CESR-c Wigglers

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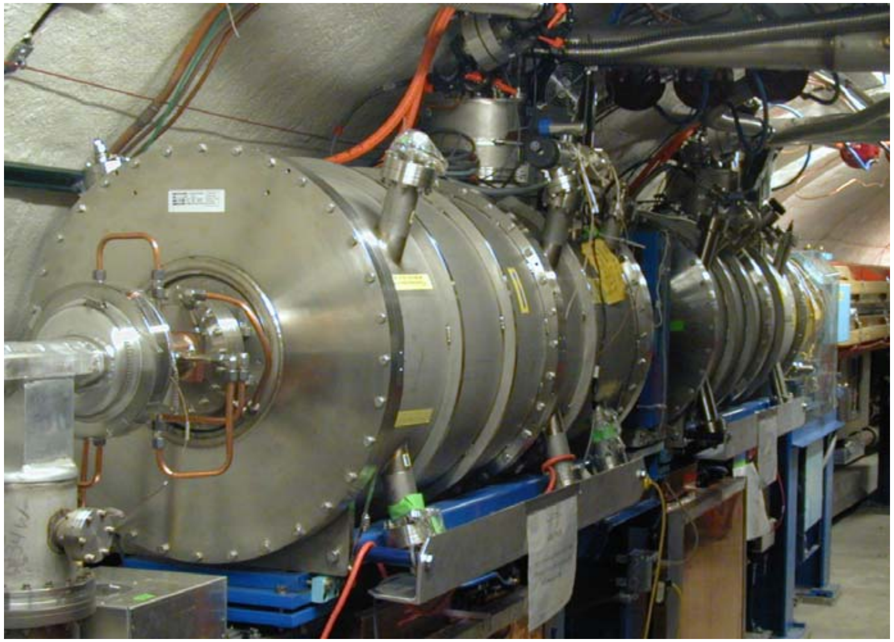
CESR-c Wiggler main characteristics

- 2.1T peak field, 40cm period, 20cm pole width, 7.62cm gap, 9x5cm beam clearance. Operation range from 2.1T to 1.4T
- 8 poles (asymmetric magnetic design)
- Iron poles & superconductive coils (superferric technology)
- Cryogenic performance:
  ~1.3W at 4K and ~40W at 77K
- Wigglers used to:
  - Enhance radiation damping
  - control beam emittance

2 wiggler cluster in ring →



Contents

- Why we need wiggler magnets
- Setting the main parameters: peak field, length, period, technology, magnetic design
- Production, magnetic field measurement, quality control and cost.
- Wigglers characterization with beam and model benchmarking.
- Summary

Why we need wigglers

In 2001 the decision was made to modify CESR to provide luminosity over the energy range from 1.5 to 2.5 GeV/beam.

- Without wigglers, luminosity $L \sim E^{(4:7)}$ (empirical law) will be decreased by factor of 60 to 1200.

Not acceptable, need wigglers !

- With wigglers, beam energy spread $\sigma_e/E \sim Bw^{1/2}$, damping rate $1/\tau \sim B^2 wLw$, horizontal beam emittance $\varepsilon_x \sim BwHw$

Luminosity ~ 3×10^{32} [1/sec/cm], reduction factor ~ 4

Setting the main parameters: peak field and total length

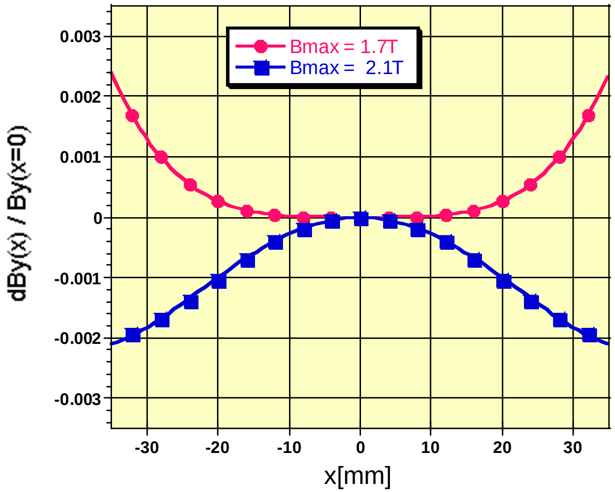
- Peak field (Bw) is limited by maximum allowed energy spread: $\sigma_e/E \sim 8e\text{-}4$ => Bw ~ 2.1T
- Active length (Lw) should be enough to recover damping rate: $1/\tau \sim 30\ \text{sec}^{-1}$ => Lw ~ 18m
- Period: Longer period results in weaker cubic non-linearity, but increases orbit excursion which increase sensitivity to field non-uniformity across wiggler poles. Reasonable compromise: $\lambda = 40$**cm**

$$\Delta y' = -\frac{B_w^2 L}{2(B\rho)^2}\left[y + \frac{2}{3}\left(\frac{2\pi}{\lambda}\right)^2 y^3 + \ldots\right]$$

$$\Delta x' = -\frac{L x_p}{2(B\rho)}\frac{\partial B_y(x)}{\partial x}; \quad x_p = \frac{B_w}{B\rho}\left(\frac{\lambda}{2\pi}\right)^2$$

Expected field non-uniformity for 20cm pole width and 7 cm gap →

Vertical field variation across 20cm pole. From 3D model calculation



Setting the main parameters: technology

Modular design, ~ 1.5m per unit, with 5cm x 9cm beam clearance.

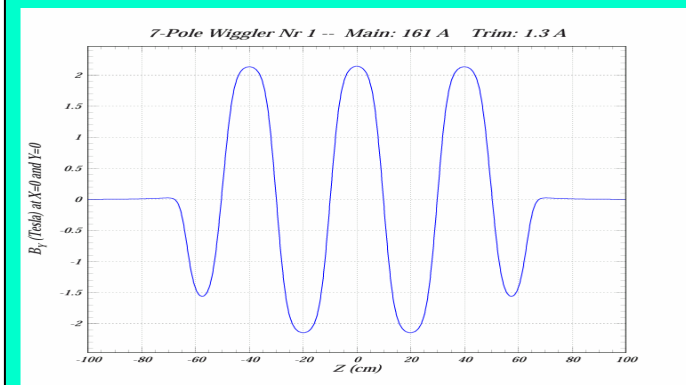
- Normal conducting copper/iron. Similar sized magnets required ~300kW/wiggler.
- Permanent magnet (NdFeB). 2T in 5cm x 9cm gap difficult, BIG magnets, $$, must be opened or removed for 5GeV running.
- Superferric technology (iron poles & superconducting coils) only viable option for high (2T) fields over given beam aperture.

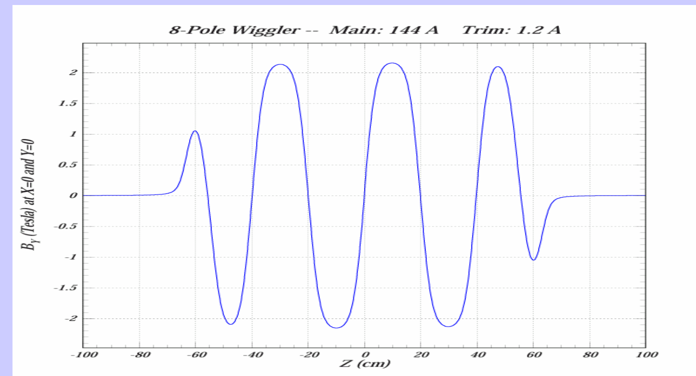
From D.Rice presentation: CESR-c Wiggler Manufacture - PAC 2003

Setting the main parameters: type of symmetry

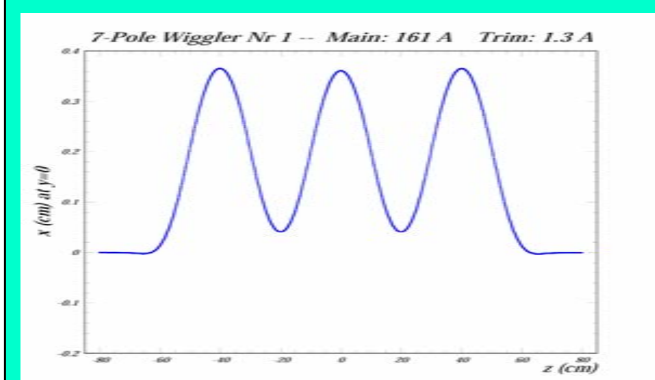
	7 poles (symmetric)	8 poles (asymmetric)
Poles length [cm]	15+20+20+20+20+20+15 = 130	10+15+20+20+20+20+15+10 = 130
Bmax/pole [T]	-1.6/2.1/-2.1/2.1/-2.1/2.1/-1.6	-1.1/2.1/-2.1/2.1/-2.1/2.1/-2.1/1.1

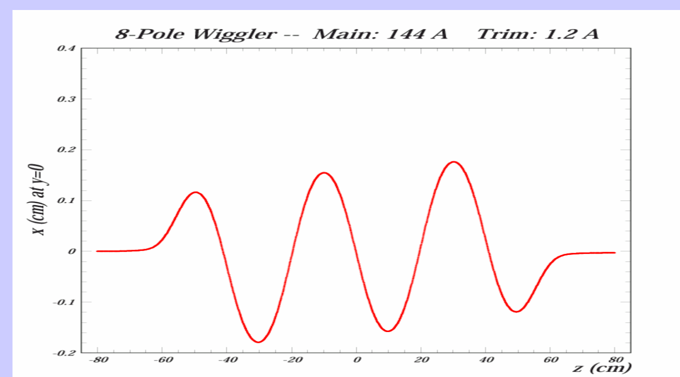
Field along magnet





Beam trajectory



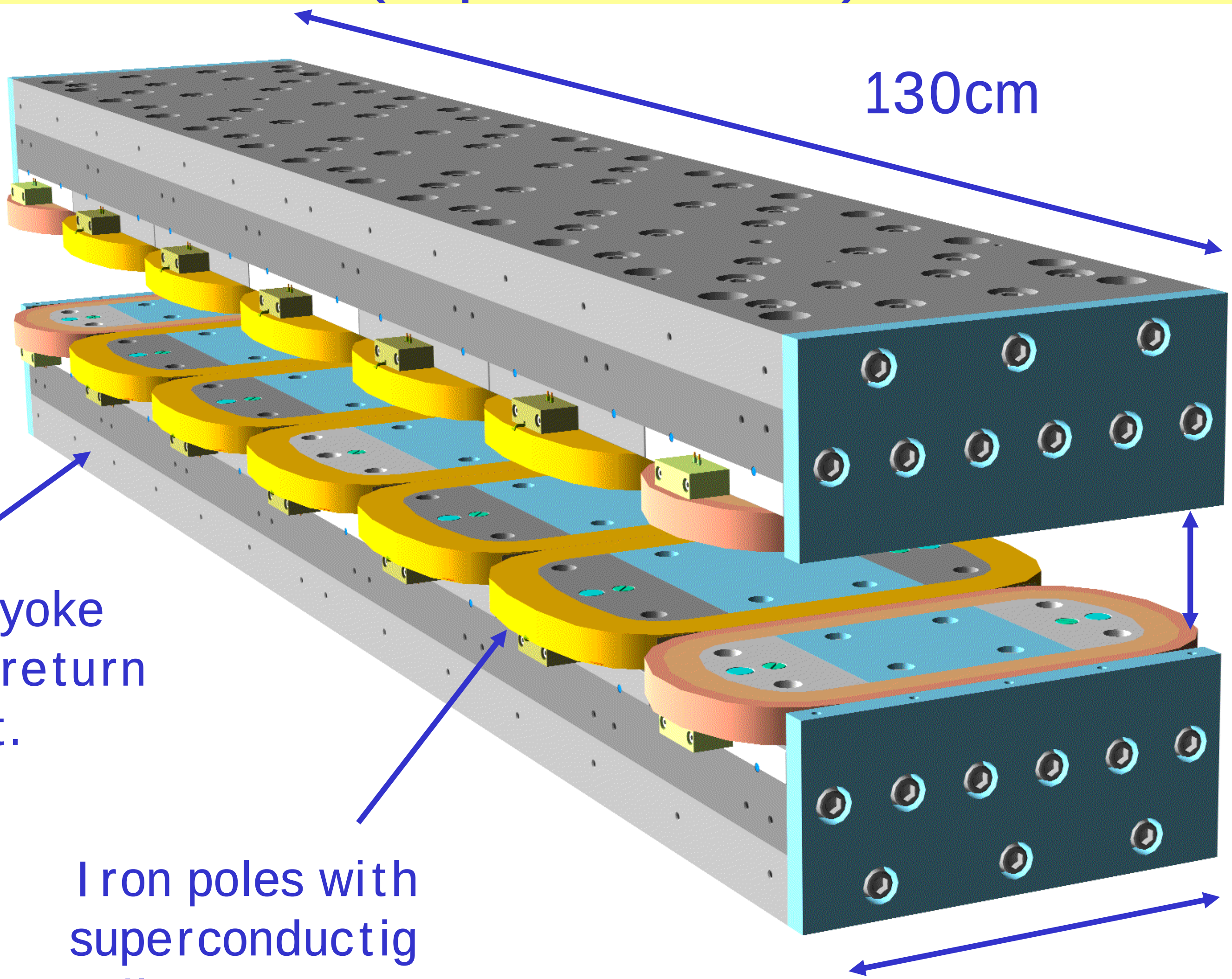


Setting the main parameters: type of symmetry

- Symmetric design (7 poles)
  - Cubic non-linearity (vertical) 5% smaller for fixed damping
  - Only 2 types of poles (vs. 3)
- Asymmetric design (8 poles)
  - Horizontal orbit excursion two times smaller
  - Integrated magnetic field quality is not sensitive to systematic errors on in poles.
  - Maintains linearity over wider range of excitation levels

Units 1 & 2 are 7-pole, units 3 and up are 8-pole.
We built 16 units total

Production: cold mass general view (7-pole version)

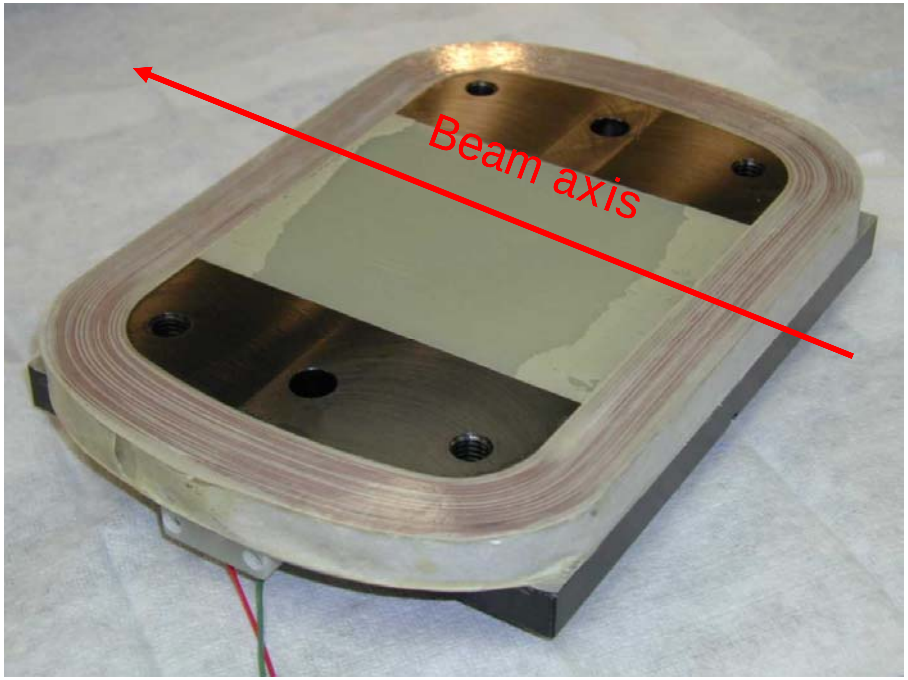


7cm thick "yoke plate" flux return and support.

Iron poles with superconductig coils

Production: Coil Winding

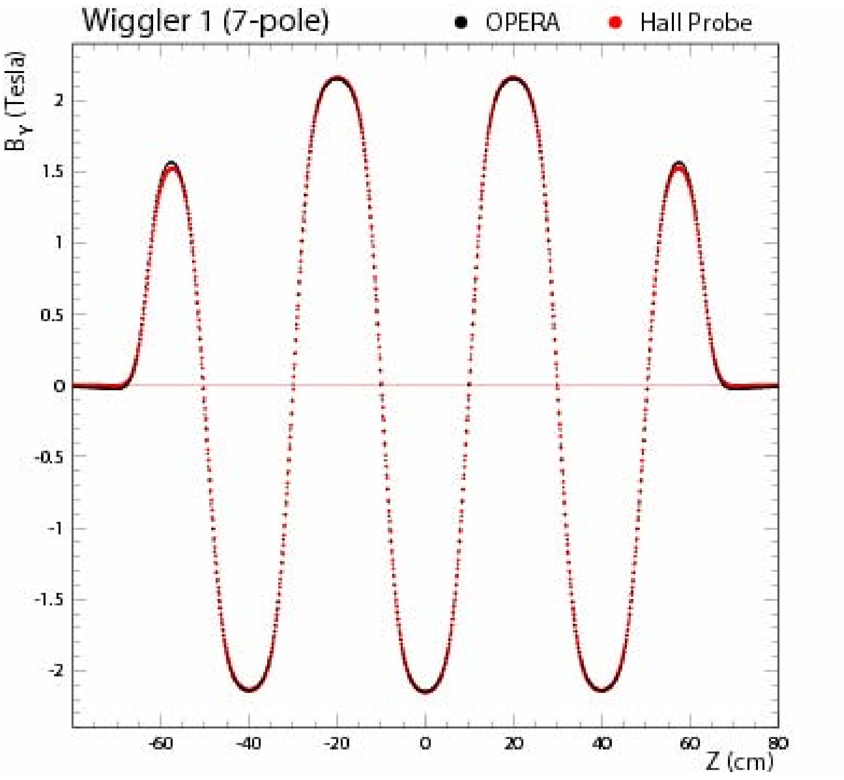
- **Coils are wound directly on individual machined iron poles.**
- **Main poles 660 turns, 0.75 mm, 70 filament wire**
- **Wet wound with Epotek T905™ epoxy**
- **Clamped with shim blocks every 5 layers to maintain mechanical tolerances.**
- **Experienced winder produces 1/day**



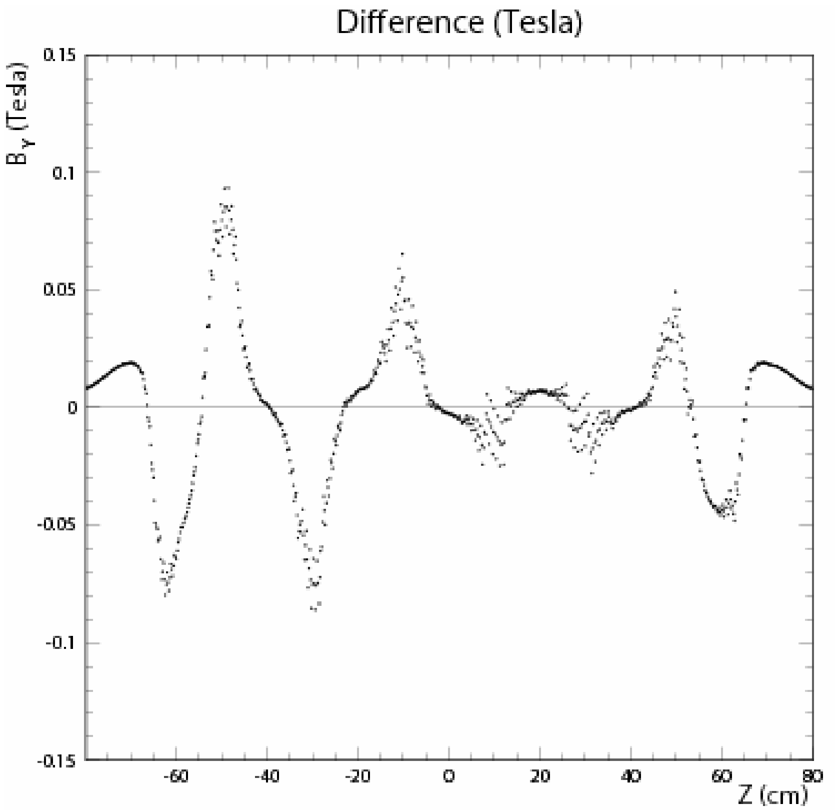
From D.Rice presentation: CESR-c Wiggler Manufacture - PAC 2003

Magnetic field measurement: field mapping with Hall probe

Wiggler #1, 7poles



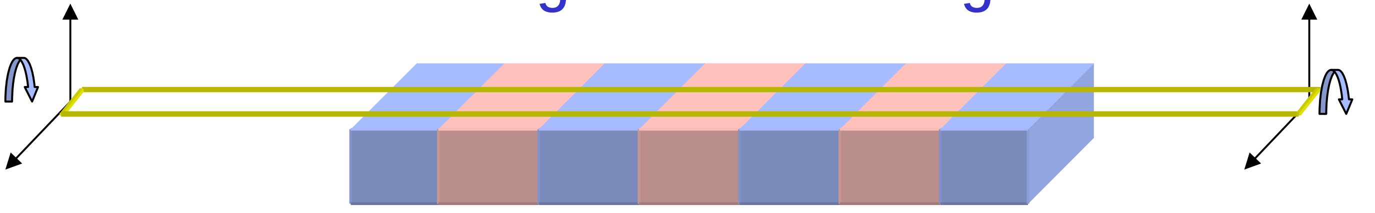
By(z), Hall probe measurement and model calculation



Difference between measurement and calculation

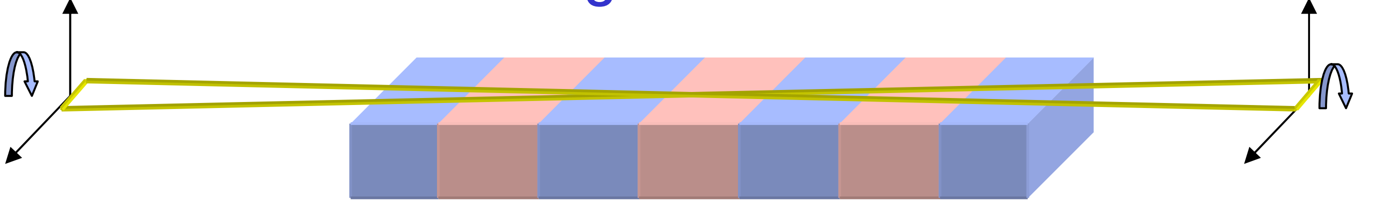
Magnetic field measurement: field integrals measurement with stretched coil

First integral with straight coil:



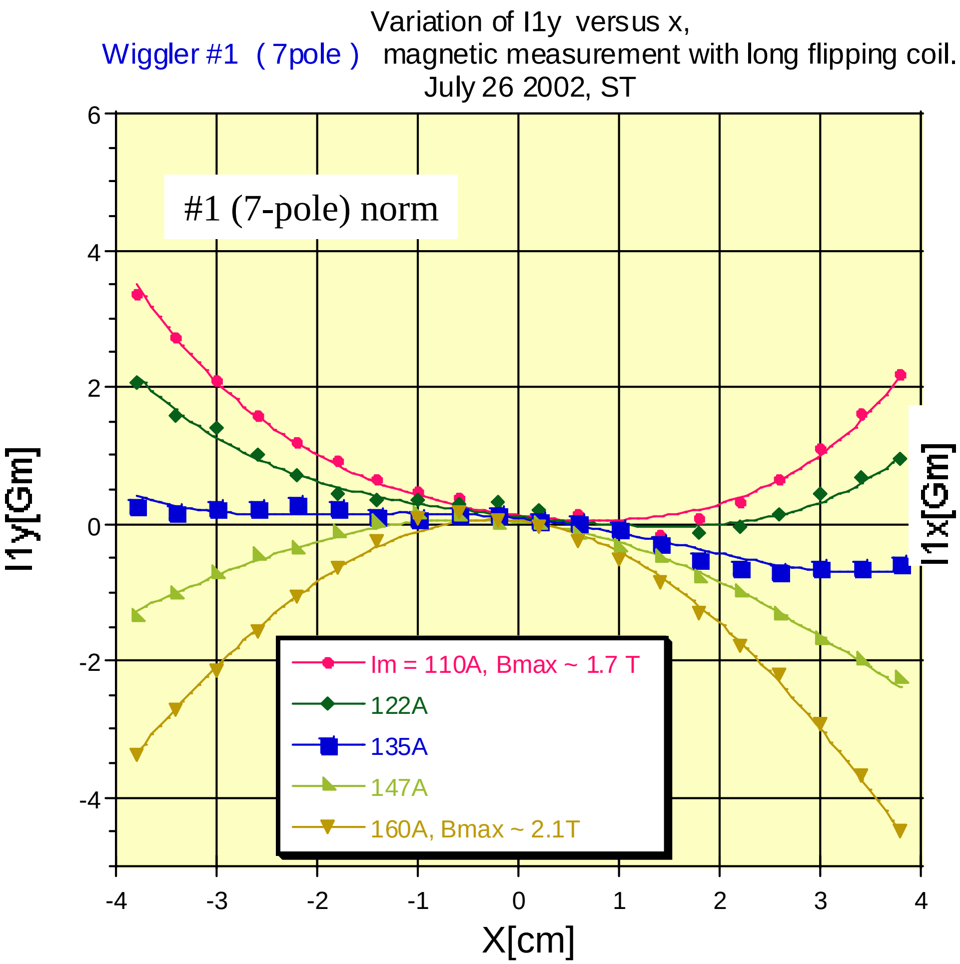
$$\tilde{I}_1 = \frac{Flux_{st}}{a_0} = \frac{1}{a_0}\int_0^l a_0 B(z)dz = \int_0^l B(z)dz = I_1$$

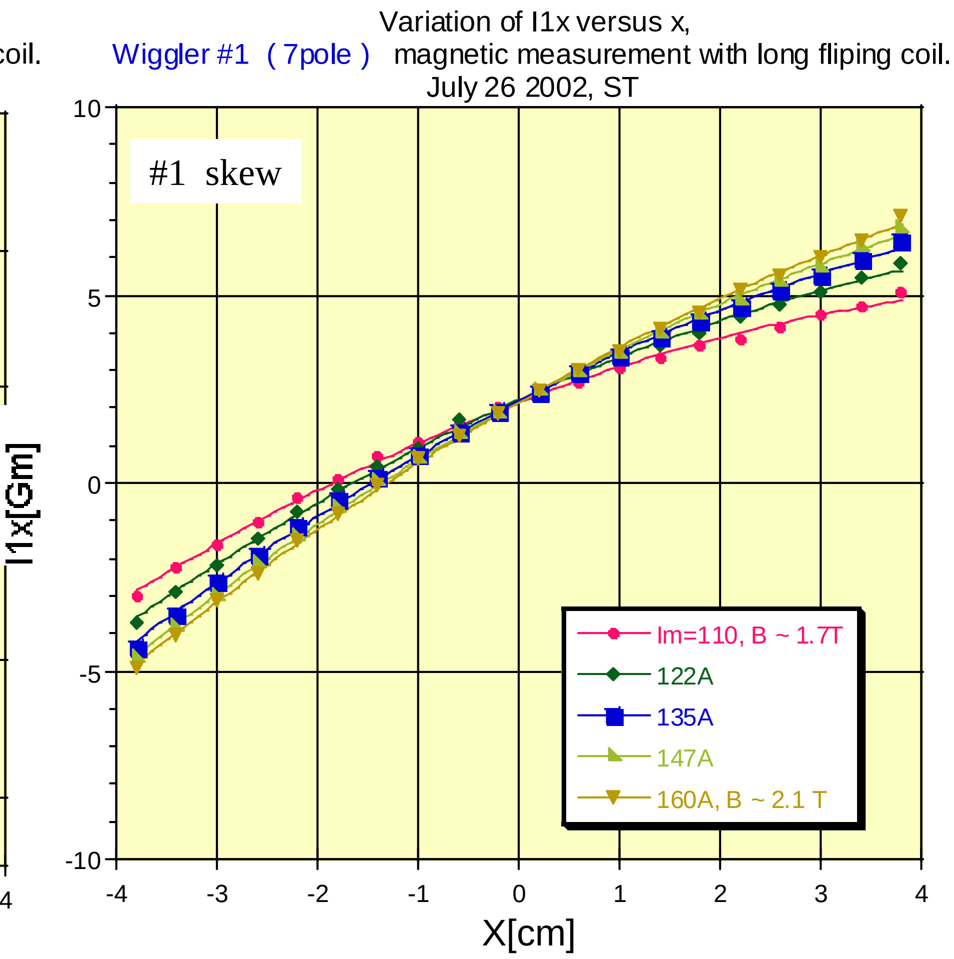
Second integral with twisted coil:



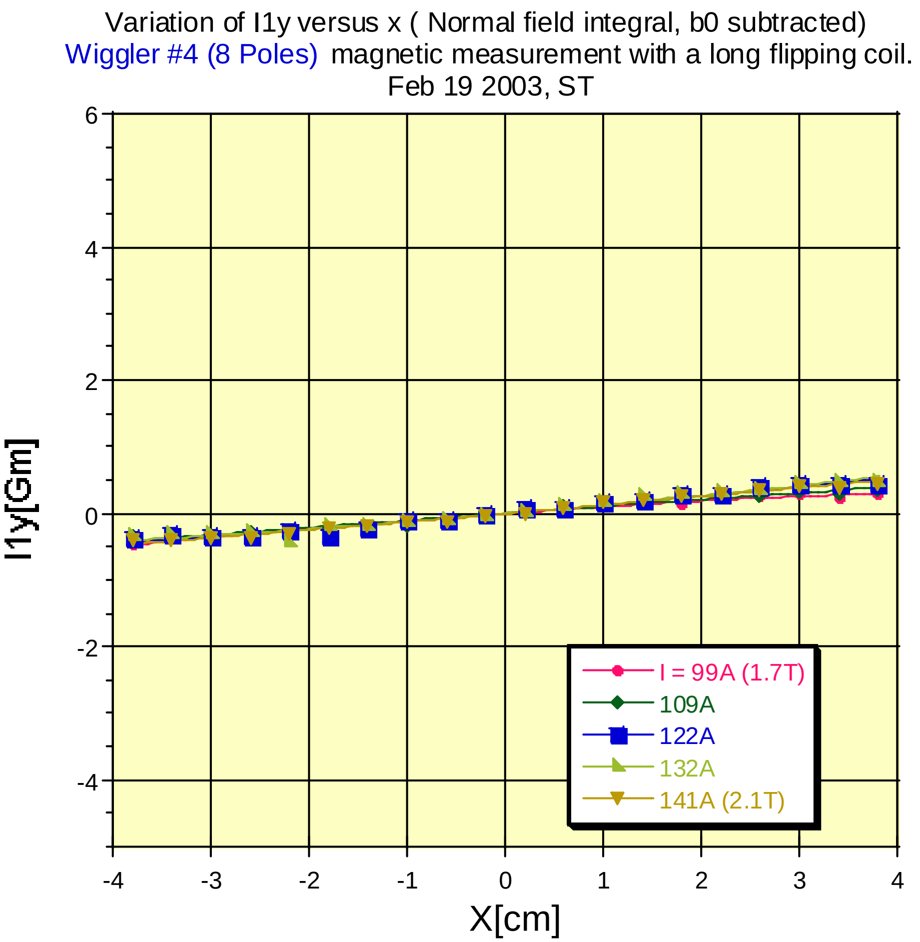
$$\tilde{I}_2 = \frac{Flux_{tw}}{a_0} = \frac{1}{a_0}\int_0^l B(z)a(z)dz = \frac{1}{a_0}\int_0^l B(z)a_0(1-\frac{2z}{l})dz = \int_0^l B(z)dz - \frac{2}{l}\int_0^l B(z)zdz = I_1 - \frac{2}{l}I_2$$

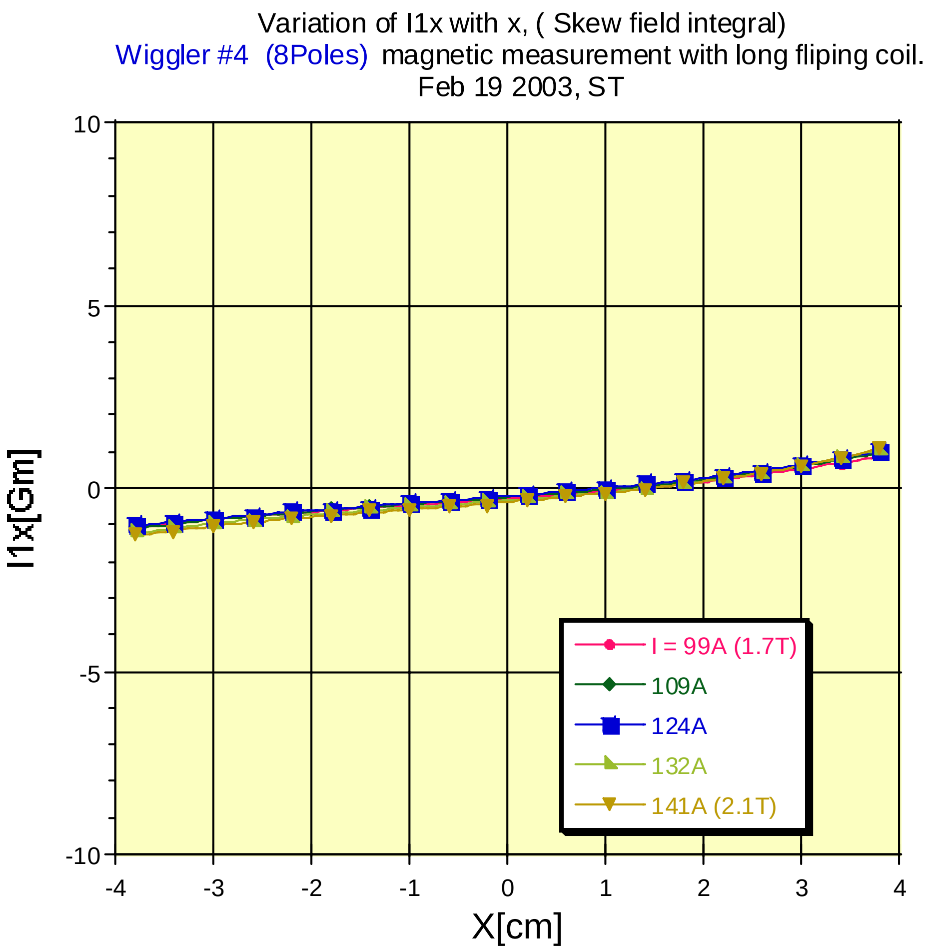
Magnetic field measurement: wiggler #1(7pole) stretched coil measurement





Magnetic field measurement: wiggler #4(8pole) stretched coil measurement



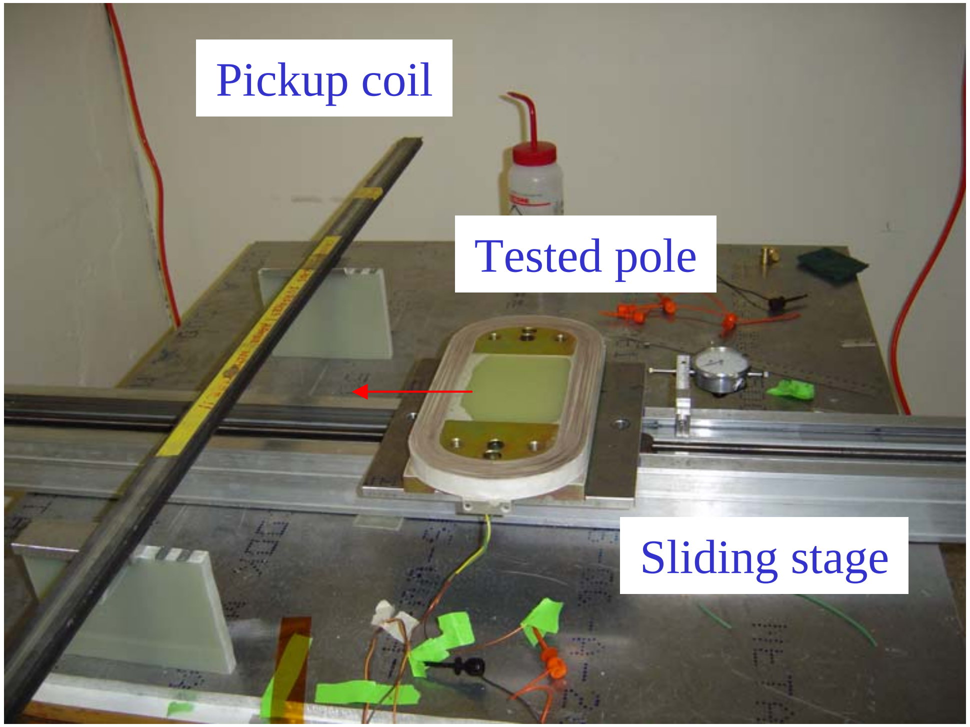


Production: pole quality control

Warm magnetic field measurement setup for pole testing, Imax~ 1A.

Compare tested pole field profile with reference.

- Check for missing turns
- Turn-to-turn shorting



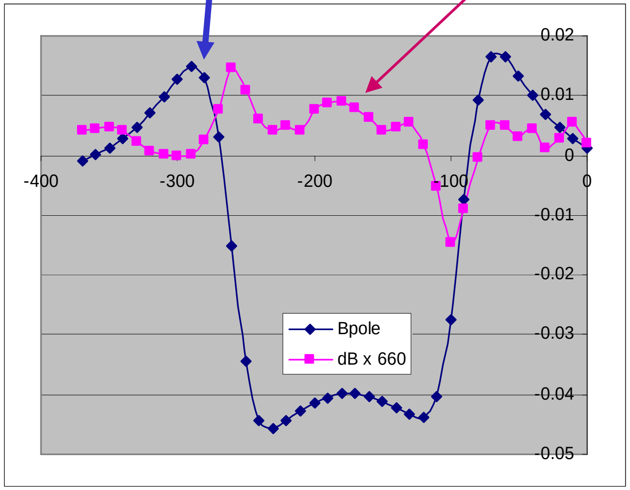
"z" scan (along beam axis)

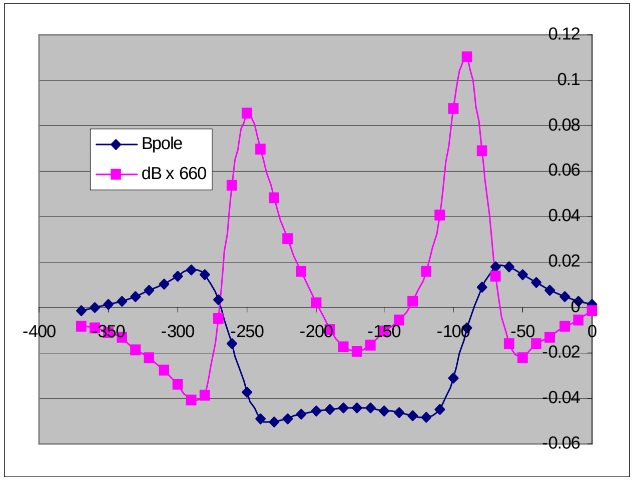
Production: quality control
shorts, missing turns checking

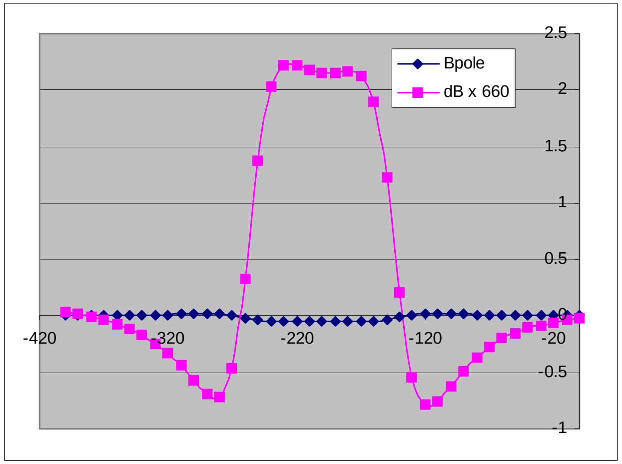
Warm magnetic measurement: "z" scan (along beam axis)

Tested pole field profile

Difference from reference pole (x 660)





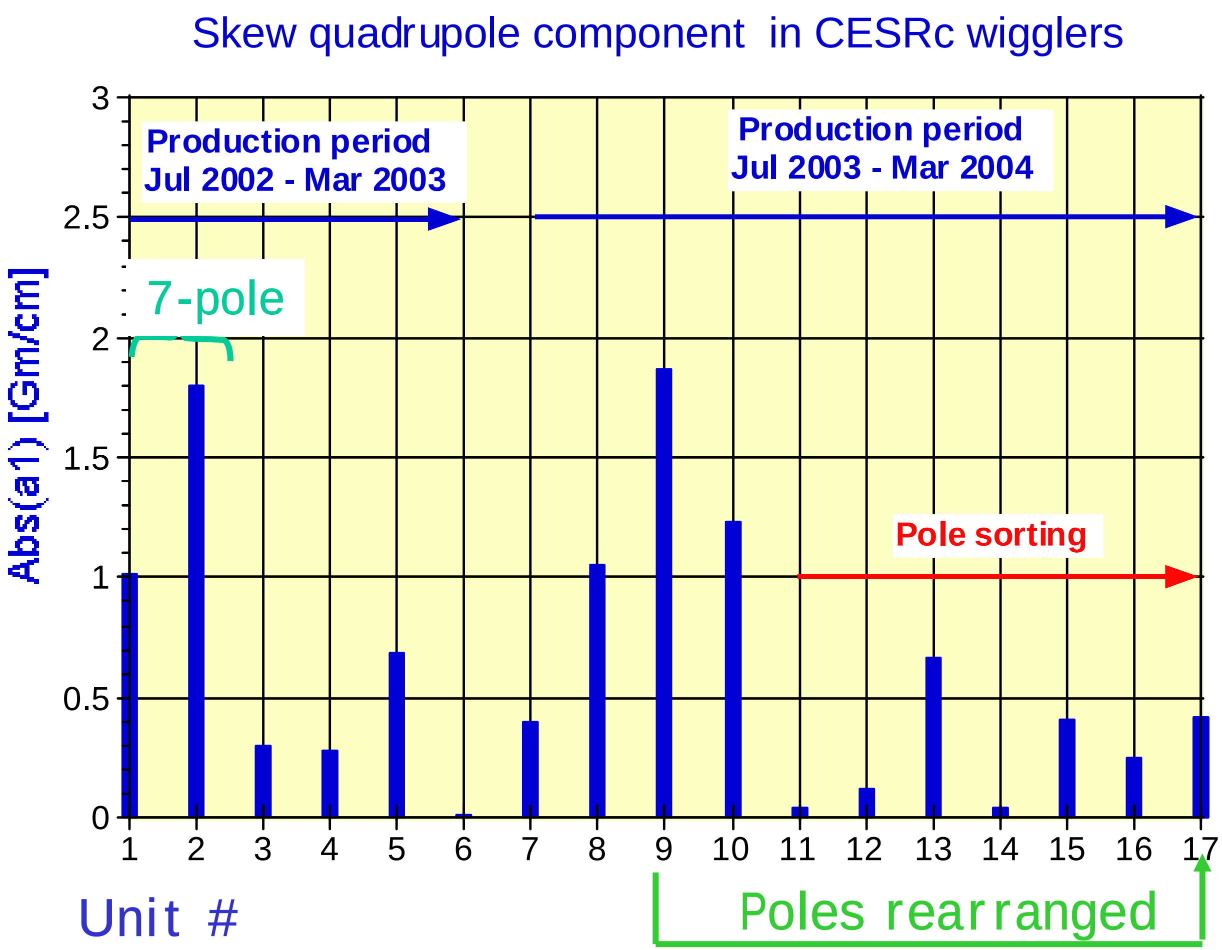


Repeatability

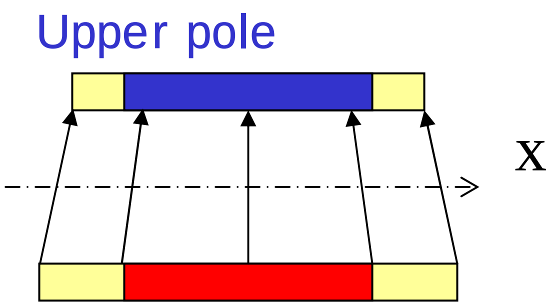
Good pole

Bad pole, 2 layers (40turns) shorted

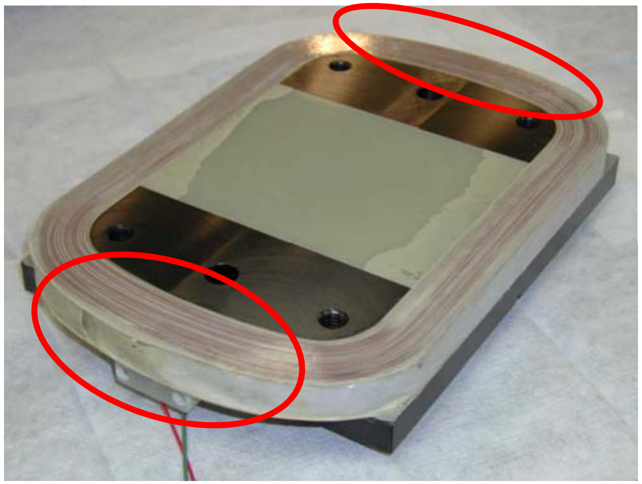
Production: quality control
a1 - problem



Explanation: variation in coil geometry

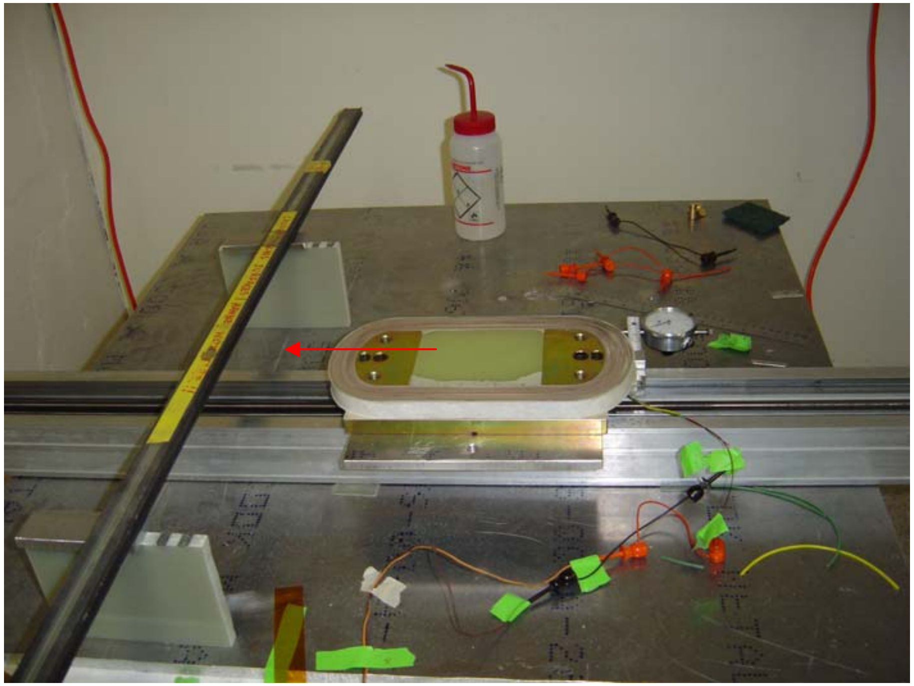


$B_x \propto x$

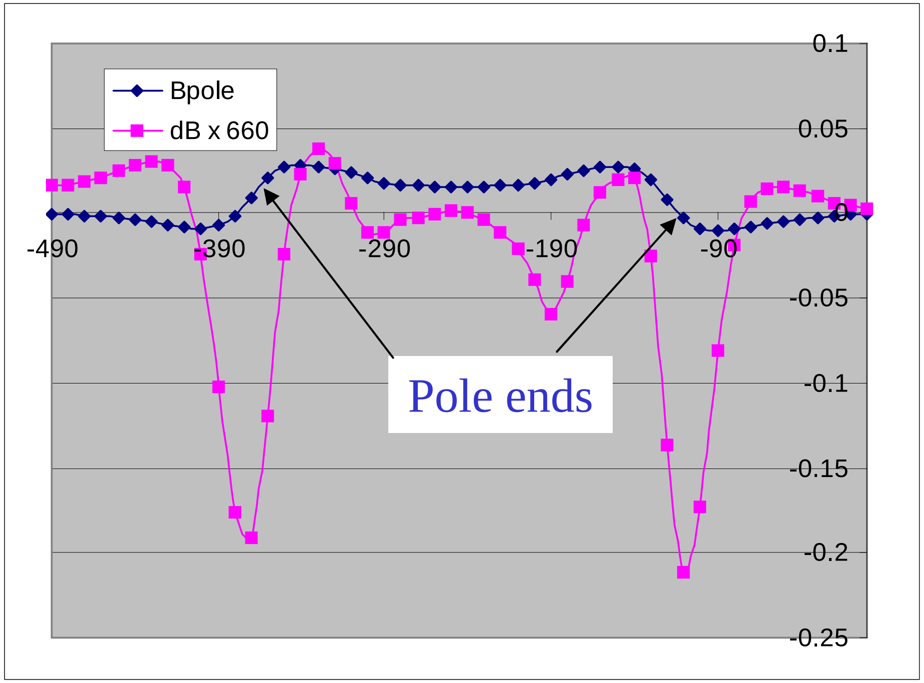


Production: quality control
a1 - problem

Warm magnetic measurement: "x" scan



"x" scan (across beam axis)



Two peaks at the pole ends indicated that tested pole -0.4mm narrower than "reference".

Wiggler a1 component effect on coupling
One wiggler (Oct 2002) and 12 wiggler (Jan 2005) optics

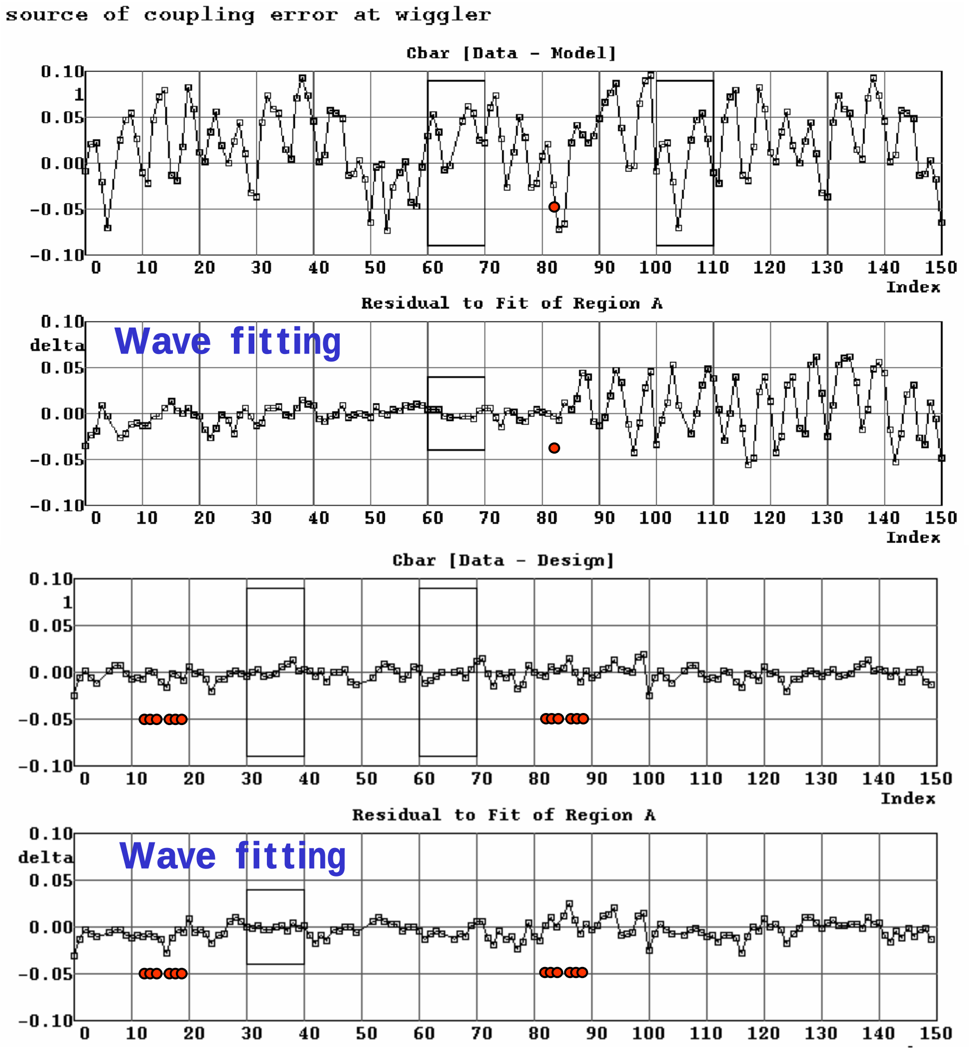
- Wiggler location

Nov 2002, One wiggler (#1) optics.

Wave analysis indicated coupling source (~ 2Gm/cm) at wiggler location, ~1.5Gm/cm from magnetic measurement.

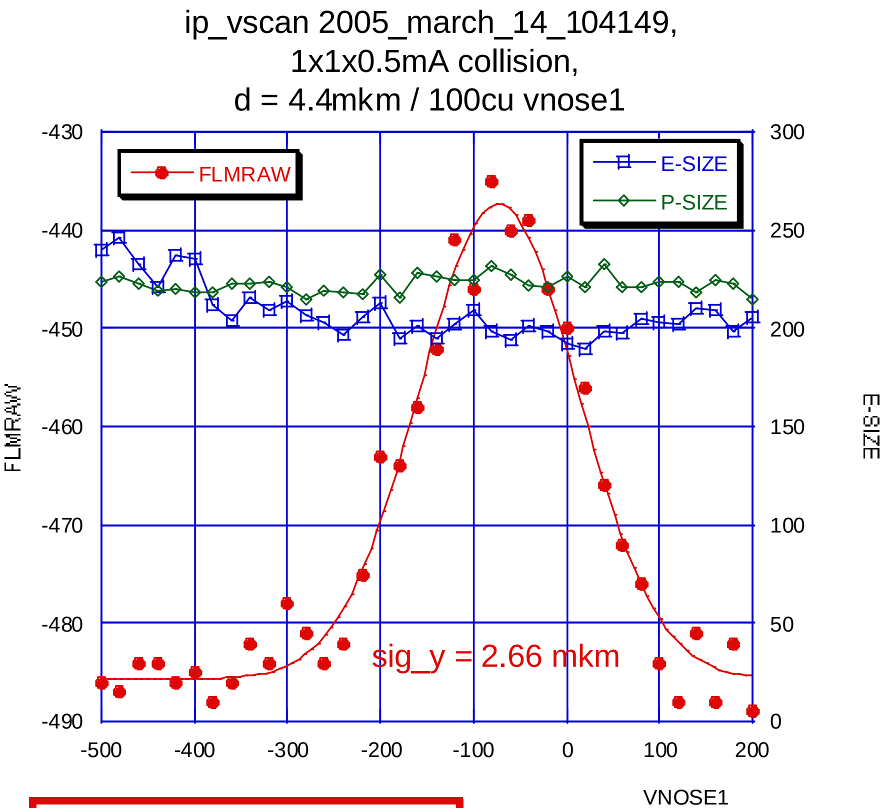
Jan 2005, 12 wigglers optics.

Wave analysis indicated no coupling source at wigglers location.



Wiggler a1 component effect on coupling

Vertical beam emittance



y = m1 + m2 * exp(-(M0-m3)^2/4/m4^2)		
	Value	Error
m1	-485.72	0.85505
m2	48.351	1.5231
m3	-72.909	2.8486
m4	60.442	2.509
Chisq	314.67	NA
R	0.98501	NA

eps_y = 6.4e-10m,
eps_y / eps_x = 5.7e-3

March 14 2005, Luminosity as a function of vertical beam separation at IP.

Vertical beam size at IP ~ 2.7mkm
Vertical to horizontal emittamce ratio ~ 5.7e-3.

Production: resources and cost

- When in full production, committed resources are:
  - Sr. Technical & Supervisory: **5.0** FTE
  - Technical support: **13** FTE

- Approximate cost per wiggler unit for parts and outside machining and manufacturing below $100k

- Results in production of one wiggler every ~3 weeks

Wiggler characterization with beam and model benchmarking.

Model

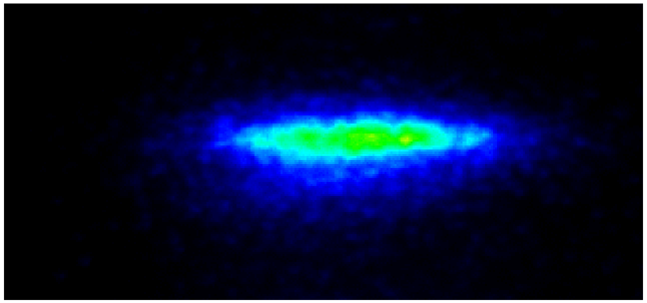
- Based on BMAD subroutine library (homemade): http://www.lns.cornell.edu/~dcs/bmad (D. Sagan)
- Wiggler model used calculated 3D field map. Details are in "ICFA Beam Dyn.Newslett.31:48-52,2003" by D.Sagan, et. al.

Comparison between measurement and prediction (model benchmarking).

- Bunch length and beam energy spread
- Tune variation with wiggler field
- Tune variation with beam position in wiggler
- Tune variation with amplitude (octupole moment)

Wiggler characterization with beam and model benchmarking.

Bunch length and beam energy spread



Streak camera measurement

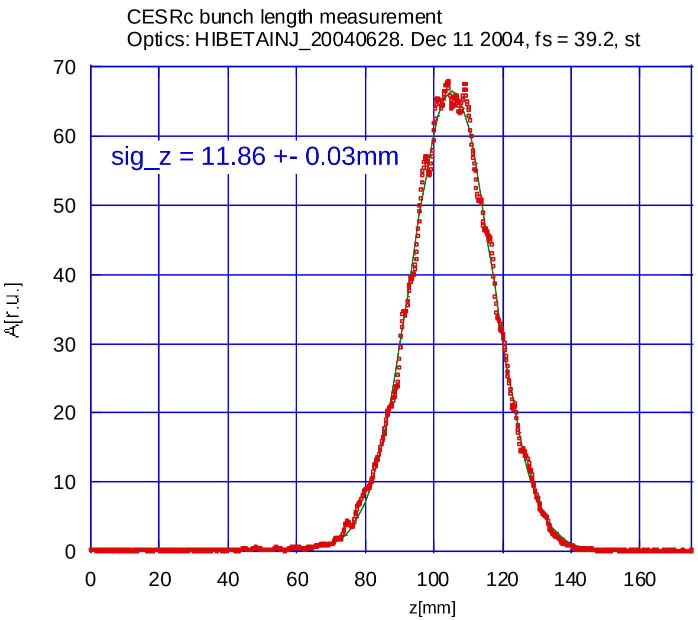
$$\frac{\sigma_E}{E} = \frac{2\pi f_s}{\alpha c}\sigma_z;\ f_s \approx 39kHz,$$

$$\alpha = 0.011,\ \sigma_z = 11.86mm$$

$$\Rightarrow \frac{\sigma_E}{E} = 8.62\times10^{-4}$$

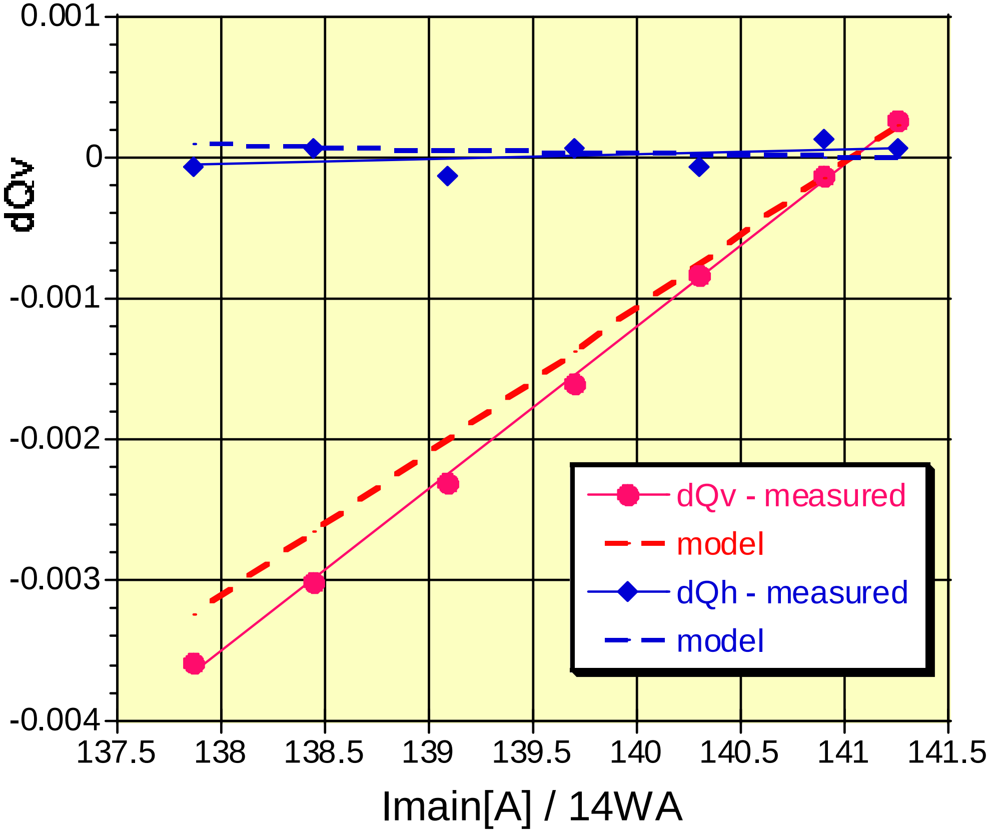
Model prediction: $\frac{\sigma_E}{E} = 8.47\times10^{-4}$

(72% from wigglers)



Wigglers characterization with beam and model benchmarking

Vetical tune variation with wiggler 14WA current, measurement and calculation
CESRc MS, Feb 14 2005



Tune variation with wiggler (14WA) current.

$$\Delta Q \approx \frac{1}{4\pi}\beta\frac{1}{f}$$

$$\frac{1}{f} = \frac{dy'}{dy} \propto \left(\frac{B(I)}{B}\right)^2$$

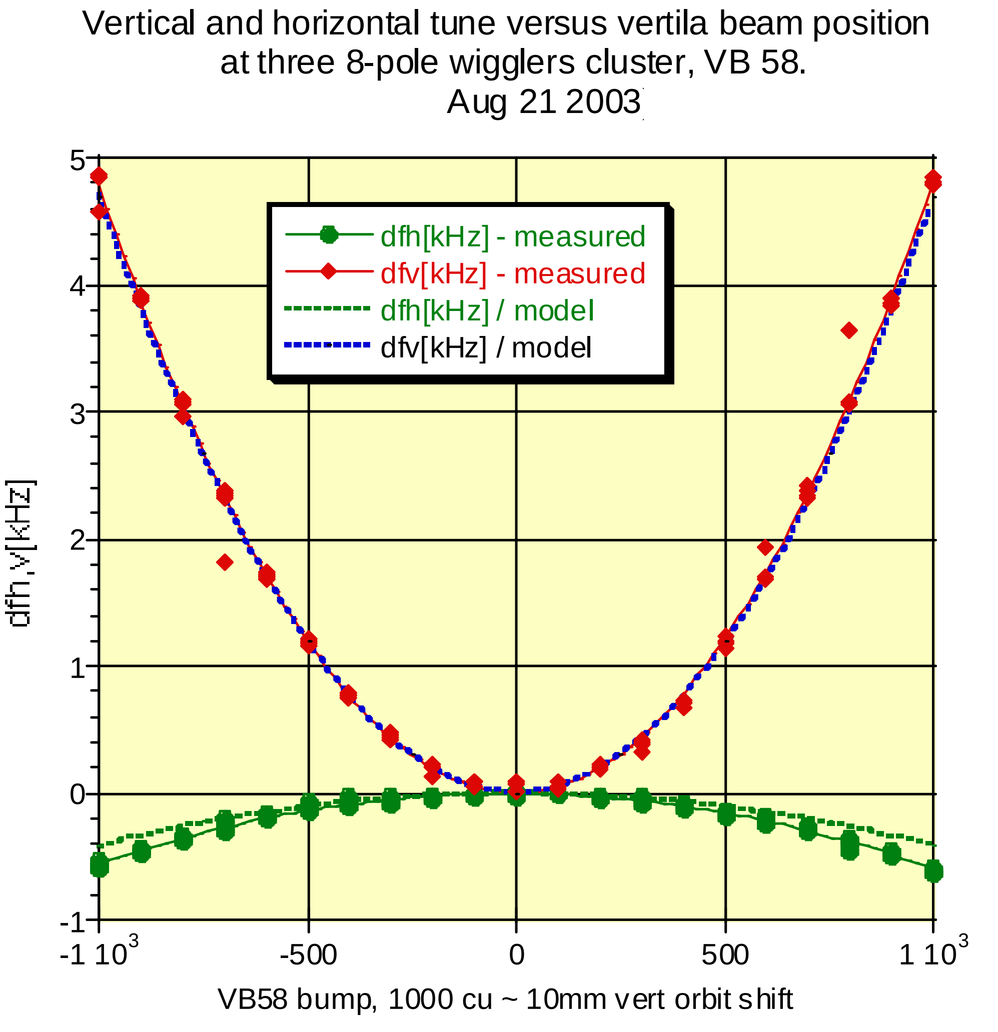
	Value	Error
dQh/dI (model)	-2.97e-5	6.7e-13
dQh/dI (measl)	3.5e-5	2.9e-5
dQv/dl (model)	0.00102	2.0e-11
dQv/dl (meas)	0.00115	1.67e-05

Wiggler characterization with beam and model benchmarking

Tune variation with beam position in 18E cluster (3wigglers).

Vertical and horizontal tunes measured as a function of vertical orbit position in wigglers

$$df_{h,v} = 1kHz \Rightarrow dQ_{h,v} = 0.0025$$



Wiggler characterization with beam and model benchmarking

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Vertical and horizontal tunes measured as a function of horizontal orbit position in wigglers

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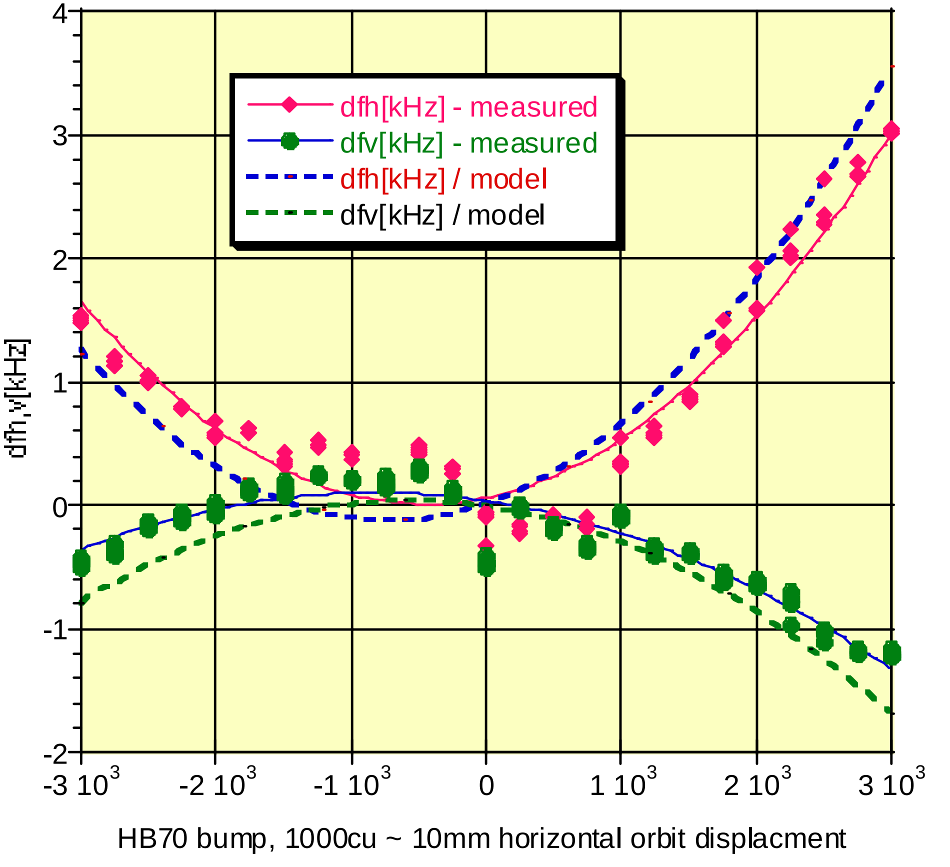
Vertical and horizontal tune versus horizontal beam position at three 8-pole wigglers cluster, HB 70. Aug 21 2003



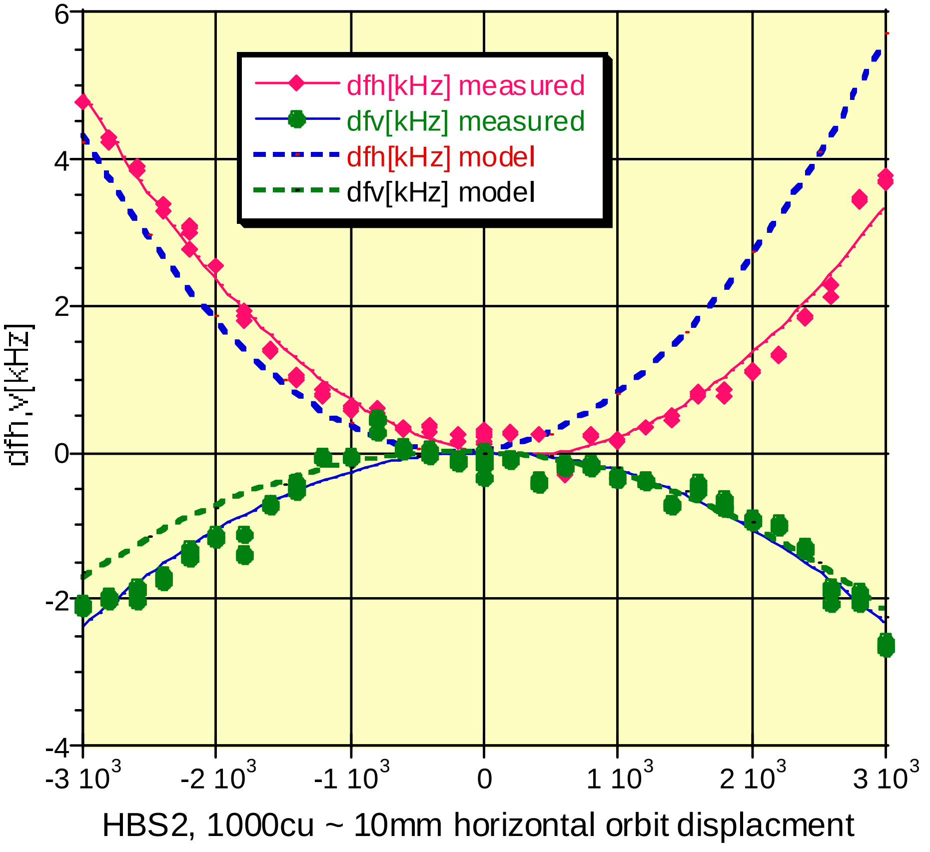
Wiggler characterization with beam and model benchmarking

Tune variation with beam position in 18W cluster (3wigglers).

Vertical and horizontal tunes measured as a function of horizontal orbit position in wigglers

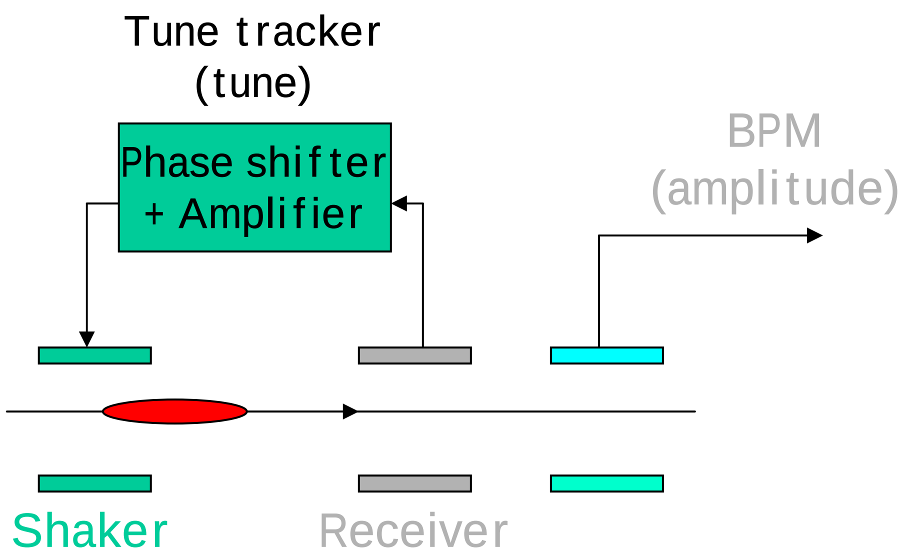
$$df_{h,v} = 1kHz \Rightarrow dQ_{h,v} = 0.0025$$

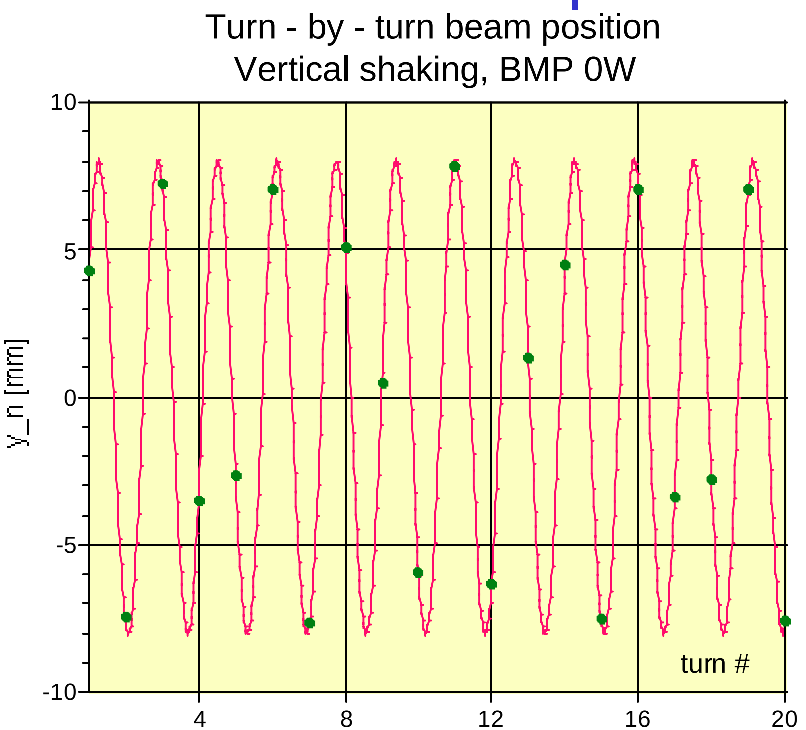
Vertical and horizontal tune versus horizontal beam position at three wigglers cluster, wig1_18w, wig2_18w, wig3_18w (July 8 2004)



Wiggler characterization with beam and model benchmarking

Setup for measurement of tune variation with amplitude.



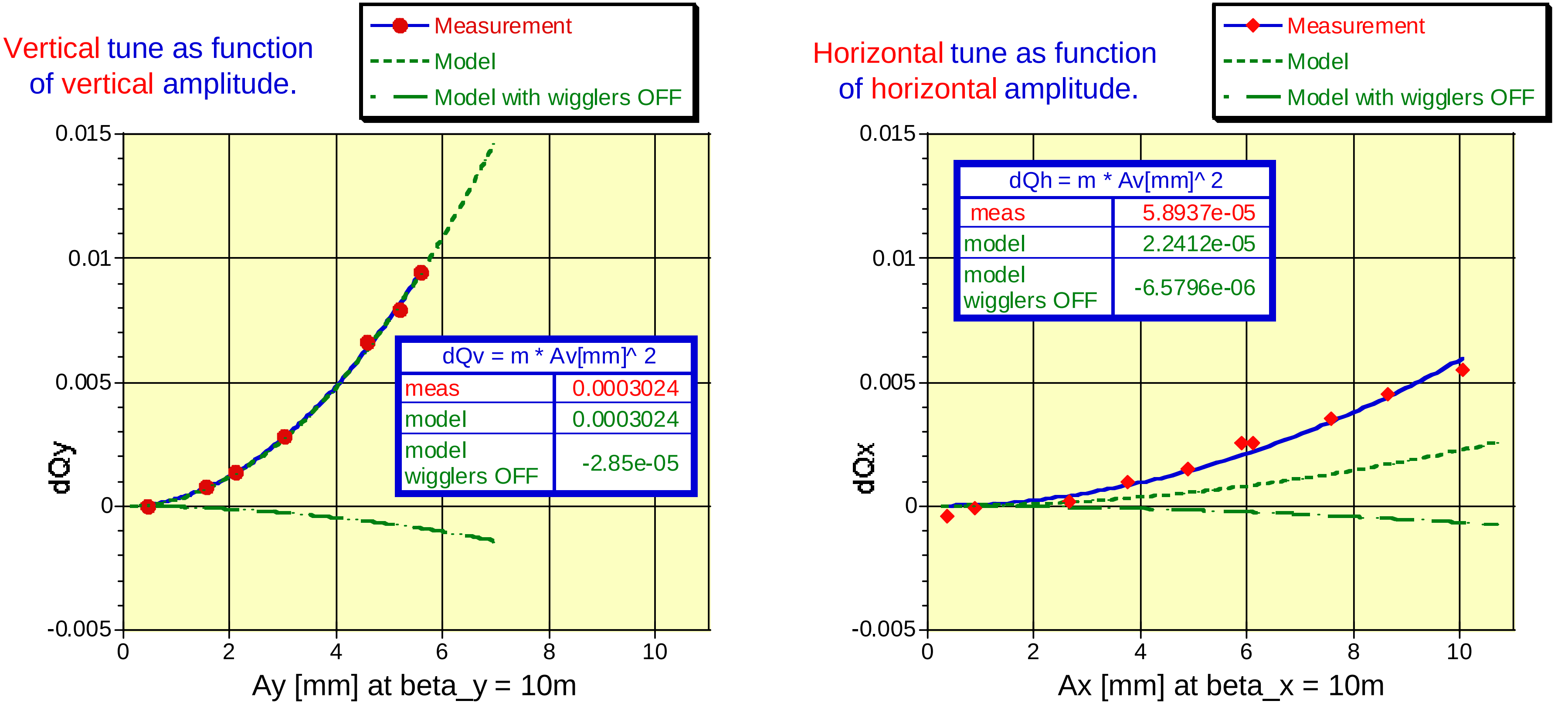


y = Ay*cos((m0-m2)*360*Qy)		
	Value	Error
Ay[mm]	8.007	0.062
m2	4.5137	0.0030
Qy	0.61565	0.0002

Tune tracker provides beam resonance shaking with stable amplitude horizontal/vertical plane.

Wiggler characterization with beam and model benchmarking.

Measured and calculated dependence of vertical/horizontal tune versus vertical/horizontal amplitude



Summary

- We have built 16 superferric wigglers, 12 of them have been installed in the ring and now under operation.

- Beam based wiggler characterization is in good agreement with model.

  We have good wigglers and reliable model

- So far, we have not seen beam performance degrading due to wiggler field nonlinearities.