Numerical modeling of the electrons confinement in the multicusp magnetic trap

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A charge-exchange target for neutralizing a negative ion beam with energies up to 10 MeV and higher requires the development of a highly efficient plasma trap which allows to form and confine plasma with a linear density up to 10^{17} cm^{-2} and higher.

The magnetic systems in which the condition of magnetohydrodynamic stability of the plasma is satisfied are most interesting to obtain a high-density plasma.

The electron confinement efficiency in a magnetic trap with a quasi-spherically symmetric multicusp magnetic field geometry with a "minimum B" at the center of the system, in which all cusps are point-type cusps is studied using numerical methods.

The results of numerical experiments are compared with a collisionless model of particle motion in a trap.

The multi-turn charge-exchange injection from linear accelerator LU- 30 to the proton synchrotron U-1.5 (buster) will allow to several times raise the intensity of the IHEP U-70 accelerator complex

- ❑Foil as the first stripping target (neutralizer) at an energy of 30 MeV is a significant technical problem.
  - Limited lifetime of foil
  - Difficulties of fabrication thin foils and operations of moving foils in the accelerator beam

Alternatives to foil stripping targets
($n_e\, l \sim 10^{17}$ cm^{-2} , $\tau_c \approx 30 \mu s$, minimum gas load)
should be considered

Gas and Plasma Stripping Targets

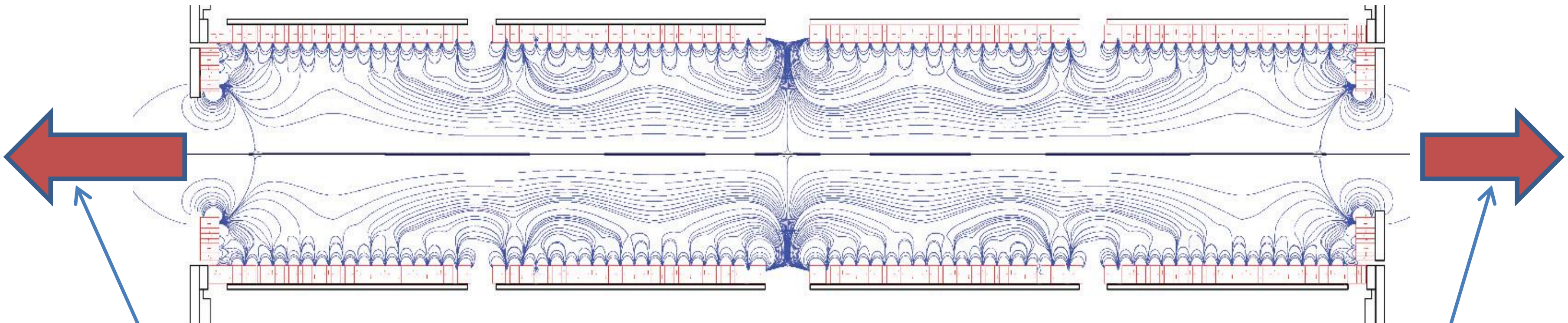
Gas Stripping Targets

- high gas load on the accelerator's vacuum system

Plasma Stripping Targets

- ❖ the equilibrium yield of neutrals is almost 1.5 times higher [G.I. Dimov, A.A. Ivanov, G.V. Roslyakov, Sov.J. Plasma Phys. **6**, 933 (1980).],
- ❖ it is possible to localize all target plasma particles in a limited area of the ion beam duct at an ionization degree close to 100% in order to reduce the influence of the working target on the vacuum conditions in the channel of the negative ion accelerator

AXISYMMETRIC MULTICUSP MAGNETIC TRAP WITH SET OF RING CUSPS

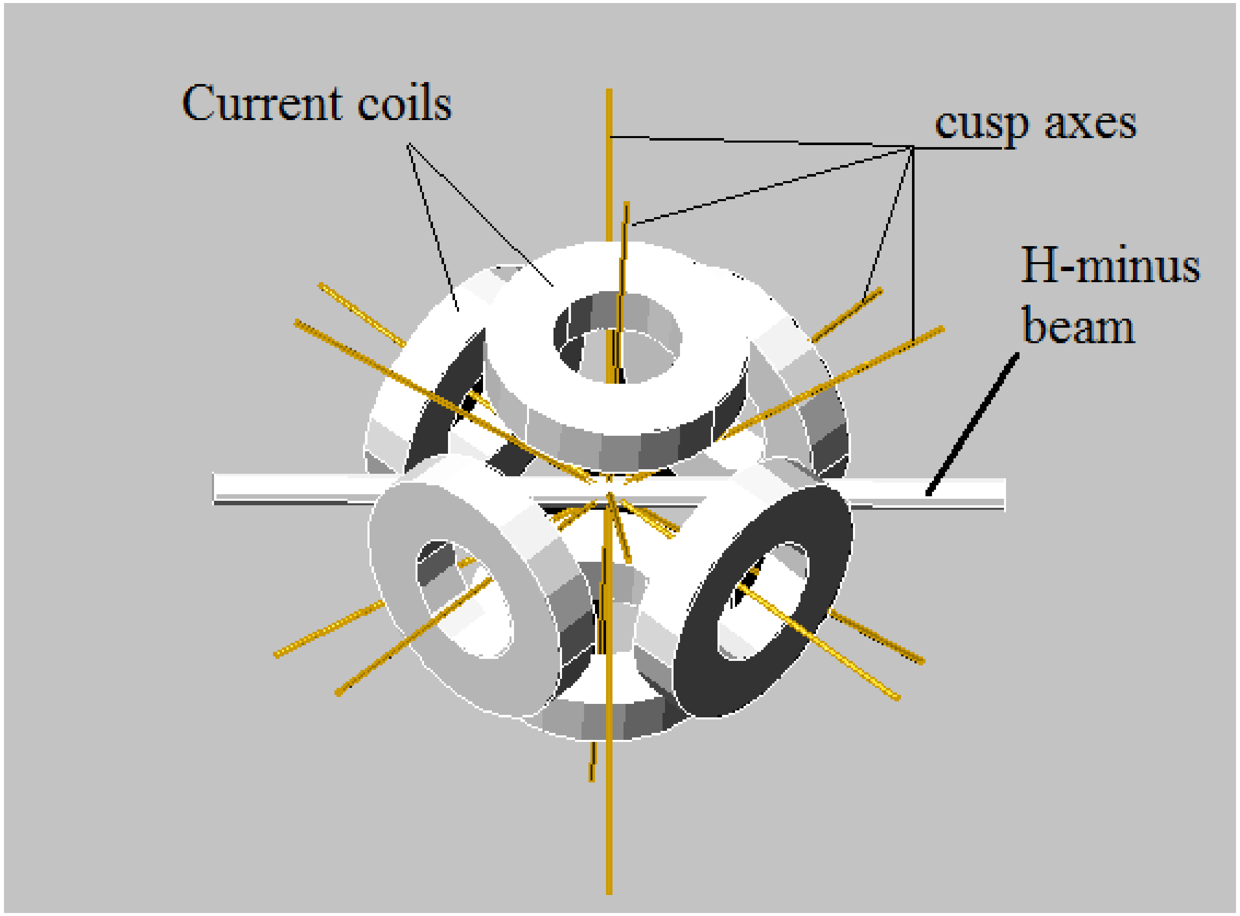


[I.S. Emelev and A.A. Ivanov AIP Conference Proceedings **2052**, 070005 (2018)]

The plasma flow through the end holes leads to significant additional load on the vacuum system of the negative ion accelerator

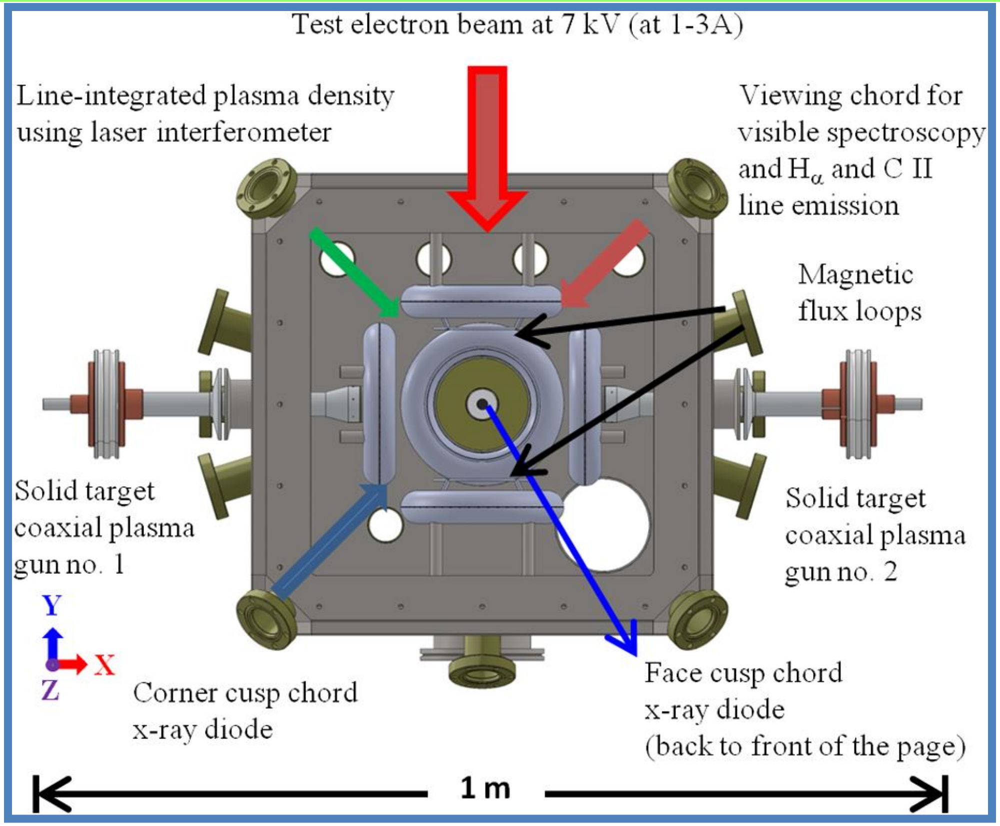
The goal is to reduce the gas load

Quasi-spherically symmetric multicusp magnetic field geometry with only point-type cusps and axis of the beam does not coincide with any of the cusp axes could be considered



Previously, it was shown in experiment that high-density plasma can be produced in such a trap

[J. Park, N. A. Krall, P. E. Sieck e.a. Phys. Rev. X **5**(021024) , 021024-1,(2015)]



$n_e \approx 9 \bullet 10^{21}\ m^{-3}$

$\tau_c \approx 10\ \mu s$

Unfortunately, data on the confinement time from the plasma and trap parameters are not provided.

It is necessary to study the dependence of the electron confinement time on the magnetic field and electron energy by numerical methods

“Simple” collisionless model for electrons confinement

[N.A. Krall, M. Coleman, K. C. Maffei e.a., Forming and Maintaining a Potential Well in a Quasispherical Magnetic Trap, Physics of Plasma, 2(1), 1995]

$$\boxed{\tau_e = \tau_{transit} \times M^* = \frac{2R}{v} \times M^*} \qquad (1)$$

$M^* = \dfrac{B_0}{B_{min}}$ - mirror ratio for a point cusp

B_{min} - induction of a magnetic field at the point where the adiabatic invariant for an electron begins to be conserved

$$L \equiv {}^{B}/_{|\nabla \mathrm{B}|} \approx r_L \qquad (2)$$

$$B = B_0 \left(\frac{r}{R}\right)^n$$

$$L = r_L = \frac{mv}{qB}$$

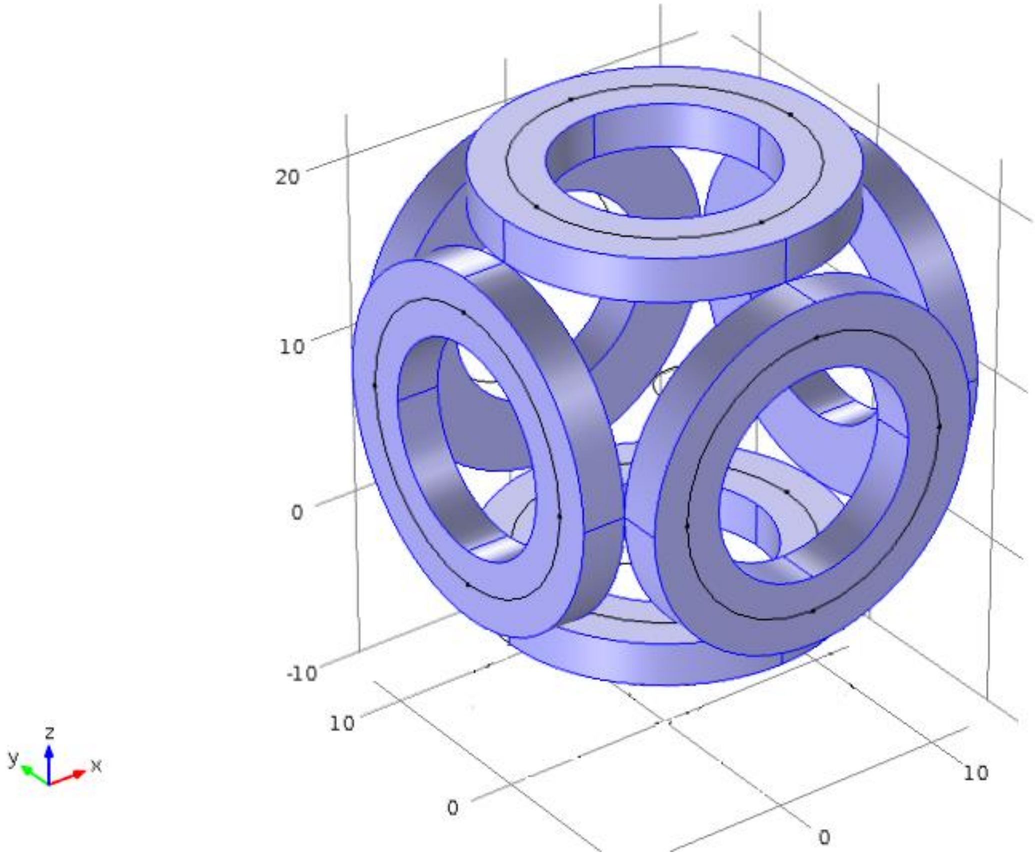
equating the scale L to the Larmor radius we get B min

$$B_{min} = (B_0)^{\frac{1}{n+1}} \left(\frac{nmv}{q}\right)^{\frac{n}{n+1}} R^{-\frac{n}{n+1}} \quad (3)$$

$$\tau_c = \tau_{transit} \times M^* = 2^{\frac{1}{2(n+1)}} R^{\frac{2n+1}{n+1}} (n)^{-\frac{n}{n+1}} \times (qB_0)^{\frac{n}{n+1}} m^{\frac{1}{2(n+1)}} E^{-\frac{2n+1}{2(n+1)}} \quad (4)$$

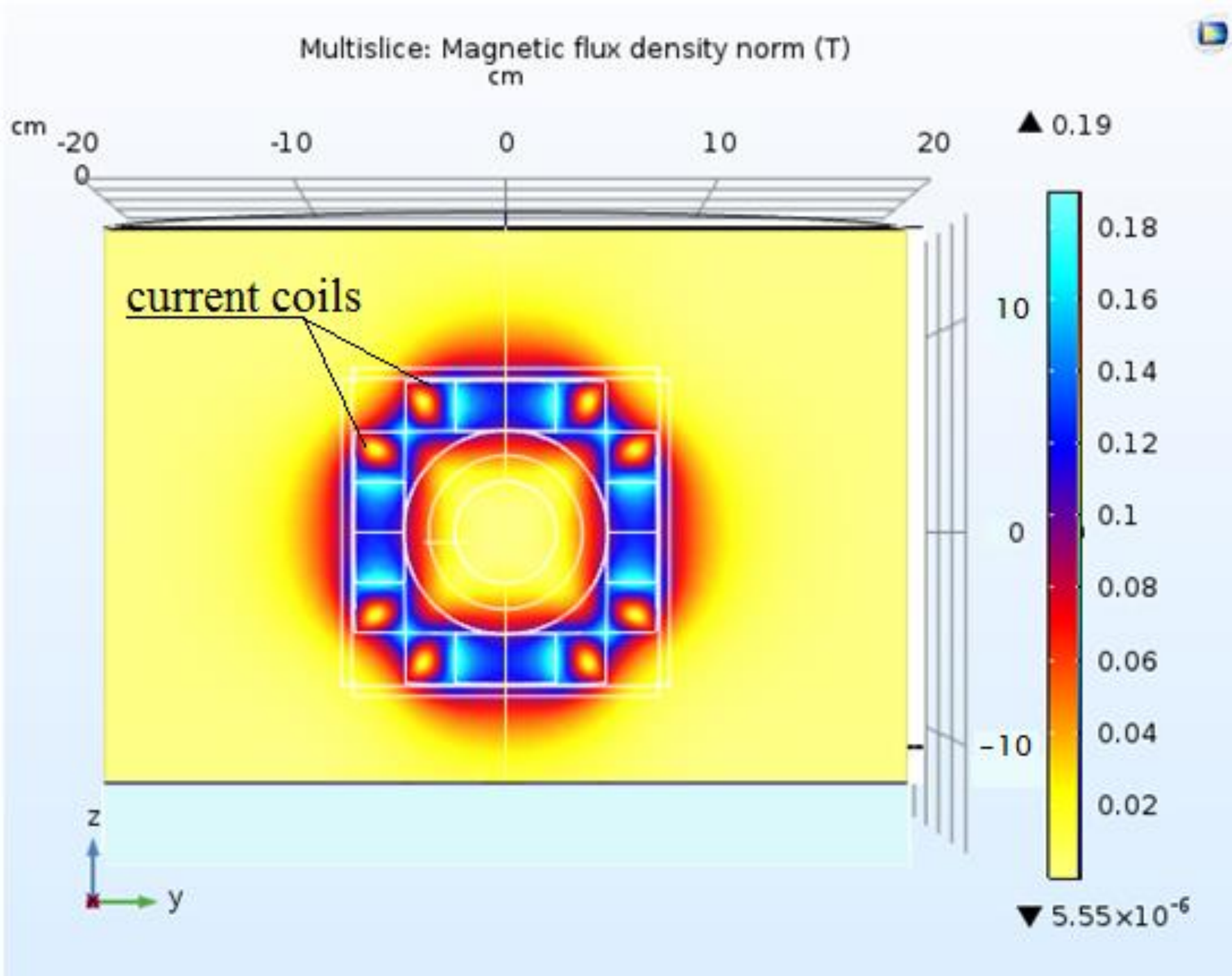
next we need the value of index “n” of the power function

To verify the dependences of the confinement time of sample particles in this trap on the magnetic field induction and electron energy, resulting from the relation (4), numerical experiments were performed.

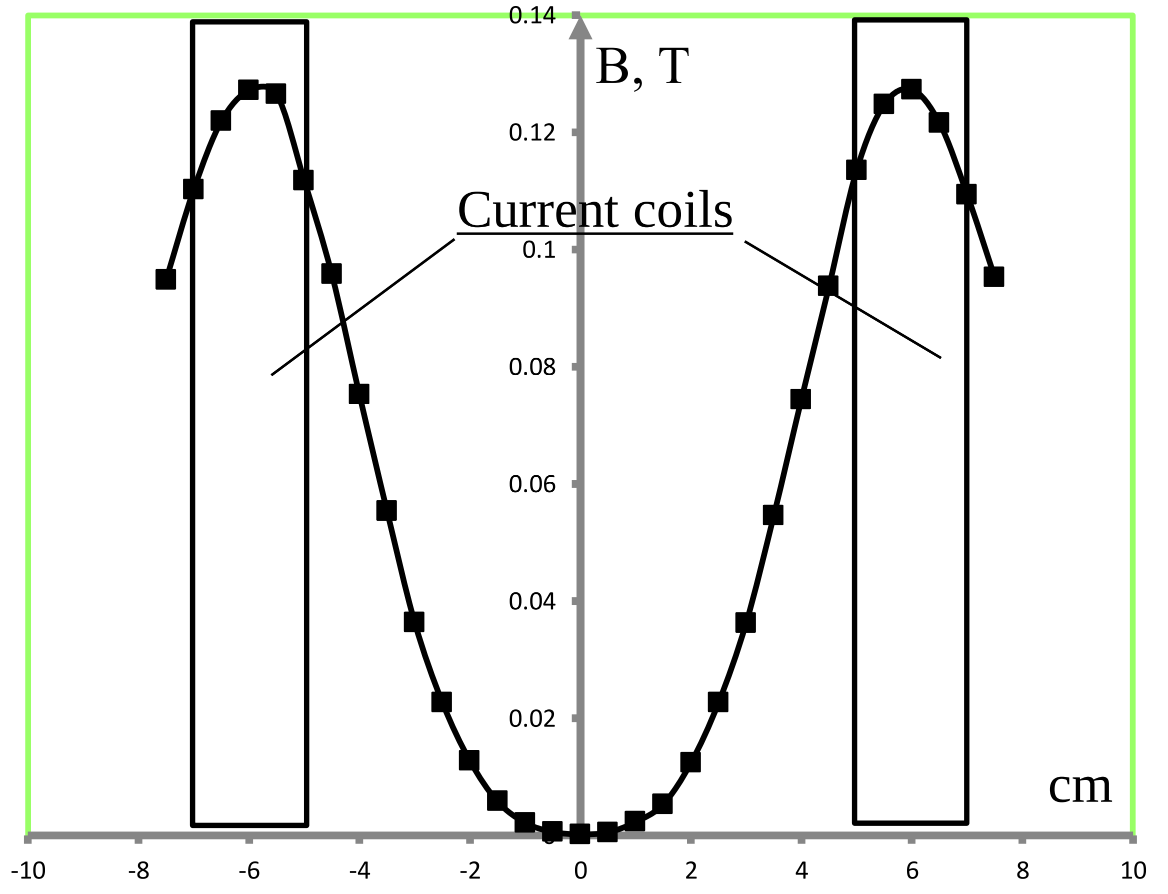


Numerical simulations

- Numerical experiments were performed using the COMSOL Multiphysics® 5.3a software package, which allows simulating the 3-dimensional geometry of magnetic fields and electrons motion.
- The center of the magnetic system is located at a point with coordinates (0,0,0).
- The magnetic field in the model system is created by six identical current coils located on the faces of a cube with an edge length of 10 cm
- The centers of the inner ends of the coils have coordinates (5,0,0), (-5,0,0), (0,5,0), (0,-5,0), (0,0,5), (0,0,-5) cm.
- The current value varied from 62.5 to 500 A (5…40kA·turns)
- the magnetic field induction at a cusp B_0 at these values varied from 0.0635 T to 0.508 T.



Distribution of magnetic field induction for the current value in coils 10 kA·turns in the plane X=0



Distribution of the magnetic induction value along the Z axis (X=0, Y=0). For reference, the position of two current coils on the z axis is indicated.
As a result of approximating the values of magnetic induction by a power function, the index n≈5/2 was obtained

Accordingly, with n≈5/2 τ_c takes the form

$$\tau_c = \tau_{transit} \times M^* \approx 1{,}4 \times 10^{-2} \times R^{12/7} \times B^{5/7} \times E^{-6/7} \quad (5)$$

were R– in m, E- in eV, B– in T

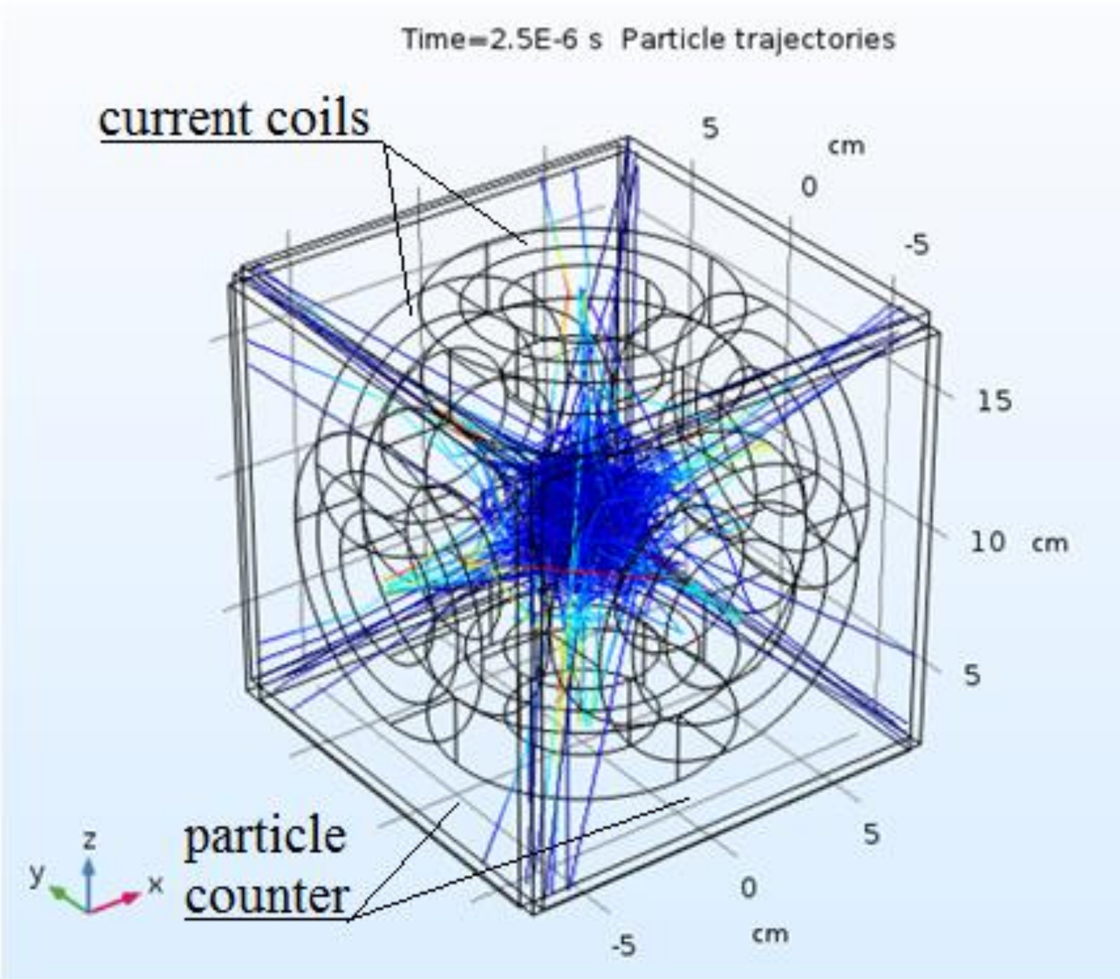
Particle Tracing

Electron emission was modeled from a disk-shaped surface with a radius of 1 cm, located inside a magnetic system with the coordinates of the disk center (0,0,0) cm. Electrons were emitted from the disk surface into a hemisphere.

The particle counter registered electrons that reached the edges of a cube with an edge length of 14 cm centered at a point (0,0,0) completely covering the magnetic system.

Numerical experiments with the energy of emitted electrons 1.4; 3; 5; 7; 10; 12; 20; 50 eV and value of induction B_0 0.0635 T, 0.127 T, 0.19 T, 0.254 T, 0.317 T, 0.508 T were performed .

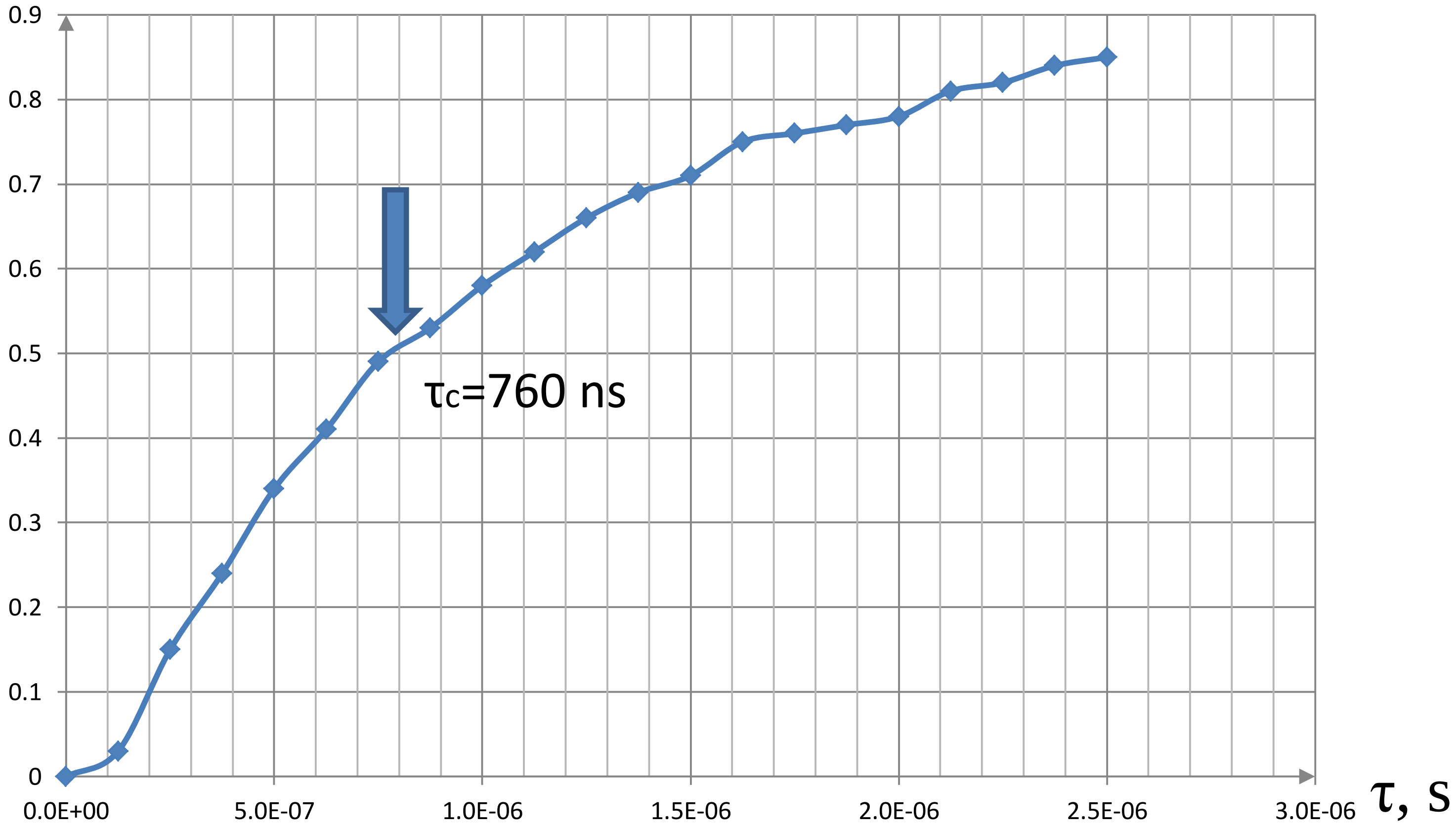
In each numerical experiment, 100 electrons were emitted. An example of trajectories for the electron energy of 10 eV at the value B_0=0.127 T (10 kA·turns) is shown.



Electrons leave the system through cusps with axes through the centers of the faces or vertices of the cube.

For the electron confinement time τ_C, was taken the time during which half of the original number of emitted electrons flew out to the particle counter.

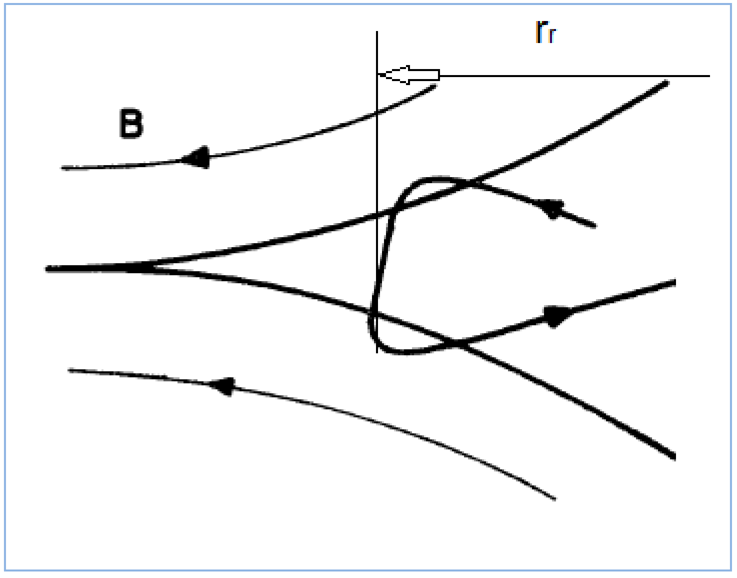
Ratio of particles that left the trap



10 eV 10 kA·turns (B_0 = 0,125 T)

A significant difference between the values of the confinement time τ_C, obtained in numerical experiments and calculated in accordance with the formula (5) was found.

To explain these discrepancies, it was assumed that the value R (the size of the system) in the formula (1) should be replaced by the value r_r , where r_r is the distance from the center to the point, where the particle is reflected from the magnetic field mirror.



$$\frac{B_r(r_r)}{B_{min}} = \frac{E}{E_\perp}$$

Bmin is the field at the point at which electrons become adiabatic,
E - full kinetic energy of the electron,
E⊥ is the kinetic energy of the transverse motion at the point at which electrons become adiabatic

Using the Bmin from (3), the value r_r is found and substituted for R in (4) to calculate τ_c. Thus, instead of formula (5), we get the value for τ_c

$$\tau_c = \left(\frac{E}{E_\perp}\right)^{\frac{1}{n}} 2^{\frac{1}{(n+1)}} R^{\frac{2n}{n+1}} (n)^{-\frac{n-1}{n+1}} (qB_0)^{\frac{n-1}{n+1}} m^{\frac{1}{(n+1)}} E^{-\frac{n}{n+1}} =$$

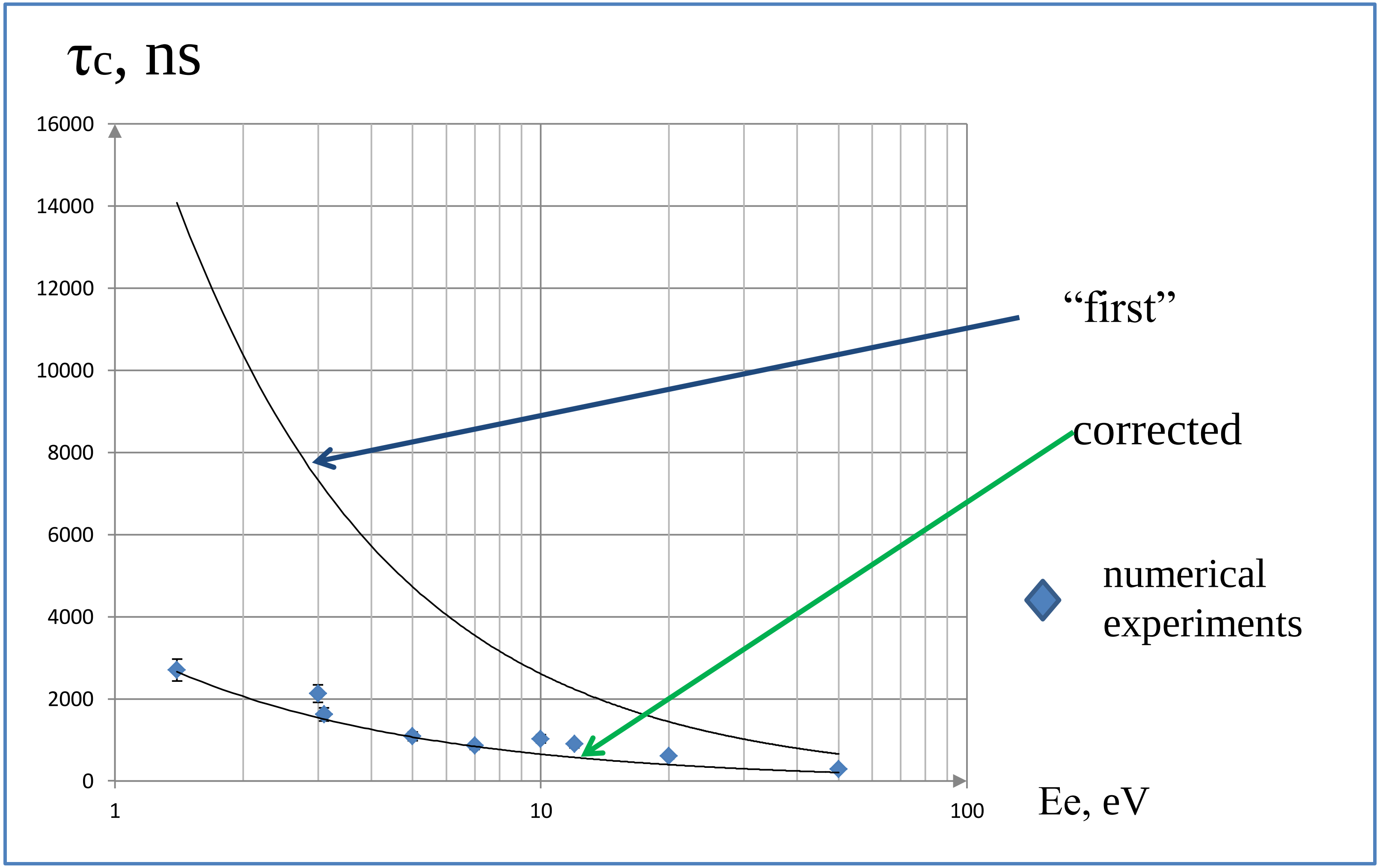
$$\approx \left(\frac{E}{E_\perp}\right)^{2/5} \times 5 \times 10^{-4} \times R^{10/7} \times B_0^{3/7} \times E^{-5/7}$$

assuming $\langle E_\perp \rangle = {}^2/_3\, E$

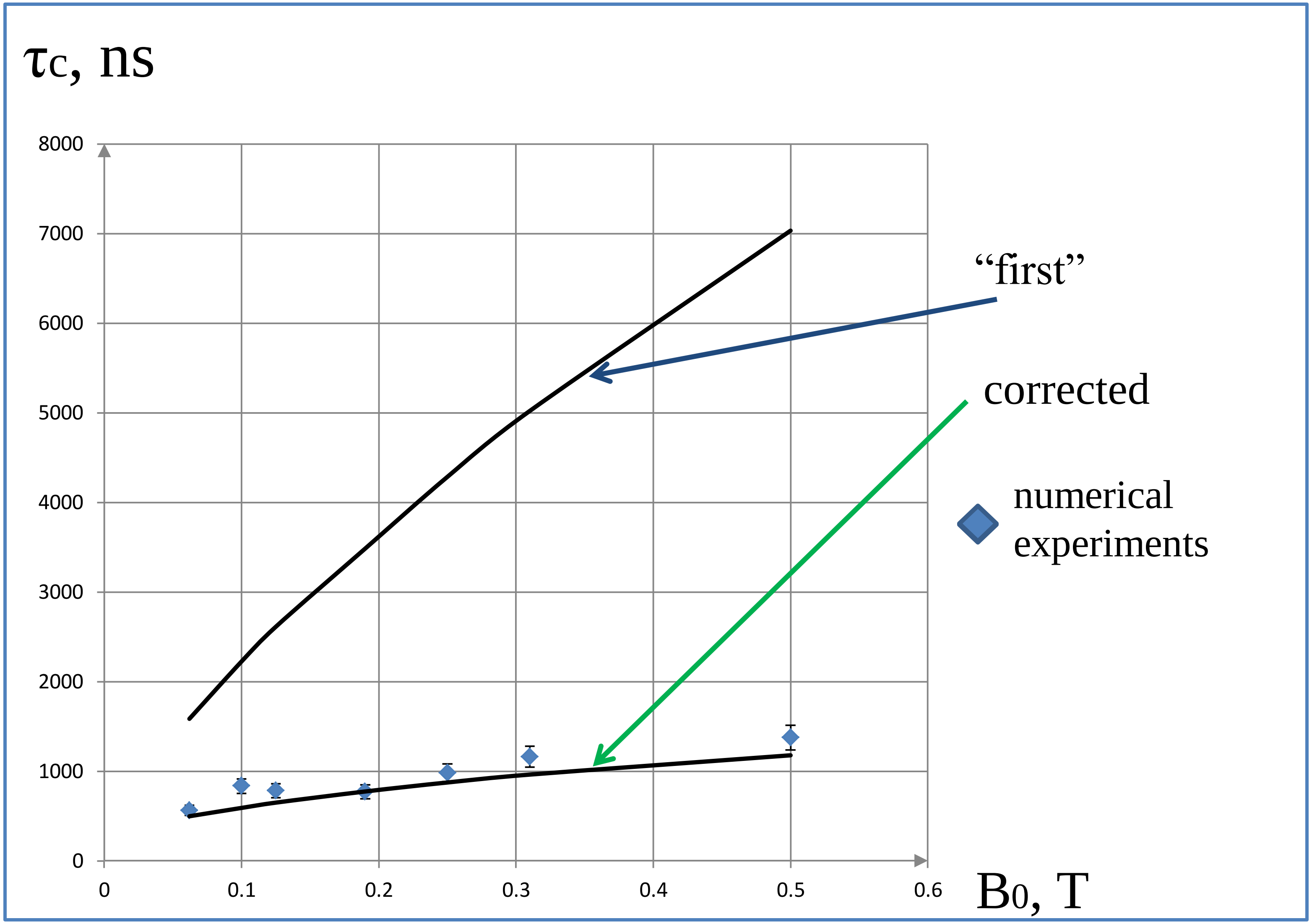
We get the corrected formula

$$\boxed{\tau_c \approx 6 \times 10^{-4} \times R^{10/7} \times B_0^{3/7} \times E^{-5/7} \quad (6)}$$

Electron confinement time



Electron confinement time



As we can see, the updated formula for the confinement time corresponds fairly well to the results of numerical experiments

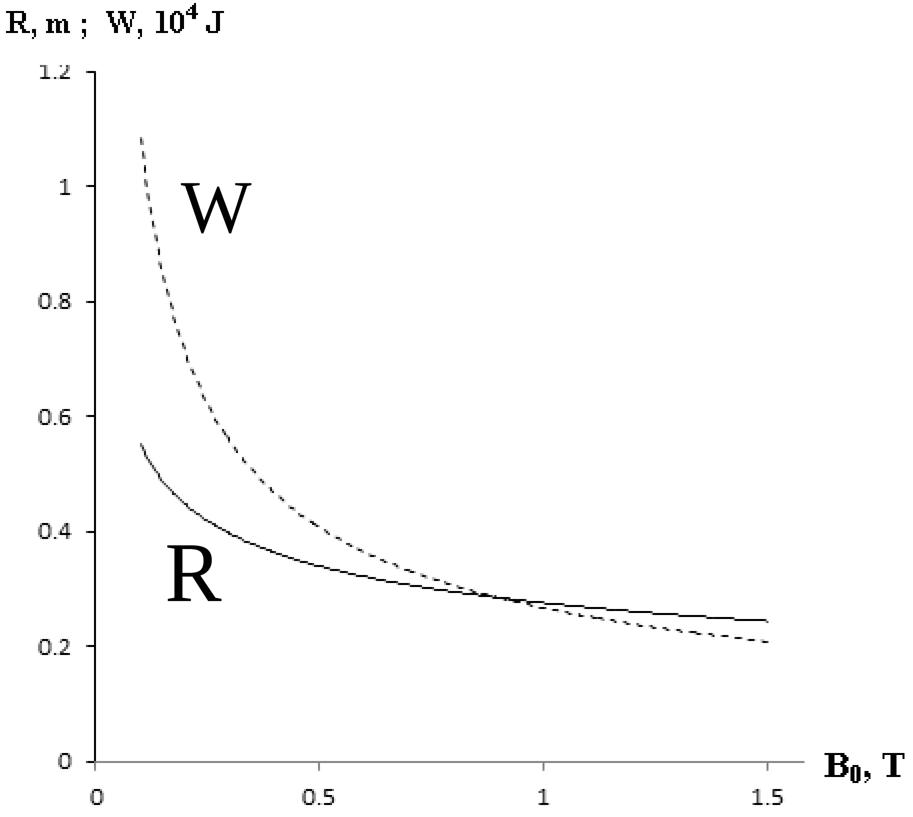
Based on this, formula (6) can be used for scaling parameters when designing a target plasma trap

To obtain the confinement time $\tau_C \approx 30$ μs (this is necessary for injection into the proton synchrotron U-1.5), assuming an average plasma electron energy of about 5 eV, based on the formula (6), it is necessary to obtain a parameter $R^{10/7} B_0^{3/7}$ of about 0.17

To achieve the maximum yield of neutral atoms at a beam energy of 30 MeV, the thickness of the plasma target must be $n_e l = n_e 2\sqrt{2} R \approx 10^{21}$ m^{-2}, i.e. the electron density is $n_e \approx {}^{3.5 \cdot 10^{20}}/_{R}$ m^{-2} .

Assuming the energy price of the ion ω of the created plasma is about 150 eV (which is close to the values in the experiment [J. Park, N. A. Krall, P. E. Sieck, e.a]), the energy required to create a plasma should be $W = \omega \times n_e \times {}^4/_3\, \pi R^3 \approx 3{,}6 \cdot 10^4 \times R^2$ J

system radius and required energy



Based on these data, it seems optimal to choose the value of the magnetic field in the cusp in the range of 0.5... 1 T, while the radius of the system lies in the range of 0.28 to 0.34 m, and the energy required to create a plasma lies in the range of 2.6 ... 4 kJ.

Conclusion

- ❖ The representation of electron motion in the collisionless approximation in the form of reflections from individual mirrors and free flights through the central region of the magnetic field with loss of adiabaticity, taking into account the dependence of the reflection point position on the electron energy, is quite well consistent with the results of numerical modeling

- ❖ The values of the magnetic field induction, the system size, and the energy consumed are considered acceptable for creating a plasma target of a beam neutralizer with an energy of 30 MeV and a duration of 30 μs for the implementation of multi-turn charge-exchange injection from a linear accelerator LU-30 to a proton synchrotron U-1.5.

thank you
for your attention