# MI Large Aperture Quad (WQB) Project

## Part 2 – Installation & Operation

*Beams-doc #2479*

# AD Credits

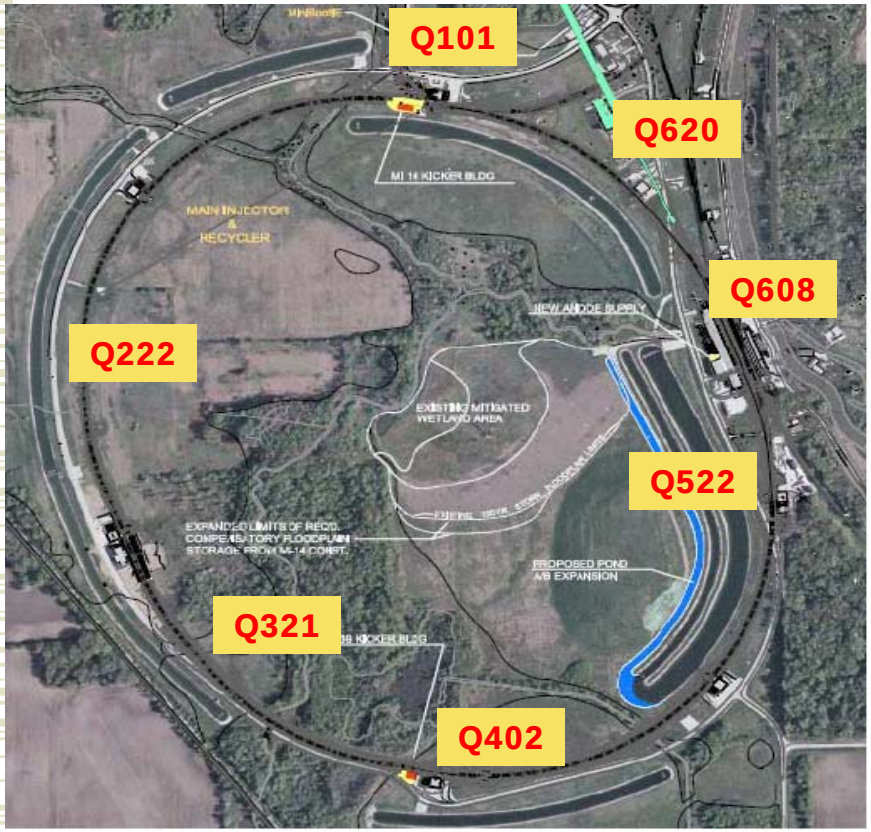
- **Mechanical Support:** *L. Valerio, L. Nobrega, M. Albertus and the installation group*
- **Electrical Support:** *L. Bartelson, D. Wolff*
- **Instrumentation:** *J. Fitzgerald, J. Crisp, R. Webber, M. Wendt, M. Olson*
- **ES&H:** *D. White*
- **Survey:** *T. Sager and C. Wilson and their group*
- **MI:** *I. Kourbanis, B. Brown, D. Capista, M. Yang*
- **Other Depts:** *B. Hendricks, D. Johnson, F. Ostiguy, P. Prieto, R. Andrews*
- Funded by the **Proton Plan**.

# Celebration of Completion of WQBs

# Scope of the WQB Project

- To design, fabricate and bench-test 9 WQBs
- To design, fabricate and bench-test 9 EXWA BPMs
- To install 7 WQBs and 7 EXWA BPMs during the 2006 shutdown (the rest for spares)
- To install 7 trim coil power supplies
- To commission the WQBs and new BPMs

# Location of WQBs

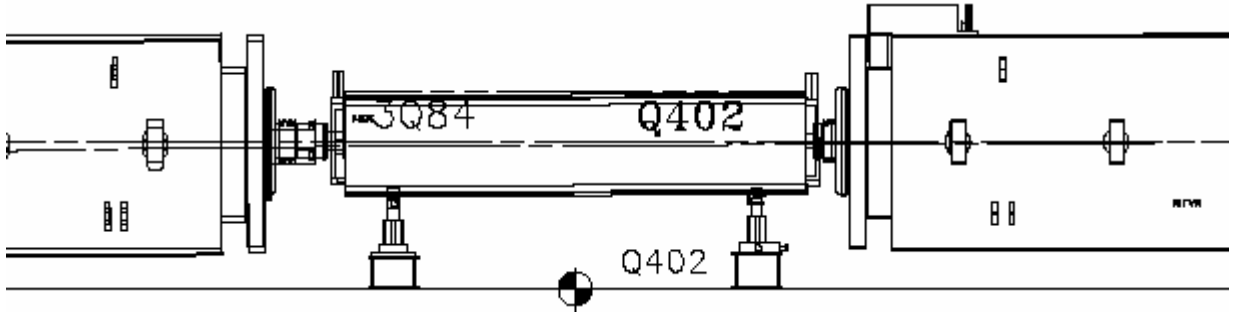



Q222

# WQB, New BPM and the Old Quads

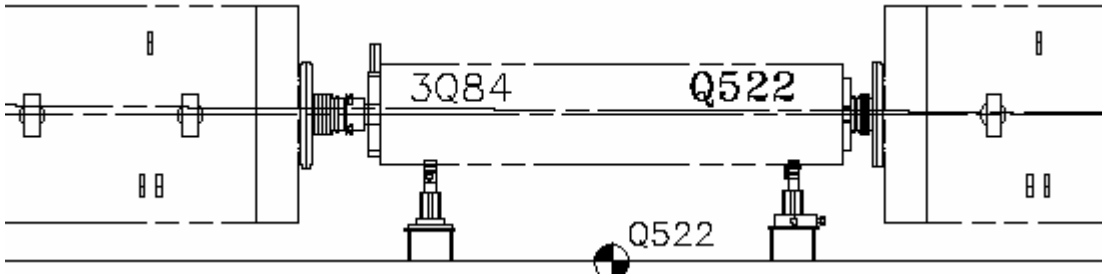
| Location | WQB Serial No. | EXWA BPM Serial No. | Old Quad Serial No. | Old Quad Radioactivity |
|---|---|---|---|---|
| Q101 | WQB 001 | EXWA 01 | IQG 333 | CLASS 2 |
| Q222 | WQB 007 | EXWA 07 | IQB 045 | CLASS 2 |
| Q321 | WQB 006 | EXWA 08 | IQB 071 | CLASS 1 |
| Q402 | WQB 004 | EXWA 04 | IQE 065 | CLASS 3 |
| Q522 | WQB 003 | EXWA 02 | IQE 072 (*) | CLASS 2 (*) |
| Q608 | WQB 005 | EXWA 05 | IQE 225 | CLASS 2 |
| Q620 | WQB 002 | EXWA 06 | IQE 134 | CLASS 3 |

(*) IQE 072 was relocated from Q522 to Q521. The old quad at Q521 was IQB 177, which was removed from the ring and is a CLASS 2 magnet.



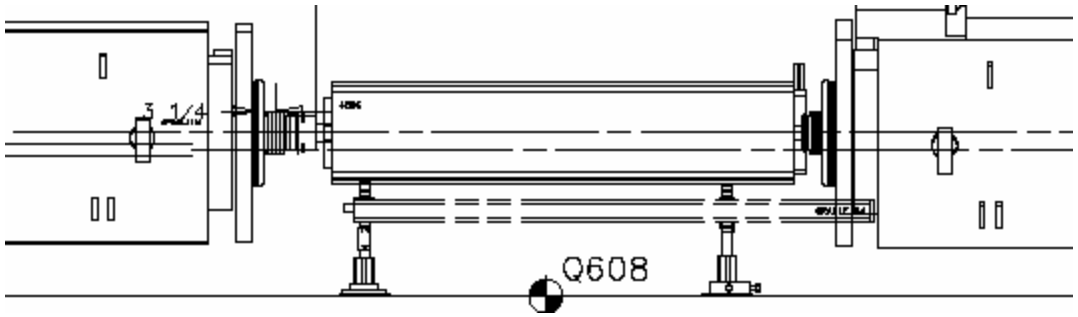

**IQE**

**wide BPM to be replaced**



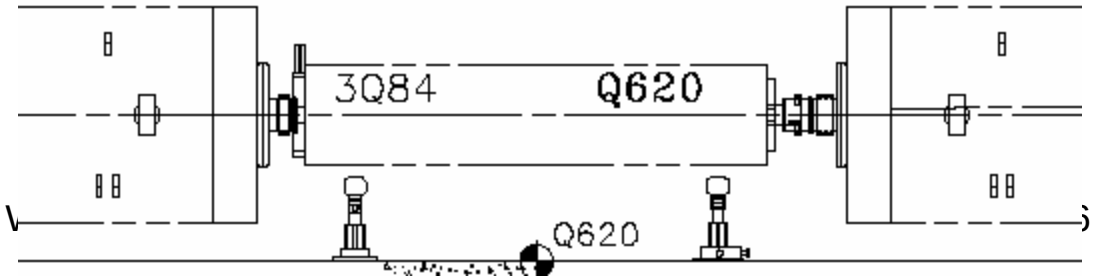

**IQE**

**wide BPM to be replaced**



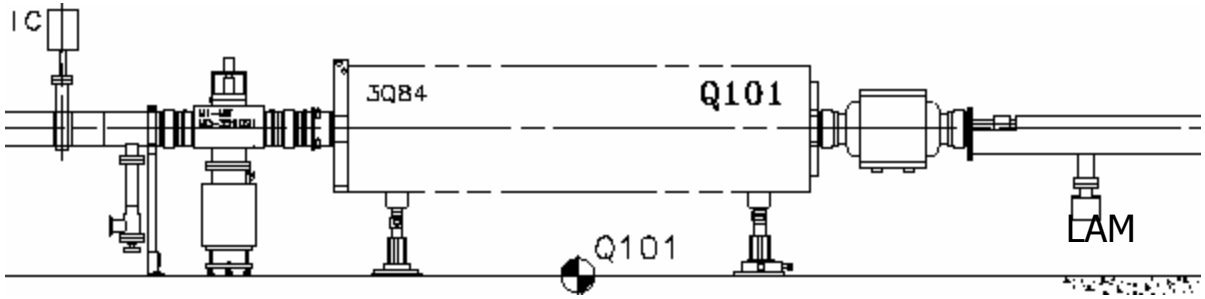

**IQE**

**wide BPM to be replaced**



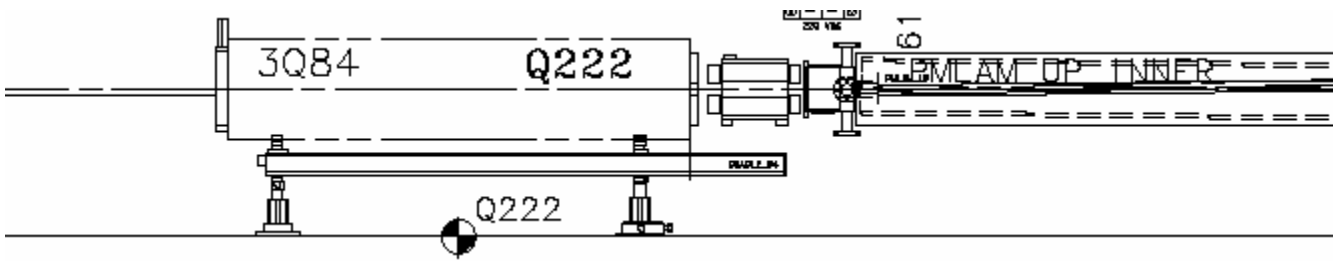

**IQE**

**wide BPM to be replaced**



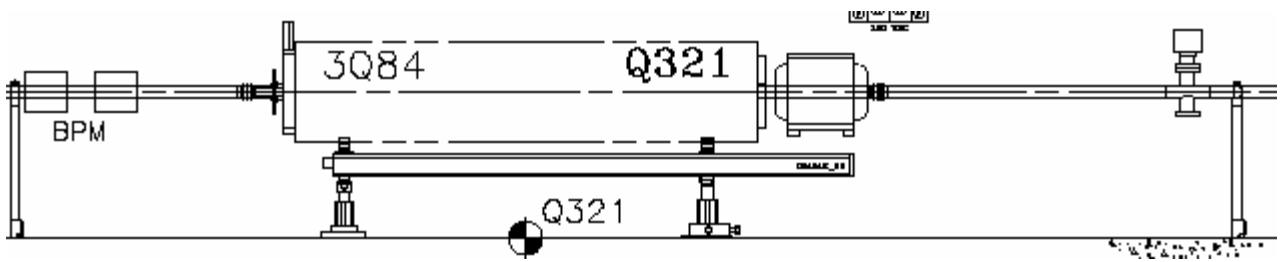

**IQG**

**wide BPM to be replaced**




**IQB**

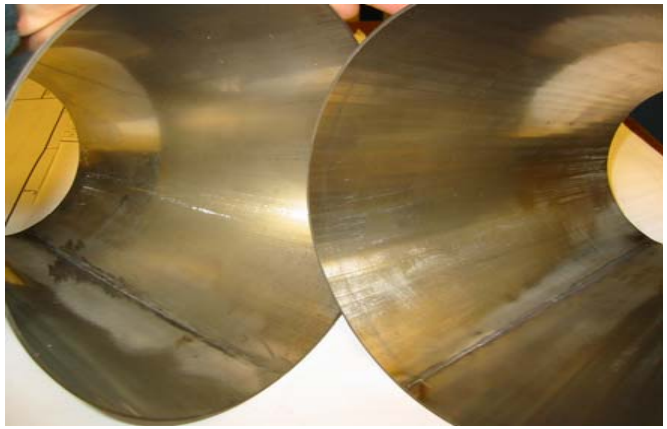
**normal BPM to be replaced**

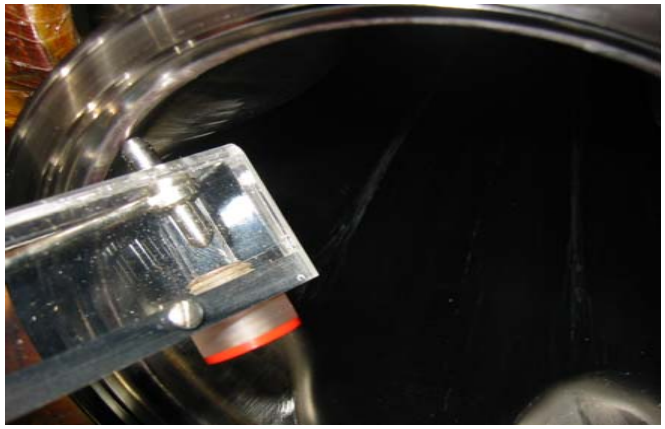



**IQB**

**normal BPM to be replaced**

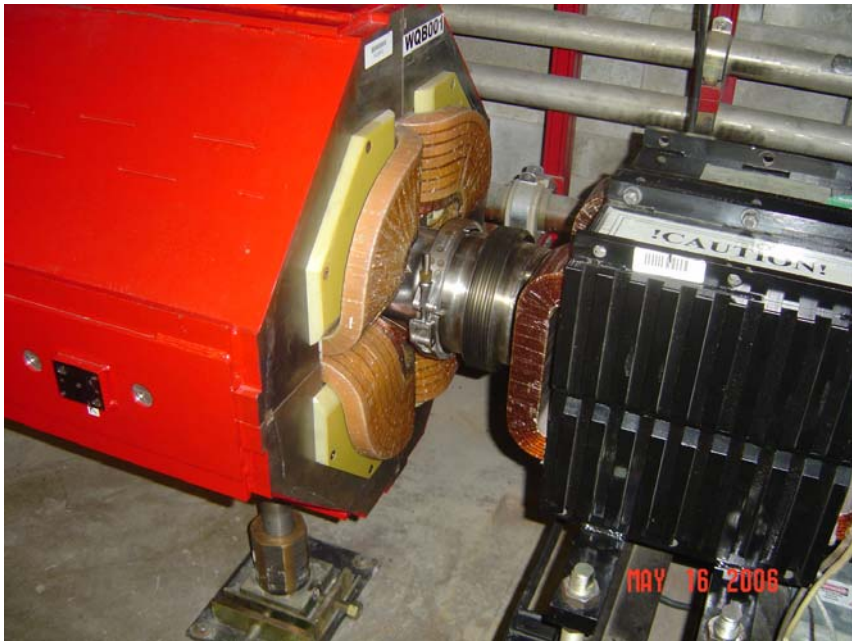
# De-magnetize Cone Welding (L. Valerio)



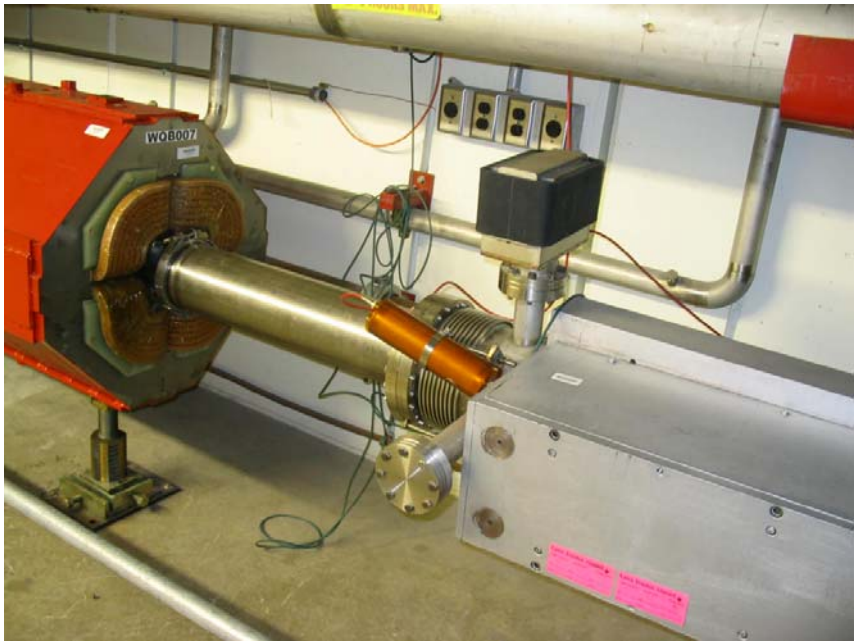


- Lessons from LEP (CERN) and DESY3 (DESY) in early '90s
- All transition pieces were heat treated before installation
- Before heat treatment:
  μ(weld) = 1.10 ~ 1.15
- After heat treatment:
  μ(weld) < 1.01

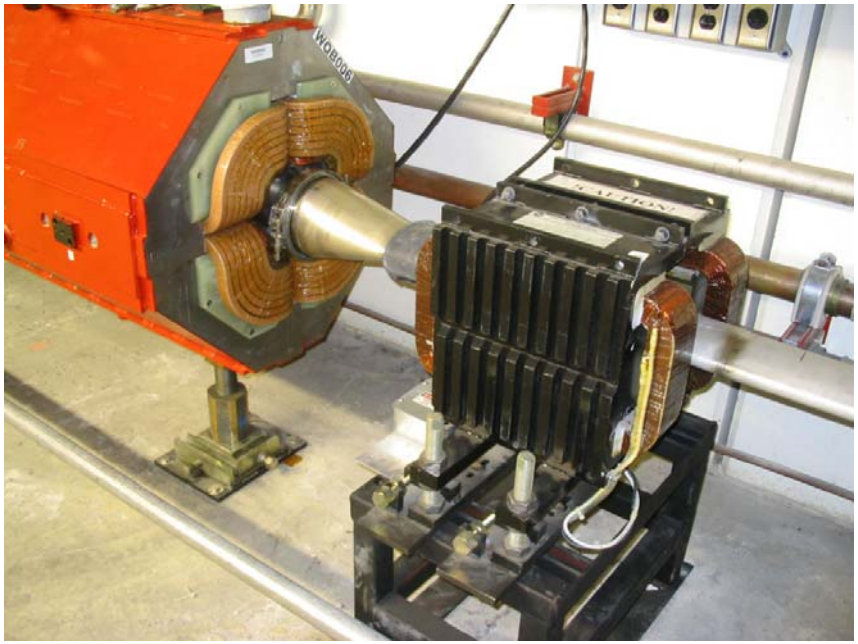
# BPM 101 (EXWA 01, WQB 001)



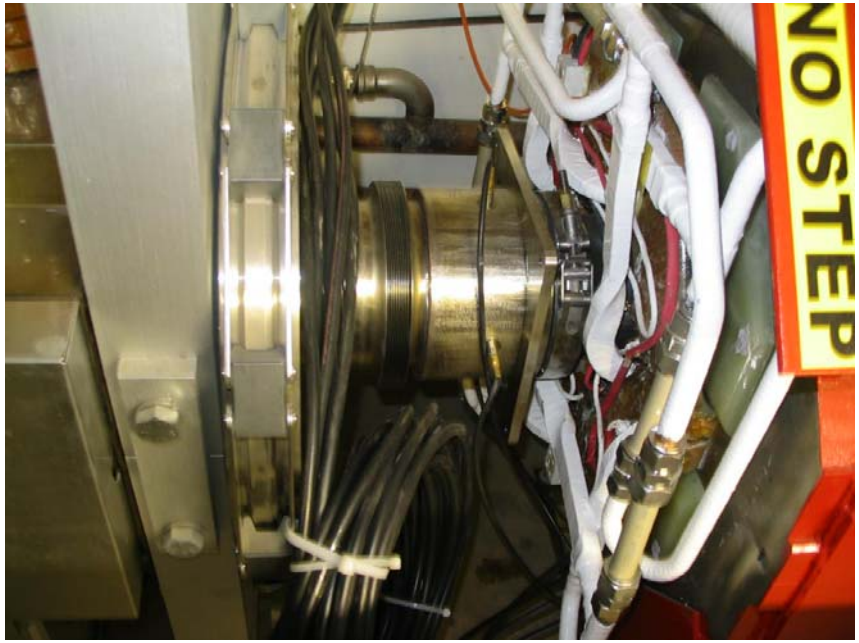
# BPM 222 (EXWA 07, WQB 007)

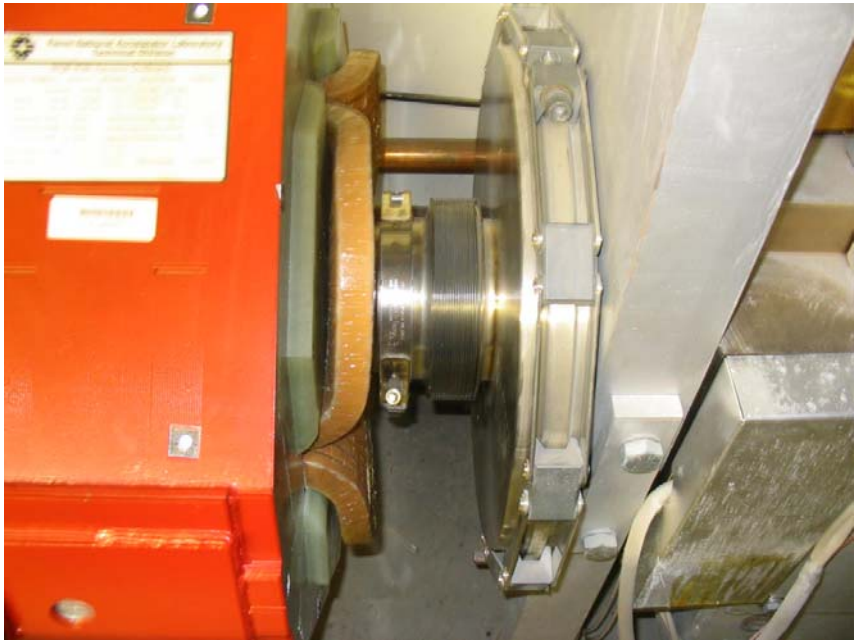


# BPM 321 (EXWA 08, WQB 006)

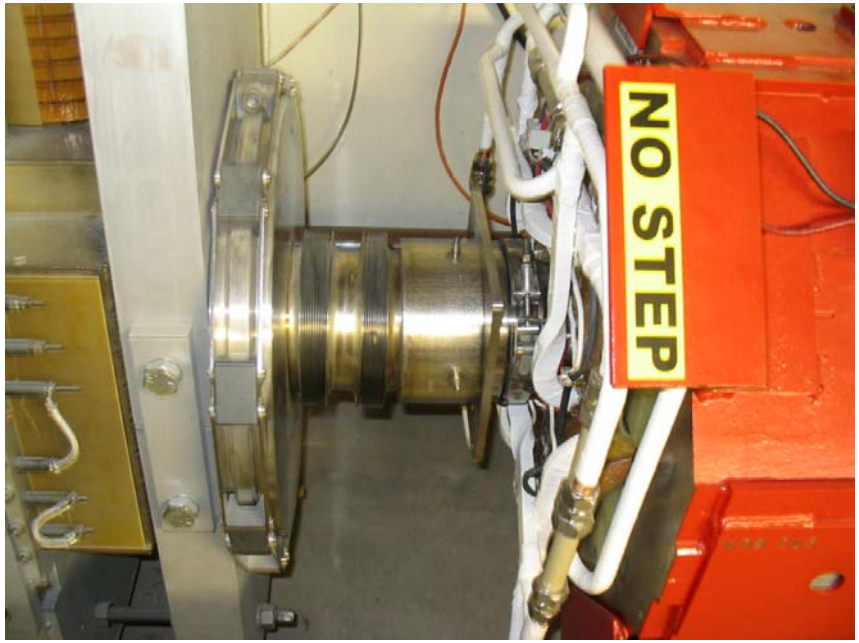


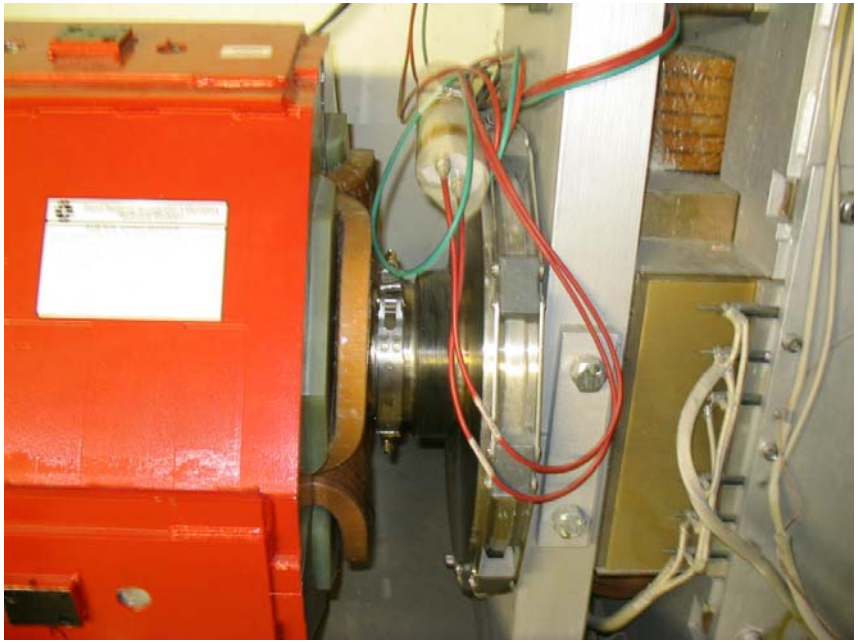
# BPM 402 (EXWA 04, WQB 004)



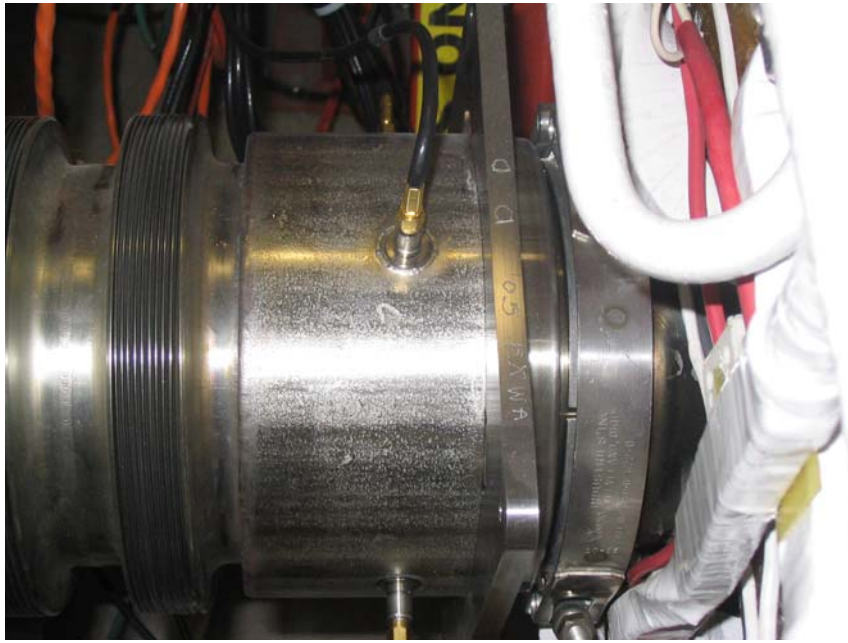



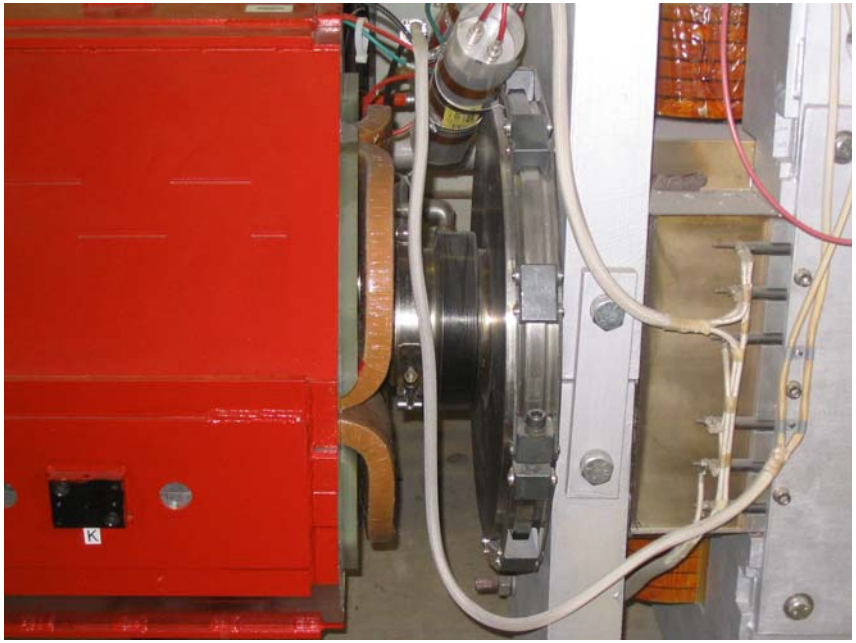
# BPM 522 (EXWA 02, WQB 003)



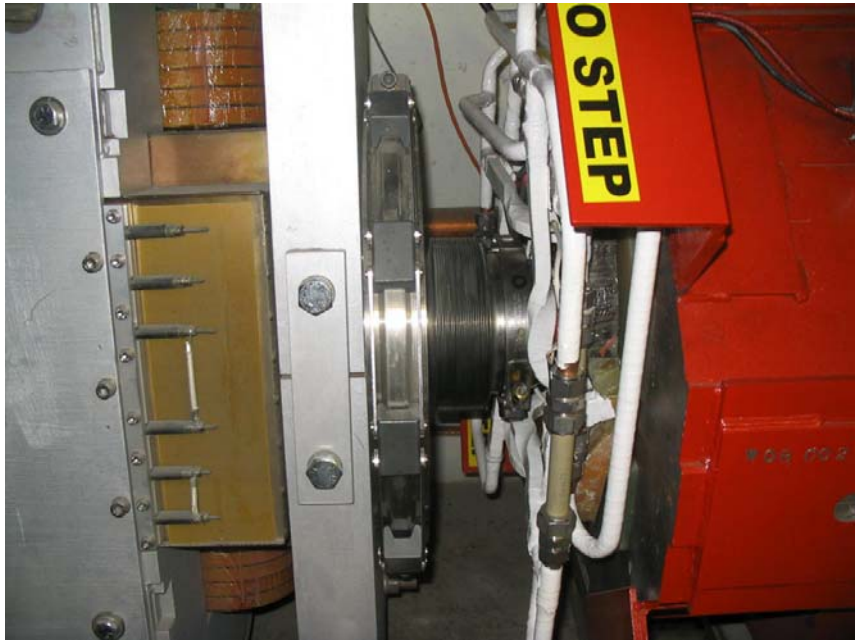



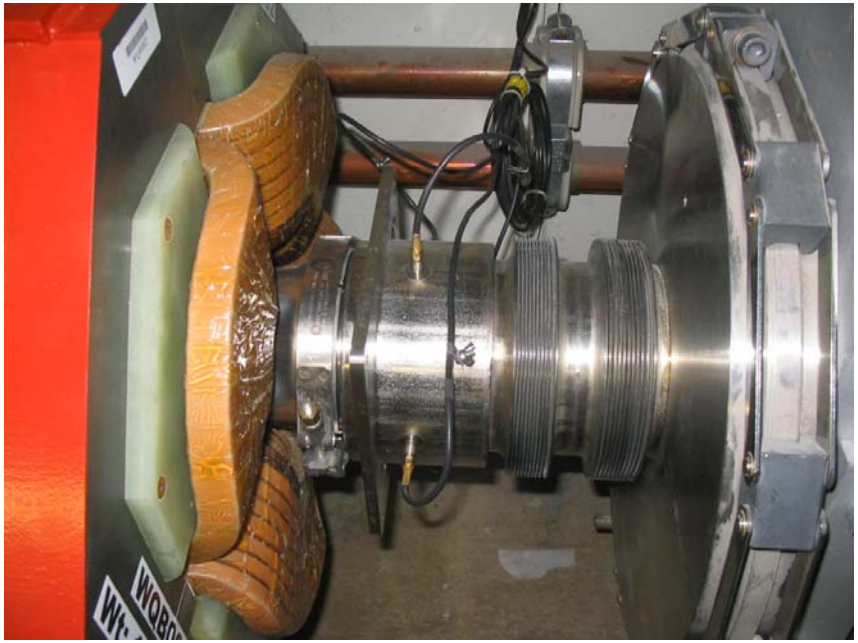
# BPM 608 (EXWA 05, WQB 005)





# BPM 620 (EXWA 06, WQB 002)



# Electron Probe downstream from Q521 (IQE)

Electron probe

# WQB Field Quality Requirements

1. Large good field region: ± 2″ (an increase of ±10 mm)
2. Small tracking error throughout the cycle: integrated field error w.r.t. IQB < 10 units (0.1%)

*Estimate of lattice perturbation*

- One WQB at location 1with integrated field error of 1%:

  $q = B'L/B\rho \times 1\% = 0.001\ \mathrm{m}^{-1}$

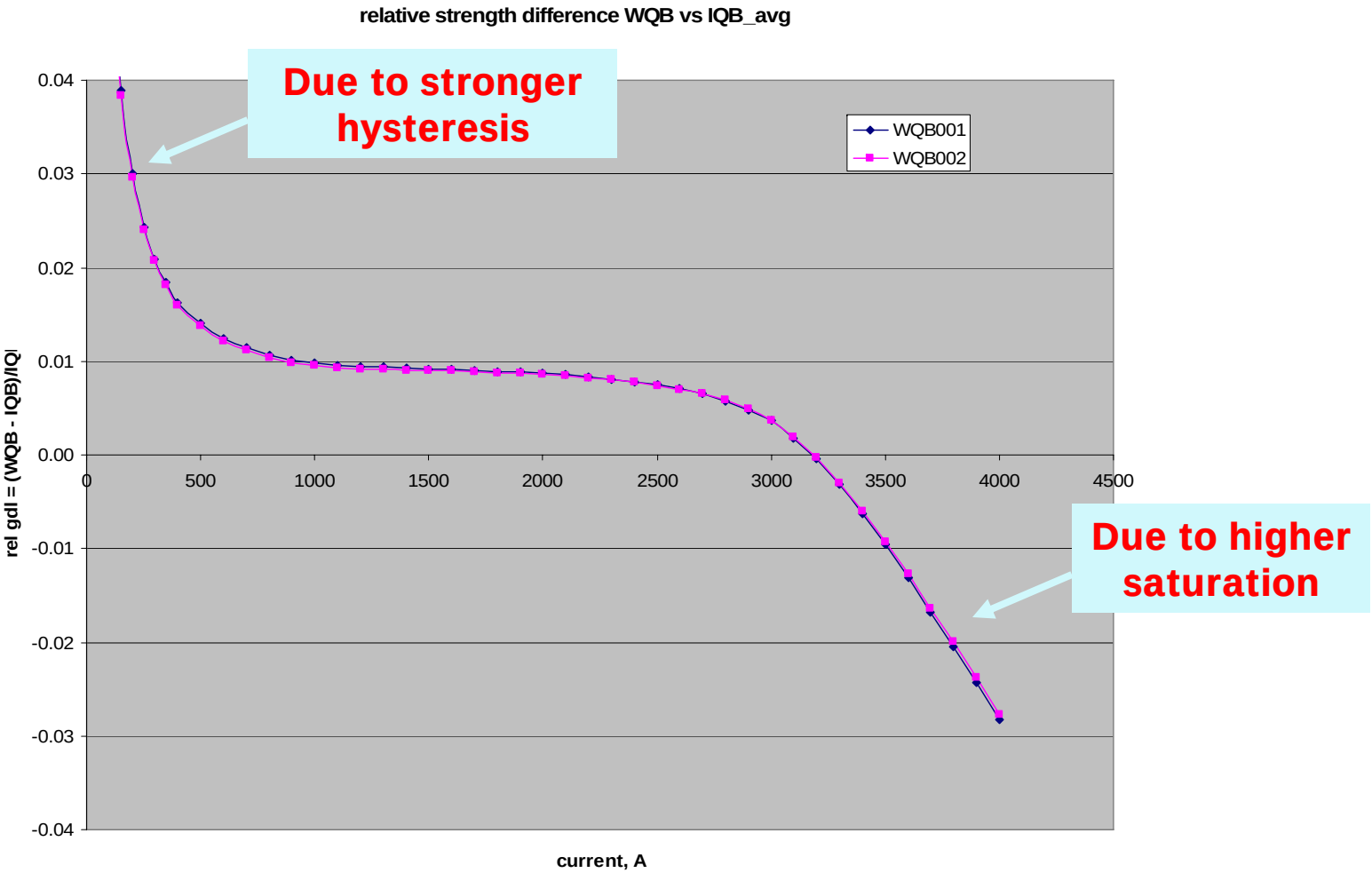
- Tune change:

  $\Delta\nu(x) = q \times \beta_1 / 4\pi = 0.0045$

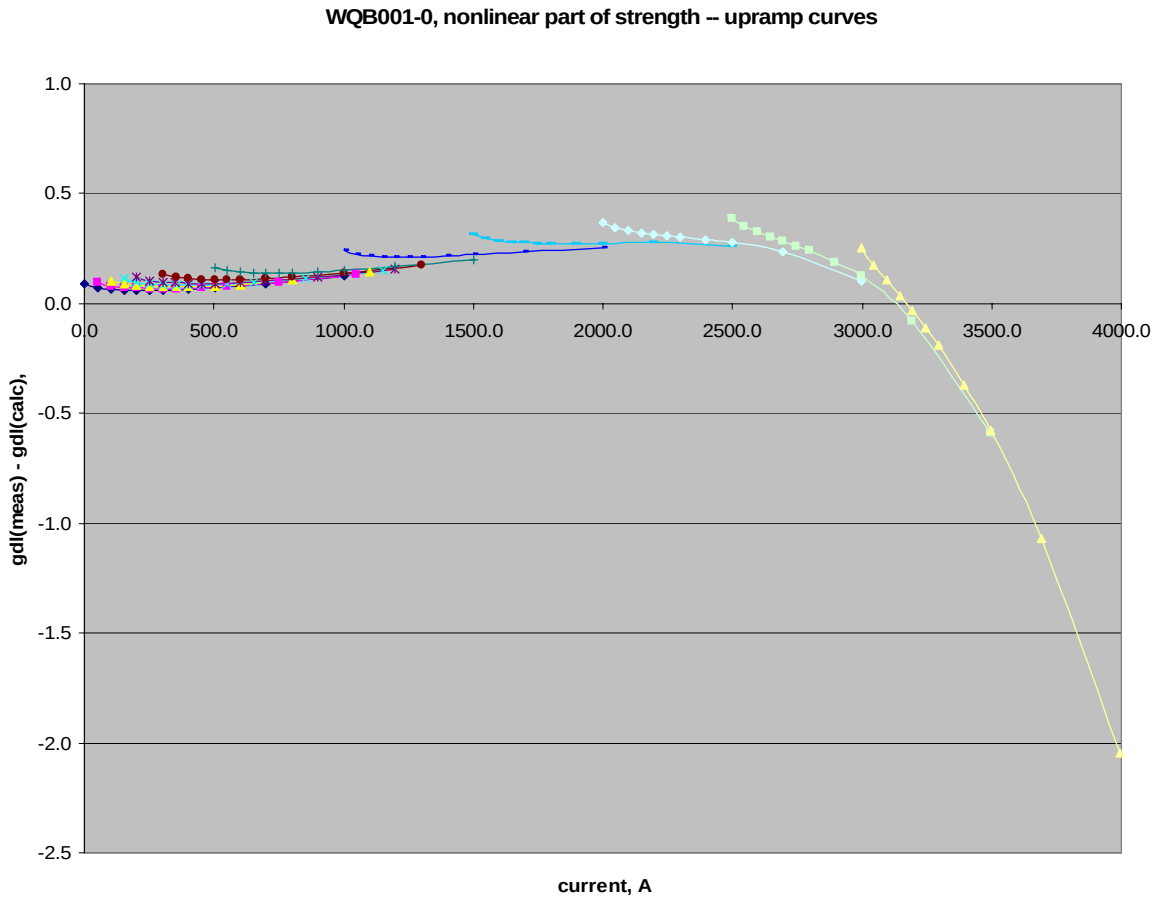
  Beta-wave at location 2:

  $\Delta\beta_2 / \beta_2 = -q \times \beta_1 \times \sin 2\psi = -5.7\%$

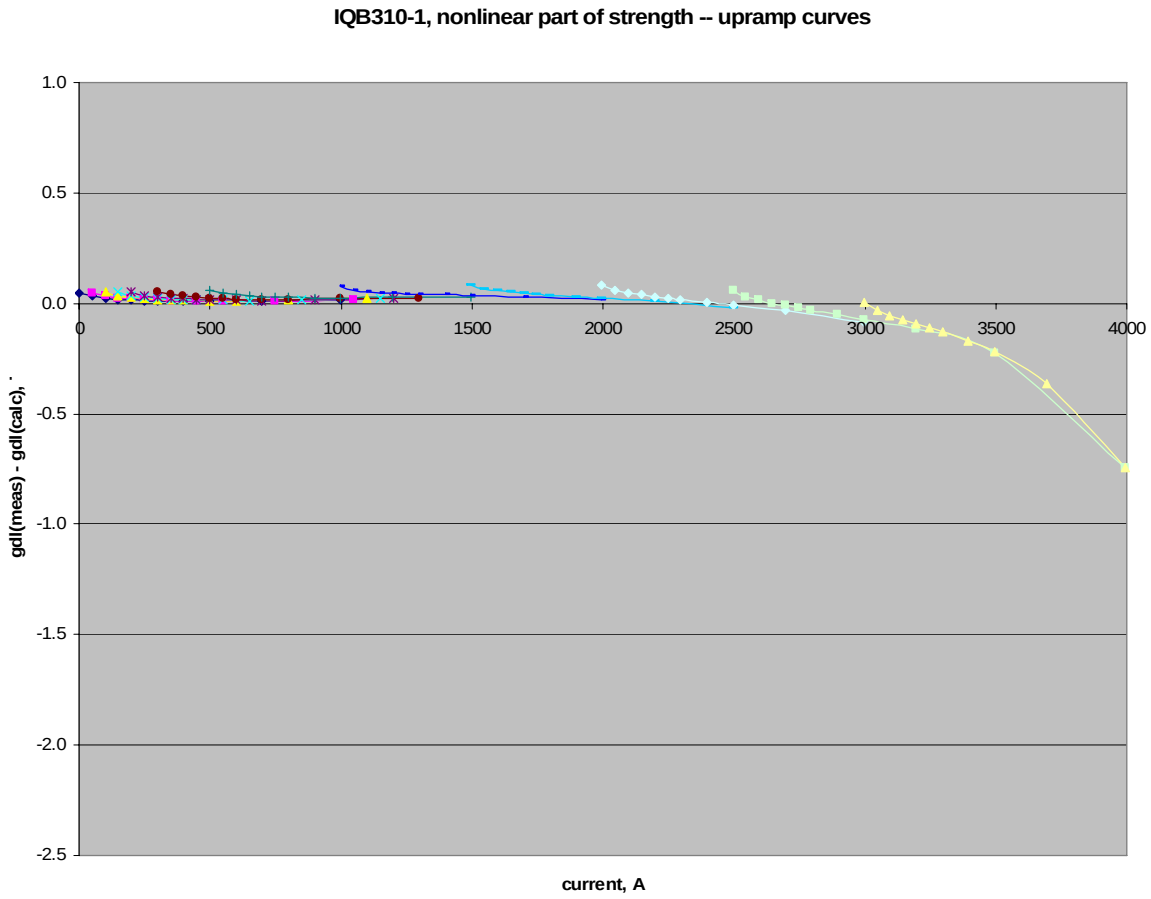
# Relative Strength Difference between WQB and IQB



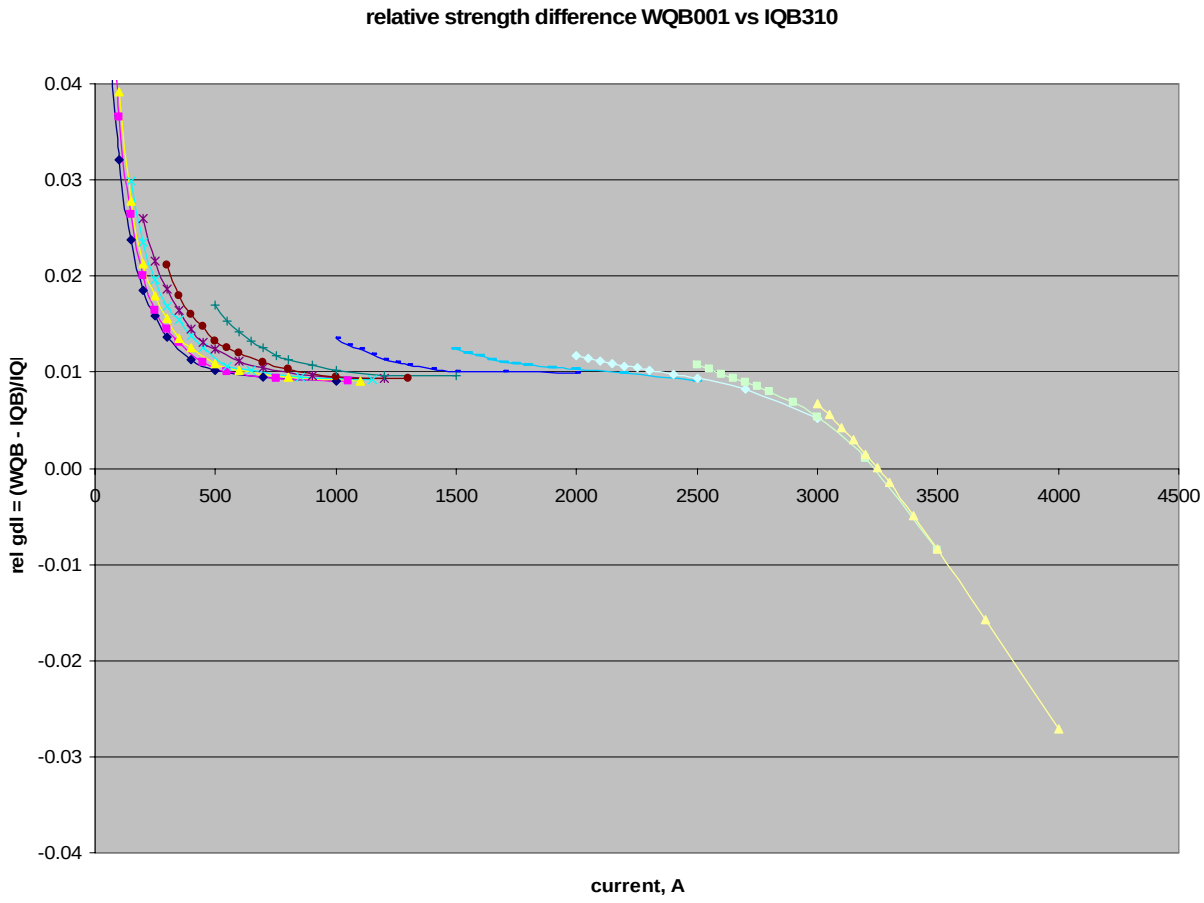
# WQB Hysteresis (upramp)



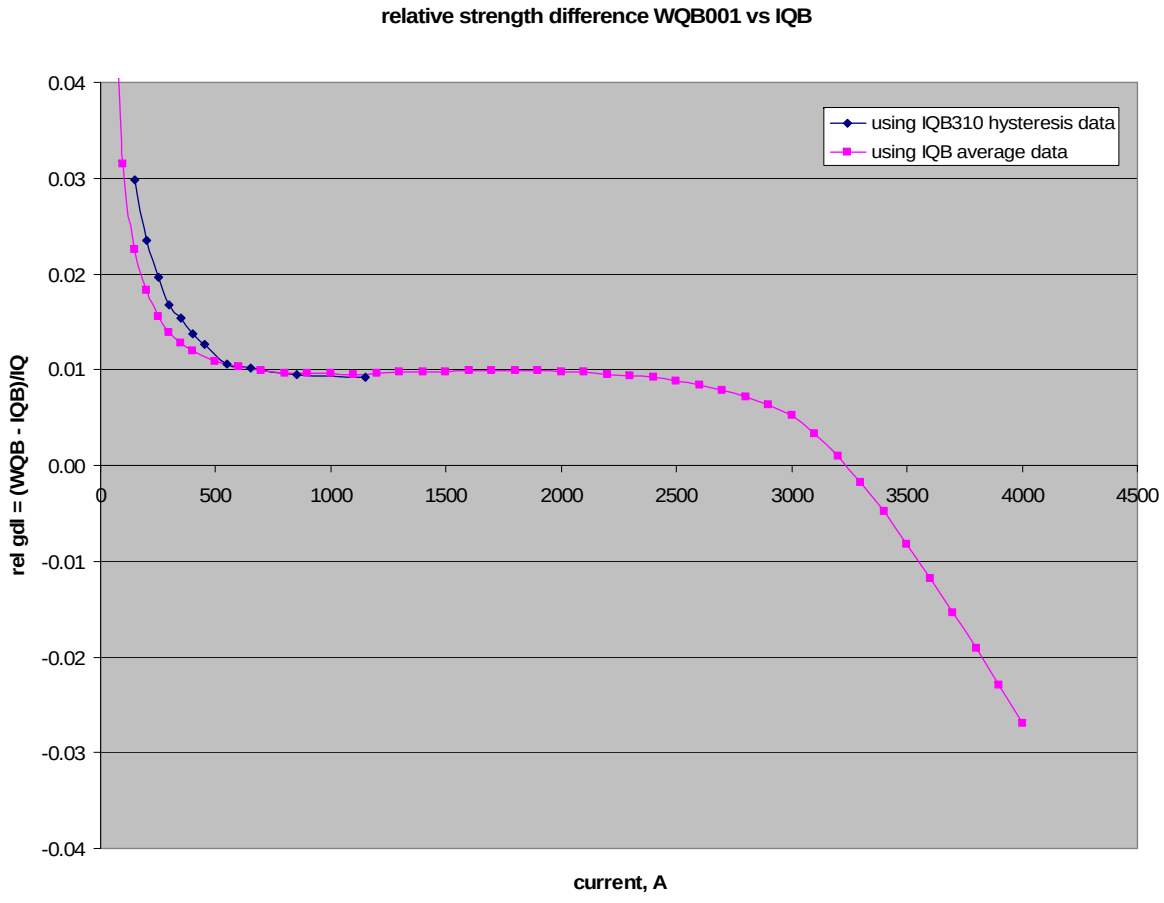
# IQB310 Hysteresis (upramp)



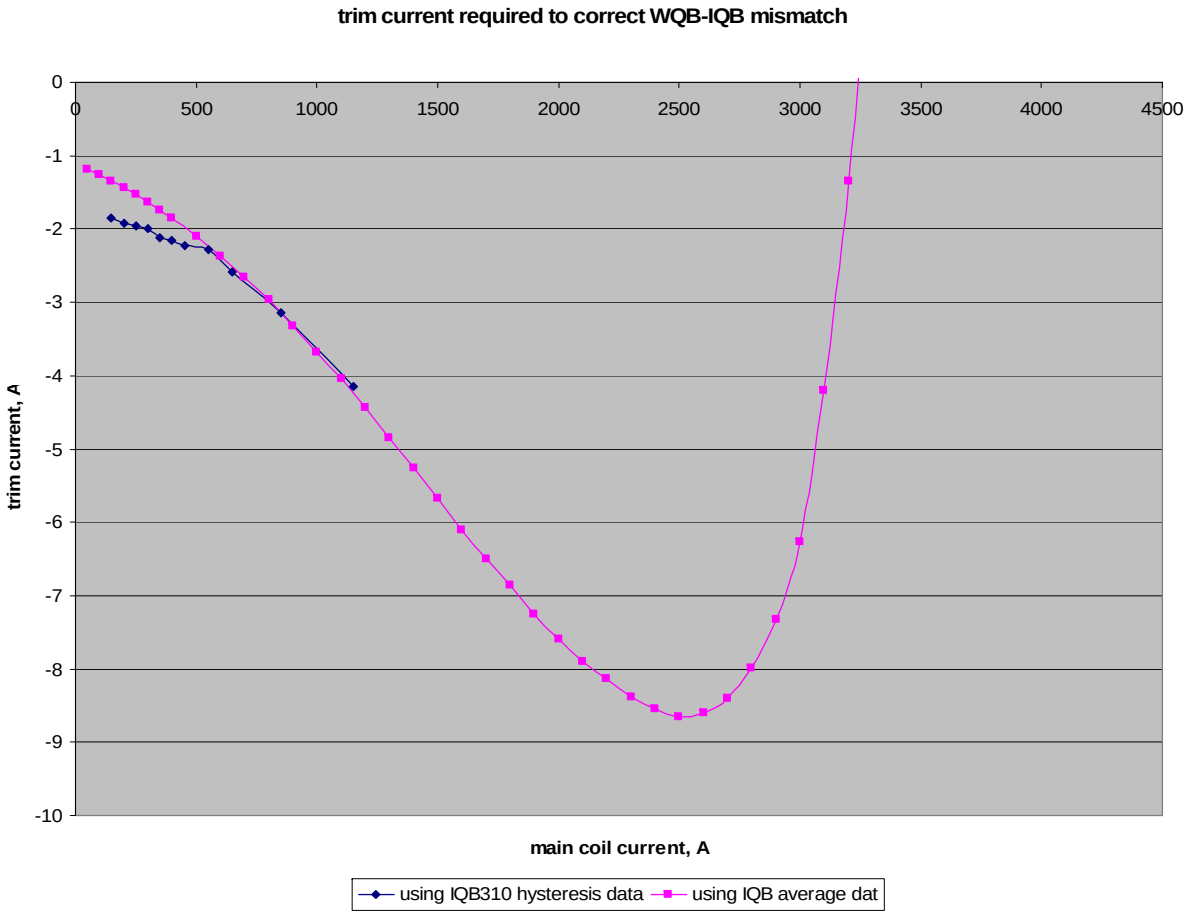
# Hysteresis Difference between WQB and IQB



# Relative Strength Difference between WQB and IQB Including Hysteresis Effect (reset at 150A)



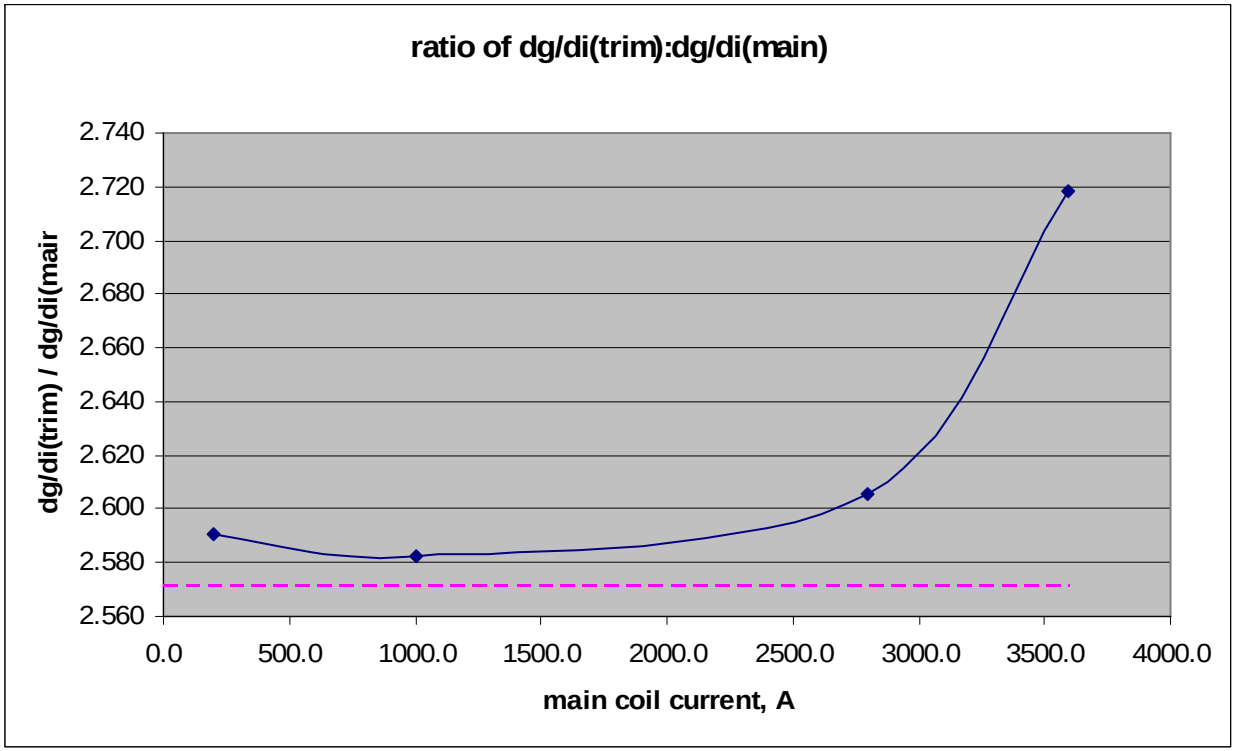
# Trim Current with & w/o Hysteresis Effect



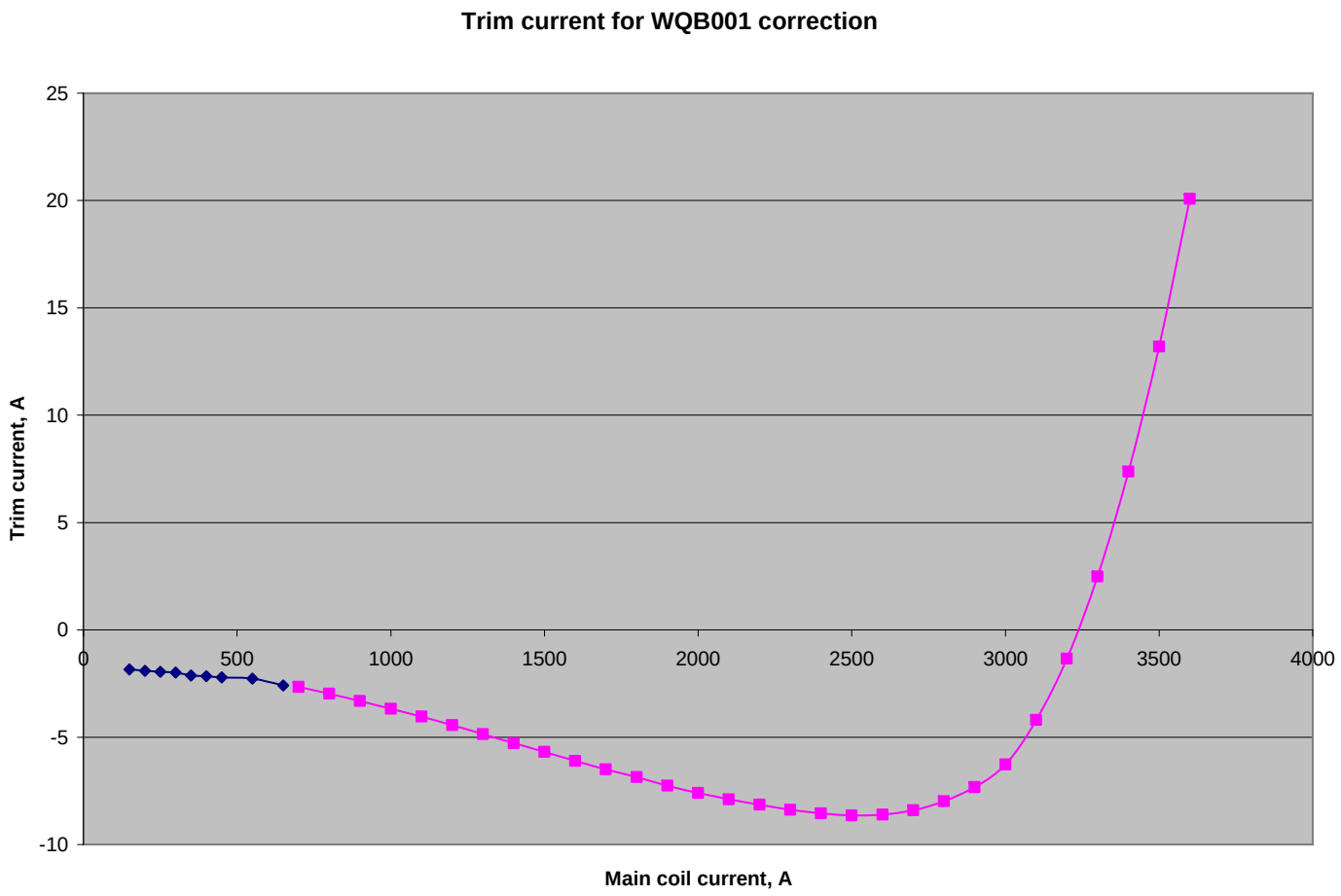
# **Trim Current Anomaly** (M. Tartaglia)

strength ratio expected = 2.571

| current | dg/di (main) | dg/di (trim) | ratio | % anomaly |
|---|---|---|---|---|
| 202.68 | 0.012237 | 0.031702 | 2.591 | 0.75% |
| 1000.59 | 0.012361 | 0.031919 | 2.582 | 0.42% |
| 2796.16 | 0.011846 | 0.030861 | 2.605 | 1.31% |
| 3594.15 | 0.009656 | 0.026247 | 2.718 | 5.71% |



# Required Trim Current Setting Including Hysteresis and Anomaly Effects



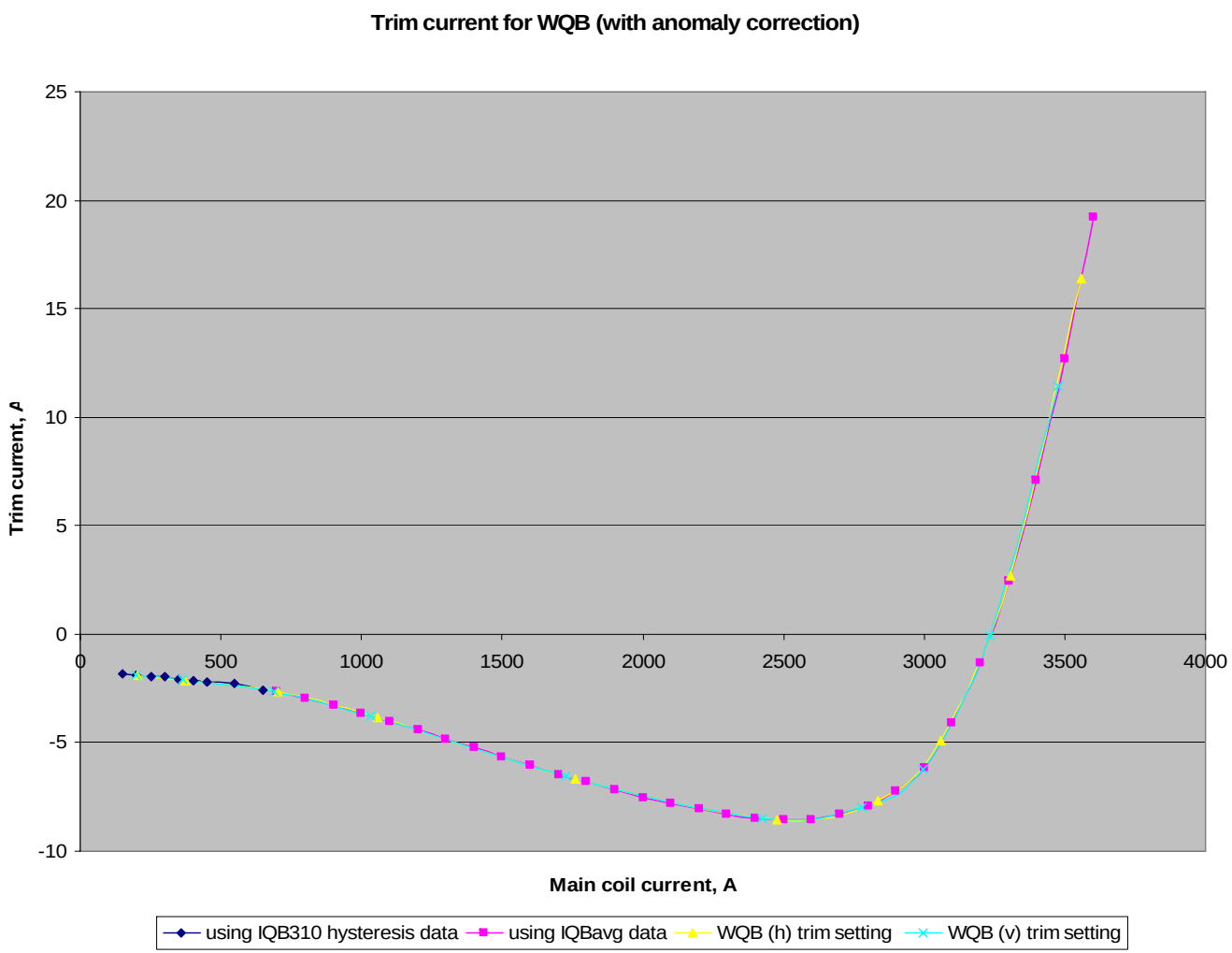
# Trim Coil & Power Supply (L. Bartelson)

| | |
|---|---|
| Trim coil turns per pole | 18 |
| Max current | 28 A |
| Resistance per magnet | 0.75 Ω |
| Inductance per magnet | 0.03 H |
| Power supply current control accuracy | 1% |

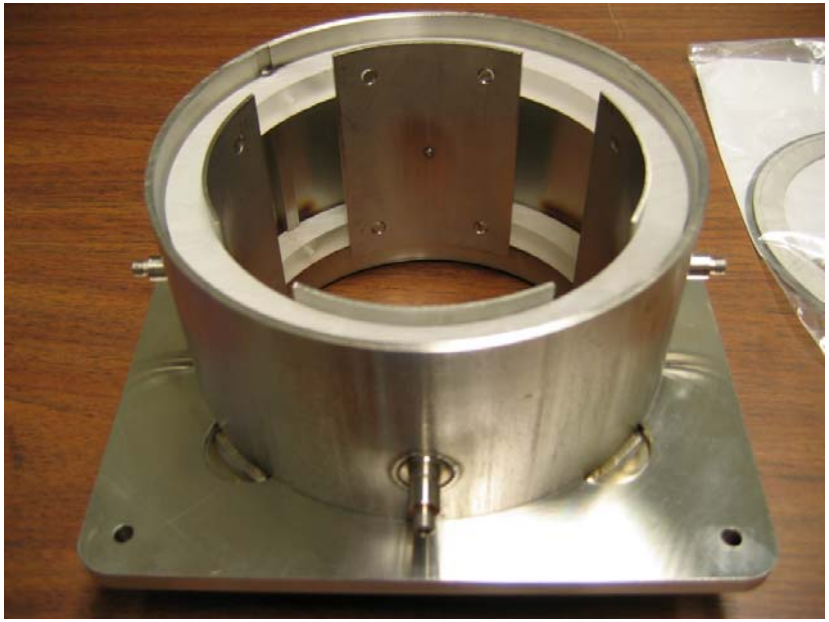
# WQB Trim Current Table

| Momentum (GeV/c) | Trim current (A) WQB 222, 402, 522, 608, 620 | Trim current (A) WQB 101, 321 |
|---|---|---|
| 8.882 | –1.894 | –1.891 |
| 8.9494 | –1.895 | –1.892 |
| 9.0999 | –1.898 | –1.895 |
| 9.4993 | –1.905 | –1.901 |
| 9.9974 | –1.914 | –1.911 |
| 11.497 | –1.941 | –1.937 |
| 13.997 | –2.037 | –2.018 |
| 16 | –2.116 | –2.112 |
| 30 | –2.643 | –2.622 |
| 45 | –3.854 | –3.778 |
| 75 | –6.668 | –6.538 |
| 105 | –8.547 | –8.498 |
| 120 | –7.667 | –8.005 |
| 130 | –4.902 | –6.213 |
| 140 | +2.689 | –0.062 |
| 150 | +16.385 | +11.433 |

# WQB Trim Current Plot



# EXWA BPM (L. Valerio, J. Fitzgerald)



- Electrode ID = 5.625”
- Extended angle = 60°
- Installation specs:
  - Offset (relative to the quad center) < 5 mils (0.13 mm)
  - Roll < 1° (17 mrad)

# New BPM Requirements

- Each new EXWA BPM measures both H and V.
- **Need new scaling to translate decibels to mm.**
- **Need new offset table for database.**
  - Horizontal beam position:

*pos = BPM reading + bpm_offset – survey_offset + orbit_offset – electrical_offset*

  - Vertical beam position:

*pos = BPM reading + bpm_offset + survey_offset – electrical_offset*

# New Scaling

1. Analytic: (Chou, ANL/APS/IN/ACCPHY/89-3, 1989)

$$\text{pos (mm)} = A \times R(\text{mm}) \times \frac{1-\sqrt{1-x^2}}{x}$$

*A* = constant

*R* = pickup radius = 0.5 x 5.625” = 71.4375 mm

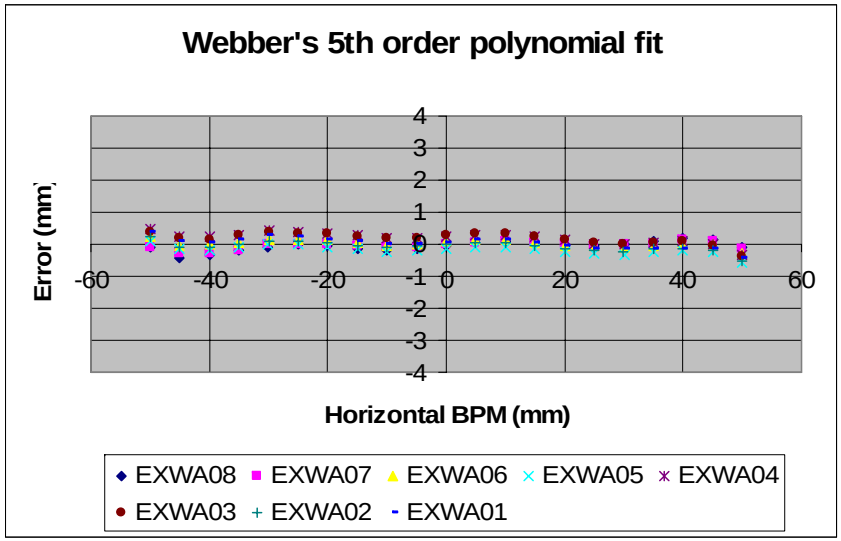
*x* = difference / sum = [10^(A/20) – 10^(B/20)] / [10^(A/20) + 10^(B/20)]

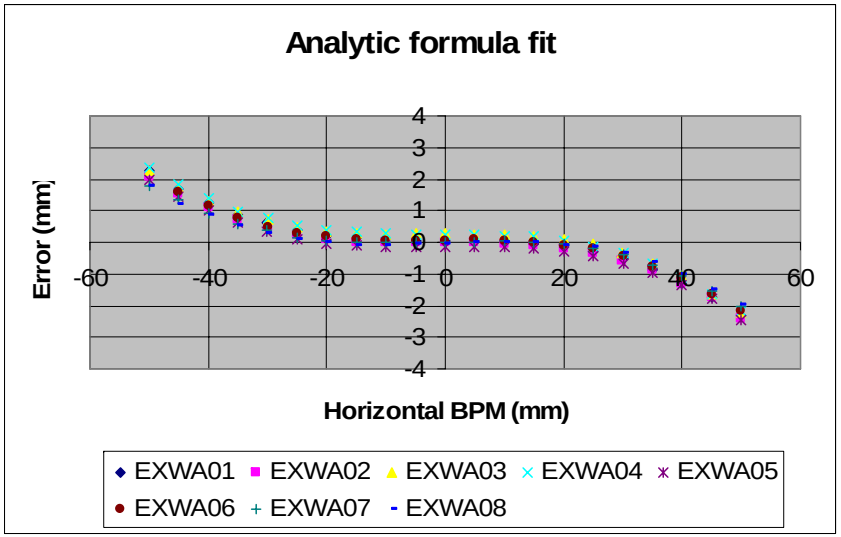
2. Webber’s empirical 5th order polynomial (beams-doc #2280):

$$\text{pos (mm)} = 43.513\,x + 5.432\,x^3 + 21.071\,x^5$$

# Fitting to Raw Data in beams-doc #2007

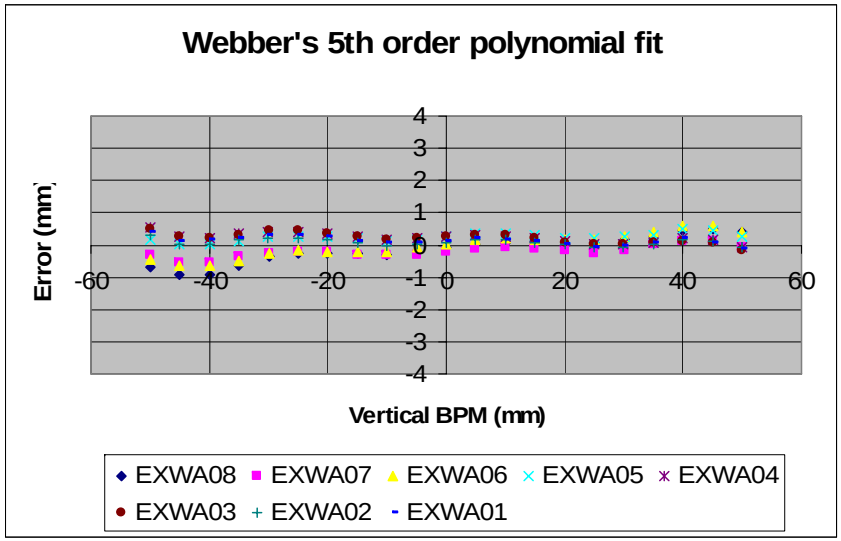
**Horizontal**

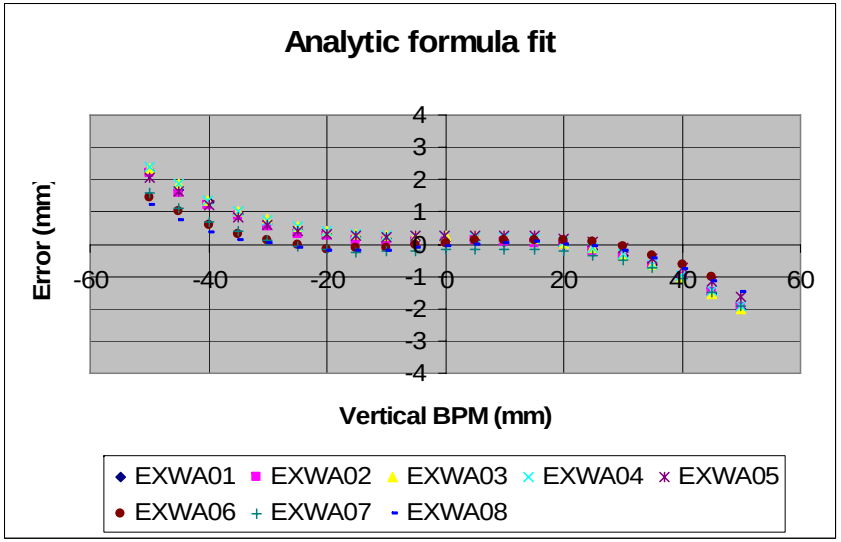


# Fitting to Raw Data in beams-doc #2007

**Vertical**



# Hendricks Offset Table

- Established 8 years ago in 1998
- survey_offset from *Thornton Murphy* (missing: 522, 523, 602-608, 619, 620)
- bpm_offset and electrical_offset from *Jim Crisp*
- orbit_offset from *Dave Johnson*

| name | bpm_offset | survey_offset | orbit_offset | electrical_offset |
|---|---|---|---|---|
| I:HP100 | -0.290000 | 0.010000 | 0.000000 | 0.130000 |
| I:HP102 | -0.380000 | 0.060000 | 0.000000 | 0.760000 |
| I:HP104 | 1.160000 | -0.480000 | 0.000000 | 0.300000 |
| I:HP106 | 0.010000 | 0.450000 | 0.000000 | 0.380000 |
| I:HP108 | -1.930000 | -0.270000 | 0.000000 | 0.210000 |
| I:HP110 | -0.270000 | -0.470000 | 0.000000 | -0.370000 |
| I:HP112 | 0.750000 | -0.140000 | 0.000000 | 0.380000 |
| I:HP114 | 0.280000 | 0.180000 | 0.000000 | 0.550000 |
| I:HP116 | -0.560000 | -0.420000 | 0.000000 | -1.960000 |
| I:HP118 | 0.630000 | -0.490000 | 0.000000 | -0.200000 |
| I:HP120 | -1.020000 | 0.290000 | 0.000000 | -0.950000 |
| I:HP122 | -0.860000 | -0.440000 | 0.000000 | 0.710000 |
| I:HP124 | -1.530000 | 0.160000 | 0.000000 | -0.540000 |
| I:HP126 | 0.980000 | 0.180000 | 0.000000 | 0.210000 |
| I:HP128 | 0.310000 | -0.050000 | 0.000000 | 0.050000 |
| I:HP130 | -1.710000 | 0.360000 | 0.000000 | 0.380000 |
| I:HP202 | 0.640000 | -0.290000 | 0.000000 | 0.050000 |
| I:HP204 | 0.200000 | -0.340000 | 0.000000 | 0.800000 |

# **New survey_offset** (T. Sager)

- Offset of the BPM mechanical center relative to the WQB center
- Sign convention:
  - Horizontal: + pointing inward (namely, facing the proton direction, the left-hand-side is positive)
  - Vertical: + pointing upward
  - Roll: + indicating clockwise roll relative to proton direction

| Location | Horizontal (mm) | Vertical (mm) | Roll (mrad) |
|---|---|---|---|
| BPM101 (WQB001) | –0.108 | –0.751 | –0.13 |
| BPM222 (WQB007) | +0.143 | –0.775 | +0.54 |
| BPM321 (WQB006) | +1.143 | –1.301 | –0.85 |
| BPM402 (WQB004) | +0.552 | –0.178 | –0.25 |
| BPM522 (WQB003) | +1.209 | –1.826 | +0.41 |
| BPM608 (WQB005) | –0.339 | +0.547 | +0.47 |
| BPM620 (WQB002) | +0.322 | –1.556 | +0.67 |
| Q521 | +0.178 | +0.229 | –1.04 |

# **New bpm_offset** (J. Fitzgerald)

- Offset between the BPM mechanical and electrical center
- Calculated using Fitzgerald's raw data in #2007
- Sign convention:
  - Horizontal: + pointing outward (namely, facing the proton direction, the right-hand-side is positive)
  - Vertical: + pointing upward

| Location | Horizontal (mm) | Vertical (mm) |
|---|---|---|
| BPM101 (EXWA01) | –0.0703 | +0.1373 |
| BPM222 (EXWA07) | –0.0232 | –0.1918 |
| BPM321 (EXWA08) | +0.0535 | –0.0846 |
| BPM402 (EXWA04) | –0.2485 | +0.2421 |
| BPM522 (EXWA02) | +0.0217 | +0.0809 |
| BPM608 (EXWA05) | +0.1516 | +0.2693 |
| BPM620 (EXWA06) | –0.0723 | –0.0138 |

# **New electrical_offset** (R. Webber)

- Offset from cables and other electronics
- All long cables were measured and documented in beams-doc #2288.
- Other electronics should have no contribution:
  - Upstairs new electronics are calibrated to zero gain difference
  - Combining box and the short cables are believed to have negligible contribution
- Correction is done by multiplying A signal by the respective values in this listing

| Location | 2.5MHz_B/A_xmsn | 53MHz_B/A_xmsn |
|---|---|---|
| I:HP101 | 0.9993 | 0.9907 |
| I:HP222 | 1.002 | 0.9868 |
| I:HP321 | 0.9984 | 0.9871 |
| I:HP402 | 0.9942 | 0.9986 |
| I:HP522 | 1.002 | 0.9975 |
| I:HP608 | 0.9961 | 0.9944 |
| I:HP620 | 0.9981 | 1.014 |
| I:VP101 | 0.9989 | 0.9907 |
| I:VP222 | 0.9983 | 0.9868 |
| I:VP321 | 0.9993 | 0.9871 |
| I:VP402 | 0.999 | 0.9986 |
| I:VP522 | 1 | 0.9975 |
| I:VP602 | 0.9991 | 0.9944 |
| I:VP620 | 1.002 | 1.014 |

# Lattice Measurement

- **1-bump - Closed Orbit Displacement from a single dipole kick:**

$$\Delta x(s) = \Delta\theta_0 \times \frac{\sqrt{\beta_0 \beta(s)}}{2\sin(\pi\nu)} \cos\left[\pi\nu - \left|\psi(s) - \psi_0\right|\right]$$

$$\Delta\theta_0 = \frac{\Delta(Bl)_0}{B\rho}$$

Tune: $\nu(x)$ = 26.42, $\nu(y)$ = 25.44

@ 8.889 GeV/c: $B\rho$ = 29.65 T-m

Steering magnet strength (T-m/A): $x$ = 0.007157, $y$ = 0.003166

- **3-bump ratio:**

$$\theta_1 + \theta_2 + \theta_3 = 0$$

$$\theta_2 = -\theta_1 \left(\frac{\beta_1}{\beta_2}\right)^{1/2} \frac{\sin\psi_{13}}{\sin\psi_{23}}$$

$$\theta_3 = -\theta_1 \left(\frac{\beta_1}{\beta_3}\right)^{1/2} \frac{\sin\psi_{12}}{\sin\psi_{23}}$$

# Beta Function Measurement

Change the $j^{th}$ steering magnet's current by $\Delta I_j$ and measure closed orbit change $\Delta x_j$ at the $j^{th}$ BPM:

$$\beta_j = 2 \times \tan(\pi\nu) \times (B\rho) \times \left( \frac{\Delta \int B_j ds}{\Delta I_j} \right)^{-1} \times \left( \frac{\Delta x_j}{\Delta I_j} \right)$$

Tune: $\nu(x) = 26.42$, $\nu(y) = 25.44$

@ 8.889 GeV/c: $B\rho = 29.65$ T-m

Steering magnet strength (T-m/A): $x = 0.007157$, $y = 0.003166$

**Measured closed orbit matrix diagonal element (m/A)**

$$\beta_j(x) = 32270 \times \left( \frac{\Delta x_j}{\Delta I_j} \right)$$

$$\beta_j(y) = 98187 \times \left( \frac{\Delta y_j}{\Delta I_j} \right)$$

# 3-Bump: Prediction vs. Measurement

| Element | beta (m) | phase advance (x 2pi) | kick ratio (calculated) | COD-1 (mm/A) | COD-2 (mm/A) | COD-3 (mm/A) | Total COD (mm/0.25A) | Prieto's meas. (mm/0.25A) | 1998's (mm/0.25A) |
|---|---|---|---|---|---|---|---|---|---|
| V641 | 39.060 | -0.132 | 1.0000 | | | | | | |
| V101 | 56.360 | 0.115 | -0.1208 | | | | | | |
| VP101 | 56.668 | 0.122 | | 2.50 | -0.09 | 2.58 | 1.25 | 1.48 | 1.23 |
| V103 | 34.833 | 0.345 | 1.0672 | | | | | | |
| | | | | | | | | | |
| H220 | 53.630 | 6.349 | 1.0000 | | | | | | |
| H222 | 52.917 | 6.607 | -0.0893 | | | | | | |
| HP222 | 53.400 | 6.613 | | 6.29 | -0.17 | 6.70 | 3.21 | 3.44 | 3.1 |
| H224 | 41.778 | 6.835 | 1.1425 | | | | | | |
| | | | | | | | | | |
| V319 | 49.462 | 9.89 | 1.0000 | | | | | | |
| V321 | 58.773 | 10.136 | -0.2100 | | | | | | |
| VP321 | 59.233 | 10.142 | | 2.88 | -0.15 | 3.00 | 1.43 | 1.56 | 1.43 |
| V323 | 39.392 | 10.354 | 1.1432 | | | | | | |
| | | | | | | | | | |
| H400 | 51.912 | 13.208 | 1.0000 | | | | | | |
| H402 | 39.483 | 13.453 | 0.0723 | | | | | | |
| HP402 | 54.614 | 13.472 | | 6.26 | 0.15 | 6.49 | 3.22 | 3.75 | 2.72 |
| H404 | 54.357 | 13.718 | 0.9811 | | | | | | |
| | | | | | | | | | |
| H520 | 53.630 | 19.561 | 1.0000 | | | | | | |
| H522 | 38.311 | 19.807 | -0.1041 | | | | | | |
| HP522 | 52.918 | 19.826 | | 6.25 | -0.21 | 6.63 | 3.17 | | 2.72 |
| H524 | 41.778 | 20.047 | 1.1349 | | | | | | |
| | | | | | | | | | |
| H606 | 53.300 | 21.852 | 1.0000 | | | | | | |
| H608 | 55.558 | 22.103 | -0.0989 | | | | | | |
| HP608 | 55.888 | 22.109 | | 6.51 | -0.20 | 6.80 | 3.28 | | 2.78 |
| H610 | 39.509 | 22.336 | 1.1681 | | | | | | |
| | | | | | | | | | |
| H618 | 38.616 | 23.396 | 1.0000 | | | | | | |
| H620 | 38.206 | 23.646 | -0.0696 | | | | | | |
| HP620 | 55.753 | 23.626 | | 5.74 | -0.15 | 5.52 | 2.78 | | 2.3 |
| H622 | 54.029 | 23.885 | 0.8474 | | | | | | |

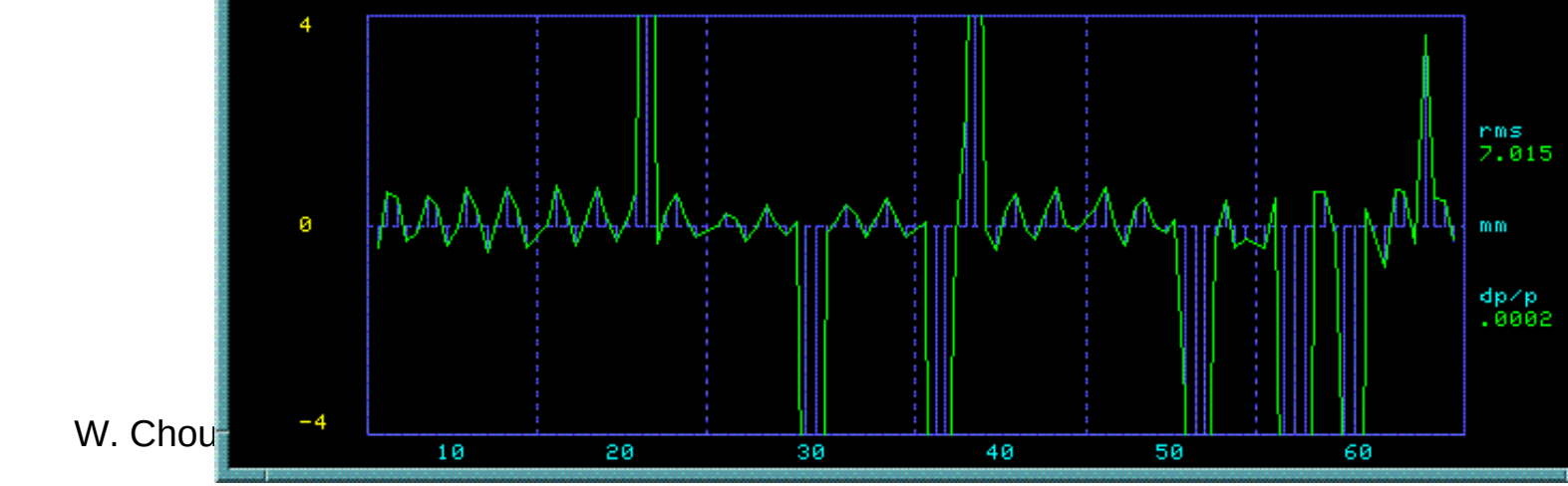
# Reference Closed Orbit (H)

VMS GxPB 1: FILE 556: 8 Gev $29 7 E12

FILE 556: 8 Gev $29 7 E12 .194 sec

DISPLAY - Frame 0 Horizontal 20-JUL-2006 13:50:35

| | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|
| 00 ... | -.43 | | | .0786 | | |
| 02 ... | .6476 | .0273 | -.0199 | -26.38 | .3049 | -.4395 |
| 04 ... | .5259 | .7858 | .2326 | -7.882 | .7279 | .537 |
| 06 ... | -.3114 | .2455 | .1142 | -.2195 | .0165 | -10.5 |
| 08 ... | -.1365 | -.3684 | -.3136 | 2.187 | -.3841 | -31.93 |
| 10 ... | .57 | .1665 | -.0529 | 12.89 | .3486 | -23.04 |
| 12 ... | .4083 | .7202 | .3867 | -.0564 | .5169 | .6218 |
| 14 ... | -.3716 | .1916 | .0852 | -.4821 | -.0351 | .65 |
| 16 ... | -.0787 | -.2874 | -.1991 | .2819 | -.1459 | -.176 |
| 18 ... | .7426 | .1156 | .0751 | .6037 | .092 | -5.137 |
| 20 ... | .3041 | .6333 | -9.522 | -.1141 | -3.401 | -33.69 |
| 22 ... | -.5294 | 15.03 | -16.88 | -.2463 | -25.31 | .3281 |
| 24 ... | .0777 | -.3494 | -.1559 | .28 | -8.133 | -.1986 |
| 26 ... | .7354 | .2724 | .0834 | .7066 | -.2446 | -.8169 |
| 28 ... | .2819 | .5961 | .4117 | .0117 | .4906 | .6751 |
| 30 ... | -.4259 | .045 | .1947 | -.0959 | -.4281 | .6404 |
| 32 ... | | -.2326 | -.215 | | -.2615 | -.3317 |
| 34 ... | | | .15 | | | 3.664 |
| 36 ... | | | .5004 | | | .5041 |
| 38 ... | | | .1307 | | | .48 |
| 40 ... | | | -.2293 | | | -.3122 |



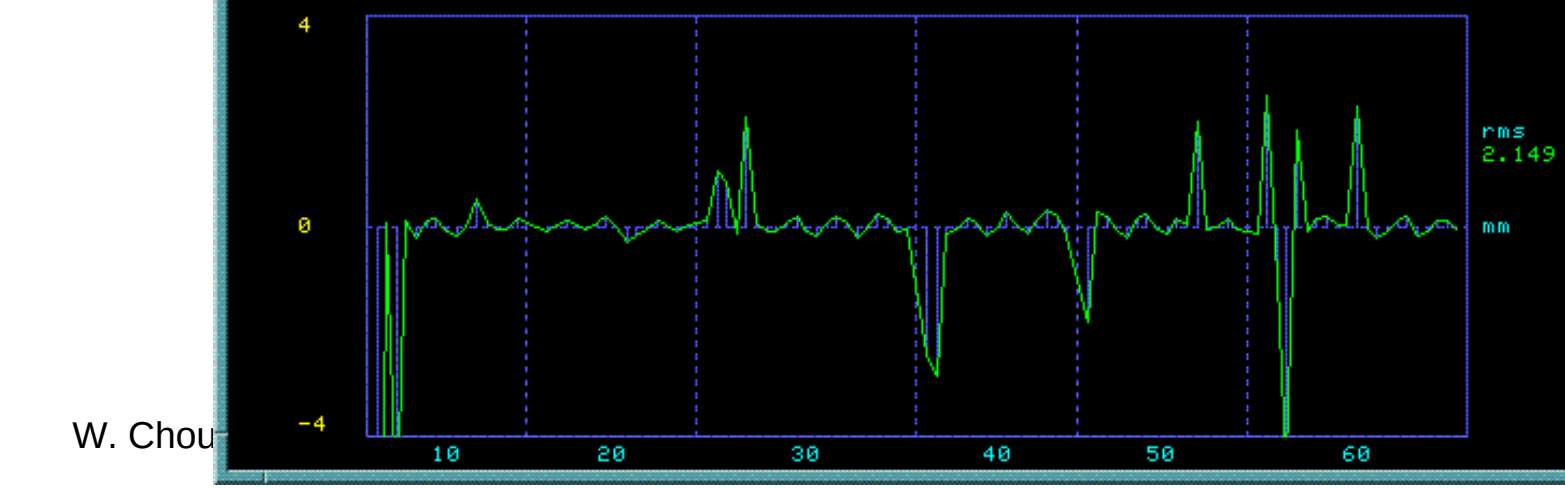
# Reference Closed Orbit (V)

VMS GxPB 1: FILE 556: 8 Gev $29 7 E12

FILE 556: 8 Gev $29 7 E12 .194 sec

DISPLAY - Frame 0 Vertical 20-JUL-2006 13:50:35

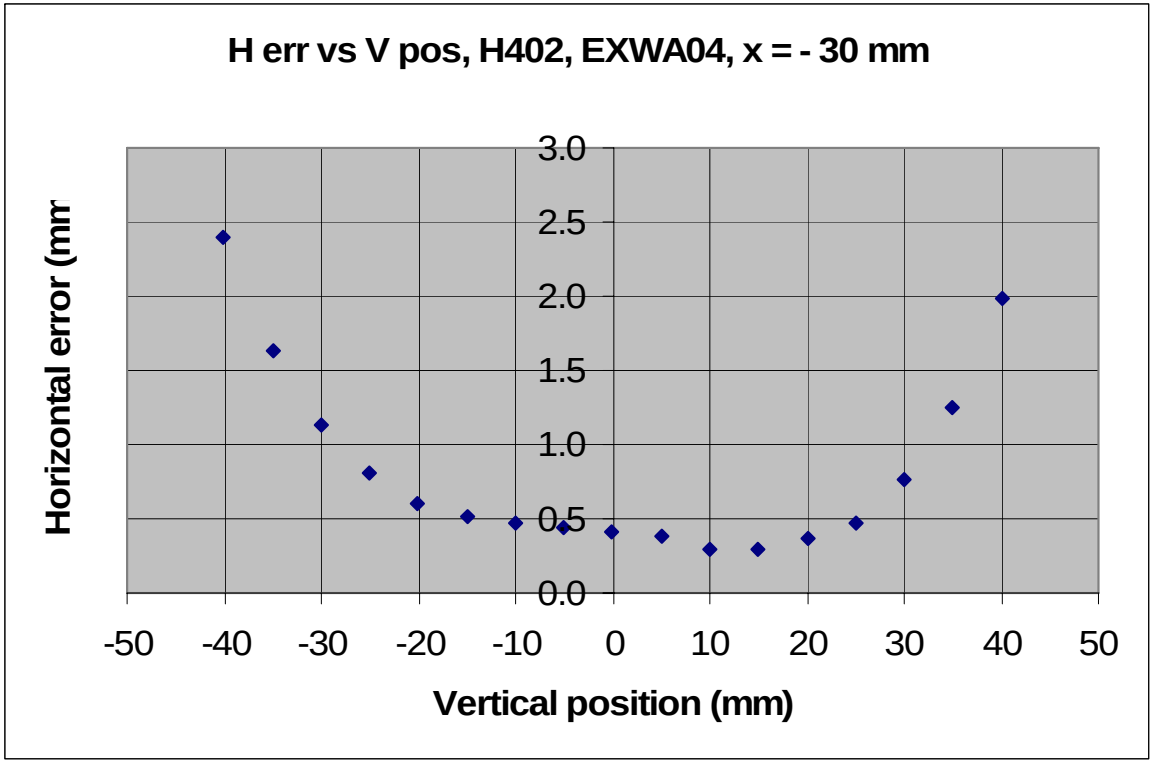
| | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|
| 01 ... | -19.52 | -.001 | .1035 | -2.434 | -1.813 | -.1545 |
| 03 ... | .0652 | -.0921 | 1.034 | -2.87 | .2526 | 2.502 |
| 05 ... | -5.743 | .0169 | .858 | -.1255 | .1951 | -1.021 |
| 07 ... | .09 | .1202 | -.1473 | -.055 | -.0626 | -4.598 |
| 09 ... | -.2036 | .0395 | 2.089 | .1506 | -.2224 | 1.816 |
| 11 ... | .12 | -.046 | .0567 | .0812 | .1474 | -.093 |
| 13 ... | .1574 | .0642 | -.108 | -.171 | .2323 | .153 |
| 15 ... | -.0818 | .177 | -.1116 | -.0051 | -.0477 | .1902 |
| 17 ... | -.1623 | .0019 | .0701 | .2908 | -.1448 | .0048 |
| 19 ... | -.0054 | -.2854 | .2092 | .0377 | .149 | .0177 |
| 21 ... | .5136 | -.1759 | -.0994 | -.1267 | .0309 | 2.296 |
| 23 ... | .0597 | -.0386 | -.1639 | .0948 | 1.994 | -.075 |
| 25 ... | -.0498 | .115 | .0565 | .2959 | -.0505 | -.2324 |
| 27 ... | -.0471 | .0092 | .1864 | .2062 | -.0281 | -.093 |
| 29 ... | .1306 | -.0872 | .0478 | -.1838 | .1401 | .1049 |
| 31 ... | | .0354 | -.2075 | | -.0515 | .1774 |
| 33 ... | | | -.0608 | | | -.1948 |
| 35 ... | | | .2375 | | | -.1148 |
| 37 ... | | | .1528 | | | .1262 |
| 39 ... | | | -.0954 | | | .1252 |
| 41 ... | | | -.0542 | | | -.0502 |



# Reference Closed Orbit at WQBs

| Q101 | Q222 | Q321 | Q402 | Q522 | Q608 | Q620 |
|---|---|---|---|---|---|---|
| –19.52mm (V) | 15.03mm (H) | –0.0994mm (V) | –26.38mm (H) | –25.31mm (H) | –31.93mm (H) | –33.69mm (H) |

# BPM H402 (EXWA04)
# Calibrated Error between Raw Data and Polynomial Fit



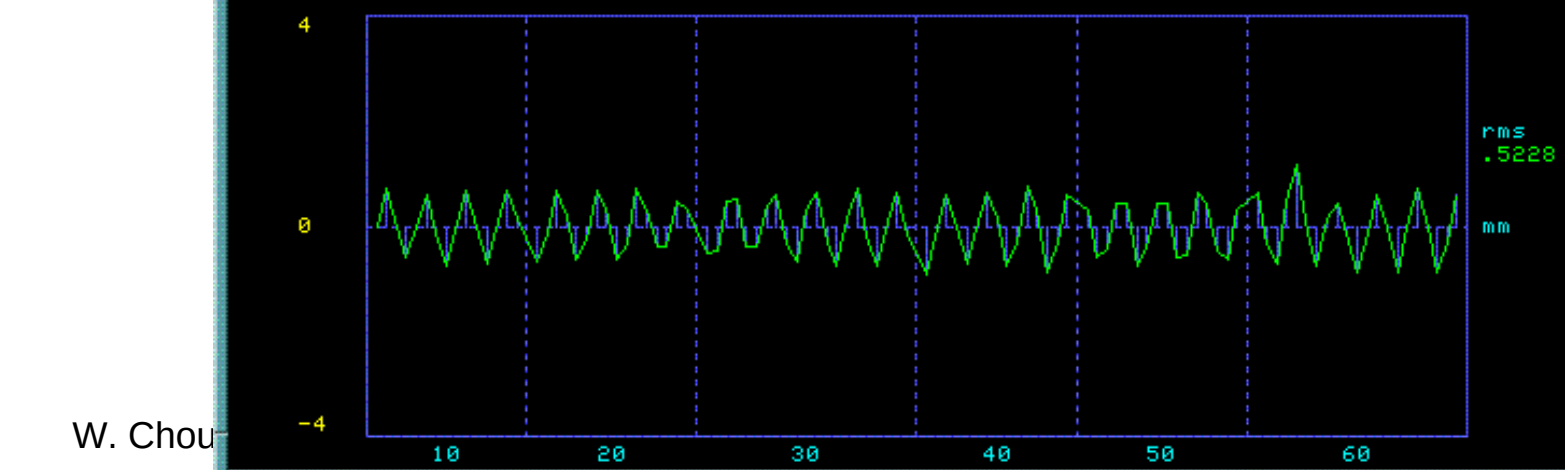
# 1-Bump Difference Orbit: V101 – 0.25 A

VMS GxPB 1: BPM DIFF Plot: 556 - 0

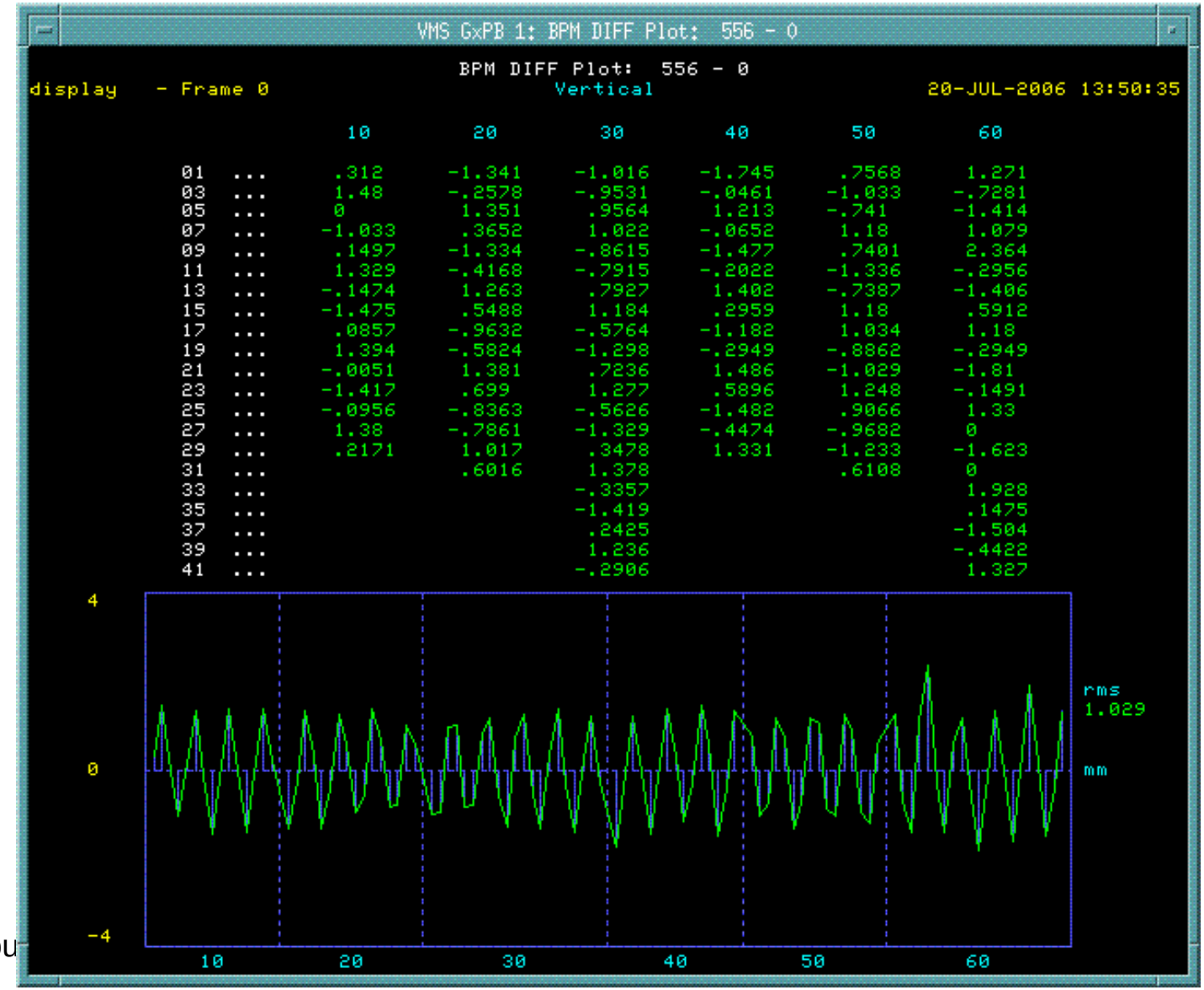
BPM DIFF Plot: 556 - 0

display - Frame 0 Vertical 20-JUL-2006 13:50:35

| | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|
| 01 ... | 0 | -.665 | -.5066 | -.9036 | .3014 | .6325 |
| 03 ... | .7382 | -.1313 | -.4807 | -.0326 | -.5897 | -.3592 |
| 05 ... | 0 | .6666 | .4642 | .5975 | -.444 | -.7072 |
| 07 ... | -.5898 | .1964 | .531 | -.0317 | .4422 | .4586 |
| 09 ... | 0 | -.6419 | -.4073 | -.7267 | .4446 | 1.184 |
| 11 ... | .5898 | -.258 | -.4082 | -.0622 | -.7401 | -.1479 |
| 13 ... | -.1474 | .6817 | .4141 | .651 | -.4429 | -.7735 |
| 15 ... | -.7688 | .3567 | .581 | .1479 | .4423 | .1476 |
| 17 ... | .0699 | -.6194 | -.3322 | -.7394 | .4426 | .4422 |
| 19 ... | .6829 | -.3658 | -.6885 | -.2949 | -.5912 | -.1475 |
| 21 ... | -.0356 | .7188 | .3319 | .7457 | -.5366 | -.8977 |
| 23 ... | -.7287 | .3316 | .6427 | .2948 | .648 | -.1491 |
| 25 ... | -.0768 | -.4018 | -.2939 | -.8911 | .4525 | .5924 |
| 27 ... | .6808 | -.4084 | -.767 | -.298 | -.4746 | 0 |
| 29 ... | .1351 | .4864 | .1362 | .5932 | -.6313 | -.8851 |
| 31 ... | | .2985 | .739 | | .307 | 0 |
| 33 ... | | | -.1756 | | | .7382 |
| 35 ... | | | -.7588 | | | 0 |
| 37 ... | | | .1161 | | | -.8977 |
| 39 ... | | | .6244 | | | -.2948 |
| 41 ... | | | -.1615 | | | .5898 |



# 1-Bump Difference Orbit: V101 – 0.5 A




| | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|
| 01 ... | .312 | -1.341 | -1.016 | -1.745 | .7568 | 1.271 |
| 03 ... | 1.48 | -.2578 | -.9531 | -.0461 | -1.033 | -.7281 |
| 05 ... | 0 | 1.351 | .9564 | 1.213 | -.741 | -1.414 |
| 07 ... | -1.033 | .3652 | 1.022 | -.0652 | 1.18 | 1.079 |
| 09 ... | .1497 | -1.334 | -.8615 | -1.477 | .7401 | 2.364 |
| 11 ... | 1.329 | -.4168 | -.7915 | -.2022 | -1.336 | -.2956 |
| 13 ... | -.1474 | 1.263 | .7927 | 1.402 | -.7387 | -1.406 |
| 15 ... | -1.475 | .5488 | 1.184 | .2959 | 1.18 | .5912 |
| 17 ... | .0857 | -.9632 | -.5764 | -1.182 | 1.034 | 1.18 |
| 19 ... | 1.394 | -.5824 | -1.298 | -.2949 | -.8862 | -.2949 |
| 21 ... | -.0051 | 1.381 | .7236 | 1.486 | -1.029 | -1.81 |
| 23 ... | -1.417 | .699 | 1.277 | .5896 | 1.248 | -.1491 |
| 25 ... | -.0956 | -.8363 | -.5626 | -1.482 | .9066 | 1.33 |
| 27 ... | 1.38 | -.7861 | -1.329 | -.4474 | -.9682 | 0 |
| 29 ... | .2171 | 1.017 | .3478 | 1.331 | -1.233 | -1.623 |
| 31 ... | | .6016 | 1.378 | | .6108 | 0 |
| 33 ... | | | -.3357 | | | 1.928 |
| 35 ... | | | -1.419 | | | .1475 |
| 37 ... | | | .2425 | | | -1.504 |
| 39 ... | | | 1.236 | | | -.4422 |
| 41 ... | | | -.2906 | | | 1.327 |

# 1-Bump: Prediction vs. Measurement (ΔI > 0)

| Loction | MAD beta | MAD phase advance | C.O.D. expected | C.O.D. measured | C.O.D. expected | C.O.D. measured |
|---|---|---|---|---|---|---|
| | (m) | (x 2pi) | (mm/0.25A) | (mm/0.25A) | (mm/0.5A) | (mm/0.5A) |
| V101 | 56.360 | 0.115 | | | | |
| VP101 | 56.668 | 0.122 | -0.1735 | -0.2965 | -0.3470 | -0.2965 |
| VP321 | 59.233 | 10.142 | -0.2717 | -0.3512 | -0.5435 | -0.7025 |
| | | | | | | |
| V321 | 58.773 | 10.136 | | | | |
| VP101 | 56.668 | 0.122 | -0.2105 | 0 | -0.4211 | -0.2965 |
| VP321 | 59.233 | 10.142 | -0.1762 | -0.2321 | -0.3524 | -0.6183 |
| | | | | | | |
| H222 | 52.917 | 6.607 | | | | |
| HP222 | 53.400 | 6.613 | 0.4618 | 0.4632 | 0.9236 | 0.8246 |
| HP402 | 54.614 | 13.472 | -0.9481 | -0.9872 | -1.8962 | -2.003 |
| HP522 | 52.918 | 19.826 | 1.6439 | 1.646 | 3.2877 | 3.44 |
| HP608 | 55.888 | 22.109 | -0.4315 | -0.6631 | -0.8629 | -0.6631 |
| HP620 | 55.753 | 23.626 | 0.6026 | 1.272 | 1.2053 | 1.935 |
| | | | | | | |
| H402 | 39.483 | 13.453 | | | | |
| HP222 | 53.400 | 6.613 | -0.9839 | -1.003 | -1.9678 | -2.073 |
| HP402 | 54.614 | 13.472 | 0.5152 | 0.6795 | 1.0304 | 1.346 |
| HP522 | 52.918 | 19.826 | 0.7463 | 0.6002 | 1.4926 | 1.478 |
| HP608 | 55.888 | 22.109 | -1.3749 | -2.545 | -2.7498 | -3.714 |
| HP620 | 55.753 | 23.626 | 1.4181 | 2.617 | 2.8361 | 4.041 |
| | | | | | | |
| H522 | 38.311 | 19.807 | | | | |
| HP222 | 53.400 | 6.613 | 1.3989 | 1.442 | 2.7978 | 2.823 |
| HP402 | 54.614 | 13.472 | 1.0120 | 1.18 | 2.0241 | 2.23 |
| HP522 | 52.918 | 19.826 | 0.4996 | 0.4751 | 0.9991 | 1.11 |
| HP608 | 55.888 | 22.109 | 1.2101 | 1.384 | 2.4202 | 2.848 |
| HP620 | 55.753 | 23.626 | -1.1188 | -1.203 | -2.2376 | -2.341 |

| | | | | | | |
|---|---|---|---|---|---|---|
| H608 | 55.558 | 22.103 | | | | |
| HP222 | 53.400 | 6.613 | -0.3075 | -0.1182 | -0.6150 | -0.1999 |
| HP402 | 54.614 | 13.472 | -1.5017 | -1.217 | -3.0034 | -2.463 |
| HP522 | 52.918 | 19.826 | 1.5434 | 1.408 | 3.0868 | 3.014 |
| HP608 | 55.888 | 22.109 | 0.4841 | 0.6821 | 0.9682 | 1.384 |
| HP620 | 55.753 | 23.626 | -0.6579 | -0.6097 | -1.3159 | -1.203 |
| | | | | | | |
| H620 | 38.206 | 23.646 | | | | |
| HP222 | 53.400 | 6.613 | 0.6145 | 0.6193 | 1.2290 | 1.169 |
| HP402 | 54.614 | 13.472 | 1.3827 | 1.593 | 2.7654 | 3.143 |
| HP522 | 52.918 | 19.826 | -1.0829 | -1.335 | -2.1659 | -2.512 |
| HP608 | 55.888 | 22.109 | -0.6610 | -0.6631 | -1.3219 | -1.935 |
| HP620 | 55.753 | 23.626 | 0.5205 | 1.272 | 1.0410 | 1.935 |

- While 3-bump measurements were in agreement with the lattice model, 1-bump results were less satisfactory.
- A plausible explanation is the cancellation of errors when three CODs are summed up for 3-bump. In other words, 1-bump is more sensitive to errors.
- Large discrepancy observed at HP620 needs further investigation.

# 1-Bump: Prediction vs. Measurement (ΔI < 0)

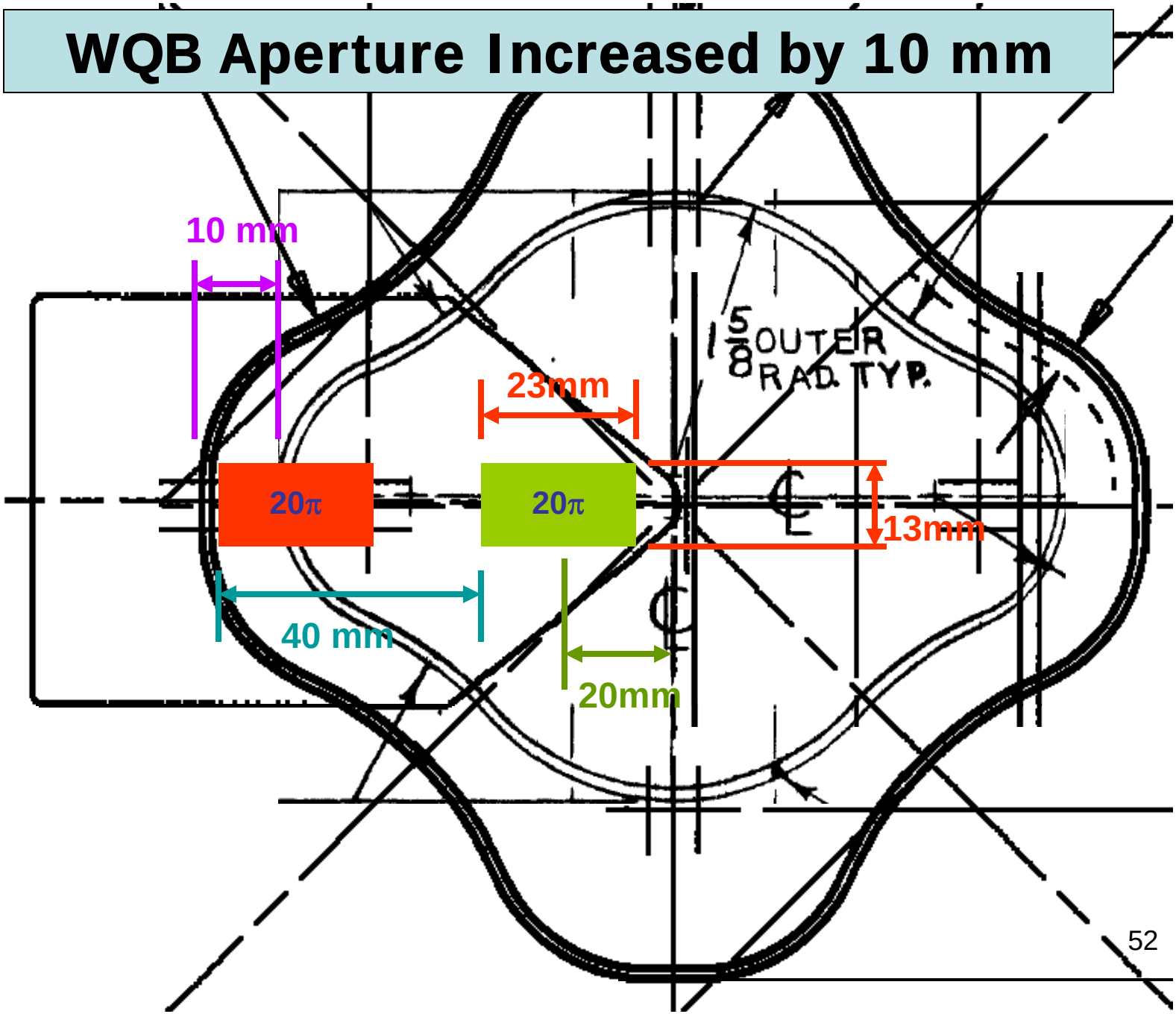
| Loction | MAD beta (m) | MAD phase advance (x 2pi) | C.O.D. expected (mm/-0.25A) | C.O.D. measured (mm/-0.25A) | C.O.D. expected (mm/-0.5A) | C.O.D. measured (mm/-0.5A) |
|---|---|---|---|---|---|---|
| V101 | 56.360 | 0.115 | | | | |
| VP101 | 56.668 | 0.122 | 0.1831 | 0 | 0.3661 | 0.312 |
| VP321 | 59.233 | 10.142 | 0.2814 | 0.3319 | 0.5628 | 0.7236 |
| | | | | | | |
| V321 | 58.773 | 10.136 | | | | |
| VP101 | 56.668 | 0.122 | 0.2203 | 0 | 0.4406 | 0.312 |
| VP321 | 59.233 | 10.142 | 0.1862 | 0.3292 | 0.3724 | 0.5279 |
| | | | | | | |
| H222 | 52.917 | 6.607 | | | | |
| HP222 | 53.400 | 6.613 | -0.4688 | -0.4744 | -0.9375 | -0.7809 |
| HP402 | 54.614 | 13.472 | 0.9435 | 1.062 | 1.8869 | 2.135 |
| HP522 | 52.918 | 19.826 | -1.6452 | -1.764 | -3.2904 | -3.55 |
| HP608 | 55.888 | 22.109 | 0.4386 | 0.6631 | 0.8772 | 0.6631 |
| HP620 | 55.753 | 23.626 | -0.6097 | 0 | -1.2194 | -0.6097 |
| | | | | | | |
| H402 | 39.483 | 13.453 | | | | |
| HP222 | 53.400 | 6.613 | 0.9807 | 1.477 | 1.9613 | 2.112 |
| HP402 | 54.614 | 13.472 | -0.5213 | -0.8037 | -1.0425 | -1.082 |
| HP522 | 52.918 | 19.826 | -0.7421 | -0.4471 | -1.4842 | -1.589 |
| HP608 | 55.888 | 22.109 | 1.3783 | 1.345 | 2.7567 | 4.276 |
| HP620 | 55.753 | 23.626 | -1.4209 | -1.78 | -2.8419 | -2.887 |
| | | | | | | |
| H522 | 38.311 | 19.807 | | | | |
| HP222 | 53.400 | 6.613 | -1.4009 | -1.32 | -2.8019 | -2.835 |
| HP402 | 54.614 | 13.472 | -1.0090 | -1.139 | -2.0180 | -2.219 |
| HP522 | 52.918 | 19.826 | -0.5054 | -0.6965 | -1.0109 | -1.26 |
| HP608 | 55.888 | 22.109 | -1.2082 | -1.881 | -2.4163 | -3.612 |
| HP620 | 55.753 | 23.626 | 1.1162 | 1.935 | 2.2325 | 3.319 |

| | | | | | | |
|---|---|---|---|---|---|---|
| H608 | 55.558 | 22.103 | | | | |
| HP222 | 53.400 | 6.613 | 0.3146 | 0.2581 | 0.6293 | 0.2631 |
| HP402 | 54.614 | 13.472 | 1.5066 | 1.359 | 3.0132 | 2.637 |
| HP522 | 52.918 | 19.826 | -1.5422 | -1.501 | -3.0844 | -3.026 |
| HP608 | 55.888 | 22.109 | -0.4914 | -1.272 | -0.9828 | -1.881 |
| HP620 | 55.753 | 23.626 | 0.6652 | 1.935 | 1.3303 | 2.617 |
| | | | | | | |
| H620 | 38.206 | 23.646 | | | | |
| HP222 | 53.400 | 6.613 | -0.6203 | -0.5655 | -1.2406 | -1.143 |
| HP402 | 54.614 | 13.472 | -1.3855 | -1.533 | -2.7709 | -3.018 |
| HP522 | 52.918 | 19.826 | 1.0804 | 1.132 | 2.1608 | 2.51 |
| HP608 | 55.888 | 22.109 | 0.6668 | 0.6631 | 1.3337 | 2.047 |
| HP620 | 55.753 | 23.626 | -0.5265 | 0 | -1.0530 | -0.6097 |

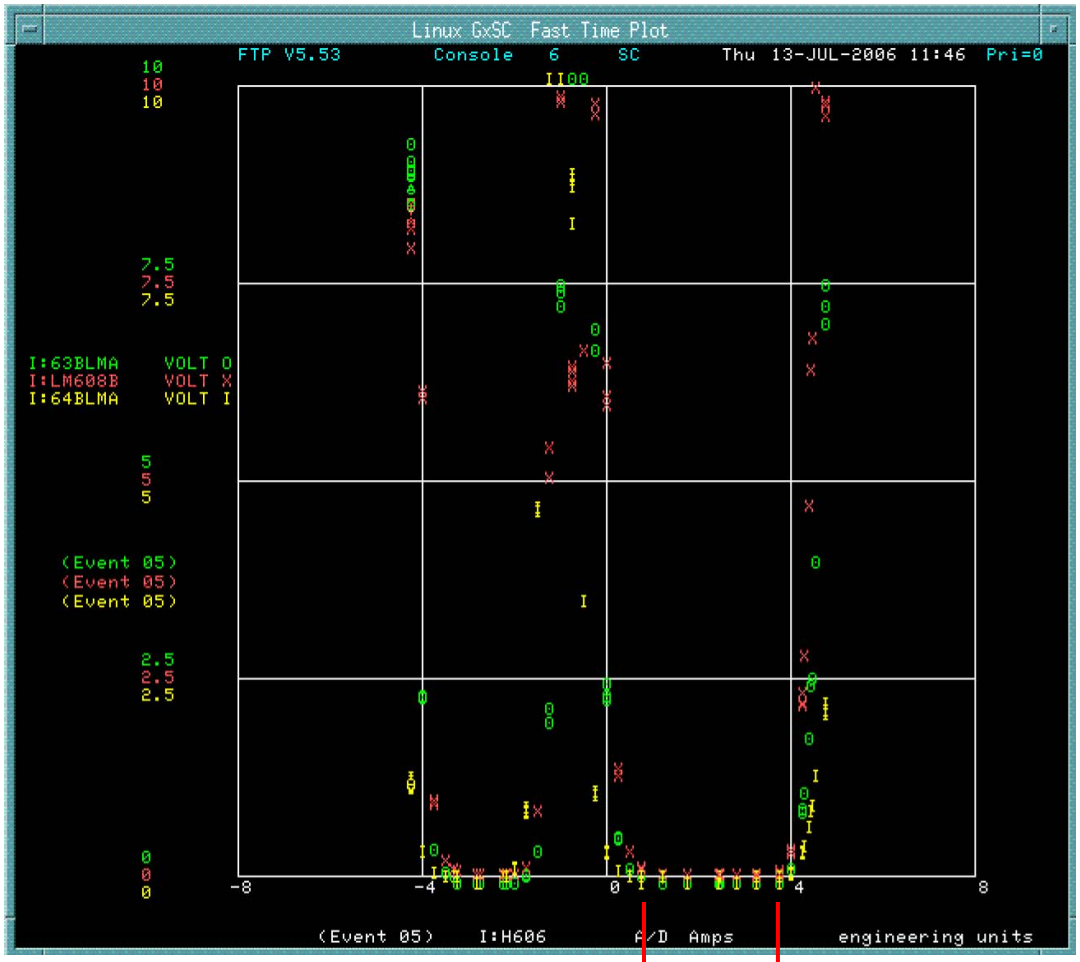
# Aperture and Acceptance Increase

- **Physical aperture:**
  - Old IQB: D = 3.286”
  - New WQB: D = 4.347”
  - An increase of 1.06”, or 32%
  - Verified by 1-turn measurement
- **Machine acceptance:**
  - Limited by dynamic aperture, i.e., by good field region
  - Increase by 50%, from 40$\pi$ to 60$\pi$
  - Verified by undetectable dose on WQBs

# WQB Aperture Increased by 10 mm

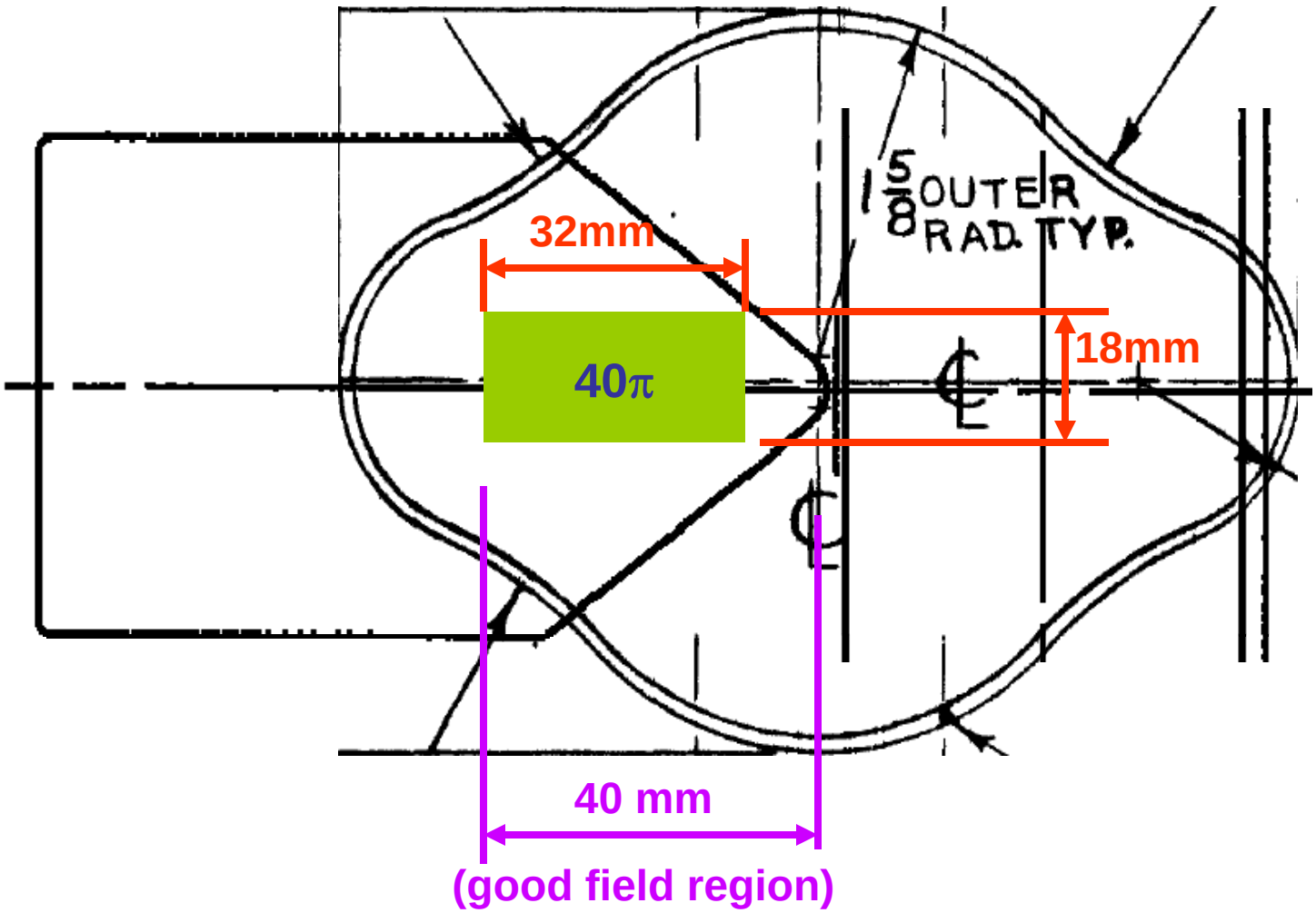


# **Aperture Scanning** (M. Yang)

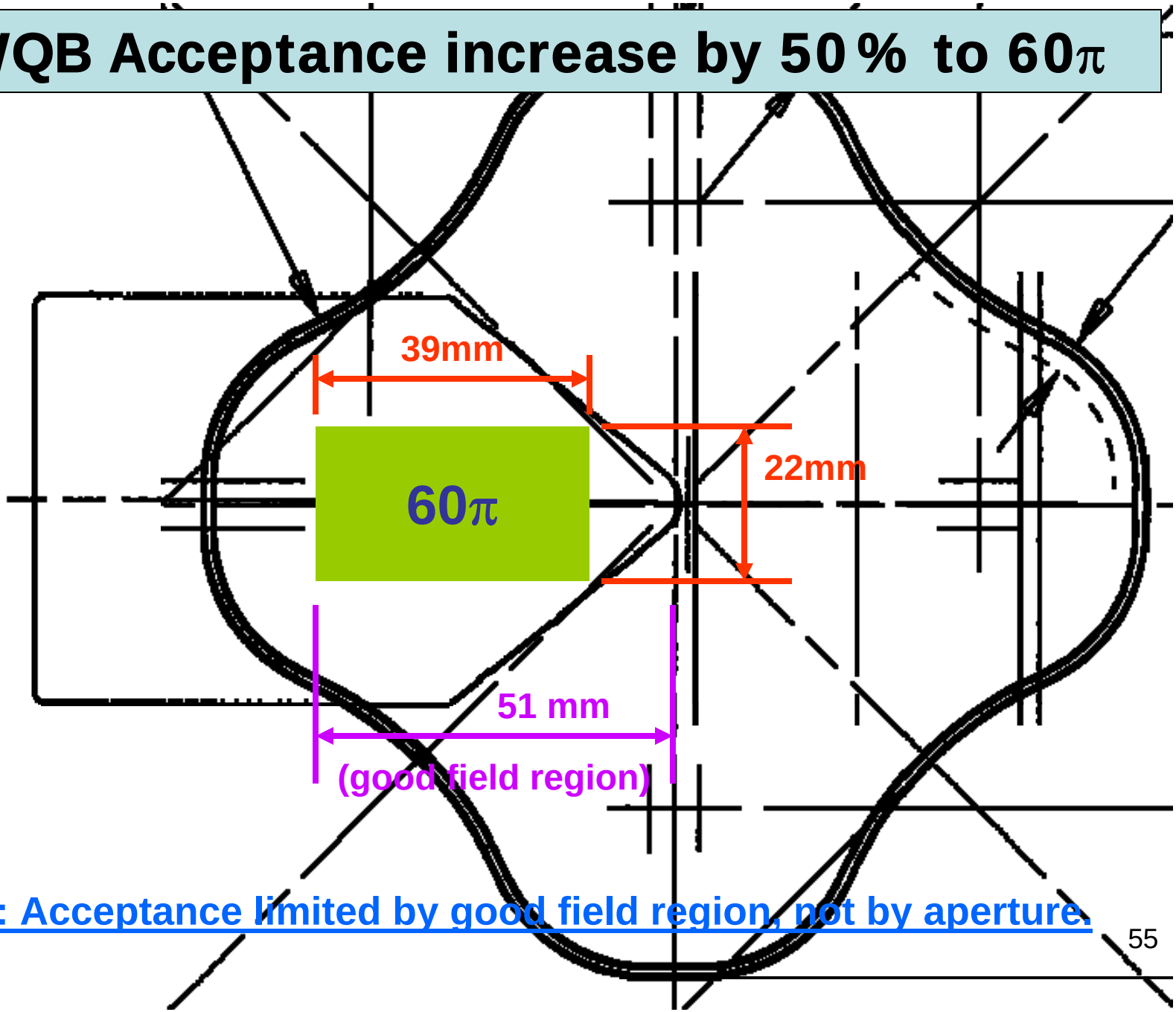



**39mm (was 30mm)**

# Old IQB Design Acceptance 40π

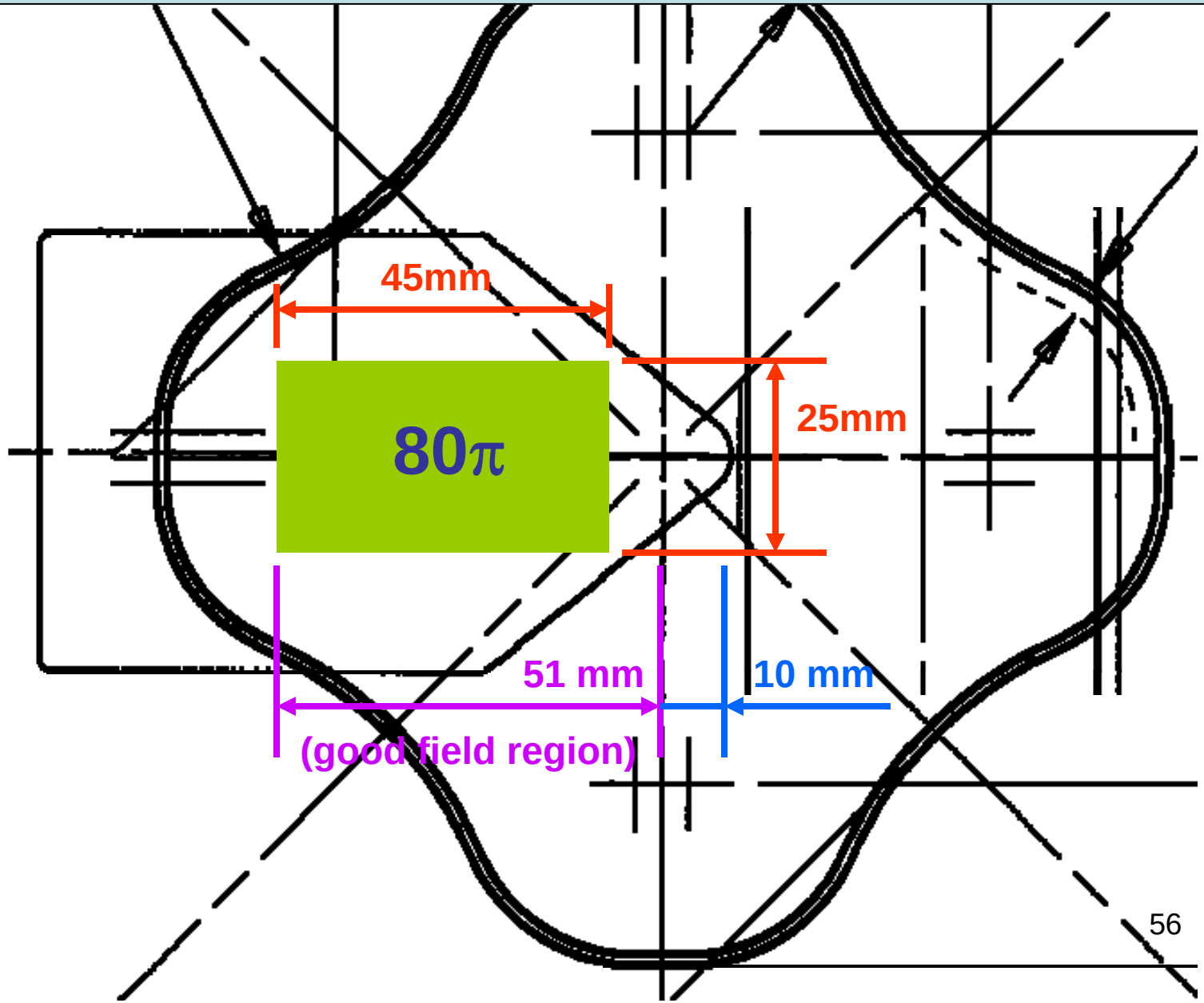


# WQB Acceptance increase by 50% to 60π




Note: Acceptance limited by good field region, not by aperture.

# Moving Lambertson 10mm, Acceptance increased to 80π



# Summary

- TD did a wonderful job and delivered high quality WQB magnets to AD. It was another example of the beautiful collaboration between the two divisions.
- A number of AD departments worked together seamlessly to make the installation and commissioning of the WQBs and new BPMs a success.
- The WQB aperture and acceptance increases meet the requirement.
- The perturbation to the lattice is minimal.
- Further improvement in acceptance is possible by moving the Lambertson magnets (planned for next shutdown).
- Many thanks to all people involved in this project. It was a pleasure and privilege to work with these guys.

# Questions?