Wiggler Optimization for Emittance Control: Experience at CESR-c

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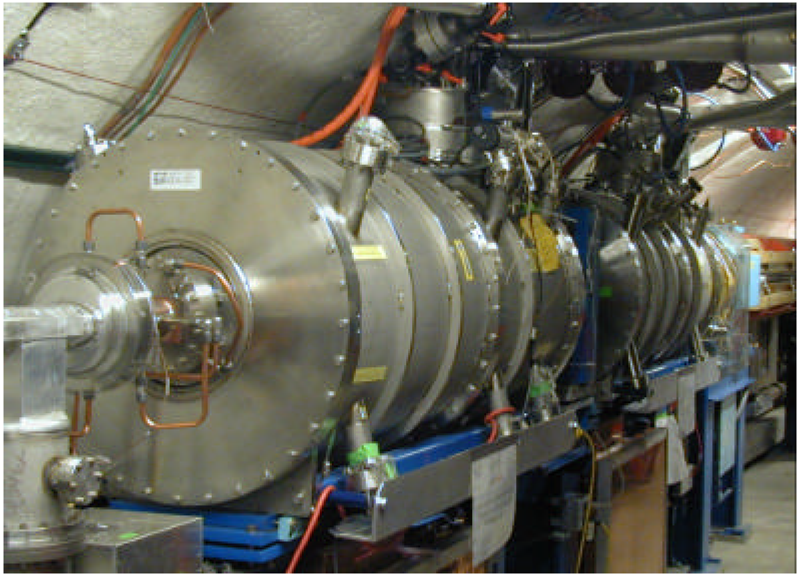
CESR-c Wiggler main characteristics

- 2.1T peak field, 40cm period, 20cm pole width, 7.62cm gap, 9x5cm beam clearance
- 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.
- Conclusion

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 $1/\tau \sim B^2wLw$, horizontal beam emittance $\varepsilon_x \sim BwHw$

Luminosity ~ $3x10^{32}$ [1/sec/cm], reduction factor ~ 4

Setting the main parameters: peak field and total length

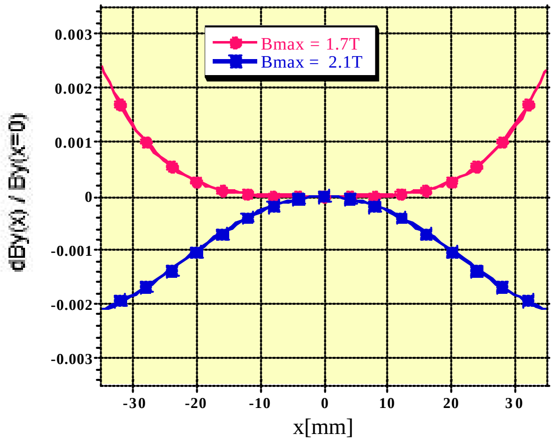
- Peak field (Bw) is limited by maximum allowed energy spread: $\sigma_e/E \sim 8e\text{-}4$ => Bw ~ 2.1T
- Active length (Lw) should be enough to recover damping rate: $1/\tau \sim 30\ \text{sec}^{-1}$ => Lw ~ 18m
- Period: Longer period results in weaker cubic non-linearity, but increases orbit excursion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

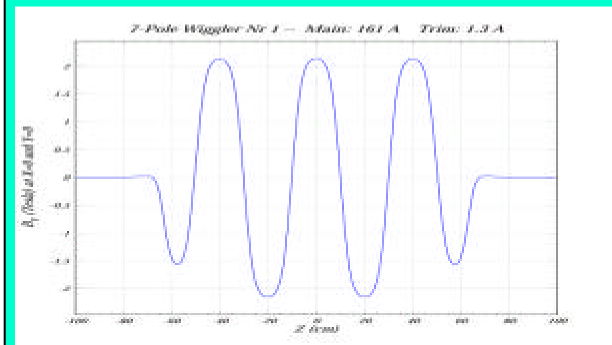
- Normal conducting copper/iron. Similar sized magnets required ~300kW/wiggler.
- Permanent magnet (NdFeB). 2T in 5cm x 9cm gap difficult, BIG magnets, $$, must be opened or removed for 5GeV running.
- Superferric technology (iron poles & superconducting coils) only viable option for high (2T) fields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

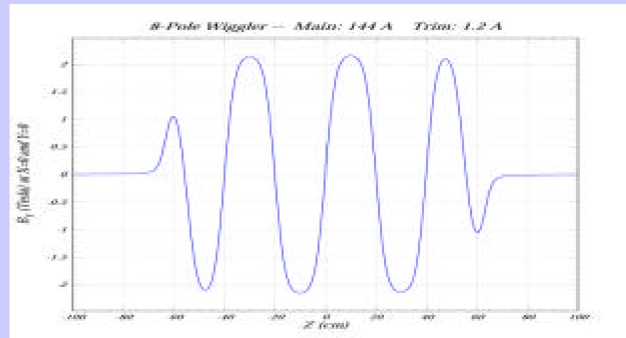
From D.Rice presentation: CESR-c Wiggler Manufacture - PAC 2003

Setting the main parameters: type of symmetry

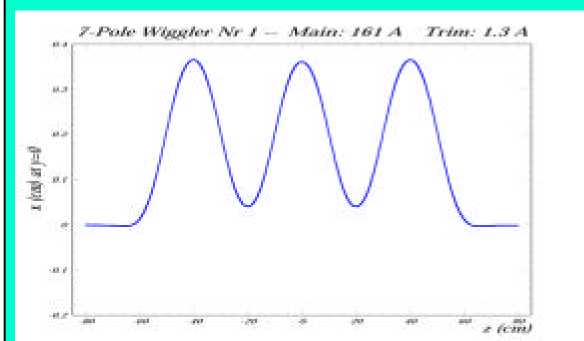
	7 poles (symmetric)	8 poles (asymmetric)
Poles length [cm]	15+20+20+20+20+20+15 = 130	10+15+20+20+20+20+15+10 = 130
Bmax/pole [T]	-1.6/2.1/-2.1/2.1/-2.1/2.1/-1.6	-1.1/2.1/-2.1/2.1/-2.1/2.1/-2.1/1.1

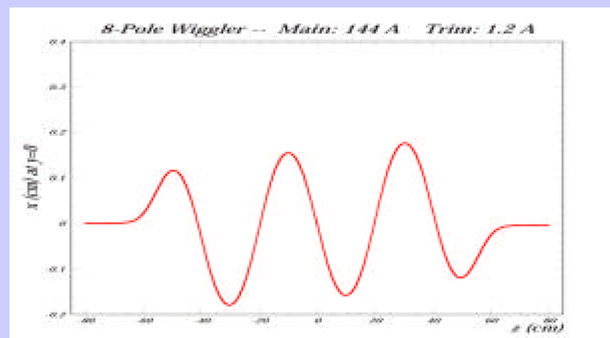
Field along magnet





Beam trajectory



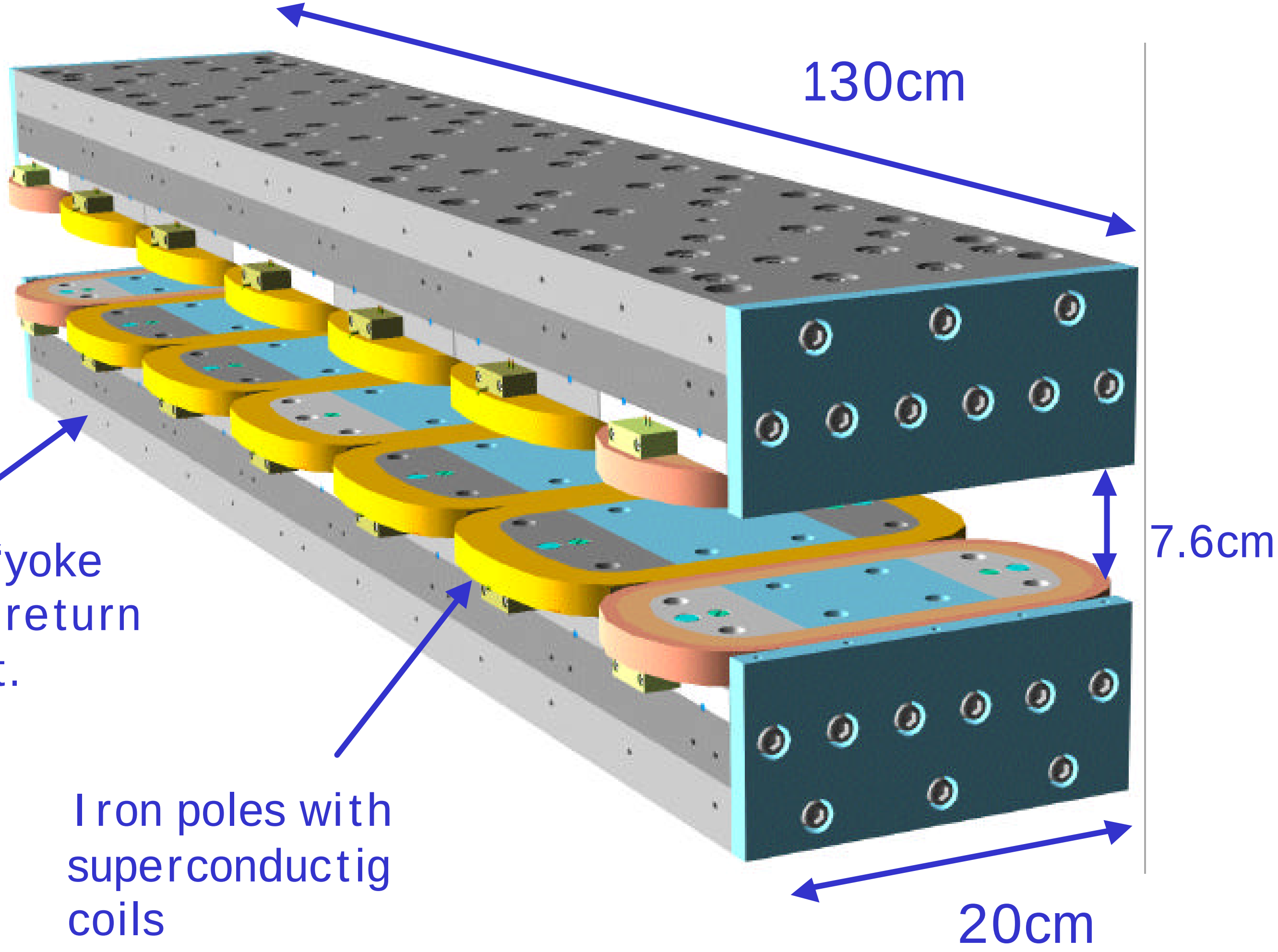


Setting the main parameters: type of symmetry

- 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)

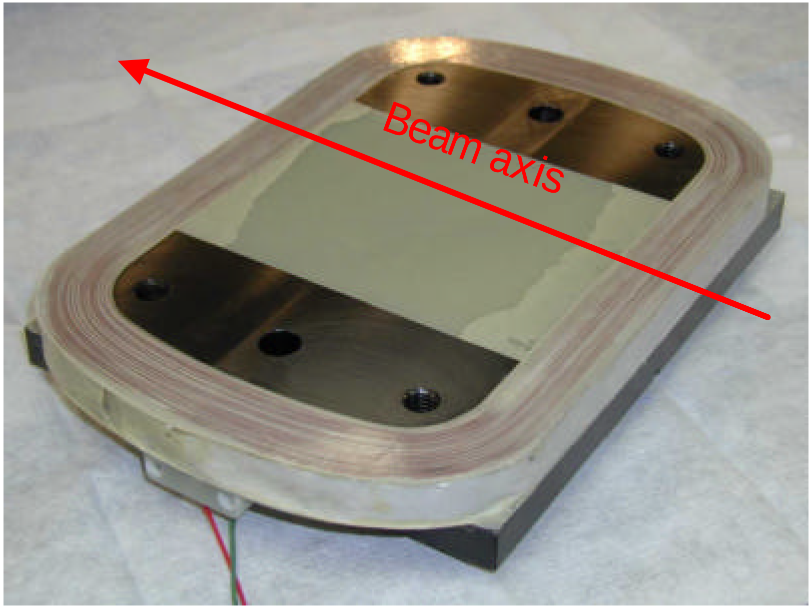


7cm thick “yoke plate” flux return and support.

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 T905Ô 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

Production: Coil Winding

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

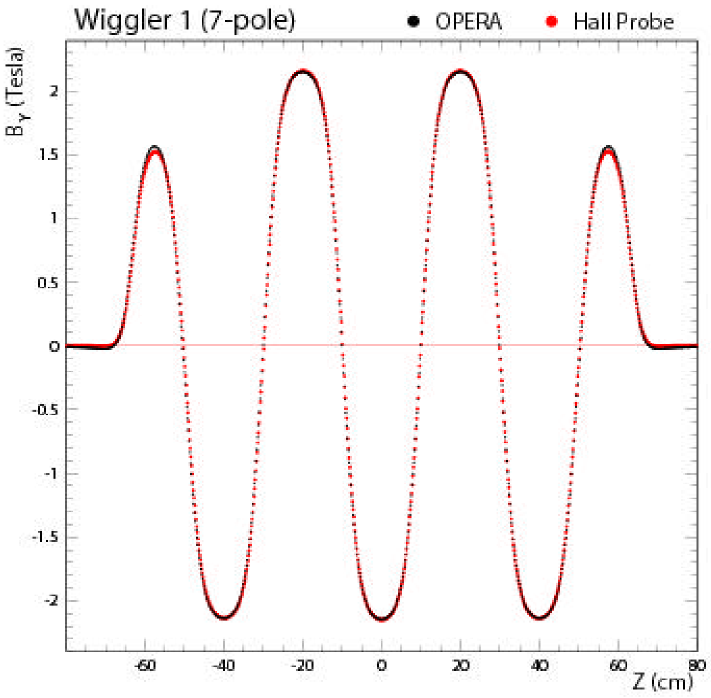
Production: Assembly with preload

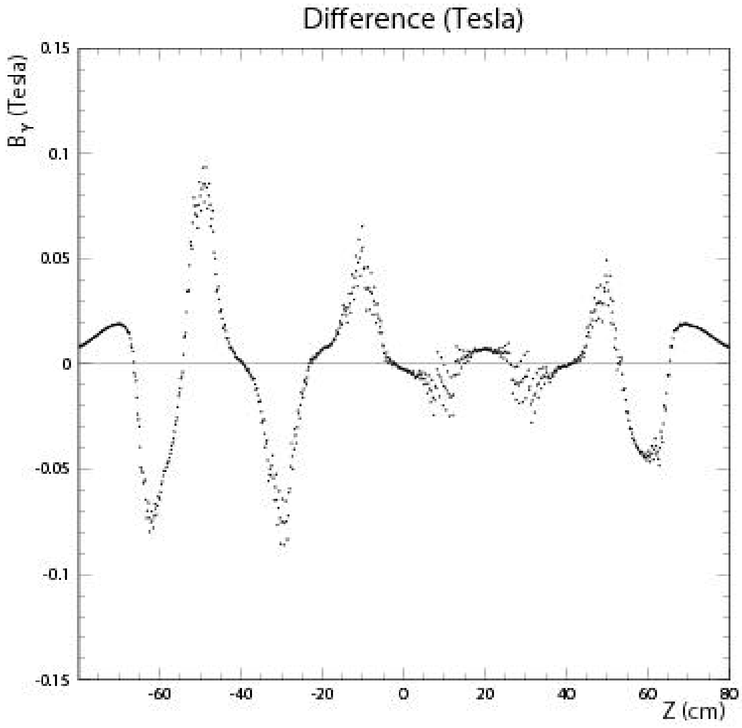
- The finished pole pieces are placed on a 70 mm thick "yoke plate" flux return and support.
- Magnetic force & cooldown shrinkage require large preload on coils – 16 Ton Û 40 MPa pressure

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

Magnetic field measurement: field mapping with Hall probe

Wiggler #1, 7poles



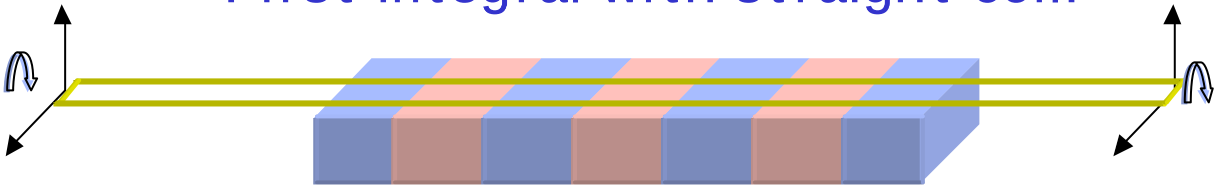


By(z), Hall probe measurement and model calculation

Difference between measurement and calculation

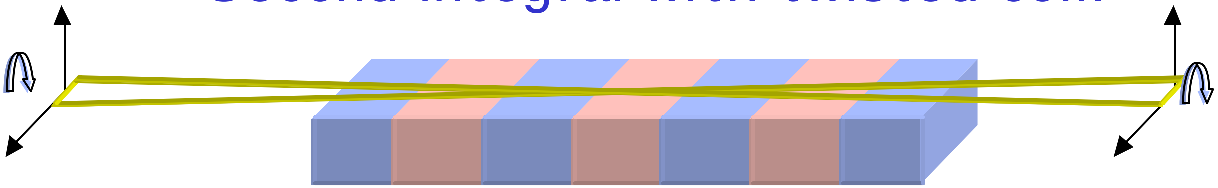
Magnetic field measurement: field integrals measurement with stretched coil

First integral with straight coil:



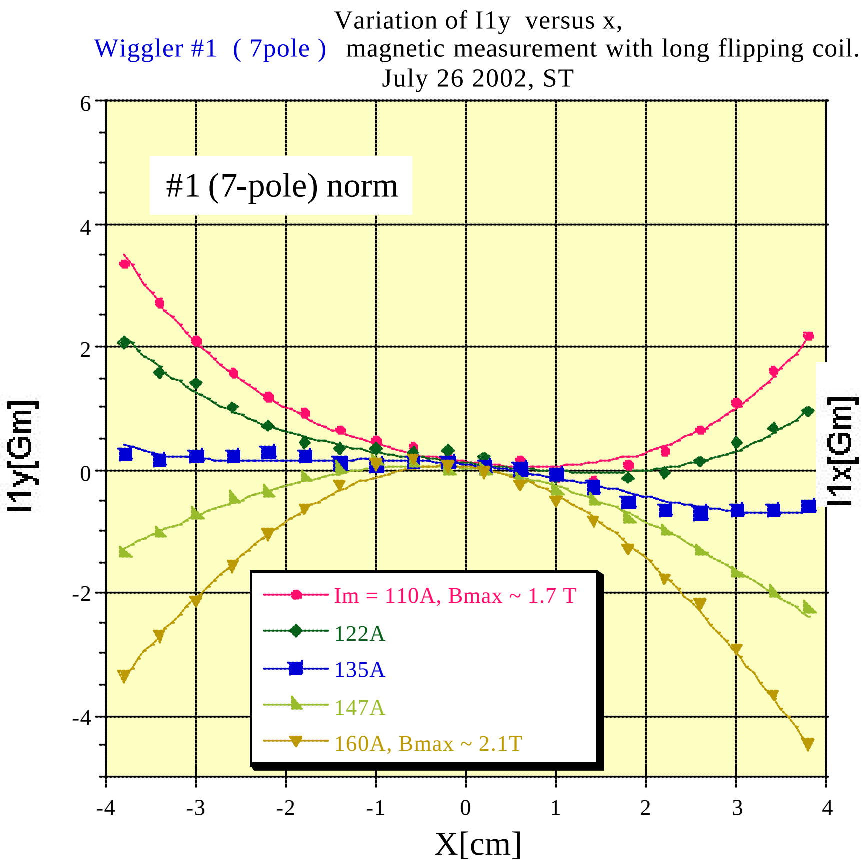
$$\tilde{I}_1 = \frac{Flux_{st}}{a_0} = \frac{1}{a_0}\int_0^l a_0 B(z)dz = \int_0^l B(z)dz = I_1$$

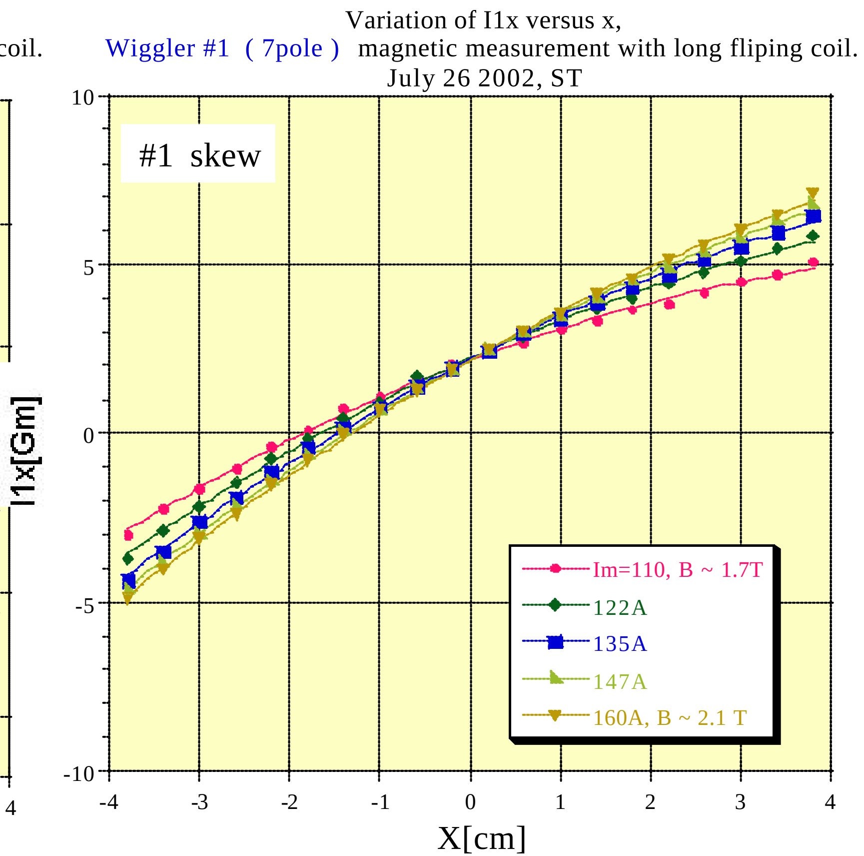
Second integral with twisted coil:



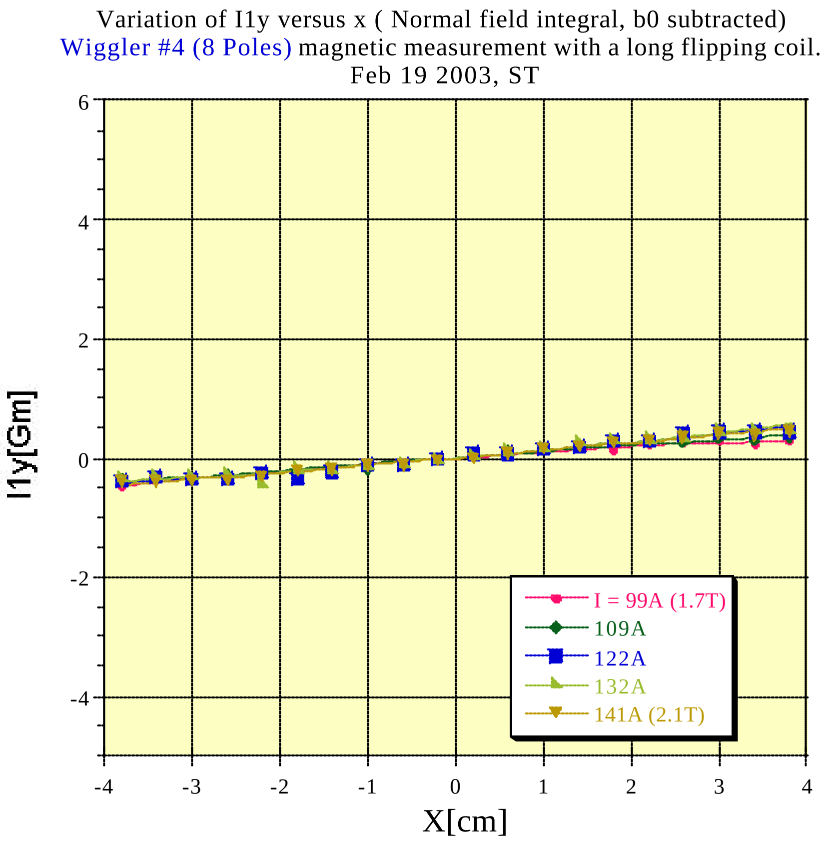
$$\tilde{I}_2 = \frac{Flux_{tw}}{a_0} = \frac{1}{a_0}\int_0^l B(z)a(z)dz = \frac{1}{a_0}\int_0^l B(z)a_0(1-\frac{2z}{l})dz = \int_0^l B(z)dz - \frac{2}{l}\int_0^l B(z)zdz = I_1 - \frac{2}{l}I_2$$

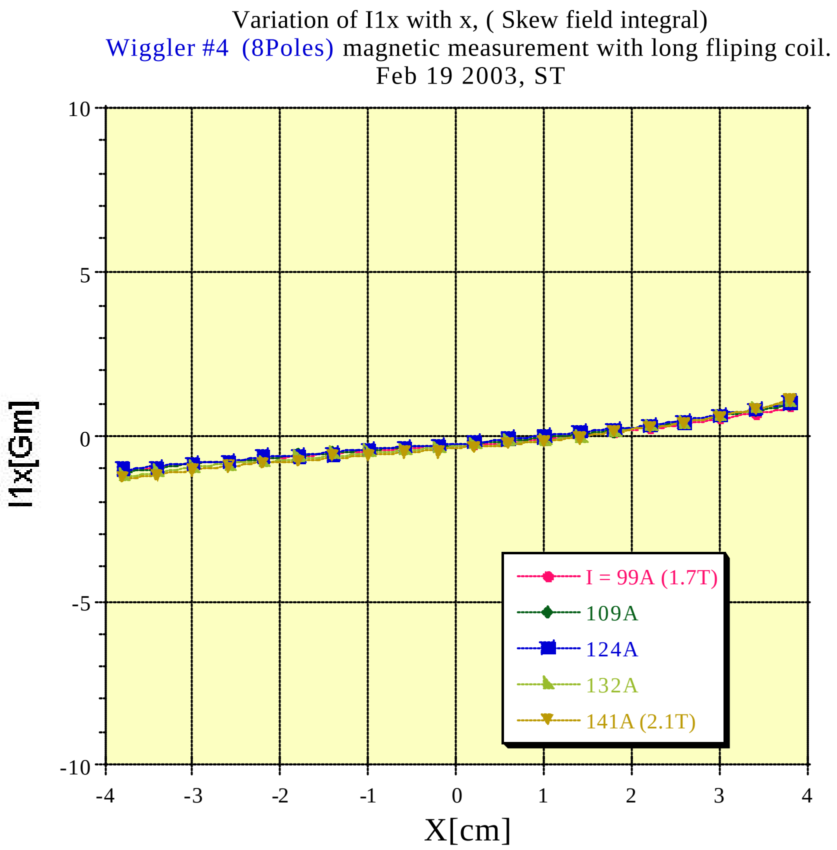
Magnetic field measurement: wiggler #1(7pole) stretched coil measurement





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



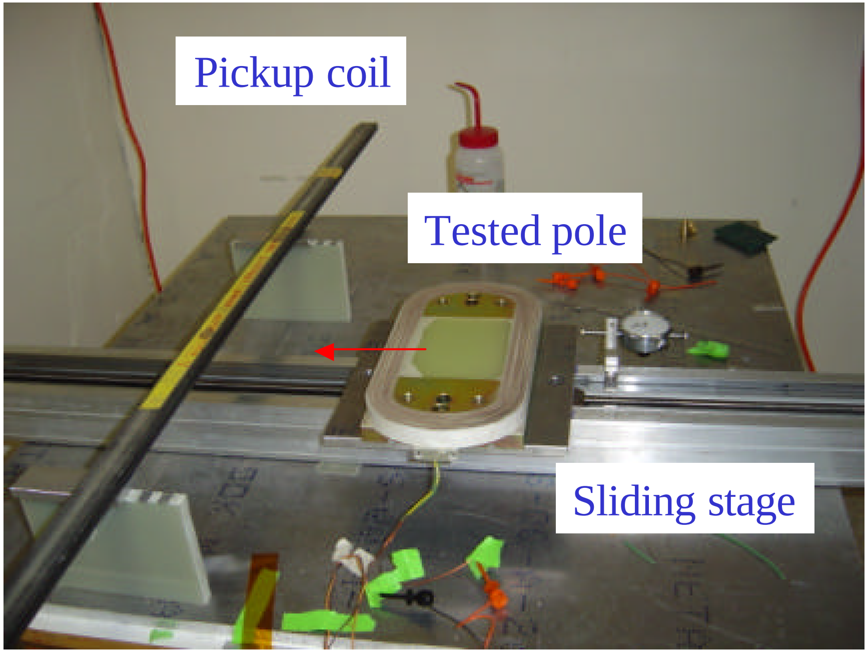


Production: pole quality control

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



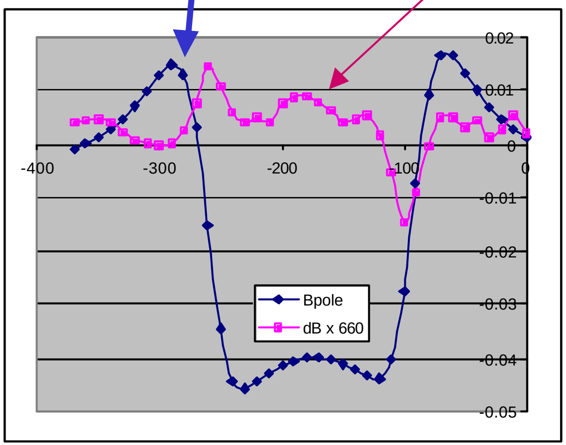
"z" scan (along beam axis)

Production: quality control shorts, missing turns checking

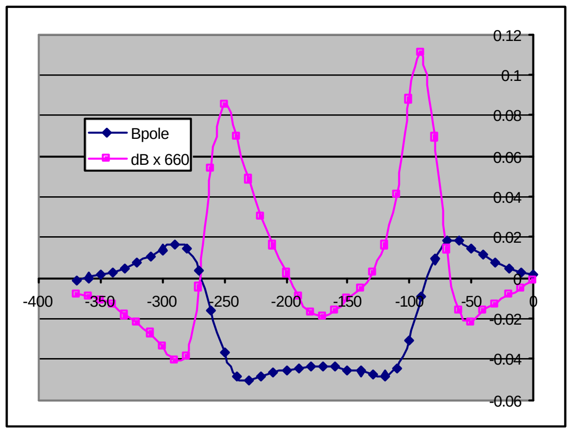
Warm magnetic measurement: "z" scan (along beam axis)

Tested pole field profile

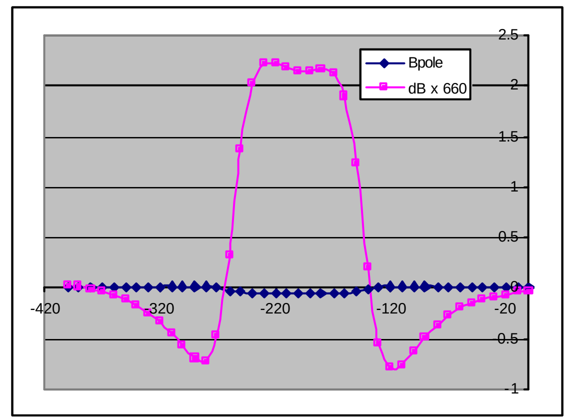
Difference from reference pole (x 660)



Repeatability



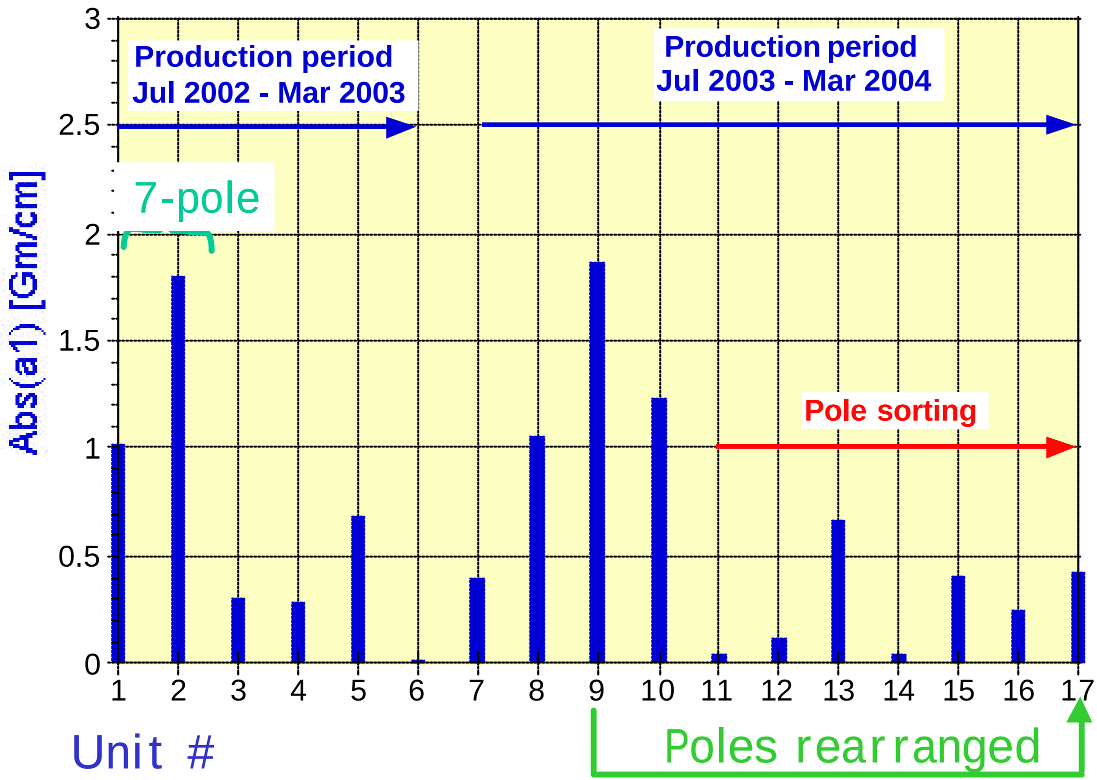
Good pole



Bad pole, 2 layers (40turns) shorted

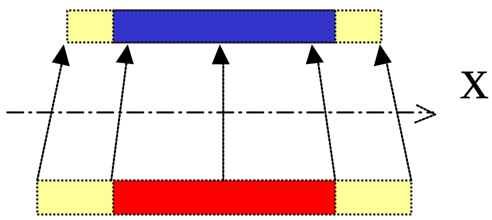
Production: quality control
a1 - problem

Skew quadrupole component in CESRc wigglers

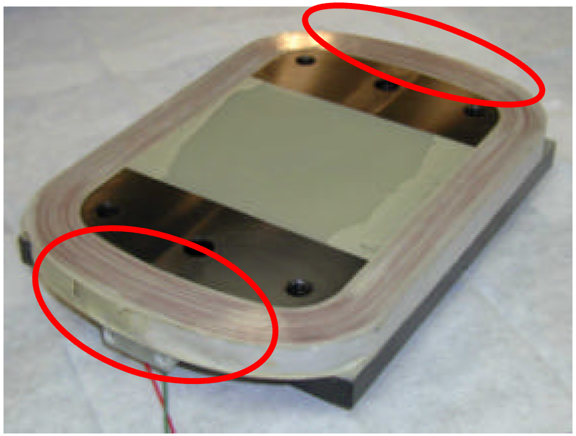


Explanation: variation in coil geometry

Upper pole

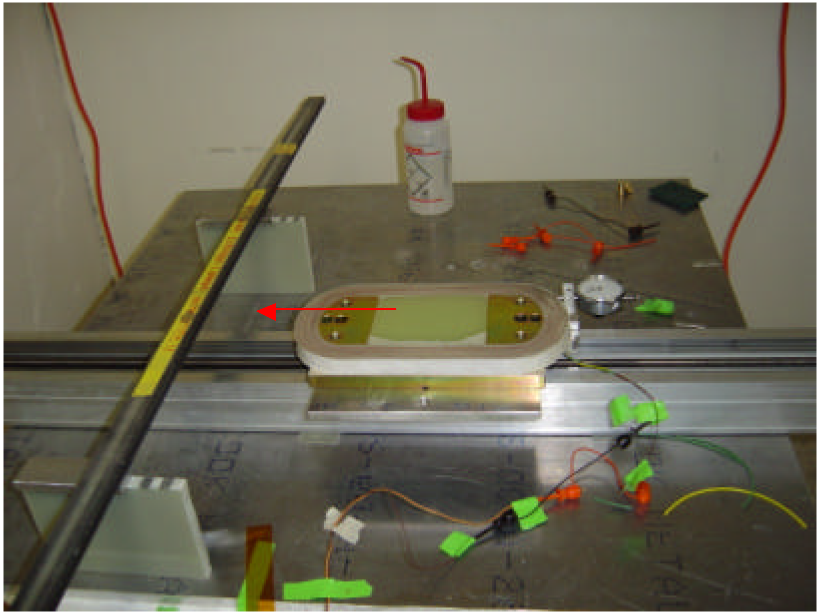


Lower pole $B_x \propto x$

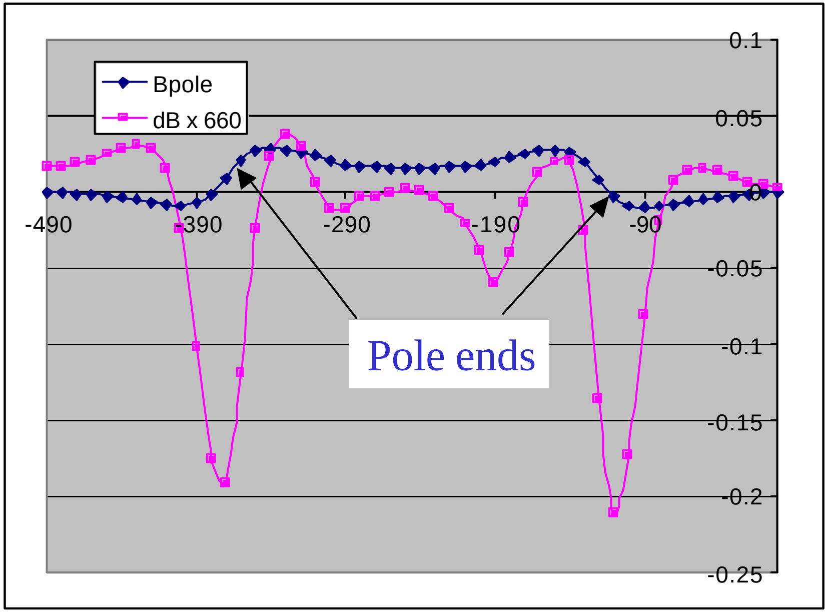


Production: quality control
a1 - problem

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

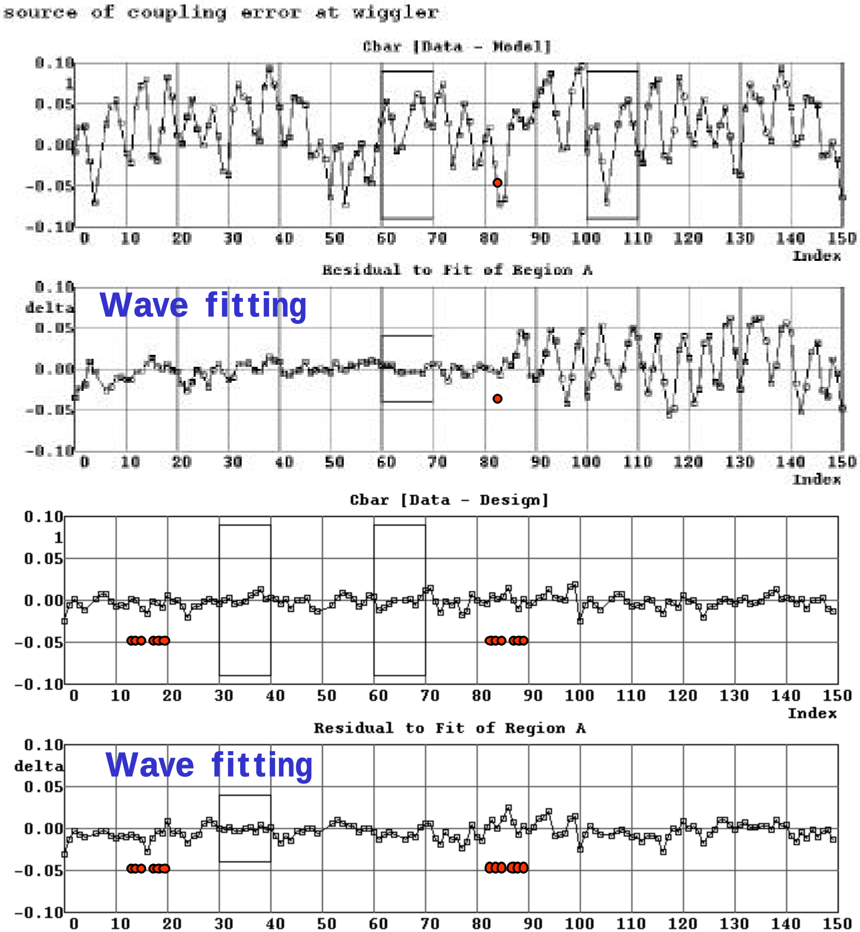
- Wiggler location

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.



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

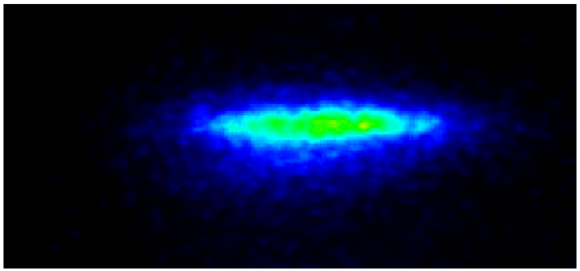
- Based on BMAD subroutine library (homemade): http://www.lns.cornell.edu/~dcs/bmad (D. Sagan)
- Wiggler model used calculated 3D field map. Details are in "ICFA Beam Dyn.Newslett.31:48-52,2003" by D.Sagan, et. al.

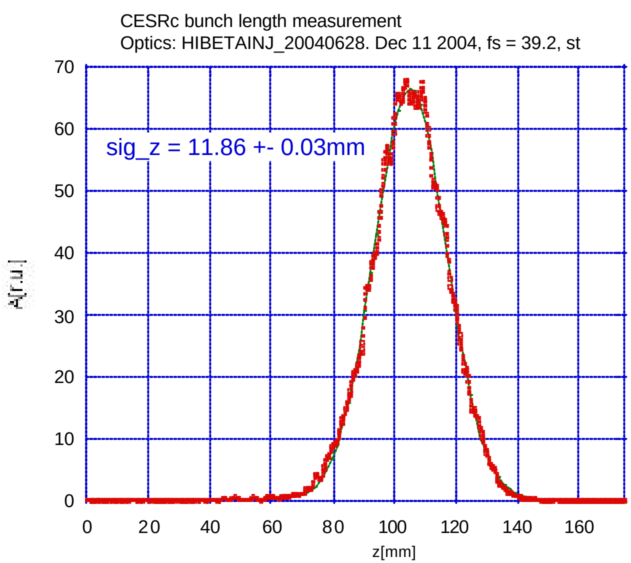
Comparison between measurement and prediction (model benchmarking).

- 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

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

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

$$\Rightarrow \frac{\sigma_E}{E} = 8.62\times 10^{-4}$$

Model prediction: $\frac{\sigma_E}{E} = 8.47\times 10^{-4}$

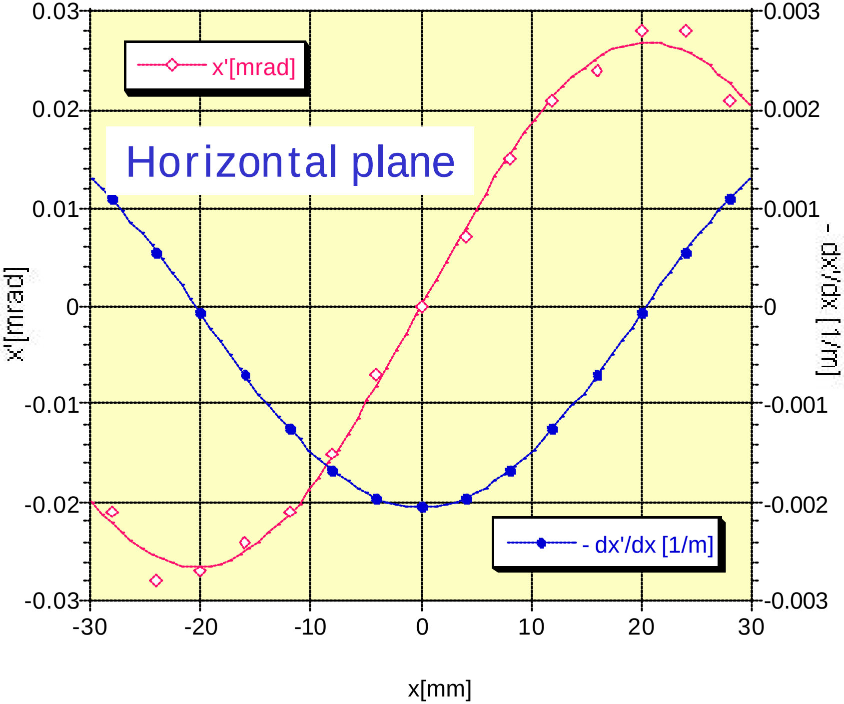
(72% from wigglers)

Wiggler characterization with beam and model benchmarking.

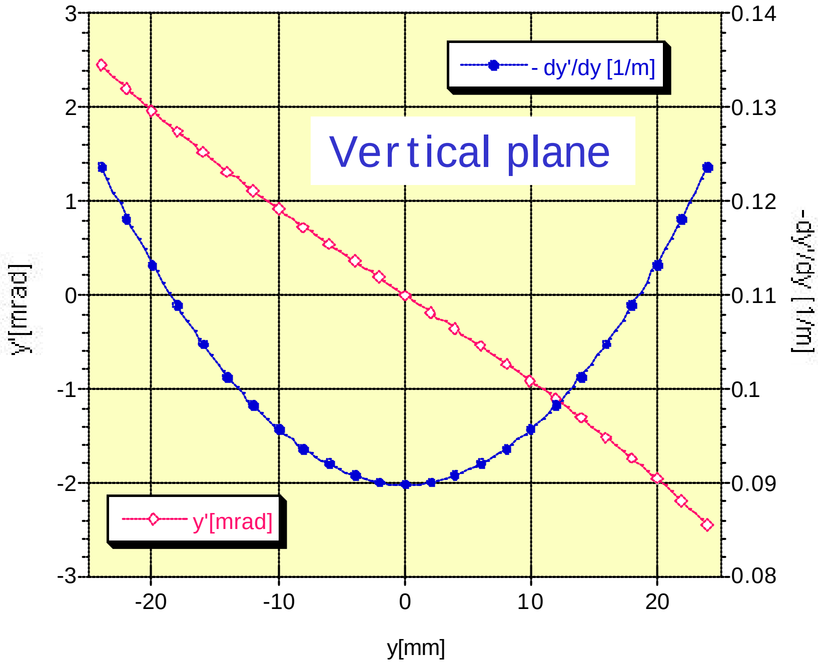
Tune variation with beam position, model

Wiggler transfer functions, x'(x) and y'(y) and local focusing effect.

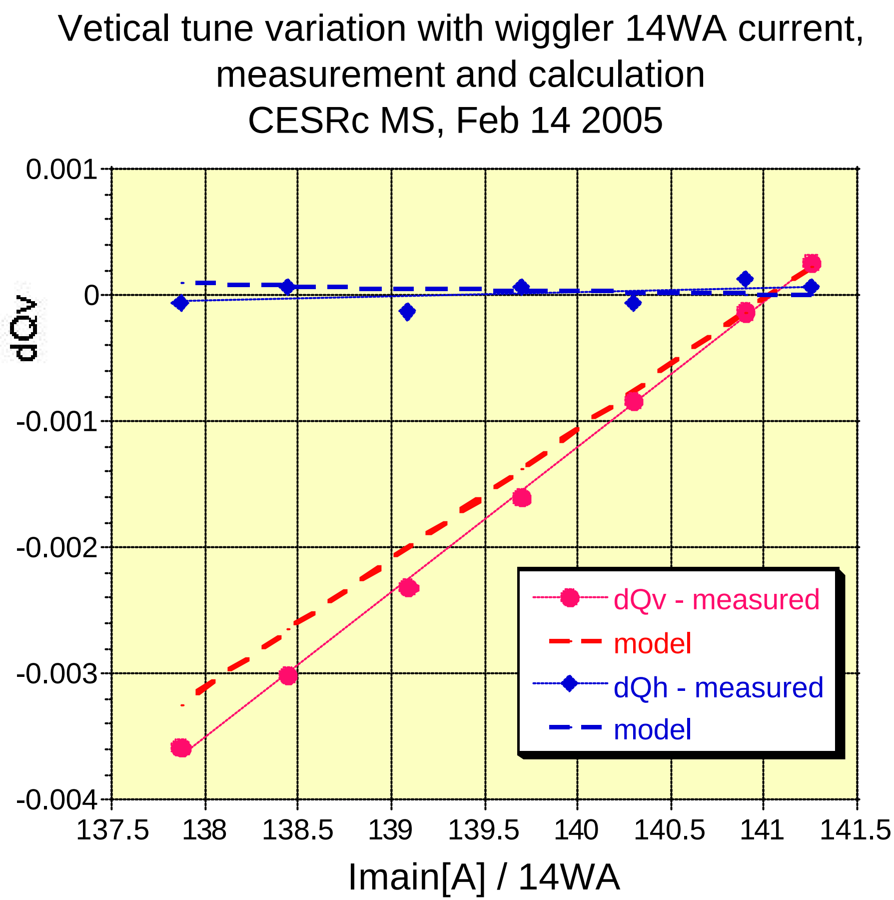
Horizontal transfer function (x' vs x) and
local focusing effect (dx'/dx) calculated with
tracking trough 3D wiggler magnetic field



Vertical transfer function (y' vs y) and
local focusing (-dy'/dy) calculated with
tracking trough 3D wiggler magnetic field



Wigglers characterization with beam and model benchmarking



Tune variation with wiggler (14WA) current.

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

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

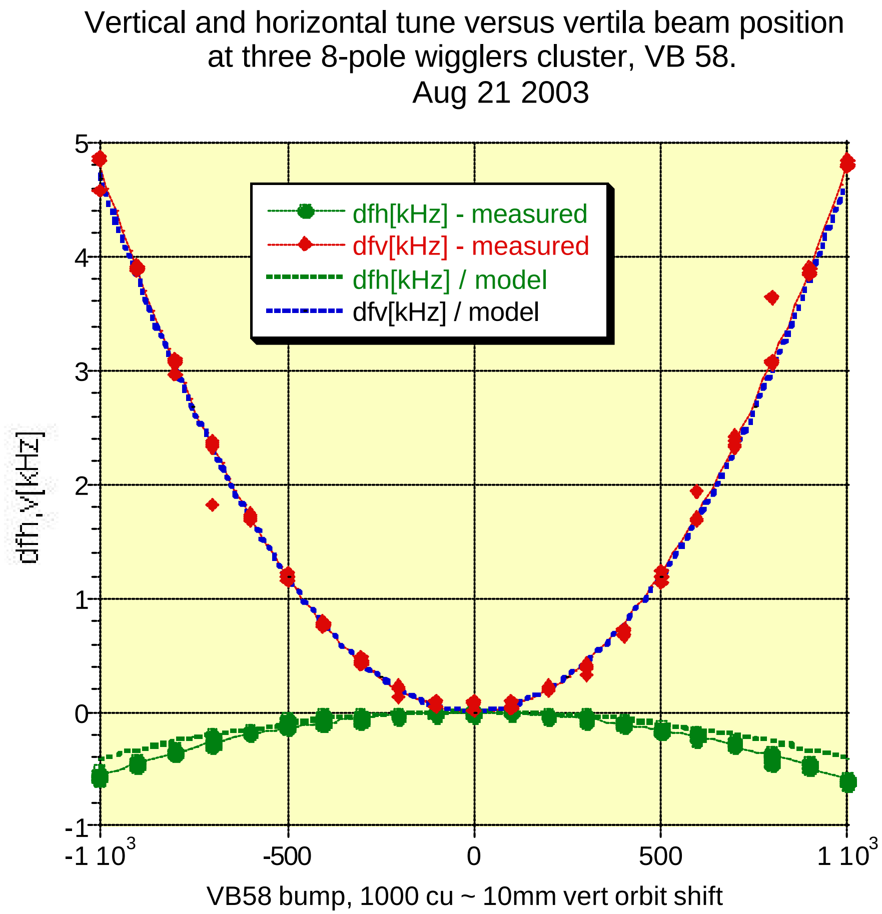
	Value	Error
dQh/dI (model)	-2.97e-5	6.7e-13
dQh/dI (measI)	3.5e-5	2.9e-5
dQv/dI (model)	0.00102	2.0e-11
dQv/dI (meas)	0.00115	1.67e-05

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

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



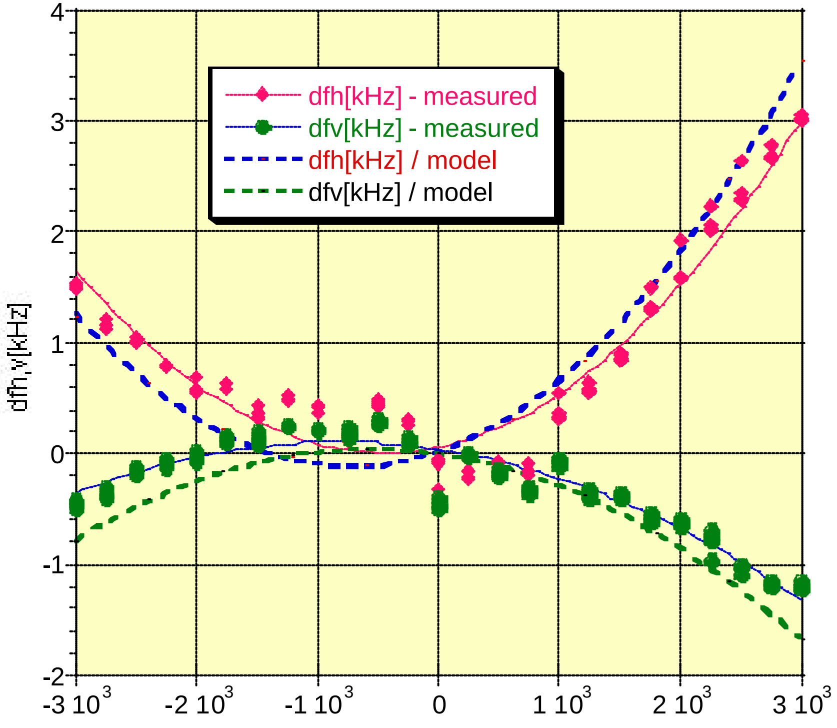
Wiggler characterization with beam and model benchmarking

Tune variation with beam position in 18E 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 8-pole wigglers cluster, HB 70.
Aug 21 2003



HB70 bump, 1000cu ~ 10mm horizontal orbit displacment

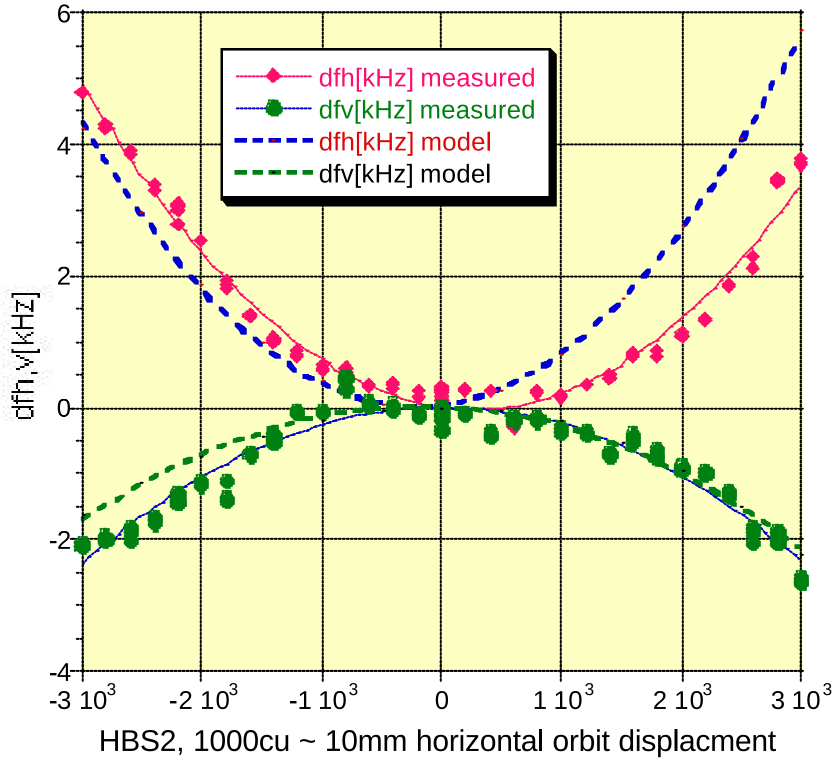
Wiggler characterization with beam and model benchmarking

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

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

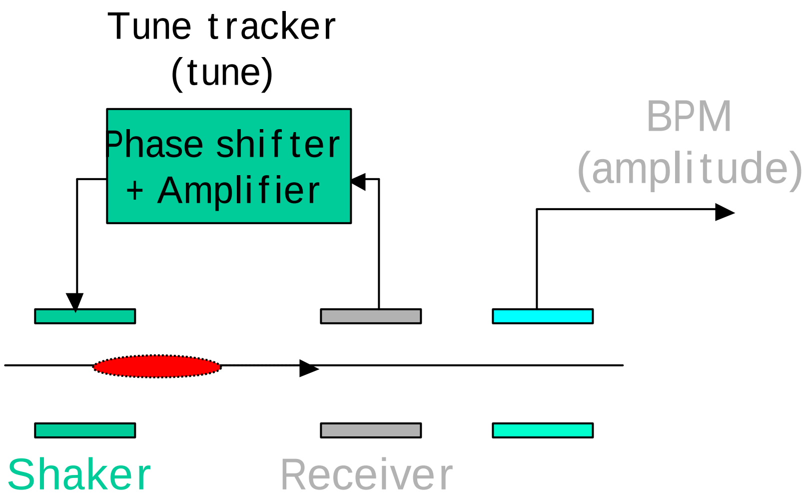
$$df_{h,v} = 1kHz \;\Rightarrow\; dQ_{h,v} = 0.0025$$

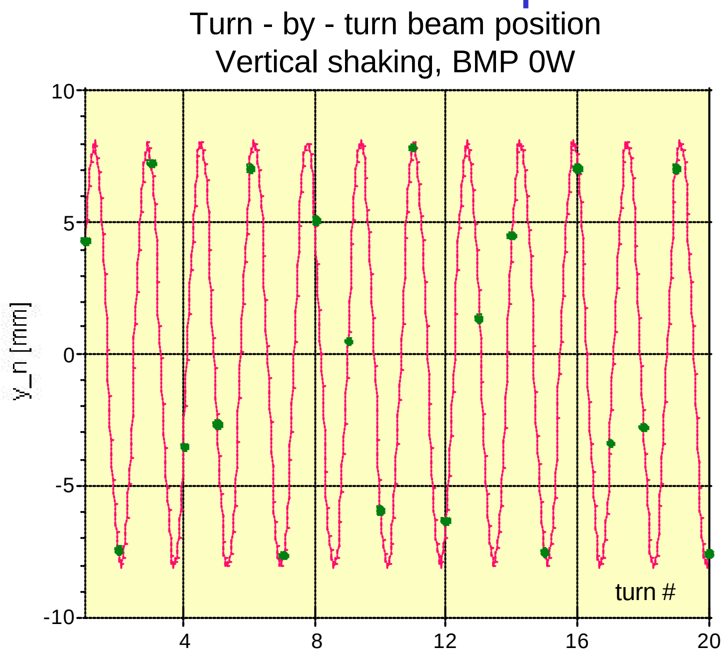
Vertical and horizontal tune versus horizontal beam position at three wigglers cluster, wig1_18w, wig2_18w, wig3_18w (July 8 2004)



Wiggler characterization with beam and model benchmarking

Setup for measurement of tune variation with amplitude.





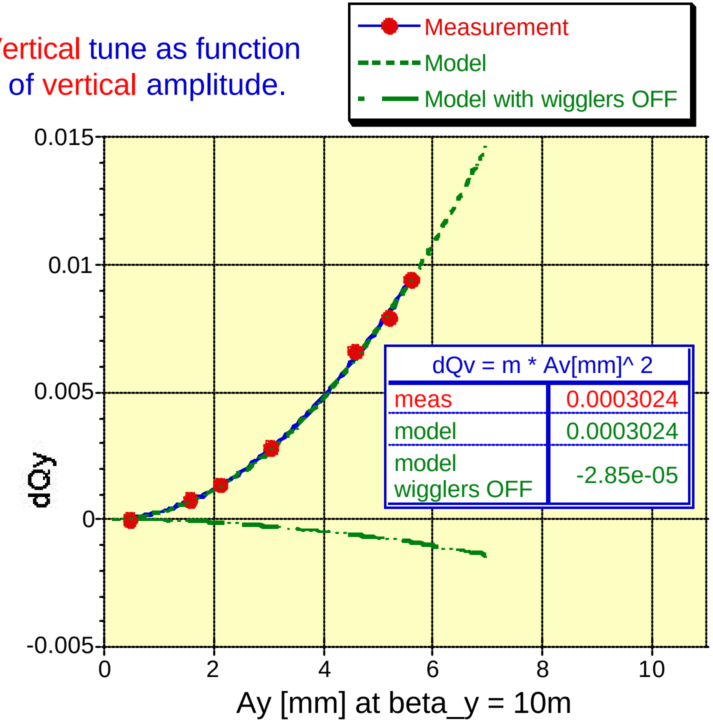
y = Ay*cos((m0-m2)*360*Qy)		
	Value	Error
Ay[mm]	8.007	0.062
m2	4.5137	0.0030
Qy	0.61565	0.0002

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

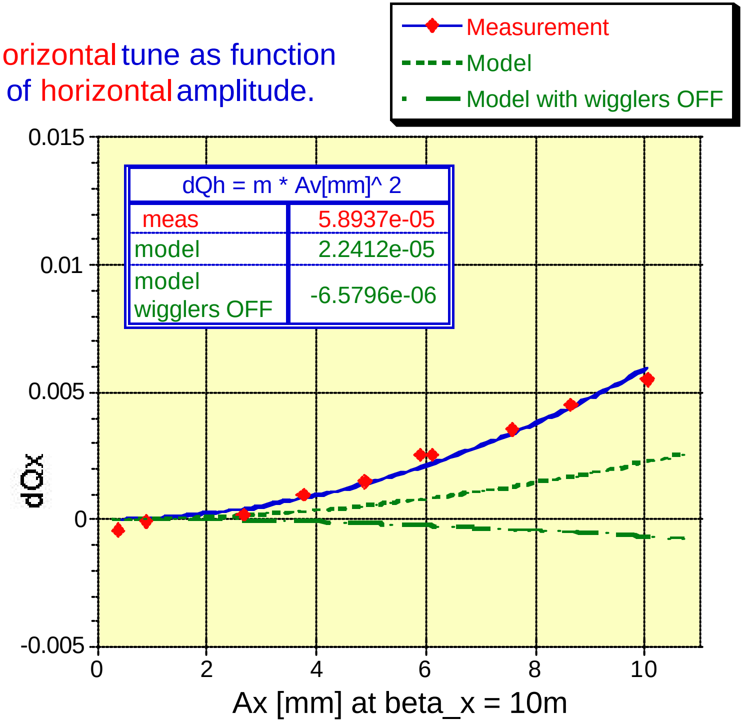
Wiggler characterization with beam and model benchmarking.

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

Vertical tune as function of vertical amplitude.



Horizontal tune as function of horizontal amplitude.



Conclusion

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

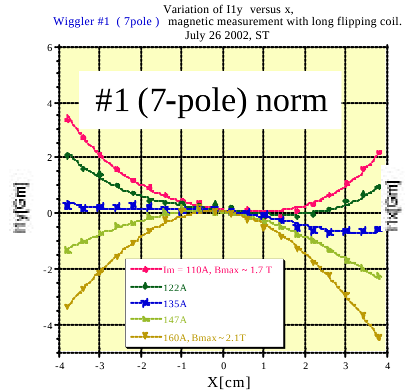
- Beam based wiggler characterization is in good agreement with model.

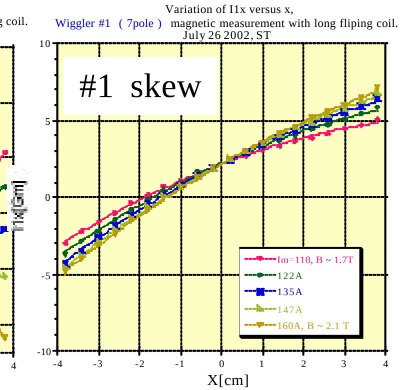
  We have good wigglers and reliable model

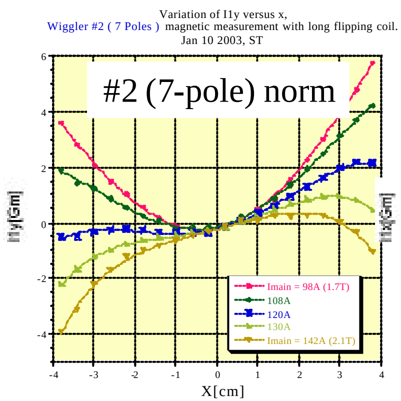
- So far, we have not seen beam performance degrading due to wiggler field nonlinearities.

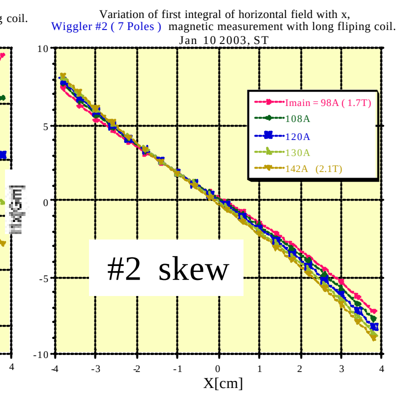
  Very positive experience.

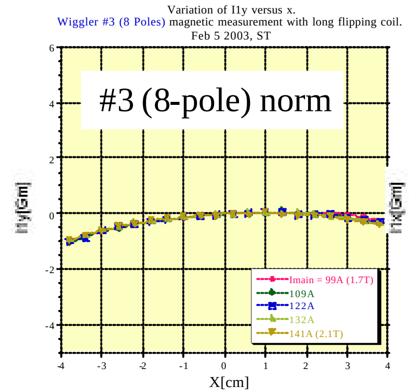
Magnetic measurement summary.
Units 1 and 2 are 7-pole, units 3 and up are 8-pole

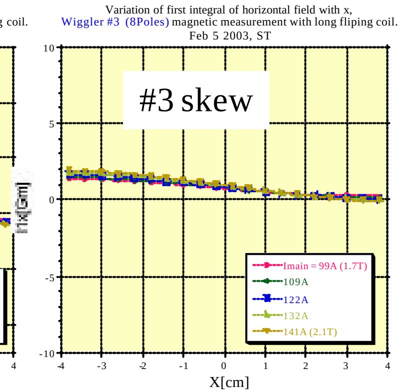


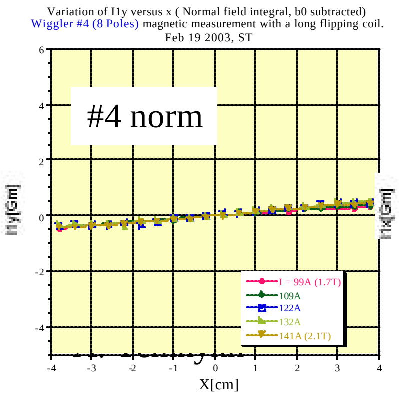


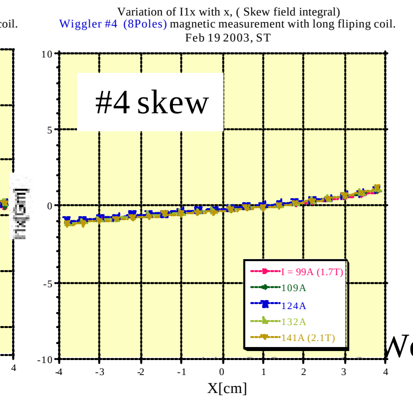




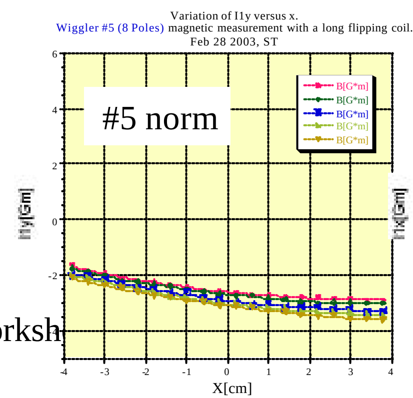


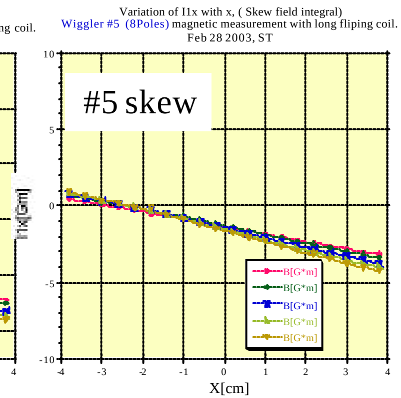


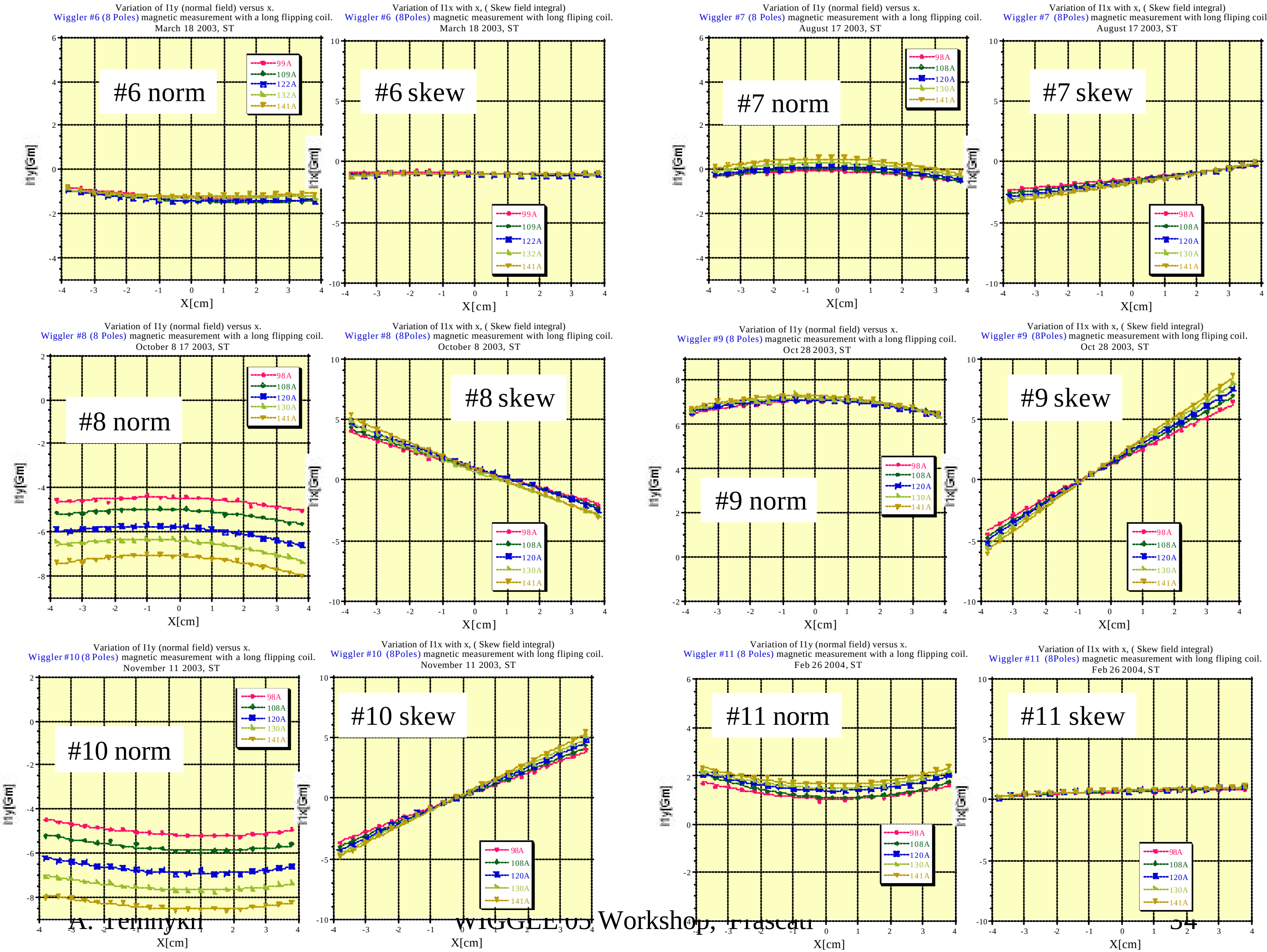




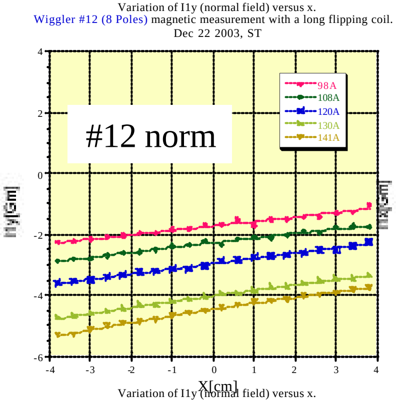
Worksh

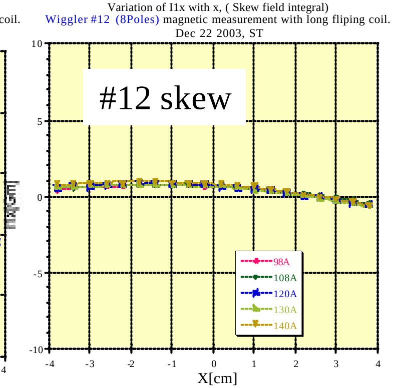


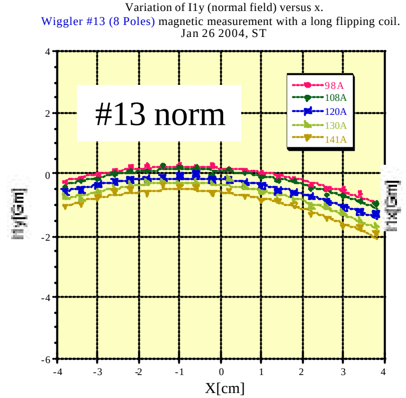


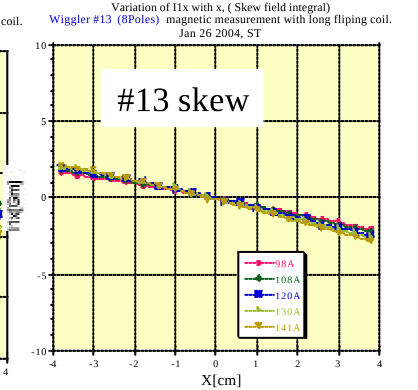


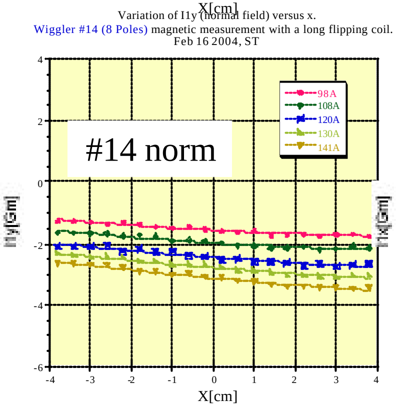
Variation of I1y (normal field) versus x.
Wiggler #6 (8 Poles) magnetic measurement with a long flipping coil.
March 18 2003, ST
#6 norm
99A
109A
122A
132A
141A
I1y[Gm]
X[cm]
Variation of I1x with x, (Skew field integral)
Wiggler #6 (8Poles) magnetic measurement with long fliping coil.
March 18 2003, ST
#6 skew
I1x[Gm]
X[cm]
Variation of I1y (normal field) versus x.
Wiggler #7 (8 Poles) magnetic measurement with a long flipping coil.
August 17 2003, ST
#7 norm
98A
108A
120A
130A
141A
Variation of I1x with x, (Skew field integral)
Wiggler #7 (8Poles) magnetic measurement with long fliping coil.
August 17 2003, ST
#7 skew
Variation of I1y (normal field) versus x.
Wiggler #8 (8 Poles) magnetic measurement with a long flipping coil.
October 8 17 2003, ST
#8 norm
Variation of I1x with x, (Skew field integral)
Wiggler #8 (8Poles) magnetic measurement with long fliping coil.
October 8 2003, ST
#8 skew
Variation of I1y (normal field) versus x.
Wiggler #9 (8 Poles) magnetic measurement with a long flipping coil.
Oct 28 2003, ST
#9 norm
Variation of I1x with x, (Skew field integral)
Wiggler #9 (8Poles) magnetic measurement with long fliping coil.
Oct 28 2003, ST
#9 skew
Variation of I1y (normal field) versus x.
Wiggler #10 (8 Poles) magnetic measurement with a long flipping coil.
November 11 2003, ST
#10 norm
Variation of I1x with x, (Skew field integral)
Wiggler #10 (8Poles) magnetic measurement with long fliping coil.
November 11 2003, ST
#10 skew
Variation of I1y (normal field) versus x.
Wiggler #11 (8 Poles) magnetic measurement with a long flipping coil.
Feb 26 2004, ST
#11 norm
Variation of I1x with x, (Skew field integral)
Wiggler #11 (8Poles) magnetic measurement with long fliping coil.
Feb 26 2004, ST
#11 skew

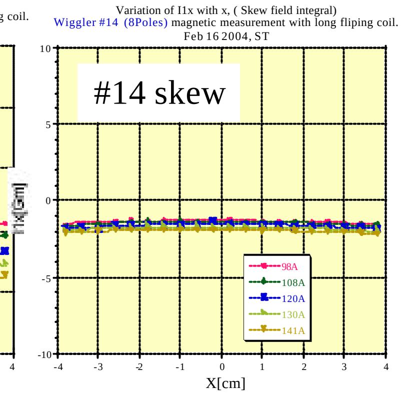

Variation of I1y (normal field) versus x.
Wiggler #12 (8 Poles) magnetic measurement with a long flipping coil.
Dec 22 2003, ST
#12 norm
98A
108A
120A
130A
141A
I1y[Gm]
X[cm]

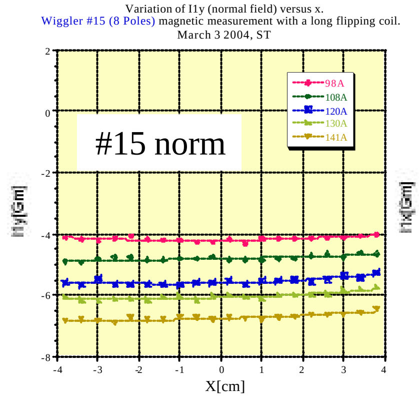

Variation of I1x with x, (Skew field integral)
Wiggler #12 (8Poles) magnetic measurement with long fliping coil.
Dec 22 2003, ST
#12 skew
98A
108A
120A
130A
140A
I1x[Gm]
X[cm]

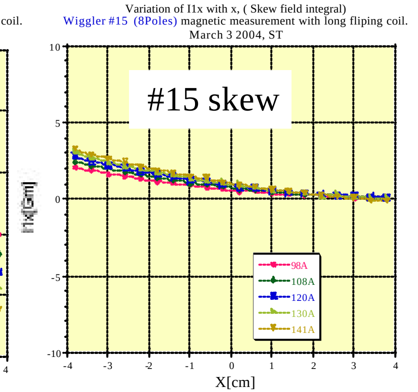

Variation of I1y (normal field) versus x.
Wiggler #13 (8 Poles) magnetic measurement with a long flipping coil.
Jan 26 2004, ST
#13 norm
98A
108A
120A
130A
141A
I1y[Gm]
X[cm]

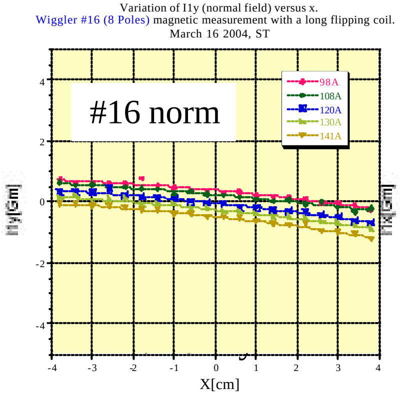

Variation of I1x with x, (Skew field integral)
Wiggler #13 (8Poles) magnetic measurement with long fliping coil.
Jan 26 2004, ST
#13 skew
98A
108A
120A
130A
141A
I1x[Gm]
X[cm]

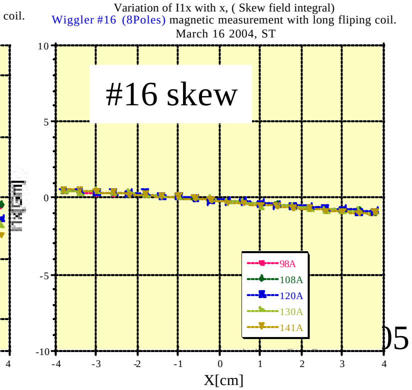

Variation of I1y (normal field) versus x.
Wiggler #14 (8 Poles) magnetic measurement with a long flipping coil.
Feb 16 2004, ST
#14 norm
98A
108A
120A
130A
141A
I1y[Gm]
X[cm]

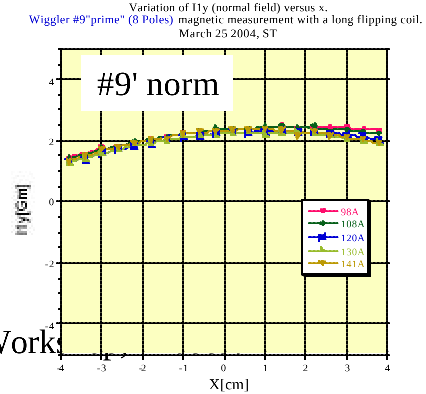

Variation of I1x with x, (Skew field integral)
Wiggler #14 (8Poles) magnetic measurement with long fliping coil.
Feb 16 2004, ST
#14 skew
98A
108A
120A
130A
141A
I1x[Gm]
X[cm]

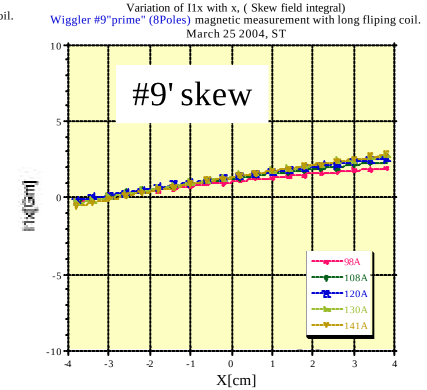

Variation of I1y (normal field) versus x.
Wiggler #15 (8 Poles) magnetic measurement with a long flipping coil.
March 3 2004, ST
#15 norm
98A
108A
120A
130A
141A
I1y[Gm]
X[cm]


Variation of I1x with x, (Skew field integral)
Wiggler #15 (8Poles) magnetic measurement with long fliping coil.
March 3 2004, ST
#15 skew
98A
108A
120A
130A
141A
I1x[Gm]
X[cm]


Variation of I1y (normal field) versus x.
Wiggler #16 (8 Poles) magnetic measurement with a long flipping coil.
March 16 2004, ST
#16 norm
98A
108A
120A
130A
141A
I1y[Gm]
X[cm]

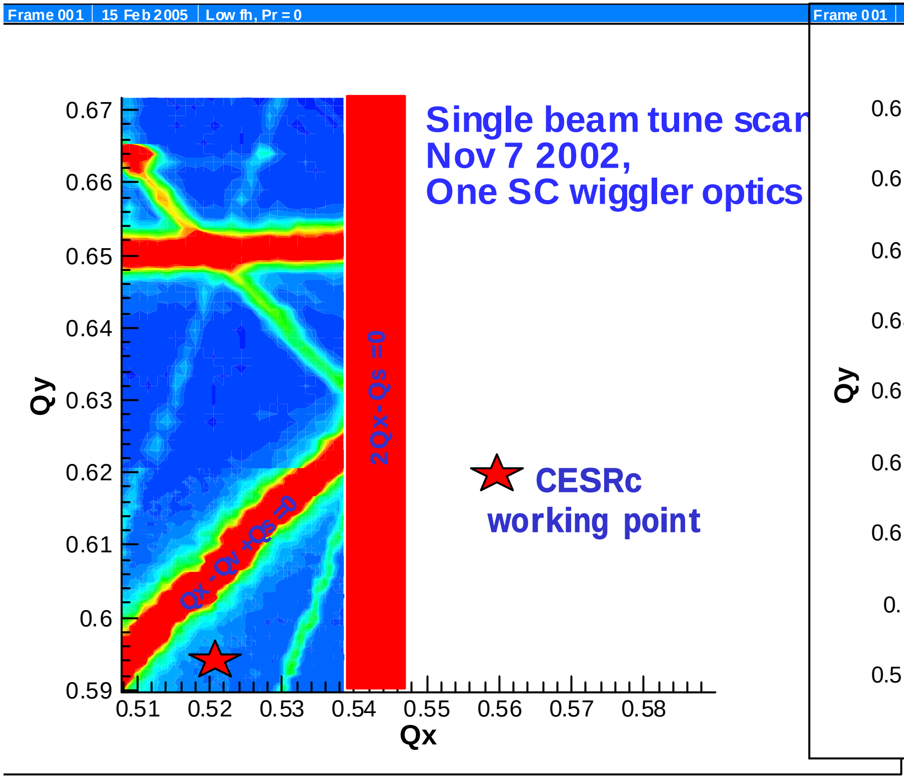

Variation of I1x with x, (Skew field integral)
Wiggler #16 (8Poles) magnetic measurement with long fliping coil.
March 16 2004, ST
#16 skew
98A
108A
120A
130A
141A
I1x[Gm]
X[cm]

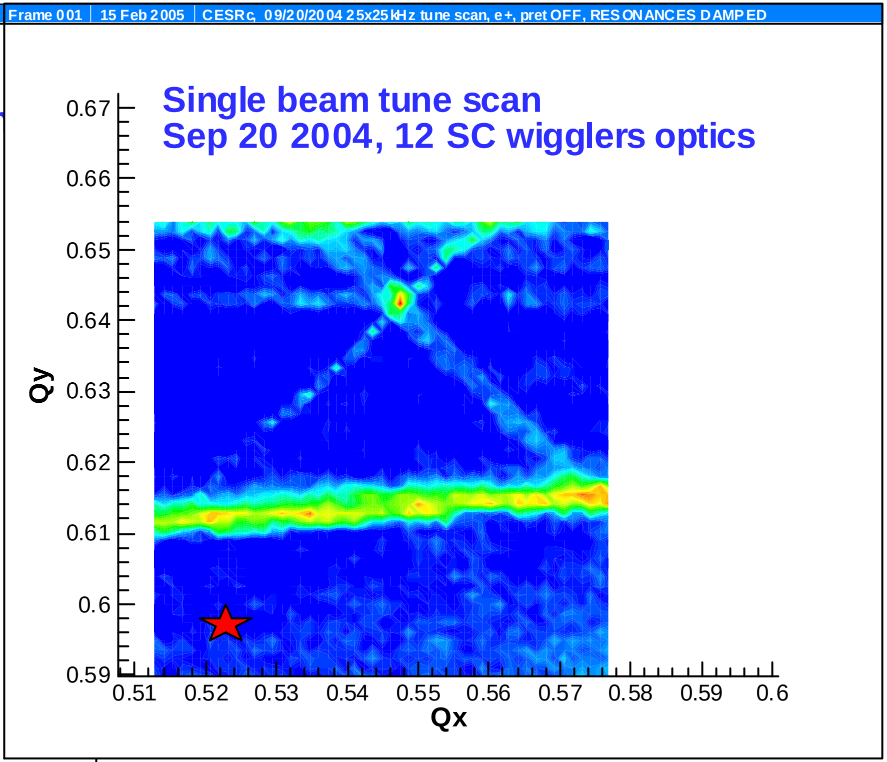

Variation of I1y (normal field) versus x.
Wiggler #9"prime" (8 Poles) magnetic measurement with a long flipping coil.
March 25 2004, ST
#9' norm
98A
108A
120A
130A
141A
I1y[Gm]
X[cm]


Variation of I1x with x, (Skew field integral)
Wiggler #9"prime" (8Poles) magnetic measurement with long fliping coil.
March 25 2004, ST
#9' skew
98A
108A
120A
130A
141A
I1x[Gm]
X[cm]

Ring characterization with beam: tune plane mapping.

Vertical beam size (vertical beam emittance) versus tune





Nov 2002, One wiggler optics

Sept 2004, 12 wigglers optics with better tuned nonlinearities (Sextupoles and skew sextupoles)