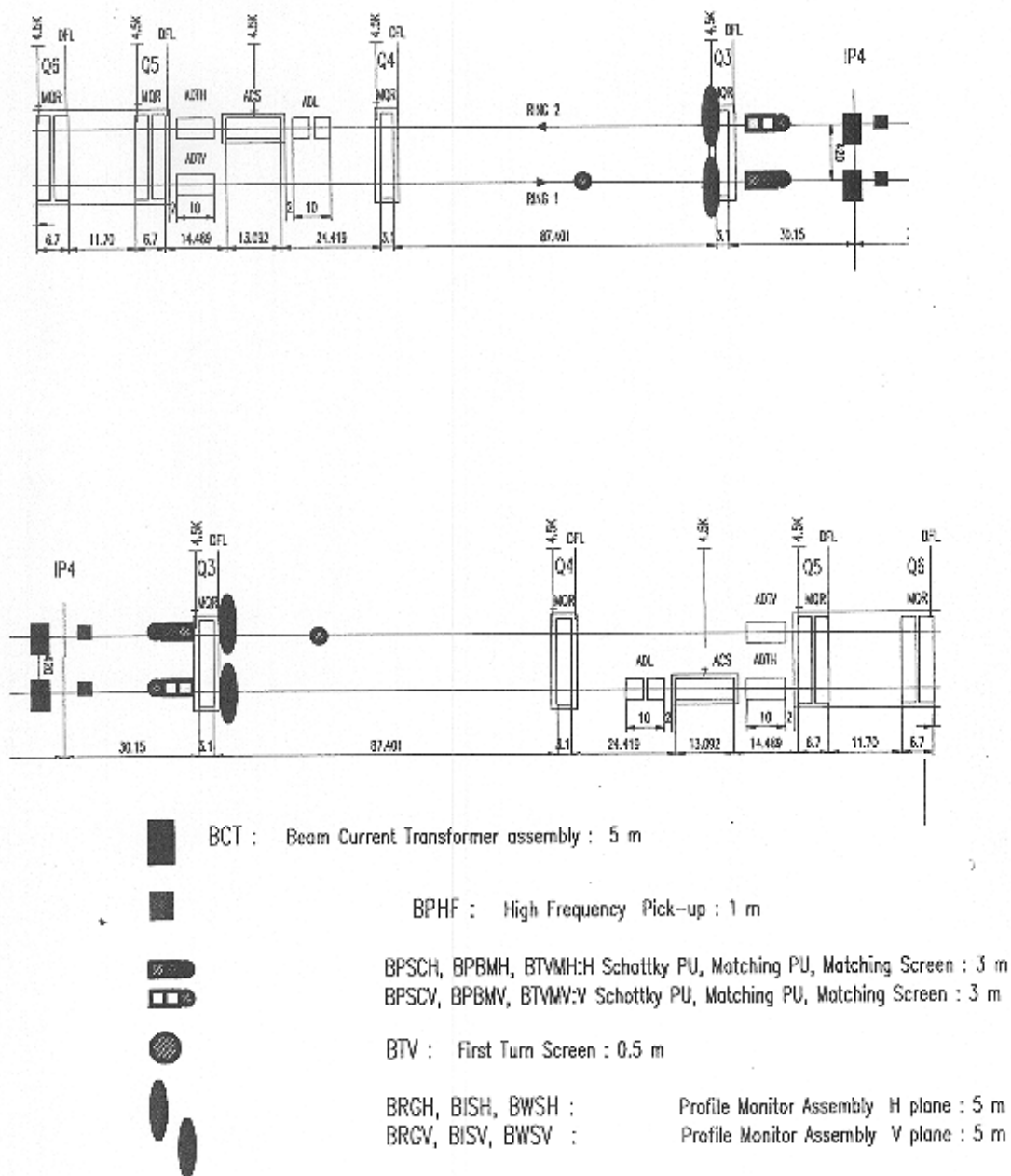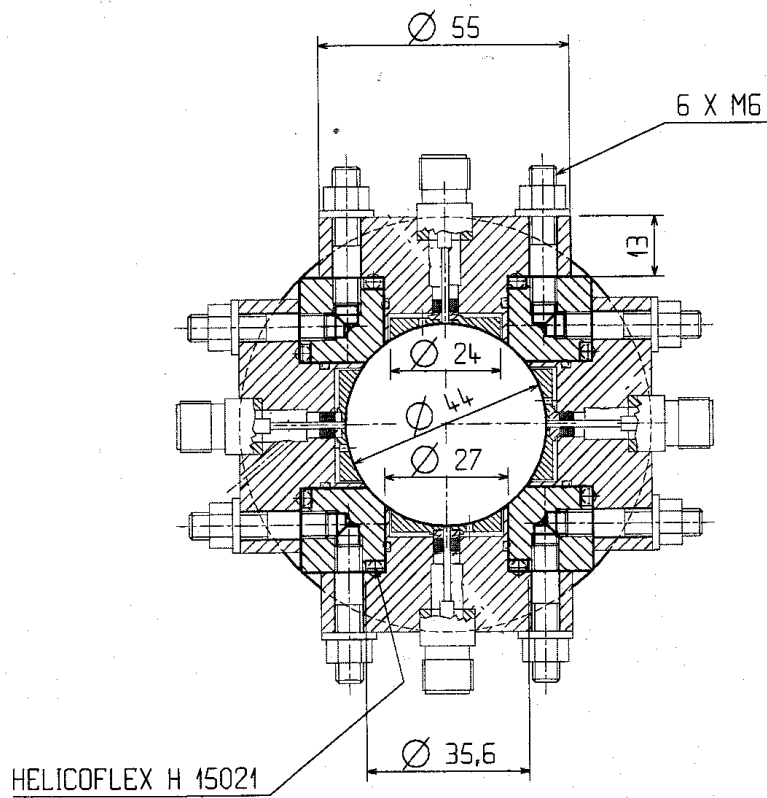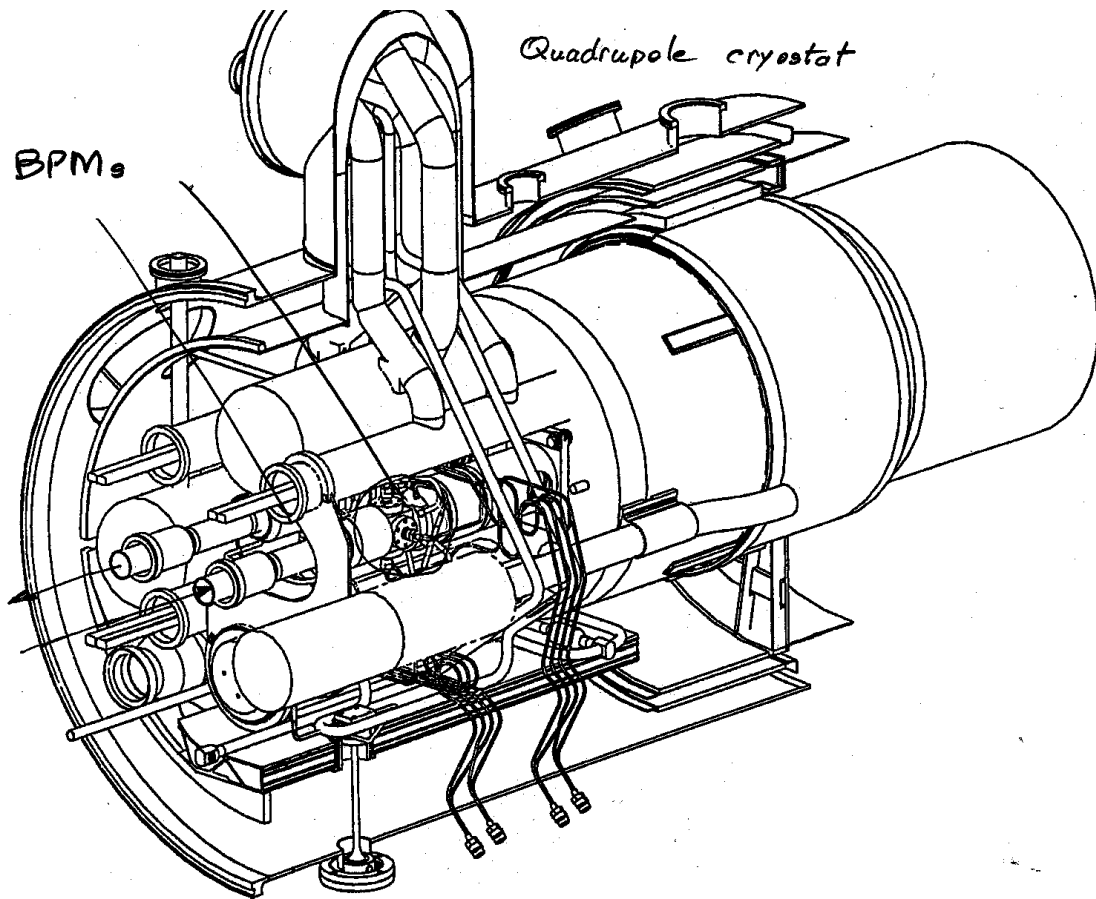Figure 4: Layout of insertion region 4 with associated instruments.
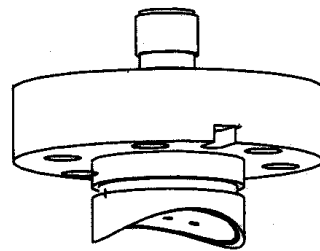
# A Review of the LHC Beam Instrumentation

## Table 1: LHC BPM Distribution
(button electrodes except in Inner Triplets)

|  | Adjacent Quadrupole (number/type) | Temperature (K) | Coil Aperture (mm) | Aperture # | BPM # |
|---|---|---|---|---|---|
| arcs | 360 MQ | 1.9 | 56 | 2 | 720 |
| **Dispersion Suppressors in all insertions:** Q11 | 16 MQ | 1.9 | 56 | 2 | 32 |
| in insertions 3 / 7: Q10 / Q9 / Q8 | 12 MQL | 1.9 | 56 | 2 | 24 |
| in insertions 1/2/4/5/6/8: Q10 / Q9 / Q8 | 36 MQM or MQML | 1.9 | 56 | 2 | 60 /12 C Cs combined BPM |
| **Matching. Sections** 1/5 Q7 | 4 MQM | 1.9 | 56 | 2 | 8 |
| Q6 | 4 MQML | 4.5 | 56 | 2 | 8 |
| Q5 | 4 MQML | 4.5 | 56 | 2 | 8 |
| Q4 | 4 MQM | 4.5 | 56 | 2 | 8 |
| 2/8 Q7 | 4 MQM | 1.9 | 56 | 2 | 8 |
| Q6 | 4 MQM | 1.9 | 56 | 2 | 8 |
| Q5 | 2 MQY / 2 MQM | 4.5 | 70 / 56 | 2 | 4 / 4 |
| Q4 | 2 MQY / 2 MQM | 4.5 | 70 / 56 | 2 | 4 / 4 |
| **Inner Triplets 1/2/5/8** |  |  |  |  | 8 8 |
| Q2b | 8 MQX | 1.9 | 70 | 1 | |
| Q1 | 8 MQX | 1.9 | 70 | 1 | bi-directional strips |
| **Cleaning Insertions 3/7** Q7 | 4 MQ | 1.9 | 56 | 2 | 8 |
| Q6 | 4 MQW | warm | 46 | 2 | 8 |
| Q5 | 4 MQW | warm | 46 | 2 | 8 |
| Q4 | 4 MQW | warm | 46 | 2 | 8 |
| **RF Insertion 4** Q7 | 2MQM | 1.9 | 56 | 2 | 4 C |
| Q6 | 2MQMLR | 4.5 | 56 | 2 | 4 |
| Q5 | 2MQMLR | 4.5 | 56 | 2 | 4 |
| Q4 | 2MQMR | 4.5 | 56 | 2 | 4 |
| Q3 | 2MQMR | 4.5 | 56 | 2 | 4 |
| **Dump Insertion 6** Q5 | 2 MQY | 4.5 | 70 | 2 | 4 |
| Q4 | 2 MQY | 4.5 | 70 | 2 | 4 |

Quadrupole cryostat

BPMs

pick-ups made
of four buttons

Ø 55

6 X M6

13

Ø 24

Ø 44

Ø 27

Ø 35,6

HELICOFLEX H 15021

AXONOMETRIC VIEW

# NARROW BAND NORMALISER
## *(PHASE PROCESSOR)*

**(LEP)**

Pick-up signal

Band pass filter

A

$\Phi = 0°$

$\Phi = -90°$

$\Phi = -90°$

$\Phi = 0°$

A - jB

Zero crossing detector (Comparator)

B

B - jA

Delay = $\lambda / 4$

Zero crossing detector (Comparator)

XOR

Position encoded in *duty cycle* of XOR output
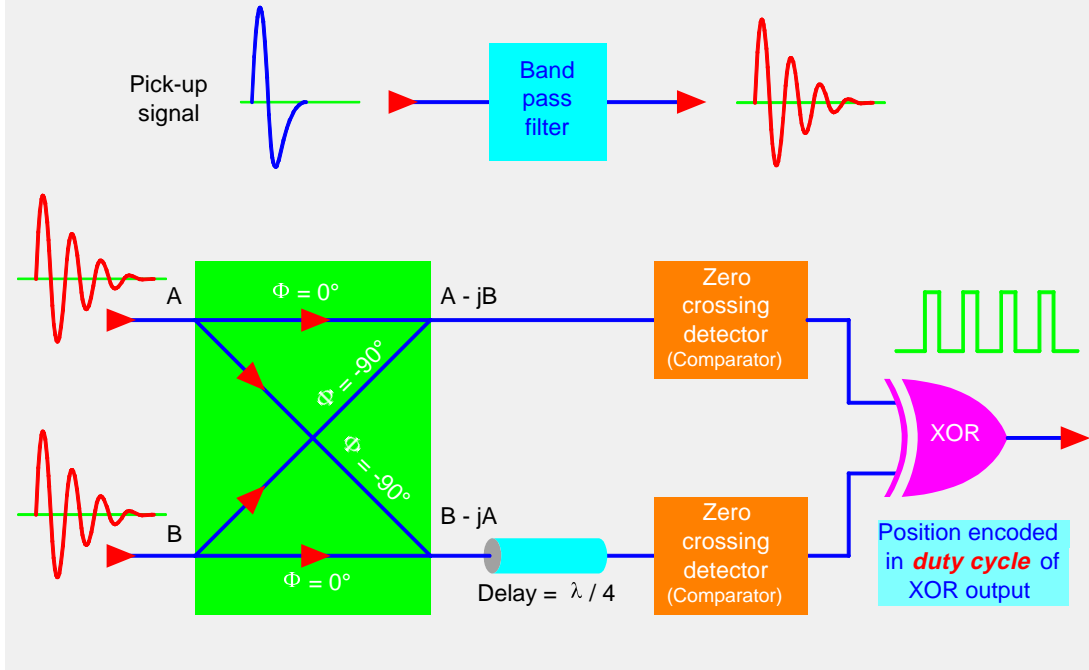
# WIDE BAND NORMALISER
## *(TIME PROCESSOR)*

Pick-up signal

Low pass filter

A

Delay = 0

Delay = $T_1$

Delay = $T_1$

Delay = 0

A + B( $T_1$ )

Zero crossing detector (Comparator)

B

B + A( $T_1$ )

Delay = $T_2$

Zero crossing detector (Comparator)

Flip-Flop

Position encoded in *pulse width* of Flip-Flop output
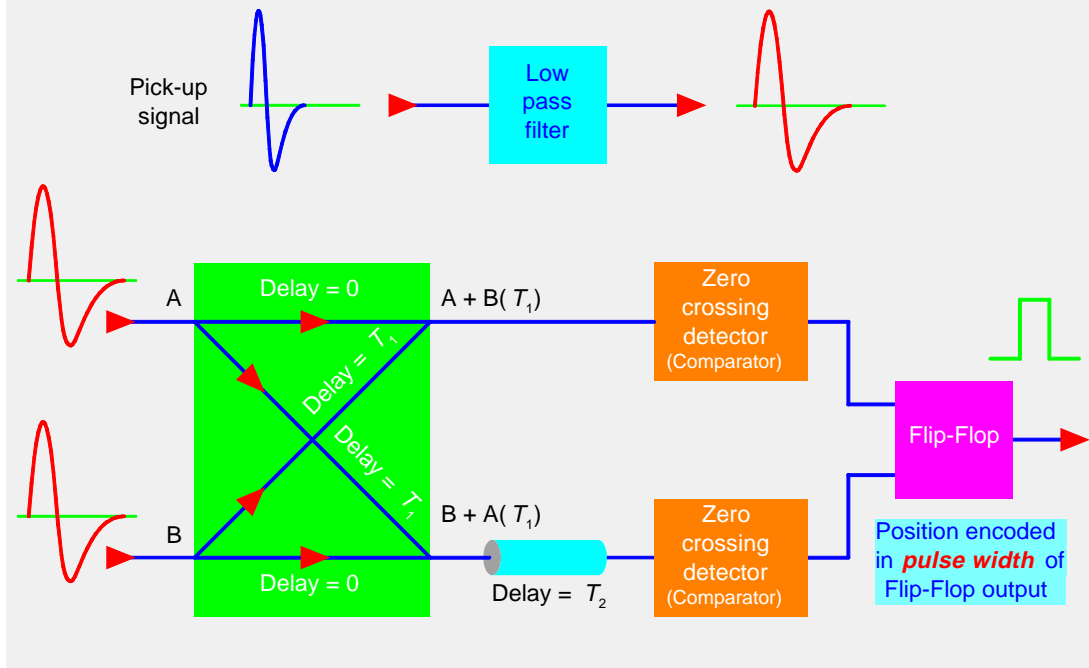
## NORMALISED SIGNALS
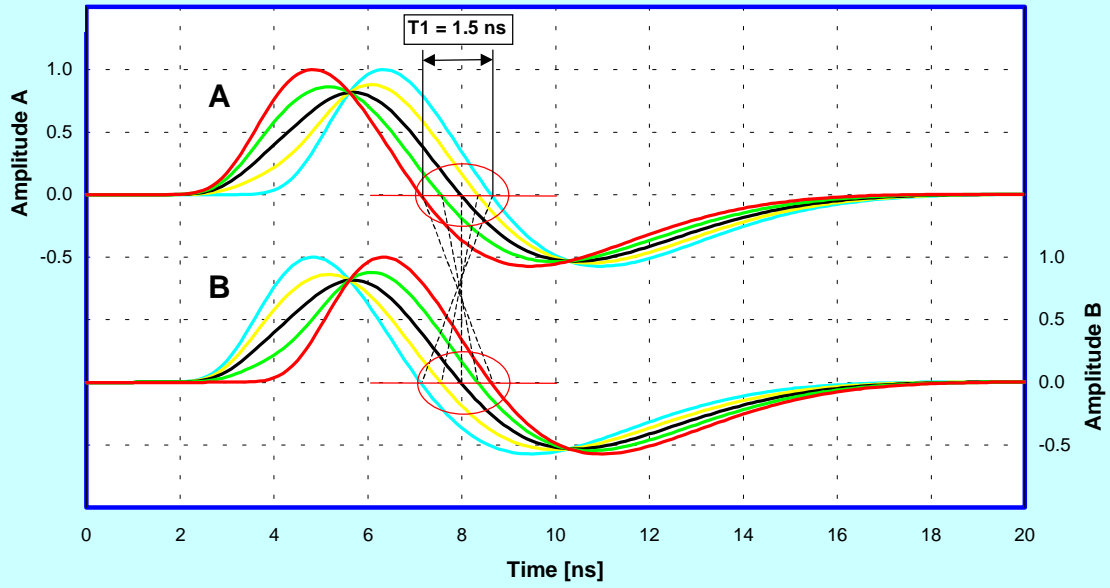


## 'WBTN' PROTOTYPE
## LINEARITY vs POSITION
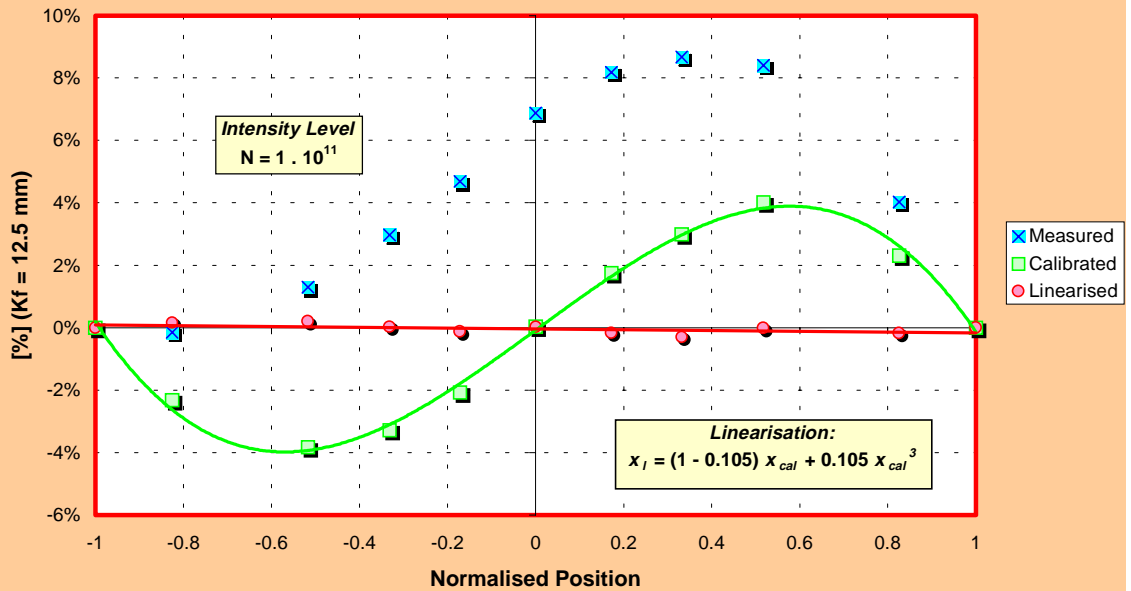
# Bunch position measurements

| Bunch type | Pilot | | Nominal | |
|---|---|---|---|---|
| Mode | Traj. | Orbit | Traj. | Orbit |
| Accuracy | 1.5 mm | 1 mm | 150 μm | 100 μm |
| Resolution | 0.5 mm | 0.2 mm | 50 μm | 5 μm |

*data taking at 40 MHz*

**Diagnostics:**

- **Injection trajectories + closed orbits**
- **Harmonic analysis ⇒ machine optics**
- **Measurement of tranverse coupling**
- **Measurement of momentum dispersion**
- **Pacman bunch orbits**
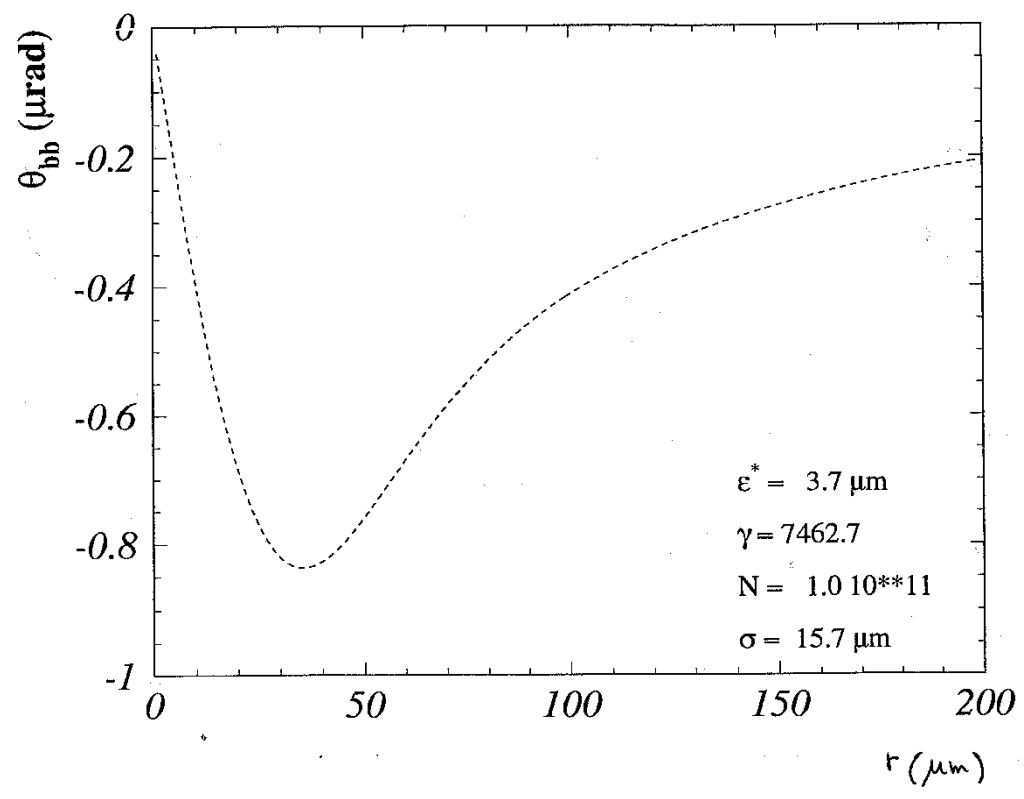- **Optimisation of luminosity/beam-beam deflection**

## BPM ACQUISITION SYSTEM
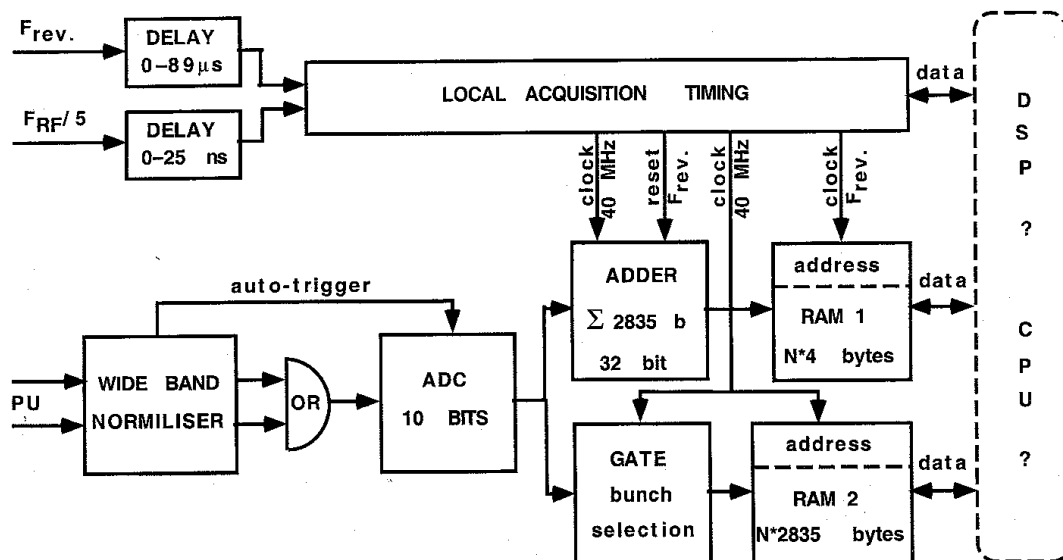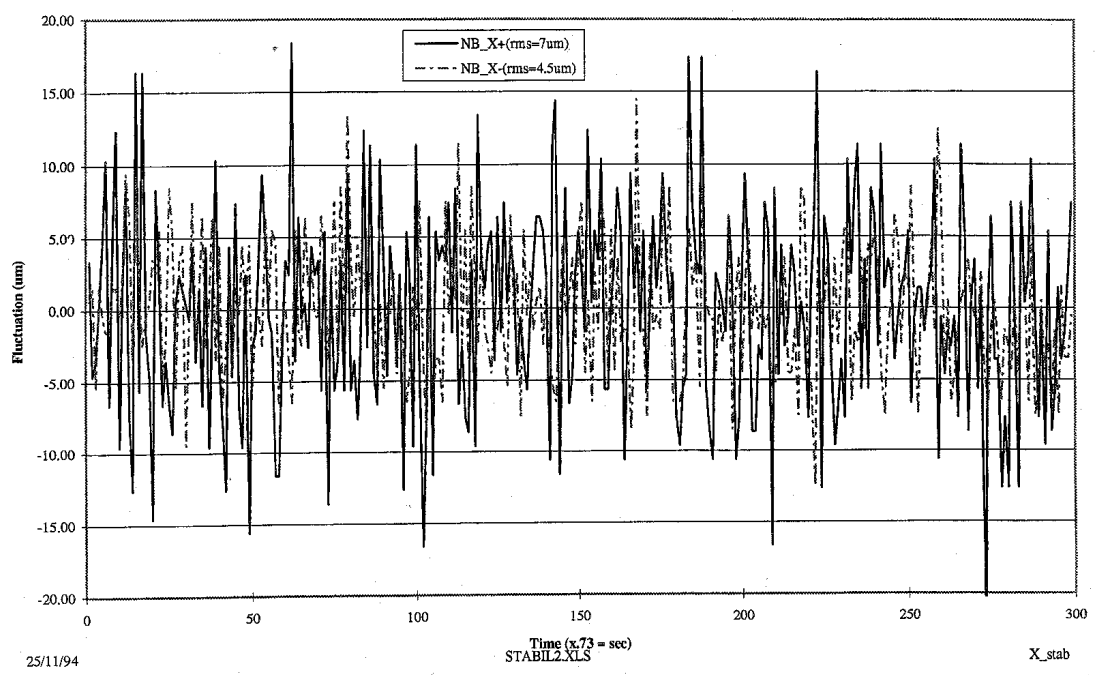
# Beam synchronous timing

UJ56

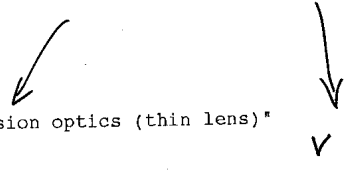RE52    RE58

RE48    RE62

US45    US65

RE42    RE68

RE38    RE72

UJ33    UJ76

RE32    RE78

10 Km    8 Km

PCR

RE28    RE82

6 Km    5 Km    US85

US25    4 Km

RE22    RE88

RE18    RE12

US15
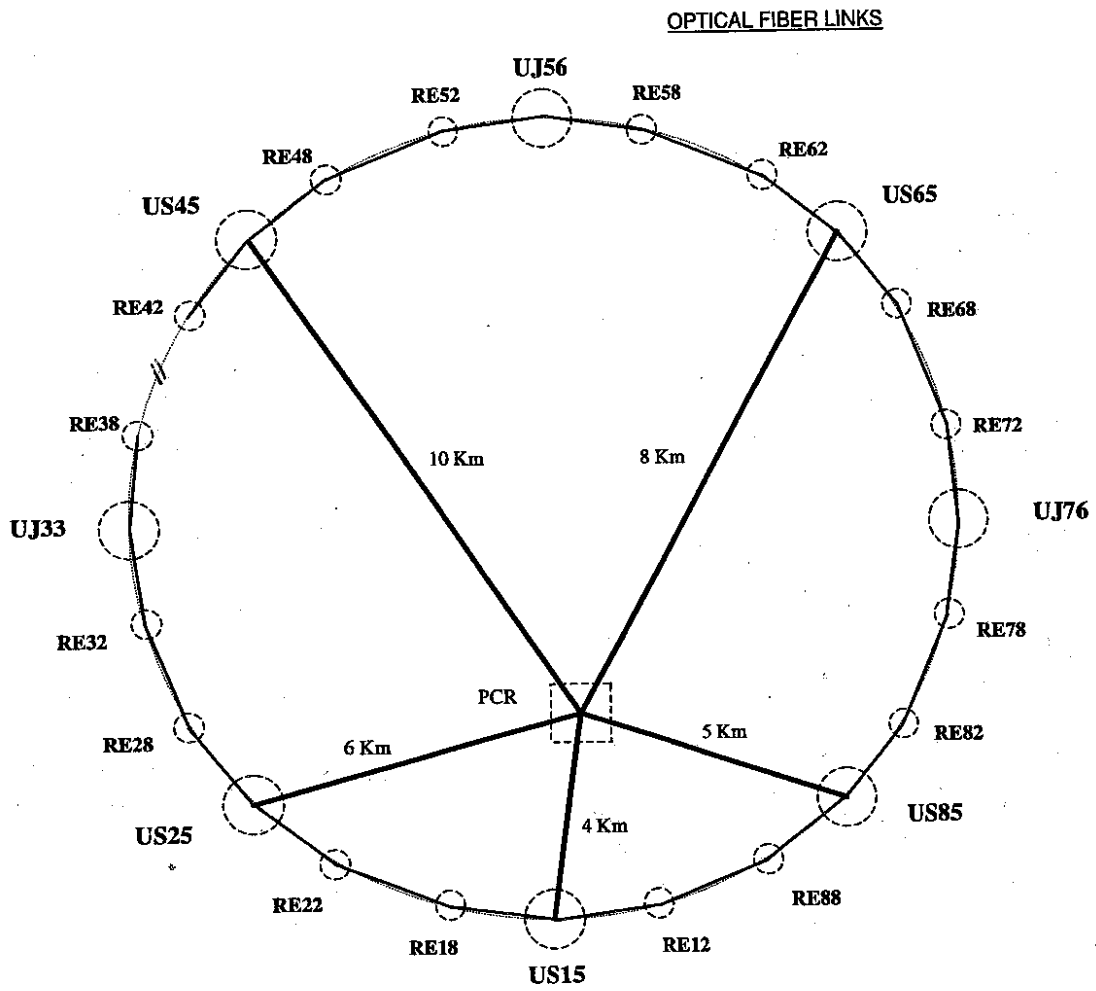
# Kick at bunch crossing



$\varepsilon^* = 3.7\ \mu m$

$\gamma = 7462.7$

$N = 1.0\ 10{**}11$

$\sigma = 15.7\ \mu m$

prepared by G. Vismara

**X Stability** measured in LEP



NB_X+(rms=7um)
NB_X-(rms=4.5um)

STABIL2.XLS

X_stab

| * NAME | S | BETX | MUX | BETY | MUY |
|---|---|---|---|---|---|
| $ %16s | %e | %e | %e | %e | %e |
| @ GAMTR | %e | 54.3786 | | | |
| @ ALFA | %e | .338177E-03 | | | |
| @ XIY | %e | 1.73999 | | bunch displacement due to max b-b kick | |
| @ XIX | %e | 1.76691 | | | |
| @ QY | %e | 59.3200 | | | |
| @ QX | %e | 63.3100 | | | |
| @ CIRCUM | %1e | 26658.8640000 | | | |
| @ DELTA | %e | .000000E+00 | | | |
| @ TYPE | %08s | "OPTICS" | | | |
| @ COMMENT | %48s | " lhc version 6.-2 collision optics (thin lens)" | | | |
| @ ORIGIN | %20s | "MAD 8.20/0  HP/UX"  H | | V | |
| @ DATE | %08s | "24/03/99" | | | |
| @ TIME | %08s | "16.46.45" | | | |
| "IP1" | | .000000E+00 | .000000E+00 | .500012 | .000000E+0 |
| "PU.Q1.R1" | 22.6900 | .500017 | .246500 | 1030.15  22µ | .246478 |
| "Q1.R1" | 26.1500 | 1030.14  22µ | .246976 | 1485.21 | .246931 |
| "Q2A.R1" | 34.5500 | 1257.03 | .248068 | 4099.35 | .247476 |
| "Q2B.R1" | 41.0500 | 1173.06 | .248827 | 4542.92 | .247704 |
| "PU.Q3.R1" | 44.8100 | 1750.50 | .249106 | 3573.56  42µ | .247850 |
| "Q3.R1" | 50.4500 | 2708.35  37 µ | .249357 | 2237.68 | .248176 |
| "Q4.R1" | 169.550 | 4474.78 | .263742 | 1627.56 | .258474 |
| "PU.Q4.R1" | 171.560 | 361.375 | .264652 | 1551.83  28µ | .258674 |
| "Q5.R1" | 196.490 | 344.651  13µ | .278867 | 565.529 | .262969 |
| "PU.Q5.R1" | 199.200 | 220.474 | .280937 | 523.991  16µ | .263766 |
| "Q6.R1" | 229.490 | 194.614  10µ | .431509 | 278.682 | .276322 |
| "PU.Q6.R1" | 232.200 | 7.24741 | .498831 | 253.241 | .277942 |
| "PU.Q7.R1" | 258.484 | 6.04335 | .710371 | 57.5716 | .312866 |
| "Q7A.R1" | 262.174 | 121.260 | .714664 | 43.5312 | .324737 |
| "Q7B.R1" | 265.974 | 151.056 | .718511 | 38.5764 | .339845 |
| "PU.QD8.R1" | 301.144 | 156.555 | .848744 | 112.114 | .431187 |
| "PU.QF9.R1" | 340.209 | 14.3795 | 1.07097 | 37.3729 | .525683 |
| "PU.QD10.R1" | 380.674 | 125.982 | 1.15178 | 175.846 | .619940 |
| "PU.QF11.R1" | 433.759 | 43.0331 | 1.27271 | 47.5057 | .710709 |

**Beam separation around IP5**

RING 2

RING 1

Q5 MQ · DFB · Q4 MQ · D2 MBR · DQR · TAN · D1 MBXW · DFB · INNER TRIPLET · TAS · IP1 · TAS

29.9 · 23.839 · 9.45 · 73.625 · 23.9 · 30.6 · 23 · 23

3.225 · 3.4 · 0.7 · 4.2

ATLAS · ● BPM

TAS · IP1 · TAS · INNER TRIPLET · DFB · D1 MBXW · TAN · DQR · D2 MBR · Q4 MQ · DFB · Q5 MQ

23 · 23 · 30.6 · 23.9 · 73.625 · 9.45 · 23.839

4.2 · 3.4 · 3.225

1.9K 4.5K · 4.5K · 4.5K 1.9K
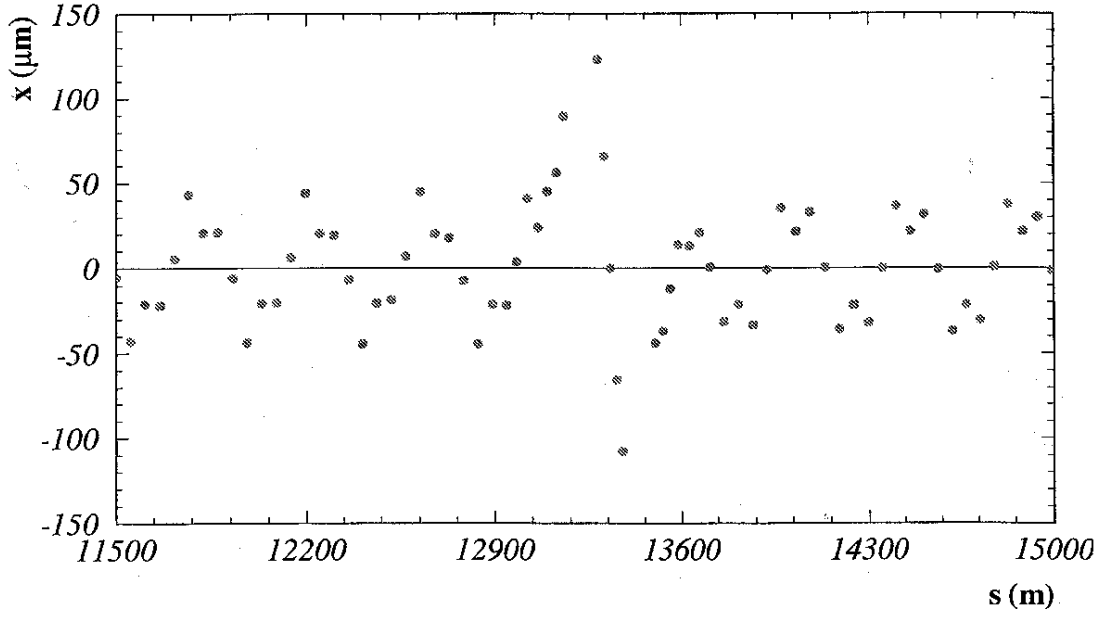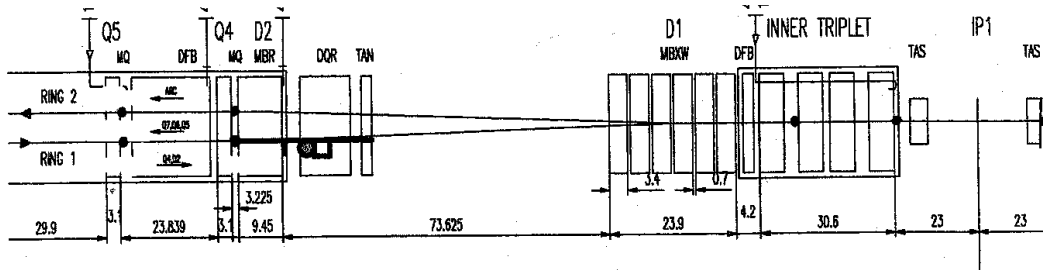
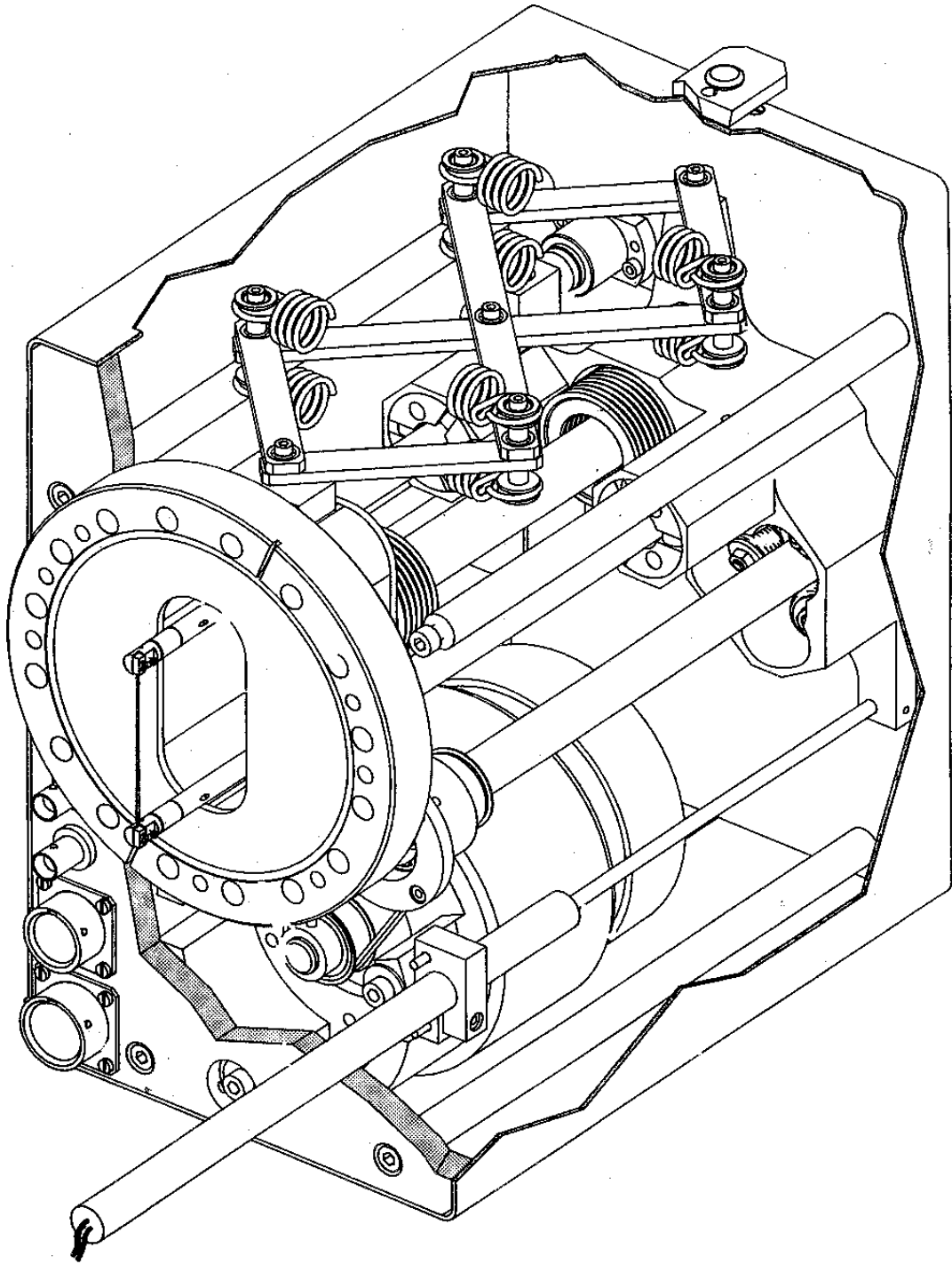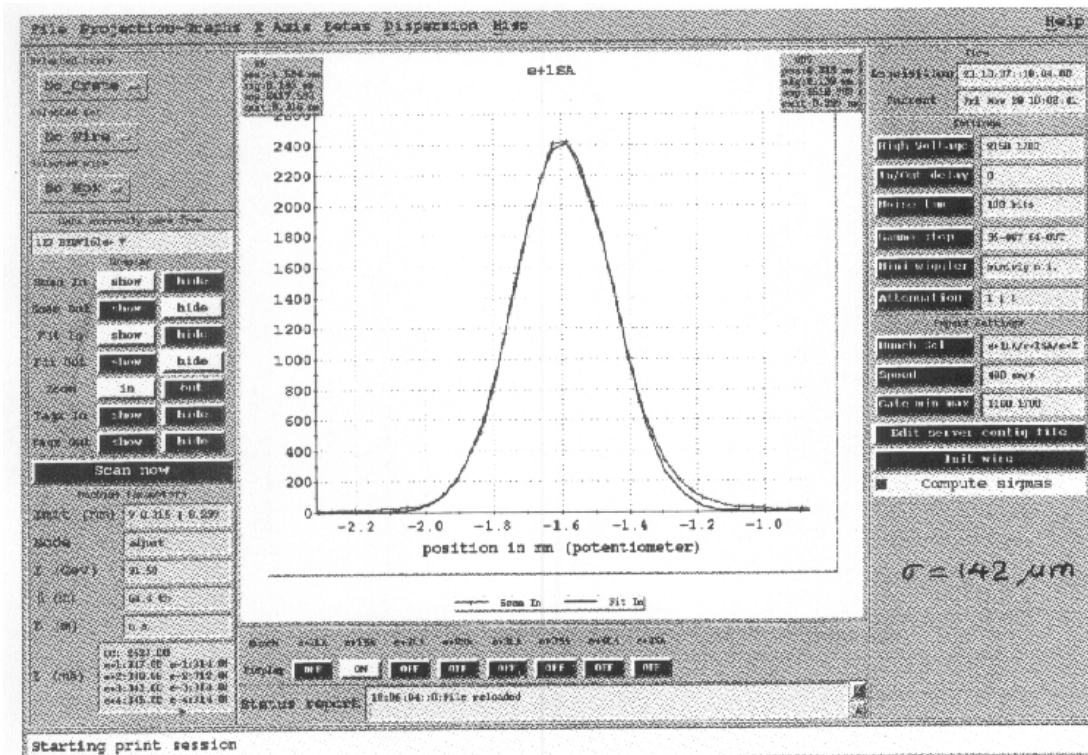0 · 20 · 40 · 60 · 80 · 100 · 120 · 140 · 160 · 180 · 200 m
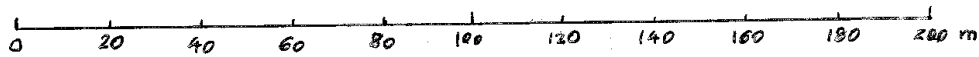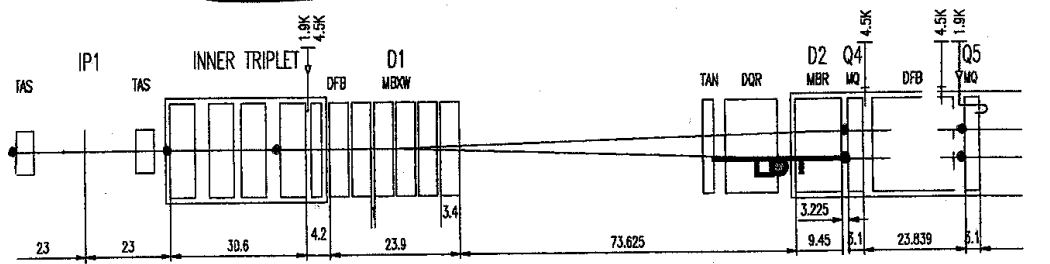
Emission      Detector

**BSRT :  Synchrotron  Radiation  Monitor : 35 m**

LEP wire scanner

# Beam Size Measurements



$\sigma = 142 \,\mu m$

# Production of synchrotron light in LEP dipoles
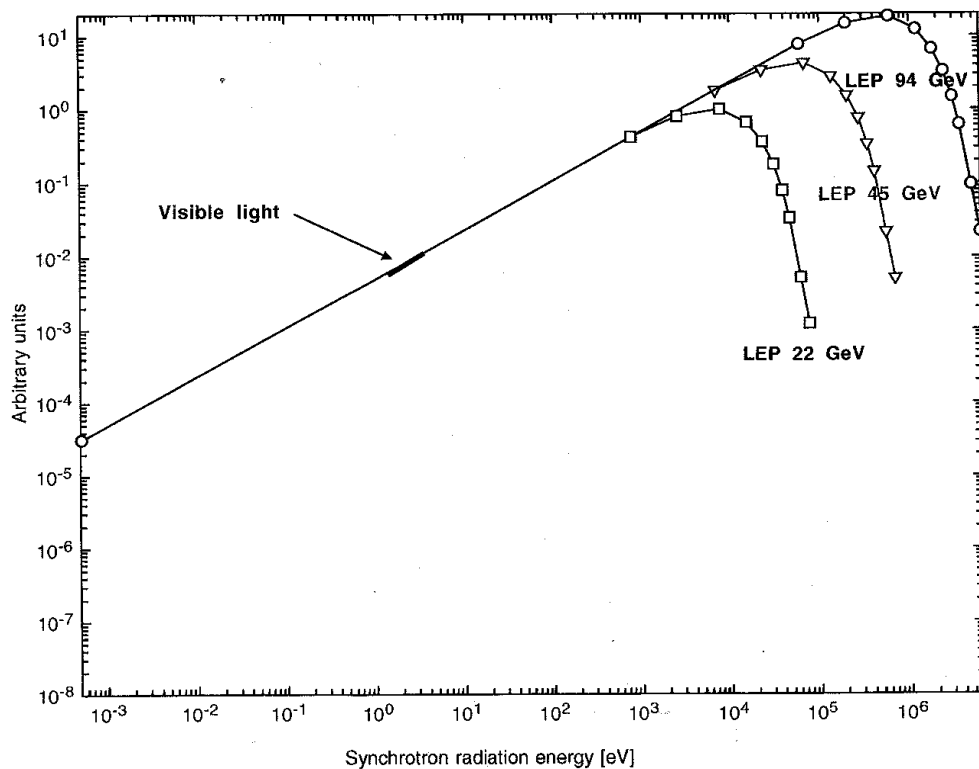


# Production of synchrotron light in LHC D2 dipoles

IP 1/5 →
at 136 m

RING 1
→

♦-3.4-♦  ♦------ 9.45 --------- ♦- 2.6 - ♦-- 3.8 - ♦  ♦-3.8 - ♦  ♦- 3.8 -♦   ♦-- 3.9 -♦
                                                0.5         0.5        1.0

♦--------------------- > 16 m  ?? ---------------♦

■ sourve  below  1 TeV     ▦ source above 1 TeV          ▮  extraction
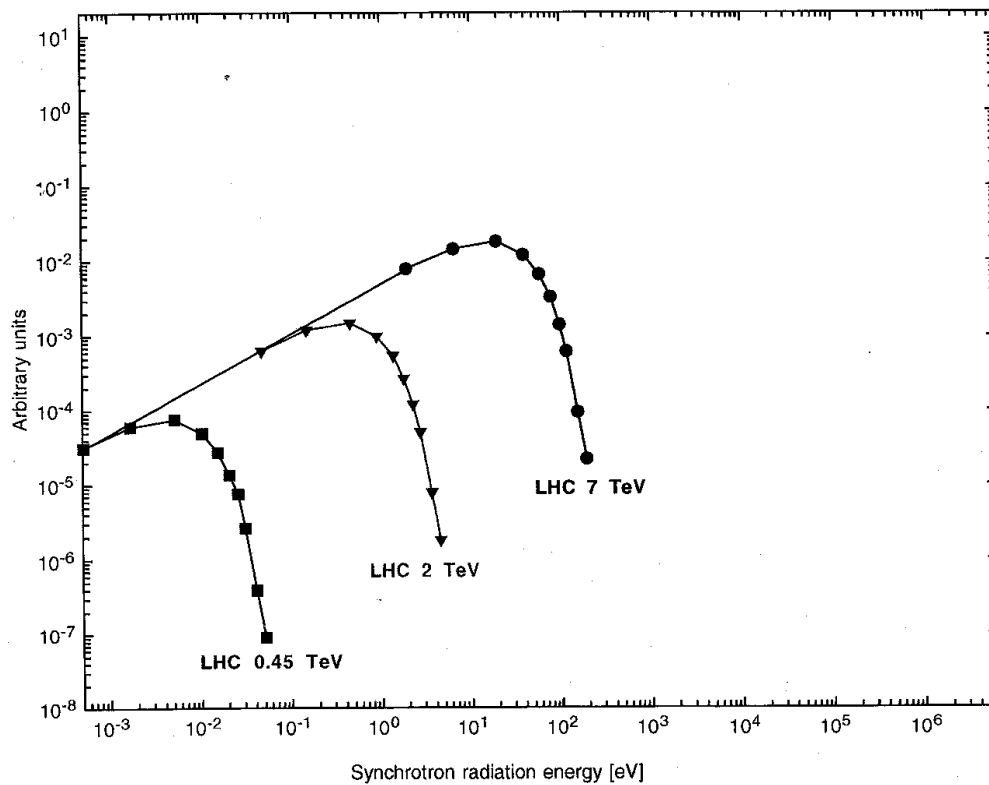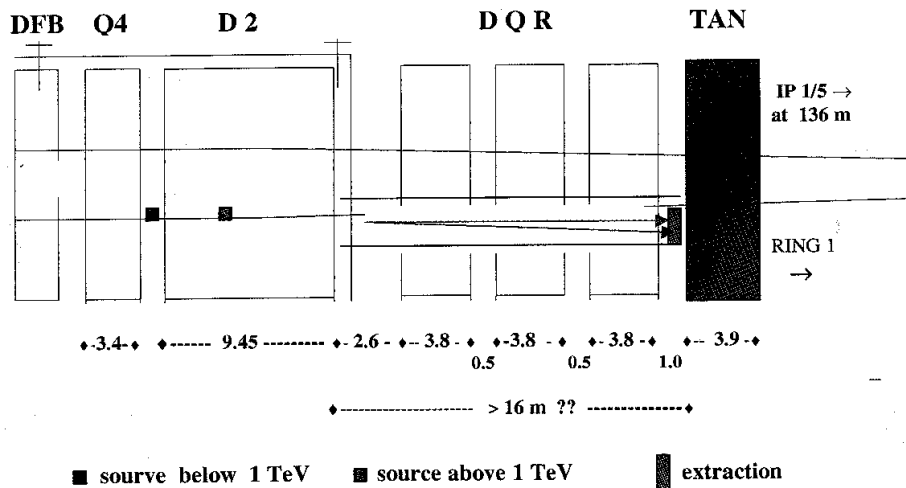
*Synchrotron Radiation Monitor Lay-out*
*in IR1 or IR5*

# Number of photons emitted at one bunch passage

$B = 3.3\ T$

$E = 7\ TeV$

$\rho = \dfrac{10\ p\ [GeV/c]}{3\ B\ [T]} = \dfrac{7\ 10^{4}}{10} = 7000\ m$

$\gamma = 7462$

$\lambda_c = \dfrac{4\pi\rho}{3\gamma^3} = 70\ nm$

$\lambda = 200\ nm$

$y = 70/200 = 0.35$

$k = \Delta\lambda/\lambda = 40/200 = 0.2$

$\Delta\varepsilon = k\ \varepsilon\ [eV] = \dfrac{k\ 1240}{\lambda\ [nm]} = .12\quad eV$

$N_{\Delta\varepsilon} = 10^{16}\ \gamma\ \lambda_c\ G_0(y)\ \Delta\varepsilon\ q\ [mC]\ \alpha\ [m\,rad]$

$q = 1.1\times10^{11}\times1.6\ 10^{-19} = 1.8\ 10^{-8}\ C$

$\alpha = \dfrac{1\ m}{7000\ m} = .14\ mrad$

$G_0(0.35) = 2.6$

$\boxed{N_\varphi = 10^{16}\ 7462\ 70\ 10^{-9}\ 2.6\ .12\ 1.8\ 10^{-5}\ .14 = 4\ 10^{6}}$

# FAST MULTI-PROFILES

PHOTO-MULTIPLICATEUR
MULTI-ANODES

Anode 1

Anode 16

AMP

AMP

ADC
8 bits

ADC
8 bits

RAM
8x16

RAM
8x16

CLOCK 40 MHz   Δt=25ns

Profil Vertical

1                    16

Optique

Beam

Feuille
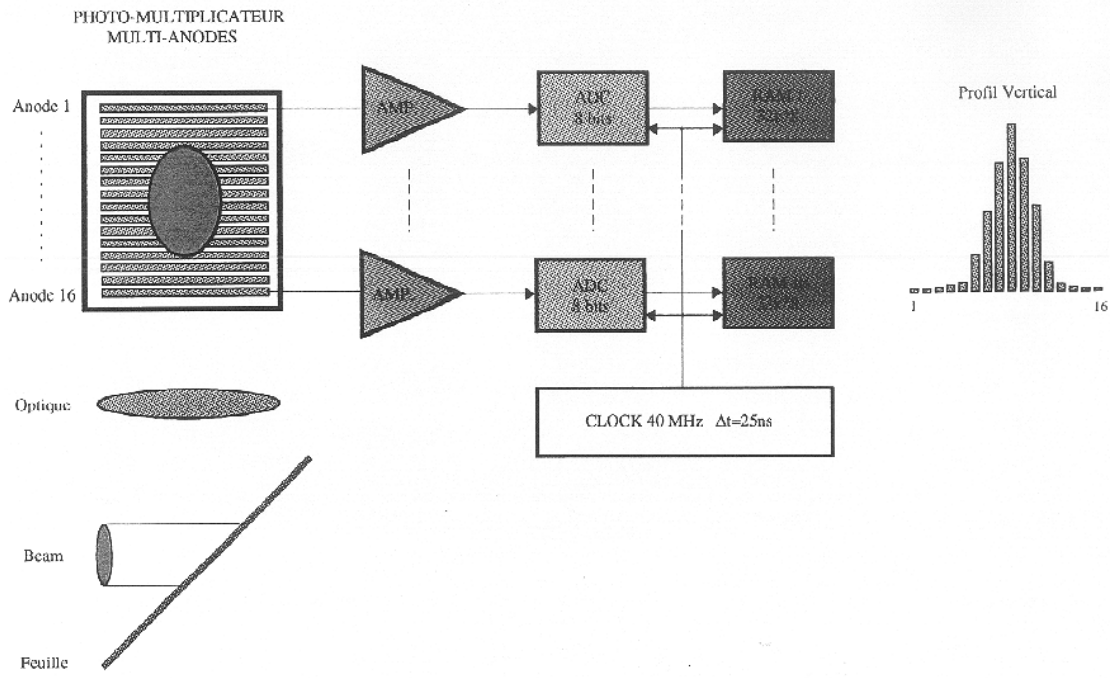
# Profile measurement with transverse ion beam



$Ar^+ \approx 1 nA$

$z$

$z_0$ $\vec{V_0}$

Ion

$\theta$

$z_f$

$r$

$x$

$O$

$S$

1  2  2

3

5

SPS : 0.27 A



Y1, Y2
PLATES

X1, X2
PLATES

APERTURE

A

OBJECTIVE
LENS (FOCUS)

DRIFT TUBE

DEFLECTOR
PLATE
(EX05F ONLY)

DEFLECTOR
BLOCK
(EX05F ONLY)

GUN BODY

DIFFERENTIAL
PUMPING RESTRICTOR

12 WAY
FEED THROUGH

GAS FEED
RESTRICTOR
(EX05F ONLY)

CONDENSER
LENS

SOURCE
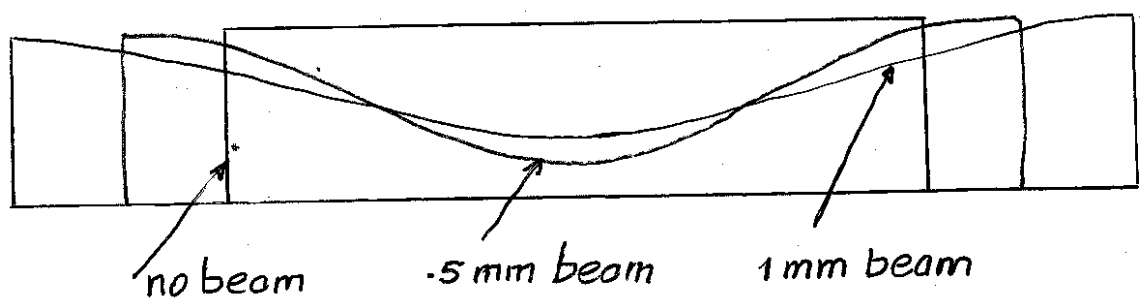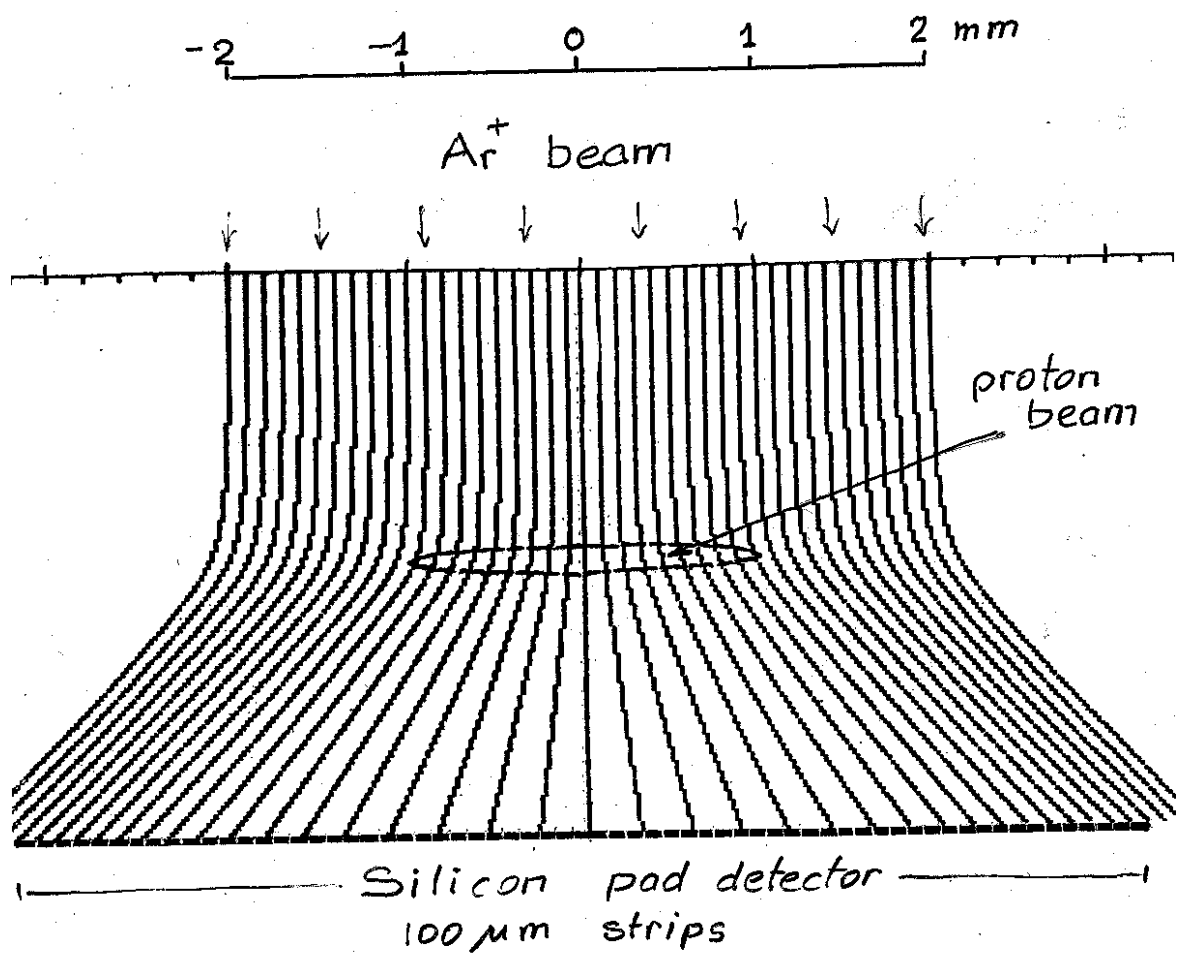ASSEMBLY

EXTRACTOR

ION SOURCE
COVER

GAS
CONNECTOR

ION SOURCE
MESH PLATE
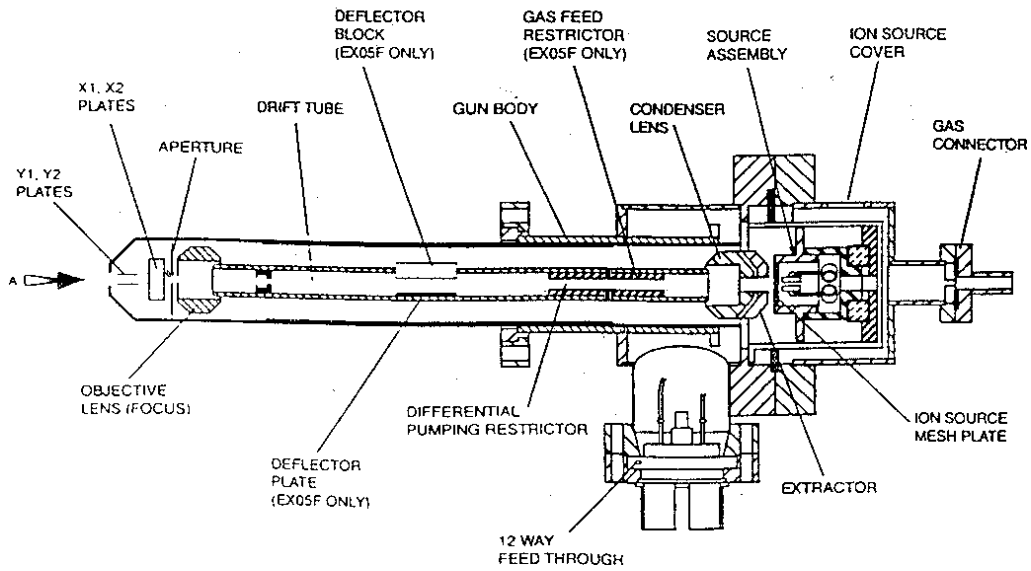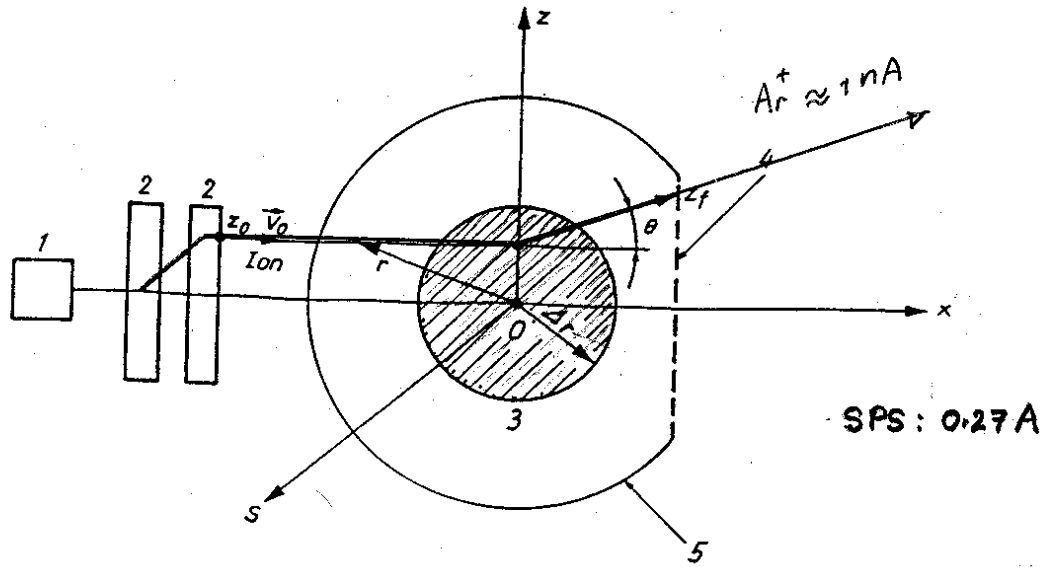
**Deflection of 2 keV ions vs impact parameter (N=(3.7-3.8)*10^13 during the measurement and n=8.93*10^9 ppb for calculations, Ti=3200-4200 ms)**



*measured Aug. 98*

- Experimental deflection , mrad
- Calculation, RMS=1 mm
- Calculation, RMS=2 mm
- Calculation, RMS=3 mm

Deflection, mrad

Impact parameter, mm
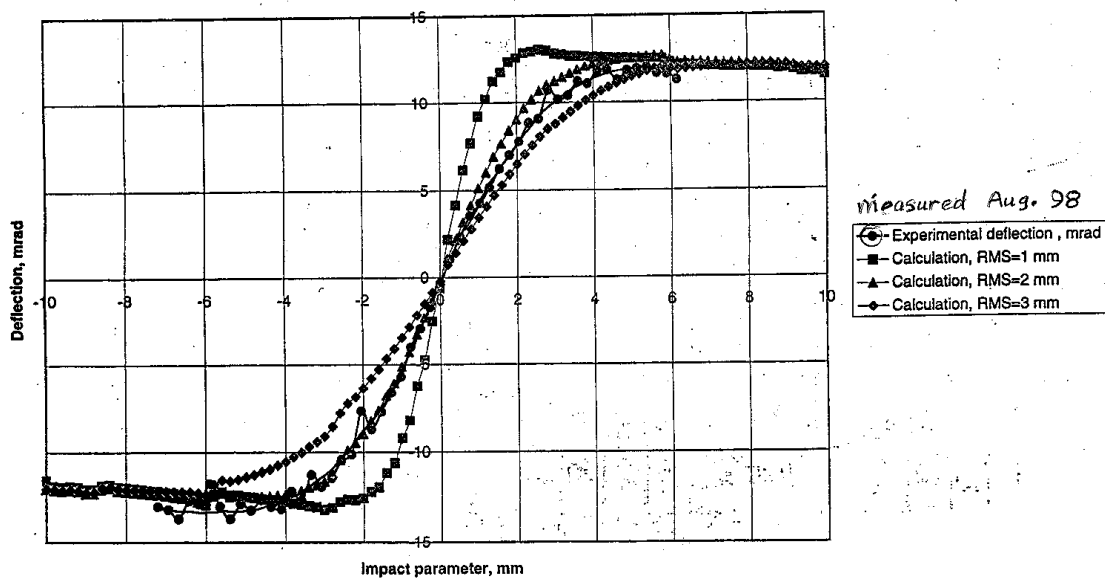
## Ion (Xe) profile on detector



σ=0.5 mm
σ=1 mm
σ=2 mm

Normalized ion density

Tranverse position in millimeters

-2    -1    0    1    2 mm

Ar⁺ beam

proton beam

Silicon pad detector
100 μm strips

no beam    .5 mm beam    1 mm beam
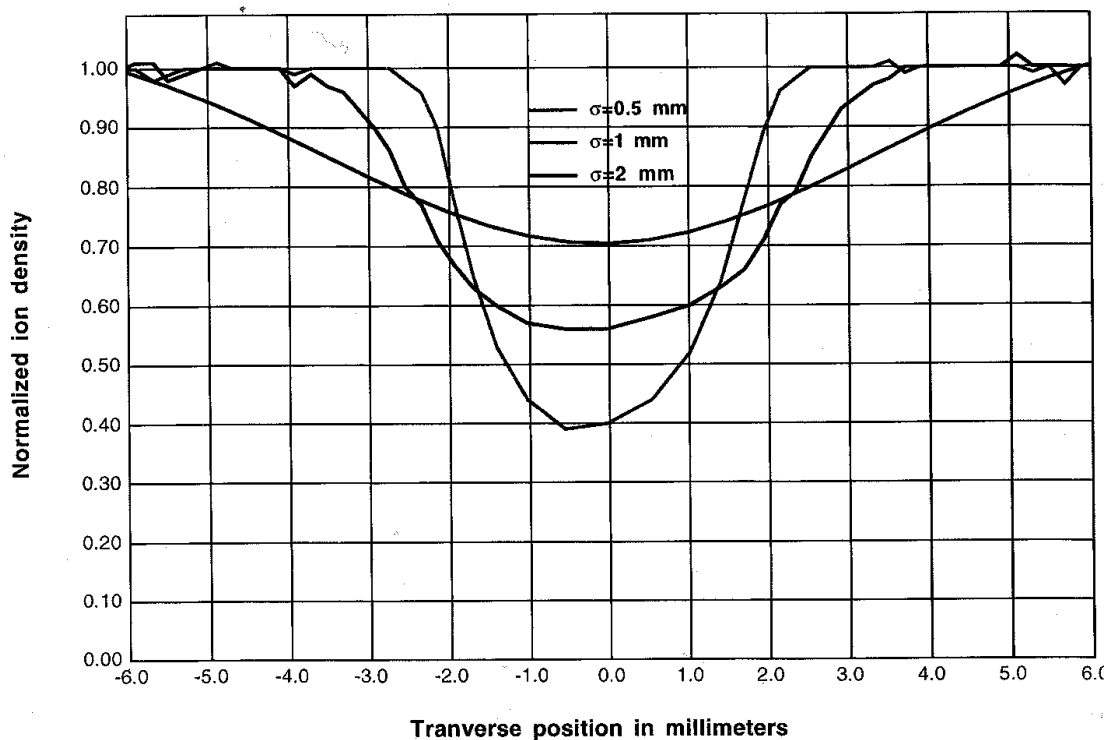
# Beam size measurement device

$\phi = 100\,mm$

Vacuum chamber

residual gas $\approx 10^{-8}\,Torr$

magnetic shielding

$\sim 2000/s$

$H^+$

beam

$i \approx 500\,mA$

$\sigma = 300 - 1200\,\mu m$

magnetic field $\sim 300\,G$

magnet core

magnet windings

cation detector

$10^2 \times (v/c)^2$

$v^2$

·32
·30
·28
·26
·24
·22
·20

·4  ·6  ·8  1          2 mm

$\sigma$
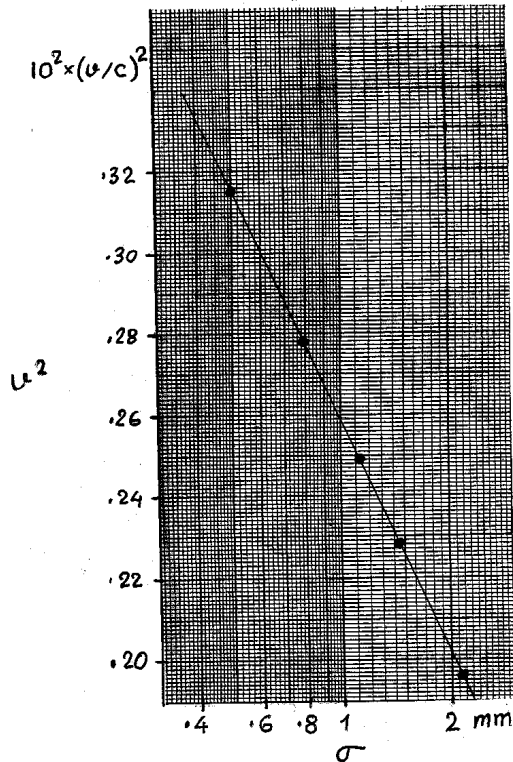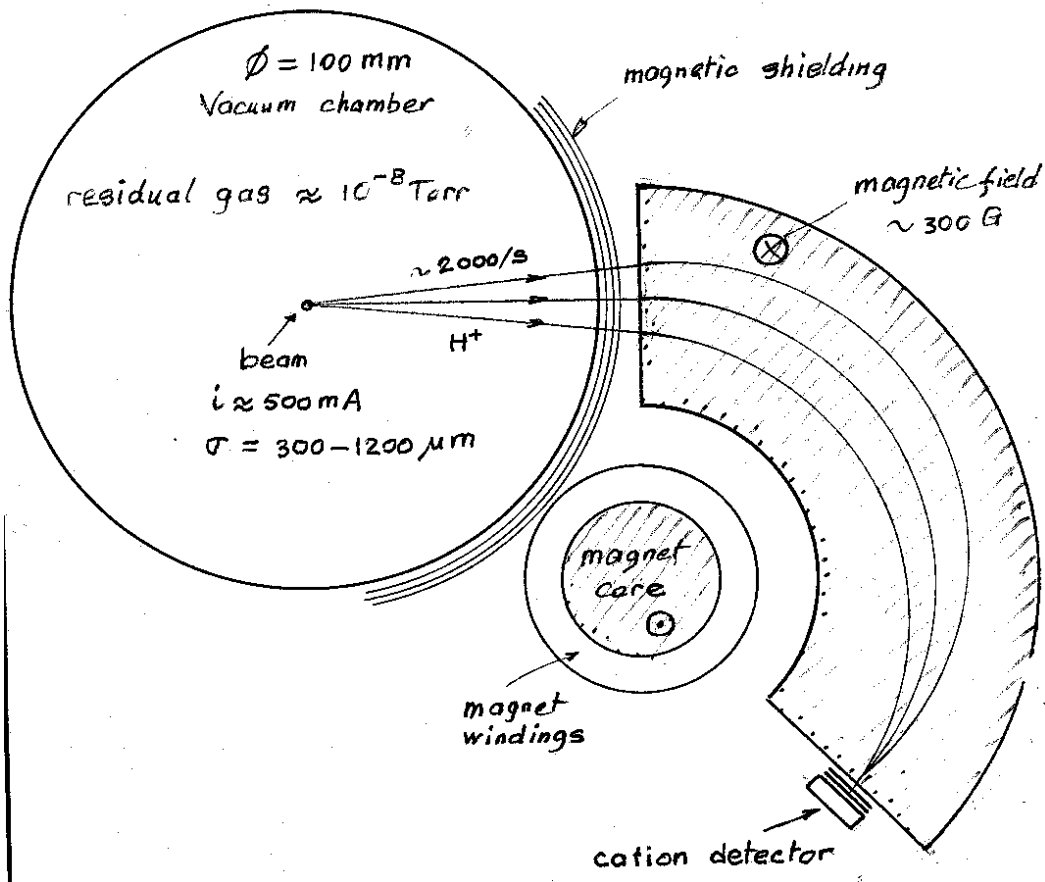
For round beam

$v^2 = A - \alpha \ln \sigma$

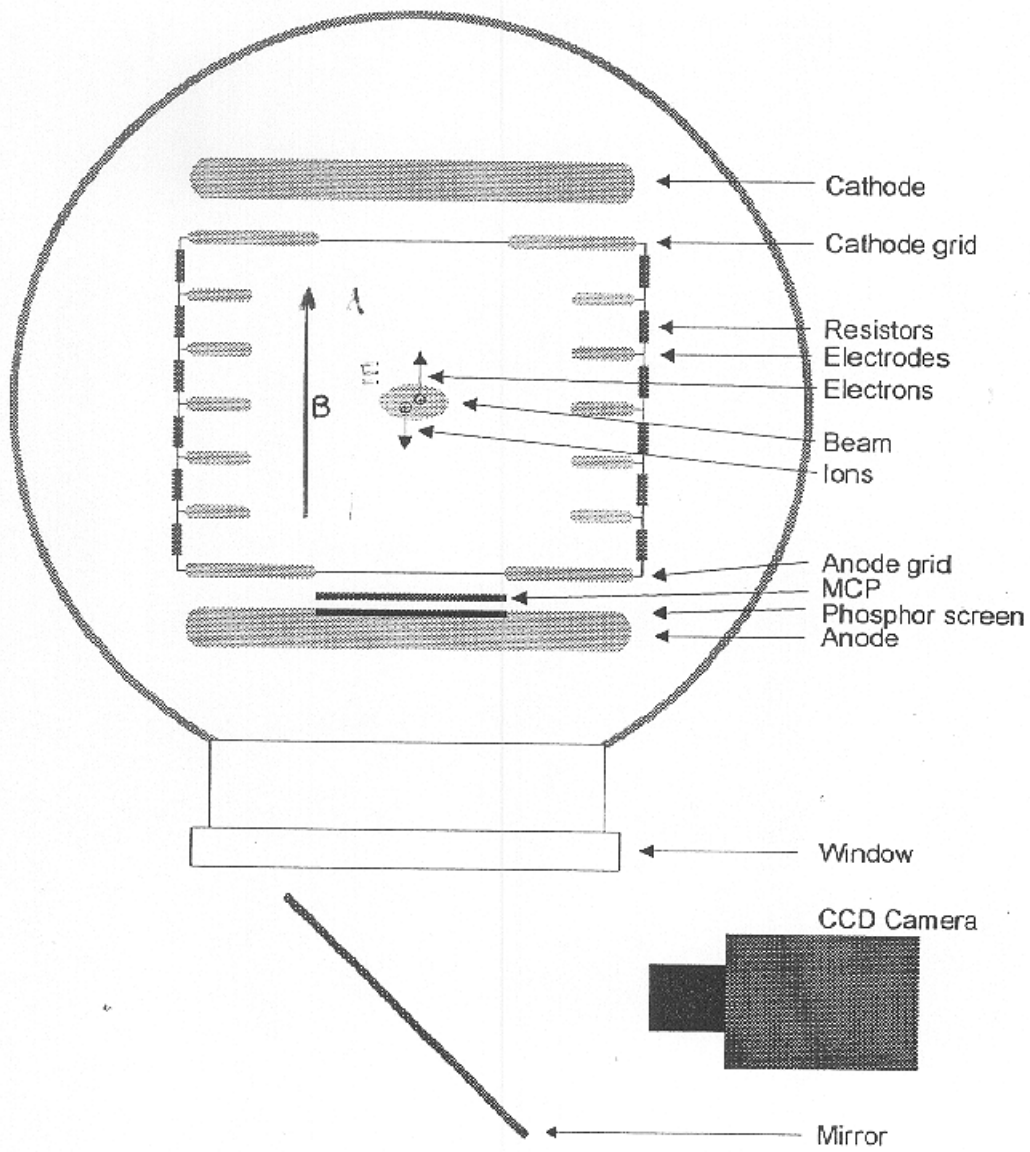$v^2 = (\cdot 258 - \cdot 0816 \ln \sigma) \times 10^2$

For elliptical beam

$v^2 = A - \alpha \ln\left(\frac{a+b}{2}\right)$

Sensitivity

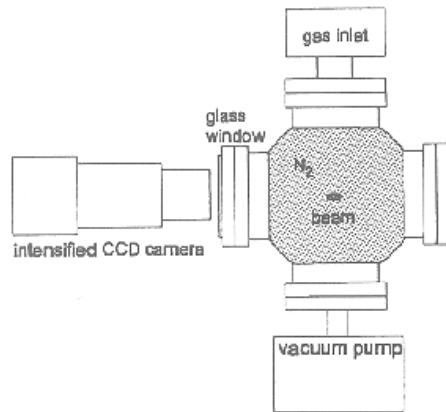$\dfrac{d\sigma}{\sigma} = \dfrac{2v^2}{\alpha}\dfrac{dv}{v}$
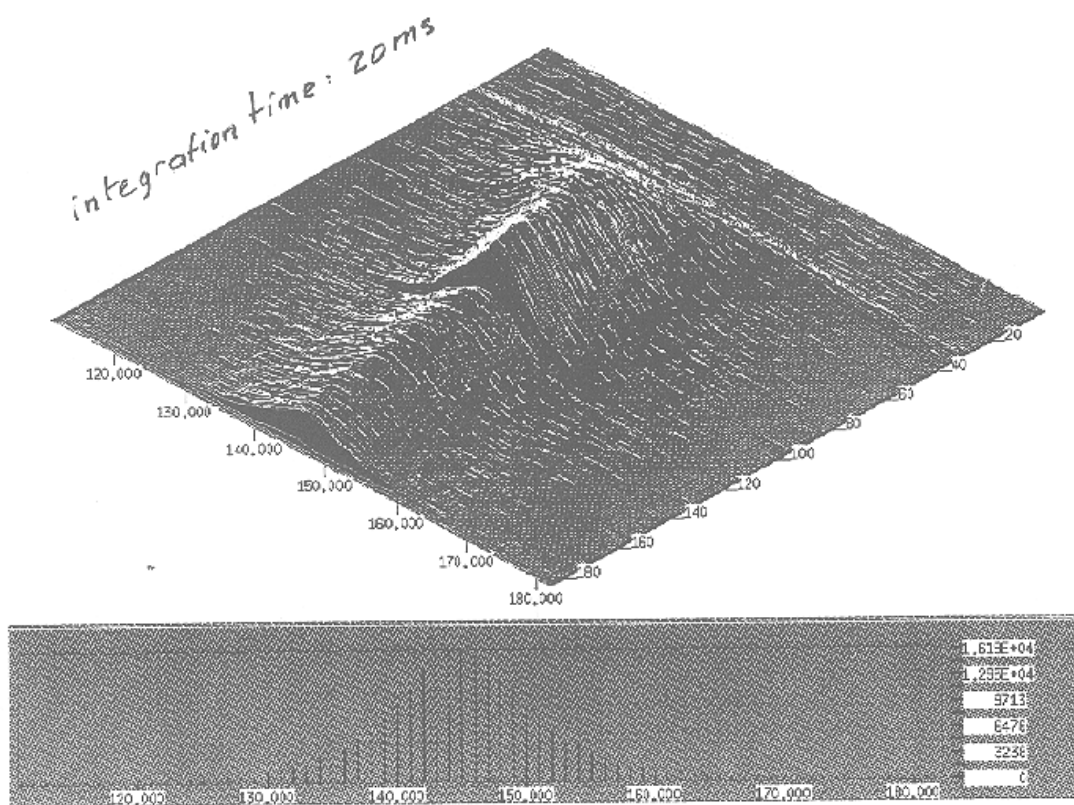
6.4  for $\sigma = 1\,mm$

9.5  for $\sigma = 200\,\mu m$

Cathode

Cathode grid

Resistors
Electrodes
Electrons

Beam
Ions

Anode grid
MCP
Phosphor screen
Anode

Window

CCD Camera

Mirror

DESY Restgas Ionisation Profile Monitor used at CERN

# LSS4 Luminescence Gas Test Monitor



$$I_b = 2 \times 10^{13} \rho$$

integration time: 20ms



| | |
|---|---|
| | 1.619E+04 |
| | 1.295E+04 |
| | 9713 |
| | 6476 |
| | 3238 |
| | 0 |

$\sigma = 860 \mu m$

Preliminary results with Nitrogen at $10^{-5}$ to $10^{-6}$ Torr