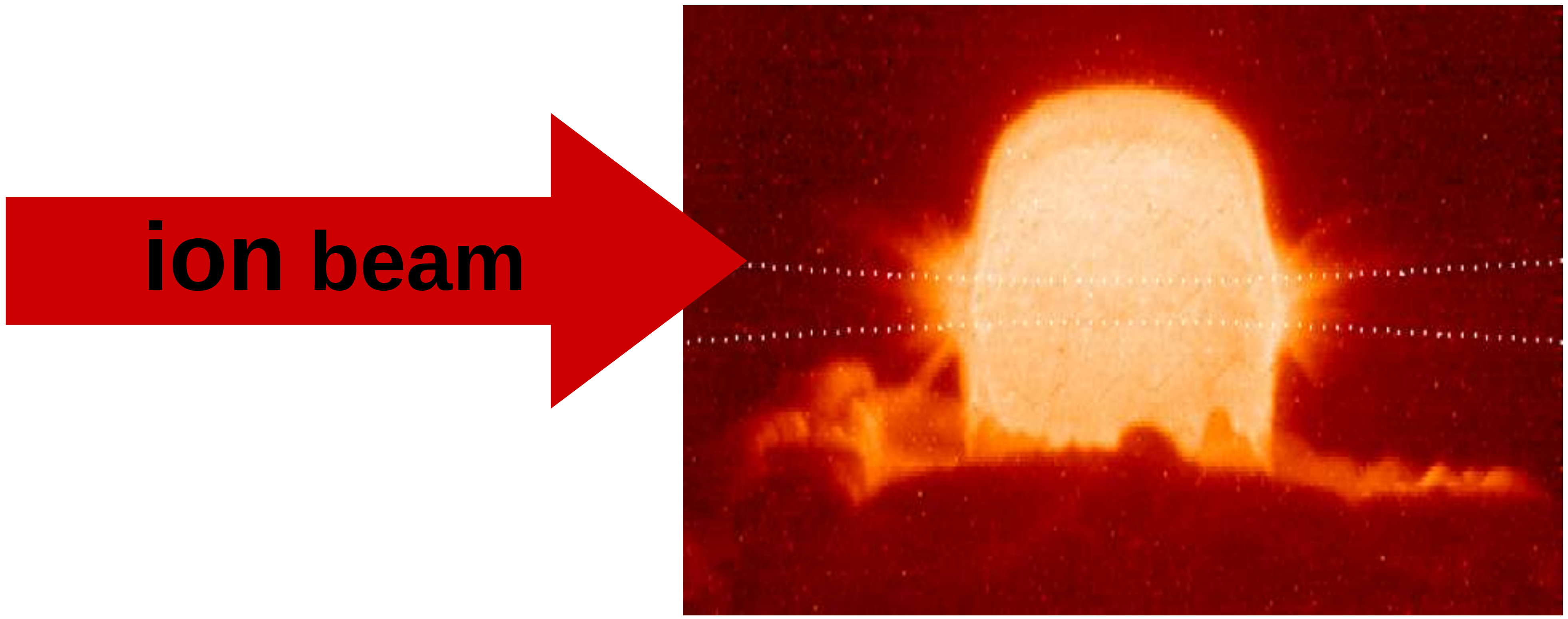
THE NONLINEAR TRANSFORMATION OF A IONS BEAM IN THE PLASMA LENS

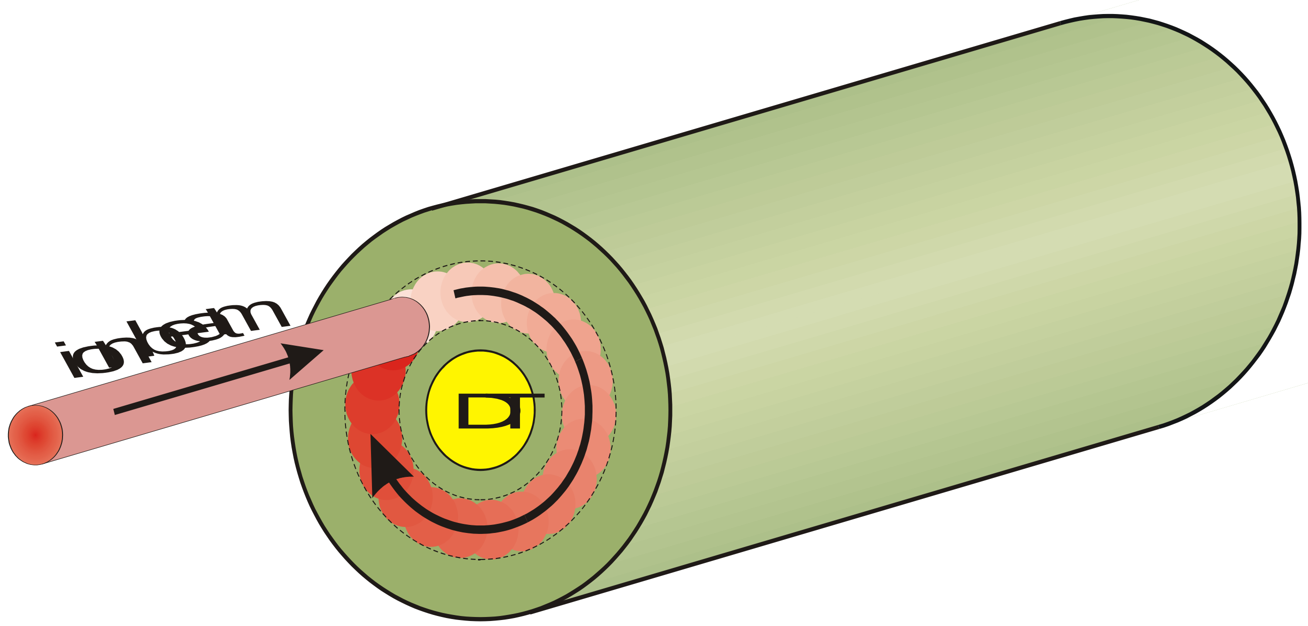
Institute for Theoretical and Experimental Physics, Moscow, Russia

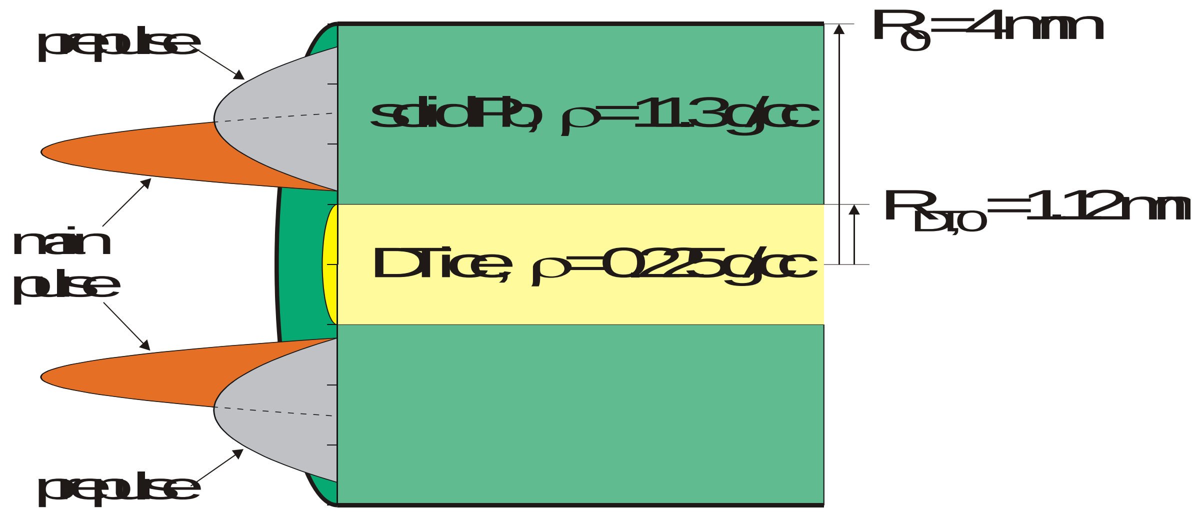
A.Drozdovskiy, N.Alexeev, S.Drozdovskiy, A.Golubev, Yu.Novozhilov, P.Sasorov, V.Yanenko

Heavy-ion beam is an tool for investigating high energy densities in matter and heavy ion driven inertial confinement fusion

•

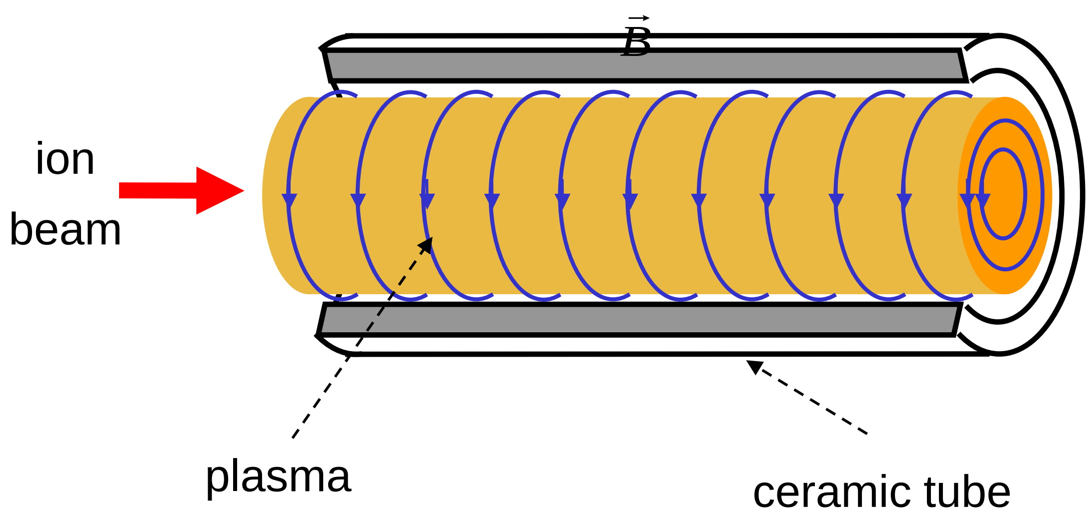


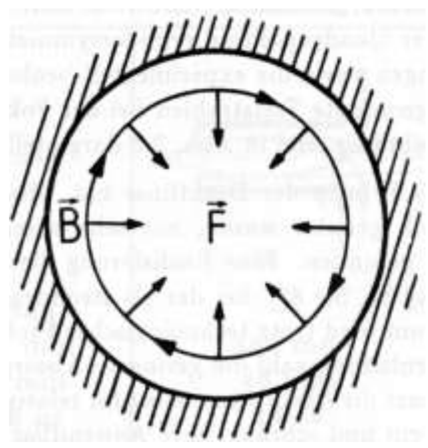




Initial target configuration and radial beam intensity profile

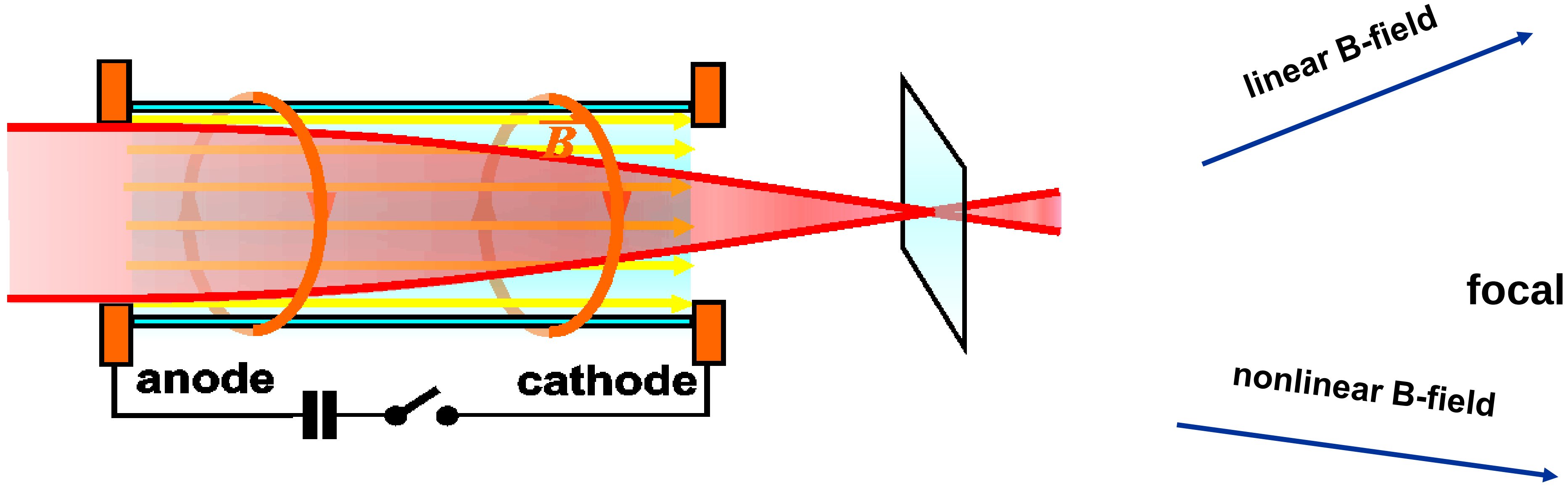
Ion focusing in a plasma lens

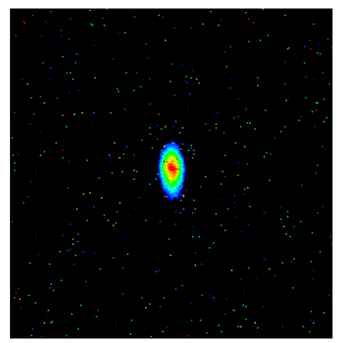




$$F = Z e v_z B_\varphi(r)$$

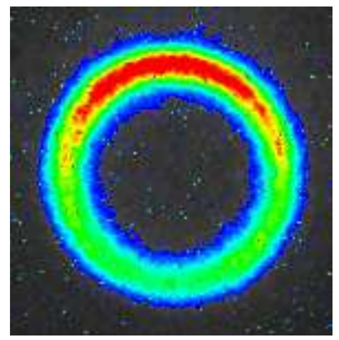
$$B = \frac{\mu_0}{2} j r$$





$d_{min} \sim \varepsilon I^{-1/2}$.

focal beam spots at GSI on SIS

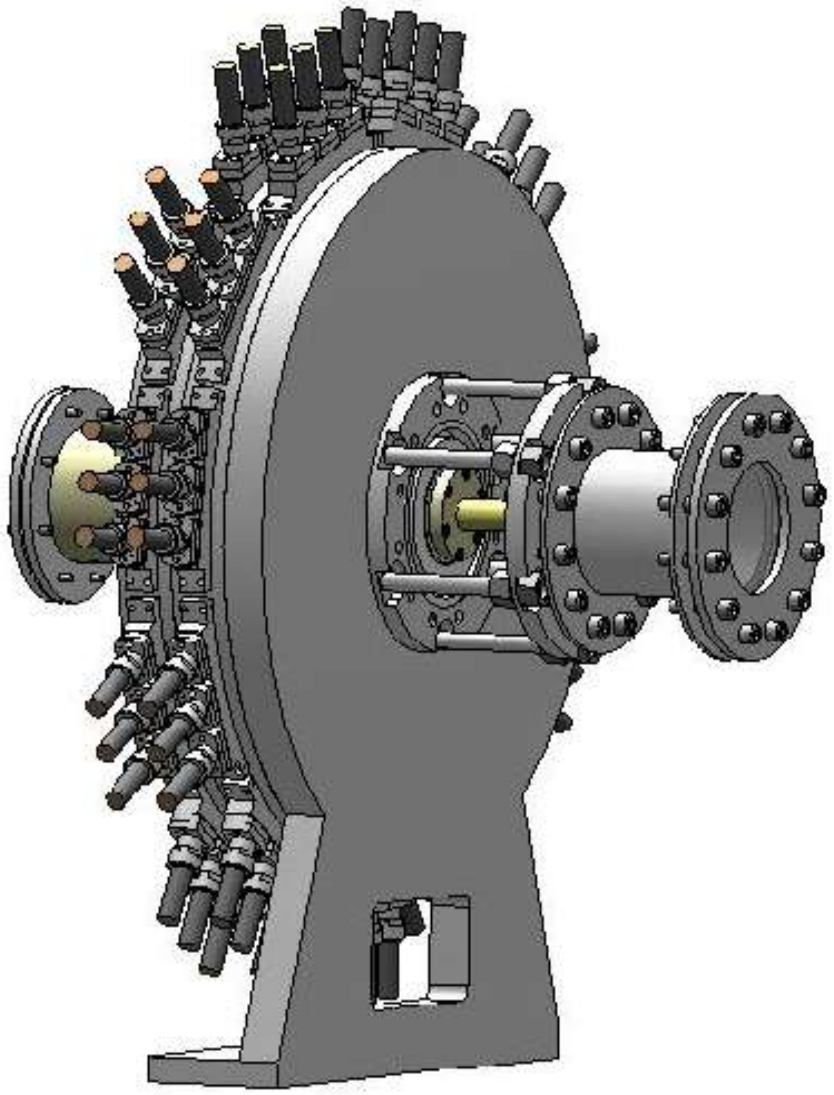


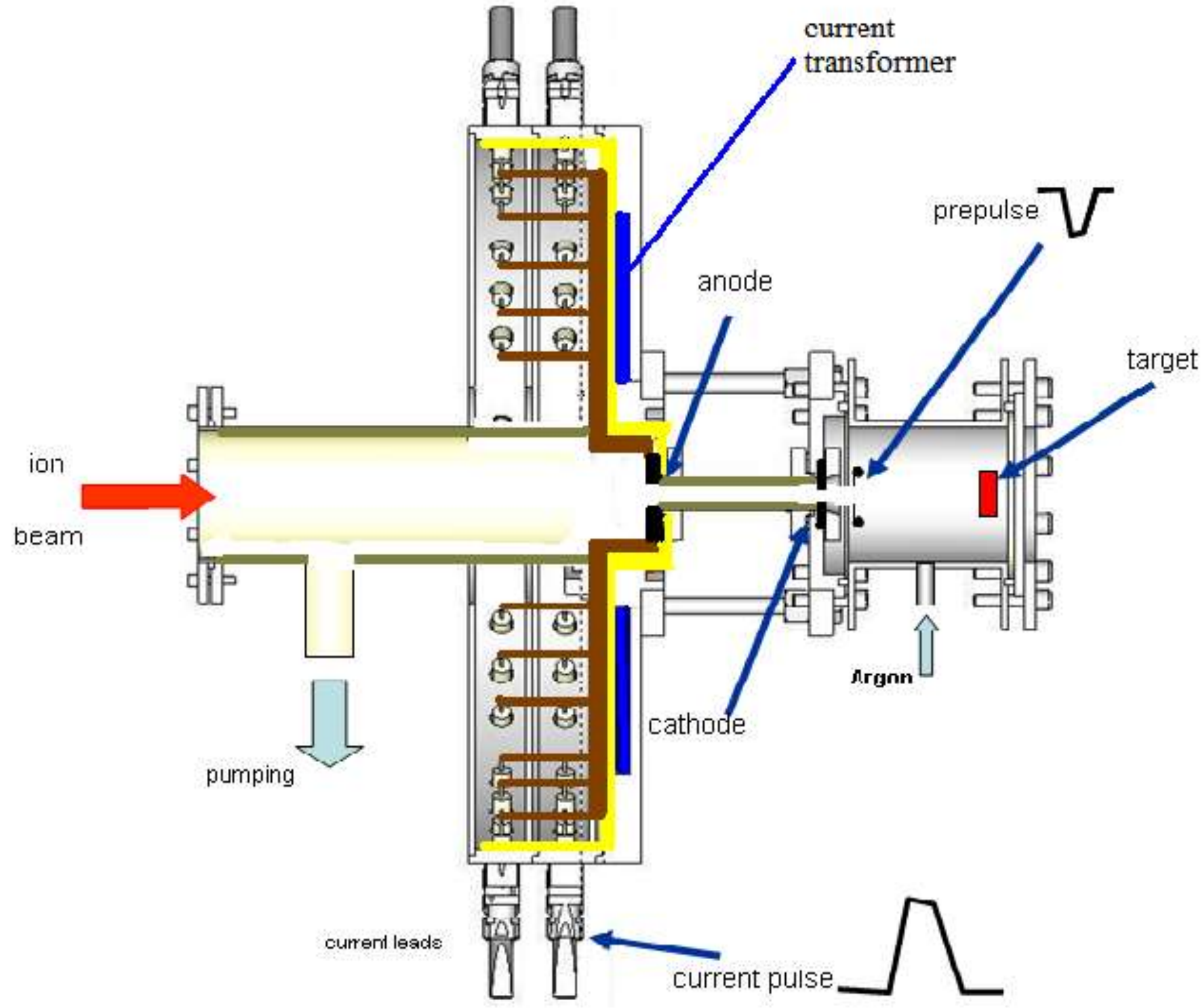
Advantages of plasma lens :

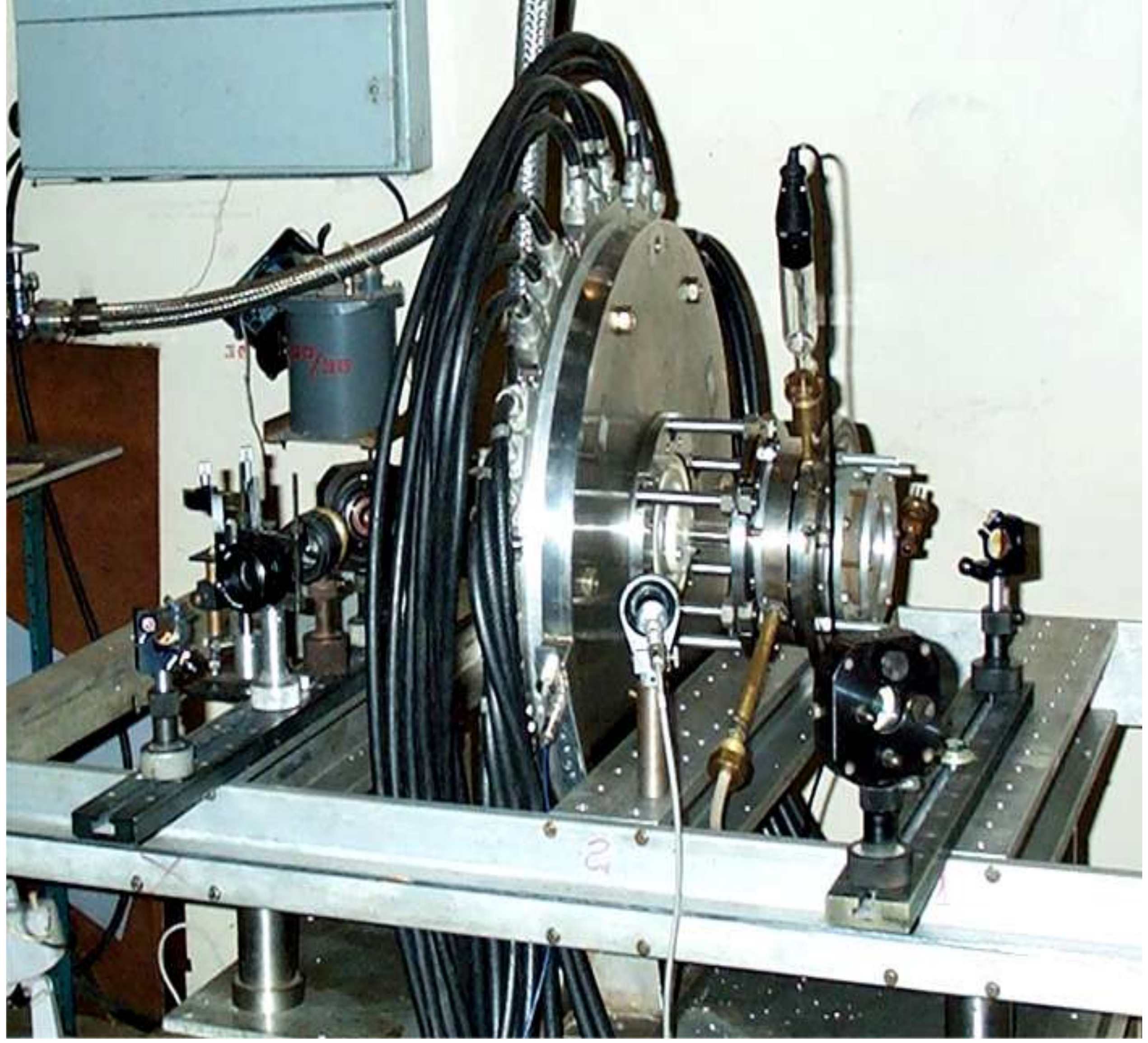
- focusing power is proportional to the magnetic field strength;
- there is no limit for the magnetic field magnitude connected with saturation;
- charge neutralization of ion beam into the plasma lens ;

Scheme of plasma lens

•





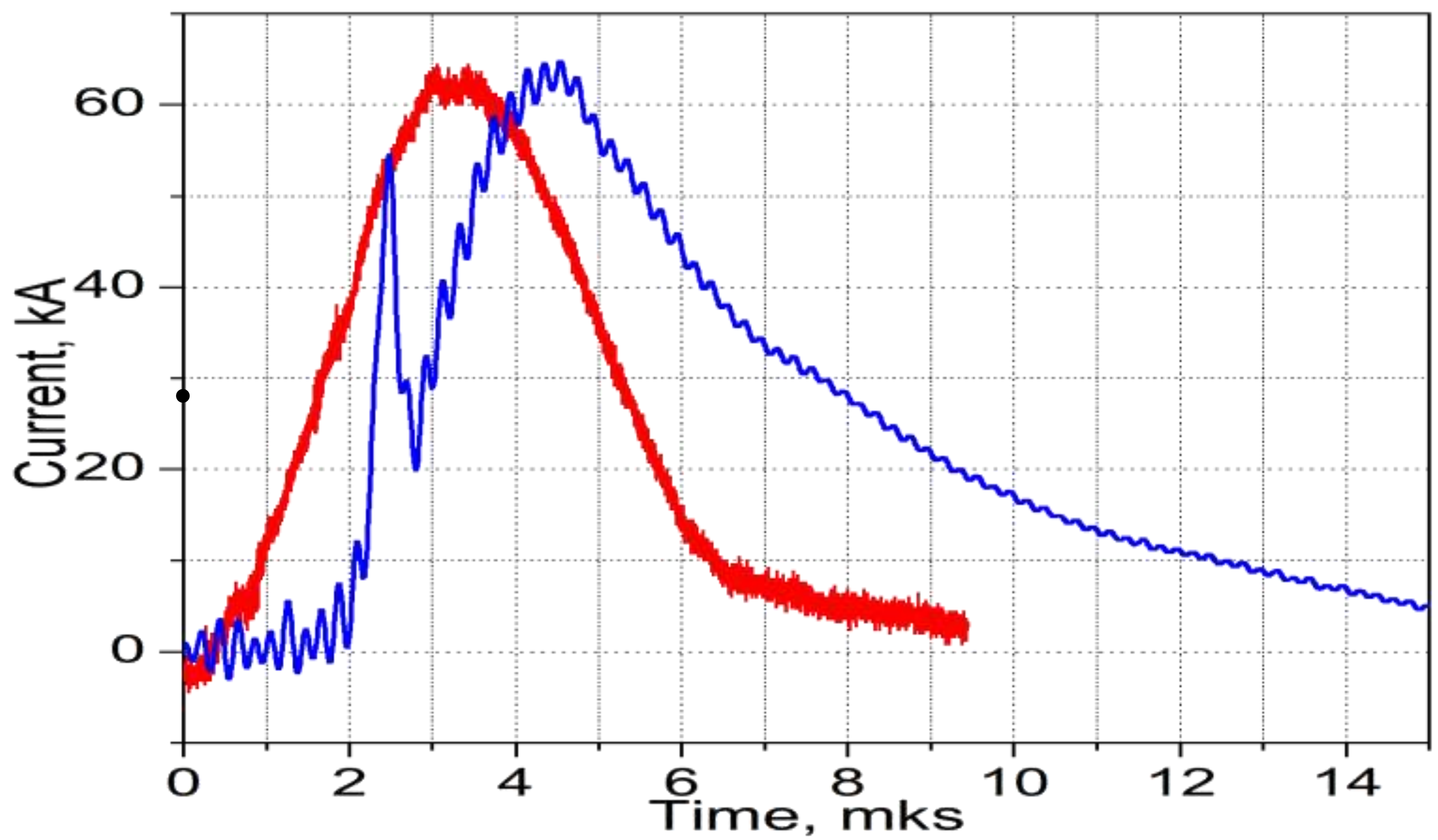


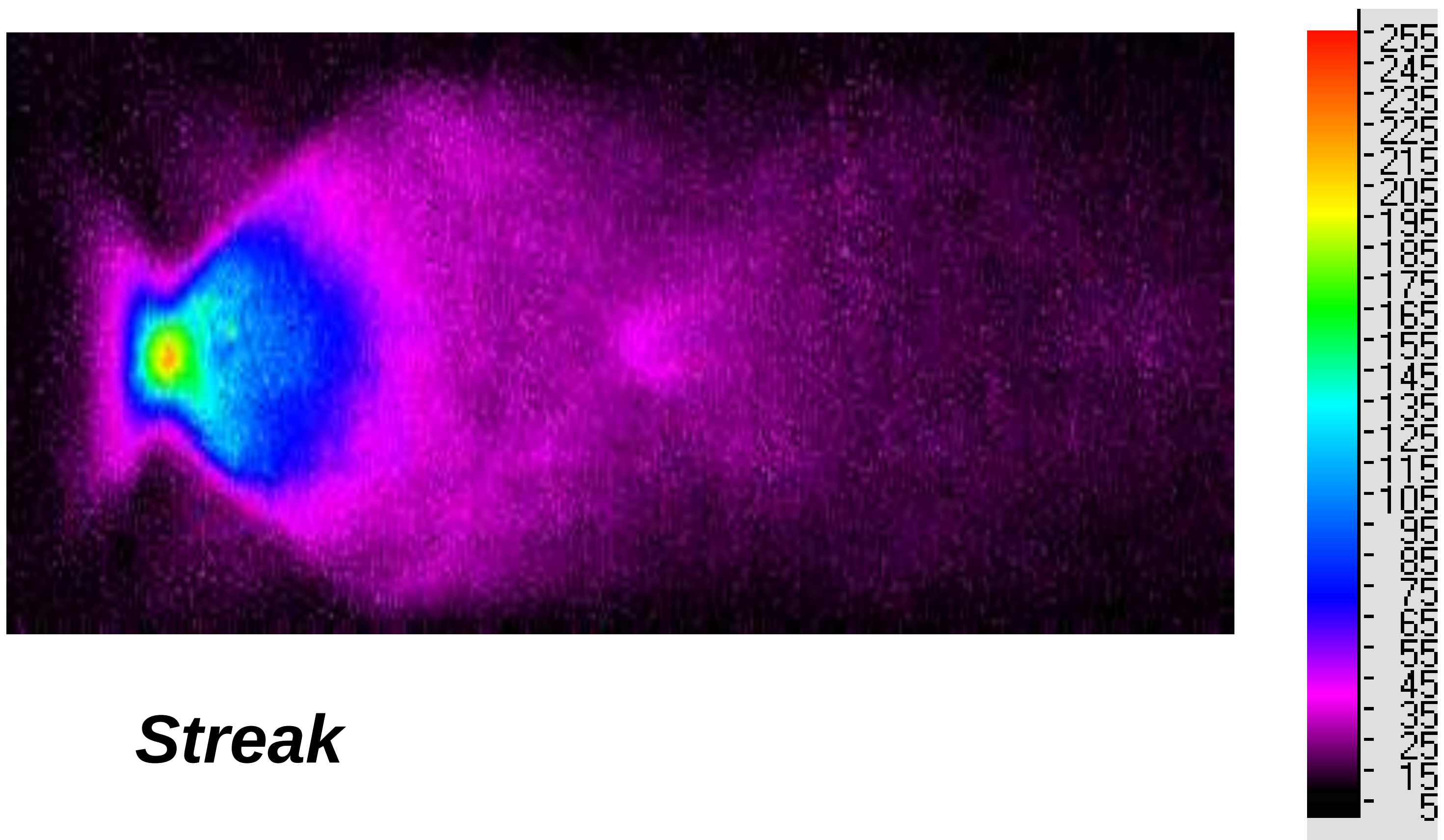
ИТЭФ Москва

Параметры генератора разрядного тока	Емкость C = 25 - 160 мкФ, Напряжение $V_{мах}$ = 20 кВ
Коммутатор (2 шт)	Тиратрон TDI1-150k/25
Размеры керамической разрядной трубки	Длина – 10 см, диаметр 2см
Длительность импульса разрядного тока	T = 5 мкс при C = 25 мкФ, T = 20 мкс при C = 160 мкФ
Максимальный ток плазменного разряда	I = 200 кА при T = 5 мкс, I = 400 кА при T = 200 мкс

The plasma discharge current 120 кA

Discharge





Streak

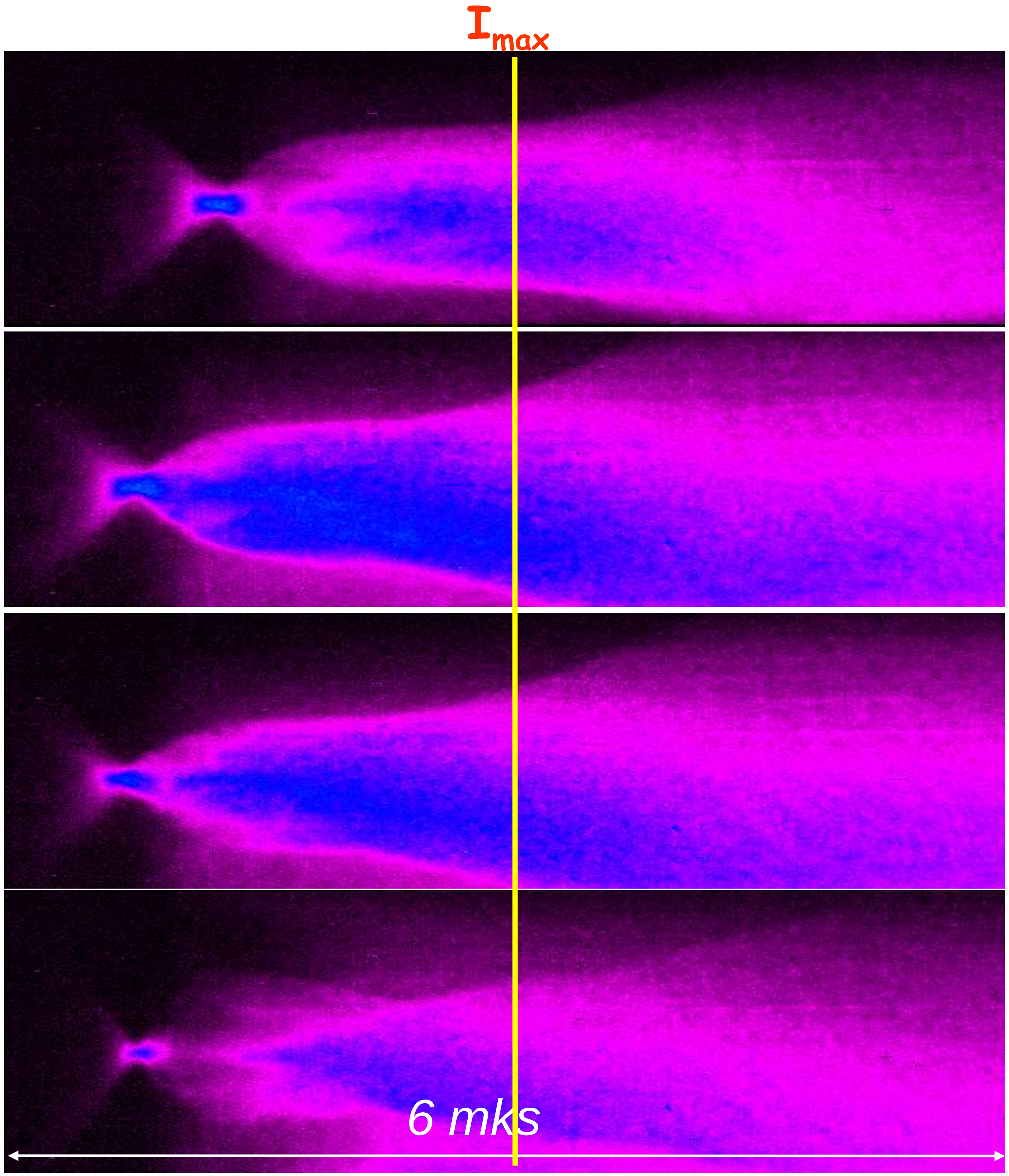
$T \sim 17$ eV (200 000 °K)

$P \sim 400$ bar

$n_e \sim 1\text{-}2 \cdot 10^{19}$ 1/cm3

$Z_i^{max} \sim 7$

Argon Plasma dynamics



Discharge current – 120 кА
Pressure – 3 Torr

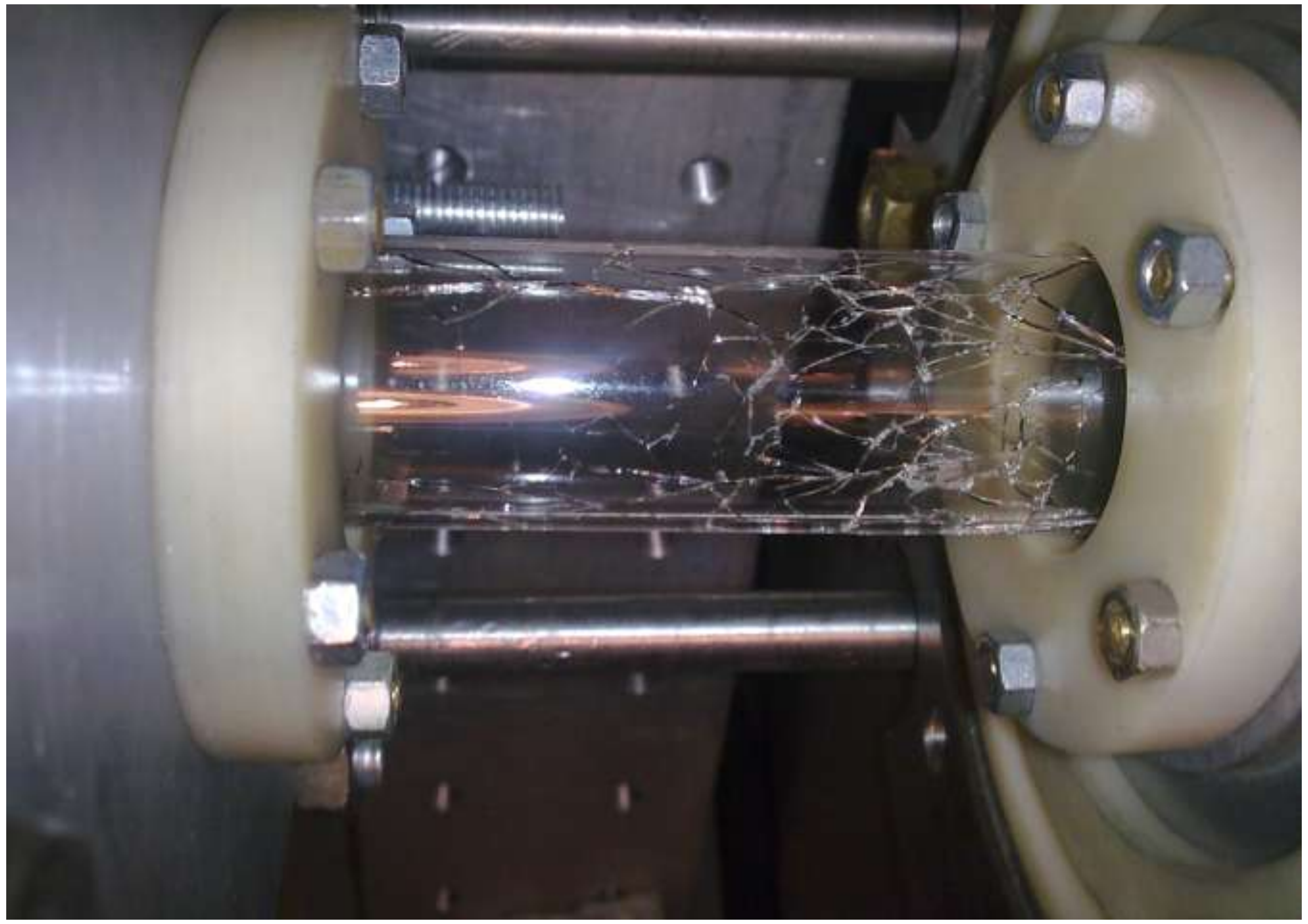
Discharge current – 160 кА
Pressure – 3 Torr

Discharge current – 180 кА
Pressure – 3 Torr

Discharge current – 200 кА
Pressure – 3 Torr

The discharge tubes

•



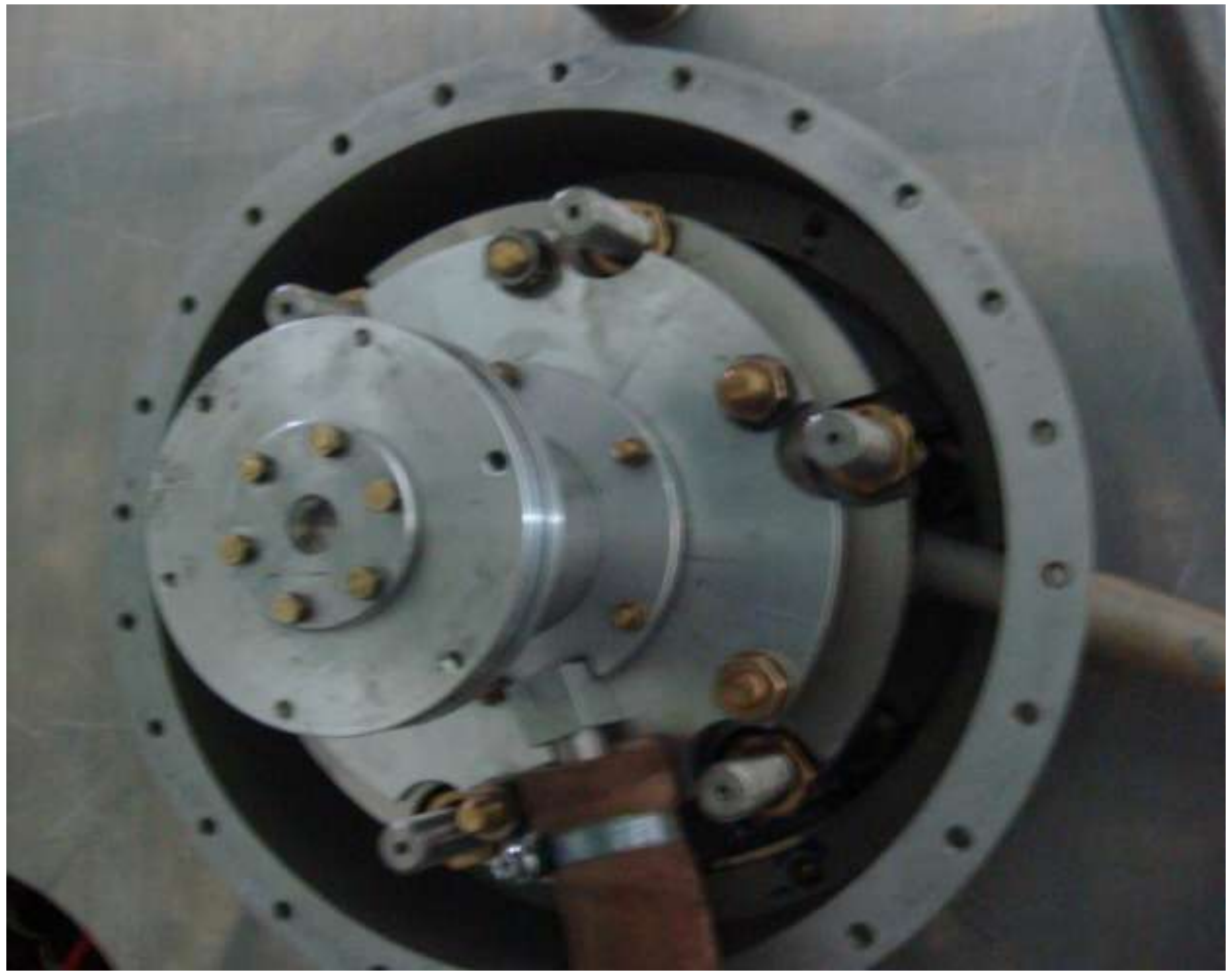
Quartz

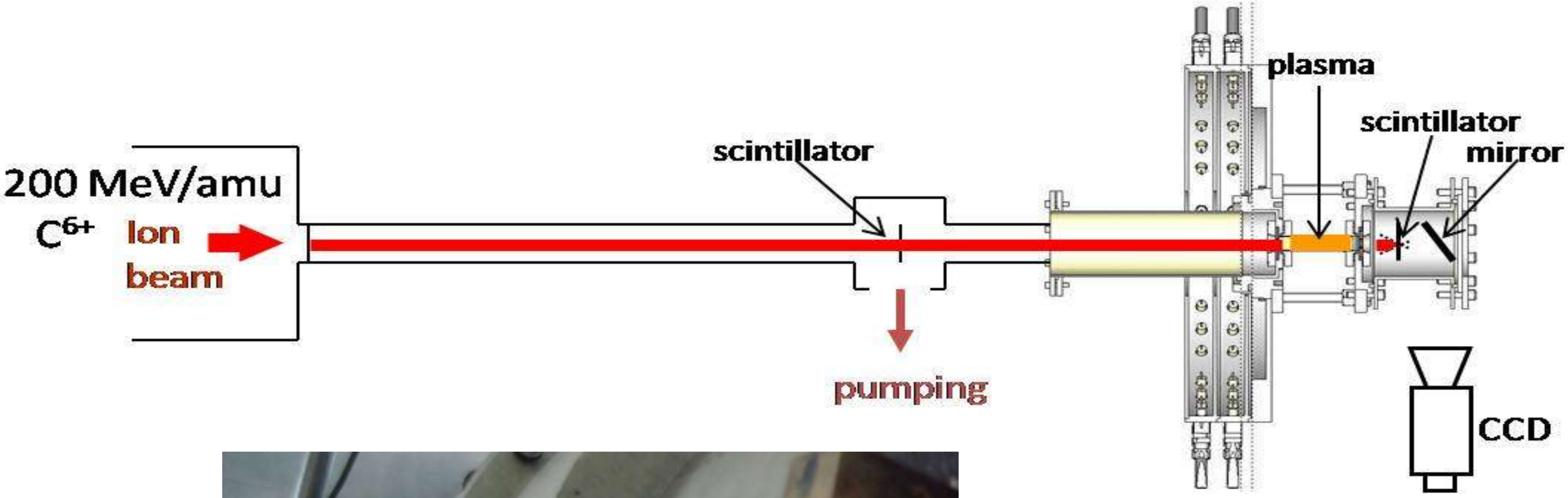
(max current 100 kA)

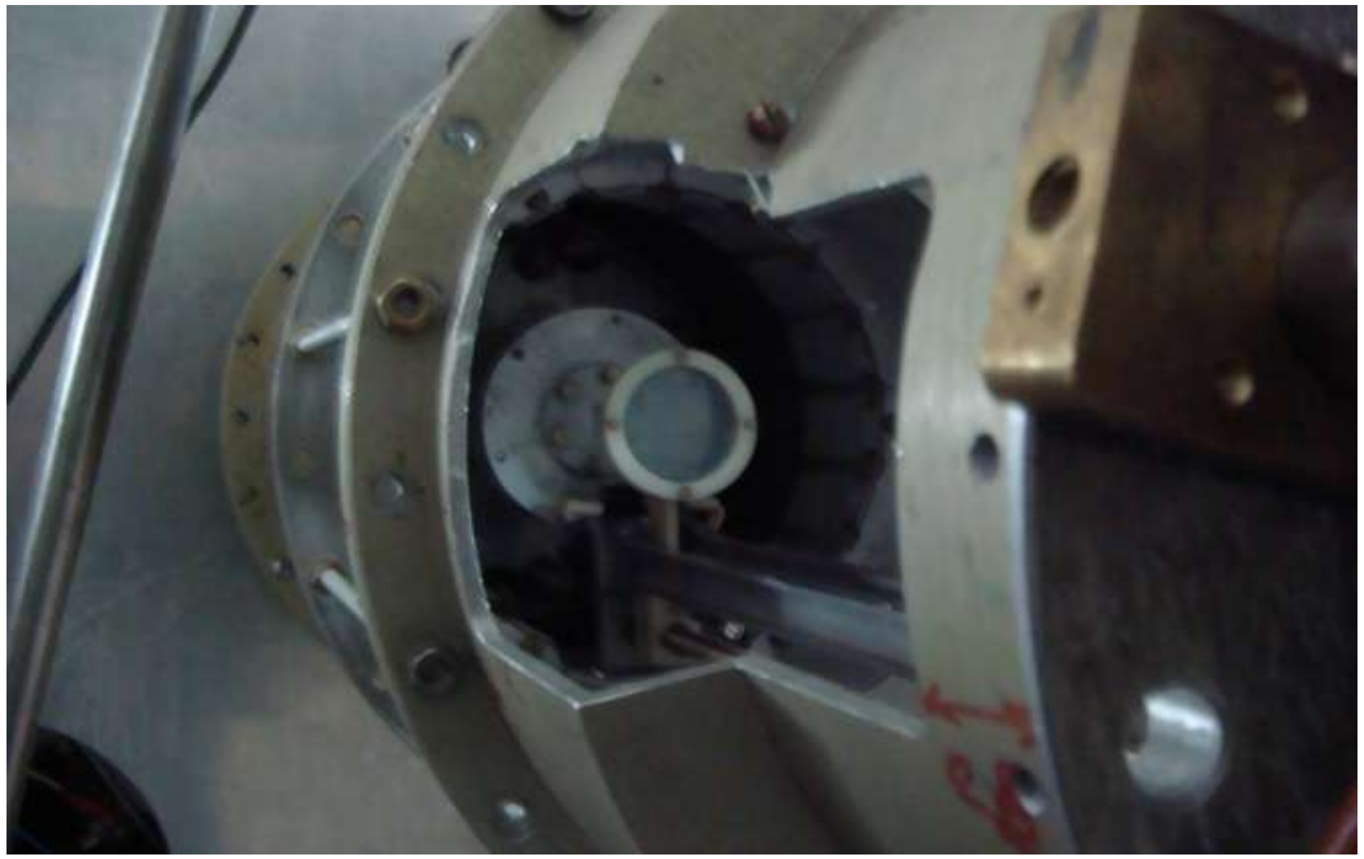
Ceramic

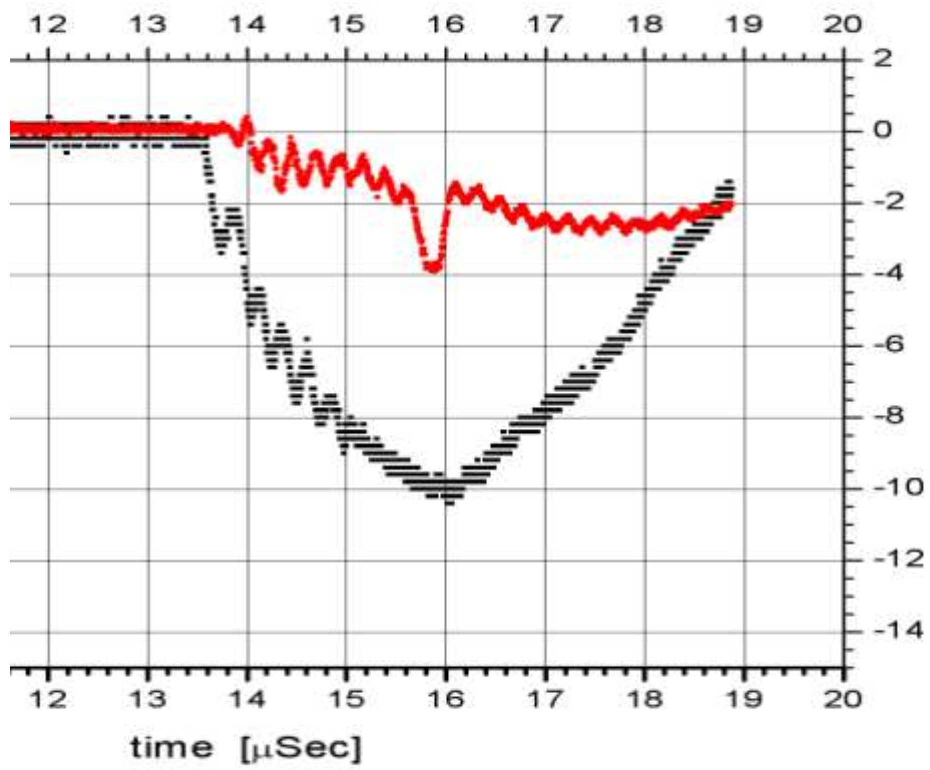
Выходное «окно» плазменной линзы

•

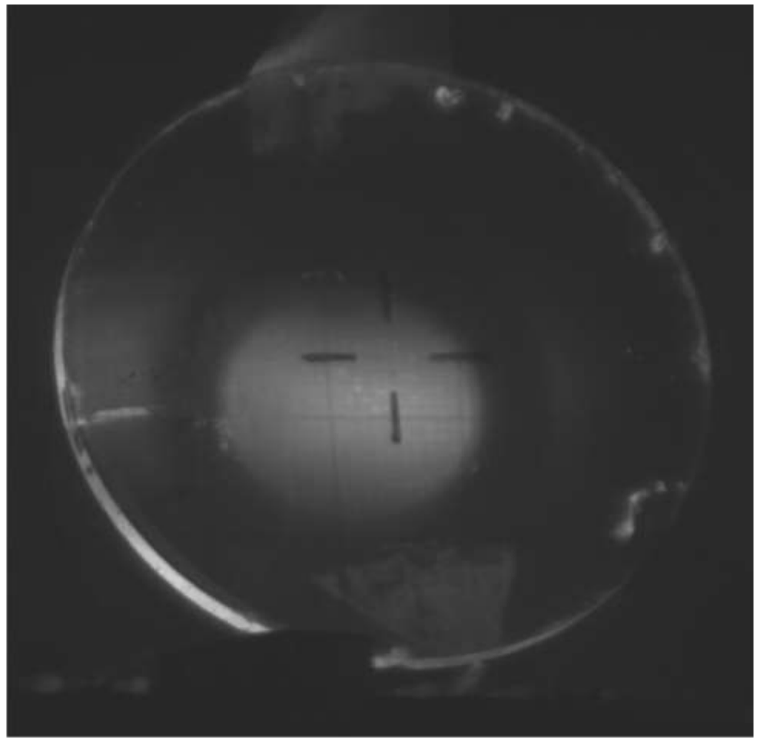


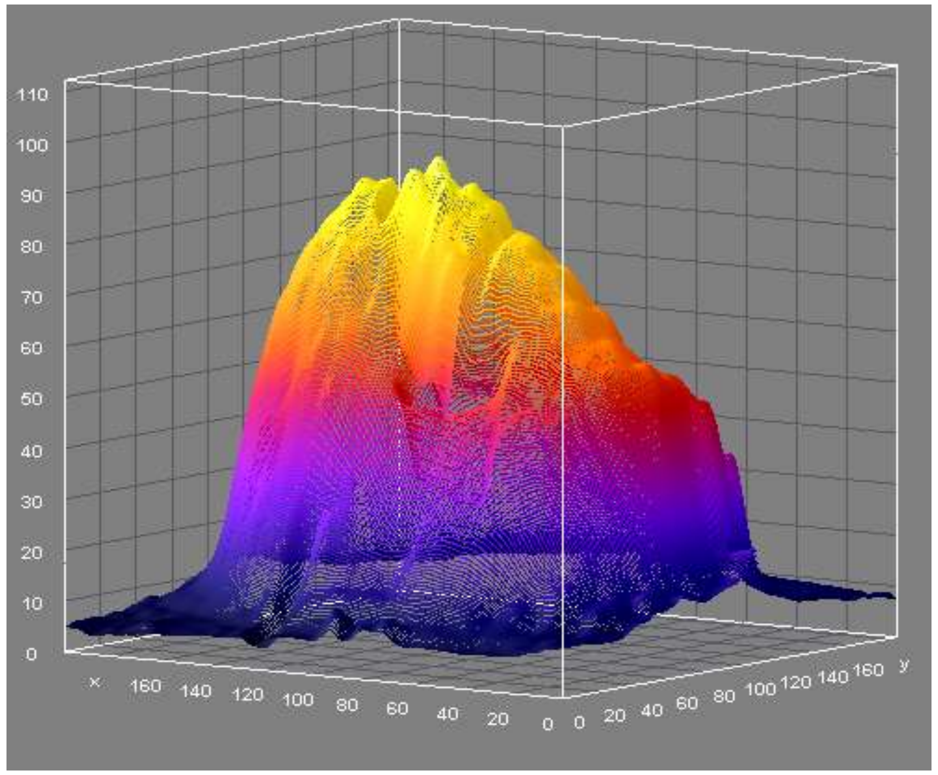

200 MeV/amu
C6+
Ion
beam
scintillator
pumping
plasma
scintillator
mirror
CCD

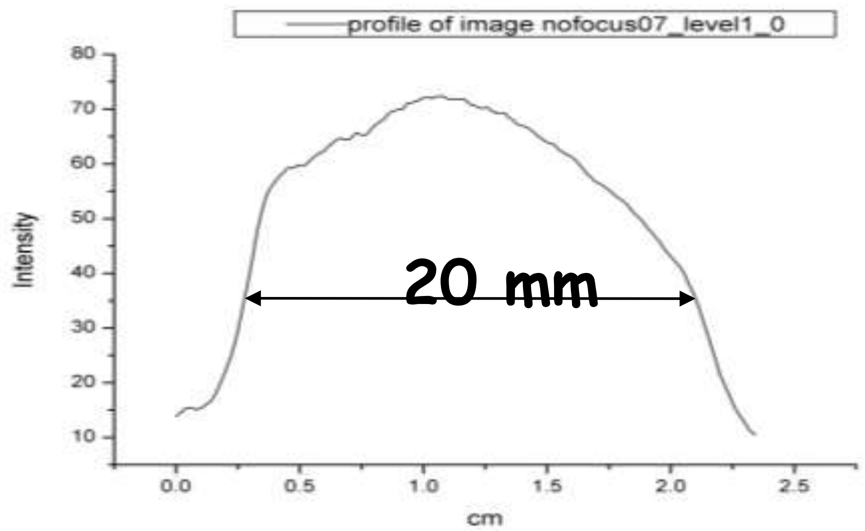


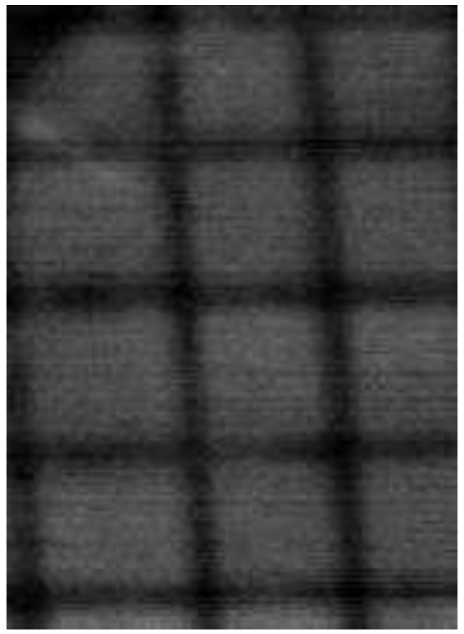

12 13 14 15 16 17 18 19 20
2 0 -2 -4 -6 -8 -10 -12 -14
time [μSec]

Results of focusing C6+ ions

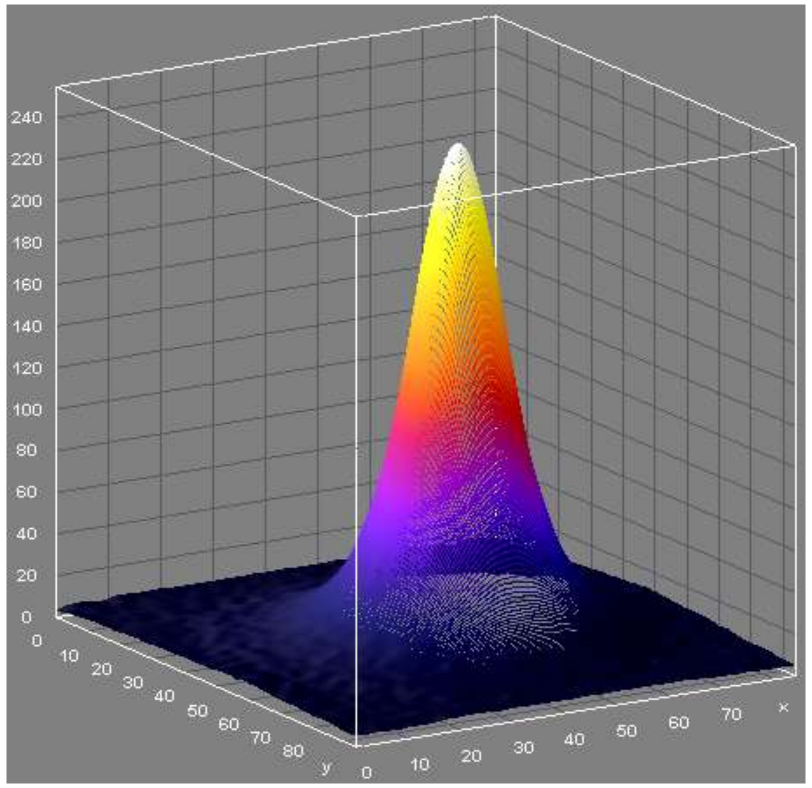


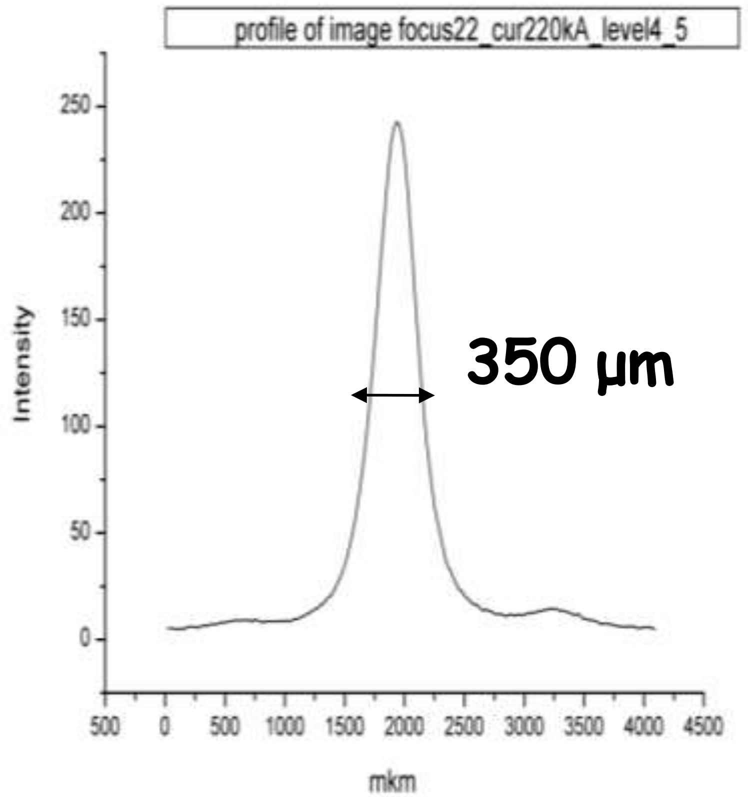






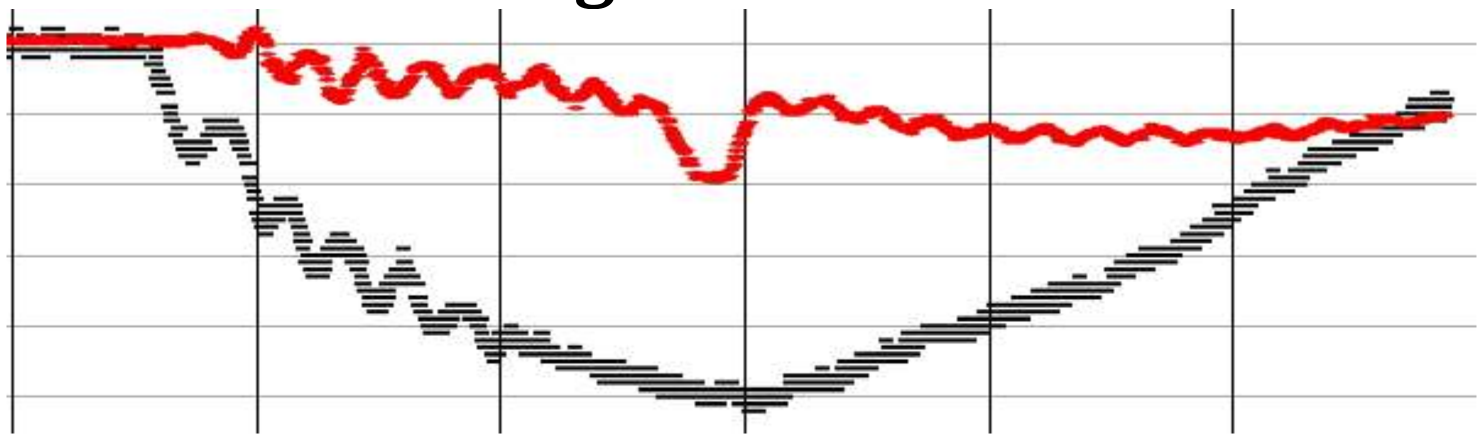
The beam spot photography
(grid spacing –1mm)

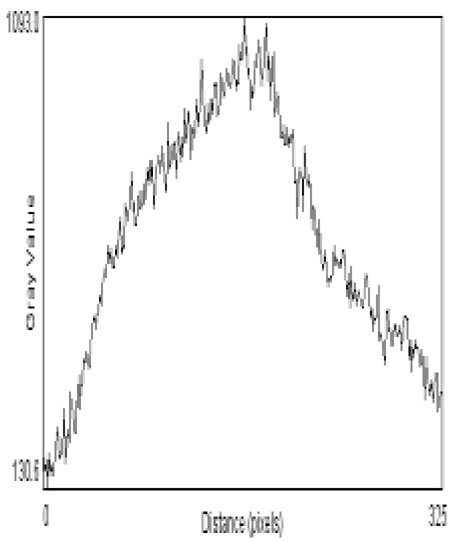


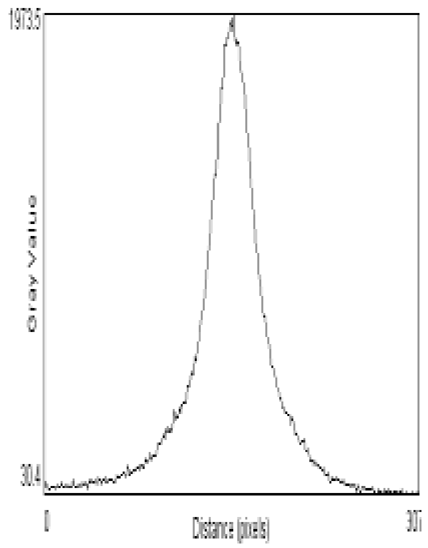


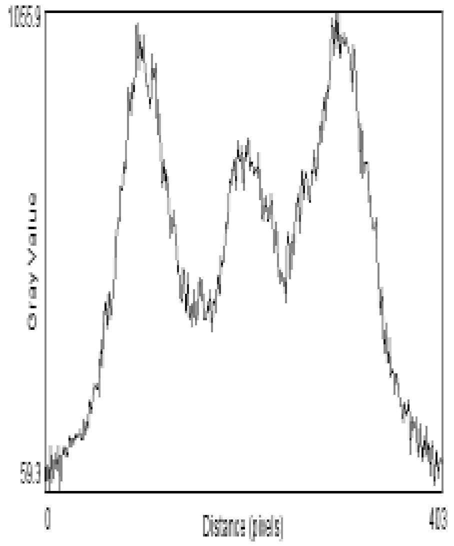
Beam of Fe^{+26} ions for the injection of ions into the lens at the time T after discharge switch

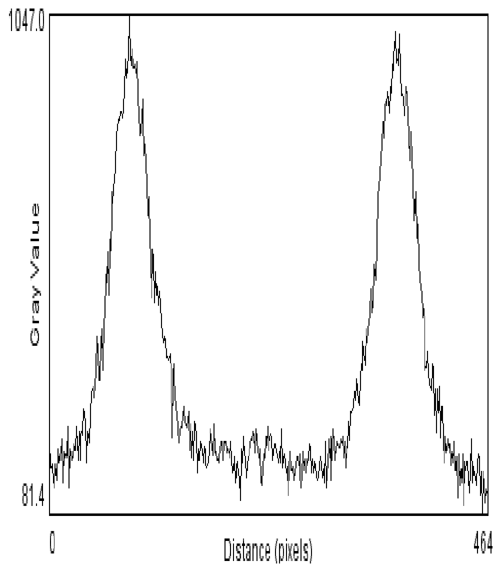
-  

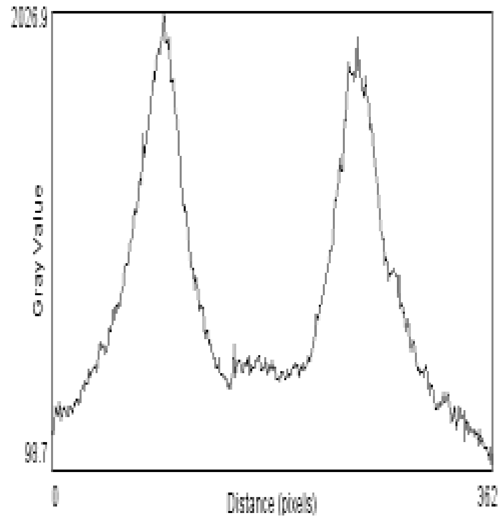




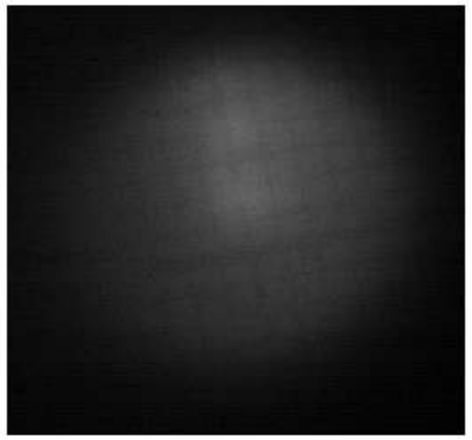
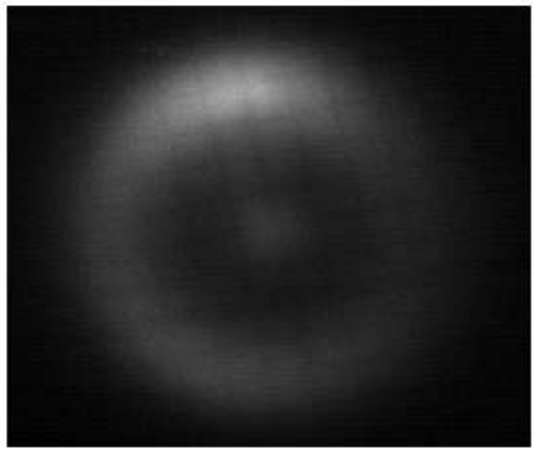
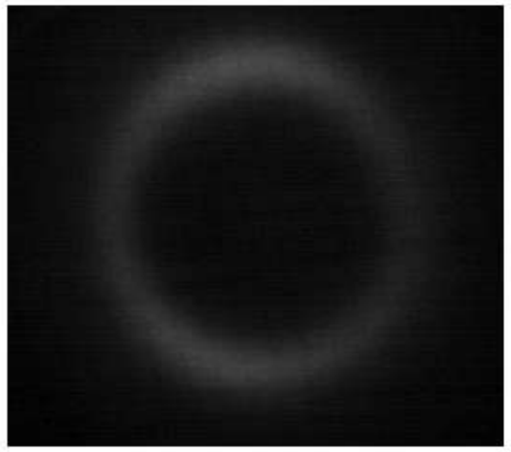
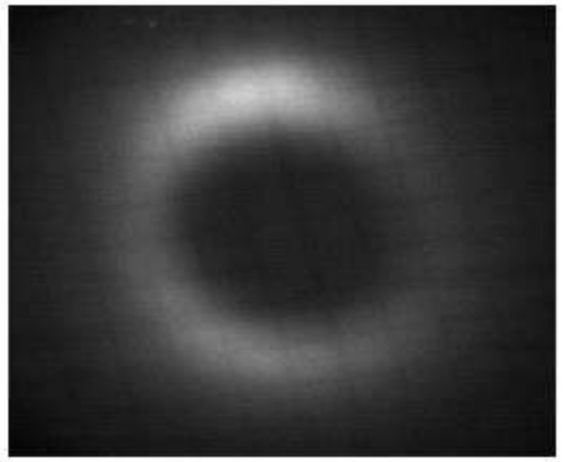








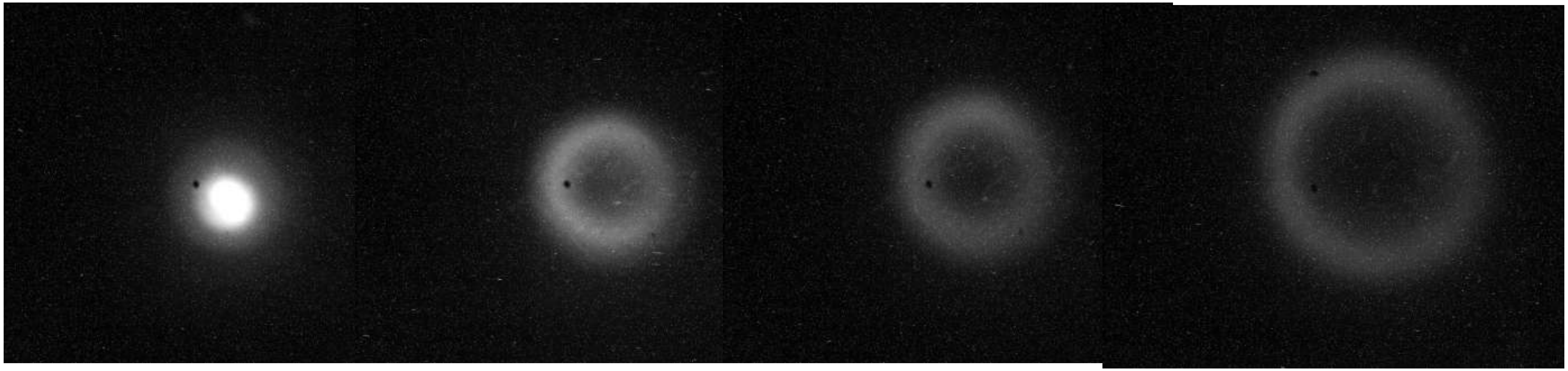
T = 0 μs | *T = 0.5 μs* | *T = 1.5 μs* | *T = 1.7 μs* | *T = 2.3 μs*

Shaping ion beam into hollow cylindrical form

Radius ringlike light output from a scintillator

4 mm **8 mm** **10 mm** **15 mm**



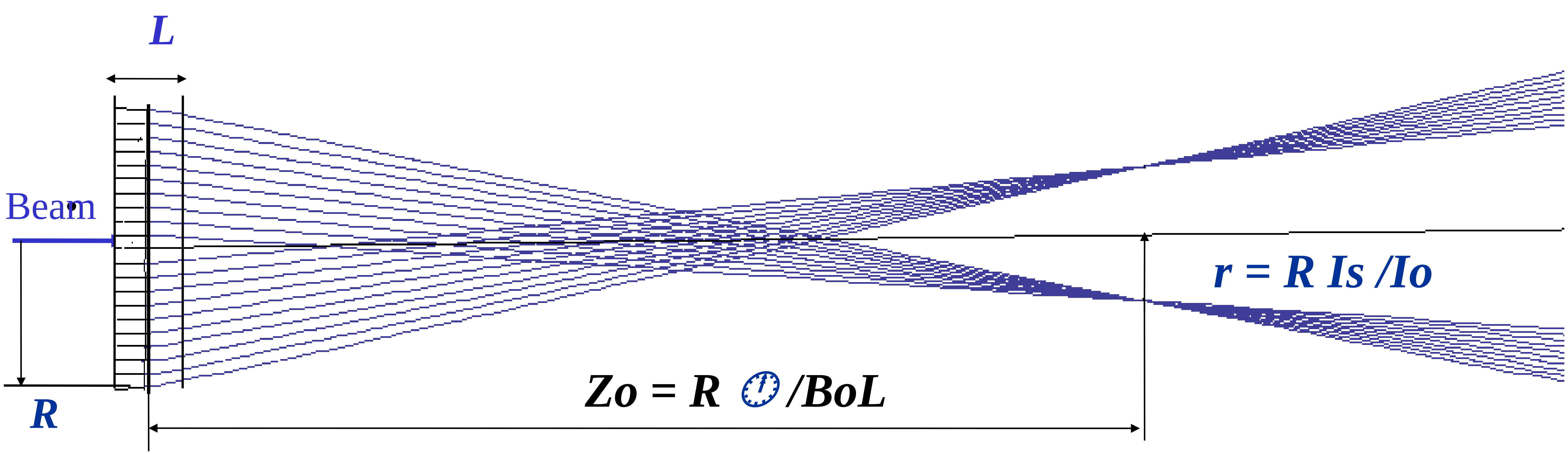
0.2 m **0.3 m** **0.35 m** **0.45 m**

Distance from the end of the discharge tube

The plasma lens parameters:

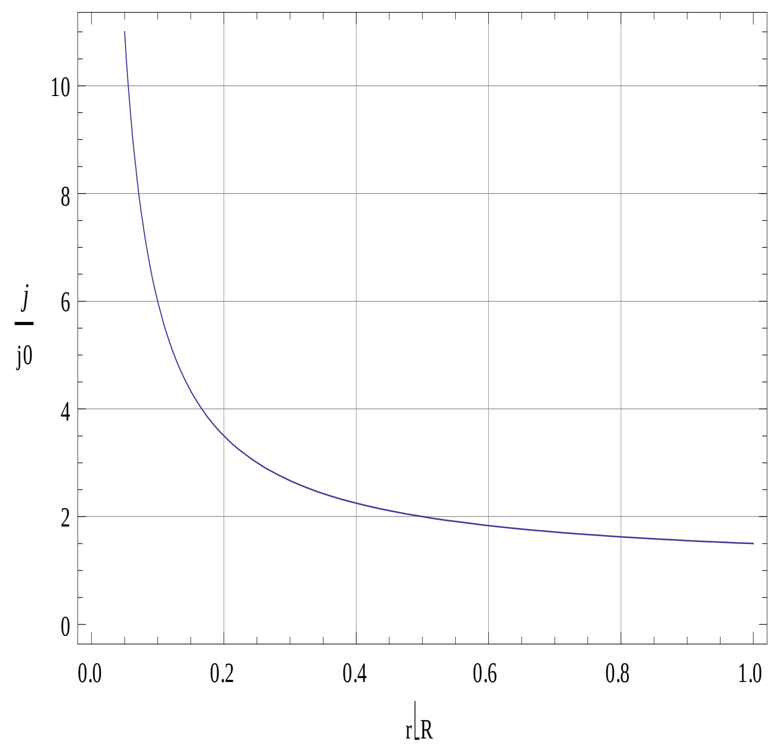
maximum current - 130 kA, argon pressure - 6.8 mbar

Forming ideal hollow beams (thin lens)

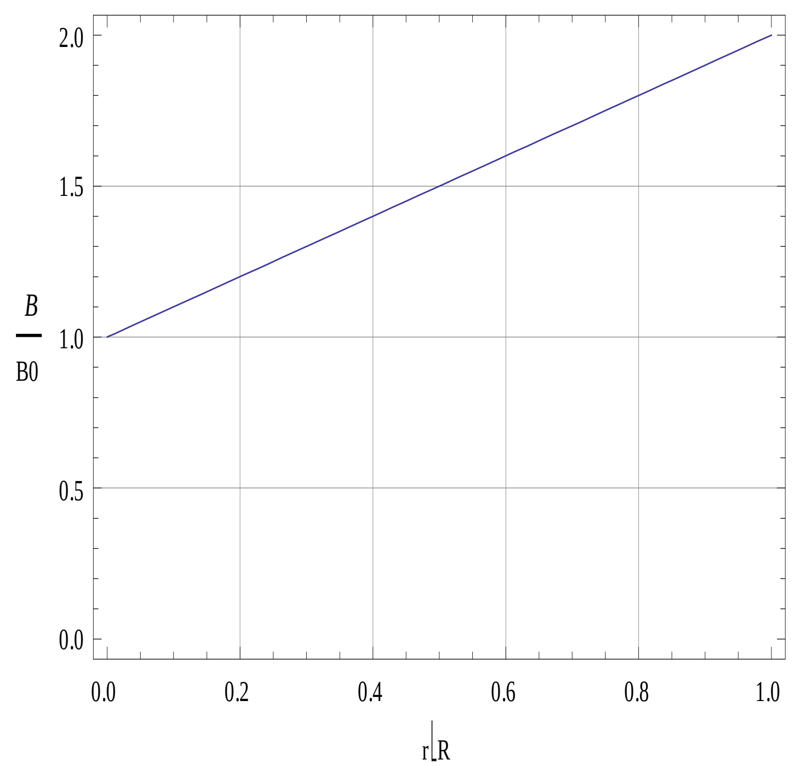


🕐 –the beam rigidity, ***Bo*** –field strength due to uniform discharge current Io of radius ***R***.

The paraxial beam is converted to a ring, if the distribution of the discharge current density is a superposition of the homogeneous and the singular distribution



j = Io/πR2 + Is /2πRr

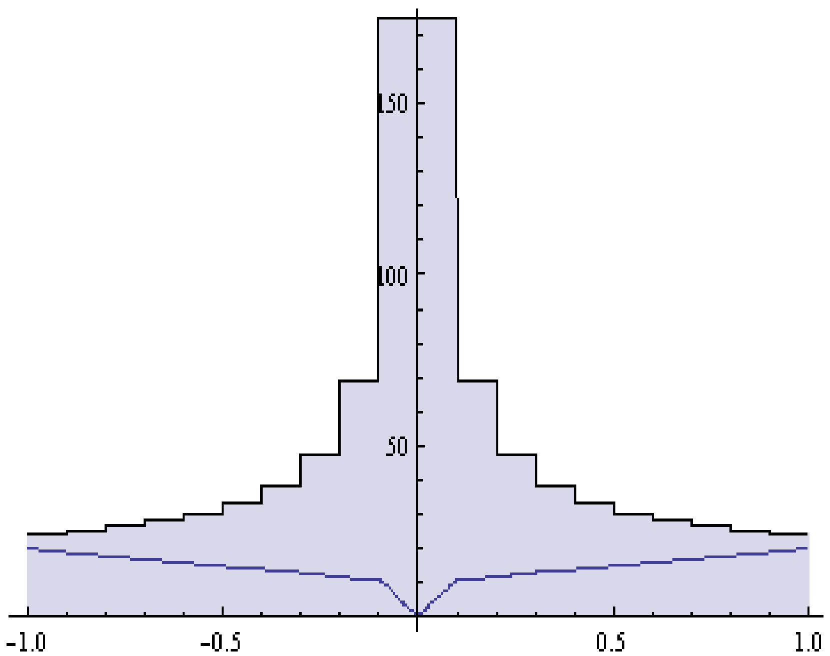


B = Bo (r/R + Is /Io).

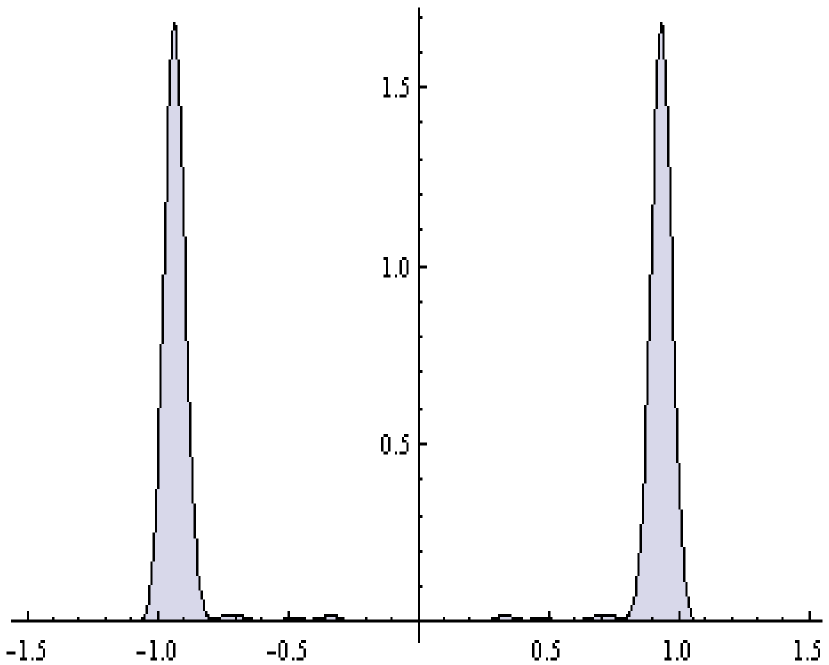
Distribution of ion density

Upon receipt of a hollow beam, satisfying the practical requirements, which admit the nonzero thickness of the annular layer and the nonzero density of particles inside the cavity, the distribution of the discharge current should not be so extreme.

Distribution of ion density for $Z_0 = 42$ см $Is / Io = 1$ and $Is + Io = 120$ kA

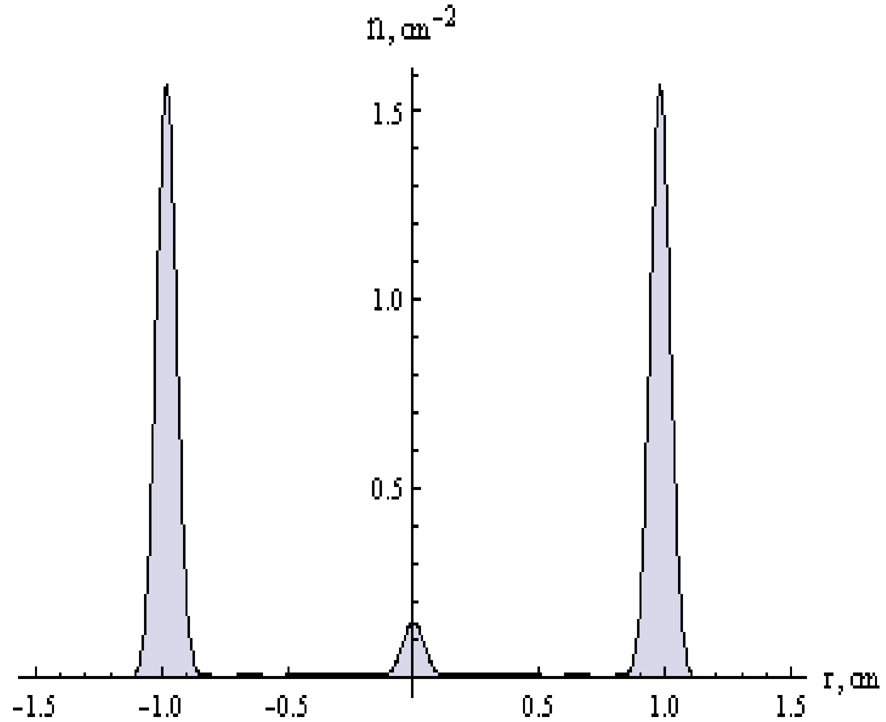


The discrete distribution for discharge current



E = 0

The discrete distribution for discharge current

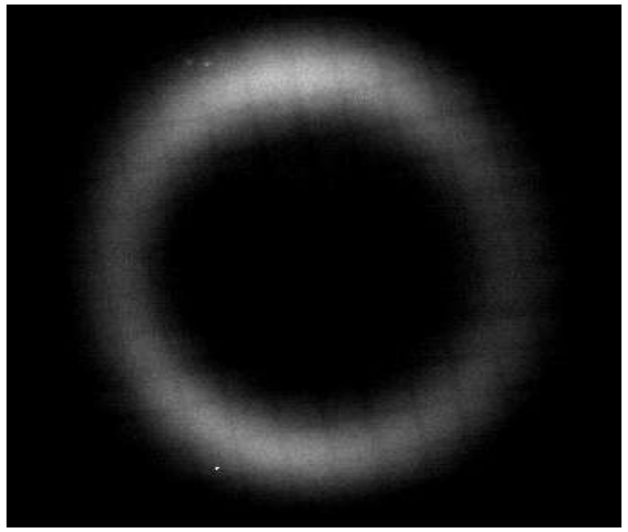


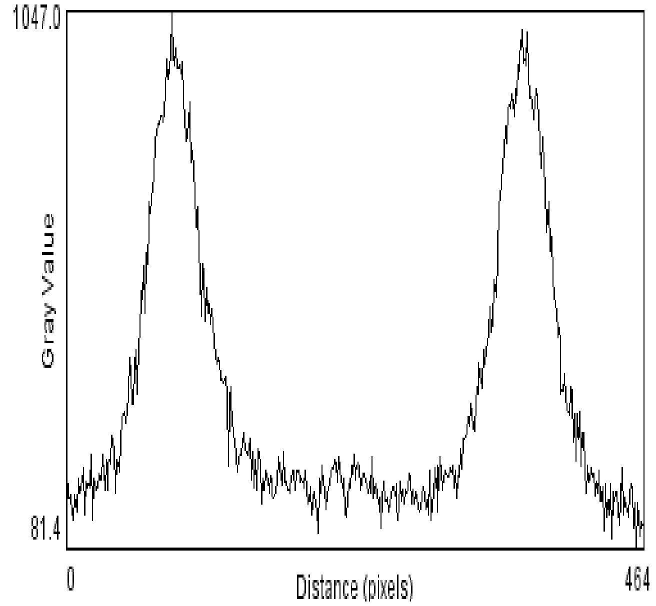
E=10 mm mrad

The analytic distribution for discharge current

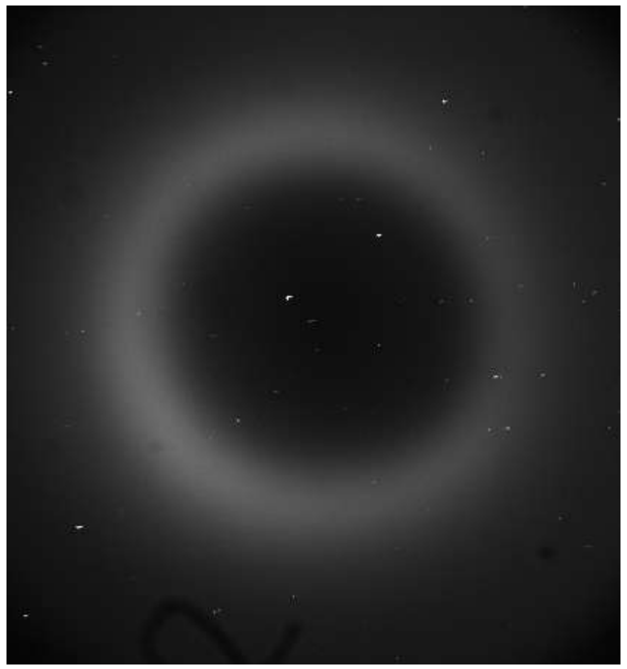
The real size of phase volume of a focused beam eliminates the effect of differences between the actual current distribution in the plasma lens from the model of an ideal thin lens.

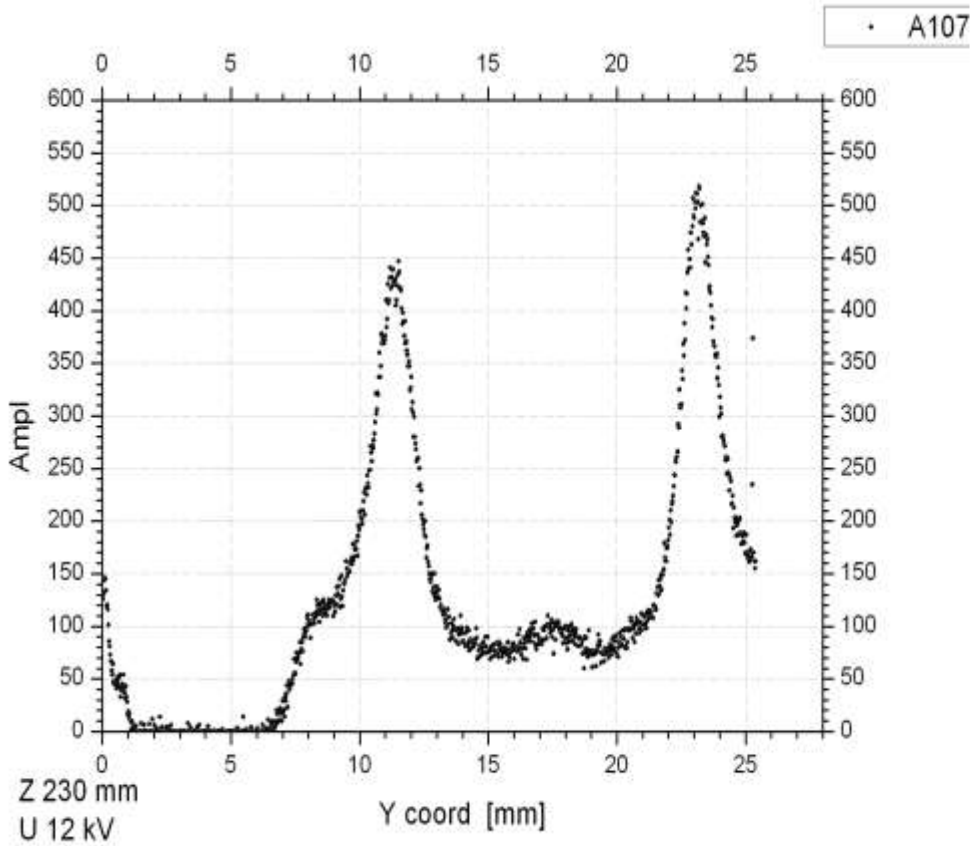
The light output from a scintillator





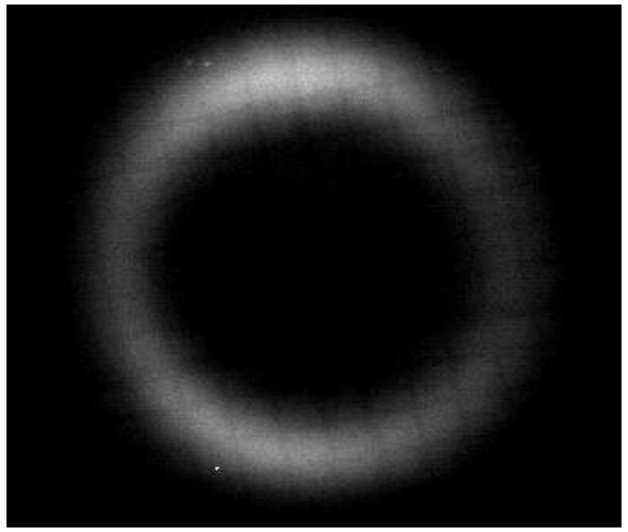
The distribution of ion Fe^{+26} in time 1.7 μs behind discharge switch for distances 30 см and discharge current 150 кA. The ring diameter - 9 мм .

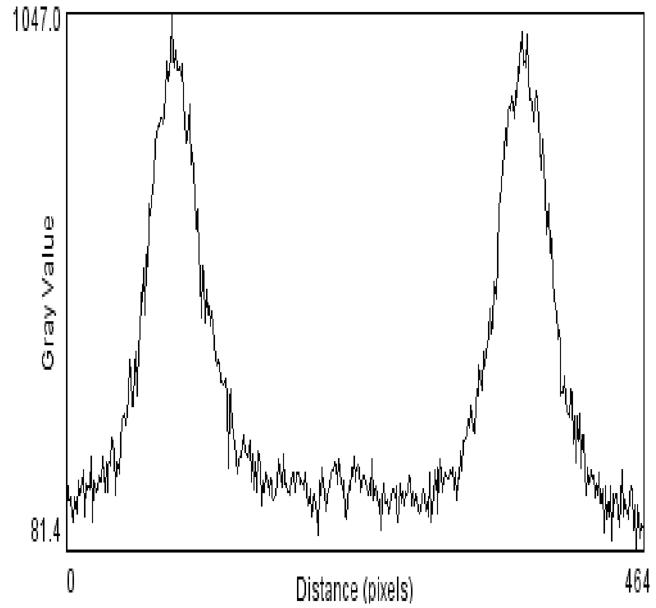




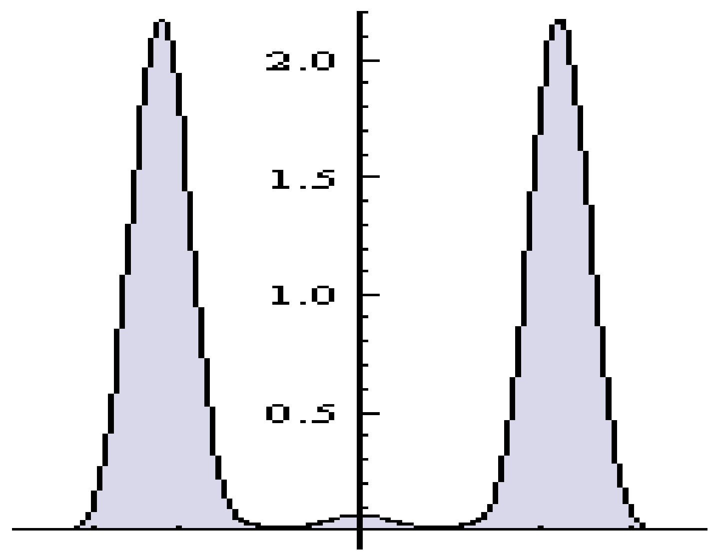
The distribution of ion C^{+6} for distances 23 см and discharge current 150 кA. The ring diameter - 11 мм.

The light output from a scintillator





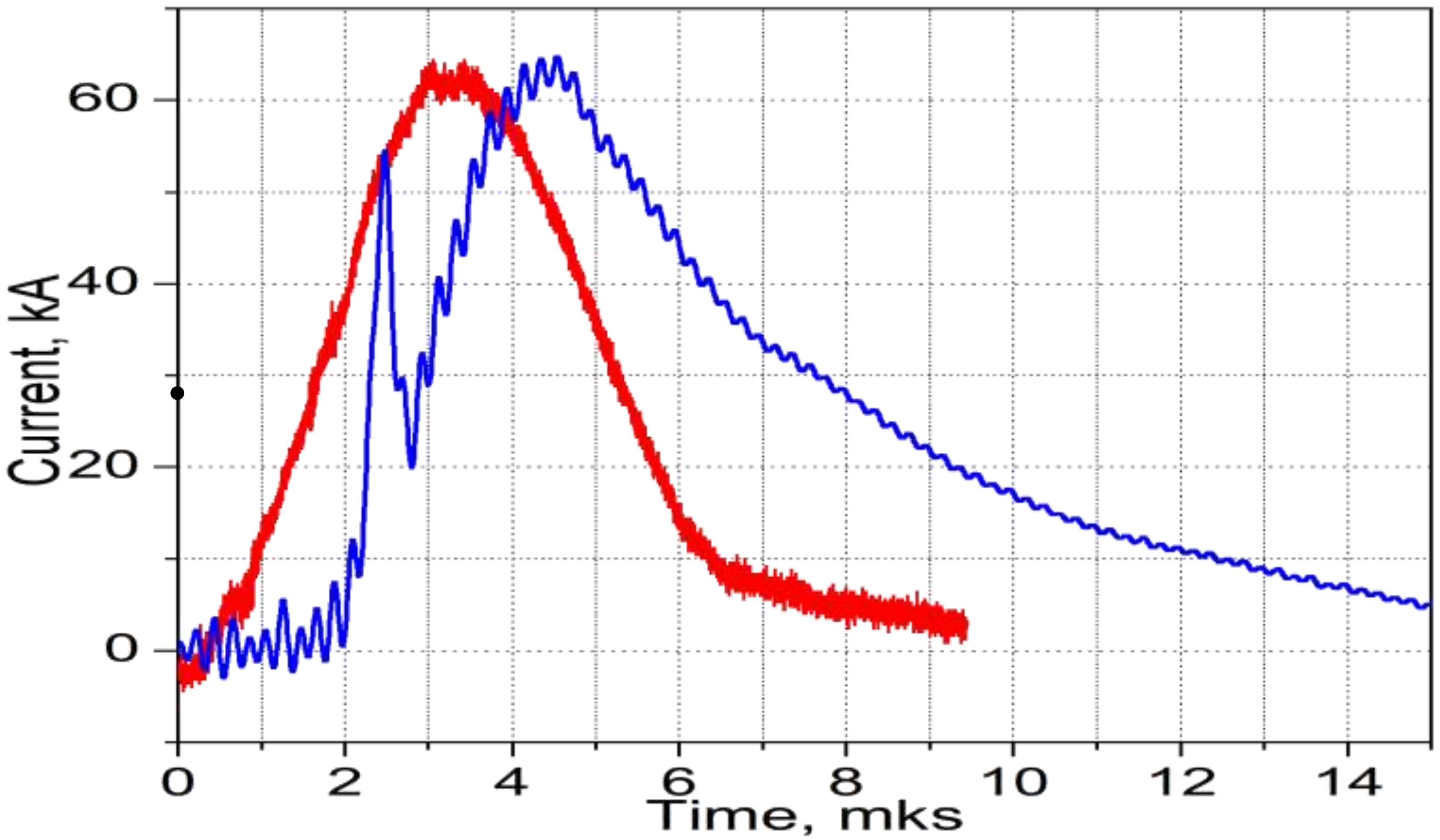
The distribution of ion Fe^{+26} in time 1.7 μs behind discharge switch for distances 30 см and discharge current 150 кА. The ring diameter - 9 мм .



The light output from a scintillator and the distribution of ion Fe+26 density calculated in the model approximation for the experimental condition.

The plasma discharge current 120 кА

Discharge

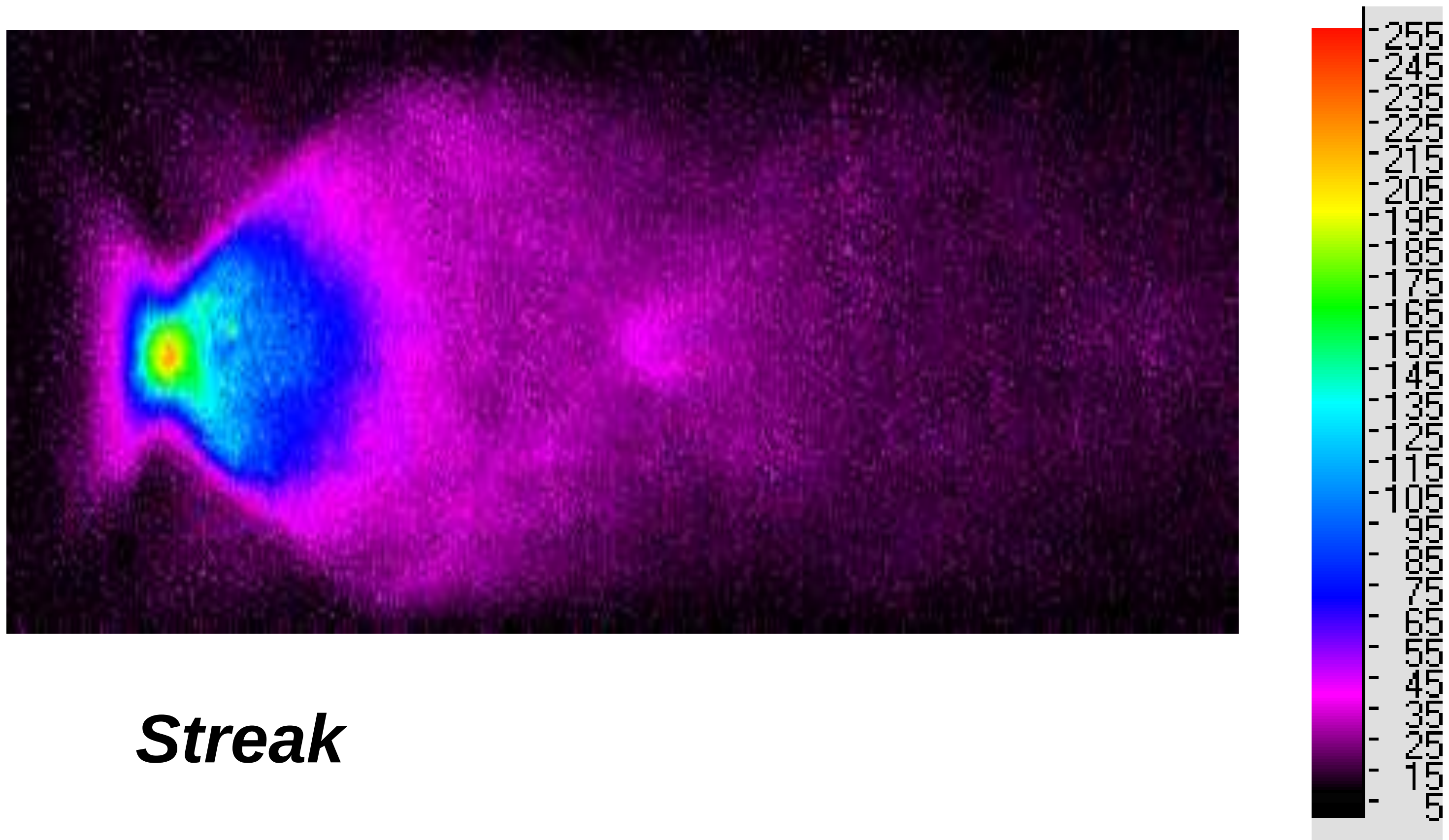


$T \sim 17$ eV (200 000 °K)

$P \sim 400$ bar

$n_e \sim 1\text{-}2 \cdot 10^{19}$ 1/cm3

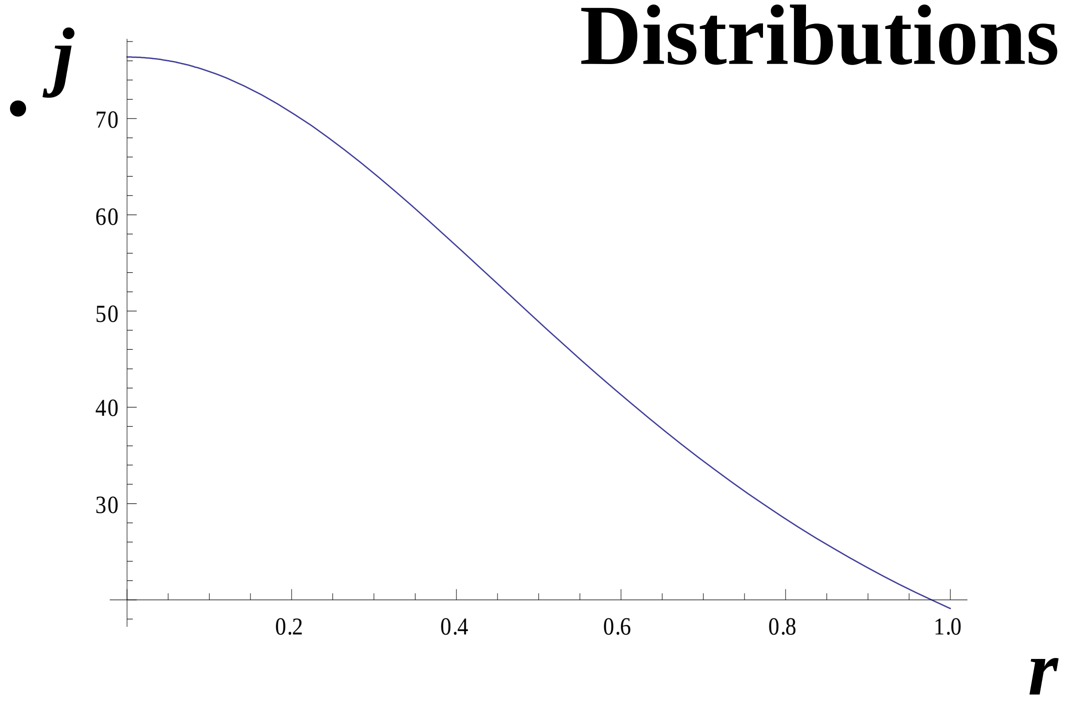
$Z_i^{max} \sim 7$



Streak

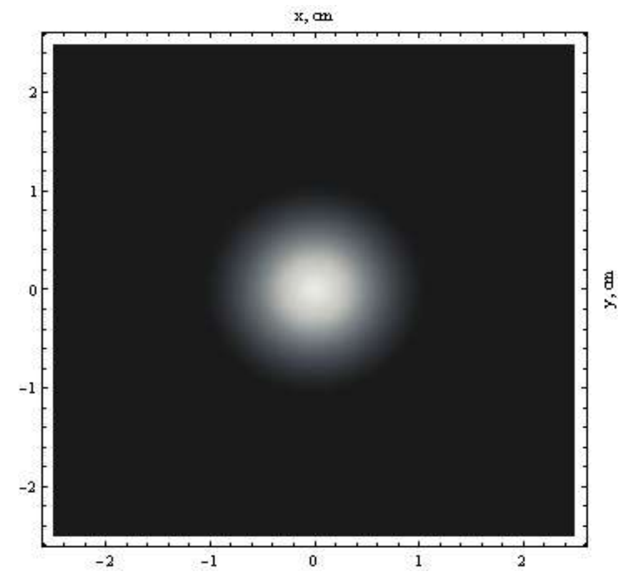
FORMATION OF THE HOMOGENEOUS BEAM

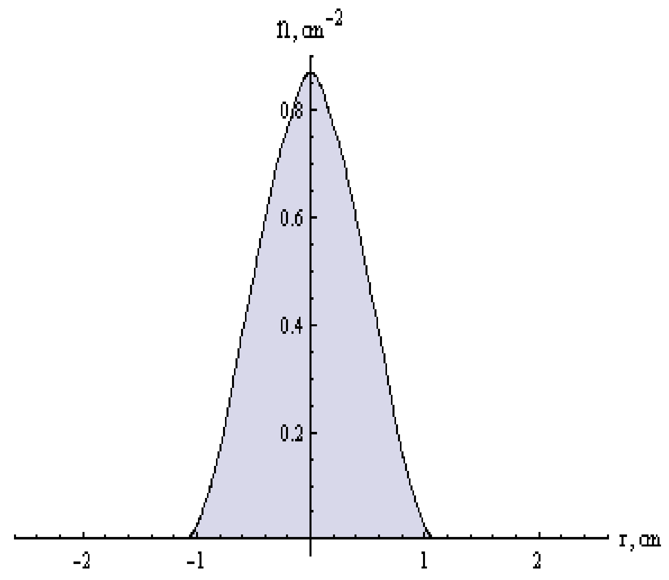
Distributions of density of ions in a beam of C+6 (200 MeV/n)



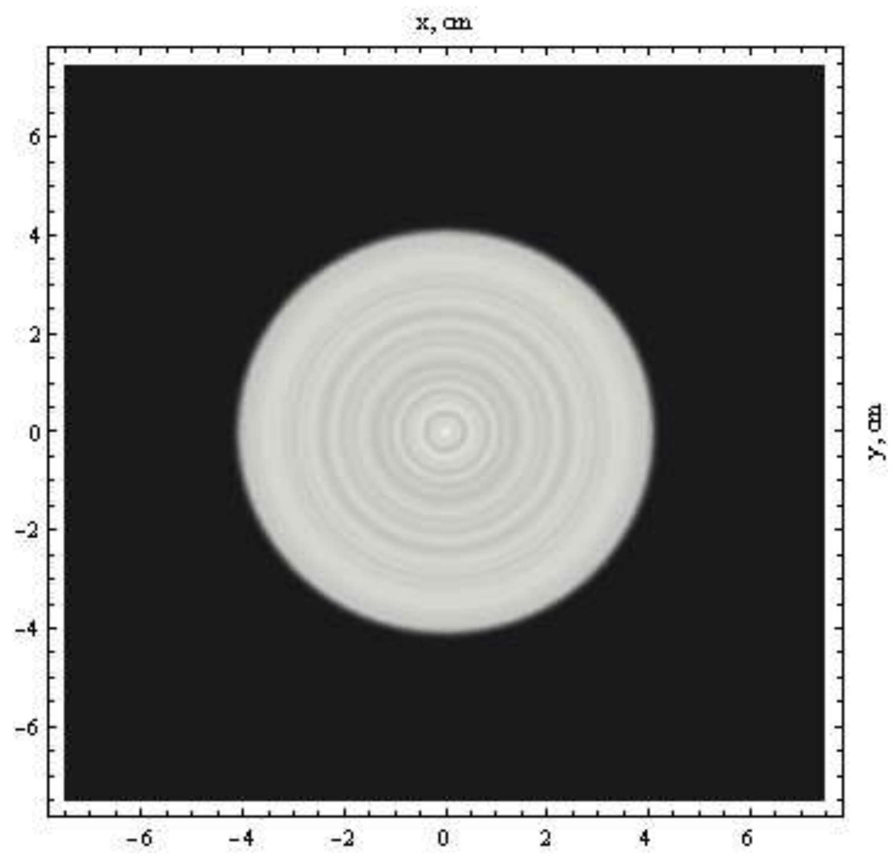
Equilibrium Bennet's distribution

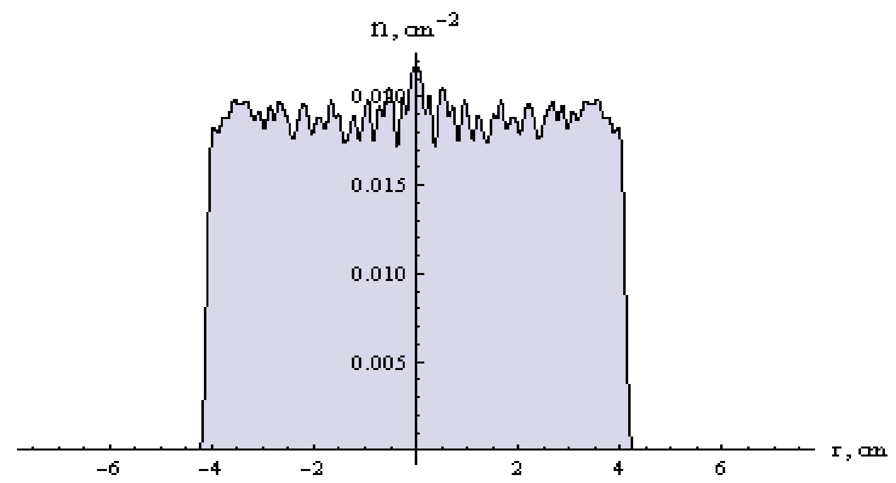
$$j = Io / \pi R^2 (1 + (r/R)^2)^2$$





The initial Gaussian distribution.

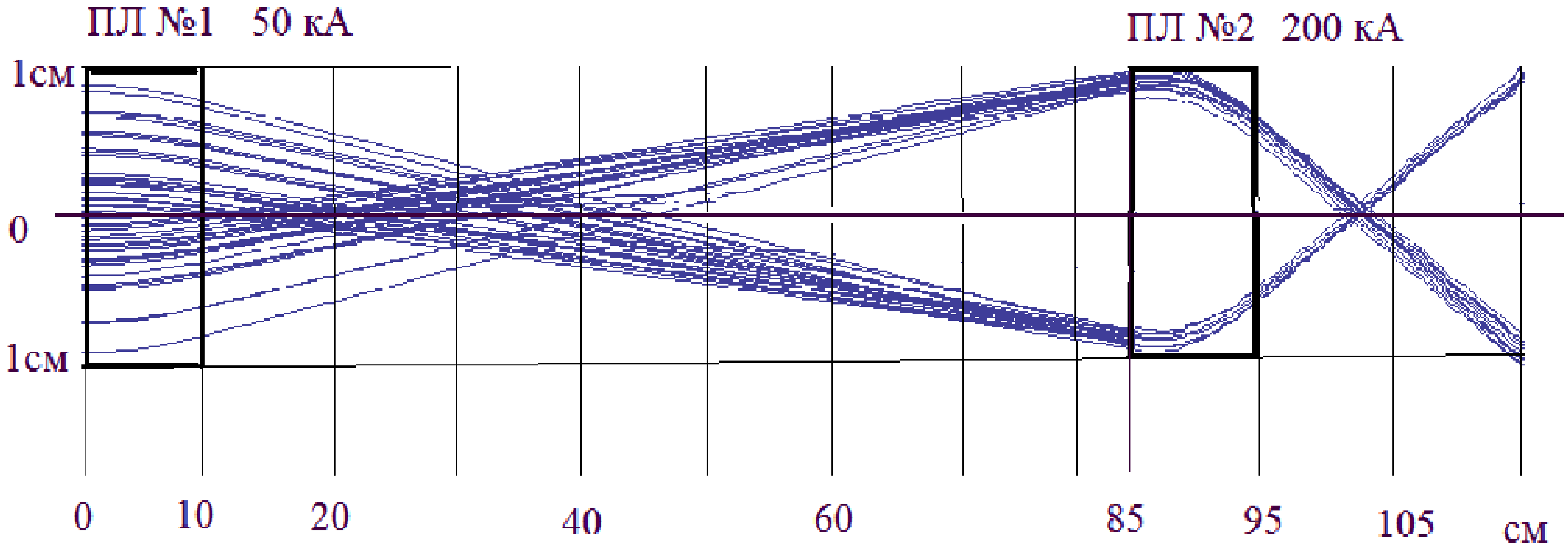


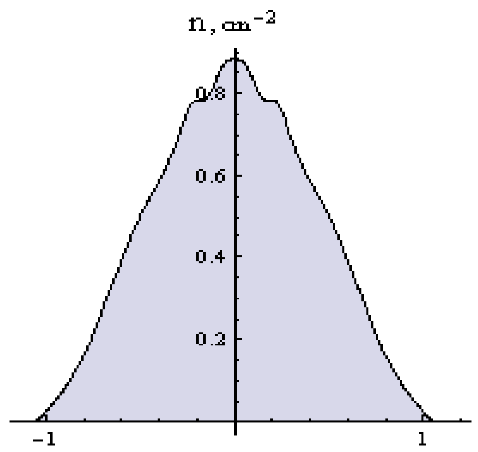


Transformed distributions at position of 150 cm behind the lens

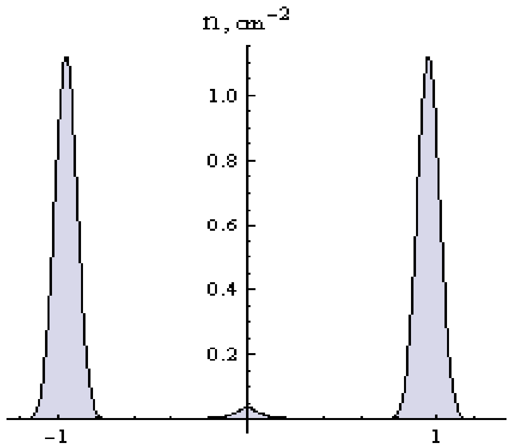
TWO-DIMENSIONAL TRANSFORMATION OF THE BEAM

•

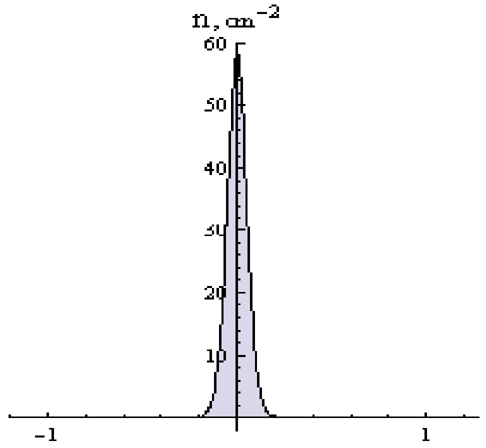




Пучок на входе в ПЛ №1



Пучок на входе в ПЛ № 2



Пучок в фокусе

CONCLUSION

The plasma lens can carry out not only sharp focusing of ions beam with considerable reduction of their sizes. At those stages of the plasma discharge at which the magnetic field is nonlinear, formation of other interesting configurations of beams is possible.

The plasma lens provides formation of hollow beams of ions in a wide range of parameters that allows to consider it as a possible variant of a terminal lens for realization of inertial thermonuclear synthesis.

The plasma lens can be used for transformation of beams with Gaussian distribution of particles density in a beams with homogeneous spatial distribution.

Application of the several plasma lenses which are in different stages of the plasma discharge, presumes to create some nontrivial spatial configurations of ions beams.

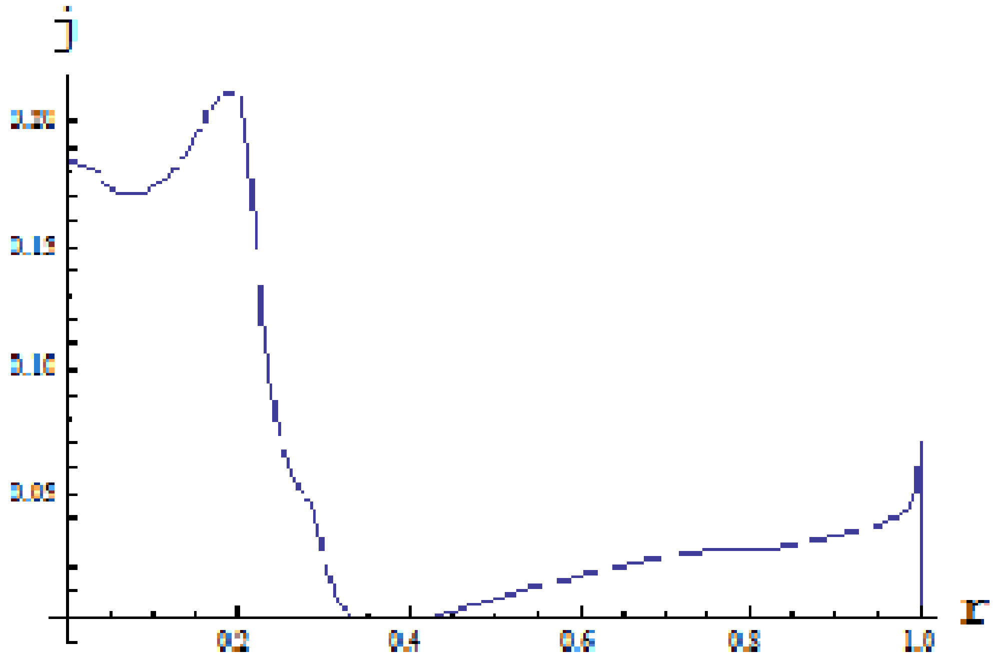
The plasma lens represents the universal tool for investigation of plasma discharges.

ИТЭФ
Москва

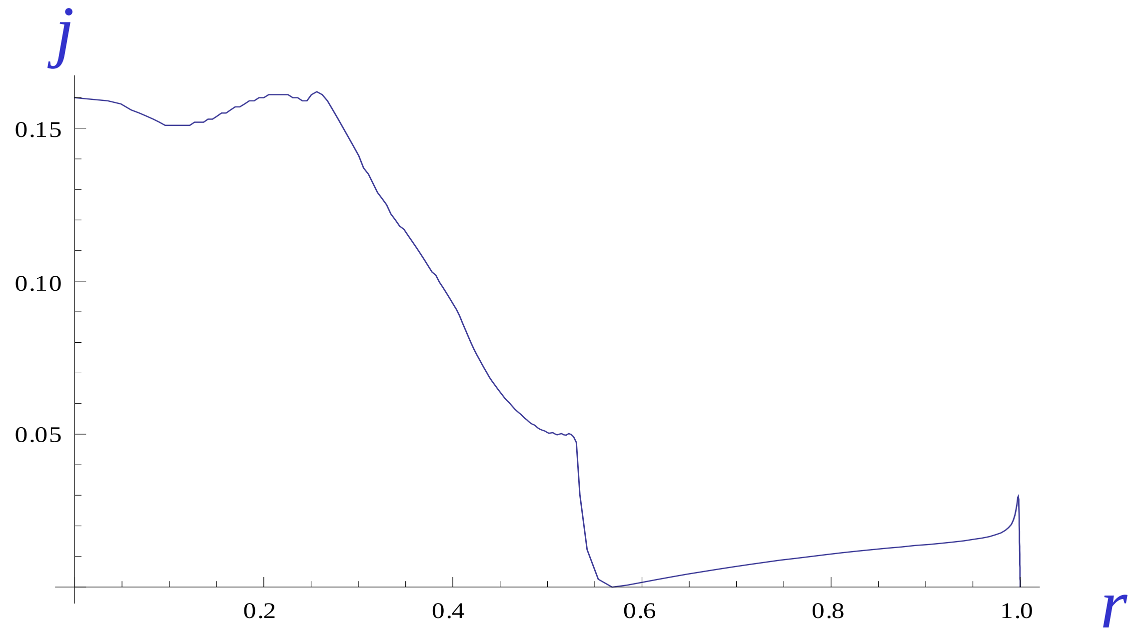
Simulations of the plasma lens in the MHD

(a vaporation of the wall material is taken into account)

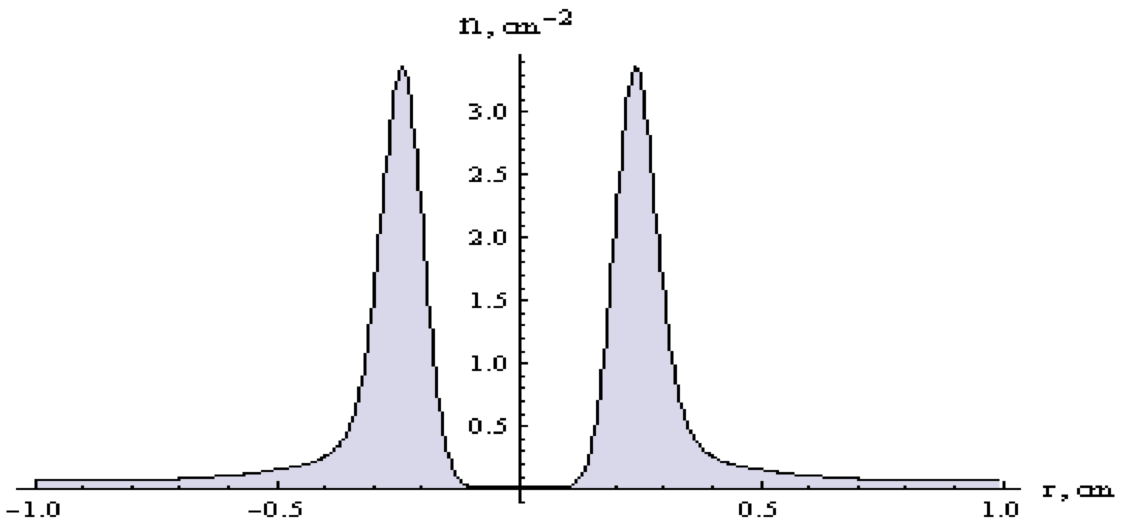
The pinch time T = $1.5\ \mu s$

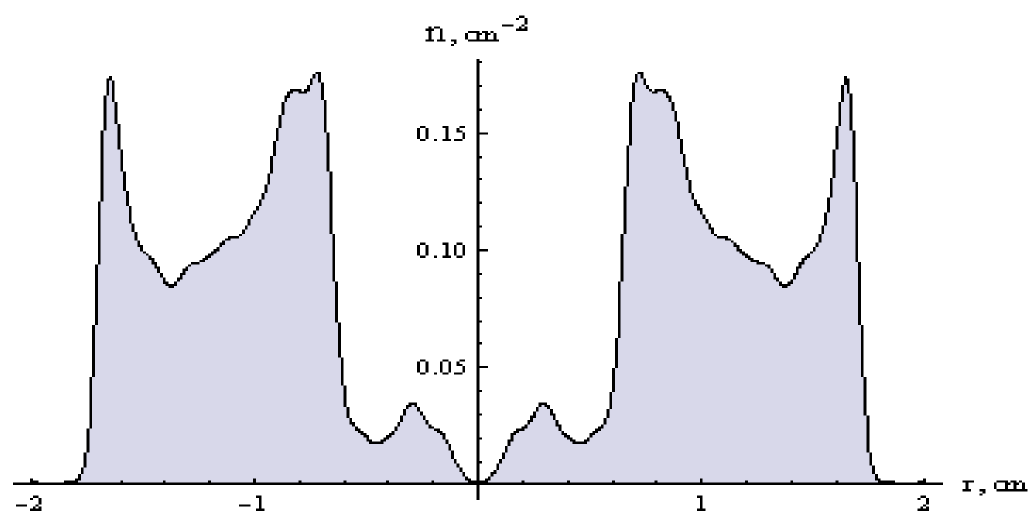


The maximum time T = $2.5\ \mu s$



The discrete distribution for discharge current of the argon plasma

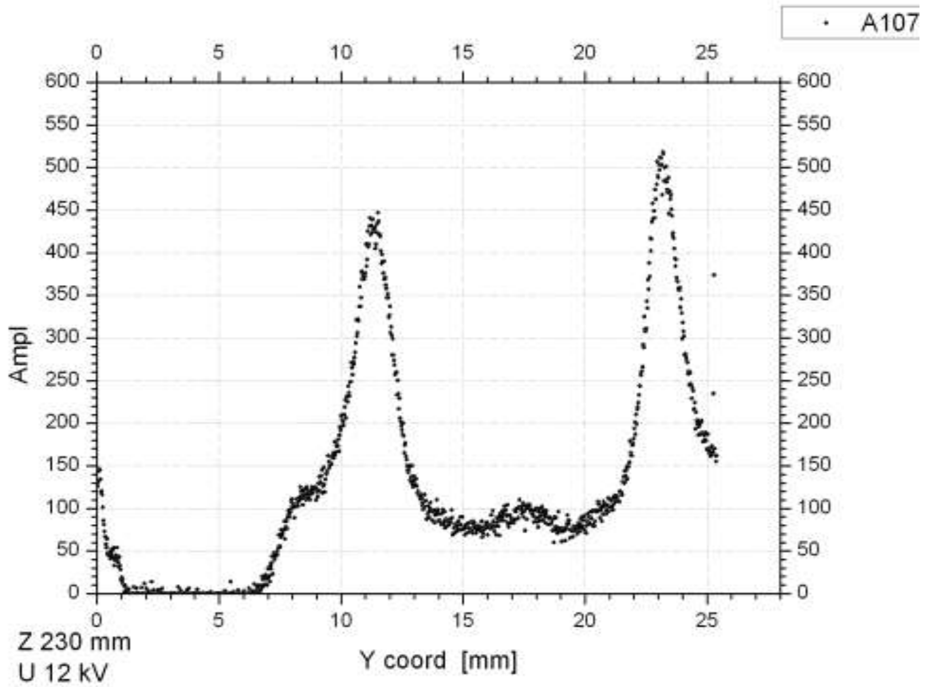




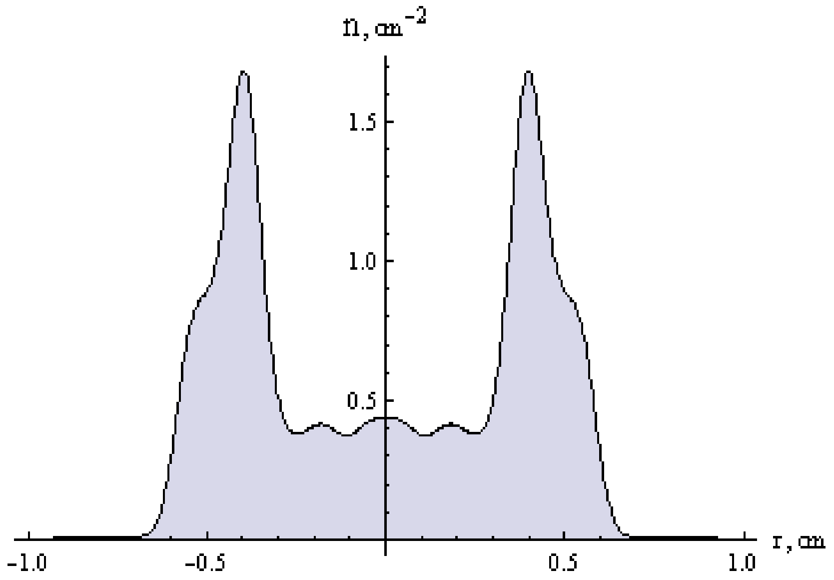
The distribution of ion C+6

Моделирование

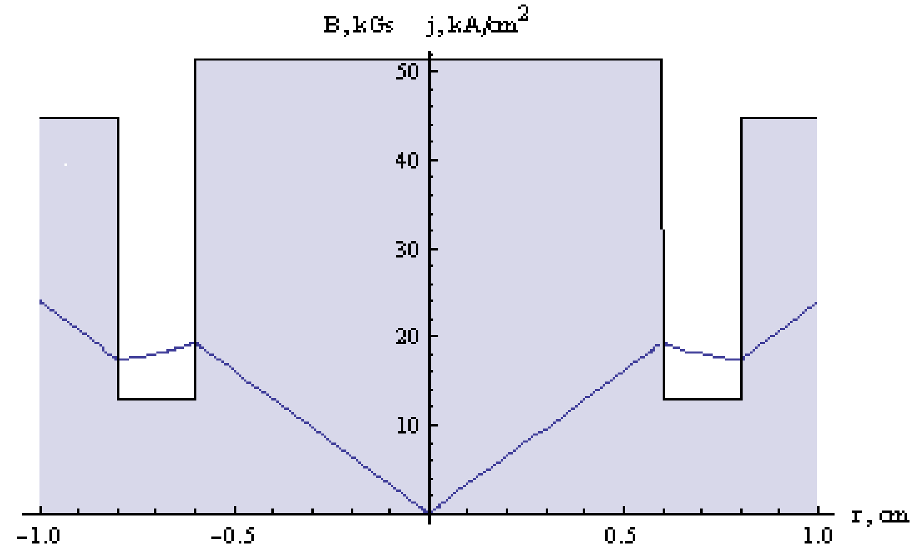
В результате численного моделирования прохождения реального пучка ионов через плазменную линзу с различными распределениями разрядного тока был определен тип распределения, при котором формируется трубчатый пучок, подобный



Эксперимент

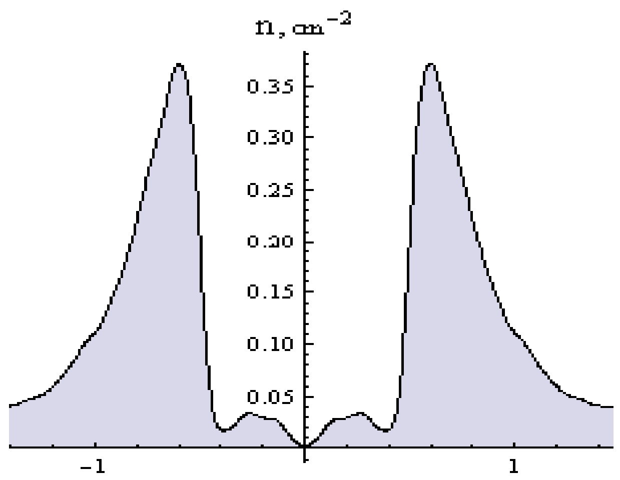


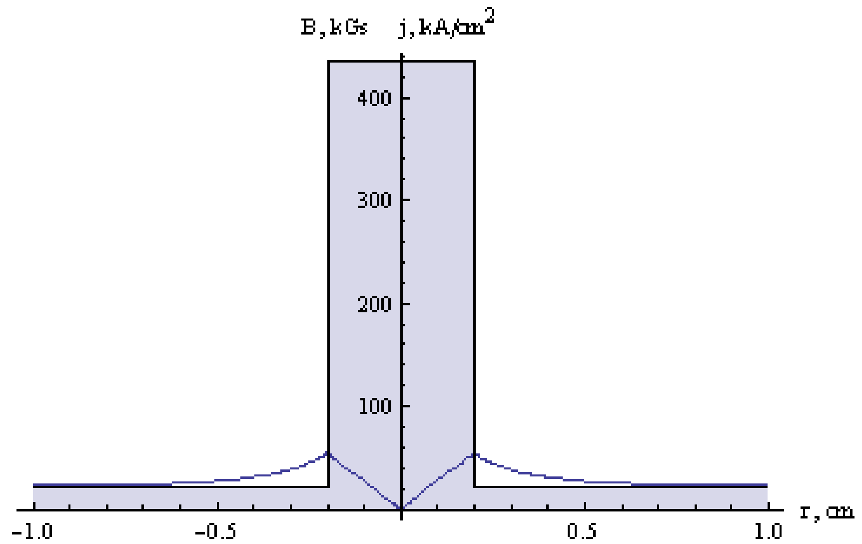
Расчет



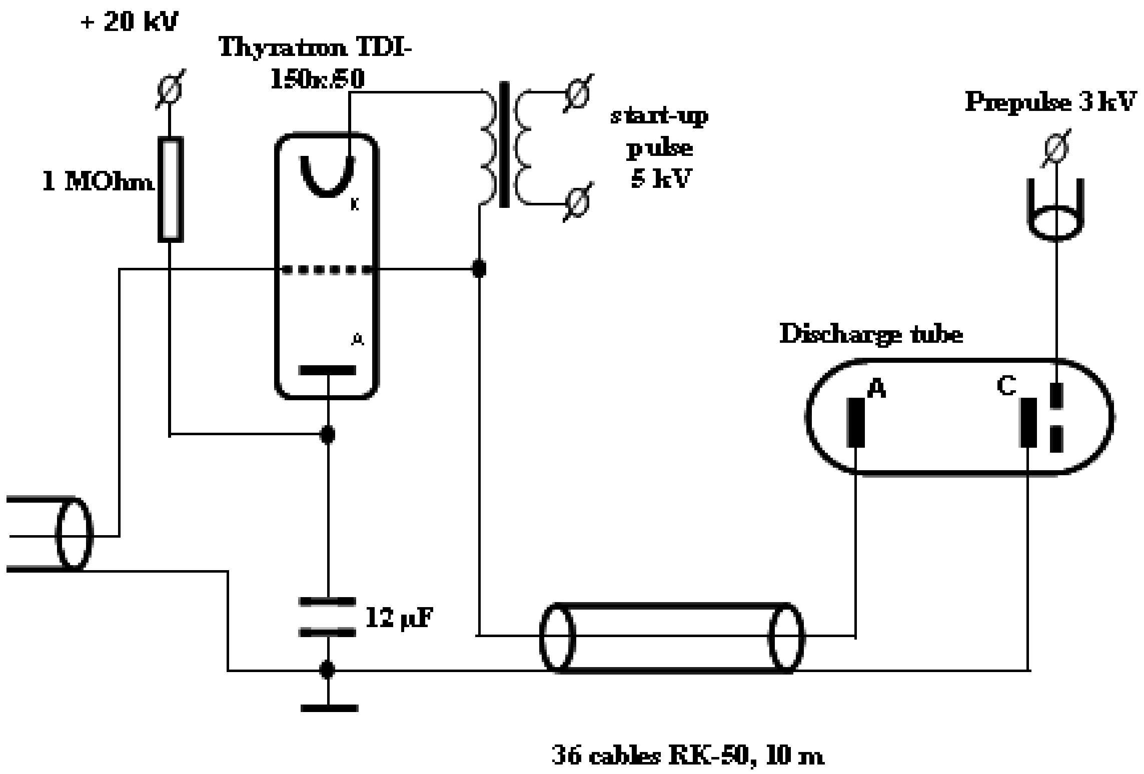
Распределение разрядного тока

Распределение плотности ионов при z=230 мм



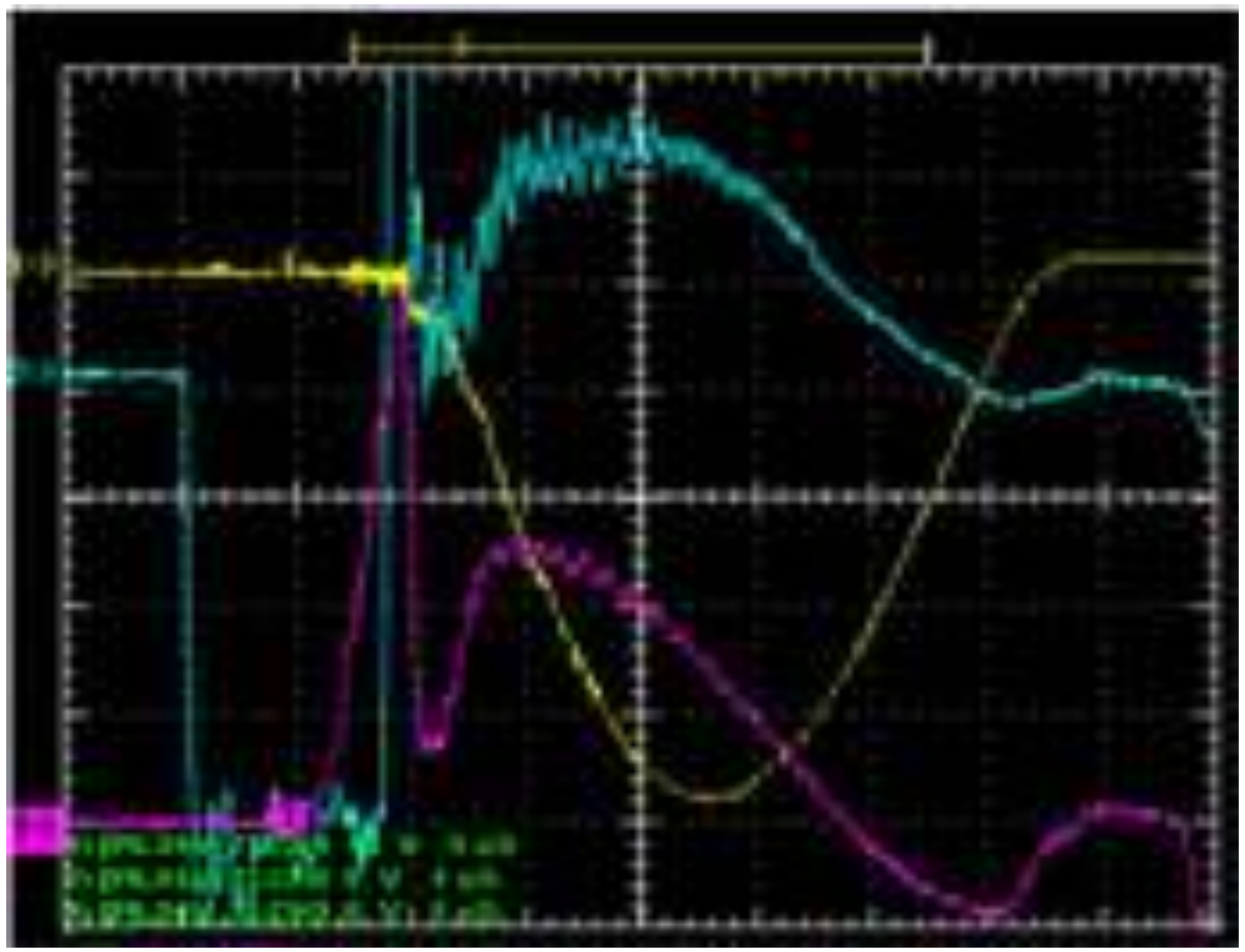


Principle electic scheme of plasma lens



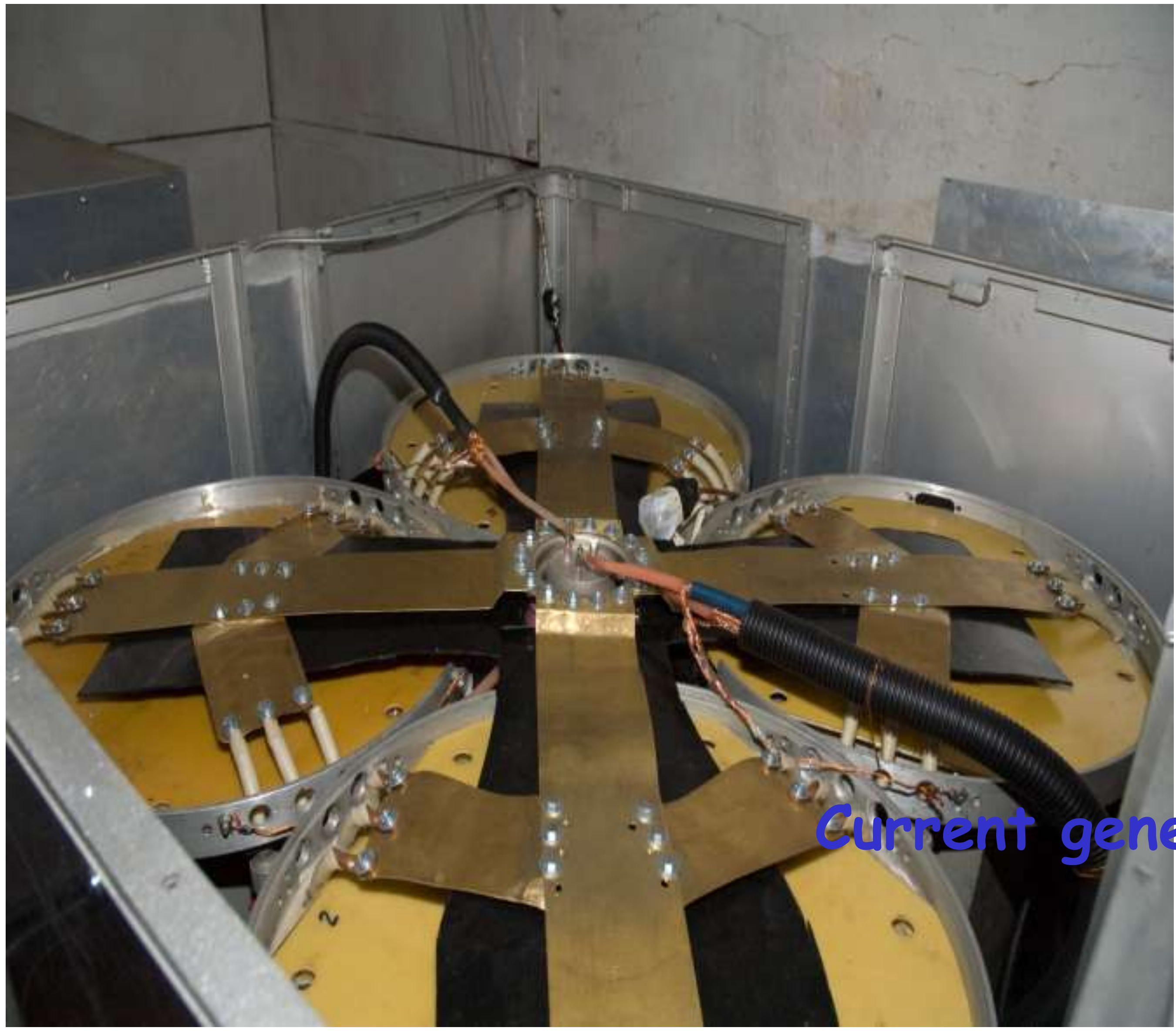
Амплитуда разрядного тока - $I = 0.5\, V*(C/L)^{1/2}$

Длительность импульса тока - $T_{1/2} = \pi(C*L)^{1/2}$.

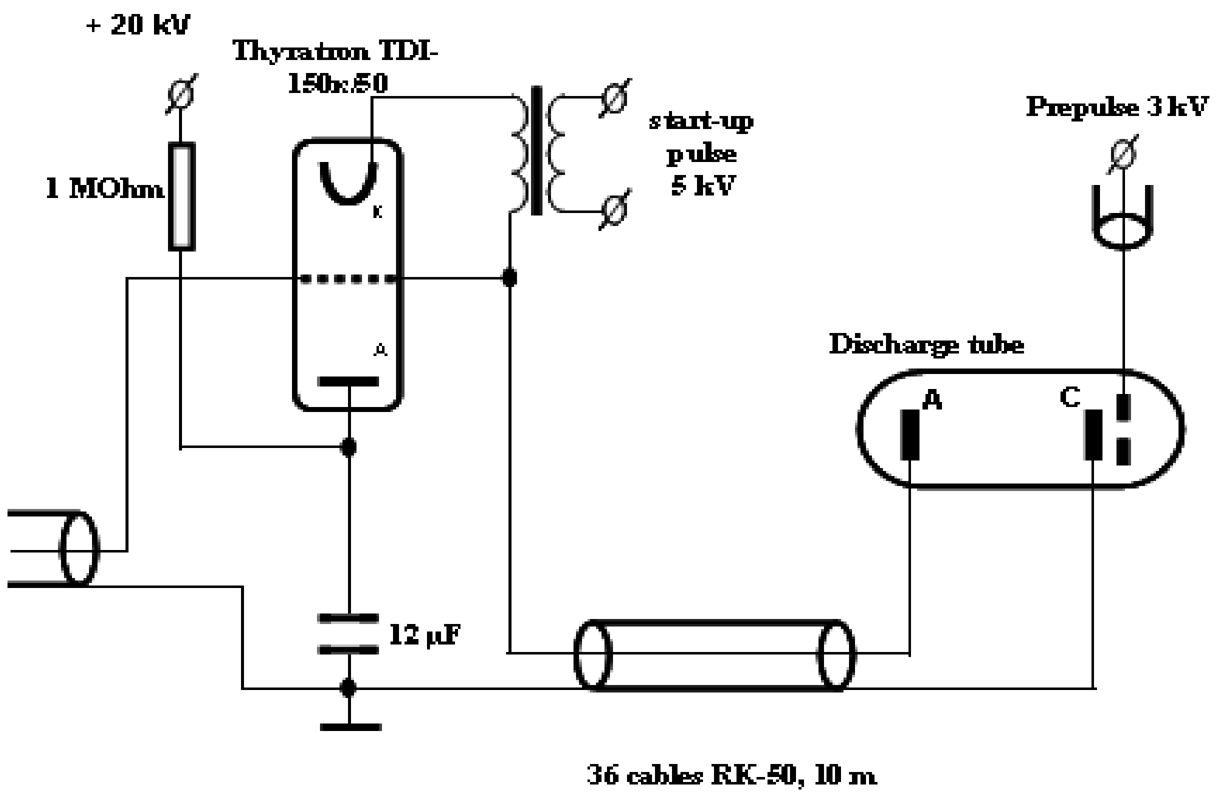


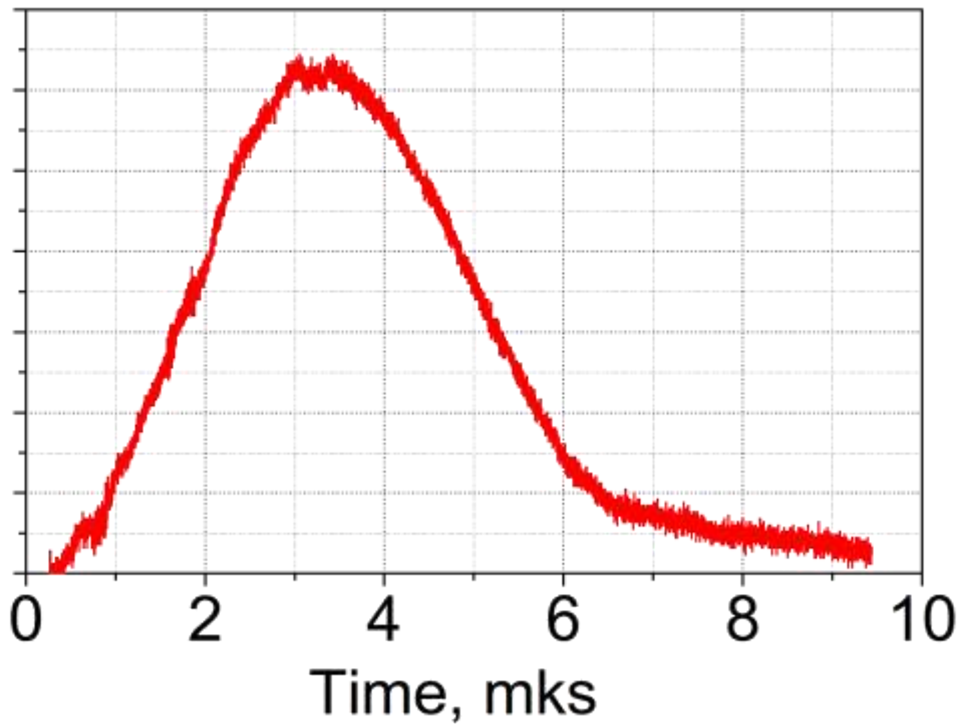
Oscillograms of the discharge current amplitude of 200kA (voltage signal from the Rogovski belt). The middle curve shows variation of the pre-ionization voltage. The lower curve shows variation of the discharge voltage

Current generator (two modules)



Current generator (two modules)





Characteristics of different plasma lens developments

	Accelerator	Particle	Energy MeV/u	Discharge	Results
Berkeley, 1950	Cyclotron	protons	350	wall stabilized, 4 kA (thin lens)	factor 3 in spot radius reduction
Brookhaven 1965	AGS	pions, kaons	4000	z-pinch with stabilizing Bz-field 500 kA (thin lens)	factor 3 in count rates
Nagaoka, 1988	ETIGO-I	protons	1	50 kA (thin lens)	factor 3-4 in radius
CERN, 1983-1993	PS / AC	protons, antiprot	3500	z-pinch, 400..500 kA (thin lens)	70 mrad collecting angle
GSI, 1990-2000	SIS	various	100-300	wall-stabilized, 150-350 kA(thin lens)	factor 30 in radius, limited emittance
Berkeley, 1995-1996	ESQ-Injector	K+	0.045	wall stabilized, 3..12 kA (adiabatic lens)	80% transport efficiency, factor 30 in intensity