# BEAM-BASED ALIGNMENT OF A HELICAL UNDULATOR

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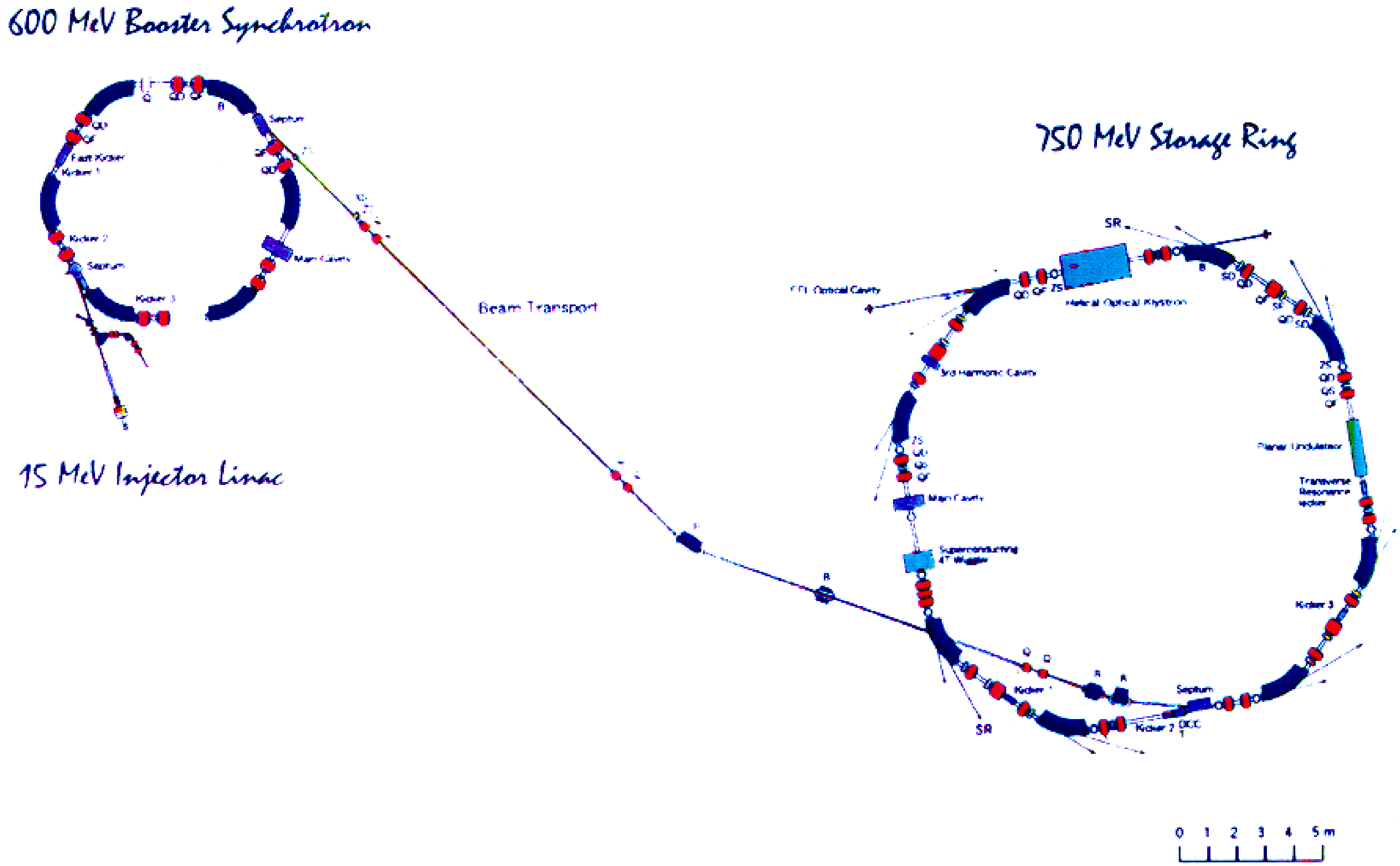



The UVSOR Accelerator Complex

# Insertion Devices

## Superconducting Wiggler

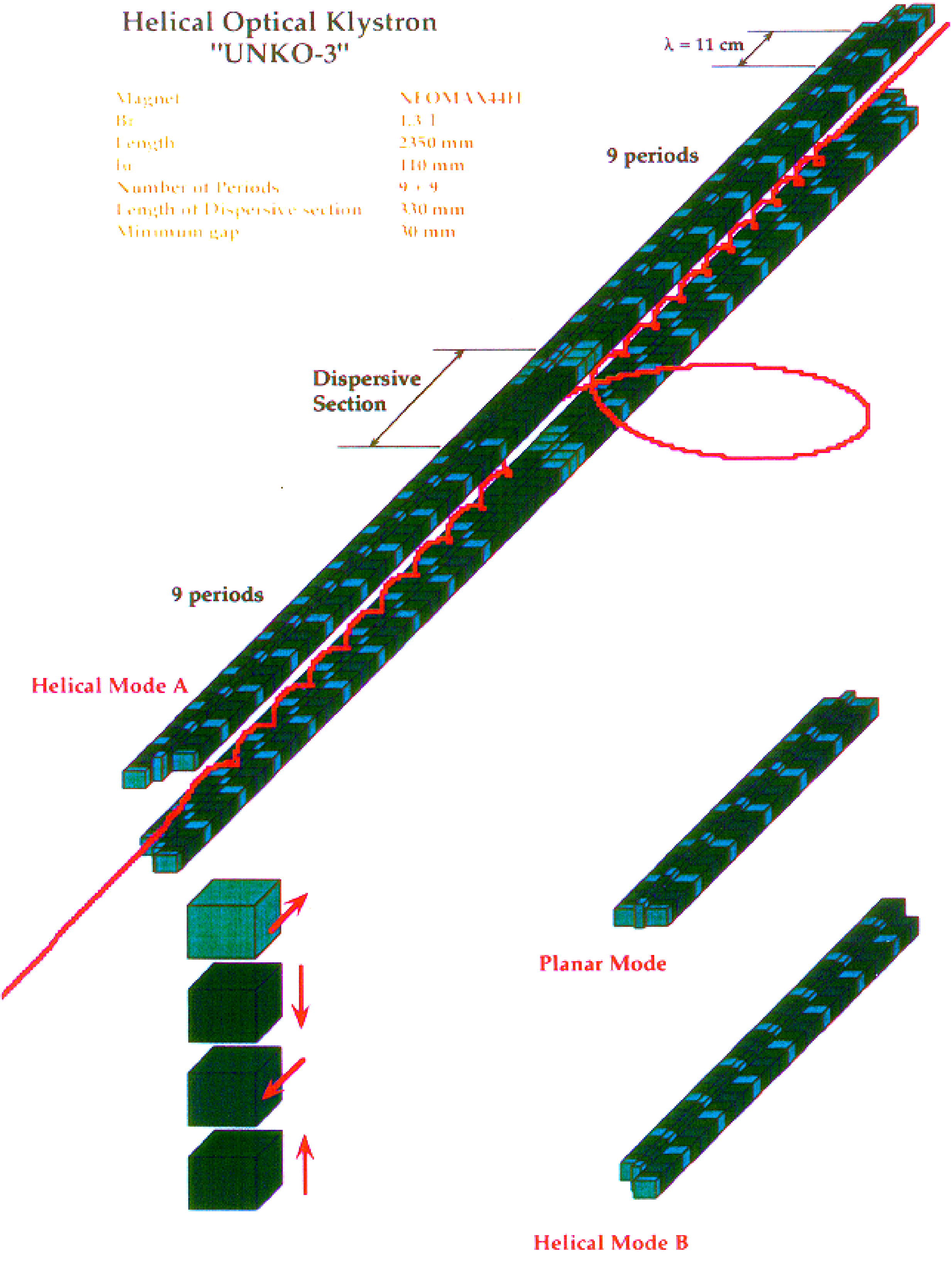
| | |
|---|---|
| Wiggler type | Wavelength shifter |
| Number of poles | 3 |
| Magnetic field | 4 T max. |
| Critical energy | 1.5 keV @ 750 MeV |

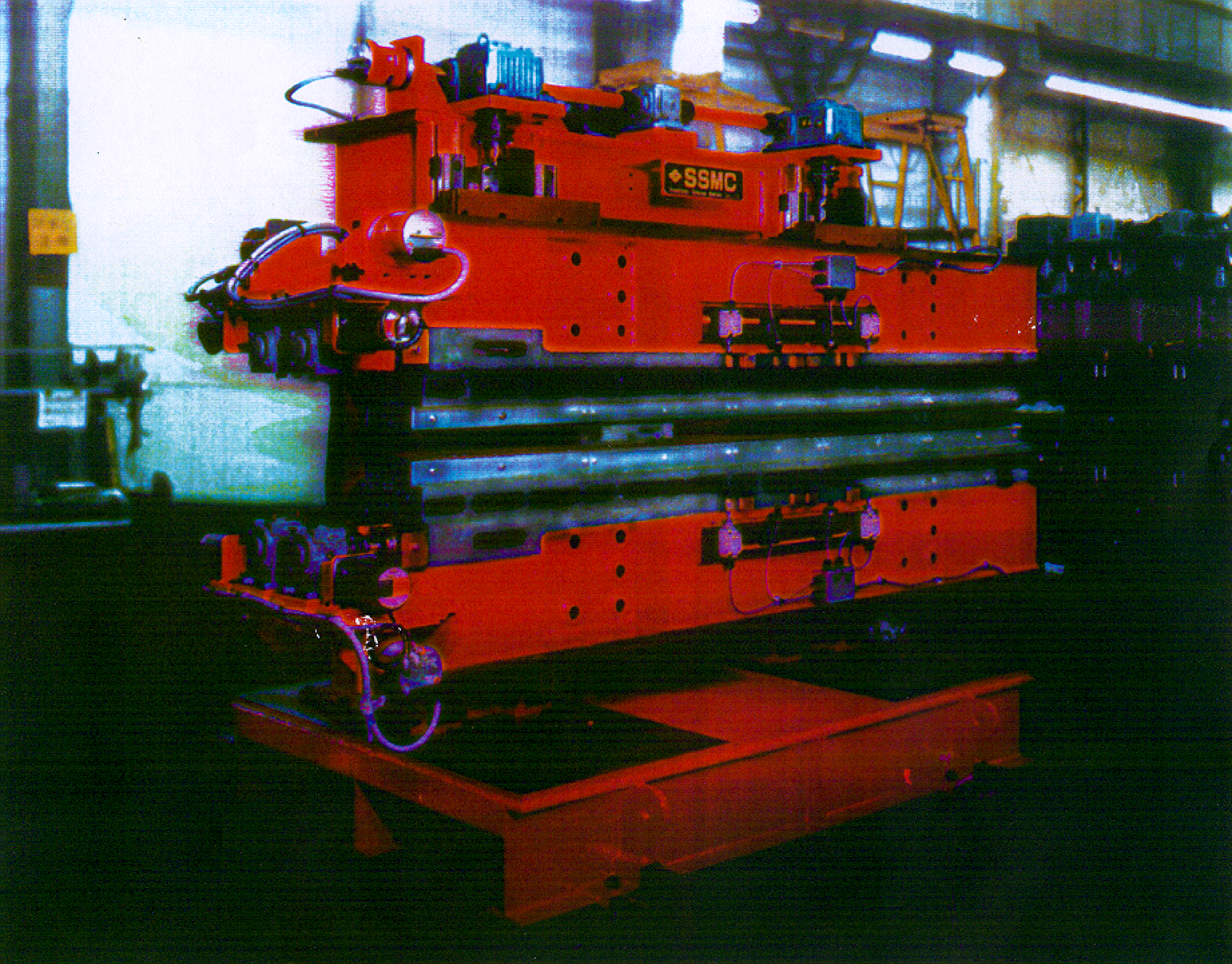
## Planar Undulator

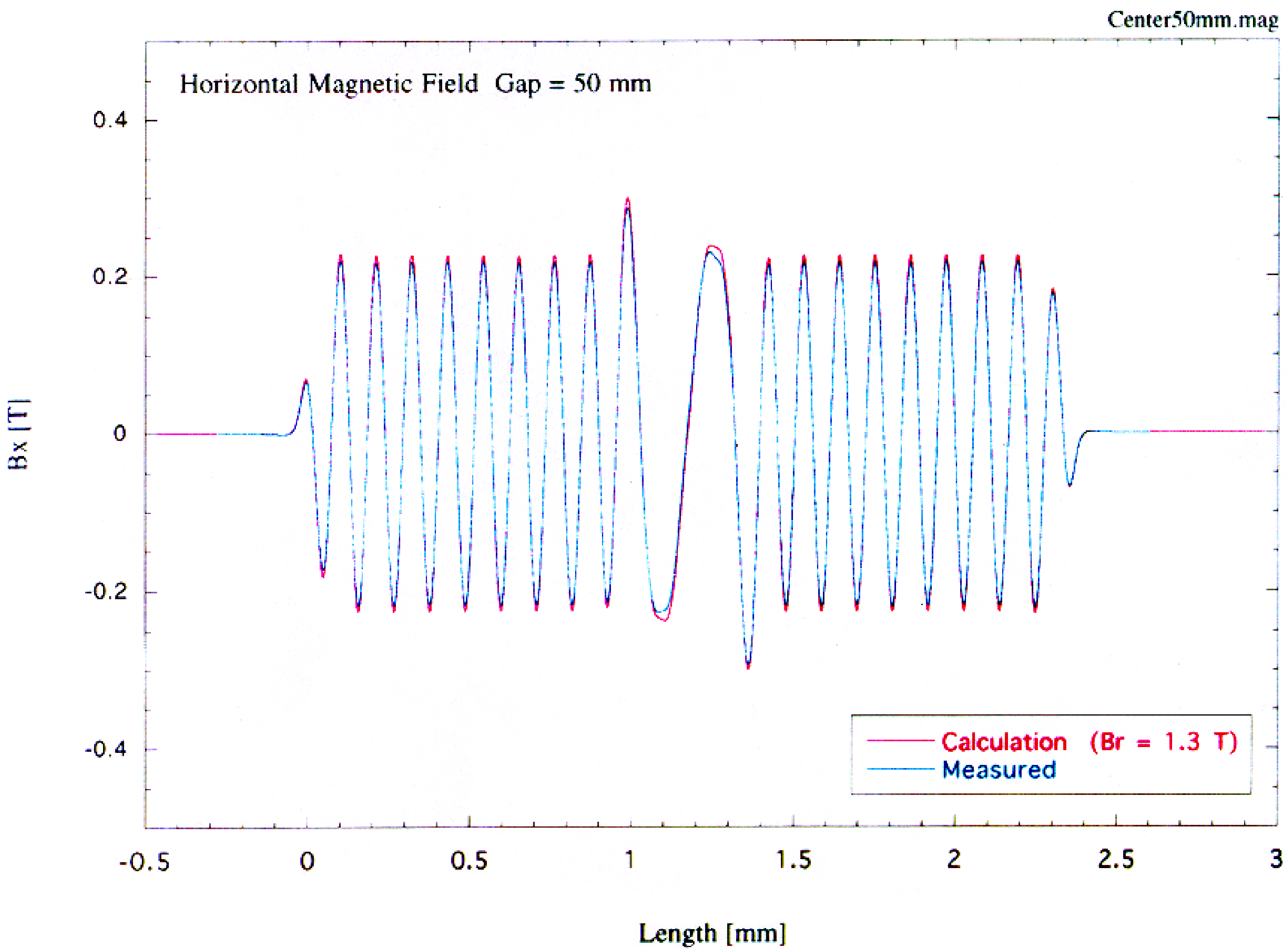
| | |
|---|---|
| Number of periods | 24 |
| Period length | 8.4 cm |
| Total length | 201.6 cm |
| Remanent field | 0.9 T |
| Available gap | 30 - 90 mm |
| Deflection parameter K | 0.6 - 3.6 |
| 1st harm. photon energy | 8 - 52 eV @ 750 MeV |

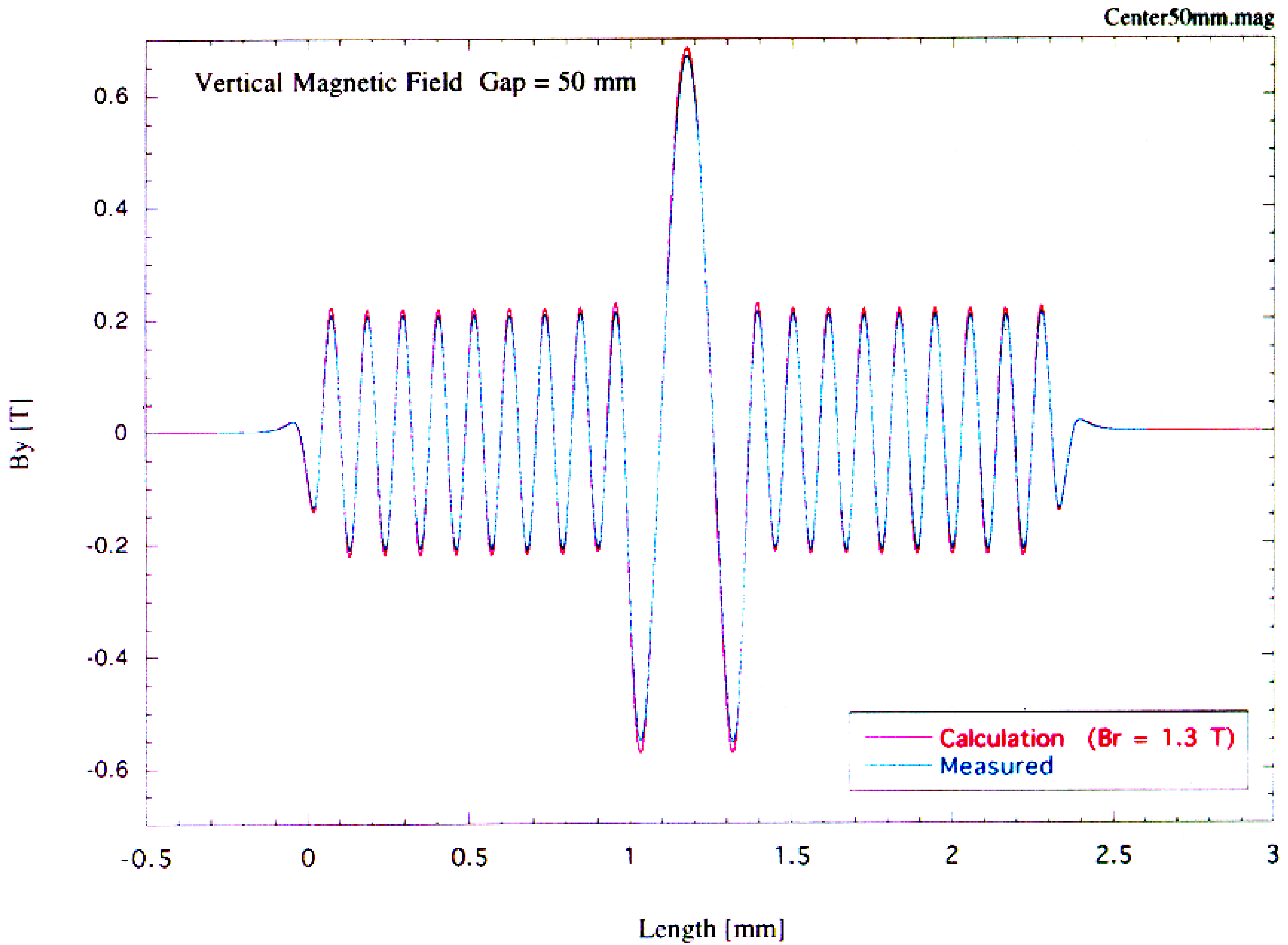
## Helical Optical Klystron Undulator (for FEL)

| | |
|---|---|
| Number of periods | 18 (9 × 2) |
| Period length | 11 cm |
| Length of buncher | 33 cm |
| Total Length | 235.12 cm |
| Remanent field | 1.3 T |
| Available gap | 30 - 150 mm |
| Deflection parameter K | 0.07 - 4.6 (Helical mode)<br>0.15 - 8.5 (Planar mode) |
| 1st harm. photon energy | 2 - 45 eV @ 750 MeV (Helical mode) |


Helical Optical Klystron
"UNKO-3"
Magnet NEOMAX44H
Br 1.3 T
Length 2350 mm
λu 110 mm
Number of Periods 9 + 9
Length of Dispersive section 330 mm
Minimum gap 30 mm
λ = 11 cm
9 periods
Dispersive Section
9 periods
Helical Mode A
Planar Mode
Helical Mode B


SSMC


Center50mm.mag
Horizontal Magnetic Field Gap = 50 mm
0.4
0.2
0
-0.2
-0.4
Bx [T]
-0.5
0
0.5
1
1.5
2
2.5
3
Length [mm]
Calculation (Br = 1.3 T)
Measured



Center50mm.mag
Vertical Magnetic Field Gap = 50 mm
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
By [T]
-0.5
0
0.5
1
1.5
2
2.5
3
Length [mm]
Calculation (Br = 1.3 T)
Measured

# ISSUES OF UNDULATORS FOR (LOW ENERGY) STORAGE RINGS

1. Additional Focusing Power ($B_Z$ on off-axis)

   0-th order Quadrupole $$k\,l = \frac{B_o^{\,2}\,\lambda_p\,N_p}{2\,(B\rho)^2} \quad [T/m]$$

   Very important effect for low energy machines.
   Long undulator is also critical issue for even high energy machines.

2. Multipole Focusing Power (Multipole fields in Curvilinear system)

   Inhomogeneous field gives complicate multipoles on the beam trajectory.

3. Errors

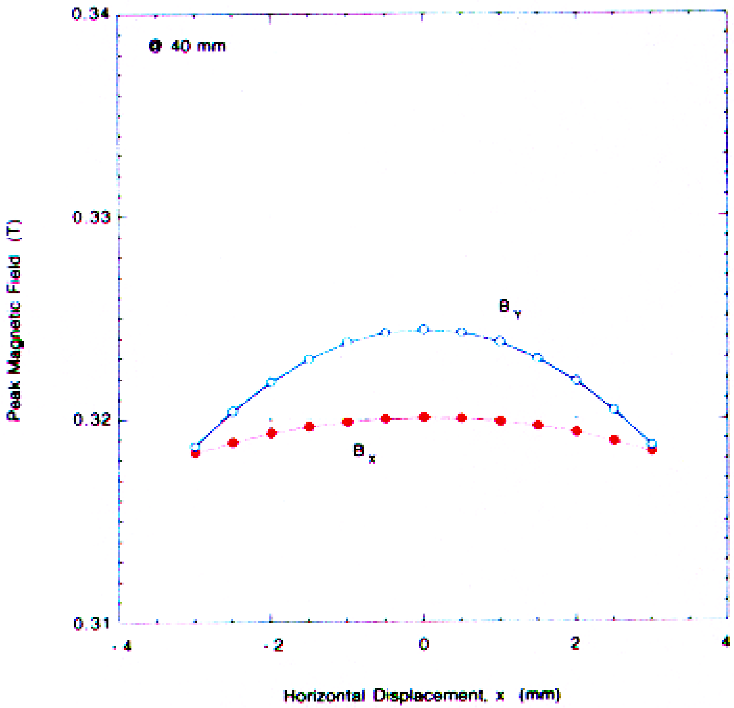
   Magnetic field measurements are always correct ?

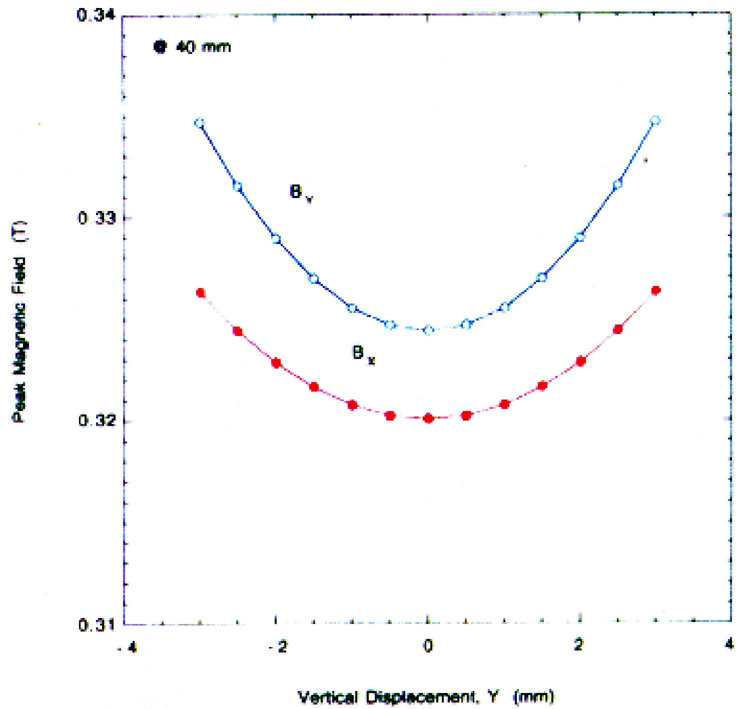
   How we correct COD ?

   COD correction is not equivalent to correction of beam trajectory in the undulator.

# Characteristics of Magnetic Fields in UNKO-3

Very narrow uniform region.
Same displacement dependences for inhomogeneous $B_X$ and $B_Y$ fields



To satisfy eq. (10),

$$\frac{\partial^2 g}{\partial x^2}+\frac{\partial^2 g}{\partial y^2}=\left(-k_x{}^2+k_y{}^2\right)\cos\left(k_x x\right)\cosh\left(k_y y\right) \quad \text{and} \quad \frac{\partial^2 f}{\partial x^2}+\frac{\partial^2 f}{\partial y^2}=\left(-j_x{}^2+j_y{}^2\right)\cos\left(j_x x\right)\cosh\left(j_y y\right) \tag{12}$$

then conditions

$$k_p{}^2=-k_x{}^2+k_y{}^2 \quad \text{and} \quad k_p{}^2=-j_x{}^2+j_y{}^2 \tag{13}$$

are required.

The longitudinal field can be obtained from $\frac{\partial B_Z}{\partial z}=-\frac{\partial B_X}{\partial x}-\frac{\partial B_Y}{\partial y}$

Finally

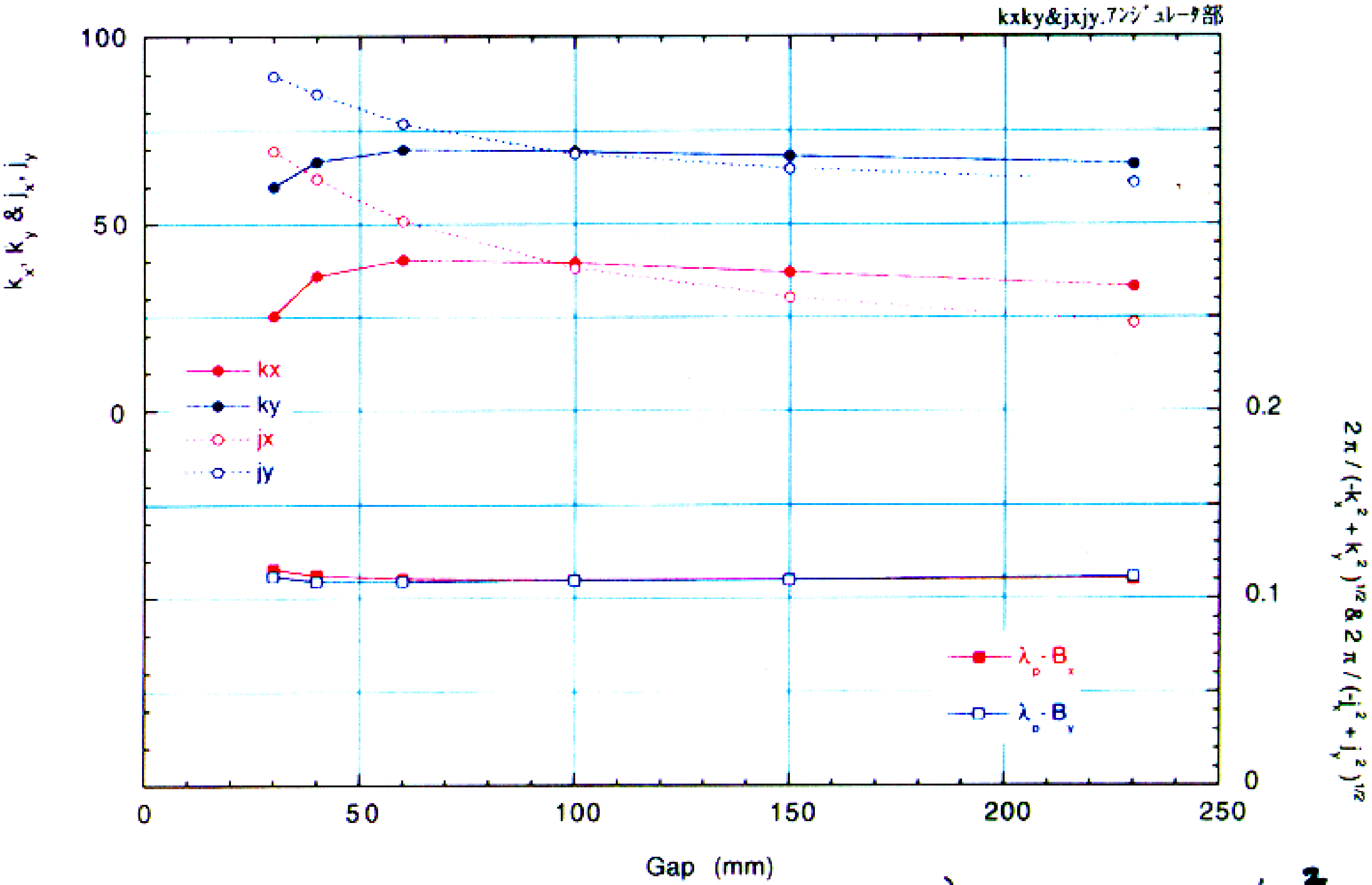
$$B_x=B_x^0\cos\left(k_x x\right)\cosh\left(k_y y\right)\sin\left(k_p z\right)$$

$$B_y=B_y^0\cos\left(j_y x\right)\cosh\left(j_y y\right)\cos\left(k_p z\right)$$

$$B_z=-B_x^0\frac{k_x}{k_p}\sin\left(k_x x\right)\cosh\left(k_y y\right)\cos\left(k_p z\right)-B_y^0\frac{j_y}{k_p}\cos\left(j_x x\right)\sinh\left(j_y y\right)\sin\left(k_p z\right)$$

$$k_p{}^2=-k_x{}^2+k_y{}^2=-j_x{}^2+j_y{}^2$$

# Inhomogenous parameters ($k_x$, $k_y$, $j_x$, $j_y$) deduced from magnetic field calculation




$\lambda_p = 0.11\ m$ $\quad k_p^2 = -k_x^2 + k_y^2 - j_x^2 + j_y^2$

# UNDULATOR SECTION (per one period)

## Horizontal Plane

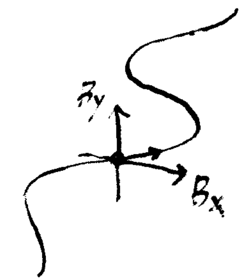
Quadrupole ($kl$)

$$\frac{\lambda_p}{2\,B\rho\,k_p^{\,2}}\left(B_x^{0\,2}\,k_x^{\,2}+B_y^{0\,2}\,j_x^{\,2}\right)+\frac{\lambda_p}{16\,B\rho^4\,k_p^{\,6}}\left(B_x^{0\,4}\,k_x^{\,2}k_y^{\,2}+3\,B_x^{0\,2}\,B_y^{0\,2}\,j_x^{\,2}j_x^{\,2}\right)$$

defocus may be very small

Skew-Q like ($x\,y^2$)

$$\frac{\lambda_p}{4\,B\rho\,k_p^{\,2}}\left(B_x^{0\,2}\,k_x^{\,2}\,k_y^{\,2}+B_y^{0\,2}\,j_x^{\,2}j_y^{\,2}\right)$$




## Vertical Plane

Quadrupole ($kl$)

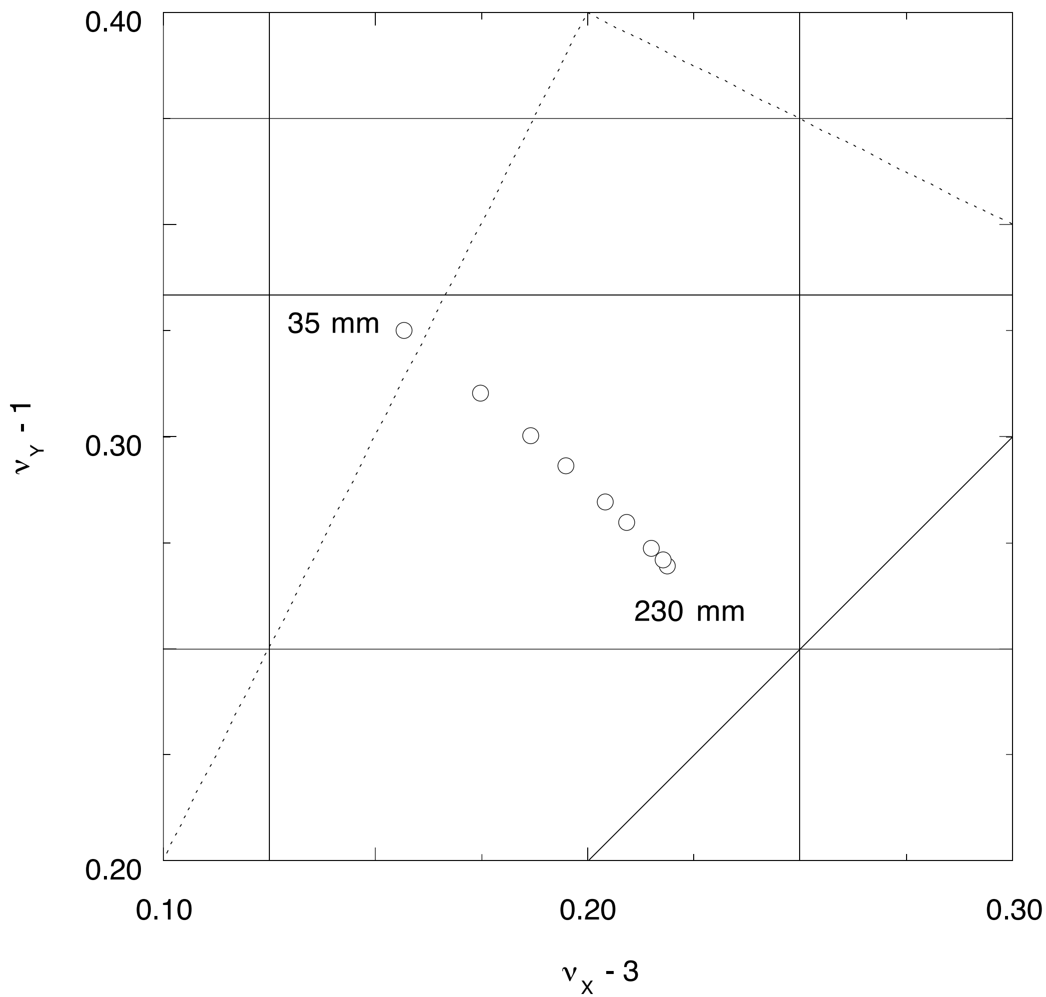
$$-\frac{\lambda_p}{2\,B\rho\,k_p^{\,2}}\left(B_x^{0\,2}\,k_y^{\,2}+B_y^{0\,2}\,j_y^{\,2}\right)+\frac{\lambda_p}{16\,B\rho^4\,k_p^{\,6}}\left(B_y^{0\,4}\,j_x^{\,2}j_y^{\,2}+3\,B_x^{0\,2}\,B_y^{0\,2}\,k_x^{\,2}\,k_x^{\,2}\right)$$

focus may be very small

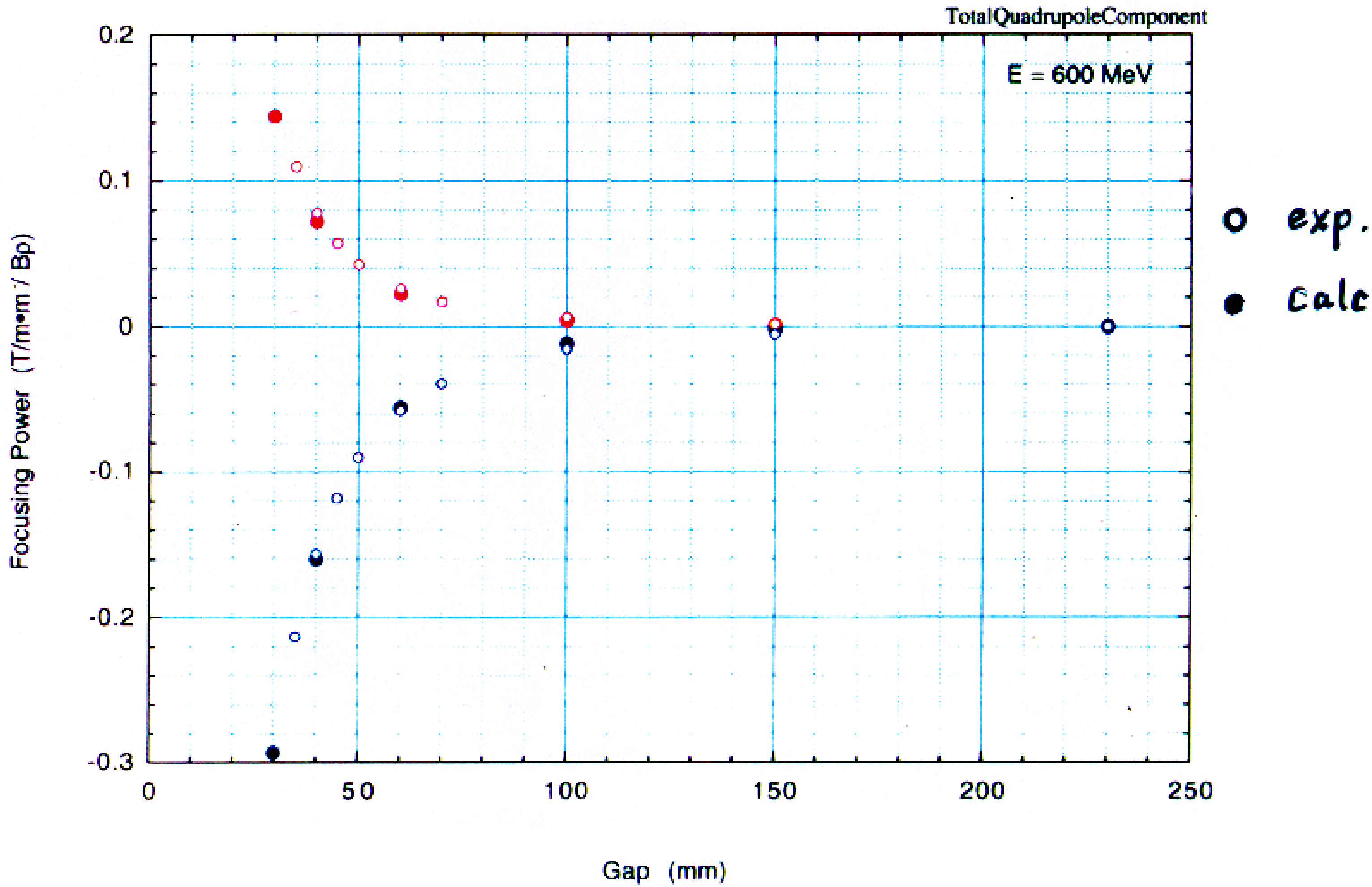
Skew-Q like ($x\,y^2$)

$$\frac{\lambda_p}{4\,B\rho\,k_p^{\,2}}\left(B_x^{0\,2}\,k_x^{\,2}\,k_y^{\,2}+B_y^{0\,2}\,j_x^{\,2}j_y^{\,2}\right)$$

# Tune shift due to UNKO-3

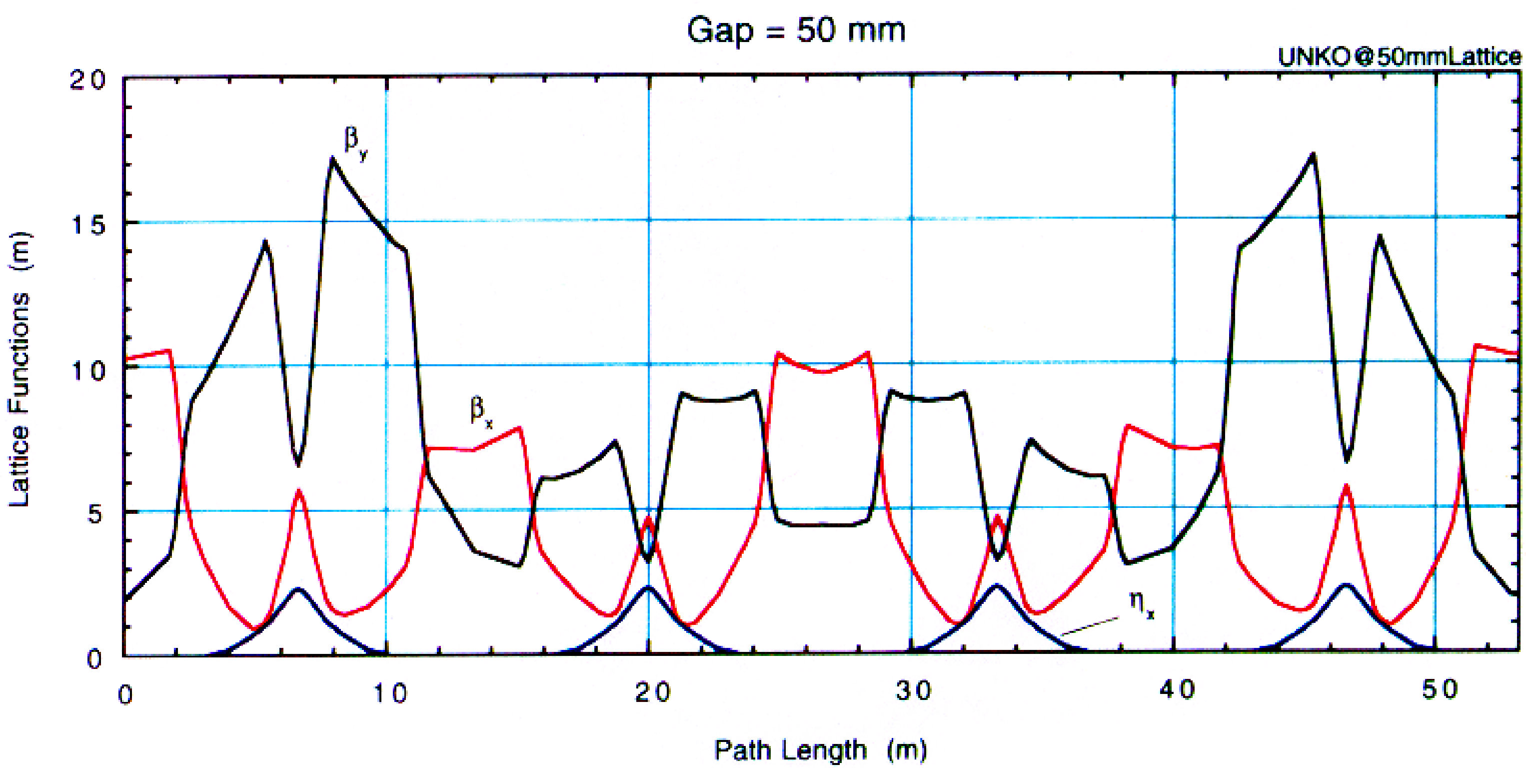


# Quadrupole strength (Open circles : experiment)



## Distortion of lattice function due to Q-strength of UNKO-3

| | | |
|---|---|---|
| Number of Quadrupoles to correct | symmetry | 4 |
| | phase advance | + 2 |

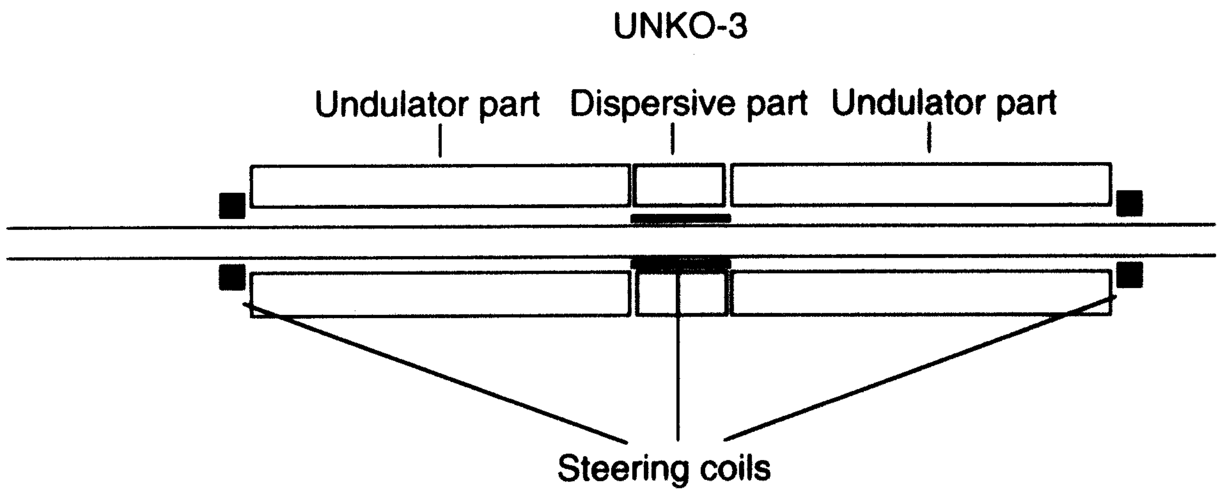



No solution gap < 45 mm

→ Quadrupole correction

# DIPOLEERRORS

**Three possible correction points**




Dipole error source is devided into three positions !

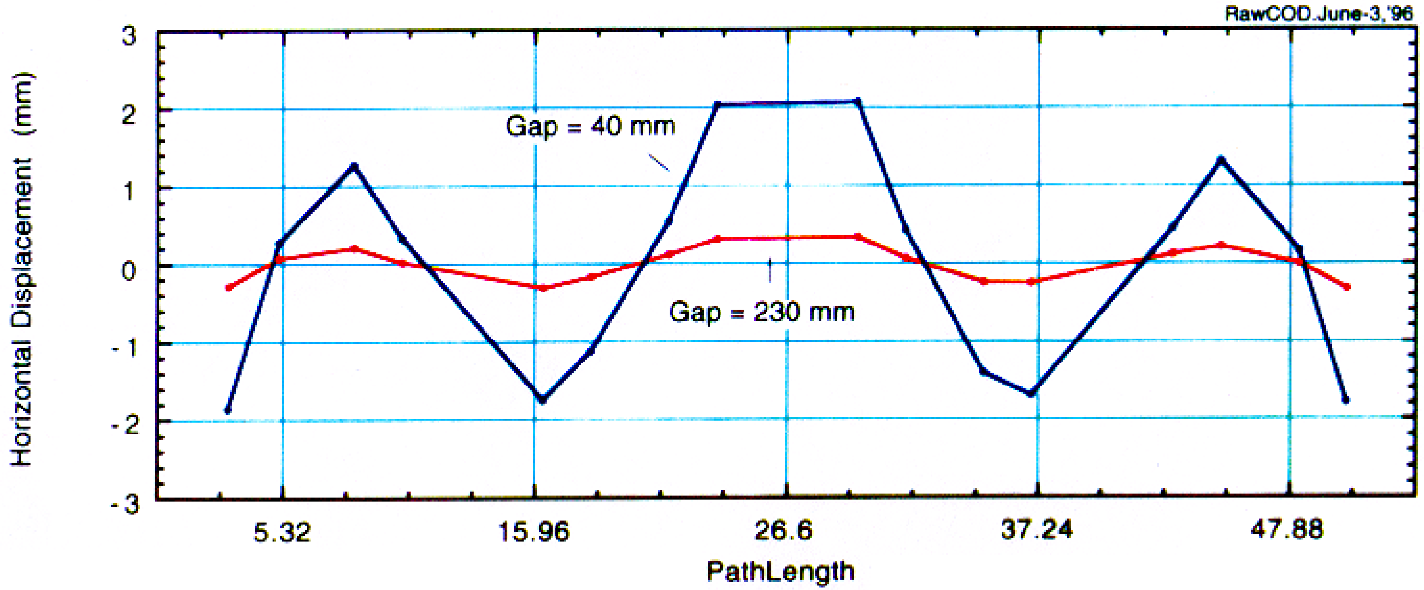
COD due to dipole kick can be written as

$$COD(s) = \frac{\theta_{kick}}{2}\sqrt{\beta(s)\,\beta(s_{kick})}\;\frac{\cos \nu\left[\pi - \left|\phi(s) - \phi(s_{kick})\right|\right]}{\sin \pi \nu}$$

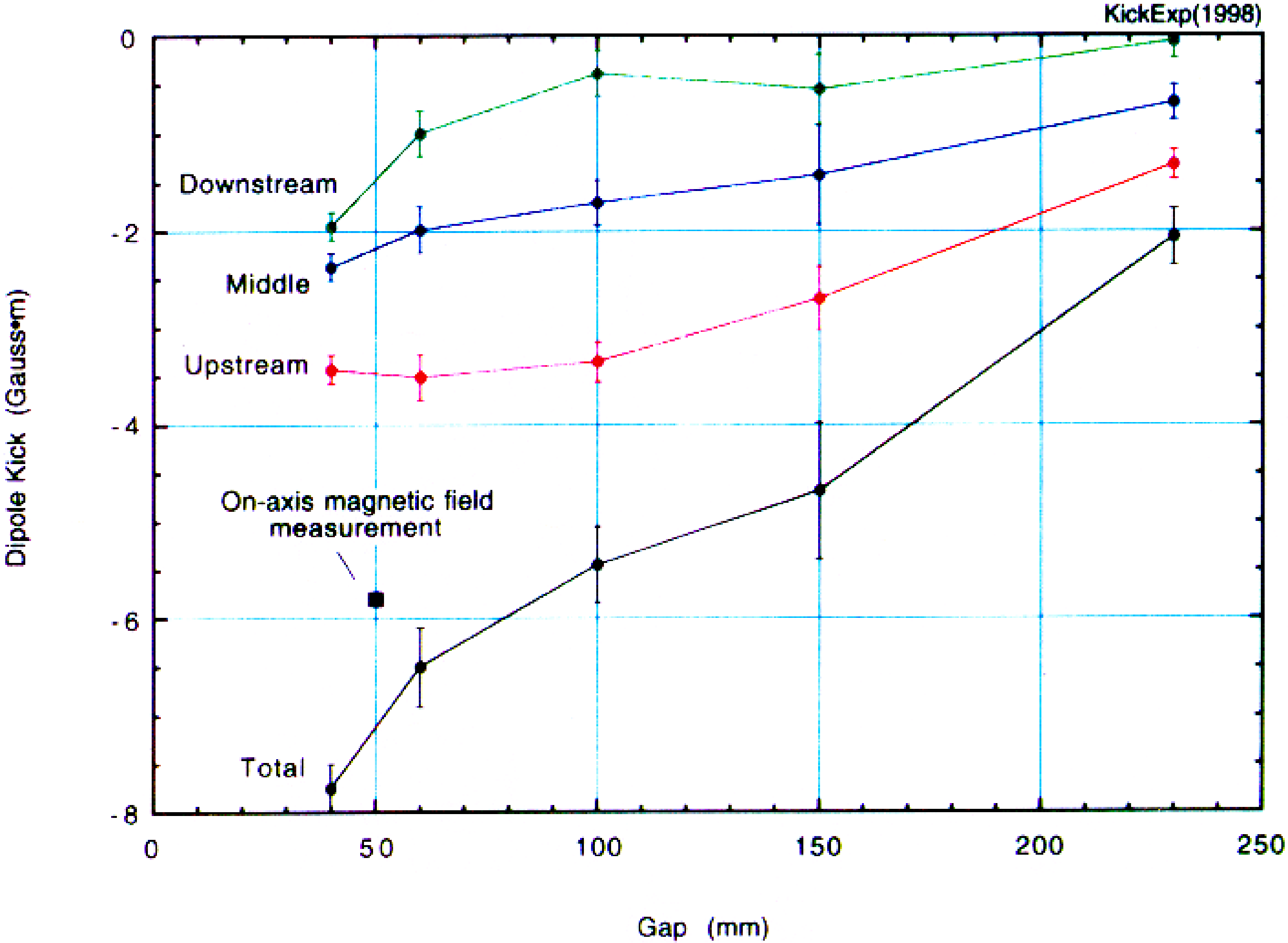
COD Phase analysis with 3 kick sources

$$COD(s) = \theta^1_{kick}\, u'(s^1_{kick}) + \theta^2_{kick}\, u'(s^2_{kick}) + \theta^3_{kick}\, u'(s^3_{kick}) \qquad u'(s^n_{kick}) = \frac{1}{2}\sqrt{\beta(s)\,\beta(s^n_{kick})}\;\frac{\cos \nu\left[\pi - \left|\phi(s) - \phi(s^n_{kick})\right|\right]}{\sin \pi\nu}$$

Using 16-BPM data for Least Square Fitting to derive $\theta^n_{kick}$, and $u'(s^n_{kick})$ is not only able to be calculated from Lattice Function but also can be measured by using well-calibrated steerings.



## Horizontal Dipole Kicks Derived from COD Phase Analysis

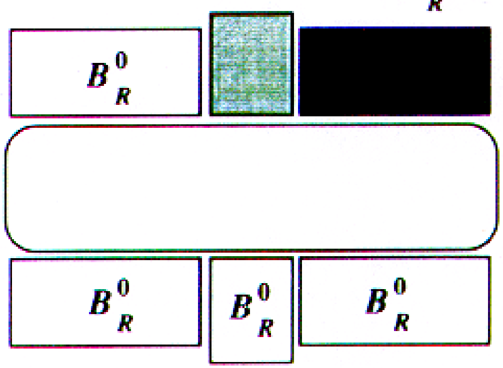


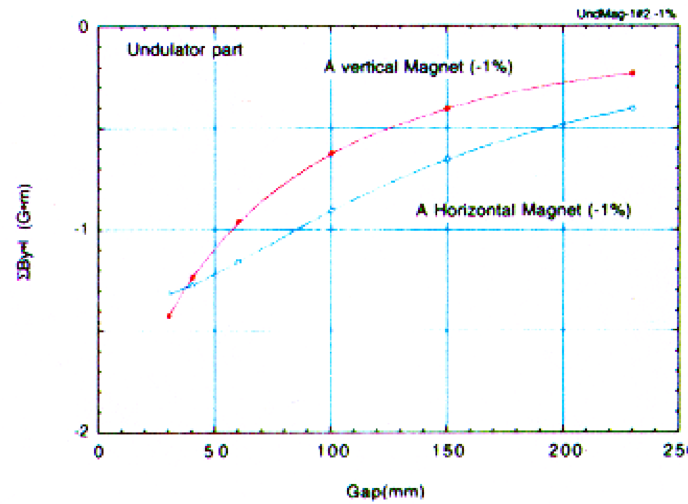
## How do we know "Error Sources" ?

Horizontal Magnetic Field => Composed field of Vertical and Horizontal Magnets

$$B_R = B_R^0 + \Delta B_R$$

$$B_R = B_R^0 + \Delta B_R$$

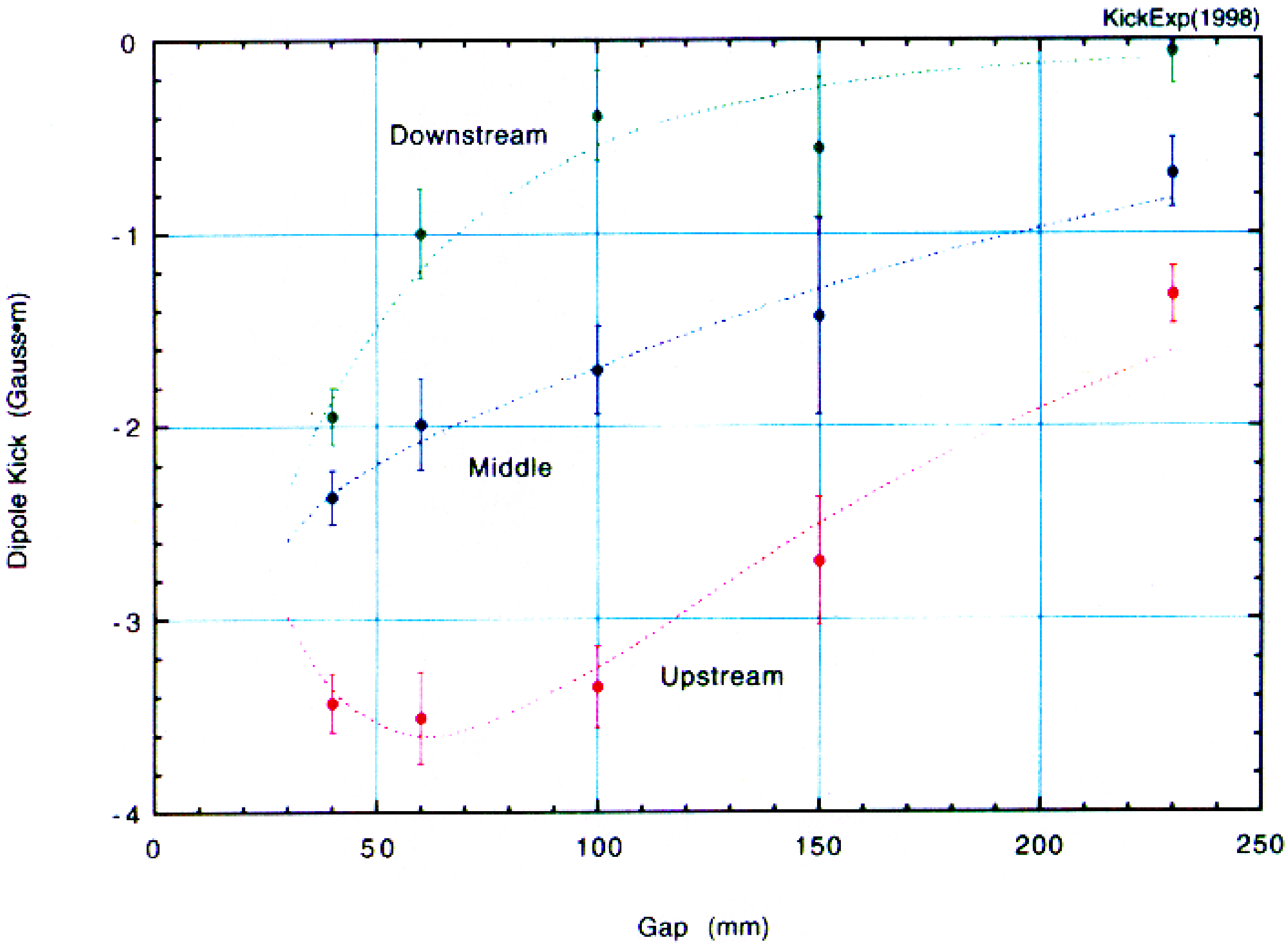



**Fitted results ($\Delta B_R$ / $B_R$)**

| | Upstream | Middle | Downstream |
|---|---|---|---|
| Vertical Magnet | + 3.3 % | + 0.8 % | - 3.0 % |
| Horizontal Magnet | - 5.9 % | - 1.1 % | + 1.5 % |

# Analysis of 3 error sources

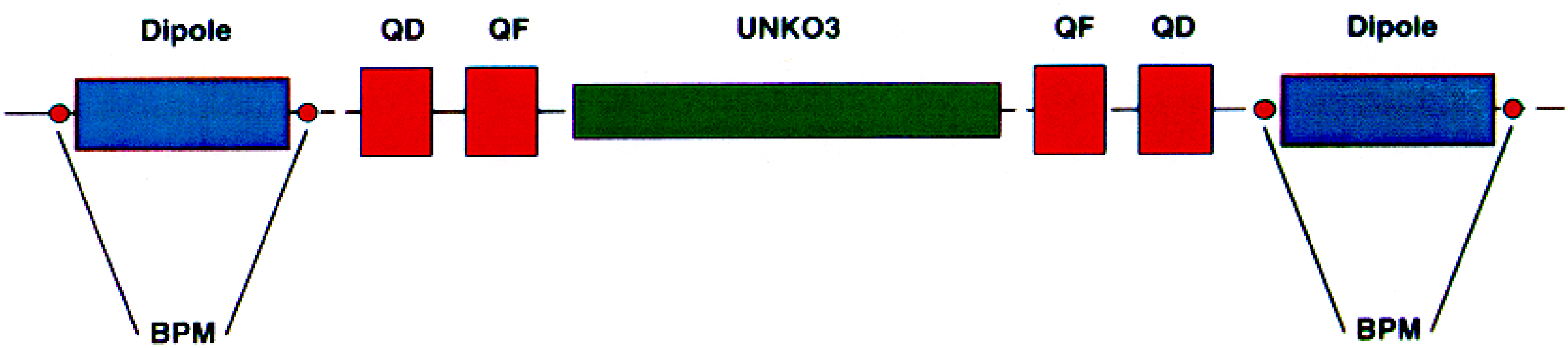


# BEAM-BASEDALIGNMENTOF QUADRUPOLESAND UNDULATOR

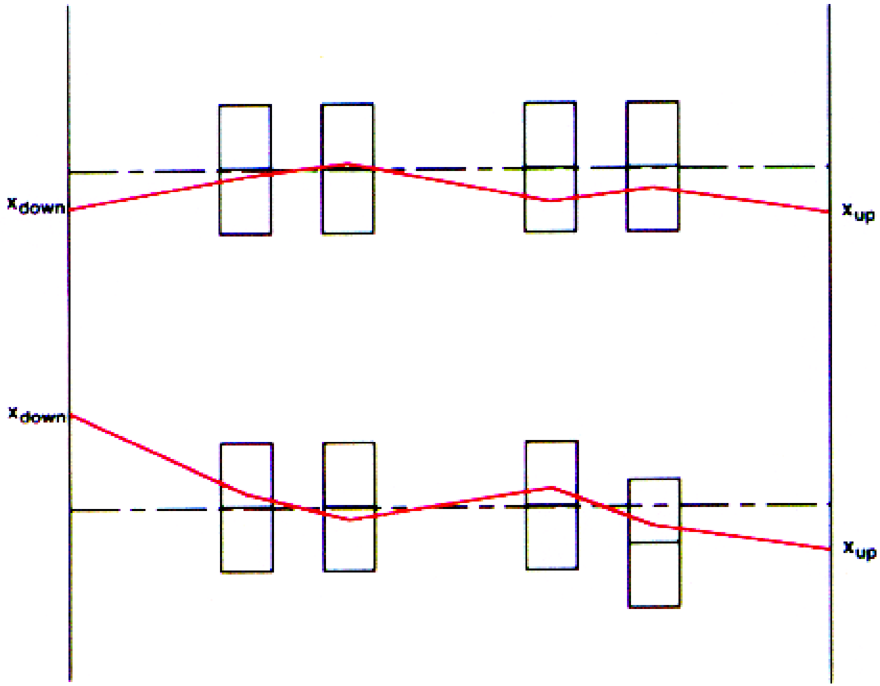
UNKO-3 : Very strong quadrupole strength for both horizontal and vertical directions !

Beam off-axis of Q-magnetic center : Quadrupole kick in the undulator
Beam on-axis : Straight trajectory

There are not enough number of BPMs on the UVSOR ! (not common problem)




Before the undulator is put on the storage ring, we should know **misalignment of Quadrupoles !!!!**




If there is no misalignment,

$$\vec{x}_{down} = \tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\tilde{Q}_2\tilde{L}_2\tilde{Q}_1\tilde{L}_1\vec{x}_{up}$$

If a Q-magnetis misaligned

$$\vec{x}_{down} = \tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\tilde{Q}_2\tilde{L}_2\tilde{Q}_1\tilde{L}_1\vec{x}_{up} + \tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\tilde{Q}_2\tilde{L}_2\vec{K}_1$$

Taking all Q-misalignments into account,

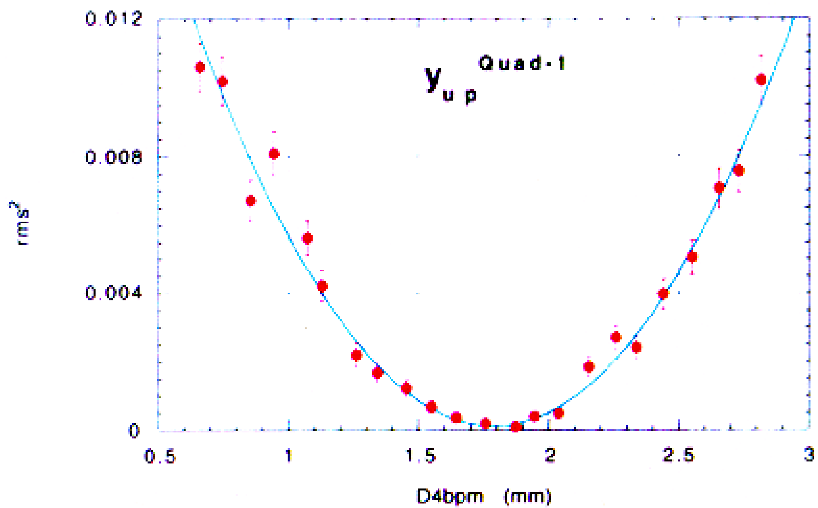
$$\vec{x}_{down} = \tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\tilde{Q}_2\tilde{L}_2\tilde{Q}_1\tilde{L}_1\vec{x}_{up} + \tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\tilde{Q}_2\tilde{L}_2\vec{K}_1 + \tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\vec{K}_2 + \tilde{L}_5\tilde{Q}_4\tilde{L}_4\vec{K}_3 + \tilde{L}_5\vec{K}_4$$

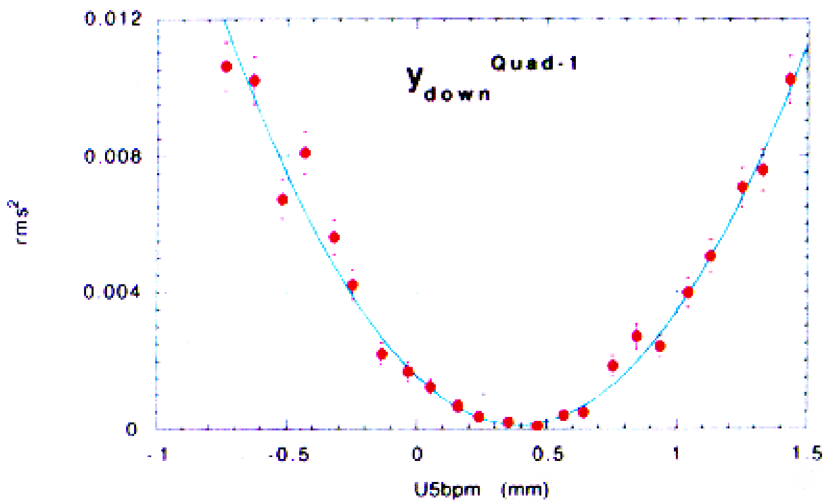
or

$$\vec{x}_{down} = \tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\tilde{Q}_2\tilde{L}_2\tilde{Q}_1\tilde{L}_1\vec{x}_{up} + \left|\tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\tilde{Q}_2\tilde{L}_2\left(\tilde{Q}_1 - \tilde{e}\right)\right|\begin{pmatrix} -c_1 \\ 0 \end{pmatrix}$$

$$+ \left|\tilde{L}_5\tilde{Q}_4\tilde{L}_4\tilde{Q}_3\tilde{L}_3\left(\tilde{Q}_2 - \tilde{e}\right)\right|\begin{pmatrix} -c_2 \\ 0 \end{pmatrix} + \left|\tilde{L}_5\tilde{Q}_4\tilde{L}_4\left(\tilde{Q}_3 - \tilde{e}\right)\right|\begin{pmatrix} -c_3 \\ 0 \end{pmatrix} + \left|\tilde{L}_5\left(\tilde{Q}_4 - \tilde{e}\right)\right|\begin{pmatrix} -c_4 \\ 0 \end{pmatrix}$$

$$\frac{\Delta k}{k} \approx 5\%$$




| | Displacement (mm) | |
|---|---|---|
| | Horizontal | Vertical |
| Quad-1 | - 0.71 | + 1.67 |
| Quad-2 | - 0.64 | + 1.31 |
| Quad-3 | - 0.71 | + 0.73 |
| Quad-4 | - 0.90 | + 0.42 |

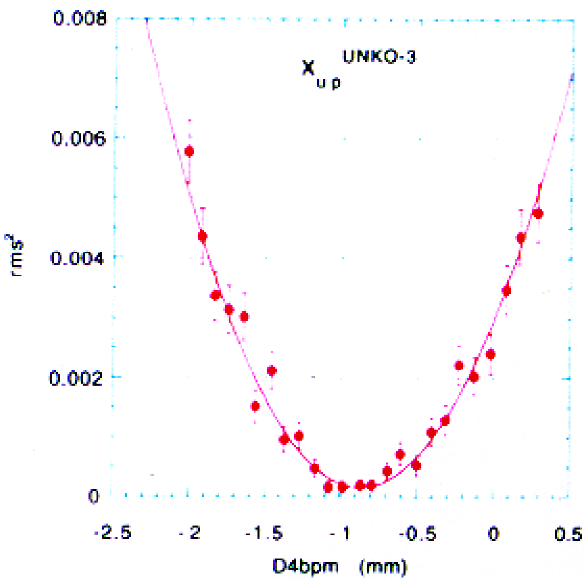
The displacement is a distance from a line connected to the BPM centers.

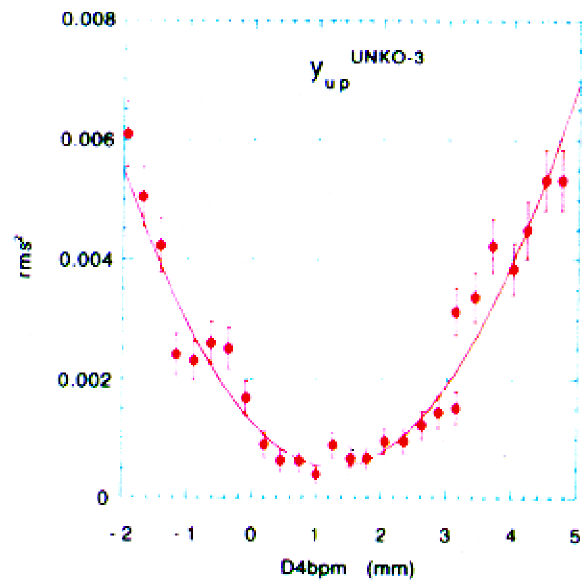
## Measurement of UNKO-3 Position

Definition of "UNKO-3's center" is a magnetic center of the Quadrupole strength !

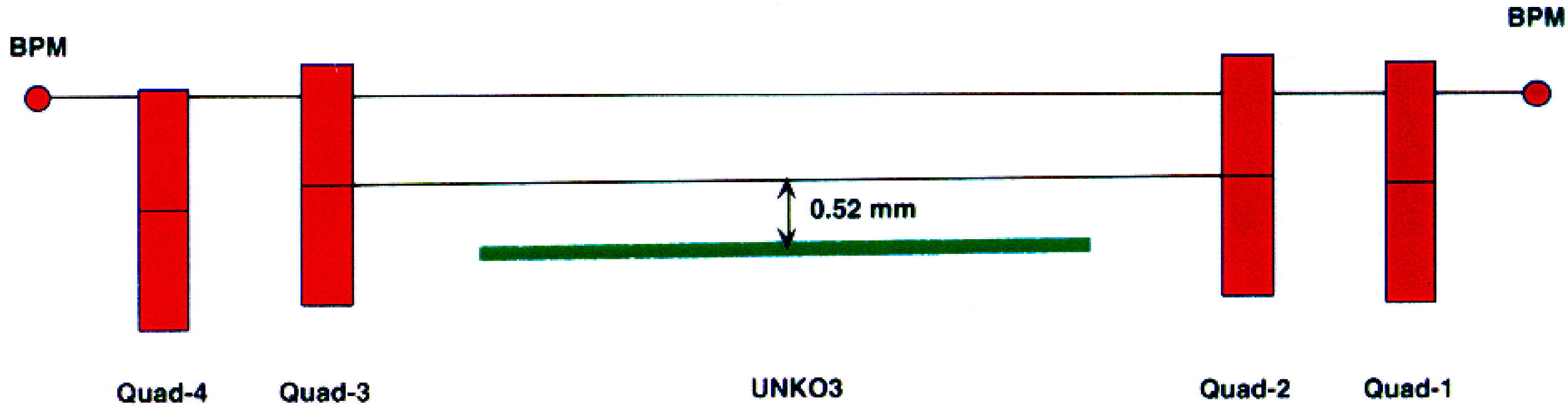
**Forget tilt !!**

- Because the Q-magnets center are already known, the transfer matrix including UNKO-3's quadrupole strength is much more simple.
- By changing the gap, quadrupole strength of the UNKO-3 can be varied, then we can derive the aboslute position of the magnetic center of UNKO-3.



## UNKO-3 Horizontal Position




## UNKO-3 Vertical Position