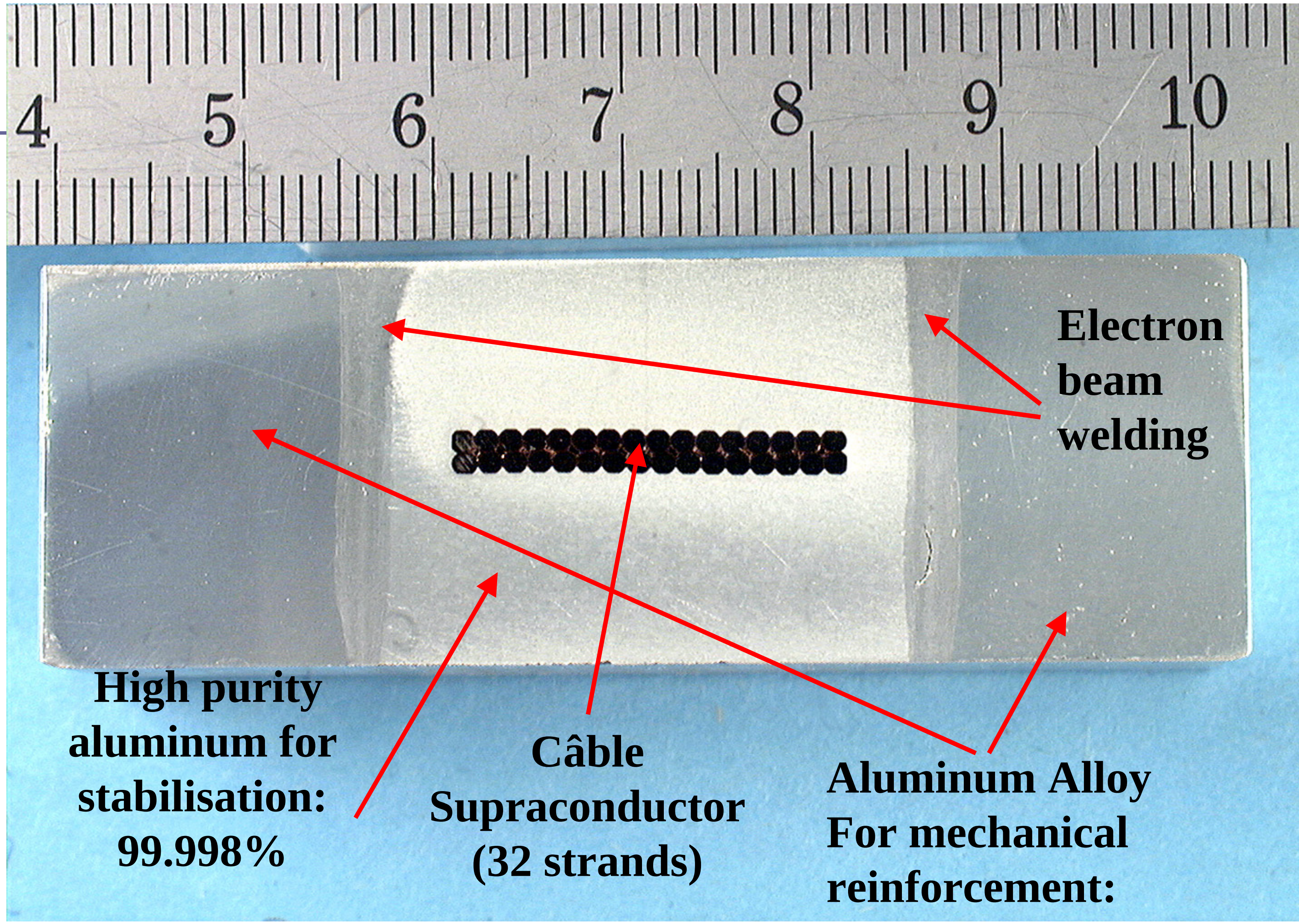
- Magnetic pressure is 6.4MPa
- Conductor 20 kA reinforced mechanically by aluminum alloy
- Stress=

- Winding in 5 modules, each of 4 layers chacun. The winding is practised in an outer mandrel

- Magnetic pressure 6.25 MPa
- Attraction force between modules: 6.25 MPa*20m2=12000 tons

- Stores energy 11,6 kJ/kg in the cold mass

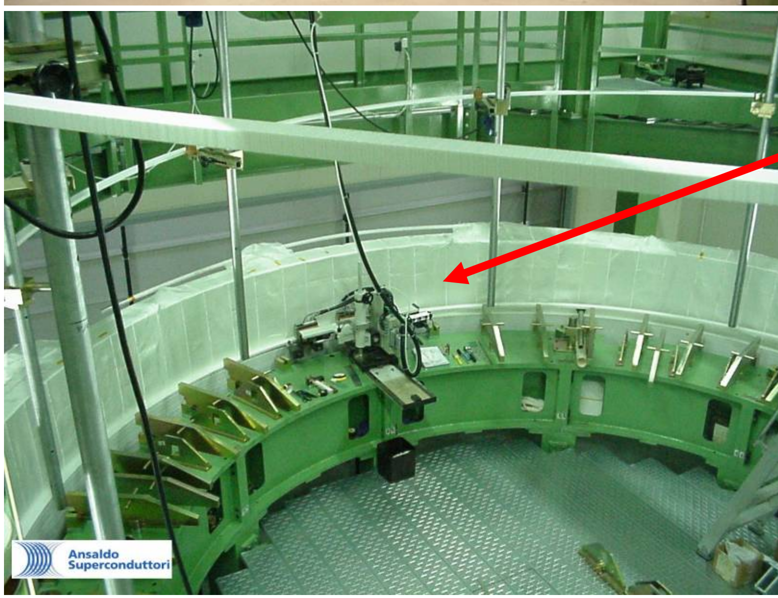
CMS conductor



Manufacturing of modules (06/04)

Polymérisation
CB-1

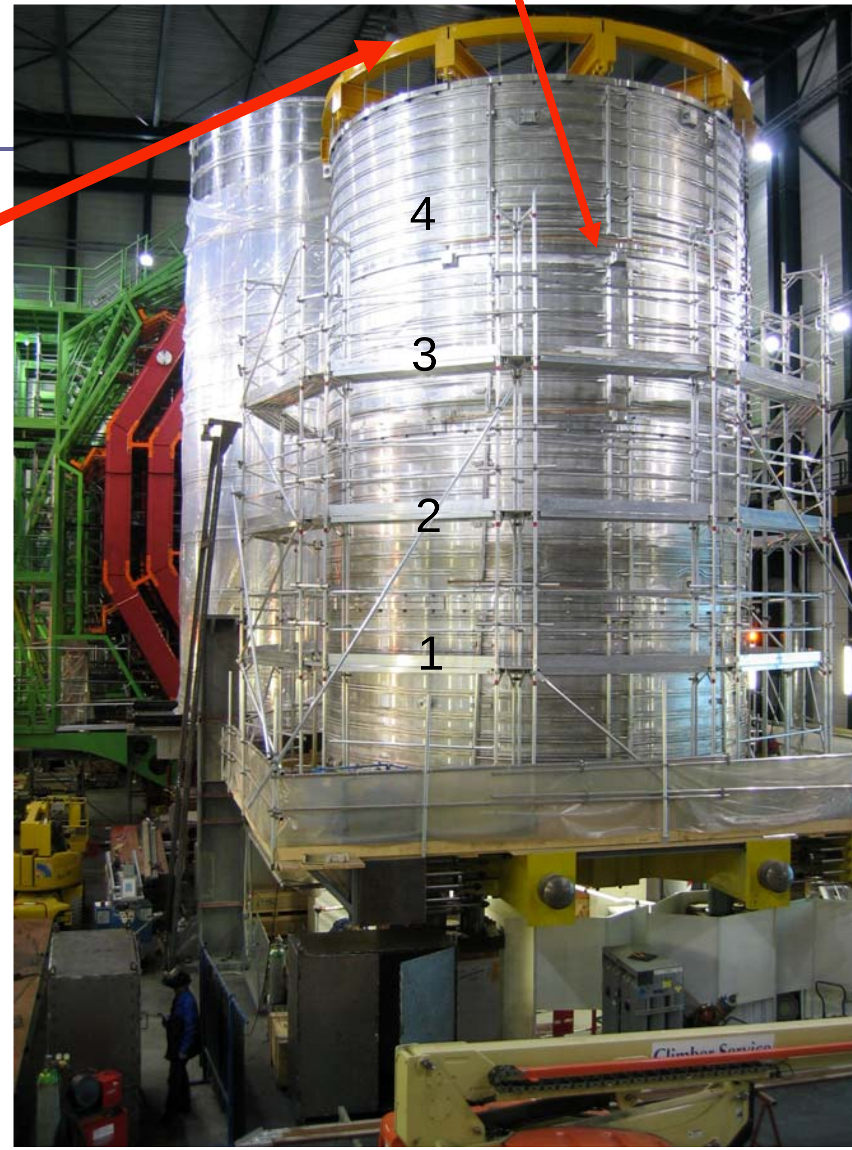
Finition CB0



Winding CB+1

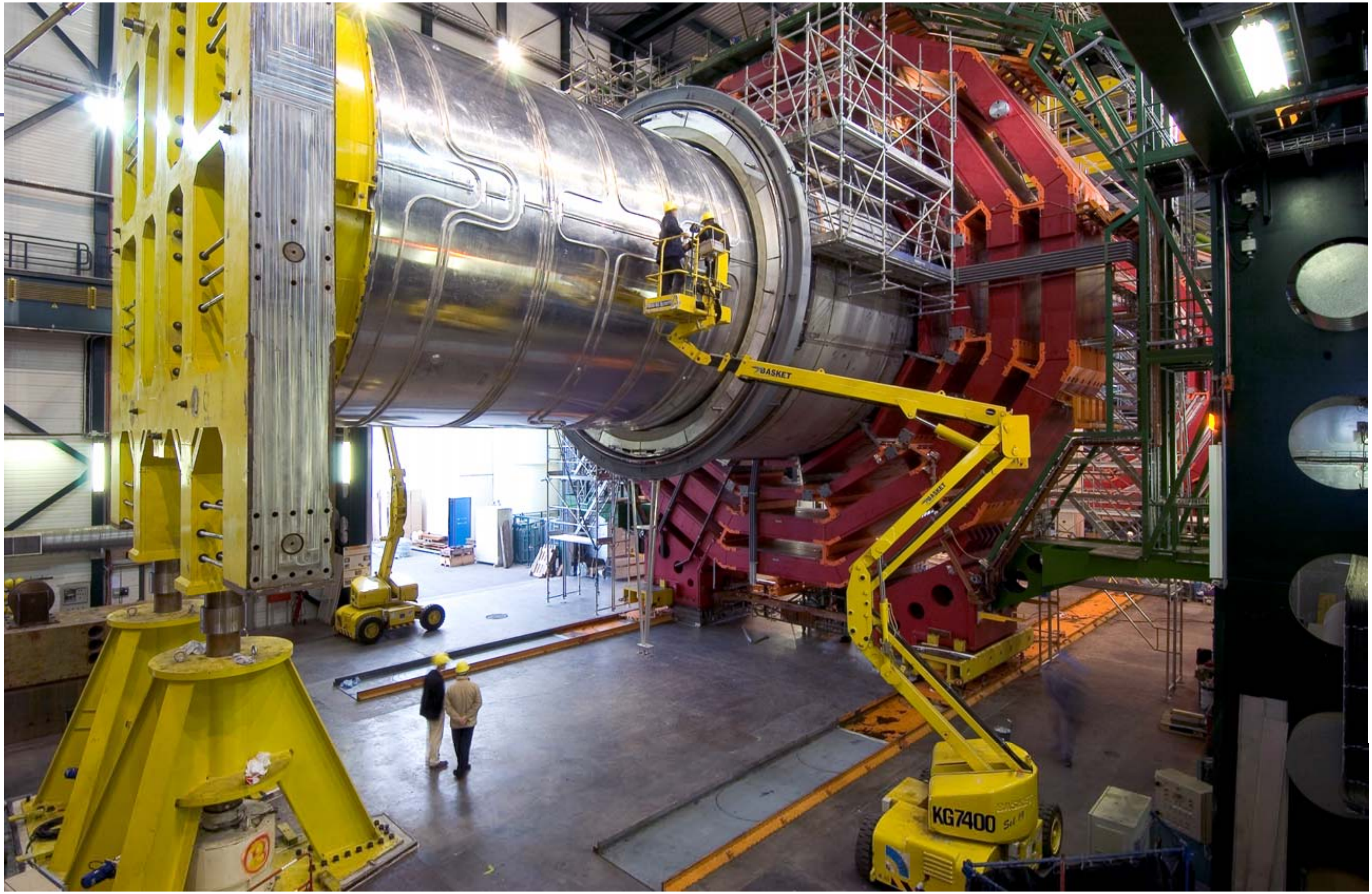
outer
cylinder
CB+2

Assemblage de la bobine en vertical

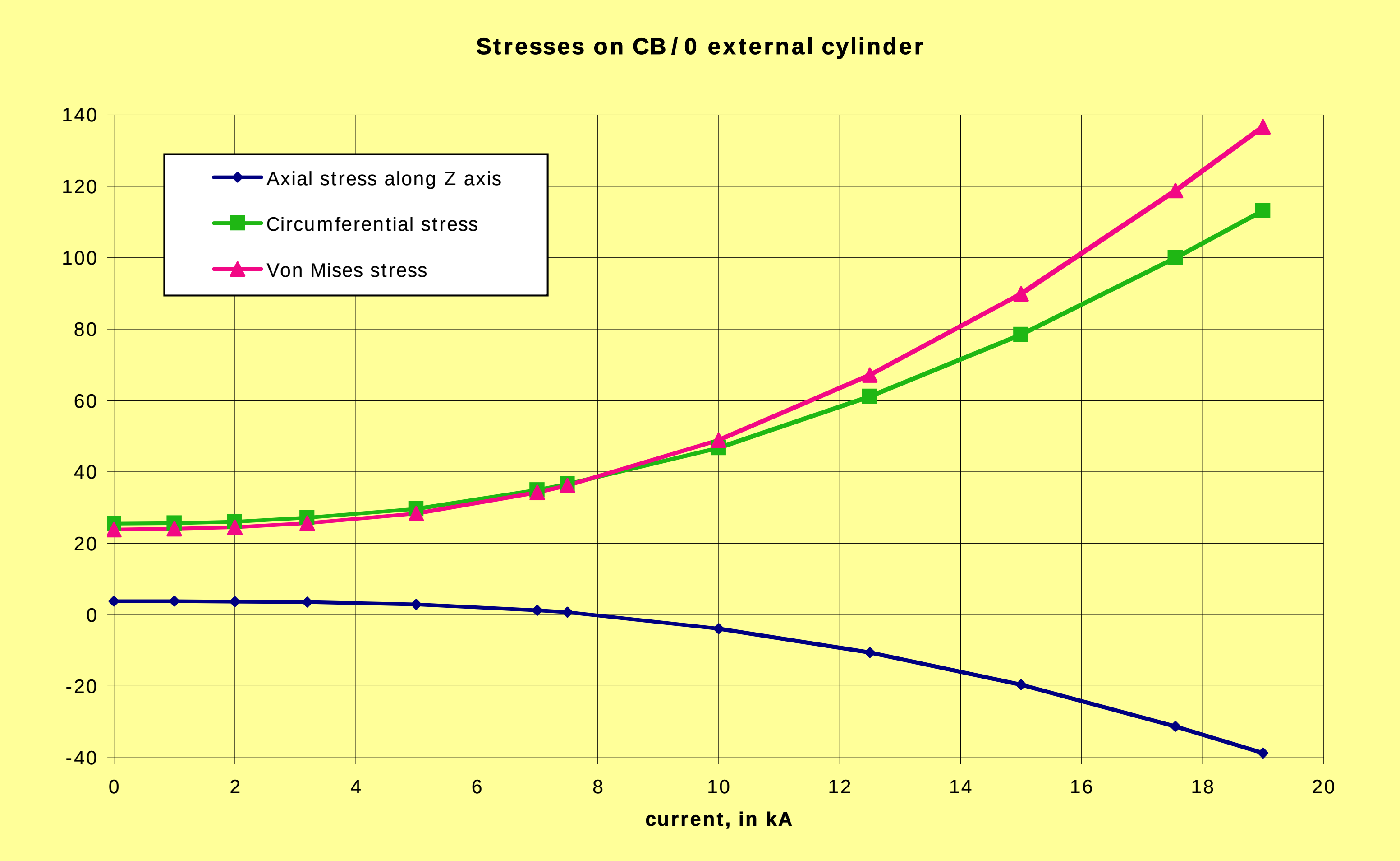


Rings between the modules are taking the axial attraction force or 12000 tons which is just magnetic pressure (6MPa) cross the section(20 m2)

Août 05 : insertion of cold mass in the vacuum vessel



Efforts on the cold mass



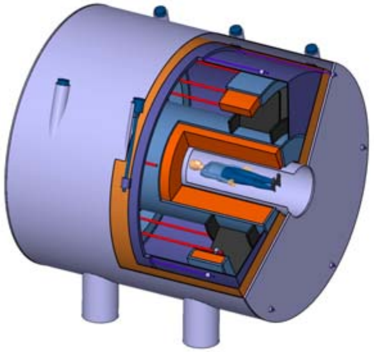
- Contrainte de Von Mises mesurée à 4T : 138 MPa
- En accord complet avec les calculs de 1998.

MRI limits

Magnet 1.5T (GE) SHFJ/CEA

Magnet 3.0T (Bruker) SHFJ

Magnet 9.4 T GE 600 mm (USA)



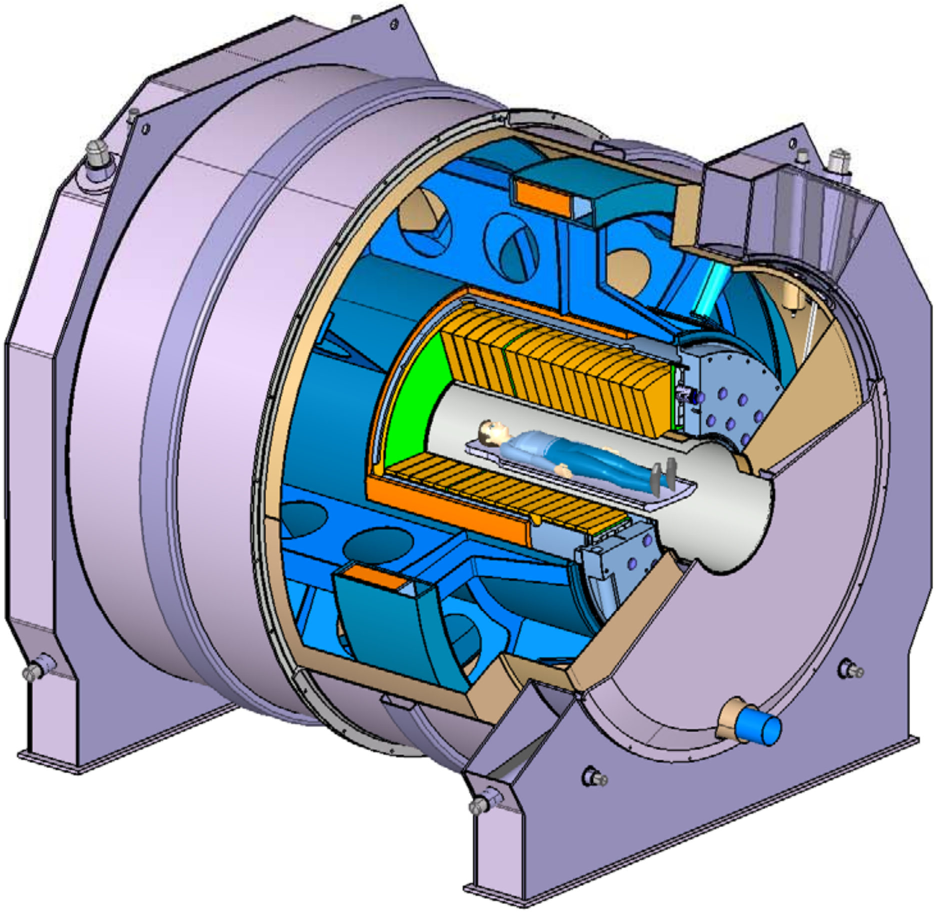
Iseult 11.7 T

1 mm
1s

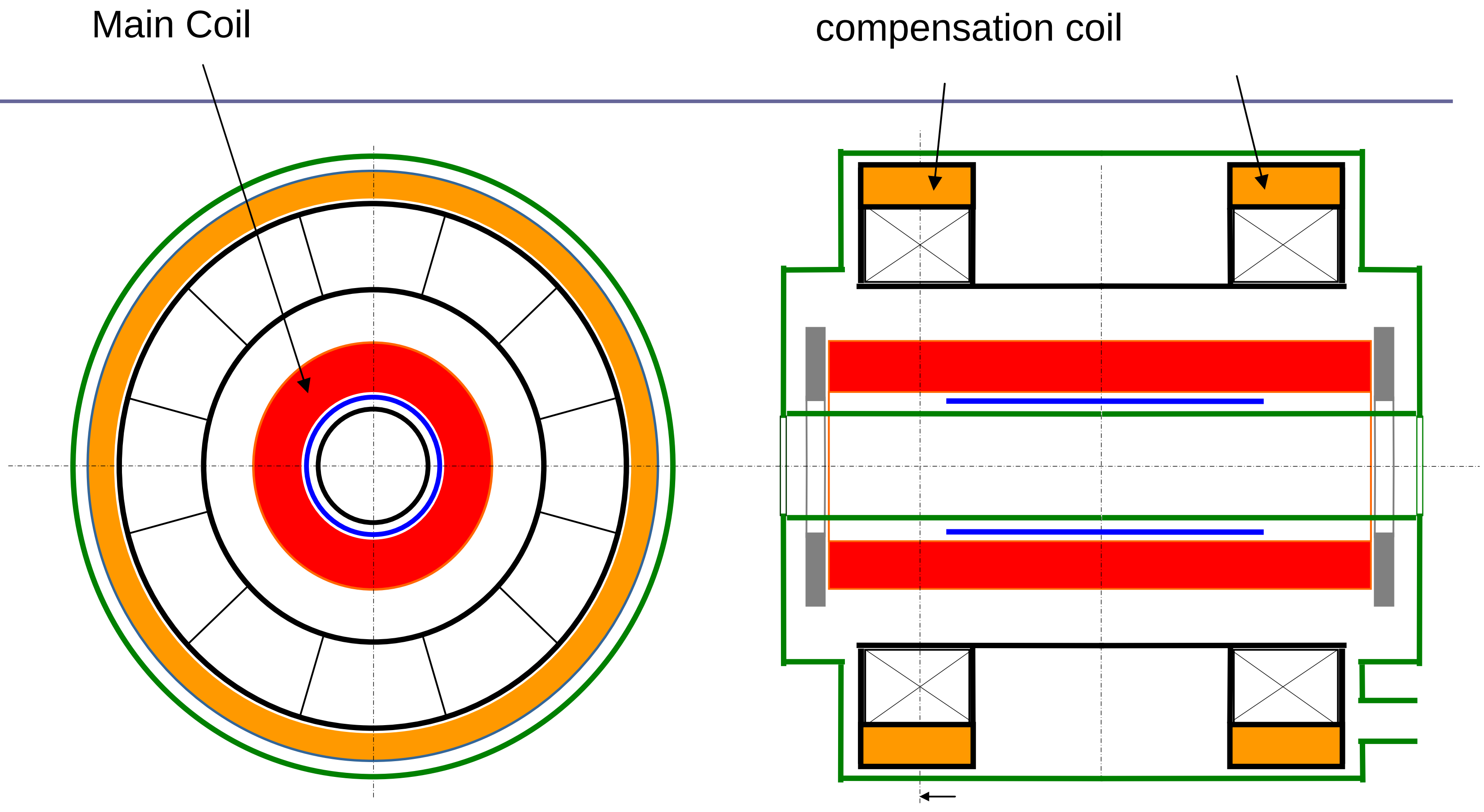
Increase spatial and time resolution →

0.1 mm
0.1s

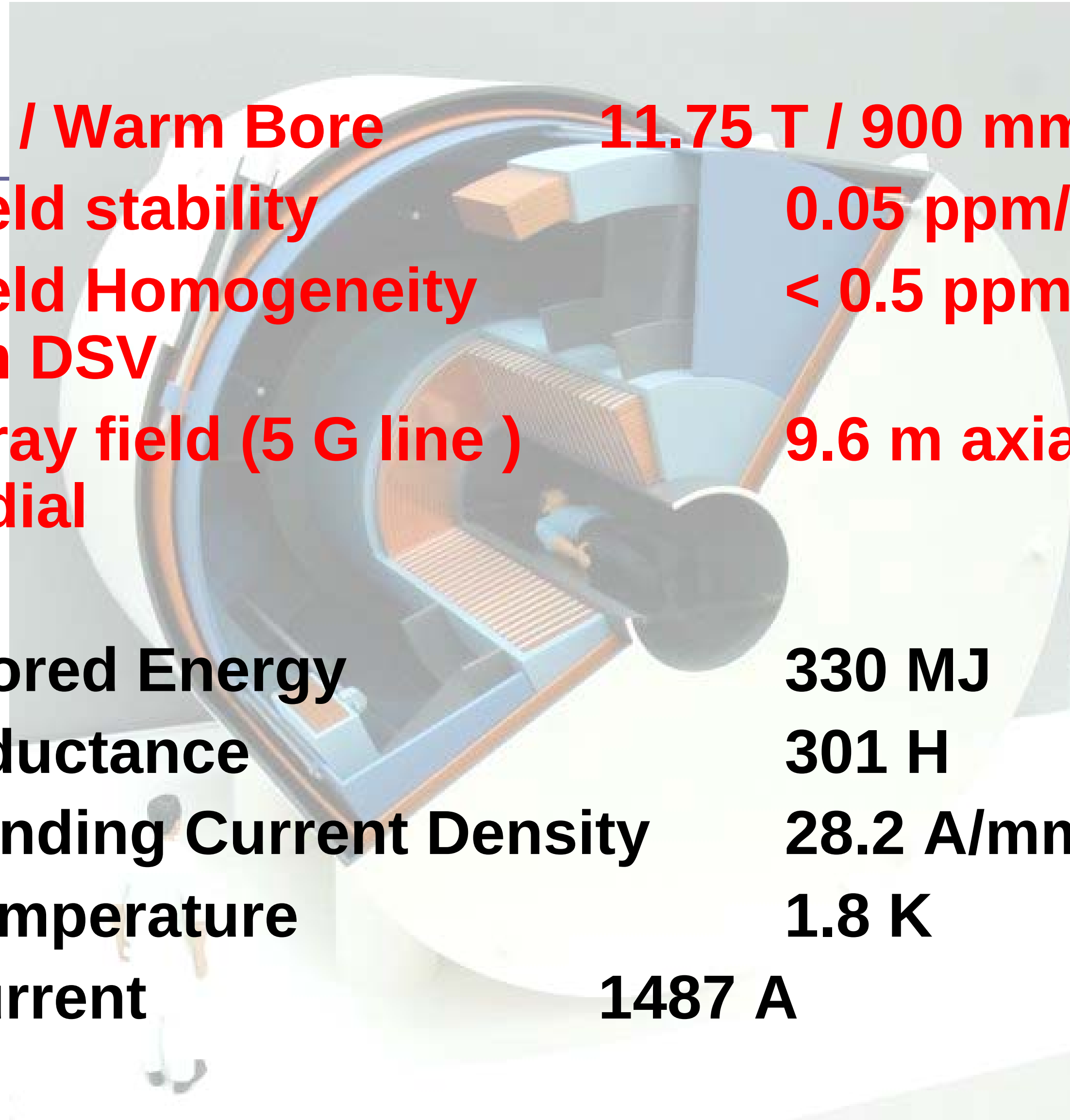
MRI Magnet architecture



Winding



Main parameters of the ISEULT Magnet

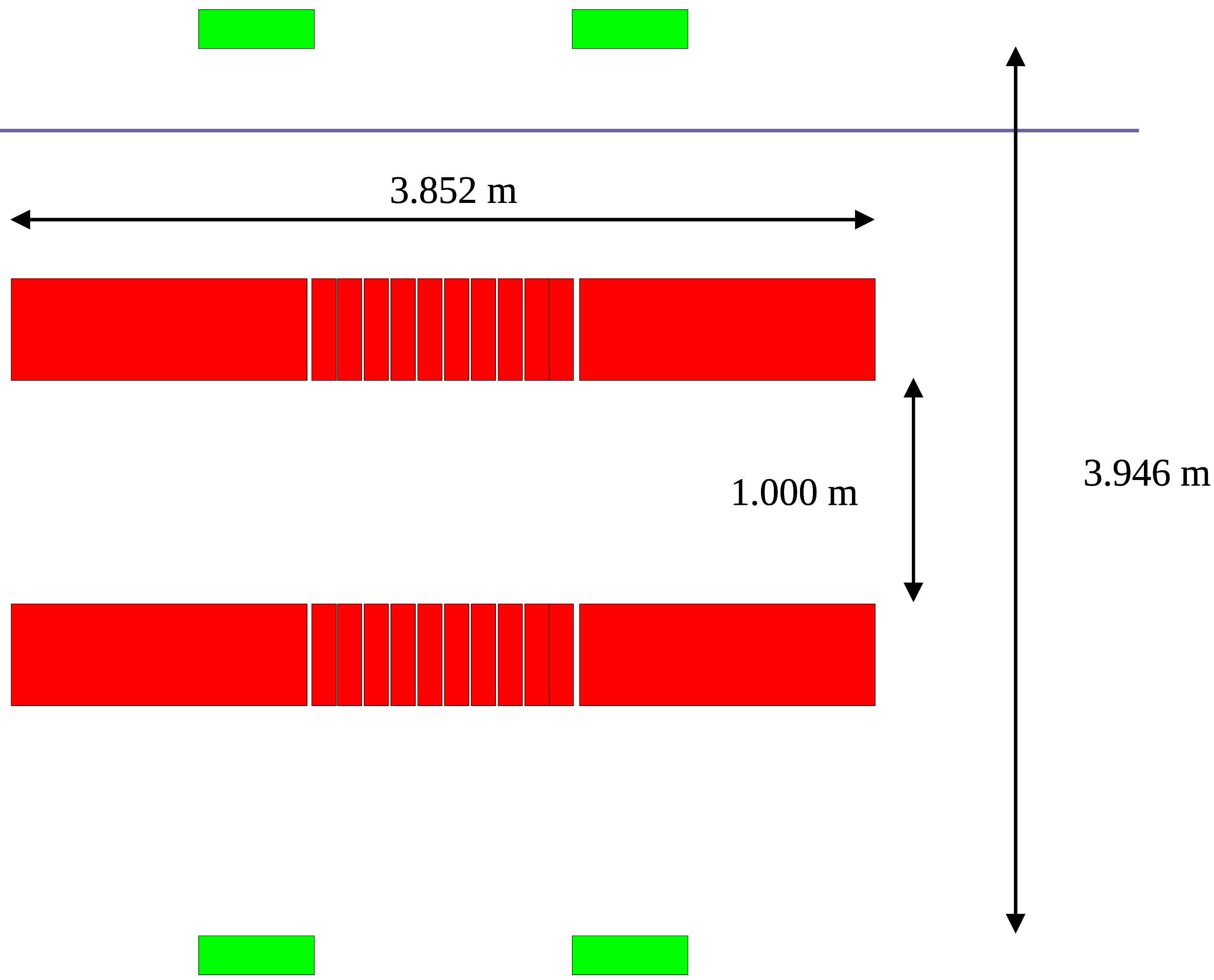


- B0 / Warm Bore 11.75 T / 900 mm
- Field stability 0.05 ppm/hr
- Field Homogeneity < 0.5 ppm over 22 cm DSV
- Stray field (5 G line) 9.6 m axial, 5.1 m radial

- Stored Energy 330 MJ
- Inductance 301 H
- Winding Current Density 28.2 A/mm²
- Temperature 1.8 K
- Current 1487 A

- Conductor size 9.2 mm x 4.6 mm
- Conductor weight 60 t of NbTi

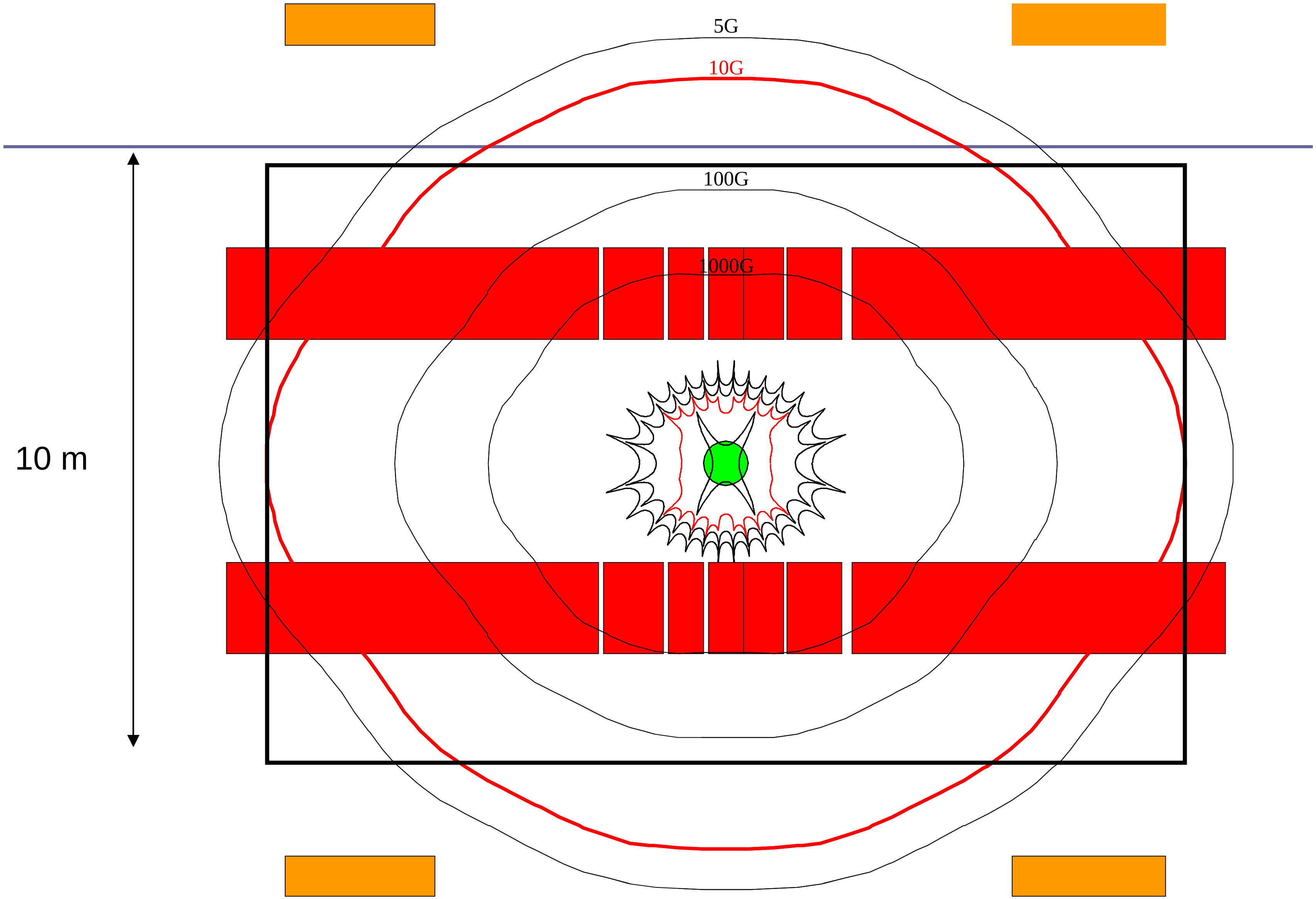
Winding pack design



For magnetic shielding anti coils are used with :

B1*S1=-B0*S0

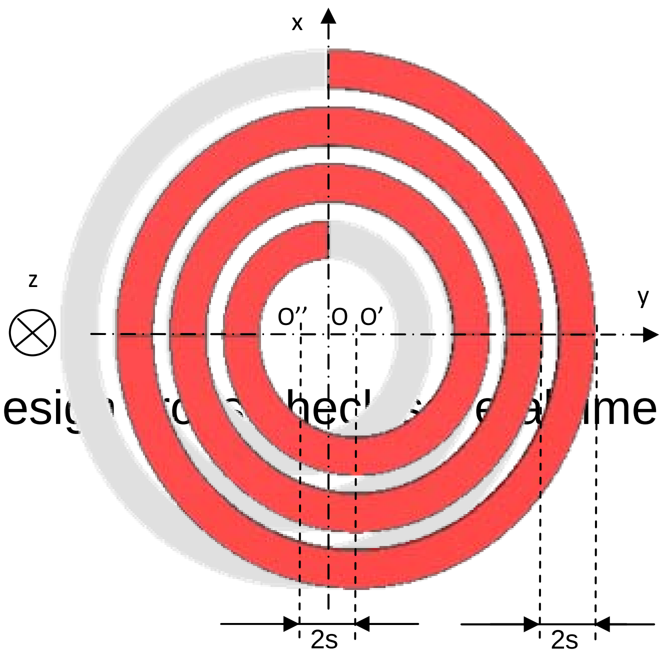
Rôle du blindage actif (2/2)

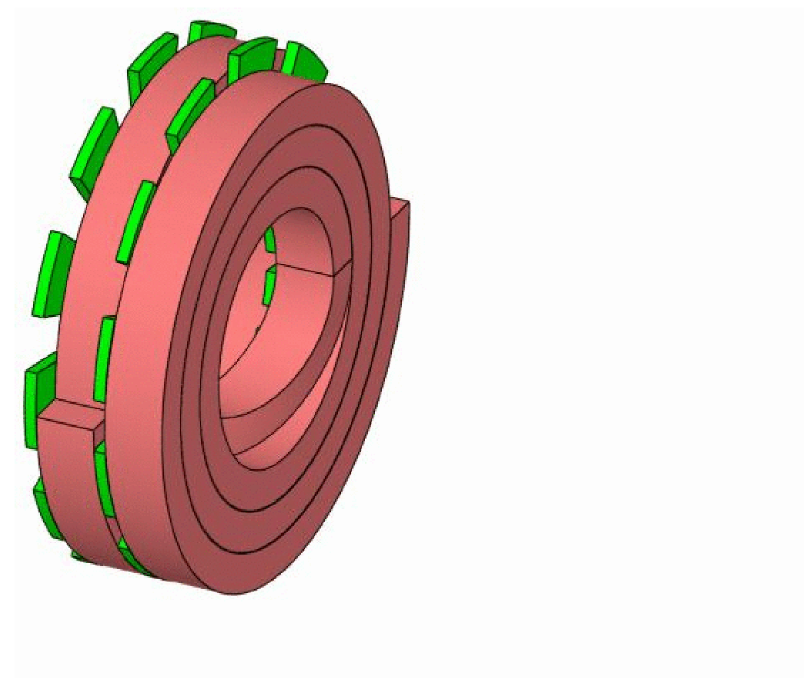


Winding pack design

- Original Double Pancake design
  - The objective is to design a magnet theoretically **intrinsically** homogeneous

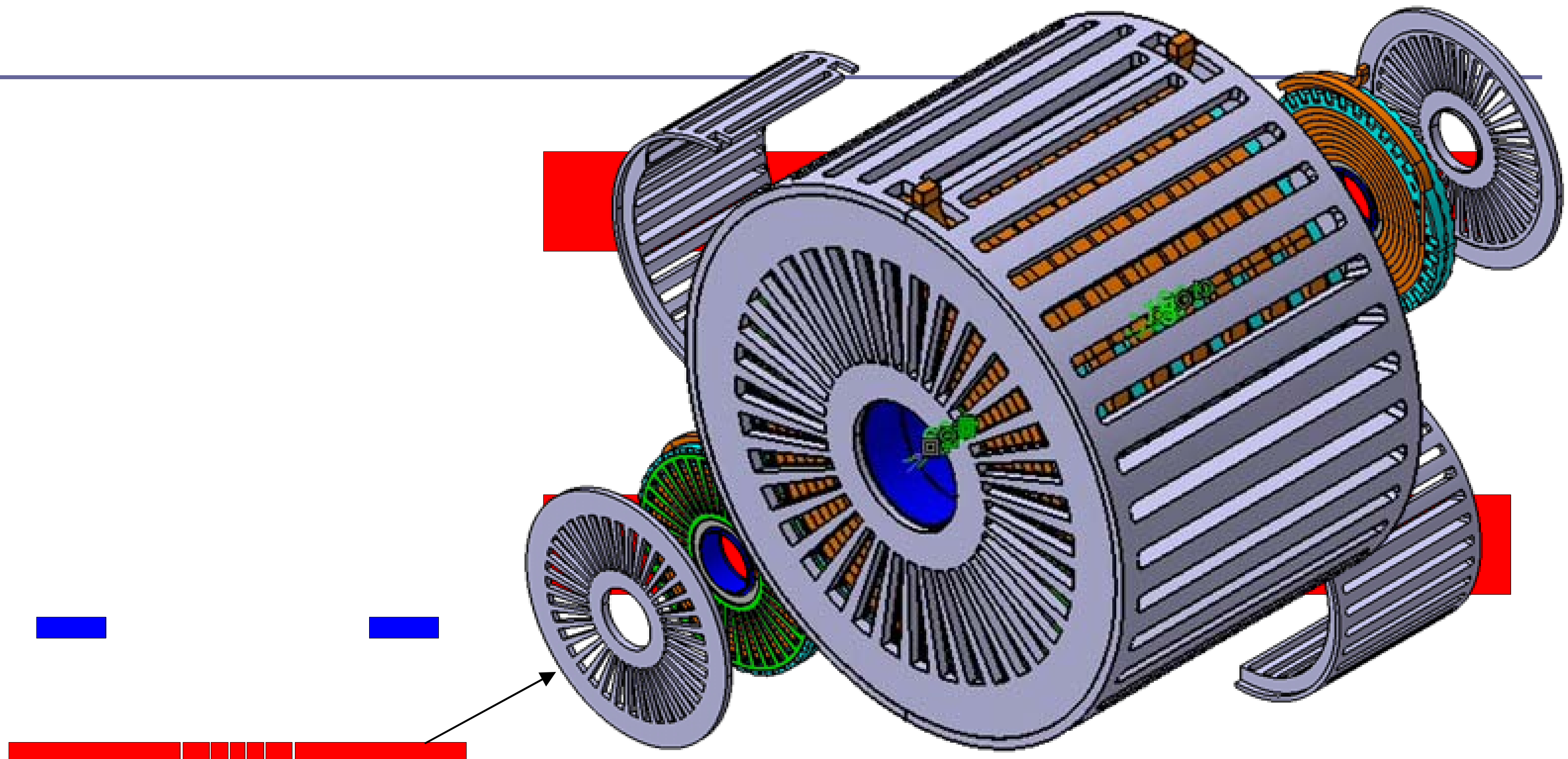
$$B_z(r,\theta,\varphi) = B_0 + \sum_{n=1}^{\infty} r^n \left[Z_n P_n(\cos\theta) + \sum_{m=1}^{n} \begin{pmatrix} \cancel{X_n^m} \cos m\varphi \\ + \\ \cancel{Y_n^m} \sin m\varphi \end{pmatrix} W_n^m P_n^m(\cos\theta) \right]$$



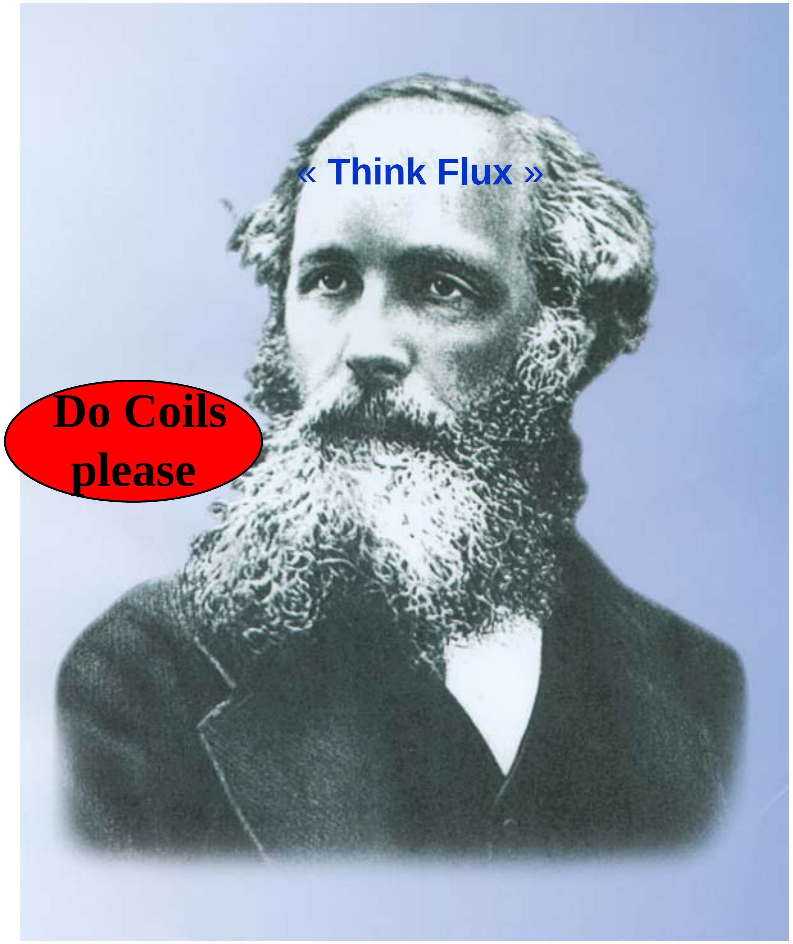


- Desig[illegible]ime

Assembly of the double pancakes

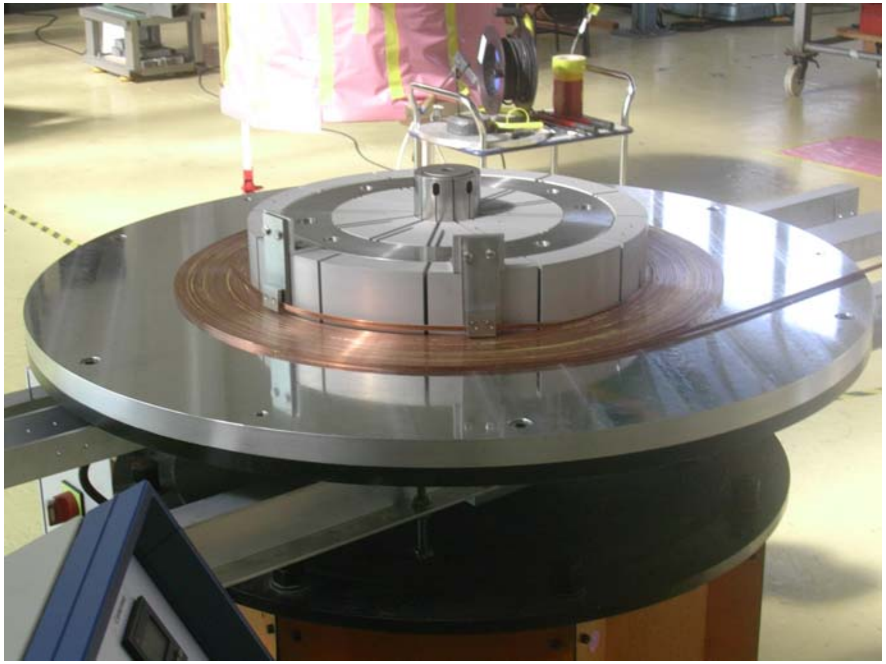


Summary and Conclusion



James Clerk MAXWELL

I hope I have given you a flavour the magic world of solenoids

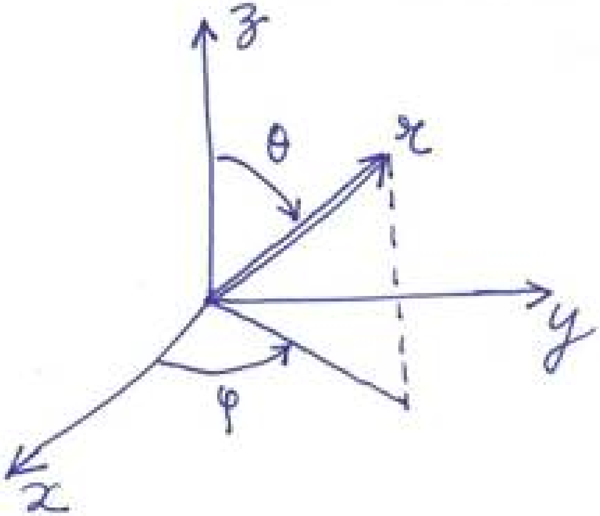


Field Analysis of Solenoidal Coil

$$H_z(r,\theta,\varphi) = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty} r^n (n+m+1) P_n^m(u)\left(A_n^m \cos m\varphi + B_n^m \sin m\varphi\right)$$

Spherical Harmonics.

with $u = \cos\theta$



If $\frac{\partial}{\partial\varphi} = 0$

$$H_z(z) = \sum_{n=0}^{\infty} z^n (n+1) A_n^0$$