History & perspective of IMMW's

And a bit of "La Mola" summary

Alec Harvey LANL
MMW1 & MMW2

Branko Berkes SIN (PSI)
MMW3 & MMW4

MMW1 1981 (30 years ago)
In Los Alamos

No documents left
As well for
MMW5 BNL
IMMW6 LBL

History – the early times

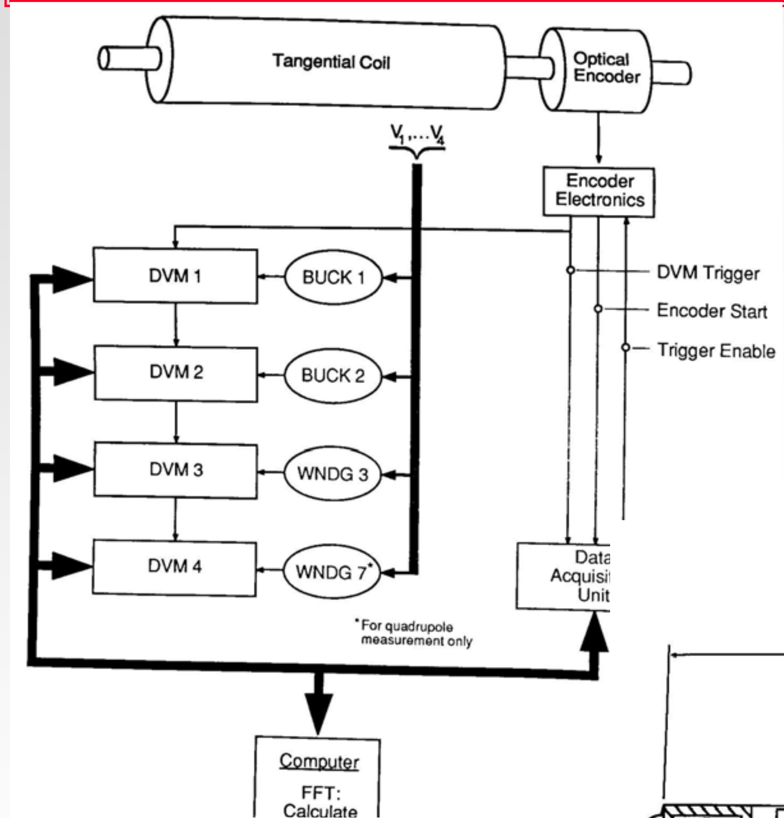
MMW-1	Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, February 1981	[6 p.]
MMW-2	Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, May 1982	[12 p.]
MMW-3	Swiss Institute for Nuclear Research (SIN now PSI), Villigen, Switzerland, September 1983	[25 p.]
MMW-4	Swiss Institute for Nuclear Research (SIN now PSI), Villigen, Switzerland, September 1985	[34 p.]
MMW-5	Brookhaven National Laboratory (BNL) , Brookhaven, New York, September 1987	[63 p.]
IMMW-6	Lawrence Berkeley Laboratory (LBL) , Berkeley, California, September 1989	

- Informal discussions
- No documents archived

  Apart from Knud Henrichsen Web site

? Prehistory ? – the early times

The BNL Mole @ IMMW1987 (?)
(from SSC Task Force report)



2 controversies

- **Analog vs. digital bucking**
- **DVM vs. Integrators (disappeared)**

SSC FIELD MEASURING PROBE

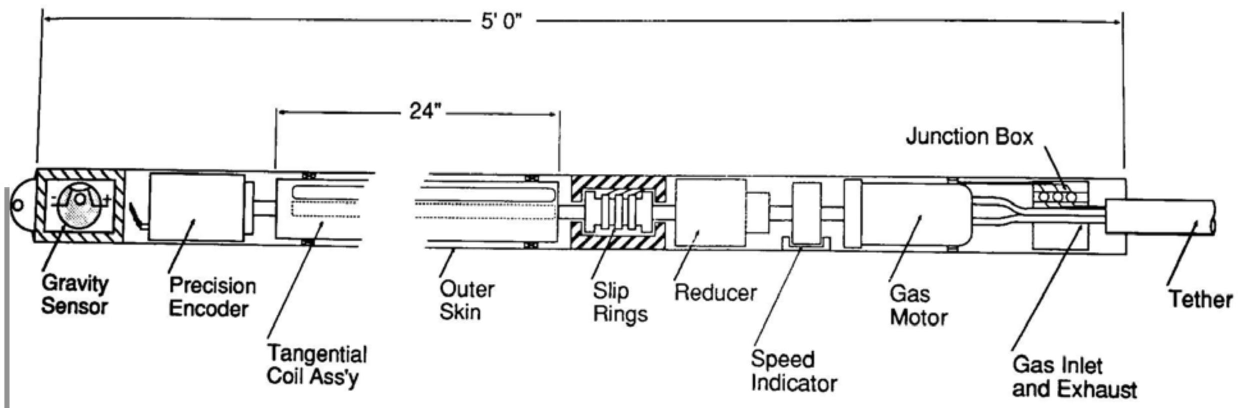


Fig. 12 The BNL mole.

The dream (or absolute necessity) of a fully flexible mole is still there [FNAL, CERN]

? Prehistory ? – the early times

MMW-1 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, February 1981

MMW-2 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, May 1982

MMW-3 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1983

MMW-4 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1985 (2 pictures)

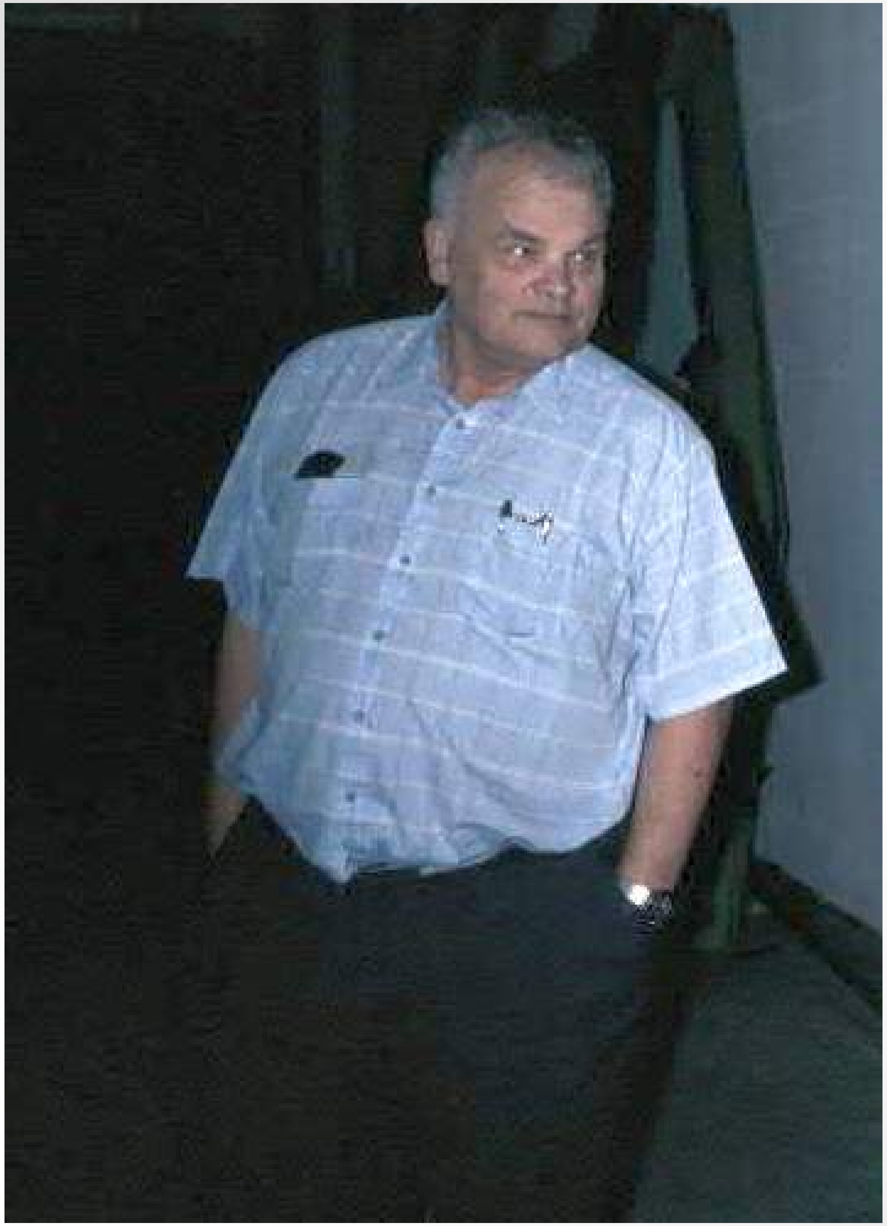
MMW-5 Brookhaven National Laboratory (BNL) ,
Brookhaven, New York, September 1987

IMMW-6 Lawrence Berkeley Laboratory (LBL) ,
Berkeley, California, September 1989

History starts

IMMW-7 Gesellschaft für Schwerionenforschung (GSI) ,
Darmstadt, Germany, June 1991

IMMW-7 (GSI) , Darmstadt, June 1991



Simple Measurement of Subharmonics in
High Order Multipoles

K. Halbach
LBL

Magn. Measurement Workshop, GSI, 1991

- Motivation: Characterization of high order multipoles will become increasingly important with more frequent use of high quality sextu- and octu-poles. (Regular + modified)
- Principle of measurement is best explained by going through practical example of ideal octupole + small perturbation:
- Assume one pole is radially displaced by $\varepsilon = \Delta r / r_{ap} \ll 1$.

  From perturbation effect tables, with
  $Z = (x+iy)/r_{ap} = z/r_{ap}$; $B_0 = |\text{octupole field}|$ at $|z| = r_{ap}$

IMMW-7 (GSI) , Darmstadt, June 1991

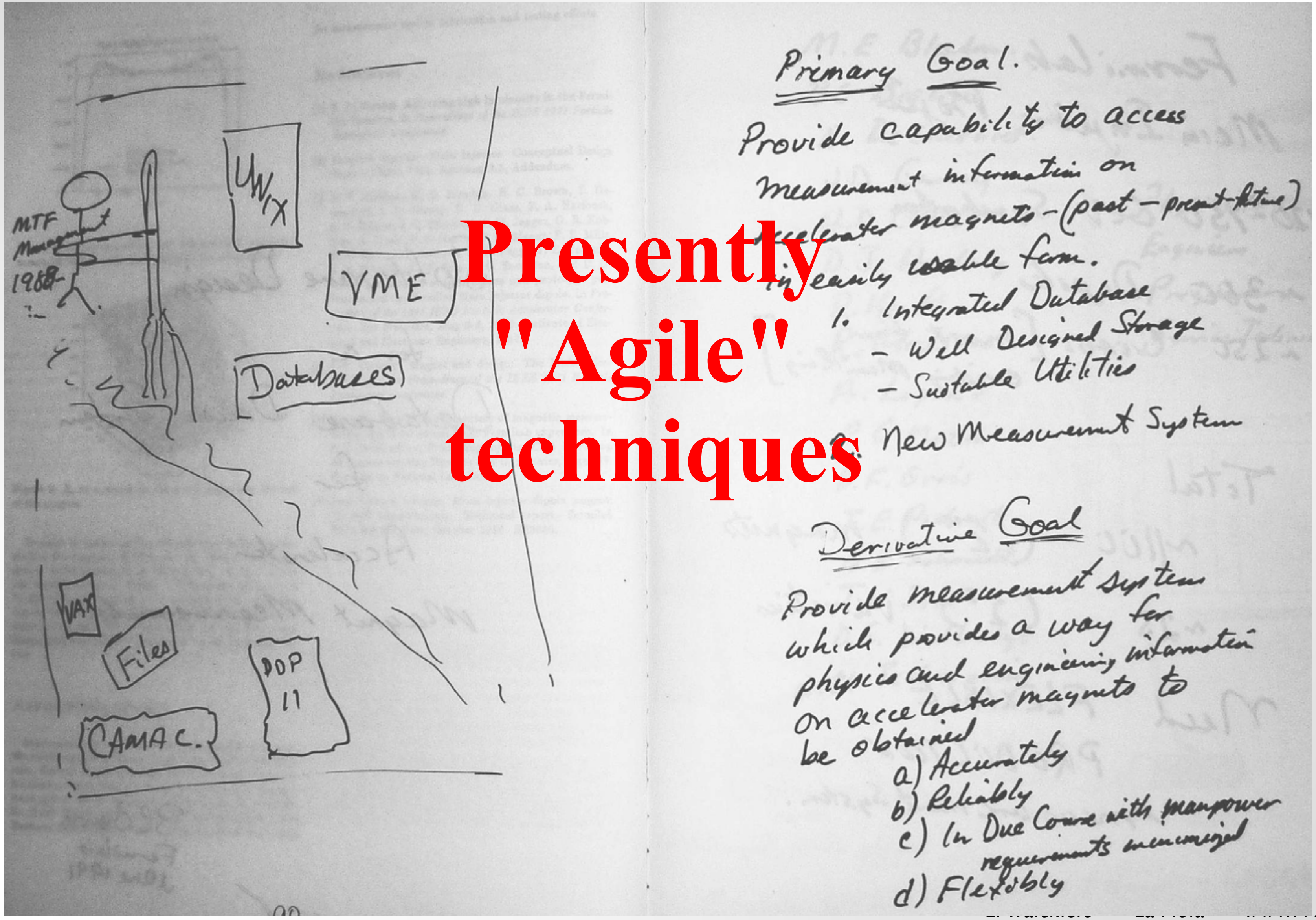
K. Halbach :

- Poisson 2D, then 3D
- Fish then Superfish
- The Halbach type permanent magnets
- 1st publication on "bucking coils" [1979]

Mechanical imprecisions matter

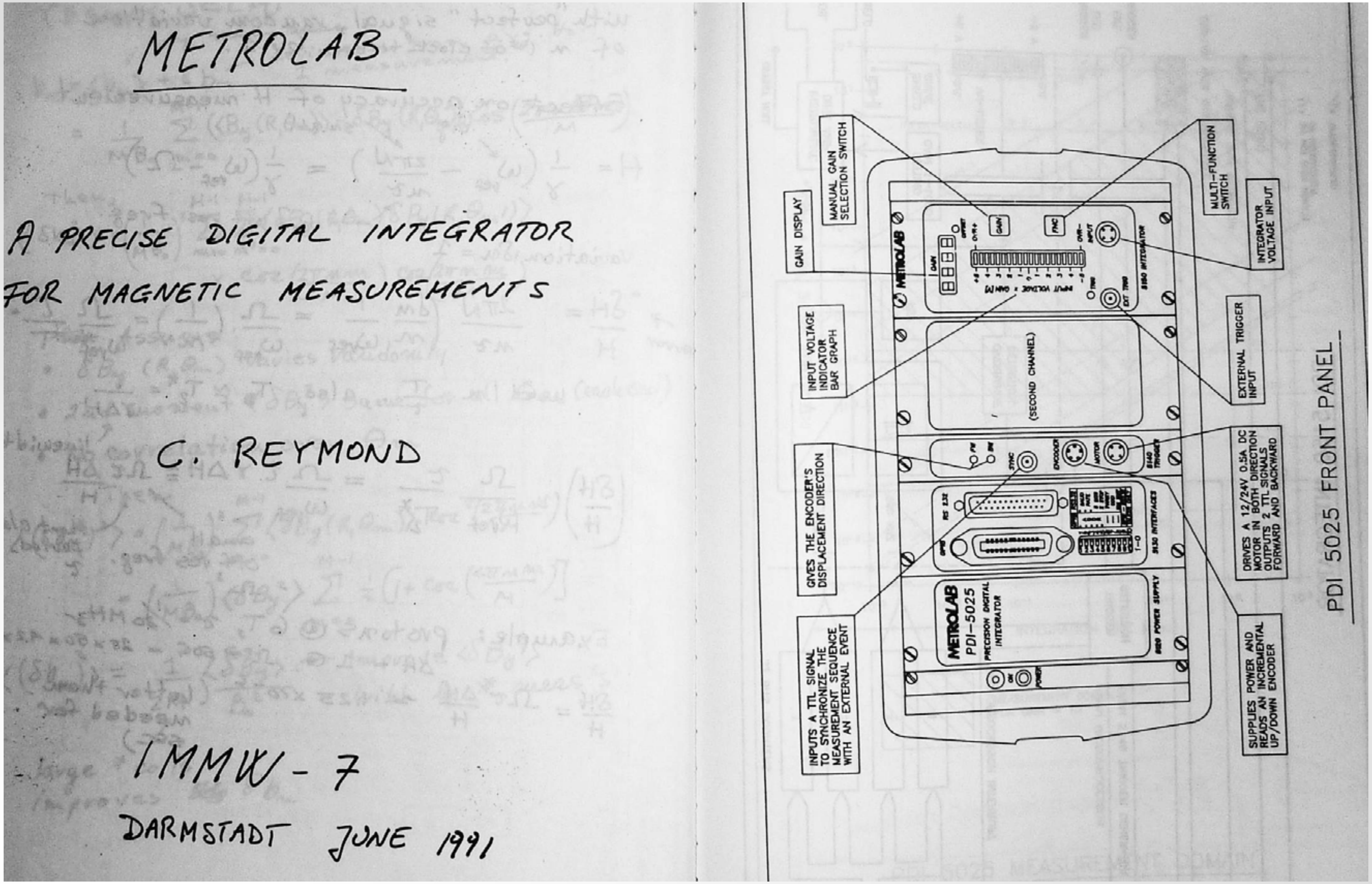
- Computers were used for calculations (FFT)
- Hand-written slides (so no easy proceedings)

Documenting Software diagrams

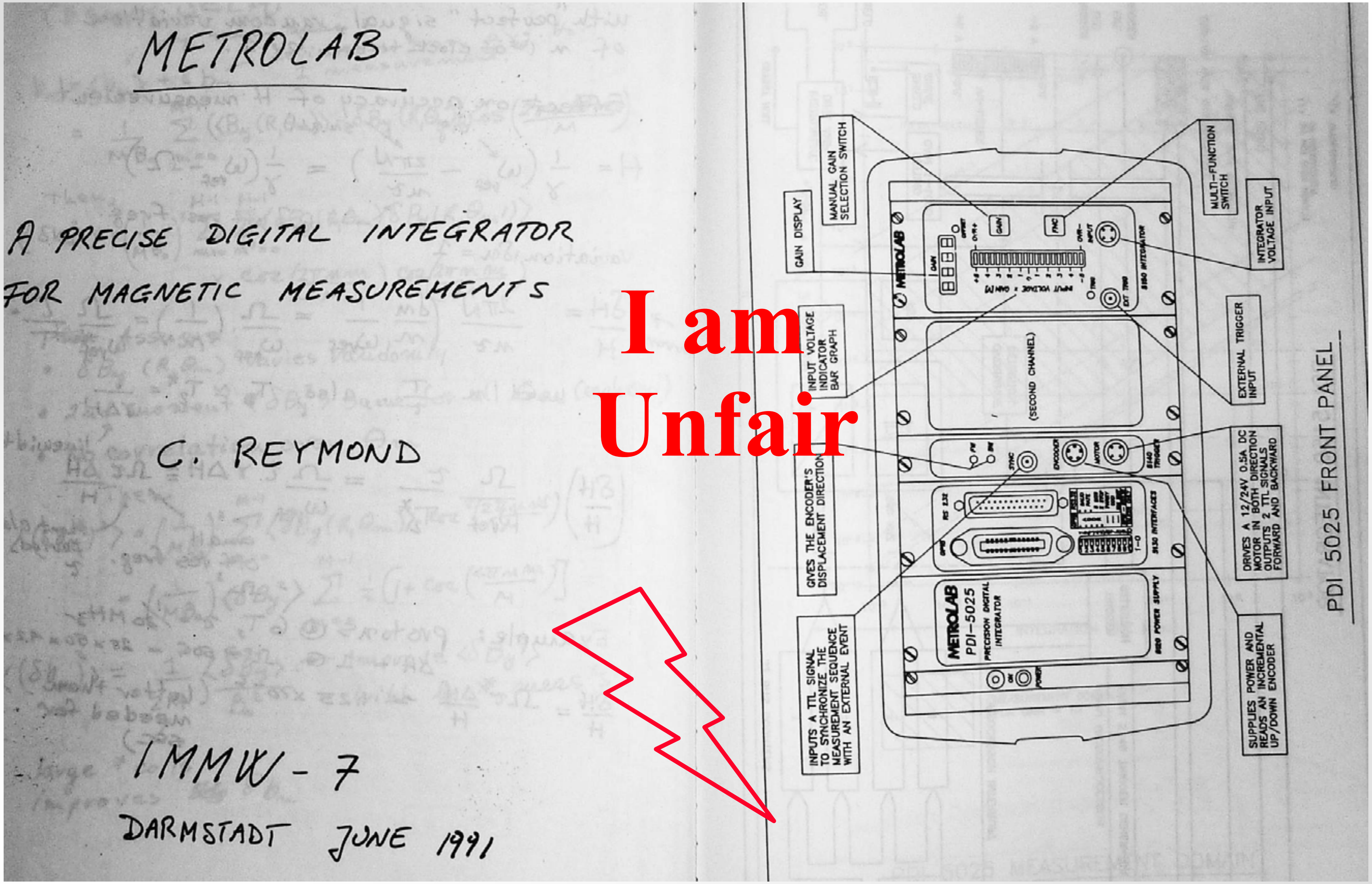


Presently "Agile" techniques

And Even ??


METROLAB
A PRECISE DIGITAL INTEGRATOR
FOR MAGNETIC MEASUREMENTS
C. REYMOND
IMMW - 7
DARMSTADT JUNE 1991
GAIN DISPLAY
MANUAL GAIN SELECTION SWITCH
MULTI-FUNCTION SWITCH
INTEGRATOR VOLTAGE INPUT
INPUT VOLTAGE INDICATOR BAR GRAPH
EXTERNAL TRIGGER INPUT
GIVES THE ENCODER'S DISPLACEMENT DIRECTION
DRIVES A 12/24V 0.5A DC MOTOR IN BOTH DIRECTION OUTPUTS 2 TTL SIGNALS FORWARD AND BACKWARD
INPUTS A TTL SIGNAL TO SYNCHRONIZE THE MEASUREMENT SEQUENCE WITH AN EXTERNAL EVENT
SUPPLIES POWER AND READS AN INCREMENTAL UP/DOWN ENCODER
METROLAB PDI-5025 PRECISION DIGITAL INTEGRATOR
PDI 5025 FRONT PANEL

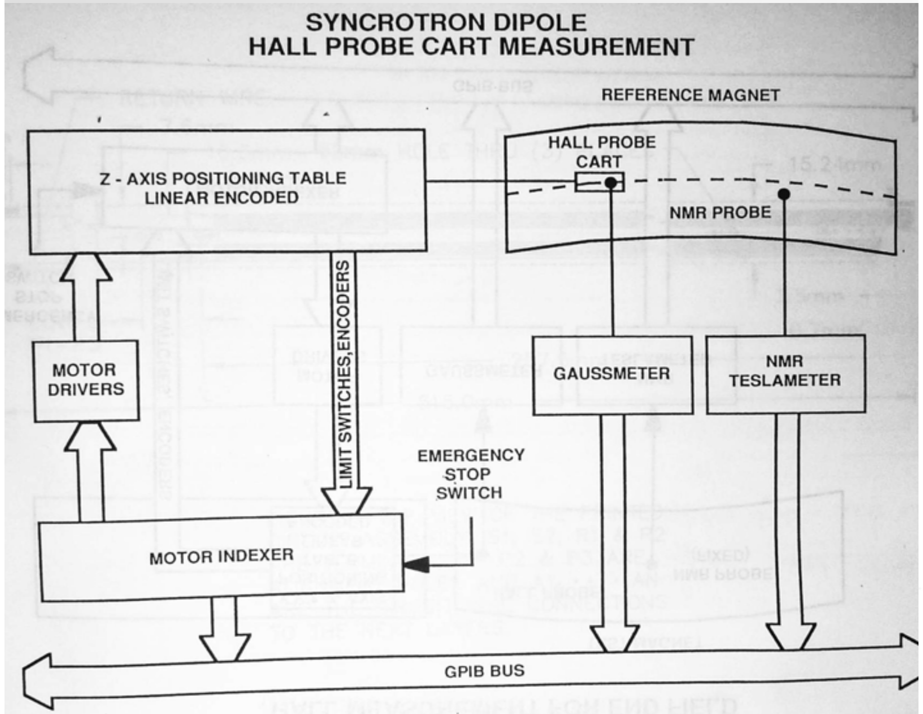
And Even ??

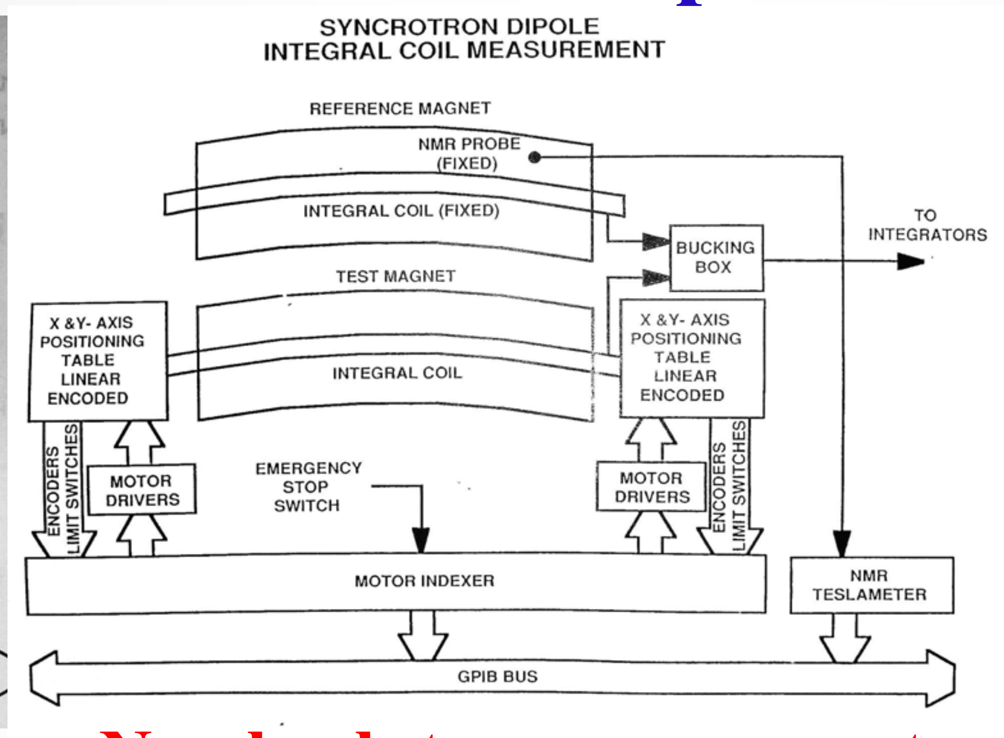


I am Unfair

Issues : Absolute Calibration, Curved magnets

Saclay Industrial Bench for ESRF Dipoles





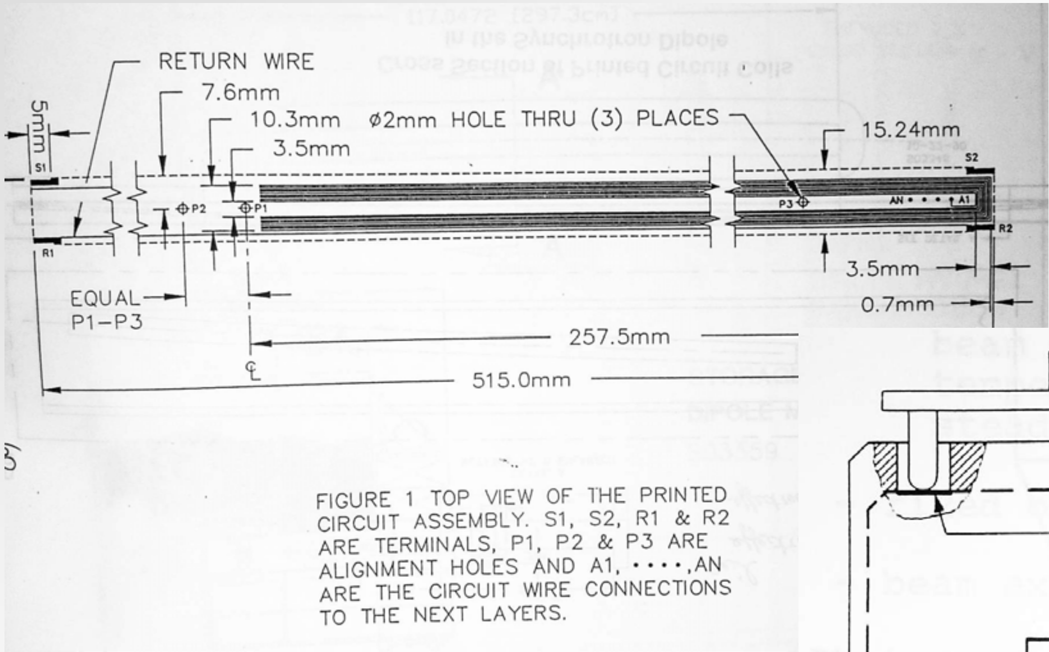
Tedious 3D scanning **No absolute measurement**

(SPS dipoles still measured against a reference dipole)

No description for curved magnets

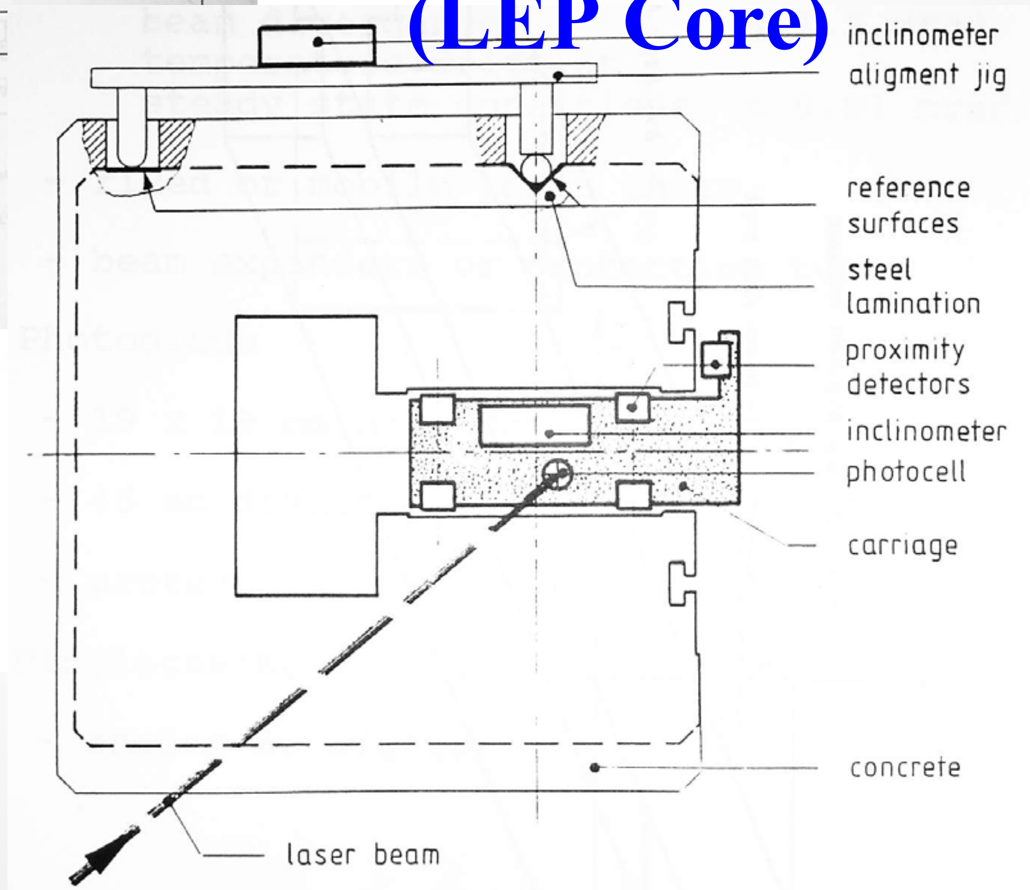
IMMW (18 , 19, …)

The 1980's: Ideas were there



Printed Circuit Coils (Argonne)

Measuring Yoke gap without conductor (LEP Core)



GSI 1991 : More on Collaboration with Industry

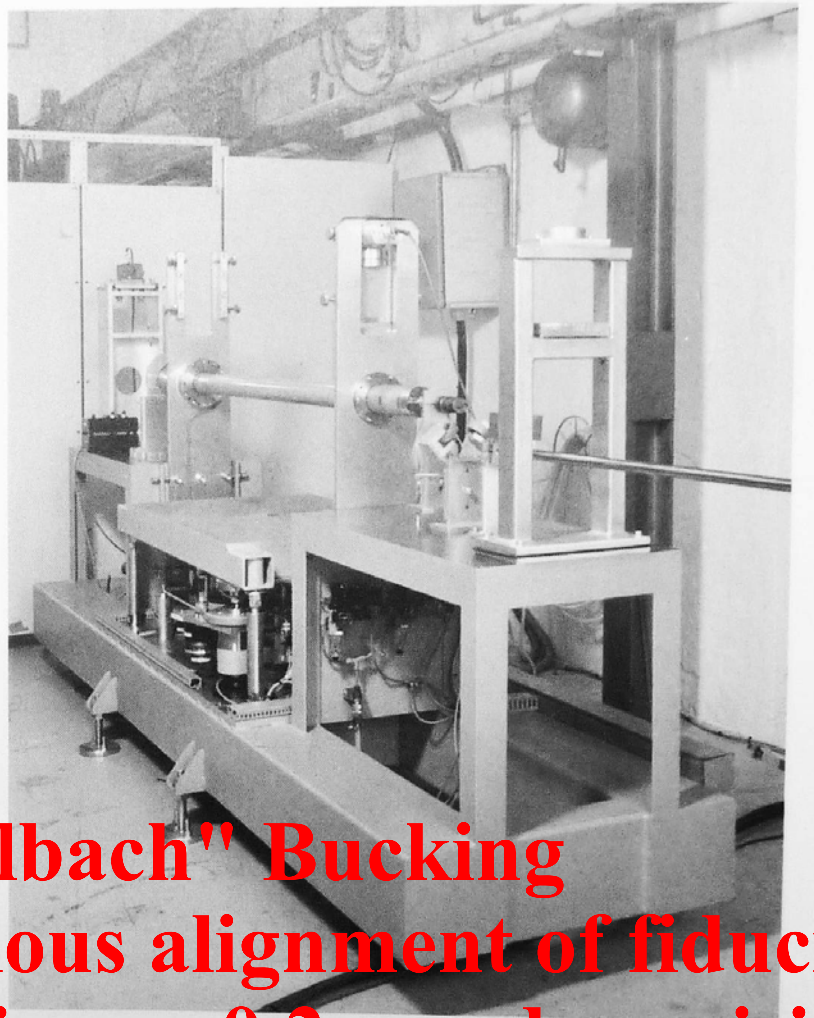
MULTIPOLE MAGNET MEASUREMENT SYSTEM TO ESRF, GRENOBLE, FRANCE

The first two multipole magnet measurement systems manufactured by Danfysik have now been delivered to ESRF, Grenoble. The design is based on a CERN system developed during the construction of LEP.

The measurement system is designed for semi automatic testing of multipole magnets with a computer controlled alignment and data logging system; a coupled laser device defines the final positioning of targets.

In 1989 Danfysik signed a contract with ESRF, Grenoble, to produce two basically similar systems; they are now delivered complete with test bench, laser system, PC computer and software. By taking up a license from CERN for this high precision test system Danfysik have added another product into our world of magnet testing technology.

An order for a similar system for quality control of the magnets for the ADVANCED PHOTON SOURCE at Argonne National Laboratory, USA, is now under construction.



- "Halbach" Bucking
- Tedious alignment of fiducials (10 micron, 0.2 mrad precision)

GSI IMMW : Defining our "Units"

- R_{ref} used everywhere :
  1" for SSC , 25 mm for Hera
  59 mm for LEP, 10 mm then 17 mm for LHC
- B_1 = dipole in Europe, quadrupole in USA
- $B_2 = G_c * R_{ref}$ = Field @ Rref
- $b_3 = B_3/B_2$

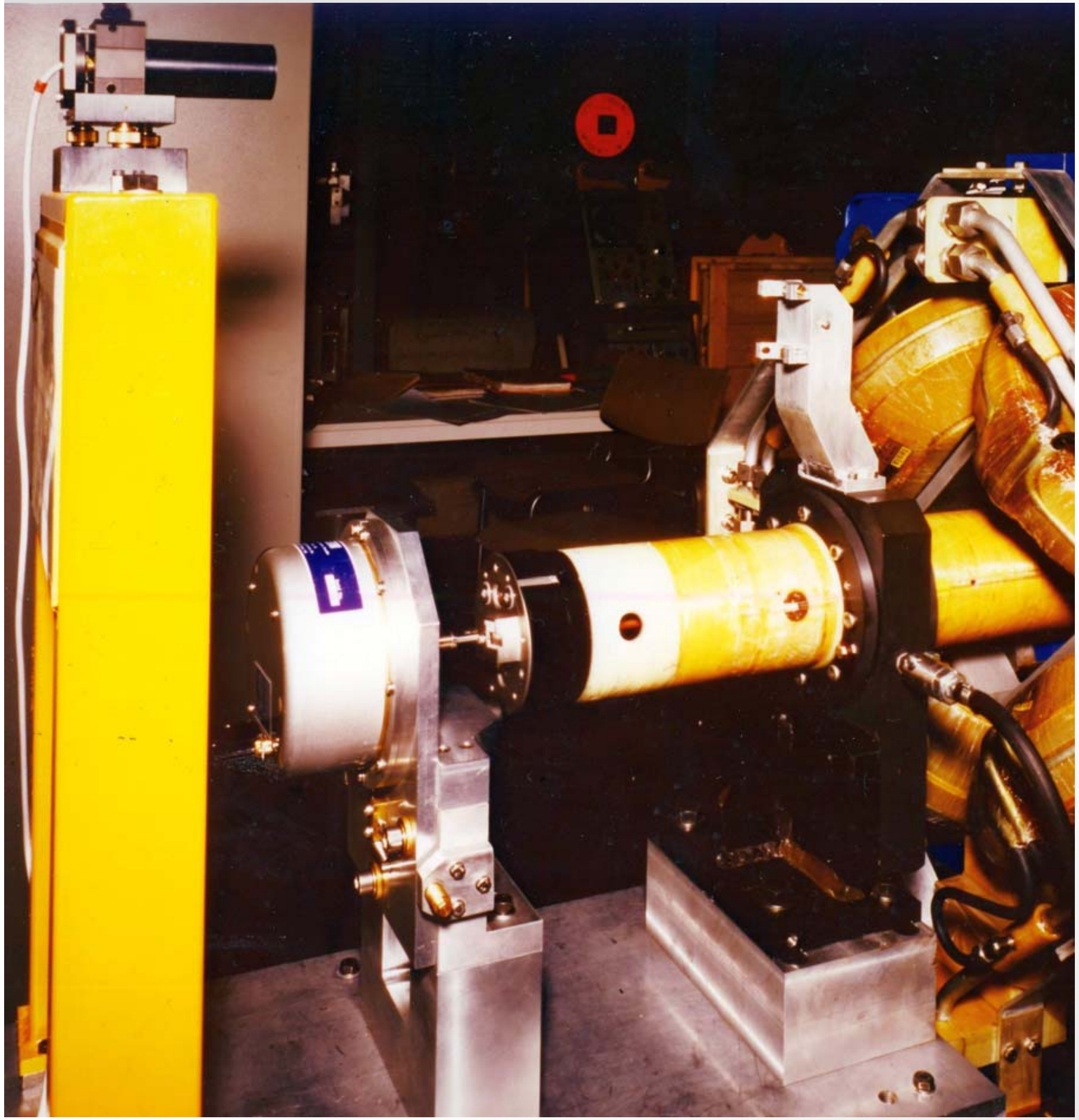
Today :

- formalism for undulators linking beam optics to tuning of manufacturing (ESRF works on it : transfer matrix ?)
- Still missing for curved magnets

The labs (have to) define

- the measurements standards
- how they are measured and unambiguously cross-controled

Years of development based on external progress

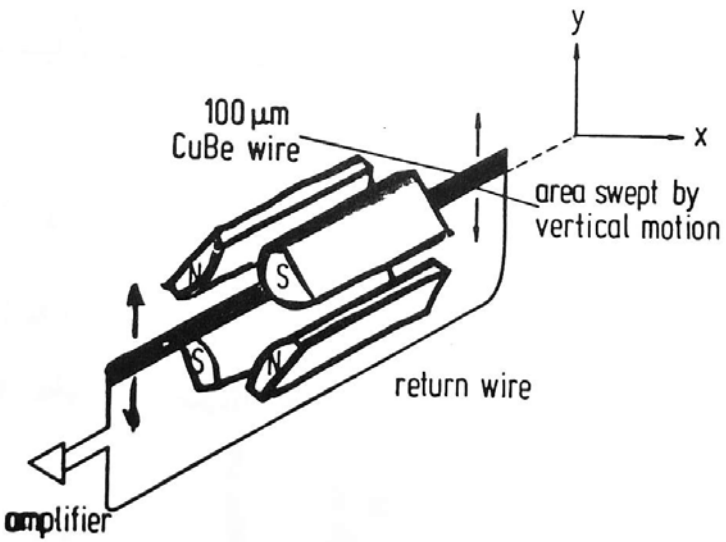


- Absolute (costly) to incremental encoders (cf. Fermilab mole)
- Air bearings (now ceramic bearings)
- Mech. Reference Jigs "home made" laser line (now Leica or Faro)
- Stretched Litz wire (SSW Calibration, coils, PCB)

1986 (SLAC) to IMMW 1991

"Stretched Wire" System

- CuBe wire, 100 μm (low susceptibility) in warm finger, return wire outside magnet
- measurements by horizontal and vertical movements
- flux change recorded with v/f
- measurements as function of wire tension to correct for sagging effects



SSW : calibration for Gradient

- SLAC (dipole spectrometer)
- Desy for Hera
- Cern (Lep quads)
- Fermilab

? Prehistory ? – the early times

MMW-1 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, February 1981

MMW-2 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, May 1982

MMW-3 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1983

MMW-4 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1985 (2 pictures)

MMW-5 Brookhaven National Laboratory (BNL) ,
Brookhaven, New York, September 1987

IMMW-6 Lawrence Berkeley Laboratory (LBL) ,
Berkeley, California, September 1989

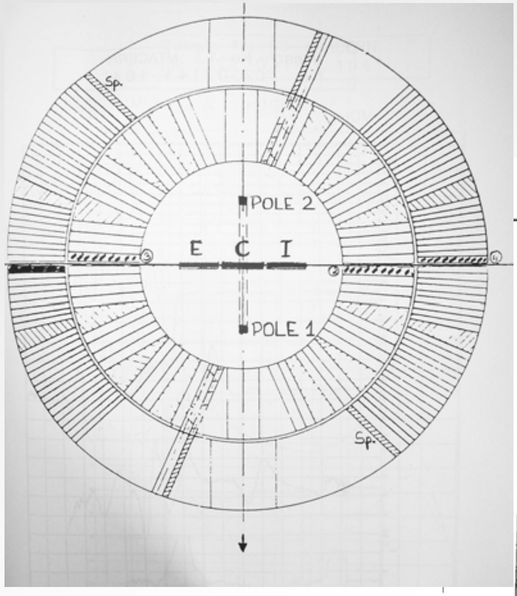
History starts

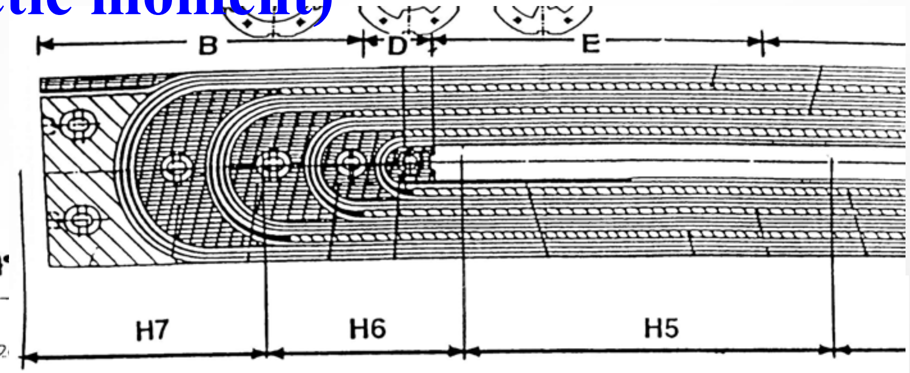
IMMW-7 Gesellschaft für Schwerionenforschung (GSI) ,
Darmstadt, Germany, June 1991

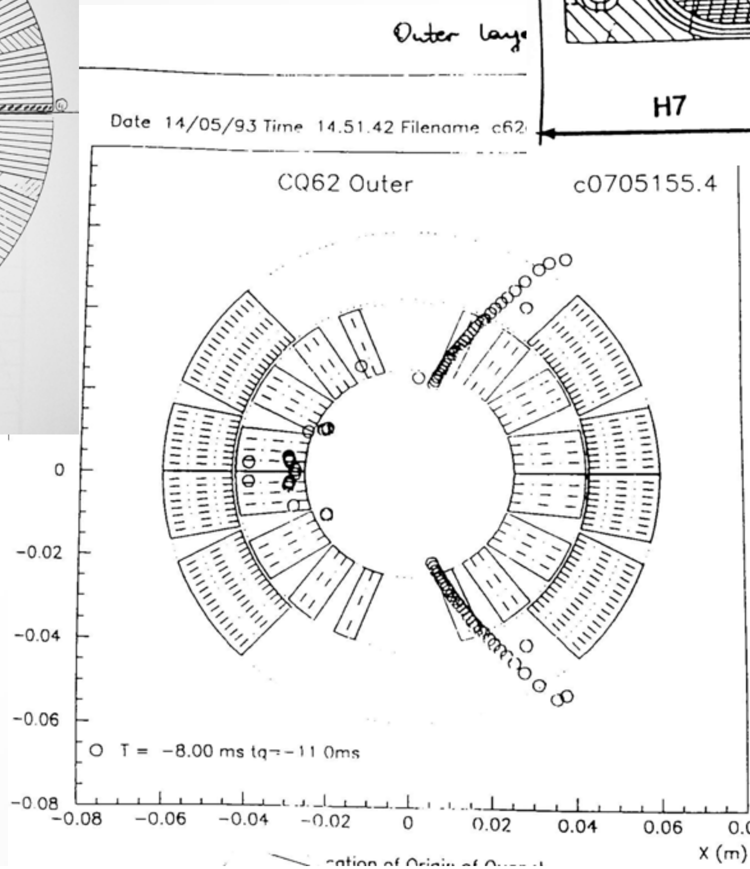
IMMW-8 SSC, Waxahachie, Texas, September 1993
(no proceedings)

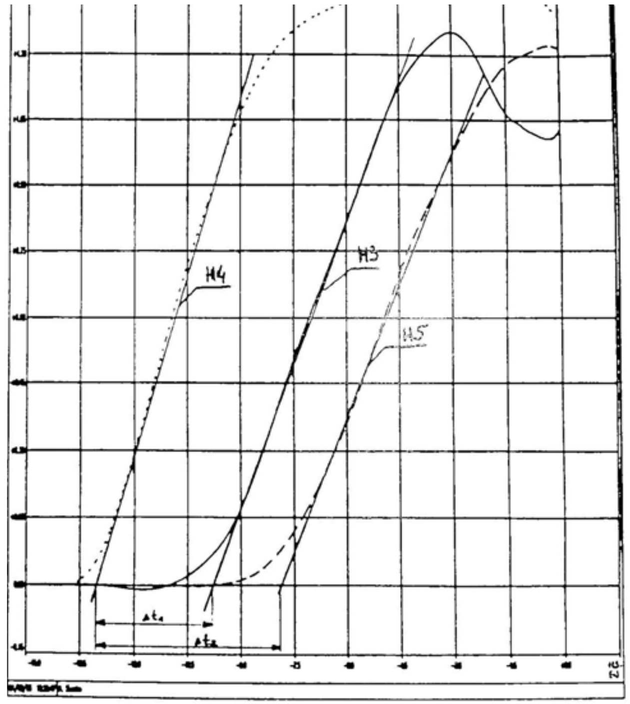
Waxahachie 1993 : the quench antenna

Use our measuring shafts (or more dedicated coils) to locate in the 2 D cross-section the quench or the longitudinal propagation (the quench gives a dipolar magnetic moment)









IMMW's

MMW-1 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, February 1981

MMW-2 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, May 1982

MMW-3 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1983

MMW-4 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1985 (2 pictures)

MMW-5 Brookhaven National Laboratory (BNL) ,
Brookhaven, New York, September 1987

IMMW-6 Lawrence Berkeley Laboratory (LBL) ,
Berkeley, California, September 1989

IMMW-7 Gesellschaft für Schwerionenforschung (GSI) ,
Darmstadt, Germany, June 1991

IMMW-8 SSC, Waxahachie, Texas, September 1993

IMMW-9 Saclay (CEA) , France, June 1995

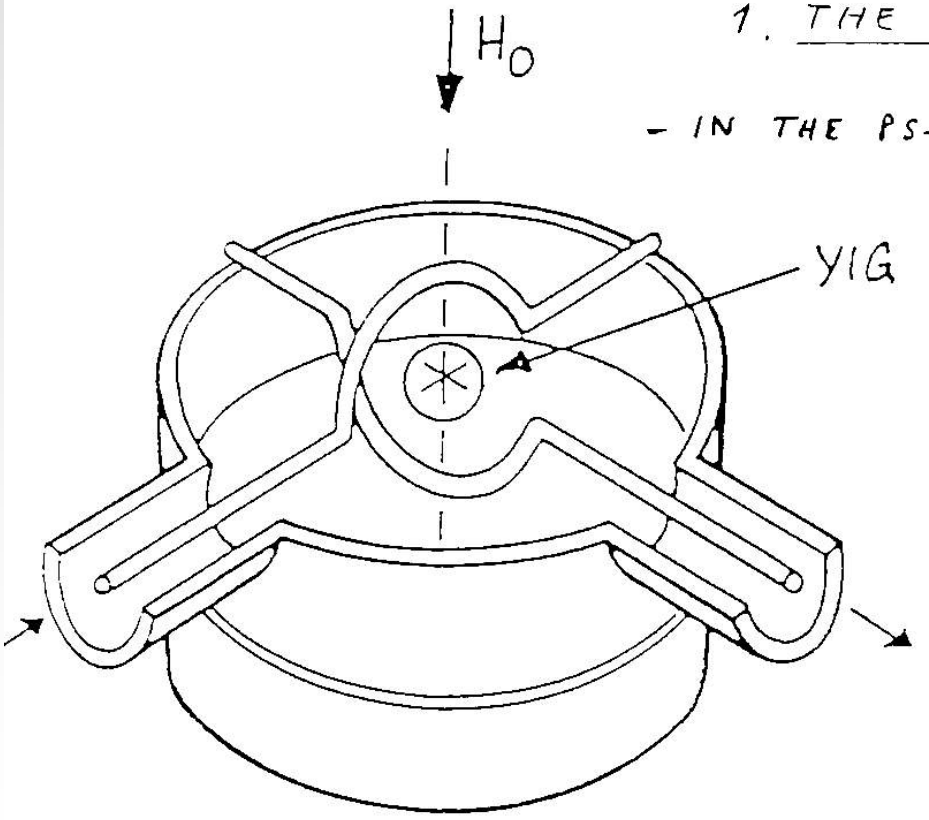
Saclay 1995

USE OF A NMR PROBE AS A FIELD MARKER FOR AN ACCELERATOR

F. Caspers, D. Cornuet

1. THE PRACTICAL SITUATION

- IN THE PS-BOOSTER THE B-FIELD IS GIVEN BY AN



Coupling structure of a single-stage filter

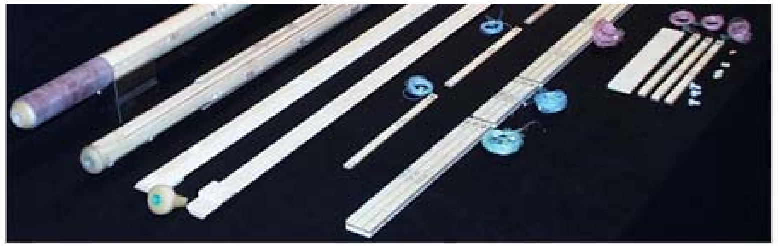
Saclay 1995

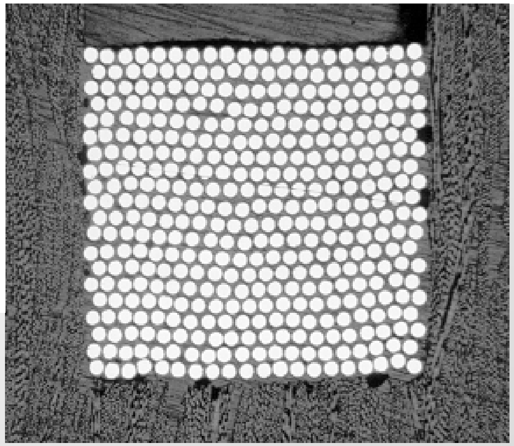
New development in search coil design and fabrication

J. Billan , S. Bidon, F. Fischer, C. Sanz
CERN

General considerations:

1. How to make **long** and precise **coils** with very **small wires** ?
2. **Square winding** cross-section allows to replace it by its barycenter in harmonic calculation
3. Winding several layers with a **small single wire** (low tension) degenarates quickly in a **randomly shaped winding**.
4. Dispersions in surface areas and axis directions are large
   - electronic bucking and skew coils required
   - bucking ratios of 1000 ex.: - a 6 *mm* width coil → 6 µ*m* coil accuracy
5. Utilization of **multiwire flat cable** makes winding much more easier
6. but **connection** more complicated





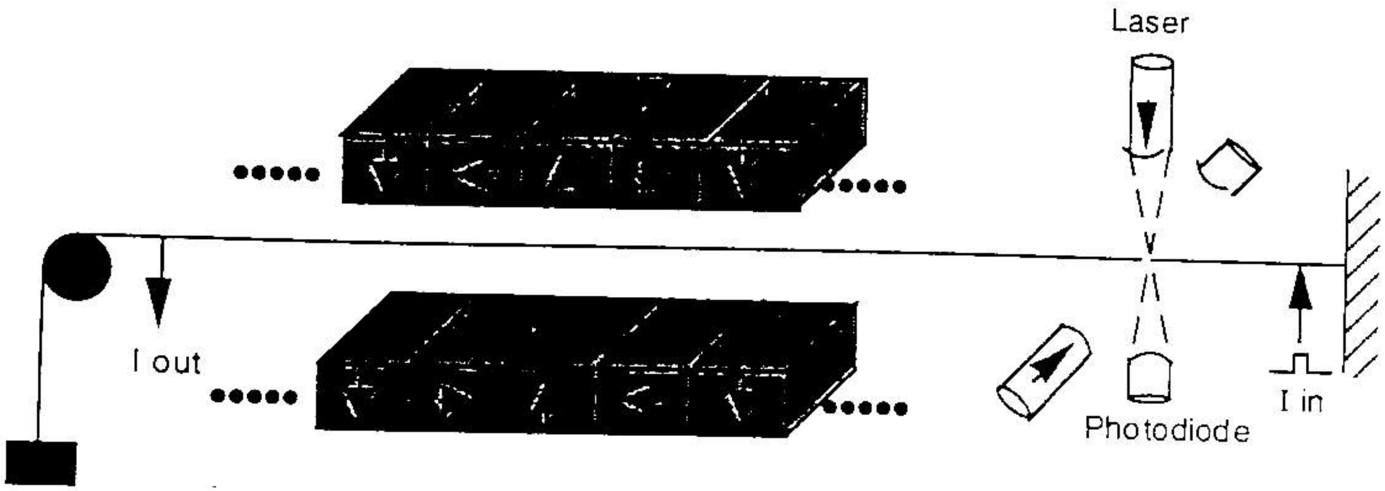
Still the highest density (Nturns / mm^2)

Saclay 1995

4. Magnetic measurement developments:

4.1. The pulsed wire (ESRF/Los Alamos laboratory):

* Used in the past for FELs



A pulse is applied to the wire -> inducing a sound wave

ESRF and BNL then SLAC

IMMW's

MMW-1 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, February 1981

MMW-2 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, May 1982

MMW-3 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1983

MMW-4 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1985 (2 pictures)

MMW-5 Brookhaven National Laboratory (BNL) ,
Brookhaven, New York, September 1987

IMMW-6 Lawrence Berkeley Laboratory (LBL) ,
Berkeley, California, September 1989

IMMW-7 Gesellschaft für Schwerionenforschung (GSI) ,
Darmstadt, Germany, June 1991

IMMW-8 SSC, Waxahachie, Texas, September 1993

IMMW-9 Saclay (CEA) , France, June 1995

IMMW-10 Fermilab, Illinois, October 1997

IMMW 97 : New accelerators need new or renewed methods

Overview of Recycler Ring Magnetic Measurements

IMMW-X
Fermilab, 10/14/97
H.D. Glass

Recycler Ring: 8 GeV storage ring for p-bars (part of Fermilab Main Injector upgrade)
Ring made of permanent magnets:
- ~340 combined function gradient magnets (4 different pole styles)
- ~75 quadrupoles (several different strengths)
- ~handful of specialty magnets (Lambertsons, mirror gradients)

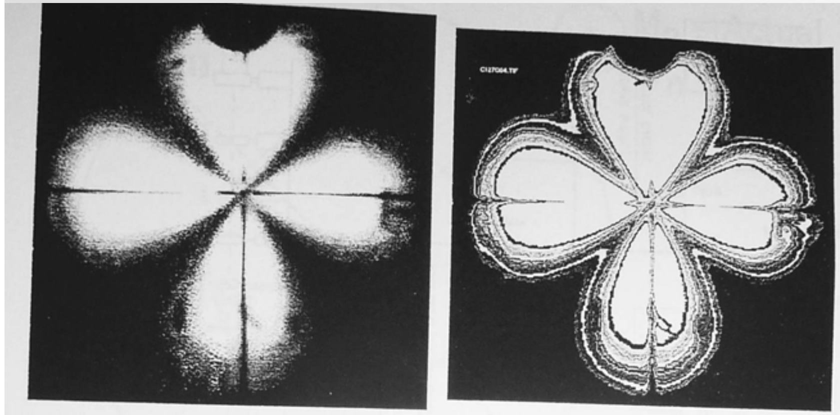
Permanent magnet measurements

ILC & CLIC Small aperture magnets

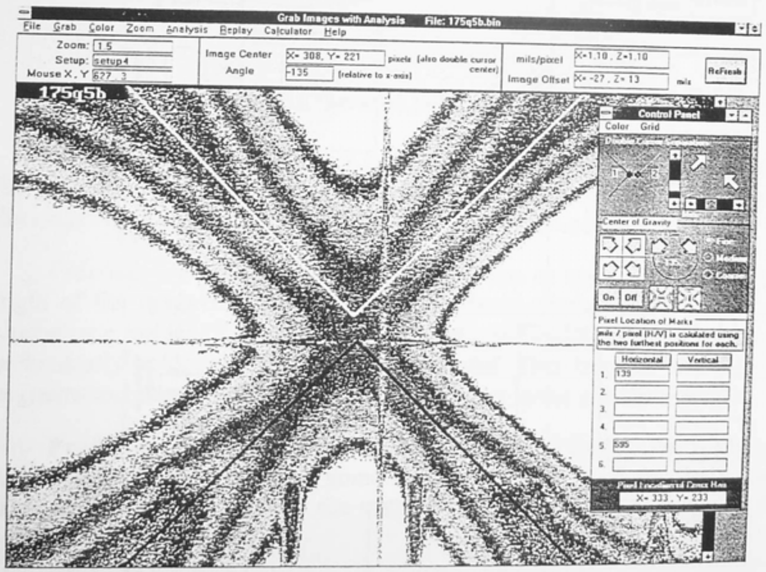
A CLIC Test Facility (CTF) is therefore set up (see Fig. 1) and enters in its phase II where 30 magnets of two types I and II. The two types have the same coils, they only differ from their yokes and inner diameters (D = 10 mm and 30 mm respectively, see table 1).

Fermilab, 1997 : Axis finding (BNL)

Colloïdal Cell

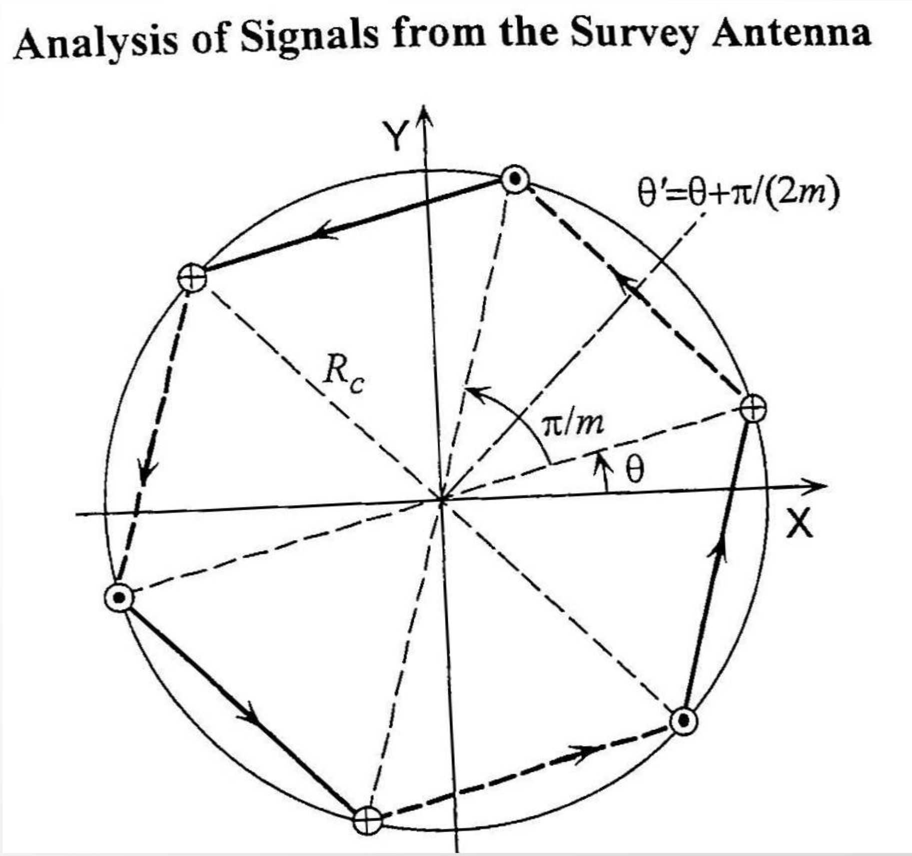


Colloidal Cell Pattern in a Quadrupole Magnet at High Field.



Colloidal Cell Pattern in a Quadrupole Magnet at Low Field.

Dedicated antenna for R.T. measurement (precursor of CERN AC Mole – IMMW11-14)



SSW became the refence method to calibrate our integral systems

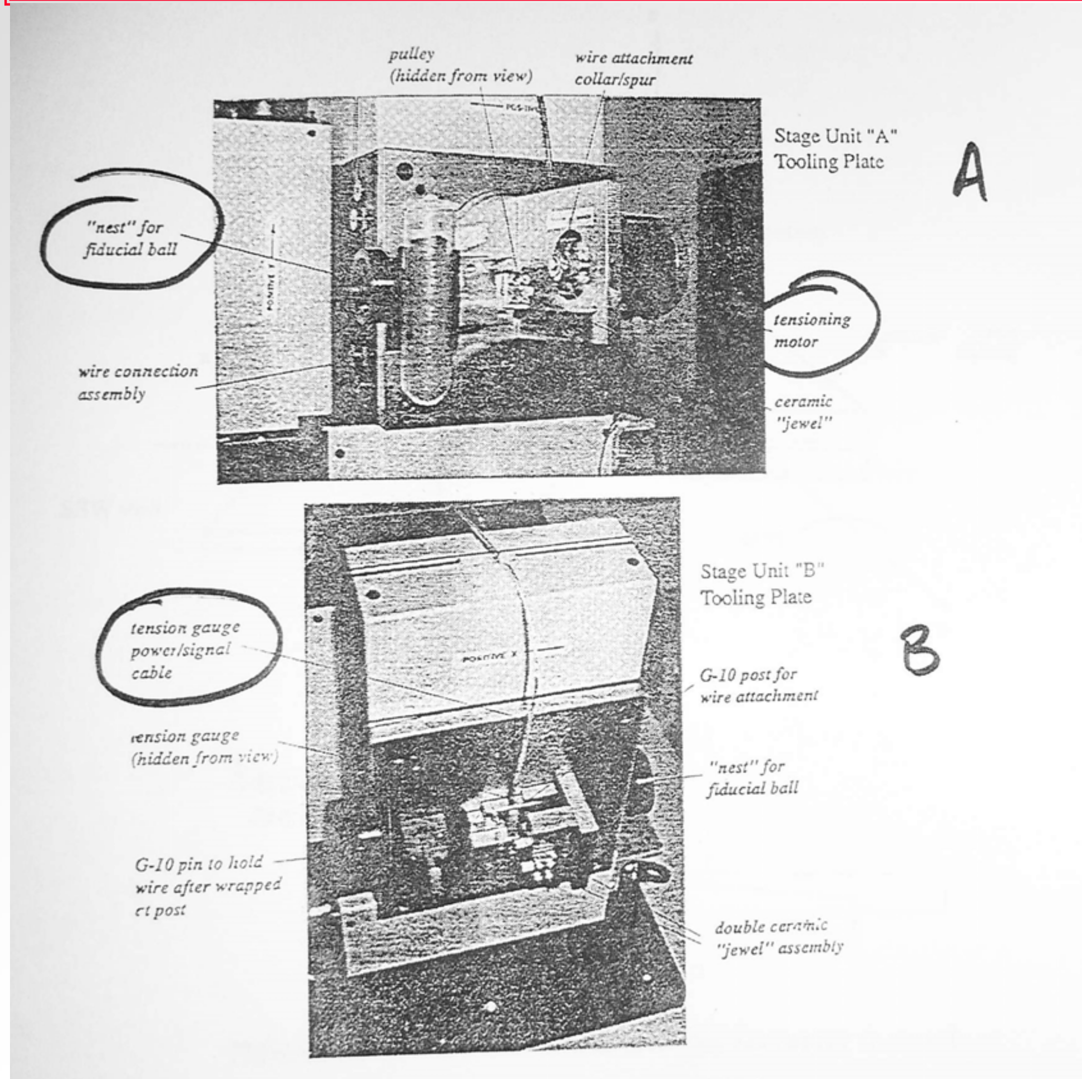
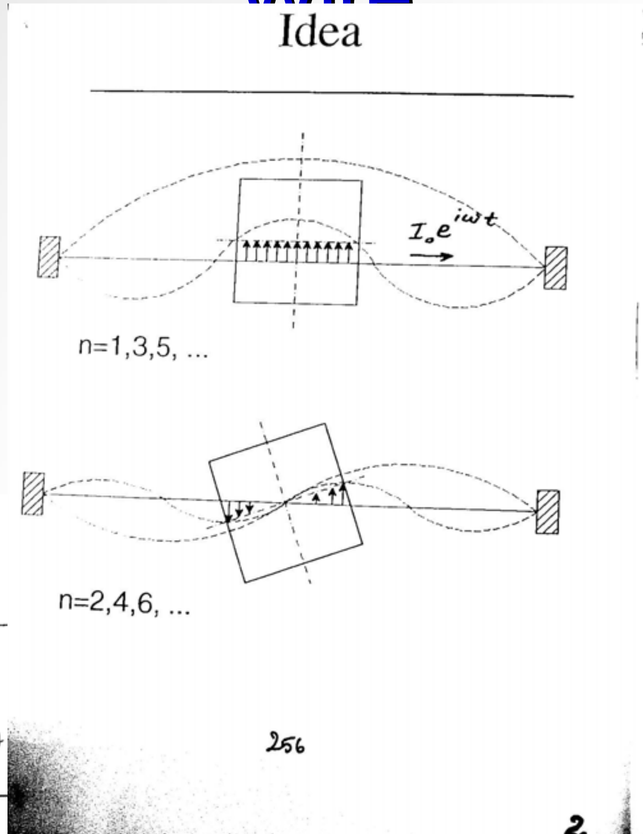


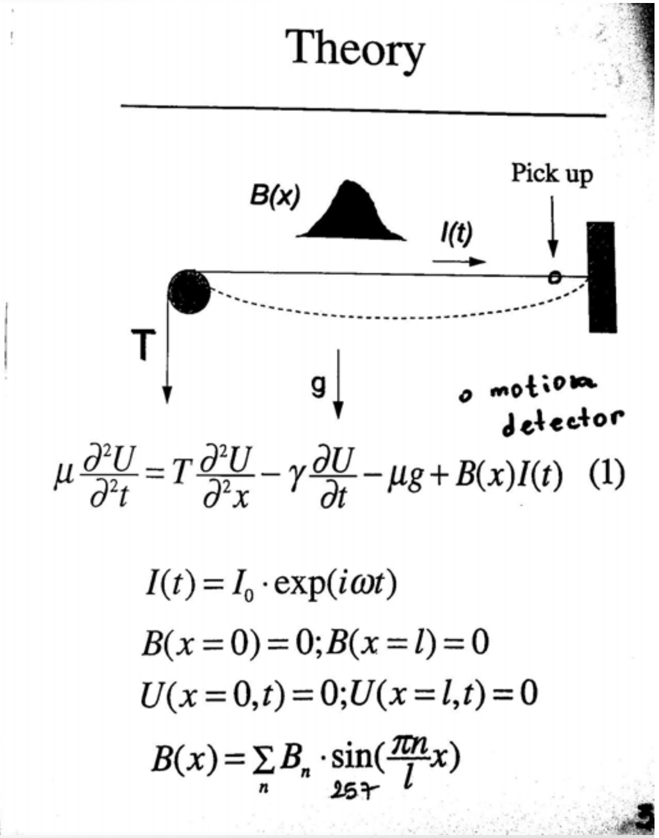
Figure 5: Stage unit wire support and tensioning

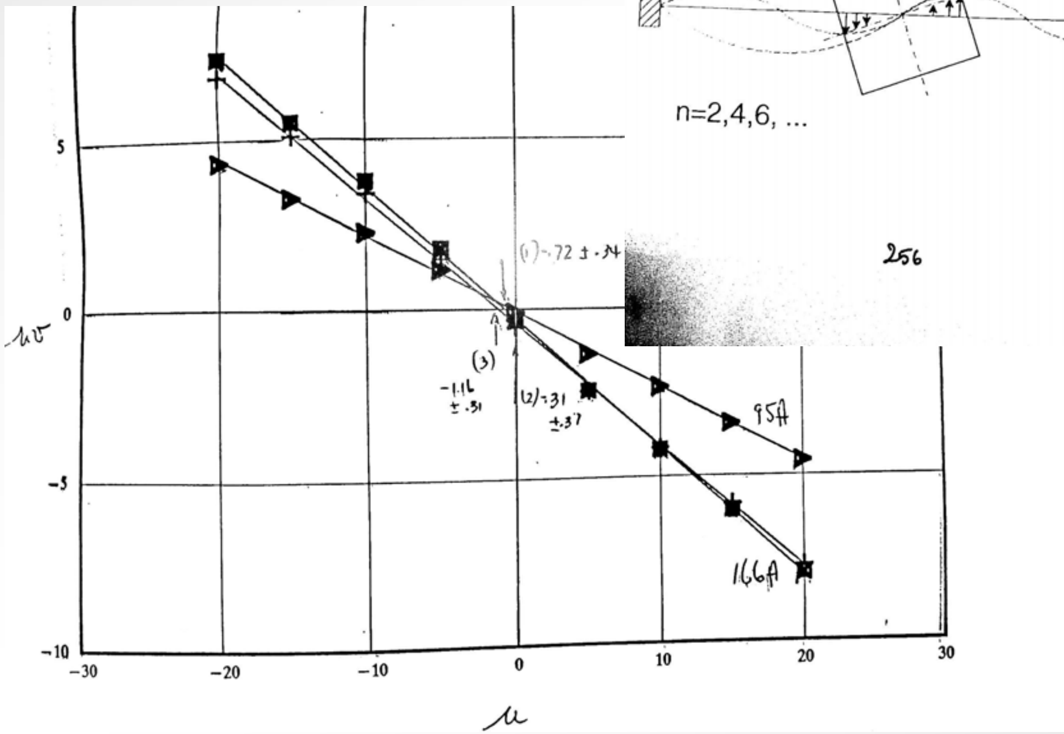
FNAL
J. Dimarco

Fermilab, 1997 : Axis finding by Vibrating Wire

A. Themnik
Cornell







Fermilab, 1997 : Axis of Solenoid

D. Cornuet
CERN

MAGNETIC AXIS

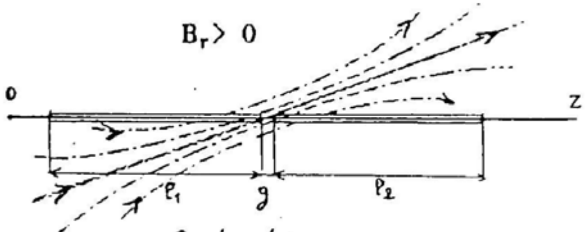
OF A SOLENOID

WITH A COMPOSITE INTEGRAL COIL

Search coil consisting in 2 coils (or 3
(ℓ_1 and ℓ_2 with gap g)
(or ℓ_1, ℓ_2 and ℓ_3 with total gaps g)
is rotated 180°.

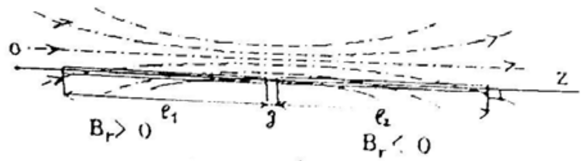
As : specific constant of the integral coil (in m

Fig. 1



Rotation

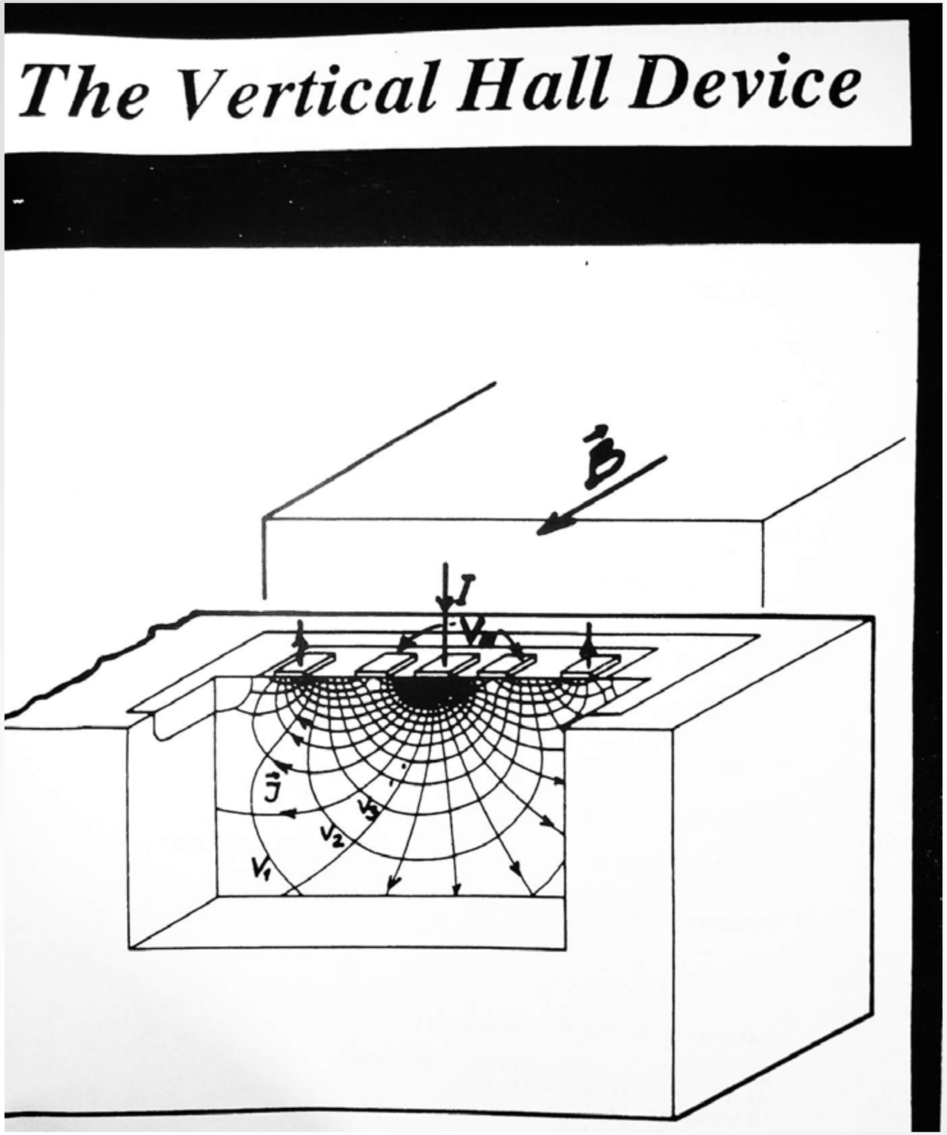
Fig. 2



Offset

Use of a shaft with several longitudinal coils

Fermilab, 1997 : 2D & 3D Hall probes



High Accuracy 3D Hall Microsystems

Ch. Schott, F. Burger, D. Manic and R.S. Popovic
Institute for Microsystems
Department of Microtechnology
Swiss Federal Institute of Technology (EPFL)
Lausanne, Switzerland
R. Racz, Sentron AG, Zug, Switzerland

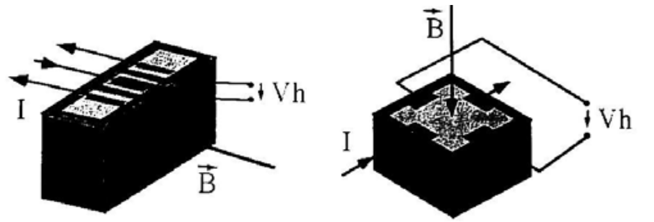


Figure 1 : Operating principles of vertical and horizontal Hall device

Merged Integrated Device

Topology

The merged integrated device consists of a pair of merged vertical Hall devices in the center and four horizontal plates distributed in the corners of the central cross (fig. 2). The vertical sensors have a common center current contact and the structure guarantees for precise measurement of the two in-plane components in the same spot. The field component perpendicular to the sensor plane can be measured as the average signal of the four horizontal devices. The outside dimension of the sensor are 400µm x 400 µm.

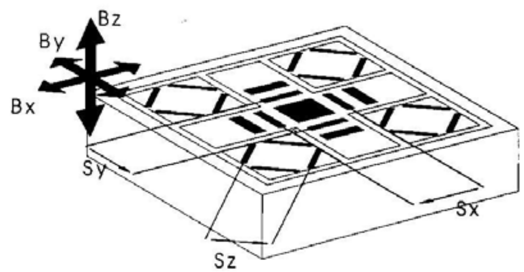


Figure 2 : Topology of the merged integrated device

Fermilab, 1997 : Who will take over ?

Knud Henrichsen starts to learn Web

A List of Magnet Measurement Publications

- more than 300 references with keywords
- ASCII-file for simple handling and retrieval
- can be used on HP-95 and similar pocket devices
- available by e-mail or on DOS diskette
- a list of manufacturers of magnet measurement equipment has also been compiled

IMMW's

MMW-1 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, February 1981
MMW-2 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, May 1982
MMW-3 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1983
MMW-4 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1985 (2 pictures)
MMW-5 Brookhaven National Laboratory (BNL) ,
Brookhaven, New York, September 1987
IMMW-6 Lawrence Berkeley Laboratory (LBL) ,
Berkeley, California, September 1989
IMMW-7 Gesellschaft für Schwerionenforschung (GSI) ,
Darmstadt, Germany, June 1991
IMMW-8 SSC, Waxahachie, Texas, September 1993
IMMW-9 Saclay (CEA) , France, June 1995
IMMW-10 Fermilab, Illinois, October 1997
IMMW-11 Brookhaven National Laboratory, New York, October 1999
(I have the CDRom)

BROOKHAVEN
NATIONAL LABORATORY

Automated Polarity Checking for RHIC Magnet Assemblies

Richard Thomas, Wing Louie,
George Ganetis, Animesh Jain,
and Peter Wanderer

RHIC Project

Brookhaven National Laboratory

IMMW11 BNL 1999

An AC field static system for measuring the magnetic axis of LHC superconducting magnets in warm condition

J. Billan

Abstract

The choice of a 3D-laser tracker for controlling several delicate operations during the fabrication process of the LHC magnets gave us the idea of using a single mole to measure simultaneously the centre axis of the cold bore tube and the magnetic axis of the magnet.
This mole houses, at the same cross-section point, four tangential coils for detecting the magnetic axis, a corner cube for detecting the centre of the mole and a mechanical system for centring the mole inside the cold bore tube.
Here we describe the principle, the equipment and preliminary results related especially to the measurement of the magnetic axis.

MMW-1 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, February 1981
MMW-2 Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, May 1982
MMW-3 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1983
MMW-4 Swiss Institute for Nuclear Research (SIN now PSI),
Villigen, Switzerland, September 1985 (2 pictures)
MMW-5 Brookhaven National Laboratory (BNL) ,
Brookhaven, New York, September 1987
IMMW-6 Lawrence Berkeley Laboratory (LBL) ,
Berkeley, California, September 1989
IMMW-7 Gesellschaft für Schwerionenforschung (GSI) ,
Darmstadt, Germany, June 1991
IMMW-8 SSC, Waxahachie, Texas, September 1993
IMMW-9 Saclay (CEA) , France, June 1995
IMMW-10 Fermilab, Illinois, October 1997
IMMW-11 Brookhaven National Laboratory, New York, October 1999
IMMW-12 European Synchrotron Radiation Facility, Grenoble, October 2001
IMMW-13 Stanford Linear Accelerator Center (SLAC), California, May 2003
IMMW-14 European Organization for Nuclear Research (CERN), September 2005
IMMW-15 Fermilab, Illinois, August 2007
IMMW-16 Paul Scherrer Institute (PSI),Villigen, Switzerland, October 2009

IMMW12 ESRF 2001

Wigglers & Undulators

- Characterise permanent magnets
- 3D scanners
- SSW , pulsed wire, Vibrating wire

IMMW12 ESRF 2001

Calibration of Hall sensors in three dimensions

Progress on the 3D calibration of Hall sensors.
Calibration of a large number of 3D sensors with an automated set-up.
Comparison with absolute measurements.
Results from users.
A calibrator build for a 13 Tesla solenoid at GHMFL, Grenoble and first results
at 4.5 Tesla.
A new high precision 3D B-sensor of high simplicity using discreet Hall sensors.

Primary authors : Dr. BERGSMA, Felix (CERN)

The perfect 3D Hall probe is still under development
What about arrays of Hall probes (undulators)   ?

IMMW14 Cern 2005

Apple II undulator: a way to investigate planar and angular Hall probe effects

content :
A permanent magnet Apple II type undulator was built at Elettra and a block sorting process was done in order to minimize the effects of magnetic errors on Trajectories and angles of the electron beam. To check and optimize these corrections, Stretched
Wire and Hall Plate measurements were performed. While the Stretched Wire system provides a clean measurement of field integrals, the Hall Plates are affected by angular misalignment of the probes and planar Hall effect. The latter could be separately analyzed using the possibility offered by the adjustable magnetic undulator structure to change the direction of the main field from vertical to horizontal. Final compensation is achieved comparing Hall Plate and Stretched Wire field integral measurement result.

Primary authors : Dr. KNAPIC, Cristina (Sincrotrone Trieste S.C.p.A.)

Do we reach limits with Hall Probes to measure Effects on the beam of Undulators ?

- **The perfect 3D Hall probe is still missing**
- **2 Hall probes on same substrate to measure gradient instead of field ?**

IMMW14 Cern 2005

Measurements of Field Harmonics at Very High Ramp Rates

Field quality in accelerator magnets is expressed in terms of harmonic coefficients in a Fourier series, which are typically measured under DC conditions using a rotating coil. The technique of rotating coils has also been extended to measurements under AC conditions, but only for relatively slow ramps (well below 0.1 T/s). Currently, there is no well established technique for measuring all the field harmonics at very high ramp rates (1 T/s and above). We have developed a prototype system to characterize the field quality of magnets at very high ramp rates. This new measurement system consists of 16 printed circuit tangential windings which are held stationary while the magnet is ramped. The induced signals in all the windings are then analyzed to obtain the field harmonics. This paper will describe the data analysis procedure, and present the results of measurements at ramp rates of 1.5 to 4.0 T/s in a prototype dipole designed and built at BNL for operation at such high ramp rates.

Primary authors : Dr. JAIN, Animesh (Brookhaven National Laboratory, USA)

More on Multipole measured during ramp @ IMMW15 FNAL

IMMW15 Fermilab 2007

Hall Probe Polarity Checker

Polarity Testing the New Booster Corrector Magnets

Andrzej Makulski, Dana Walbridge

Fermilab

Accuracy limits

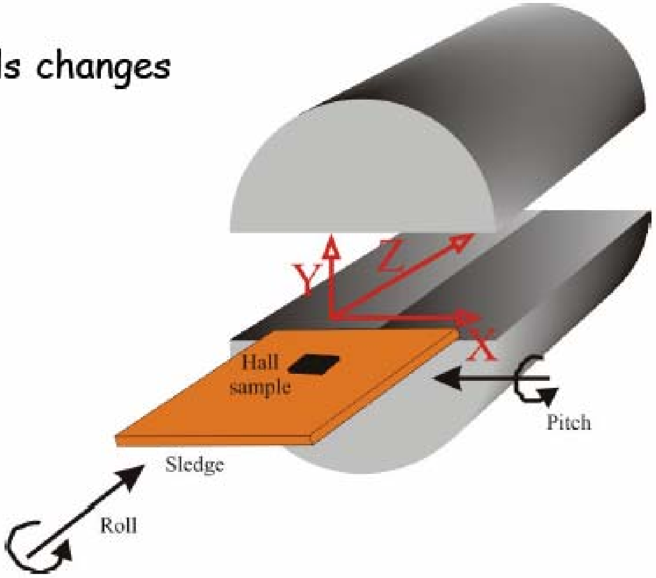
Relative alignment precision of guiding rails 20µm.
For the Hall probe in the middle the distance to coils changes by 10µm.

In x-direction the field is fairly uniform
⇒ error is negligible

In y-direction the 10µm yields according to [1] with λu=0.015 to:

$$\cosh\left(\frac{2\pi\Delta y}{\lambda_u}\right) = 1 + \frac{\Delta B}{B}$$

$\Delta B/B = 9 * 10^{-6}$



In longitudinal direction $\Delta z < 5$ µm

The angle errors cause a $\Delta B/B < 5 * 10^{-8}$

⇒ Limiting factor on B is the Hall probe accuracy

[1] Zachary Wolf, "Requirements for the LCLS Undulator magnetic measurement bench", Technical report # LCLS-TN-0, 4-8 http:/www-ssrl.slac.stanford.edu/lcls/technotes

IMMW16 PSI : In vacuum measurement

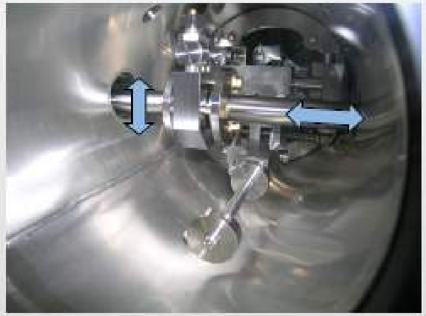
ESRF

Magnetic measurement benches

A Light for Science

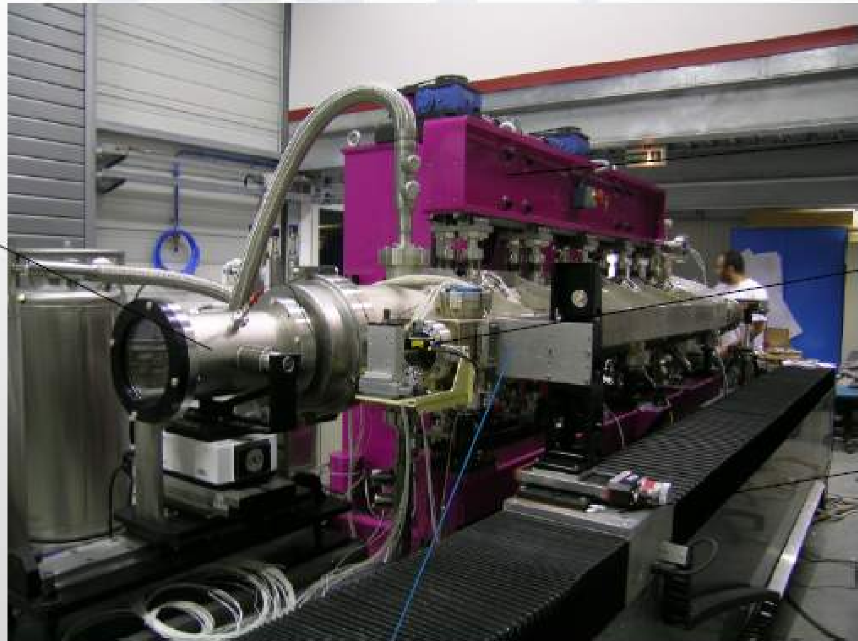
Magnetic measurements performed in-vacuum (~ 10^{-6} mbar)
No motorization in vacuum, dedicated vacuum chamber

Stretched Wire
- Field integral measurements
- Gap measurements



Vertical motion ± 3 mm

Horizontal motion ± 25 mm



Undulator

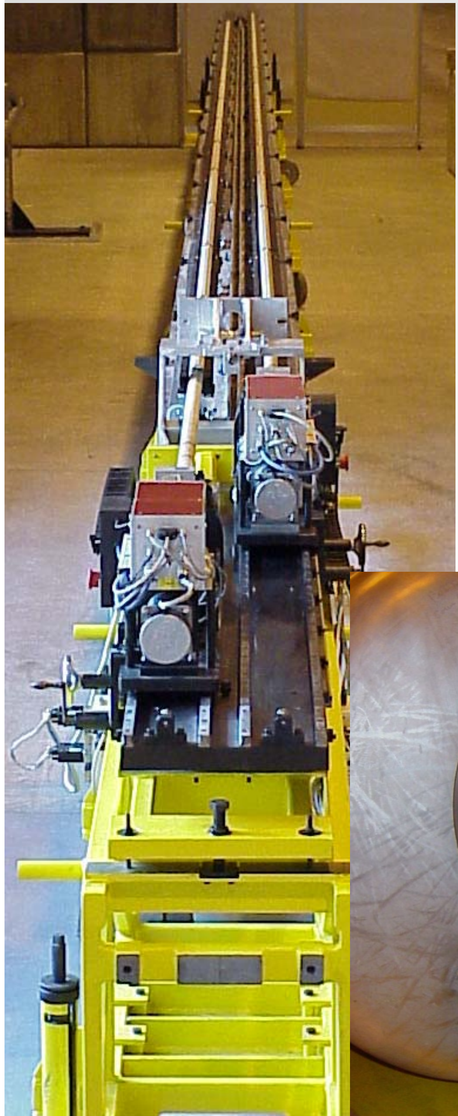
Laser interferometer

External motorization

Inner guide rail

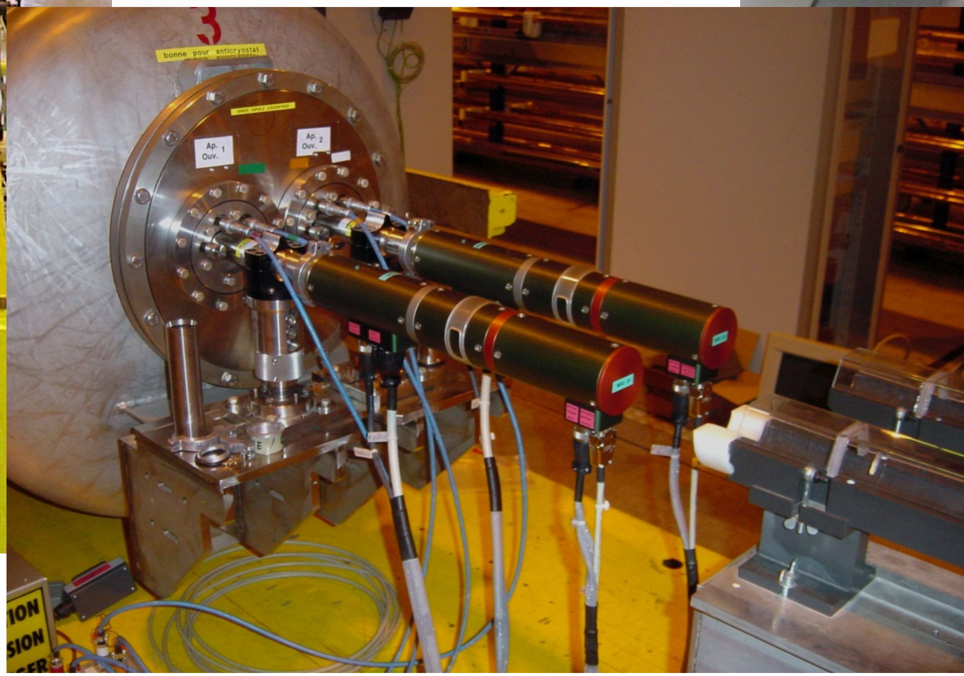
Hall probe assembly
- magnetic coupling with external motion
- Acquisition speed 30mm/sec
- 3 field components
- 25 000 pts/channel (2.4 m)

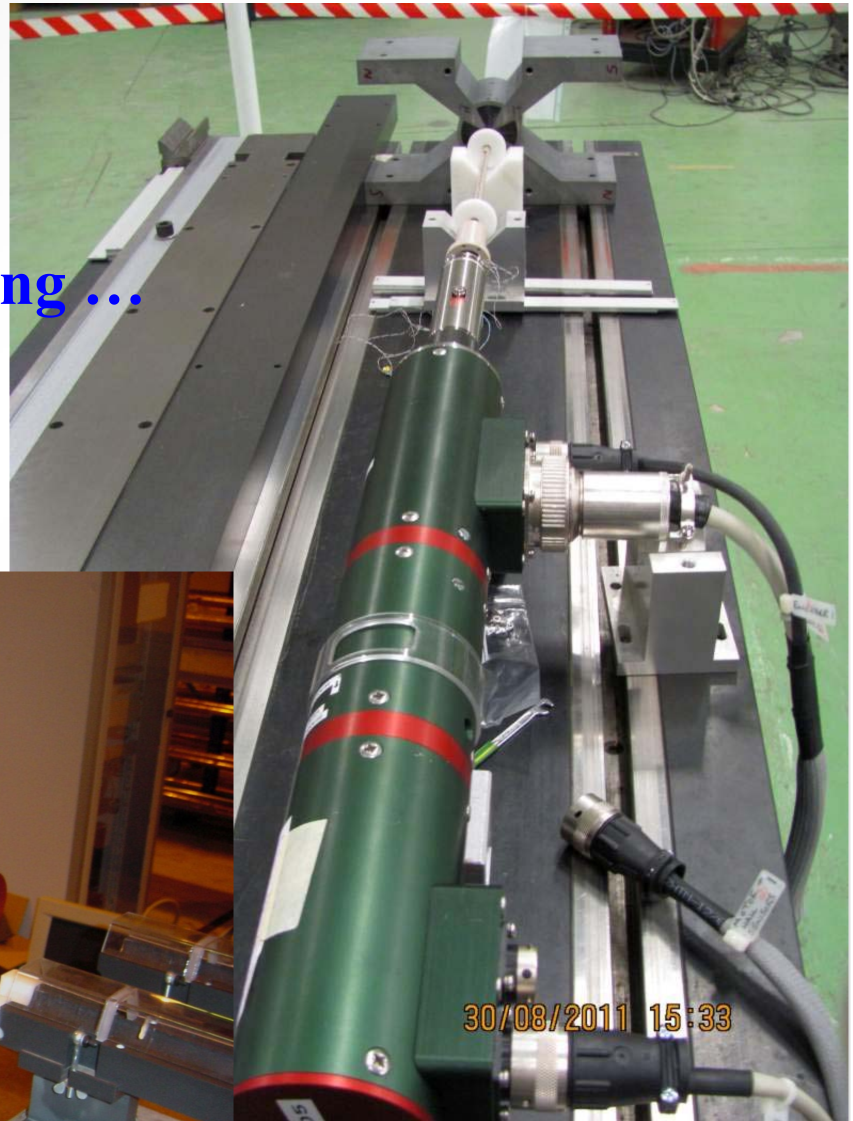
Going smaller & smaller



TRU to MRU
(Micro Rotating Unit)
To
Macro (Maxi !) Rotating …

Each factor 10
Cost 10 (?) * more





Going smaller & smaller implies more and more electronic resolution

The Trends : the Rref are smaller going from :

- **AGS , PS**
- **SPS then Tevatron**
- **SSC, Hera, LHC**
- **CLIC, ILC / Undulators**

Tools : from flip to rotating coils to SSW to VW

What is the noise limit with a coil (SSW) ?

- **100 nV·s (10 nV ·s ? ≈ 1 gauss *cm^2) for 1 s**
- **For t > 1 s : drift (and drift stability) issues**
- **For t < 1 s : noise from current supply or other external sources**

Thank You

Gracias

Many thanks
for the whole workshop

Merci

Vielen Dank