CESR-c Status and Accelerator Physics

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for the LEPP staff

30th Advanced ICFA Beam Dynamics Workshop on
High Luminosity e+e- Collisions

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Stanford, California

(Many slides courtesy of A.B. Temnykh
from a presentation at Alghero Workshop
Sept. 10-13, 2003)

CESR Layout

Principal Features:

768 m Circumference

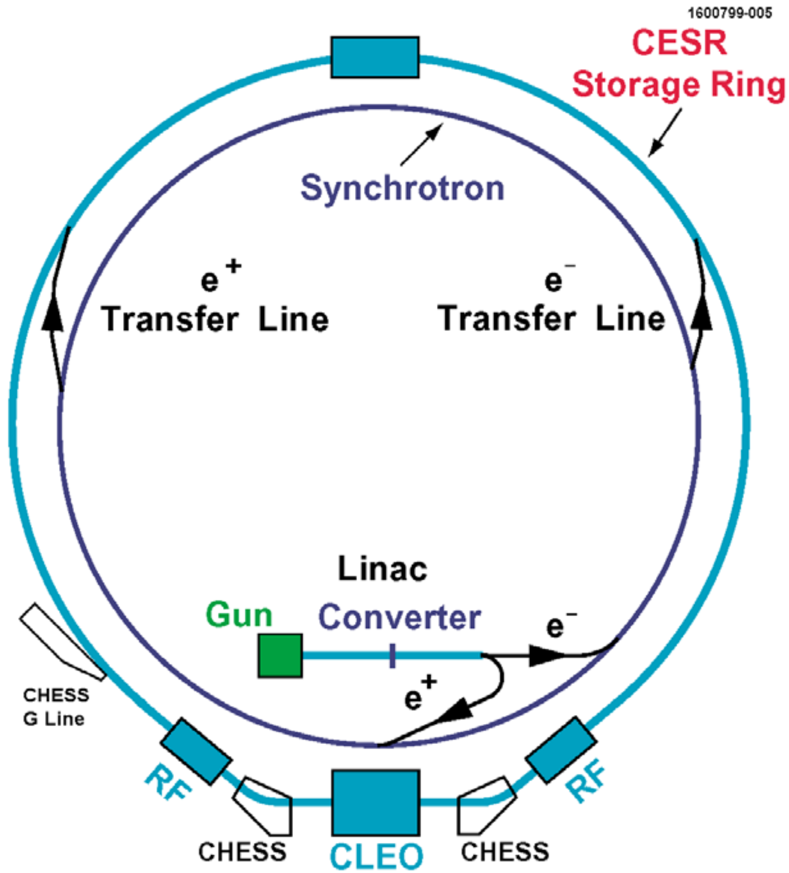
1.5-6 GeV beam energy
(8 GeV design energy)

I_{beam} > **350 mA @ 5.3 GeV**

L > 1.2 x 10^{33} $cm^{-2}sec^{-1}$ @$\Upsilon(4S)$

45 bunches each e+, e-

Full energy, multibunch injector

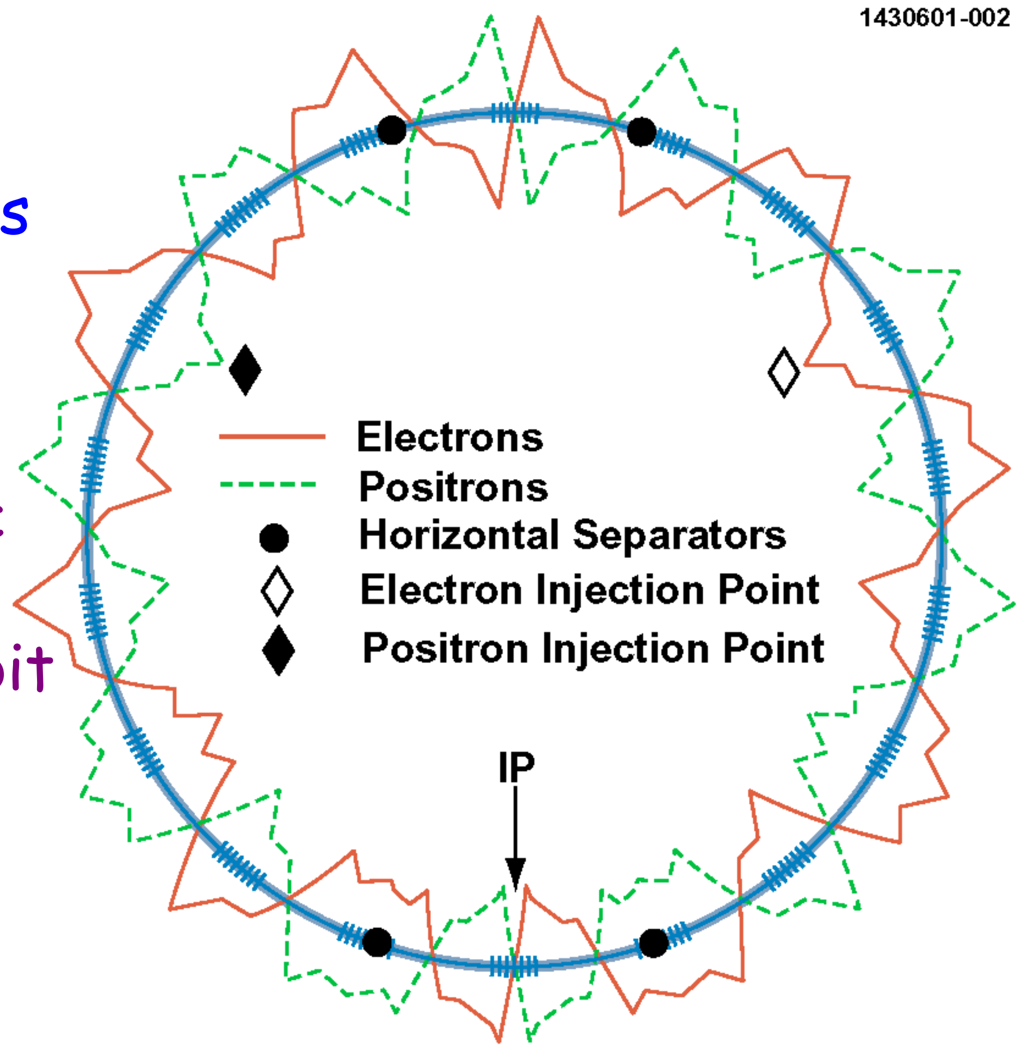


CESR Layout (2)

45 bunches per beam

⇒ **89** parasitic crossings

Separation with (4) horizontal electrostatic separators – ± 20 mm horizontal orbit



CESR-c Objectives

We are modifying CESR to provide high luminosity colliding beams over the (beam) energy range from 1.5 to 5.6 GeV.

Energies (E_{beam}) of interest :

J/ψ:	*1.55 GeV*
Charm threshold (ψ''):	*1.885 GeV*
Above $D\bar{D}$ threshold:	*2.1-2.5 GeV*
ϒ states:	*4.7-5.6 GeV*

Parameters

Beam Energy [GeV]	1.55	1.88	2.5	5.3
Luminosity [$\div 10^{30}$]	150	300	500	1250
i_b [mA/bunch]	2.8	4.0	5.1	8.0
I_{beam} [mA/beam]	130	180	230	370
ξ_y	0.035	0.04	0.04	0.06
ξ_x	0.028	0.036	0.034	0.03
σ_E/E_0 [$\times 10^3$]	0.75	0.81	0.79	0.64
$\tau_{x,y}$ [msec]	69	55	52	22
B_W [Tesla]	2.1	2.1	1.75	1.2
β_y^* [cm]	1.0	1.0	1.0	1.8
ε_x [nm-rad]	230	220	215	220

Energy Reach - CESR-c

CESR-c conversion -

- Optimize luminosity @ 1.5 to 2.5 GeV
- Maintain performance at 5.3 GeV

Major operational impact 5.3 → 1.9 GeV

- Radiation decreases ÷**60**
- Damping time increases **x22**
  - (Injection time, instability thresholds, luminosity)
- Beam rigidity reduced ÷2.5
  - (Instability thresholds, increased sensitivity to p.s. ripple, perturbations to design guide field – e.g. LR BBI)

Modifications for CESR-c

1. Recover radiation damping lost at low energy
   Install ~16 m of 2.1 T wigglers to control emittance and damping times.
2. Replace "thick" Ti windows in injection transport lines
3. Minor modifications to power supplies to reduce ripple.
4. Extend energy range, reduce spot size at IP.
   Replace PM IR quads with S.C. quads for full energy range, lower β^*, p.c. separation, and better solenoid compensation.
5. Reduce bunch length in proportion to spot size
   Upgrade RF system to shorten bunch length in order to take advantage of smaller β^*.

Items 4 and 5 have been previously planned as an upgrade to CESR performance.

The wigglers are the only major change specific to low energy operation.

Scaling with wigglers
(field&length)

Scaling with wiggler field and length:
(Wiggler dominated radiation)

Damping time: $$\tau \propto \frac{1}{L_W B_W^2}$$

Horizontal Emittance: $$\varepsilon_X \propto B_W \mathcal{H}_W$$

Energy spread: $$\frac{\sigma_E}{E_0} \propto \sqrt{B_W}$$

1. **Choose B_w to limit energy spread**
2. **Choose L_w for damping time**
3. **Tailor $\mathcal{H}_w$ for desired emittance**

Wiggler Effects (Ideal wiggler)

Optics effects from an Ideal Wiggler

(infinitely wide poles, sinusoidal field $B_y(z)$ variation)

An ideal wiggler produces **vertical focusing** only –

$$\int_{wiggler} B_\chi ds = -\frac{L_W B_W^2}{2B\rho}\left(y + \frac{2}{3} k_w^2 y^3 + \ldots \right)$$

($k_w = 2\pi/\lambda_w$)

Each wiggler shifts Q_y by about 0.1 integer:

$$\Delta Q_Y \approx \frac{L_W < \beta_Y > B_W^2}{7.3x10^{-5}\gamma^2}$$

(z is along beam direction, +y is up)

Wiggler Effects (real wiggler)

Optics effects from a Real Wiggler

Real-life wigglers have a variation of mid-plane field across the pole face ($B_y(x)$) and accompanying vertical effect ($B_x(y)$)

The periodic displacement of the beam samples this field error coherently, producing a multipole like field error which increases $\propto \lambda_w^2$

$$\int_{Wiggler} B_y ds \approx -\frac{1}{2} L_W A_x \frac{dB_y}{dx} \qquad A_x = \frac{B_W \lambda_W^2}{4\pi^2 B\rho}$$

Wiggler Design

- **2.1** Tesla peak field, 40 cm pole period

  Compromise between damping rate and beam energy spread

- **50** mm full vertical beam-stay-clear

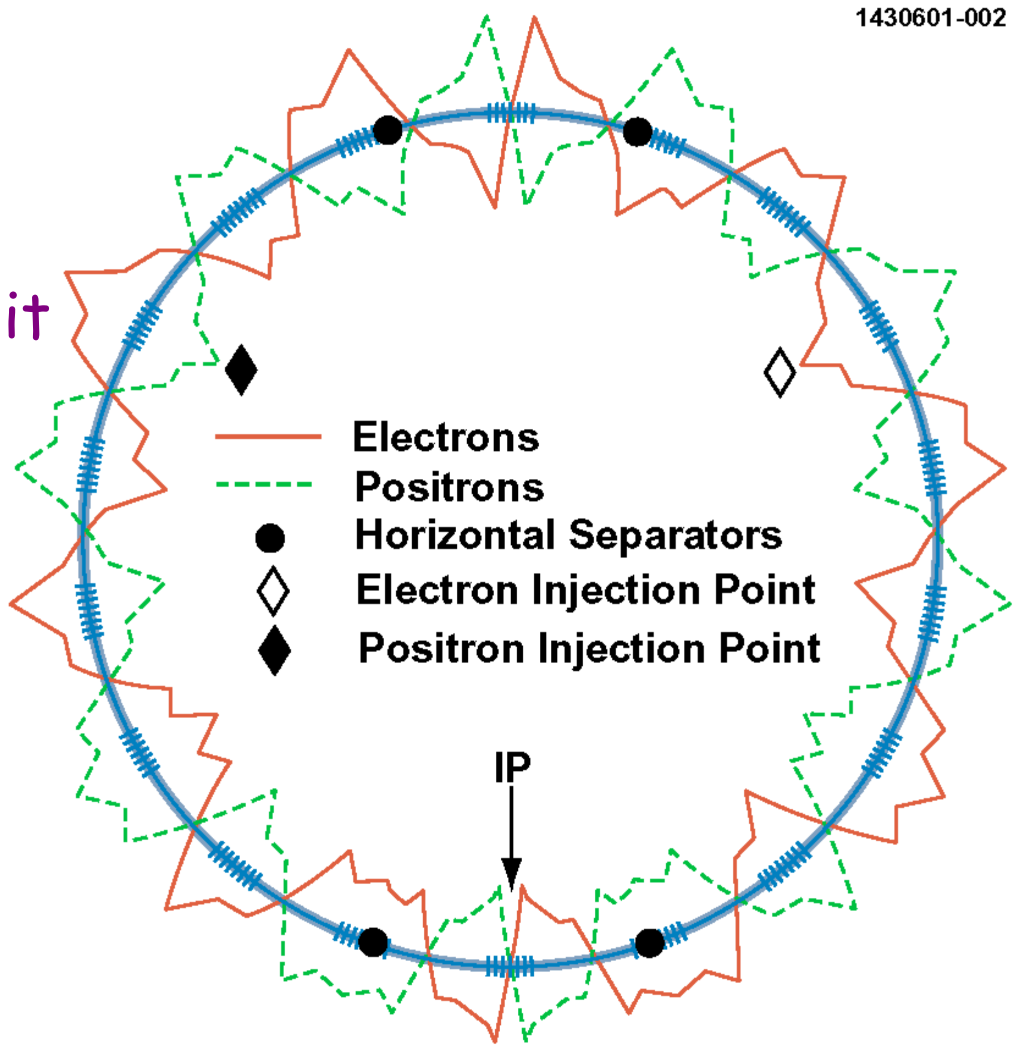
  Large vertical aperture for good lifetime w/colliding beams

- **+0, -0.3%** transverse field uniformity

  24 cm pole width
  Non-linear effects exacerbated by:
    - Large number of wigglers (90% radiation)
    - ±20 mm horizontal displacement from pretzel

CESR Pretzel

Separation with (4) horizontal electrostatic separators – ± 20 mm horizontal orbit



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  → **Superferric design**

Wiggler Design - Pole symmetry

Odd # poles (7)

- Single trim adjusts 1st integral – easily measured
- Cubic non-linearity (vertical) smaller for fixed damping
- Only 2 types of poles (vs. 3)

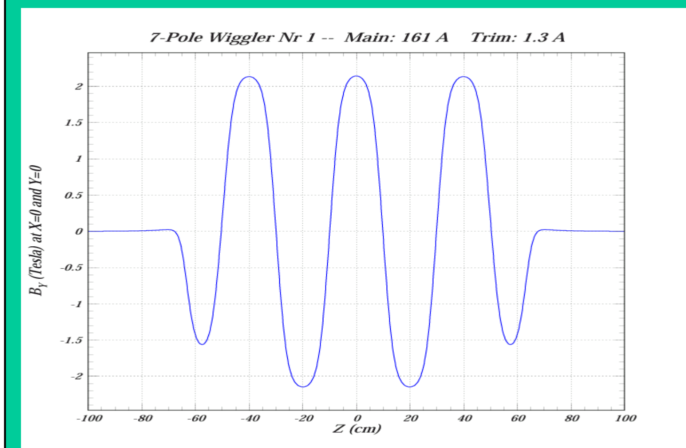
Even # poles (8)

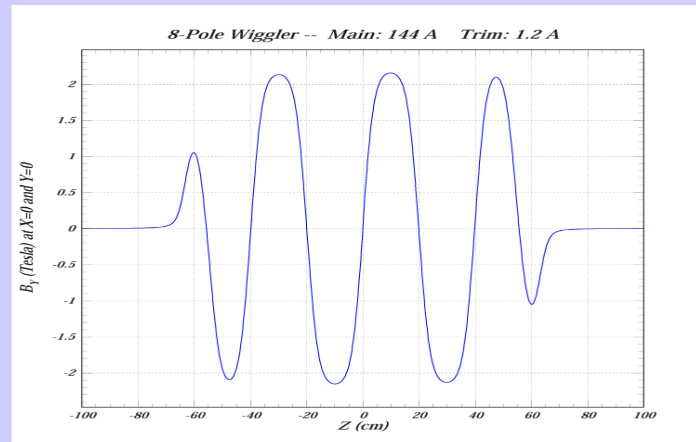
- Maintains linearity over wider range of excitation levels
- 1st integral ideally zero (but 2nd integral must be trimmed)
- Transfer function more symmetric
- Observed skew quad component (a_1) much lower.

Wiggler Design - Pole symmetry

	7 poles (symmetric)	8 poles (asymmetric)
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

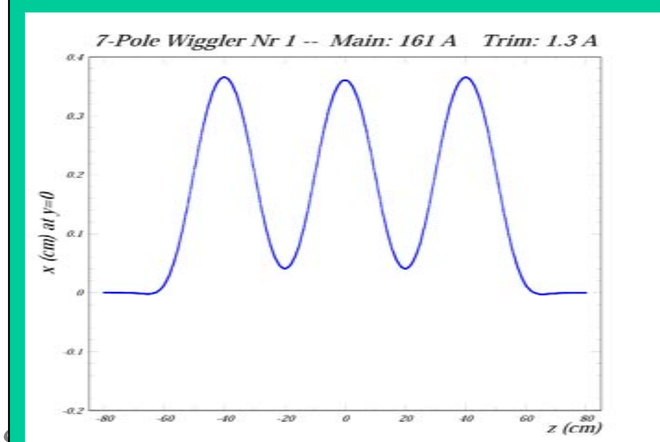
Field along magnet

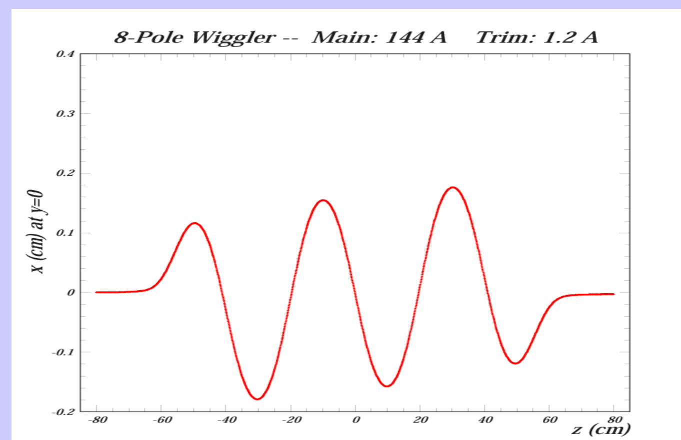




Beam trajectory

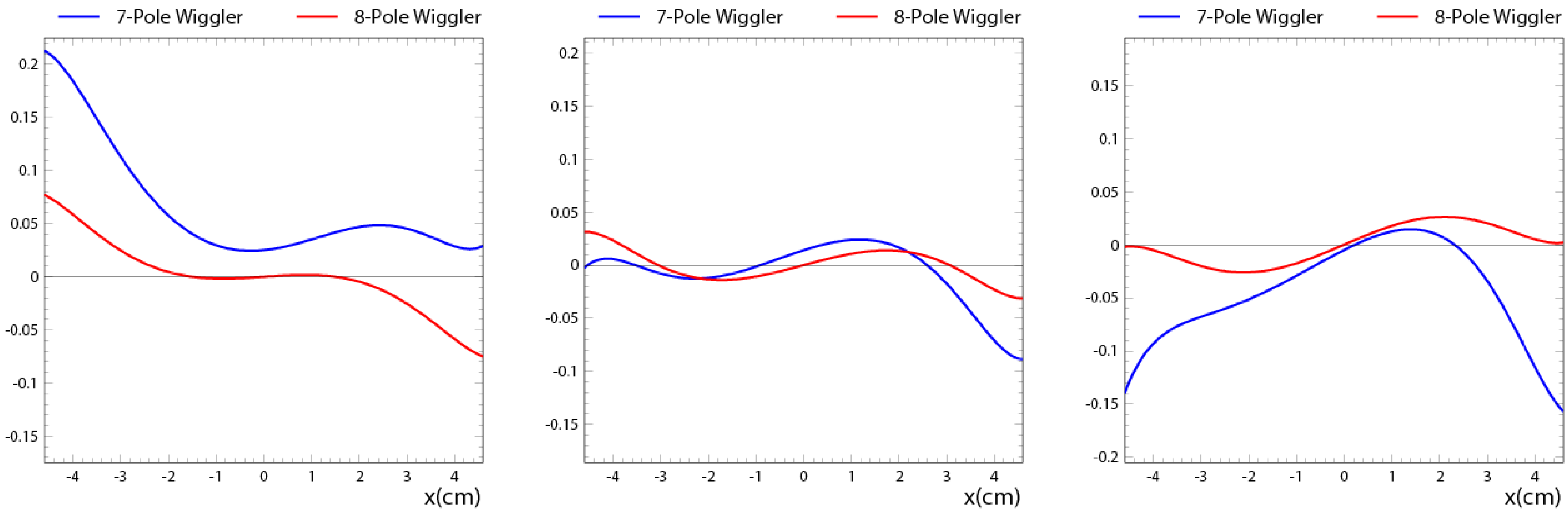
(slide from A.B. Temnykh)





Wiggler Design - Model Calculation

7-pole and 8-pole wigglers horizontal transfer function,
x ' (x, y=0) (field integrated along beam trajectory)



B max = 1.7T

B max = 1.9T

B max = 2.1T

(slide from A.B. Temnykh)

Wiggler Design - Pole symmetry

Odd # poles (7)

- Single trim adjusts 1st integral – easily measured
- Cubic non-linearity (vertical) smaller for fixed damping
- Only 2 types of poles (vs. 3)

Even # poles (8)

➡
- Maintains linearity over wider range of excitation levels
- 1st integral ideally zero (but 2nd integral must be trimmed)
- Transfer function more symmetric
- Observed skew quad component (a_1) much lower.

Units 1 & 2 are 7-pole, units 3 and up are 8-pole

Manufacturing Plan

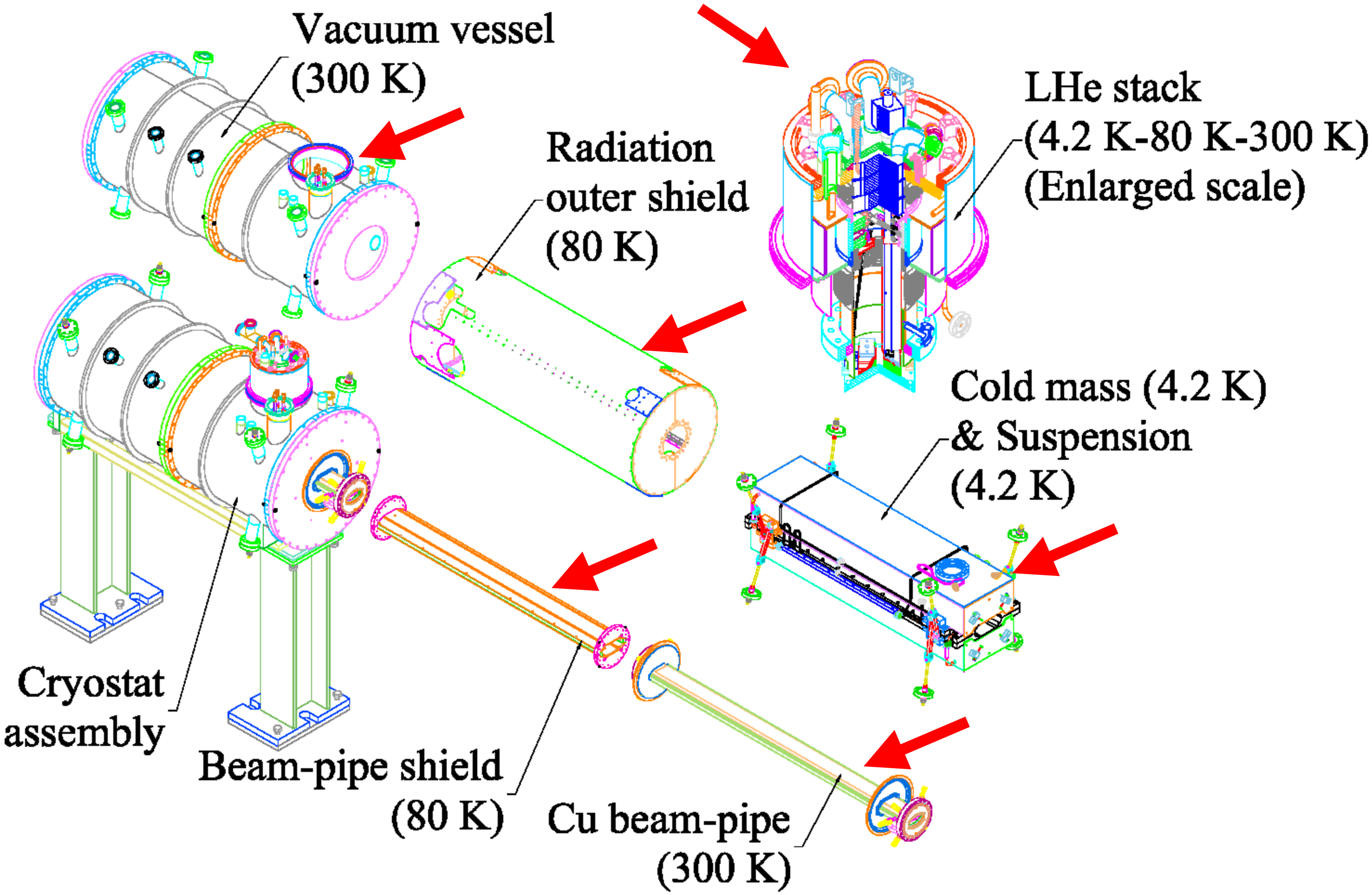
Most operations done in house

- Maintain schedule
- Control costs

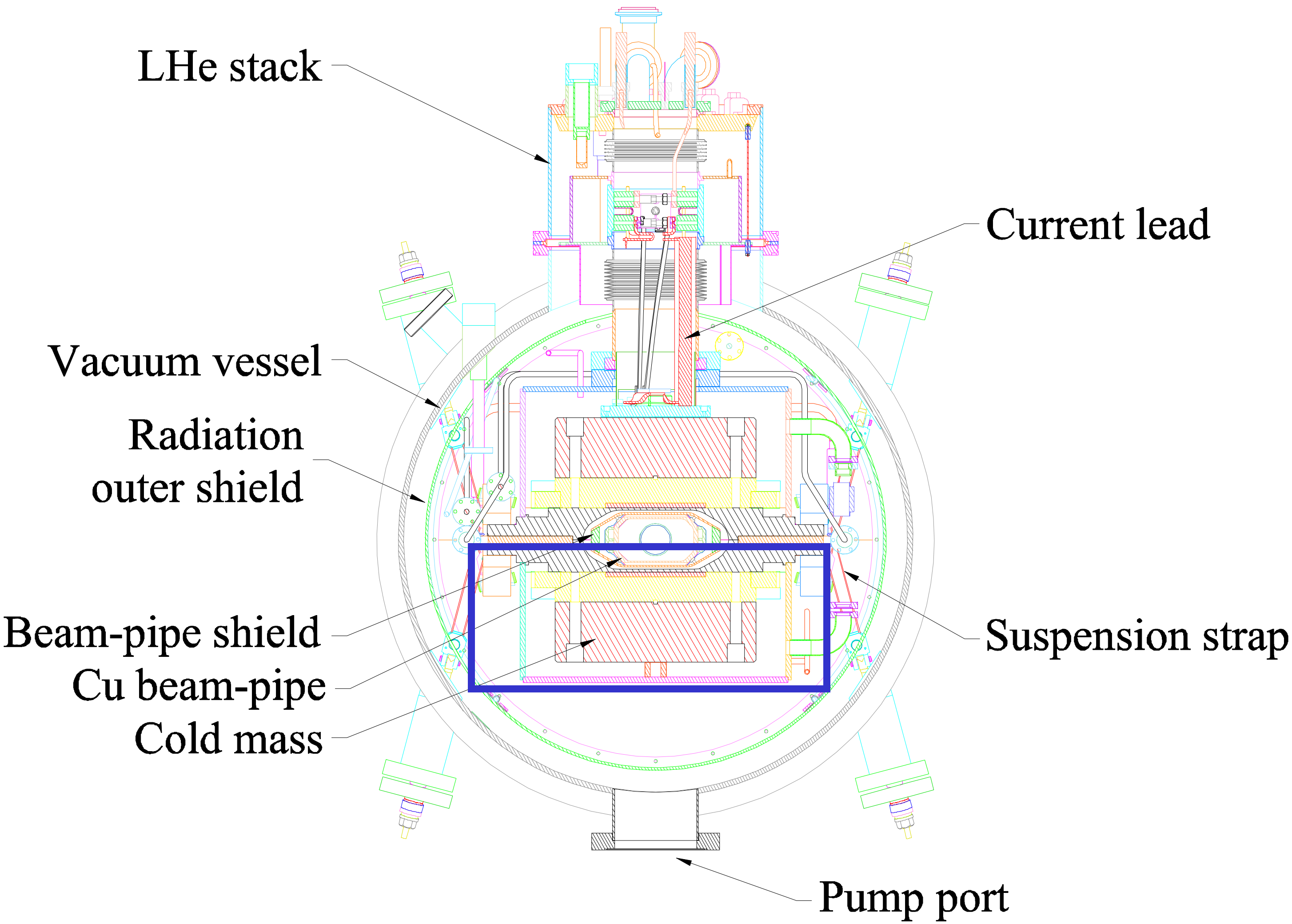
Outside work limited to:

- Machining & plating of large pieces (incl. poles)
- Fabrication & leak check of cryostat outer shell
- Fabrication of 77 K heat shields
- Cu extrusions for beam chamber

Wiggler design



Wiggler Design (2)



Components: Coil Winding

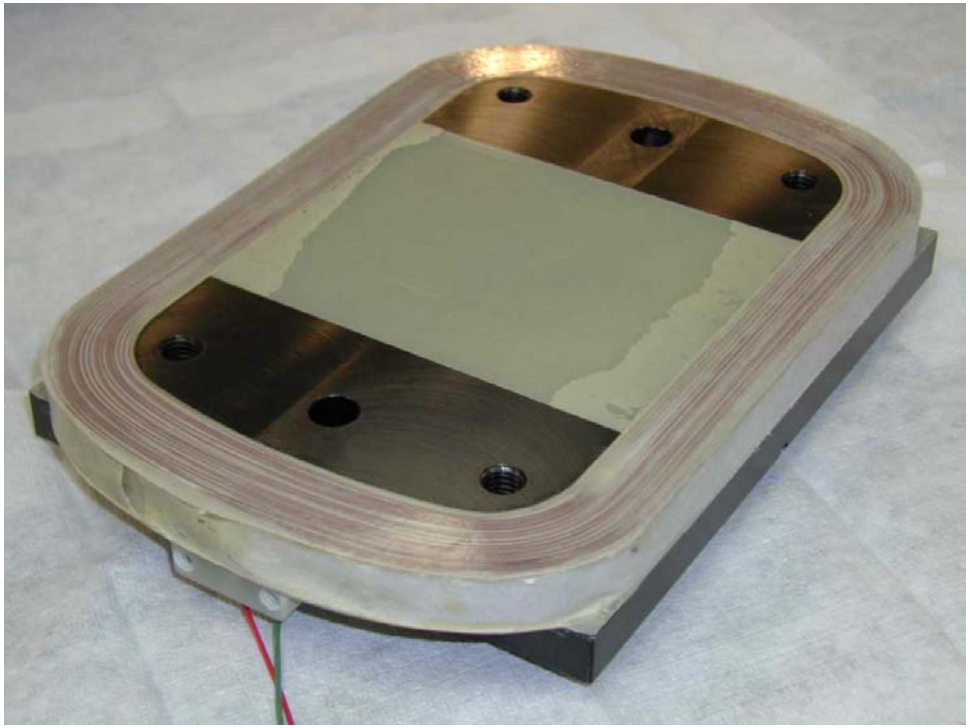
Coils are wound directly on individual machined iron poles.

Main poles 660 turns, 0.75 mm, 70 μm filament wire

Wet wound with Epotek T905™ epoxy

Clamped with shim blocks every 5 layers to maintain mechanical tolerances.

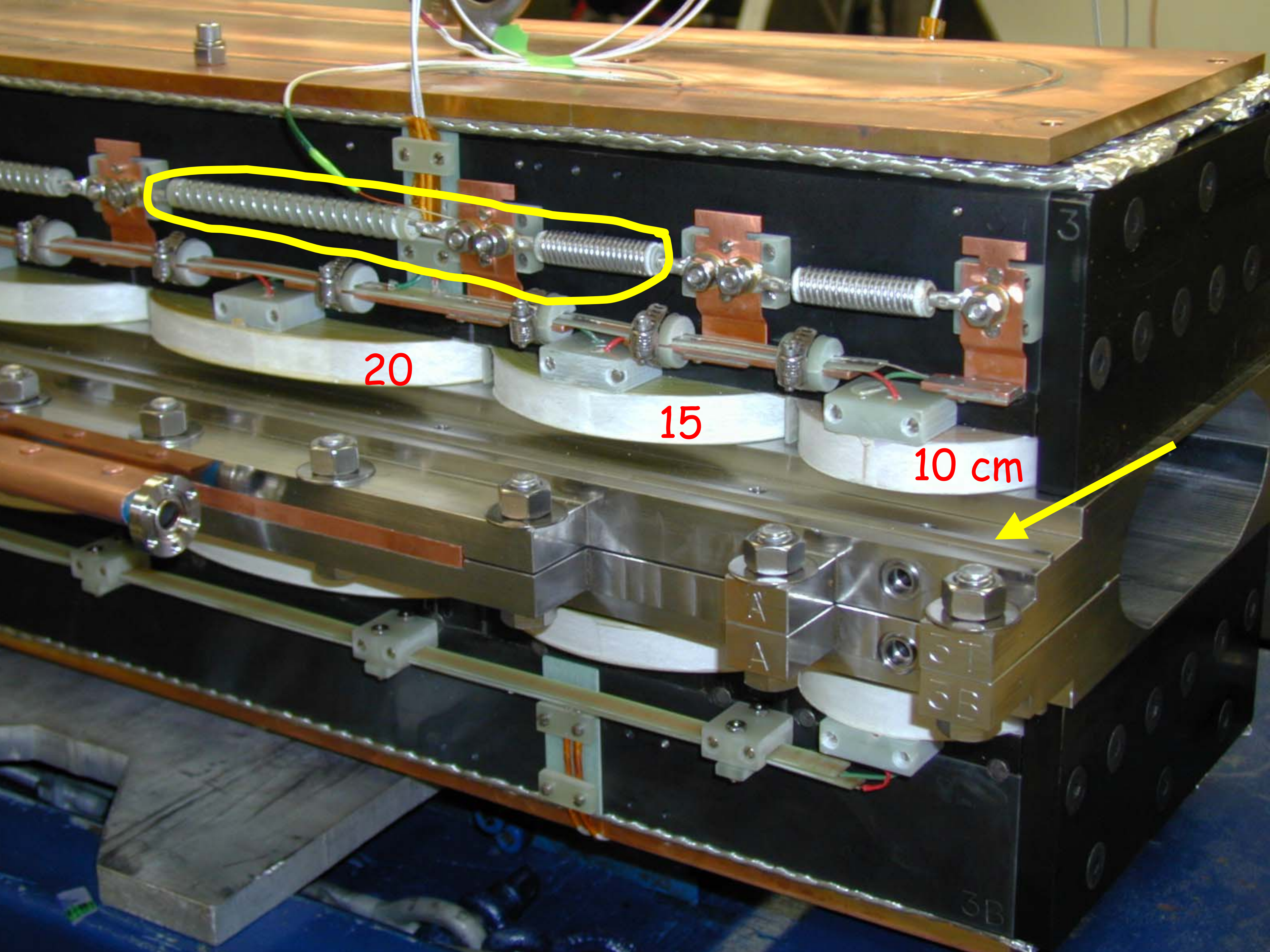
Experienced winder produces 1/day



Components: Coil Preload

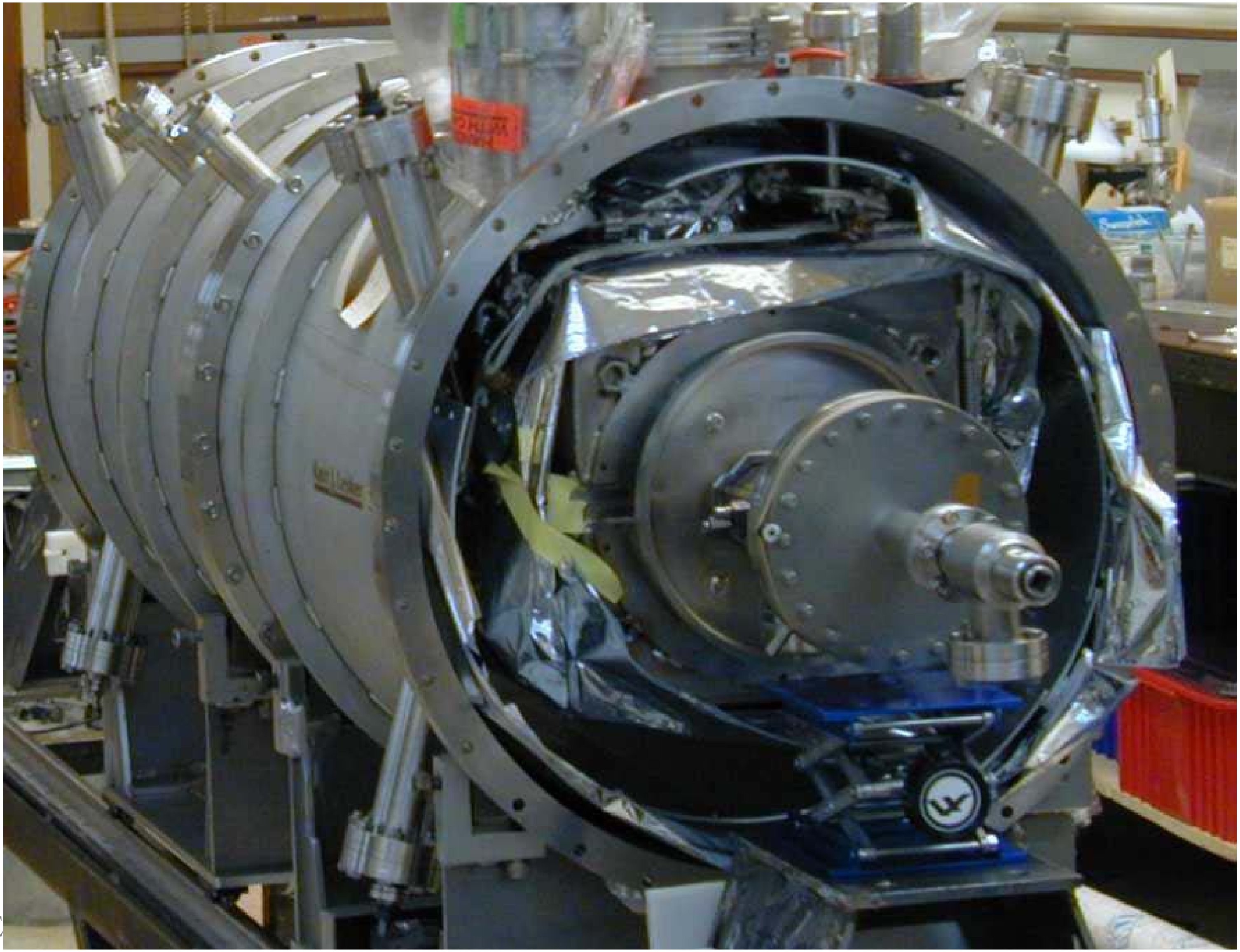
The finished pole pieces are placed on a 70 mm thick "yoke plate" flux return and support.

Magnetic force & cooldown shrinkage require large preload on coils – 16 Ton ⇔ 40 MPa pressure


20
15
10 cm

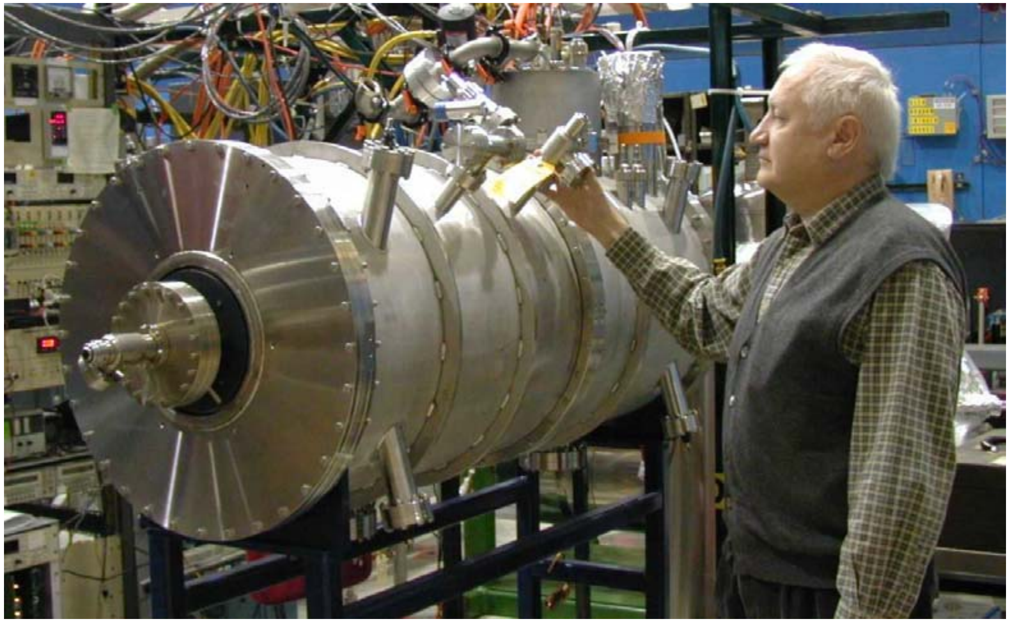
Assembly 1

Assembly 2



Training & Tests

- Magnets reach operating field (2.1 T, 141 A) with 1-3 training quenches.
- 2 days of magnetic measurements follow
- Final test to ~6% above max operating current
- LHe consumption monitored



Complete cryostat in test area

Wiggler Field Measurements

Two types of magnetic measurements are made on all wigglers:

- Longitudinal scans with high precision Hall probe at several horizontal positions
- Flip coil measurements at several horizontal positions.

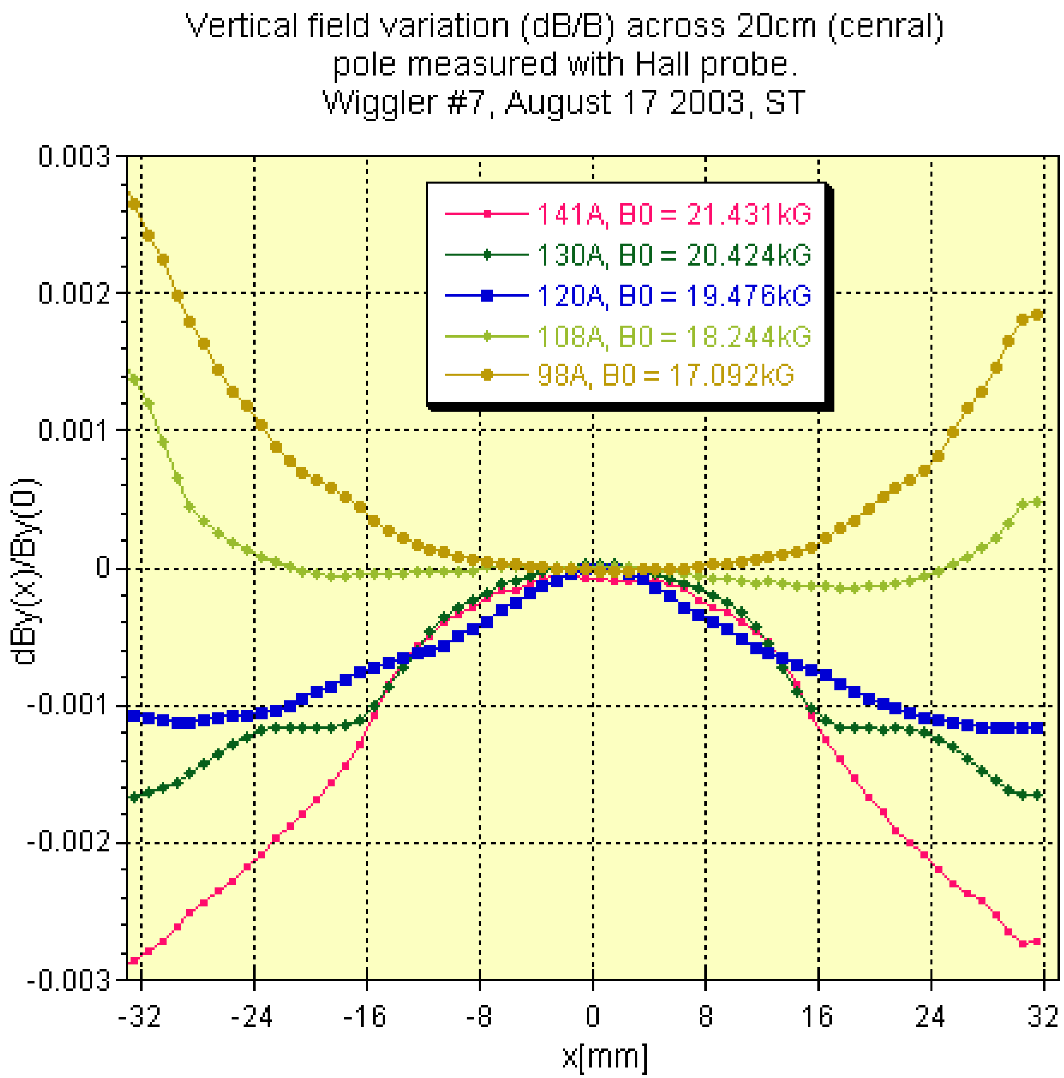
On one or a few wigglers additional measurements are made:

- Transverse scans across a single pole
- Folded flip coil measurements to measure second integral of field

Measured Field Uniformity

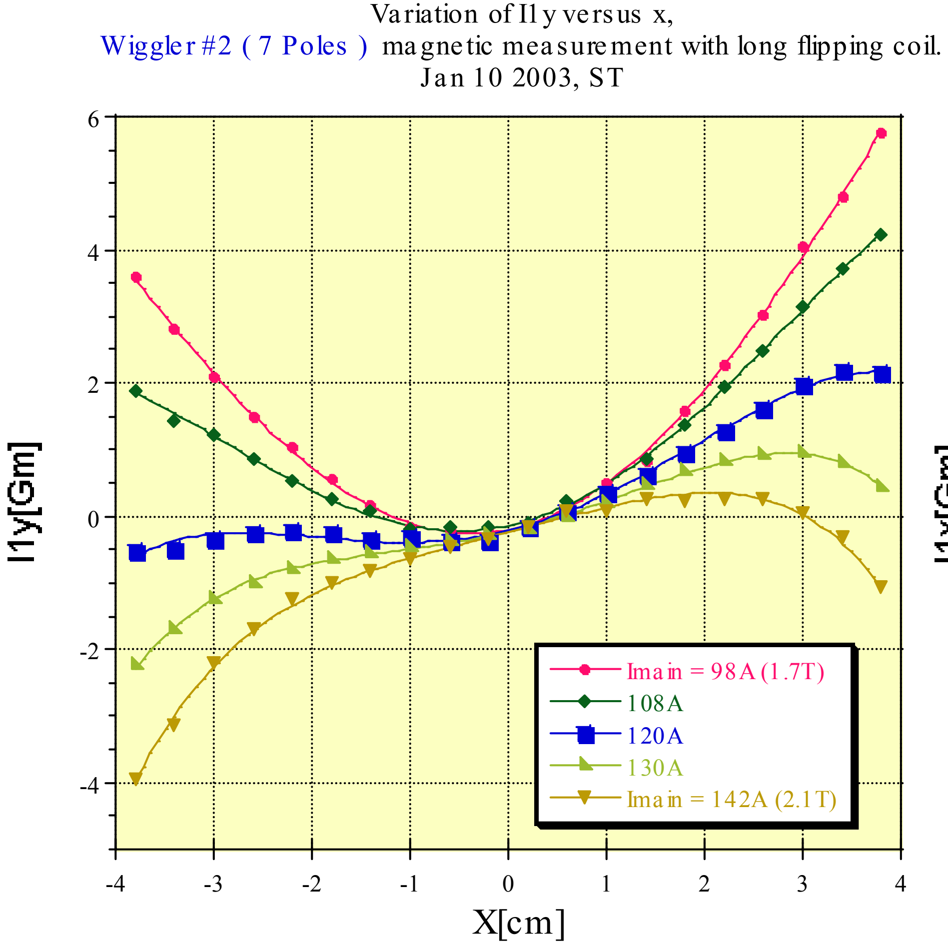
Hall probe measurements of Wiggler #7

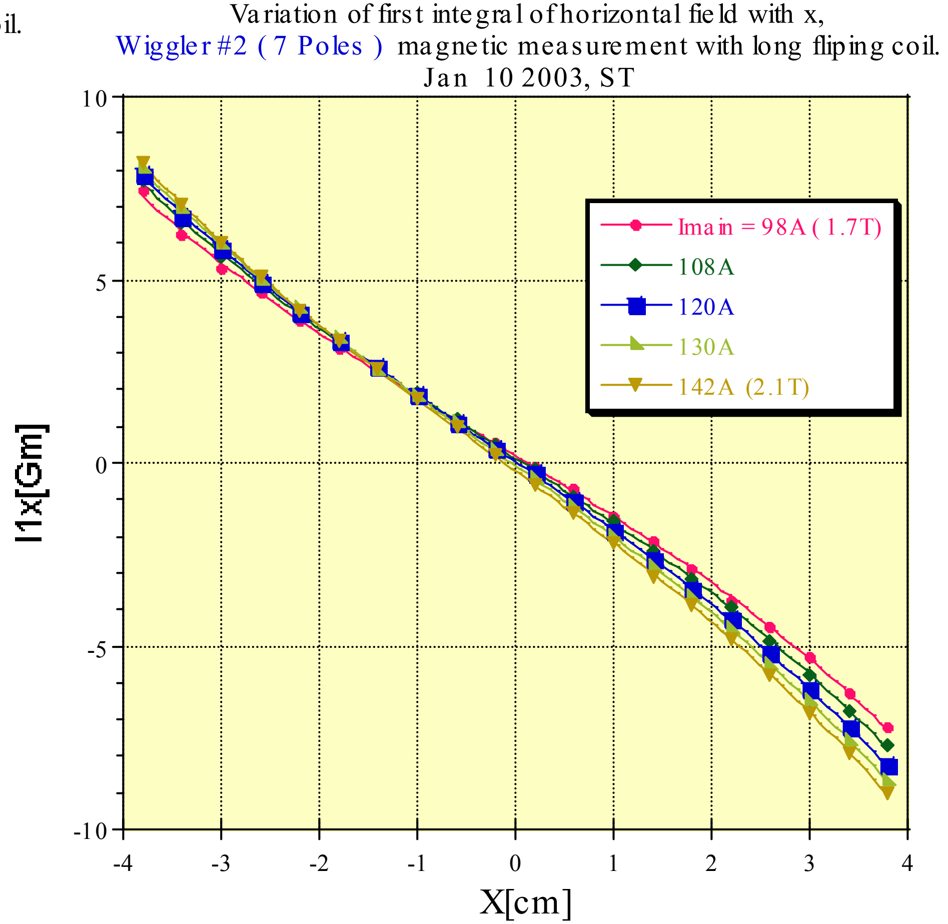
Transverse scan (horizontal) across centerline of pole.



(Plot from A.B. Temnykh)

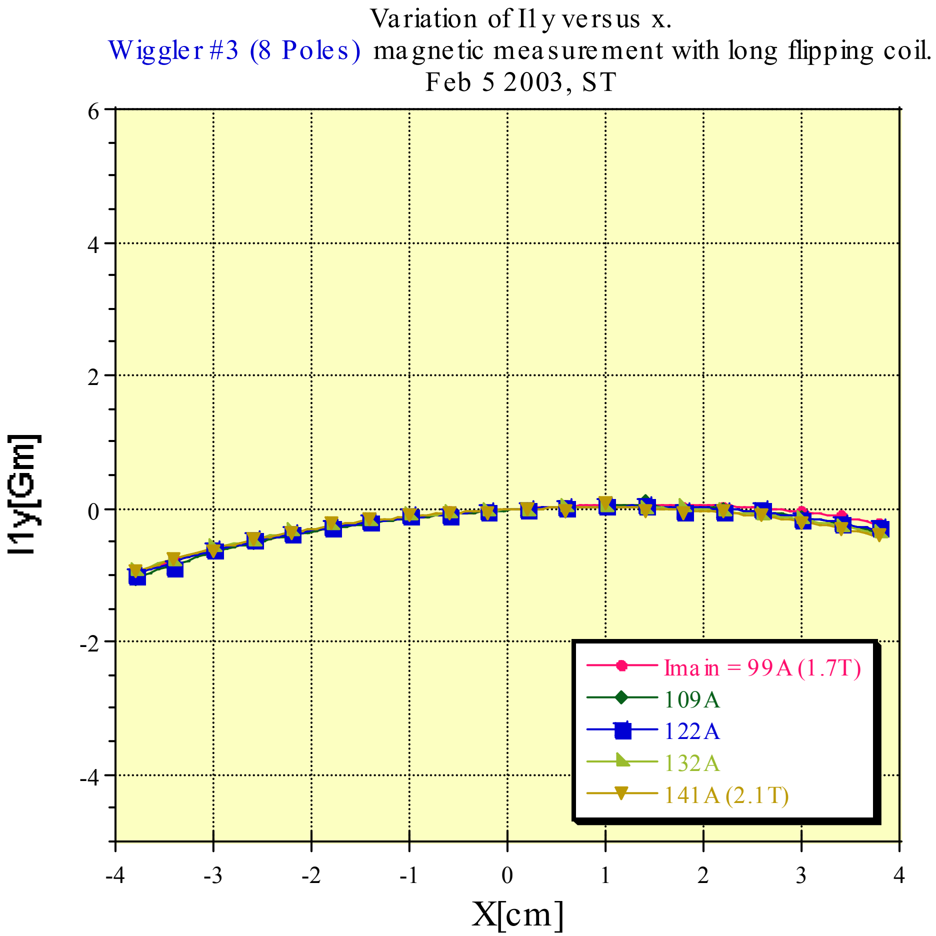
Magnetic field performance: wiggler #2 (7p) (straight line meas.)

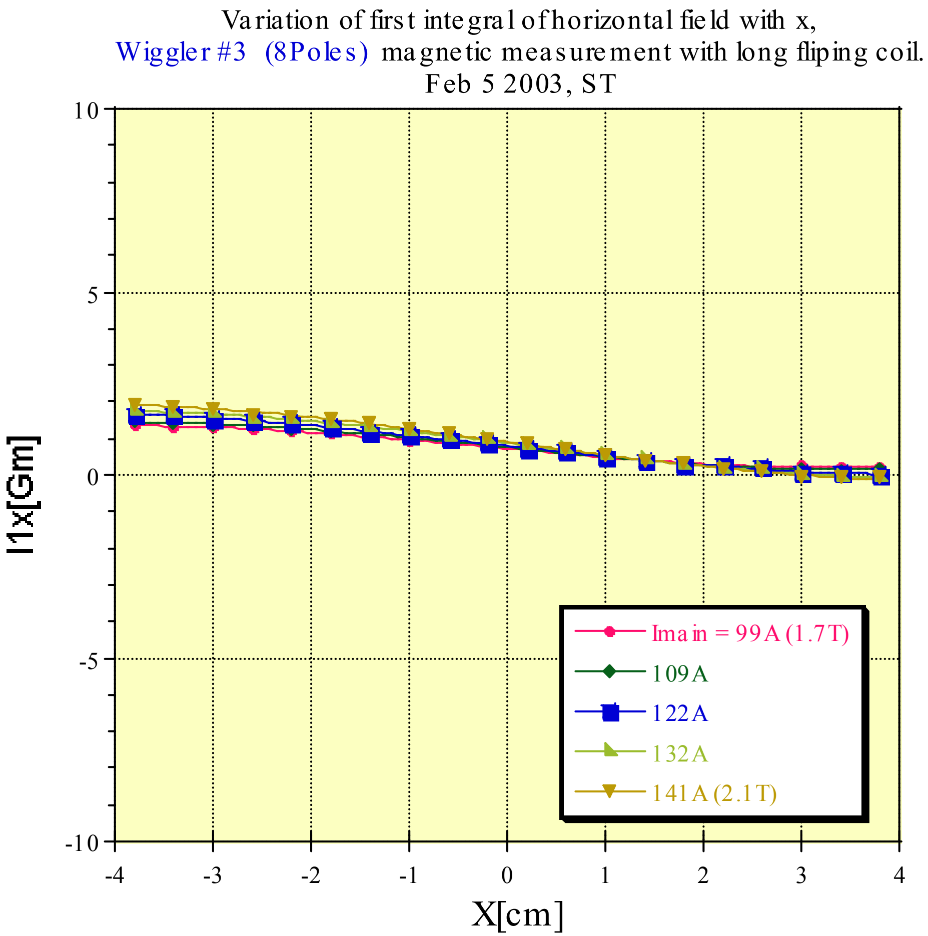




(slide from A.B. Temnykh)

Magnetic field performance: wiggler #3 (8p) (straight line meas.)

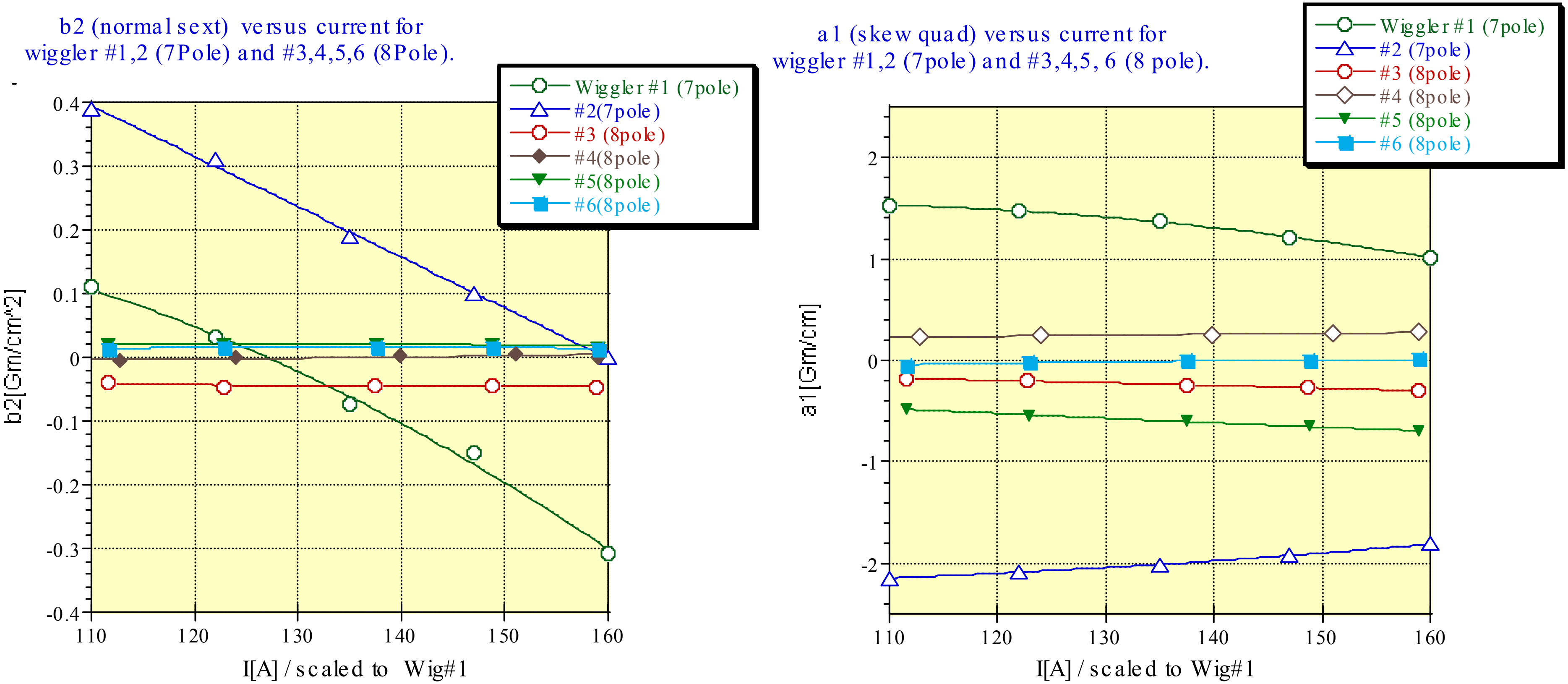




(slide from A.B. Temnykh)

Field error summary

b2 (normal sextupole) and a1(skew quad) components vs current for wigglers #1,2,3,4,5,6 (straight line meas.)



(slide from A.B. Temnykh)

Optics with wigglers

Wigglers are first order lattice elements !
(vertical focusing same as normal quad – 0.1 tune shift each)

Also must include nonlinear effects (pretzel).

Need a "simple" model of wigglers for creating optics, and a detailed symplectic model for tracking.

First tried Runga-Kutta integration of 3-D field points calculated by TOSCA/Mermaid but non-symplectic properties were problematic.

Attempt symplectic integration* but too slow for calculations

After much work with choice of basis vectors, fitting, now use Taylor map – 5^{th} order for optics creation, 7^{th} order for d.a. tracking. (Symplectic integration is also an option for tracking.)
(for details see ICFA BDP Newsletter No. 31)

* Y. Wu et al. PAC2001

Optics creation

Pretzel orbit creates separate optics for e+, e-.

CESR optics are created* by treating all focusing elements independently - optimization process.

Wiggler transfer functions modeled with 5th order Taylor map.

Constraints must be satisfied simultaneously for e+, e-.

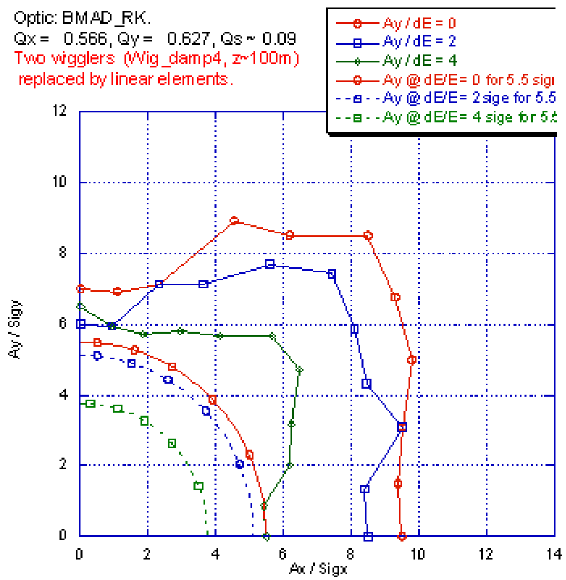
Requires tuning by expert.

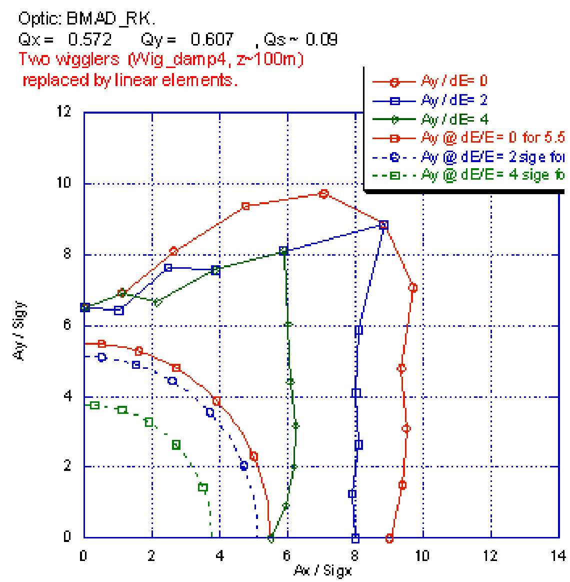
*See ICFA Beam Dynamics Newsletter No. 31
http://wwwslap.cern.ch/icfa/

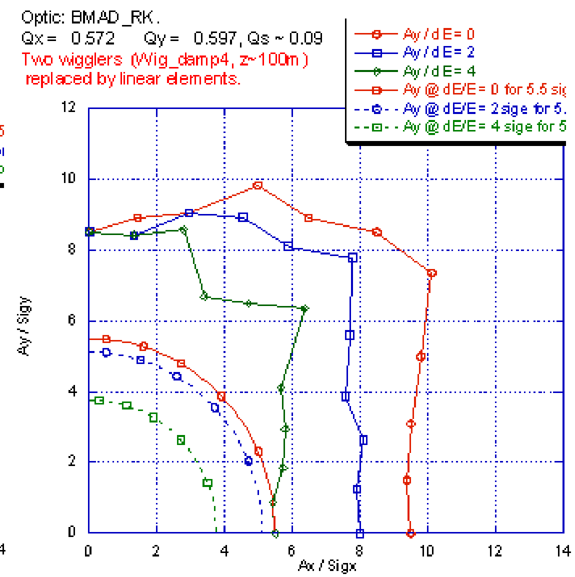
Dynamic Aperture

To provide readily usable results d.a. analysis uses:

- Actual machine physical apertures
- Full pretzel orbit
- Actual 6-pole distribution
- Full wiggler nonlinearities (7th order map or integ.)
- Magnet nonlinearities as deemed relevant
- Parasitic beam-beam interactions (optional)







Machine Studies

6 wigglers (half of final number) were installed on one side of CESR during the Summer, 2003

First priority in CESR-c machine studies was to confirm the effects of wigglers on beam dynamics.

Measurements have also been made on:

- Bunch lengthening
- Beam energy spread
- Vertical beam size vs. betatron tune
- Instability thresholds
- Parasitic crossing effects

The majority of machine studies time was spent on housekeeping, developing instrumentation, tuning injection and luminosity, and recovering from stupid mistakes.

Beam-based measurements of wiggler fields

(1) Effective wiggler fields can be explored by measuring betatron tune shift vs. beam x,y position.

Sextupoles must be turned off in region of closed orbit bump through wiggler.

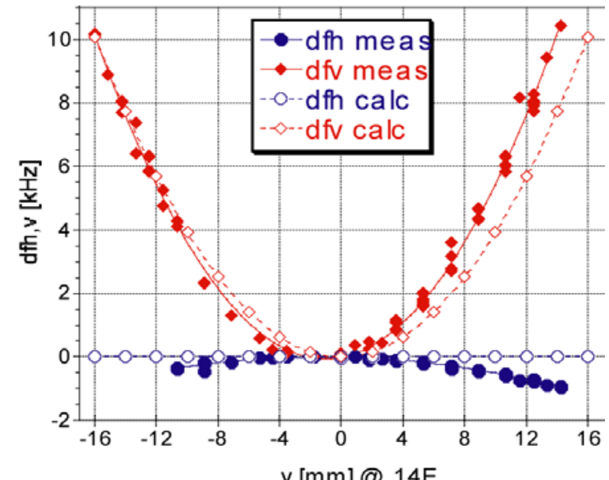
(2) The vertical beam size is recorded as betatron tunes are swept through a region.

Reveals resonance lines brought forth by wiggler nonlinearities

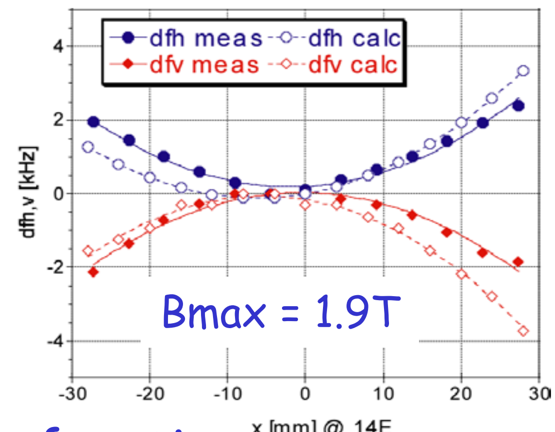
Beam based characterization: Nov 2002, one wiggler optics, wiggler #1 (7p)

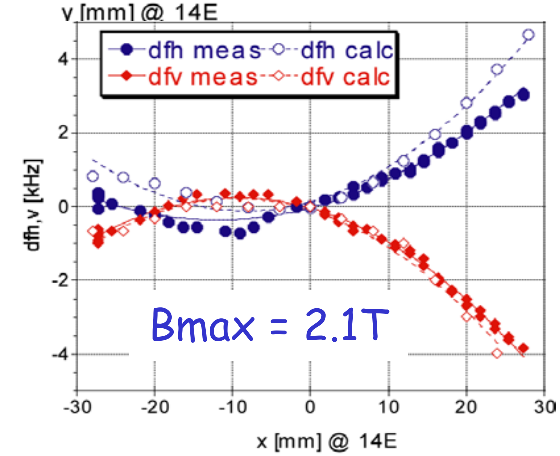
Wiggler generated tune dependence on beam position

Measured and calculated* dependence of vertical/horizontal tune versus vertical beam position in wiggler. Bmax = 2.1T



Measured and calculated* dependence of vertical/horizontal tune versus horizontal beam position in wiggler.



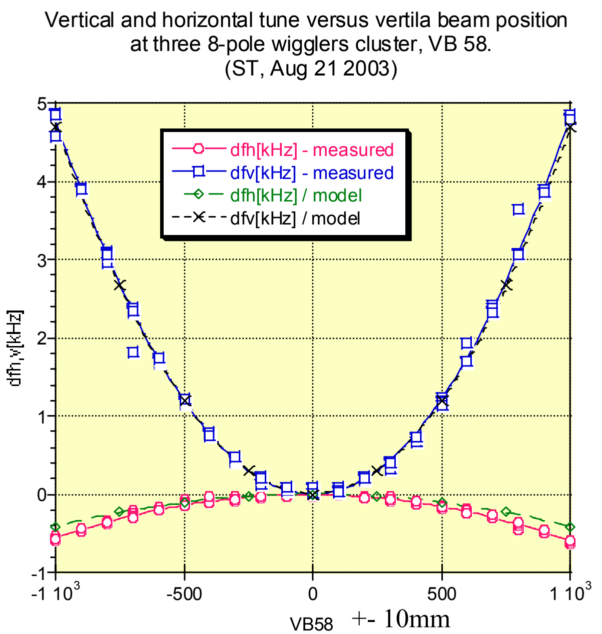


* from the wiggler transfer function

(slide from A.B. Temnykh)

Beam based characterization: Aug 2003, 6 wigglers optics (4x8p + 2x7p)

- Three 8-pole wigglers group test using local orbit distortion

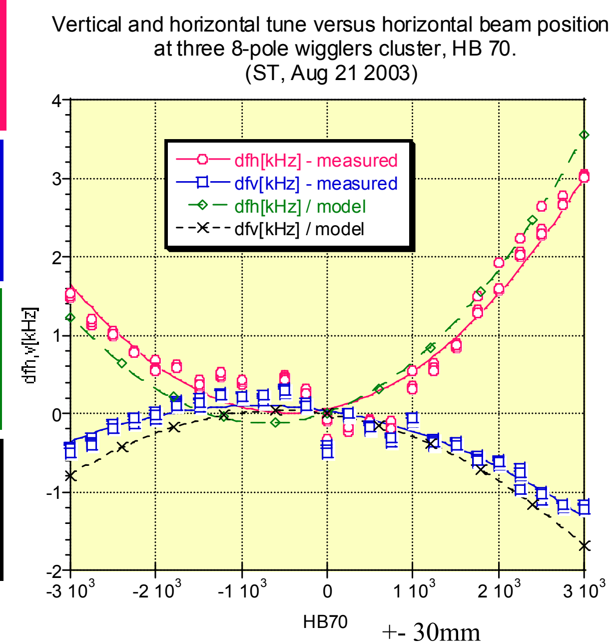


Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	-0.0022588
M1	-1.9531e-05
M2	-5.7511e-07
R	0.99344

Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	0.00051815
M1	1.983e-05
M2	4.8043e-06
R	0.99829

Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	0.0035498
M1	0
M2	-4.1385e-07
R	0.99994

Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	0.015455
M1	-2.6666e-06
M2	4.6909e-06
R	0.99997



Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	0.059295
M1	0.00022736
M2	2.5315e-07
R	0.95831

Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	0.033497
M1	-0.00016229
M2	-9.7726e-08
R	0.9352

Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	0.014522
M1	0.00038242
M2	2.6541e-07
R	0.99985

Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	-0.0040093
M1	-0.00015152
M2	-1.3727e-07
R	0.99997

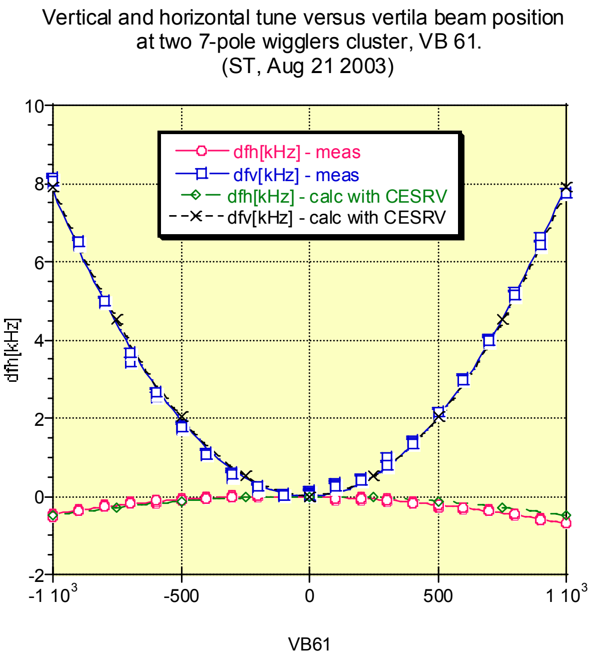
Measured and calculated tune versus vertical beam position in 18E wiggler cluster.

Measured and calculated tune versus horizontal beam position in 18E wiggler cluster.

(slide from A.B. Temnykh)

Beam based characterization: Aug 2003, 6 wigglers optics (4x8p + 2x7p)

- Two 7-pole wigglers group test using local orbit distortion.

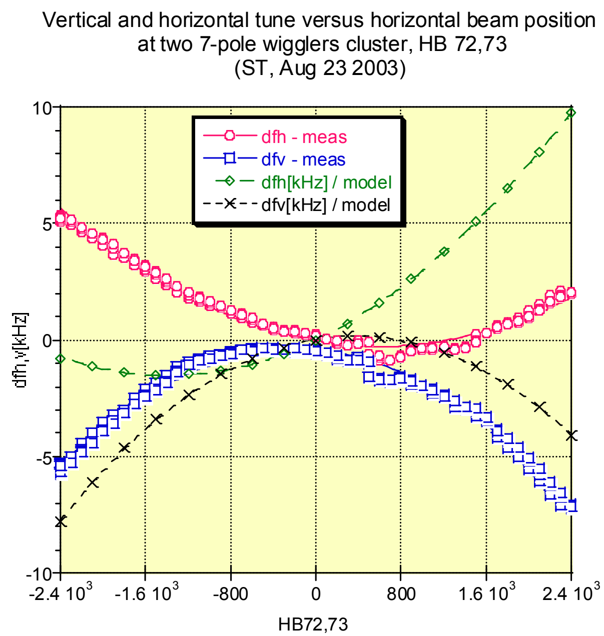


Y = M0 + M1*x + ... M8*x 8 + M9*x 9	
M0	-0.0045218
M1	-0.00012701
M2	-5.6615e-07
R	0.99225

Y = M0 + M1*x + ... M8*x 8 + M9*x 9	
M0	0.0032263
M1	7.5994e-05
M2	7.9232e-06
R	0.99856

Y = M0 + M1*x + ... M8*x 8 + M9*x 9	
M0	0.0027273
M1	2.6667e-06
M2	-4.9455e-07
R	0.9998

Y = M0 + M1*x + ... M8*x 8 + M9*x 9	
M0	0.036017
M1	0
M2	7.8816e-06
R	0.99995



Y = M0 + M1*x + ... M8*x 8 + M9*x 9	
M0	-0.03094
M1	-0.00079741
M2	6.5755e-07
R	0.98883

Y = M0 + M1*x + ... M8*x 8 + M9*x 9	
M0	-0.43478
M1	-0.00037765
M2	-1.0147e-06
R	0.99443

Y = M0 + M1*x + ... M8*x 8 + M9*x 9	
M0	0.0063468
M1	0.0021941
M2	7.8328e-07
R	0.99999

Y = M0 + M1*x + ... M8*x 8 + M9*x 9	
M0	0.036718
M1	0.00076332
M2	-1.0314e-06
R	0.9999

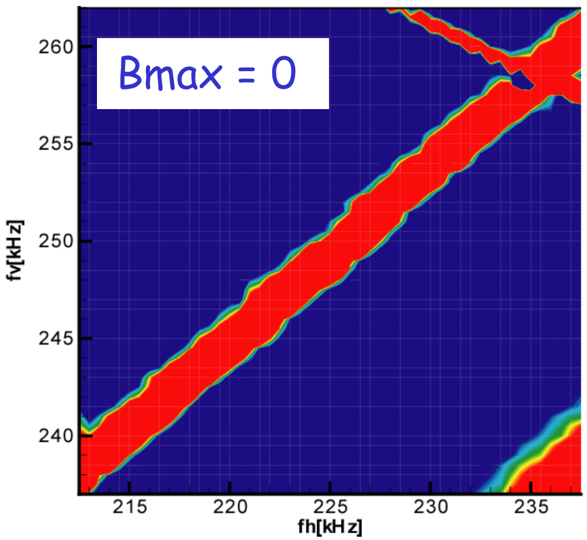
Measured and calculated tune versus vertical beam position in 14E wiggler cluster.

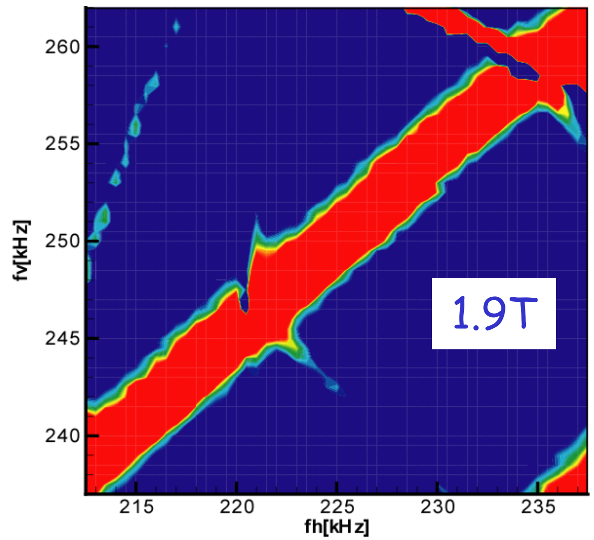
Measured and calculated tune versus horizontal beam position in 14E wiggler cluster.

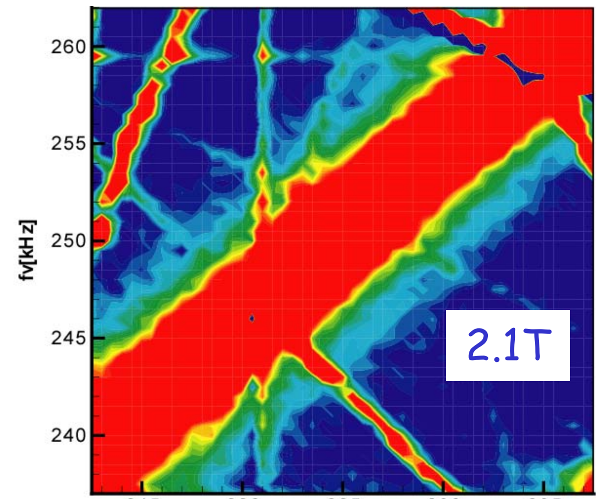
(slide from A.B. Temnykh)

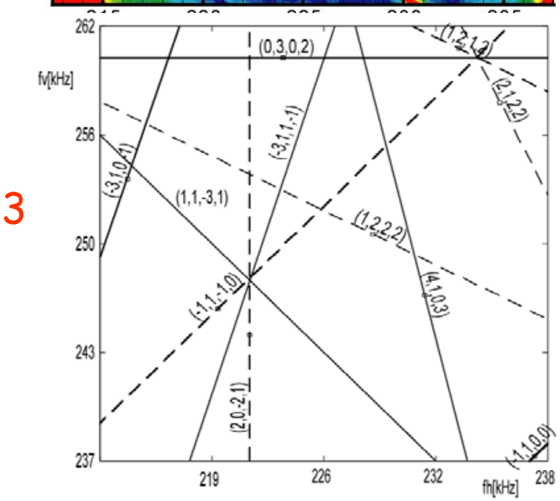
Beam based characterization:
Nov 2002, one wiggler optics, wiggler#1 (7p)

2D tune scan: vertical beam versus tune, evaluation with wiggler field









Oct. 14 2002, Optics: 1843MeV_1WIG_R3_OT, fs = 25kHz

Observed resonances

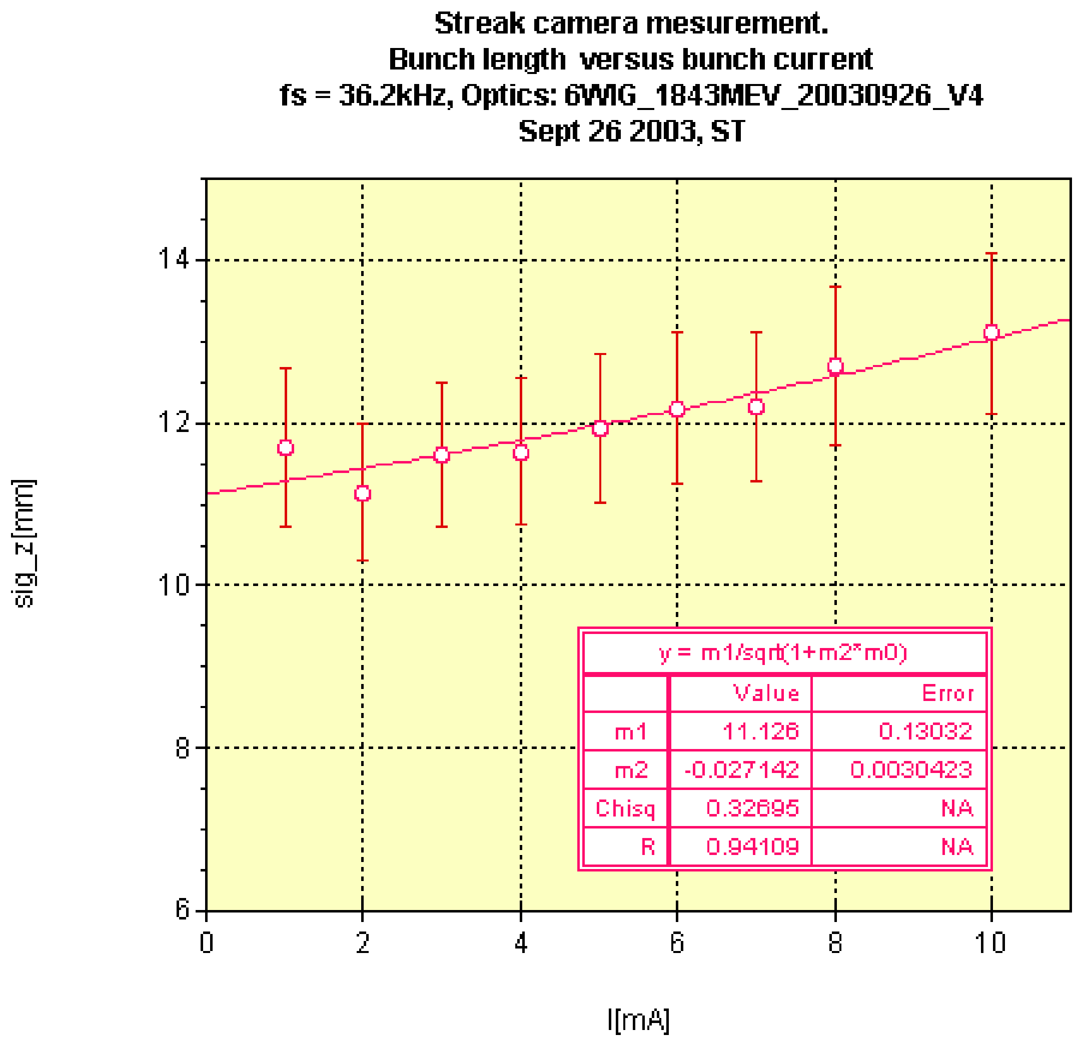
Wiggler OFF: -fh+fv = 0, -fh+fh-fs=0, fh+2fv + fs = 2f0, Pmax = 3

Wiggler ON: -3fh+fv= -f0, fh+fv-3fs=f0, 3fv=2f0, fh+2fv+2fs=2f0, 4fh+fv=3f0, 2fh+fv+2fs=2f0, 2fh-2fs=f0 and -3fh+fv+fs=-f0, Pmax = 5

(slide from A.B. Temnykh)

Bunch Lengthening

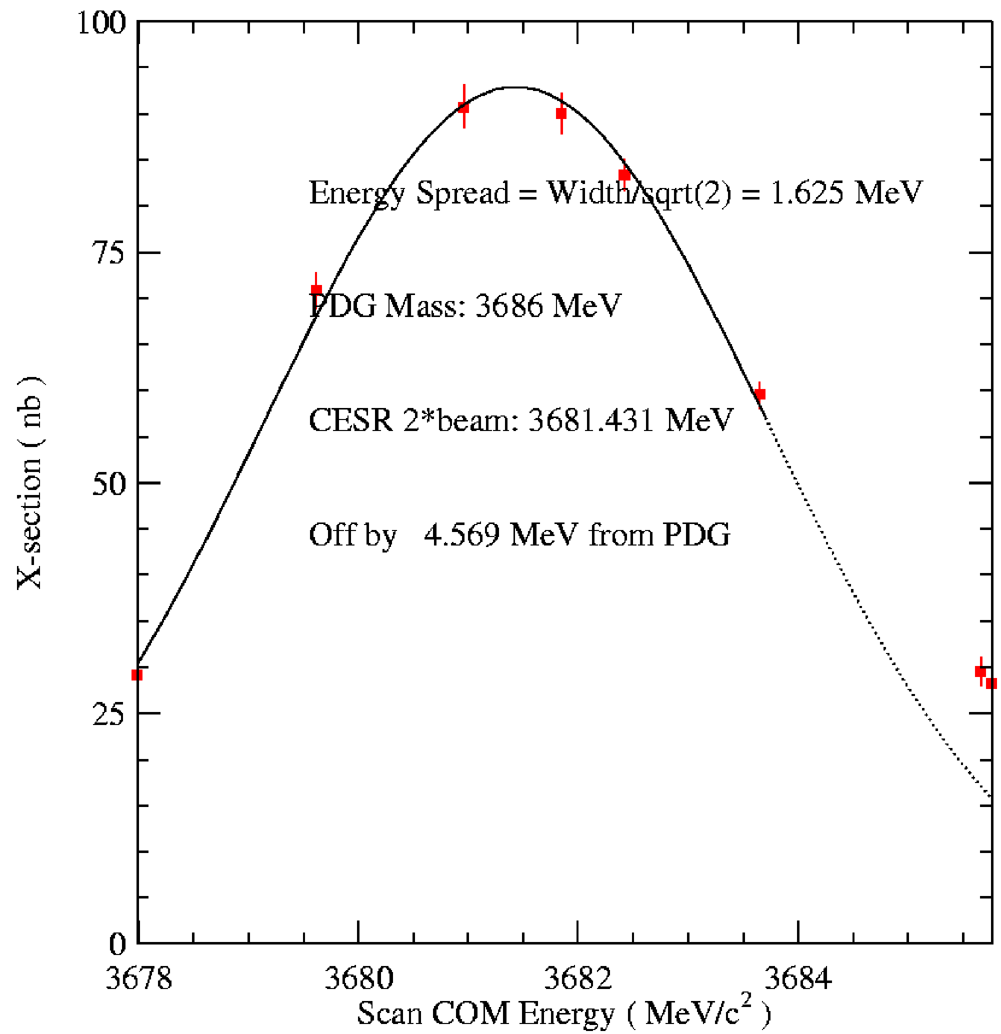
Streak camera measurements show bunch length consistent with calculations and Z/n ~ 0.22 Ω



Beam Energy Spread

A quick scan across the $\psi(2s)$ narrow resonance indicates a beam energy spread within 1 sigma (from fit) of expected value.

(6 wigglers at 2.1 Tesla)



Instability Threshold

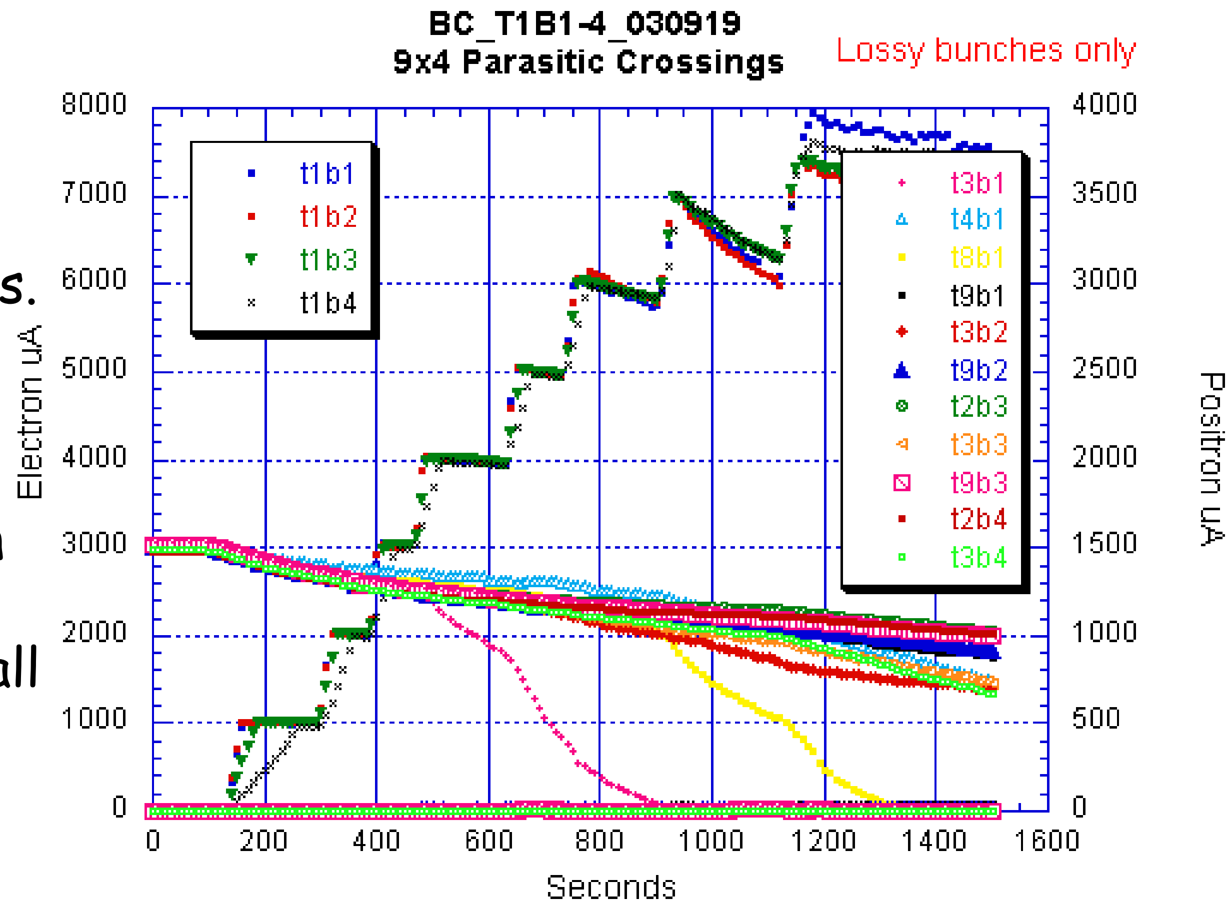
Measurements of longitudinal instability thresholds in differing conditions have been made during the past several years. (no feedback, 27 to 45 bunches). 5.3 GeV value can be scaled by E_{beam}/Tau(E)

Energy	# Wig	Tau(E)ms	I_{thresh}mA	Scaled I_{th}
5.3 GeV	0	11.4	130	130
4.2 GeV	0	24	40	49
1.88 GeV	0	255	3	2
1.88 GeV	1	110	10	5
1.88 GeV	6	45	35	12

Parasitic Crossing Effects

Procedure: Fill small current in one beam (2E10/bunch) leaving empty selected bunches.

Fill these selected bunches in opposite beam (avoiding head-on collisions) while recording currents of all bunches.



Luminosity performance

At the end of two 10-day commissioning periods the luminosity at ψ'' is ~> 2E31 /cm^2 /sec with 45 mA/beam

(~8% of design goal)

Performance is limited primarily by:

- Poorly tuned machine – arc & IR (ξ_V ~ 0.015, β^*_v~13mm)
  - ⇒ understand & correct IR & arc optics, tune, reduce β^*_V
- Injection with parasitic crossings
  - ⇒ improve optics, injector performance
- Insufficient damping
  - ⇒ install 6 more wigglers in Spring 2004 – (will also restore symmetry to optics)

Plans

A 2 month HEP run at low energy will begin later this month.

In early Spring, 2004, we will install the remaining 6 wigglers in symmetric positions in the CESR arc.

Running will resume in early Summer, alternating between dedicated HEP and x-ray production runs.

Conclusion

- ✓ The CESR-c wigglers are working superbly

  Damping is effective, nonlinear effects minimal

  Operators say tuning is "like at 5.3 GeV"

- ✓ We have so far not seen any anomalies in beam behavior from the lumped radiation

  (80% of s.r. from wigglers)

- ✓ Tuning of machine is in its infancy – there is a long way to go.

- ✓ This has been an exciting project with all laboratory work groups contributing.