The LEP Spectrometer Project

John Matheson

CERN/SL

Representing the

LEP Spectrometer Team

Groups involved:

CERN

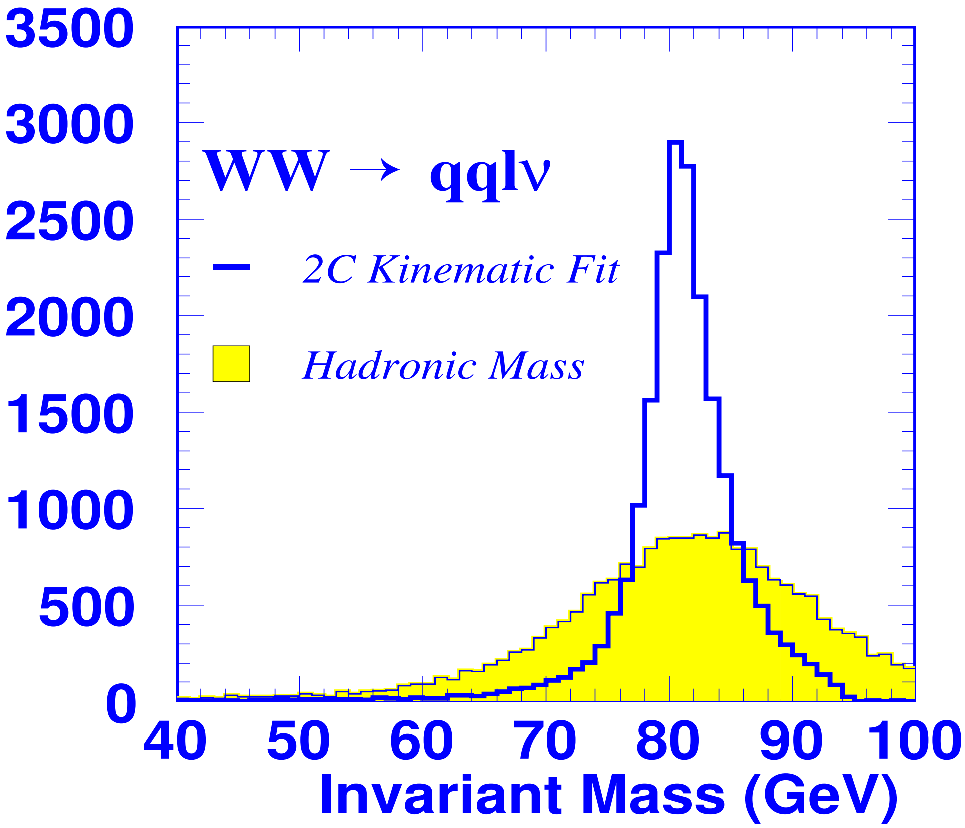
EP/OPE, EST/ESI, EST/SU, LHC/MMS, LHC/VAC
SL/BI, SL/DI, SL/MS, ST/CV

University of Aachen, University of Madrid,
Polytechnic of Milano, University of Oxford

Contents

- LEP energy requirements
- LEP energy measurements
- Principle of the spectrometer
- Layout of the spectrometer
- Magnet characterisation
- The WPS system
- The BPM system
- Measurement with the spectrometer
- Summary and Conclusions

LEP Energy Requirements



- M_Z, M_W, m_t, θ_W $\rightarrow$ **precision tests of SM**
- **Goal for LEP II:** $\delta M_W < 35 MeV$
- **Error on kinematic fit** $\delta M_W / M_W \approx \delta E_{beam} / E_{beam}$

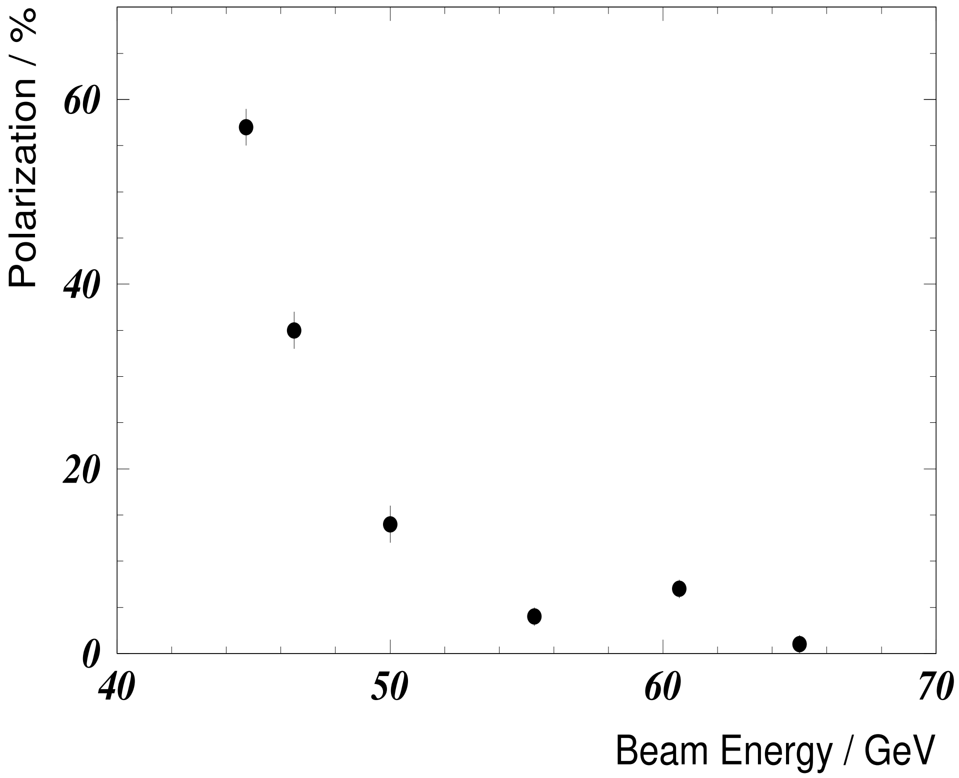
Beam energy goal: $\delta E_{beam} / E_{beam} \sim 1 \times 10^{-4}$

Polarisation

- **Spin precession in bending field:**

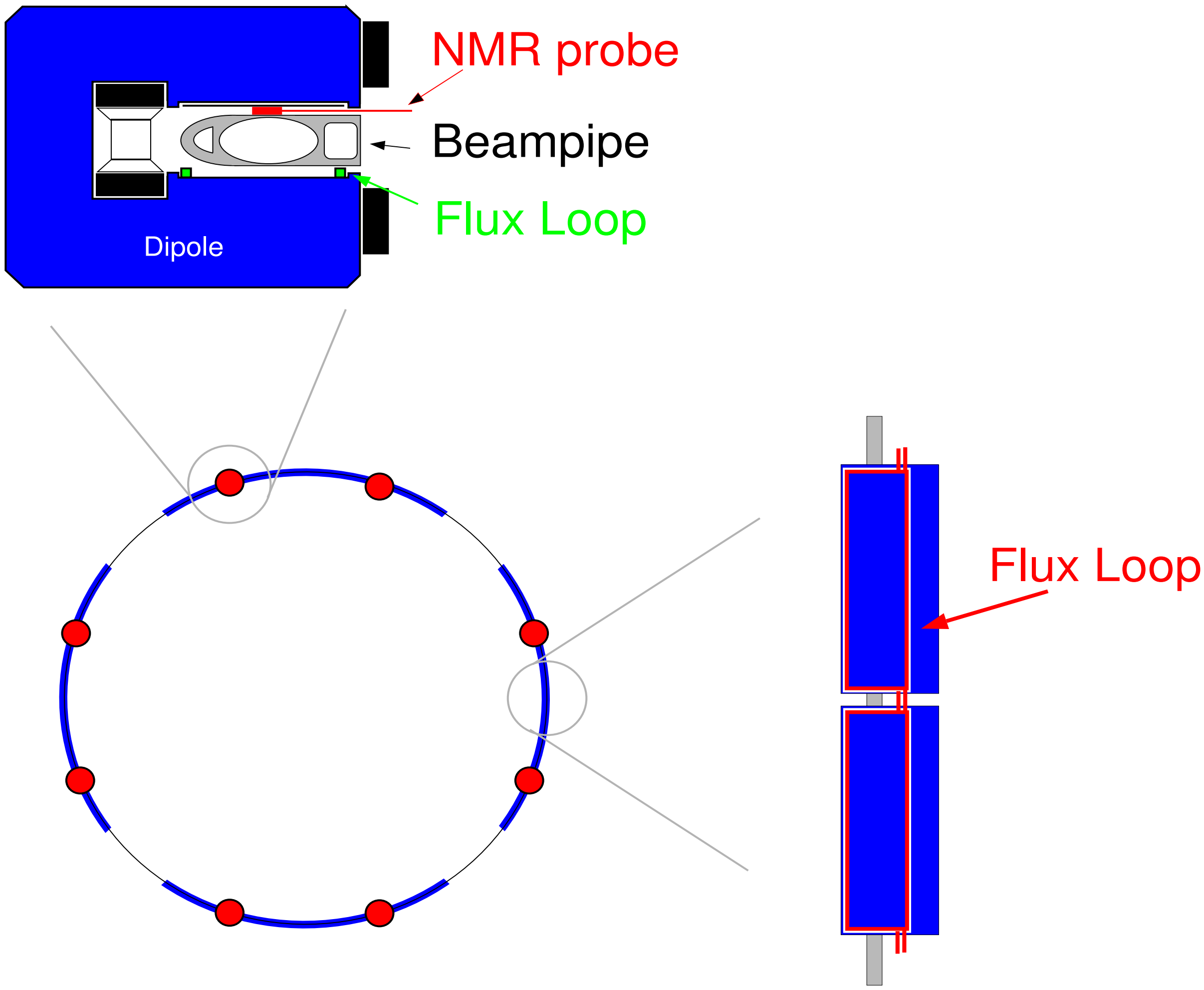
$$\nu = \frac{f_s}{f_{rev}} = \frac{(g_e - 2)/2}{m_0 c^2} E$$

- **Measure polarisation with laser Compton polarimeter**
- **Use RF kicker magnet, depolarisation if** $f = f_s$
- **Accuracy:** $\frac{\Delta E}{E} < 10^{-5}$



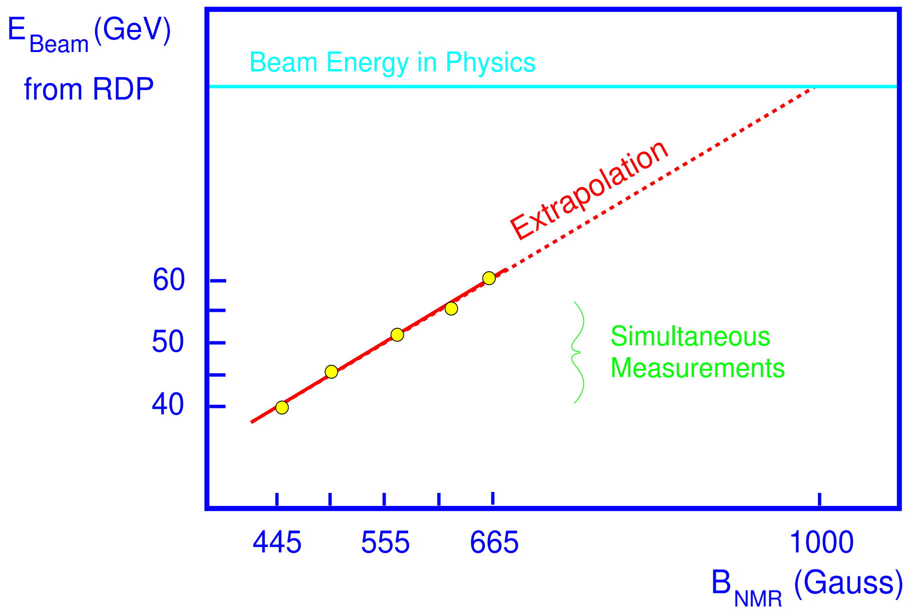
- **Depolarisation measurement up to 60 GeV only**

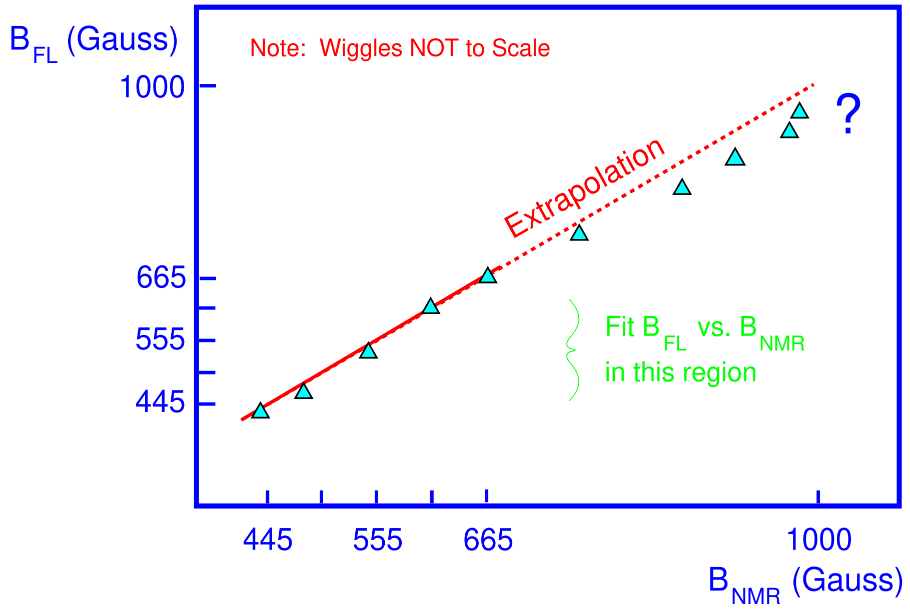
LEP Energy Measurements



- **Resonant depolarisation $\delta E_{beam} \approx 200 keV$ up to 60 GeV**
- **Measure total bending field: NMRs or Flux Loop**
- **NMRs: 24 with $\delta B/B \sim 10^{-6}$**
- **Flux Loop: $\delta B/B \sim 10^{-4}$ over 96.5% of the field**

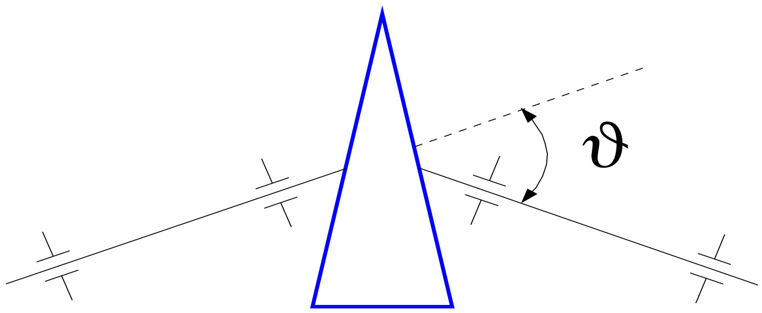
LEP Energy Measurements





- **Calibrate NMRs with resonant depolarisation**
- **Check linearity by comparison with Flux Loop**
- $\delta E_{beam}/E_{beam} = 20MeV$ **at** $E_{beam} = 95GeV$

Spectrometer Principle



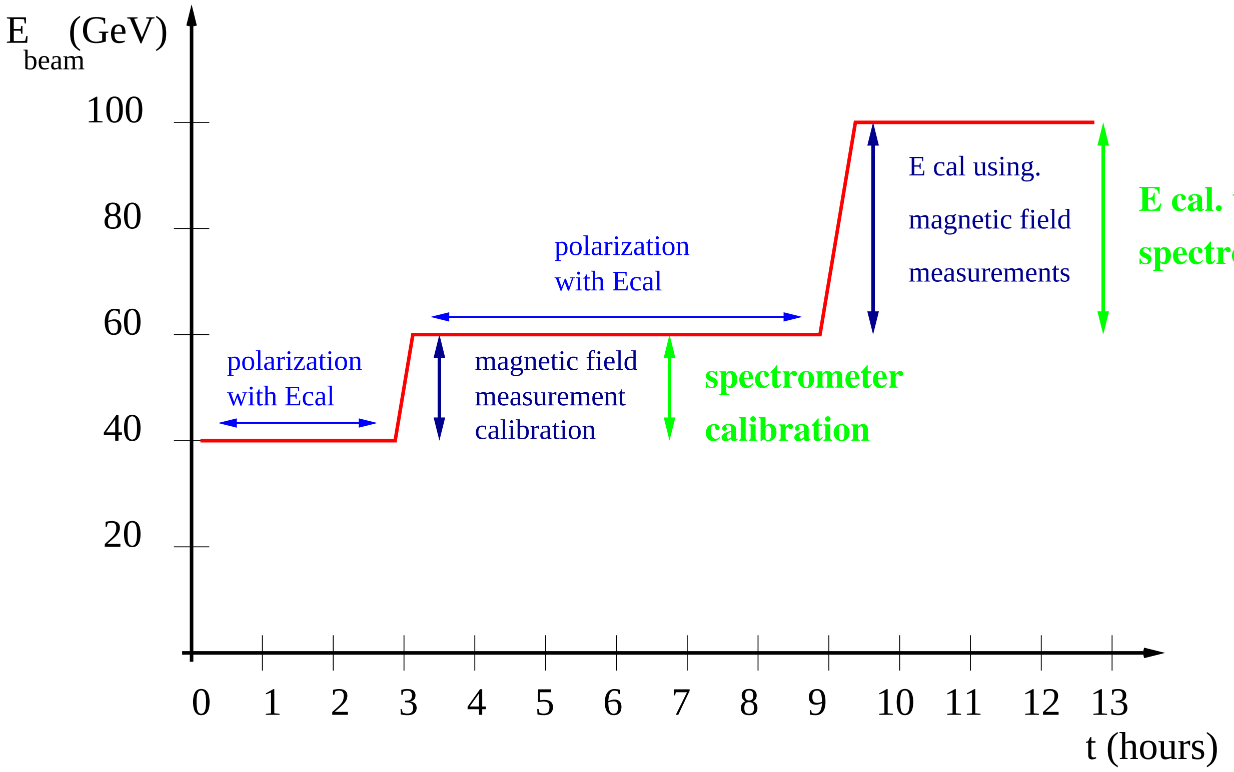
$$\vartheta \propto \frac{\int B dl}{E_{beam}}$$

Measure $\int B dl$ and ϑ to give E_{beam}

accuracy required: $\frac{\Delta E}{E} = 1 \cdot 10^{-4}$

- $\int B dl$ **from local NMRs and field map**
- **Max. error from the BPMs: 1 μm** $\rightarrow \frac{\Delta\theta}{\theta} \sim 1 \times 10^{-4}$
- **Max. error on integral magnetic field:** $\Delta B/B = 3 \times 10^{-5}$

Spectrometer Calibration

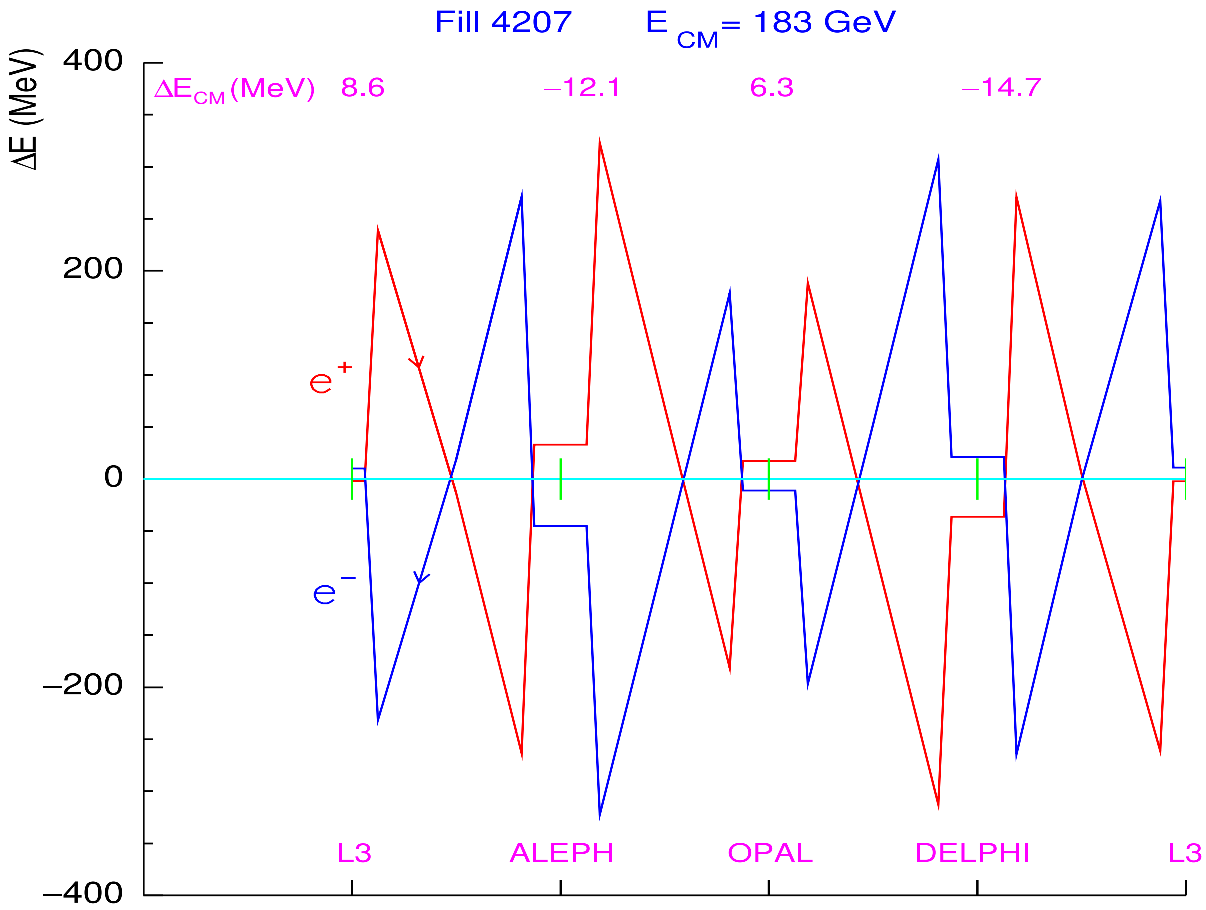


- **Spectrometer magnet ramps with LEP**
- **Spectrometer calibrated against depolarisation**
- **Ramp, relative measurement of E_{beam}:**

$$\frac{E^{100GeV}}{E^{60GeV}} = \frac{\Theta^{60GeV}}{\Theta^{100GeV}} \cdot \frac{\int B^{100GeV} dl}{\int B^{60GeV} dl}$$

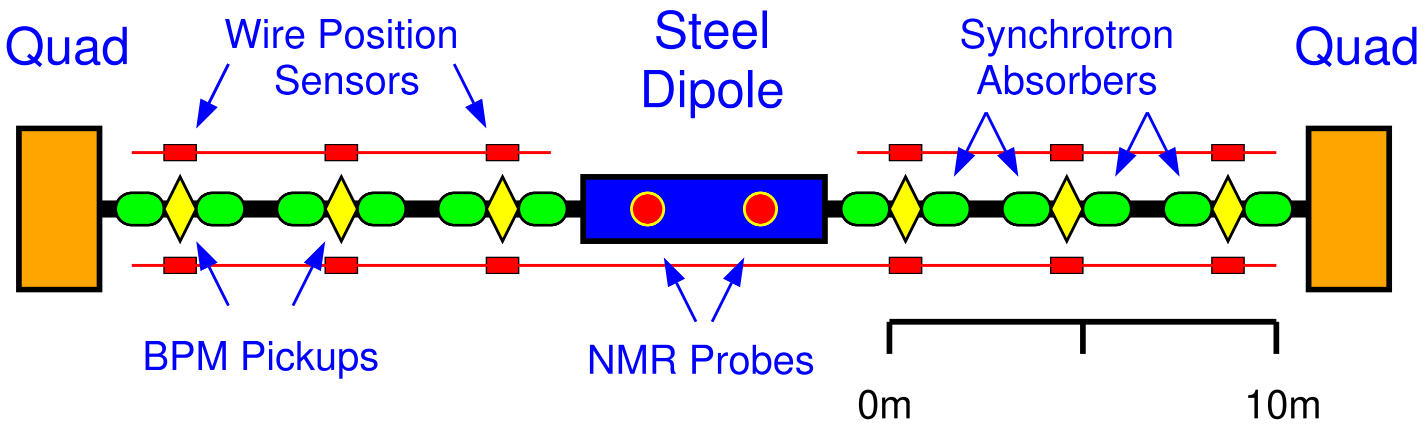
- **Only the change in θ is important**
- **Is the NMR model OK?**

RF Corrections



- **Polarisation measures mean LEP energy**
- **Spectrometer measures energy at particular point**
- **RF model $E_{POL} \rightarrow E_{SPECT}$ at polarisation energy**
- **RF model $E_{SPECT} \rightarrow E_{MEAN}$ at physics energies**

Layout of the Spectrometer

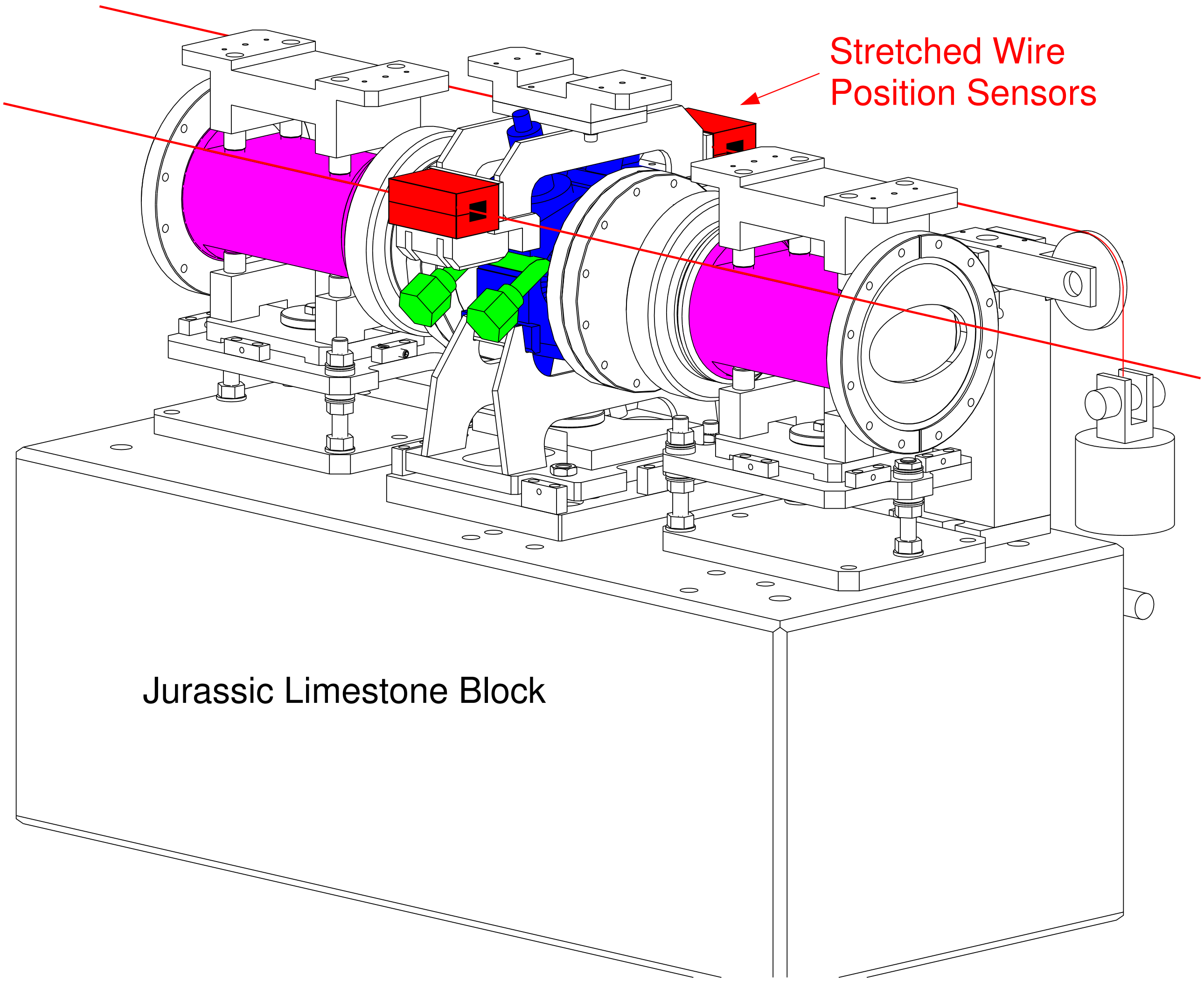


- Steel dipole magnet with NMRs, mapped
- Synchrotron radiation 0 to 1kW/m
- BPMs shielded by Cu absorbers
- Separate cooling for magnet, BPMs $< 1°C$ stability
- Wire position sensors

History of the Spectrometer

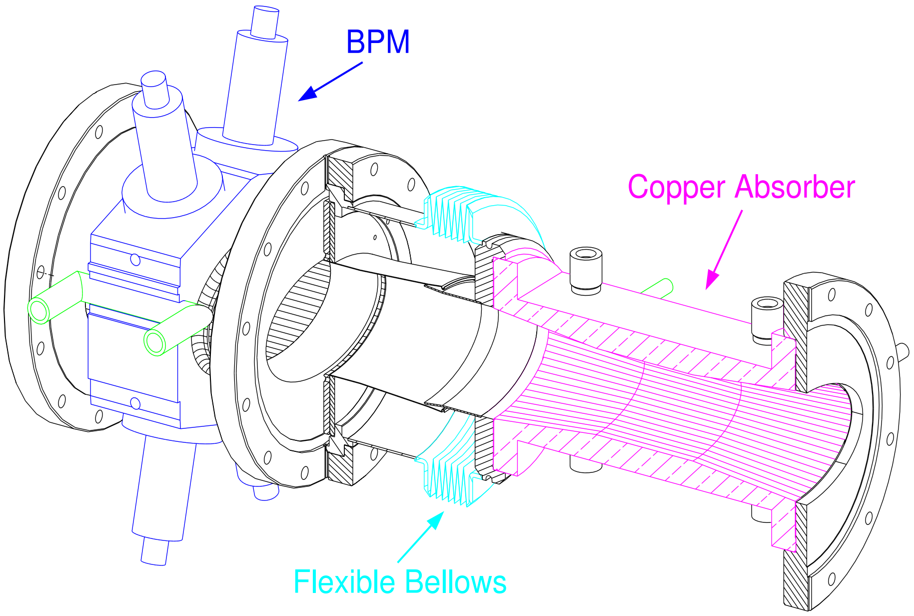
- Sept. 97: proposed by M.Hildreth, E.Torrence
- Sept. 97: becomes LEP Project, crash programme launched
- Jan. 98: approved by CERN directorate
- March 1998: RH arm installed (LEP dipole)
- LEP running 98: data from single arm
- Oct 98: new steel magnet arrives
- Shutdown 98-99:
  - magnet mapping in lab. (ISR-I8)
  - LH arm installed
  - magnet installed
  - magnet mapping in tunnel
- LEP running 99:
  - July: new BPM electronics
  - August on: comparison spectro./polarisation
  - August on: 3 ramps to physics energies
  - data analysis ongoing

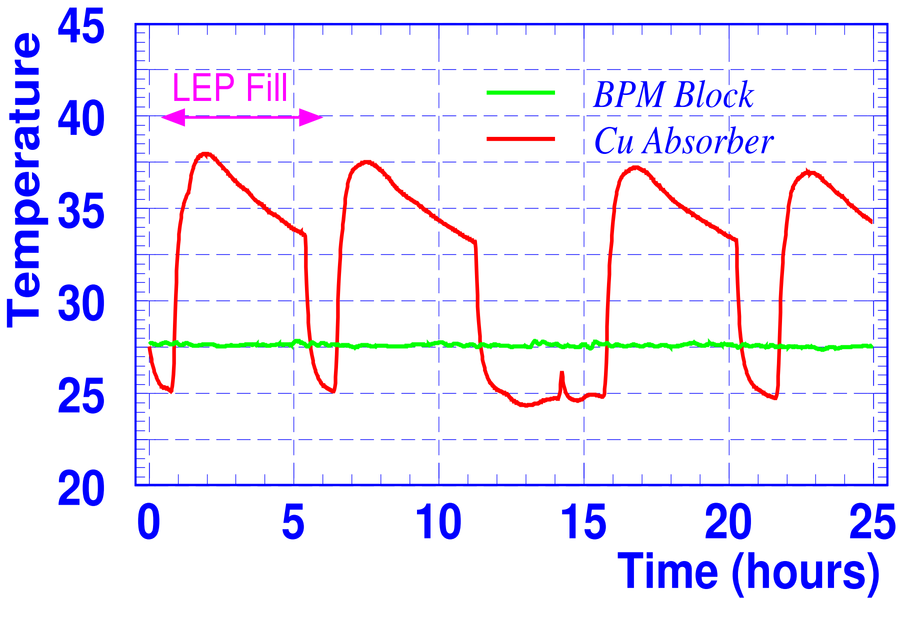
Layout of the Spectrometer



- **Separate cooling for BPMs, $\pm 0.2^{\circ}C$ stability**
- **Cu absorbers for synchrotron radiation**
- **WPSs mounted rigidly on BPM block**

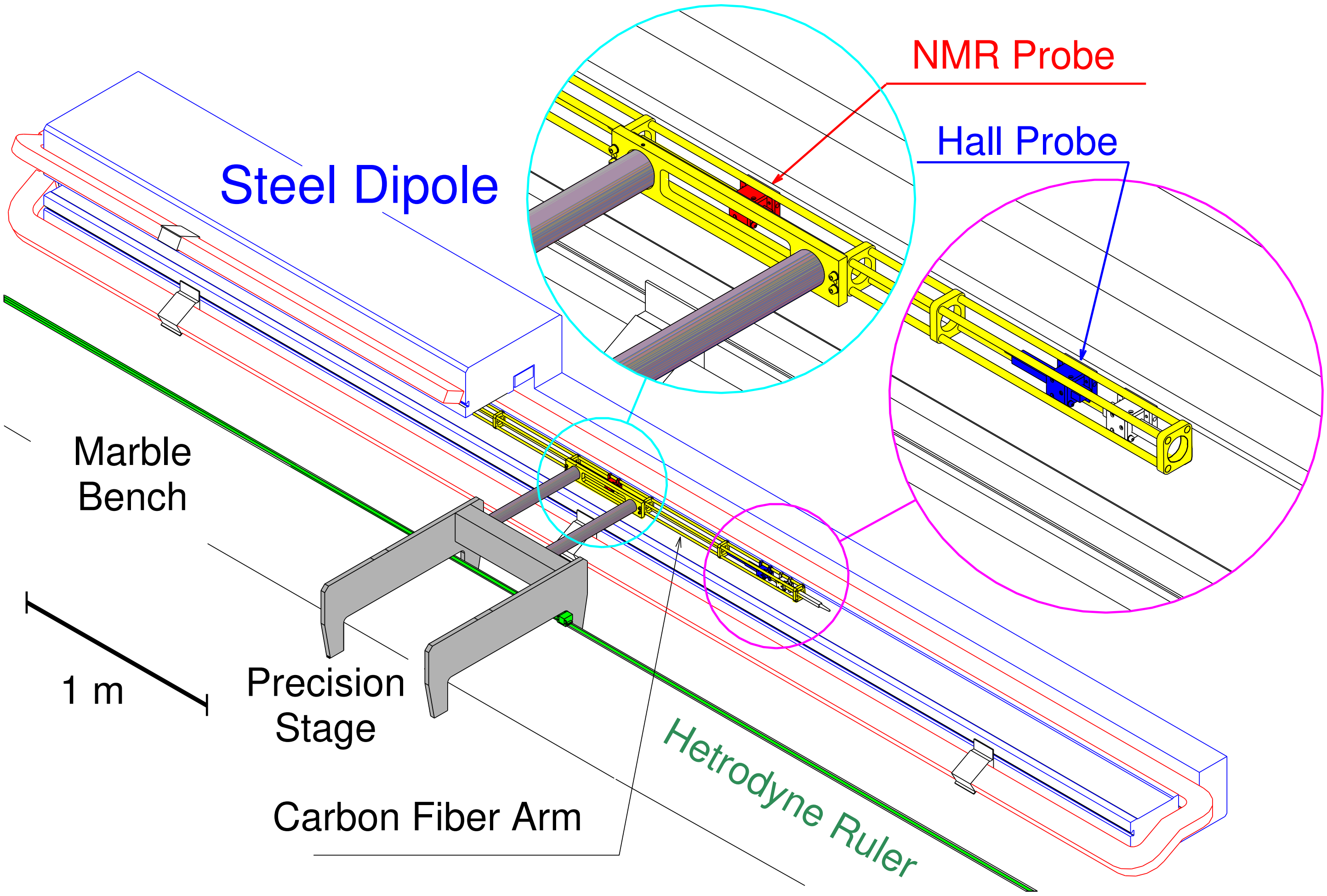
Cooling Station





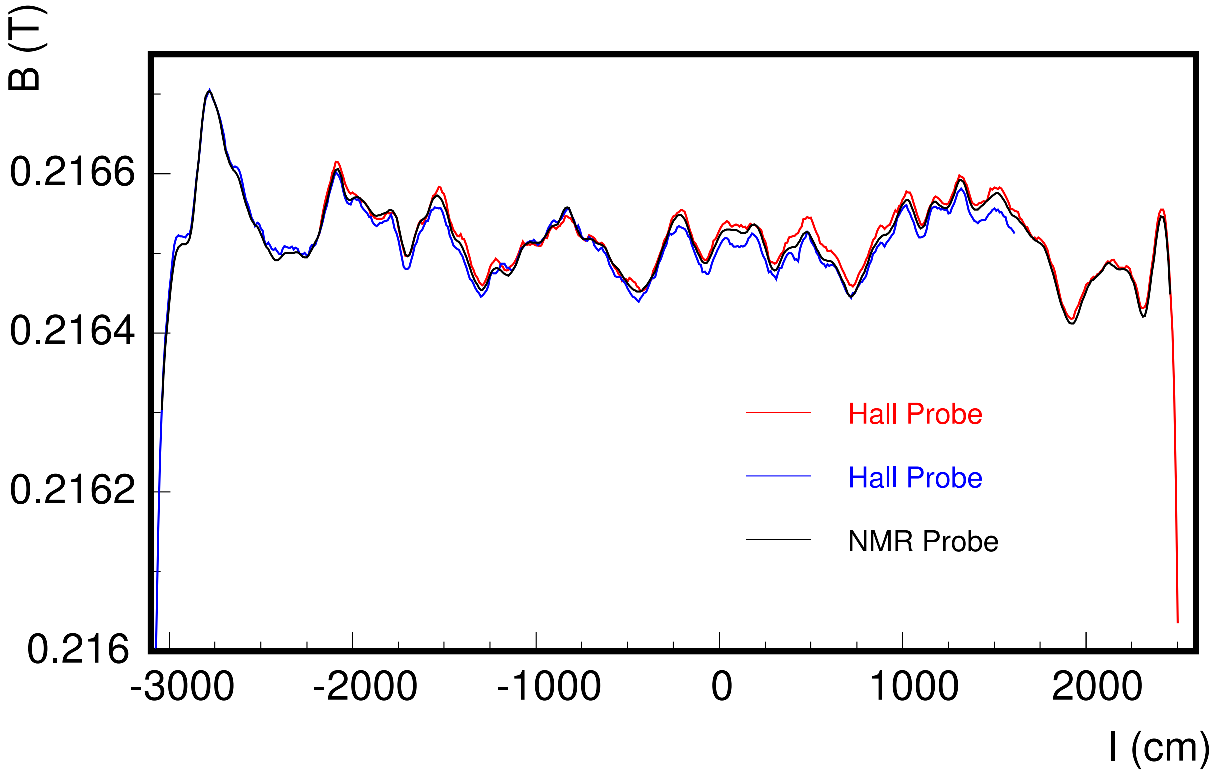
- **Synchrotron power 0 - 1kW/m,** $\propto E^4_{beam} \times I_{beam}$
- **BPM button movement** $1\mu m/1°C$

Magnet Mapping



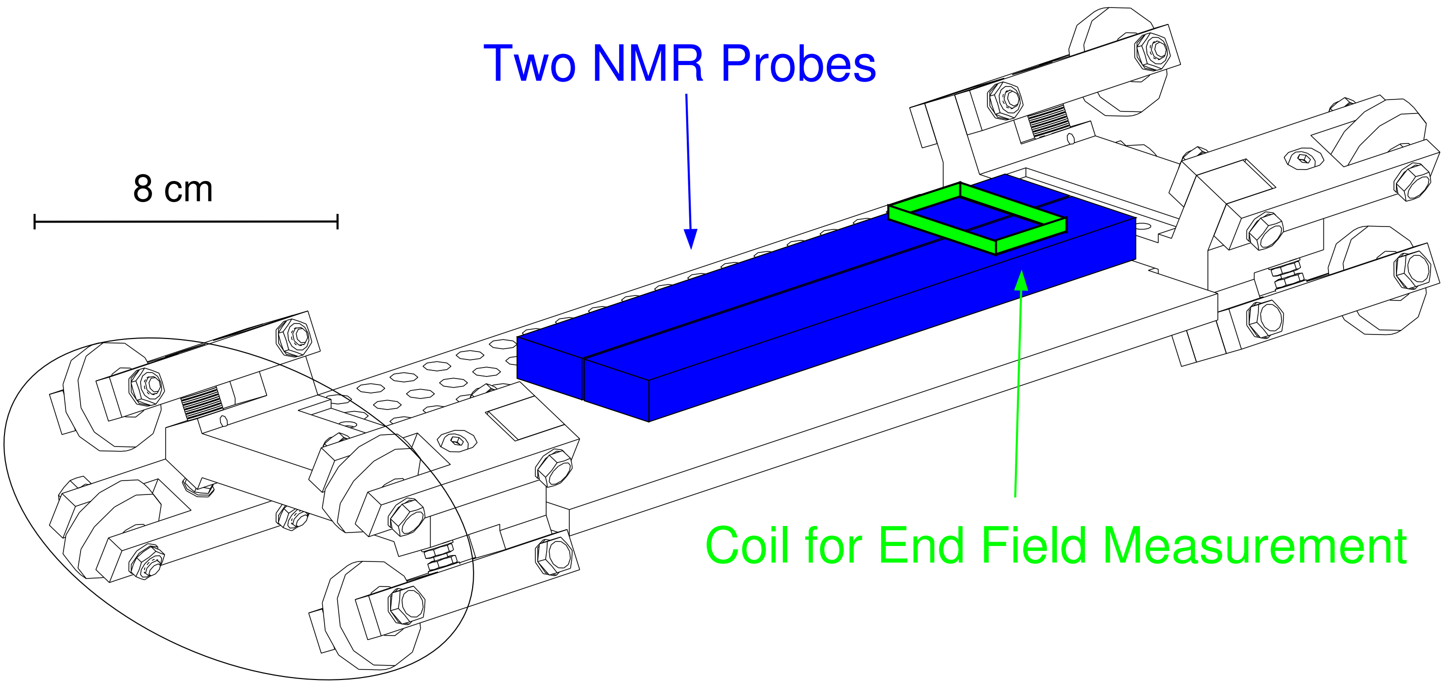
- **Relate $\int Bdl$ to B_{ref}**
- **NMR and Hall probes used to map**
- **Require 3×10^{-5} relative accuracy (small c.f. $\frac{\Delta\theta}{\theta}$)**

Magnet Mapping



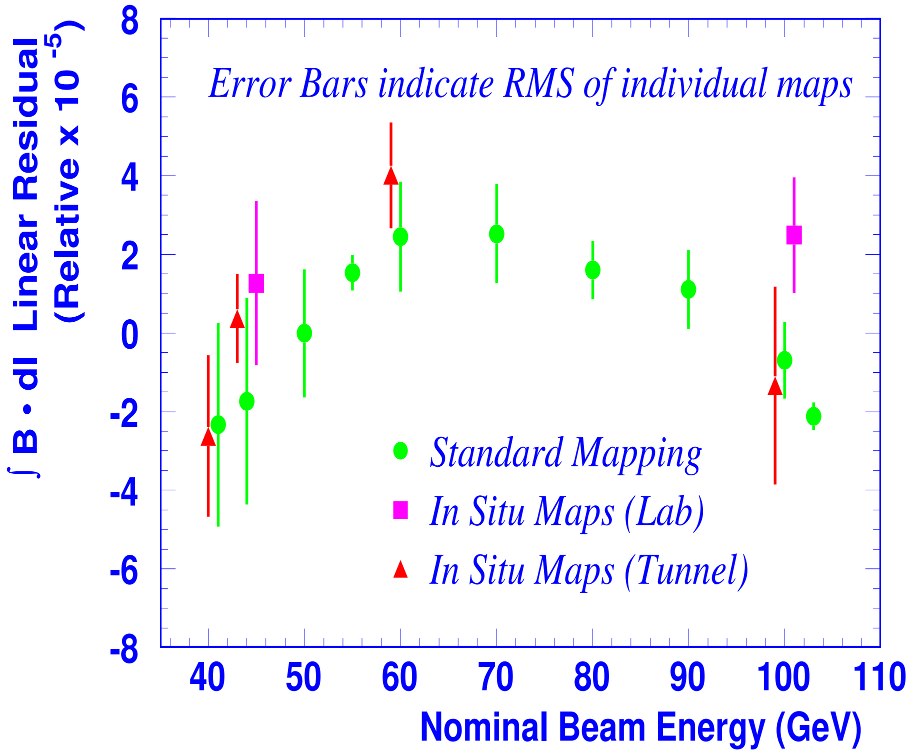
- B_{ref} **determined with 4 fixed NMR probes**
- $\int Bdl$ **determined with movable probes**
- **NMR probes** $\delta B/B \sim 10^{-6}$ **over** 90%
- **Hall probes** $\delta B/B \sim 10^{-4}$ **over** 10%
- **Temperature behaviour, field gradients also investigated**
- **Harmonic measurement and analysis**

Magnet Mapping



- **Mole allows measurement with beam pipe** *in situ*
- **Laser interferometer → mole position**
- **Mole motion by stepping motor/toothed (kevlar) belt**
- **Mole used in lab and tunnel**
- **Effect of transport lab → tunnel ?**

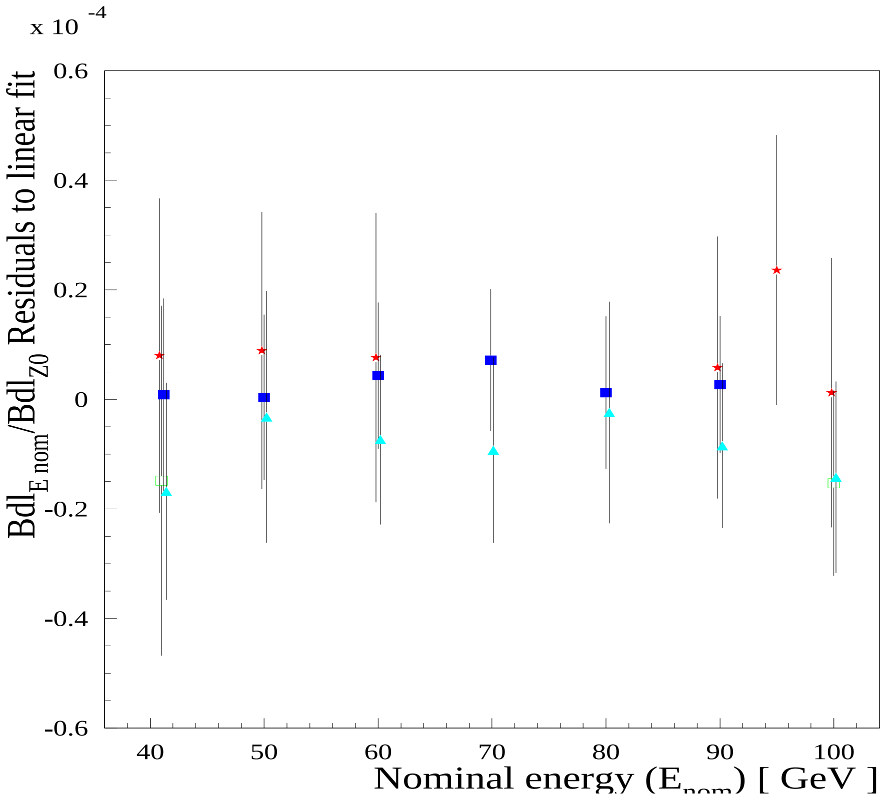
Magnet Mapping



- measurements include: lab, LEP tunnel, with/without vacuum chamber
- variation between different maps $\sim\ 3 \times 10^{-5}$

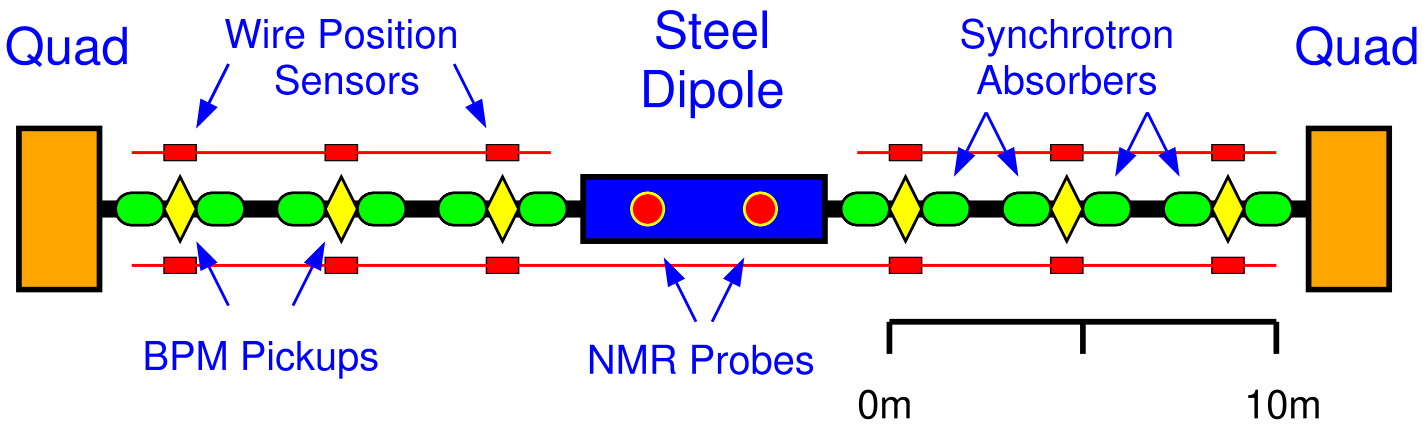
Magnet Mapping

error estimate from $\frac{\int B^{100} dl}{\int B^{44} dl} - \frac{f(B^{100}_{ref})}{f(B^{44}_{ref})}$



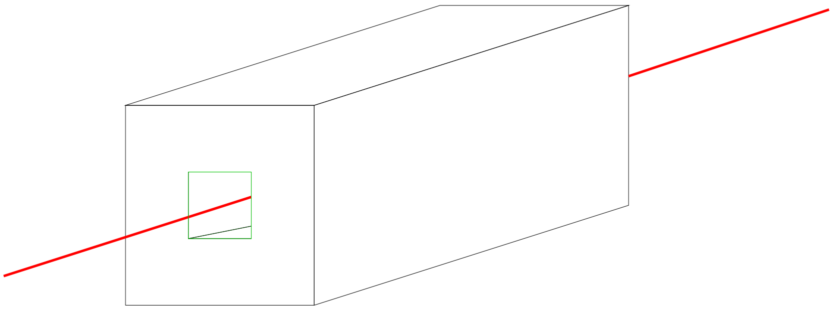
- magnet ramped in steps, compare maps with ref. probes
- variation between field integrals and predictions $< 3 \times 10^{-5}$

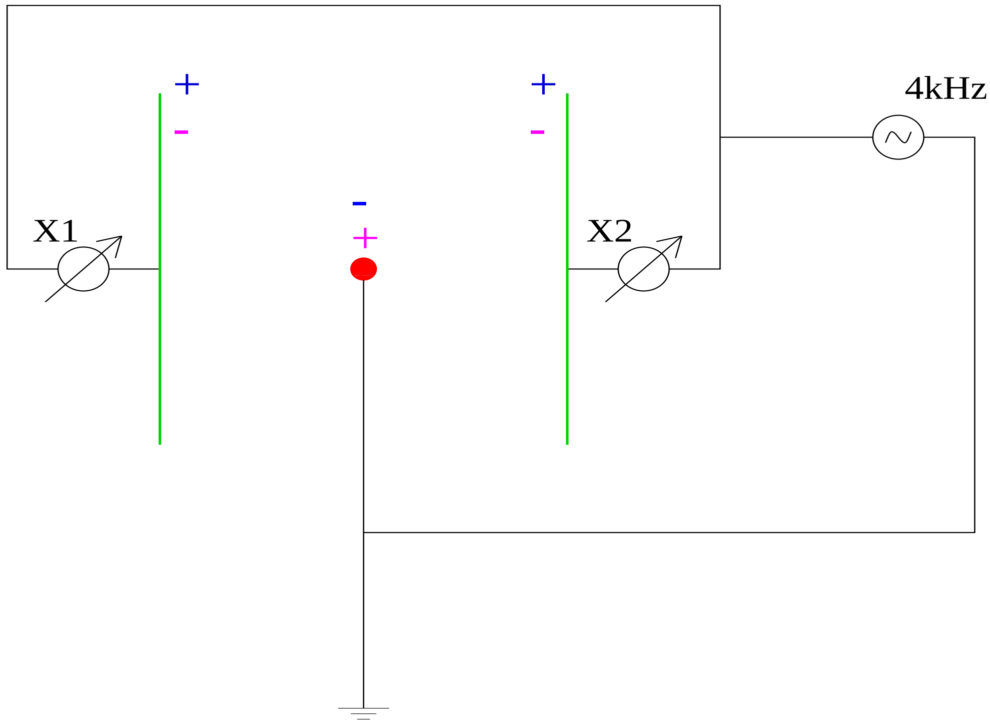
Layout of the Spectrometer - Reminder



- Synchrotron radiation 0 to 1kW/m
- WPSs monitor stability of BPMs
- 2 WPS per BPM, plus reference WPS

WPS Principle

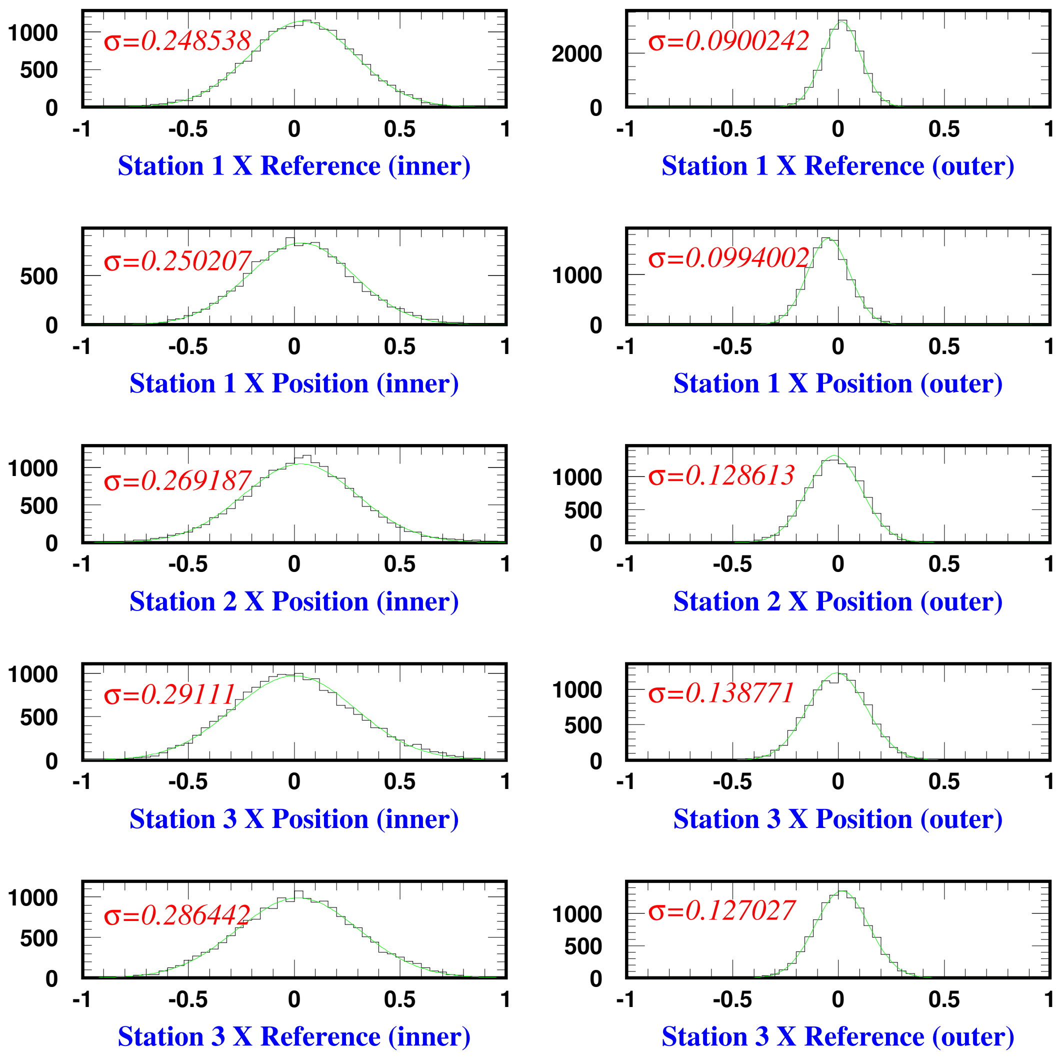




- Sensor head uses 4 planar electrodes
- Measure C between wire and each electrode

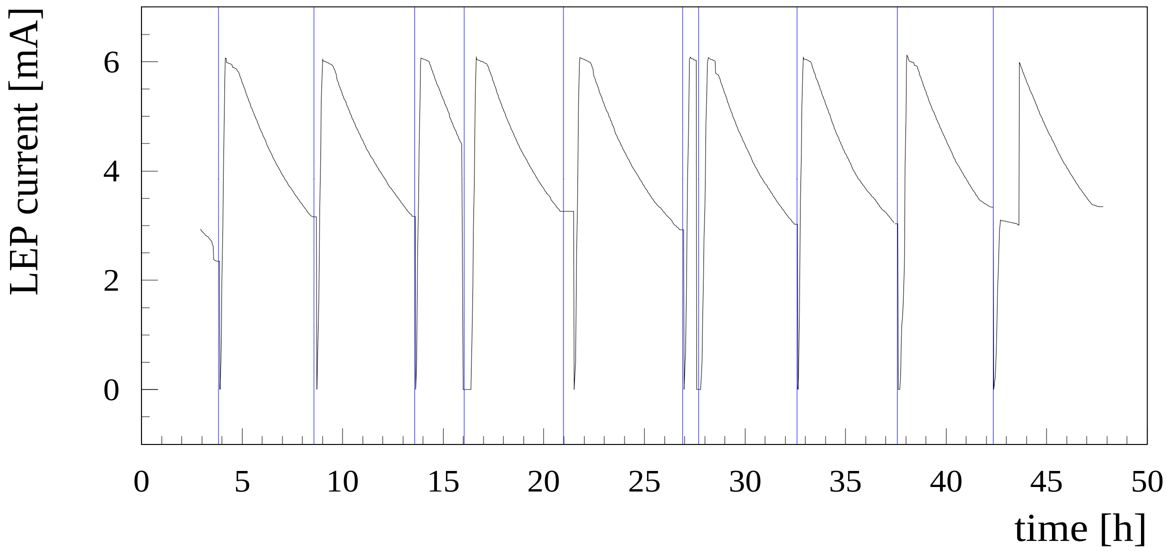
WPS Measurements

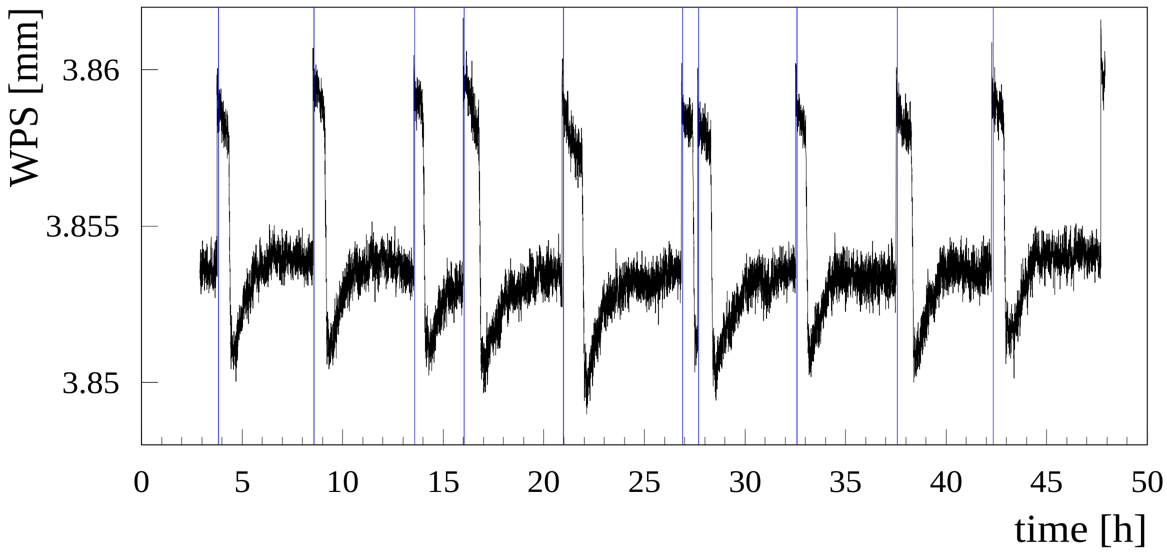
Wires - X Resolutions



- Test of WPS sensor intrinsic resolution
- Resolution $100nm \rightarrow 300nm$ - more than adequate

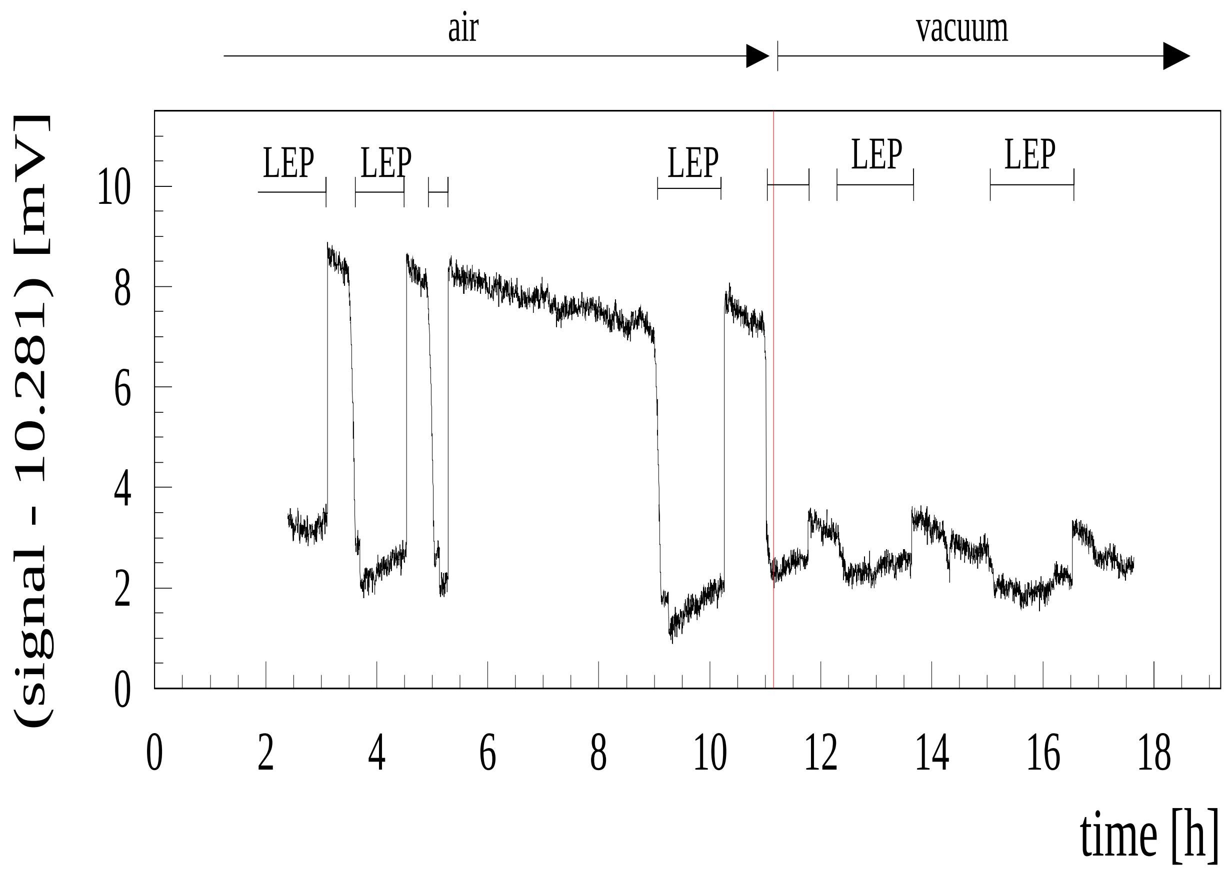
WPS Measurements





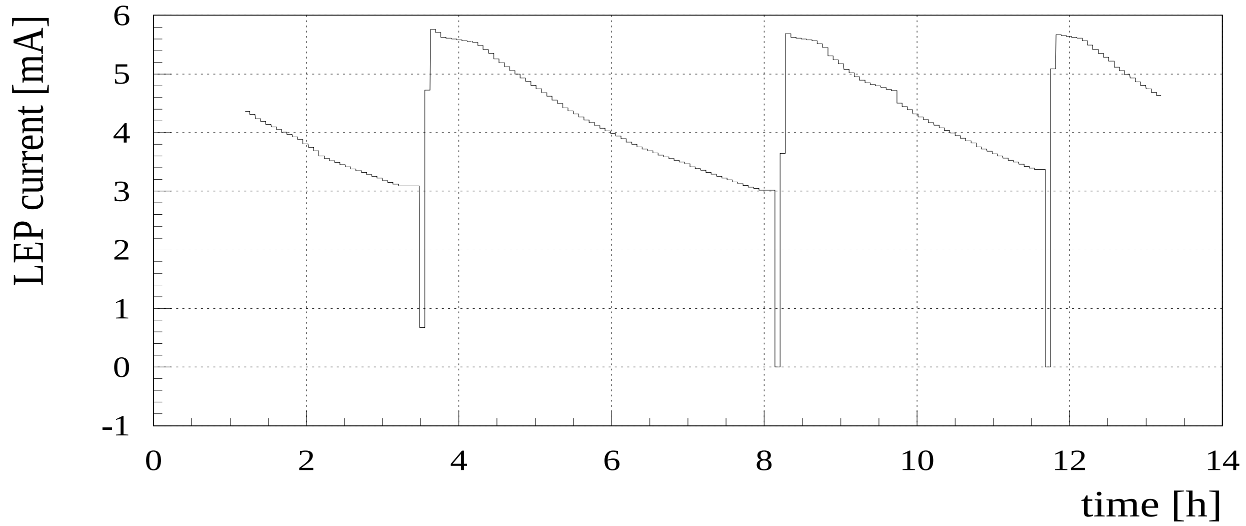
- **WPS shows excursions related to LEP fill structure**
- **Possibly caused by synchrotron radiation?**

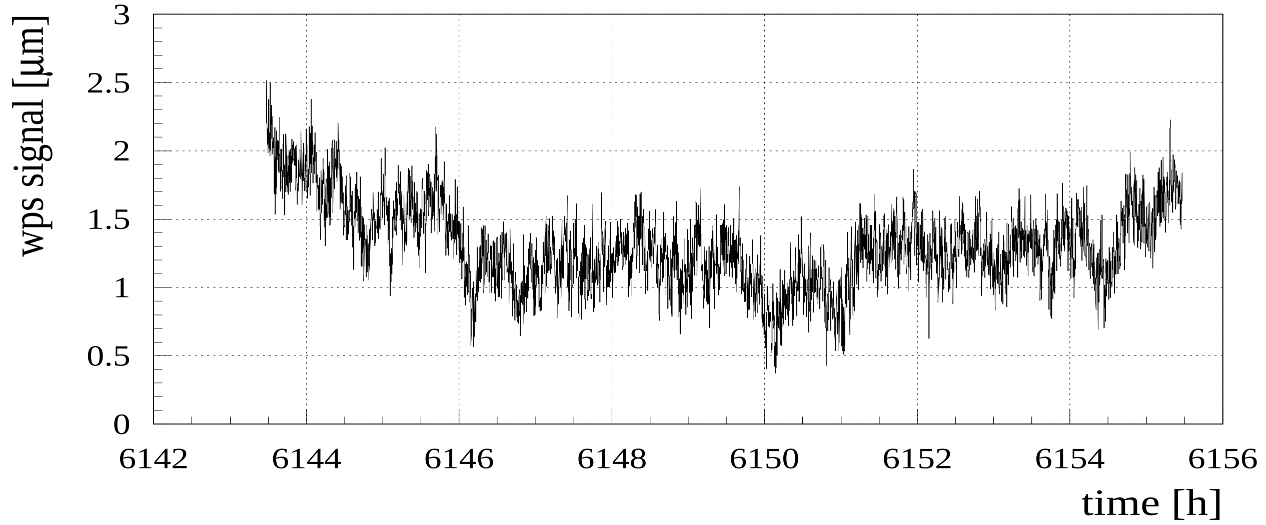
Capacitive Level Sensor



- Test with capacitive level sensor
- Sensor housing can be evacuated
- Jumps (almost) disappear *in vacuo*
- Implies jumps caused by air ionisation $\rightarrow \delta(\epsilon_R)$

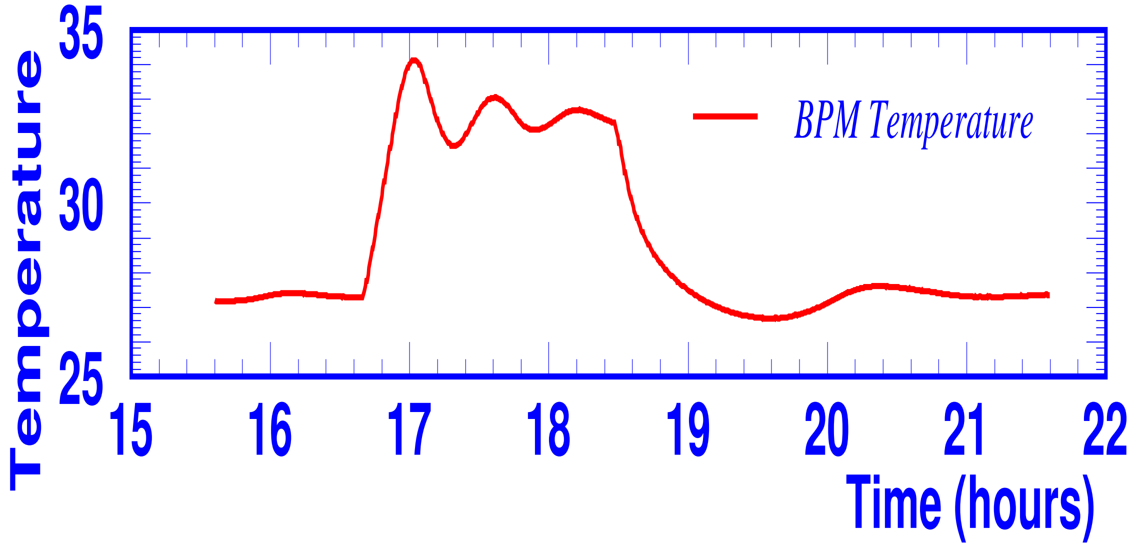
Shielding the WPS

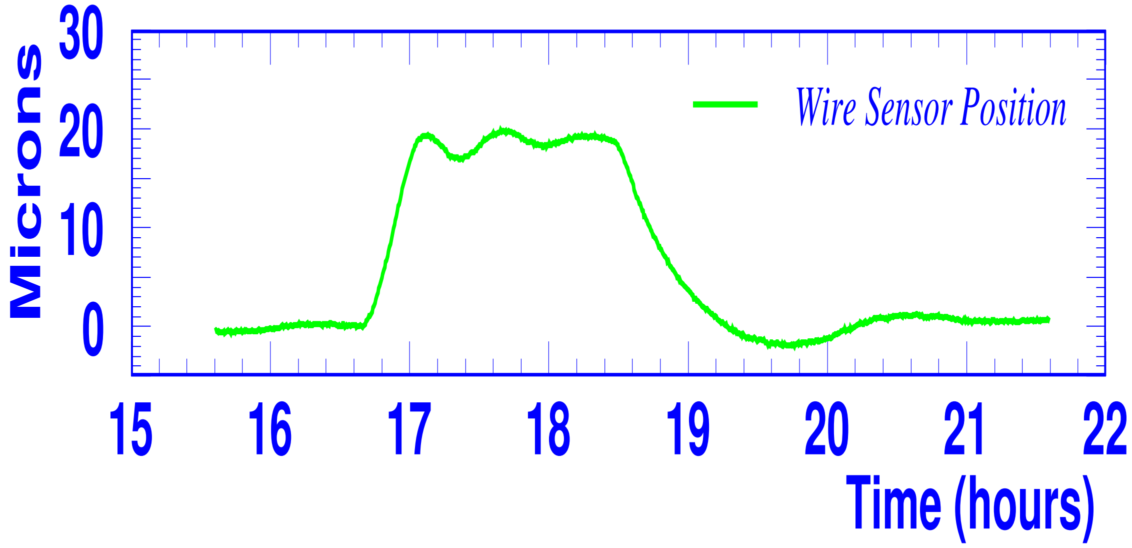




- Sensor surrounded by lead shielding
- Jumps effectively suppressed
- Now checking calibration with laser interferometer

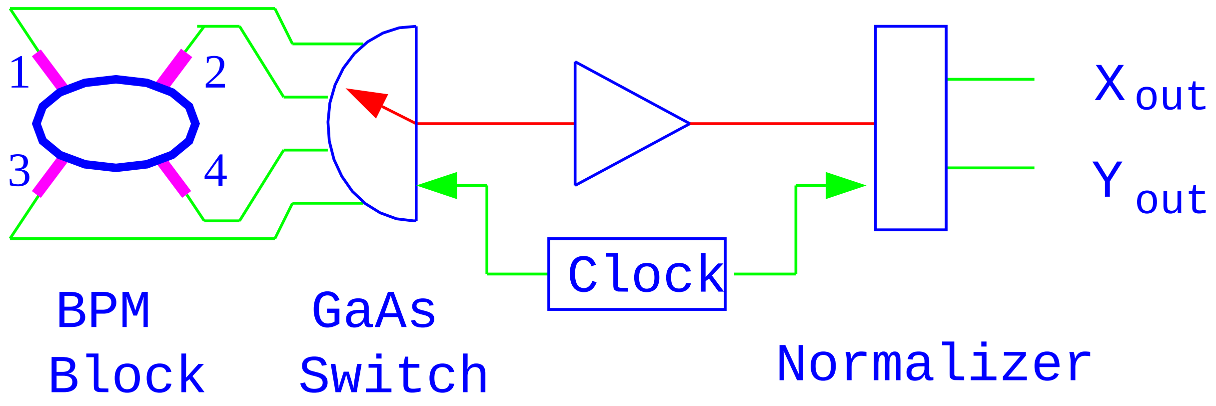
WPS Measurements





- WPS show clear correlation of movement with temperature
- Monitoring internal/external WPSs for same BPM gives expansion
- If the structure were solid Al block, expect $\sim 80\mu m/10°C$
- Observed expansion $\sim 70\mu m/10°C$

BPM Electronics

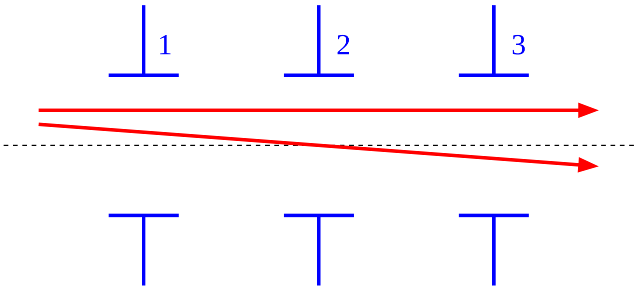


$$X_{out} = K_H \frac{(S2 - S3) - (S1 - S4)}{(S1 + S2 + S3 + S4)}$$

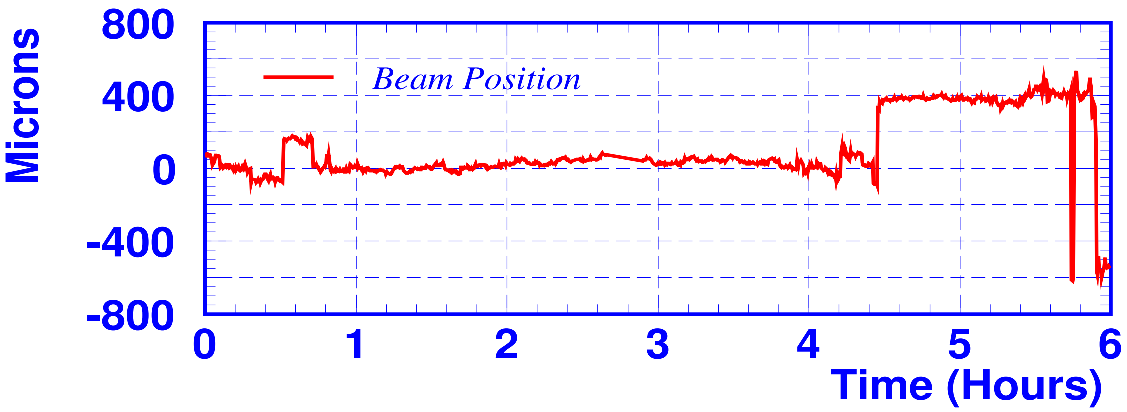
$$Y_{out} = K_V \frac{(S2 - S3) + (S1 - S4)}{(S1 + S2 + S3 + S4)}$$

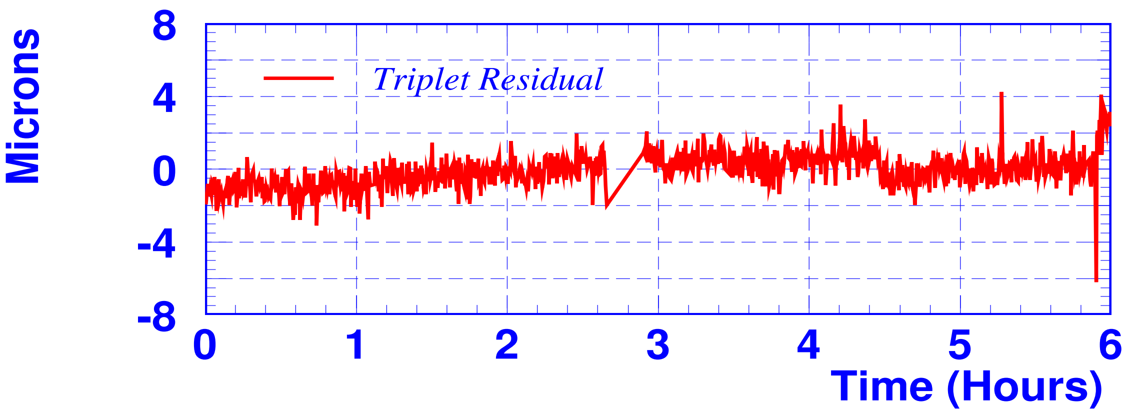
- **Common amplifier stage**
- **Custom modules produced for Spectrometer**
- **Based on synchrotron light source design, sub μm resolution**
- **Above expressions assume BPM is linear**

BPM Triplet Residual



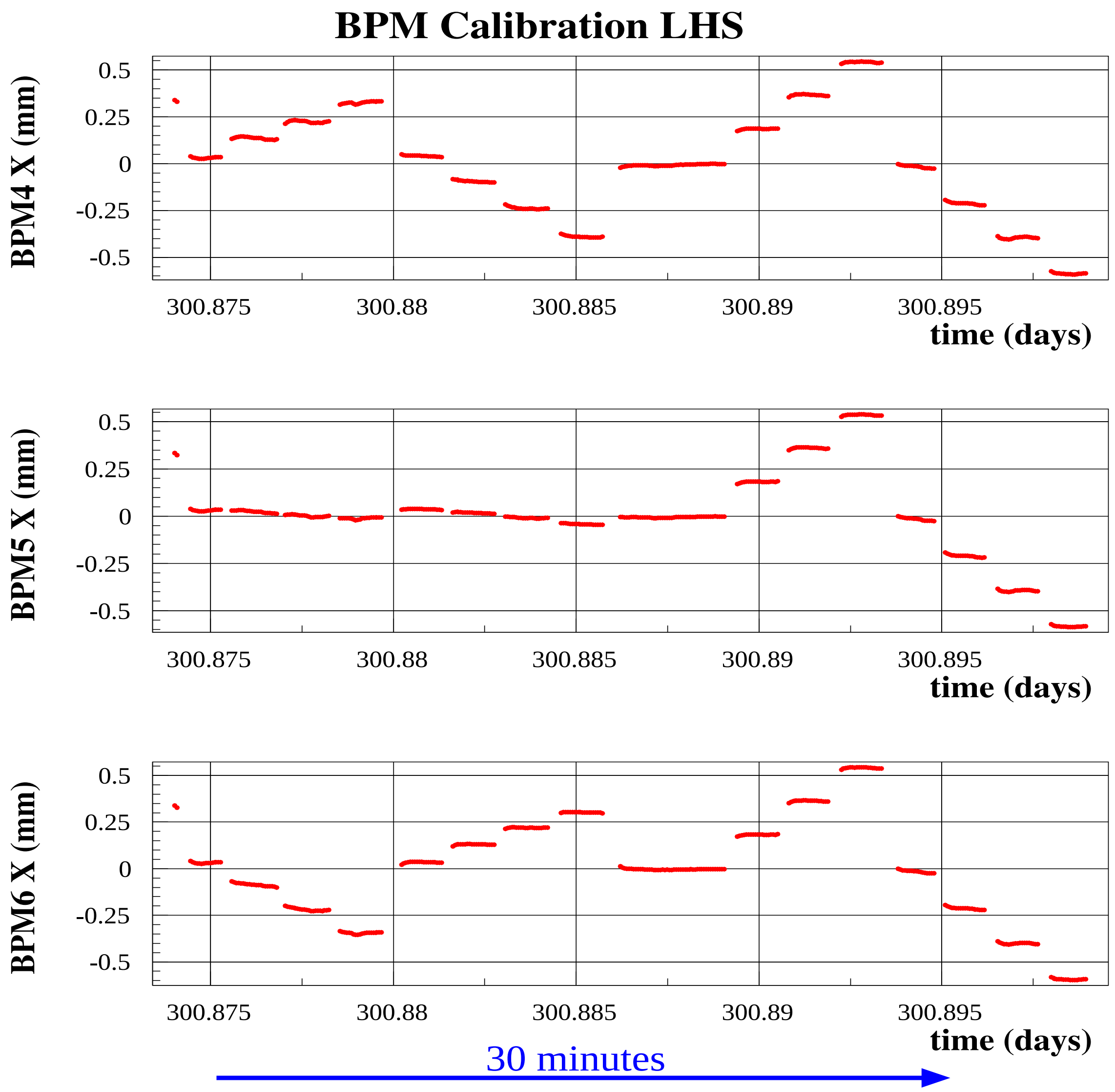
$$T = \frac{X1 + X3}{2} - X2$$





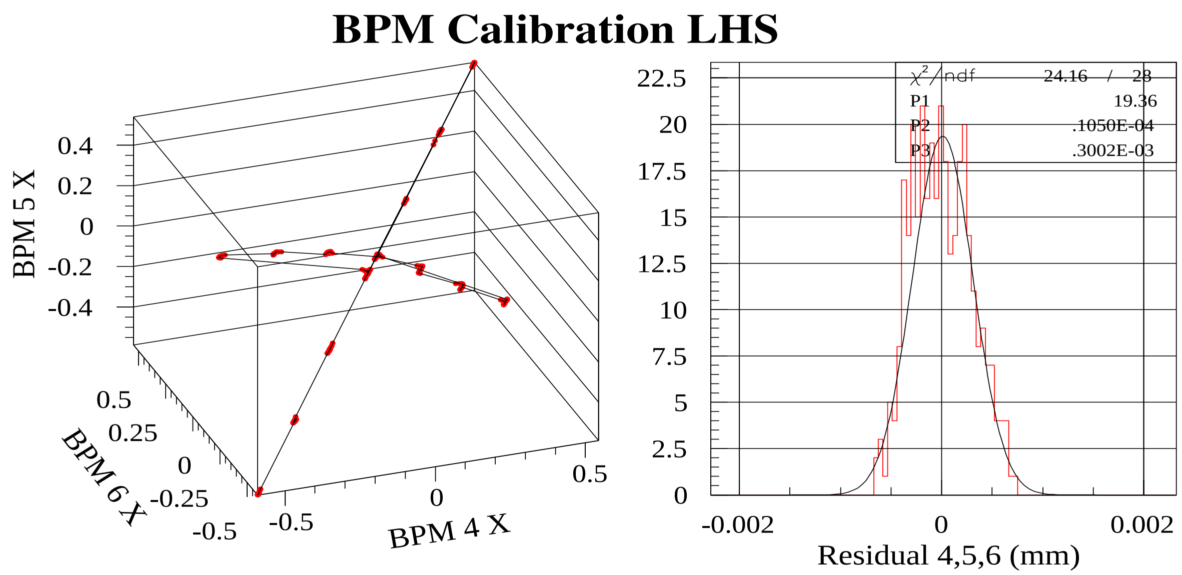
- BPMs in field-free region
- Triplet residual is a measure of BPM resolution
- Should be unaffected by parallel or angle changes

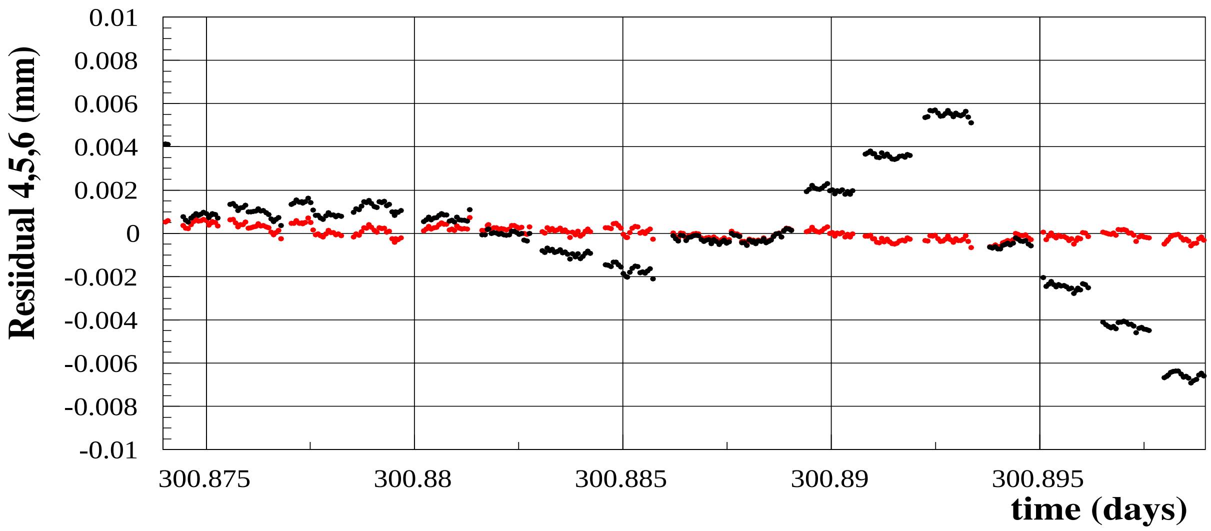
BPM Gain Calibration



- **Angle bumps centred on PU5** $X_4 = -X_6$, $X_5 = 0$
- **Parallel bumps** $X_4 = X_5 = X_6$
- **In 3D, defines the plane** $X_5 = \frac{X_4}{2} + \frac{X_6}{2}$

BPM Gain Calibration



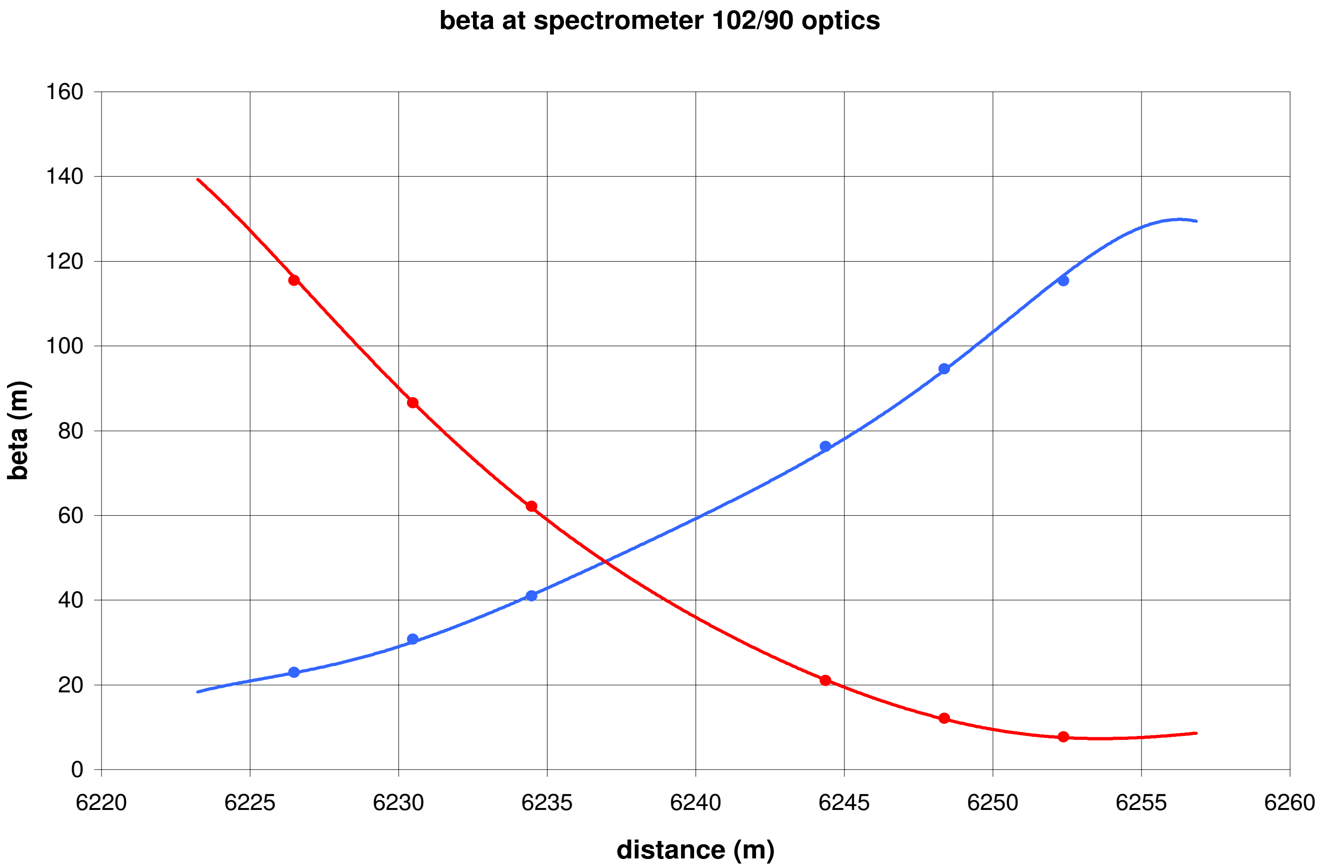


- Compare measured plane → relative gains
- Correct PU4 and PU6 to PU5
- $\sigma = 0.3\mu m$ for triplet residual after correction
- Reproducibility before/after ramp approaches 1/1000
- Only done for later fills

BPM Nonlinearities

- BPM response is nonlinear, depends on beam size
- For circular pipe and point electrodes (SL-99-799):

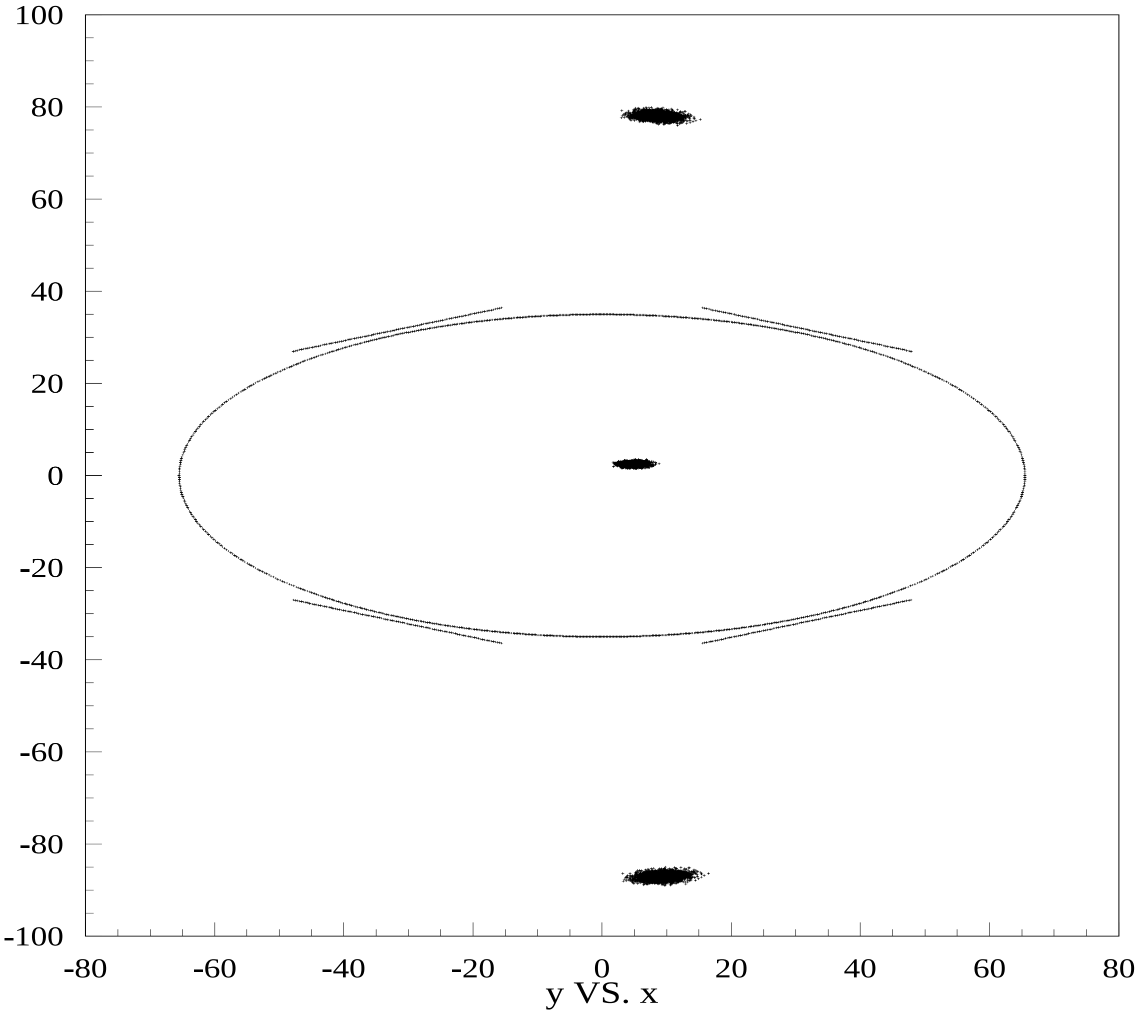
$$X_{bpm} \propto x \left\{ 1 - \left(3\frac{\sigma_x^2 - \sigma_y^2}{a^2} + \frac{x^2 - 3y^2}{a^2} \right) \right\} \quad Y_{bpm} \propto x \left\{ 1 + \left(3\frac{\sigma_x^2 - \sigma_y^2}{a^2} + \frac{3x^2 - y^2}{a^2} \right) \right\}$$



- Beam size changes along spectrometer $\sigma = \sqrt{\epsilon \beta(s)}$
- Can affect measured positions by $> 1\mu m$

Elliptical BPM Response

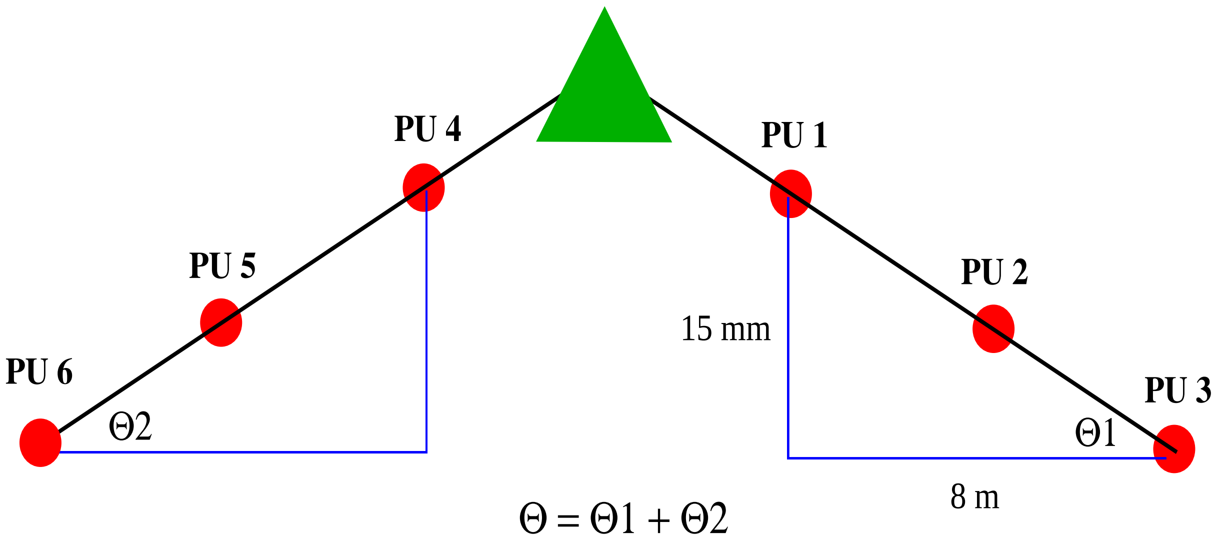
- Calculation of BPM response by image charge method
- Elliptical chamber, pencil beam - LEP Note 461 (1983)



- Add up field due to all the charges
- Realistic beam from Gaussian random numbers

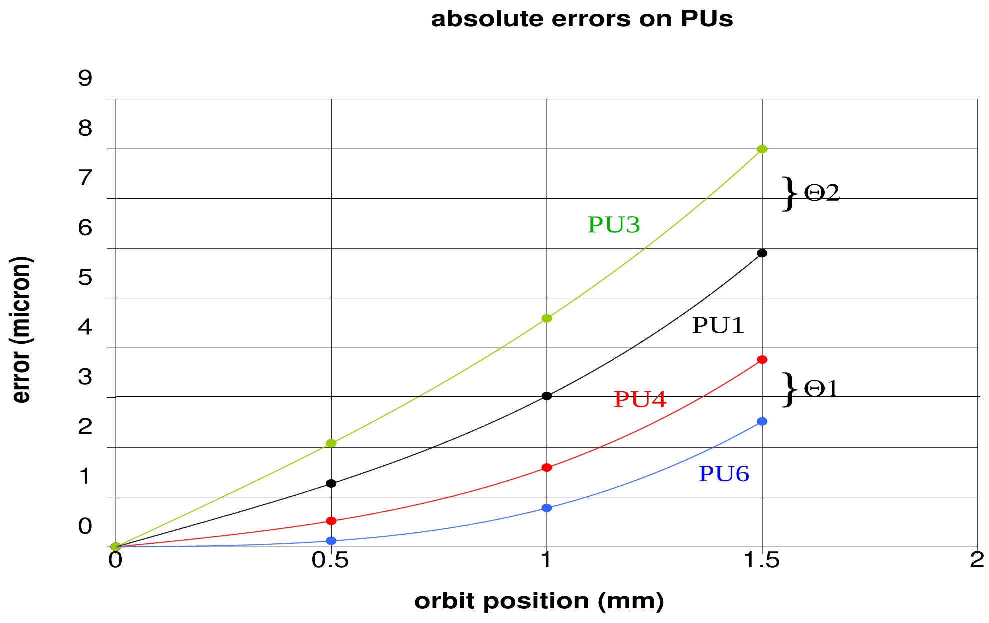
BPM Nonlinearities - Effect at Spectrometer

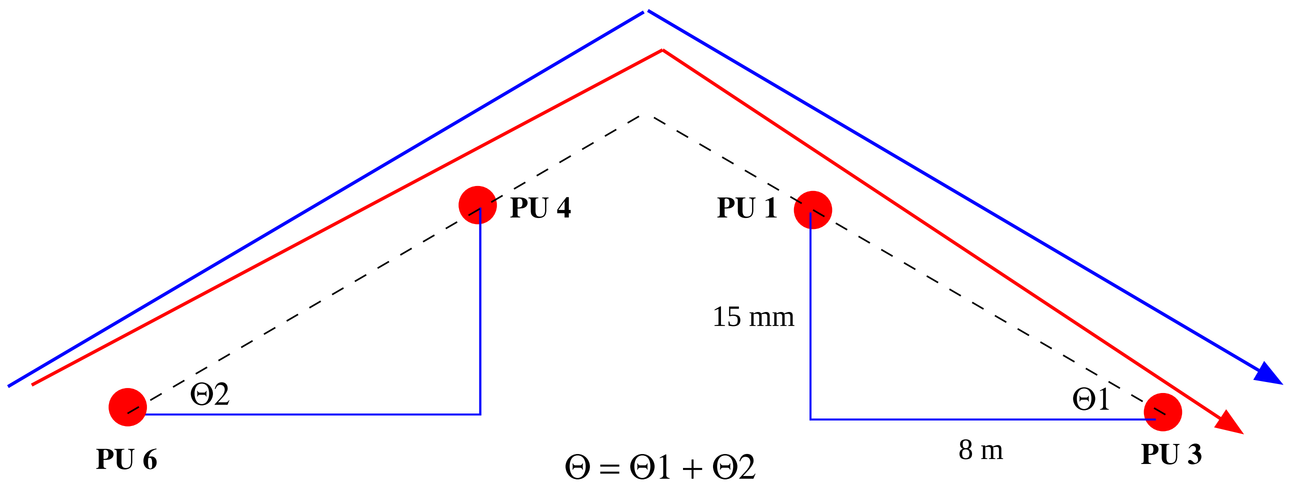
- 102/90 optics, ramping 45.6 - 94.5 GeV
- BPM alignment OK, beam at nominal angle
- BPM response calculated → spectrometer angle



- How does angle change as function of horizontal orbit?
- How accurate an orbit correction is needed?
- Effect of departure from nominal angle?
- Effect of BPM misalignment?

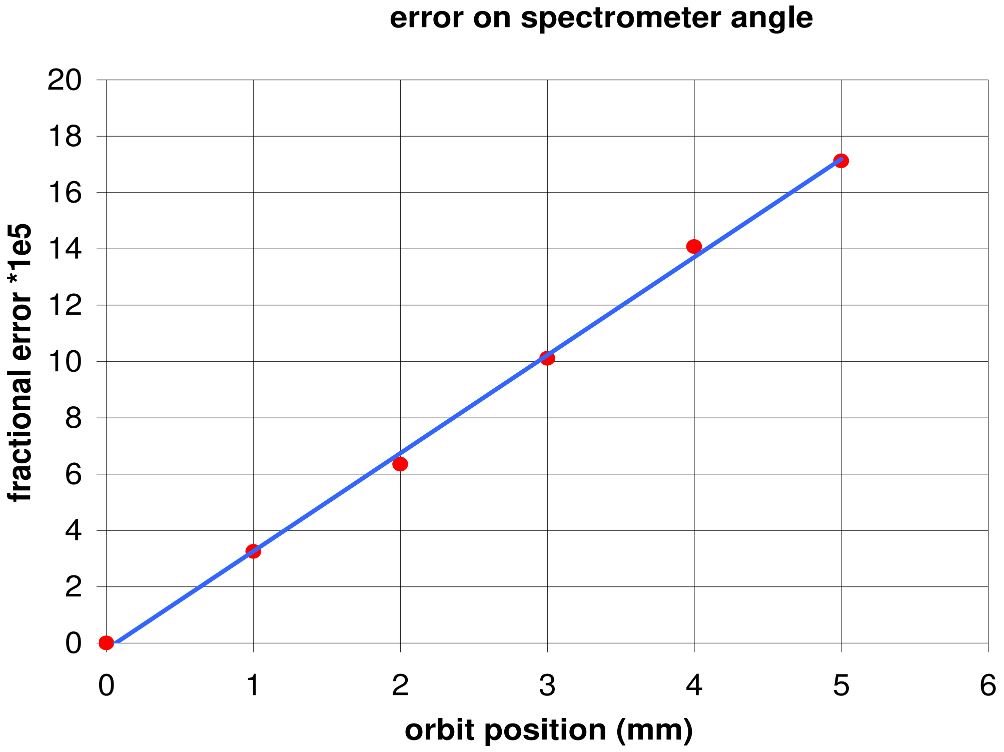
BPM Nonlinearities - Orbit Correction





- $1\mu m$ each on 4 BPMs $\rightarrow 1.2 \times 10^{-4}$
- beam size effect nearly linear with distance
- overall effect looks like rotation

BPM Nonlinearities - Orbit Correction



- effect on angle small if orbit correction to $\sim 1mm$
- control angular deviation to $\sim 25\mu rad$
- control relative BPM offsets to $\sim 250\mu m$

Measurement with the Spectrometer

beam E from depolarisation

centre beam in spectrometer
BPM gain calibration

determine angle at spectrometer
RF model: pol E => spectro E

ramp

centre beam in spectrometer
BPM gain calibration

determine angle at spectrometer
RF model: spectro E => mean E

- **NMR probes track beam energy between polarisation calibration and final angle determination**

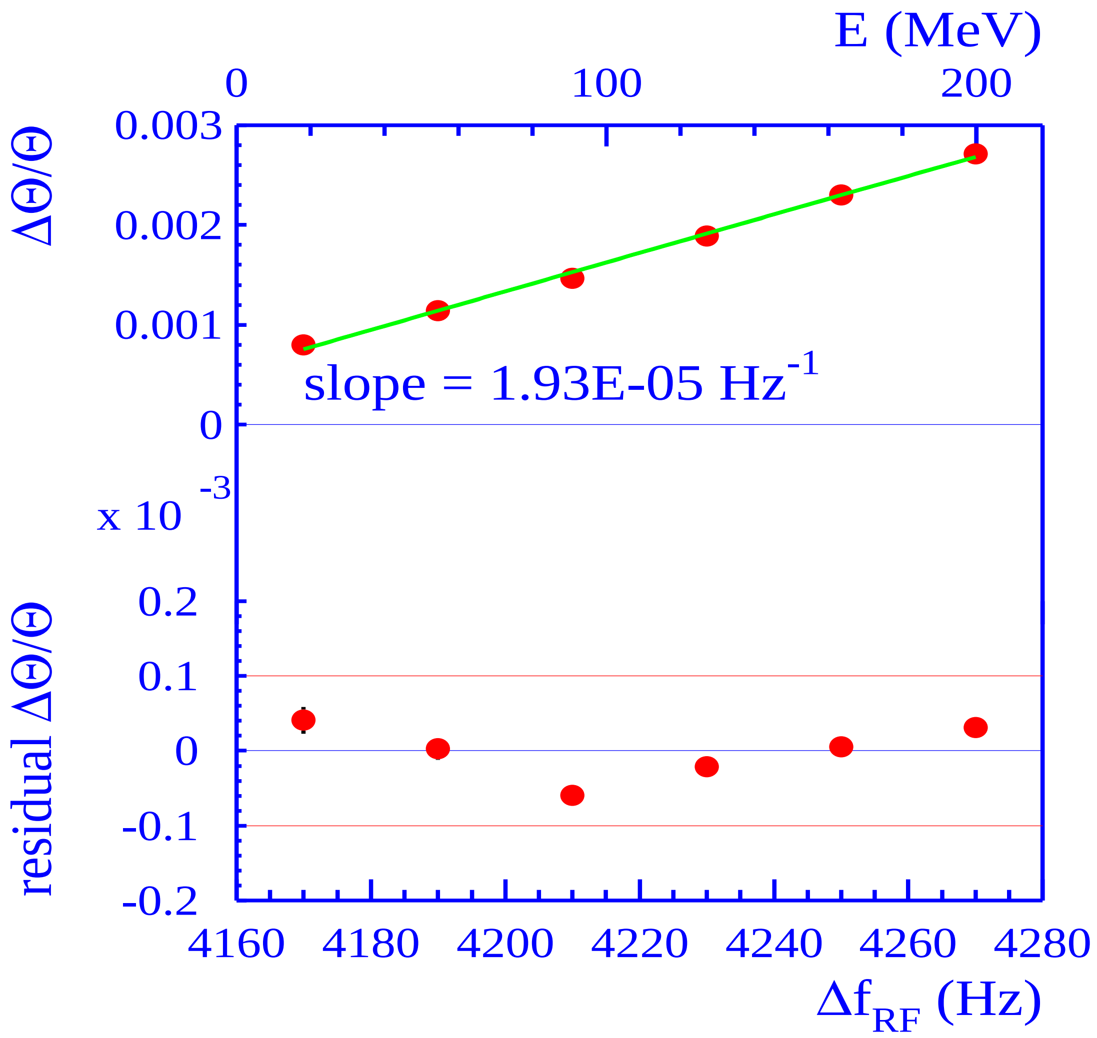
Data taken with Spectrometer

- much data since August, most taken during cryo de-icing
- analysis is still underway

date	fill	calibrated E	high E
09/09/99	6302	41 45 50 55	
20/09/99	6371	41 45 50	
25/09/99	6397	45 50	70 92
27/09/99	6404	41 45 50 55	
29/09/99	6432	45 50	90
10/10/99	6509	41 50 60	92
27/10/99	6627	45	92

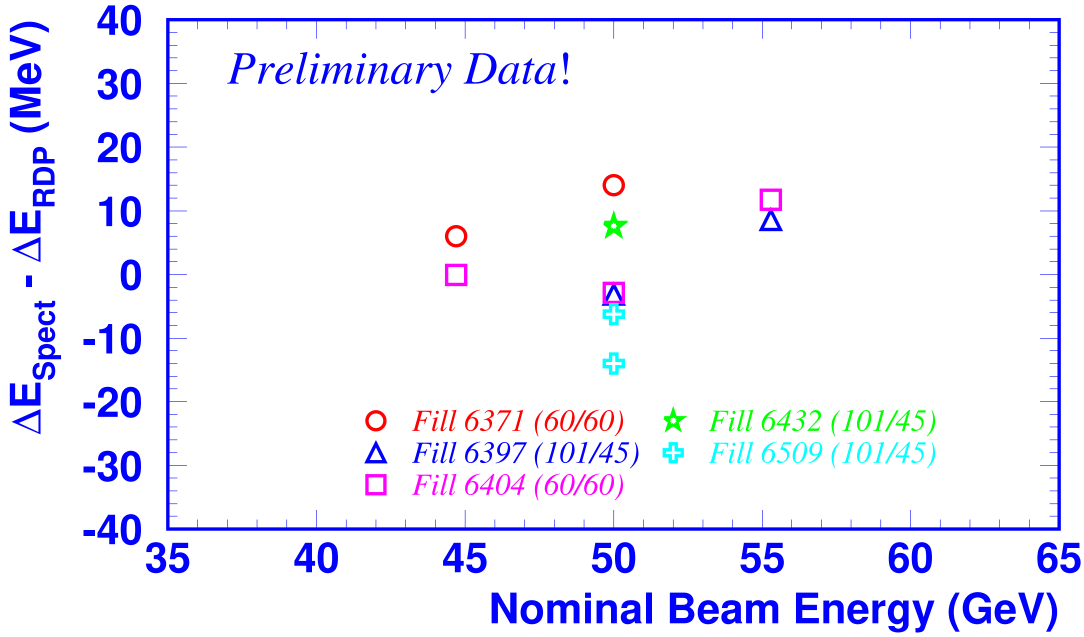
- look at RF changes as cross-check
- compare polarisation/spectrometer as cross-check
- look at ramps to physics energy

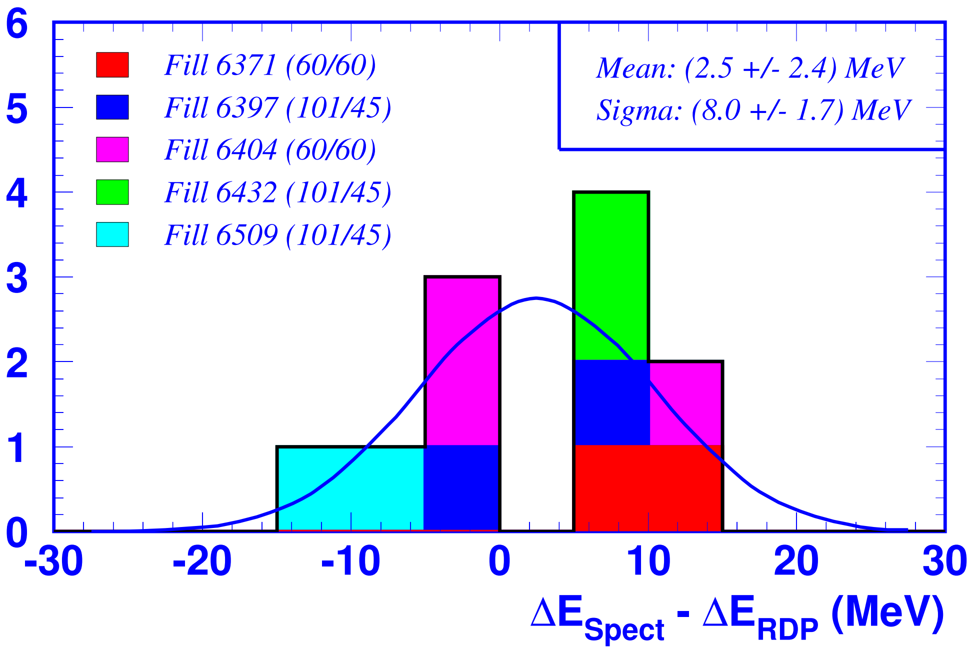
Proof of Principle



- RF frequency changes, no orbit correction
- Bending angle variation is linear with energy change
- Residual variation smaller than $1 \cdot 10^{-4}$
- Slope depends on absolute BPM calibration, to be done

Data Analysis - Pol. Energies





- Shows energy change over each ramp
- What are the errors on the measurement?

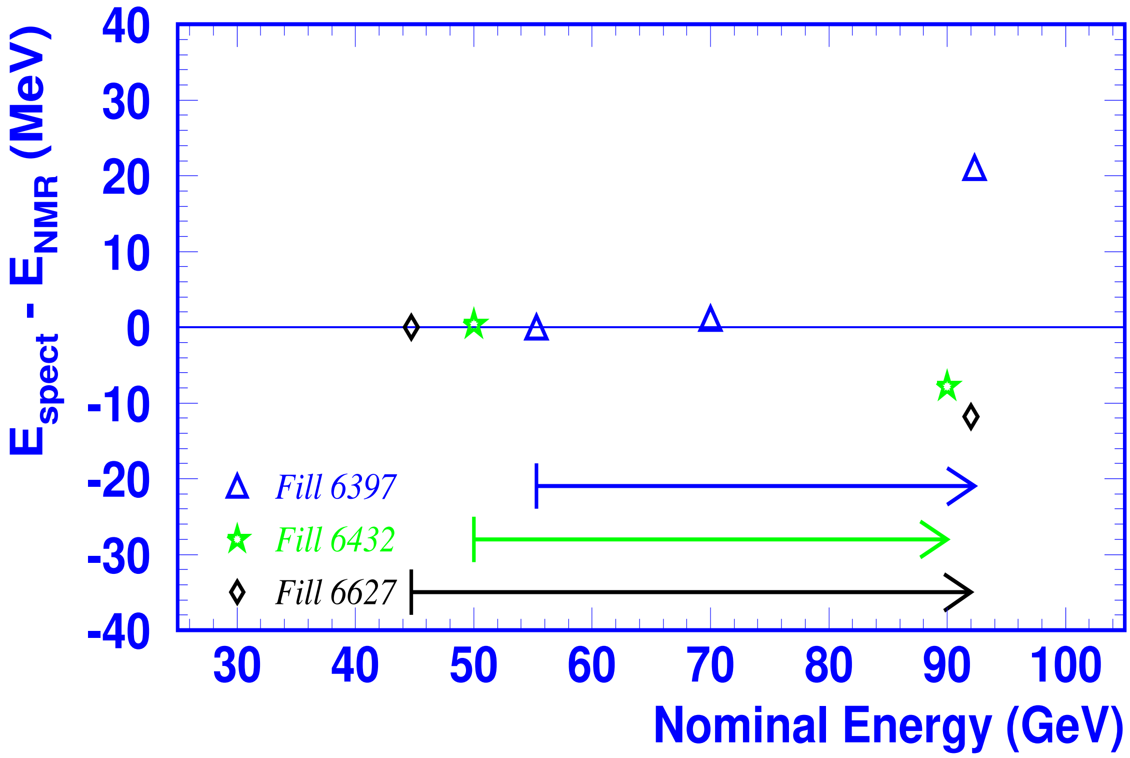
Error Analysis (preliminary)

- **What errors do we expect (in MeV)?**
- **Assume $0.7\mu m$ correlated error on the BPMs**
- **Assume $1.4\mu m$ uncorrelated error on the BPMs**

	50 GeV	100 GeV
mapping	1.5	3.0
RDP	2.0	3.0
RF model	3.0	5.5
θ_1/θ_2	6.5	13.0
total	7.6	14.7

- **At 50 GeV, compare $7.6MeV$ with 8.0 ± 1.7 measured**

Data Analysis - Physics Energies



- energy referred to last polarisable point of fill
- At 100 GeV, compare $14.7 MeV$ with $14.8 \pm 8 MeV$ measured
- can compare spectro. with NMRs: $E_{spect} - E_{NMR} = 0.3 \pm 11 MeV$
- spectrometer and flux loop energies agree $\sim 20 MeV$
- no systematic effects seen between total field and local energy measurements

Future Work

- need more high energy data
- need better understanding of errors
- run with 2 beams
- for some fills, angle change too big
- keep angle, f_{RF} constant, orbit deviations small
- absolute BPM calibration
- BPM mapping with antenna
- check BPM alignment
- improve WPS shielding
- re-map magnet after end of LEP

Summary and Conclusions

- Integral magnetic field accuracy OK
- Resolution of WPS, BPMs better than 1μm
- Beam-based calibration of BPMs to 1/1000
- Must minimise effect of BPM nonlinearities
- Preliminary energy measurements encouraging, consistent with NMRs
- Data analysis continuing