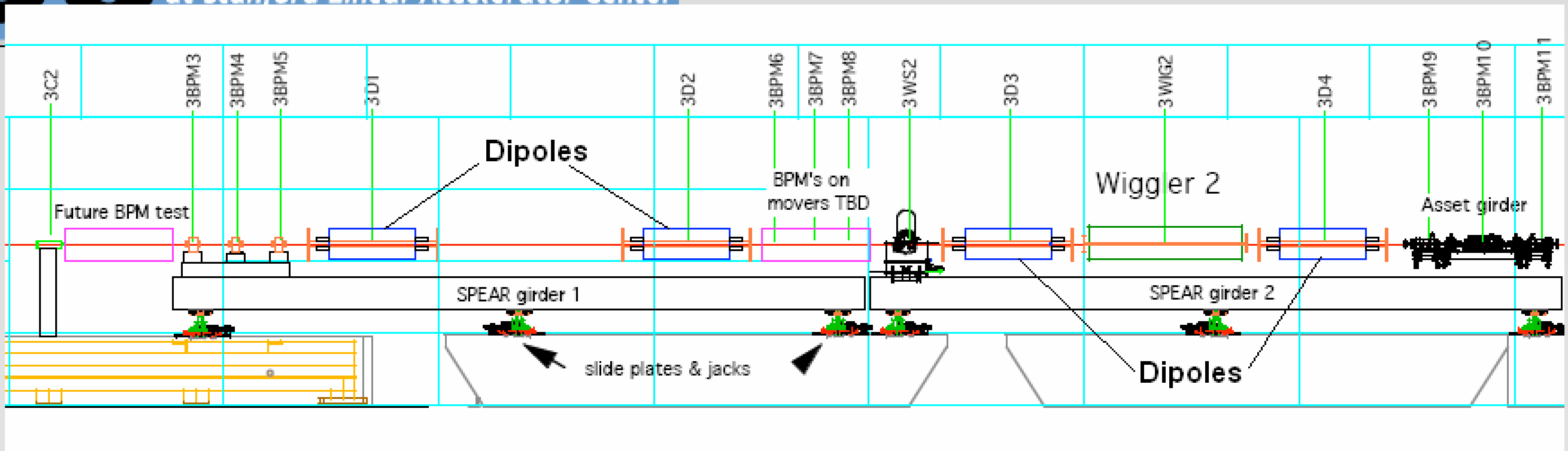
International Linear Collider
at Stanford Linear Accelerator Center

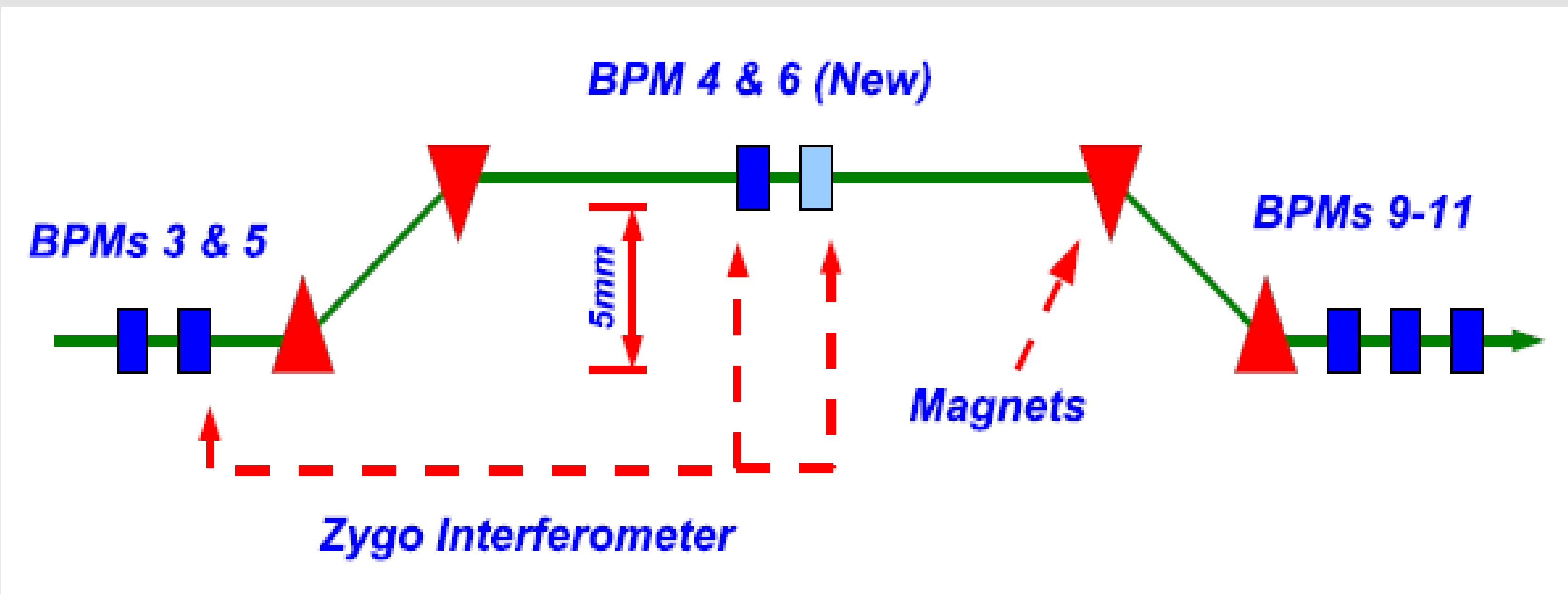
Measurements on BPM-based Energy Spectrometer in the SLAC End Station A

DESY, 7-Jun-2007

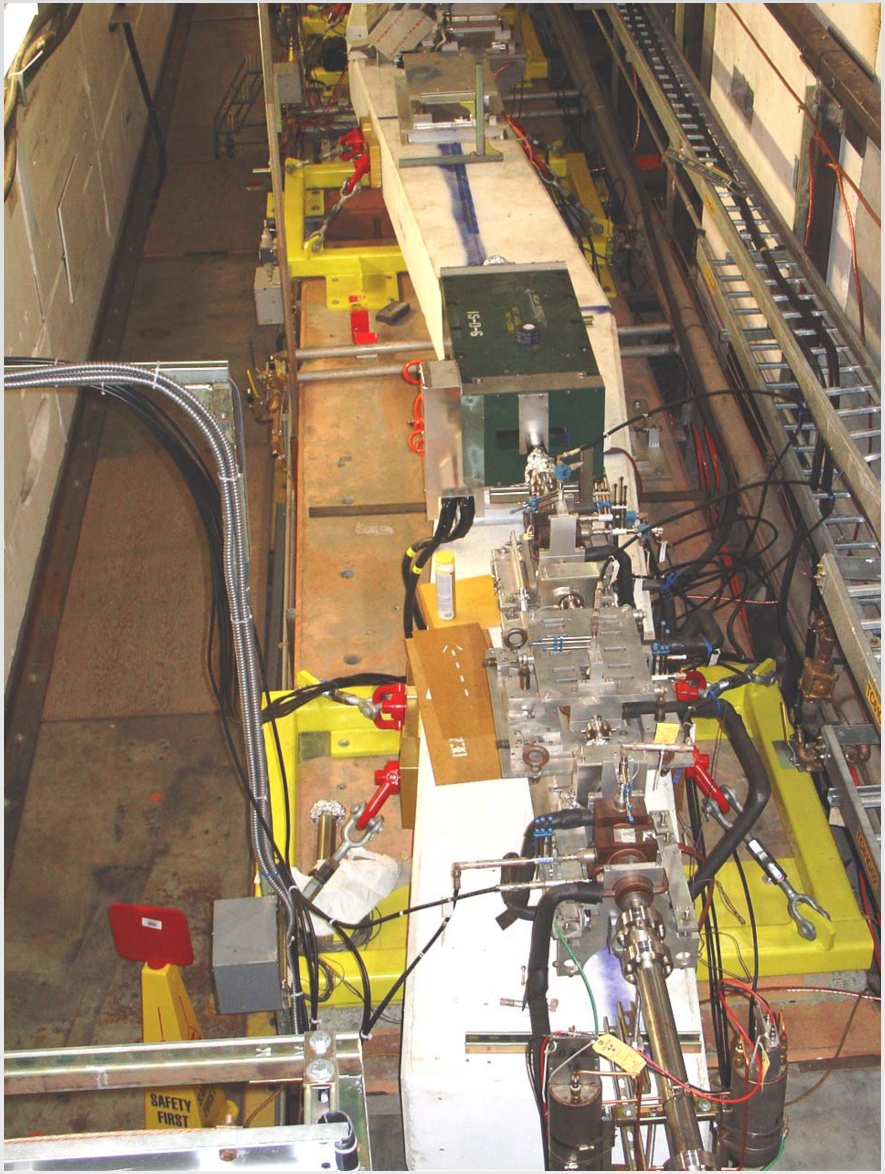
Beam Parameters at SLAC ESA and ILC

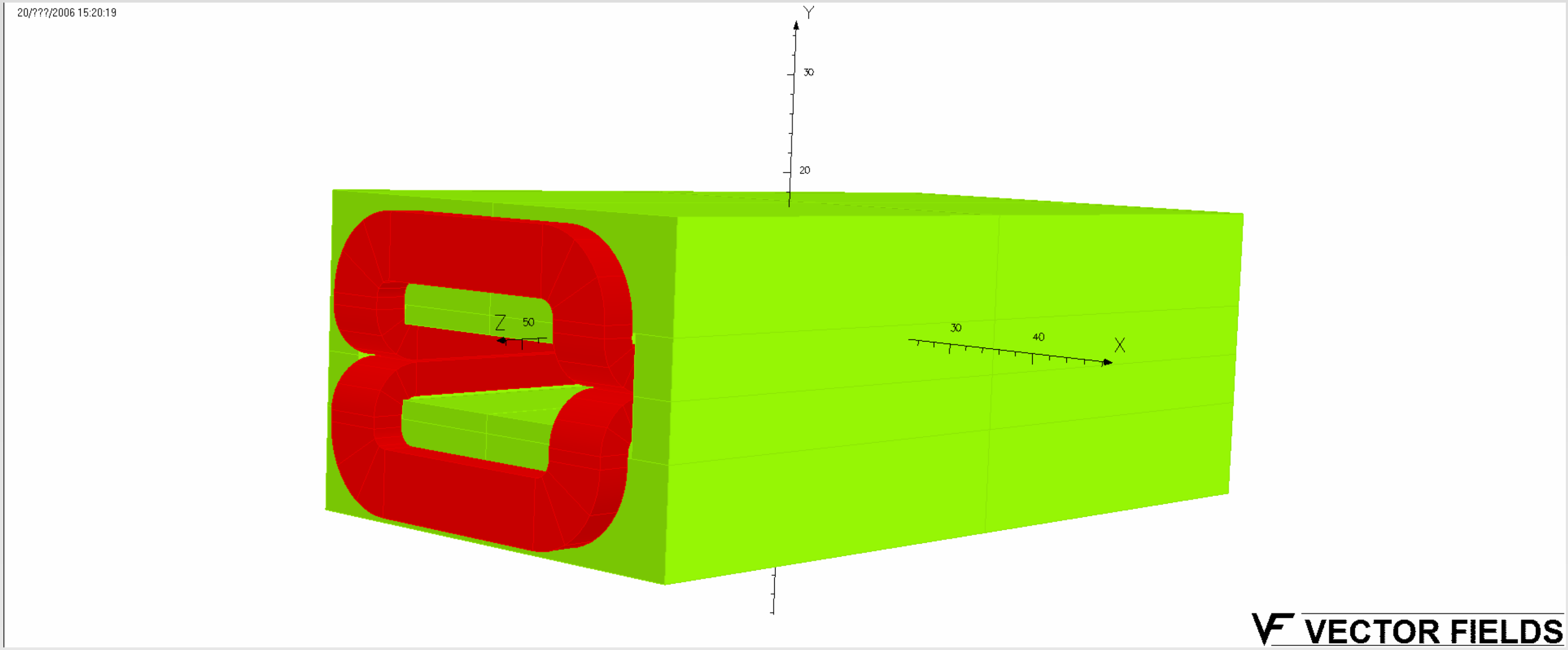
Parameter	SLAC ESA	ILC-500
Repetition Rate	10 Hz	5 Hz
Energy	28.5 GeV	250 GeV
Bunch Charge	2.0×10^{10}	2.0×10^{10}
Bunch Length	300-500 μm	300 μm
Energy Spread	0.2%	0.1%
Bunches per train	1 (2*)	2820
Microbunch spacing	- (20-400ns*)	337 ns





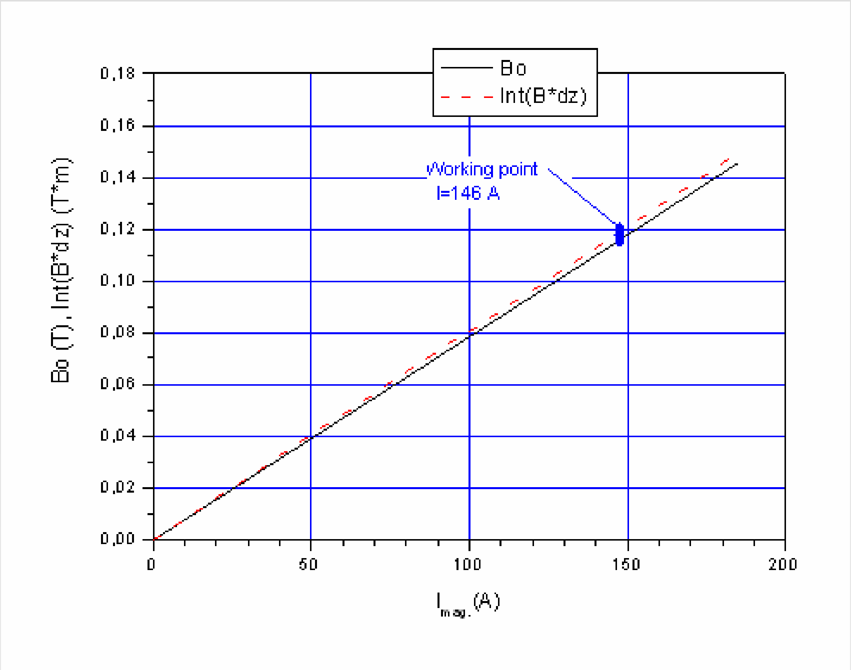
Spectrometer scheme


SAFETY
FIRST

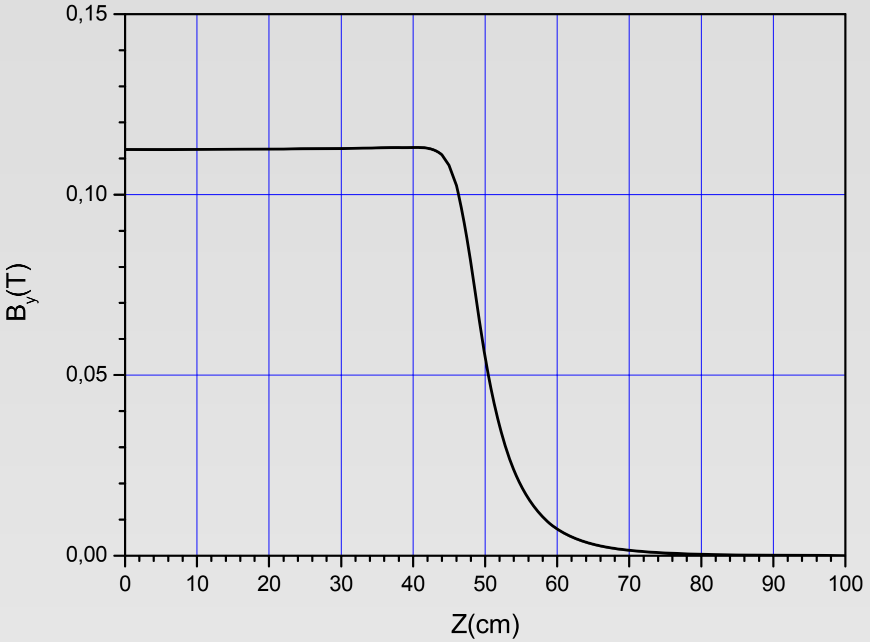


10D37 magnetic field simulations

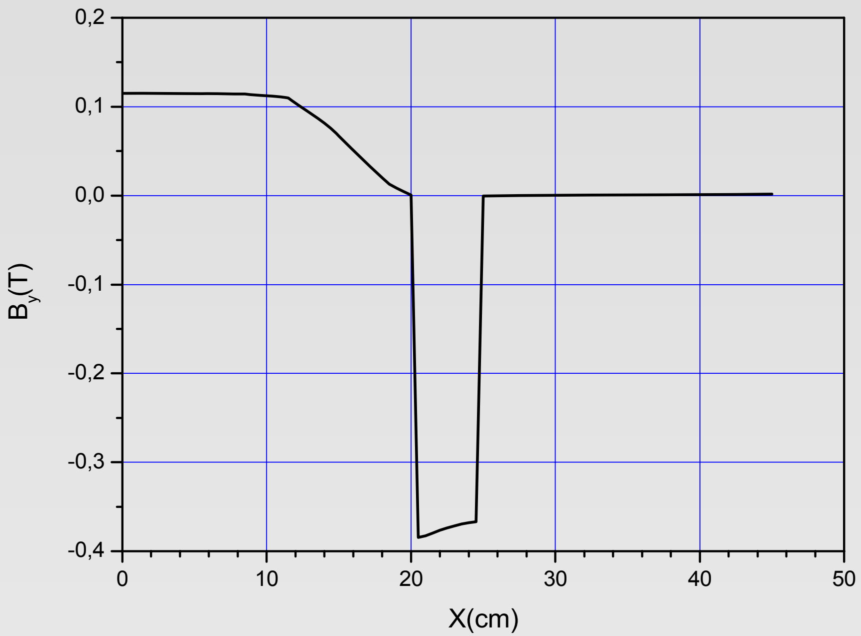
The magnetic field simulation for the 10D37 magnet was provided by the 3D TOSCA code. The magnet dimensions were taken from the SLAC drawings.



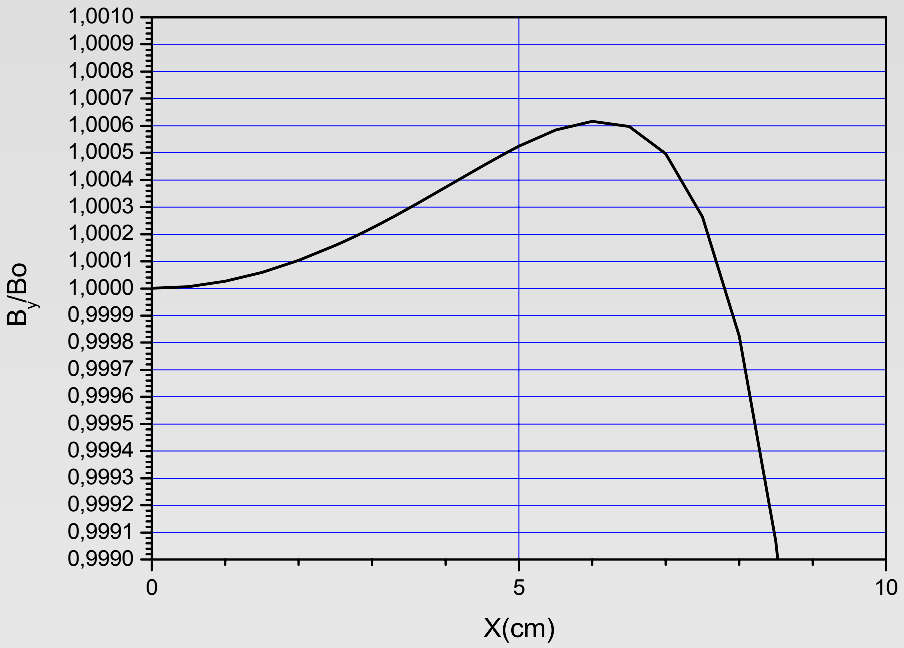
Excitation lines for 10D37 magnet without screens



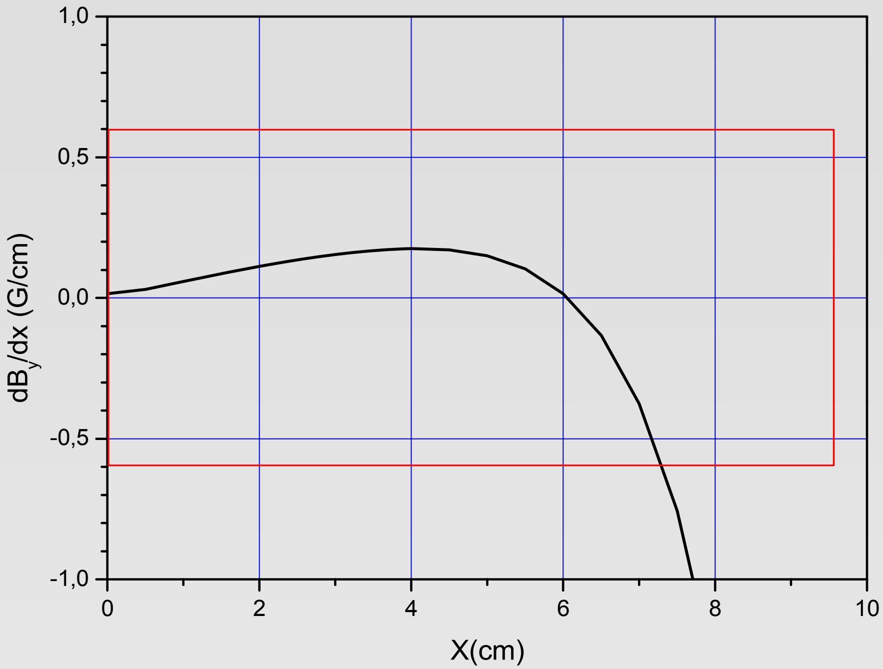
Magnetic field in the longitudinal direction



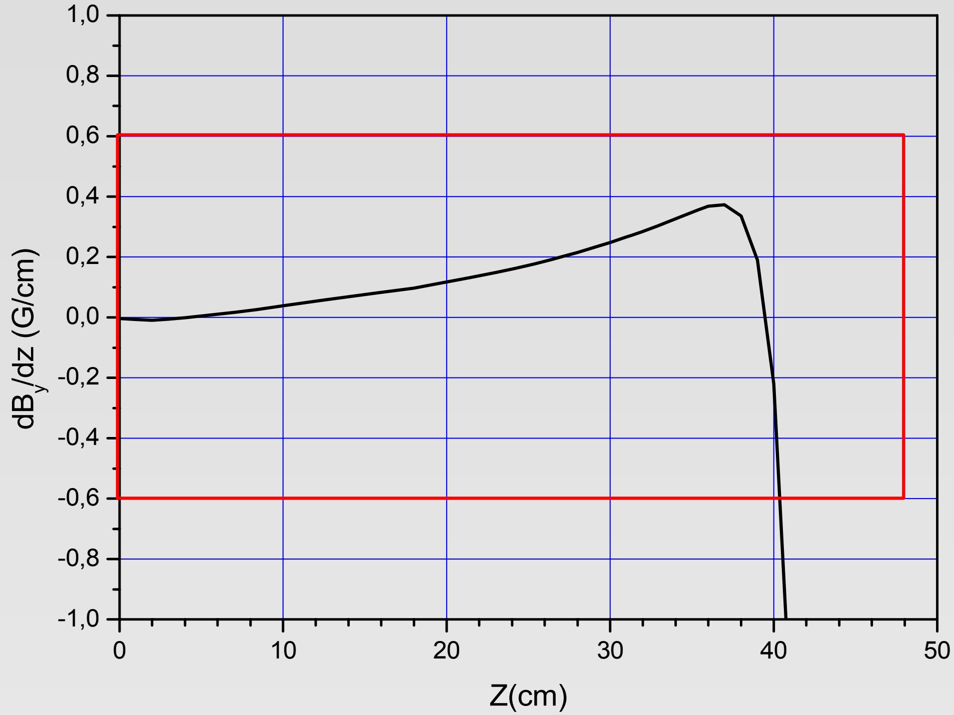
Magnetic field of the magnet in the middle transverse cross section



Normalized magnetic field in the middle cross-section of the magnet



Magnetic field gradient in the middle cross-section of the magnet

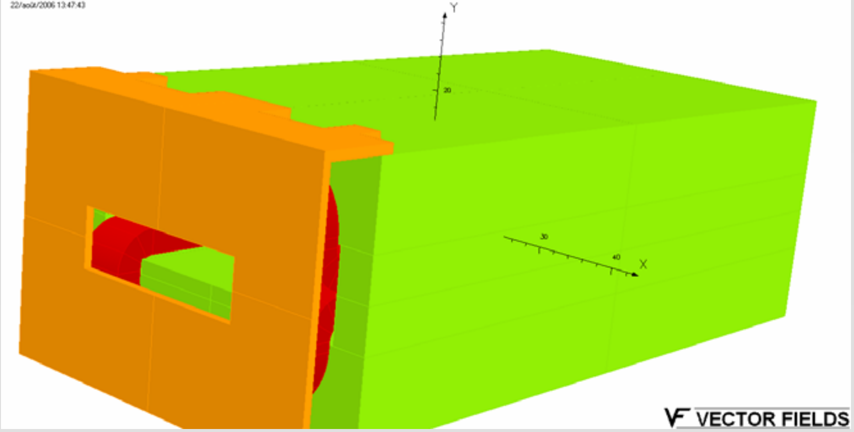


Magnetic field gradient in longitudinal direction

-NMR probe can be used up to 7 cm from the magnet center in transverse direction

NMR probe can be used to the distance 40 cm from the magnet center. This region will cover the 78% of the total field integral.

Magnet model with the screen at 7.6 cm



Some simulation results

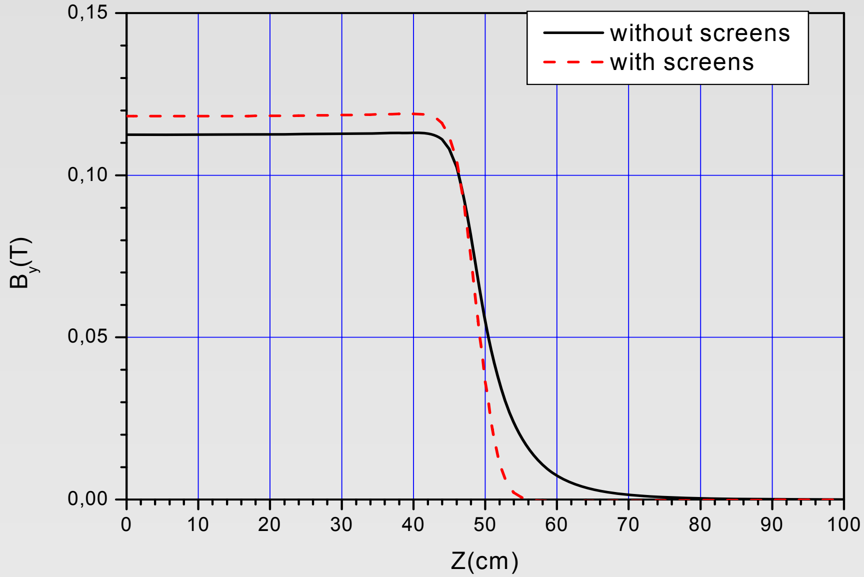
-magnetic field integral 10^{-4} uniformity region is ±15 mm

-region for possible NMR probe use is X*Z= ±7*±40 cm

-relative contribution of the fringe field to the total field integral is 22%

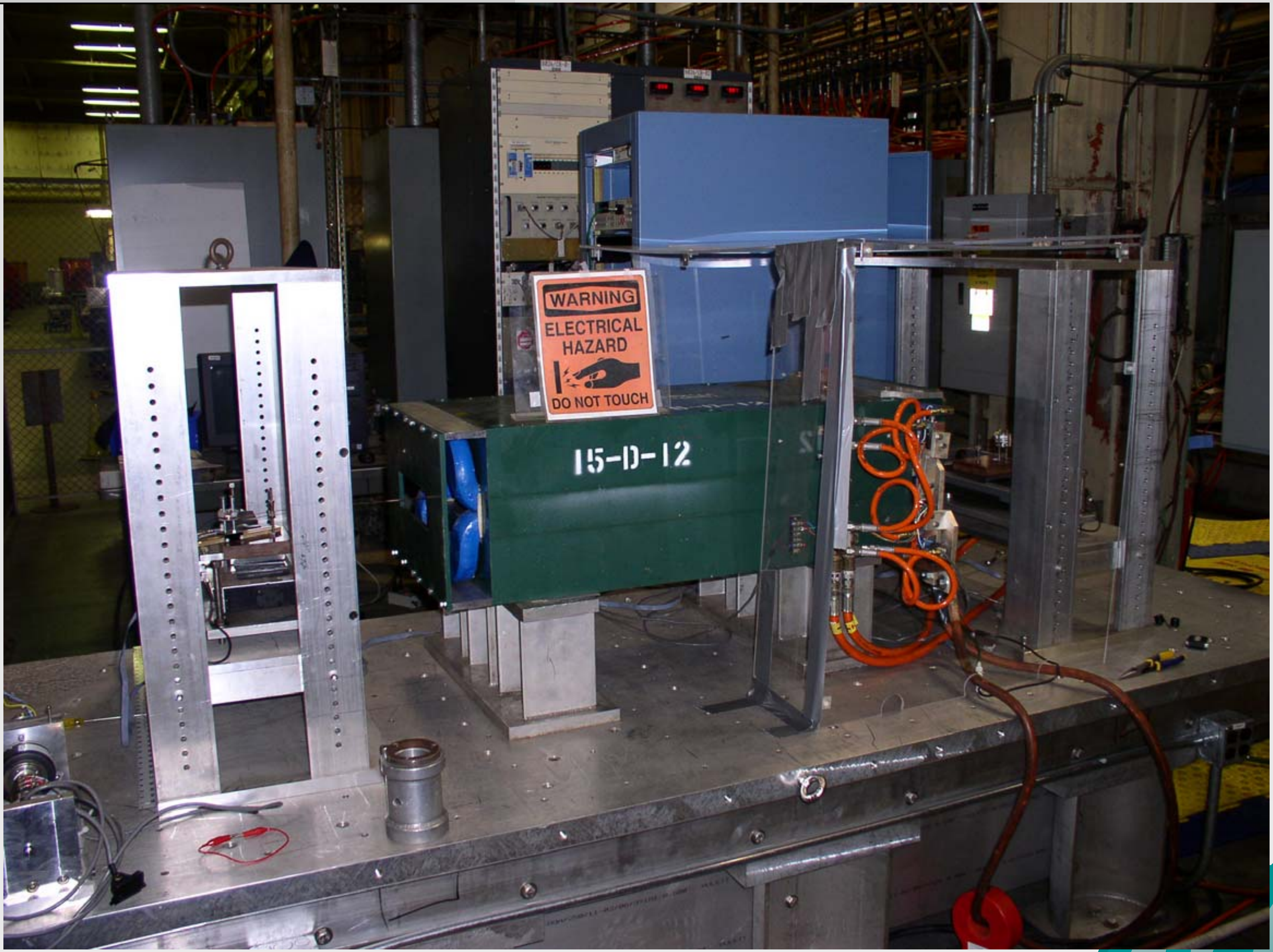
-maximal level of the magnetic field in return yoke is no more 0.4 T

-temperature factor for the magnetic field integral is $6.1\times10^{-5}\times1/C°$



Magnetic field in the longitudinal direction

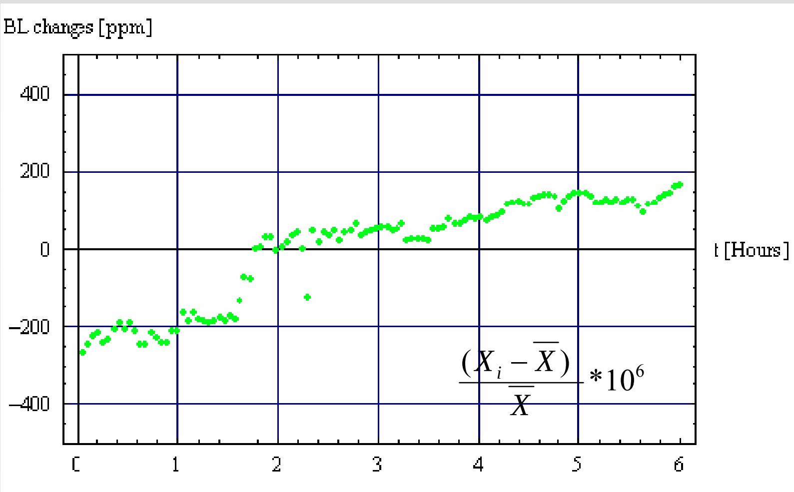
The required tolerance of the field integral measurement leads to finish measurement when the background field falls to the level of the earth field level (~ 0.3-0.5 G).
Thus, main field should to be measured at the distance ever more then 100 cm.



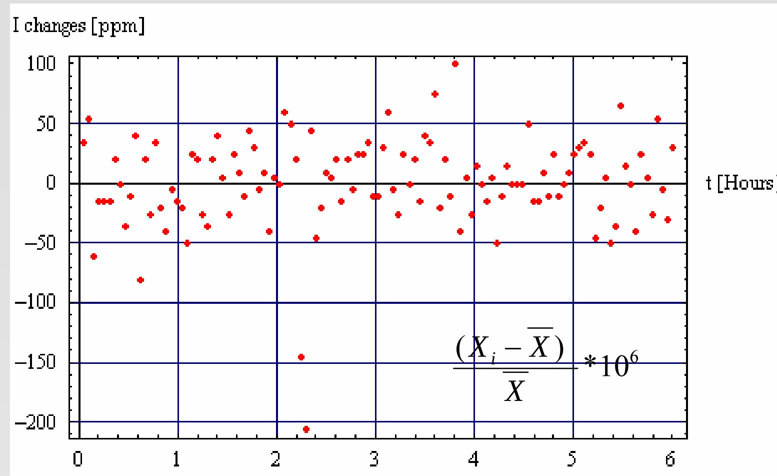
10D37 magnet in Test Laboratory

Stability Tests

6 hours at 200 A run

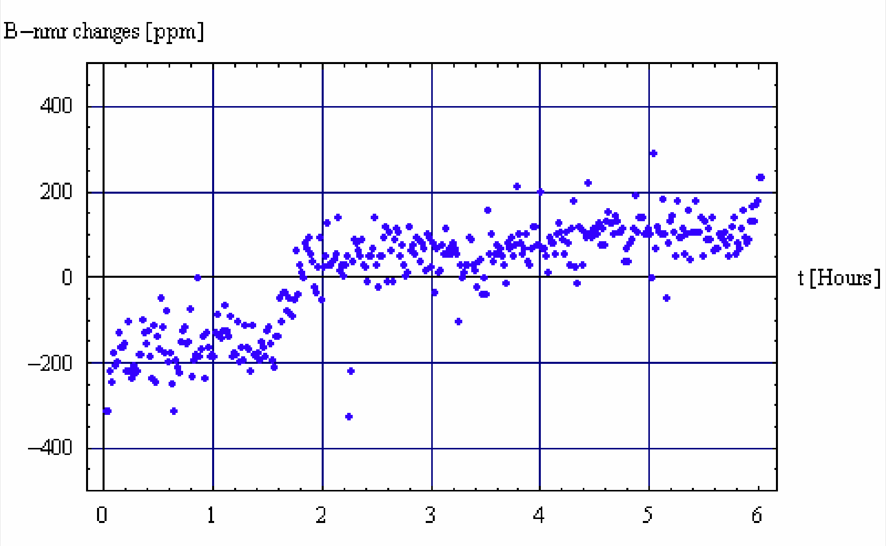


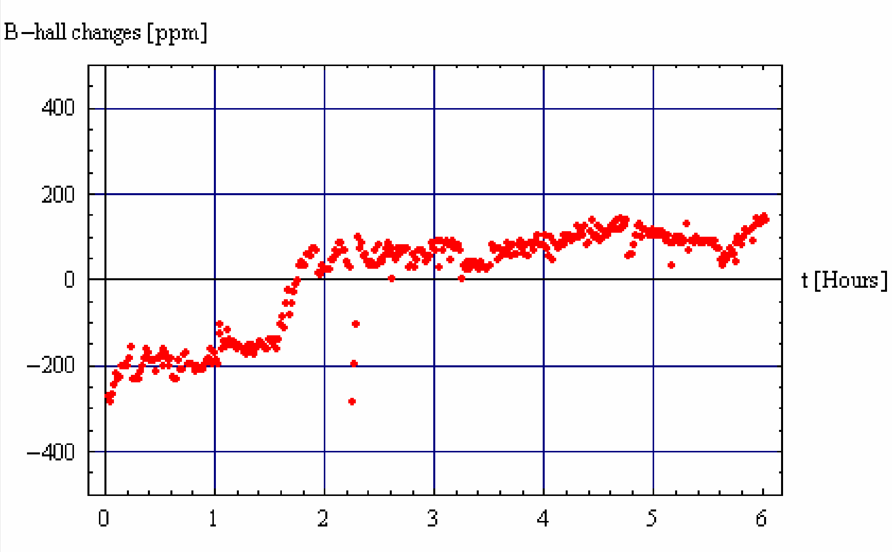
Magnetic field integral RMS stability (2σ): **270 ppm**



Power supply RMS stability (2σ): **80 ppm**

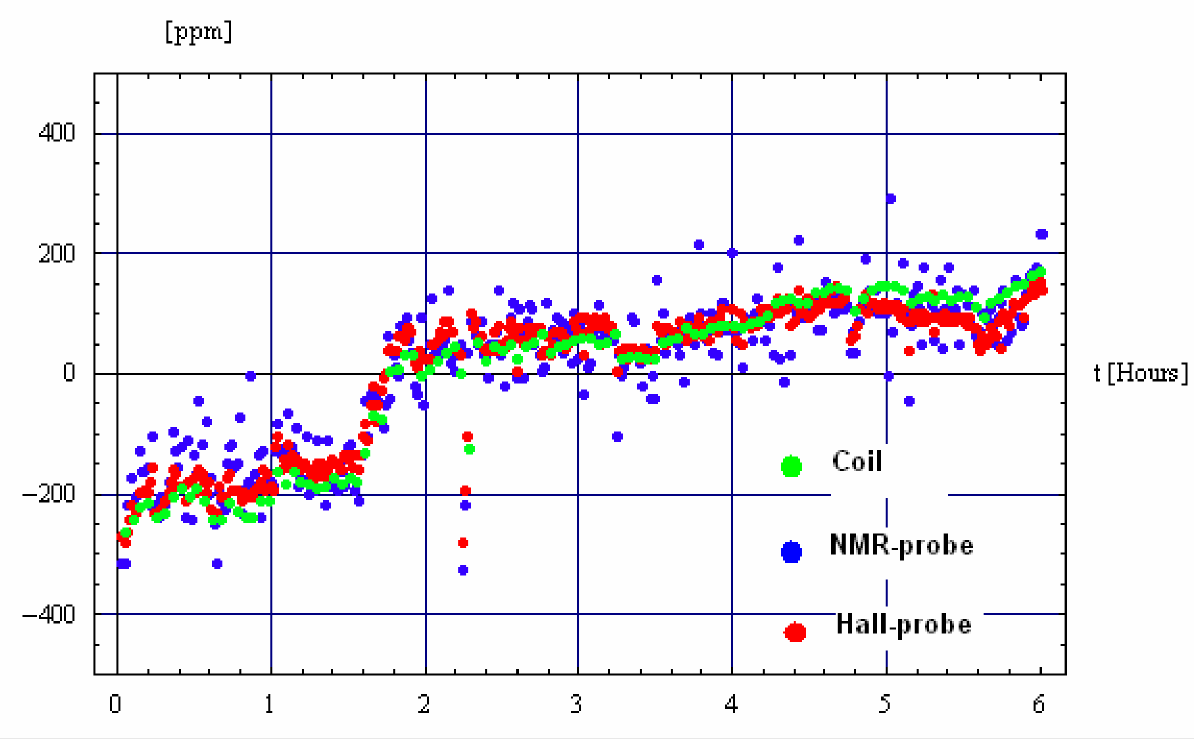
$$\overline{X} = \frac{X_i}{N} \qquad \sigma = \sqrt{\frac{(X_i - \overline{X})^2}{N-1}}$$





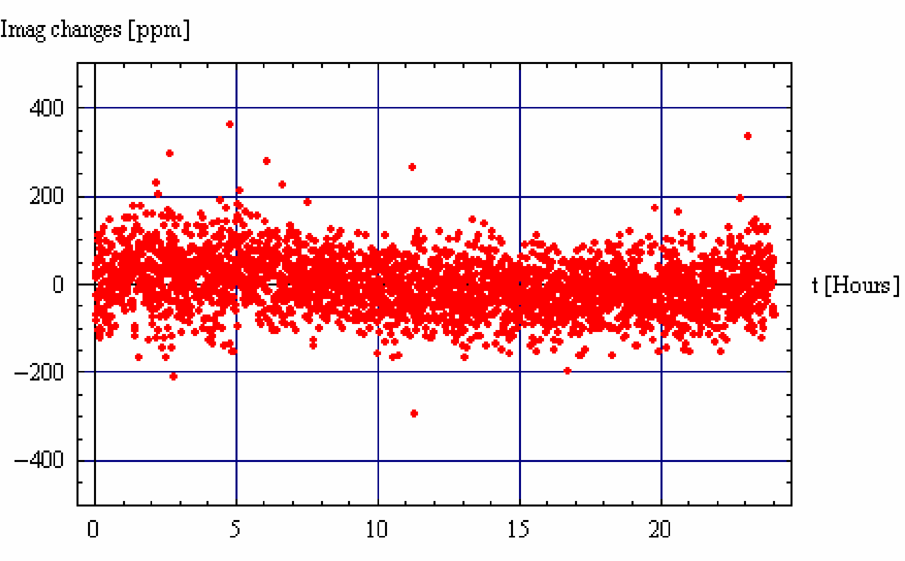
B-nmr RMS stability (2σ): **350 ppm**

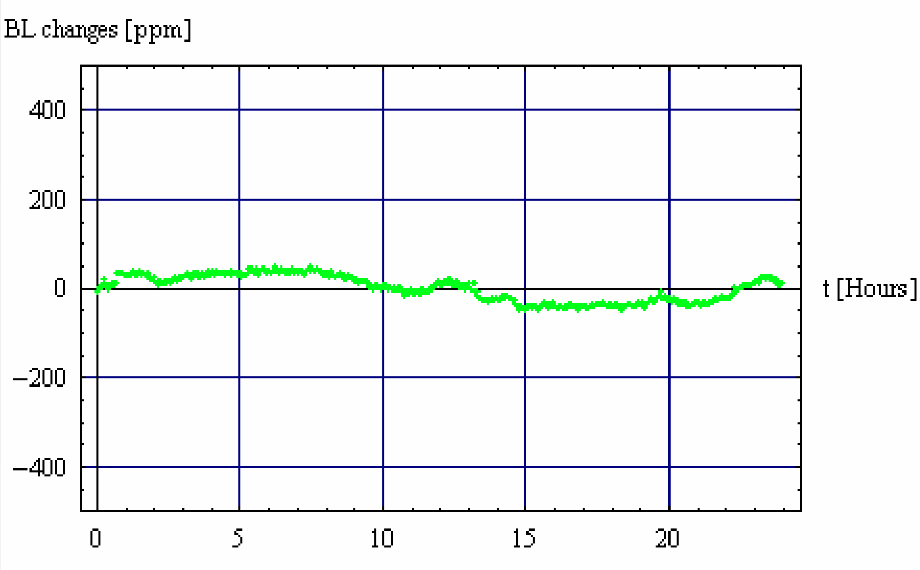
B-hall RMS stability (2σ): **350 ppm**



BdL-NMR &
BdL-Hall stability (2σ): ~ 100 ppm !

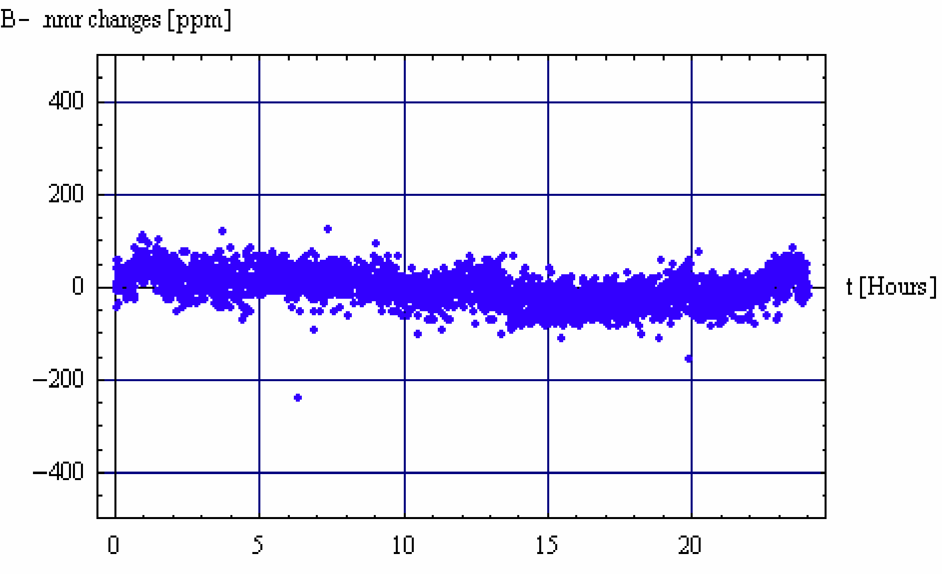
24 hours at 150 A run

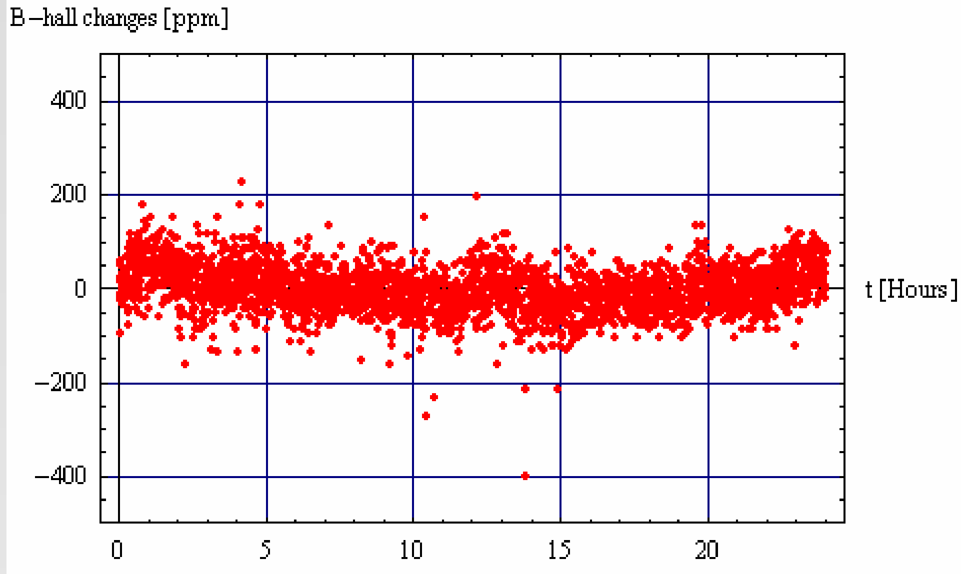




Power supply RMS stability (2σ): **130 ppm**

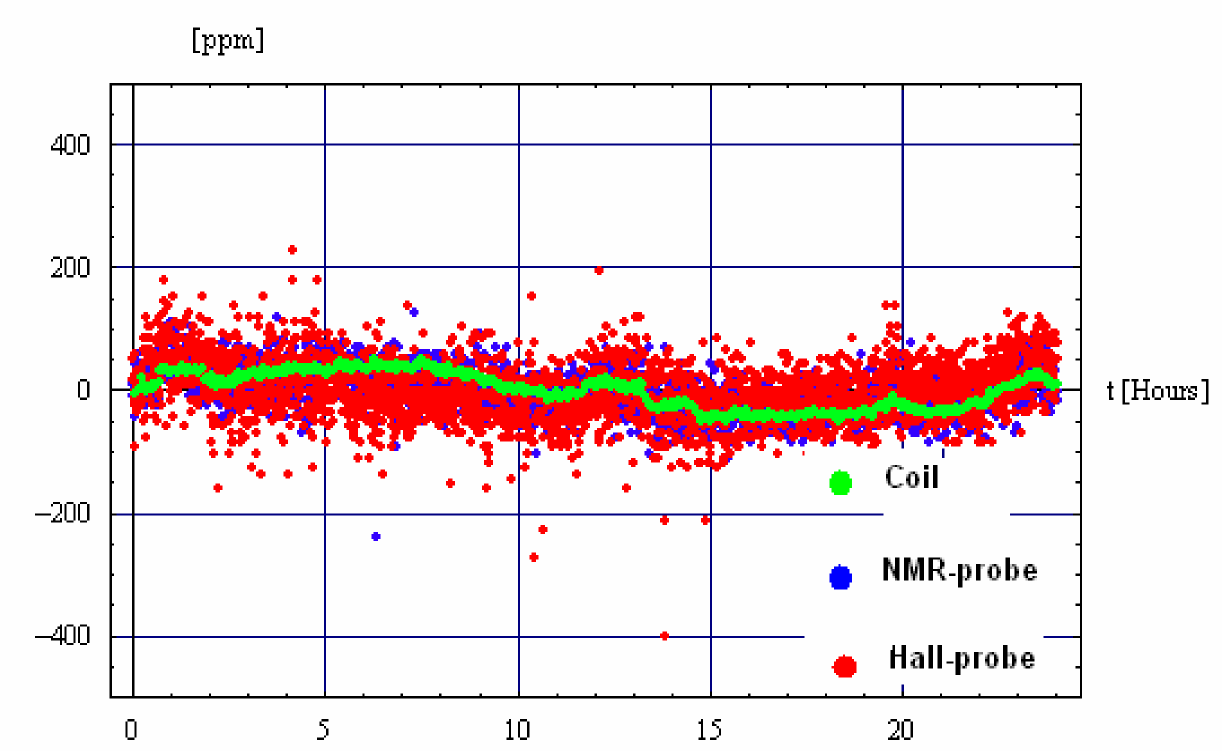
Magnetic field integral RMS stability (2σ): **60 ppm**



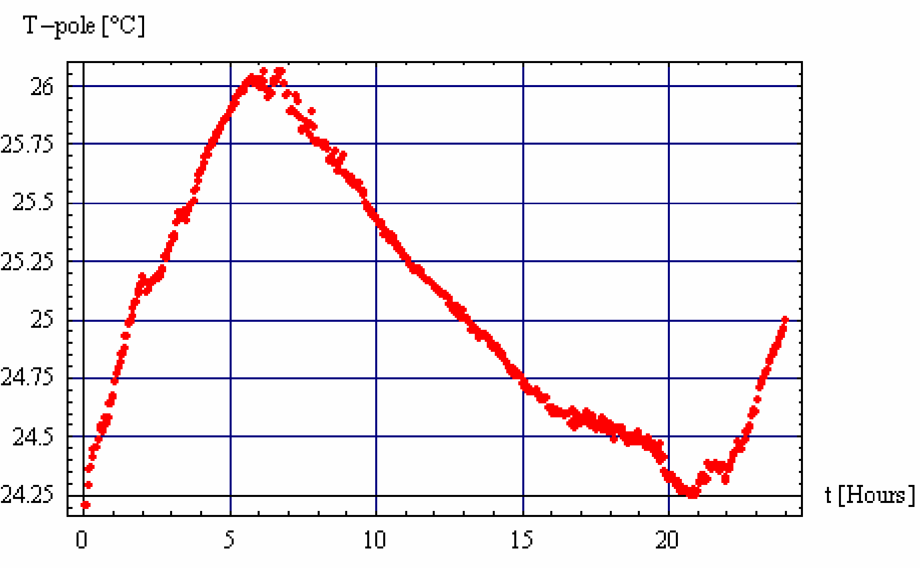


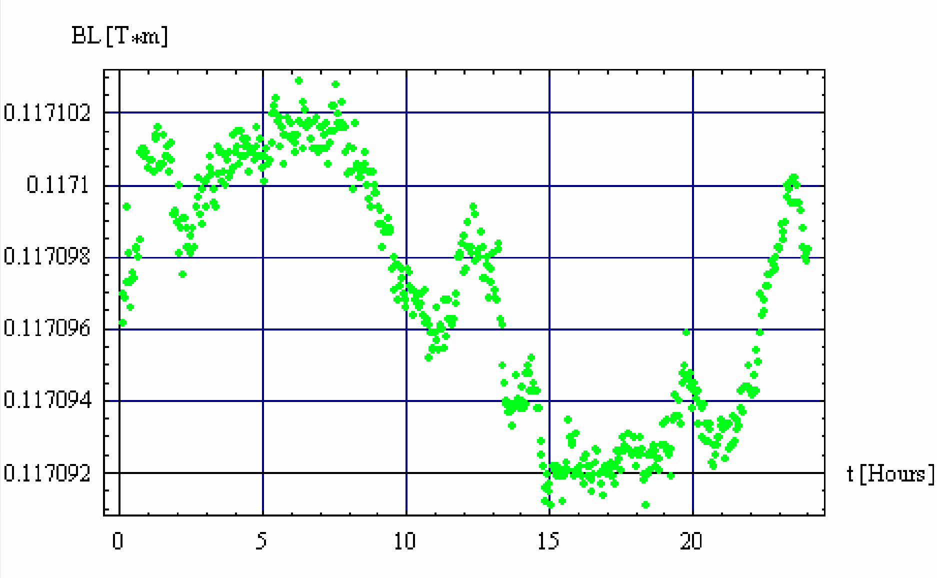
B-nmr RMS stability (2σ): **70 ppm**

B-hall RMS stability (2σ): **100 ppm**



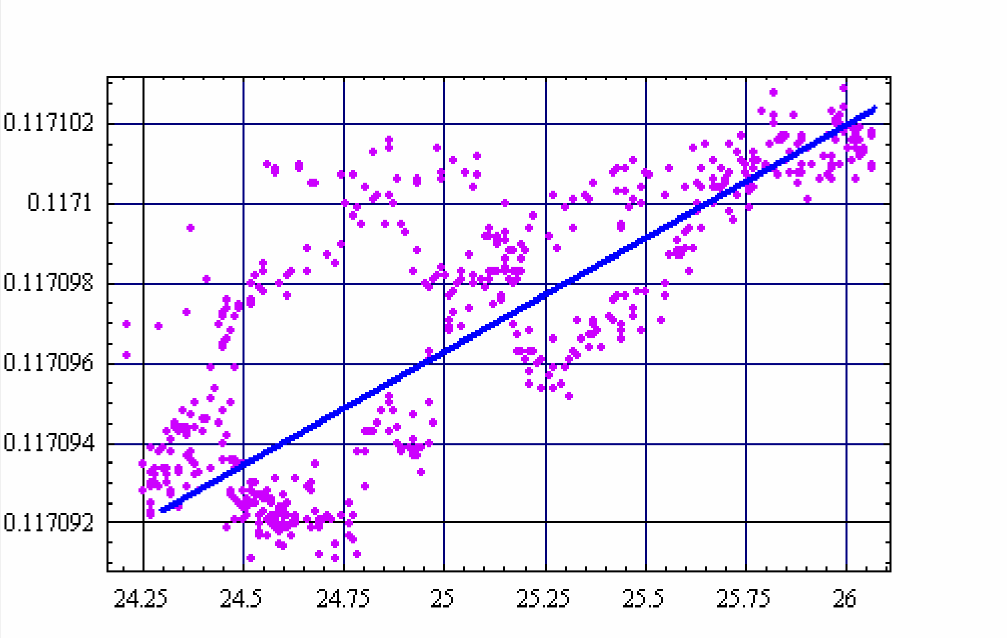
BdL-NMR &
BdL-Hall stability (2σ): ~ 100 ppm !





Temperture vs time

Field integral vs time



Dependence of the BdL integral versus temperature

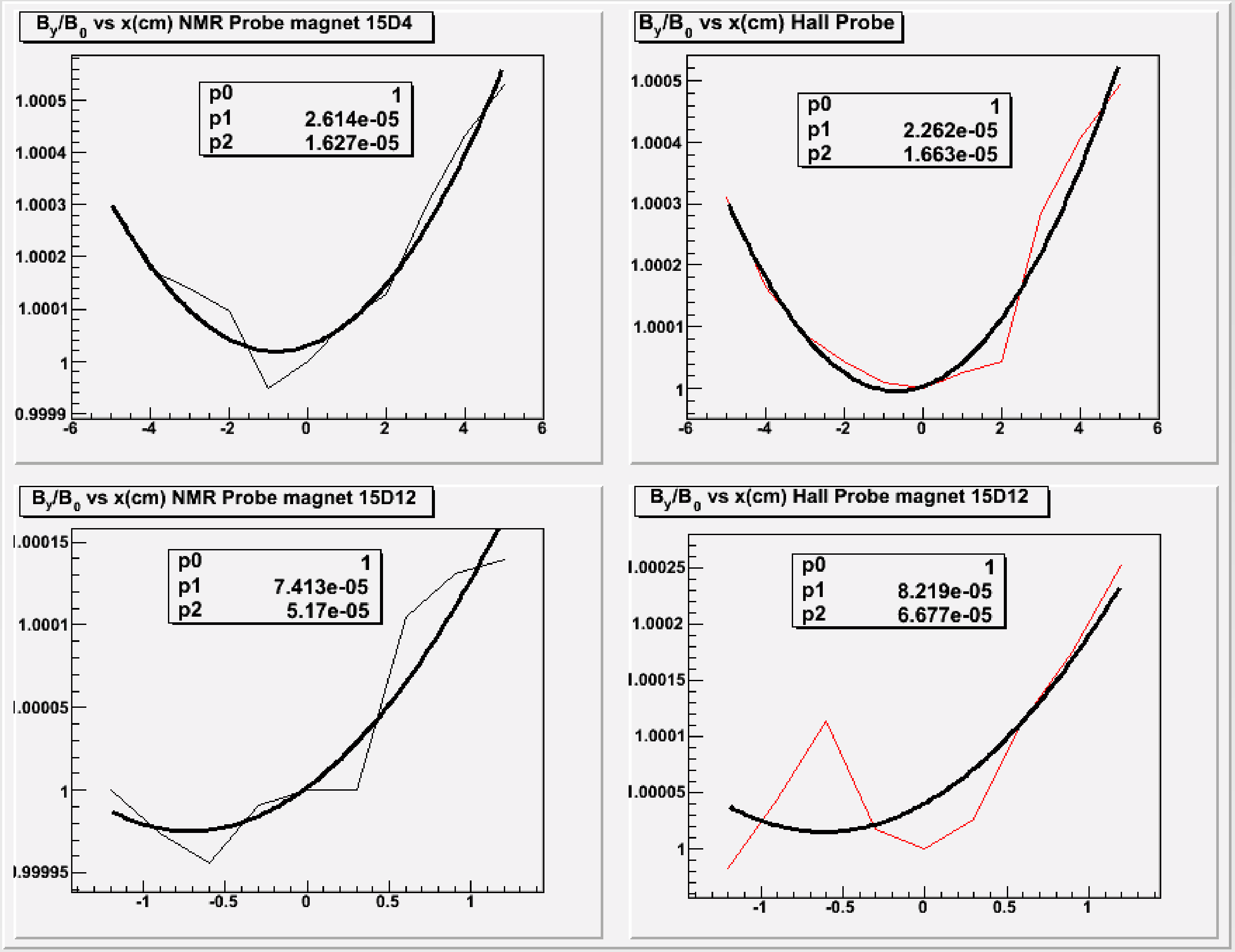
The temperature factor for the magnetic field integral is

$5.7*10^{-5}$ 1/C°

-in a good agreement with estimated one from magnetic field simulations

$6.1*10^{-5}$ 1/C°

Field mapping results

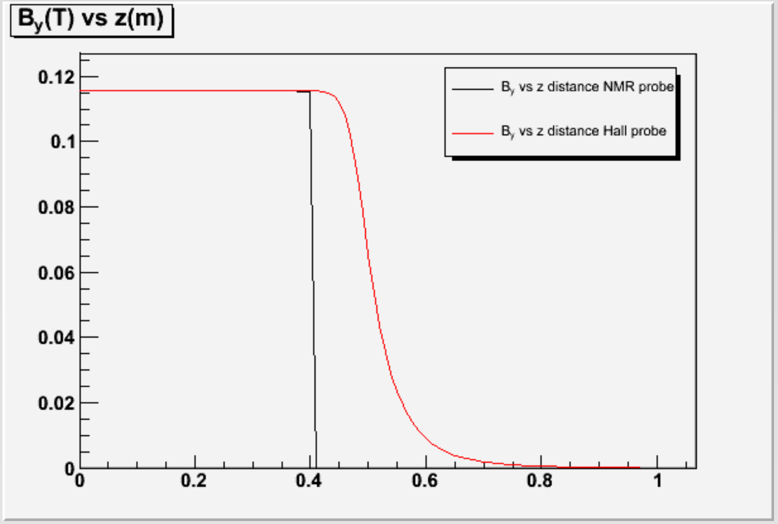


magnet 15D4

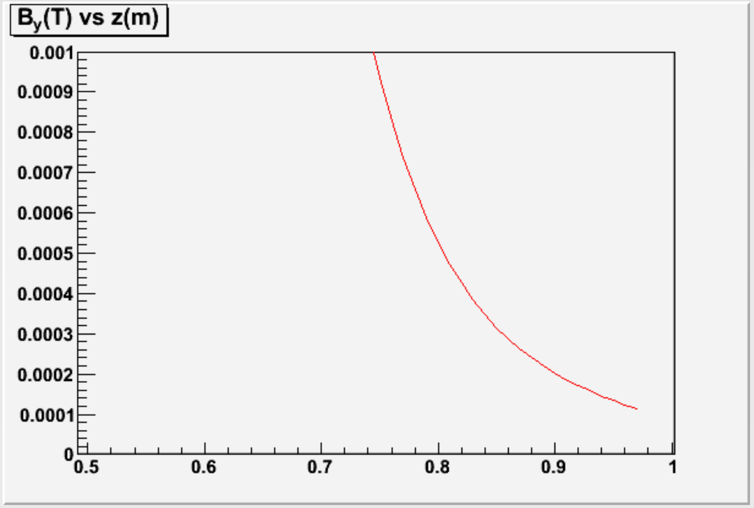
NMR = -0.8 cm
Hall = -0.7 cm

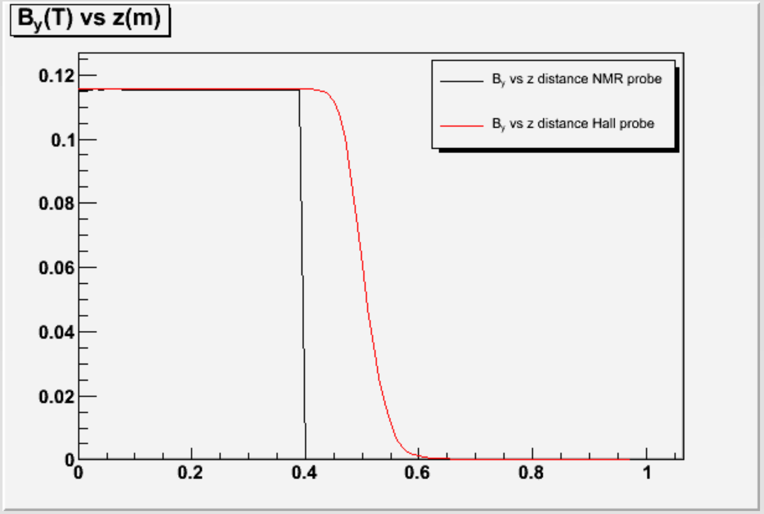
magnet 15D12

NMR = -0.7 cm
Hall = -0.6 cm

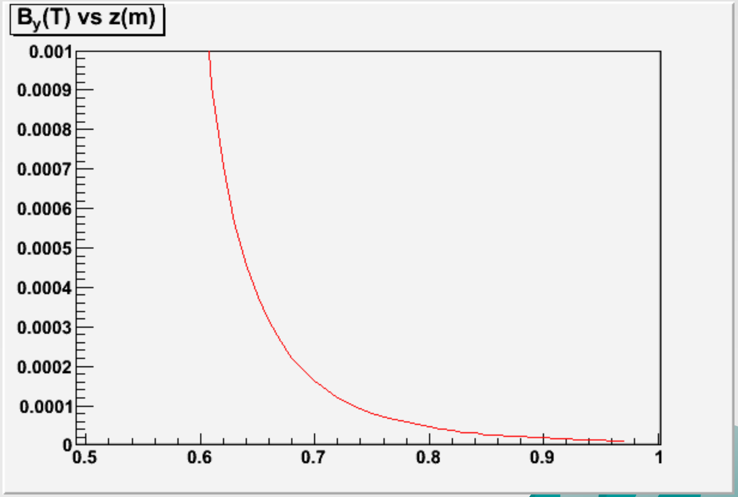


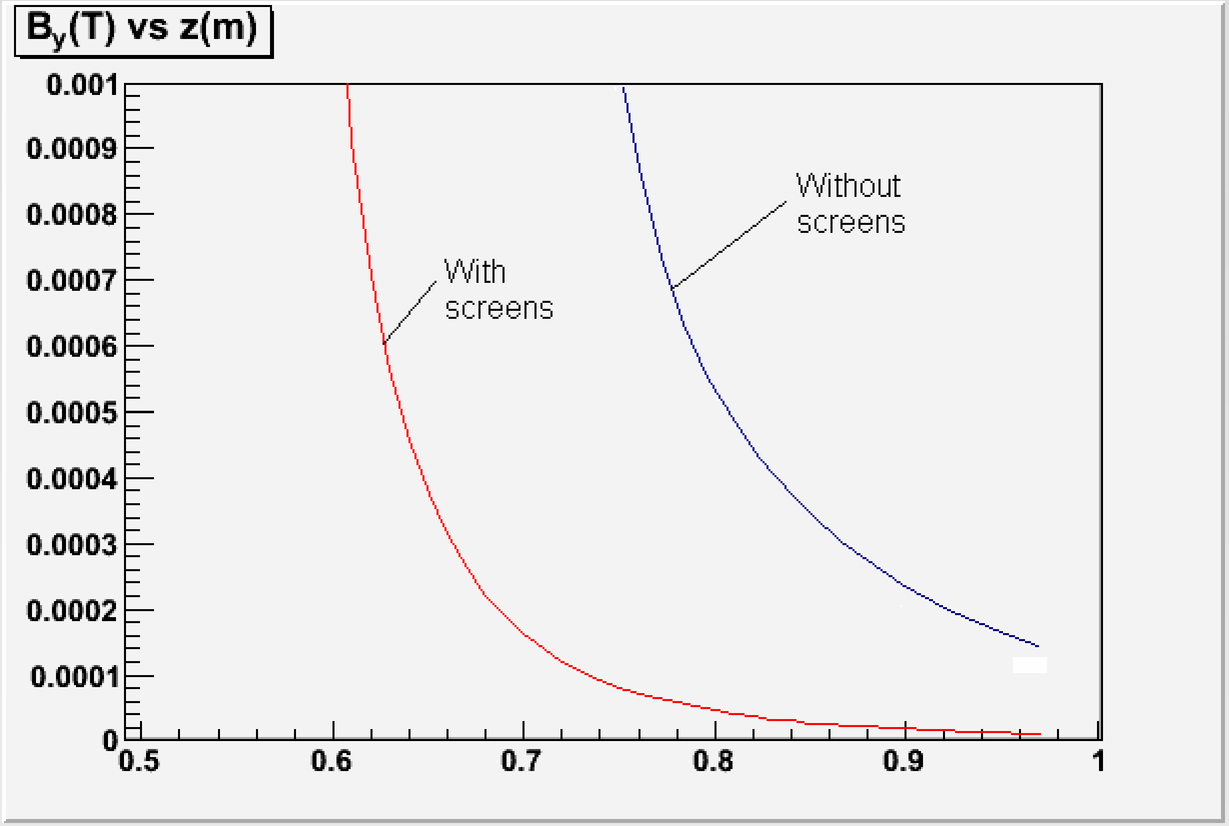
Without screens





With screens




B_y(T) vs z(m)
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0.5
0.6
0.7
0.8
0.9
1
With screens
Without screens

Measurements results:

-Magnetic field integral RMS stability (2σ): **60 ppm** (near working point – 150 A)

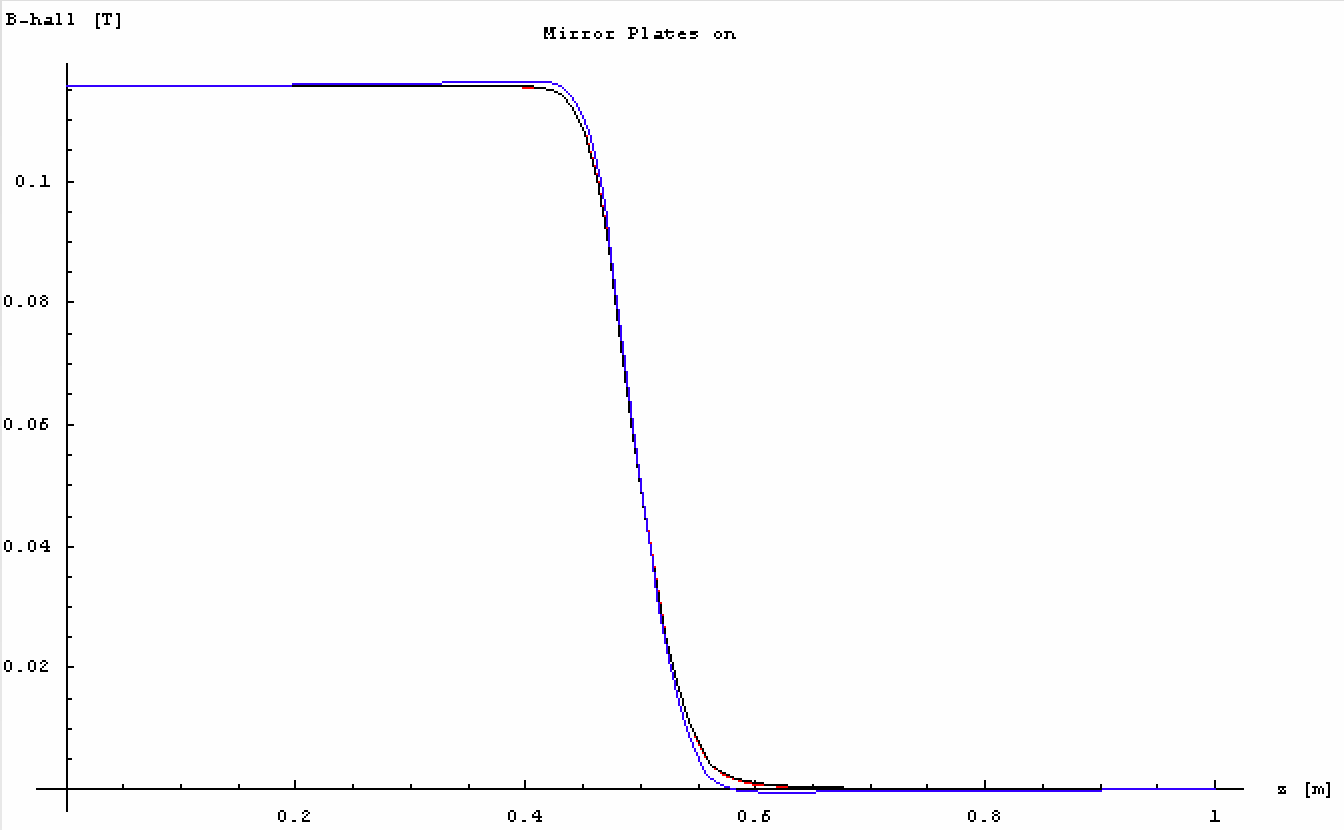
-(BdL-NMR) & (BdL-Hall) relative RMS stability (2σ): **~ 100 ppm** (both at 150 A and 200 A)

-There is a considerable dependence of magnet **pole temperature** as well as **BdL** on the day time

-The measured temperature factor for the magnetic field integral is **5.7*10^(-5) 1/C°**
in a good agreement with estimated one from magnetic field simulations **6.1*10^(-5) 1/C°**

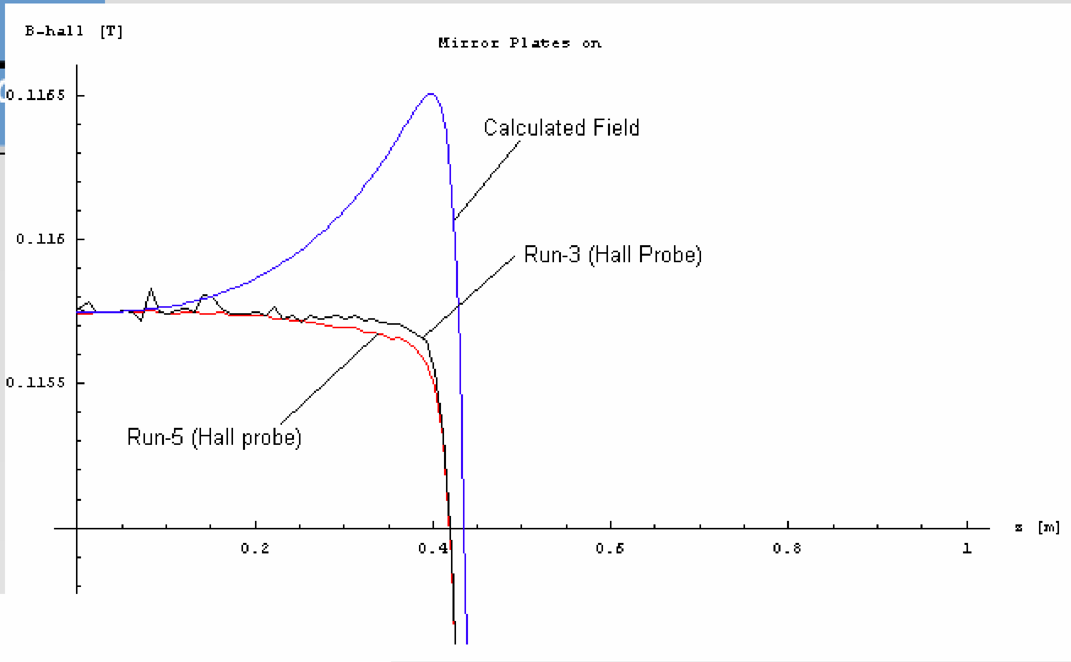
-Magnetic field integral value (**~ 0.117 T*m** when Imag ~ 150 A) is in agreement with received one **0.118 T*m** from magnet simulations

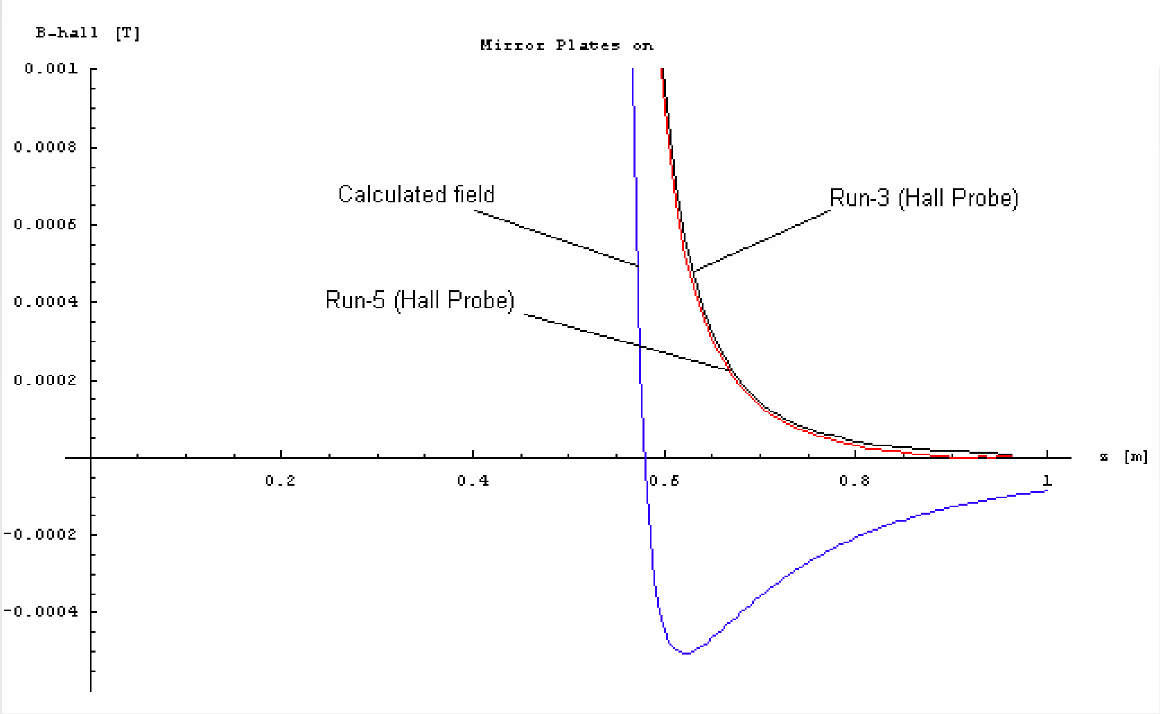
10-D-4 Run-4,5



Comparing of the measured and calculated field

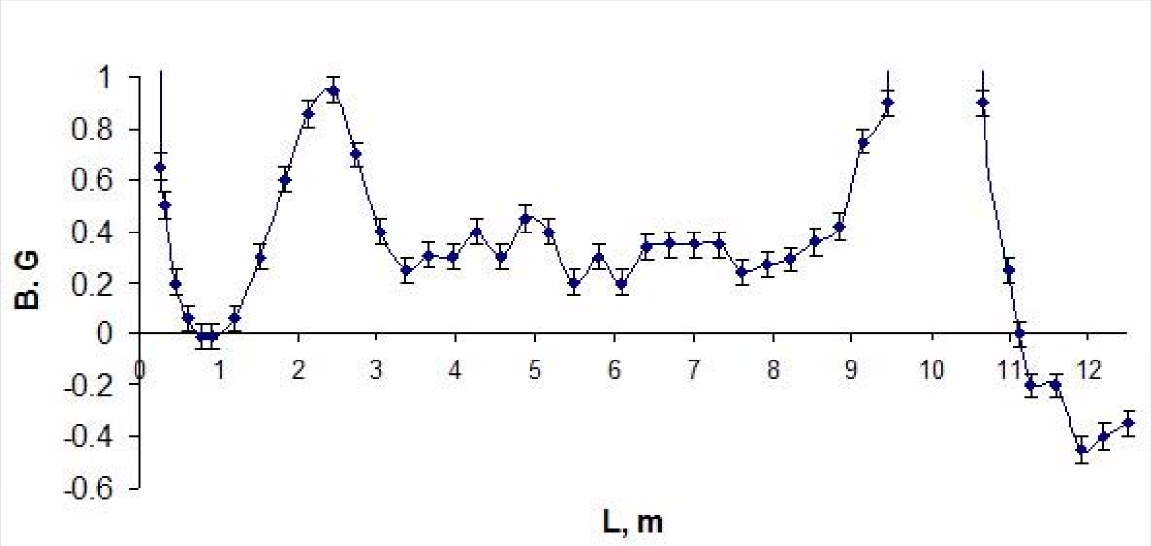
10-D-4 Run-4,5





Difference 5-7 Gauss

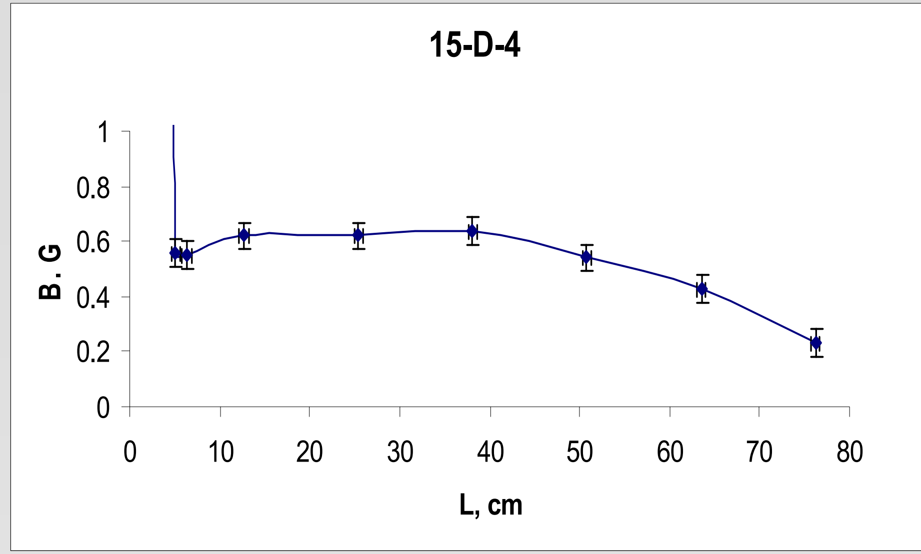
Residual field measurements



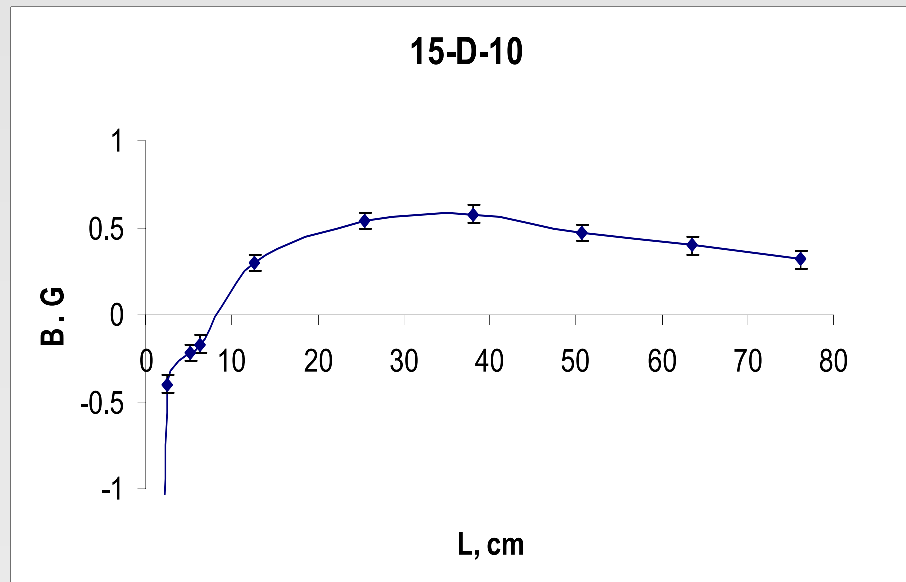
The residual magnetic field on the full chicane length (vertical component)

The anomaly behavior of the magnetic field on the distance near 10 meters is connected with the magnetic elements (impurity) in the girder.

The place of the magnetic anomaly on the concrete girder



The residual fringe magnetic field of the magnet 10D37 #15-D-4

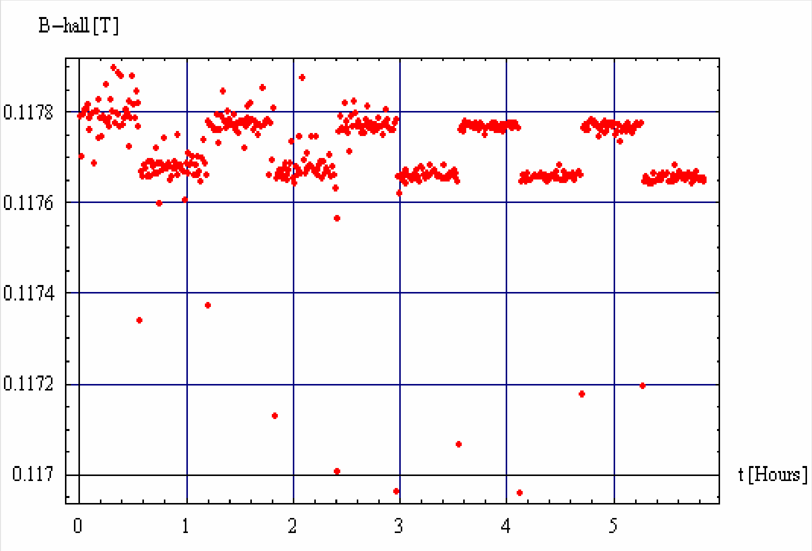


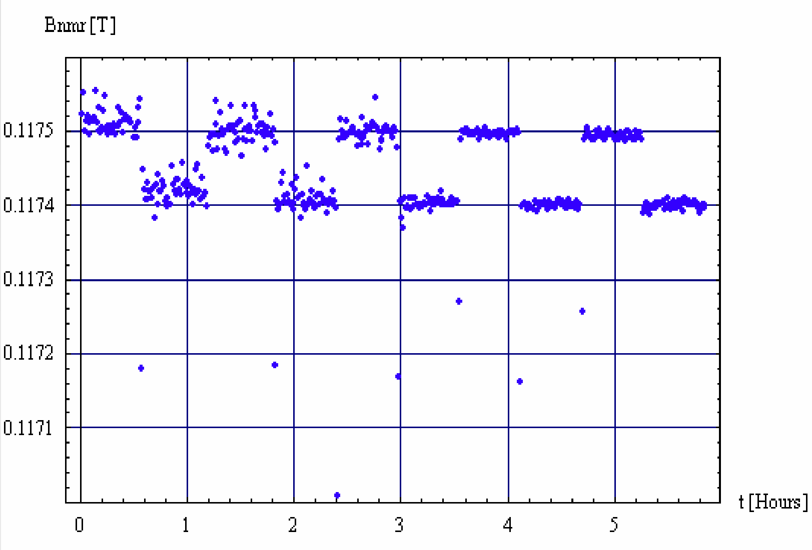
The residual fringe magnetic field of the magnet 10D37 #15-D-10

The distributions of the fringe residual magnetic field on the axis of the beam pipe outside the magnets 10D37(#15-D-4 and #15-D-10) were measured

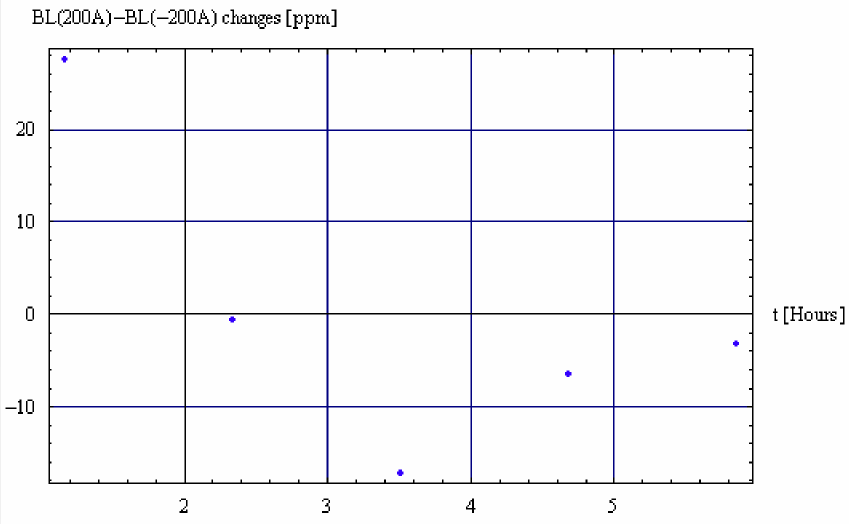
In the magnet **#15-D-4** the value of the magnetic field in the distance less then **3 cm** is more then **1 G**. In the magnet #15-D-10 this "critical" distance is less **1 cm**.
The residual magnetic field on the similar magnet **#15-D12** on the measurement stand is about **0.5 G**. All these features can be connected with the different magnetic history of the magnets.

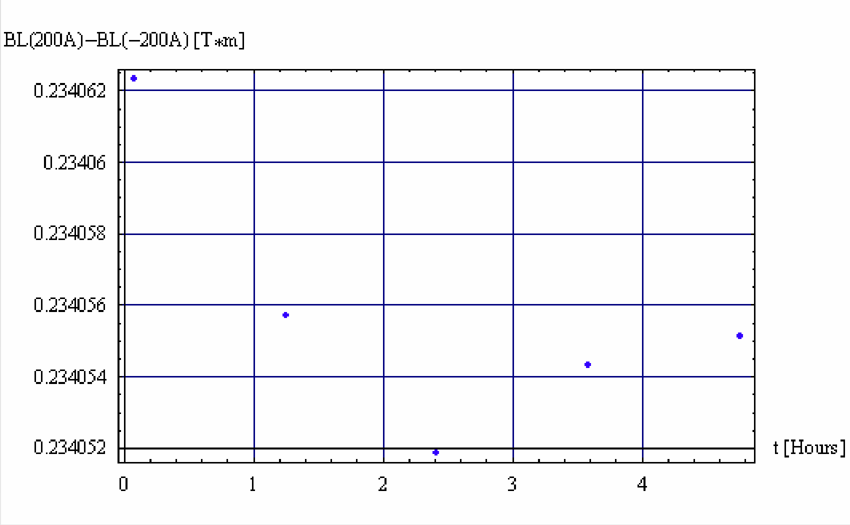
15-D-12 Run-17



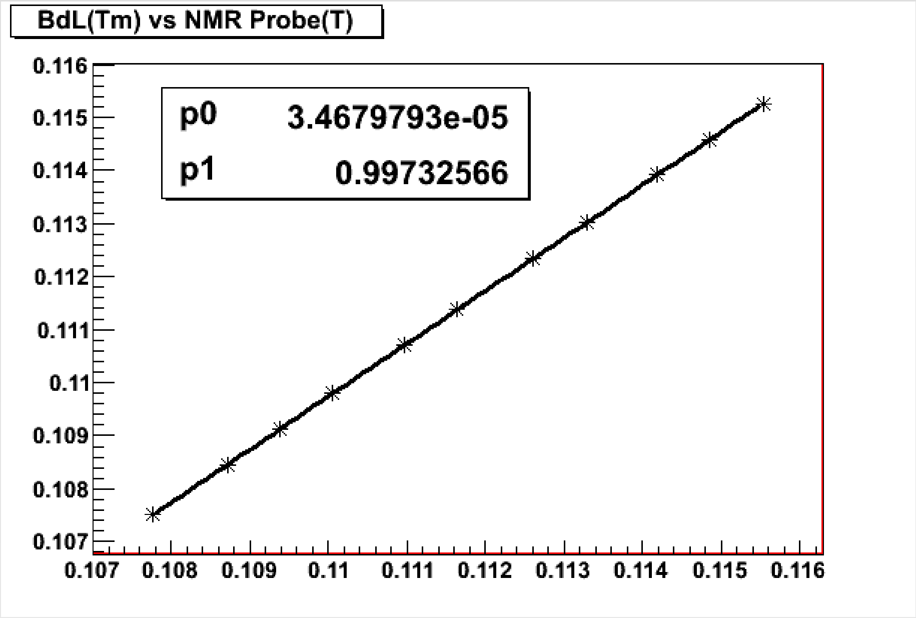


Reproducibility tests





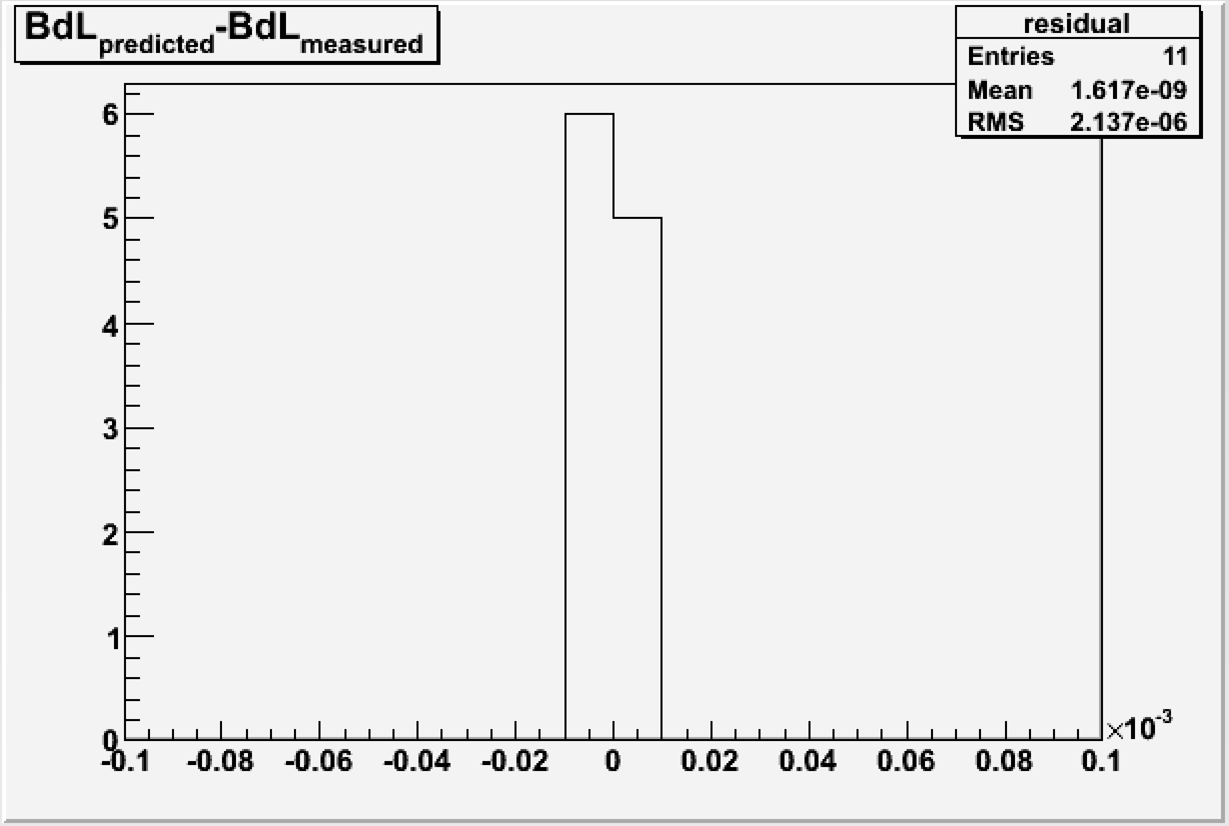
Stability of the BdL-integral difference during changing of the magnets polarity - 30 ppm !



Run 10 for 15D4:1 Amp steps from 140 to 150
Bdl-integral value vs Hall- or NMR-probe data

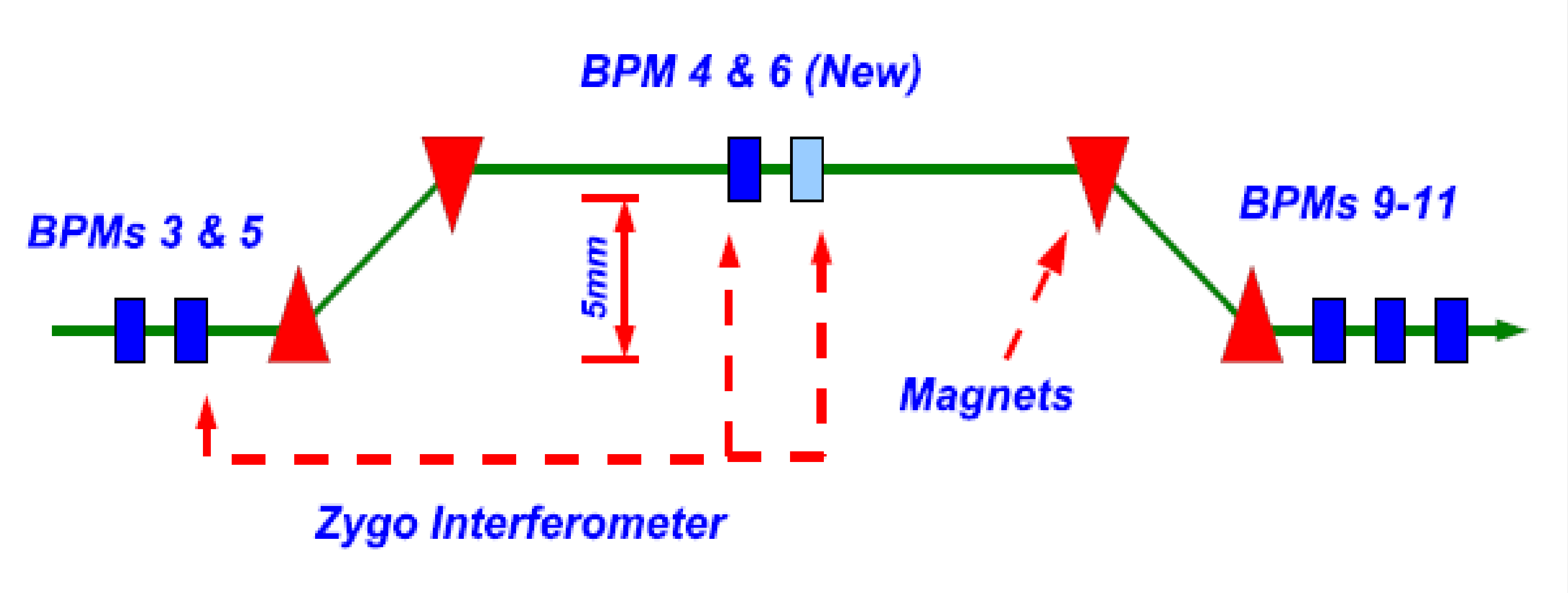
The values of the parameter are:
p1 = -0.9933275
p0 = -0.0005064
where p1 is the slope and p0 the intercept.

BdL= 0.99733*NMR-0.00035



$\sigma_{BdL}/BdL_{aver} \approx 20$ ppm

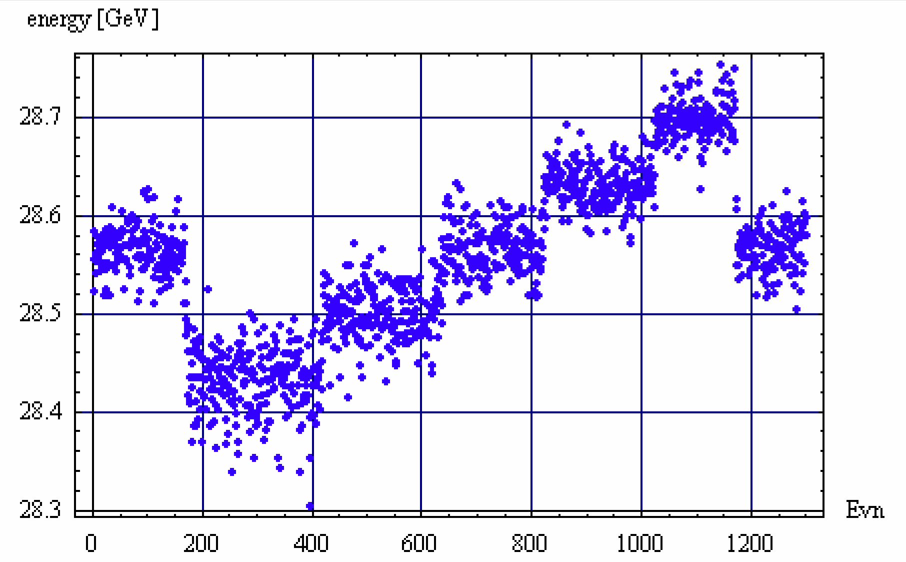
Energy measurements



Spectrometer scheme

Run-1699: magnet scan with energy feedback setpoint at each setting

I = -150 A : -200 -> 200 MeV in 5 steps from nominal value
...



May be a constant in the dependence of the BPM4 data and the real beam position changings

obtained from zygo and BPM4-data when BPM4 was moved (a=0.7376) is not so correct...

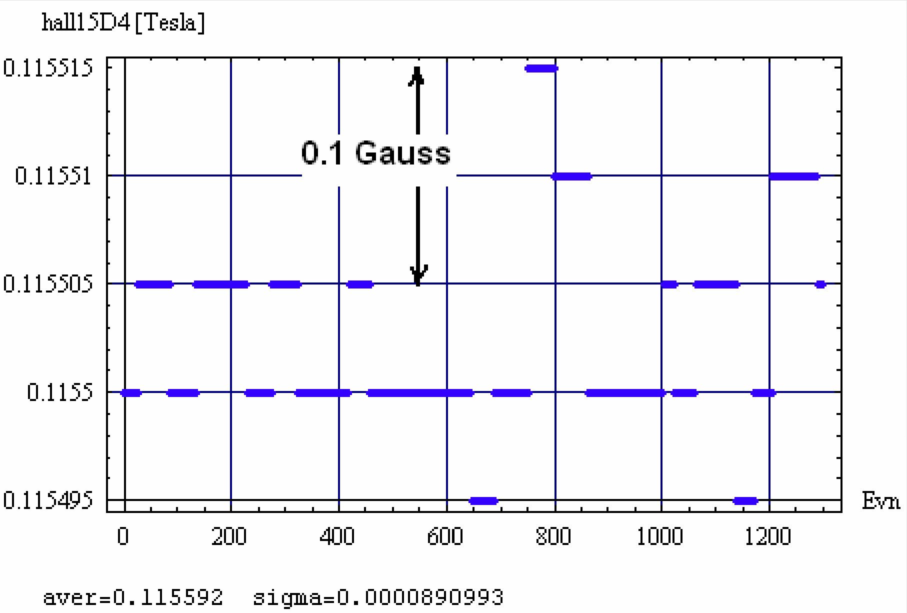
E-average =**28.58 GeV**; possible to see energy scan.

Beam deflection value calculated by taking into account BPM4 and zygo gata.

BPM **1,2** and **3,5** were used to predict the bunch position in the **BPM4**.

BdL-integral was predicted using the Hall-pobe data and obtained before dependences between hall and BdL.

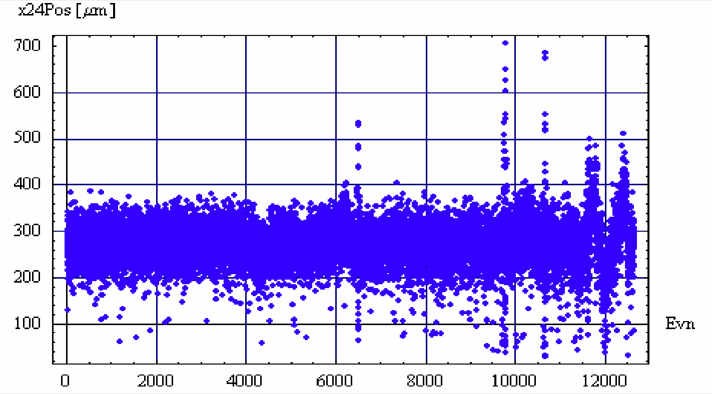
Range of the energy changing is about 350 MeV instead of 400 MeV.

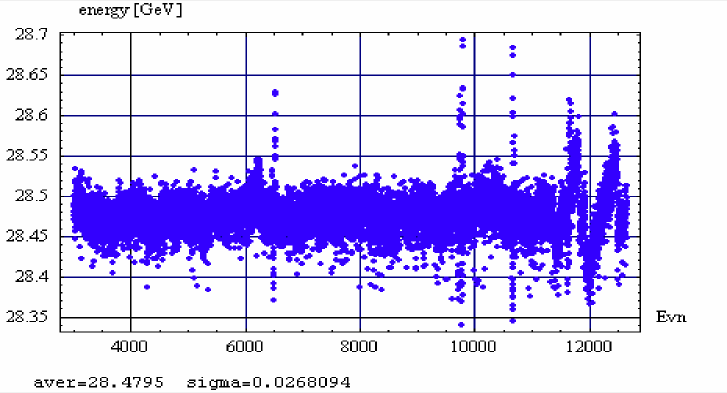

hall15D4 [Tesla]
0.115515
0.11551
0.115505
0.1155
0.115495
0
200
400
600
800
1000
1200
Evn
0.1 Gauss
aver=0.115592 sigma=0.0000890993

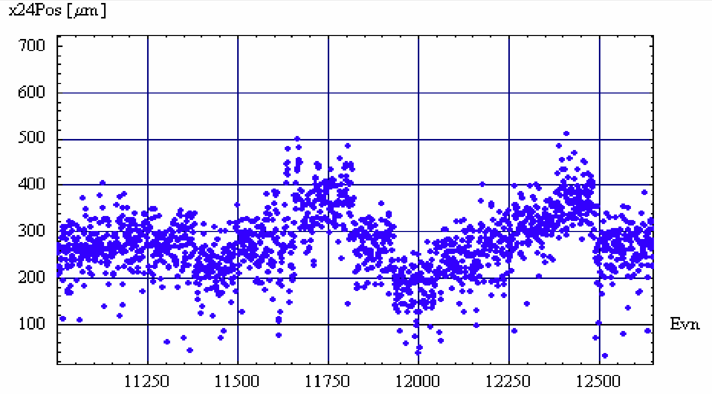
run-1952: -150A calibration

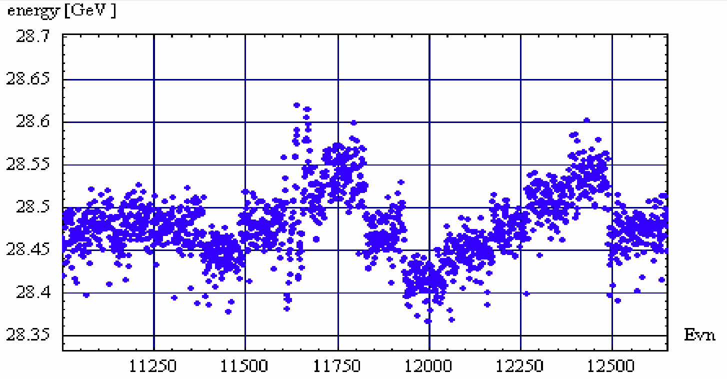
run-1959 (Cycle chicane between -150A and +150A) was used to get value of the beam deflection:
defl=((x4Pos)aver+(zmiBPM4)aver)(+150A)-((x4Pos)aver+(zmiBPM4)aver)(-150A)=9.755314424/2 mm

The value of the current during this run equals exactly **149.966A** - the same was in run-1699. So, the mean-value of the Hall probe **Bhall=1155.91 Gauss** was taken from the run-1699



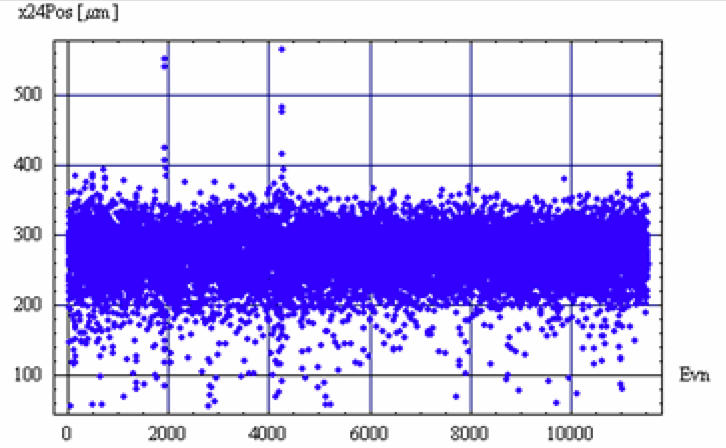


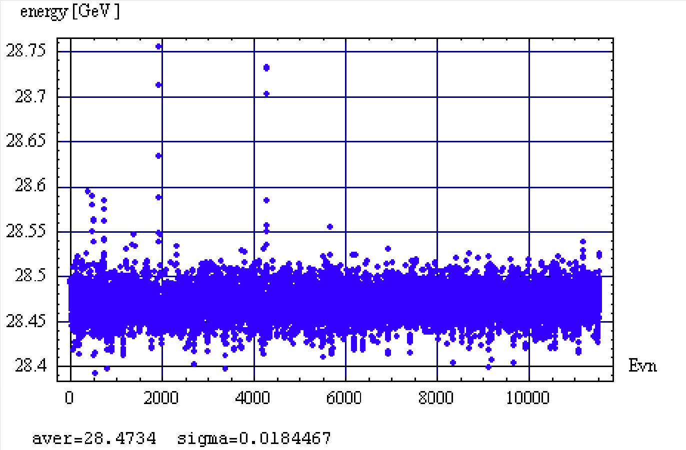




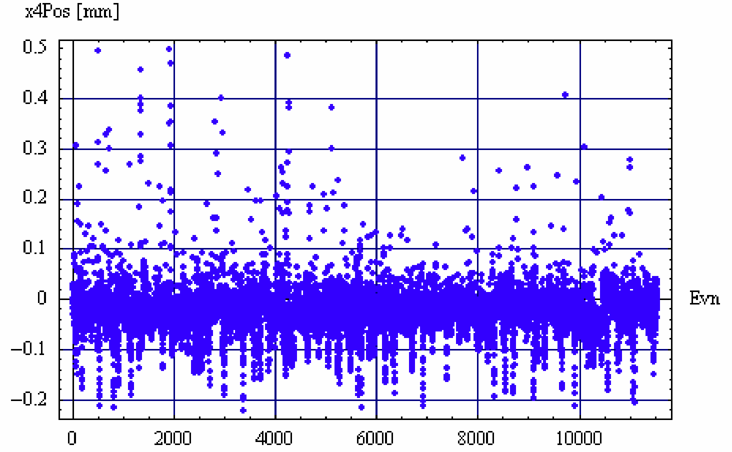
two energy scans at the end of the run are seen

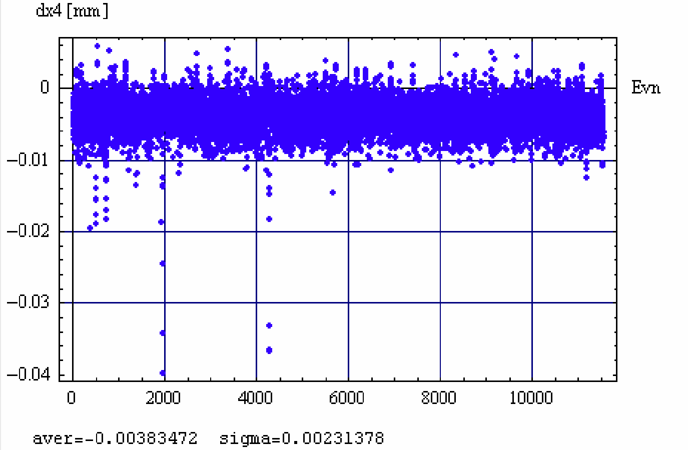
Resolution of the BPM4 in this run is about **3.4 microns**





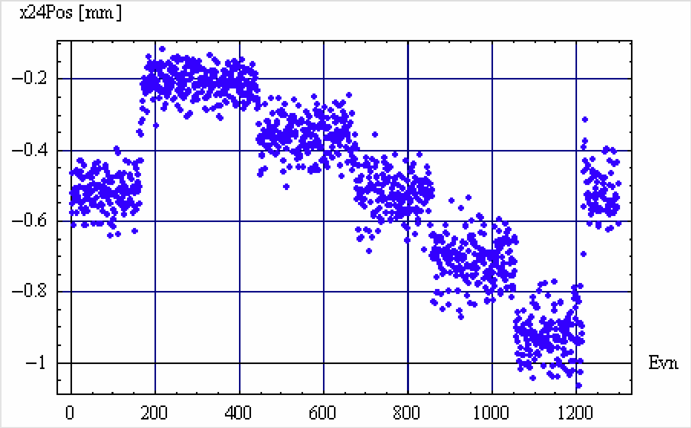
Run-1953 (-150 A stability)
Resolution of the BPM4 - 2.3 microns



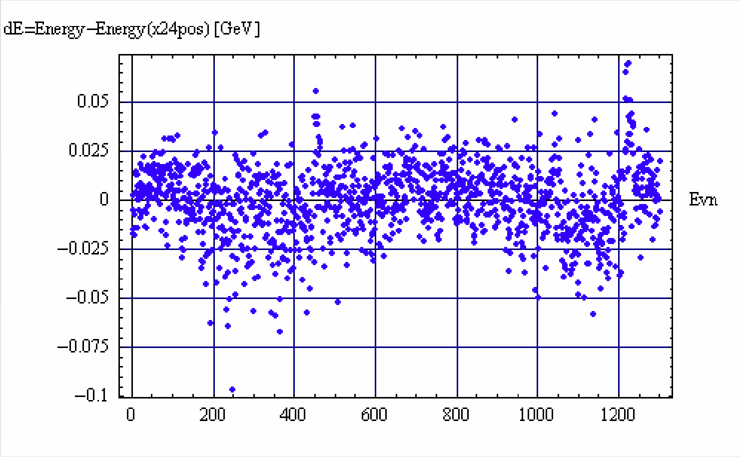


Run-1699 additional pictures

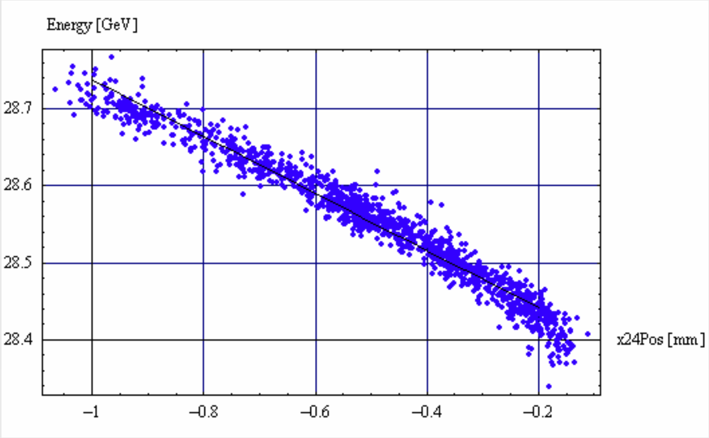
BPM-24 x-pos vs same events as in the Energy-plot:

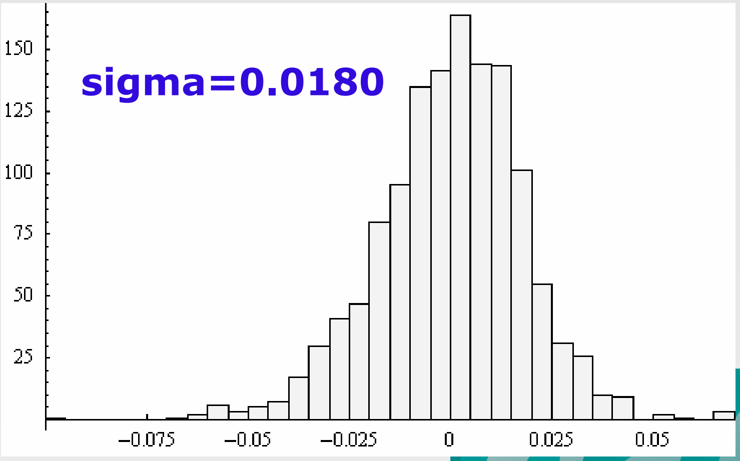


E-residual=Emeas-Ecalc using fit:



Obtained dependences of measured energy via x24pos



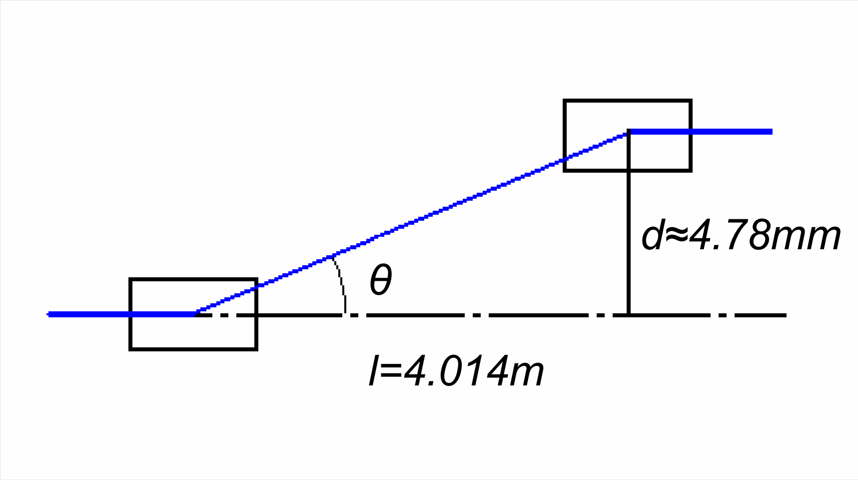


28.3678-0.36975*x24pos

Errors of the energy measurements

$$E = \frac{ce}{\theta}\int Bdl \qquad \frac{\Delta E}{E} = \sqrt{(\frac{\Delta\theta}{\theta})^2 + (\frac{\Delta\int Bdl}{\int Bdl})^2}$$

1. Accuracy of the deflection angle θ definition:



$$\theta = arctg\frac{d}{l} = f(d) \qquad |\Delta\theta| = \Delta d \cdot \frac{\partial f(d)}{\partial d}$$

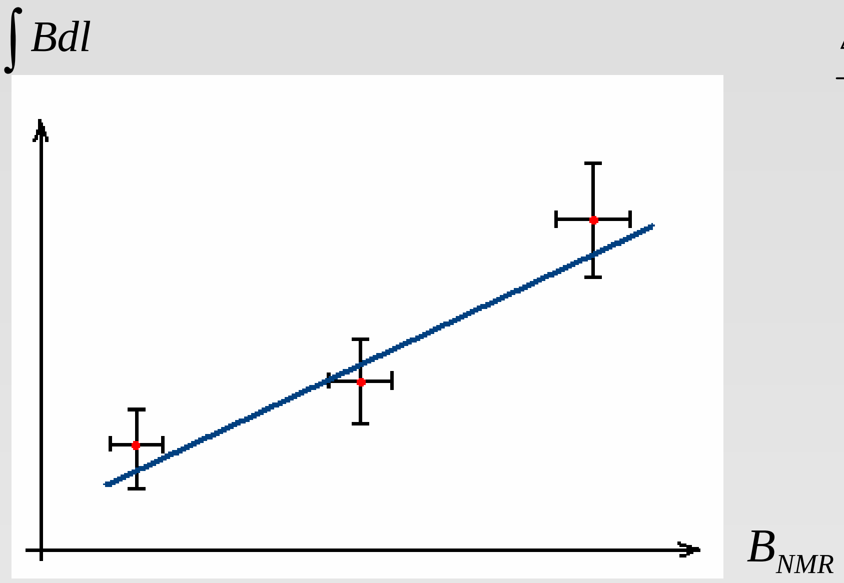
$$\frac{\Delta\theta}{\theta} = \frac{\Delta d}{d} \cdot \frac{d}{f(d)} \frac{\partial f(d)}{\partial d}$$

$$\frac{\partial f(d)}{\partial d} = \frac{1}{l \cdot (1 + \frac{d^2}{l^2})} \qquad \frac{\Delta d}{d} = \frac{1 \cdot 10^{-6}\, m}{4.78 \cdot 10^{-3}\, m}$$

$$\frac{\Delta\theta}{\theta} \cong 209 \cdot 10^{-6}$$

2. Accuracy of the *Bdl*-integral definition:

$$\int Bdl = f(B_{NMR})$$



$$\frac{\Delta\int Bdl}{\int Bdl} = \sqrt{\left(\frac{\Delta B_{NMR}}{B_{NMR}}\right)^2 + \left(\frac{\Delta\int Bdl}{\int Bdl}\right)^2_{meas} + \left(\frac{\Delta fit}{fit}\right)^2}$$

Error of the B_{NMR} measurement

Error of the *Bdl* – integral measurement by flip coil

Error of the fit

Error of the B_{NMR} measurement

Relative accuracy of the NMR by itself – **$10 \cdot 10^{-6}$**

Accuracy of the NMR-probe positioning inside the magnet - **±1mm**
leads to less than **$1 \cdot 10^{-6}$** error (in the center of the magnet field is uniform)

Tilt of the probe :

-NMR data – not sensitive

-Hall data – ***(B-B·Cos(5mrad))/B=*** **$12 \cdot 10^{-6}$**

(angle og the Hall-probe positioning ±5 mrad)

$$\frac{\Delta B_{NMR}}{B_{NMR}} \cong 16 \cdot 10^{-6}$$

Error of the ***BdL***-integral measurements by flip coil

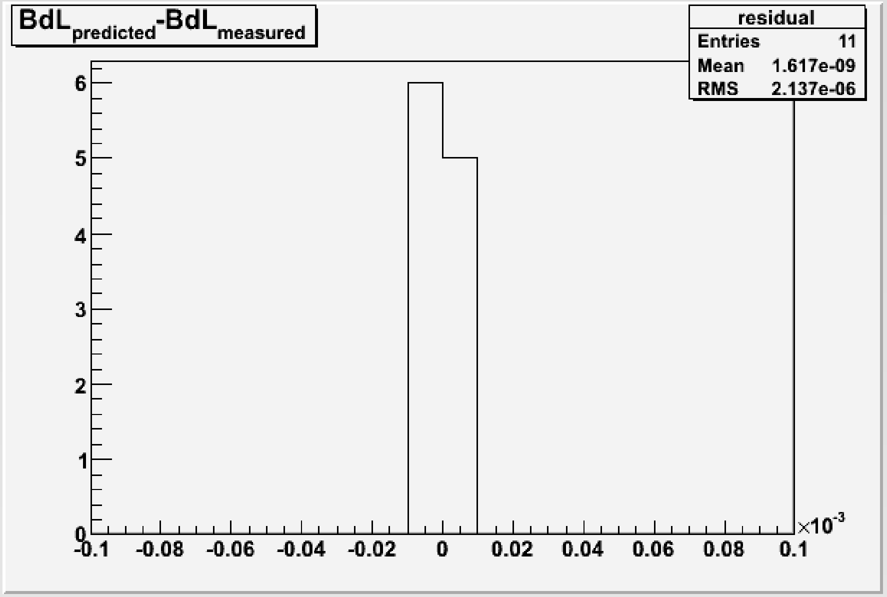
Statistical –

$\sigma_{Bdl(aver)} = 9.6 \cdot 10^{-6}$ T·m (14-D-4 Run-10 strdat.r10)

$$\frac{\sigma_{aver}}{\int Bdl} \cong \frac{9.6 \cdot 10^{-6}}{0.111} \cong 90 \cdot 10^{-6}$$

Error of the flip coil calibration
(by moving wire technique) -26ppm

Error of the ***BdL***-integral prediction by obtained fit:



$\sigma_{BdL}/BdL_{aver} \approx 20$ ppm

$$\int Bdl_{calc} - \int Bdl_{meas}$$

$$\frac{\Delta\int Bdl}{\int Bdl} = \sqrt{\left(\frac{\Delta B_{NMR}}{B_{NMR}}\right)^2 + \left(\frac{\Delta\int Bdl}{\int Bdl}\right)^2_{meas} + \left(\frac{\Delta fit}{fit}\right)^2}$$

Total error of the ***BdL***-integral definition: **$=95 \cdot 10^{-6}$**

Total energy definition accuracy:

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{\Delta\theta}{\theta}\right)^2 + \left(\frac{\Delta B_{NMR}}{B_{NMR}}\right)^2 + \left(\frac{\Delta\int Bdl}{\int Bdl}\right)^2_{meas} + \left(\frac{\Delta fit}{fit}\right)^2}$$

$=2.5\cdot10^{-4}$

Today energy measurement error:

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{\Delta\theta}{\theta}\right)^2 + \left(\frac{\Delta B_{NMR}}{B_{NMR}}\right)^2 + \left(\frac{\Delta\int Bdl}{\int Bdl}\right)^2_{meas} + \left(\frac{\Delta fit}{fit}\right)^2}$$

$= 2.5 \cdot 10^{-4}$

$$\frac{\Delta d}{d} = \frac{1 \cdot 10^{-6}\, m}{4.78 \cdot 10^{-3}\, m}$$

$$\frac{\Delta\theta}{\theta} \cong 209 \cdot 10^{-6}$$

Today energy measurement error:

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{\Delta\theta}{\theta}\right)^2 + \left(\frac{\Delta B_{NMR}}{B_{NMR}}\right)^2 + \left(\frac{\Delta\int Bdl}{\int Bdl}\right)^2_{meas} + \left(\frac{\Delta fit}{fit}\right)^2}$$ **$= 2.5\cdot 10^{-4}$**

$$\frac{\Delta B_{NMR}}{B_{NMR}} \cong 16\cdot 10^{-6}$$

$$\frac{\Delta d}{d} = \frac{1\cdot 10^{-6}\,m}{4.78\cdot 10^{-3}\,m}$$

$$\frac{\Delta\theta}{\theta} \cong 209\cdot 10^{-6}$$

Today energy measurement error:

$$\frac{\Delta E}{E} = \sqrt{(\frac{\Delta\theta}{\theta})^2 + (\frac{\Delta B_{NMR}}{B_{NMR}})^2 + (\frac{\Delta\int Bdl}{\int Bdl})^2_{meas} + (\frac{\Delta fit}{fit})^2}$$

=2.5·10^-4^ $= 2.5 \cdot 10^{-4}$

$$\frac{\Delta B_{NMR}}{B_{NMR}} \cong 16 \cdot 10^{-6}$$

$$\frac{\Delta d}{d} = \frac{1 \cdot 10^{-6}\, m}{4.78 \cdot 10^{-3}\, m}$$

$$\frac{\Delta\theta}{\theta} \cong 209 \cdot 10^{-6}$$

$$\frac{\sigma_{aver}}{\int Bdl} \cong \frac{9.6 \cdot 10^{-6}}{0.111} \cong 90 \cdot 10^{-6}$$

Error of the flip coil calibration
(by moving wire technique)
-26ppm

Today energy measurements error:

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{\Delta\theta}{\theta}\right)^2 + \left(\frac{\Delta B_{NMR}}{B_{NMR}}\right)^2 + \left(\frac{\Delta\int Bdl}{\int Bdl}\right)^2_{meas} + \left(\frac{\Delta fit}{fit}\right)^2} \quad \mathbf{= 2.5\cdot 10^{-4}}$$

$$\frac{\Delta B_{NMR}}{B_{NMR}} \cong 16\cdot 10^{-6}$$

$\sigma_{BdL}/BdL_{aver} \approx 20\cdot 10^{-6}$

$$\frac{\Delta d}{d} = \frac{1\cdot 10^{-6}\,m}{4.78\cdot 10^{-3}\,m}$$

$$\frac{\Delta\theta}{\theta} \cong 209\cdot 10^{-6}$$

$$\frac{\sigma_{aver}}{\int Bdl} \cong \frac{9.6\cdot 10^{-6}}{0.111} \cong 90\cdot 10^{-6}$$

Error of the flip coil
calibration
(by moving wire technique)
-26ppm

ILC BPM-based spectrometer magnets' main parameters

Now it is possible to formulate and estimate the laboratory and operational magnetic field integral measurement technique for ILC spectrometer magnets.

Geometrical parameters of these magnets for this moment are mainly defined but exact designs as well as parameters of the measuring devices have to be clarified during simulations and following fabrication of the prototype magnet.

Energy, GeV	50-500
Relative accuracy of energy measurement ΔE/E	$1\cdot10^{-4}$- $1\cdot10^{-5}$
Bending angle, mrad	1
Magnetic field range, T	0.05-0.5
Magnetic field integral, T·m	0.15-1.5
Relative error of magnetic field integral measurement in situ	$(1\text{-}3)\cdot10^{-5}$
Magnet iron length, m	3
Effective magnet length, m	3.045
Gap height, mm	35
Magnet type	C