CESR-c: A Wiggler-Dominated Collider

D. Rice
for the CESR Operations and Technical Support Staff

Cornell University
Laboratory for Elementary-Particle Physics

Outline of talk -

- A quick overview of CESR
- Low energy operation
- Commissioning and early measurements
- Luminosity performance and analysis
- Performance improvement efforts
- Conclusion and future

CESR History

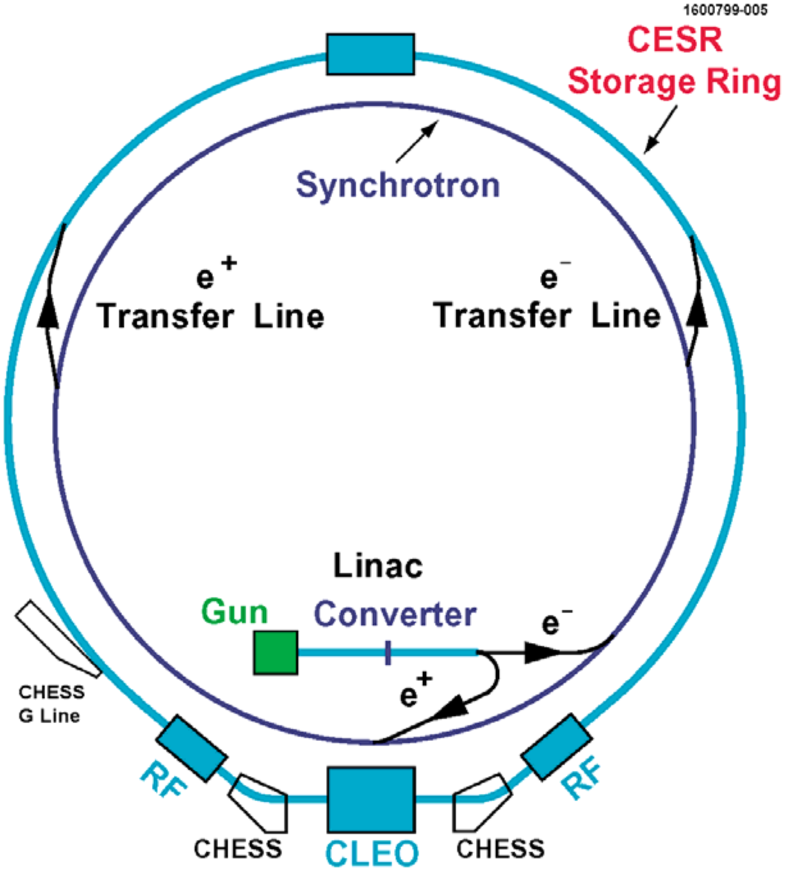
A brief history of CESR

- Operation began October, 1979
    - Design 8 GeV
    - 100mA/beam in single bunch
    - 2 interaction regions.
- A succession of upgrades led to record performance at 5.3 GeV E_{beam}
    - Mini- → micro-beta IR optics
    - Full energy, multi-bunch injection
    - Multi-bunch w/ “Pretzel” & crossing angle orbit separation
    - SC RF cavities
    - Beam diagnostic and optics design tools

CESR Layout

Principal Features:

- 768 m Circumference
- 1.5-6 GeV beam energy
  (8 GeV design energy @ 2x100 mA)
- I_{beam} > 350 mA @ 5.3 GeV
- 45 bunches each e+, e-
- Full energy, multibunch injector



>300 mA/minute, no energy ramping,
minimal changes in storage ring conditions

CESR Layout (2)

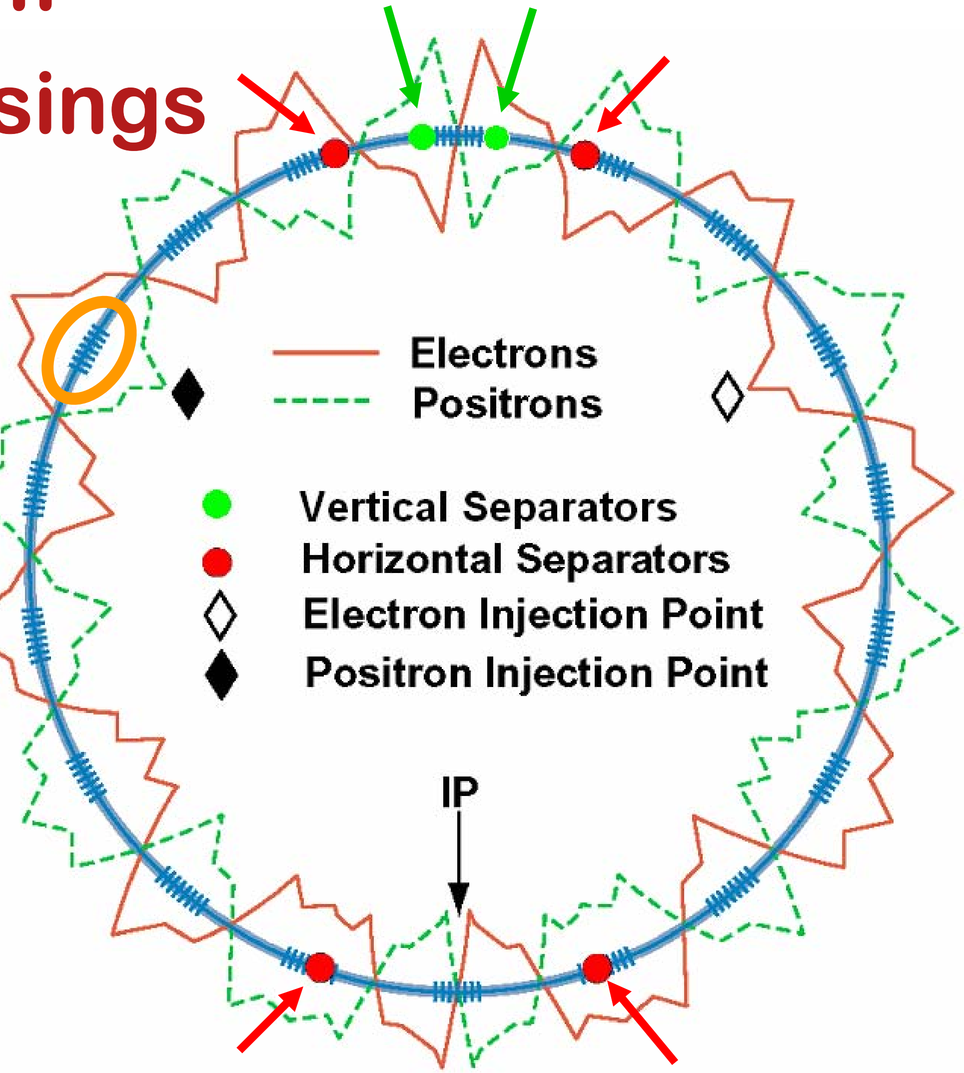
45 bunches per beam

⇒ 89 parasitic crossings

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

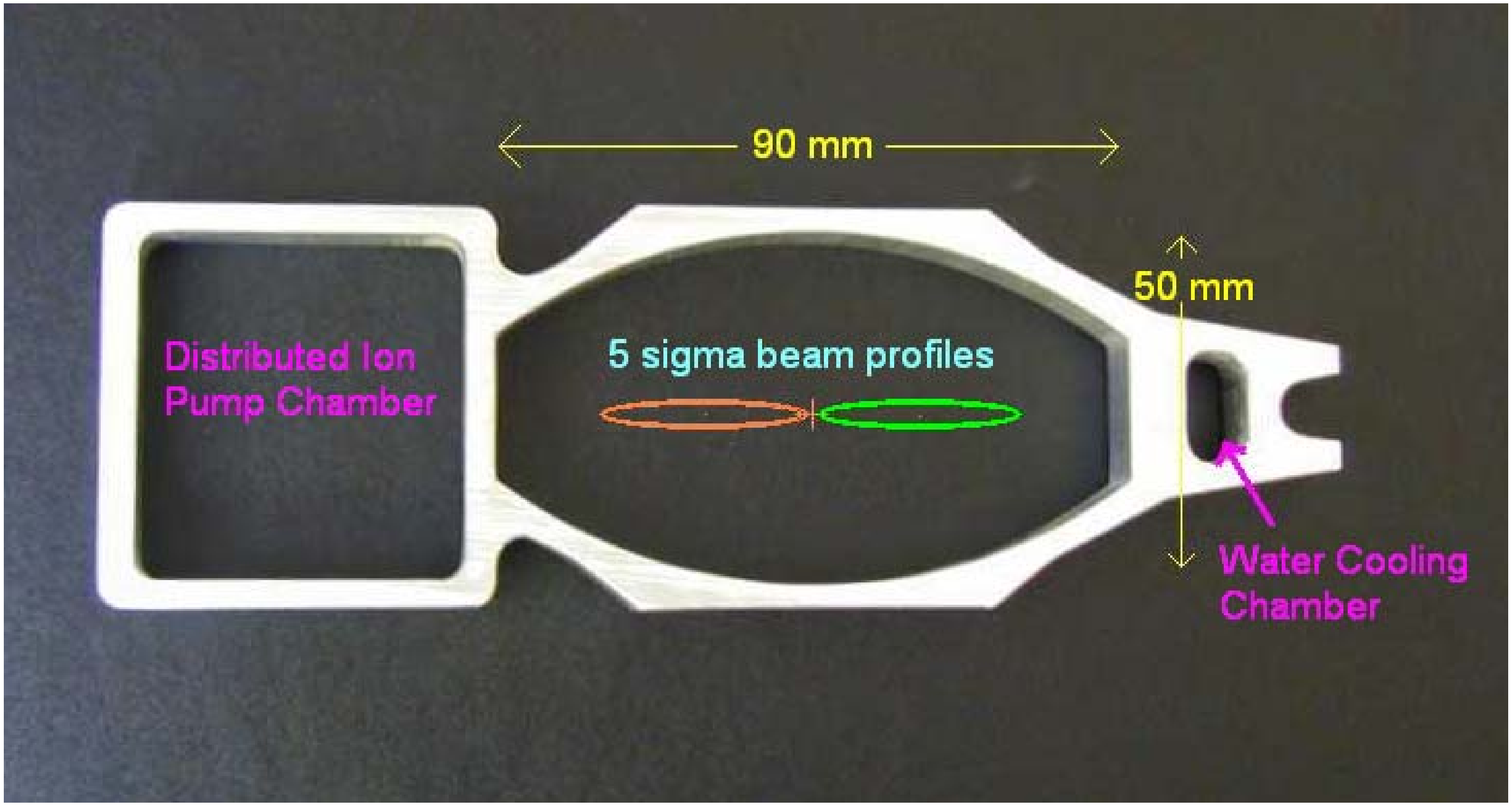
2 vertical electrostatic separators avoid collision in North IR.

Electrons and positrons collide with ±~3.5 mrad horizontal crossing angle



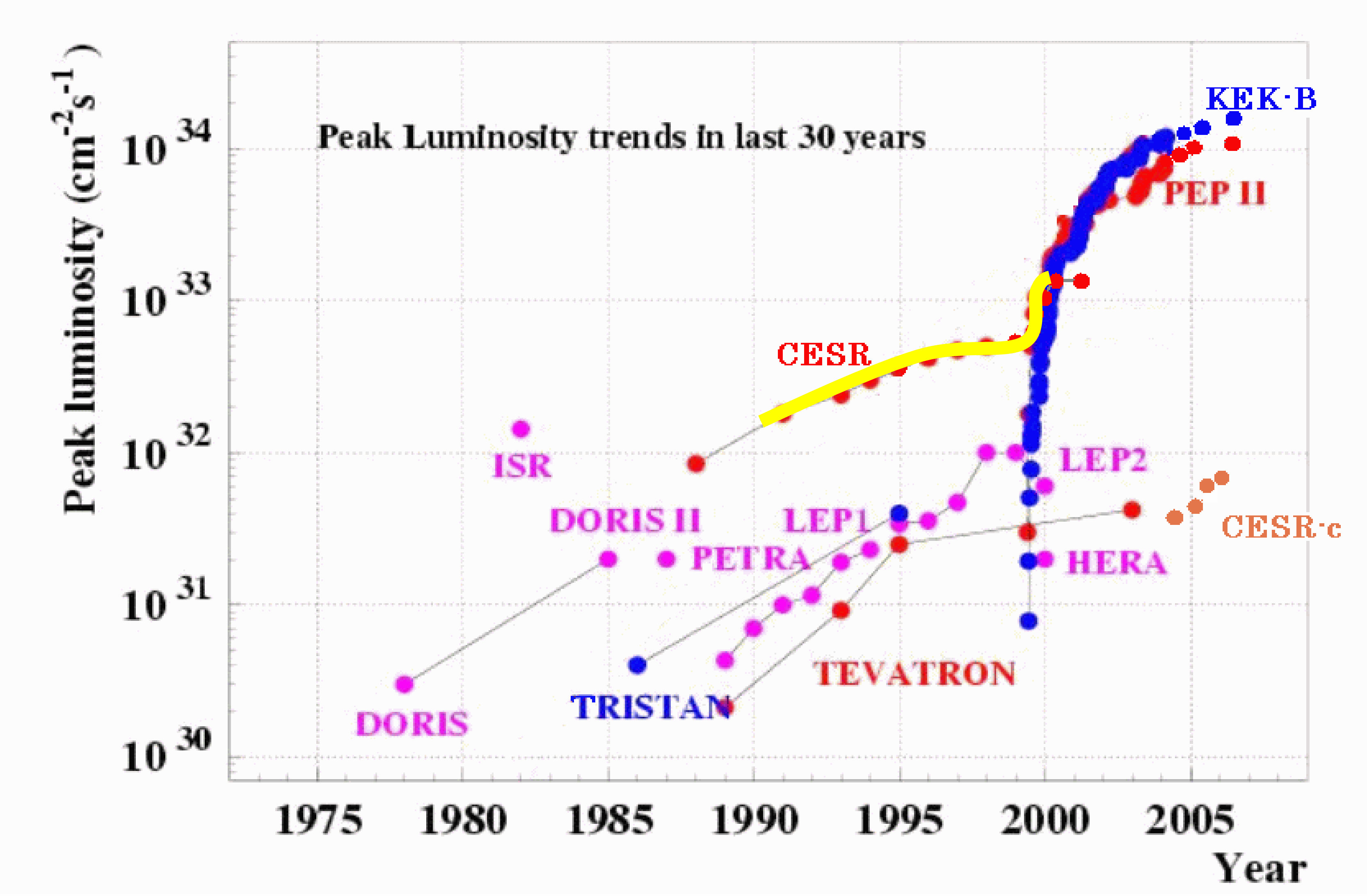
Pretzel Beams in CESR

Center-center spacing of beams at parasitic crossing points in CESR is typically 2x5 σ_H



CESR-c Today

Peak Luminosity Trends of e⁺e⁻ Colliders



Charm Physics

By 2001 it was clear that the CLEO detector's capabilities could be better utilized for CHARM physics – especially given a sufficient event sample.

This event sample with the energy resolution, particle ID, and solid angle coverage of the CLEO detector would provide an unprecedented level of precision.

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CESR-c Conversion Objectives

Optimize performance in the 1.5 to 2.5 GeV beam energy range while maintaining full 5.3 GeV (SR operation, potential Υ physics) capability.

Potential liabilities in low energy operation?

• Damping time increase	**22 → 500 ms (luminosity, injection, beam instabilities)**
• Emittance reduction	**220 → 30 nm-rad**
• Magnet field quality	**Measured - OK**
• SC IR magnets	**Newly installed – performance?**
• Electrostatic Separators	**Field errors will scale**
• Injector Emittance	**0.12 → $0.6\mathrm{x}10^{-6}$ m-rad**
• Parasitic Crossings (up to 89!)	**Scale with E? τ_{damp}?**

CESR-c Conversion

Radiation driven parameters (damping time, emittance) can be controlled:

Parameters:	5.3 GeV	1.88 GeV	/ 1.88 GeV w/wigglers:
• Horiz. emittance	230	30	/ 120-220 nm-rad
• Damping time	22	500	/ 52 ms
• Energy spread	6	2	/ 8.6 $\times 10^{-4}$ σ_E/E_o

Scaling in a wiggler-dominated storage ring:

Damping Time	Horizontal Emittance	Energy Spread
$\tau \propto \frac{1}{L_W B_W^2}$	$\varepsilon_X \propto B_W H_W$	$\frac{\sigma_E}{E_0} \propto \sqrt{B_W}$

Wiggler Effects on Optics

•Optics effects from an Ideal Wiggler

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

vertical focusing only –

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

Each wiggler shifts Q_Y by about 0.1 integer: $\Delta Q_Y \approx \frac{L_W < \beta_Y > B_W^2}{7.3x10^{-5} \gamma^2}$

•Optics effects from a Real Wiggler

Variation of mid-plane field across the pole face:

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

Wiggler Parameters

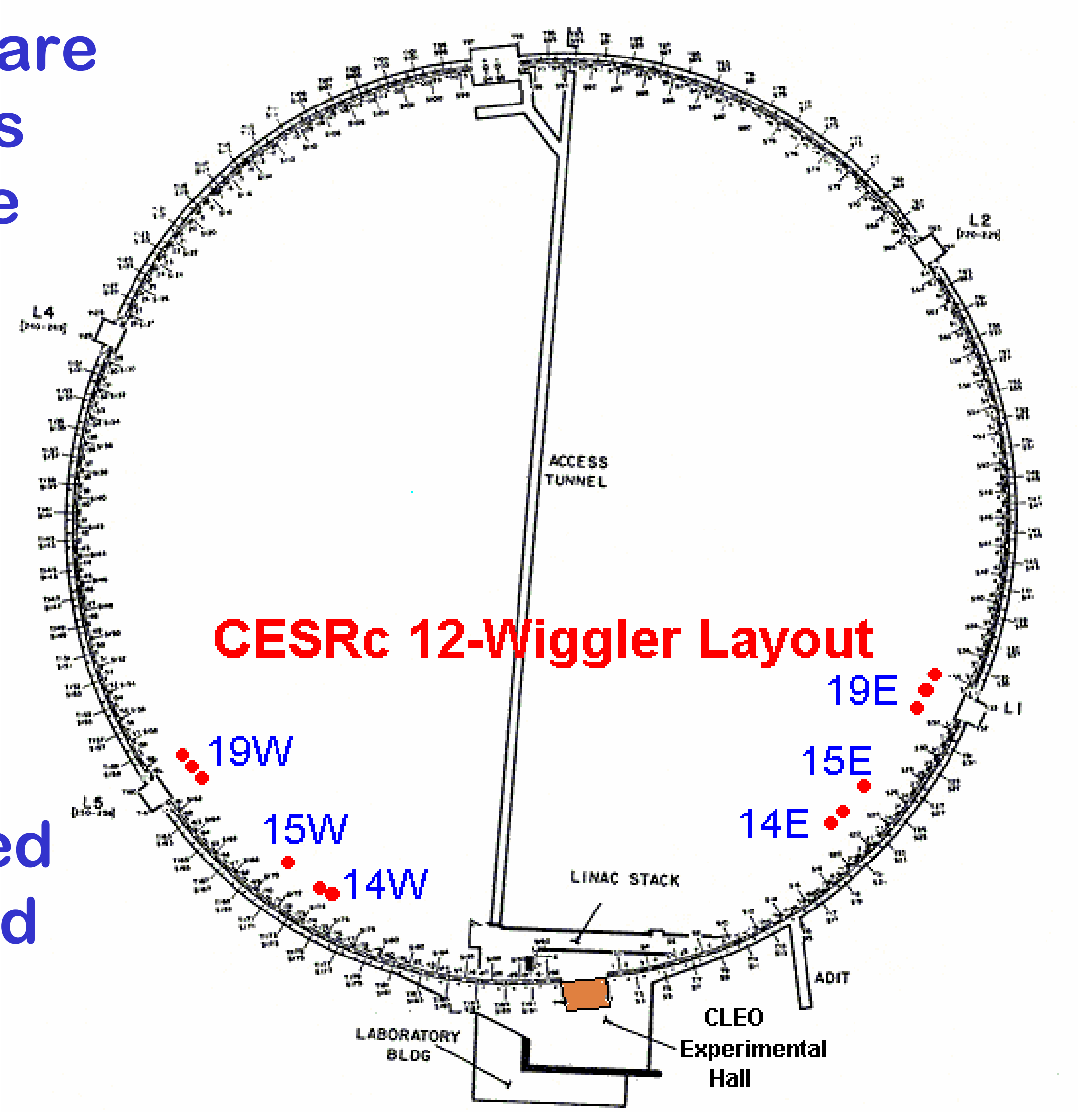
Parameter	Value
Technology	Superferric
Peak Field	1.7-2.1 T
Wiggler Length	1.3 m
Number of wigglers	12
Field period	40 cm
Transv. width of poles	23 cm
Number of poles	6-20 cm, 2-10 cm, 2-5 cm
Pole gap	7.6 cm
Operating Current (2.1 T)	185 A
Wire operating margin	50%

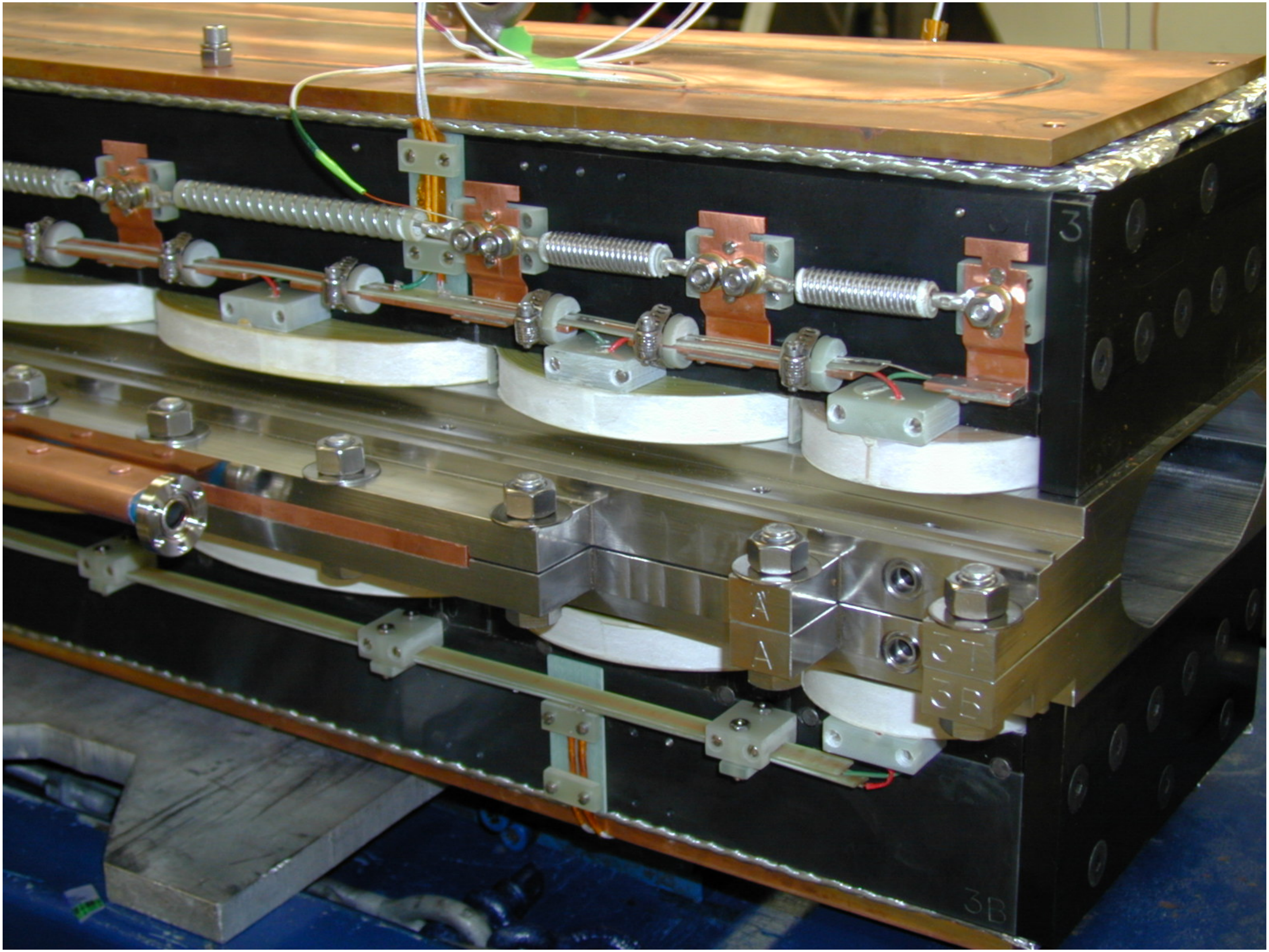
CESR-c Wiggler Layout

12 damping wigglers are distribute in 6 clusters according to available space in CESR.

Cryogen distribution, optics manipulation

A rigorous testing program characterized wiggler properties and assured minimal construction errors.

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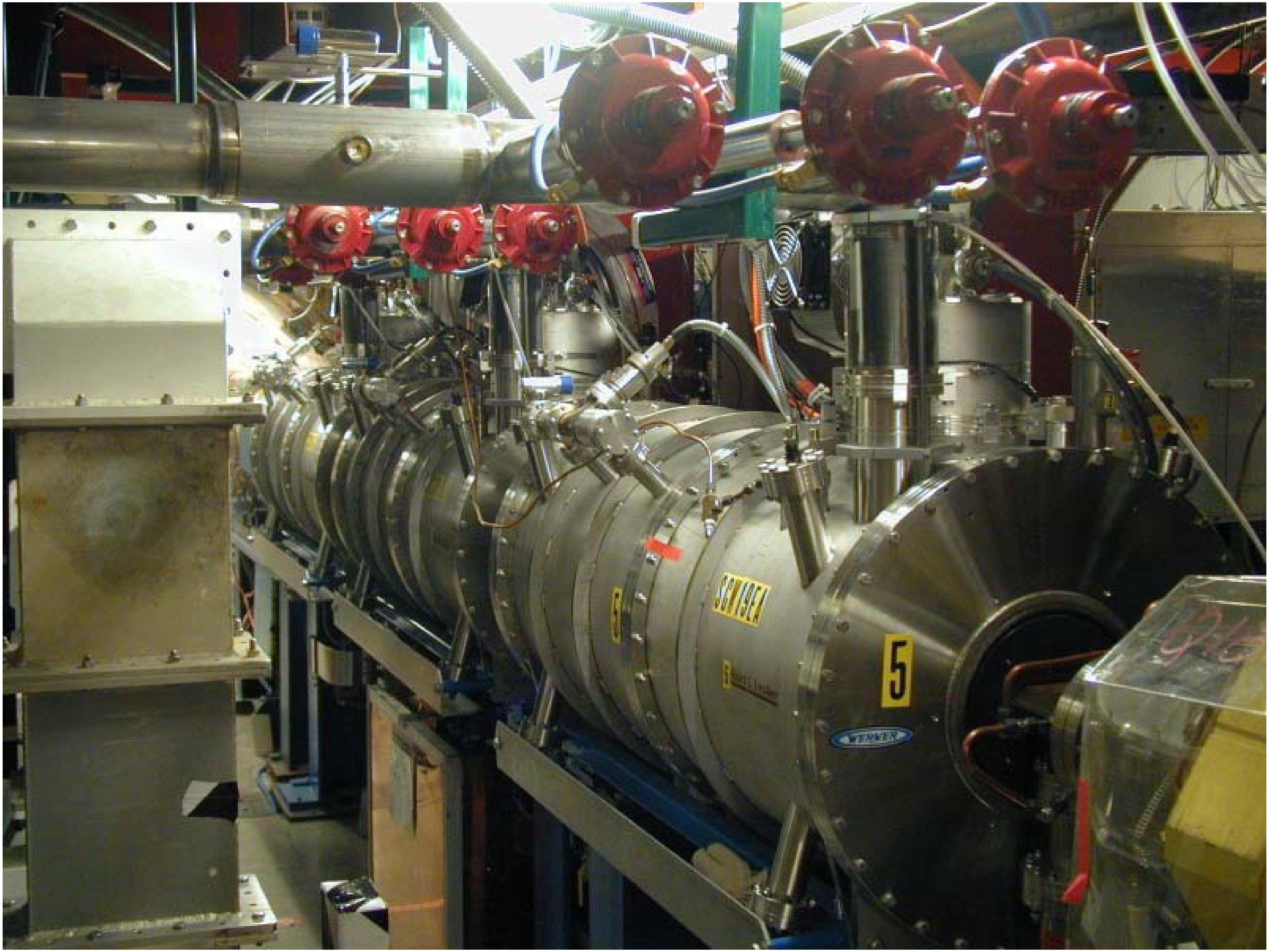
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Beam-based measurement of wigglers

- Wiggler model uses calculated 3D field map
  → 3rd order Taylor map.
  "ICFA Beam Dyn.Newslett.31:48-52,2003" by D.Sagan, et. al.

- Predict ΔQ and other parameters based on BMAD subroutine library:
  http://www.lns.cornell.edu/~dcs/bmad (D. Sagan)

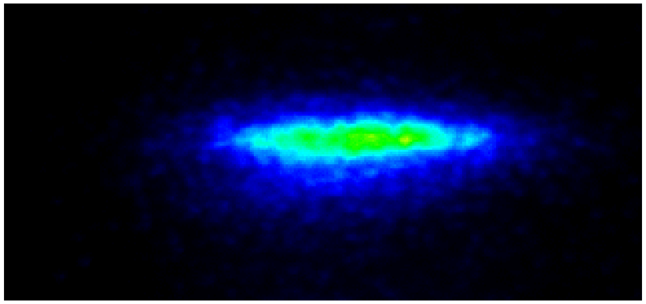
CESR-c Commissioning - Wigglers

Compare measured data with values calculated using the model:

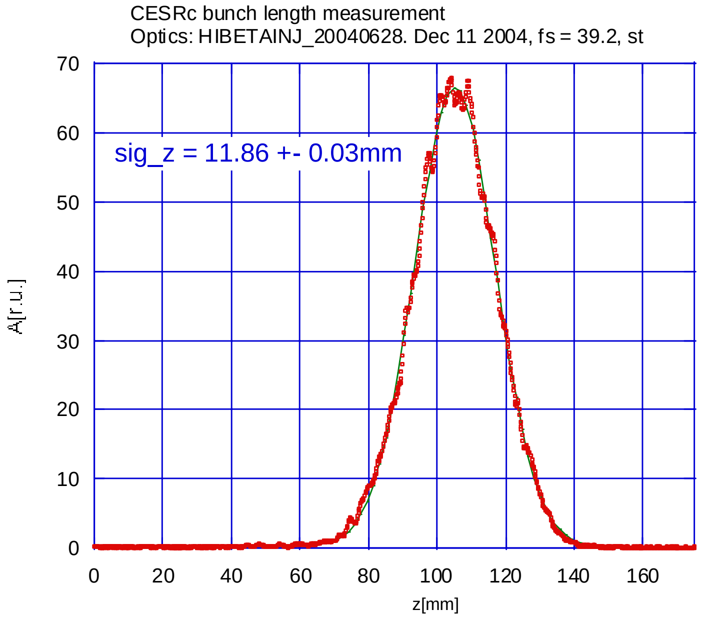
- Bunch length ⇒ beam energy spread
- ΔQ with wiggler field
- ΔQ with beam position in wiggler
- ΔQ with amplitude (octupole moment)

Bunch length ⇒ Energy spread

Streak camera measurement:



Energy spread derivable from bunch length measurement using α_P and Q_S



Measured σ_Z = 11.86 mm yields

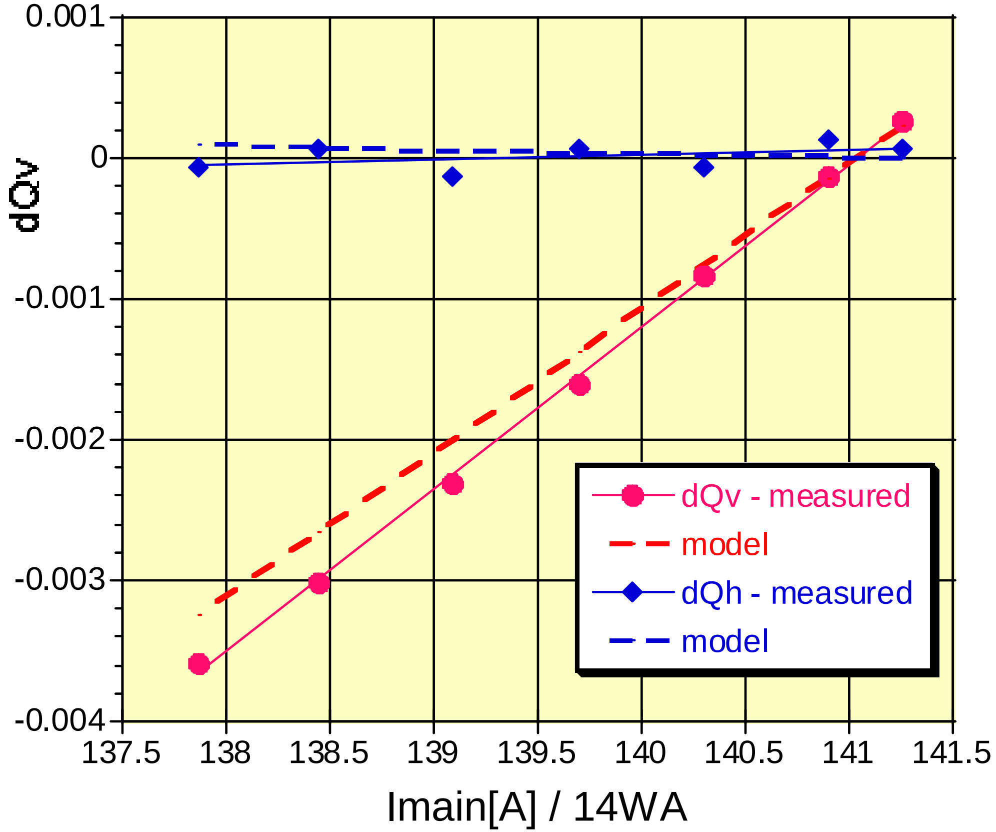
$\sigma_E/E_0 = 8.62\text{x}10^{-4}$ vs. predicted

$\sigma_E/E_0 = 8.47\text{x}10^{-4}$

Figures & data from A. Temnykh,
Wiggler Workshop, Frascati Feb. 2005

Tune shift vs. wiggler current

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



Tune variation with wiggler (14WA) current.

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

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

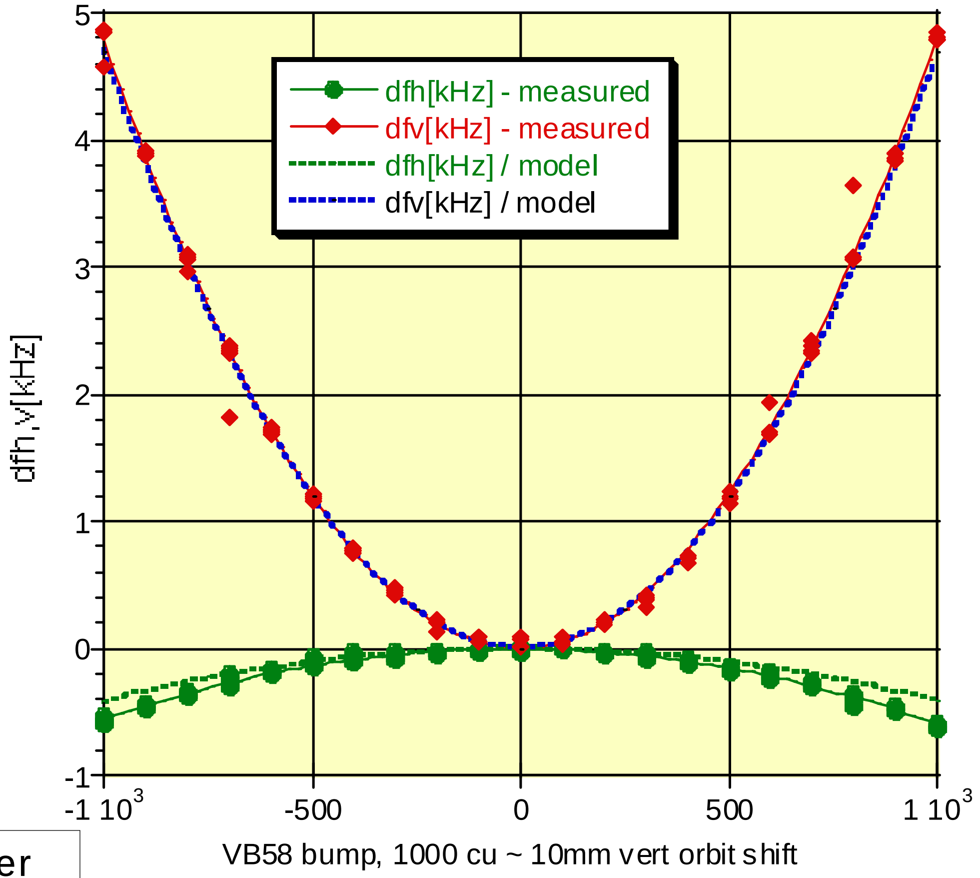
	Value	Error
dQh/dI (model)	-2.97e-5	6.7e-13
dQh/dI (measl)	3.5e-5	2.9e-5
dQv/dI (model)	0.00102	2.0e-11
dQv/dI (meas)	0.00115	1.67e-05

Slide from A. Temnykh, Wiggler Workshop, Frascati Feb. 2005

Tune shift vs. vertical beam position in wigglers

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

Vertical and horizontal tune versus vertila beam position at three 8-pole wigglers cluster, VB 58.
Aug 21 2003



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

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

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

Slide from A. Temnykh, Wiggler Workshop, Frascati Feb. 2005

Tune shift vs horizontal beam position in wigglers

$$\int_{Wiggler} B_y ds \approx -\frac{1}{2} L_W A_x \boxed{\frac{dB_y}{dx}}$$

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

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

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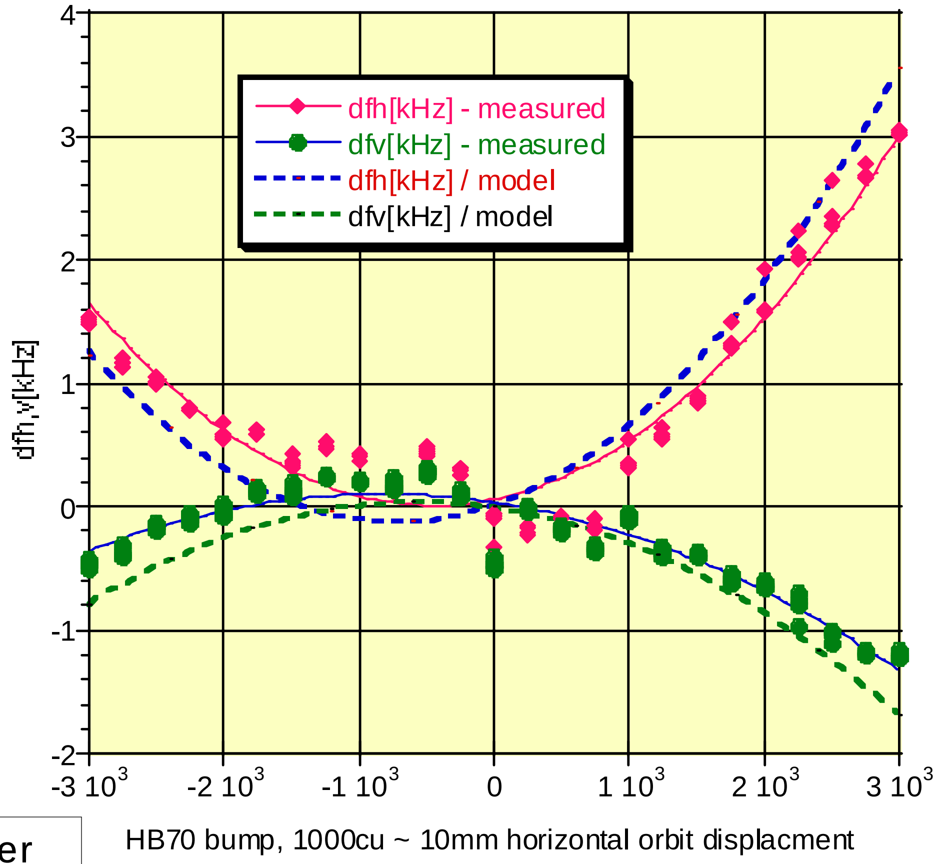
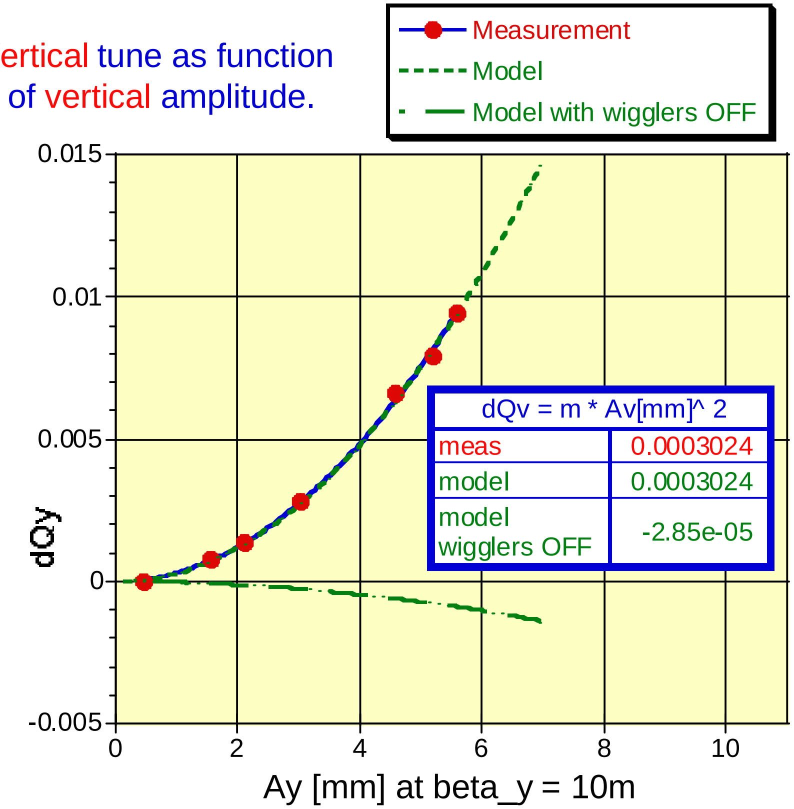


Slide from A. Temnykh, Wiggler Workshop, Frascati Feb. 2005

Tune vs amplitude

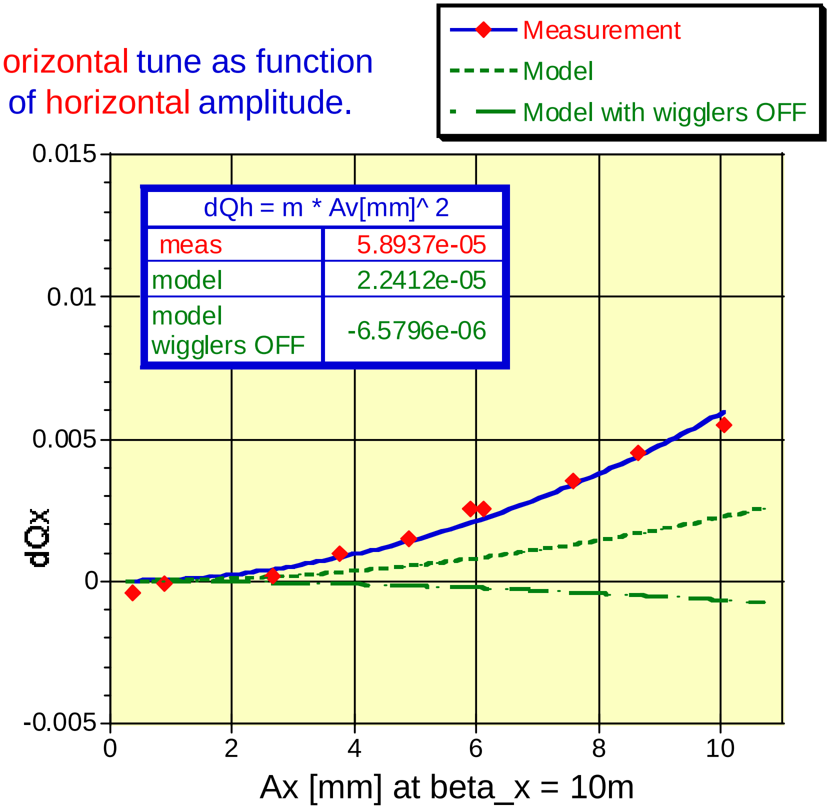
Measured and calculated dependence of vertical/horizontal tune versus vertical/horizontal amplitude

Vertical tune as function of vertical amplitude.



dQv = m * Av[mm]^ 2	
meas	0.0003024
model	0.0003024
model wigglers OFF	-2.85e-05

Horizontal tune as function of horizontal amplitude.



dQh = m * Av[mm]^ 2	
meas	5.8937e-05
model	2.2412e-05
model wigglers OFF	-6.5796e-06

Slide from A. Temnykh, Wiggler Workshop, Frascati Feb. 2005

Instabilities and Feedback

- Dipole Instabilities
  - **Longitudinal coupled bunch - Dominant Instability**
    - **Instability threshold ranges from 23-47 mA for e+: 9 trains of 1-5 bunches & 8 trains of 3-4 bunches**
      (c.f. thresholds 2.6-3 mA with wigglers off)
    - **Have stored 150 mA e+ with & without feedback**
    - **Wideband & narrowband (1x Q_S) feedback stabilizes**
  - **Horizontal & Vertical**
    - **No observed instabilities**
    - **Growth rates vs I_{beam} not measured**
    - **Generally operate with wideband feedback at low gain**
- Quadrupole etc. Instabilities
  - **None observed up to 150mA single beam**

Slide from M. Billing, July, 2005

Commissioning - Ion / EC effects

Ion effects –

- have reduced number of bunch trains from 9 to 8 to provide a clearing gap.

ECE, fast Ion effects –

- both under study *
- ECE clearly observable in single beams
- No clear effects on luminosity performance have been confirmed.

* See R. Holtzapple et al., THPAN087 and
M. Palmer in ECLOUD07

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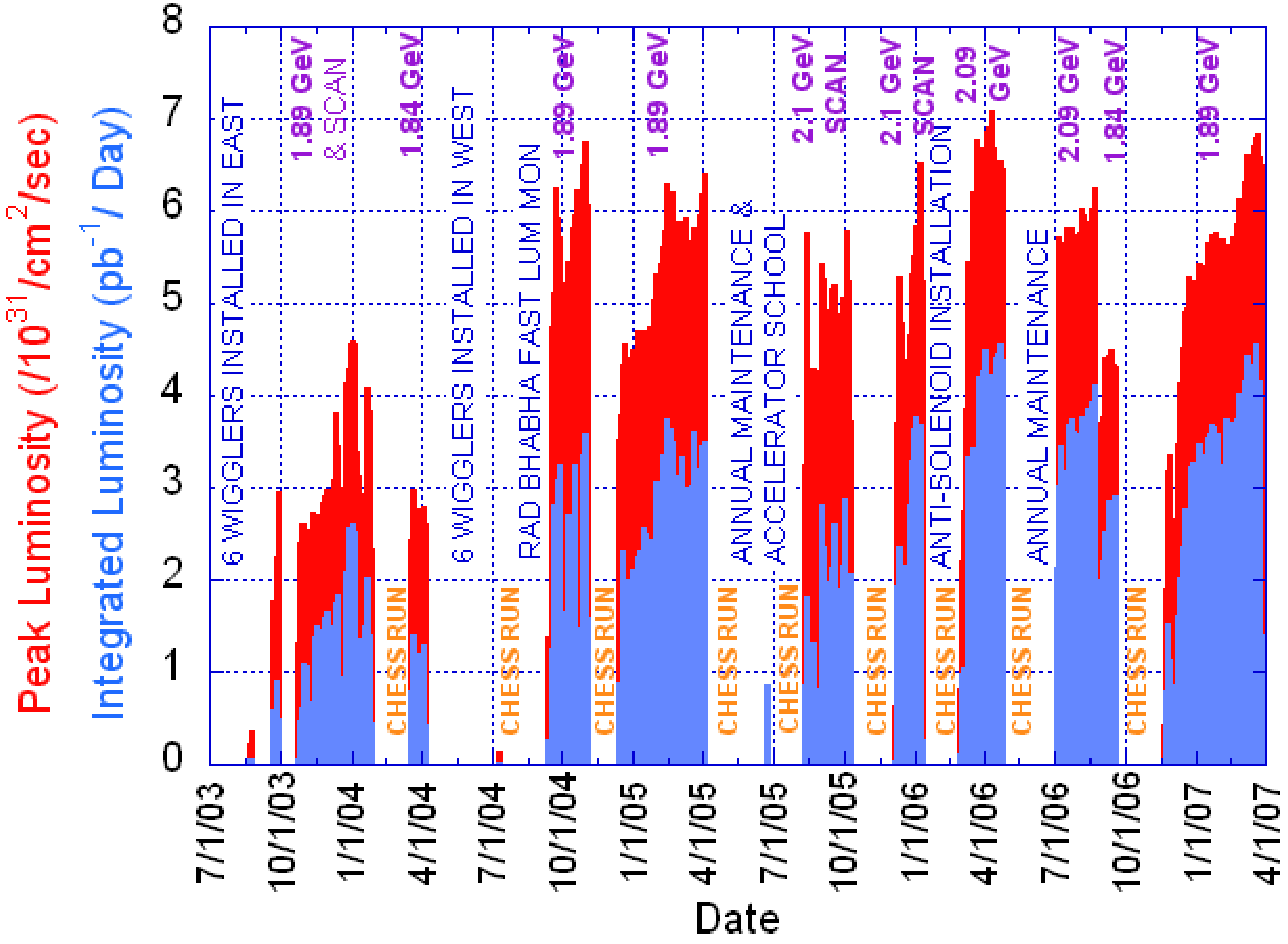
Luminosity Performance



Luminosity Performance - 2

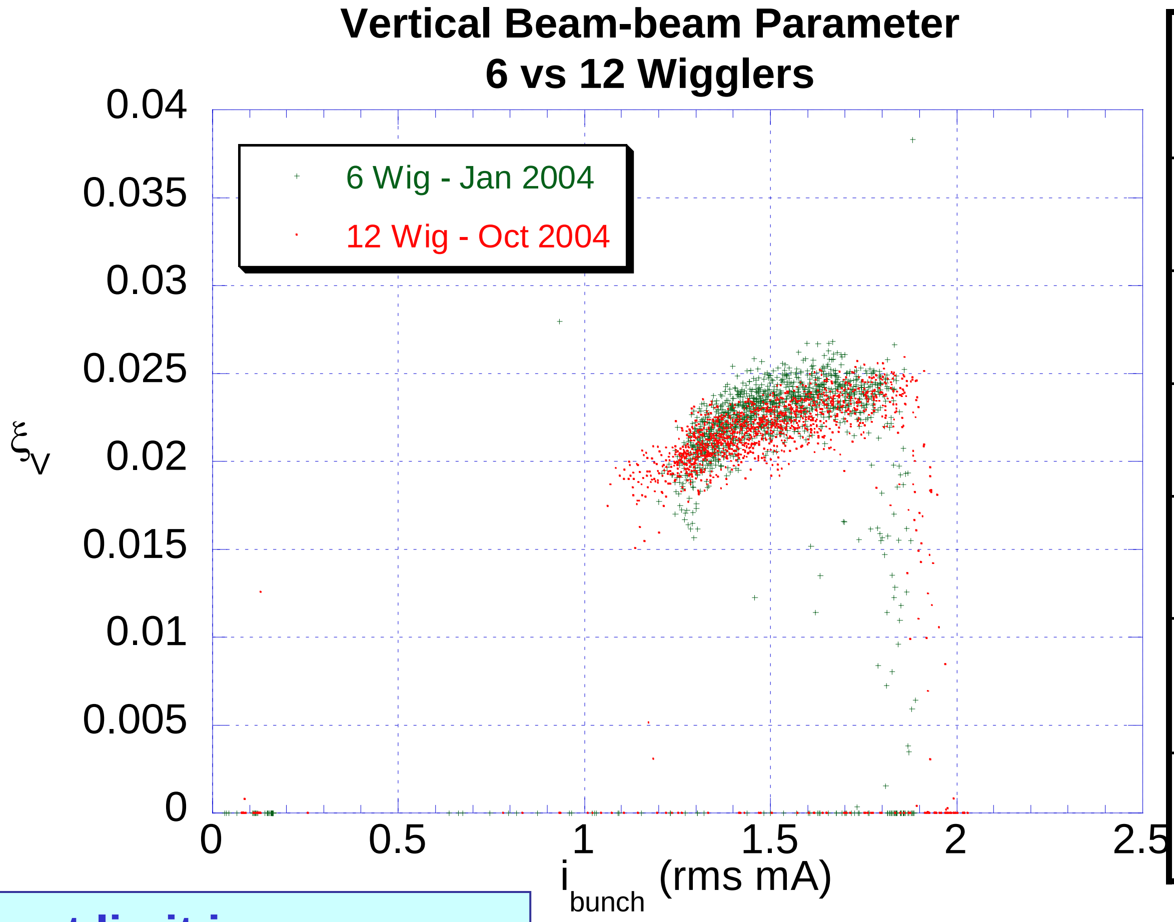
- Observations from luminosity history:
  - CESR-c luminosity approached saturation soon after all 12 wigglers were in place
  - Dedicated and talented hands-on tuning has provided the last 20-30% performance.
  - Peak luminosity varied ±15% from run to run
  - Integrated luminosity has increased more than the peak because of improvements in injection conditions and focus on duty cycle.

Look at specific parameters :

CESR-c Design vs. Actual Parameters

Beam Energy [GeV]	Achieved 5.3	Design 1.88	Achieved 1.88	Achieved 2.09
Luminosity [÷10^{30}]	1250	300	65	73
i_b [mA/bunch]	8.0 x45	4.0 x45	1.9 x40	2.6 x24
I_{beam} [mA]	370	180	75	65
ξ_y	0.06	0.04	0.023	0.03
ξ_x	0.03	0.036	0.028	0.035
σ_E/E_0 [x10^3]	0.64	0.84	0.86	0.86
$\tau_{x,y}$ [ms]	22	55	50	50
B_w [Tesla]	-	2.1	2.1	1.9
β_y^* [cm]	1.8	1.0	1.15	1.3
ε_x [nm-rad]	220	220	140	125

Beam-Beam – ξ_V 6 vs 12 wigglers



	6 Wig	12 Wig
β^*_V	.013	.0116
β^*_H	0.51	0.86
ε_X	160	135
# Bunches	32	40
σ_L	13.6 mm	11.6 mm
σ_E/E_o	8.1 E-4	8.5 E-4

Current limit is deteriorating lifetime as bunch current increases.

6 wiggler data (32 bunches)– Jan. 1, 2004

12 wiggler data (40 bunches)– Oct. 29, 2004

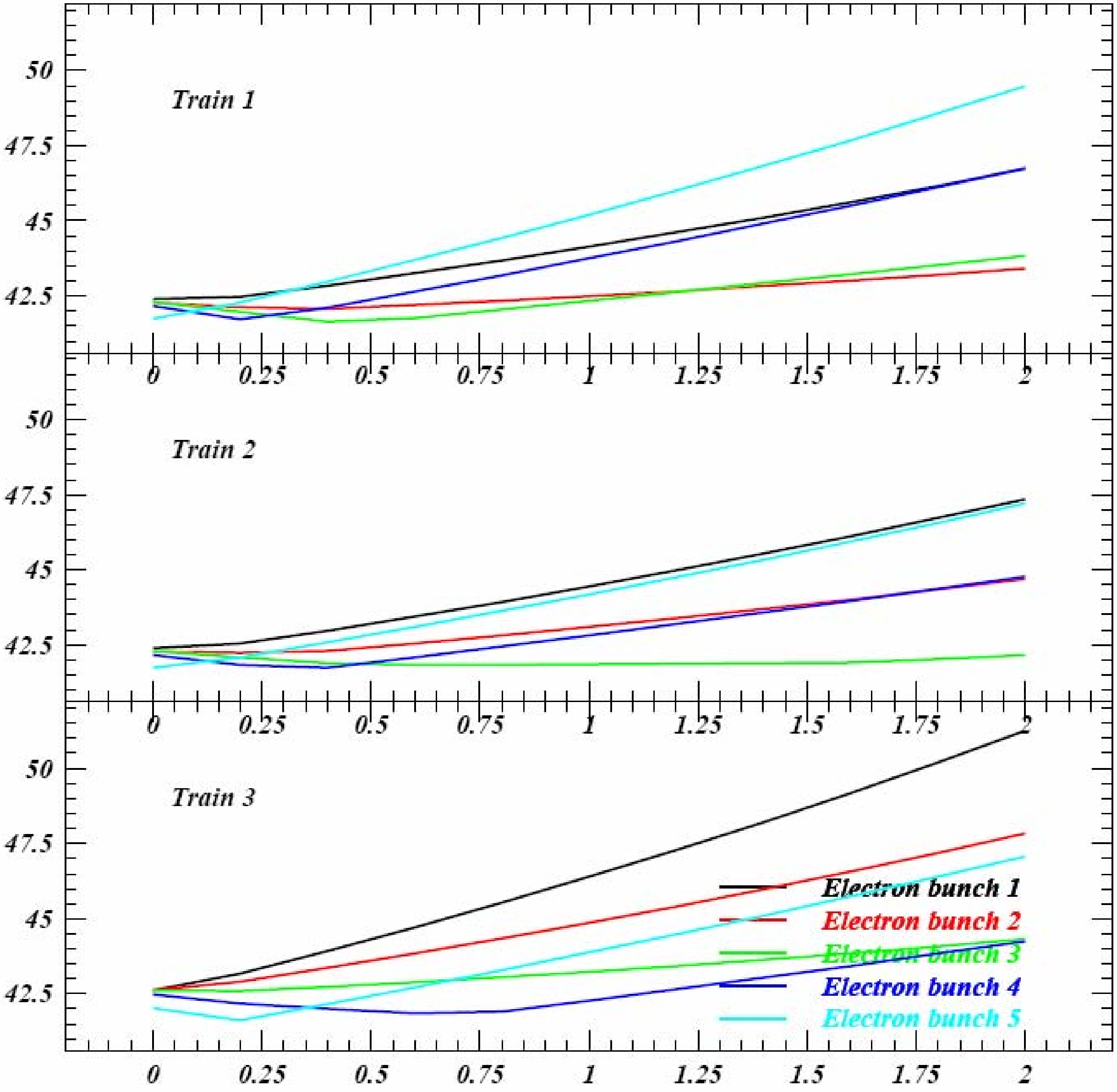
Performance Analysis

Several factors complicate optics design and performance analysis:

- Pretzel orbits create separate optics for the two beams due to sextupoles and multipoles.
- Special focusing properties of the wigglers and localized radiation effects need special treatment.
- Coherent beam-beam effects from up to 89 parasitic crossings create strong bunch-by-bunch, current dependent optics.

Parasitic B-B beta changes

Maximum horizontal β (m) vs. bunch current (mA) in opposing beam with 9x5 bunches.



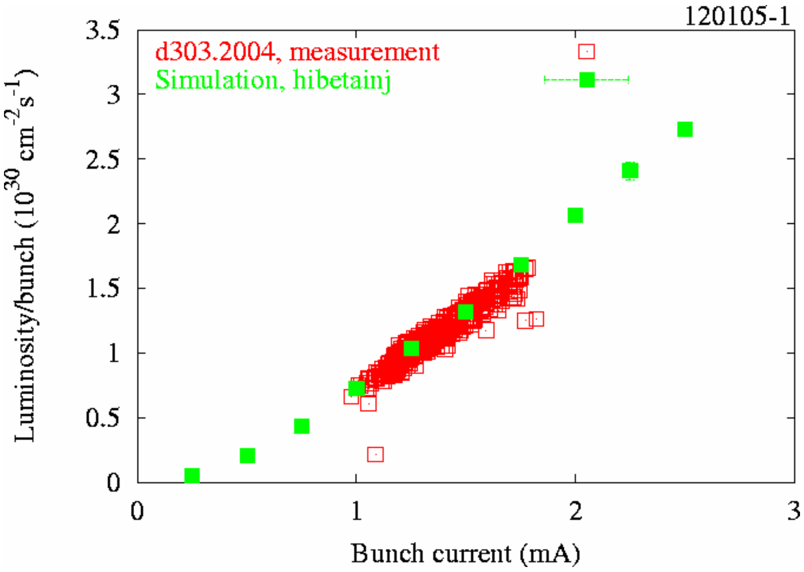
J. A. Crittenden July, 2005.

Benchmarking Model

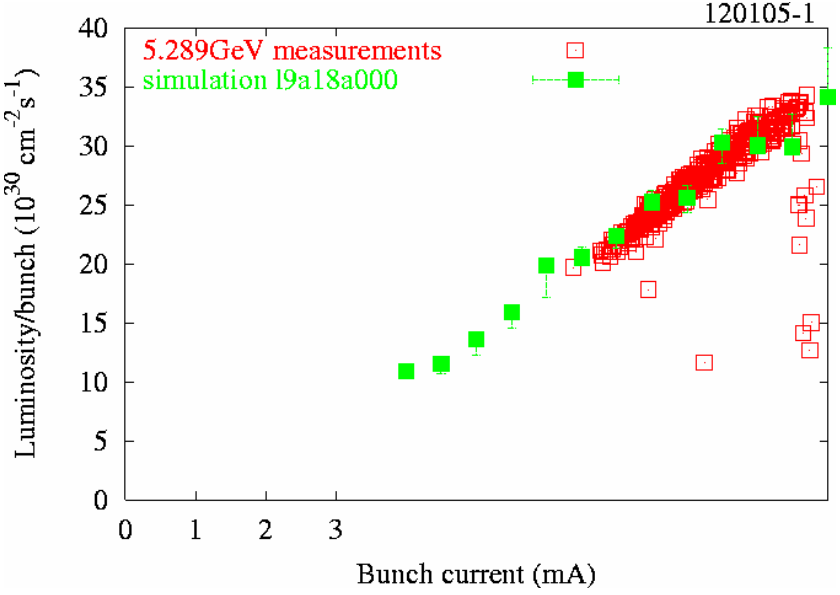
- **With the availability of a good model, simulation experiments could be carried out to assess the impact of various parameters on performance.**

Luminosity simulations compared with measurements:

1.89 GeV



5.3 GeV



http://www.lns.cornell.edu/~dlr/beambeam_simulation/

Simulation Experiments

– **Wiggler non-linearities turned off**	*- No change*
– **Low field distributed wigglers creating 50 ms damping times**	*- Better performance but only similar to lower δE*
– **Turn off pretzel & parasitic crossings**	*- <10% improvement*
– **Turn off CLEO solenoid and coupling compensation**	*- ~50% improvement in specific luminosity*
– **Add anti-solenoid coupling compensation**	*- 25-30% improvement in specific luminosity*
– **Reduce Q_S or σ_L to ½ normal**	*- Both comparable results; higher bunch current, 1.8x lum, ξ_Y 0.03 → 0.055*

Summary of performance analysis

- Beam currents have been limited by ion effects (leaving out one train) and parasitic beam-beam effects (confirmed with single-beam tests).
- The CLEO-c solenoid compensation has excessive chromaticity – introducing an anti-solenoid in the compensation scheme should improve performance.
- The high Q_S necessitated by the large energy spread is a significant limit to beam-beam performance. Reduction difficult because of pretzel orbit needs.
- Otherwise no significant effects from the wigglers have been found.

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Performance Improvement Efforts

Several programs have been carried out to improve CESR-c performance.

1. **Variations in optics, including:**
    1. interaction point optics functions
    2. injection point optics functions
    3. betatron tunes
    4. horizontal emittance
    5. compensation of CLEO solenoid field (skew quads)
    6. knobs for empirical adjustment of parameters
    7. RF voltages

Performance Improvement Efforts

Performance programs (cont.)

2. Compensation of parasitic (and primary) beam-beam effects by optics changes.
3. Addition of anti-solenoids in CLEO solenoid compensation.
4. Extensive and experienced tuning

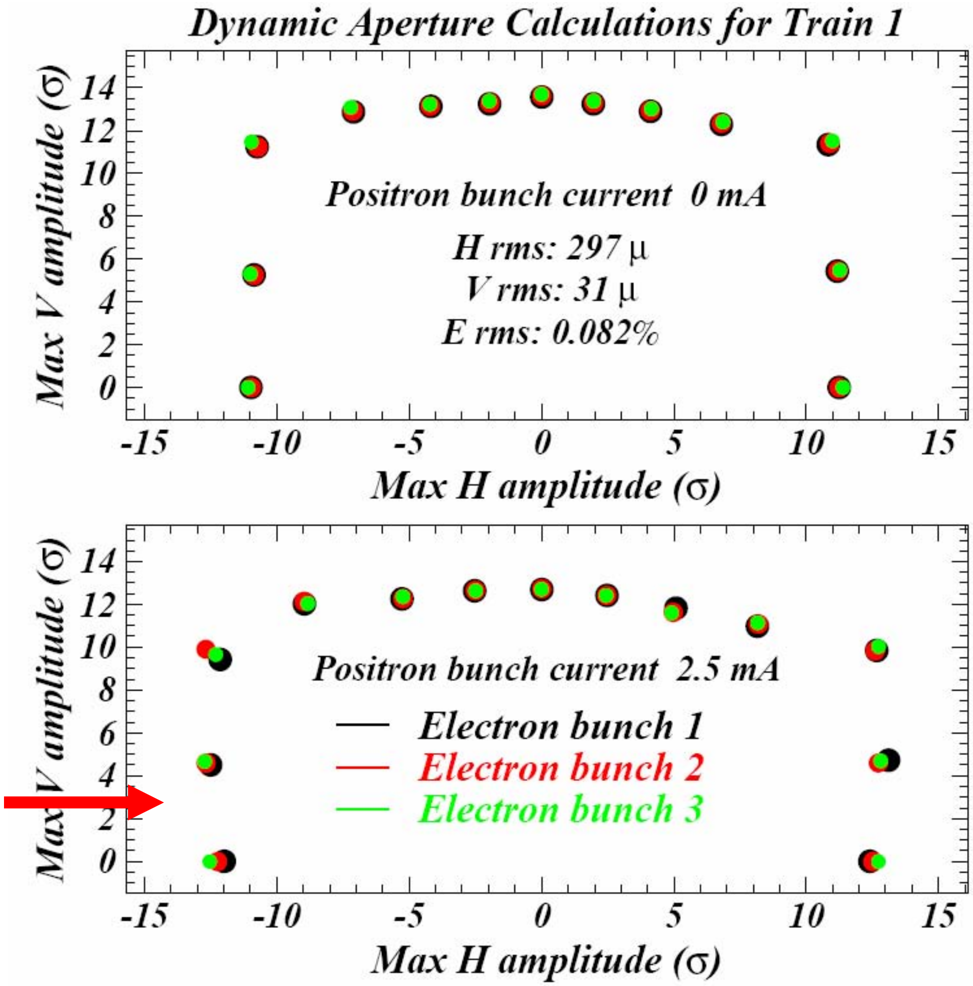
While some positive results have been seen in machine studies and operations, complications of the parasitic crossings, particularly for injection, have produced mixed results in HEP running.

Performance Improvement Efforts – BBI compensation

Current limits from parasitic B-B interactions

- Initial efforts massaged optics to reduce ΔQ, empirical parameters at parasitic crossings.
- Later efforts have computed local compensation for each cluster of bunch crossings*.

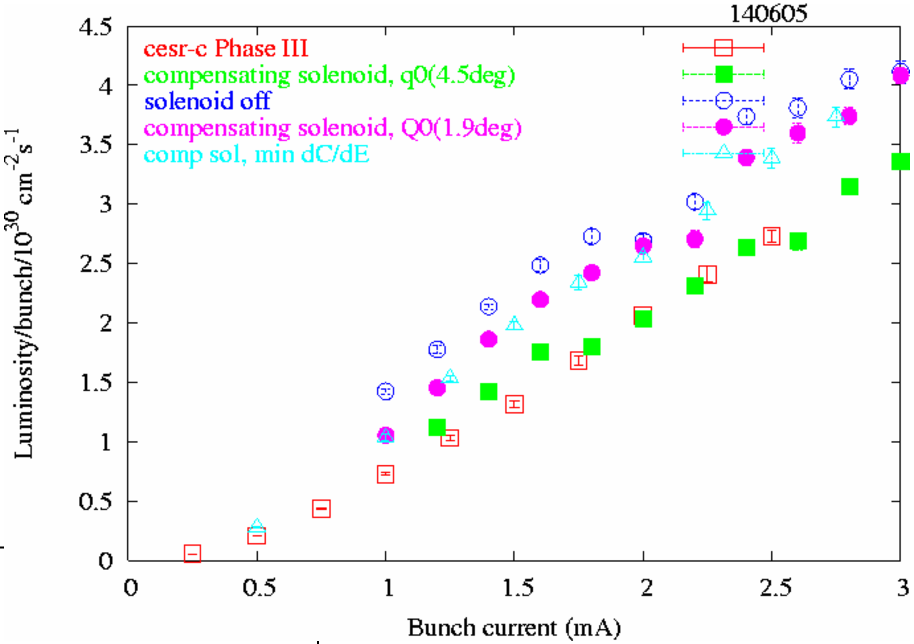
Dynamic aperture made to IMPROVE with presence of opposing beam.

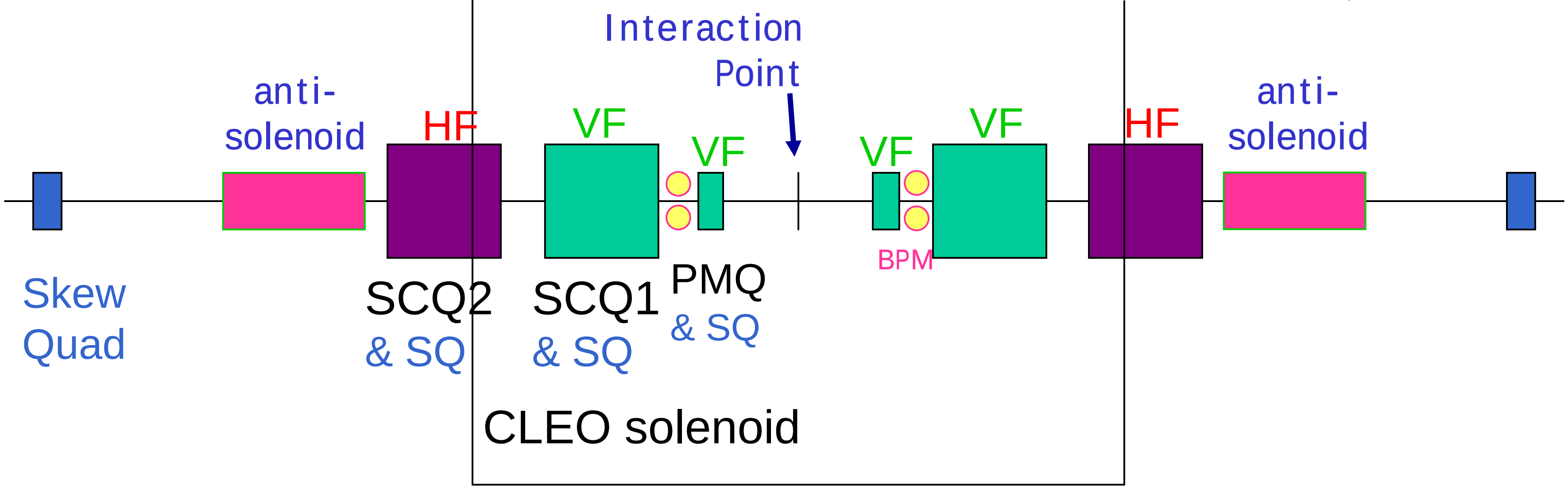


* J. Crittenden, M. Billing, “Compensation Strategy for Optical Distortions Arising from the Beam-Beam Interaction at CESR,” paper TUPAS056

Performance Improvement Efforts – anti-solenoid compensation

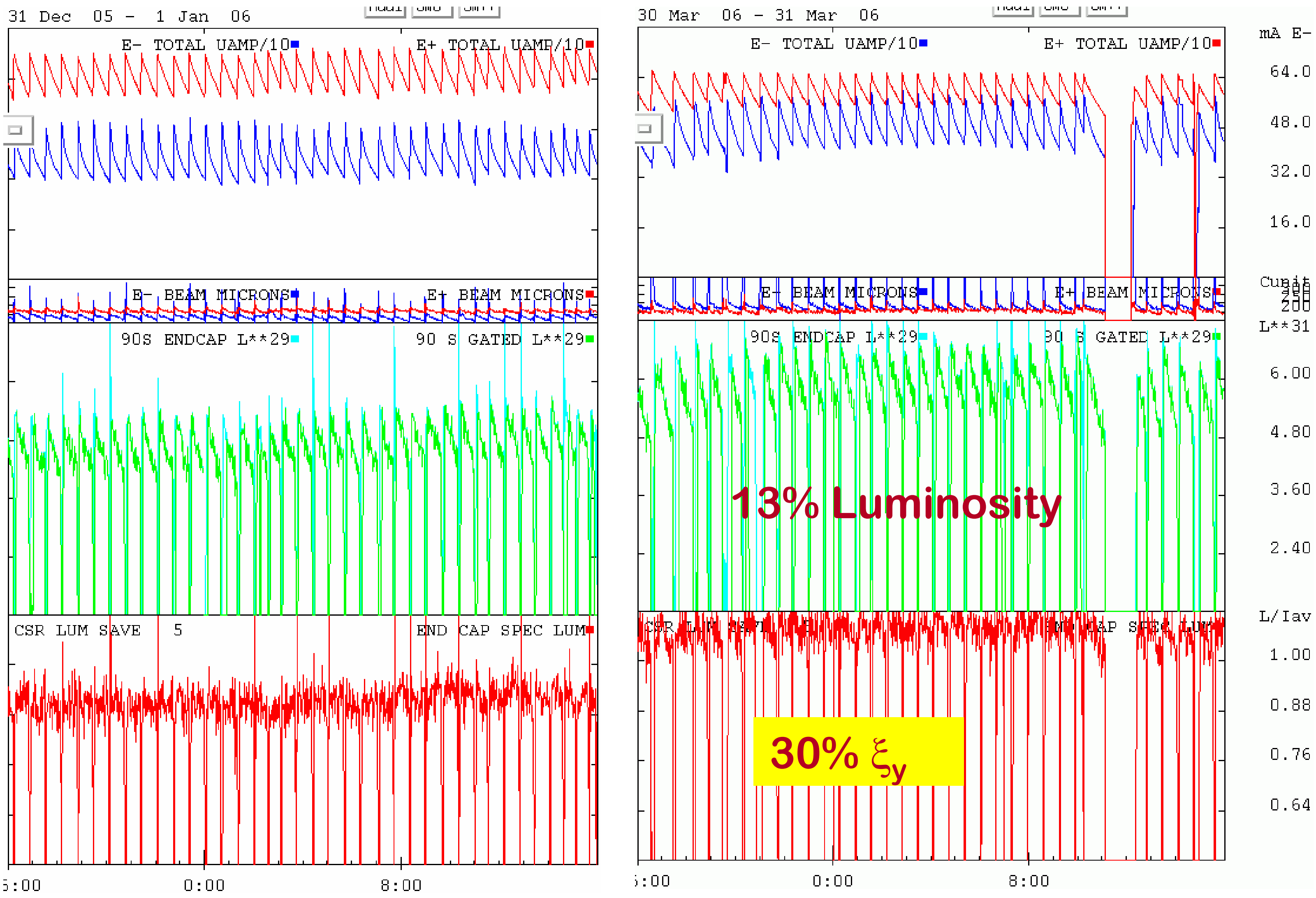
- Simulations predict luminosity improvement with introduction of anti-solenoid in compensation scheme.





Anti-solenoid Performance

CLEO-c operation before and after anti-solenoid commissioning



13% Luminosity

30% ξ_y

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CESR-c Performance Summary

- Peak luminosity 7×10^{31} cm^{-2}-sec^{-1}, integrated luminosity >4.5 pb^{-1} per day
- World data sample at $\psi(3770)$ increased > x15, plus D_S decays at (4050-4170) (4 years, running < 50%)
- CLEO-c will continue taking data through March 31, 2008
- Parasitic BBI is the primary performance limit.
- Solenoid compensation studied through simulation program and experiment – improvements seen
- Large energy spread $\Rightarrow$ high Q_S is secondary performance limit
- Other than energy spread, the wigglers have not adversely affected performance.

Future directions

Looking toward the future, CESR is an ideal test bed for accelerator R&D

- Ultimate flexibility of optics
- Powerful injector
- e+ / e- capable
- Low impedance SC RF cavities
- High quality wiggler magnets
- High quality instrumentation
- Experience manipulating optics
- Energy 1.5 – 6 GeV
- Experienced and dedicated staff

See (previous) talk by M. Palmer, MOOAKI01

Credit to CESR Operations & Technical Support Groups

Work reported has been carried out by a dedicated and talented staff:

Operations:

Dave Rubin
Mike Billing
Sergey Belomestnykh
Ryan Carey
Jerry Codner
Jim Crittenden
Richard Eshelman
Mike Forster
Steve Gray
Shlomo Greenwald
Don Hartill
John Hylas
Dan Kematick
Bob Meller
Vildan Omanovic
Mark Palmer
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Mike Sloand
Karl Smolenski
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Eugene Tanke
Sasha Temnykh
Maury Tigner
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Beth Wilcox
Meredith Williams
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