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Current Limit in the Compact Cyclotron with External Injection

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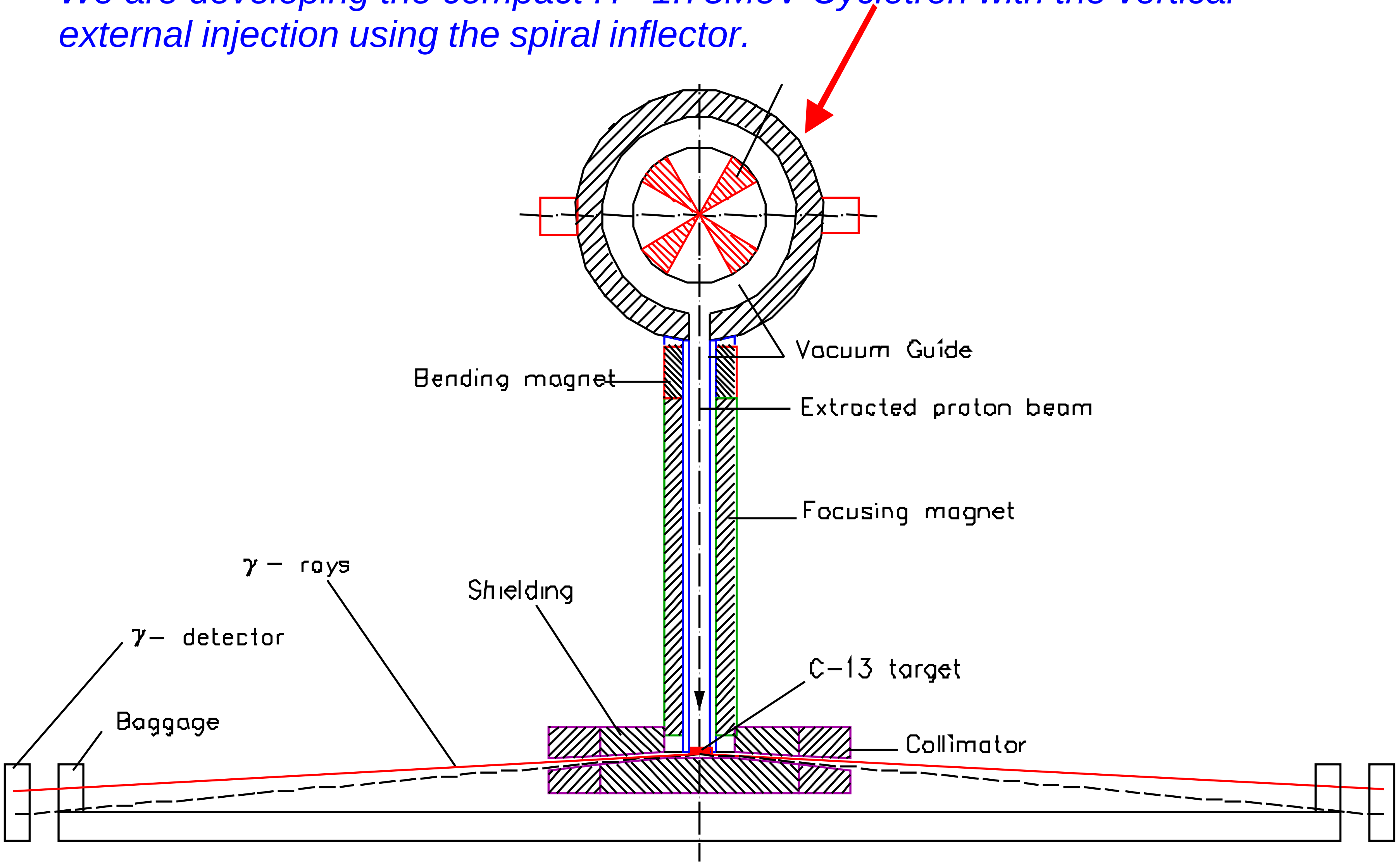
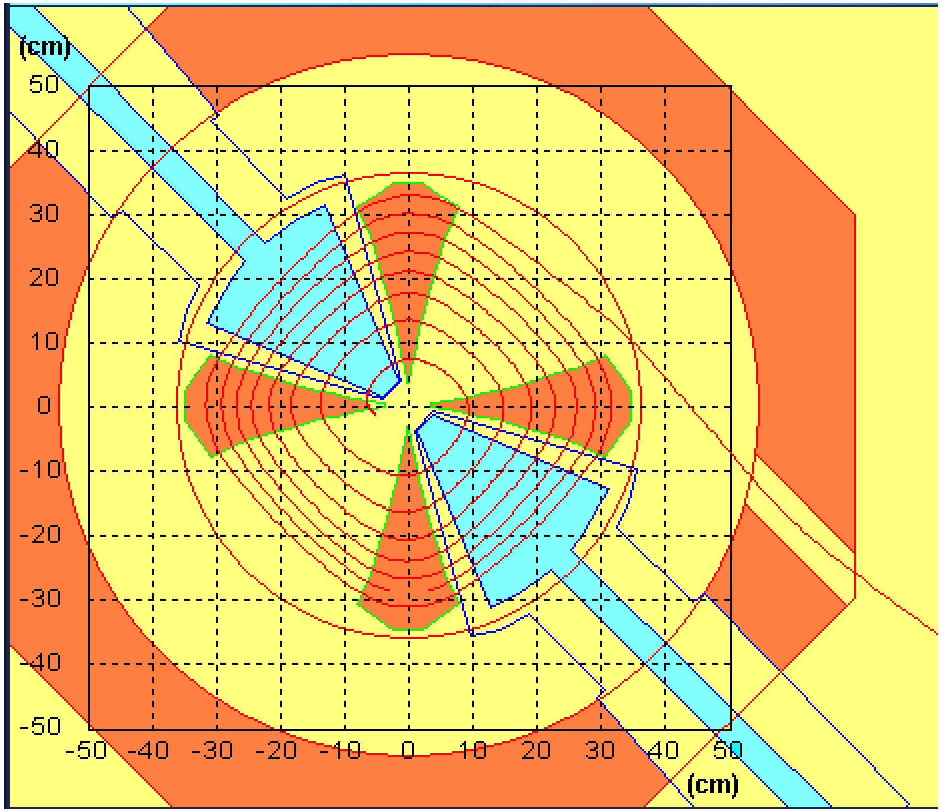
Design goals for the cyclotron: W=1.75 MeV, I=5 mA

We are developing the compact H^- 1.75MeV Cyclotron with the vertical external injection using the spiral inflector.



General layout of the explosive detection on the customs

PARAMETERS OF THE CUSTOMS CYCLOTRON (CC)



Type of ion		$H^{\bullet}$
Injection energy	(keV)	30
Average magnetic field	(T)	0.64
Number of sectors		4
Sector azimuth angle	(°)	10-30
Betatron axial frequency	$\bullet_z$	0.3- 0.8
Number of dees		2
Angular span of dees	(°)	45
RF voltage	(kV)	60
Orbital frequency	(MHz)	9.76
Harmonic number		4

Analytical estimation of the space charge influence on the beam current limit

$$(1)\qquad I_{critical} = \frac{Q^2}{M}\cdot\frac{a^2}{R_i^2}\cdot\nu^2\beta^3\gamma^3\cdot\frac{\Delta\Phi}{2\pi}\cdot I_0,\qquad I_0 = \pi\cdot 10^7 A\left(=4\pi\varepsilon_0 c\frac{E_0}{e} = \frac{938\text{Mev}}{30\Omega}\right)$$

a – average beam amplitude

$\Delta\Phi$ – beam azimuth angle

R_i – beam injection radius

ν – vertical oscillation frequency

For cyclotron under consideration a=5, R_i=56mm, ν=0.3, • =0.008, •• 1, •• =0.5rad and from(1) we find $I_{critical}$=1.5mA. For critical current $\boldsymbol{\nu}$ decreased by ~2.5 times and $\boldsymbol{a}$ increased by ~1.5 times under space charge influence.

Current beam limit, when $\boldsymbol{\nu}$ decreased down to zero.

$$(2)\qquad I_{\lim it} = \varepsilon_0 f_0 \frac{\Delta E}{e}\Delta\Phi\cdot\Delta z\cdot\nu_z^2$$

f_0- orbit frequency,

ΔE-energy gain per turn

ΔZ – beam vertical size

For f_0=9.6MHz, • E=100keV, •• =0.5rad, • z=10mm, ν_z=0.3, I_{limit}=10mA

(1) **W. Joho "High Intensity Problems in cyclotrons" Proc. of Intern. Conference on Cyclotrons, Caen, 1981, p.332**

(2) **V.P. Dmitrievsky "Meson Factories" Proc. of the International accelerator school for Young Scientists, Dubna, 1976, p.168 (in Russian)**

Our code PHASCOL has been used for particle dynamics computations in the Custom Cyclotron.

Full differential equations describing particle dynamics in electromagnetic field of cyclotron are integrated inside PHASCOL taking into account the space charge.

$$\ddot{r} = r\dot{\varphi}^2 + \frac{qc^2}{E}\left[\varepsilon_r - r\dot{\varphi}B_z + \dot{z}B_\varphi - \frac{\dot{r}}{c^2}\left(\dot{r}\varepsilon_r + r\dot{\varphi}\varepsilon_\varphi + \dot{z}\varepsilon_z\right)\right]$$

$$\ddot{z} = \frac{qc^2}{E}\left[\varepsilon_z + r\dot{\varphi}B_r - \dot{r}B_\varphi - \frac{\dot{z}}{c^2}\left(\dot{r}\varepsilon_r + r\dot{\varphi}\varepsilon_\varphi + \dot{z}\varepsilon_z\right)\right]$$

$$\ddot{\varphi} = -\frac{2\dot{r}\dot{\varphi}}{r} + \frac{qc^2}{rE}\left[\varepsilon_\varphi + \dot{r}B_z - \dot{z}B_r - \frac{r\dot{\varphi}}{c^2}\left(\dot{r}\varepsilon_r + r\dot{\varphi}\varepsilon_\varphi + \dot{z}\varepsilon_z\right)\right]$$

(r, φ, z) – coordinates, (B_r, B_φ, B_z), $(\varepsilon_r, \varepsilon_\varphi, \varepsilon_z)$ – magnetic and electric fields, q – particle charge, c – speed of light, E – total energy of particle

Particle dynamics with space charge

Electric field acting on a particle is a sum of accelerating field and space charge one

$$e_{r,j,z} = e^{RF}_{j,z} + e^{SC}_{r,j,z}$$

We have used two ways for computation of the beam electric field:

1st - method of the direct summation of the Coulomb's field created by each macroparticle.
This is PTP (particle-to-particle) method.

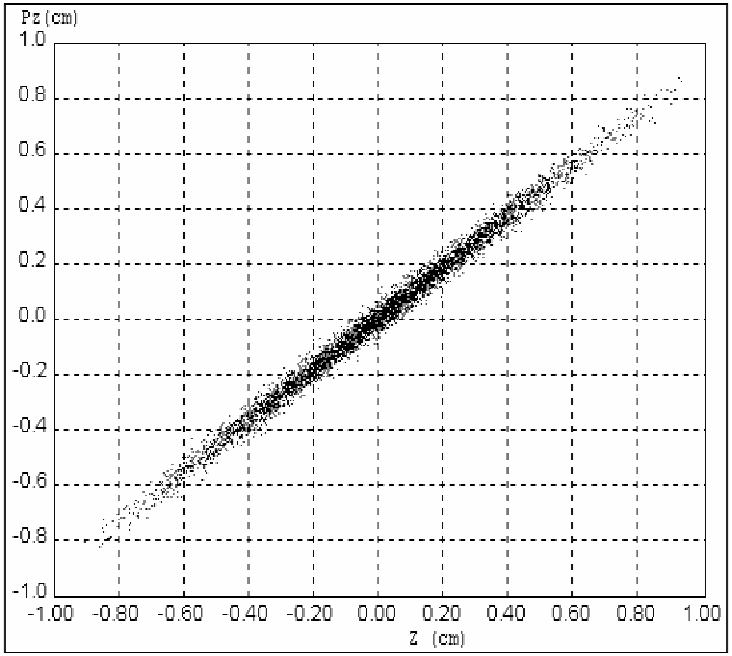
2nd - method of fast Fourier transform. This is calculation of beam electric field on a 3D grid that covers bunch. This is PIC (particle-in-cell) method.

Both methods give close results, but the second method works faster, if the number of macroparticles composes several thousand.

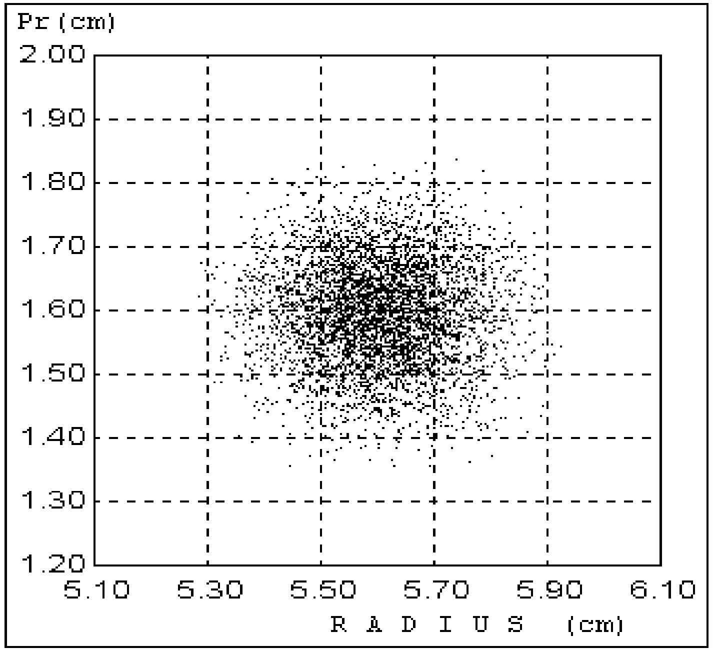
Computations of beam acceleration for ideally injected bunch

In the first stage of computations we examined the conditions of ideally injected beam. We wanted to answer a question: is it possible, in principle, to accelerate 5 mA current in the cyclotron, without worrying in this case how this current would be injected into a central region?

Set of 5000 particles was chosen around accelerated equilibrium orbit at radius 5.6 cm. Transverse emittances were equal:
e_r= e_z =125 p mm.mrad. Bunch phase width 20-60°RF



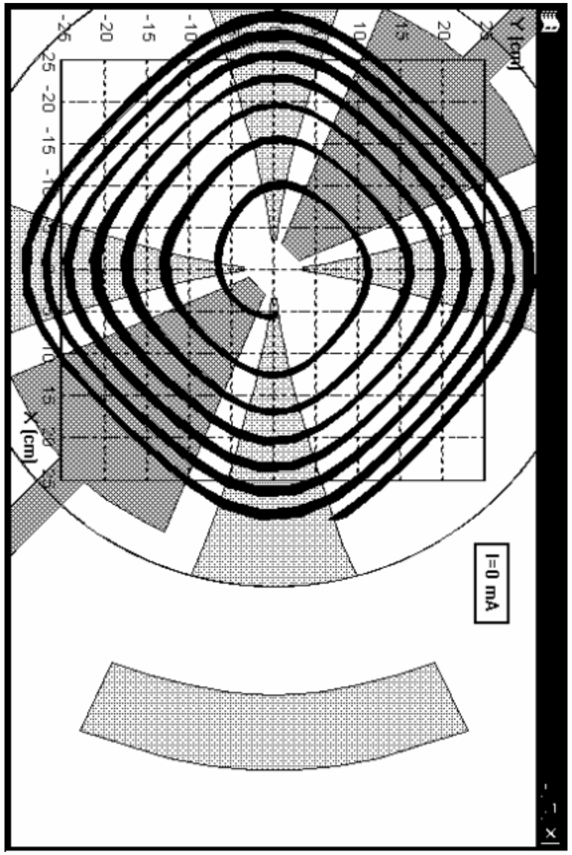
Initial position of 5000 particles on axial phase plane



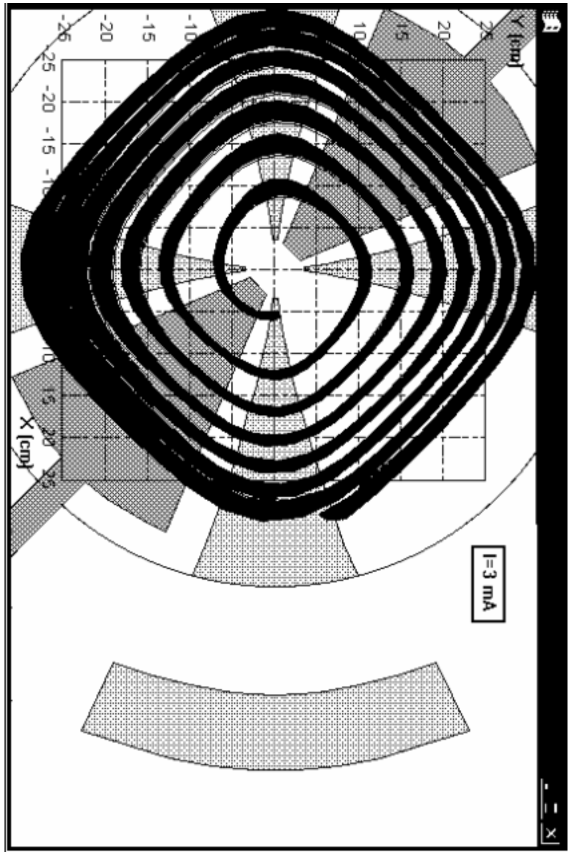
Initial position of 5000 particles on radial phase plane

Computations of beam acceleration for ideally injected bunch

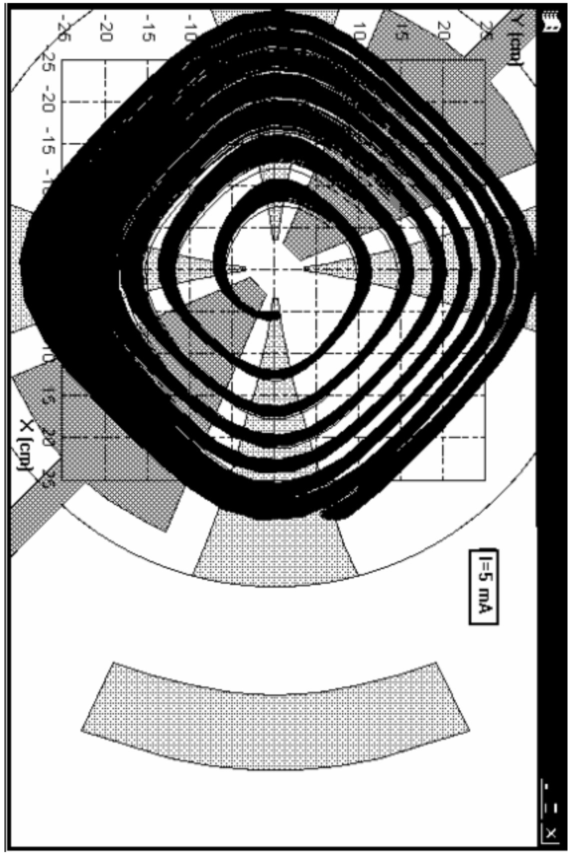
Three beam layout for different initial intensity



I=0 mA



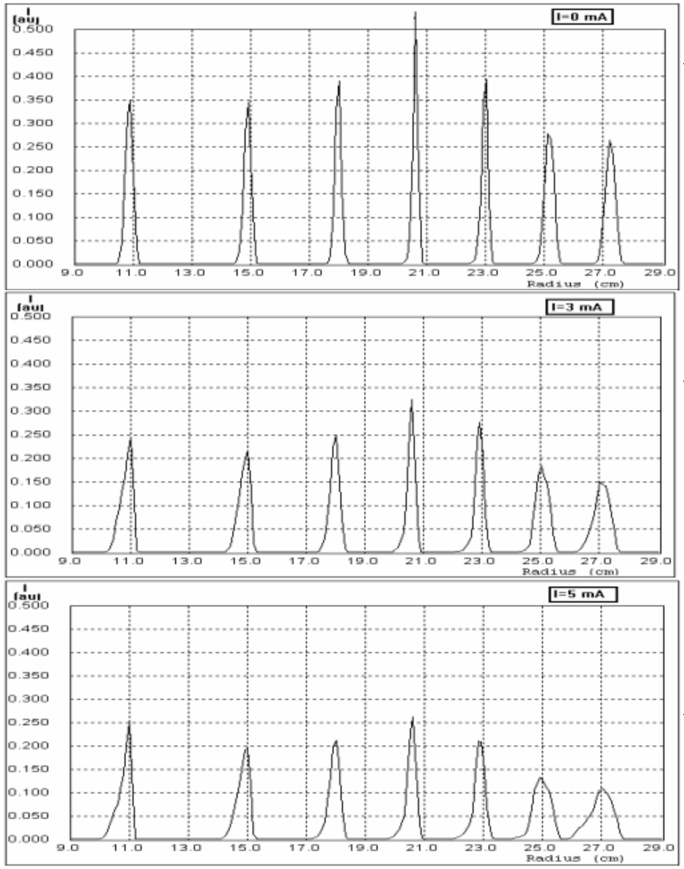
I=3 mA



I=5 mA

Computations of beam acceleration for ideally injected bunch

Differential probe signal

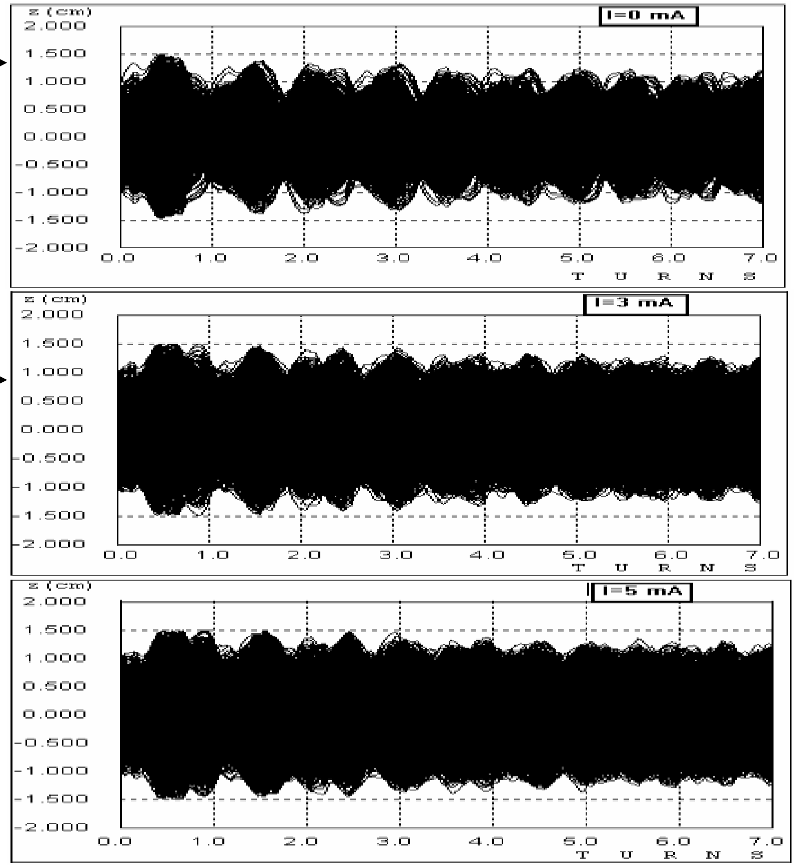


← I=0 mA →

← I=3 mA →

← I=5 mA →

Particle axial trajectories



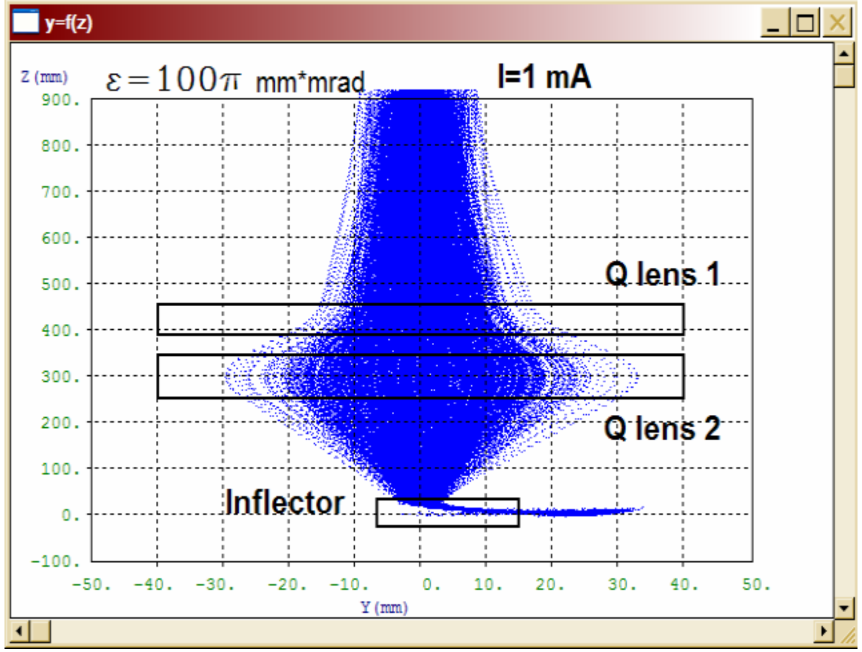
Conclusions for ideally injected beam case

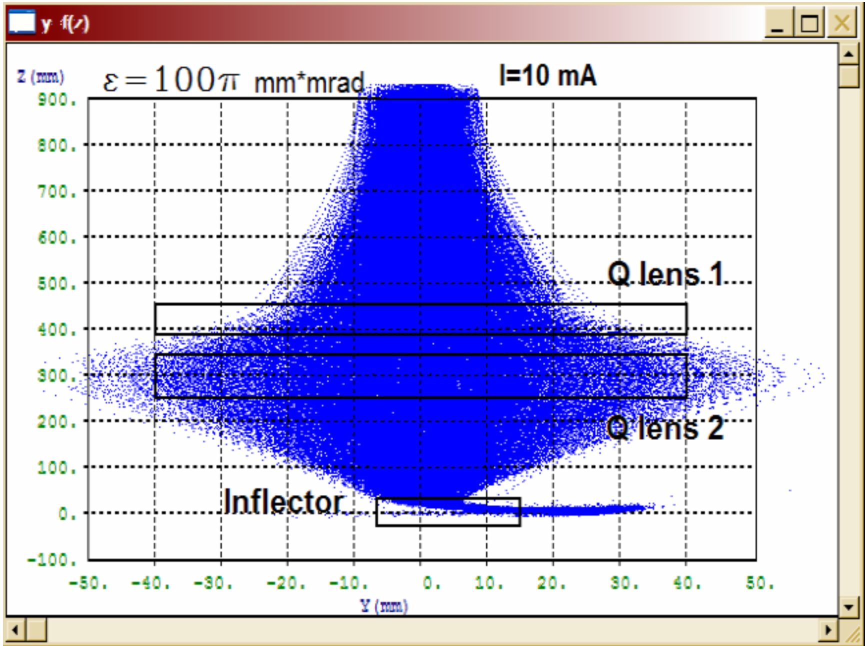
- *The focusing properties of the cyclotron magnetic field make it possible to accelerate beam with the current approximately 5 mA.*
- *Radial width of beam with current 4.3 mA on the last turn equals 18-25 mm depending on azimuth;*
- *Final root-mean-square (±2s) emittances of beam are following :er=170* p *mm.mrad, ez =130* p *mm.mrad.*

Not ideally injected beam

At the second stage of calculations we used the more realistic initial conditions, which corresponded to the passage of the beam through the injection line ended by the inflector. Selection of the beam initial parameters was done in a range 1-20 mA.

Axial injection with different beam current





Spiral inflector leads to some negative factors:

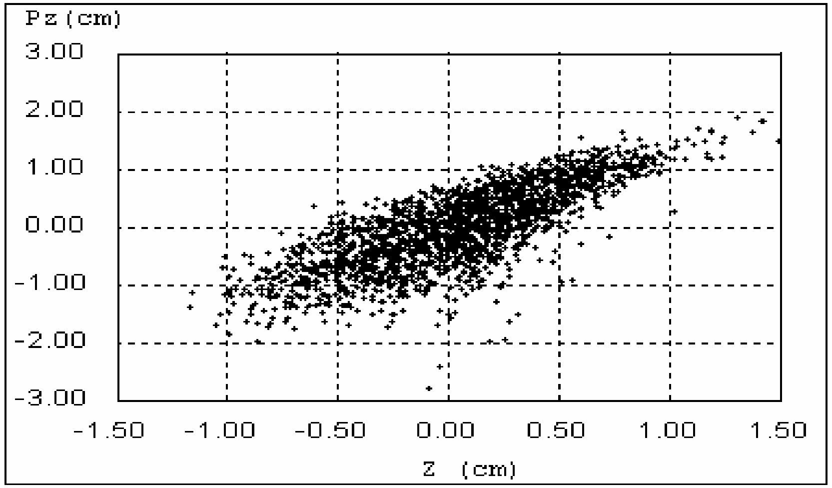
1. **Large axial divergence of beam.**

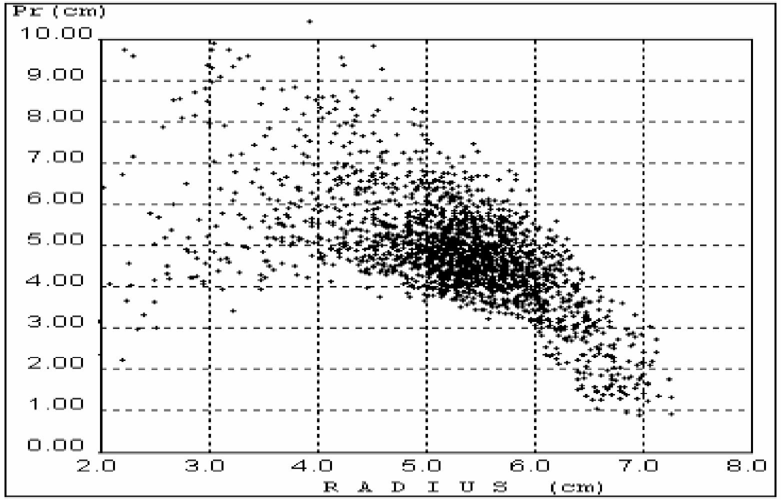
2. **Increase in the phase width of bunch.**

3. **Miss of beam in an accelerated equilibrium orbit.**

Computations of beam acceleration after inflector passage

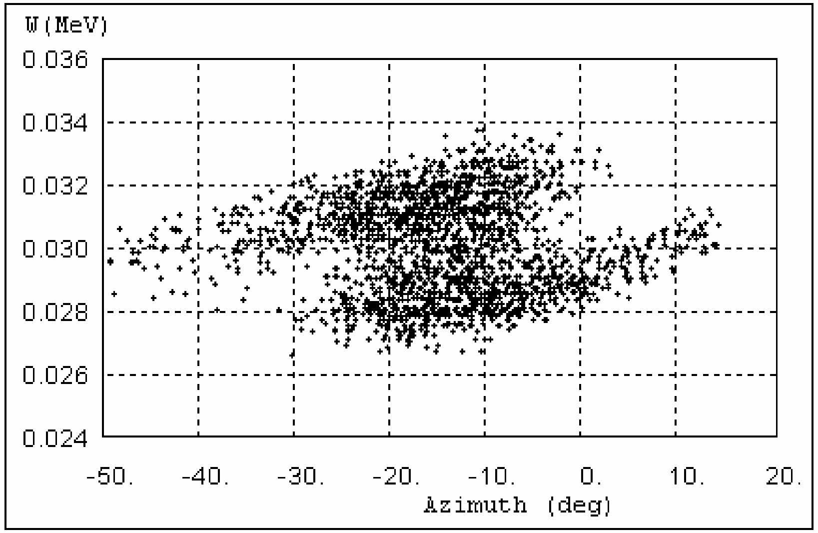
Selection of the beam initial parameters was done in a range 1-20 mA





Initial position of 2000 particles on axial phase plane

Initial position of 2000 particles on radial phase plane



Initial position of 2000 particles on plane azimuth-energy

Results for 5 mA injected beam

Computations of beam acceleration after inflector passage

Three types of losses:

1. Axial coordinate of particle is greater than half of vertical aperture (Z>15 mm)

2. Particle does not pass the window of diaphragm

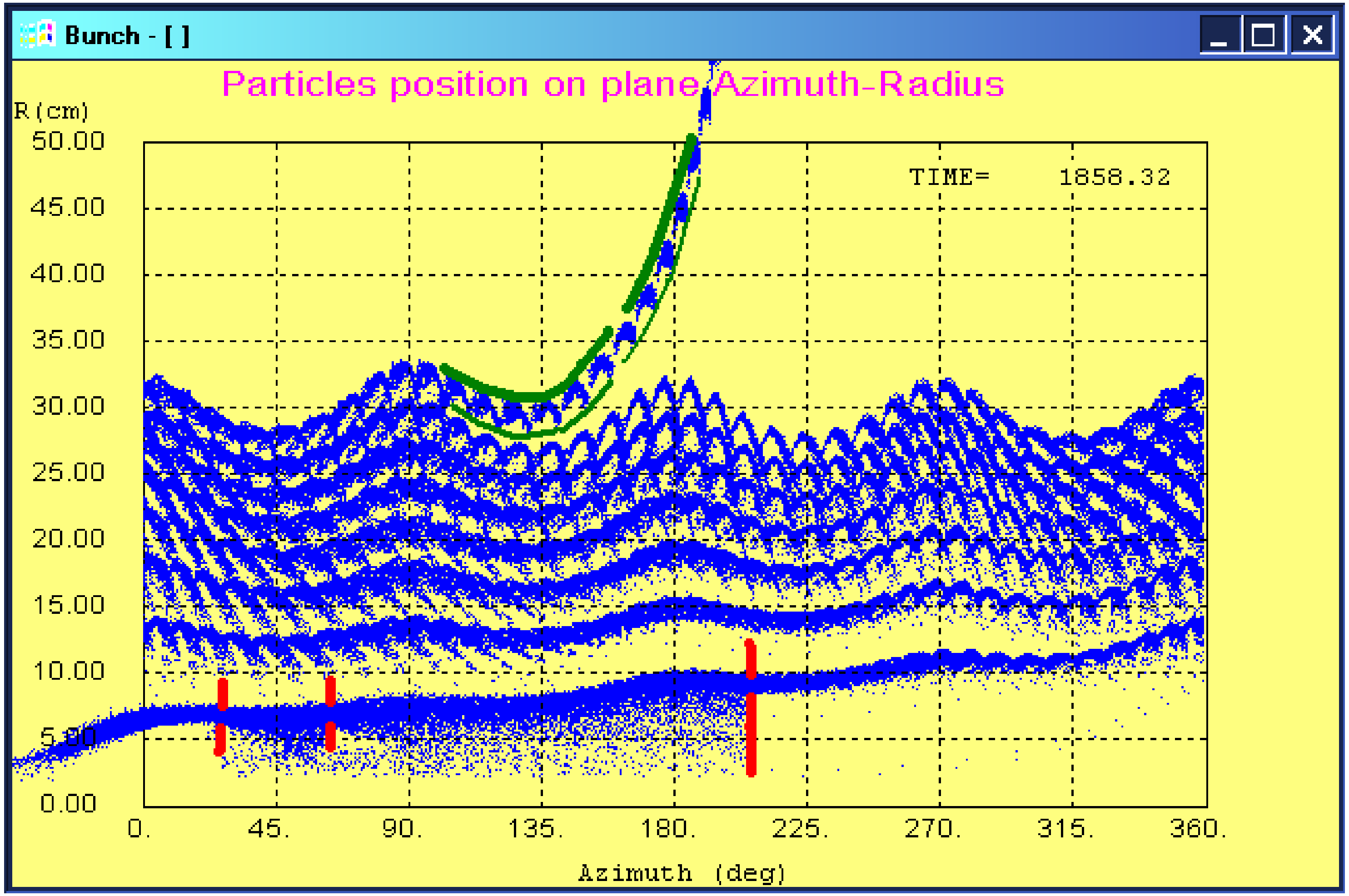
3. Particle goes to the center of cyclotron because of bad phase motion

1=Axial losses,   2+3=Radial losses

Particle dynamics has been simulated for ion source current in the range 1-20 mA.

Initial beam emittances (at ion source window) were equal 100 •   mm.mrad

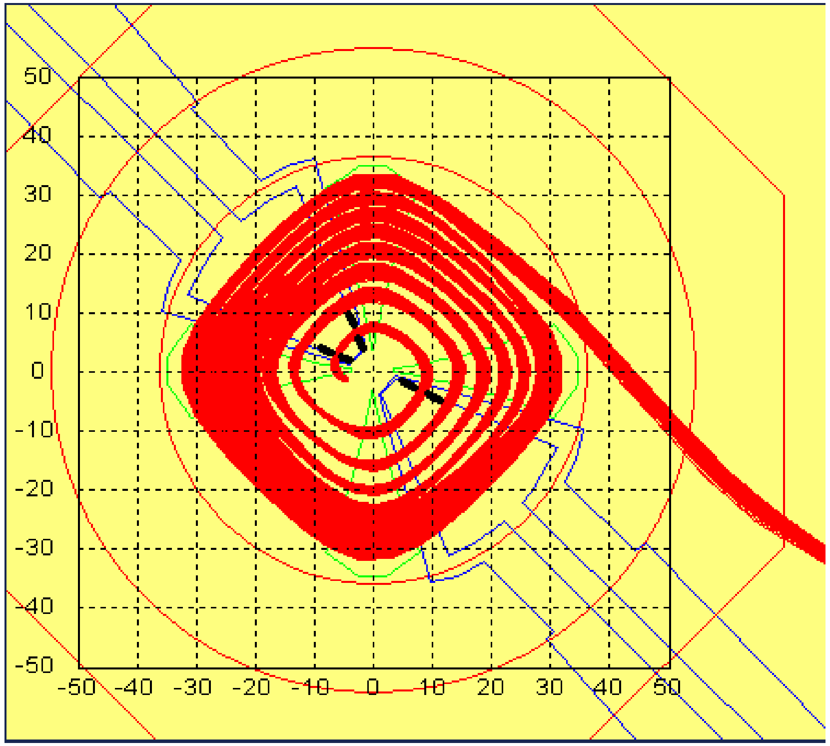
Computations of beam acceleration after inflector passage



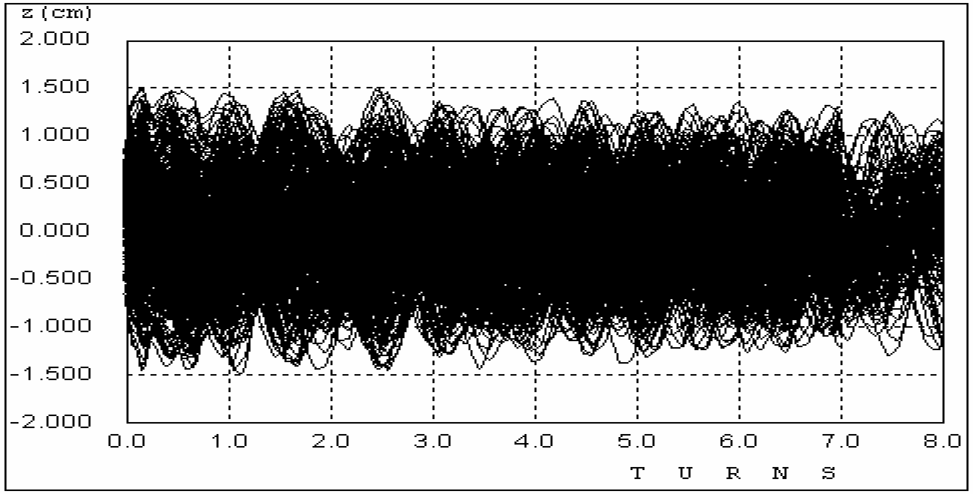
Ion source current 5 mA, Final cyclotron current 1.2 mA

Computations of beam acceleration after inflector passage

Only trajectories of the not lost particles are depicted on these graphs.

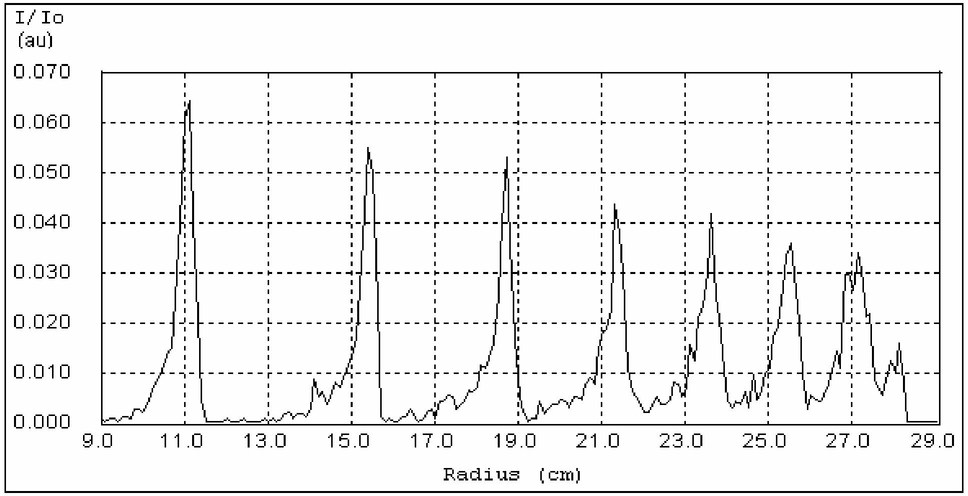


Beam layout with 3 radial diaphragms • R=20mm



Particle axial trajectories

Ion source current 5 mA,
Final cyclotron current 1.2 mA



Differential probe signal

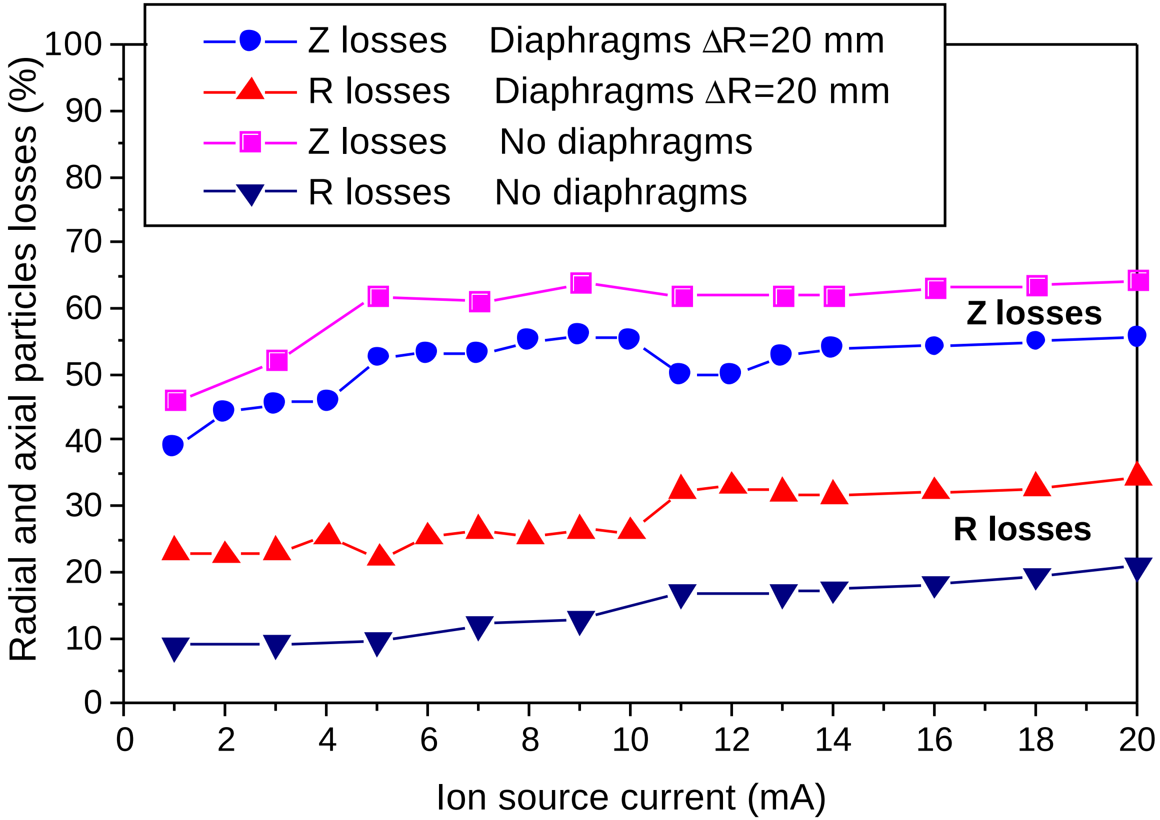
Computations of beam acceleration after inflector

Computations shows that the axial losses are in 2 – 4 times greater than radial ones.

There are two reasons of axial losses:

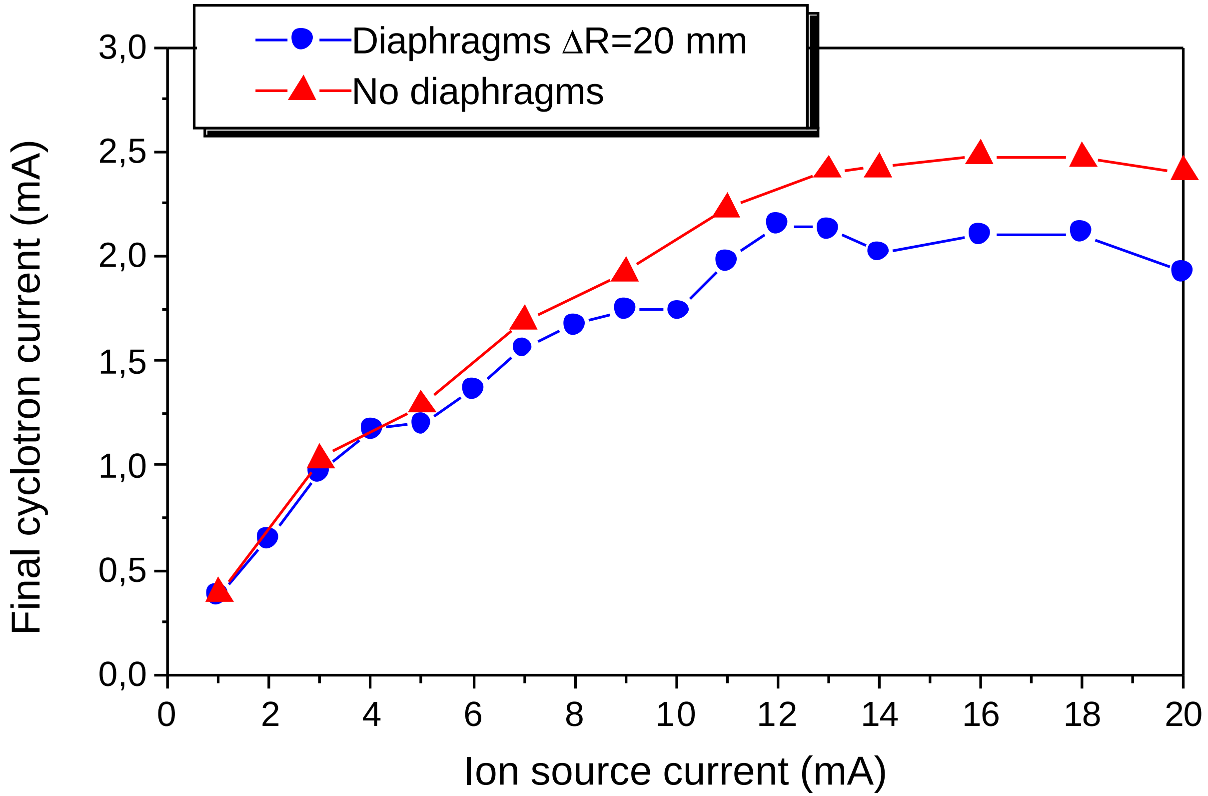
- **large initial beam axial divergence;**
- **bad RF phase for a part of the beam when it passes through the 1st accelerating gap.**

The last occurs due to large RF phase width of the bunch



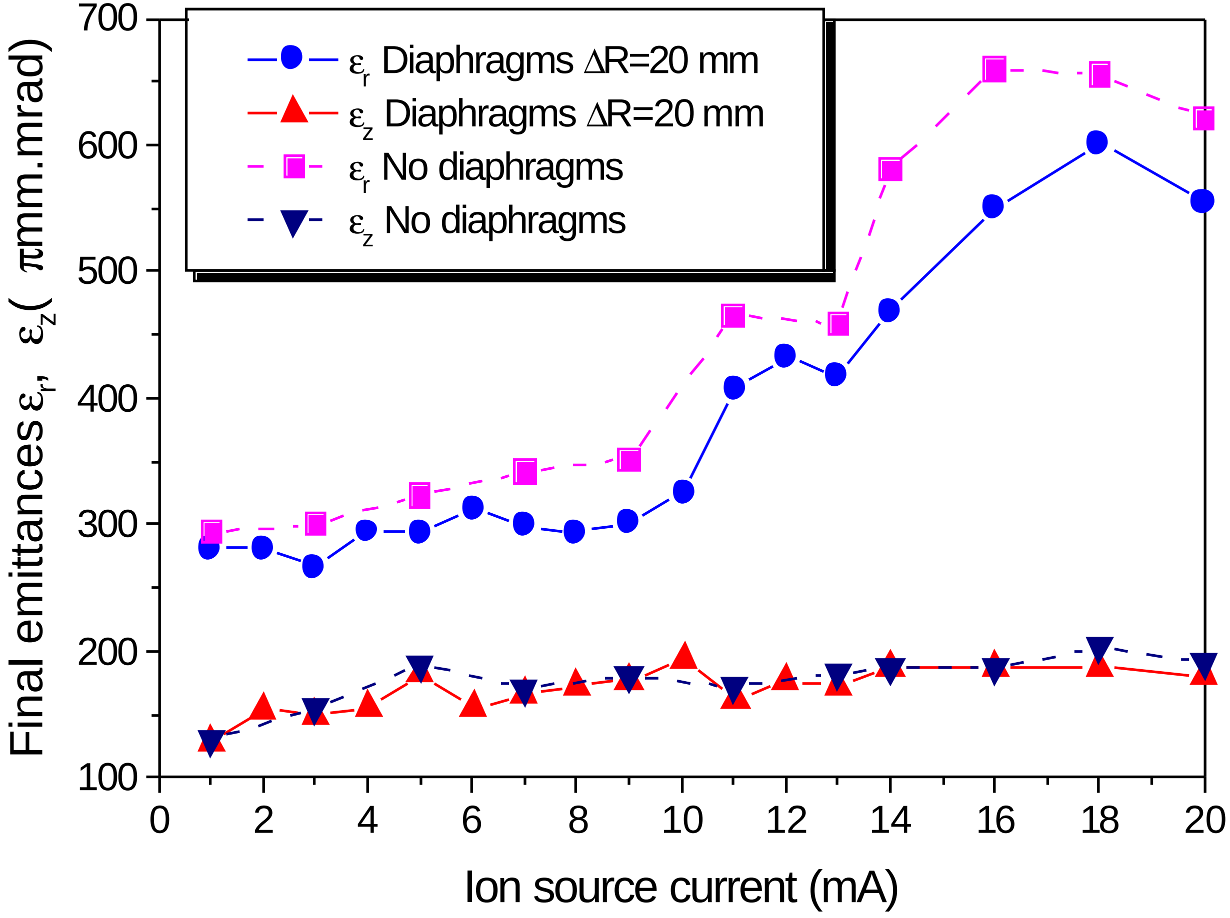
Cyclotron current at the end of acceleration versus injection current

Interpretation of the results shows that beginning from the current of injection 12 mA an increase in the internal current of cyclotron practically stops. At this moment the current of cyclotron reaches approximately 2 mA.

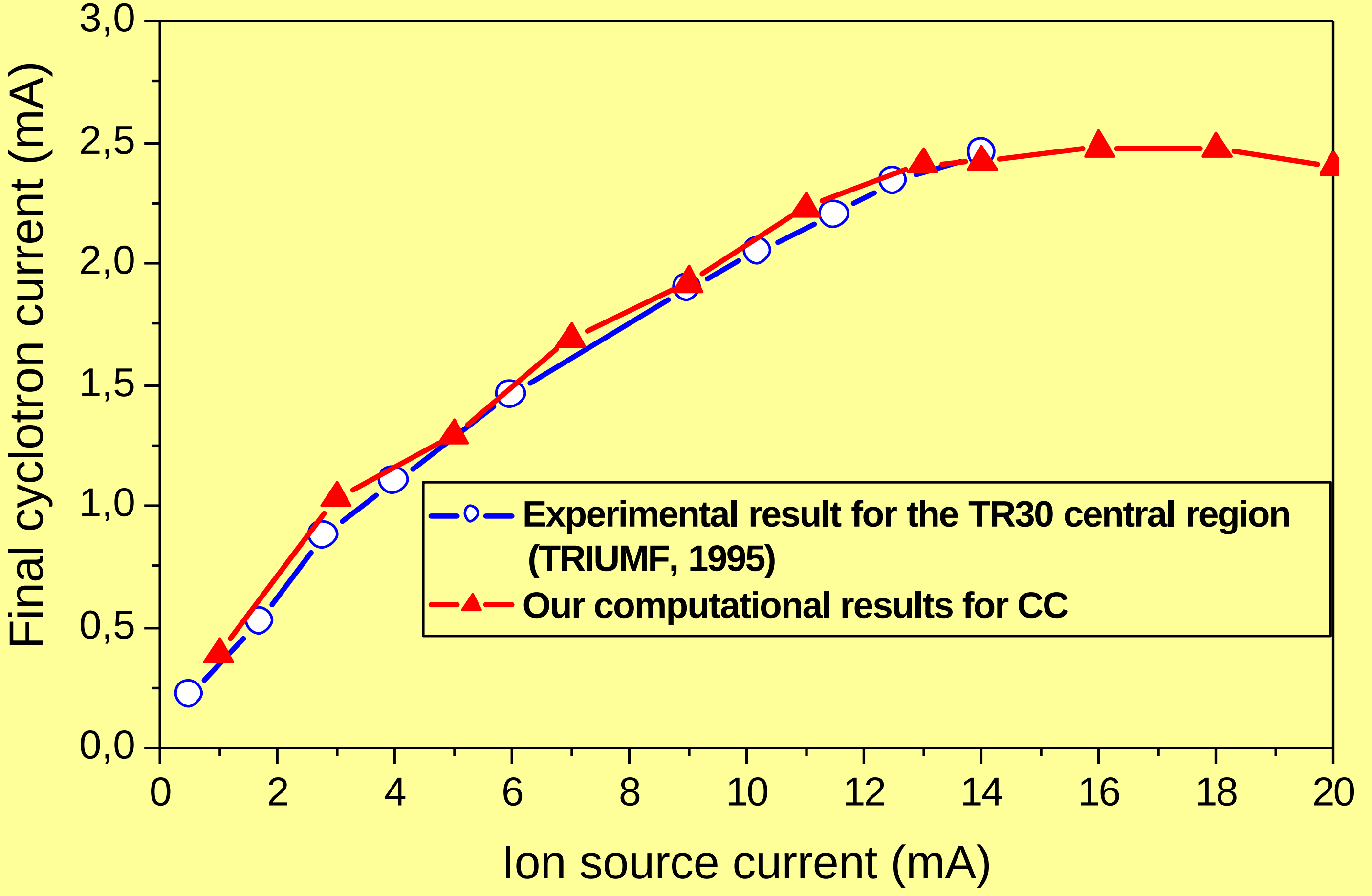


Transverse emittances at the end of acceleration versus injection current

Remarkable deterioration in the radial beam quality is observed when injection current becomes greater than 10 mA. The axial emittance of beam weakly depends on intensity, since it is determined mainly by the vertical aperture of dees.



Comparison of our numerical and TRIUMF experimental results for the cyclotrons with external injection



Final cyclotron current versus ion source current

Conclusion

- We can conclude from our computer simulation of the beam dynamics in the compact cyclotron with external injection that maximal accessible current of cyclotron is 2mA with the diaphragms and 2.5mA without ones.
- Noticeable deterioration in the beam quality is observed if the current of injection exceed 10mA.