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ELECTRON COOLED BEAM LOSSES PHENOMENA IN COSY

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Problem statement

- The COSY ring is operating for medium energy experiments in the energy range 45-2500 MeV.
- The spin filtering studies at COSY injection energy of 45 MeV was undertaken, where the main problem is the not clearly short lifetime of a beam.

First message

- Experimentally it has been shown the achievable intensity of electron cooled beams at COSY is restricted by three main beam loss phenomena: the initial losses just after injection during 5-10 s of beam cooling, the coherent self-excited oscillation of cooled beam and the long-term losses ~n x 1000 s.

Candidates for beam losses reason: hadronic interaction, single Coulomb scattering, multiple scattering, recombination and energy loss.

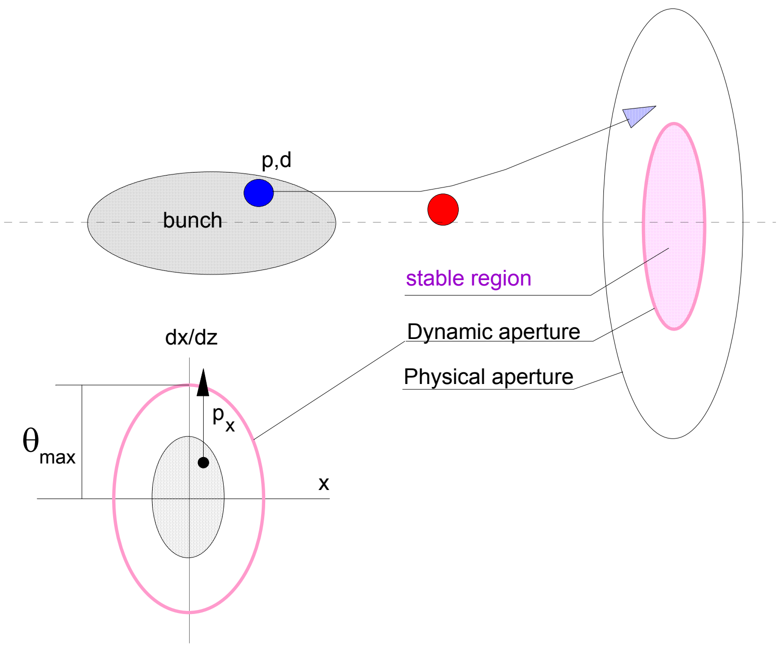
In our case it is reasonable to consider two last of them:

- **Single Coloumb scattering**
- **Multiple Coloumb scattering**

Single Coloumb scattering

The classic Rutherford scattering formula:

$$\frac{1}{\tau_{sc}} = -\frac{1}{N}\cdot\frac{dN}{dt} = \beta c \sum_j \sigma_j n_j \qquad \sigma_j = \frac{4\pi Z_j^2 r_p^2}{\beta^4 \gamma^2 \theta_{\max}^2} \qquad \theta_{\max}^2 = \frac{A_{x,y}}{\hat{\beta}}$$



Multiple Coloumb scattering

It is defined by the diffusion equation for particle distribution f:

$$\frac{\partial f}{\partial \tau} = \frac{\partial}{\partial Z}\left(Z \frac{\partial f}{\partial Z} \right)$$

with boundary condition $f(Z,0) = f_0(Z)\,,\ f(1,\tau) = 0$ and

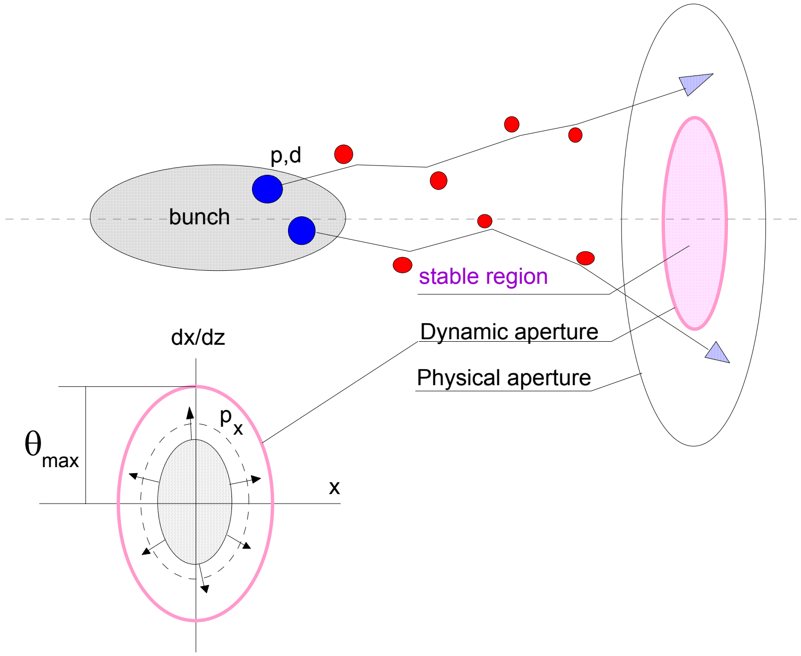
$Z = \varepsilon / A \qquad \tau = tR / A$

where $R = \hat{\beta}\left\langle \dot{\theta}^2 \right\rangle$ is the diffusion coefficient.

The beam life time has asymptotic value:

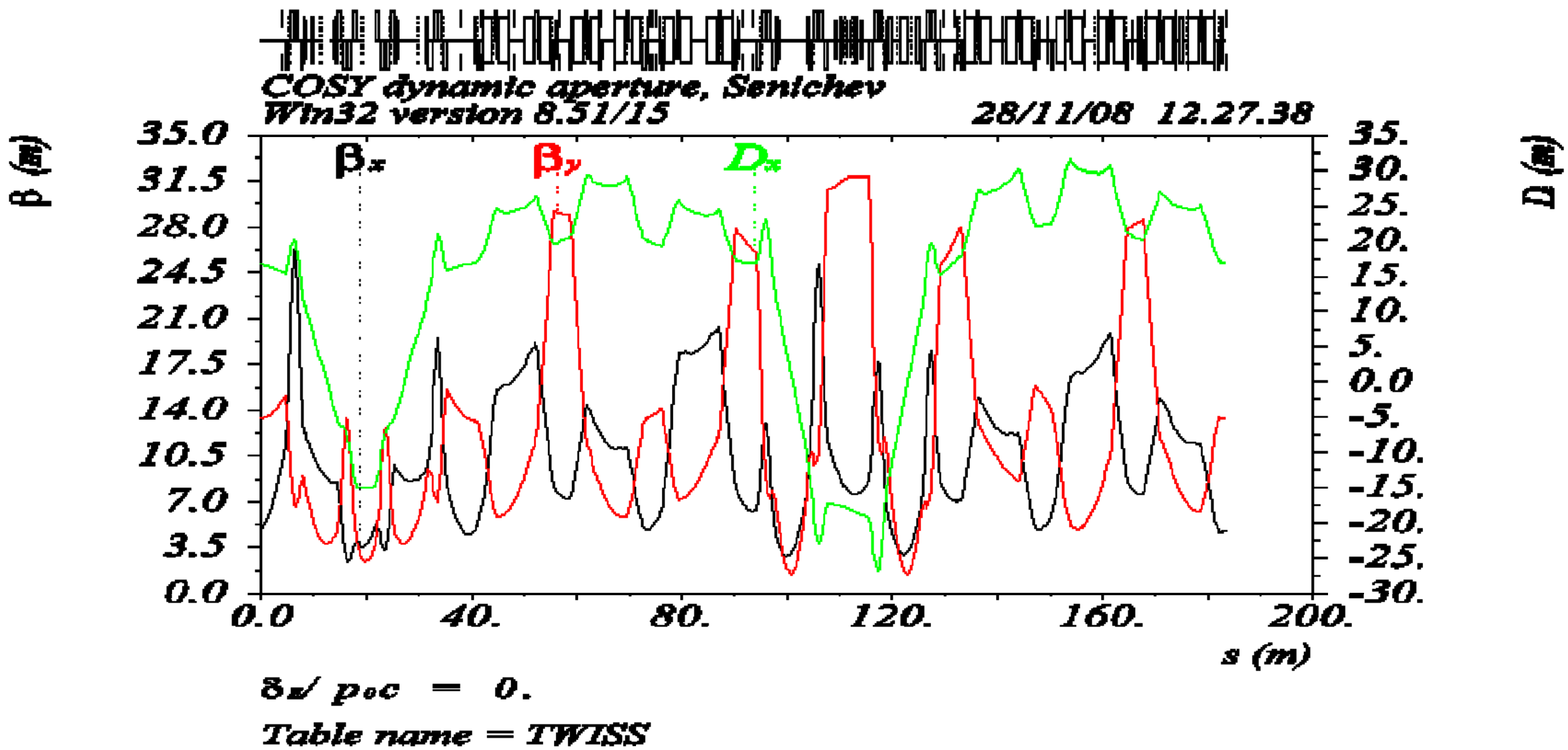
$$\tau_a = \frac{4A_{x,y}}{\lambda_1^2 \hat{\beta}\left\langle \dot{\theta}^2 \right\rangle}$$

To compute $\left\langle \dot{\theta}^2 \right\rangle$ the small angle limit of Rutherford scattering cross section is used



In both the single and multipole Coloumb scattering the rate of loss depends on the sizes of stable area

COSY lattice



COSY lattice for PAX-experiment

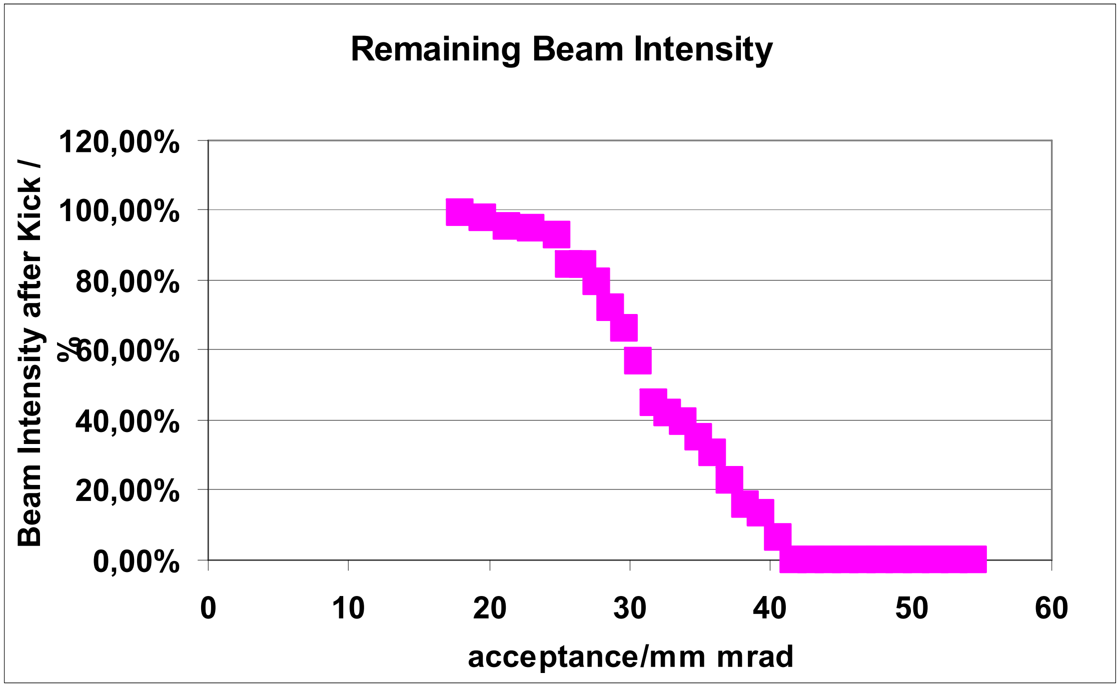
Lifetime measurements

Two different methods to measure the acceptance of the COSY ring were used:

-Measurements with a single turn angle kick of the beam using a fast kicker magnet;

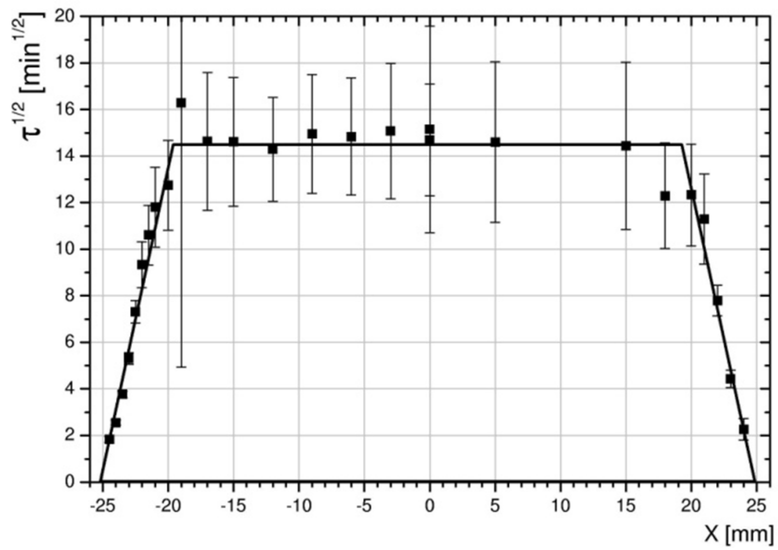
-Measurement of beam lifetime versus position of scrapers.

The measurements with a fast kicker magnet used to determine the geometric acceptance of the COSY ring yields approximately 40 µm (see fig. 1).



Acceptance measurement with fast kicker magnet.
Fractional beam intensity versus acceptance,
the acceptance is calculated from the used kick angle and
the Twiss functions at the location of the kicker

The scrapers method



Acceptance measurement with scrapers

The measurements were done with uncooled and electron cooled beam:

- Measurements agree well with the kicker measurements in the case without electron cooling;
- For electron cooled beam the measured acceptance has appeared **14 µm**

We conclude:

… or the machine acceptance was overestimated in the beam lifetime calculation, and the actual machine acceptance for a cooled beam is significantly lower ,

… or the e-beam affect on the p-beam stability

For the first time one has sounded, that the electron beam can not only cool the ion beam, but also heat it up in paper:

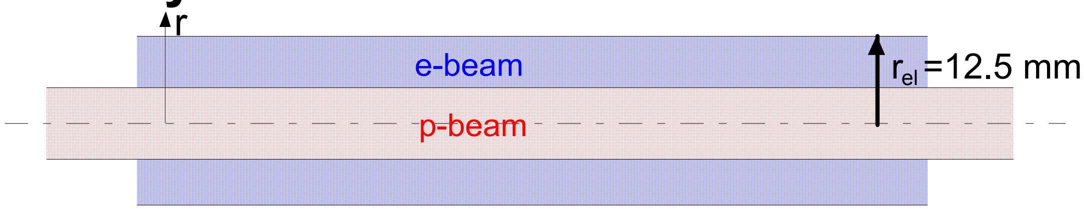
D. Reistad et al., Measurements of electron cooling and “electron heating” at CELSIUS, Workshop on Beam Cooling, 1993, CERN 94-03, pp. 183-187
and then it was analyzed in:

V. Ziemann, Resonances driven by the electric field of the electron cooler, TSL Note 98-43.

The e-beam influence on p-beam stability

The e-cooler parameters:

- **the electron current I_{el} =0.175 A**
- **the cylindrical shape with <u>almost</u> uniform distribution**
- **the radius of cylinder 12.5 mm.**



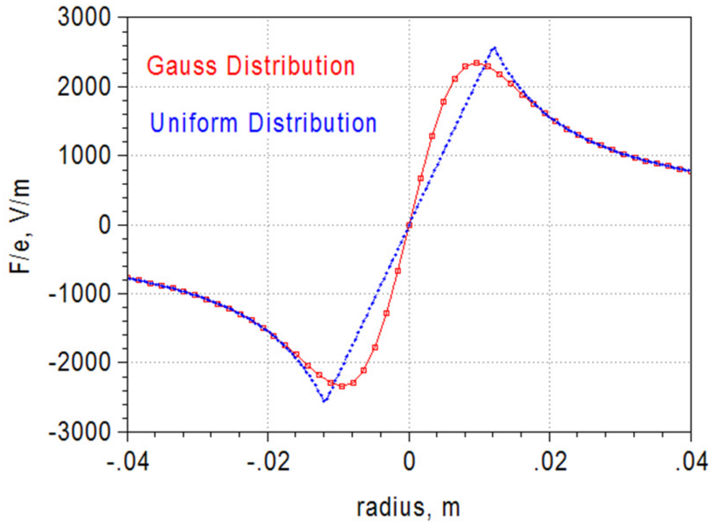
The electromagnetic force of the e-beam

The radial force of electromagnetic fields of e-beam
for the uniform distribution is described by the piecewise continuous function at $r = \sqrt{x^2 + y^2}$:

$$F_{unif} = \begin{cases} \dfrac{eI_{el}}{2\pi\varepsilon_0 c\beta\gamma^2 r_{el}^2} \cdot r, & \text{for } r < r_{el} \\ \dfrac{eI_{el}}{2\pi\varepsilon_0 c\beta\gamma^2 r} & \text{for } r > r_{el} \end{cases}$$

and for the Gaussian distribution:

$$F_{Gauss} = \frac{eI_{el}}{2\pi\varepsilon_0 c\beta\gamma^2} \cdot \frac{1}{r} \left(1 - e^{-\frac{r^2}{2\sigma_{el}^2}} \right)$$



The N-order polynomial approximation of the e-beam force

N-order polynomial approximation of the e-beam force by the minimization of the mean-square deviation in some range r<Rmax of the space charge force averaging for the uniform and Gaussian distribution correspondingly.

$$\mathrm{Min}_{r<R_{av}}\left\{\left[F_r(r)-b_1\cdot r-b_3\cdot r^3-b_5\cdot r^5-b_7\cdot r^7-b_9\cdot r^9\right]^2\right\}$$

Non-linear e-lens

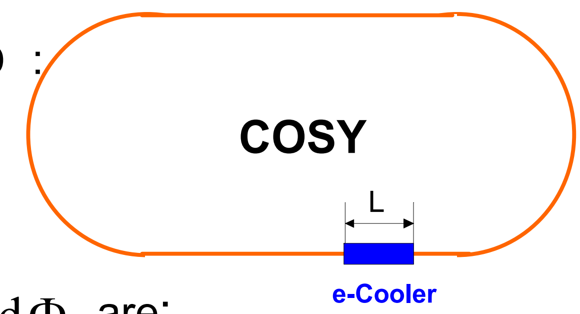
The short (L/Cir<<1) non-linear kick has the time ( ) dependence:

$$F(r,\vartheta) = \left[b_1 \cdot r + b_3 \cdot r^3 + b_5 \cdot r^5 + ...\right] \cdot \frac{2L}{C_{ir}} \left[\frac{1}{2} + \sum_{p=1} \cos p\vartheta\right]$$

all coefficients $b_n \sim I_{el}/(\beta\gamma^2\sigma_{el}^2)$

If the solution of unperturbed equation $\frac{d^2 r}{d\vartheta^2} + K(\vartheta) r = 0$:

$$r = \sqrt{\varepsilon\beta} \cdot \cos(\nu_0 \vartheta + \Phi)$$



where ε and Φ are constant,

then with the non-linearity the averaged rate of ε and Φ are:

$$\overline{\frac{d\varepsilon}{d\vartheta}} \propto \frac{1}{2\pi} \int_0^{2\pi} \sin\Phi \cdot (b_1 \cdot \varepsilon^{1/2} \cos\Phi + b_3 \cdot \varepsilon^{3/2} \cos^3\Phi + ...) \cdot \left[\frac{1}{2} + \sum_{p=1} \cos p\vartheta\right] d\Phi$$

$$\overline{\frac{d\Phi}{d\vartheta}} \propto \frac{1}{2\pi} \int_0^{2\pi} \cos\Phi \cdot (b_1 \cdot e^{1/2} \cos\Phi + b_3 \cdot \varepsilon^{3/2} \cos^3\Phi + ...) \cdot \left[\frac{1}{2} + \sum_{p=1} \cos p\vartheta\right] d\Phi$$

The octupole non-linear tune due to the e-beam

For the case when all b_n=0 and $b_3 \neq 0$ we have the pure octupole non-linear tune shift without resonant condition the non-linear tune is:

$$\delta\nu_{oct}(\bar{r}) = \overline{\frac{d\Phi}{d\vartheta}} \propto \frac{b_3}{4\pi}\int_0^{2\pi}\cos^4\Phi\, d\Phi = \frac{b_3 \cdot L\hat{\beta} \cdot \bar{r}^2}{4\pi}\cdot\frac{3}{8}\cdot 2\pi$$

The n-th order non-linear resonance

Two conditions for the non-linear resonance excitation:

1. $\overline{\frac{d\varepsilon}{d\vartheta}} \neq 0$

2. $\nu(\bar{r}) \cdot n = p$, n-resonance order, p-arbitrary integer

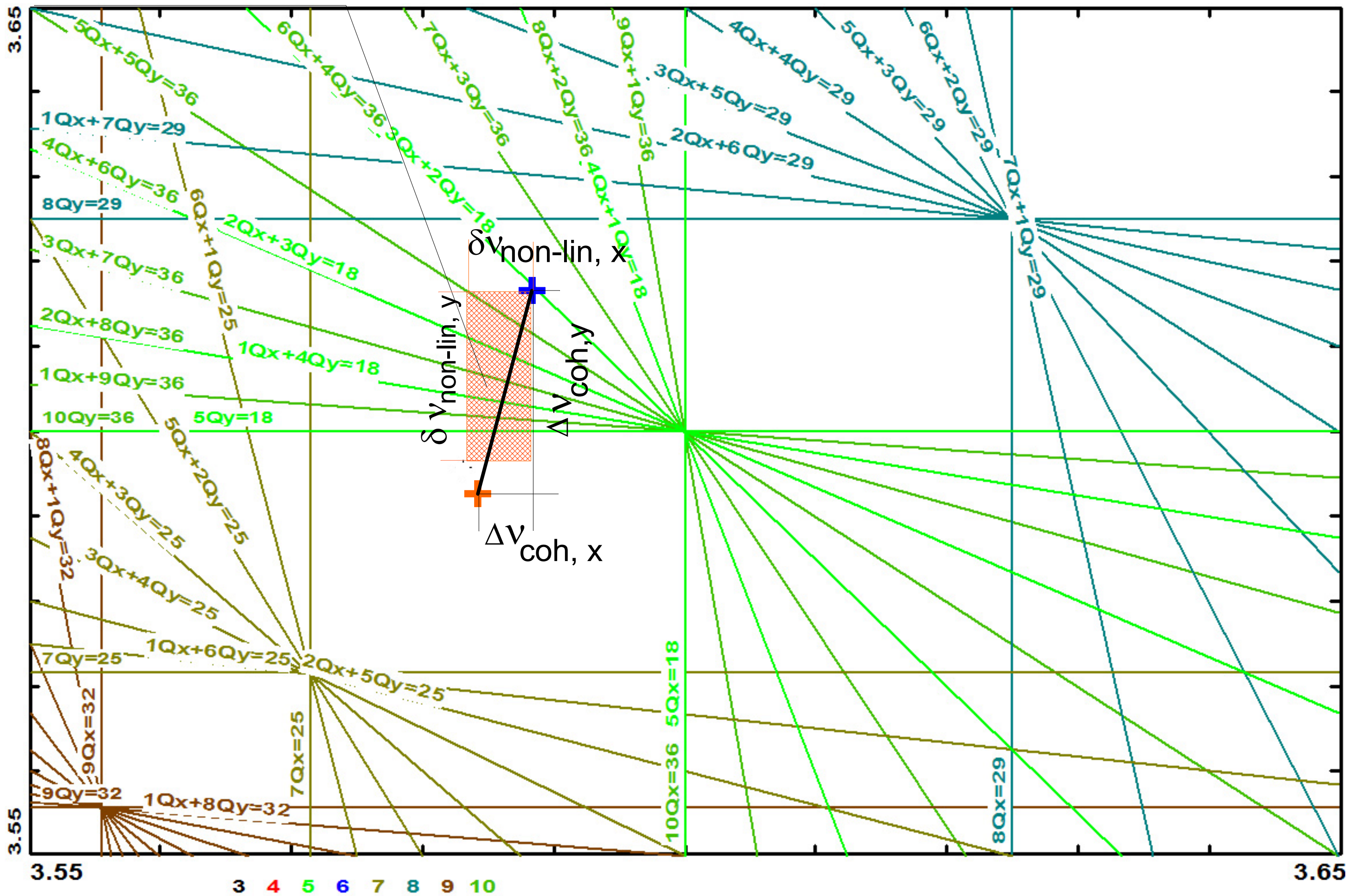
where $\nu(\bar{r}) = \nu_0 - \Delta\nu_{coh} - \delta\nu(\bar{r})$

In common case for the coherent tune shift and the non-linear tune shift of n-th order resonance:

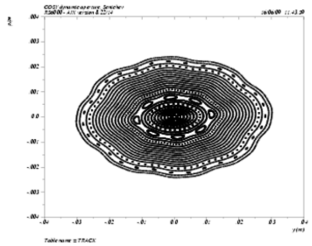
$$\Delta\nu_{coh} \sim \frac{I_{el}}{\beta\gamma^2\sigma_{el}^2} \cdot \hat{\beta} \cdot L \qquad \delta\nu(r) \sim \frac{I_{el}}{\beta\gamma^2\sigma_{el}^2} \cdot n \cdot \varepsilon^{n/2} \cdot \hat{\beta}^{n/2} \cdot L$$

In case of coaxial beams we have the even order resonances only !!!

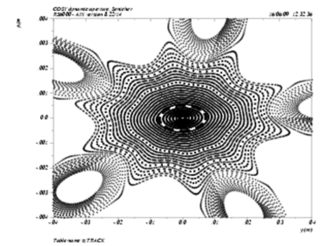
Resonance diagram: working point with tune shifts



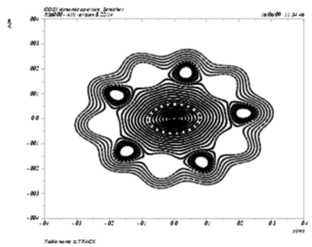
Dynamic aperture behavior in vicinity of 10-th resonance order for the monochromatic p-beam and the Gaussian e-beam versus the working point



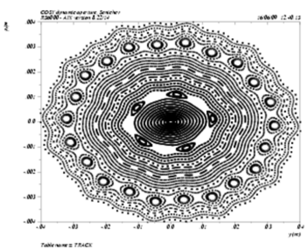
ν_y=3.64824;



ν_y=3.63969;

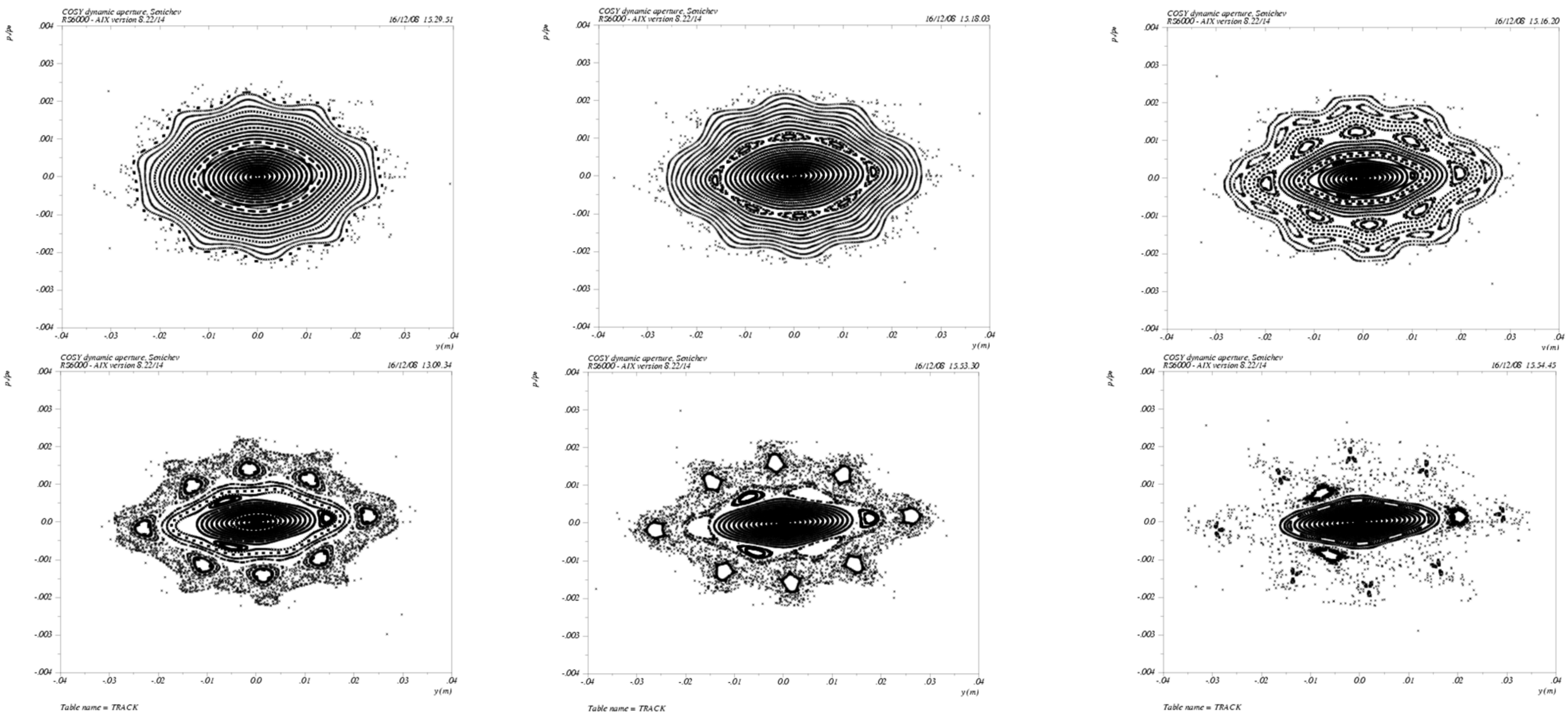


ν_y=3.63721;



ν_y=3.63260;

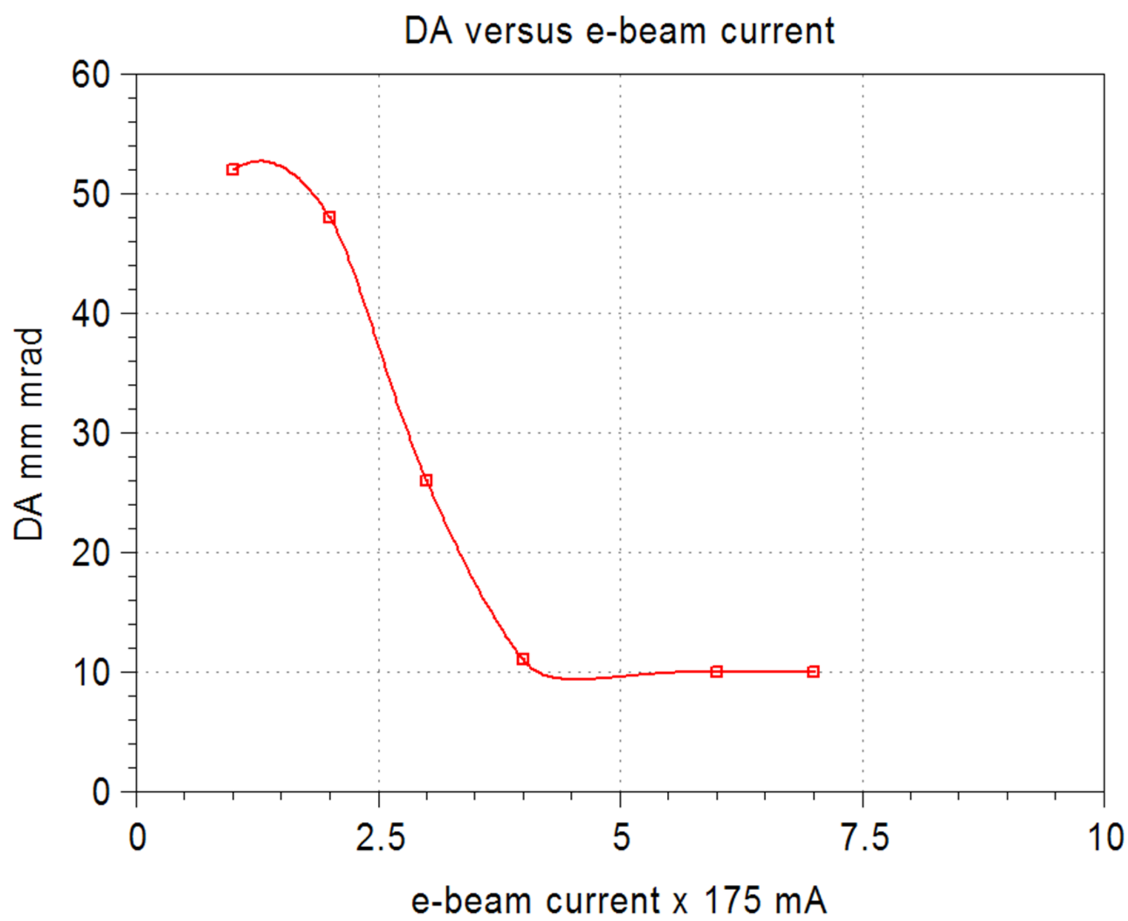
Dynamic aperture for the monochromatic p-beam and the uniform e-beam versus the e-beam current



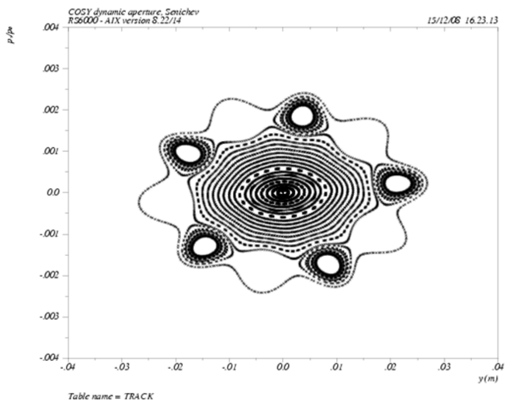
The vertical DA of the PAX lattice for monochromatic p-beam cooled by the uniform e-beam with $\sqrt{\overline{r^2}}$ = 6 mm and current 175mA (a), 2 x 0.175 mA (b), 3 x 175 mA (c), 4 x 175 mA (d), 6 x 175 mA (e), 7 x 175 mA (f)

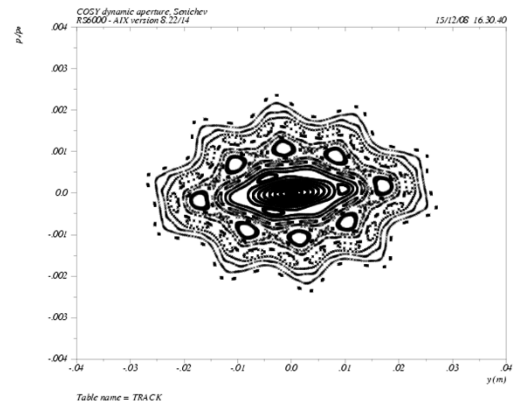
DA vs e-beam current (monochromatic p-beam and uniform e-beam)

DA vs I_e

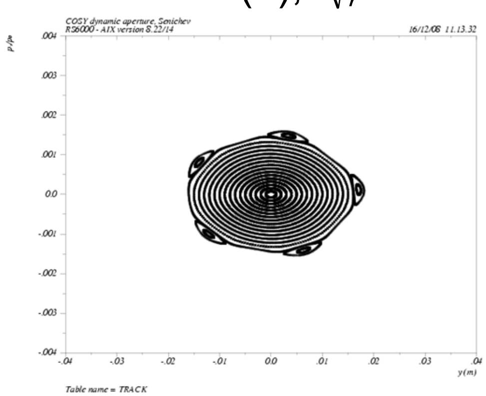


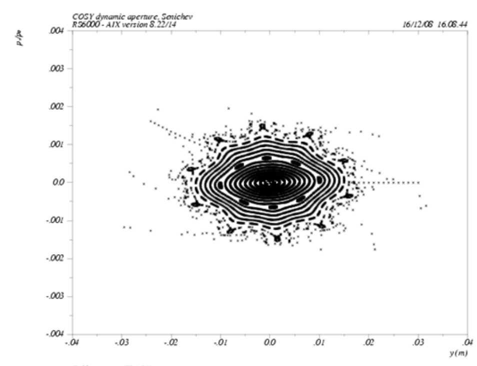
Dynamic aperture for the monochromatic p-beam cooled by Gaussian and uniform e-beam versus the e-beam size





The vertical DA of the PAX lattice for monochromatic p-beam cooled by the Gaussian e-beam with $\sqrt{\overline{r^2}}$ = 6 mm (a), $\sqrt{\overline{r^2}}$ =3 mm (b) and current 175mA





The vertical DA of the PAX lattice for monochromatic p-beam cooled by the uniform e-beam with $\sqrt{\overline{r^2}}$ = 6 mm (a), $\sqrt{\overline{r^2}}$ =3 mm (b) and current 175mA

The non-monochromatic beam with Δp/p=δ

Hamiltonian equation for Δp/p=δ:

$$H = H_0(p_x, p_y, \delta) + V(x,y,s)$$

$$H_0(p_x, p_y, x, y, z) = \frac{p_x^2 + p_y^2}{2(1+\delta)} + (K_x + \Delta K_x)\cdot\frac{x^2}{2} - (K_y + \Delta K_y)\cdot\frac{y^2}{2},$$

$$V(x,y,s) = \frac{S_x(z)}{6}\cdot x^3 + \frac{S_{xy}(z)}{2}\cdot xy^2 + \frac{O_x(z)}{24}\cdot x^4 + \frac{O_{xy}}{4}\cdot x^2y^2 + \frac{O_y}{24}\cdot y^4,$$

$$K_x = K,$$

$$\Delta K_x = \delta\cdot D\cdot S - \frac{(\delta\cdot D)^2}{2}O,$$

$$K_y = -K,$$

$$\Delta K_y = -\frac{(\delta\cdot D)^2}{2}O,$$

e-beam sextupoles → $S_{x,y} = -|\delta\cdot D\cdot O|,$

e-beam octupoles → $O_{x,y} = O.$

Each multi-pole of n-th order gives all multi-poles of 1÷(n-1)--th order in the place where D≠0, in results the <u>odd resonances</u> are excited as well

The chromaticity with and without the e-beam in COSY

The **tunes** vs the momentum

without the e-beam:

$$\nu_x = 3.58 - 8.5 \cdot \frac{\Delta p}{p_s} - 200 \cdot \left(\frac{\Delta p}{p_s}\right)^2 \qquad \nu_y = 3.596 + 0.2 \cdot \frac{\Delta p}{p_s} - 0.5 \cdot \left(\frac{\Delta p}{p_s}\right)^2$$

with e-beam:

$$\nu_x = 3.59 - 9.1 \cdot \frac{\Delta p}{p_s} - 3672 \cdot \left(\frac{\Delta p}{p_s}\right)^2 \qquad \nu_y = 3.637 - 0.8 \cdot \frac{\Delta p}{p_s} - 6110 \cdot \left(\frac{\Delta p}{p_s}\right)^2$$

The **chromaticity**

$$\varsigma_{x,y} = \frac{d\nu_{x,y}}{d\left(\frac{\Delta p}{p_s}\right)}$$

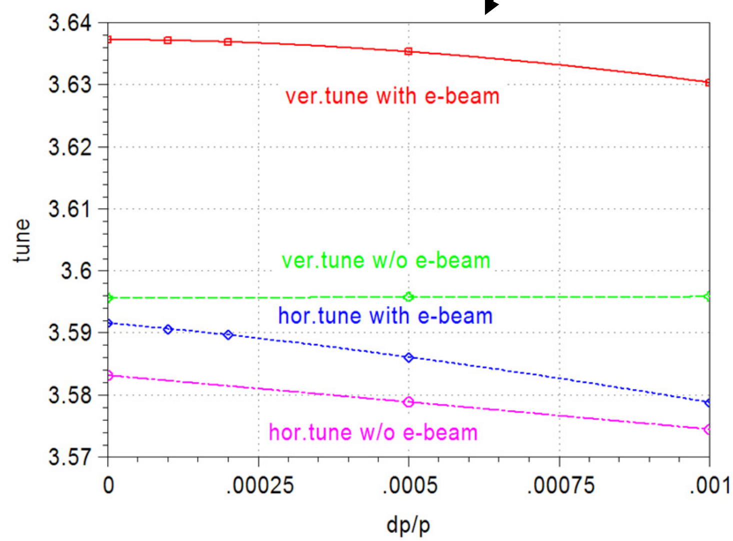
without the e-beam:

$$\varsigma_x = -8.5 - 400 \cdot \left|\frac{\Delta p}{p_s}\right| \qquad \varsigma_y = 0.2 - 1.0 \cdot \left|\frac{\Delta p}{p_s}\right|$$

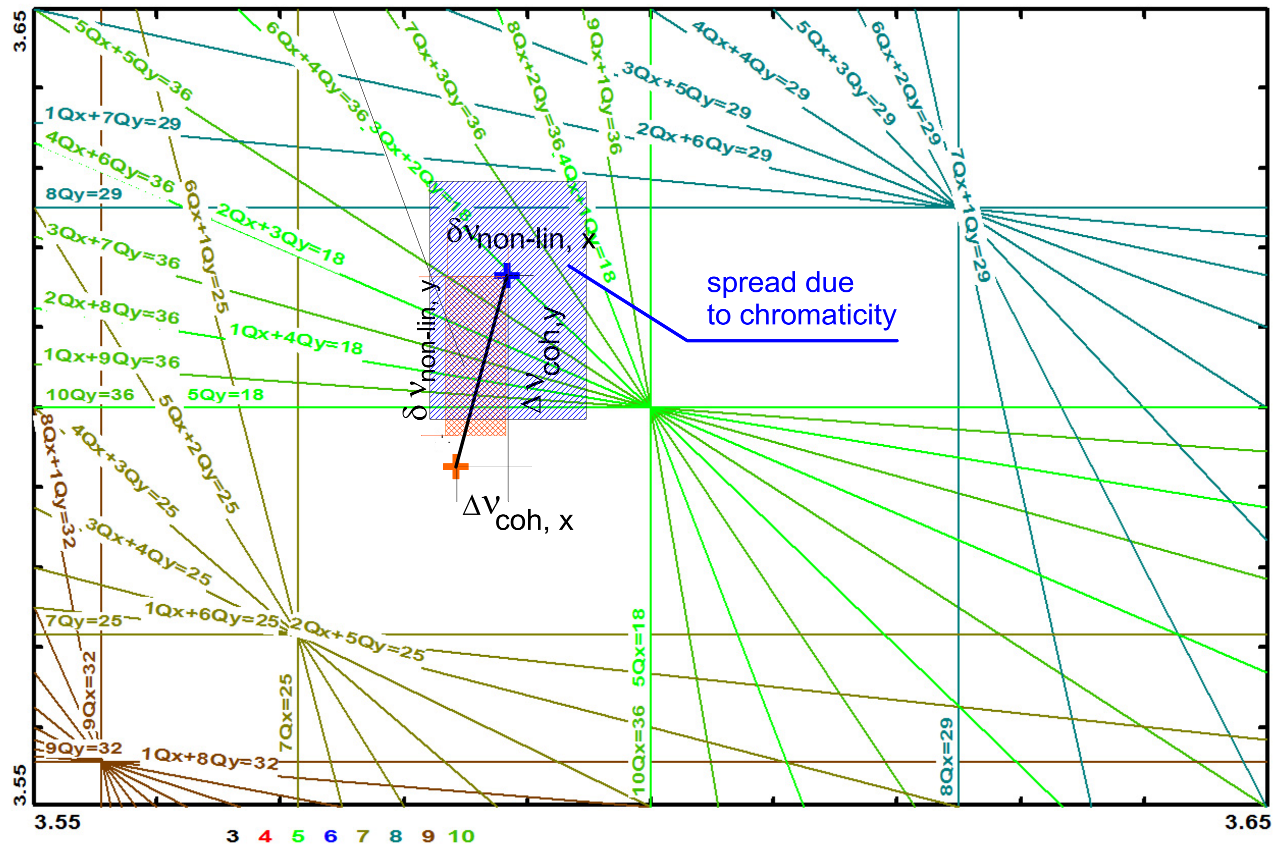
with e-beam:

$$\varsigma_x = -9.1 - 7344 \cdot \left|\frac{\Delta p}{p_s}\right| \qquad \varsigma_y = -0.8 - 12220 \cdot \left|\frac{\Delta p}{p}\right|$$

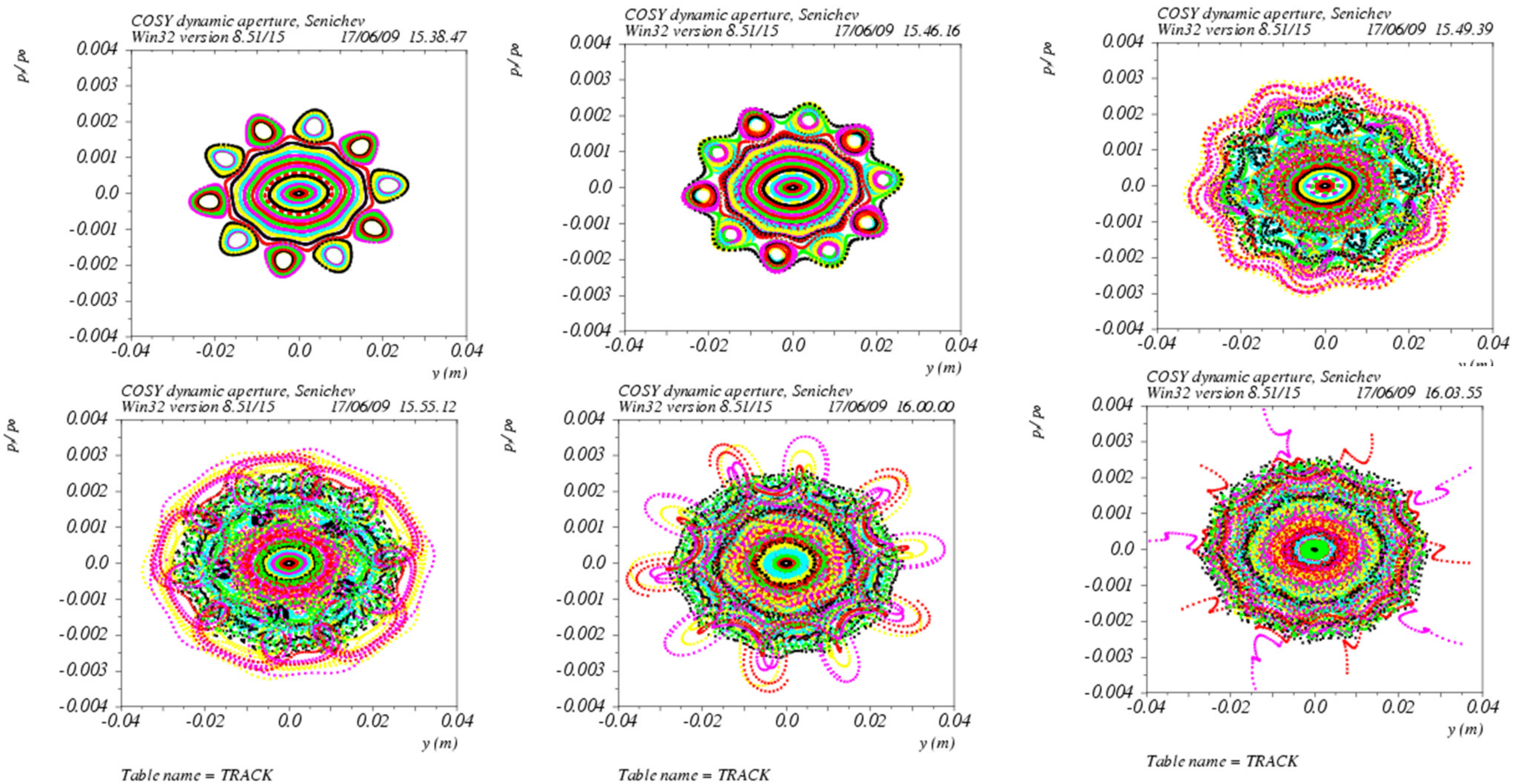
Numerical results of simulation:



Resonance diagram:
working point with tune shifts and chromaticity spread



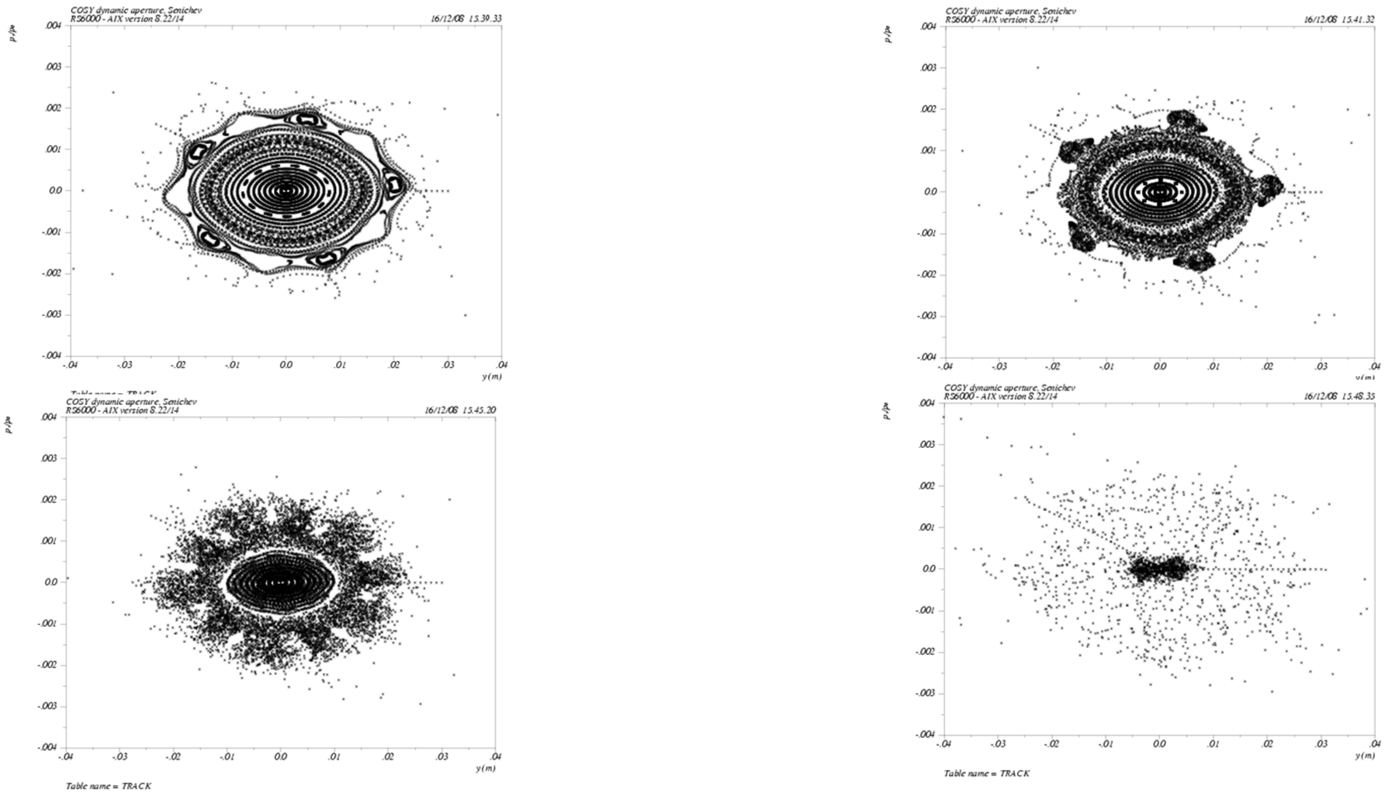
Phase trajectory for the non-monochromatic p-beam and the Gaussian e-beam versus the p-beam momentum spread



Phase trajectories at dp/p=0.0; $1\cdot10^{-4}$; $3\cdot 10^{-4}$; $5\cdot 10^{-4}$; $8\cdot 10^{-4}$; $1\cdot10^{-3}$

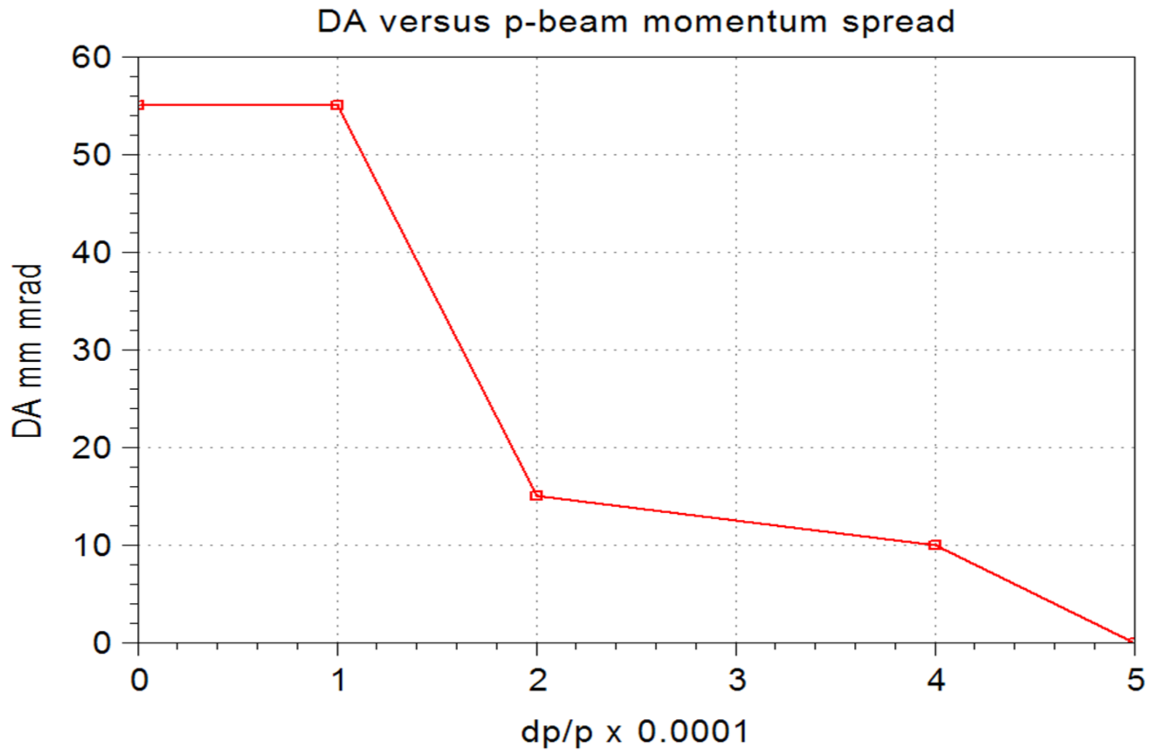
cooled by the Gaussian e-beam with $\sqrt{r^2}$ = 6 mm and current 175mA

Dynamic aperture for the non-monochromatic p-beam and the uniform e-beam versus the p-beam momentum spread

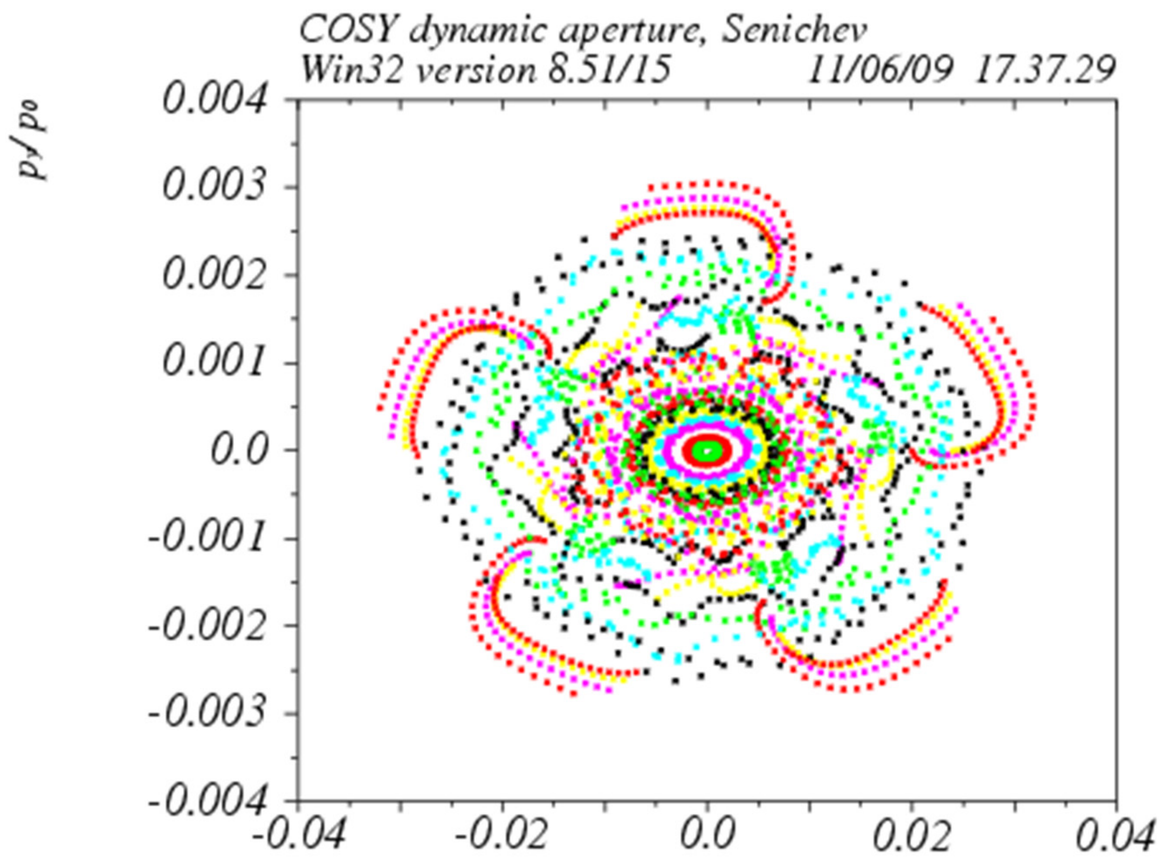


The vertical DA of the PAX lattice for non-monochromatic p-beam with $dp/p=1\cdot10^{-4}$; $2\cdot10^{-4}$; $4\cdot10^{-4}$; $5\cdot10^{-4}$ calculated for the uniform e-beam distribution with dispersion 6 mm and current 175mA

DA versus p-beam momentum spread for uniform e-beam



Diffusion process due to resonances crossing



Intermediate stage

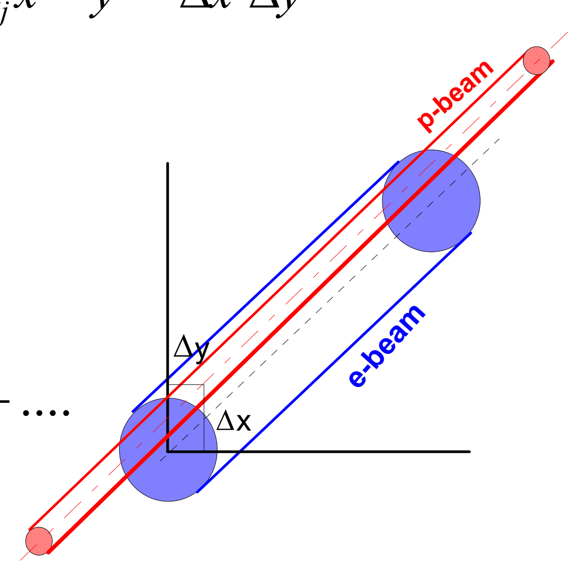
The optics with misalignments of p, e-beams

In that case any multi-pole of the n-th order:

$$x_{co}^{n} y_{co}^{m} = (x+\Delta x)^{n} \cdot (y+\Delta y)^{m} = x^{n} y^{m} + \sum_{i,j=1,m,n} a_{ij} x^{n-i} y^{m-j} \Delta x^{i} \Delta y^{j}$$

For instance the octupole in case of beams misalignment Δx and Δy:

$$\frac{b_3}{4}\left(x_{co}^{4} + y_{co}^{4}\right) = \frac{b_3}{4} \cdot \left(x^{4} + y^{4}\right) + \frac{b_3}{4} \cdot \left(4\Delta x \cdot x^{3} + 4\Delta y \cdot y^{3}\right) + \ldots.$$

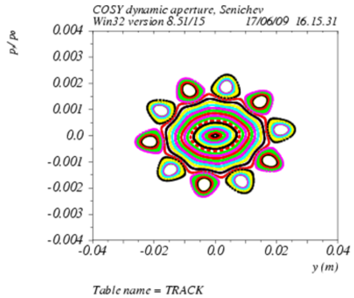


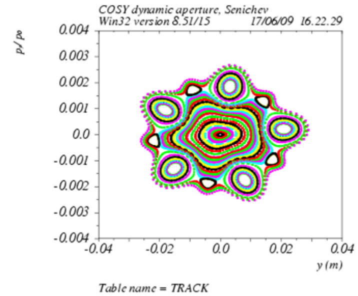
shifted octupole axial octupole induced sextupole

Each multi-pole of n-th order gives all multi-poles of 1÷(n-1)--th order in case of Δx and Δy.

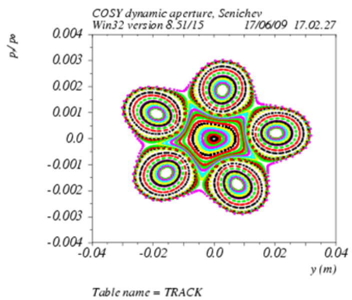
In results the <u>odd resonances</u> are excited as well !

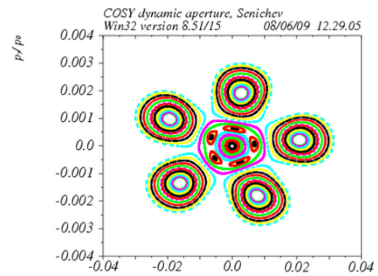
Dynamic aperture for monochromatic p-beam versus the e-beam shift off axis



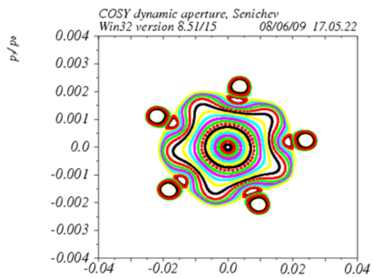


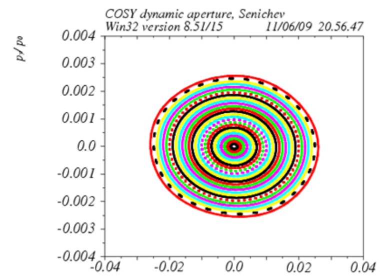
shift: 0 mm 3 mm





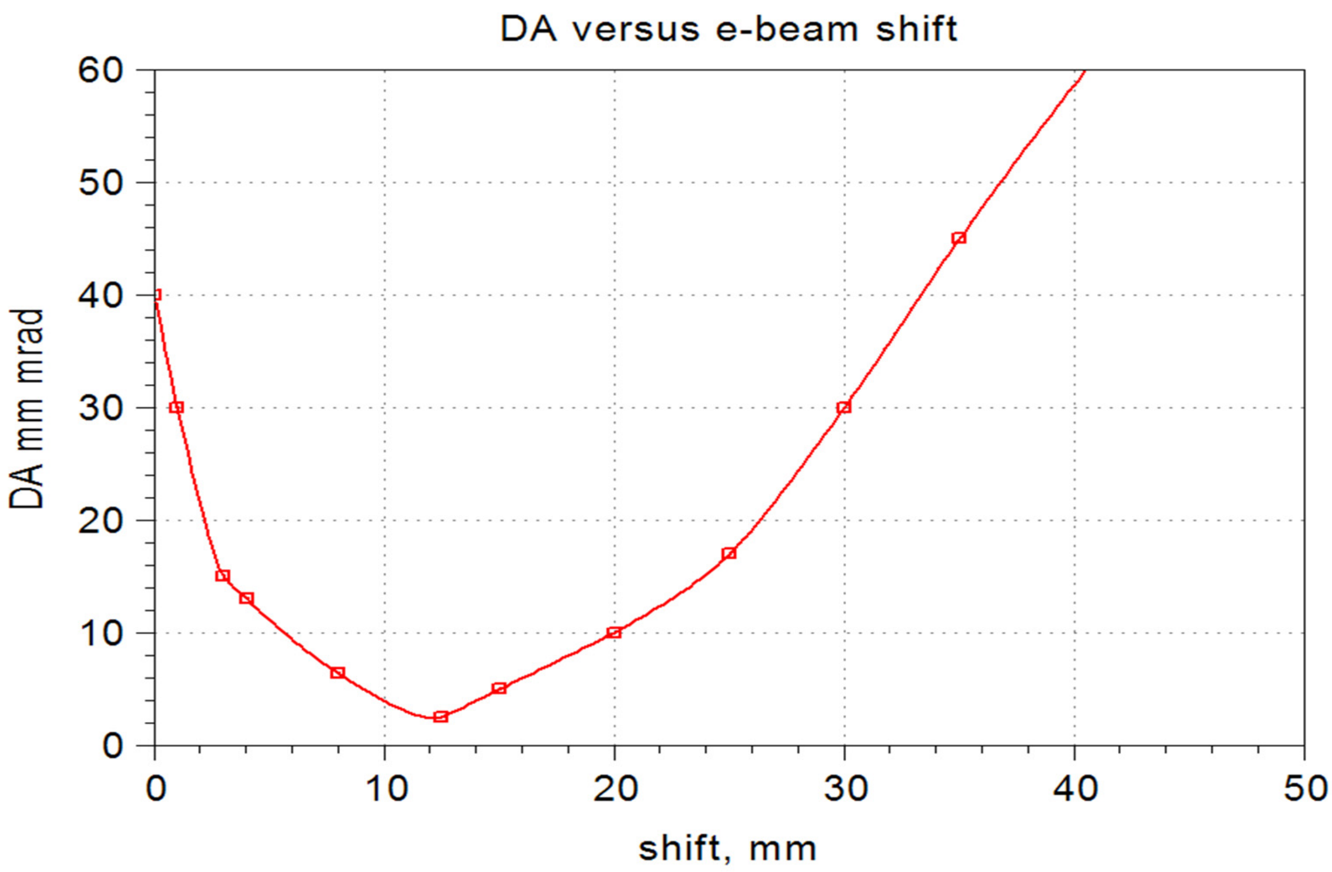
shift 8 mm 12.5 mm



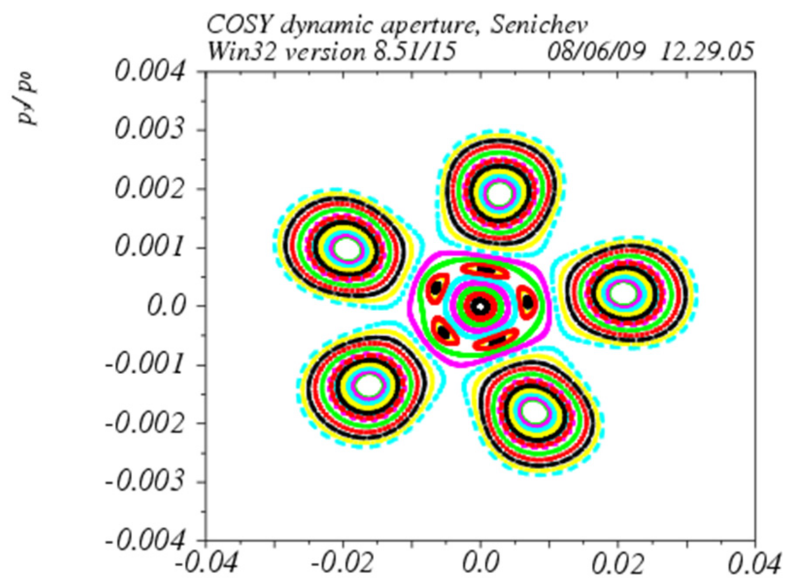


shift 25 mm 60 mm

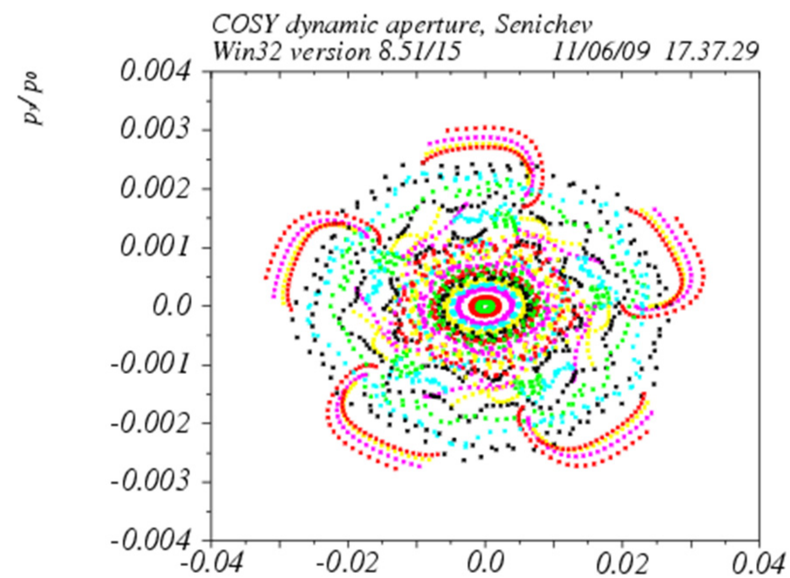
Dynamic aperture versus the e-beam shift off axis



Dynamic aperture for the shifted non-monochromatic p-beam



monochromatic p-beam
with shift 12.5 mm



non-monochromatic p-beam
with shift 12.5 mm

Conclusion:

-The dynamic and physical apertures of COSY without the e-cooler should be excluded from the candidates of the shorter ion beam life time;

-The electromagnetic field of e-beam excites the non-linear structure resonances for the p-beam and affects on the DA decreasing;

-The dynamic aperture is decreased proportionally to e-beam current;

-For coaxial e,p-beams the even resonances are excite only;

-In case of the e,p-beams misalignment the odd resonances are excited also;

-The dispersion in place of e-cooler provides the additional chromaticity induced by the e-beam

Thus the e-beam is the main reason of decreased Dynamic Aperture in COSY

Possible mechanism of losses

particles circulating on an orbit and colliding with molecules of residual gas somewhere outside of cooler deviate from axis and are grasped in one of nonlinear resonances.