Recent Beam-beam Effects and Luminosity at VEPP-2000 Collider

Dmitry Shwartz
BINP, Novosibirsk

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Motivation of the round beam use in e^+e^- collider

Luminosity increase scenario:

- ✓ Number of bunches (i.e. collision frequency)
- ✓ Bunch-by-bunch luminosity

Round Beams:

$$L = \frac{\pi \gamma^2 \xi_x \xi_y \varepsilon_x f}{r_e^2 \beta_y^*} \left(1 + \frac{\sigma_y}{\sigma_x}\right)^2 \Rightarrow L = \frac{4\pi \gamma^2 \xi^2 \varepsilon f}{r_e^2 \beta^*}$$

✓Geometric factor: $(1+\sigma_y/\sigma_x)^2 = 4$

✓Beam-beam limit enhancement: $\xi \geq 0.1$

✓IBS for low energy? Better life time!

The concept of Round Colliding Beams

Axial symmetry of counter beam force together with x-y symmetry of transfer matrix should provide additional integral of motion (angular momentum $M_z = x'y - xy'$). Particle dynamics remains nonlinear, but becomes 1D.

Lattice requirements:

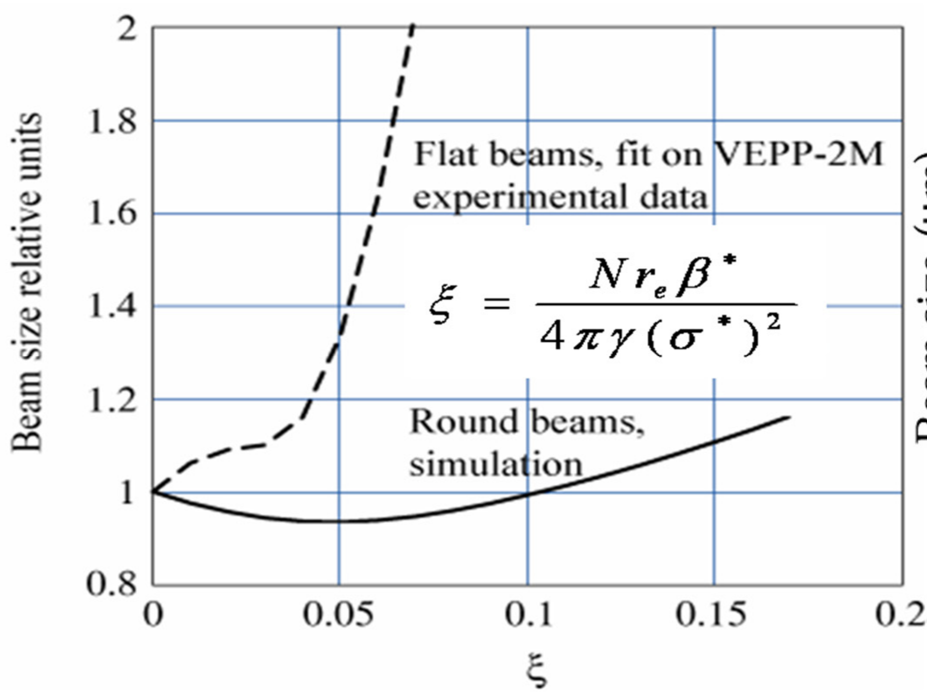
- Head-on collisions
- Small and equal β-functions at IP: $\beta_x = \beta_y$
- Equal beam emittances: $\varepsilon_x = \varepsilon_y$
- Equal fractional parts of betatron tunes: $\nu_x = \nu_y$

Round beam ($\beta_x = \beta_y$, $\varepsilon_x = \varepsilon_y$)

$M_x = M_y$ ($\beta_x = \beta_y$, $\nu_x = \nu_y$)

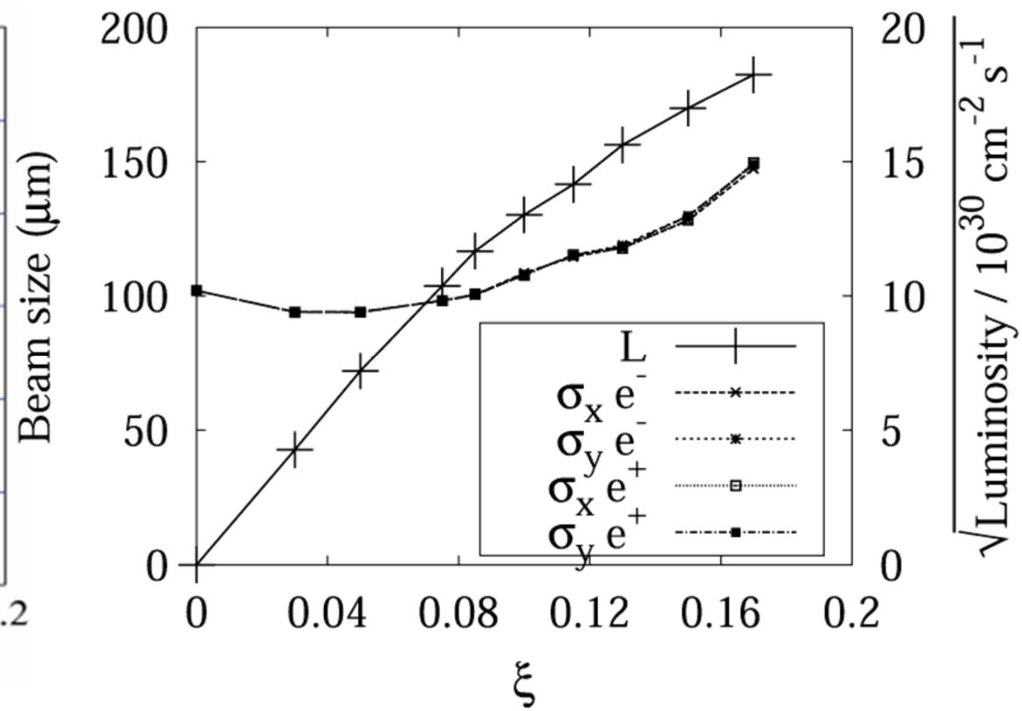
V.V.Danilov et al., EPAC'96, Barcelona, p.1149, (1996)

Historic beam-beam simulations



“Weak-Strong”

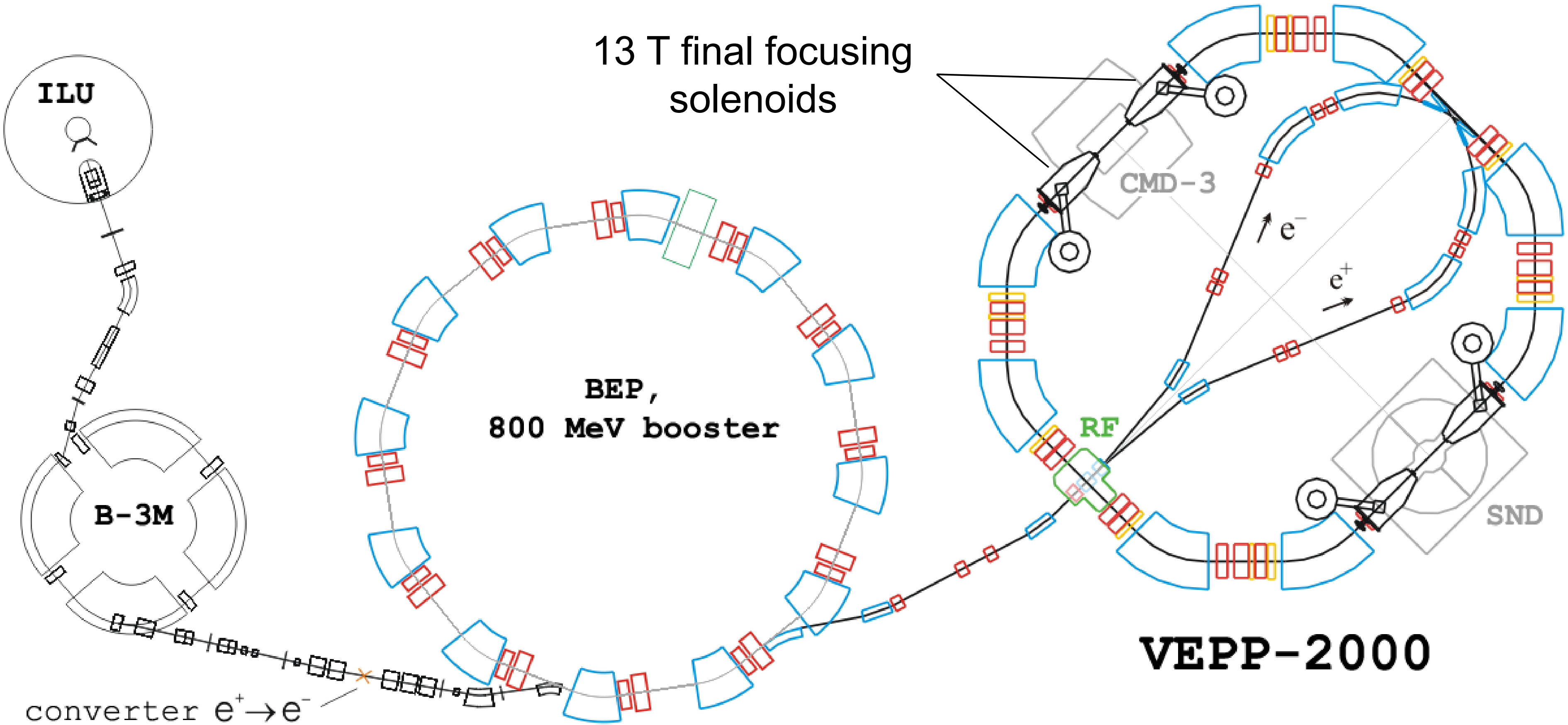
I.Nesterenko, D.Shatilov, E.Simonov, in Proc. of Mini-Workshop on “Round beams and related concepts in beam dynamics”, Fermilab, December 5-6, 1996.



“Strong-Strong”

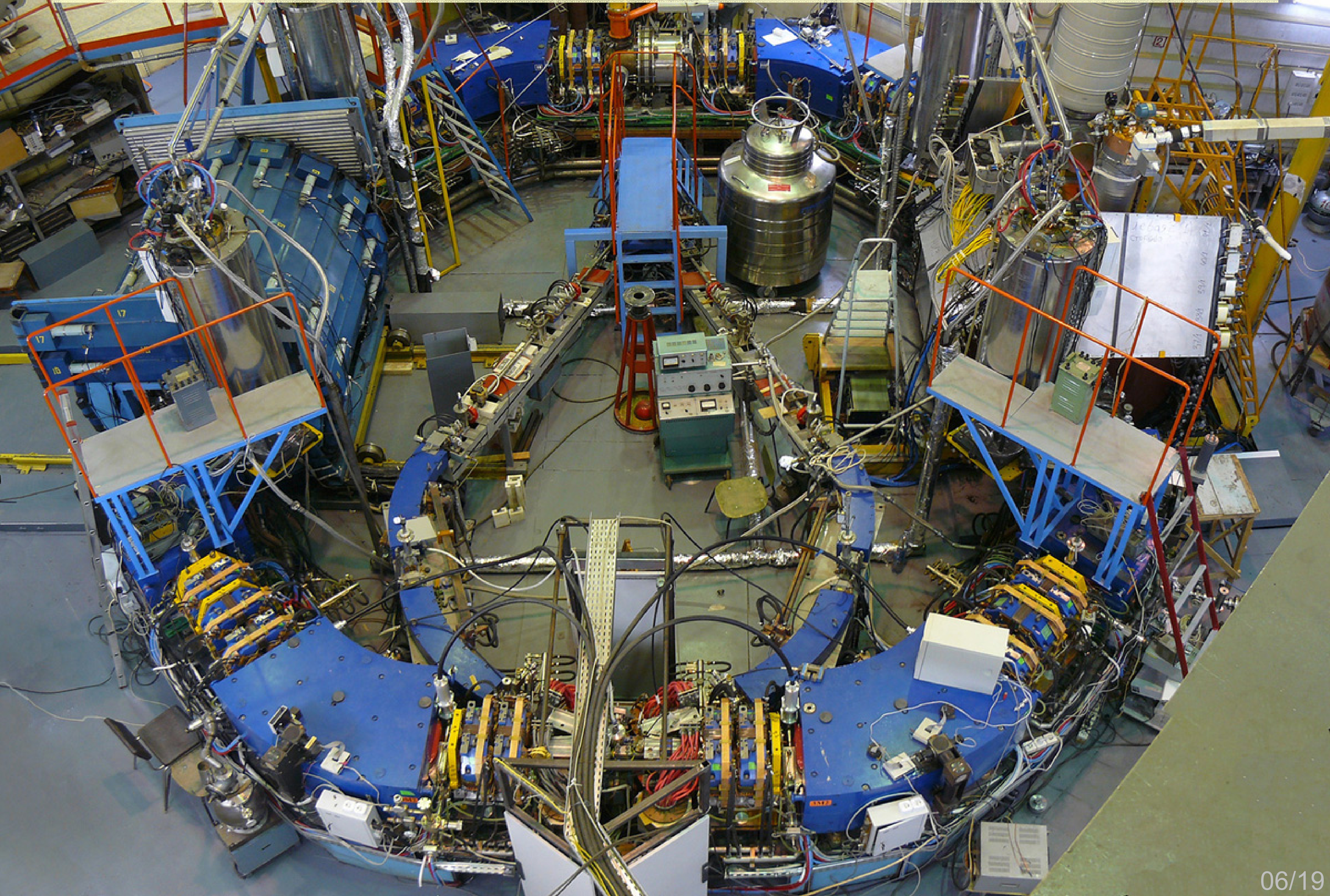
Beam size and luminosity vs. the nominal beam-beam parameter (A. Valishev, E. Perevedentsev, K. Ohmi, PAC’2003)

VEPP-2000 layout & parameters

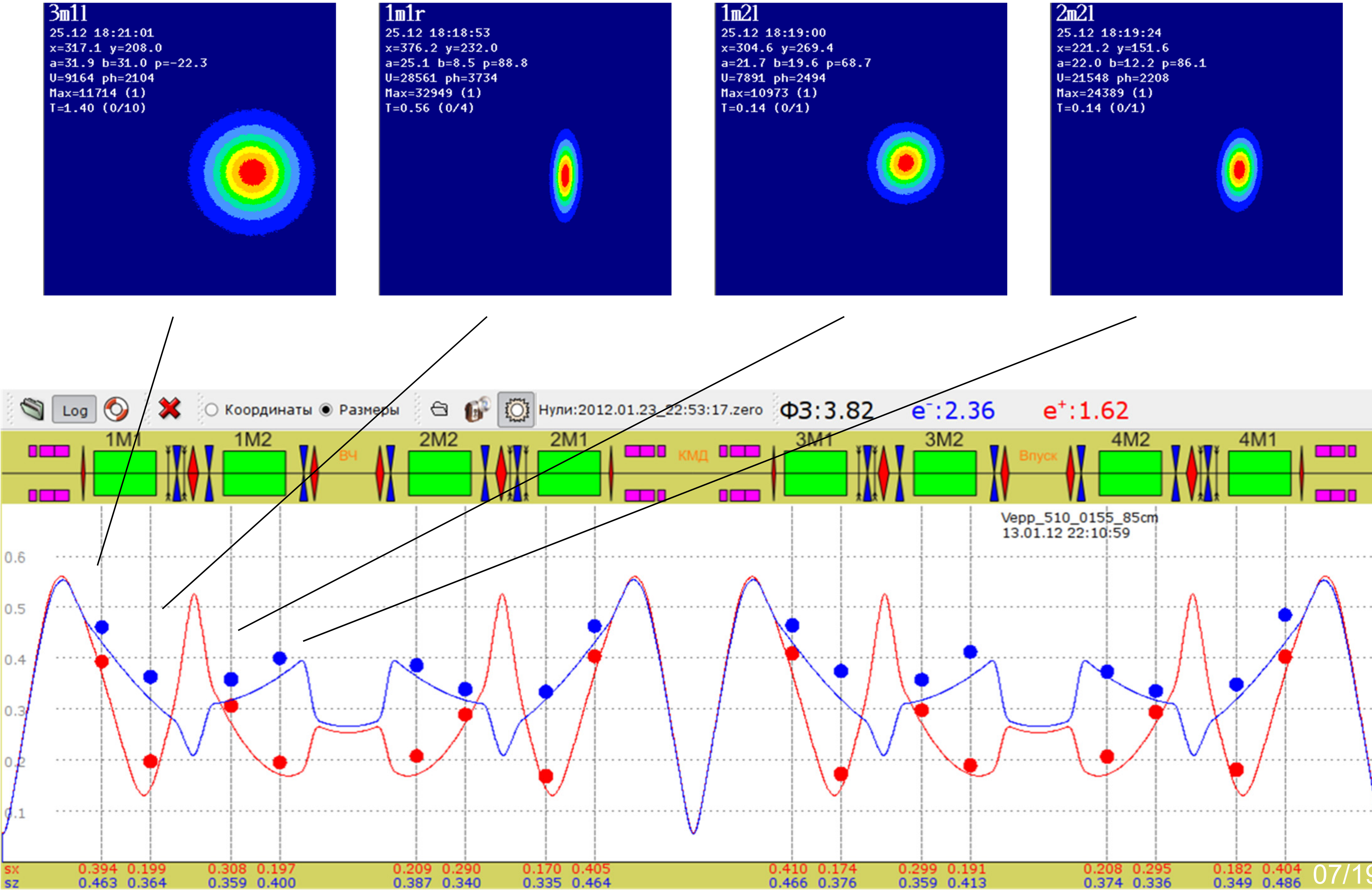


Main parameters @ 1GeV			
Circumference	24.388 m	Energy	200 ÷ 1000 MeV
Number of bunches	1	Number of particles	1×10^{11}
Betatron tunes	4.1/2.1	Beta-functions @ IP	8.5 cm
Beam-beam parameter	0.1	Luminosity	1×10^{32} cm^{-2}s^{-1}

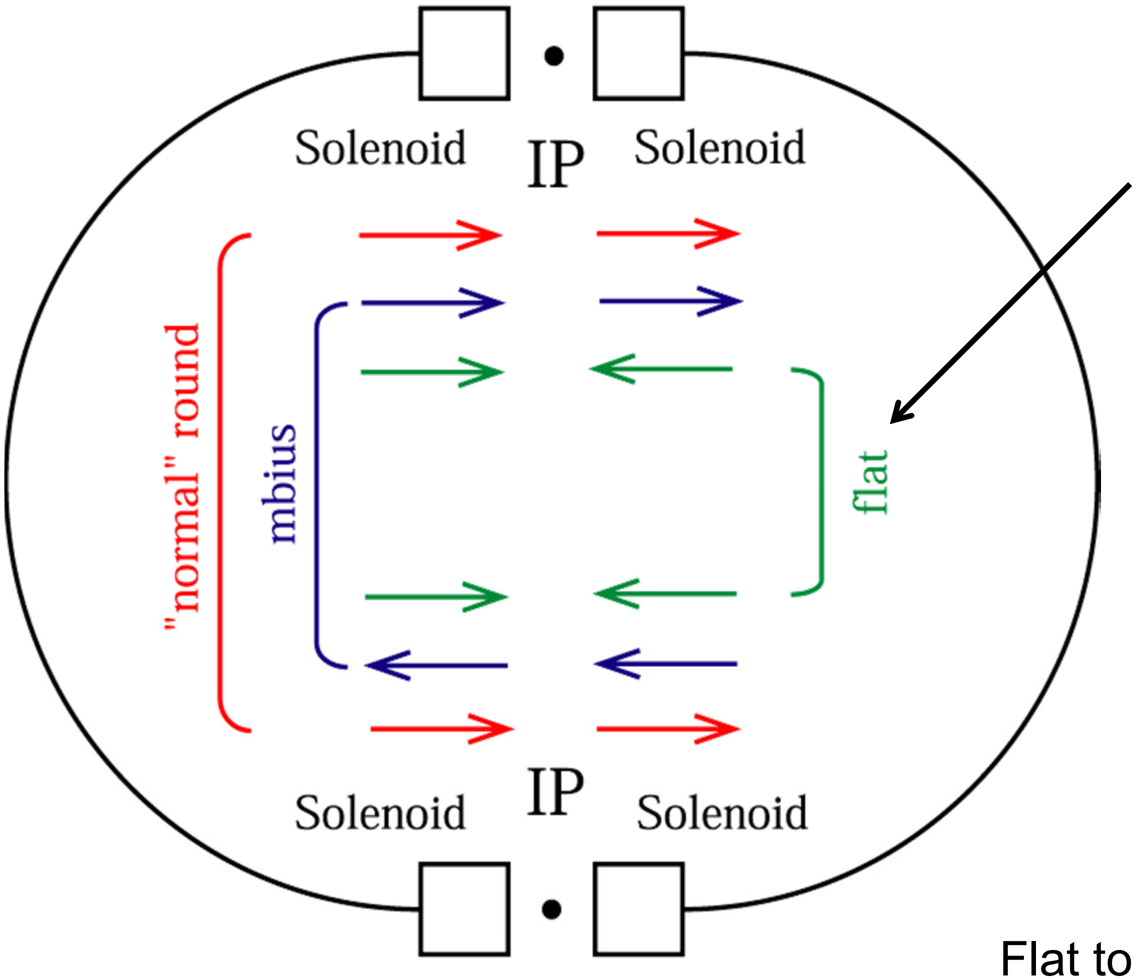
VEPP-2000



Beam size measurement by CCD cameras



Round Beams Options for VEPP-2000

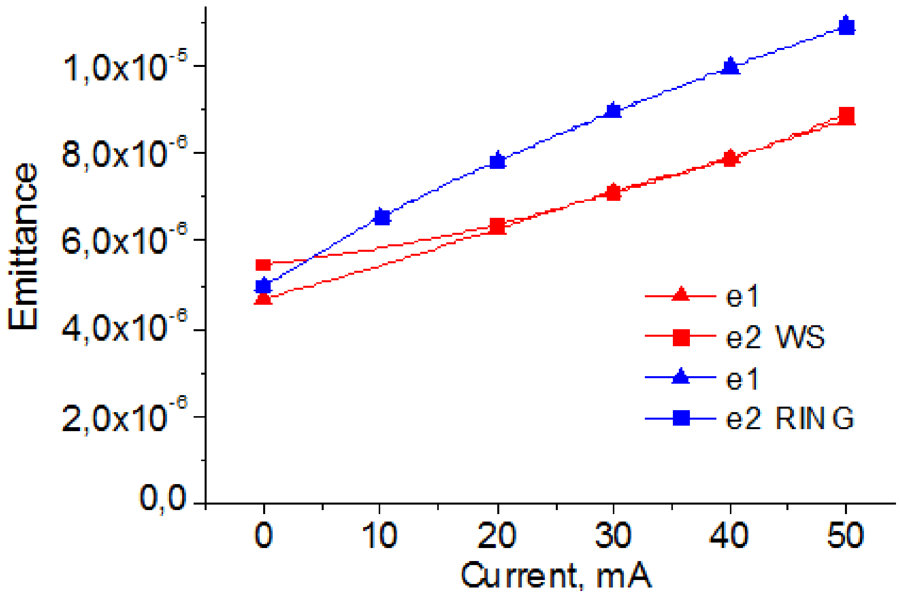


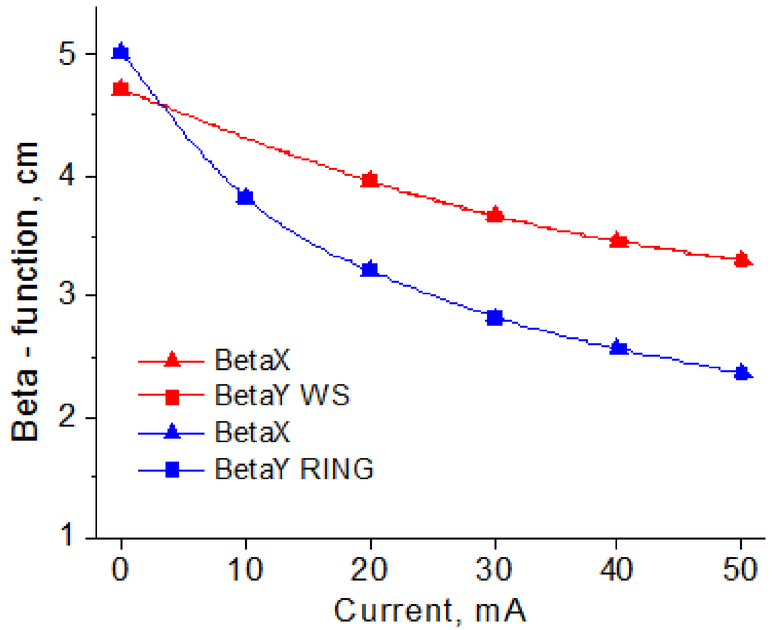
Round beam due to coupling resonance? The simplest practical solution!

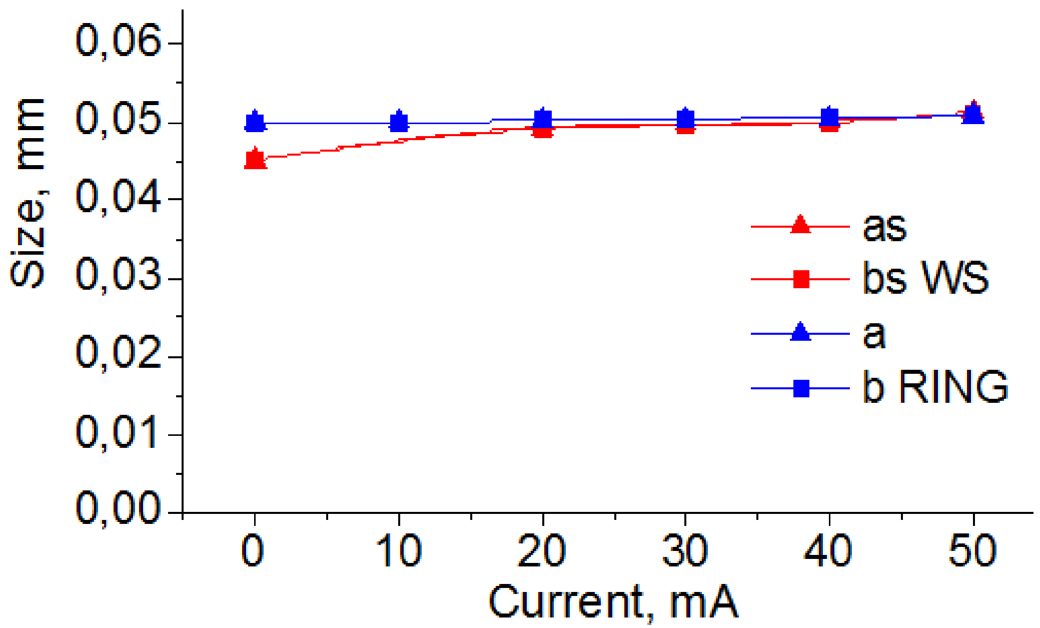
Both simulations and experimental tests showed insufficient dynamic aperture for regular work in circular modes options.

Flat to Round or Mobius change needs polarity switch in solenoids and new orbit correction.

Dynamic beta, emittance and size



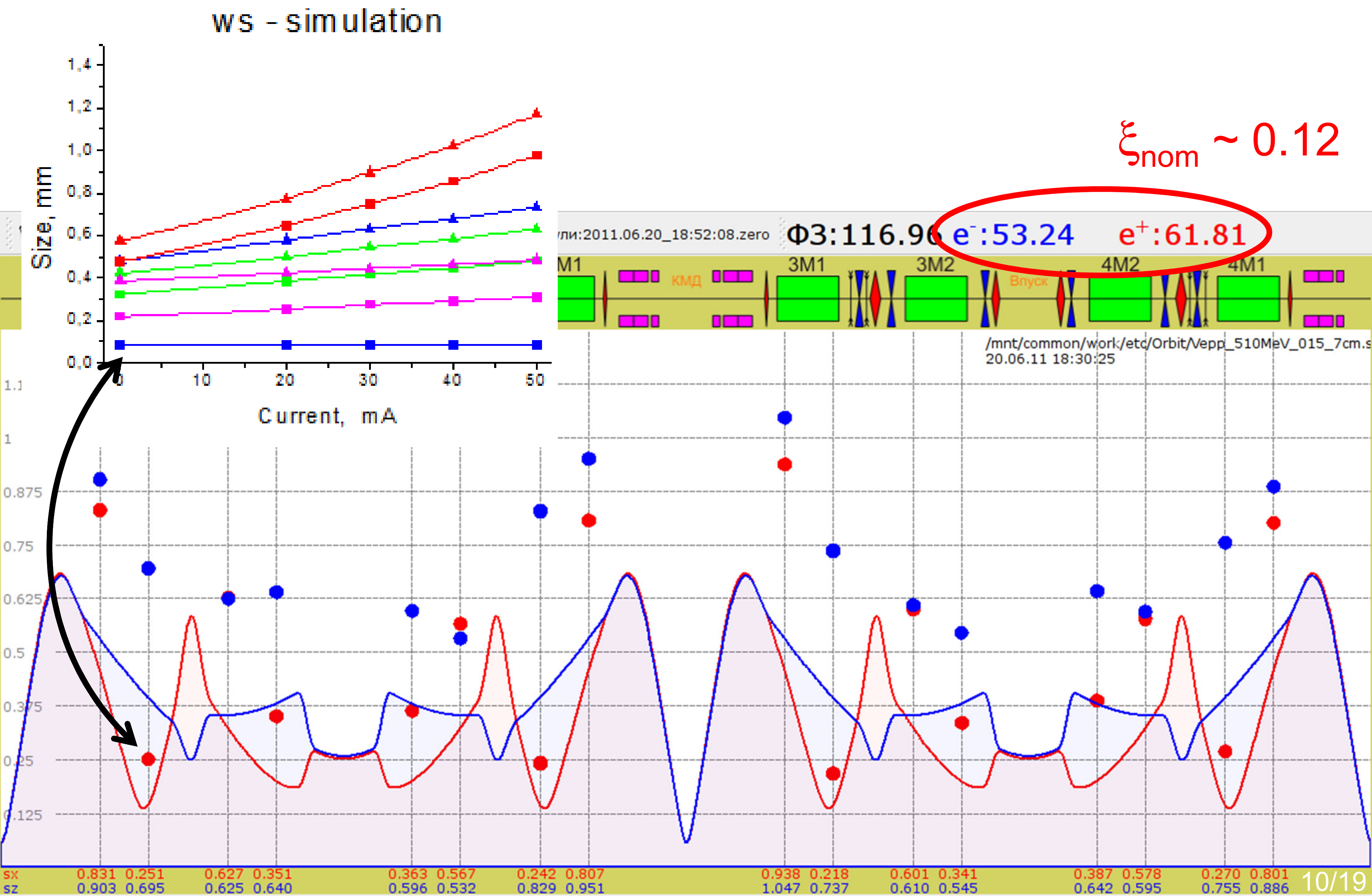




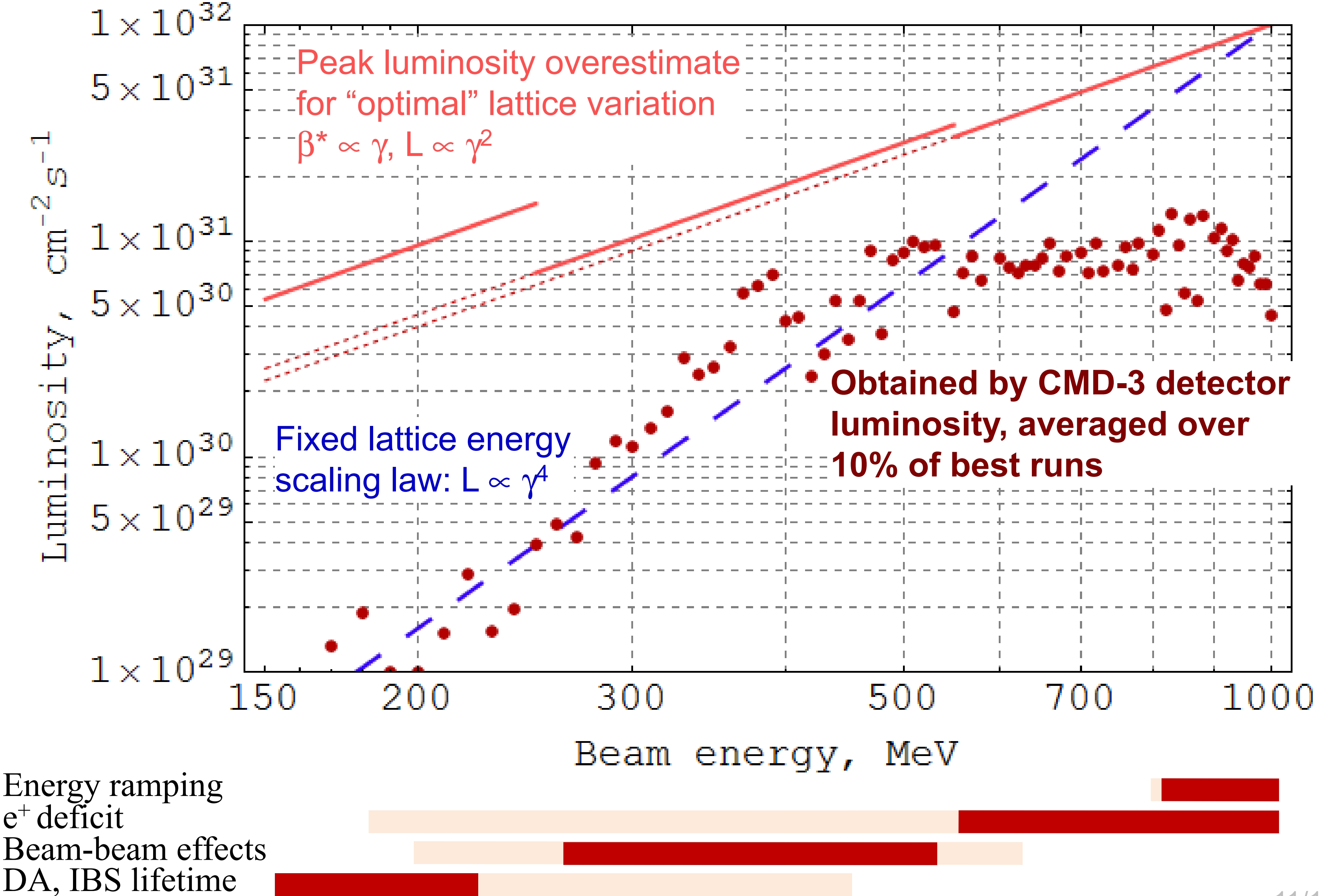
Simulations for E = 500 MeV.
50 mA corresponds to $\xi \sim 0.1$.

Invariance of beam sizes @ IP is the essential VEPP-2000 lattice feature.

Dynamic sizes at the beam-size monitors

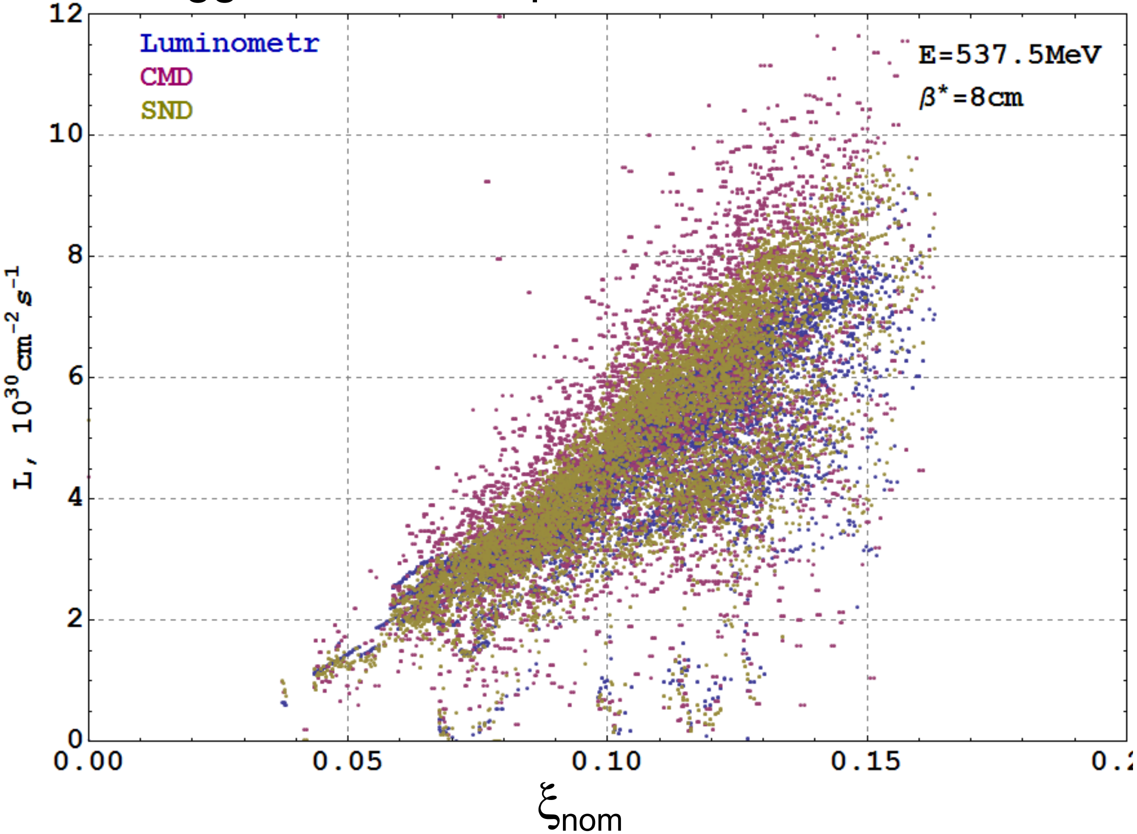


Luminosity vs. beam energy 2010-2013



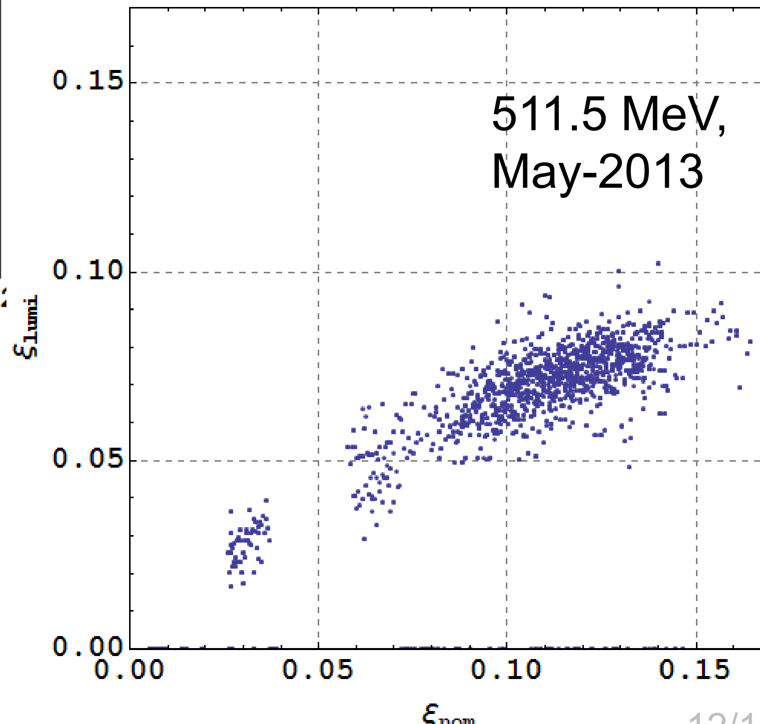
Luminosity & “achieved” ksi

Logged data example



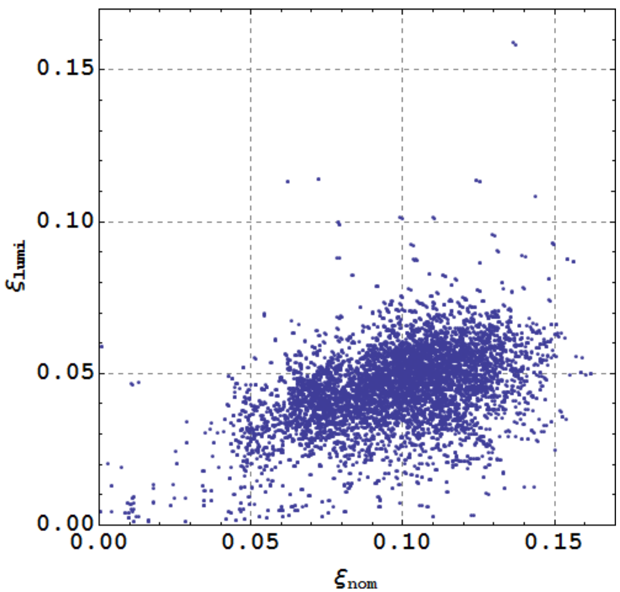
Luminosity monitoring: see A.Romanov et al. (IPAC’2014, THPME155)

$$\xi_{lumi} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{lumi}}$$



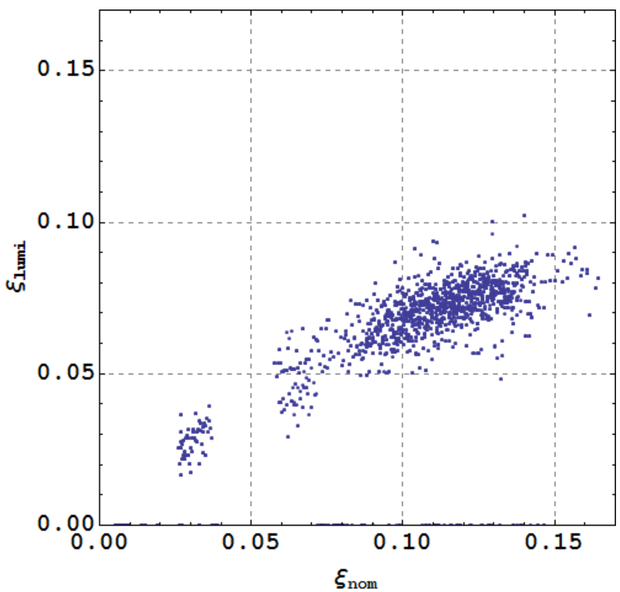
$$\xi_{nom} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{nom}}$$

Beam-beam parameter evolution



537.5 MeV, June-2011

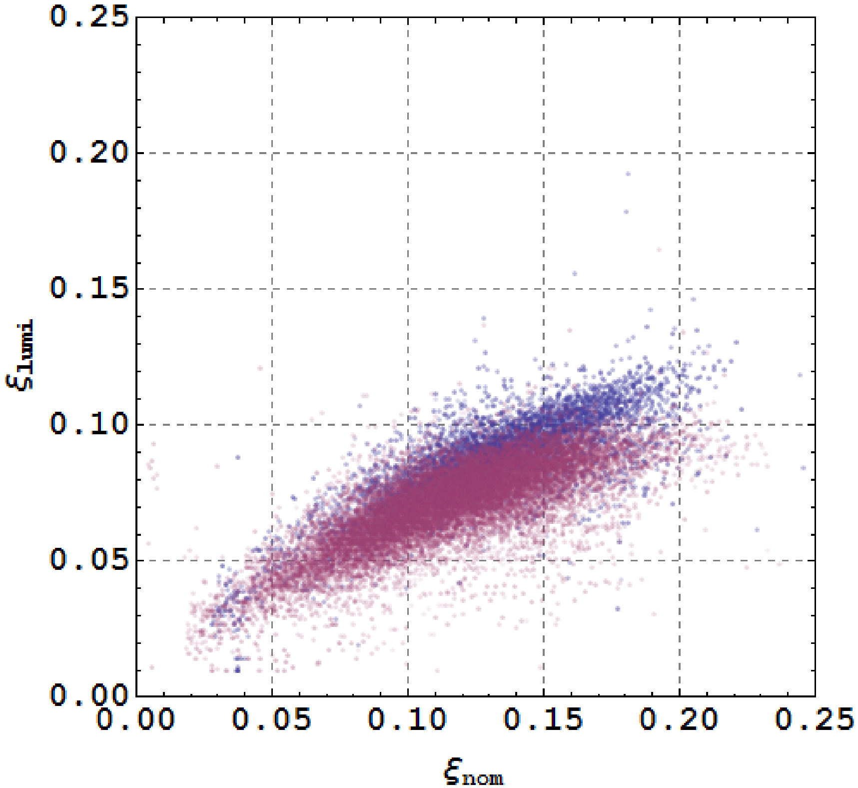
0.07



511.5 MeV, May-2013

0.08

392.5 MeV, June-2013



0.09 (purple points)

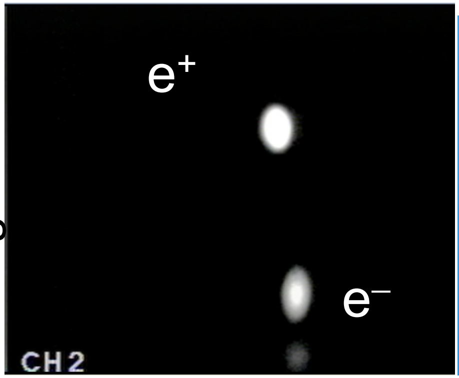
“Flip-flop” effect

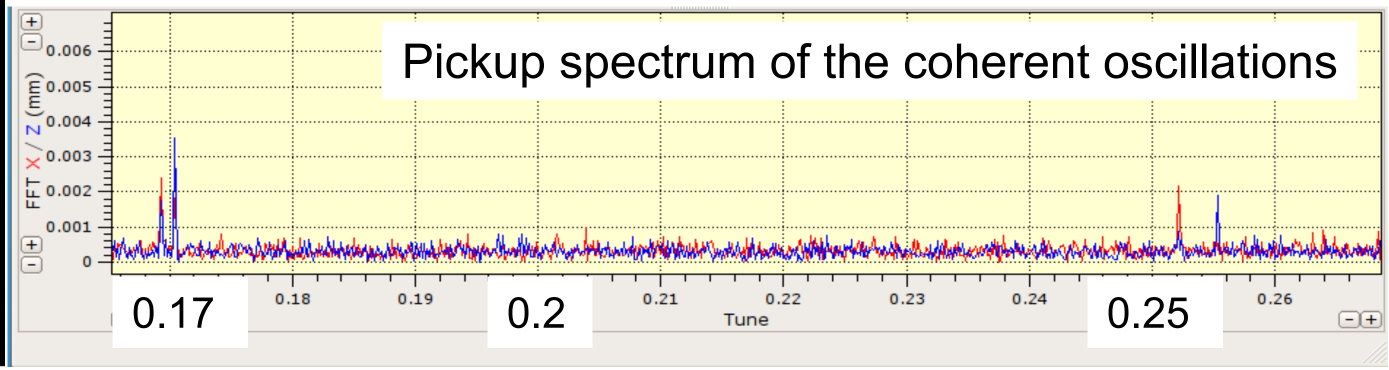
TV

σ

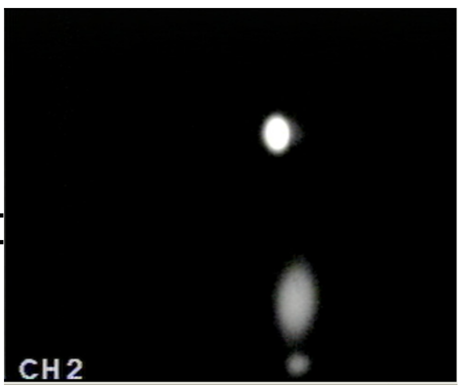
π

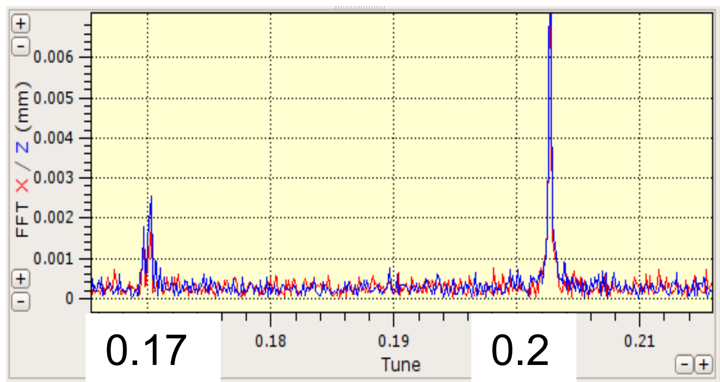
regular



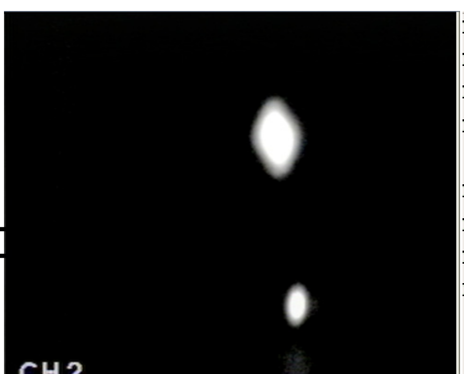


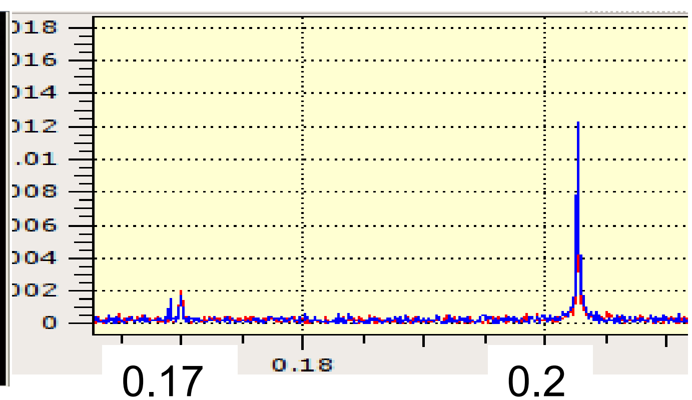
flipped e–





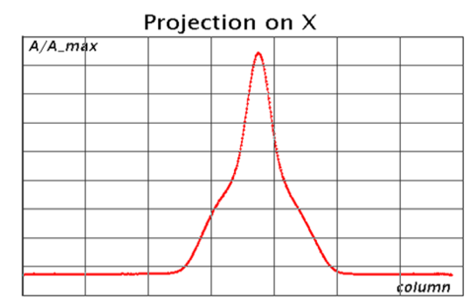
flipped e+





E = 240 MeV,

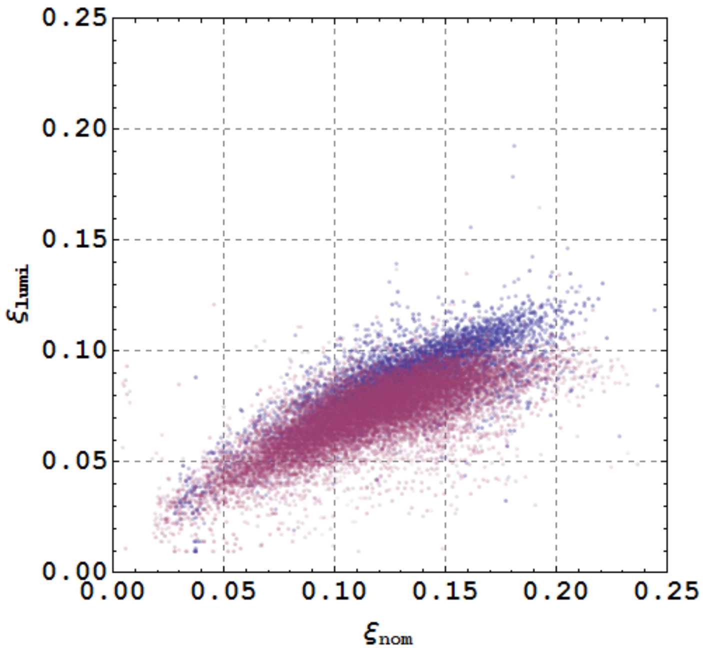
I_{beam} ~ 5×5 mA



Coherent beam-beam π-mode interaction with machine nonlinear resonances?

Beam-beam parameter crosscheck

BB-threshold improvement with beam lengthening

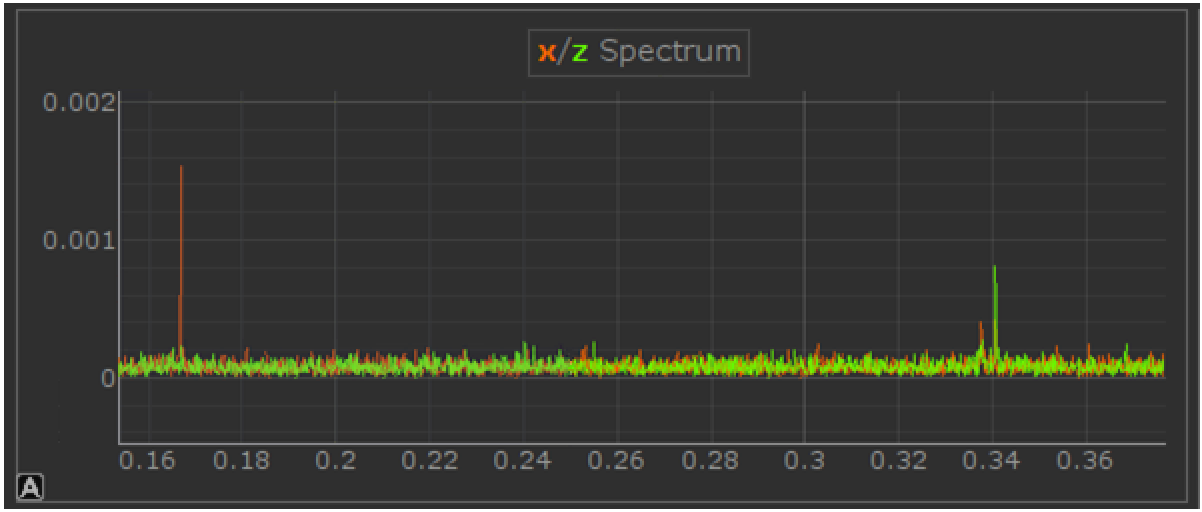


E= 392.5 MeV

35 kV (purple)

17 kV (blue)

Coherent oscillations spectrum

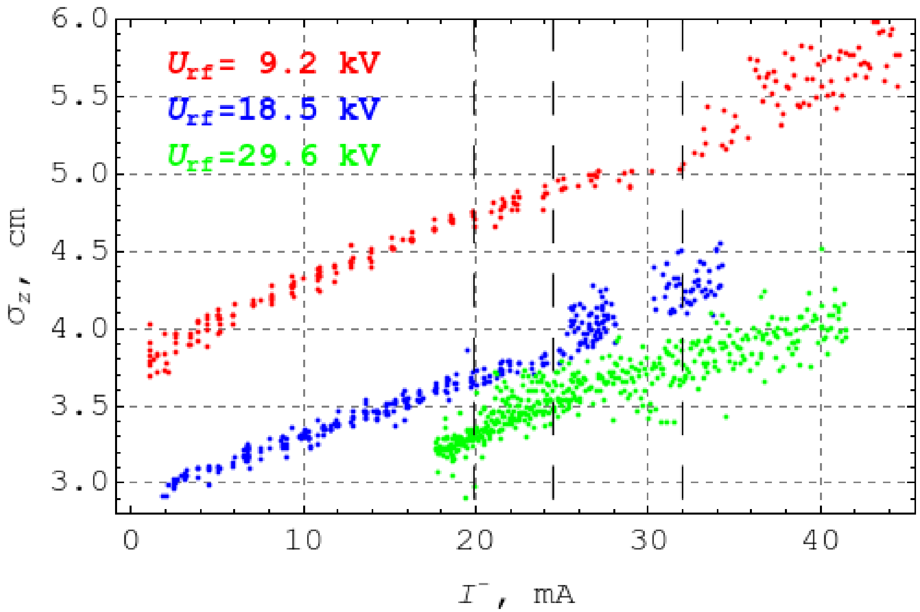


$$\Delta\nu = \arccos(\cos(\pi\nu_0) - 2\pi\xi\sin(\pi\nu_0))/\pi - \nu_0$$

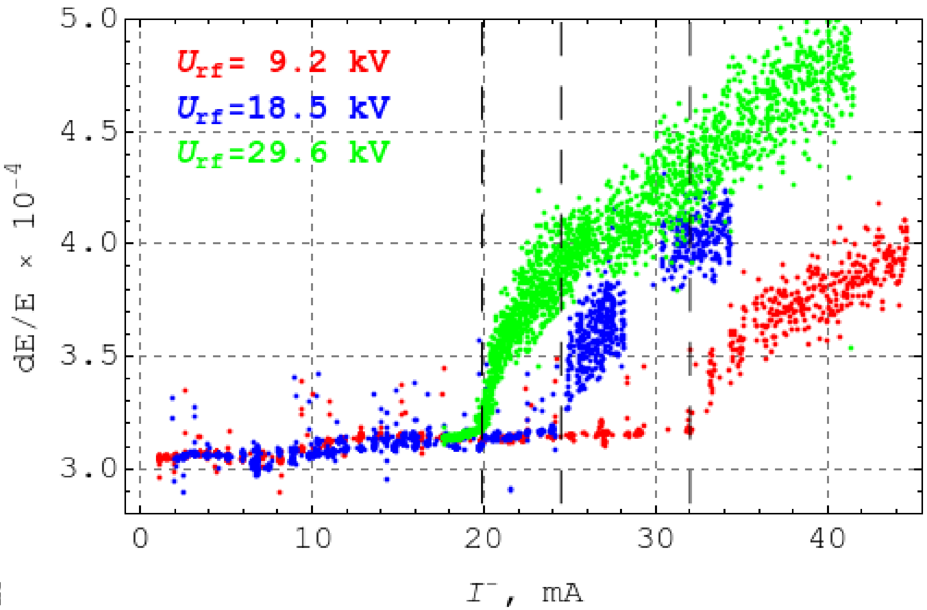
$\Delta\nu$ = 0.175 $\rightarrow$ ξ = **0.125**/IP

Yokoya factor is taken equal to 1, due to fast kick excitation, and only 8000 turns analysis.

Bunch lengthening: microwave inst.



Bunch length measurement with phi-dissector as a function of single beam current for different RF voltage @ 478 MeV.



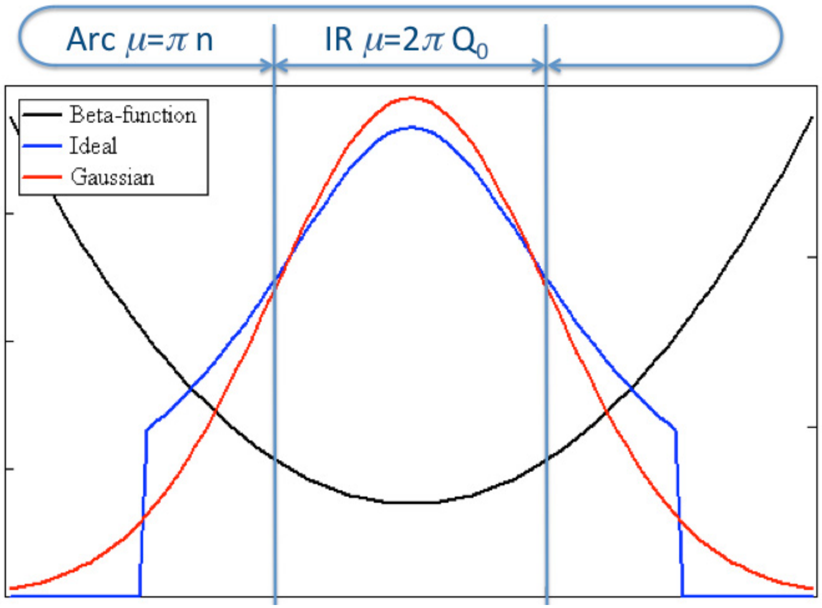
Energy spread dependence, restored from beam transverse profile measurements.

Integrable round beam?

(Danilov, Perevedentsev, 1997)

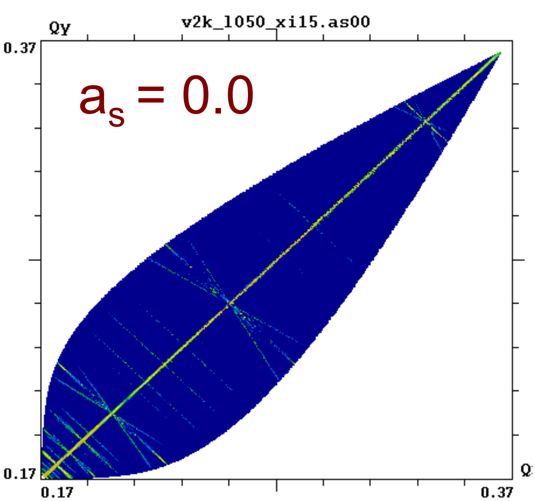
Proper profile of longitudinal distribution together with $\Delta\psi = n\pi$ betatron phase advance between IPs makes the Hamiltonian time-independent, i.e. integral of motion.

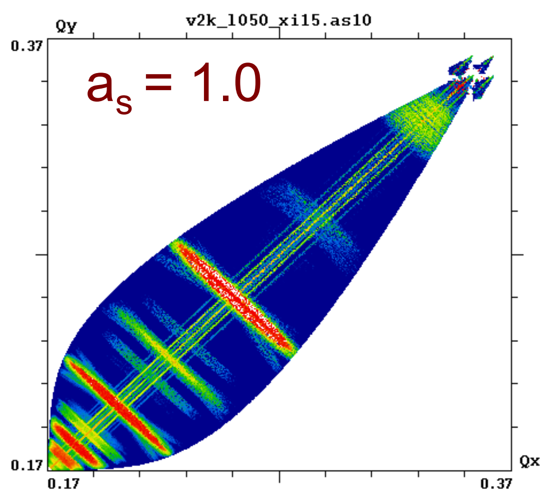
$$\rho(s) \propto \frac{1}{\beta(s)} \qquad \beta(s) = \beta^* + \frac{s^2}{\beta^*}$$



Synchrotron motion destroys full integrability

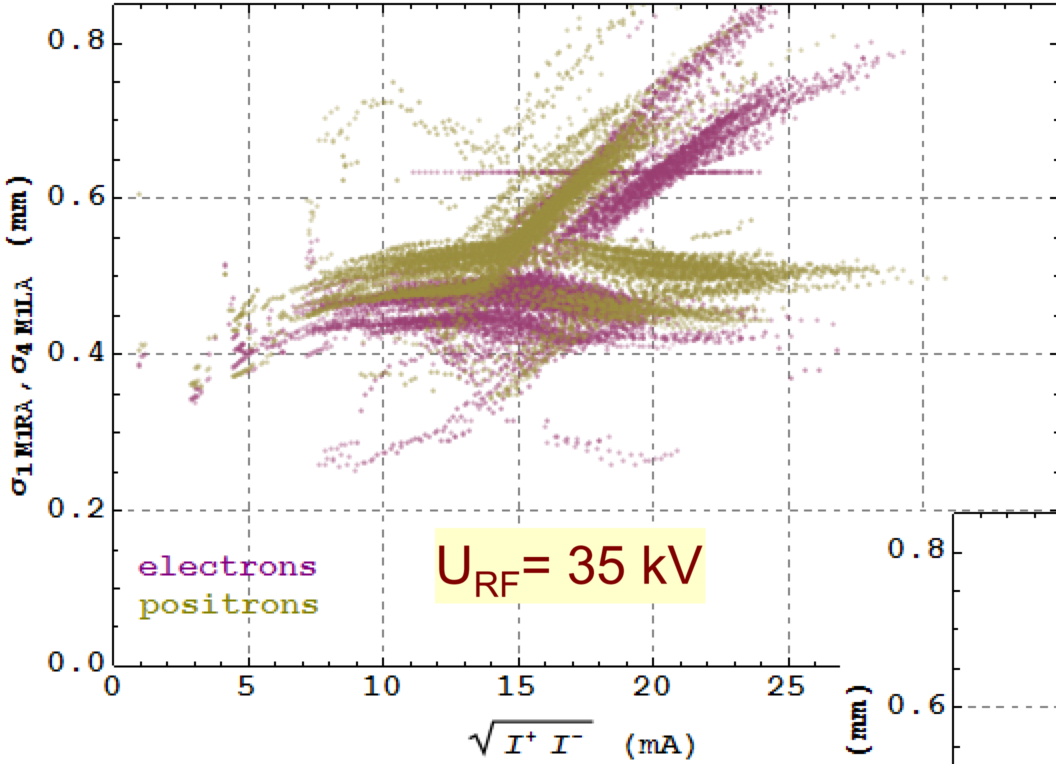
$\beta^* = 5$cm
$\sigma_s = 5$cm
$\xi = 0.15$

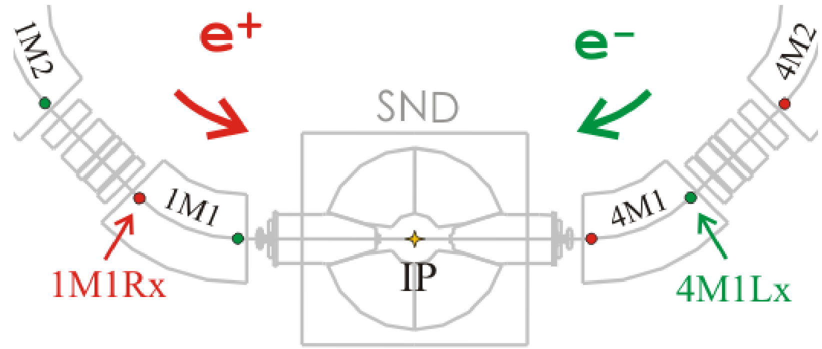




D.Shatilov, A.Valishev, NaPAC'13

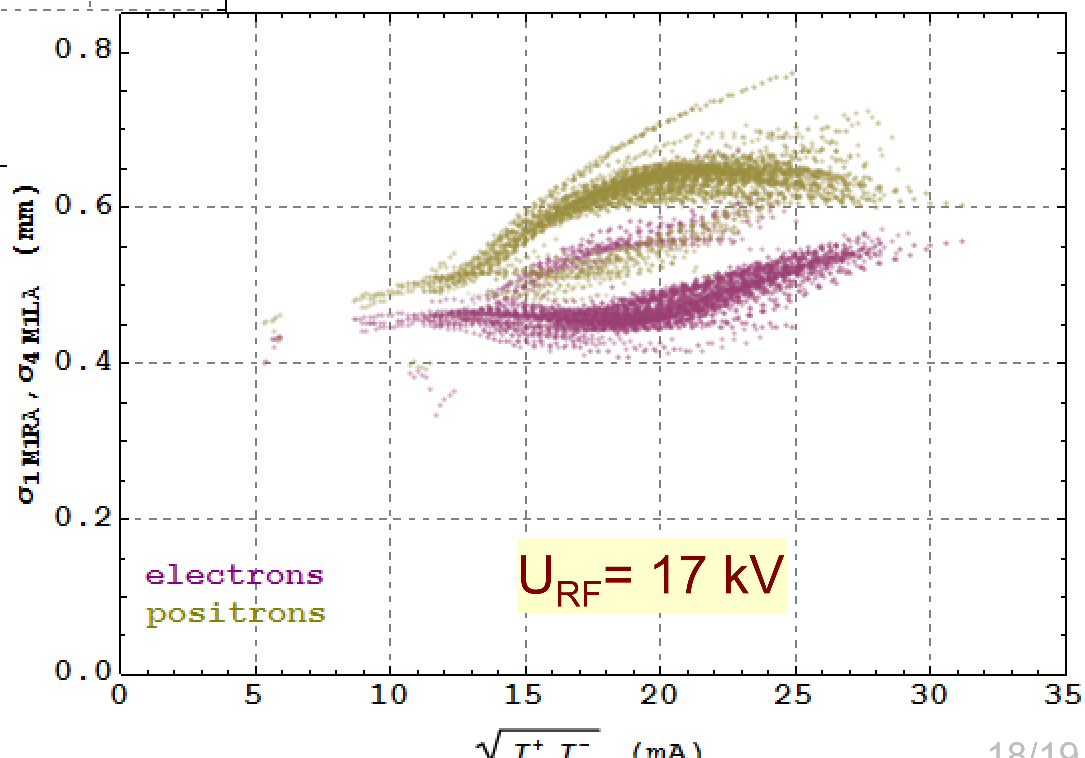
Beam sizes data analysis @ 392.5 MeV





I = 15 mA corresponds to ξ ~ 0.1

And we should keep in mind that bunch lengthening is current-dependent…

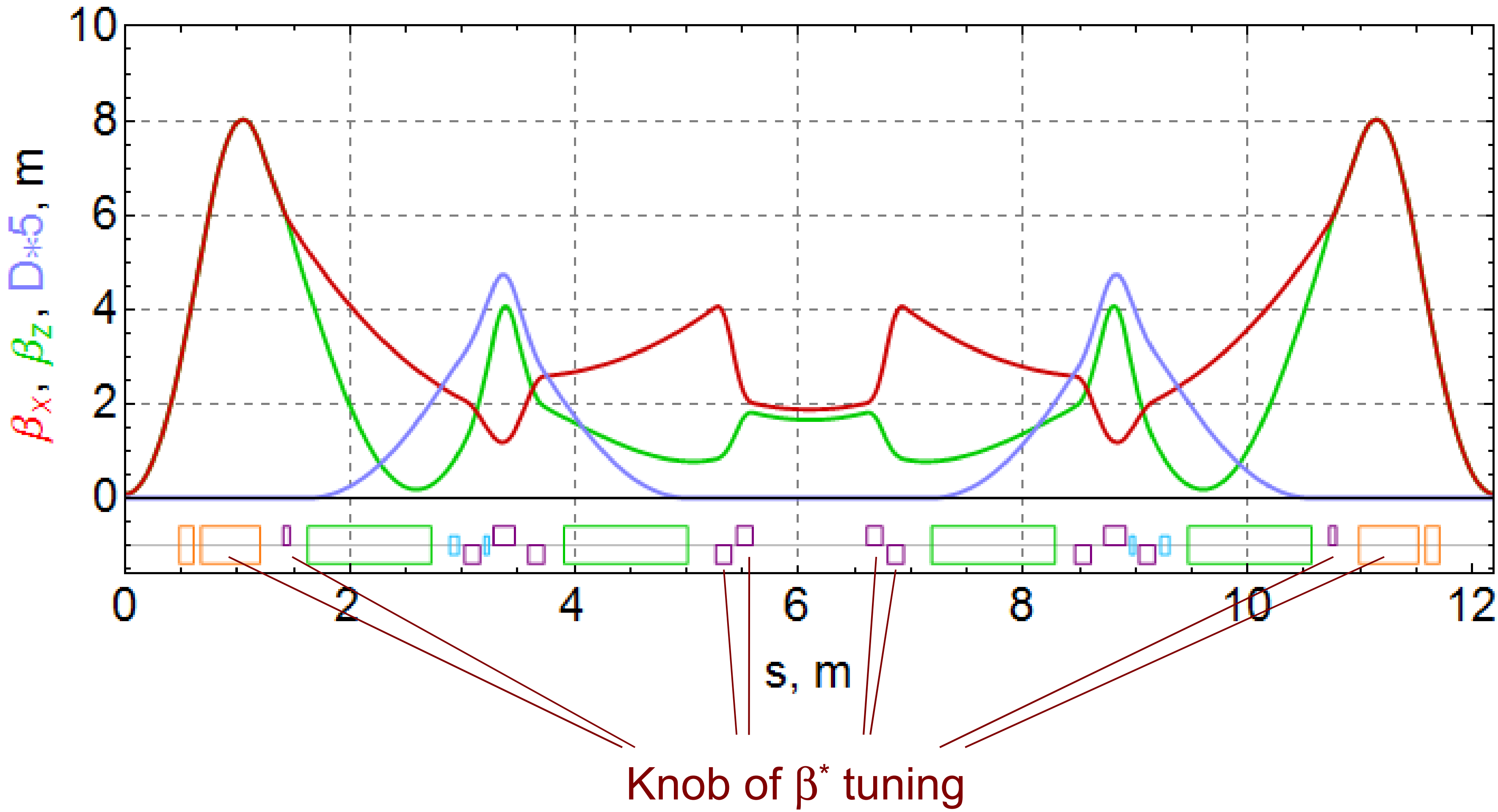


Summary

- Round beams give a serious luminosity enhancement.
- The achieved beam-beam parameter value at middle energies amounts to $\xi \sim 0.1$–0.12 during regular operation.
- “Long” bunch ($\sigma_l \sim \beta^*$) mitigates the beam-beam interaction restrictions, probably affecting on flip-flop effect.
- VEPP-2000 is taking data with two detectors across the wide energy range of 160–1000 MeV with a luminosity value two to five times higher than that achieved by its predecessor, VEPP-2M. Total luminosity integral collected by both detectors is about 110 pb^{-1}.
- To reach the target luminosity, injection chain upgrade was started.

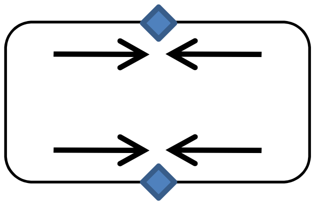
Backup slides

Lattice functions of half of the ring

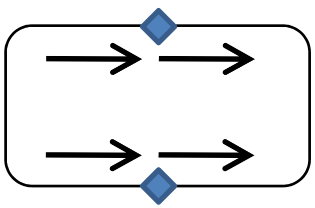


VEPP-2000 lattice special feature: β^* variation modifies radiative beam emittance in the way that $\beta^*\varepsilon = \sigma^{*2} = \text{inv}\,(\beta^*)$

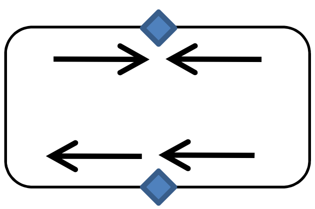
Working points for different options



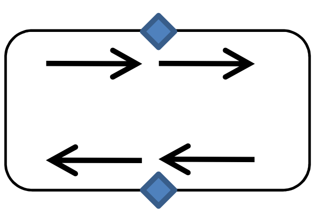
“Flat”



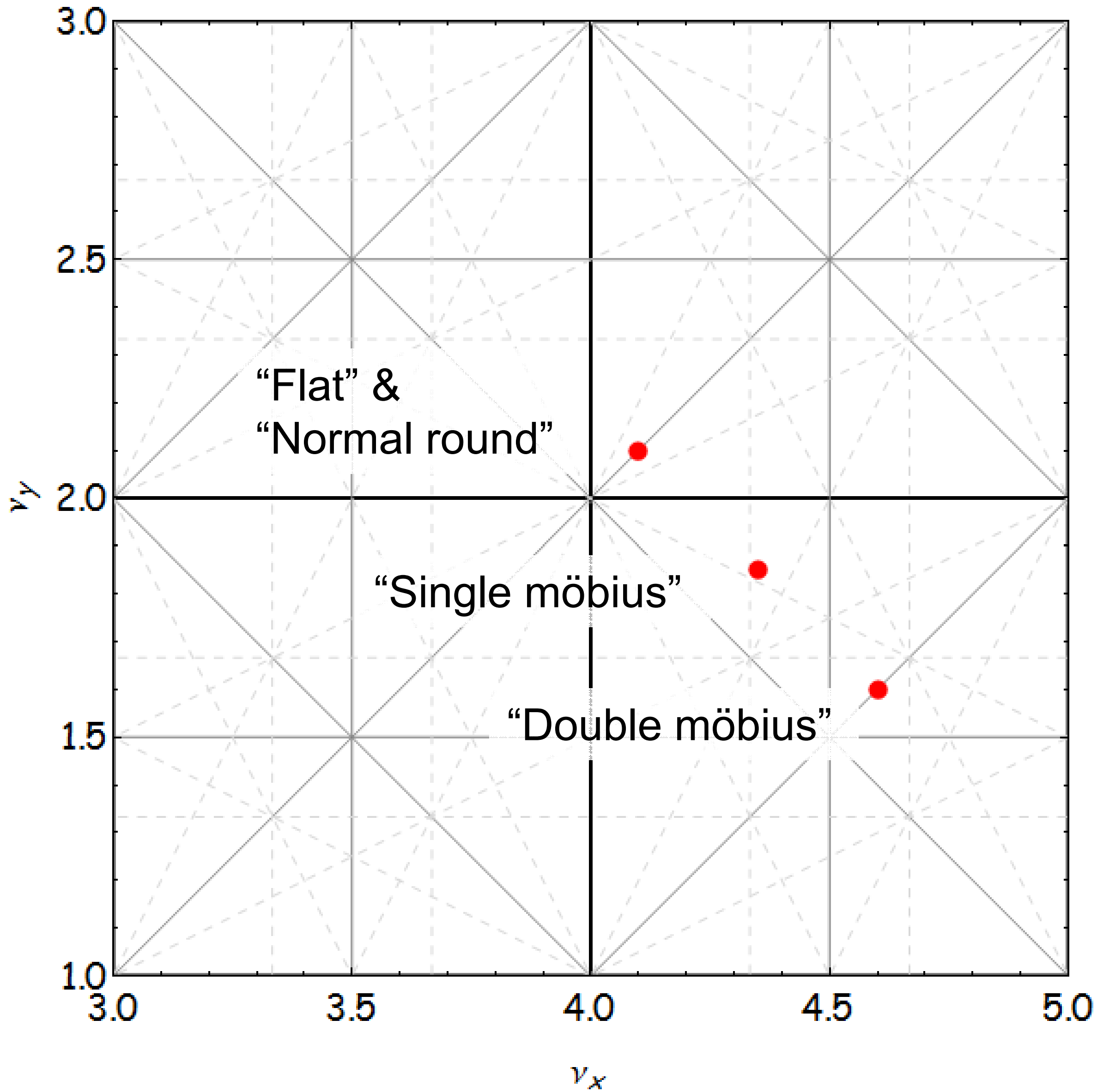
“Normal Round”



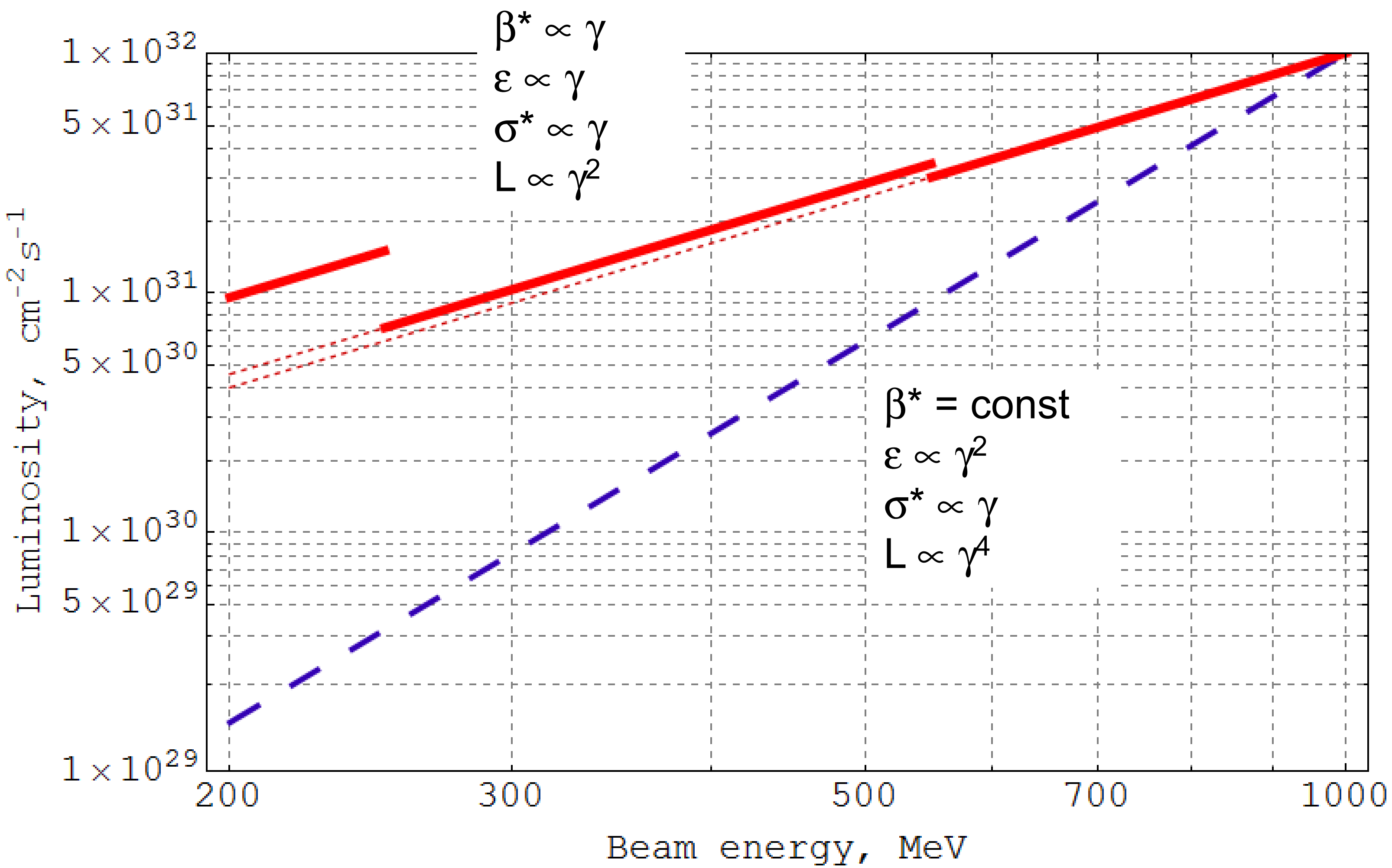
“Single möbius”



“Double möbius”



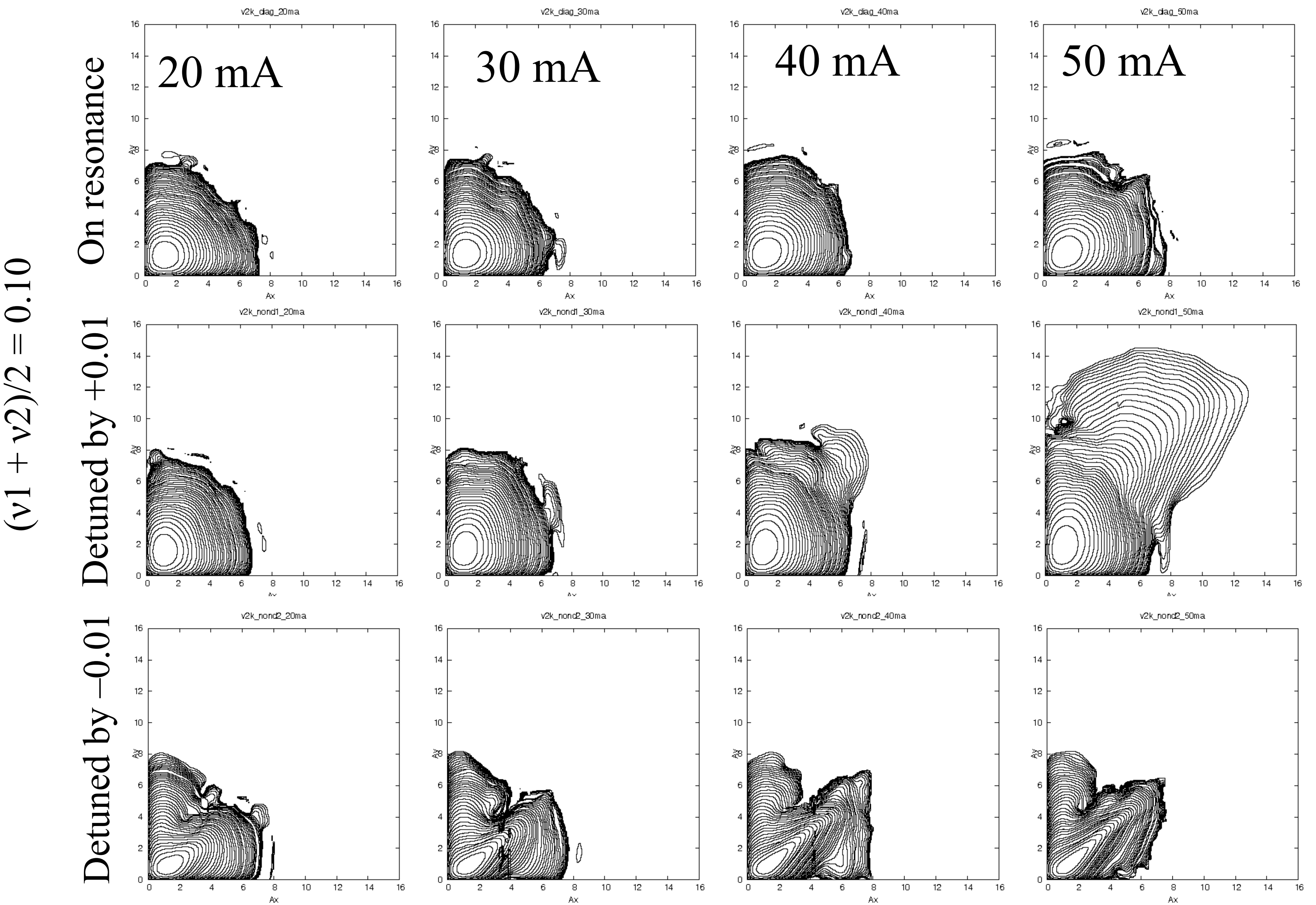
Luminosity: energy scaling approach



$$L = \frac{4\pi\gamma^2\xi^2\varepsilon f}{r_e^2\beta^*} = \frac{4\pi\gamma^2\xi^2\sigma^{*2} f}{r_e^2\beta^{*2}}$$

$$\sigma^{*2} = \varepsilon\beta^* = inv(\beta^*)$$

LIFETRAC simulations (weak-strong)



LIFETRAC predictions

1. Very high ξ threshold values for ideal linear machine lattice, ξ_{th} ~ 0.25.
2. Chromatic sextupoles affect significantly on bb-effects decreasing threshold down to ξ_{th} ~ 0.15. (Break of the angular momentum conservation by nonlinear fields asymmetric to x-y motion)
3. Working point shift from coupling resonance under diagonal ($\nu_x > \nu_z$) preferable than vise versa. (Emittances parity breaking.)
4. Uncompensated solenoids acceptable in wide range ($\delta\nu_{x,z}$ ~ 0.02) while coupling in arcs provided by skew-quadrupole fields should be avoided. (Angular momentum conservation break by skew-quads, breaking x-y symmetry of transport matrix.)
5. Inequality of x-y beta-functions in IP within 10 % tolerance does not affect on bb-effects.
6. Bb-effects do not cause emittance blow-up but reduce beam lifetime via non-Gaussian “tails” growth in transverse particles distribution.
7. Beam lifetime improves with working point approach to the integer resonance.

Qualitative agreement of all predictions with experimental experience.

Luminosity measurement via beam sizes @ CCD cameras

SND and CMD-3 luminosity monitors:

1) Slow (1 measurement ~ 1/2 minute)
2) Large statistical jitter at low beams intensities

$$L = \frac{f_0 \cdot \mathrm{N}^+ \cdot \mathrm{N}^-}{4\pi \cdot \sigma^{*2}} \Rightarrow L = \frac{f_0 \cdot \mathrm{N}^+ \cdot \mathrm{N}^-}{4\pi \cdot \sqrt{\left({\sigma^+_x}^2 + {\sigma^-_x}^2\right)\left({\sigma^+_z}^2 + {\sigma^-_z}^2\right)}}$$

Needed:

1) Beams current measurement e^+, e^- (ФЭУ)
2) 4 beam sizes σ^* (with current dependent dynamic β^* and emittance) $\Leftarrow$ reconstruction from 16 beam profile monitors.

Assumptions:

1) Lattice model **well known** (transport matrices)
2) Focusing distortion concentrated within IP vicinity.
3) Beam profile preserve **Gaussian distribution**.

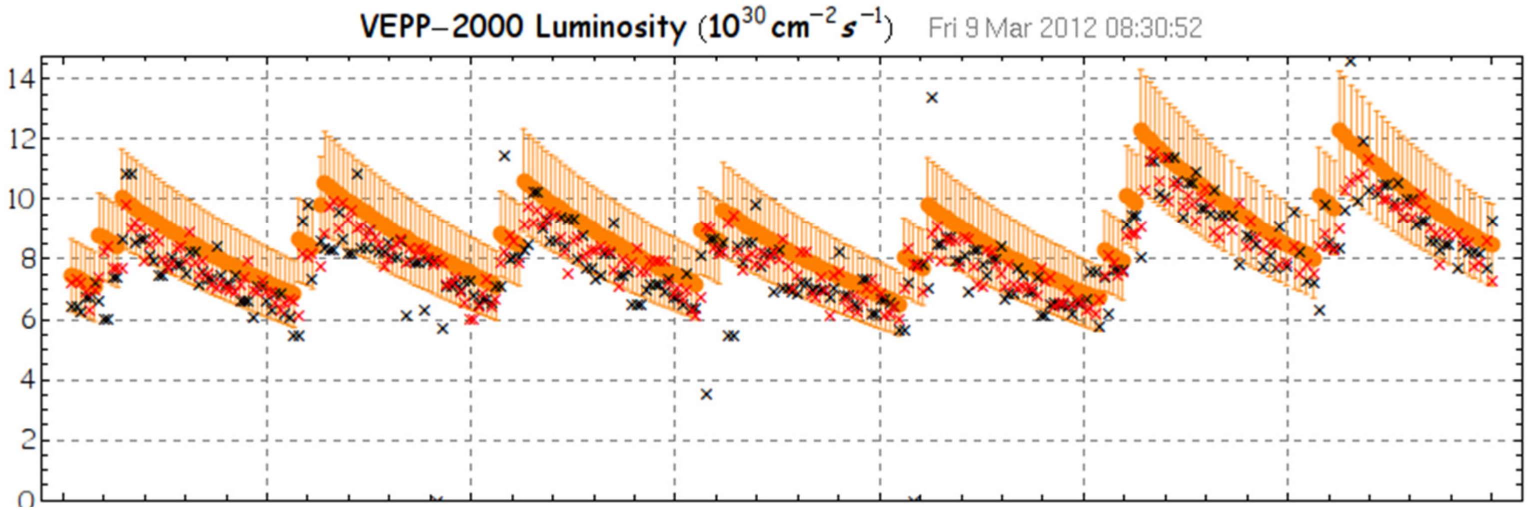
$$\beta_x^{*+}, \beta_z^{*+}, \beta_x^{*-}, \beta_z^{*-}, \varepsilon_x^+, \varepsilon_z^+, \varepsilon_x^-, \varepsilon_z^-$$

$2 \times 4 = 8$ parameters /

$8 \times 2 \times 2 = 32$ measured values.

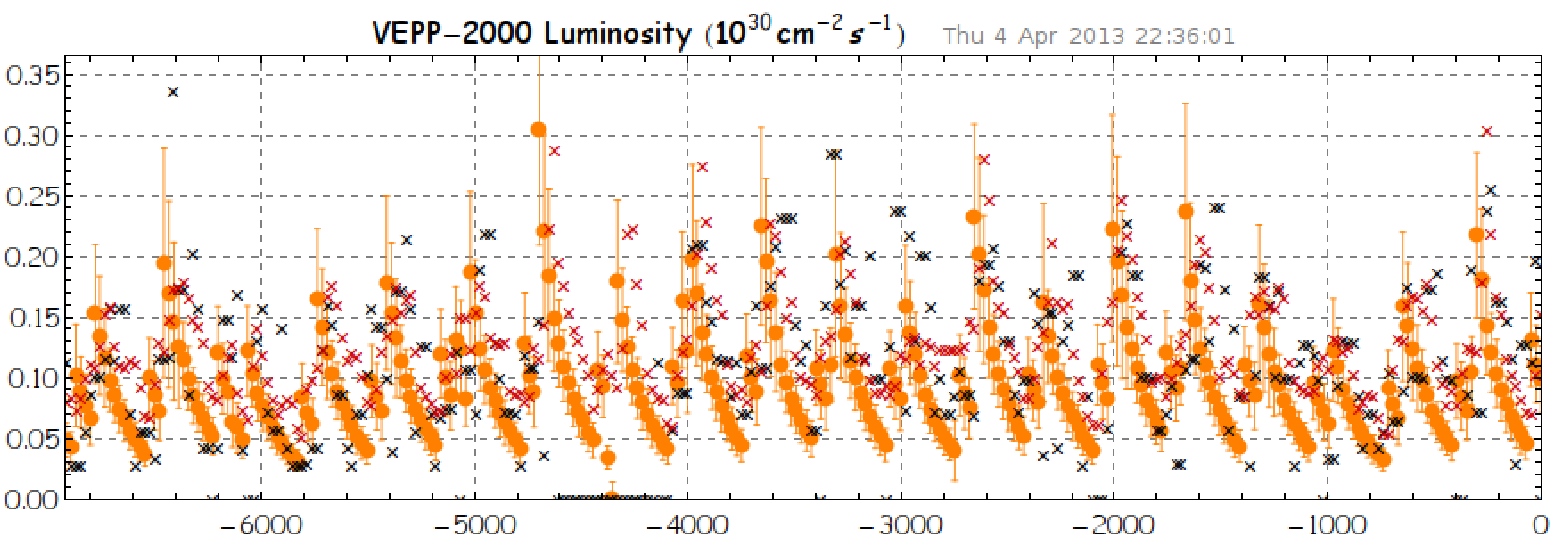
Luminosity monitor

$L = 8.477 \times 10^{30} \pm 1.37 \times 10^{30} = 30.52\ nbn^{-1}/hour$



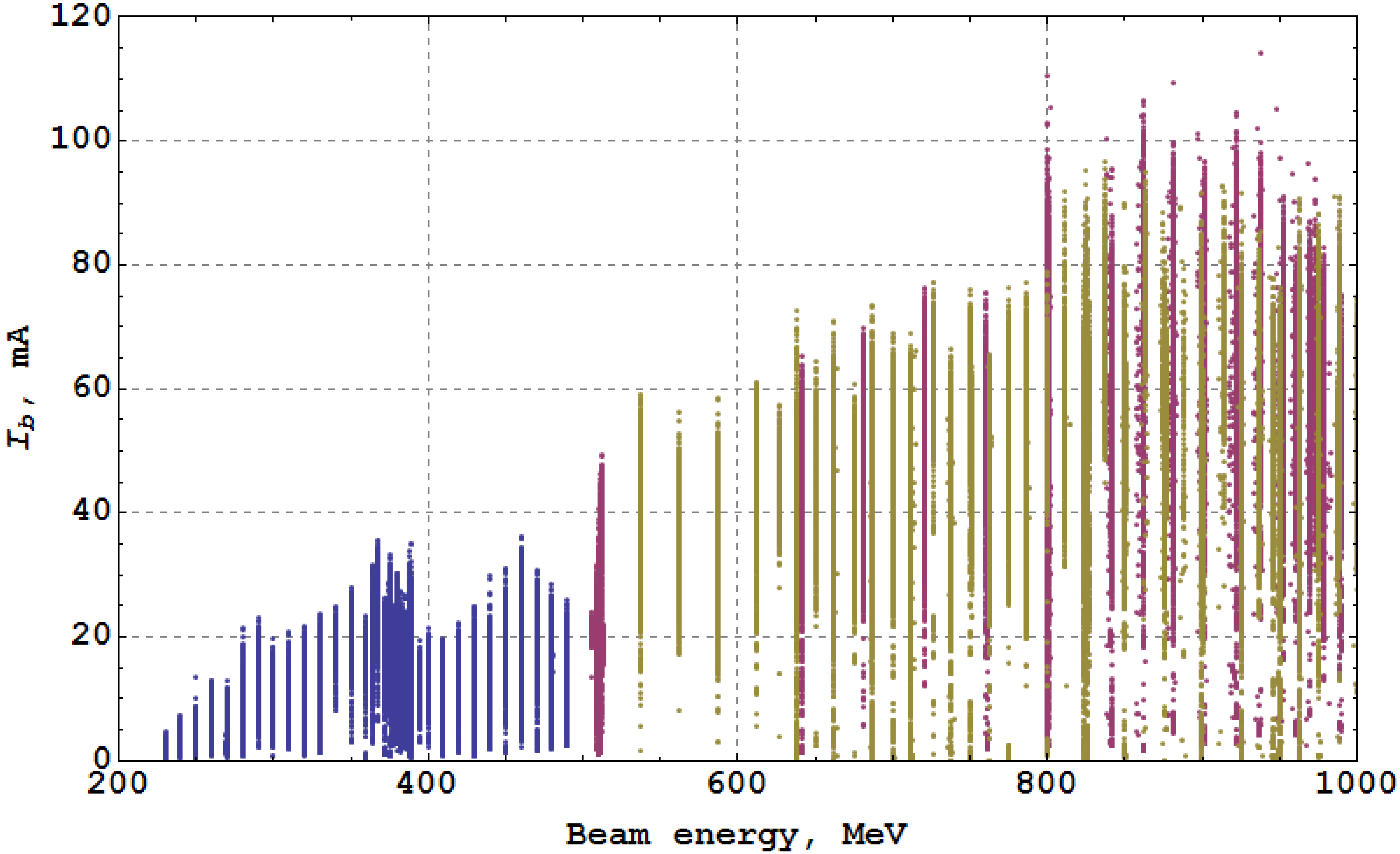
800 MeV

$L = 9.806 \times 10^{28} \pm 2.77 \times 10^{28} = 0.35\ nbn^{-1}/hour$



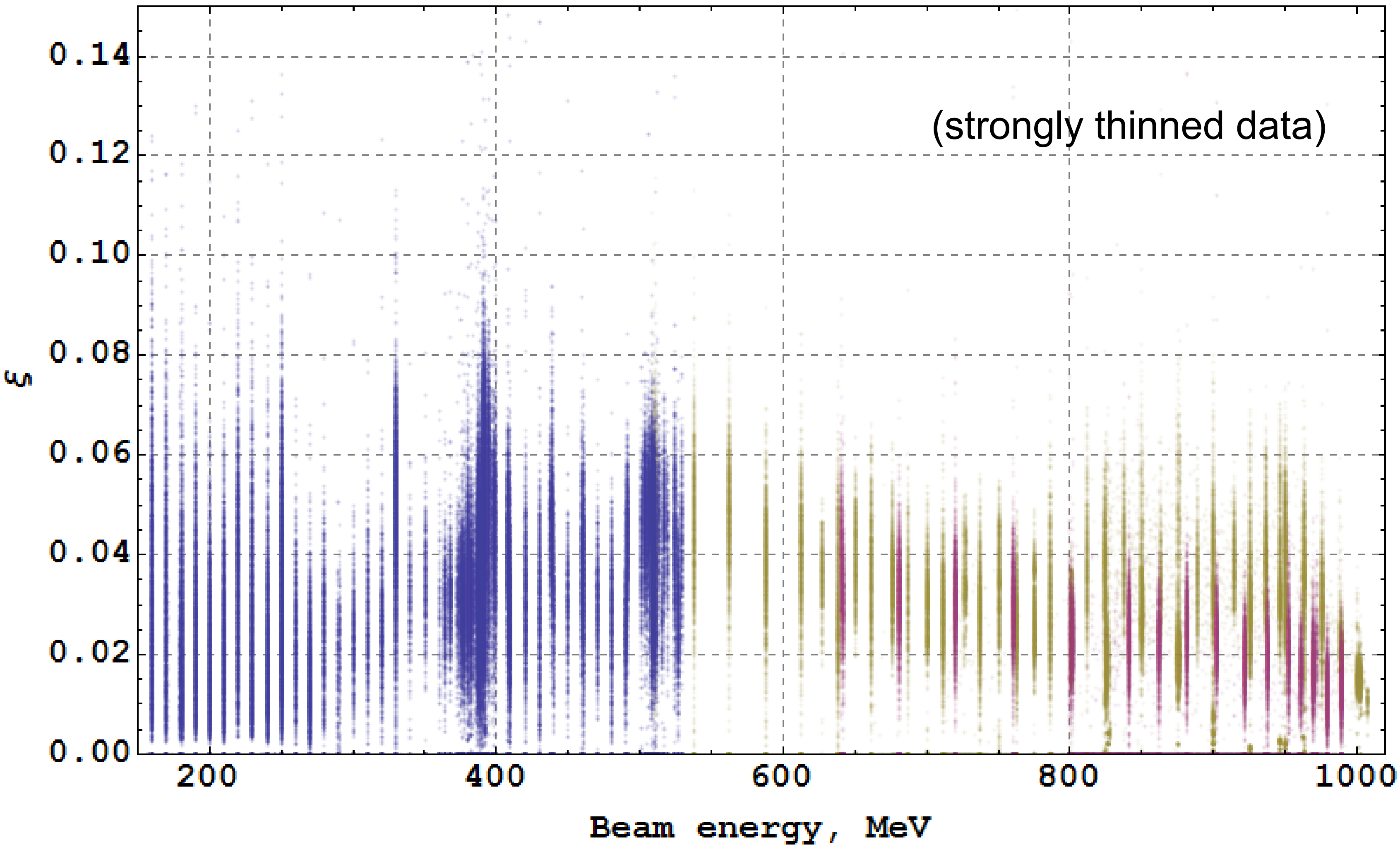
180 MeV

Beam current vs. energy

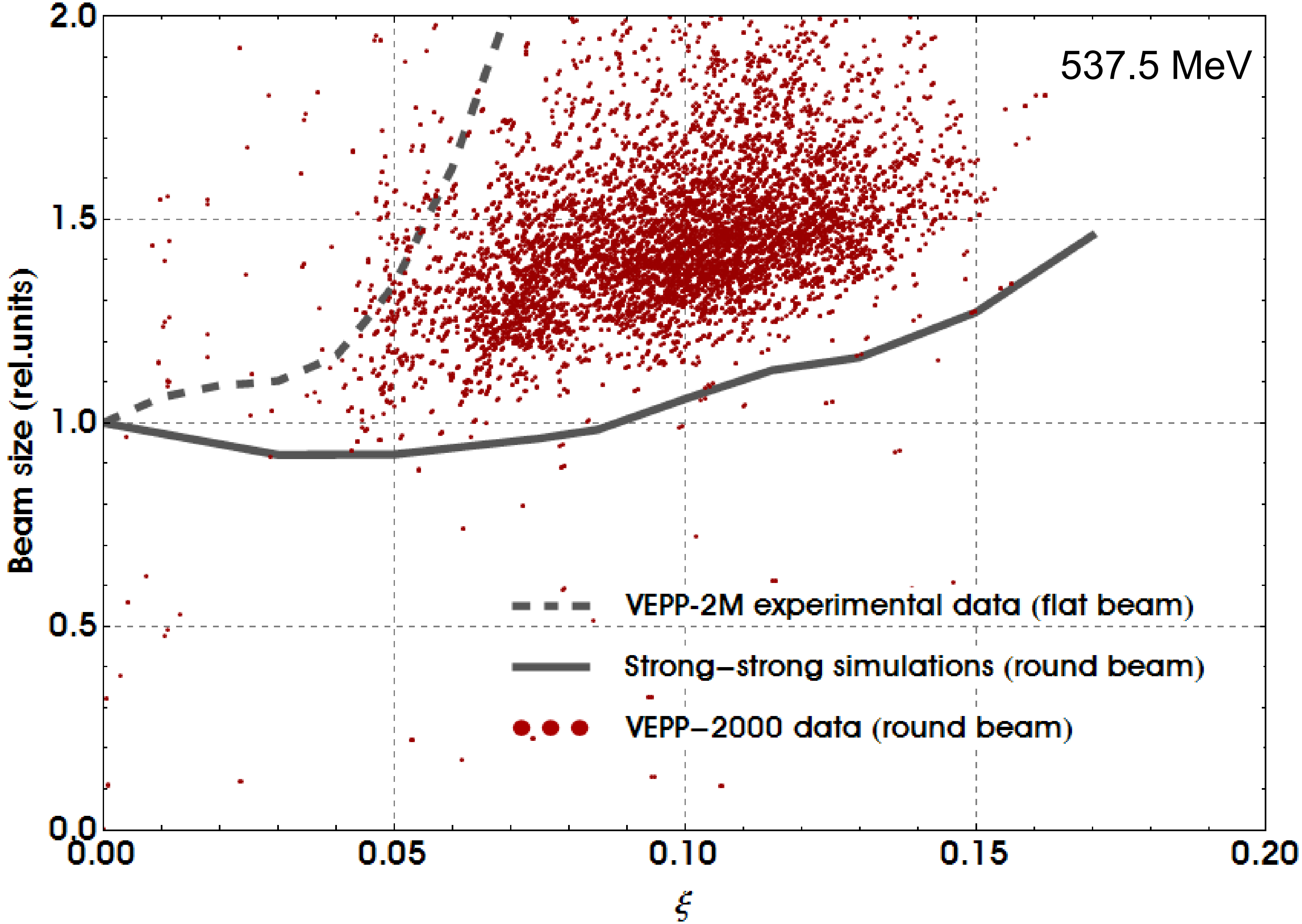


Needed: 200×200mA @ 1GeV (for L=10^{32}cm^{-2}s^{-1})

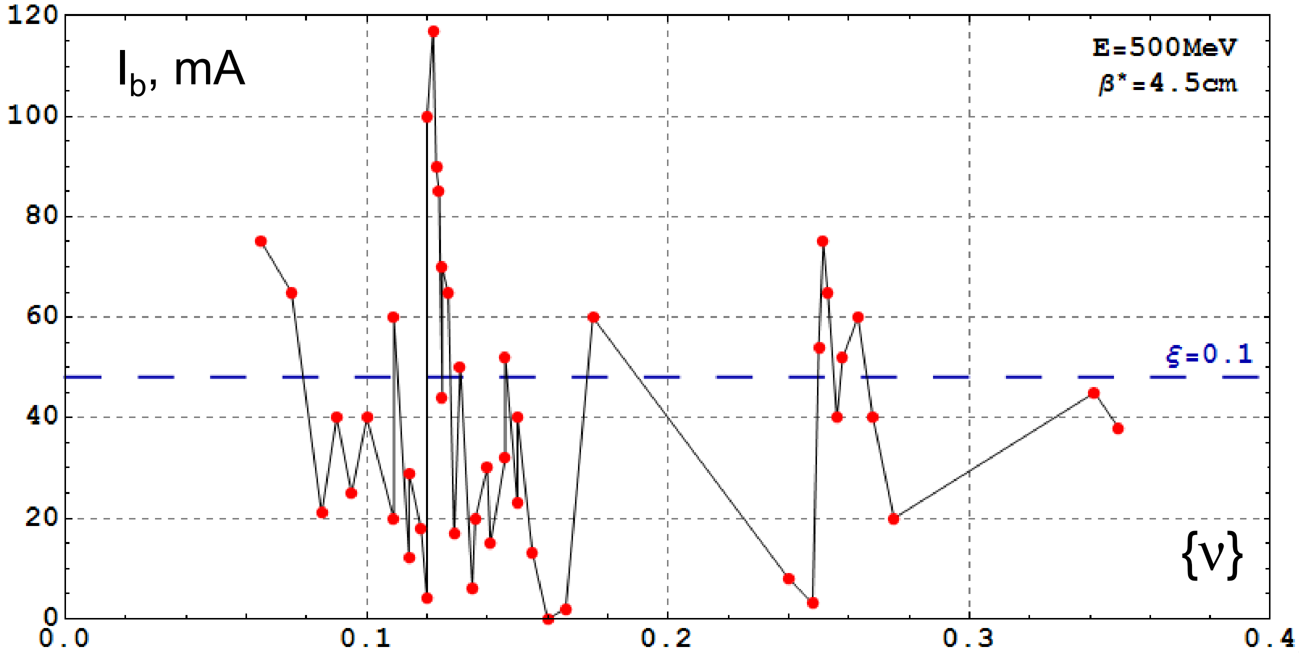
Beam-beam parameter



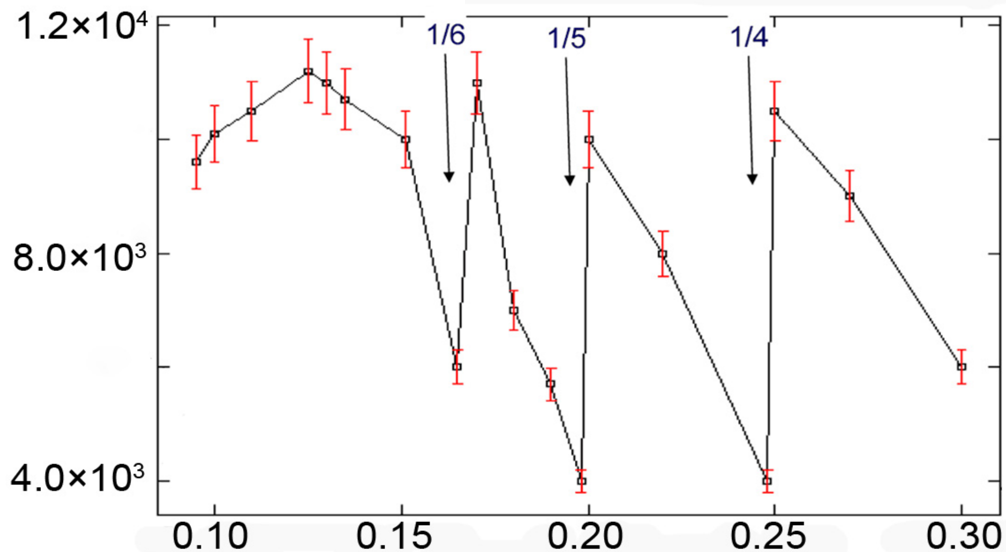
Extracted from luminosity beam size @ IP



High order resonances

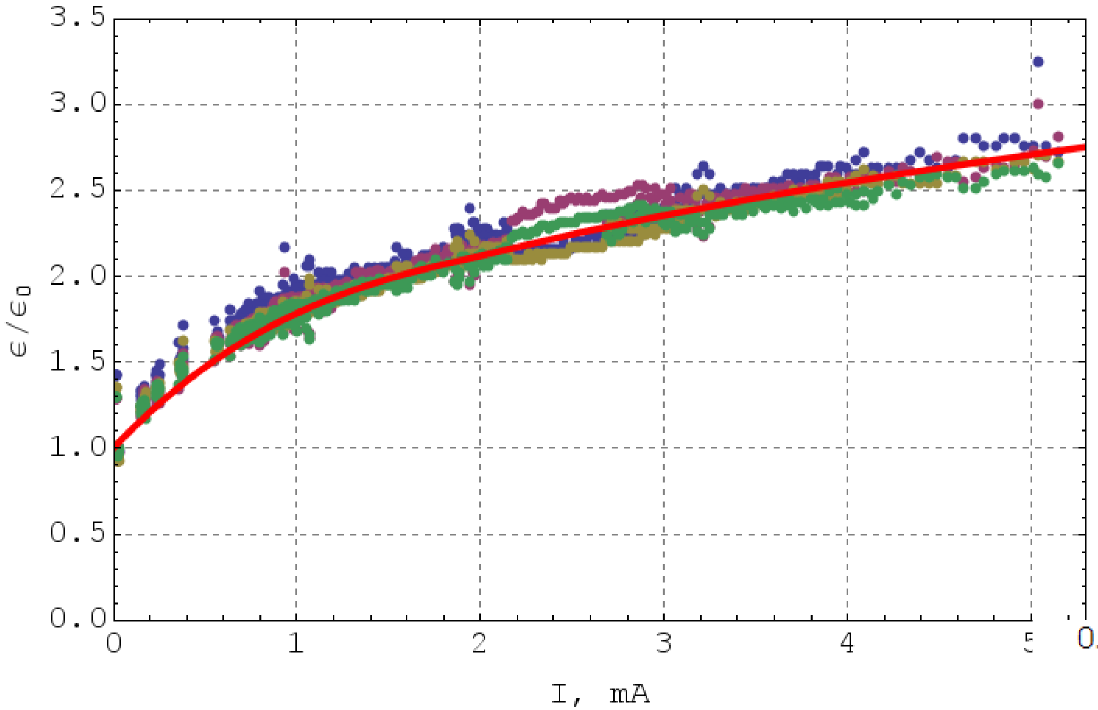


Weak-strong tune scan of threshold counter beam current value.

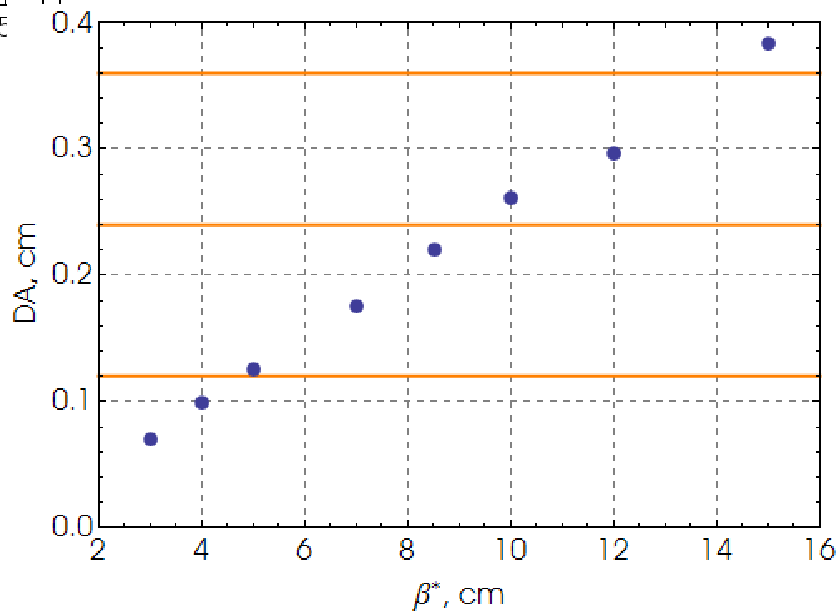


Single positron beam lifetime as a function of betatron tune. 20mA @ 500MeV

Intrabeam scattering and DA

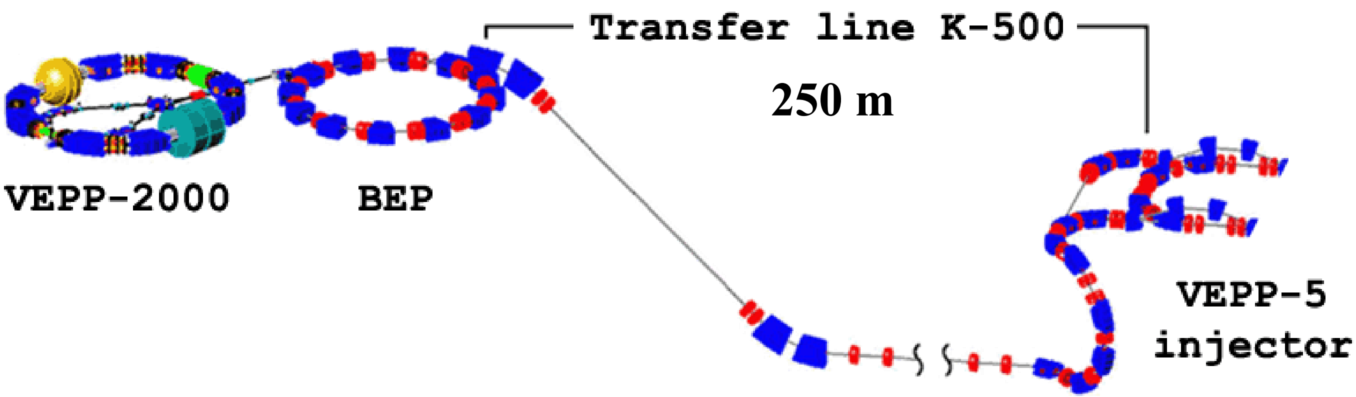


Single beam emittance growth with beam current, E=220 MeV



Calculated in simple model DA dependence with β^* variation. {ν}=0.128, E=1 GeV

Motivation: luminosity restrictions



Deficit of e^+

→ VEPP-5 injection complex

Energy ramping at VEPP-2000

1. Dead time
2. Extremely hard task: acceleration of colliding beams at bb-threshold
3. Unachievable bb-threshold at energy higher than injection value!

$$\xi = \frac{N^- r_e \beta^*}{4\pi\gamma\sigma^{*2}} \propto \frac{1}{\gamma^2}\left(or \; \frac{1}{\gamma}\right)$$

$$L = \frac{4\pi\gamma^2\xi^2\varepsilon f}{r_e^2\beta^*}$$

800 → 1000 MeV $\quad -20 \div -35\%$

$-35 \div -60\%$