Экспериментальное и теоретическое исследование эффектов встречи круглых пучков

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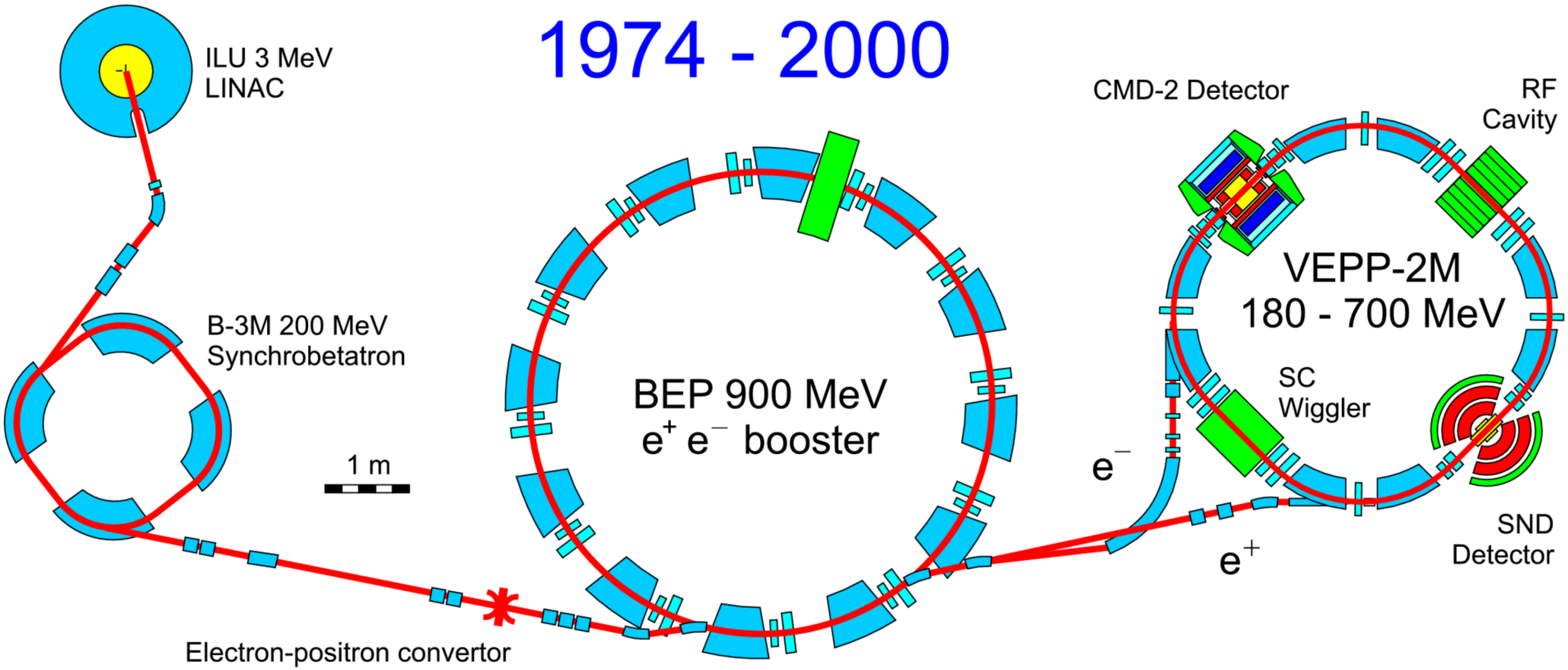
IV Черенковковские чтения:
“Новые методы в экспериментальной ядерной физике и физике частиц”
12 Апреля 2011 г., ФИАН, Москва

Outline of the talk

- From VEPP-2M to VEPP-2000
- Motivation of round colliding beams
- Options of round beams at VEPP-2000
- Beam diagnostics and results of dynamic aperture study
- Orbit and optics tuning using SVD-analysis
- Beam-beam experiments
- Weak-strong simulations
- Future work

Measurement of R in Novosibirsk



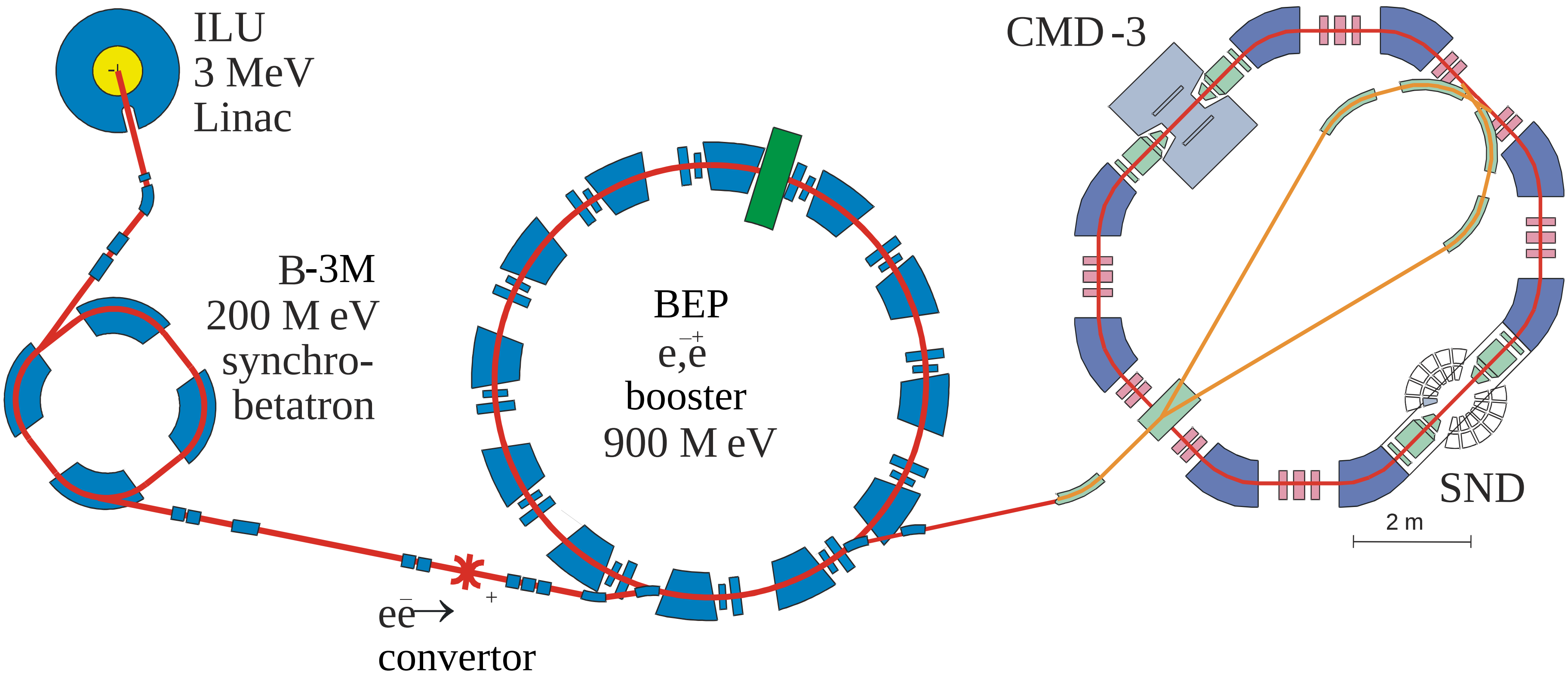
- VEPP-2M collider: 0.36-1.4 GeV in c.m., $L \approx 3 \bullet 10^{30}$ $1/cm^2s$ at 1 GeV
- Detectors CMD-2 and SND: ≈ 60 pb^{-1} collected in 1993-2000
- All major hadronic modes are measured:

$e^+e^- \rightarrow 2\pi, 3\pi, 4\pi, KK, ..$

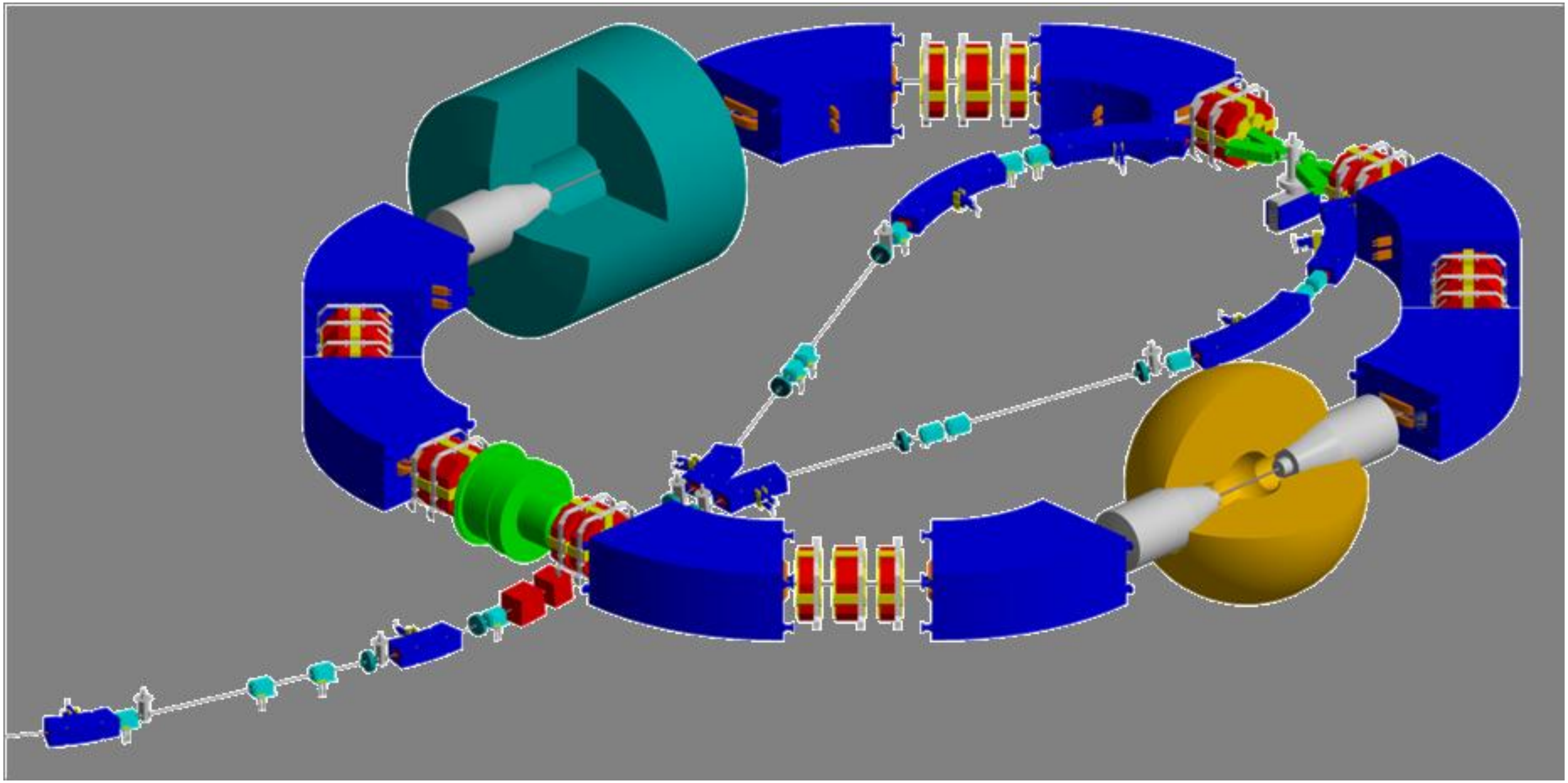
$e^+e^- \rightarrow \rho, \omega, \phi$

Still a lot of data to analyze !

VEPP-2000 complex



Cartoon view of VEPP-2000 Collider



Increasing of Luminosity

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

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

Round Beams:

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

✓Geometric factor: $1 + \sigma_x / \sigma_x{}^2 = 4$

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

✓Low beta-function: $\beta^* = 2 \div 10 \text{ cm}$

✓IBS for low energy? better life time!

The Concept of Round Colliding Beams

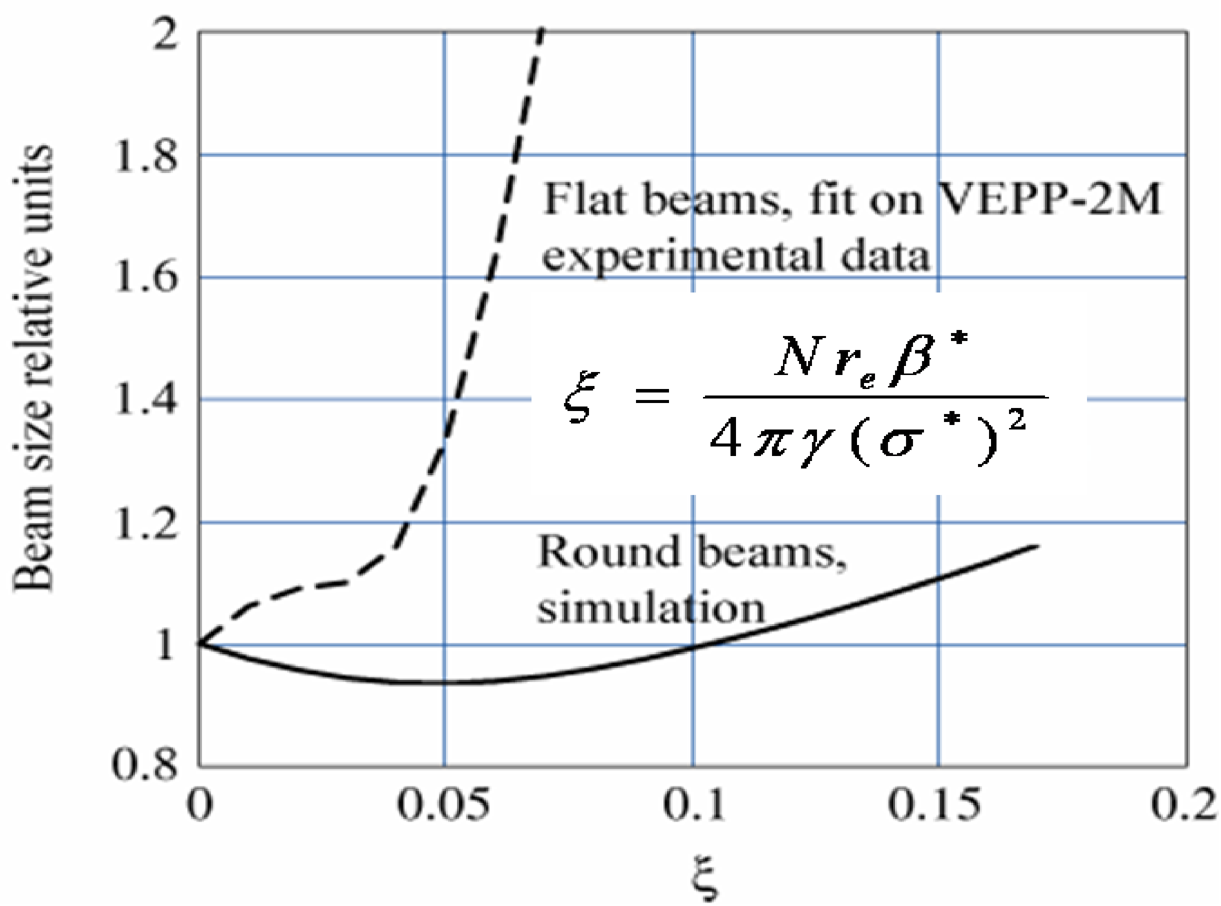
- Angular momentum conservation! $M_z = x'y - xy'$

- Small and equal β-functions at IP: $\beta_x = \beta_y$
- Equal beam emittances: why? $\varepsilon_x = \varepsilon_y$
- Equal betatron tunes: how close in reality? $\nu_x = \nu_y$
- Small and positive fractional tunes

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

Vertical size dependence on beam-beam parameter ξ

"Weak-Strong" Beam-Beam Simulations



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

«flat» – «round»

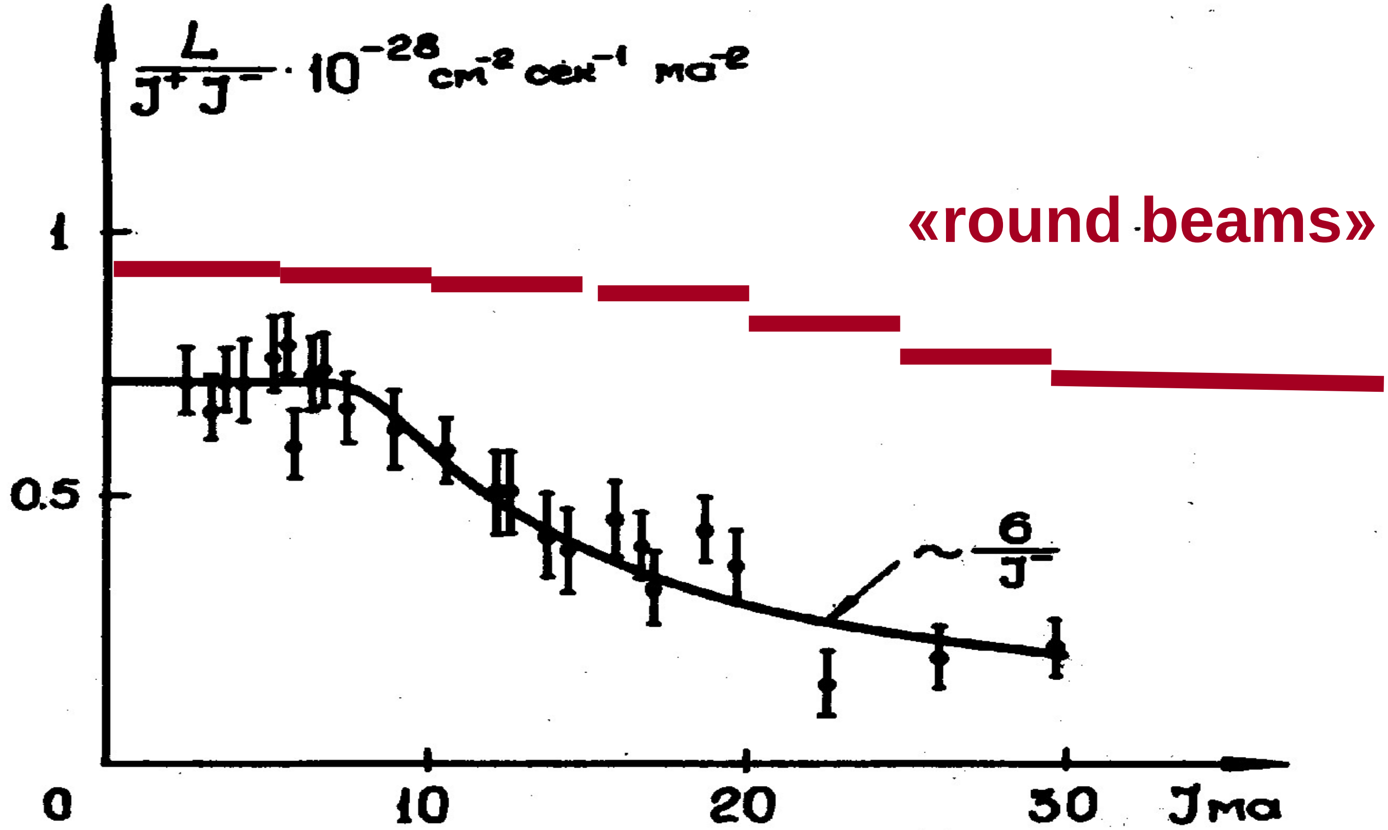
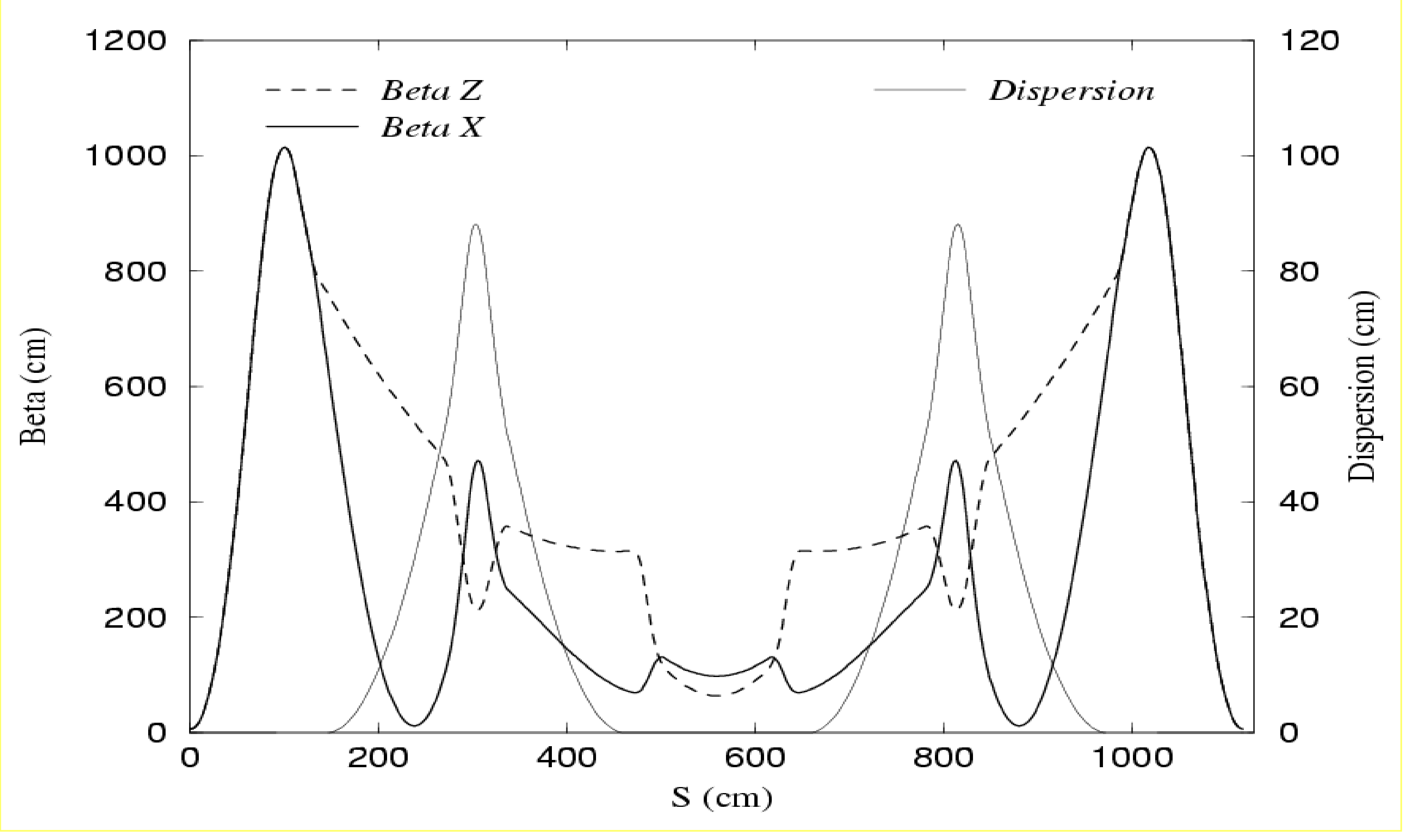


Рис.4. Зависимость удельной светимости от тока электронного пучка.

Lattice



Beta Z
Beta X
Dispersion
Beta (cm)
Dispersion (cm)
S (cm)
1200
1000
800
600
400
200
0
120
100
80
60
40
20
0
0
200
400
600
800
1000

Main Parameters of VEPP-2000

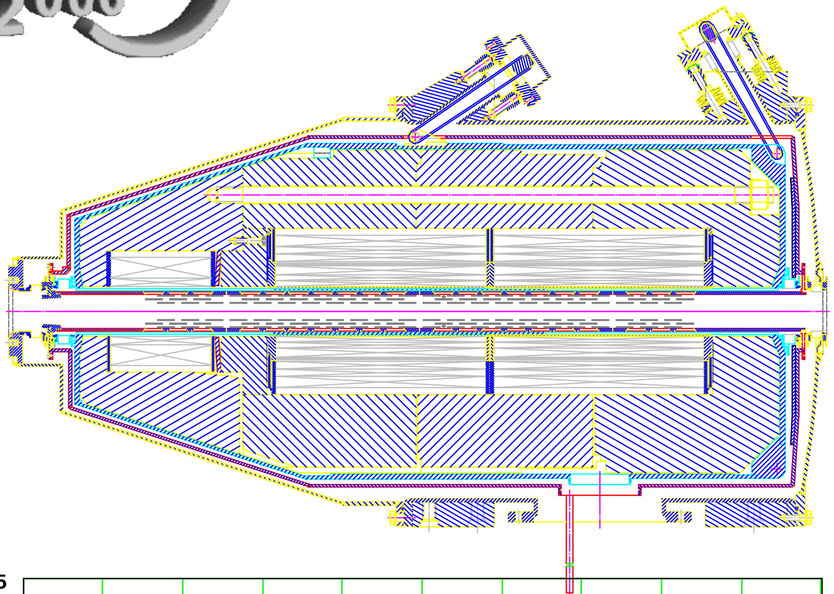
Circumference	24.38 m
RF frequency	172 MHz
RF voltage	100 kV
RF harmonic number	14
Momentum compaction	0.036
Synchrotron tune	0.0035
Energy spread	6.4×10^{-4}
Beam emittances (in the round mode)	1.29×10^{-7} m rad
Dimensionless damping decrements (x,y,s)	2.19×10^{-5}, 2.19×10^{-5}, 4.83×10^{-5}
Betatron tunes	4.05, 2.05
Betatron functions at IP	10 cm
Number of bunches per beam	1
Number of particles per bunch	1×10^{11}
Beam-beam parameter (x,y)	0.075, 0.075
Luminosity per IP (at 1 GeV)	1×10^{32} cm^{-2}s^{-1}

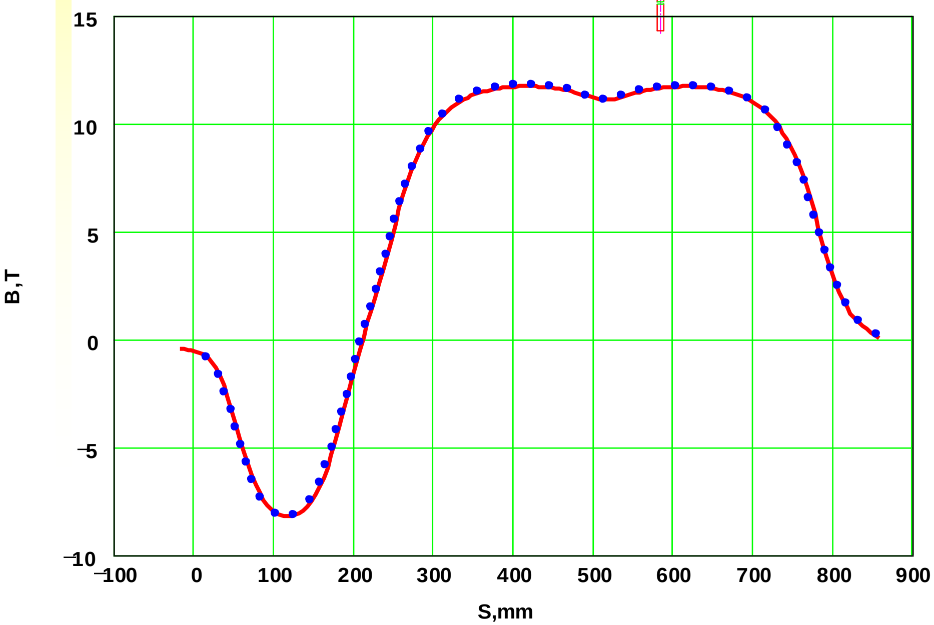
($1 \cdot 10^{31}$cm^{-2}s^{-1} at 2E=1 GeV achieved, 21.01.2008)

Physical program at VEPP-2000

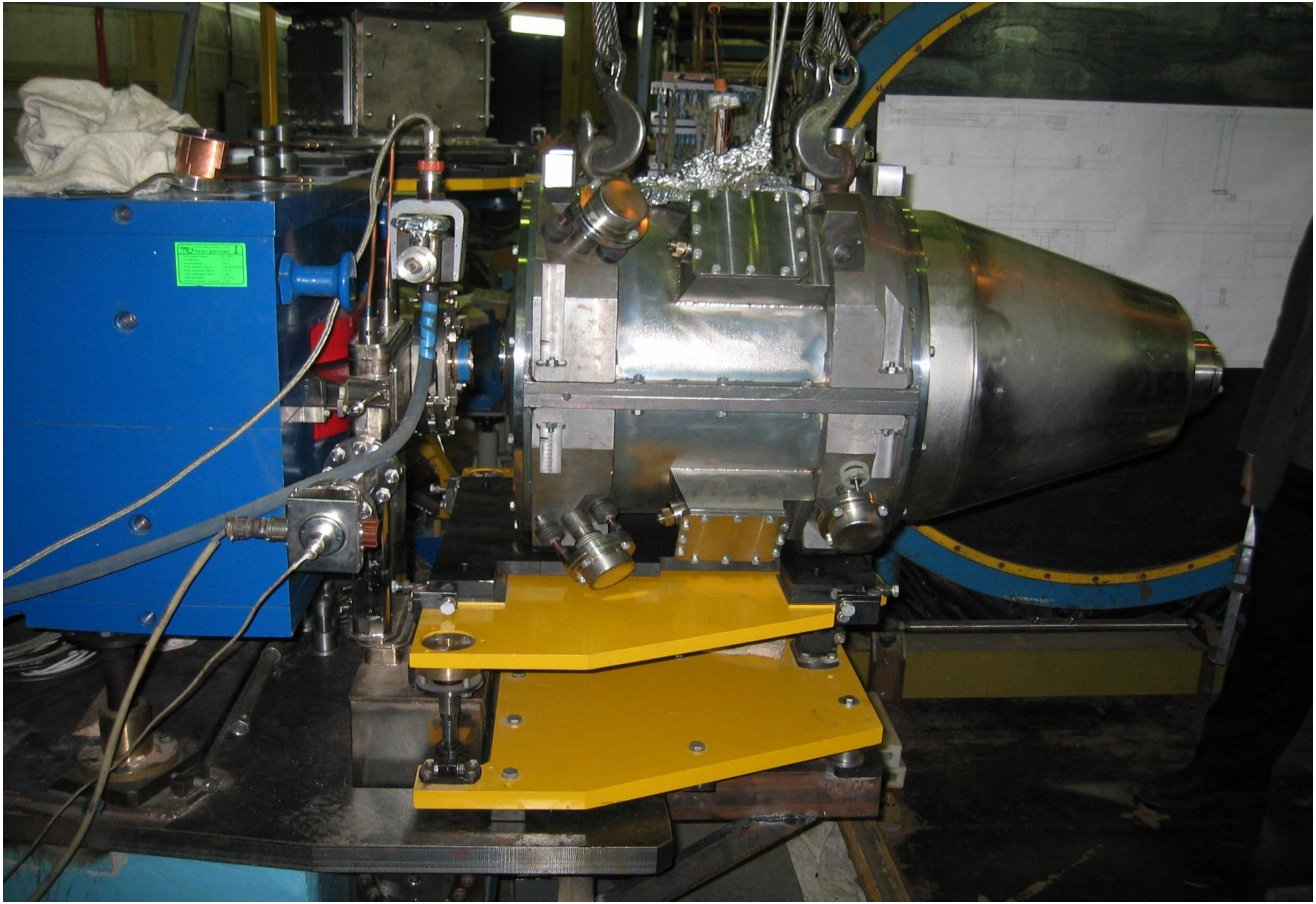
1. Precise measurement of the quantity
   $R=\sigma(e^+e^- \to hadrons)/\ \sigma(e^+e^- \to \mu^+\mu^-)$
2. Study of hadronic channels:
   $e^+e^- \to 2h, 3h, 4h \ldots, h= \pi, K, \eta$
3. Study of 'excited' vector mesons: ρ', ρ'', ω', φ',..
4. CVC tests: comparison of $e^+e^- \to$ hadr. (T=1) cross section with τ-decay spectra
5. Study of nucleon-antinucleon pair production – nucleon electromagnetic form factors, search for NNbar resonances, ..
6. Hadron production in 'radiative return' (ISR) processes
7. Two photon physics
8. Test of the QED high order processes 2->4,5

Solenoid 13.0 T



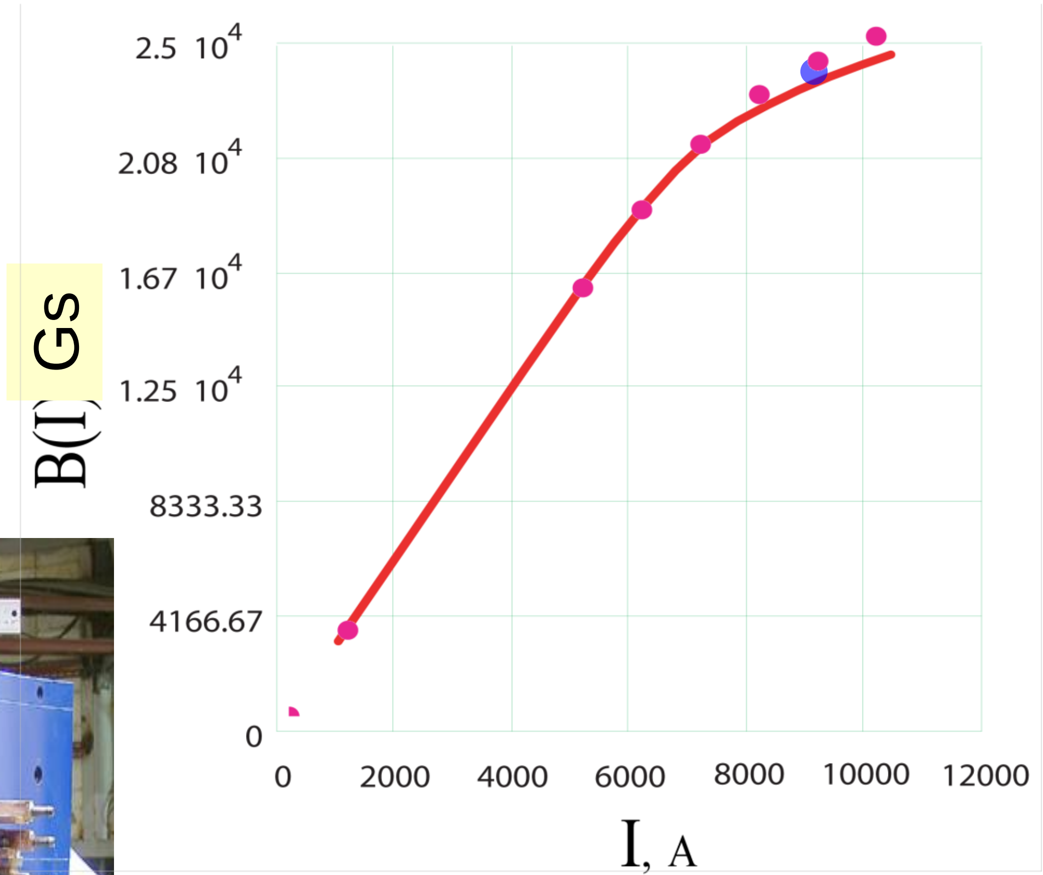


Solenoid #1

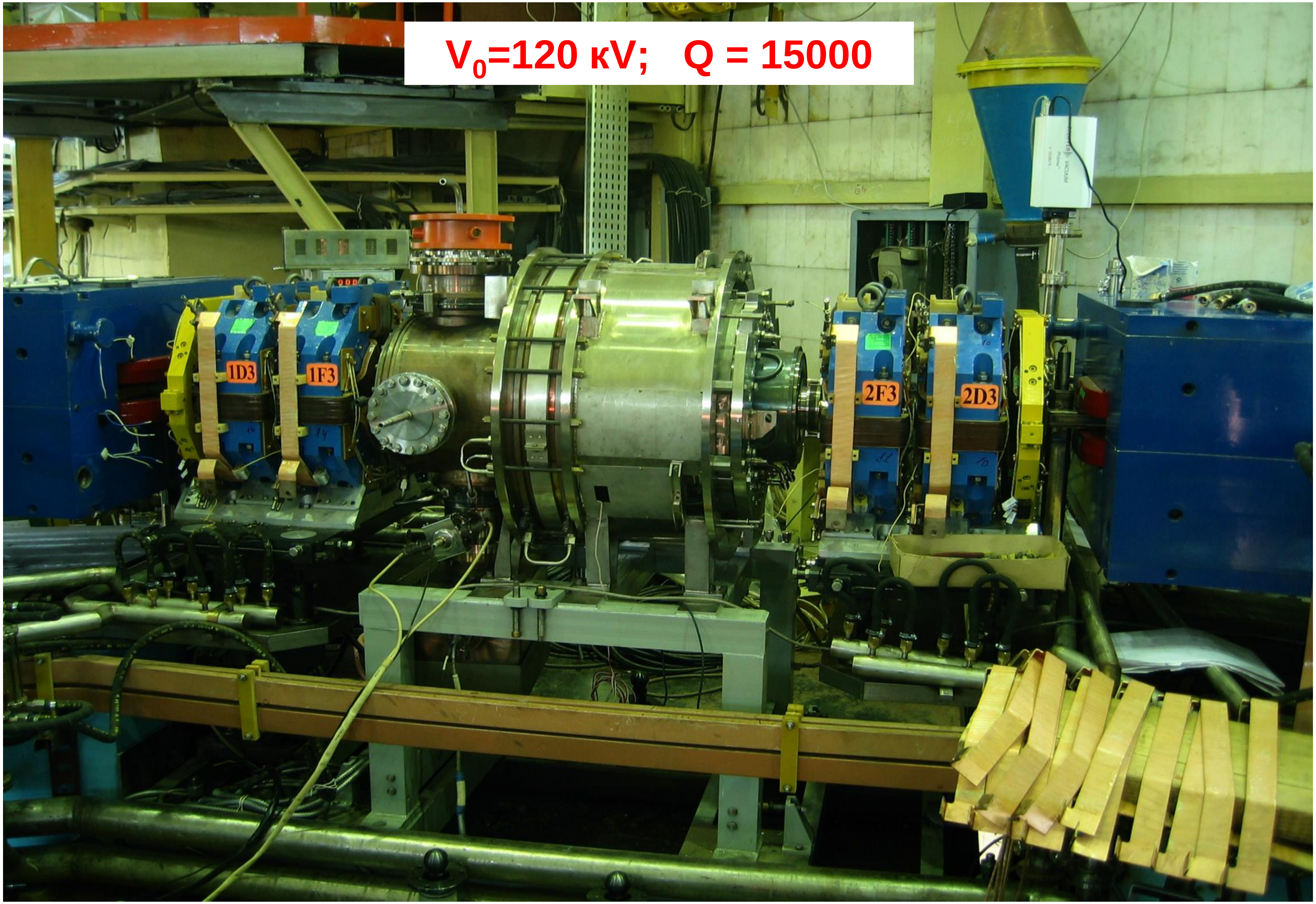


Magnetic measurement

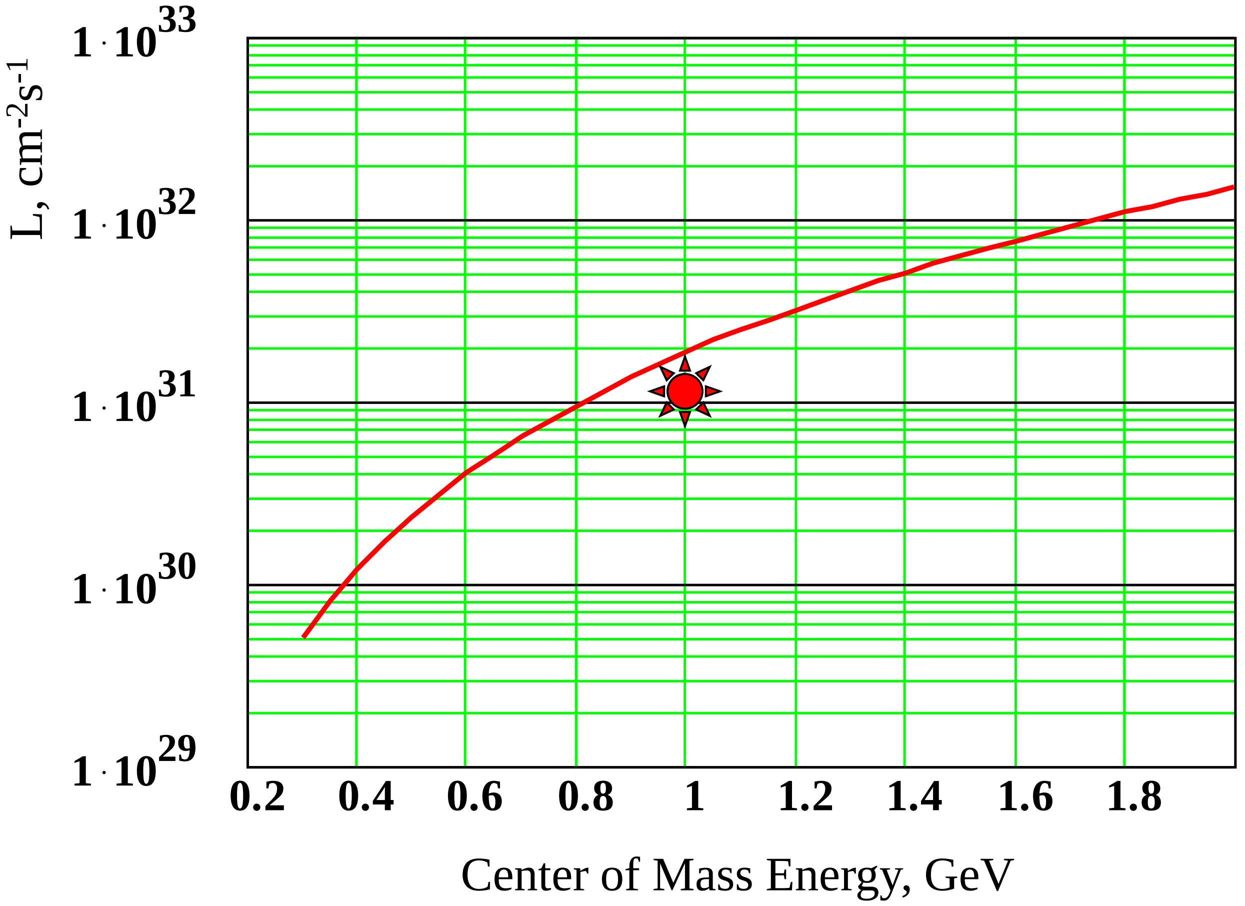
Dipole magnet (2.4 T)



Single mode RF cavity 172 MHz



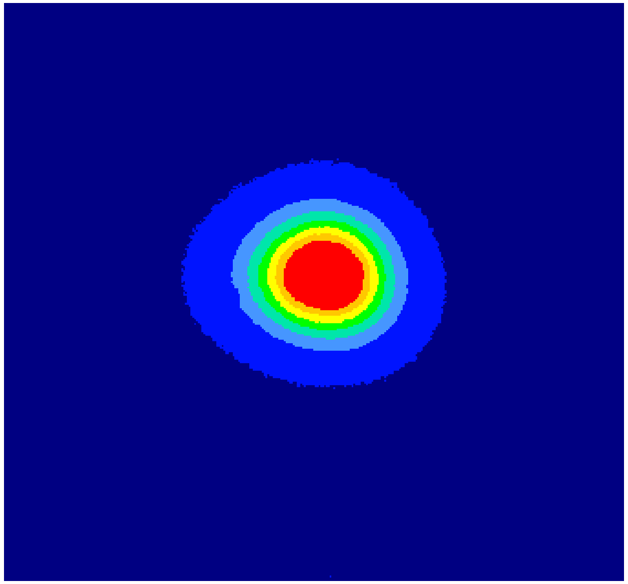
VEPP-2000 Luminosity, 23.01.2008, half-length solenoids, {nu}=0.125, beta=4.5 cm, ksi=0.08



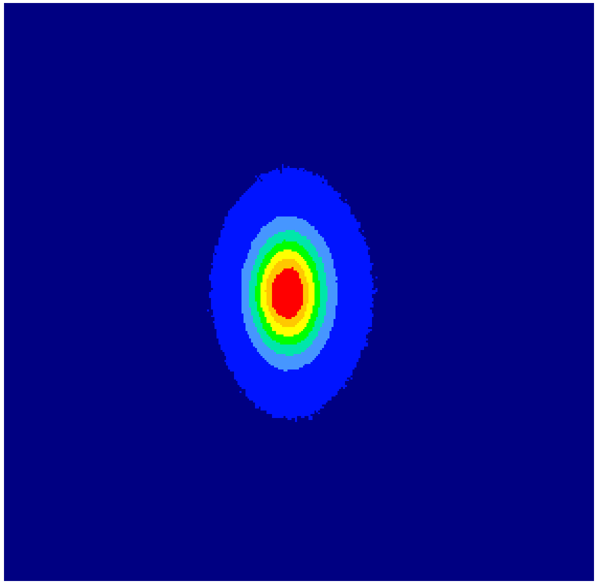
VEPP-2000 23.01.08, 22.00

Round beam observation by CCD-cameras

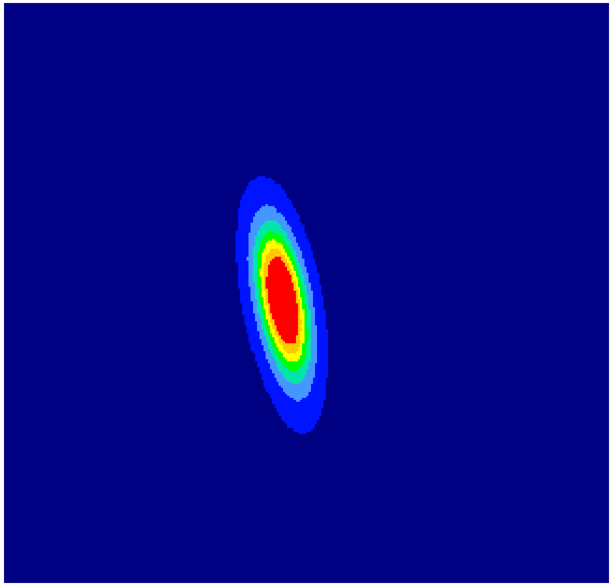
e+ beam images at 3 different places



#1 (1M2)

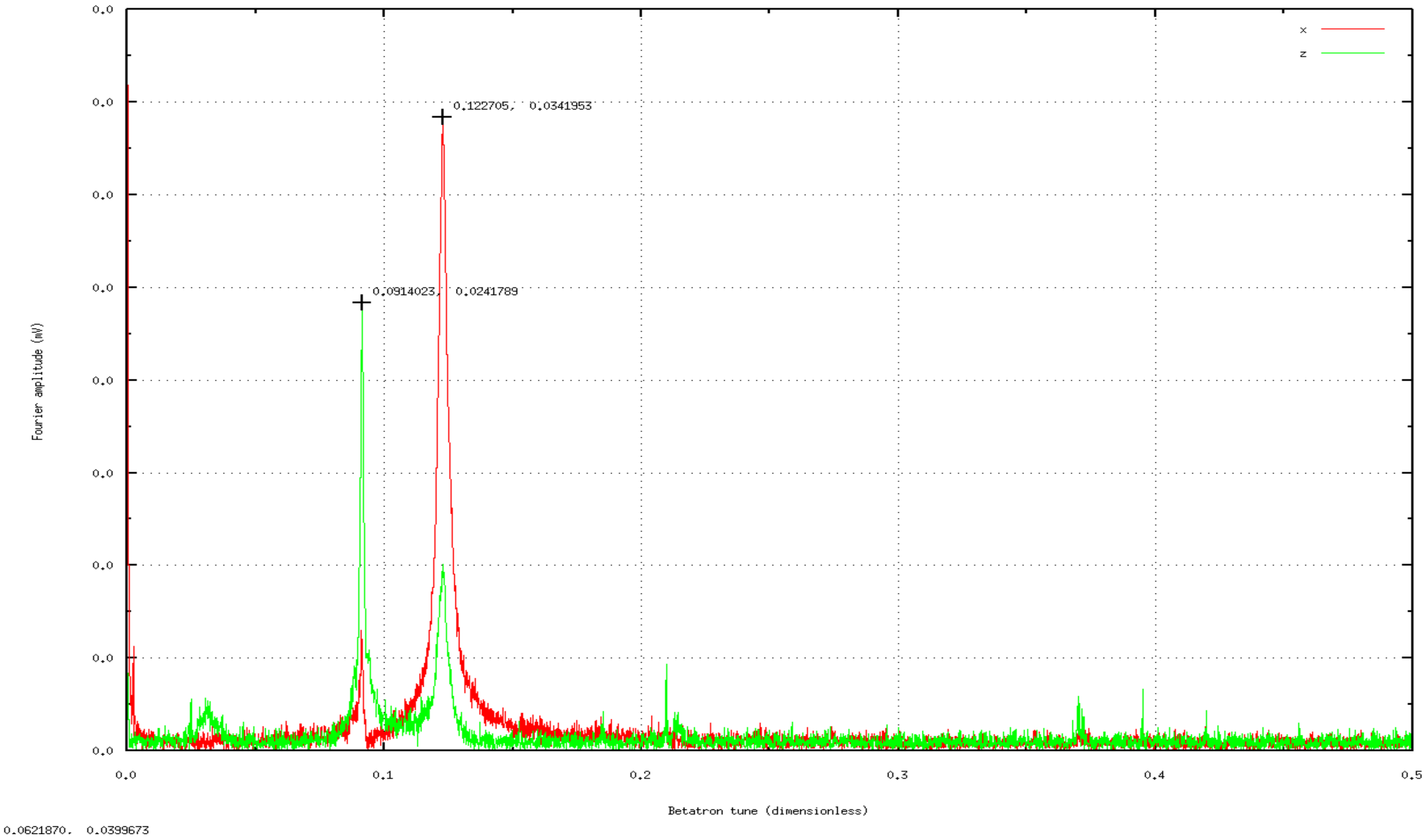


#2 (2M2)



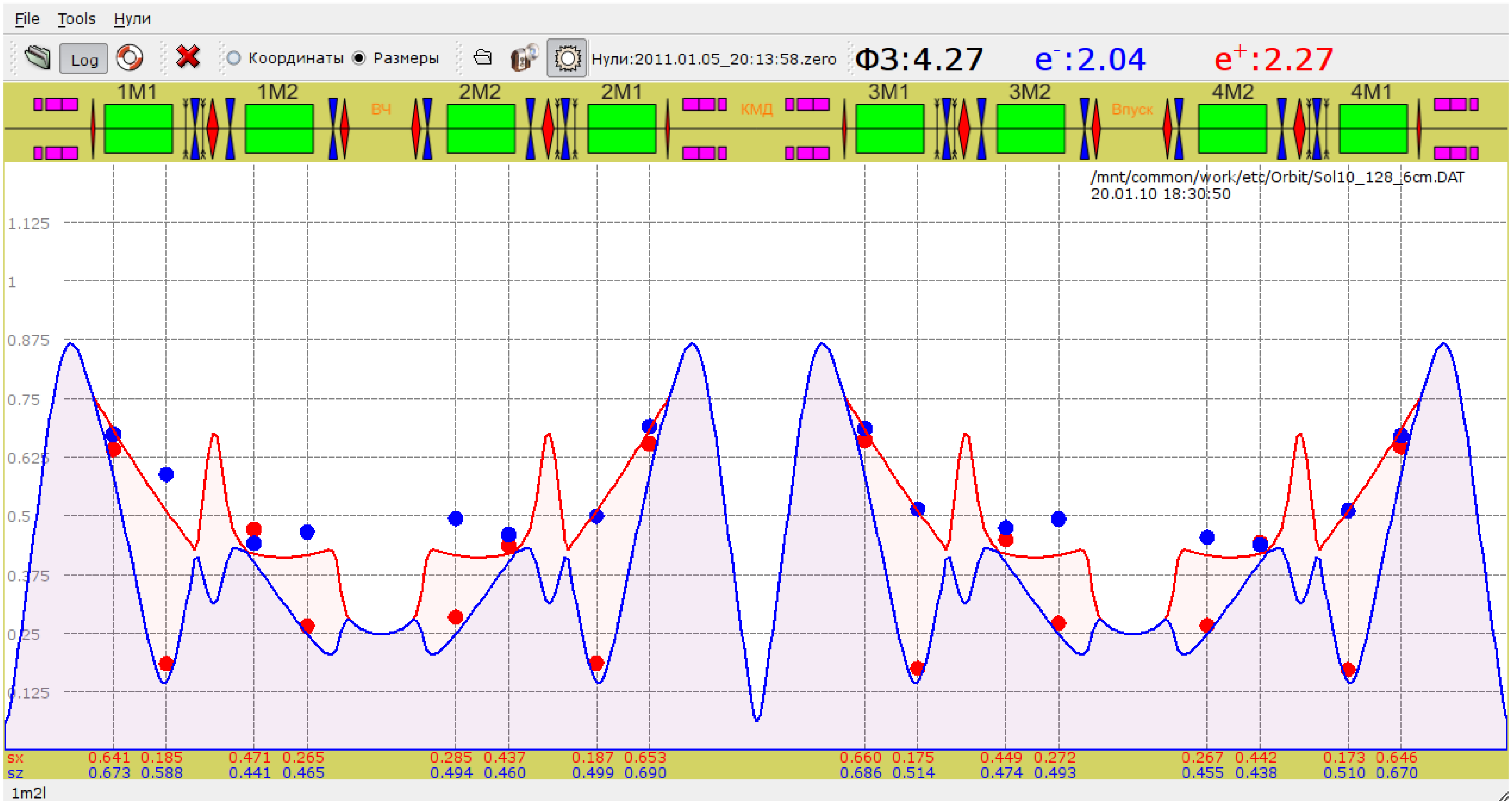
#3 (2M1)

Pick-up diagnostics

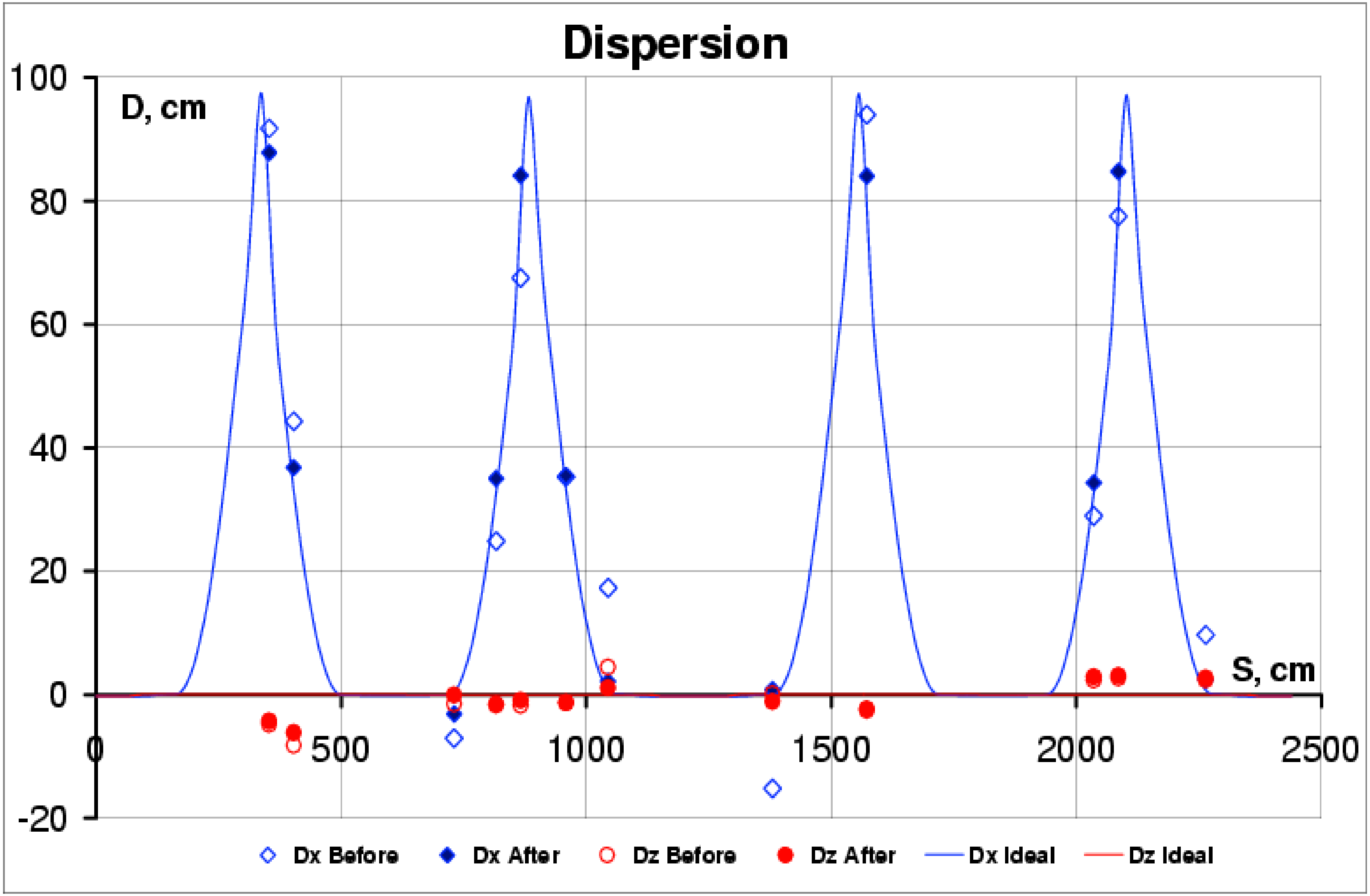


Beam size measurement by CCD cameras

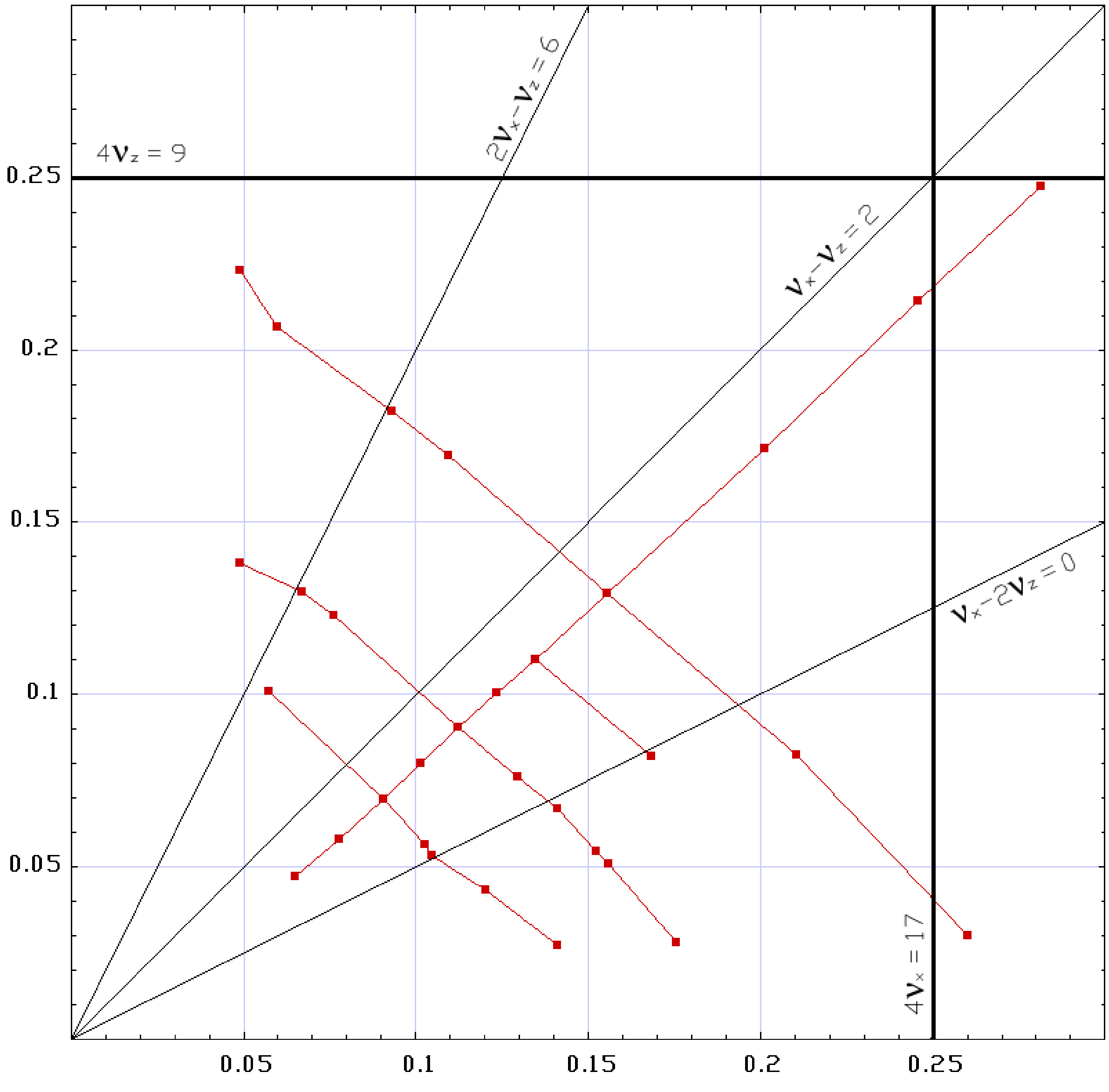
Correction of VEPP-2000 optics done by RM-analysis+SVD, A.L.Romanov



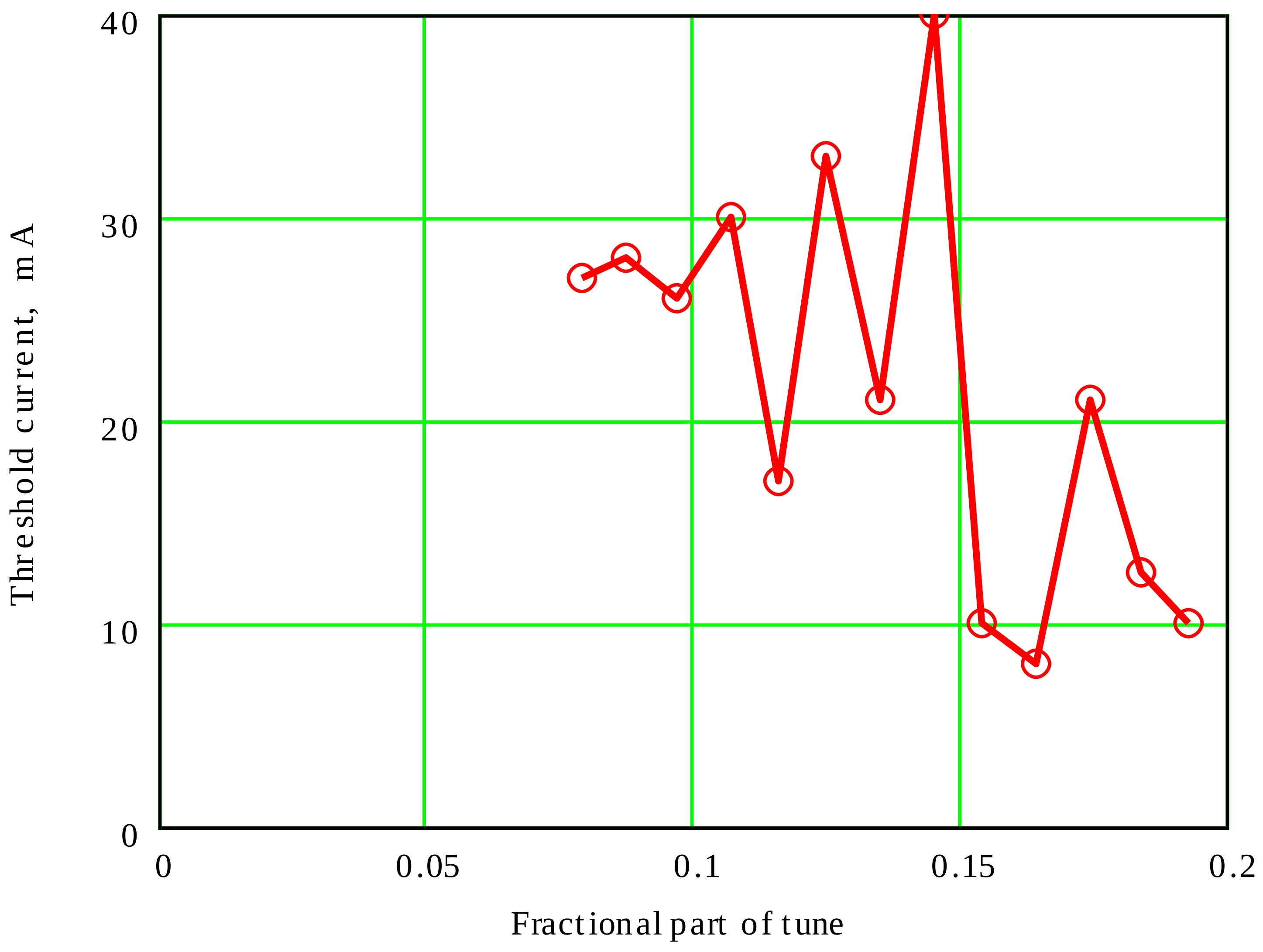
Dispersion measurement by CCD + pickups



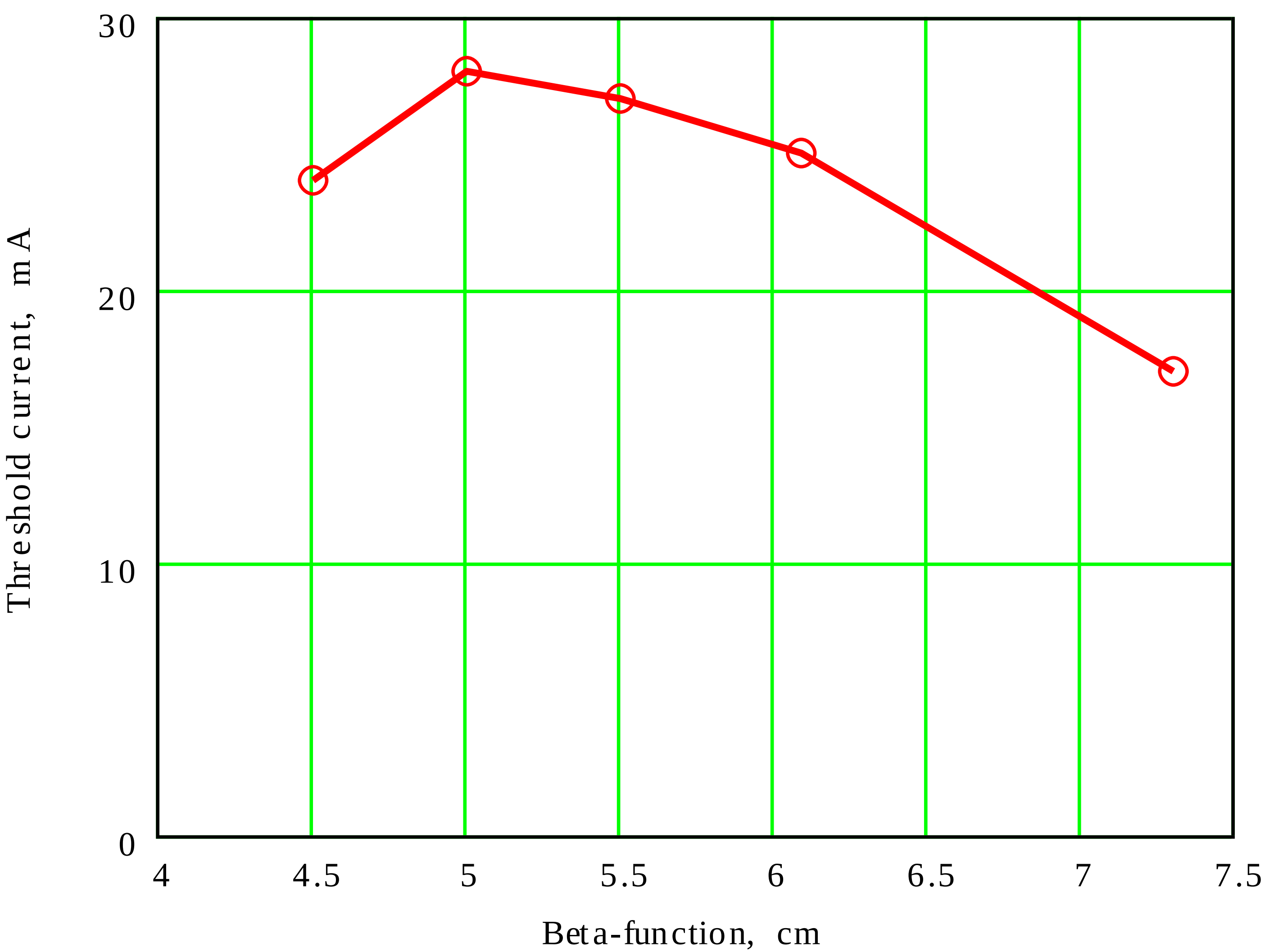
Dynamic aperture scan



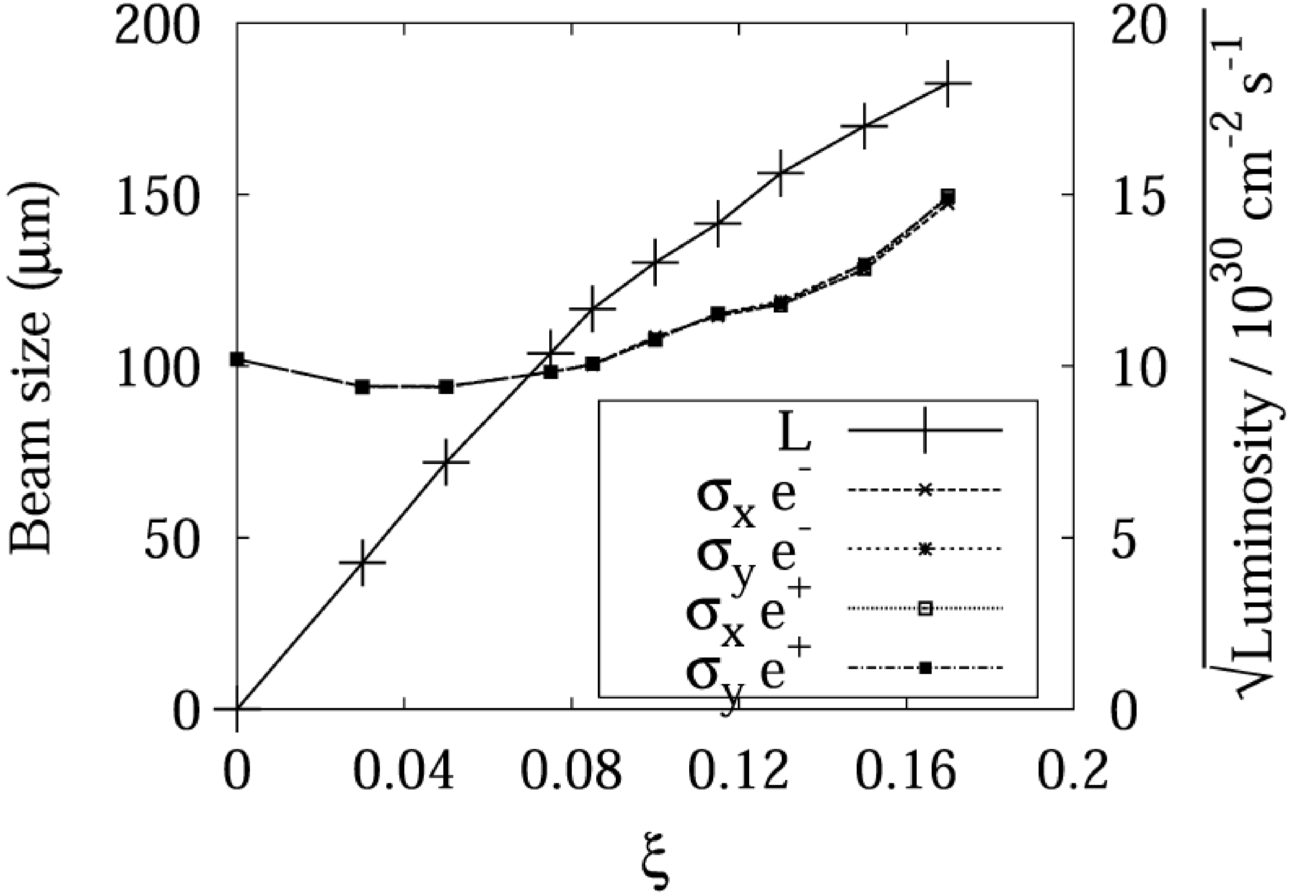
Threshold current dependence on tune



Threshold current dependence on beta

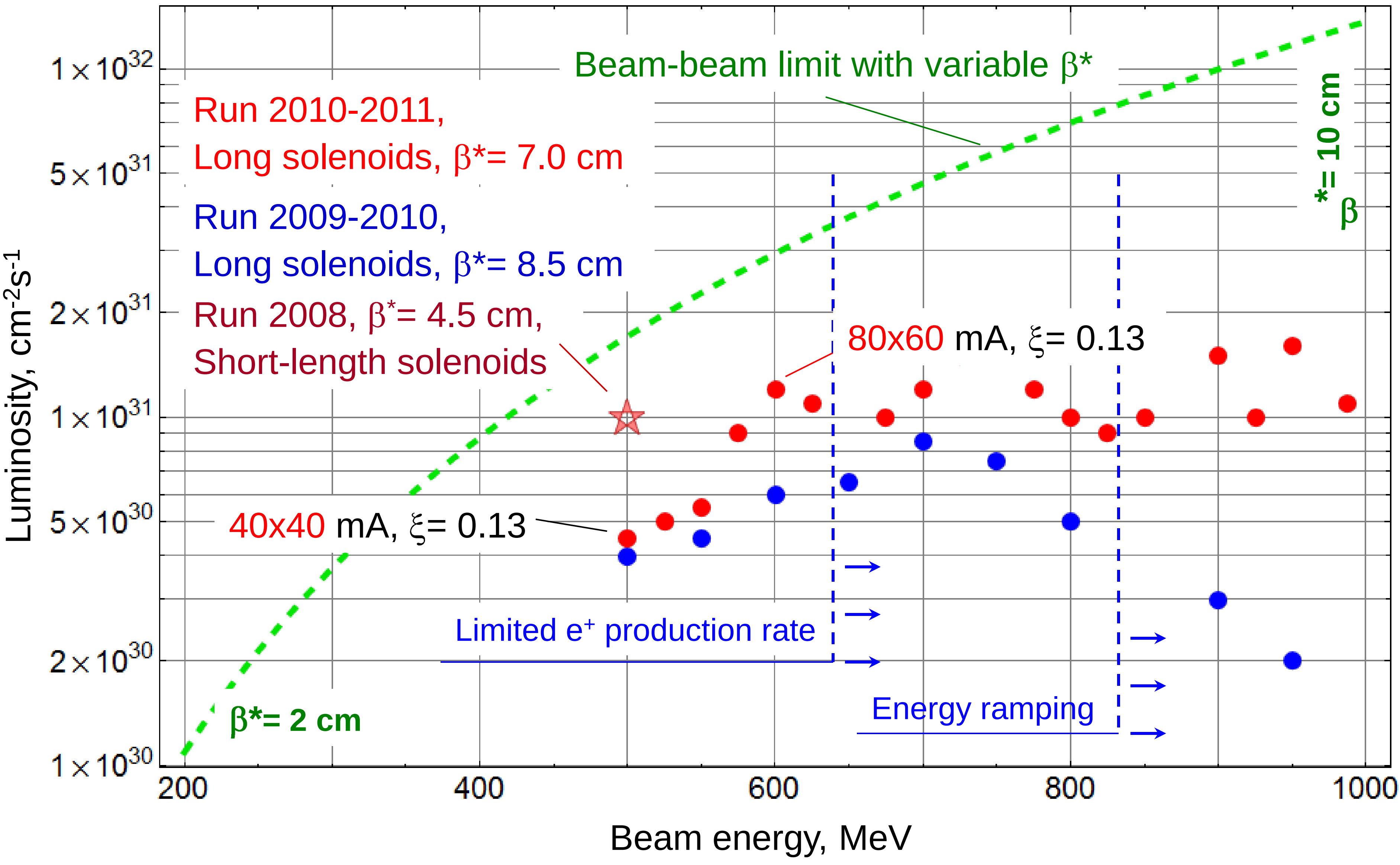


“Strong-Strong” Beam-Beam Simulations



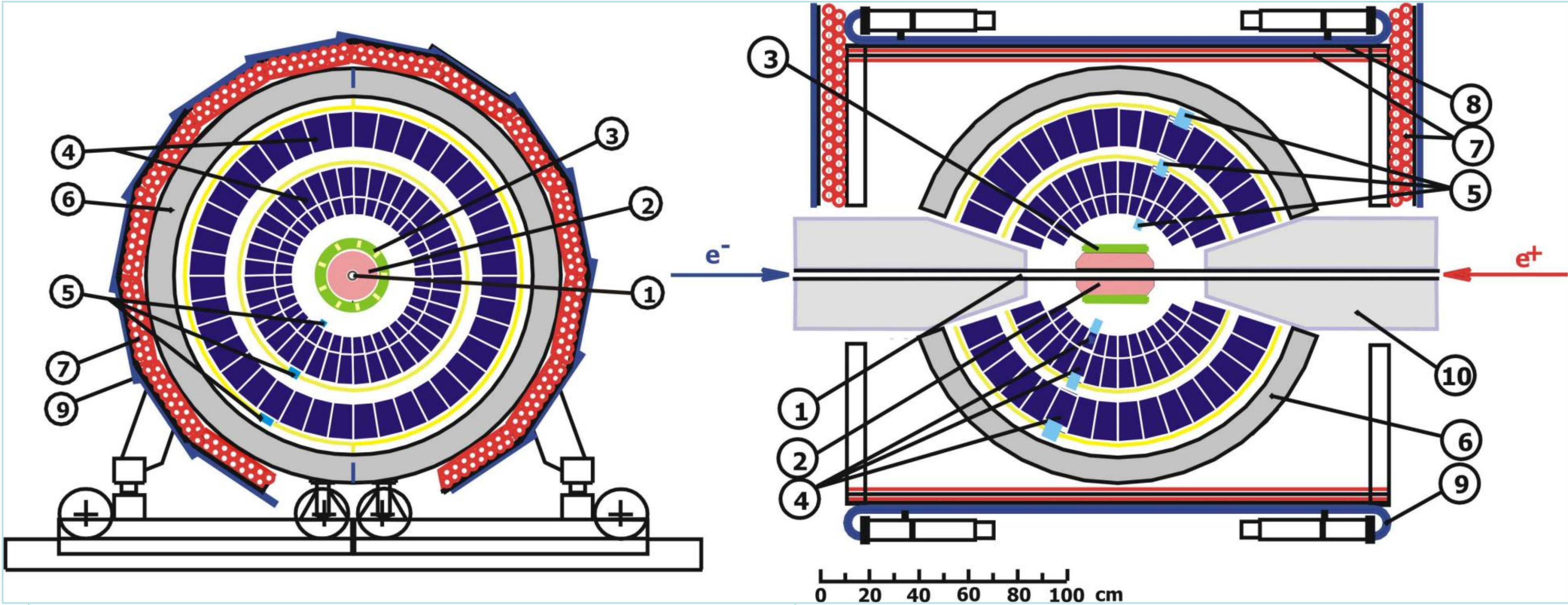
Beam size and luminosity vs. the nominal beam-beam parameter
(A. Valishev, E. Perevedentsev, K. Ohmi, *PAC’2003*)

VEPP-2000 Luminosity Studies



SND at VEPP-2000

NIM A449 (2000) 125-139



1 – beam pipe, 2 – tracking system, 3 – aerogel, 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – muon absorber, 7–9 – muon detector, 10 – focusing solenoid.

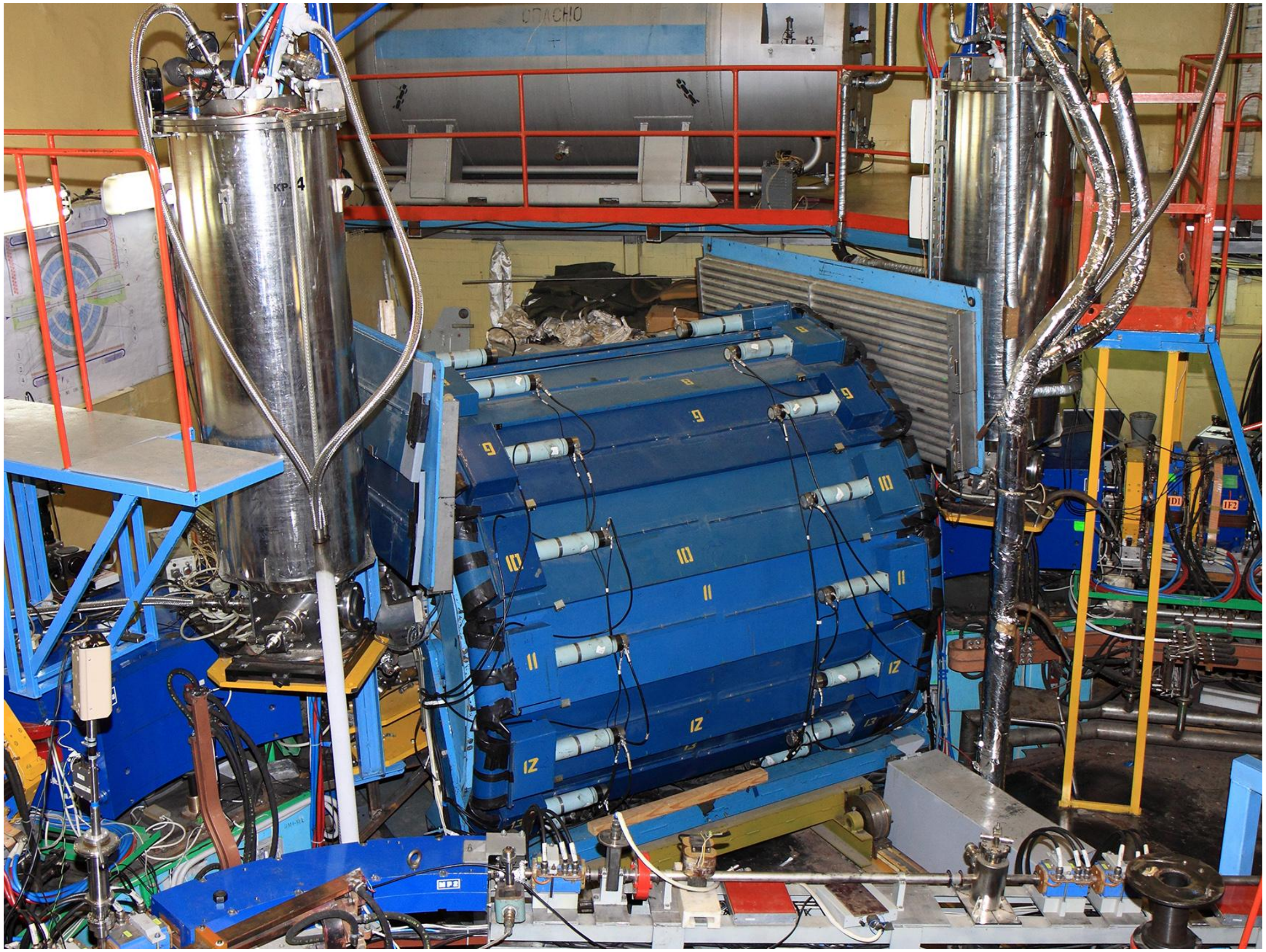
Upgrades:

1- cherenkov counter, n=1.05, 1.13 – e/πseparation E<450 MeV, π/K separation E<1 GeV,

2 –drift chamber – better tracking,

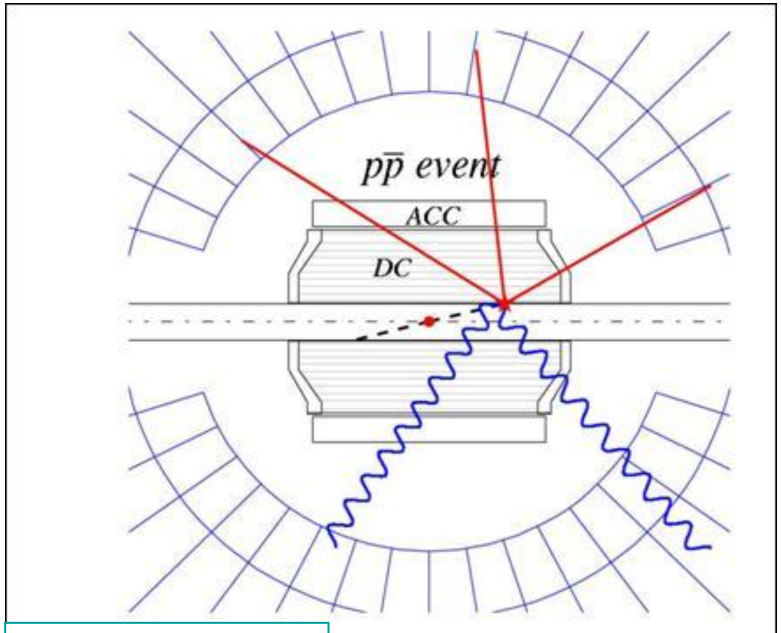
3- time of flight in EMC

SND view at VEPP-2000

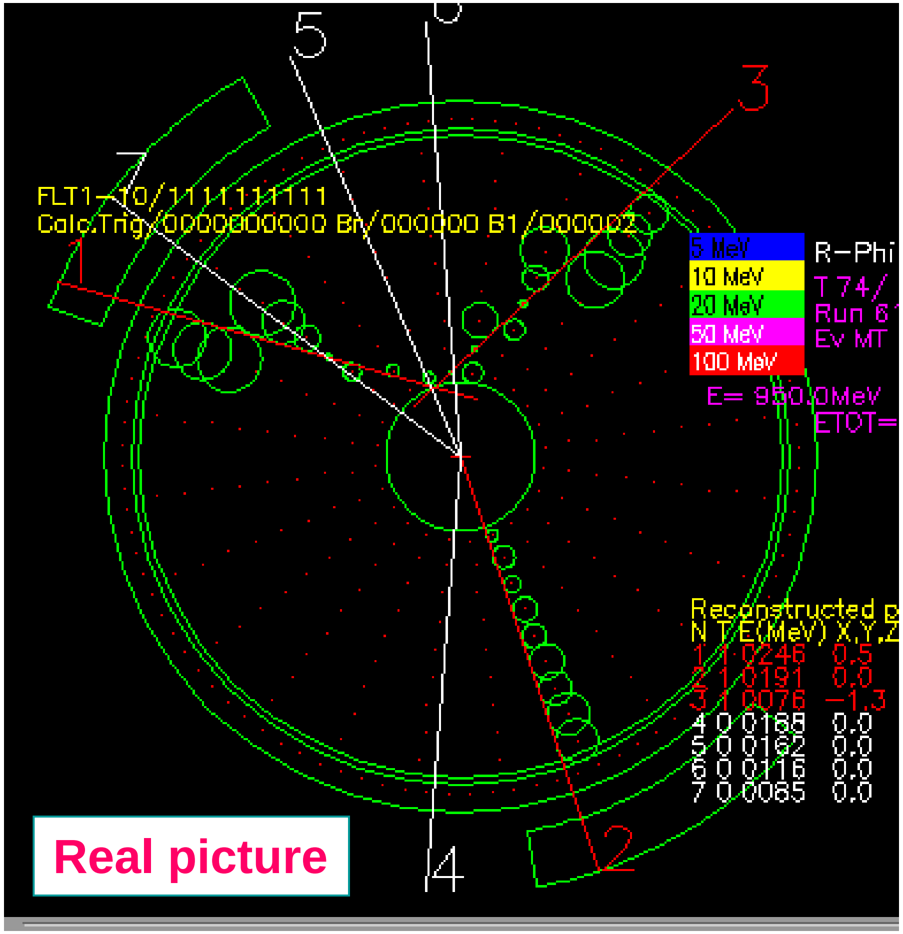


The first VEPP-2000 luminosity was measured in December 2007

MHAD10 experiment , e+e- >p pbar event, 1900 MeV

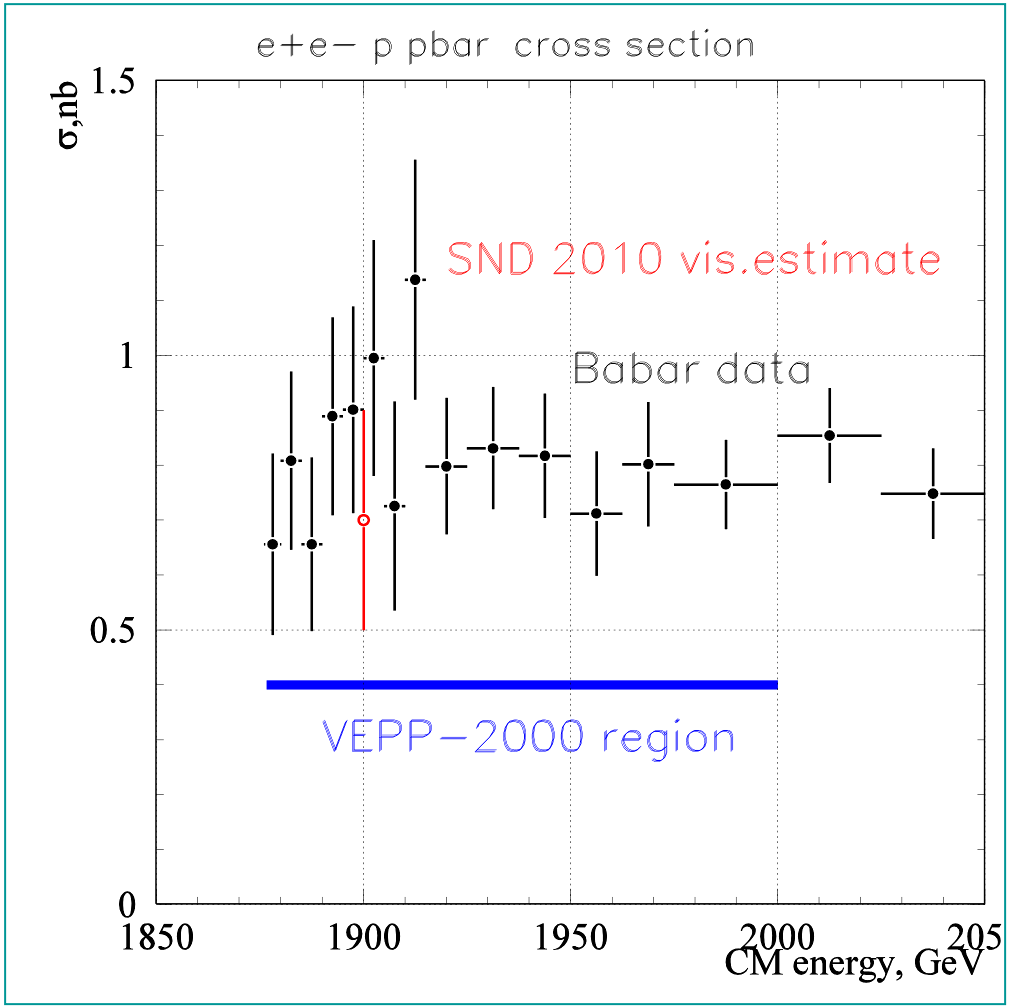


Ideal picture

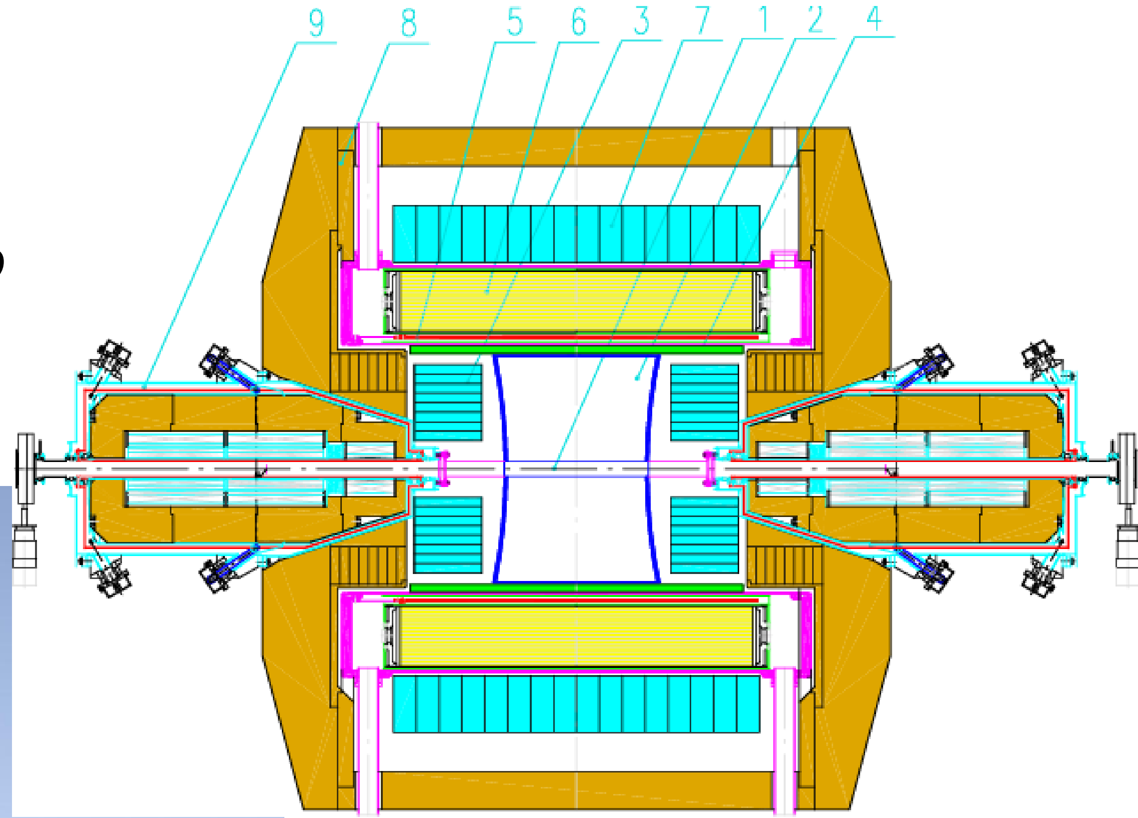


Real picture

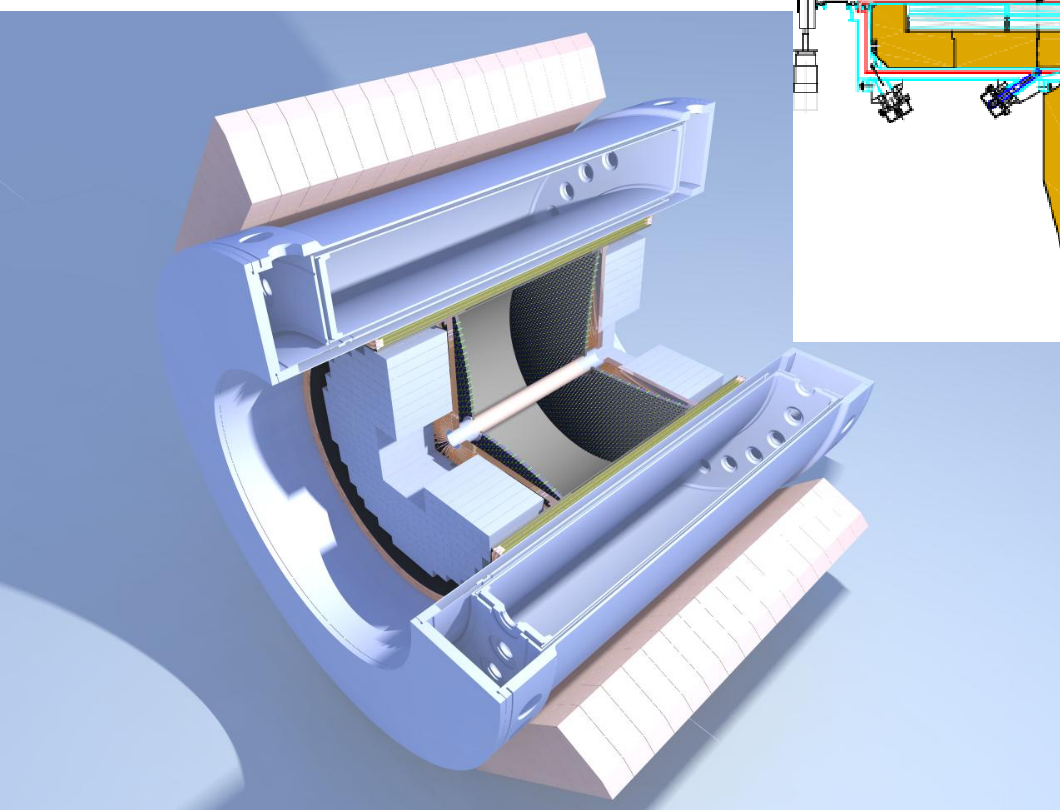
e+e- > p pbar, 2E=1900 MeV, cross section estimate



Cryogenic Magnetic Detector-3

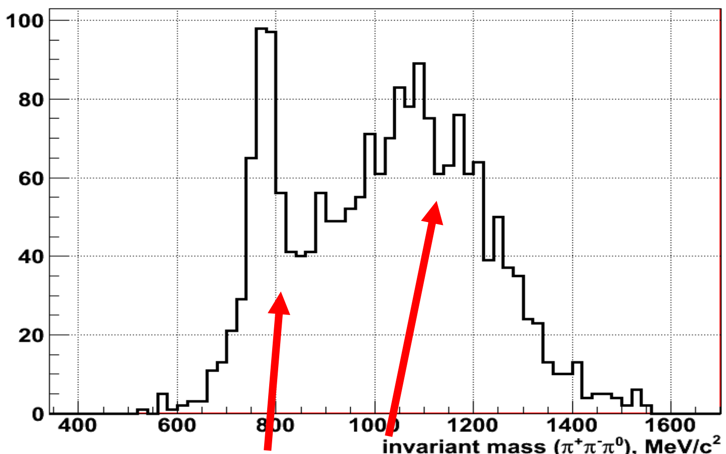


1 – vacuum chamber
2 – drift chamber
3 – electromagnetic calorimeter BGO
4 – Z – chamber
5 – CMD SC solenoid

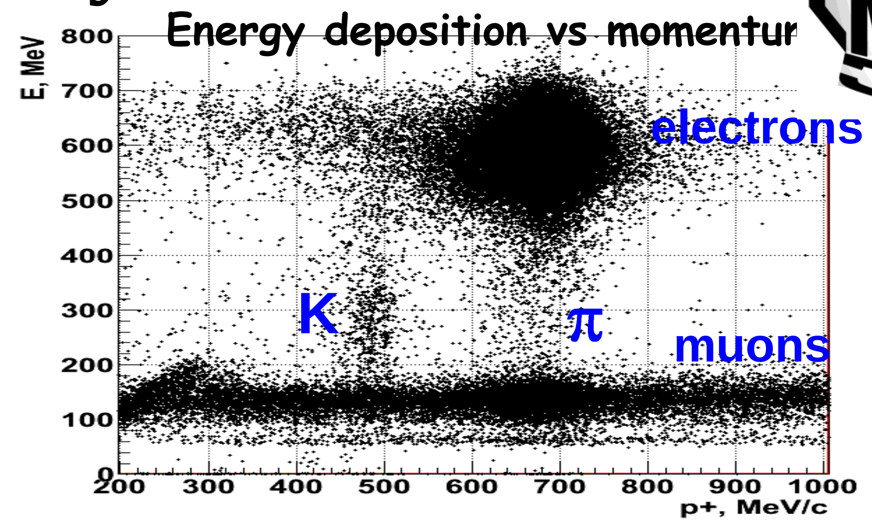


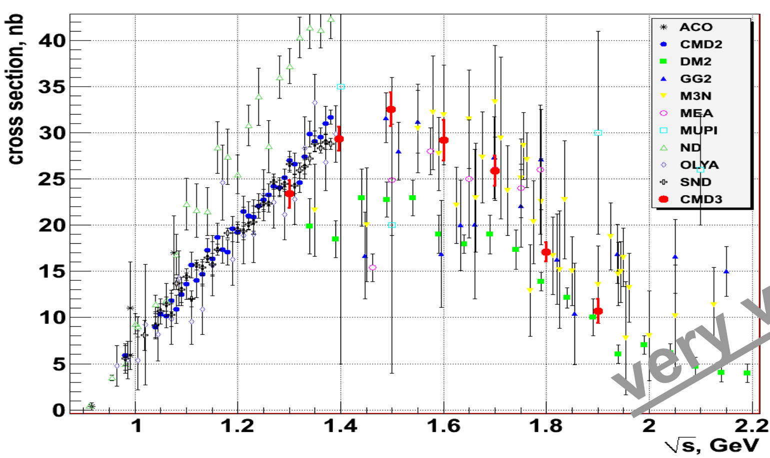
6 – electromagnetic calorimeter LXe
7 – electromagnetic calorimeter CsI
8 – yoke
9 – VEPP-2000 solenoid

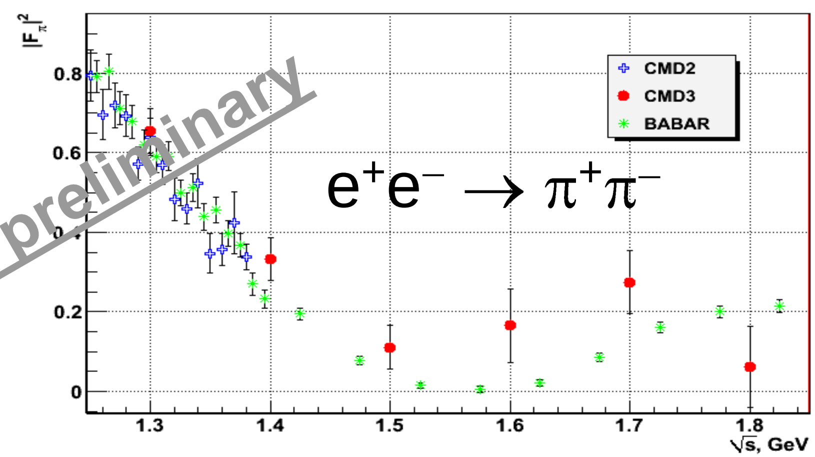
Preliminary analysis



$e^+e^- \to \omega\pi$ + $a_1\pi \to \pi^+\pi^-\pi^0\pi^0$

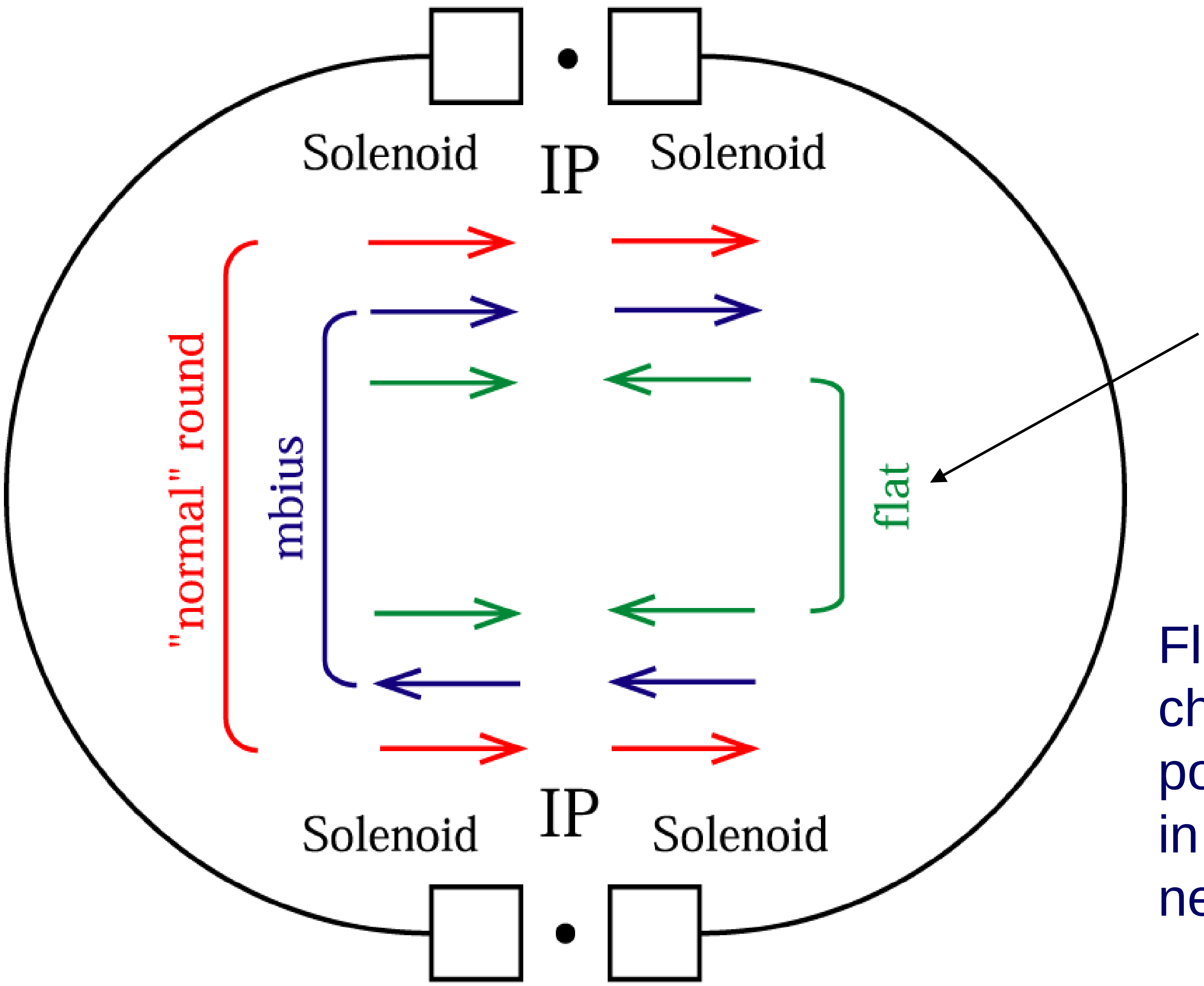






Even small statistics written in the beginning of experiments allows one to improve substantially the existing accuracy in 4π production for 2E>1.4 GeV

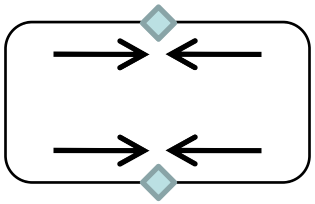
Practical Realization of Round Beams: Options for VEPP-2000

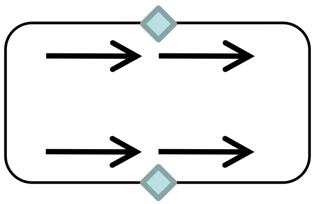


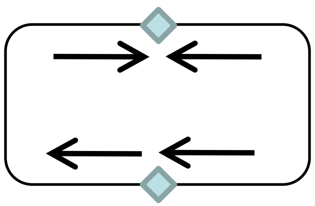
Round beam
due to coupling
resonance?
The simplest
practical solution!

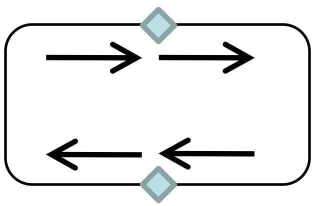
Flat to Round or Mobius
change needs
polarity switch
in solenoids and
new orbit correction.

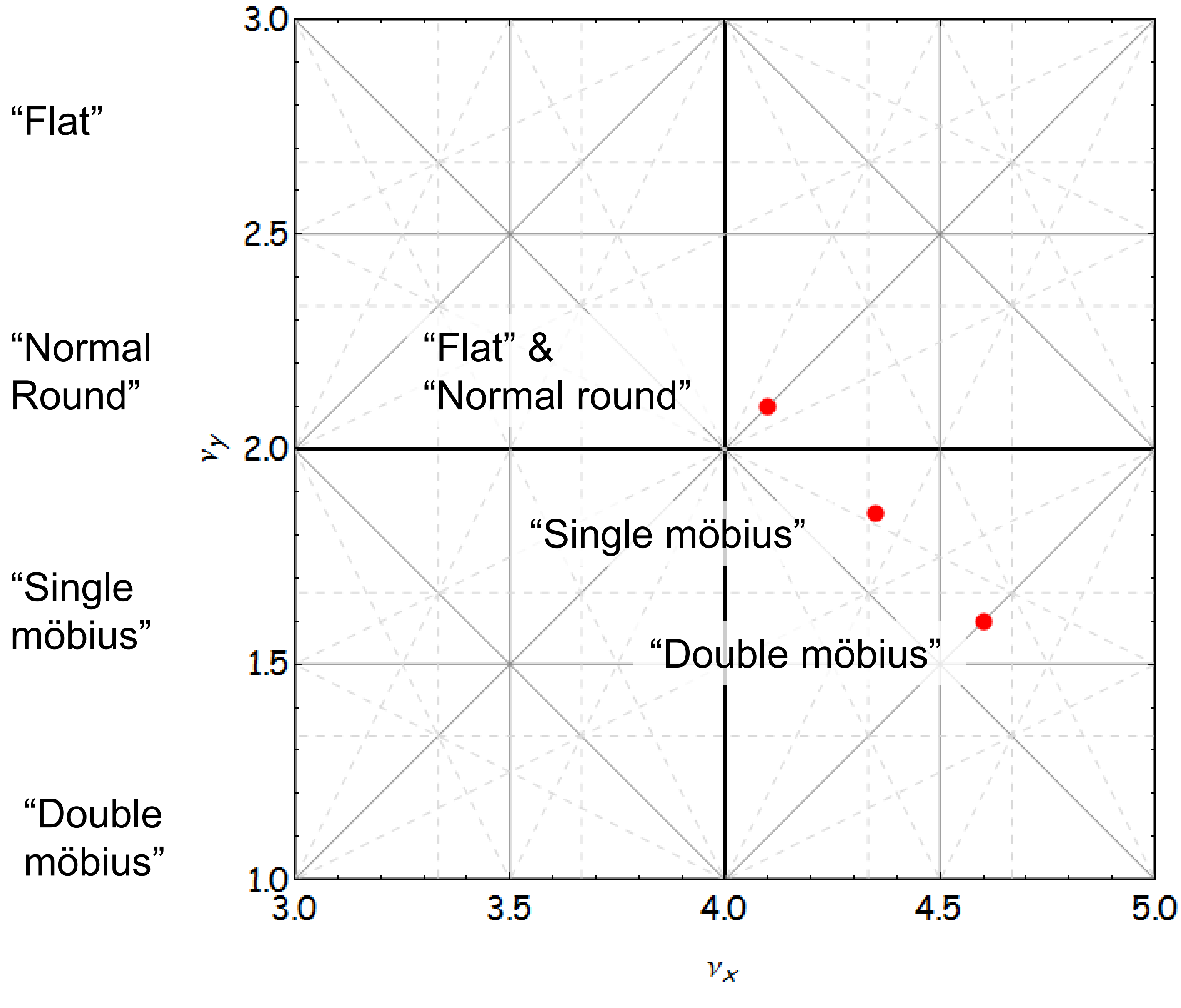
Working point for different options











Arguments in favor of work on a coupling resonance

Advantages of (+-+-) option as compared to the “basic mode” (++,-,-):

1) **Easy switch between flat and round modes of colliding beams**
2) **Better sextupole solution, hope for wider dynamic aperture**

Disadvantages not yet known

The strong-strong simulation (in progress) may show some problems in beam-beam behavior with high beam-beam parameter (~ 0.1 is needed)

This circular-mode option has been experimentally tested

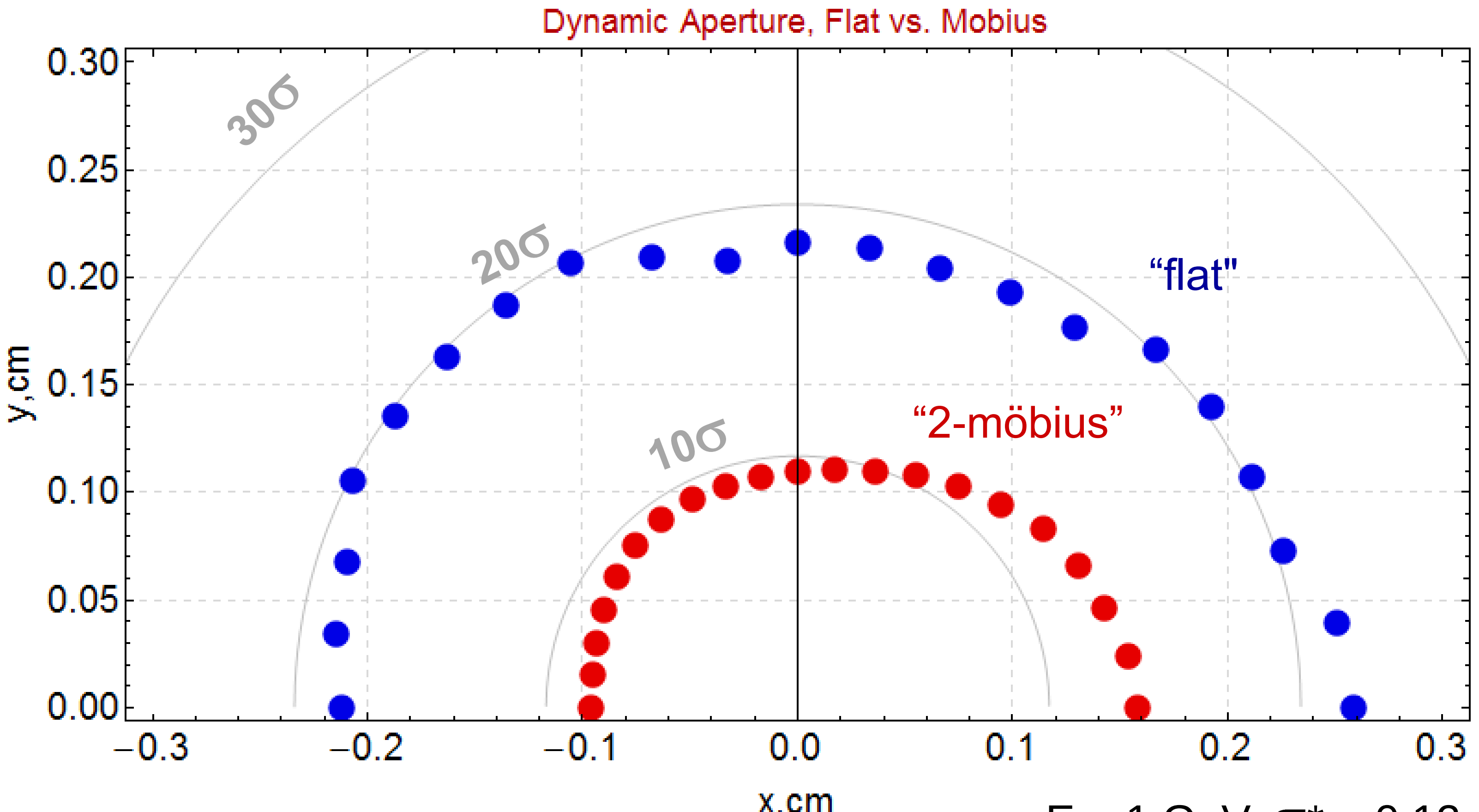
Weak-strong and strong-strong measurements have been done

Dynamic aperture simulations

1) Comparison of DA for “flat” and “2-möbius” solenoids polarity.

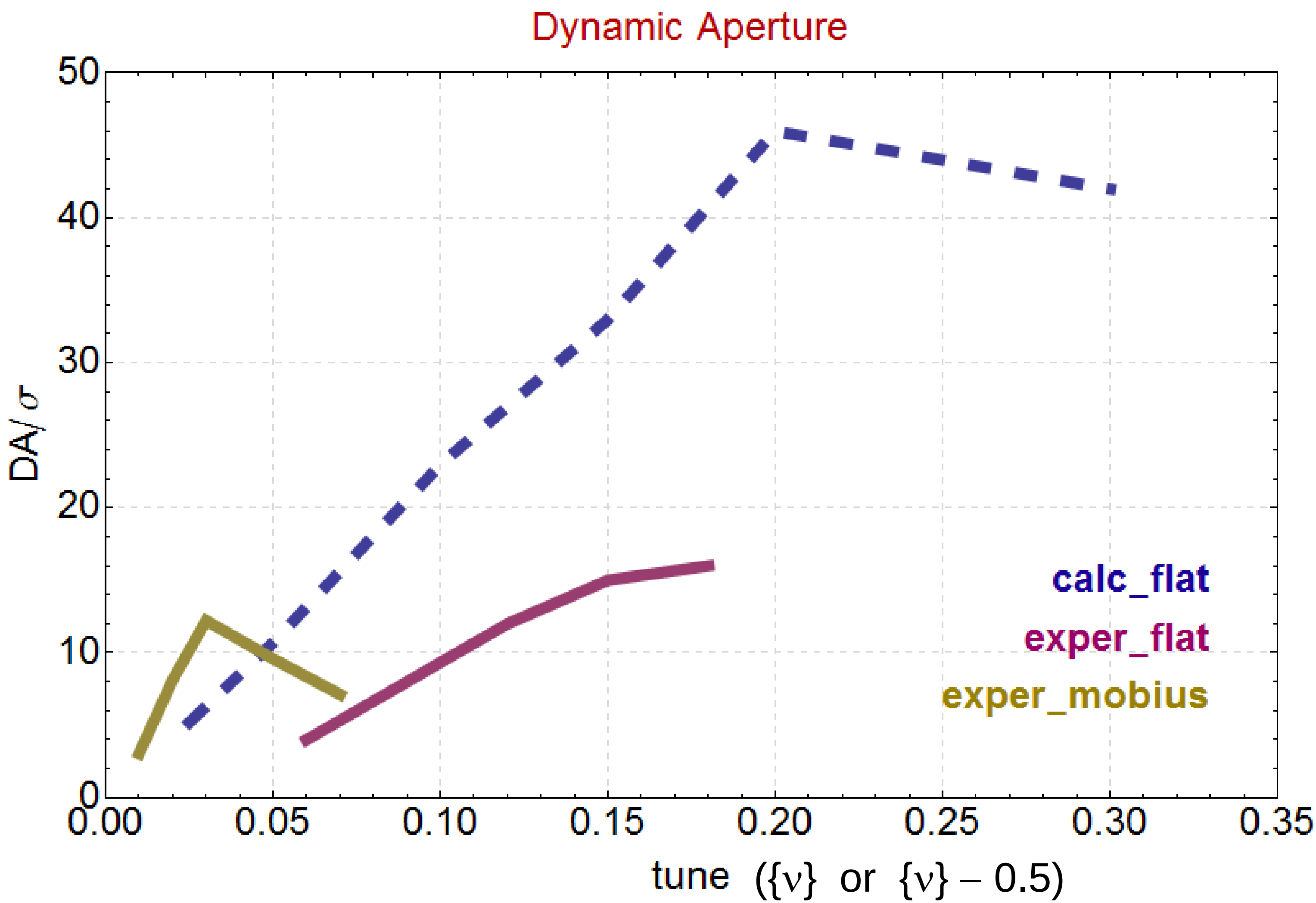
2) Identic lattice with $\beta^* = 8.5$ cm, $\{\nu\} = 0.128$.

3) Solenoids’ fringe fields – OFF. Chromatic sextupoles SX, SZ – ON.



E = 1 GeV, $\sigma^* = 0.12$ mm

DA simulations & measurements



Measurements @ E=500 MeV by pickups of kicked beam loss. “Flat” & “2-möbius” modes.

Experimental summary (0)

- VEPP–2000 is working
- «Round beams» – not a bad idea!
- Max. Lumi. achieved $1*10^{31}$ $cm^{-2}s^{-1}$ at φ-meson energy in 2008 run and $2*10^{31}$ $cm^{-2}s^{-1}$ at E=2x975 MeV in 2011
- Potentially $2*10^{31}$ $cm^{-2}s^{-1}$ possible at φ and $1.6*10^{32}$ $cm^{-2}s^{-1}$ at 2 GeV
- More positrons required! VEPP–5 injection complex will supply them in near future.

Experimental summary (1)

- After orbit and optics correction @ 509 MeV, with e+ currents <40mA as limited by injection, the maximum e- current at collision raised to ~50 mA,
- Tunes were close to the coupling resonance and separation v1 – v2 = 0.02 was caused by non-compensated solenoids needed to form the circular betatron modes. Coupling in the arcs was corrected to 1/10 of that separation.
- Different tunes (v1 + v2)/2 = 0.11 – 0.15 were tried, the limiting strong-beam current was 40% sensitive to the tune. Mostly the beam-beam measurements were done with (v1 + v2)/2 = 0.125 and β^*=5cm. Lower tunes are desirable, not available as yet.

Experimental summary (2)

- Equal emittances were obtained with the arc tunes set exactly on resonance, resulting in round beam shape @IP with $\sigma \sim 50\ \mu m$
- 10^{10} particles correspond to 20 mA, $f_0 = 12.3$ MHz, the expected luminosity with 20 x 20 mA^2 comes to $L = 4 \times 10^{30}\ cm^{-2}s^{-1}$ and the nominal $\xi = 0.04$
- The peak lumi showed the record of $\sim 10^{31}\ cm^{-2}s^{-1}$, while the max $\xi > 0.08$ was recorded in the weak-strong measurement. $\xi \sim 0.1$ was limited by the weak beam lifetime rather than beam-size blowup @IP

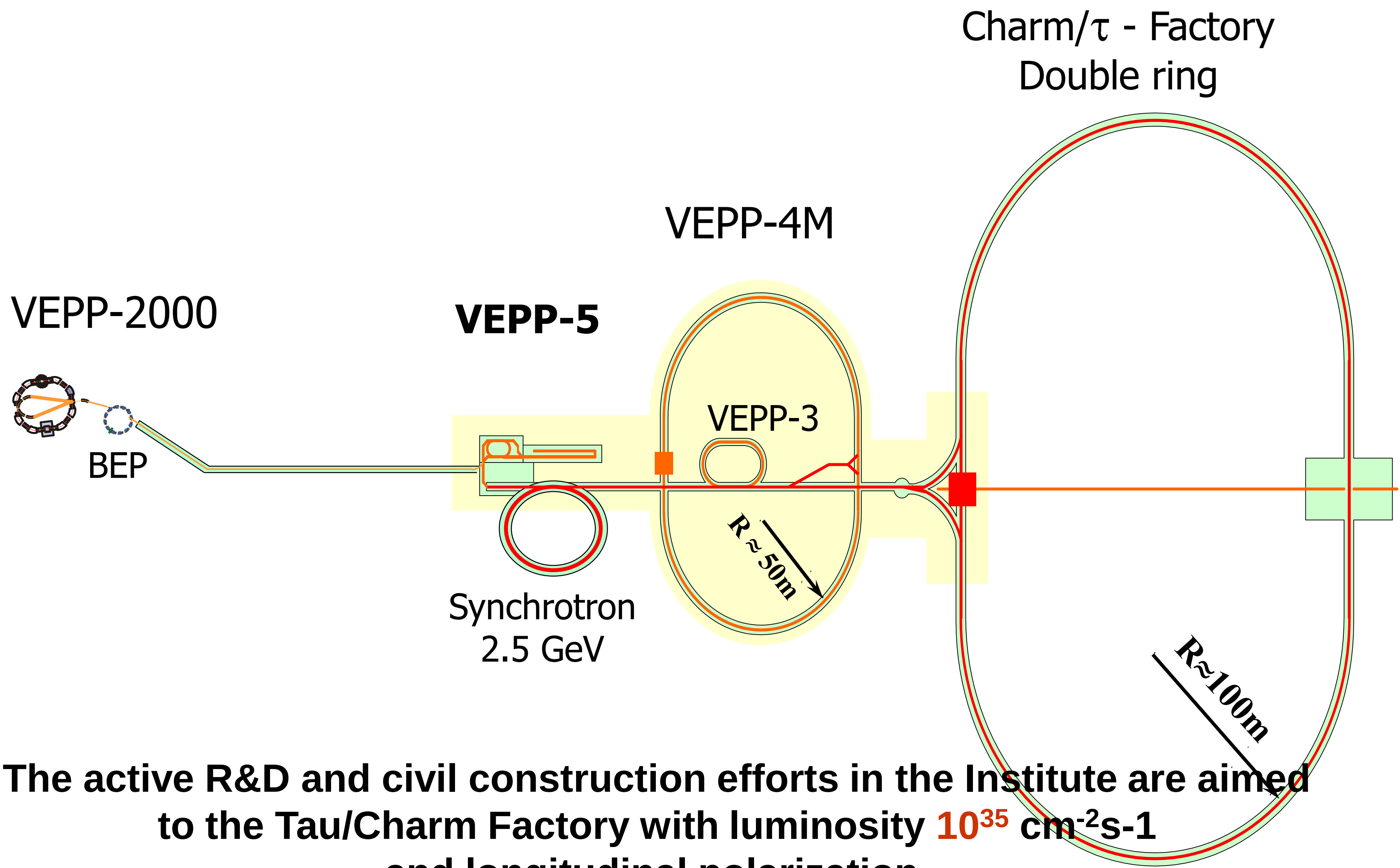
Experimental summary (3)

- Very preliminary: the specific luminosity did not degrade in the available range of ξ.
- The strong-strong measurement showed continuous current dependence of beam sizes, no evidence of strong flip-flop effects.
- The weak-strong beam size measurement at 4 positions around the ring provided plenty of data for analysis of the dynamic beta-function

Future work

- The simulation clearly predicts better lifetime for lower tunes, we urgently need understanding of problems with optics at tunes < 0.11
- Optimization of sextupoles, although not needed for DA, may he helpful for the beam tails at collision: to be checked in the weak-strong simulation.
- Strong-strong simulation is important, however a correct account of the natural chromaticity is needed in the code.
- More beam-beam studies needed to improve understanding of current-dependent beam sizes
- Basic round beam option + + – – should be experimentally tried out
- **High-luminosity operation becomes possible only after the new linac-based Injection Complex lifts the positron production limit**

Layout of injection using VEPP-5



The active R&D and civil construction efforts in the Institute are aimed to the Tau/Charm Factory with luminosity 10^{35} cm^{-2}s-1 and longitudinal polarization.

Weak-strong simulation

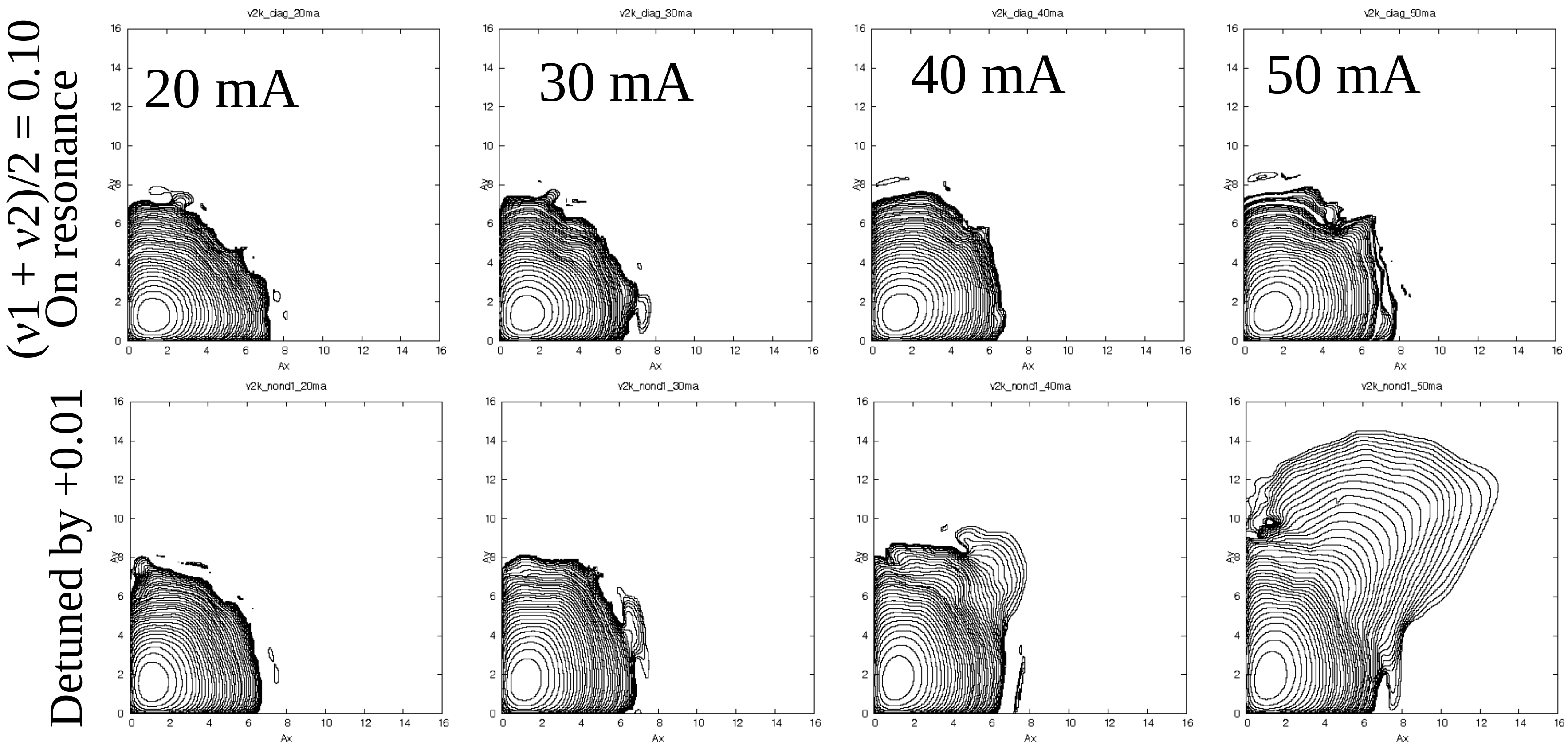
Deformation of the weak beam distribution is in question.

The simulation model for D.Shatilov's "Lifetrack" code:

1) 2-period lattice with the chromaticity correction sextupoles, synchrotron oscillations, longitudinal slicing
2) Whatever variations, E = 509 MeV and constant $\beta^* = 5$ cm, $\sigma_z = 17$mm, emittances ~46 – 48 nm
3) Tracking for 10^4 damping times ($\tau_{x,y}$~350,000 turns~28 ms)
4) Arc is tracked by P.Piminov's code, i.e. the natural chromaticity is correctly simulated, sextupoles (and other machine nonlinearities) can be included. Comparison with the previous "no sextupole" option is available.

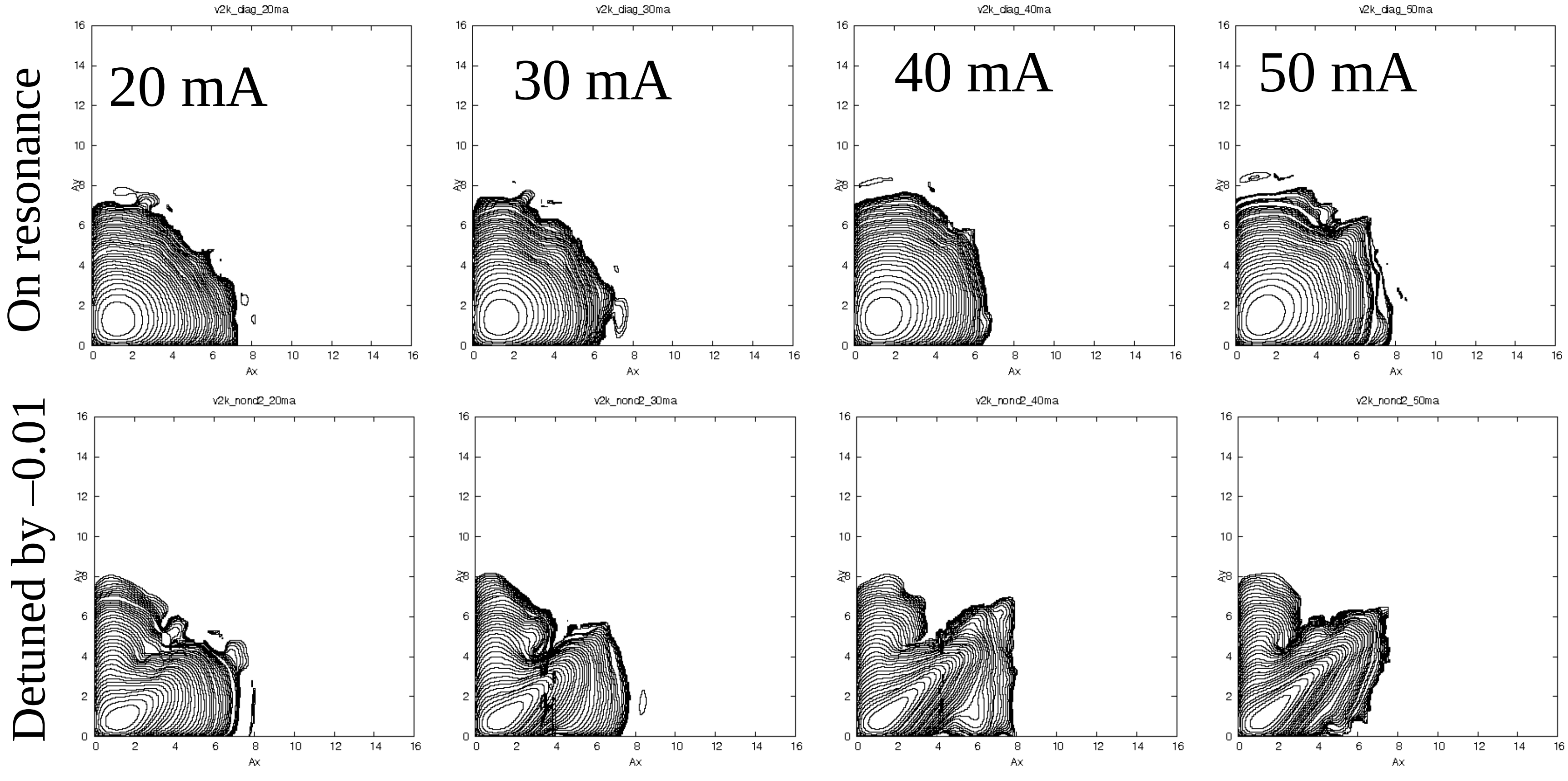
Things to be avoided in round colliding beam operation (1)

Detuning from the coupling resonance



Things to be avoided in round colliding beam operation (2)

Detuning from the coupling resonance

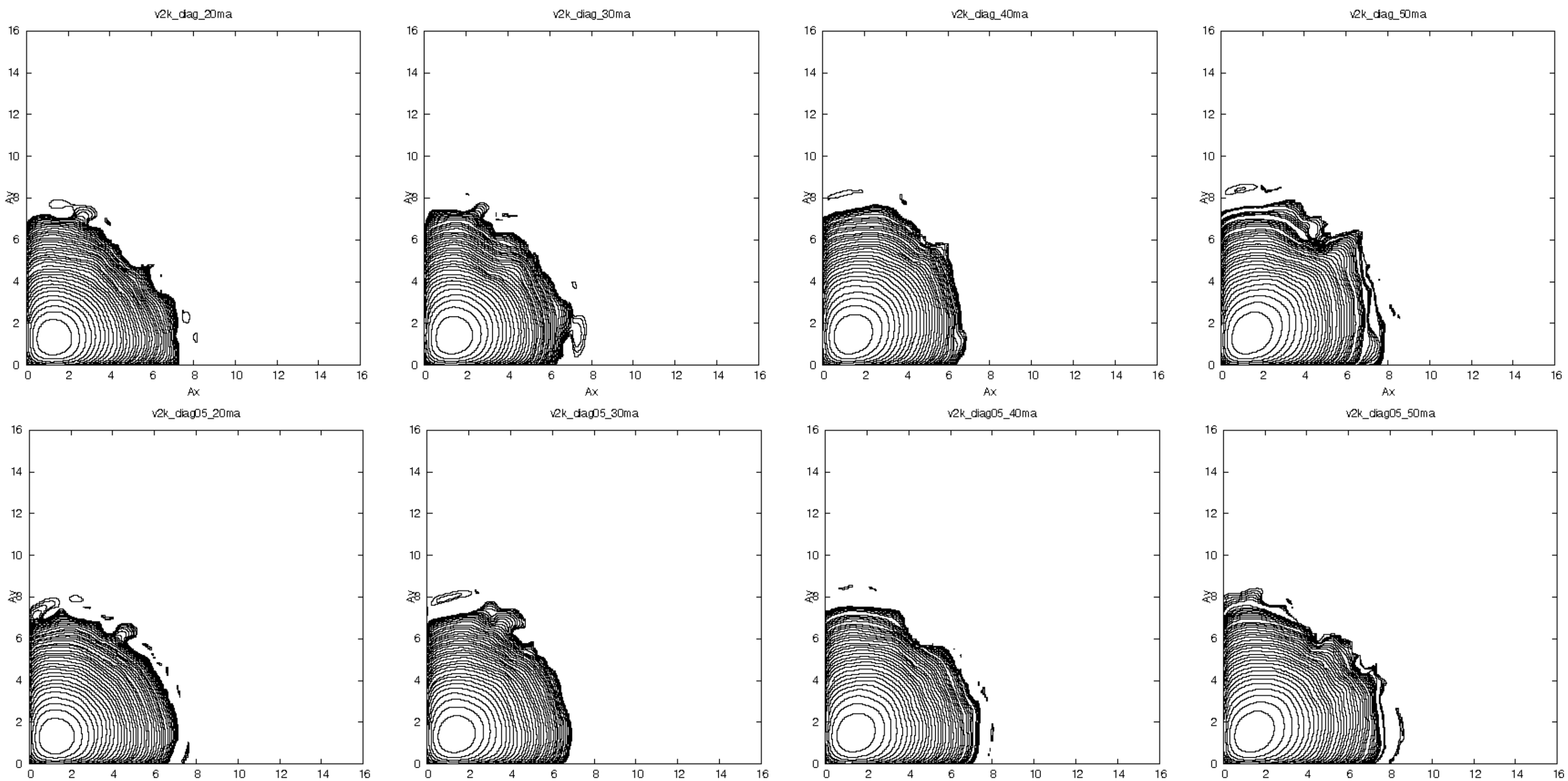


Things to be avoided in round colliding beam operation (3)

Large non-compensation of the solenoidal field

0.01

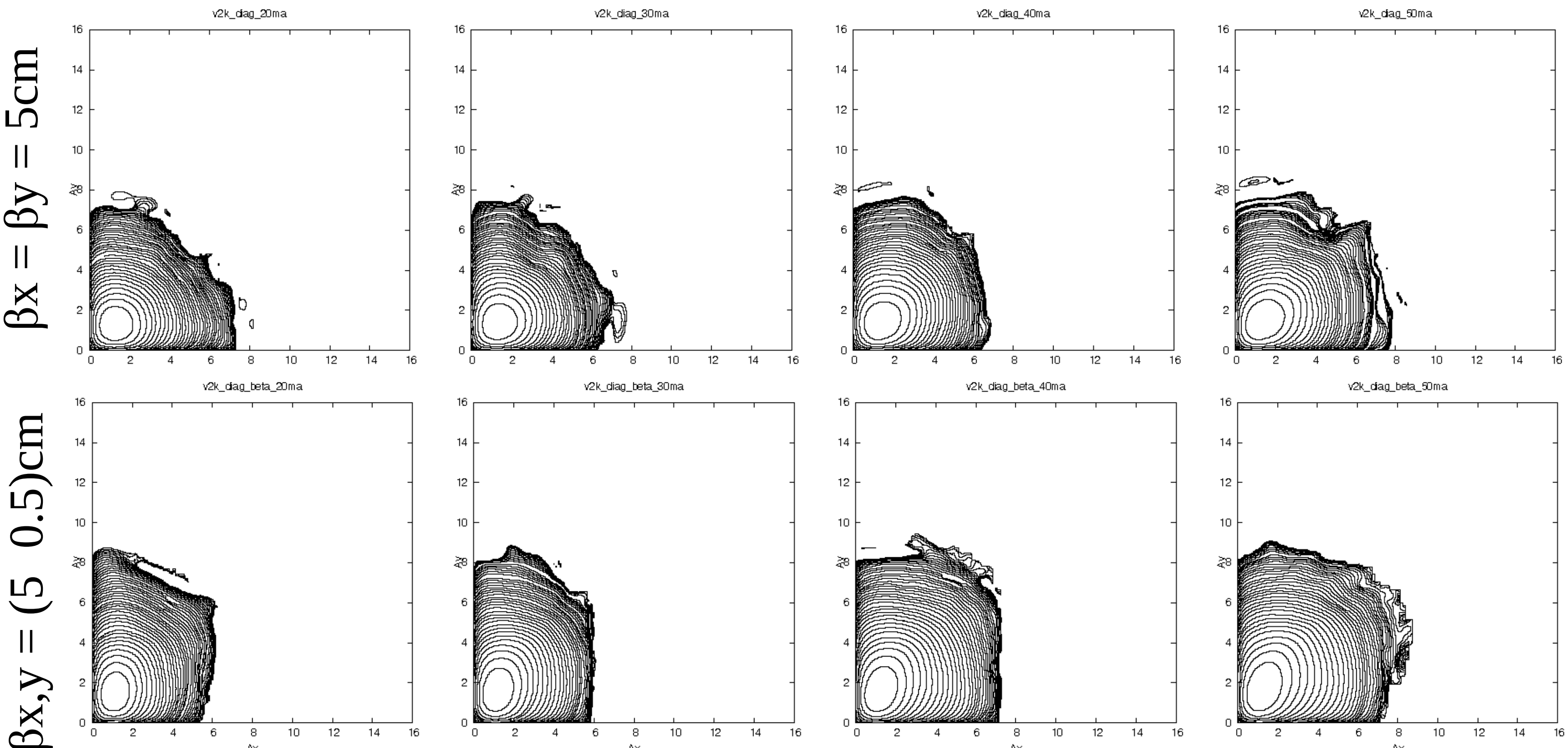
0.005



Different tune separation caused by solenoids

Things to be avoided in round colliding beam operation (4)

Non-round beta-functions @IP



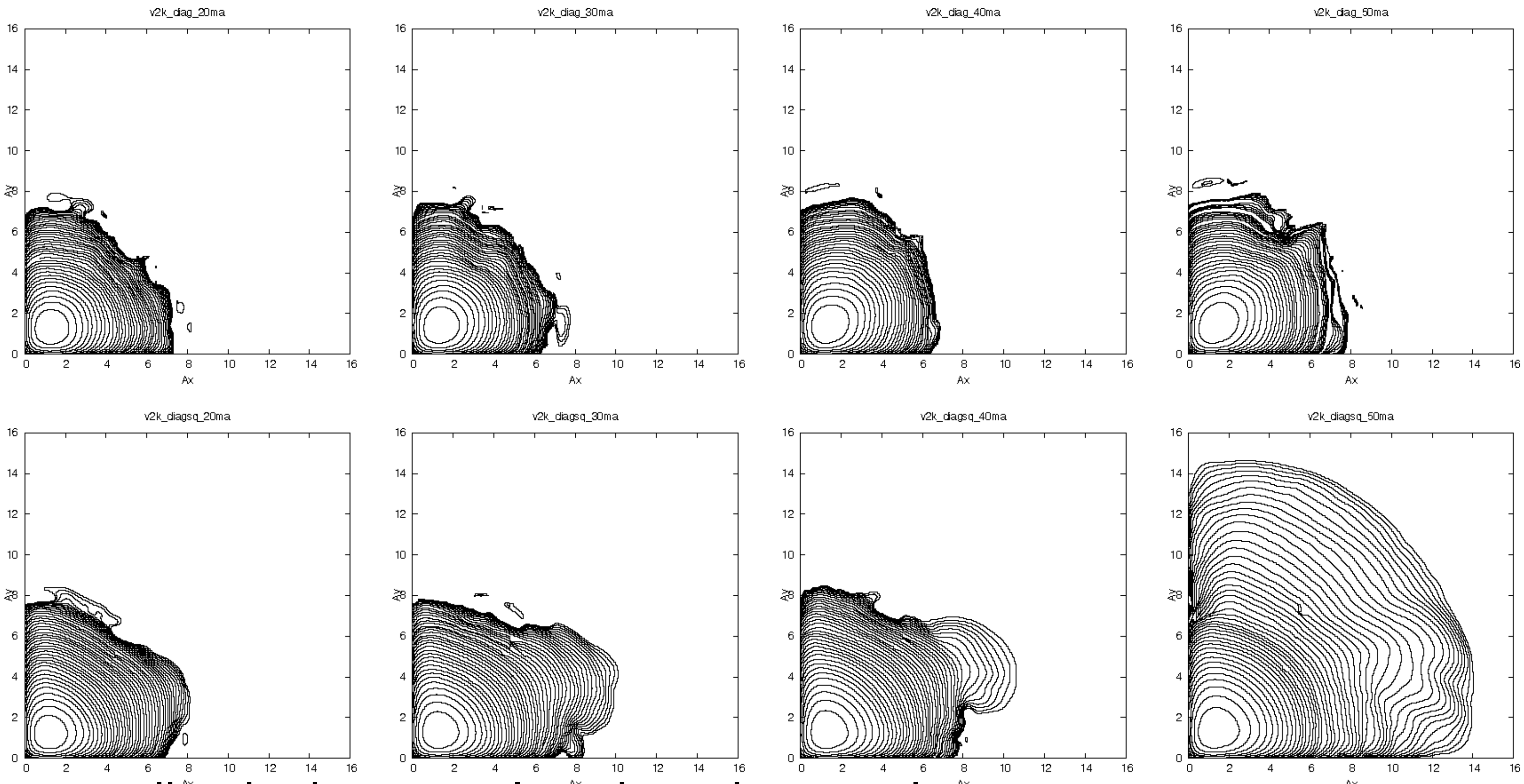
Difference in βx, βy means the angular momentum non-conservation

Things to be avoided in round colliding beam operation (5)

x-y coupling in the arcs

No coupling

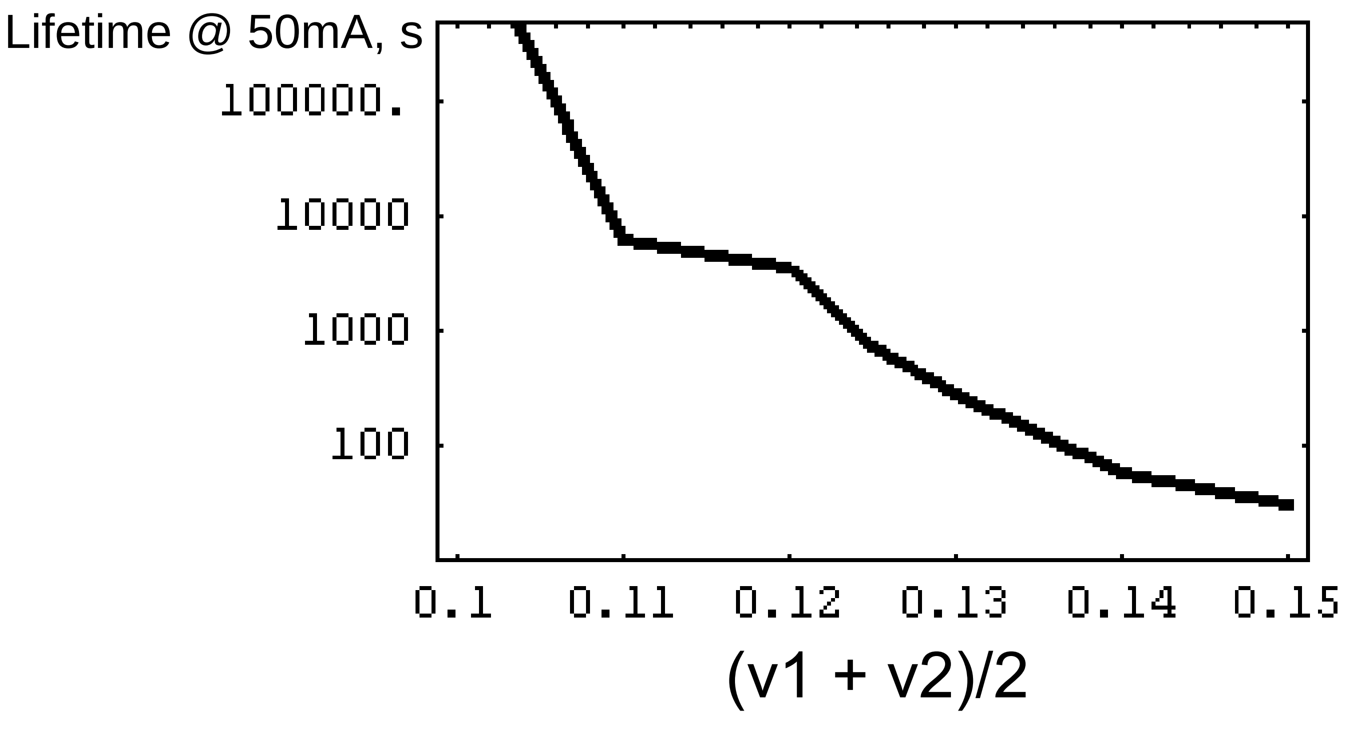
Tune separation 0.005

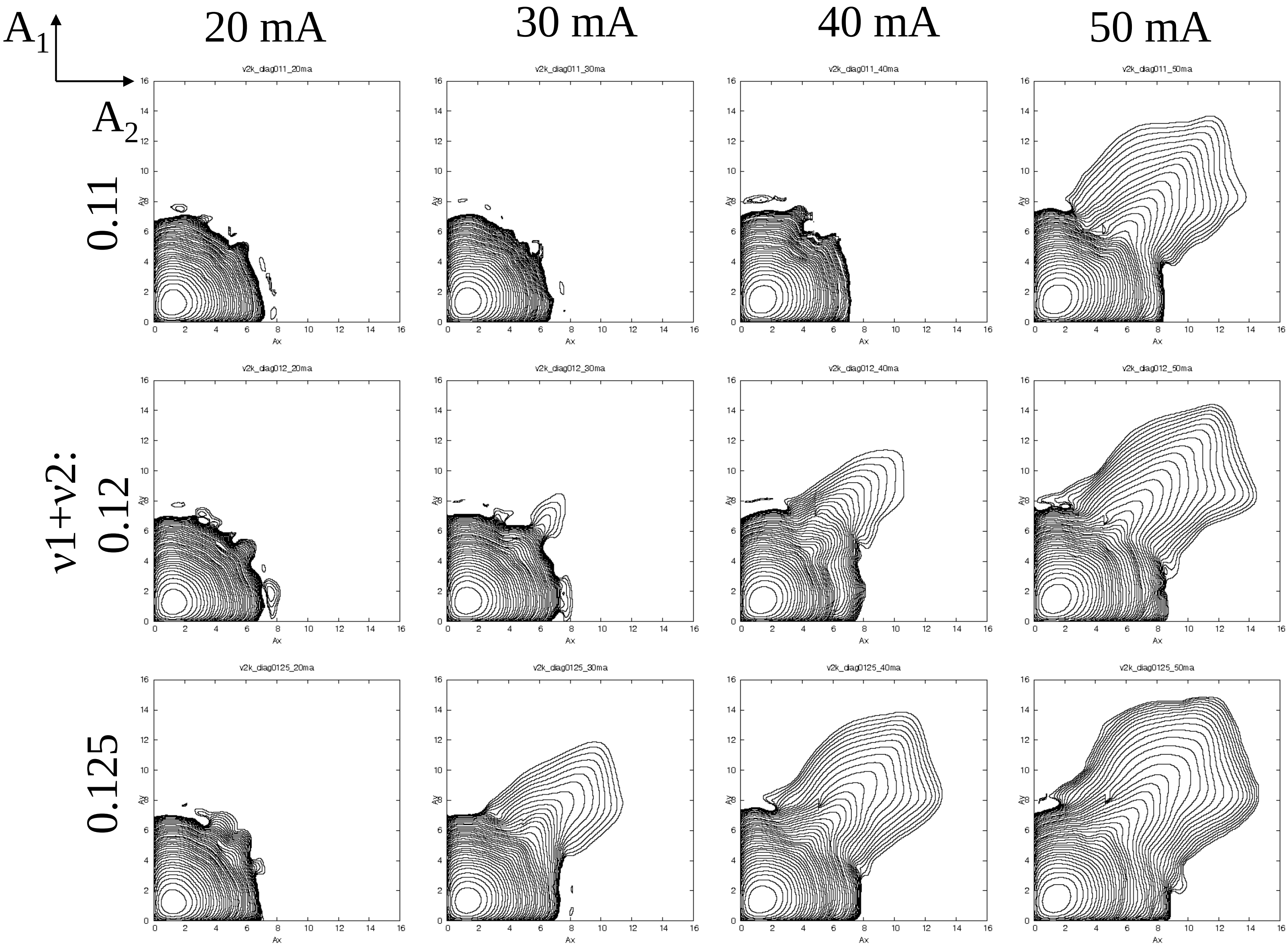


x-y coupling in the arcs also gives the angular momentum non-conservation

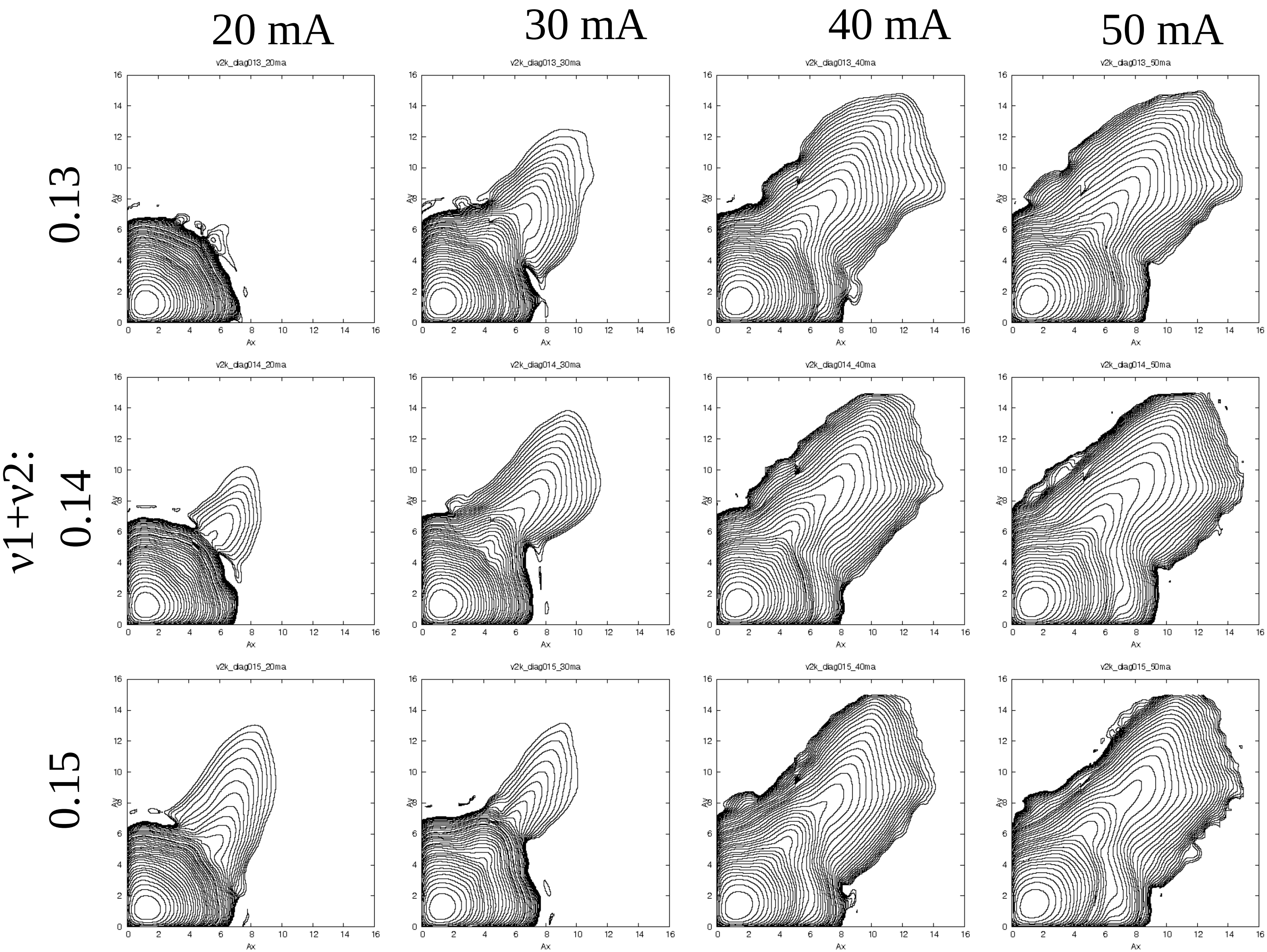
Tune scan along the diagonal

…reveals almost constant specific luminosity!
Namely, L = $1x10^{28}$ $cm^{-2}s^{-1}mA^{-2}$
Only the beam tails expand at higher tunes
and cause limitation of the beam lifetime



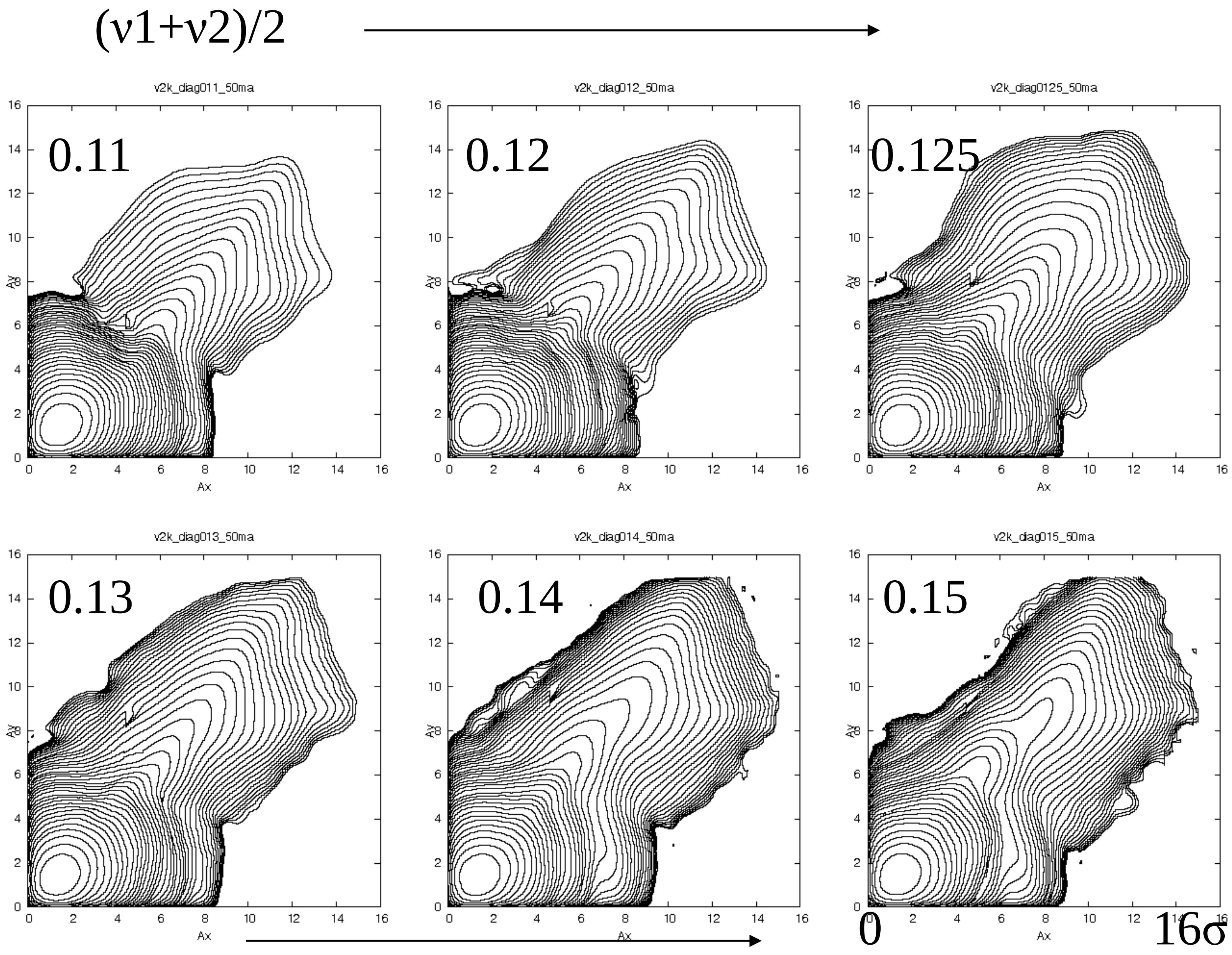


A1
A2
20 mA
30 mA
40 mA
50 mA
ν1+ν2:
0.11
0.12
0.125
v2k_diag011_20ma
v2k_diag011_30ma
v2k_diag011_40ma
v2k_diag011_50ma
v2k_diag012_20ma
v2k_diag012_30ma
v2k_diag012_40ma
v2k_diag012_50ma
v2k_diag0125_20ma
v2k_diag0125_30ma
v2k_diag0125_40ma
v2k_diag0125_50ma
Ax
Ay



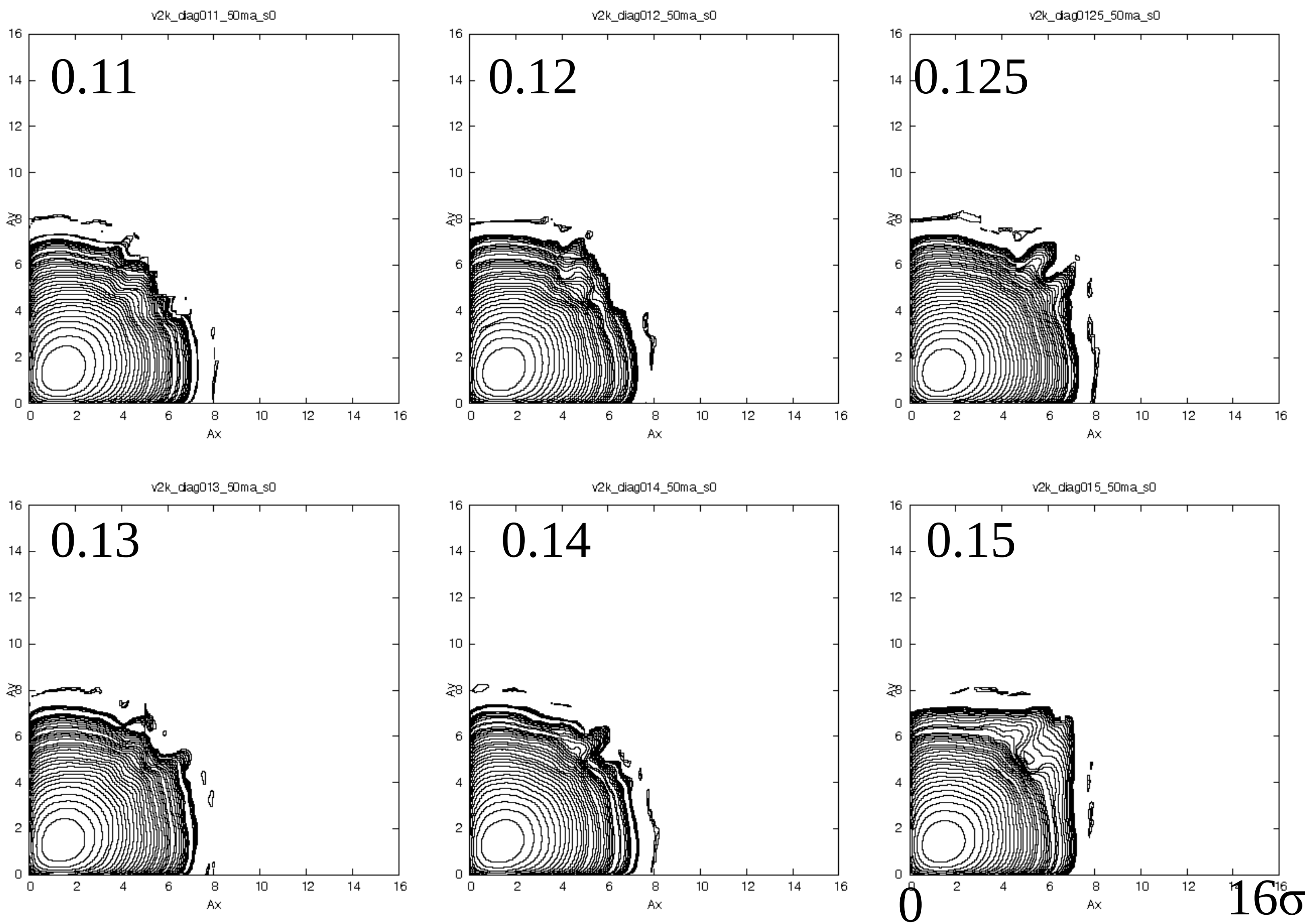
20 mA
30 mA
40 mA
50 mA
0.13
ν1+ν2:
0.14
0.15
v2k_diag013_20ma
v2k_diag013_30ma
v2k_diag013_40ma
v2k_diag013_50ma
v2k_diag014_20ma
v2k_diag014_30ma
v2k_diag014_40ma
v2k_diag014_50ma
v2k_diag015_20ma
v2k_diag015_30ma
v2k_diag015_40ma
v2k_diag015_50ma
Ax
Ay

@50mA, with sextupoles: tune dependence of the tails



@50mA, without sextupoles: very weak beam-beam effect

$(\nu 1+\nu 2)/2$ →



Sextupoles

To preserve the angular momentum, the linear optics must be an equivalent of axi-symmetric focusing and rotation (commutable).

However, a sextupole changes the angular momentum

Field: $B_x = 2xy$ Kick: $k_x = -(x^2 - y^2)$

$B_y = x^2 - y^2$ $k_y = 2xy$

The angular momentum and its change:

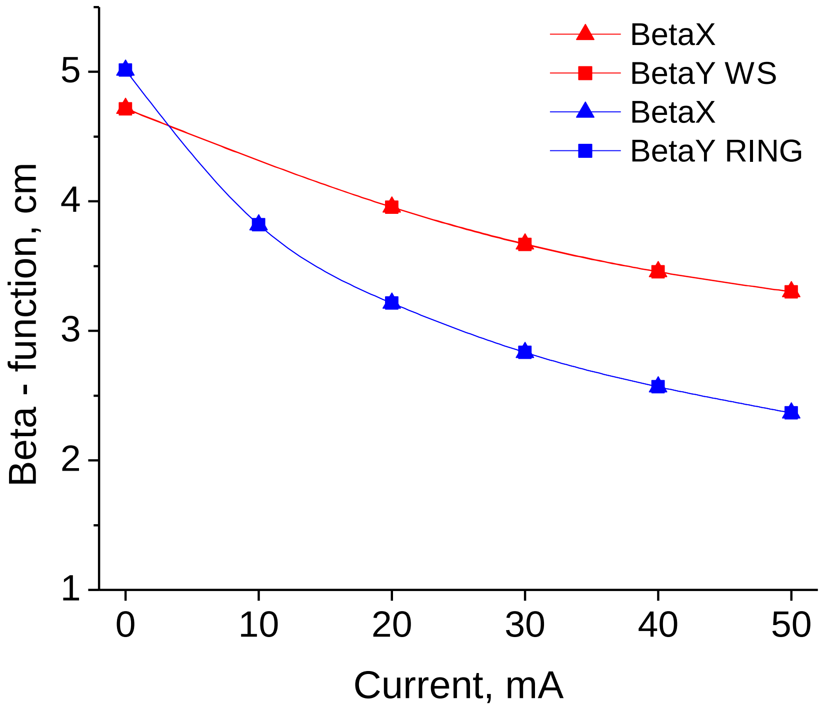
$$M = xy' - yx'$$

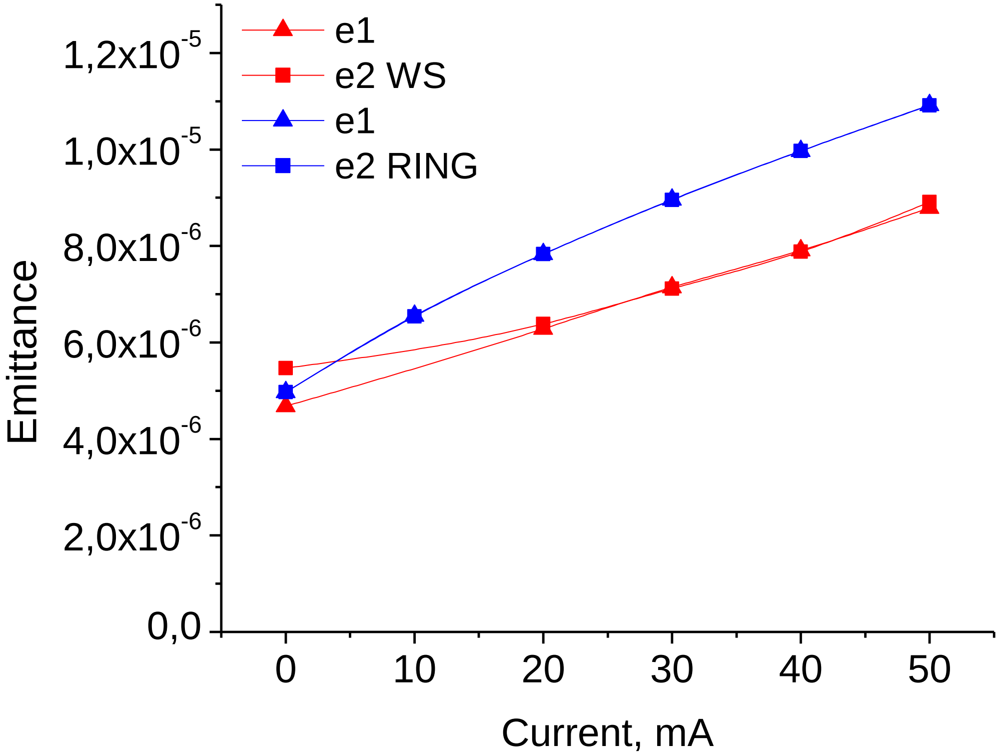
$$\Delta M = x\Delta y' - y\Delta x' = xk_y - yk_x = 3x^2y - y^3$$

Thus, the change in the angular momentum has the same form as the sextupole Hamiltonian. To 1st order in the sextupole strength, minimization of the sextupole harmonic integral improves the angular momentum conservation.

Dynamic beta, emittance and size

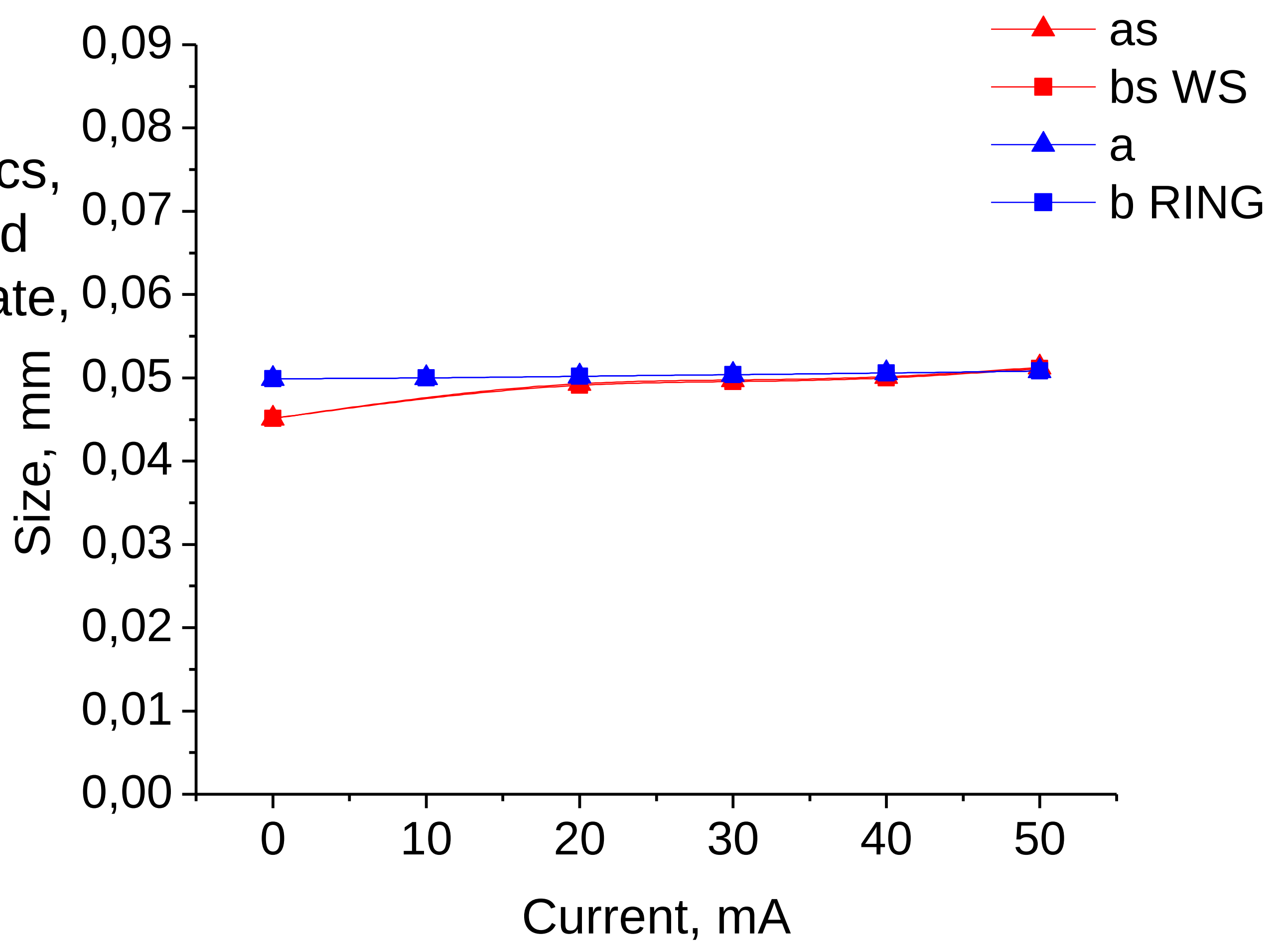
(v1 + v2)/2 = 0.125



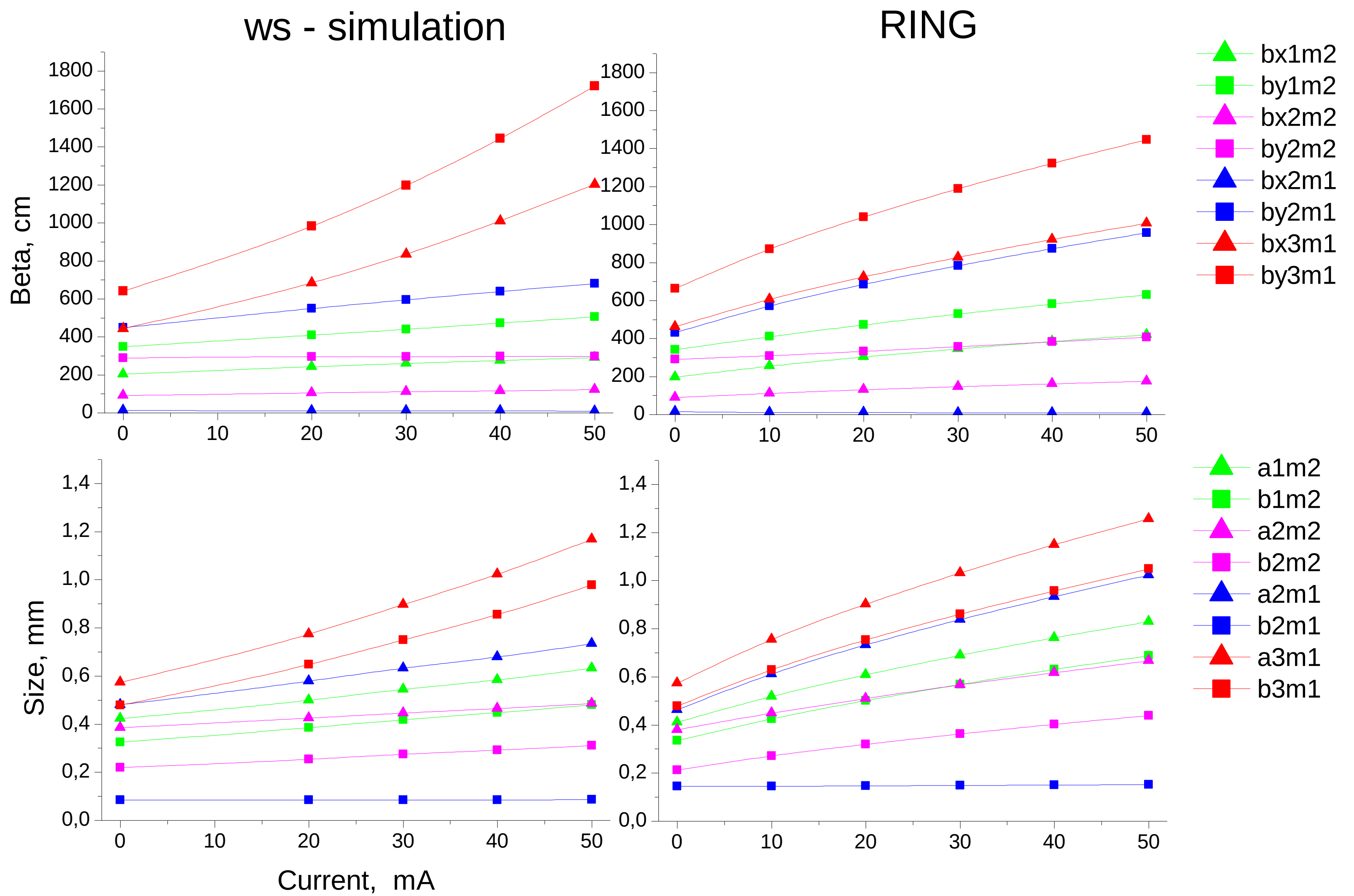


Dynamic beta, emittance and size

For VEPP-2000 optics, the dynamic beta and emittance compensate, sizes @IP = const

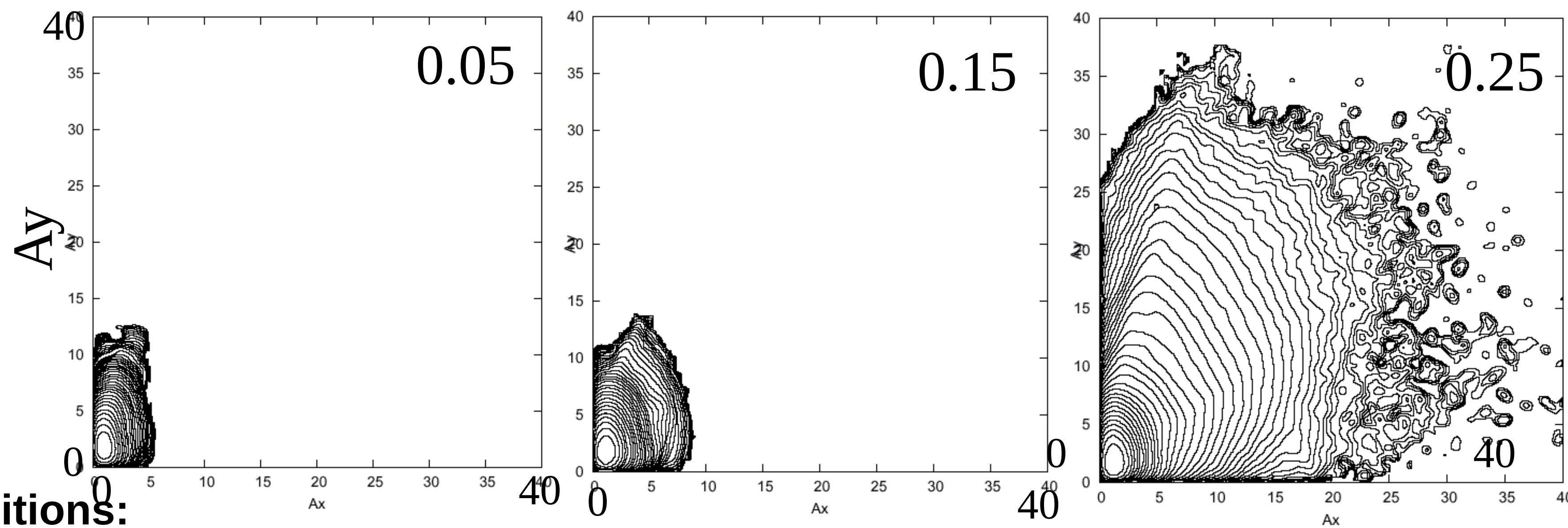


Dynamic beta and sizes at the e+ beam-size monitors



Weak-strong beam-beam simulation by D.Shatilov

The beam-beam parameter varied:



Conditions:

arc tunes separation 0.02 by the doublet (D3,F3) & F1 lenses, beta*x,y kept equal;

circular modes and a wider tune split produced by twist 0.79kGs*66.5524cm:

Qx = 4.1115, Qy=2.0893,

alpha = 0.036, Qs = 0.0028, beta*=4.5cm

bunch length: 1.74cm (50kV RF), dE/Eo = 3.5e-04

emittances: Ex = 8.464e-06, Ey = 3.065e-06 cm*rad

decrements: dx = 1.905e-06, dy = 1.998e-06, de = 4.318e-06 (per 1/2 turn)

Thanks a lot

for your attention!