Overview of the Beam Dynamics Study in CESR

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Laboratory for Elementary-Particle Physics

Outline of talk -

- A quick overview of CESR
- Colliding beam dynamics (selected topics)
  - Tune plane exploration
  - Machine resonances correction
  - Coupling differential problem
  - High synchrotron tune effect
- Single beam, long train dynamics study
- Conclusion and future

A brief history of CESR

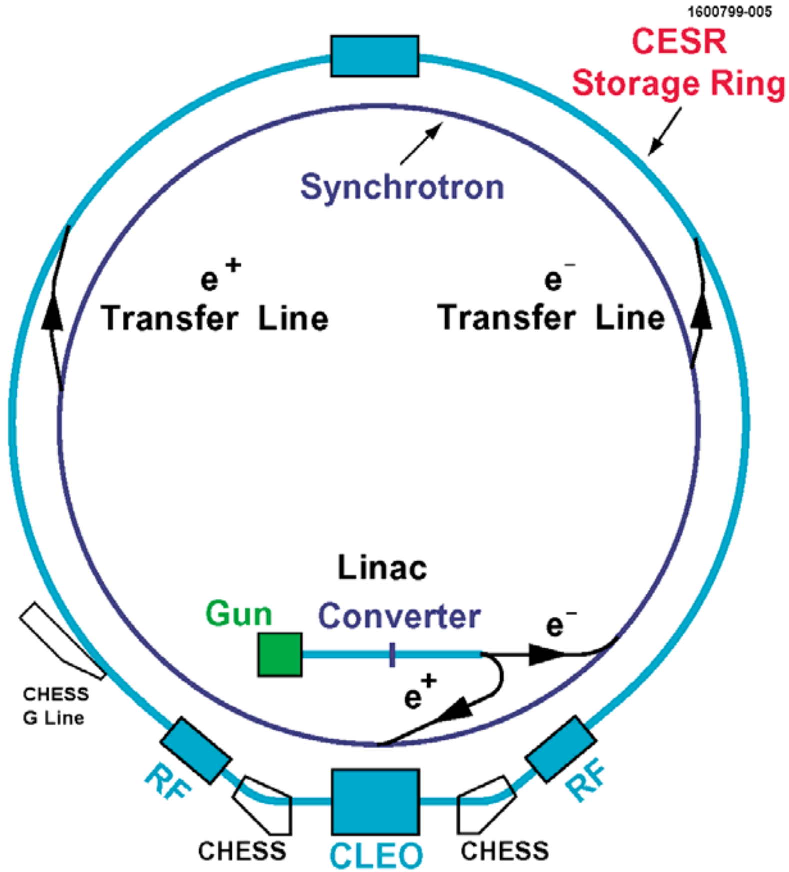
- Operation began October, 1979
  - Design 8 GeV
  - 100mA/beam in single bunch
  - 2 interaction regions.
- A succession of upgrades led to record performance at 5.3 GeV E_{beam}
  - Mini- $\rightarrow$ micro-beta IR optics
  - Full energy, multi-bunch injection
  - Multi-bunch w/ “Pretzel” & crossing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

Slide from D. Rice, PAC 2007

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

Slide from D. Rice, PAC 2007

CESR Layout (2)

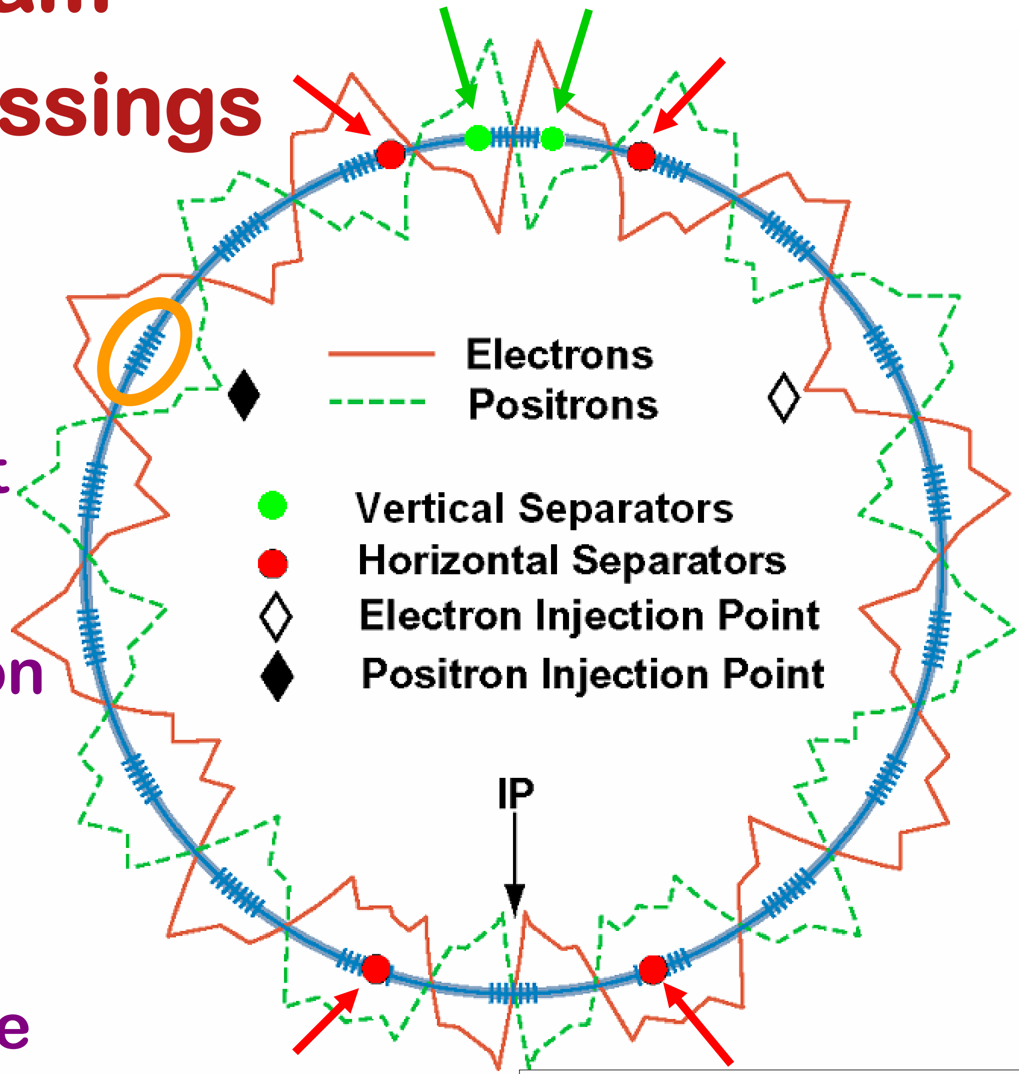
45 bunches per beam

⇒ 89 parasitic crossings

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

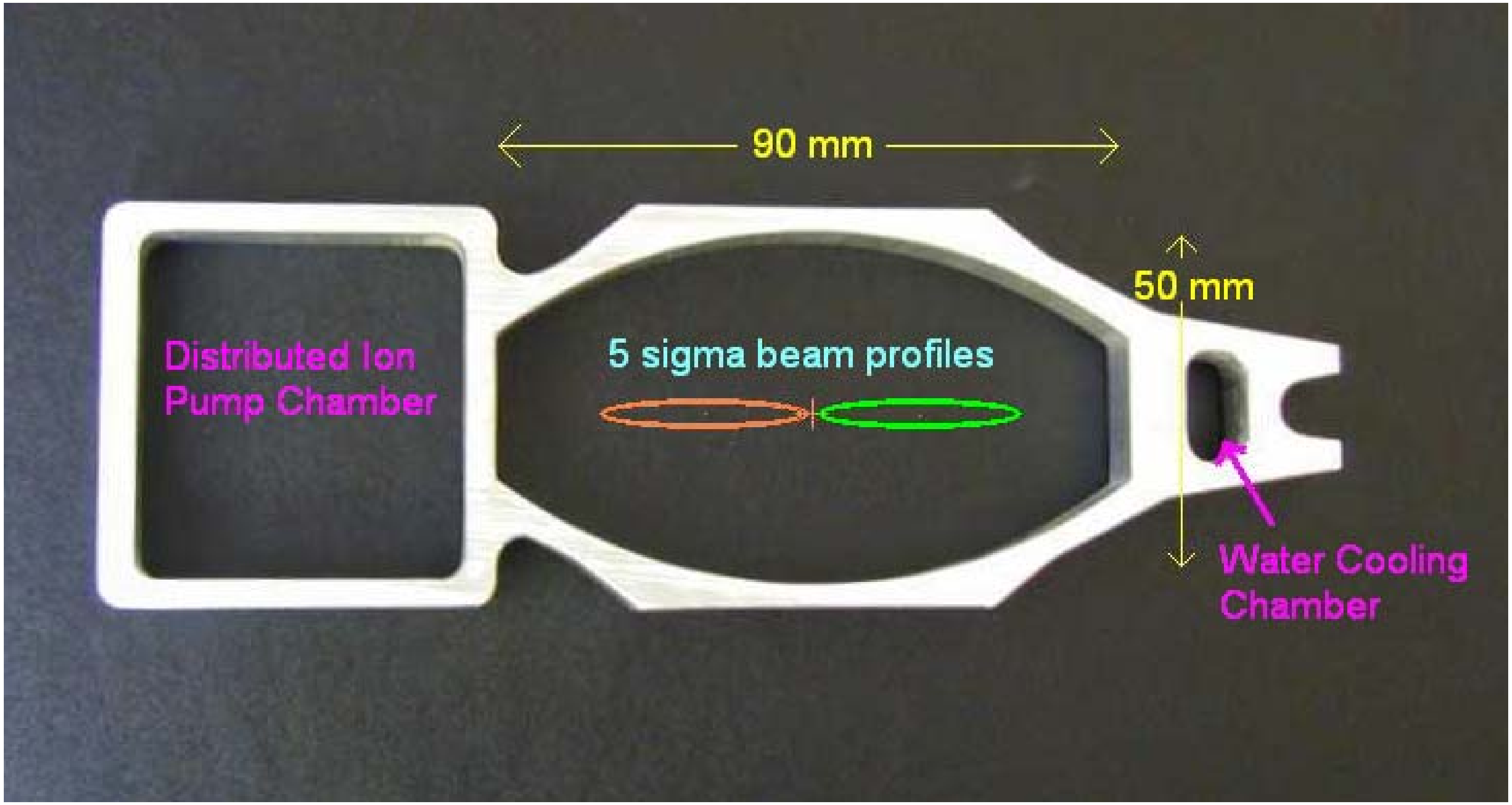
2 vertical electrostatic separators avoid collision in North IR.

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



Slide from D. Rice, PAC 2007

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



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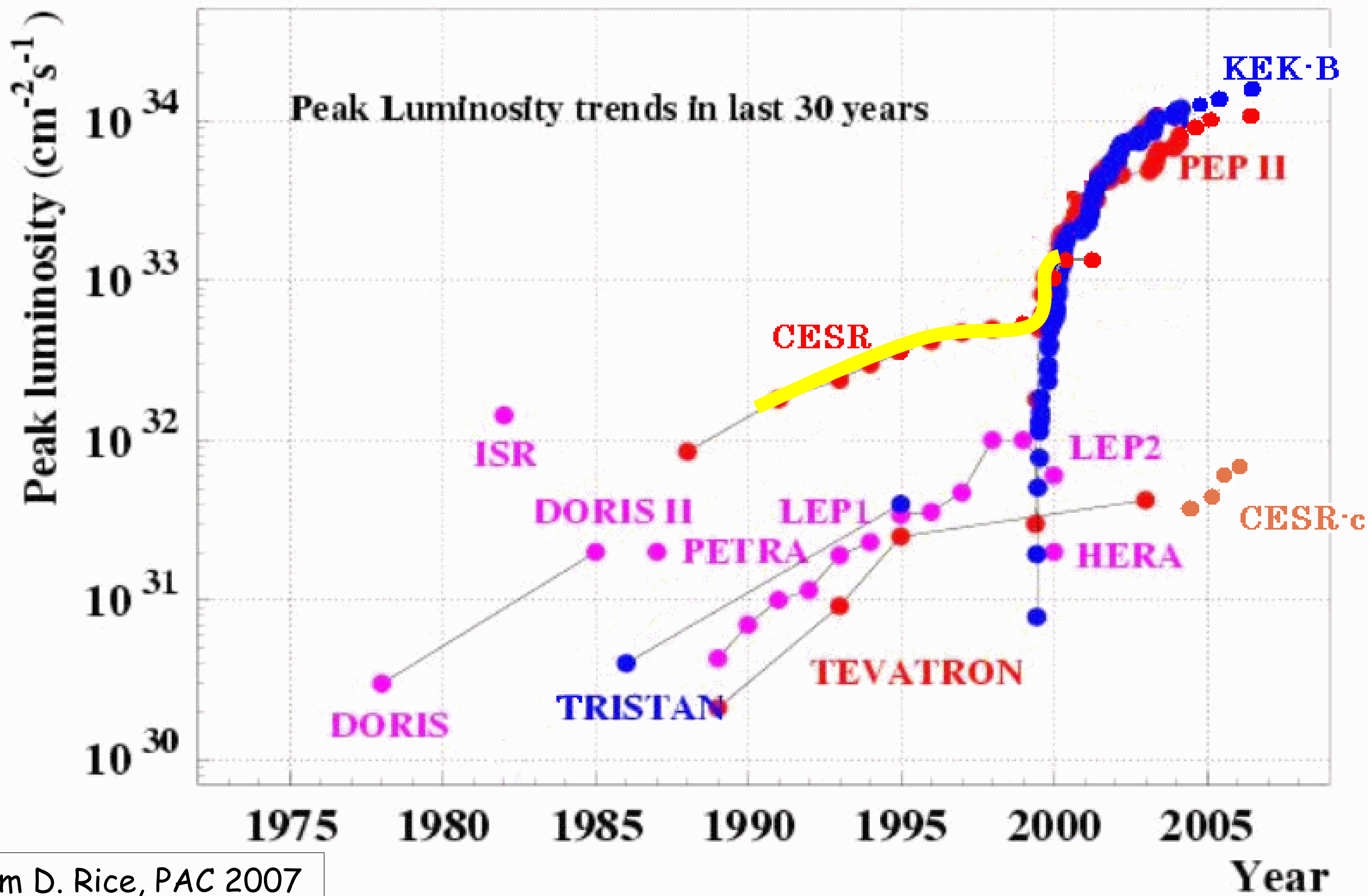
Peak Luminosity Trends of e+e- Colliders



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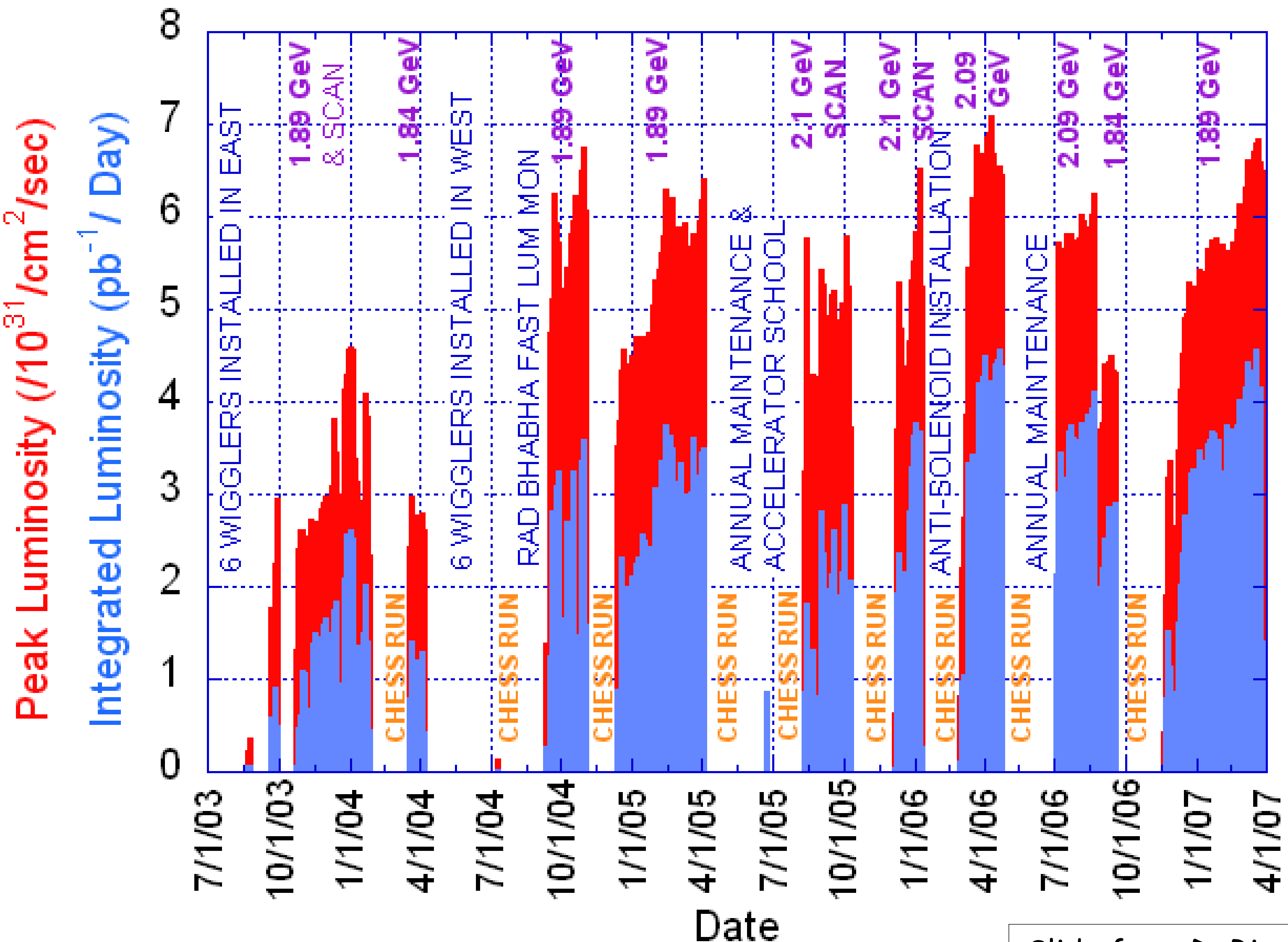
Luminosity Performance



Slide from D. Rice, PAC 2007

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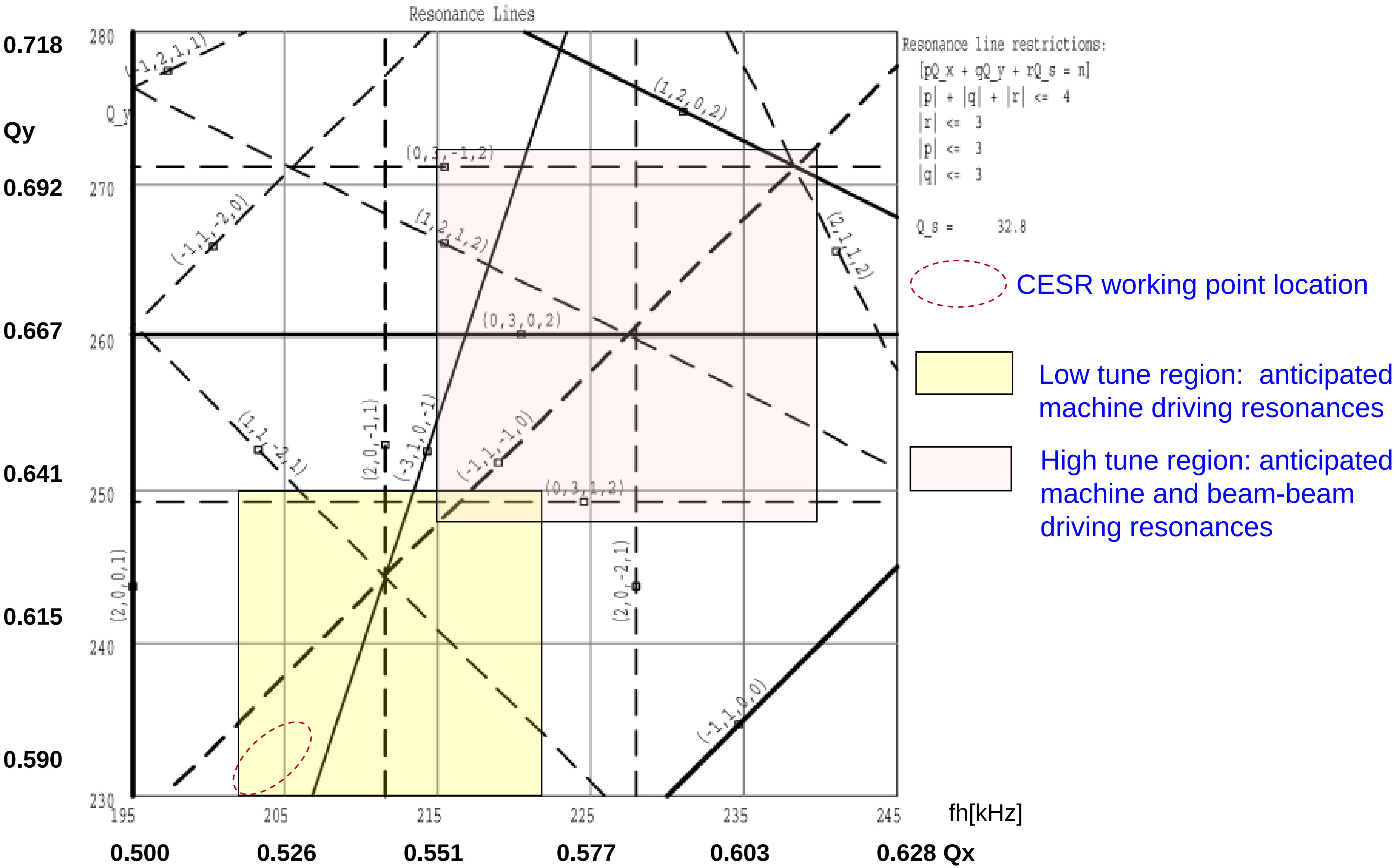
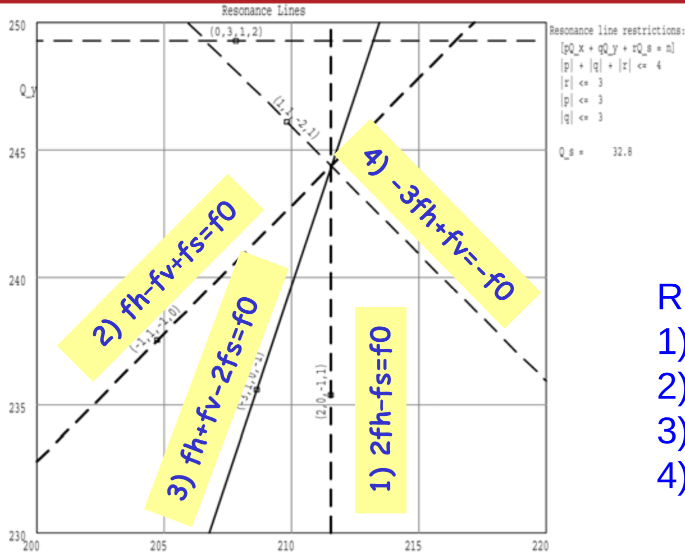
  - Machine resonances correction
  - Coupling differential problem
  - High synchrotron tune effect
- Single beam, long train dynamics study
- Conclusion and future

Tune plane exploration



Tune plane exploration:
Low tune region



Experimental conditions:

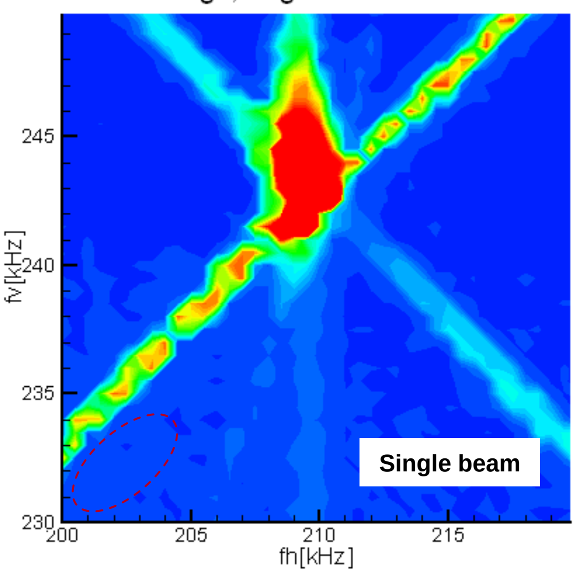
•1 x 1 head-on collision, weak-strong beam-beam interaction.

•Tune scan with vertical beam size measurement of the weak (positron) beam.

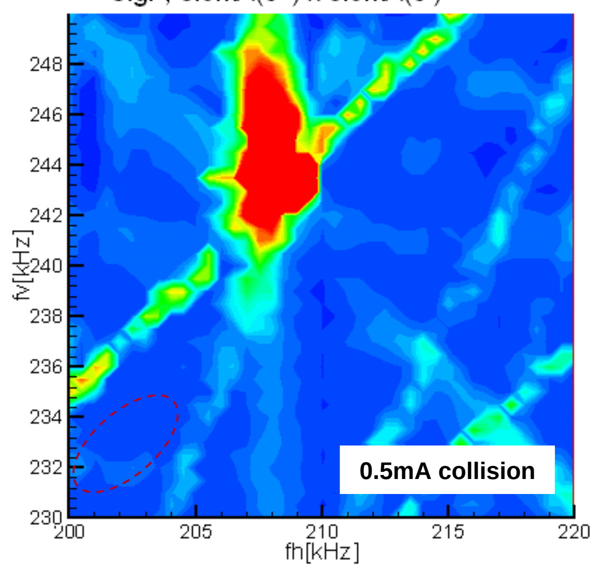
Resonance driving terms:

1) Normal sextupole moment in place with dispersion
2) Skew sextupole in place with dispersion or chromatic coupling
3) Skew octupole moment in place with dispersion
4) Skew octupole moments

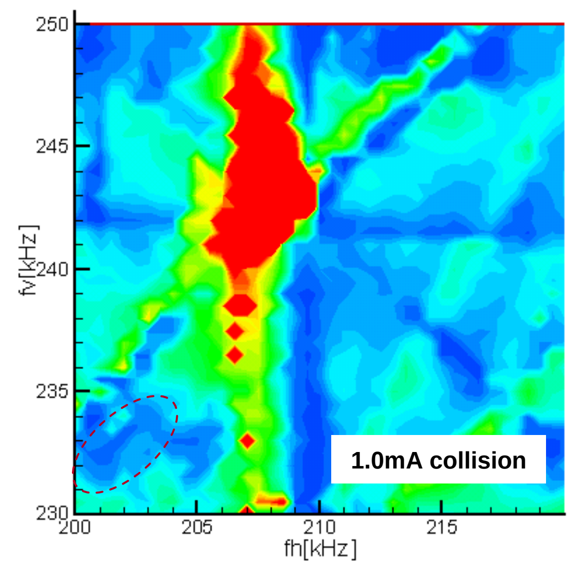
SigP, single e+ beam



SigP, 0.5mA(e+) x 0.5mA(e-)



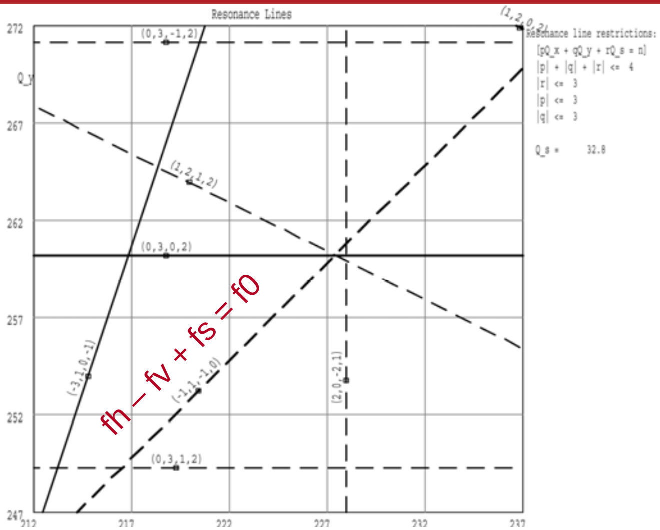
SigP, 0.5mA(e+) x 1.0mA(e-)



Seen machine resonances

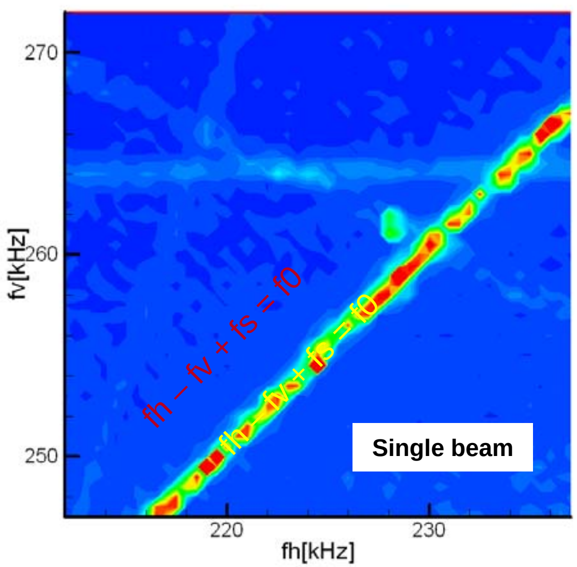
Seen machine resonance drift due to tune shift introduced by beam-beam.

Tune plane exploration:
High tune region

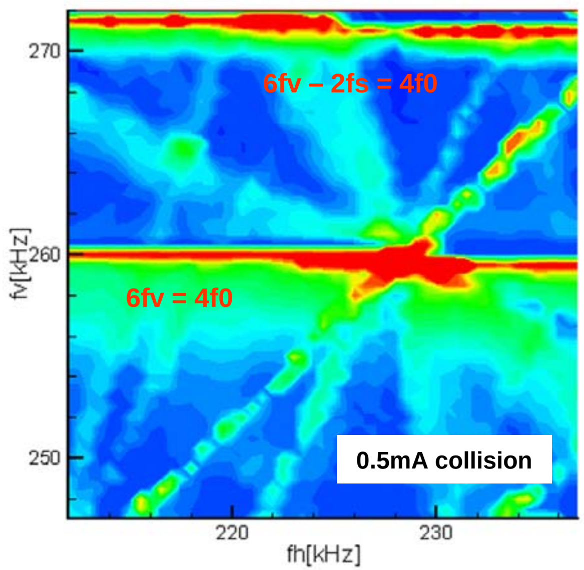


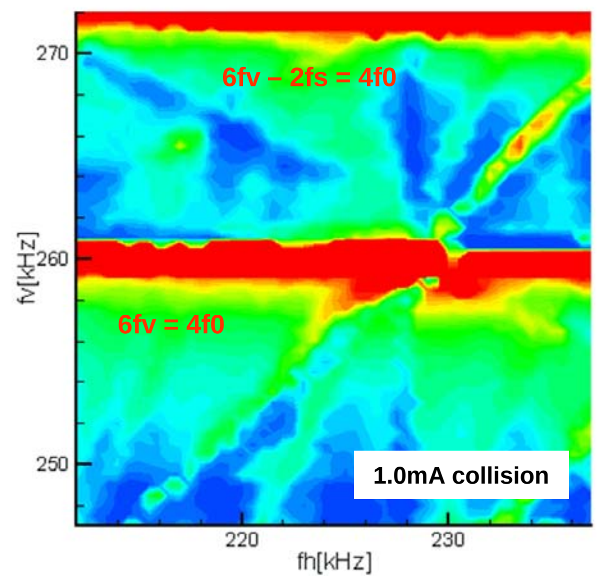
Experimental conditions:
- 1 x 1 head-on collision, weak-strong beam-beam interaction.
- Tune scan with vertical beam size measurement of the weak (positron) beam.

Less number of machine resonances, but more beam-beam driving ones



Seen machine resonance





Seen strong beam-beam driving resonances, no good place for working point

Tune plane exploration conclusion

- In the “high” tune region beam-beam performance limited by beam-beam interaction driven resonances. We can not eliminate them.

- In the “low” tune region “machine” driven resonances affect the beam-beam performance. Can we damp them ?

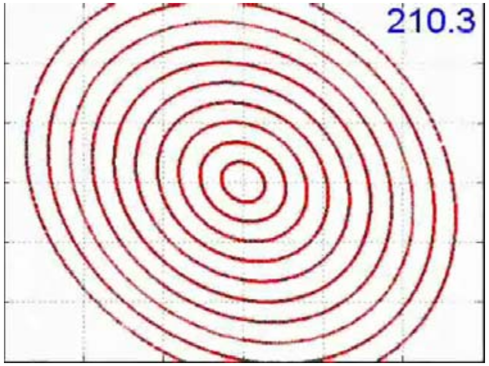
2fh – fs = f0 resonace damping

Single beam, 2D tune scan with horizontal beam size measurement.

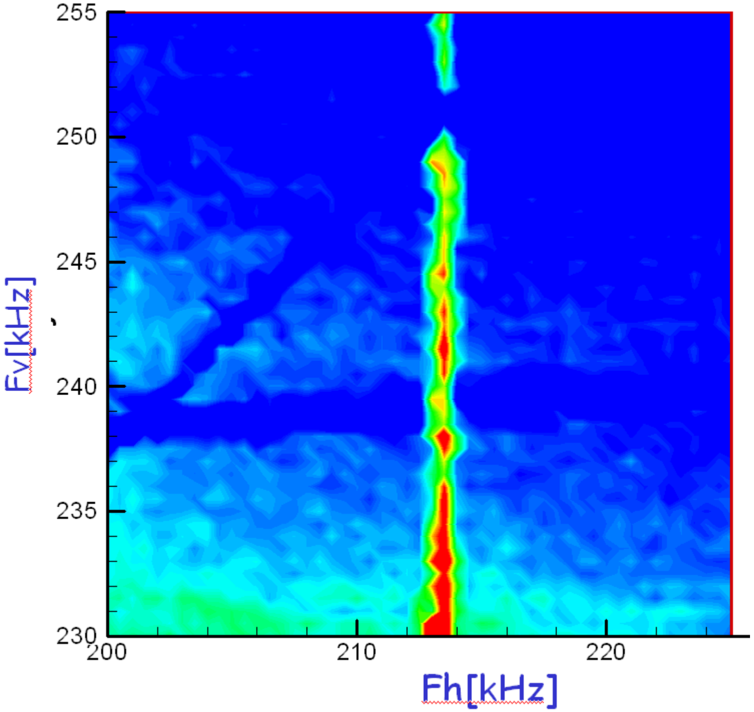
Resonance in a simple tracking model

$$x_{n+1} = x_n \cdot \cos(2\pi\nu_\beta) + x'_n \cdot \sin(2\pi\nu_\beta)$$
$$x'_{n+1} = -x_n \cdot \sin(2\pi\nu_\beta) + x'_n \cdot \cos(2\pi\nu_\beta)$$
$$+ S \cdot \left(x_n + \delta_E \cos(2\pi\nu_s n)\right)^2$$

Phase space when tune crossing resonance

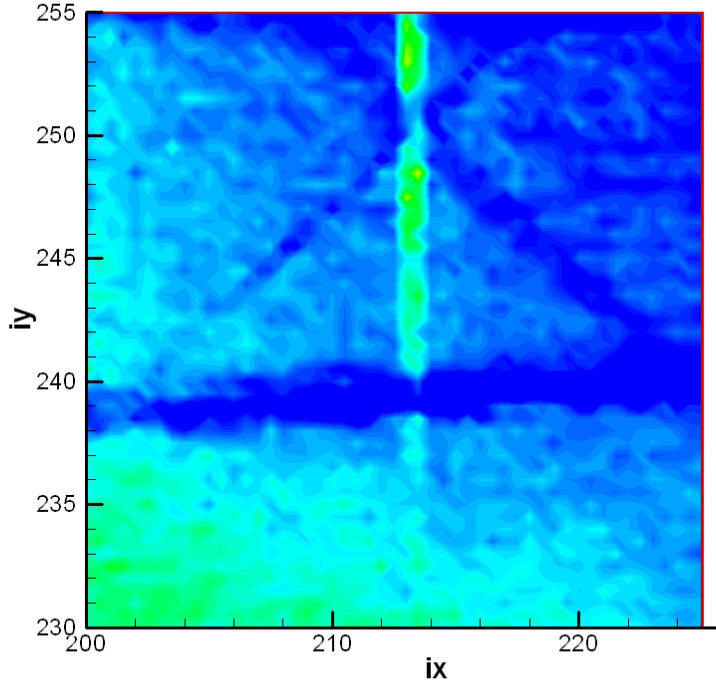


Before sextupole distribution tuning



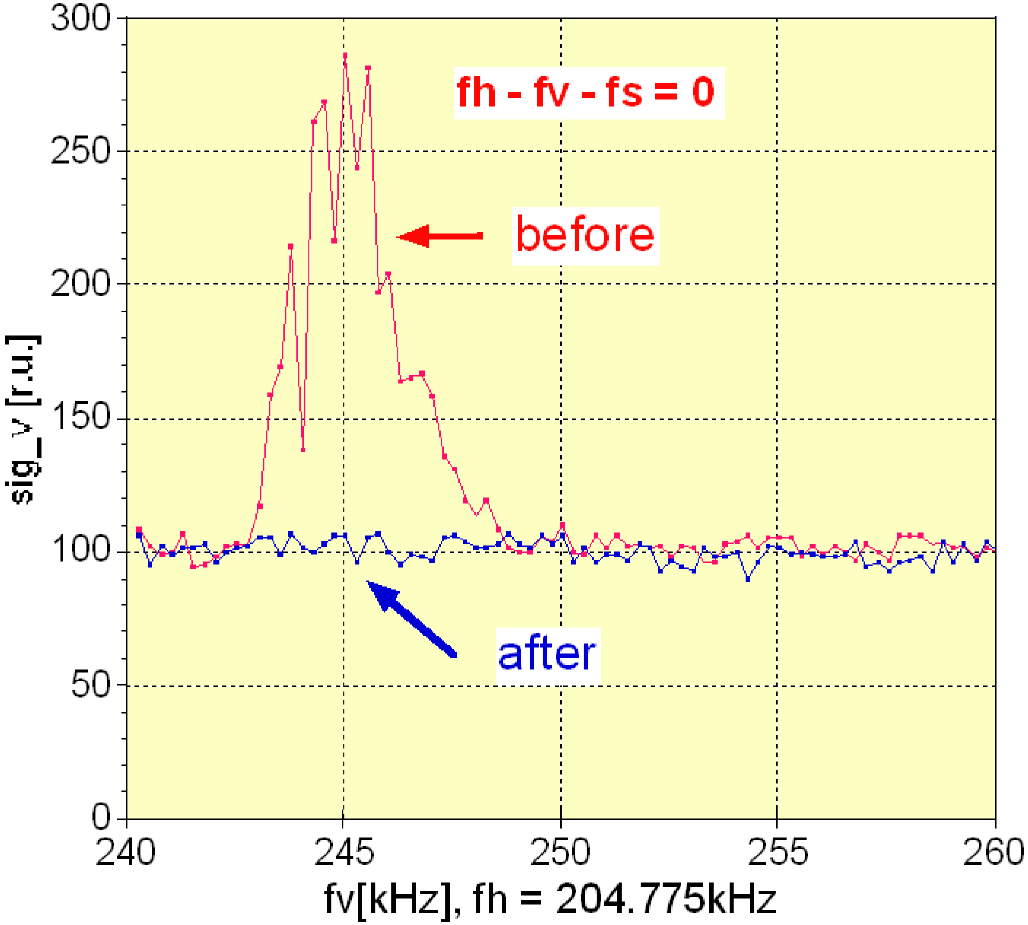
Sextupole	Delta K2L[m^{-2}]
10W	-0.272
24W	-0.311
26W	-0.041
30W	-0.034

After sextupole distribution tuning



fh – fv + fs = 0 resonance damping

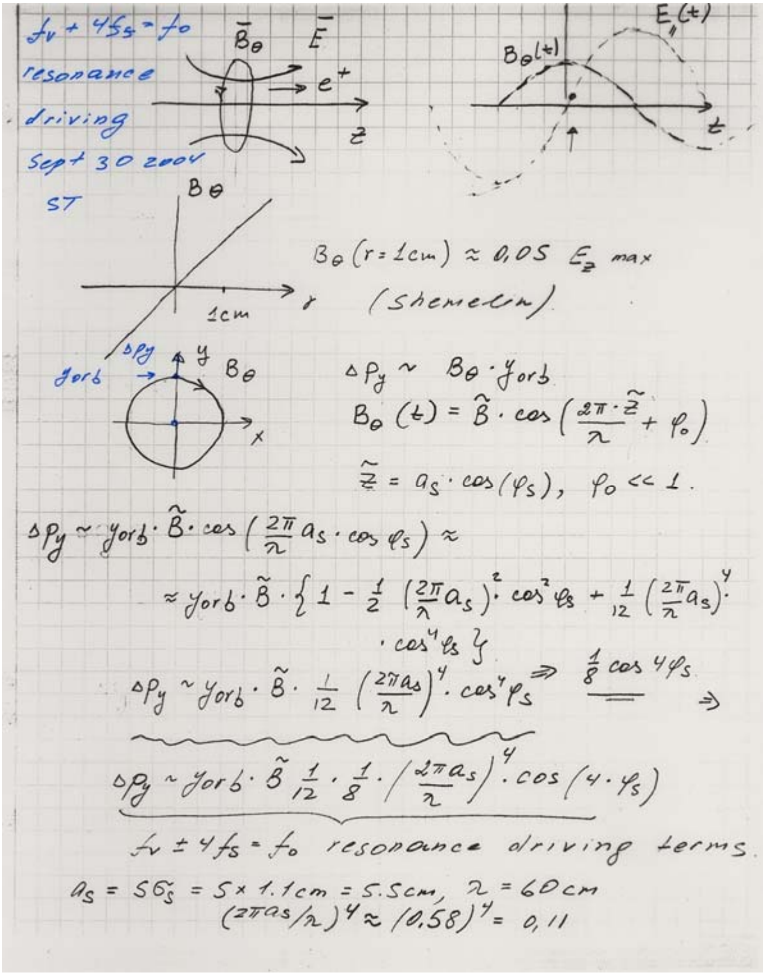
Single beam, 1D tune scan with vertical beam size measurement.

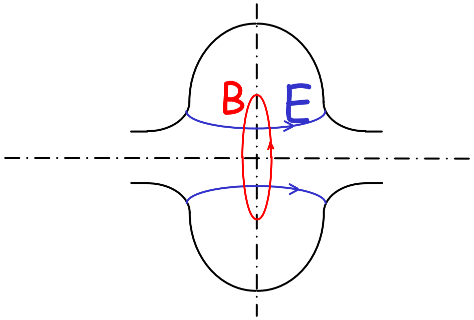


Skew – Sextupole	Delta K2L[m^{-2}]
7E	-0.11
23E	-0.055
23W	0.275

fv + 4fs = f0 resonance damping

Resonance is driving by the SRF cavity magnetic field if orbit is off center.

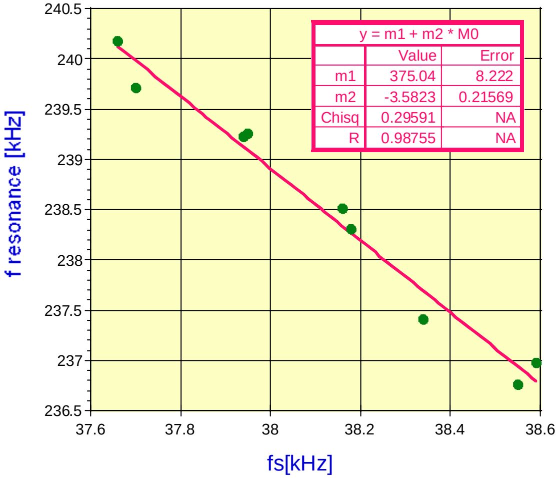


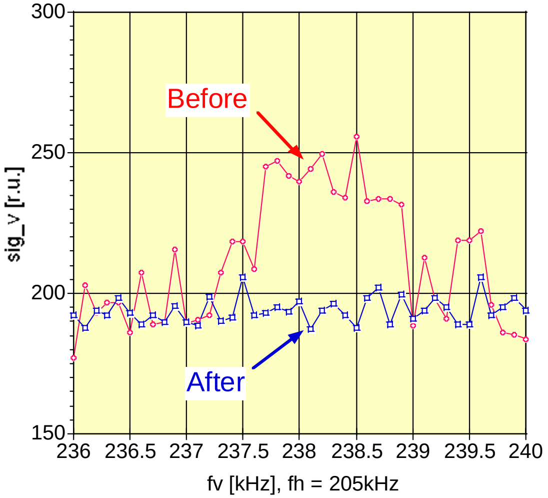


Single beam, 1D tune scan with vertical beam size measurement.

Vertical orbit bump	[mm]
West RF	1.25
East RF	-0.85

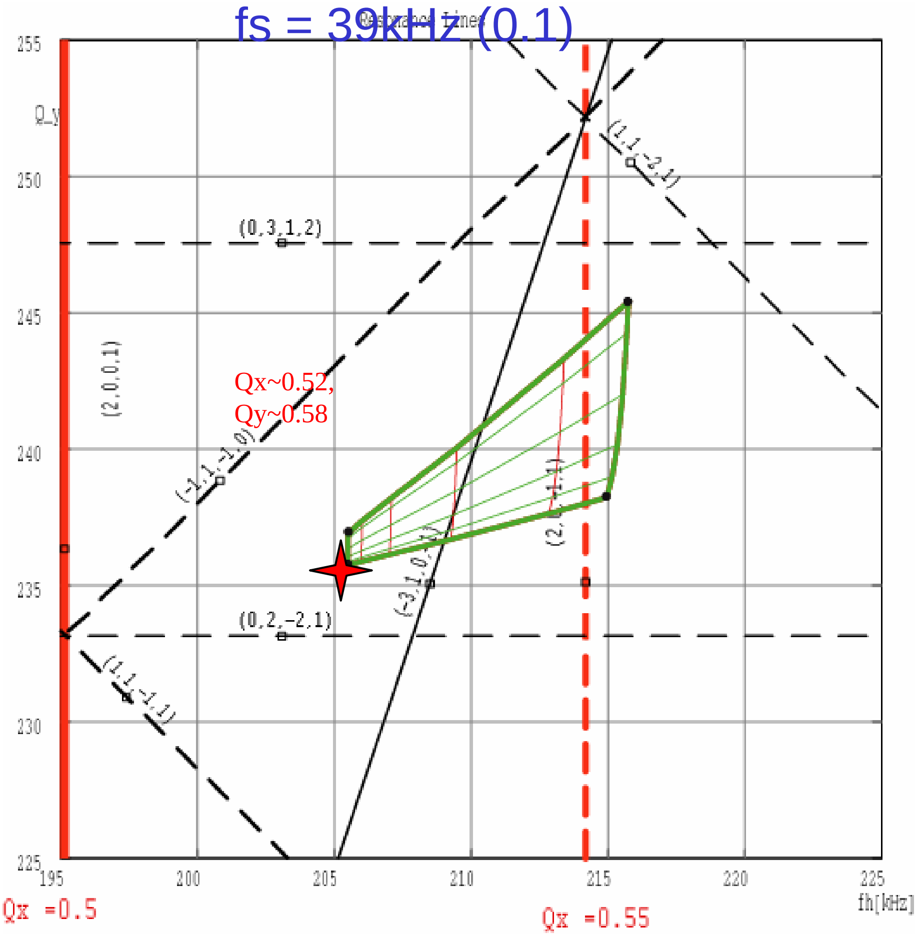
Resonance identification



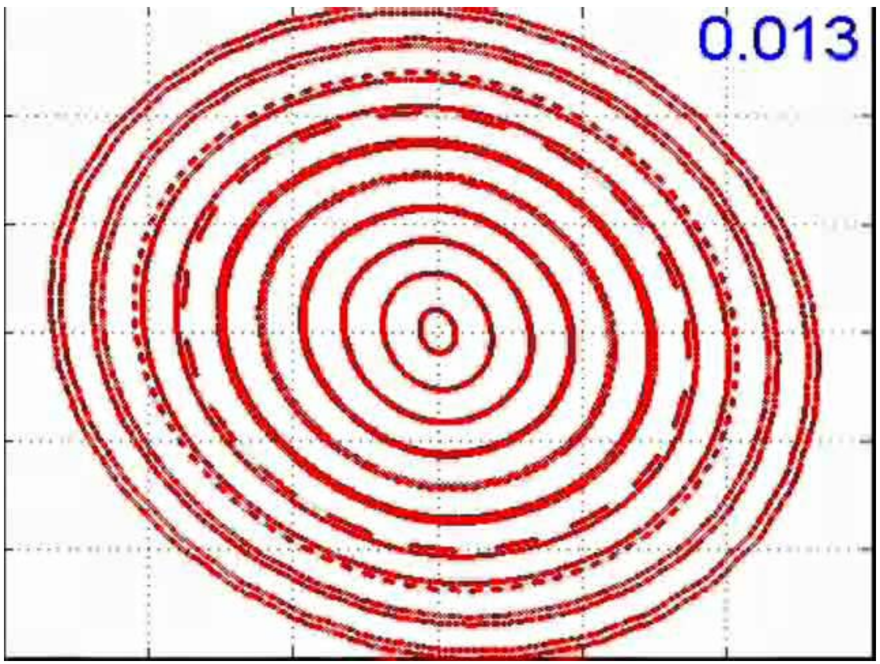


Effect of machine driving resonance 2fh - fs = f0 on beam-beam performance

Model with beam-beam interaction
and single sextupole.
fh = 208kHz (0.525)
fs = 39kHz (0.1)



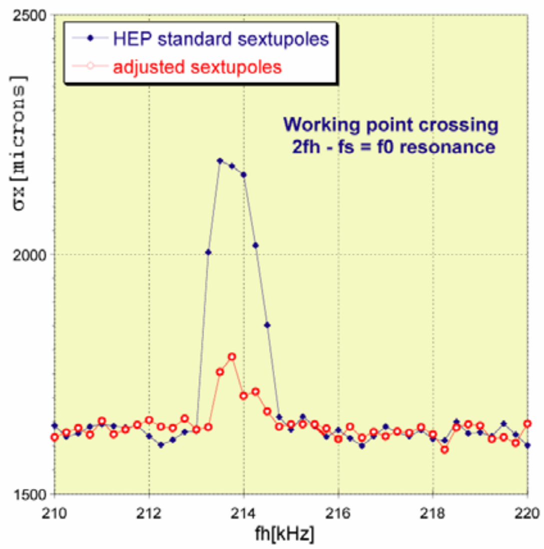
Trajectories in horizontal phase space when ξ_x increases.



Effect of 2fh – fs = f0 resonance dampimg on colliding beams performance

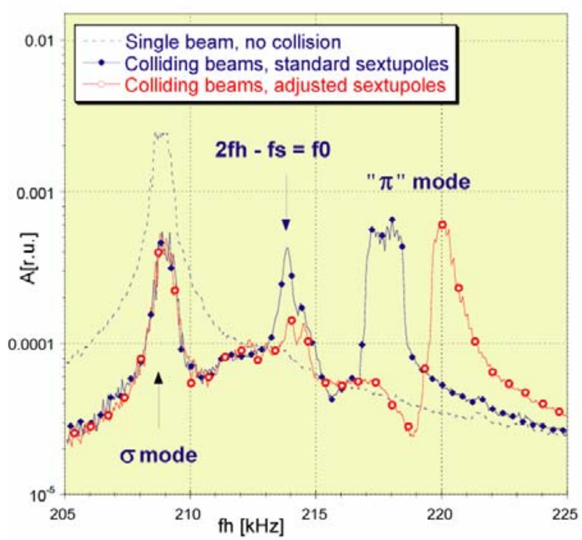
Effect of 2fh-fs=f0 resonance damping on beam-beam performanc, MS 3/30/05

Sext	Delta K2L[m^{-2}]
10W,E	-0.050
24W,E	0.004

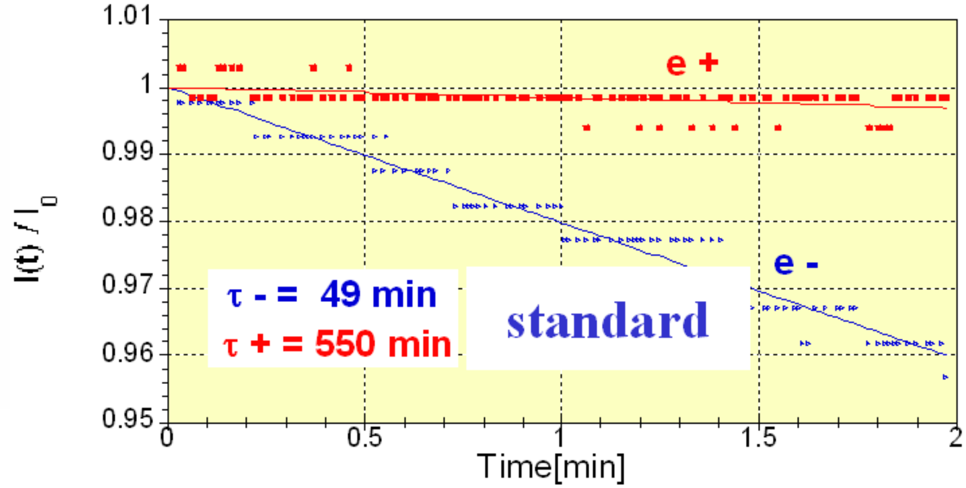


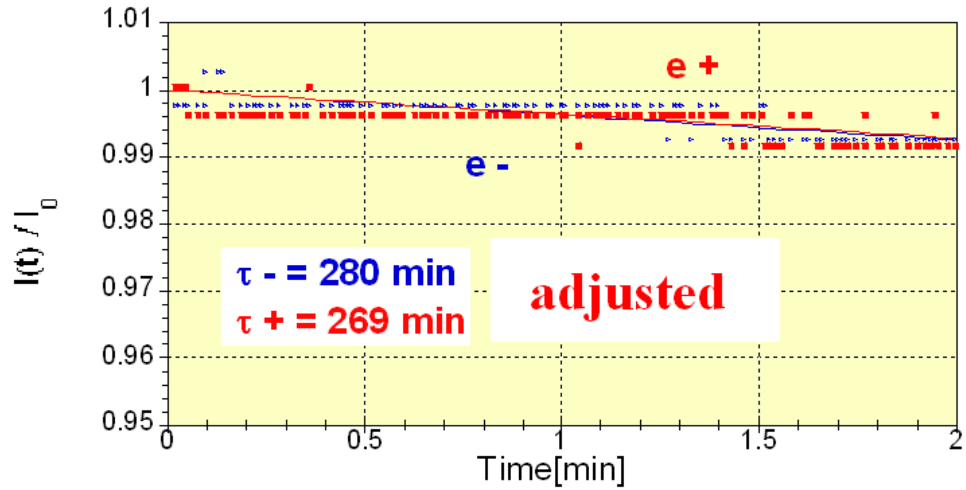
Effect on horizontal colliding beam spectrum

2x2mA colliding beams spectrum.



Effect of the resonance damping on colliding beams life time





Conclusion on resonance damping

Using available non-linear elements one can correct machine driving resonances in vicinity of the working point.

The clean tune plane enhances colliding beam performance.

Coupling diagnostics

CORRECTION OF TRANSVERSE COUPLING IN A STORAGE RING

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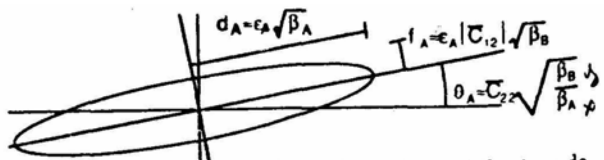

Figure 1 : Beam ellipse for weak coupling and the A mode excited

The beam center motion in x-y plane resulted from horizontal eigenmode excitation.

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RMS =      0.009
Average =     0.002
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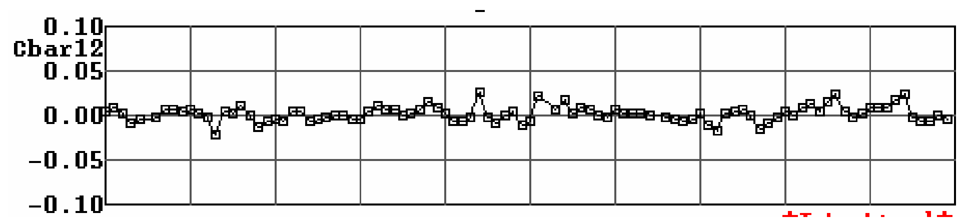
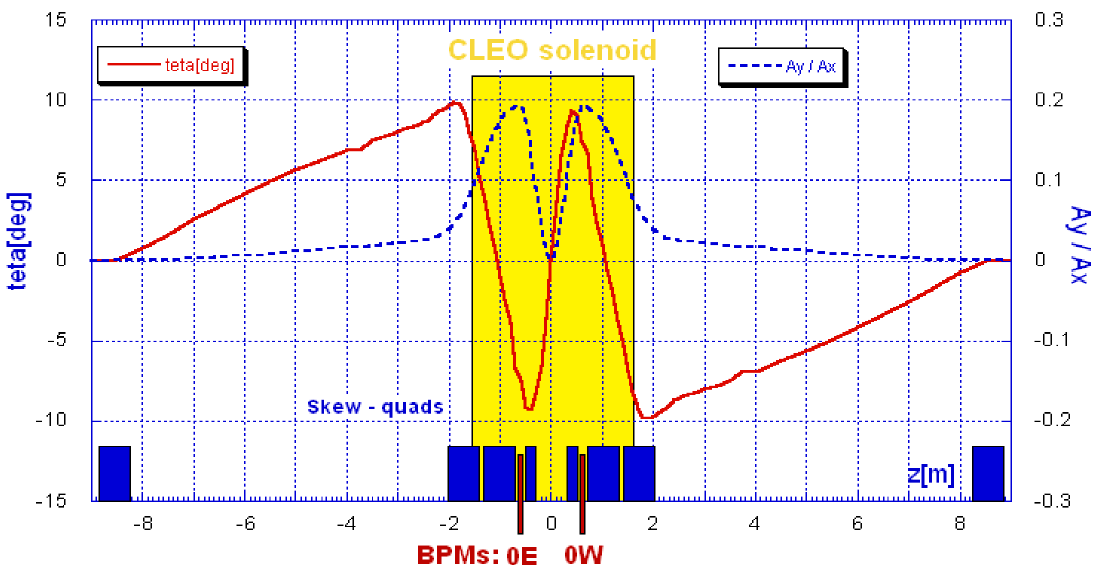


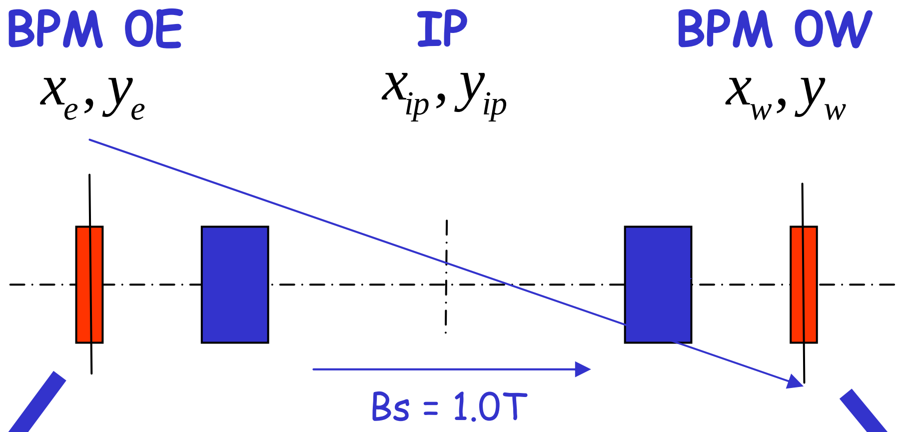
Local coupling In interaction region

The critical question: What is the coupling at the collision point ?

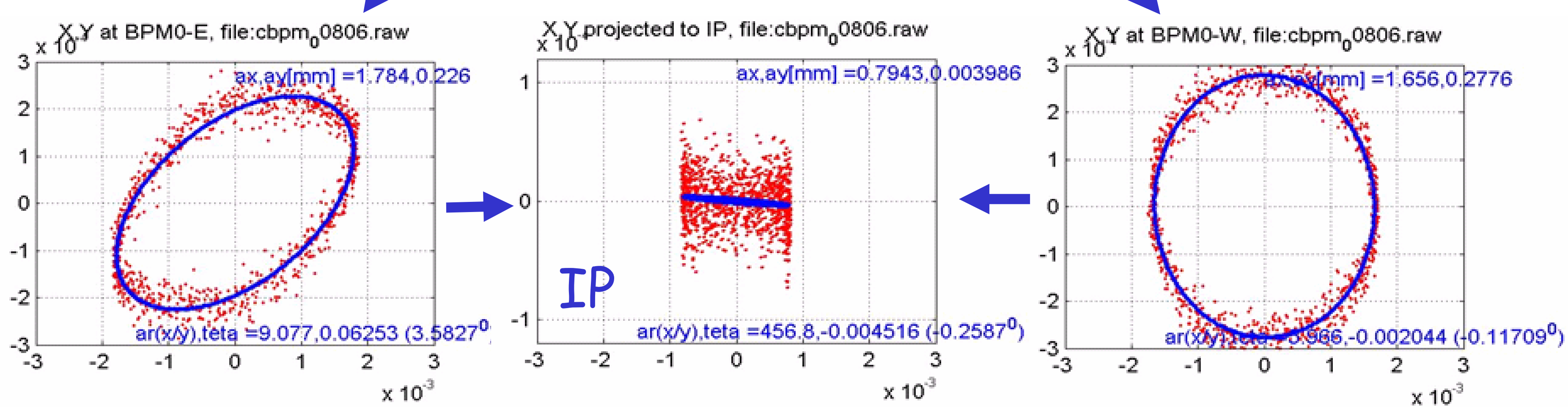


Coupling diagnostics

1000 turns turn-by-turn data with beam shaken in horizontal plane, horizontal scale 1 mm/div, vertical 0.1mm/div



$$\begin{pmatrix} x_{ip} \\ x'_{ip} \\ y_{ip} \\ y'_{ip} \end{pmatrix} = (M) \begin{pmatrix} x_e \\ x_w \\ y_e \\ y_w \end{pmatrix}$$



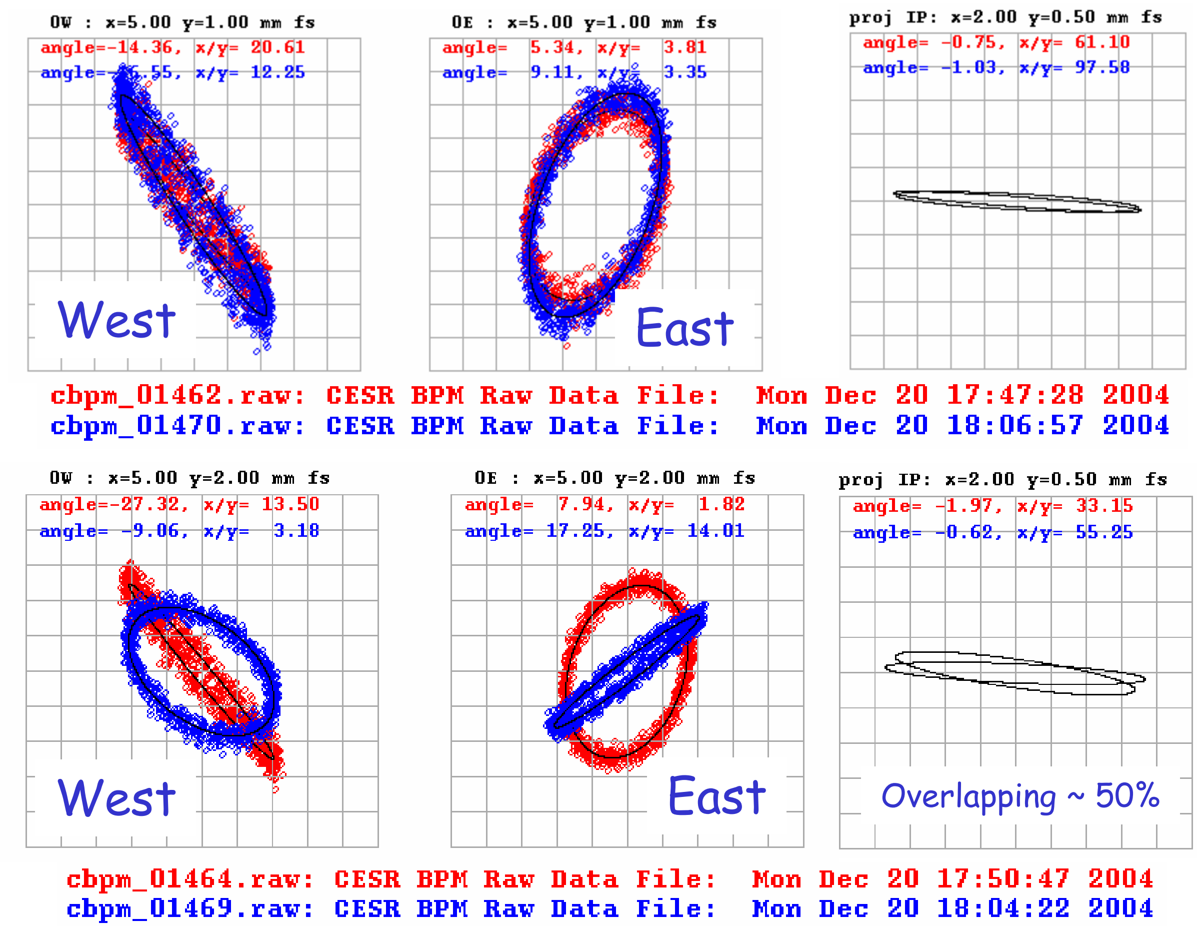
Coupling differential problem

Local coupling in arcs with all skew-sextupoles turned OFF

Pretzel OFF →

E+ beam - red
E- beam - blue

Pretzel ON →



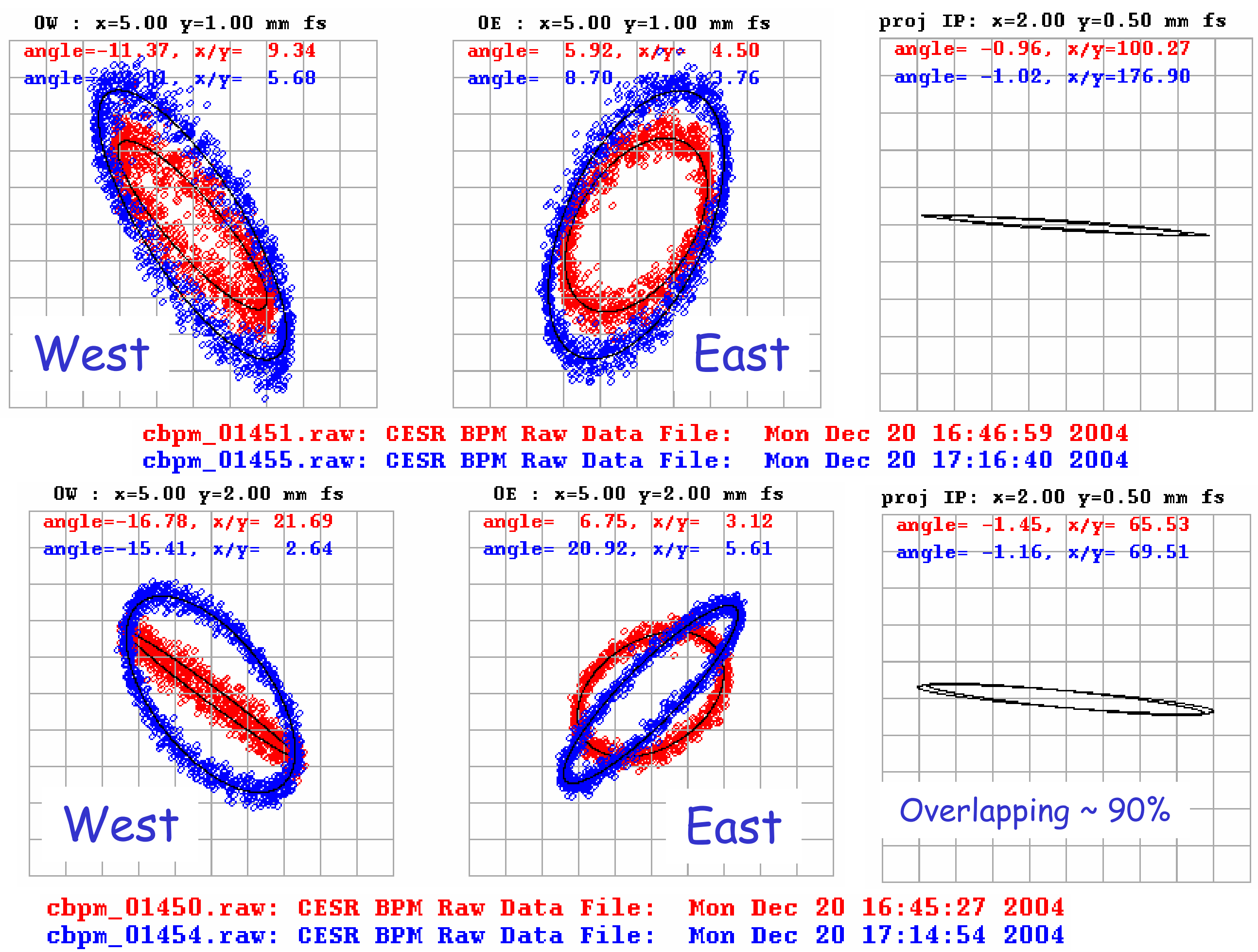
Coupling differential problem

Local coupling in arcs with skew-sextupoles empirically optimized for luminosity

Pretzel OFF →

E+ beam - red
E- beam - blue

Pretzel ON →



High synchrotron tune effect

Advanced phase modulation between collisions

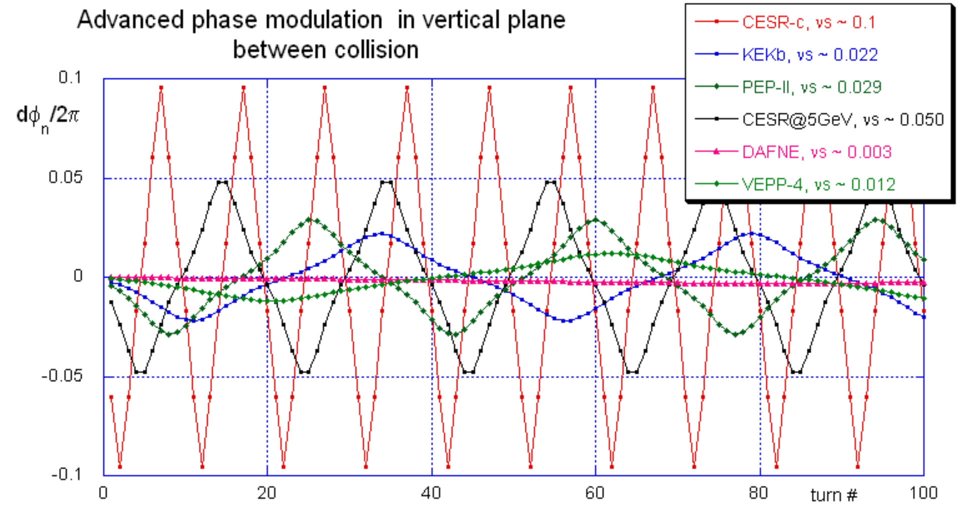
$$\beta(s)=\beta^*\left(1+\frac{s^2}{\beta^{*2}}\right);\quad \varphi(s)=\int_0^s\frac{d\tilde{s}}{\beta(\tilde{s})}$$

$s_n=\sigma_z\dfrac{a_z}{2}\cos(2\pi\nu_s\cdot n)$ - longitudinal position of collision as a function of turn number

Phase modulation between collisions:

$$\frac{\varphi(s_{n+1})-\varphi(s_n)}{2\pi}\approx\frac{1}{2\pi}\arctan\left(\frac{\sigma_z a_z}{2\beta^*}\cos\left(2\pi\nu_s\cdot(n+1)\right)\right)-\frac{1}{2\pi}\arctan\left(\frac{\sigma_z a_z}{2\beta^*}\cos(2\pi\nu_s\cdot n)\right)\approx$$

$$\approx\boxed{\frac{\nu_s\sigma_z}{\beta^*}}\frac{a_z}{2}\cos(2\pi\nu_s\cdot n)\frac{1}{\left(1+\frac{a_z^{\,2}}{8}\left(\frac{\sigma_z}{\beta^*}\right)^2\right)}$$



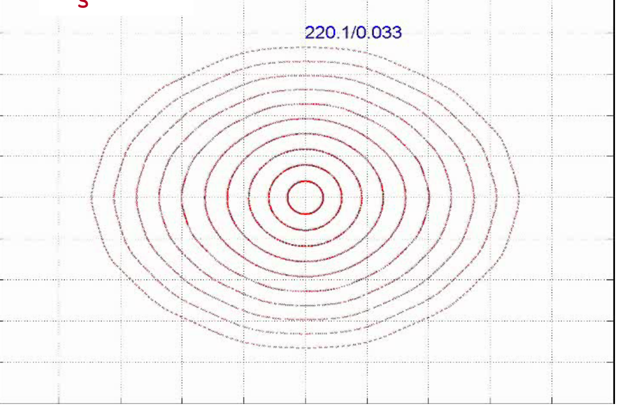
	ν_s	$d\phi_v max/2\pi$ (for $1\sigma z$ particles)	$\xi_v max$
CESR-c	**0.1**	**0.05**	**0.025**
KEKB	**0.022**	**0.011**	**0.08**
PEP-II	**0.029**	**0.014**	**0.07**
CESR@ 5GeV	**0.05**	**0.025**	**0.06**
DAFNE	**0.003**	**0.0015**	**0.045**
VEPP-4	**0.012**	**0.006**	**0.06**

High synchrotron tune effect

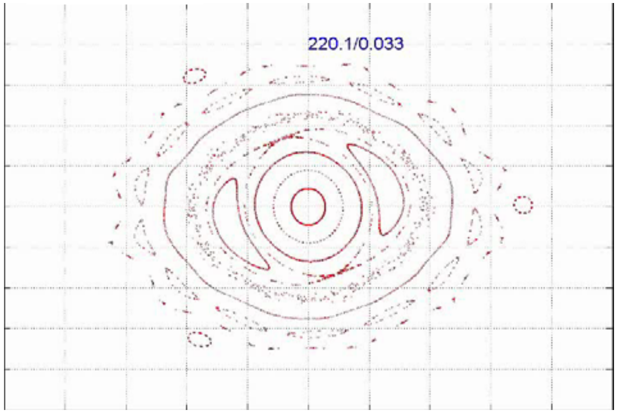
Simple tracking model with beam-beam interaction and phase modulation.

$\xi = 0.033$, $\sigma/\beta = 1$, a_s=1

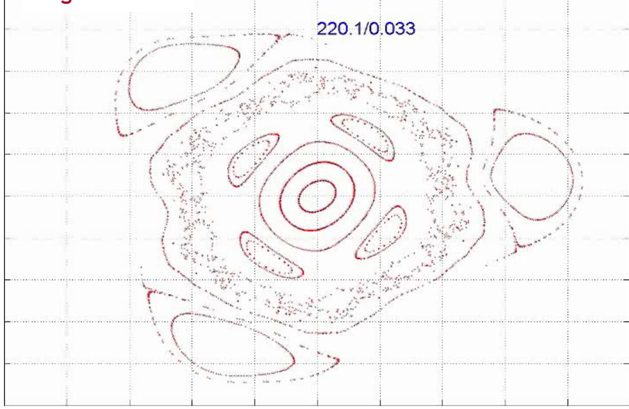
ν_s= 0.0



ν_s= 0.05

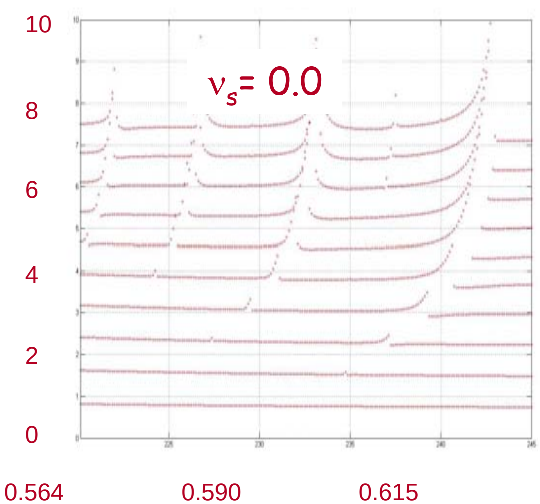


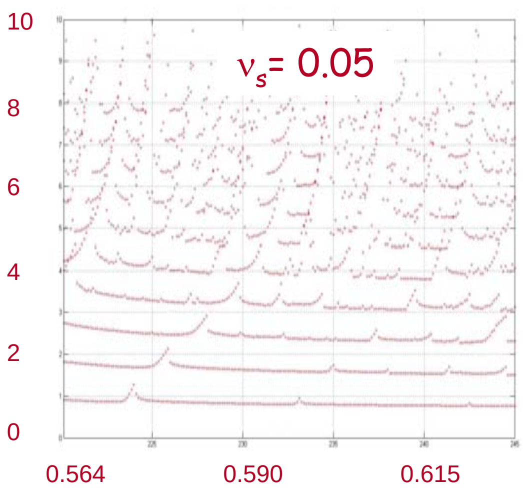
ν_s= 0.10

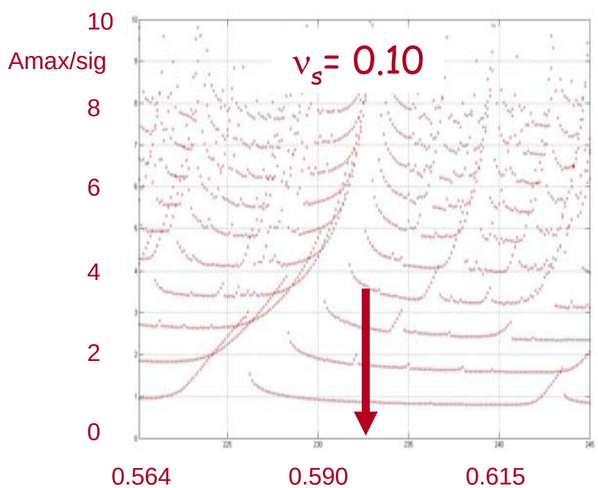


+-10σ full scale

Phase space for various tune and ν_s ; ↓ - CESR-c working point







How we can change phase modulation in machine ?

Reduce RF voltage. It will low νs , but in the same time it will increase σ_z. To keep σ_z/β_y constant we should increase β_y.

In experiment:

$$\nu_s \quad 0.1 \Rightarrow 0.05 \ \text{(reduced RF voltage);}$$

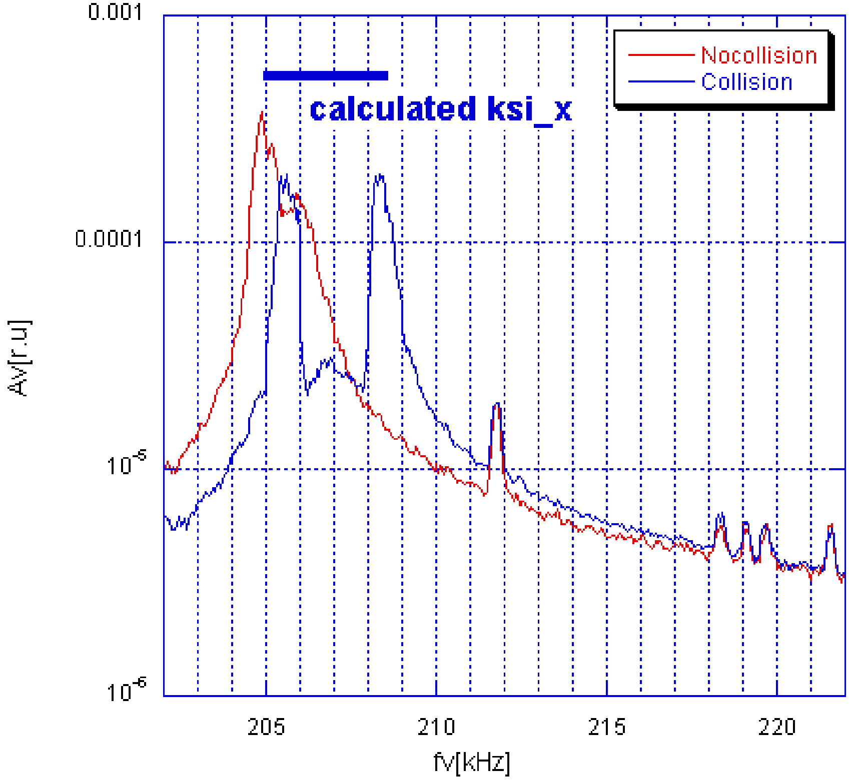
$$\sigma_z \quad 12mm \Rightarrow 24mm, \text{ have to change } \beta_{\text{y}} \text{ from 12 to 24mm.}$$

High synchrotron tune effect (experimental study)

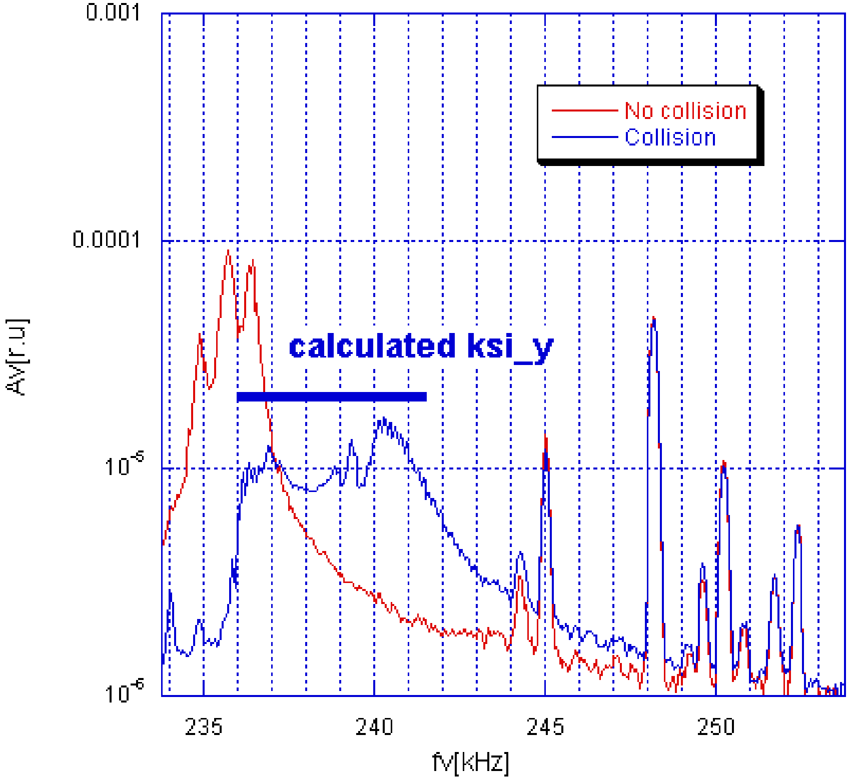
Beam-beam performance estimation from the beam spectrum measurement.

Spectrum of non-colliding and colliding beams

Horizontal plane

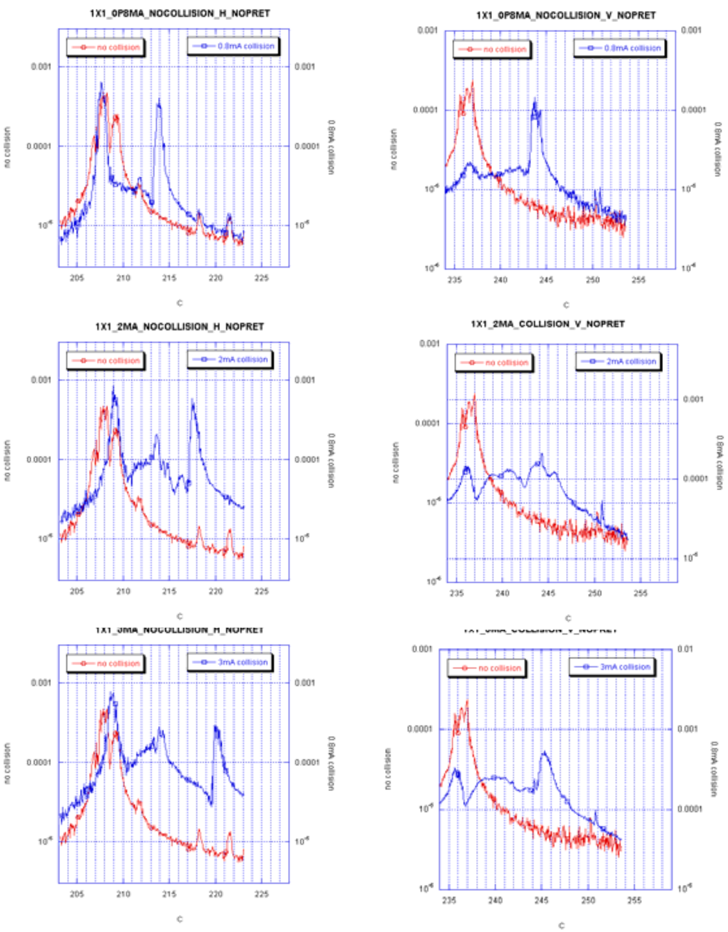


Vertical plane



High synchrotron tune effect (experimental study)

High fs optics: fs = 39kHz (ν_s=0.100), β_y=12.7mm, σ_z=12mm, $\nu_s\sigma_z/\beta_y$=0.0944



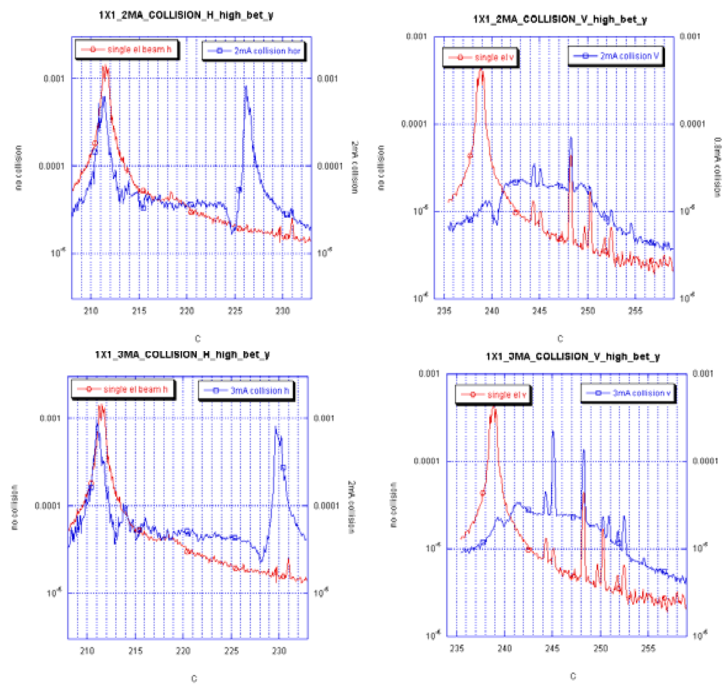
0.8x0.8mA collision
ξ_x ~ 0.015
ξ_y ~ 0.020

2.0x2.0mA collision
ξ_x ~ 0.026
ξ_y ~ 0.025

3.0x3.0mA collision
ξ_x ~ 0.041
ξ_y ~ 0.025

$\xi_{y,\,max}$ ~ 0.025

Low fs optics: fs = 18kHz, (ν_s=0.046), β_y=21.5mm, σ_z=26mm, $\nu_s\sigma_z/\beta_y$ = 0.0558



2.0x2.0mA collision
ξ_x ~ 0.041
ξ_y ~ 0.030

3.0x3.0mA collision
ξ_x ~ 0.049
ξ_y ~ 0.033

$\xi_{y,\,max}$ ~ 0.033

**With lower $\nu_s\sigma_z/\beta_y$ we have reached higher ξ_y !
(but not luminosity)**

High synchrotron tune effect (conclusion)

The use of the RF voltage for the bunch length reduction leaded to the high synchrotron tune which resulted in high modulation of the vertical phase advance between collisions.

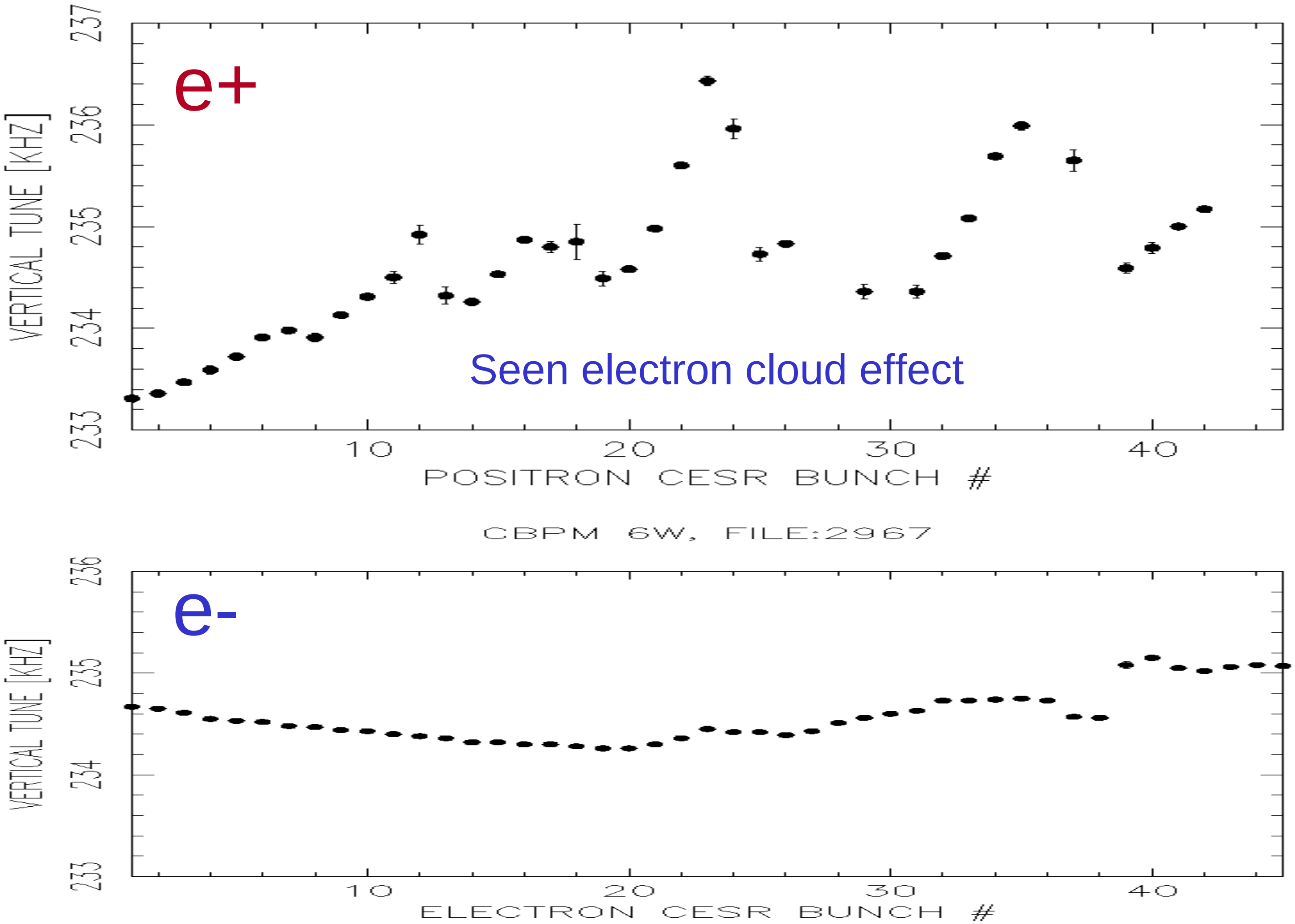
This degraded beam-beam performance.

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

Most recent beam dynamics study (single beam, long train)

45 bunches train, 4ns between bunches



Conclusion and future directions

- CESR completed HEP program. First beam 1979, last collision on March 3, 2008.
- 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
- ~30% of operating time CESR will be running as a syncrotron radiation source.

Credit to CESR Operations & Technical Support Groups

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

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