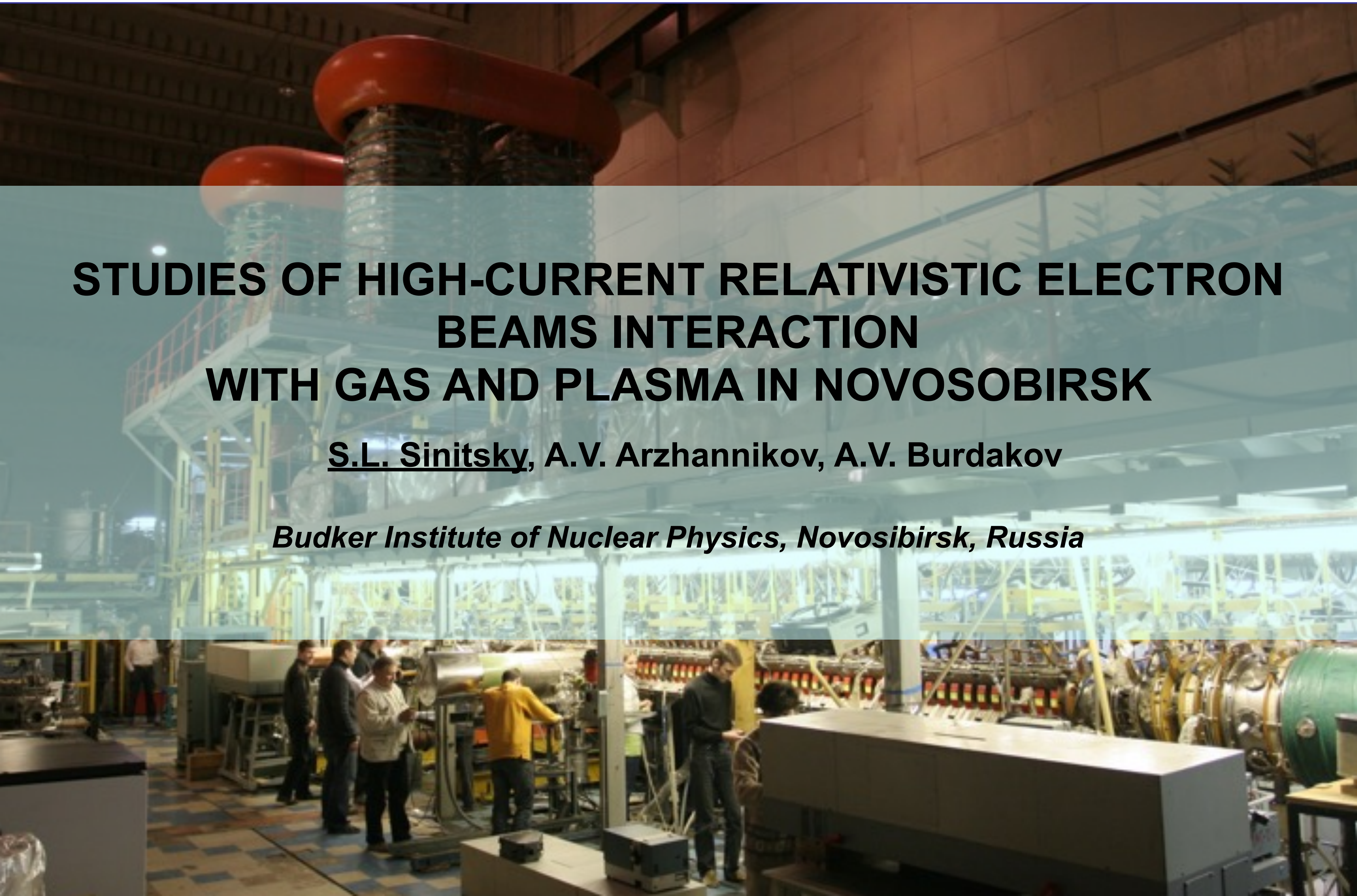
Norman Rostoker Memorial Symposium
Aug. 24-25, 2015, California, USA



STUDIES OF HIGH-CURRENT RELATIVISTIC ELECTRON BEAMS INTERACTION WITH GAS AND PLASMA IN NOVOSOBIRSK

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Outline

- *Introduction*
- *Experiments on heating plasma by 100 ns relativistic electron beams (REB)*
- *Beam-plasma interaction at 10μs REB duration*
- *Significant physical effects produced by turbulence in plasma heating and confinement*
- *Conclusions*

Experiments and theory of stable transport of high current relativistic electron beams in vacuum, gas and plasma

The last century seventies were marked by intensive studies and development of high-power relativistic electron beams and their applications.

In these years **Norman Rostoker** became one of the key researchers in this field. As a founder of the Laboratory of Plasma Studies at the Cornell University, Professor Rostoker applied a lot of efforts to the studies of intense electron beam transport under various experimental conditions. In series of his papers published in the period of 1970-1975, the results of theoretical and experimental studies of physical processes that determine an efficiency of the beam transport in plasma and gas media with and without presence of guiding magnetic field are presented [1-4].

Now, this fundamental knowledge is widely used in the modern experimental physics.

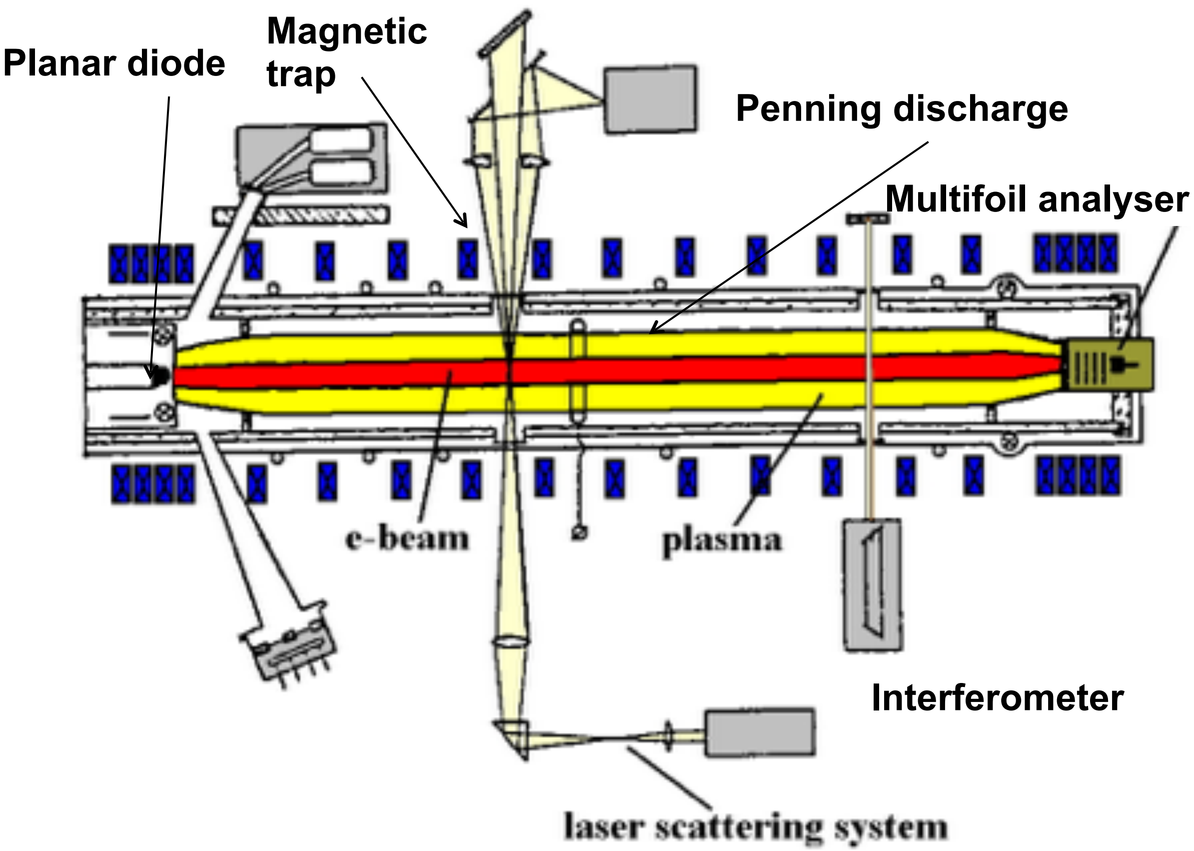
1. “On the Propagation of High-current Beams of Relativistic Electrons in Gases”
 M. L. Andrews, H. Davitian, D. A. Hammer, H. H. Fleischmann, J. A. Nation, and N. Rostoker.
 Appl. Phys. Lett. V.16, N3, p. 98, 1970.
2. “Effects of a Magnetic Guide Field on the Propagation of Intense Relativistic Electron Beams”
 M. Andrews, J. Bsura, H.H.Fleischmann, and N. Rostoker
 Physics of Fluids V. 13, N. 5, p.1322, 1970.
3. “Propagation of High Current Relativistic Electron Beams”
 D.A. Hammer and N. Rostoker,
 Physics of Fluids V. 13, N. 7, p.1831, 1970.
4. “Relativistic Electron Beam Neutralization in a Dense Magnetized Plasma”
 K.R.Chu and N. Rostoker
 Physics of Fluids V. 16, N. 9, p.1472, 1973.

Beam-plasma interaction experiments with 100 ns REBs

INAR, INAR2 (1971-1985), GOL-M (1971-2005), REBEX – (1978-1990)

The aim of research: to investigate the physics of beam-plasma interaction and to obtain plasma with sub fusion parameters in a magnetic trap

INAR-device (BINP, Novosibirsk)



Beam parameters:

Electron energy ~ 1MeV

Beam current -- from10 up to 25 kA

Beam diameter – 2-4 cm

Angular spread -- less than 0.02 rad

Plasma parameters:

Density – from 10^{14} -10^{16} cm^{-3}

Diameter- 6 cm

Length – 240cm

Magnetic field – 1-4 T

n_b/n_p – 10^{-4} – 10^{-1}

Beam current neutralization by return plasma current t=7ns after the beam start (INAR)

The aim: to find the experimental conditions for stable equilibrium transport of high-current 100ns REB in plasma

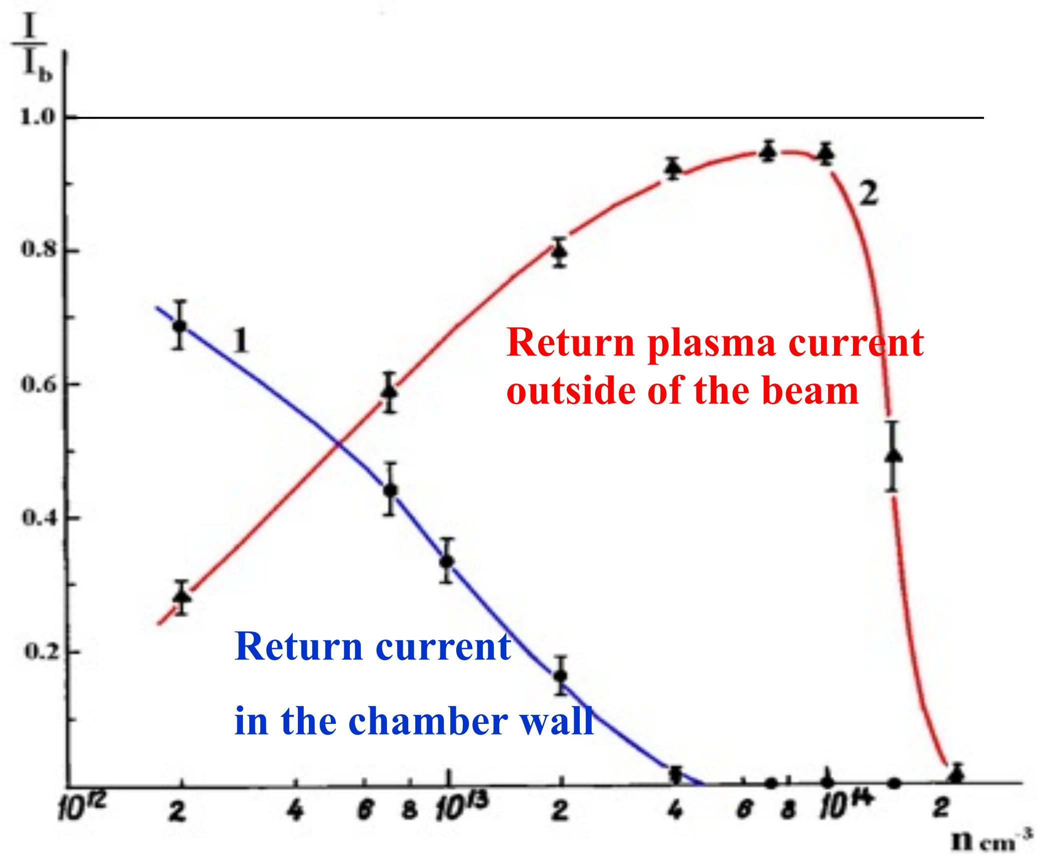
Experimental conditions:

Beam current – 10 kA,
duration – 70 ns

diameter – 2 cm
(n_b = 5x10^{11} cm^{-3})

Plasma diameter – 8 cm

Proc. XII Intern. Conf. on Phenomena in Ionized Gases, Eindhoven, 1975, 1, p 278.



The return plasma current at the increase of the plasma density switches firstly from the wall to the plasma outside the beam and then to the beam cross section. The last case is most stable in relation to instabilities (disruption of return current).

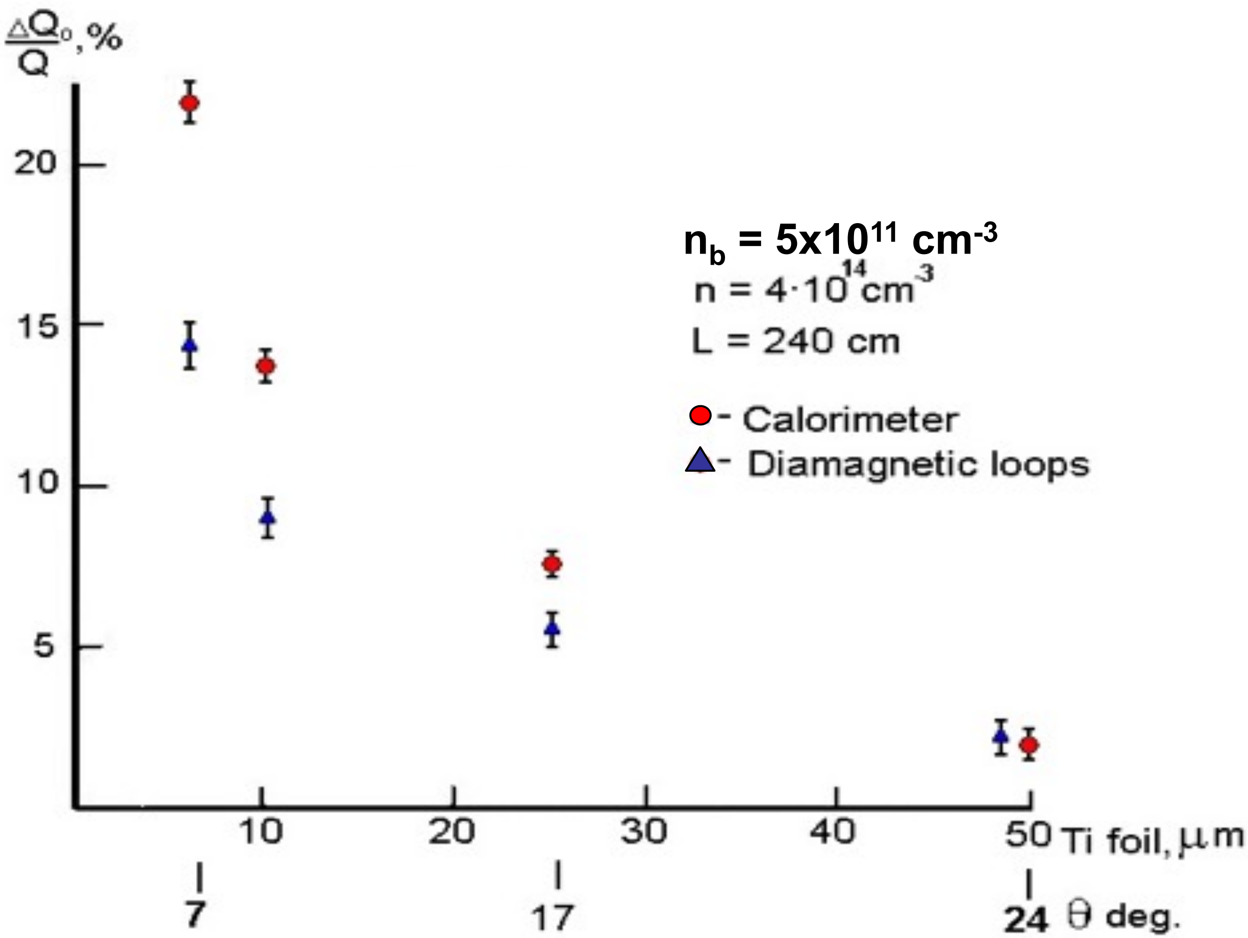
Efficiency of beam energy transfer to plasma as a function of electron angular spread (INAR)

Increment of two-stream instability

$$\Gamma \sim \omega_{pe} \frac{n_b}{n_p} \cdot \frac{1}{\gamma (\Delta\theta)^2}$$

Arzhannikov A.V. et al. JETP Letters, Vol. 27, No 3, 1978, pp 173-176.

Arzhannikov A.V. et al. Proc. of Beams 1979, Vol. I, pp 29-42



In accordance with theory the beam energy loss and the density of plasma energy inversely proportional to the angular spread of the beam electrons squared

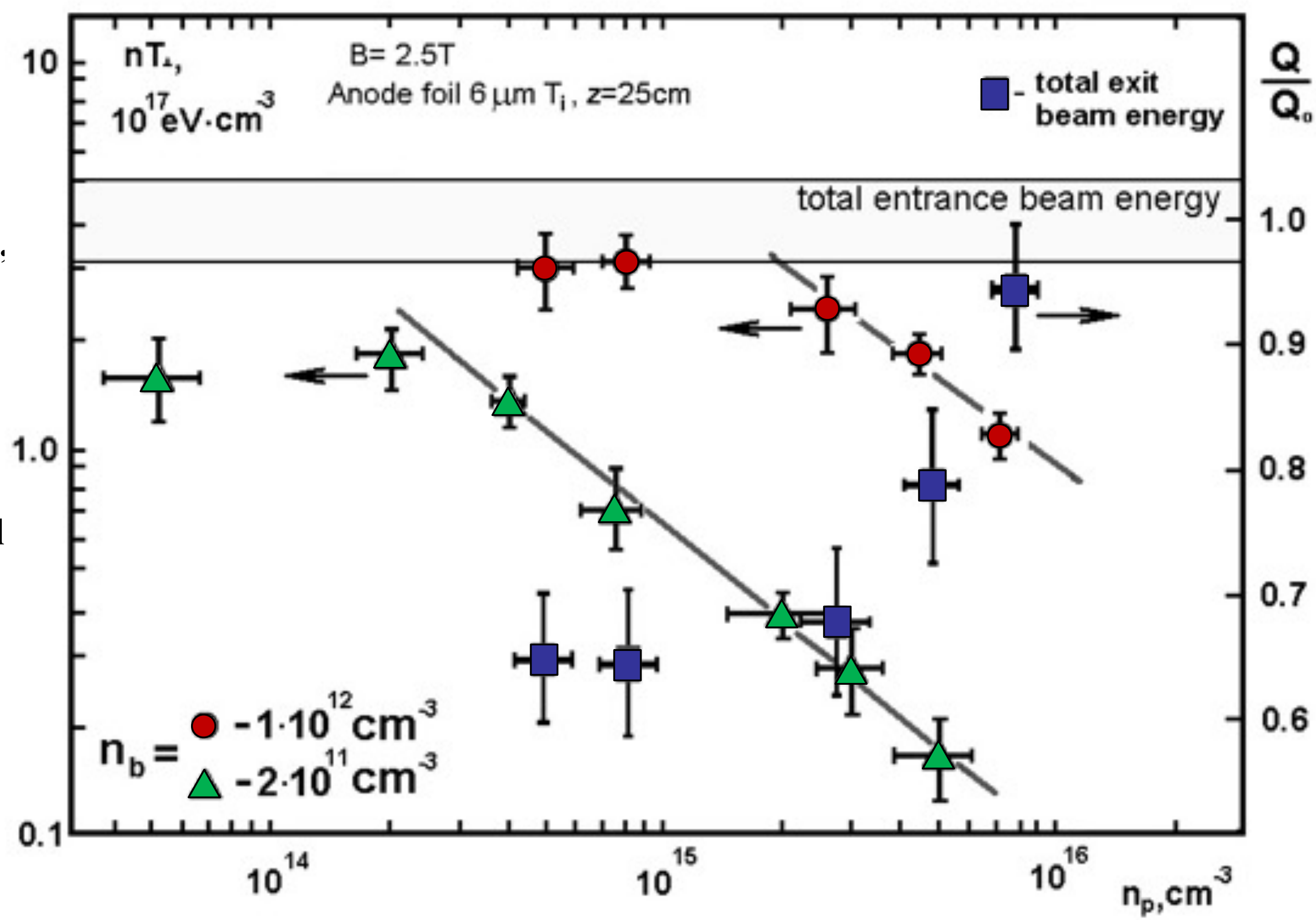
$\Gamma < \nu_{ei}$

Transverse pressure of heated plasma and beam energy loss for various beam and plasma densities (INAR)

“Plasma Physics and Controlled Nuclear Fusion Research 1978”

Vol. II, IAEA, Vienna, 1979, pp 623-637.

Arzhannikov A.V. et al Proc. of Beams 1979, Vol. I, pp 29-42

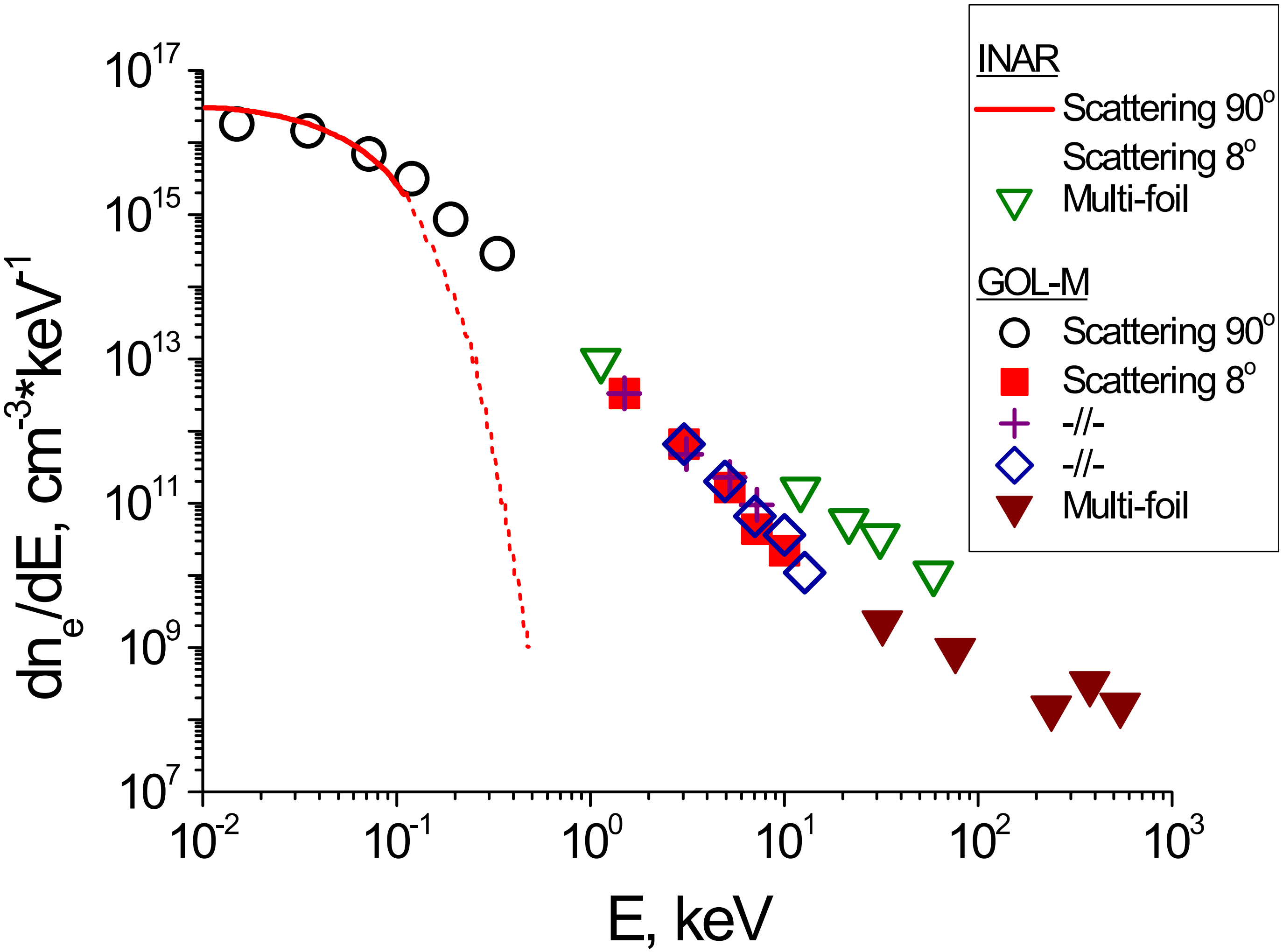


Result: the decrease of plasma energy with the increase of its density is provided by suppression of two-stream instability by e-i collisions, $\Gamma < \nu_{ei}$

Energy distribution function of the heated plasma electrons (INAR, GOL-M)

1. Arzhannikov A.V. et al. Physica Scripta. T2/2, 303-309,1982,

2. Vyacheslavov L.N., et.al. JETP Letters, Vol. 75, No. 1, 2002, pp 41-54



Result: the electron distribution function is substantially non Maxwell. The energy of the beam is predominantly transferred to the high-energy tail of Maxwell distribution.

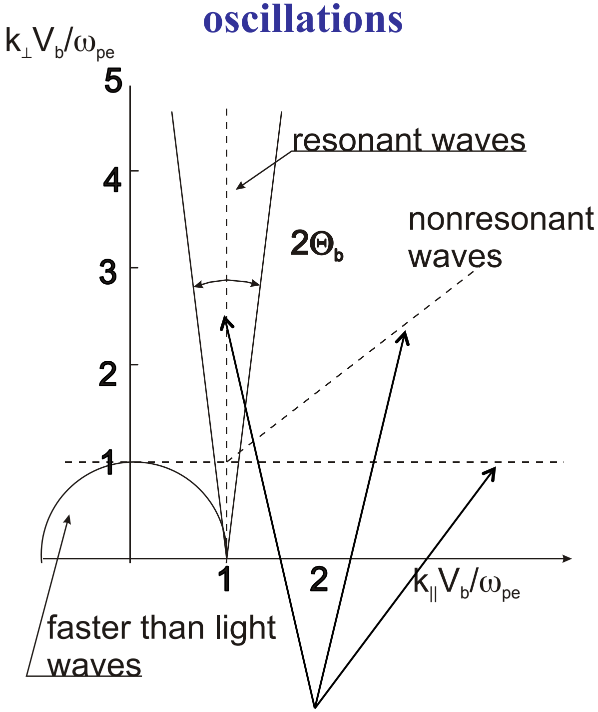
Measurements of Langmuir oscillation spectrums at GOL-M device (BINP, Novosibirsk)

Theoretical model developed by B.N. Breizman and D.D. Ryutov

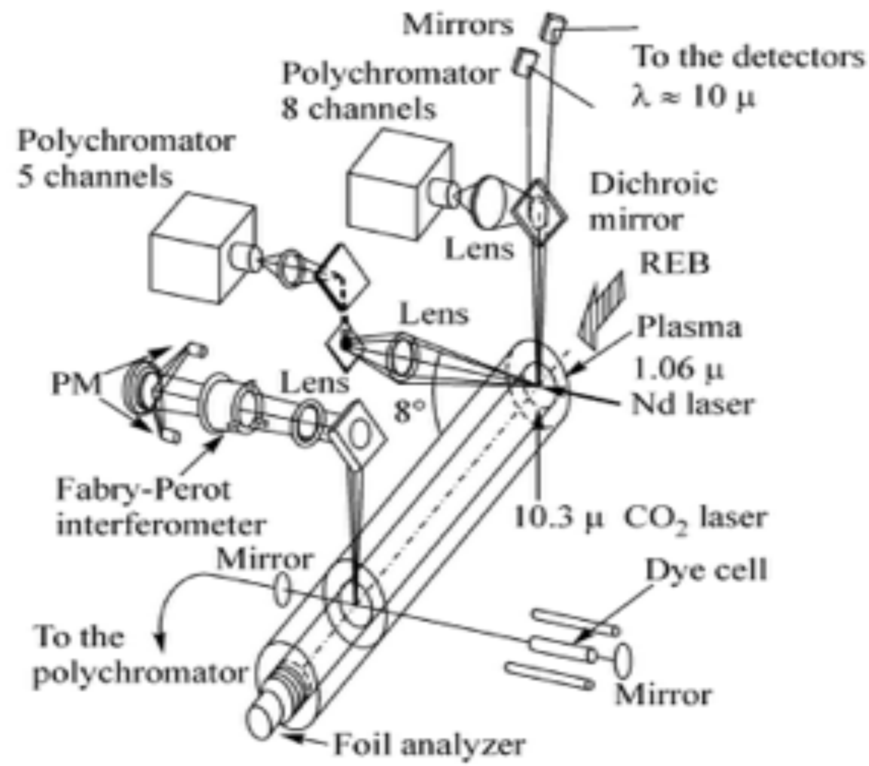
REB excites in magnetized plasma long wavelength Langmuir oscillations that meet the resonance condition:

$$\omega - k_{\|} V_{\|} = n\omega_{He}$$

Spectrum of Langmuir oscillations



Spectra measurements were carried out along lines



Beam parameters:

Electron energy ~ 0.6MeV

Particle density –3-5*10^{11}cm^{-3}

Beam diameter – 1.8 cm

n_b/n_p – 3-5*10^{-4}

Plasma parameters:

Density – 1-2*10^{15} cm^{-3}

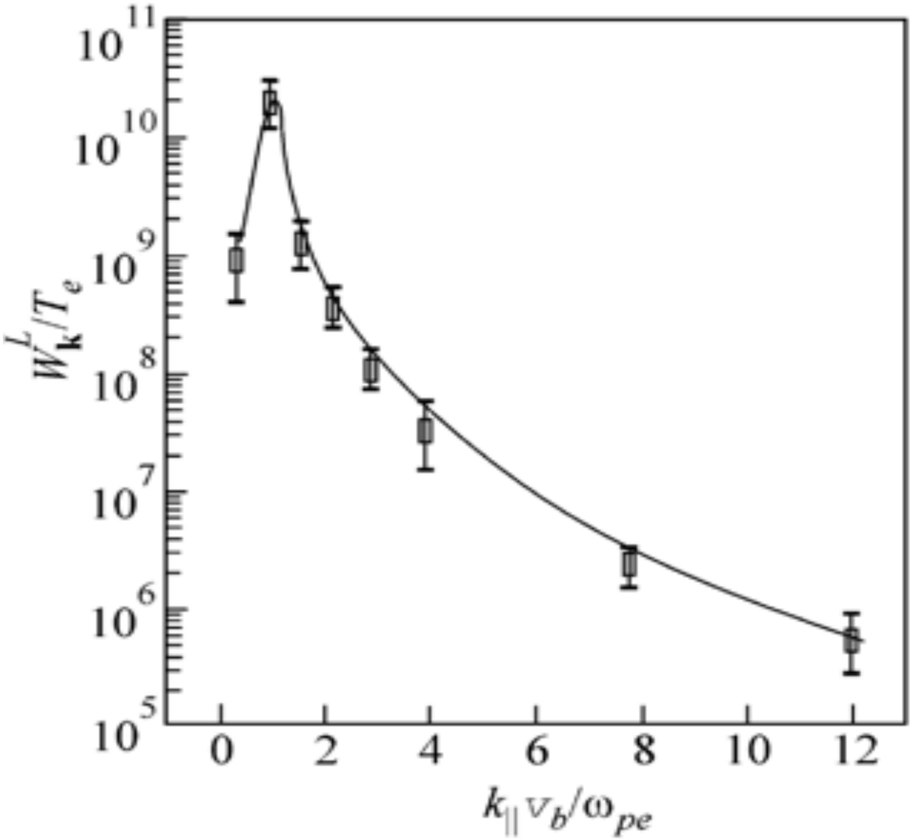
T_e – 20-60 eV

Length – 240cm

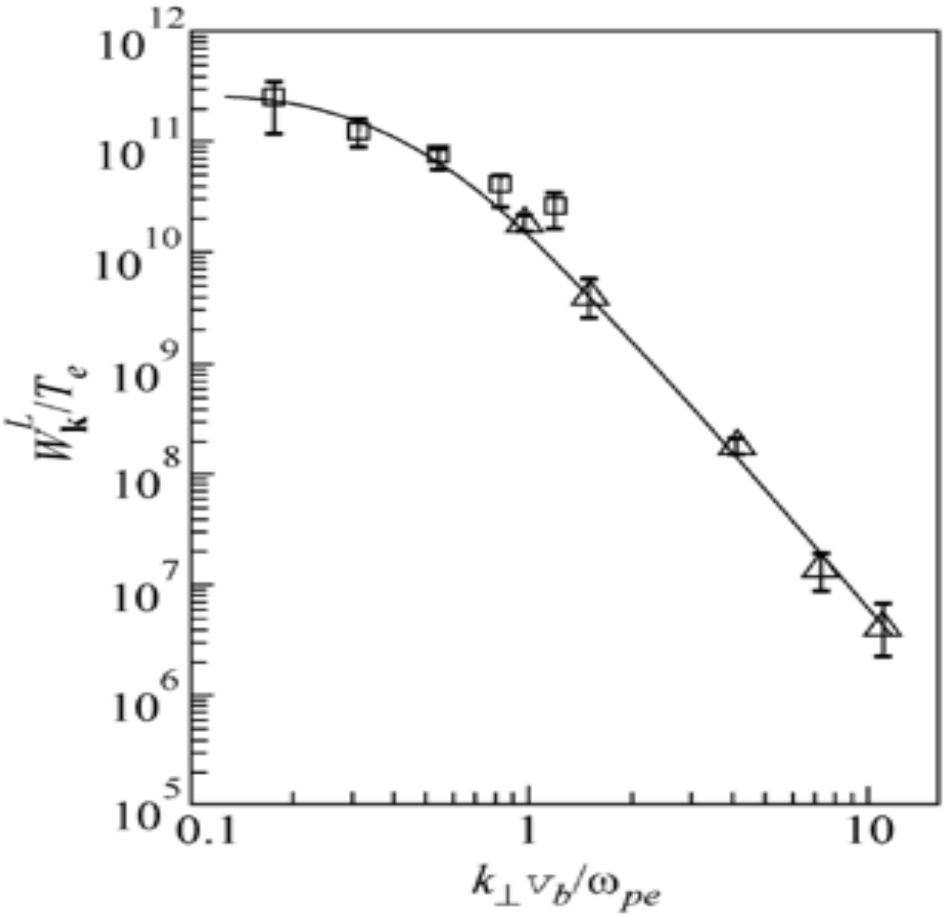
Magnetic field – 2.5 T

ω_{pe}/ω_{ce}=5/1

Measurements of Langmuir oscillation spectrums at GOL-M device



Spectrum along the line $k_{\perp}V_b/\omega_{pe}=1$

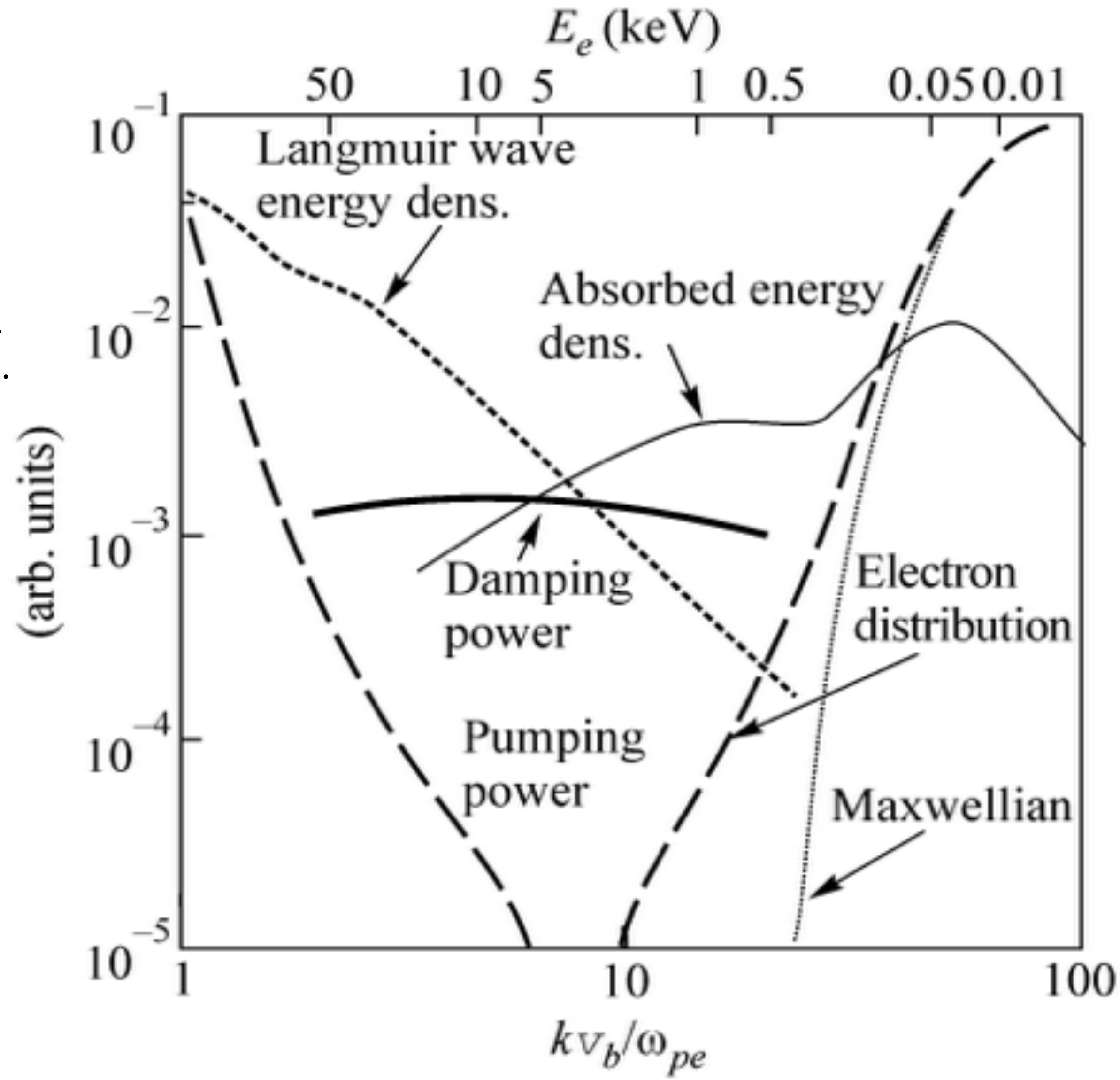


Spectrum along the line $k_{\|}V_b/\omega_{pe}=1$

“*Spectra of developed Langmuir turbulence in a nonisothermal magnetized plasma*”. Vyacheslavov L.N. et.al. Physics of Plasmas **2**, 2224 (1995)

Structure of pumping and absorption of the energy of Langmuir oscillation at GOL-M device

- Vyacheslavov L.N. et.al. Physics of Plasmas **2**, 2224 (1995)
- Vyacheslavov L.N., et.al. JETP Letters, Vol. 75, No. 1, 2002, pp 41-54.
- Plasma Phys. And Control. Fusion, 44 (2002) pp. B279-B291



Main results of the investigations with 100ns REBs

•For stable transport of high-current REB in plasma, the plasma return current should be concentrated inside the beam cross-section and this condition is reached only at plasma densities higher than $2x10^{14}$ cm^{-3}.

•It is established that two-stream instability plays the main role in the process of beam plasma interaction

•The experimental conditions have been found under which high-current REB with n_b~10^{11}-10^{12} cm^{-3} can transfer substantial part (~0.4) of its energy to a plasma with density n_p~ 10^{15}-10^{16} cm^{-3}.

•As a result of collective interaction, the distribution function of heated plasma electrons becomes essentially non-equilibrium

•The developed Langmuir turbulence excited by high-current REB in magnetized plasma has a broad spectrum with spectral density exceeding the thermal level by 5-11 orders of magnitude. Few nonlinear effects provide the oscillation energy transfer from resonant to non-resonant regions where it is absorbed by the plasma electrons.

Development of new accelerators for generating microsecond E-beams (1982-1987)

In order to raise the heated plasma parameters we had to increase an energy content of the beams by elongation of its pulse duration at keeping other experimental conditions approximately on the same level as for 100ns beams

Accelerator U-1 (1982)

Testing solutions and technologies for circular beam

Total energy stored in capacitors: 180kJ
Planar diode with anode foil 5μm plastic coated with Al, $\varnothing_{cathode}$ ~20cm
Beam parameters: E_e~1MeV, I_b~50kA, τ~5μs, Q~100kJ,
In magnetic field B=10T $\varnothing_{beam}$~3-4cm, j_b=1-2kA/cm^2

Accelerator U-2 (1986)

Testing solutions for ribbon beam and its injection in multi mirror trap

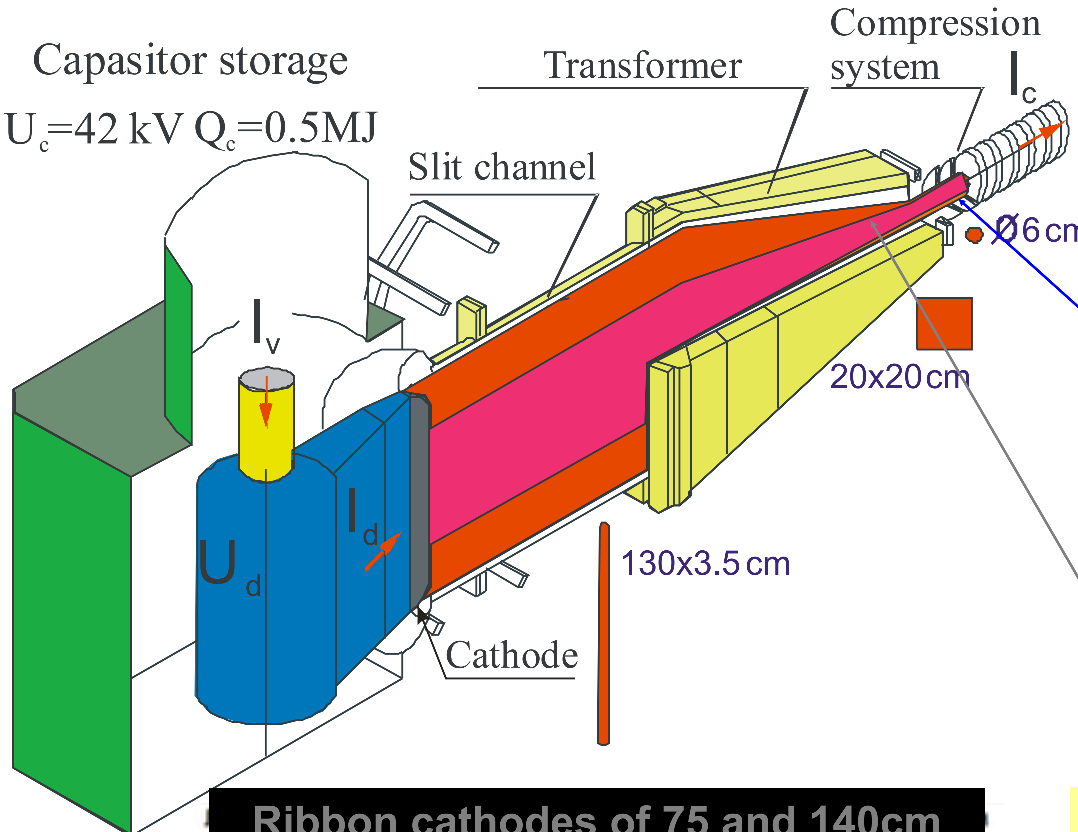
Total energy stored in capacitors: 750kJ
Magnetically insulated ribbon diode without foil, sizes of cathode 5x130cm, 5x75cm
Beam parameters: E_e~1MeV, I_b~50kA, τ~10-14μs, $Q_{ribbon\ beam}$ ~400kJ,, in magnetic field B=4T $\varnothing_{beam}$~4cm, j_b=1-2kA/cm^2, $Q_{compressed\ beam}$ ~250kJ

Accelerator U-3 (1987)

Injection of circular beam in magnetic trap

Total energy stored in capacitors: 360kJ
Planar diode with anode foil 5μm plastic coated with Al, $\varnothing_{cathode}$ ~20cm. Beam parameters: E_e~1MeV, I_b~40kA, τ~5-7μs. In magnetic field B=5T $\varnothing_{beam}$~4cm, j_b=1-3kA/cm^2, Q~100kJ,

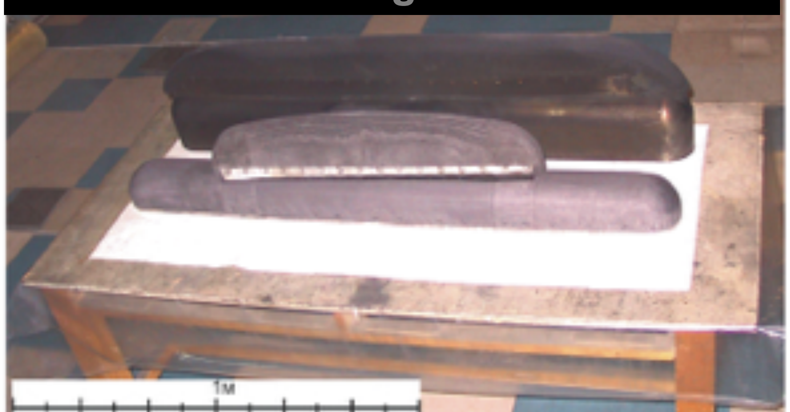
Layout of the U-2 accelerator



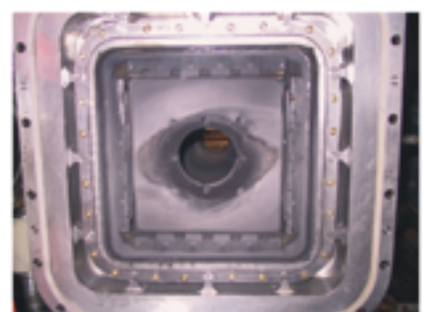
Two modes of operation

Ribbon beam	Dense ribbon beam
140x3.5cm	75x3.5cm
E_e=1MeV	E_e=1MeV
I_b=50kA	I_b=30kA
t_b=8μs	τ_b=9÷12μs
Q_b=0.4MJ	Q_b=0.25MJ
Circular beam	Circular beam
ϕ 6cm	ϕ 4cm
j=1 kA/cm²	j=2 kA/cm²
Q_b=0.2MJ	Q_b=0.15MJ

Ribbon cathodes of 75 and 140cm length

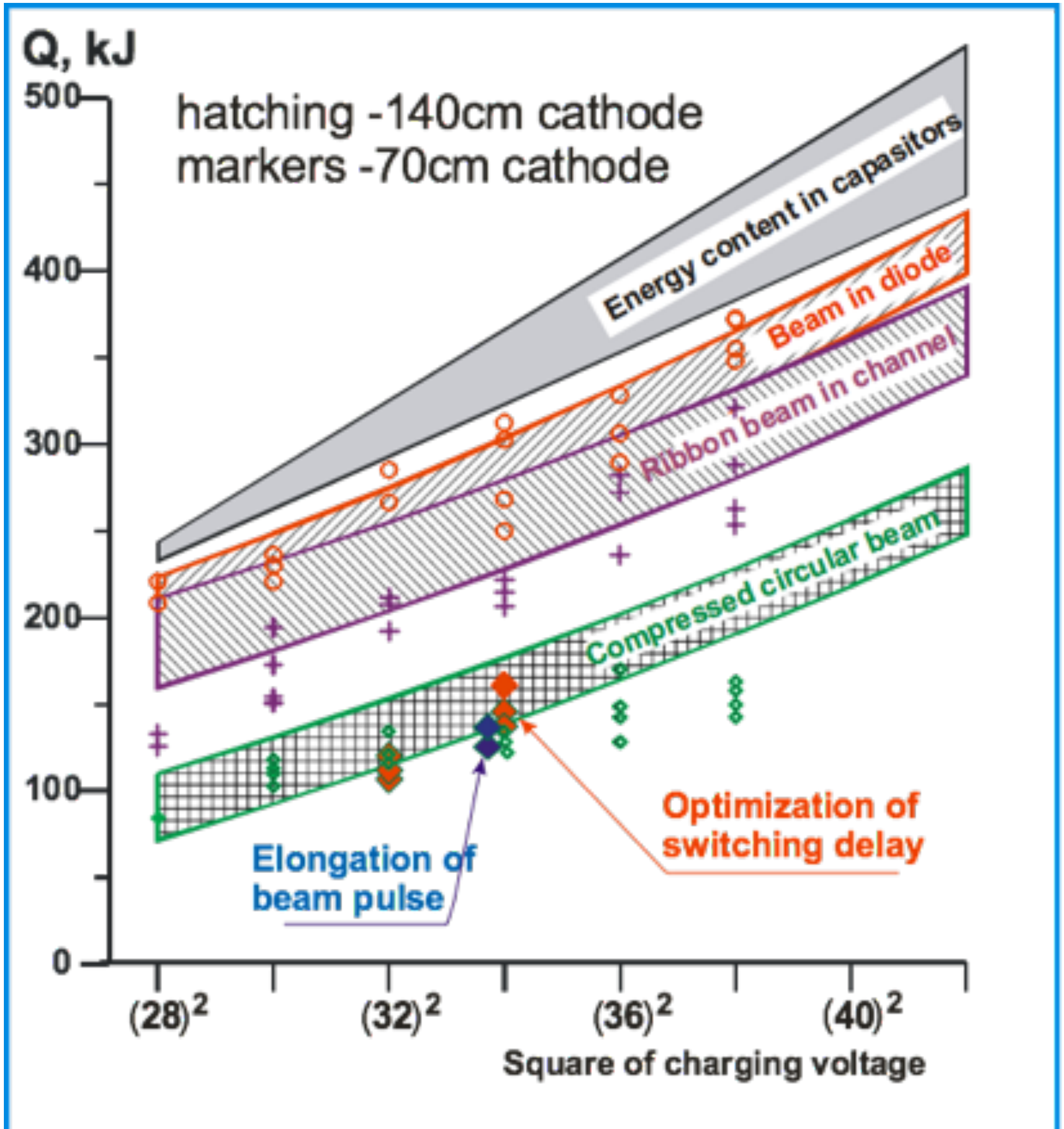


Beam imprint on entrance limiter

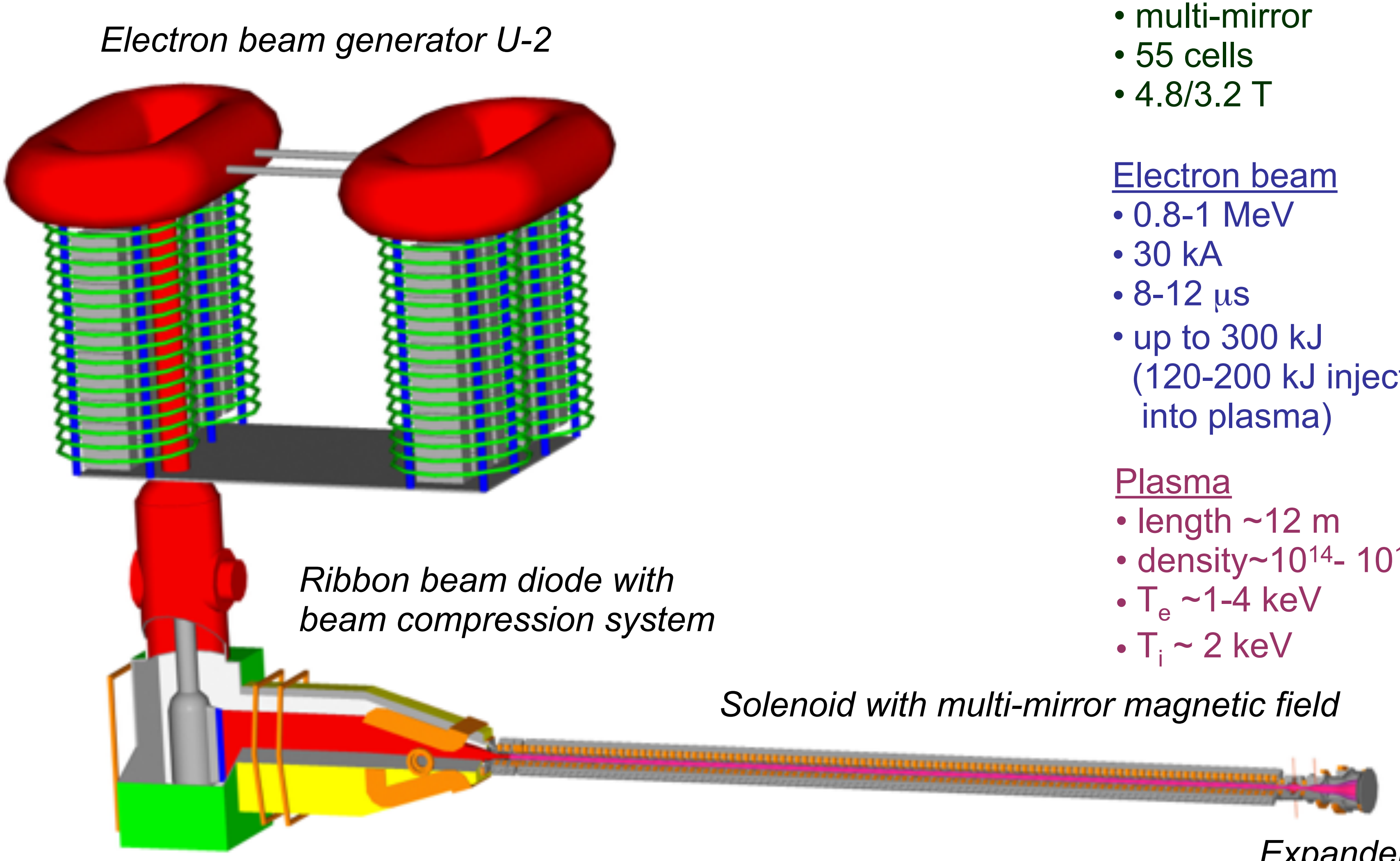


Beam imprint after compression system without limiter

BEAM ENERGY CONTENT ON CHARGING VOLTAGE



Layout of GOL-3 facility

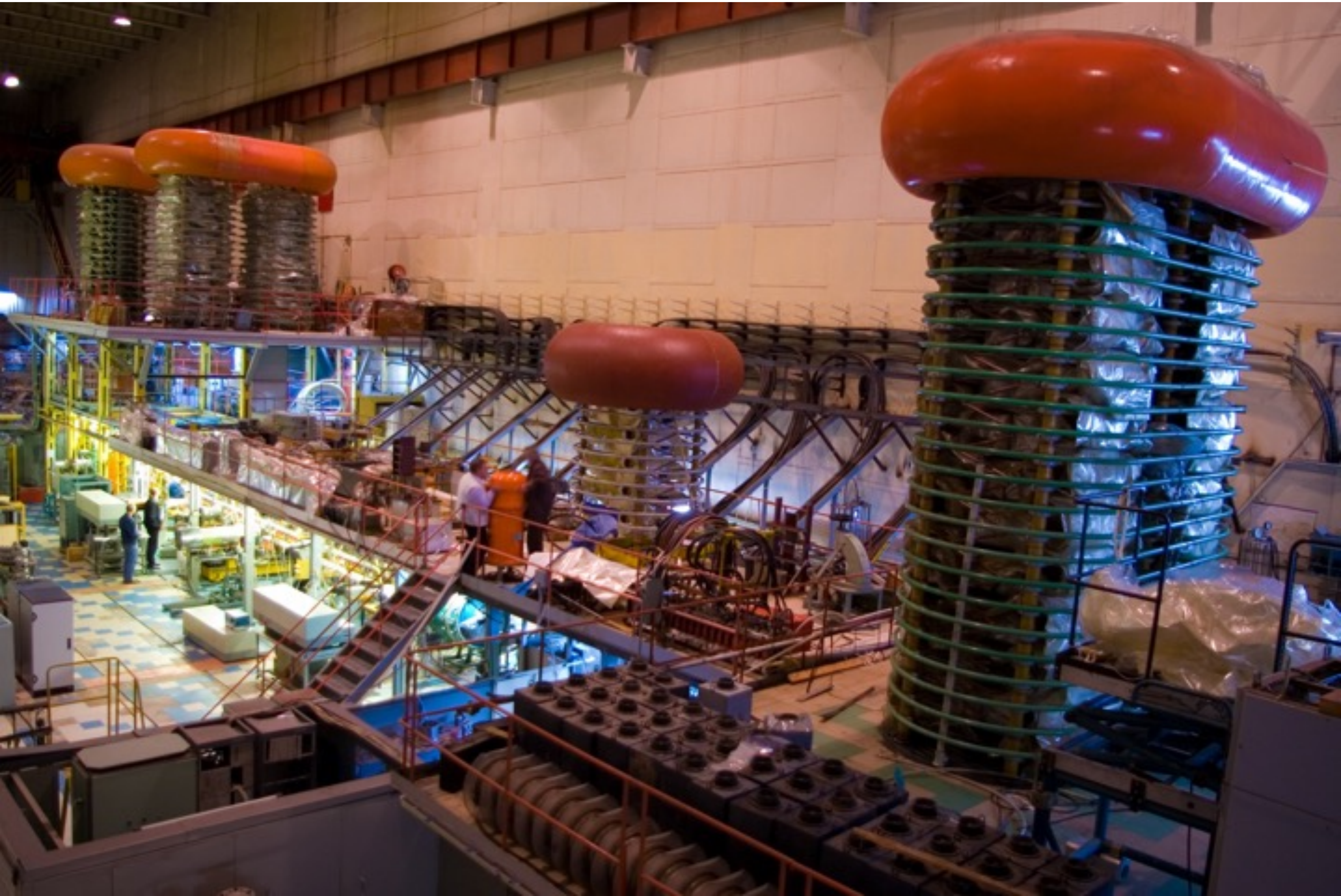


<u>Magnetic field</u>
- multi-mirror
- 55 cells
- 4.8/3.2 T

<u>Electron beam</u>
- 0.8-1 MeV
- 30 kA
- 8-12 μs
- up to 300 kJ
  (120-200 kJ injected
  into plasma)

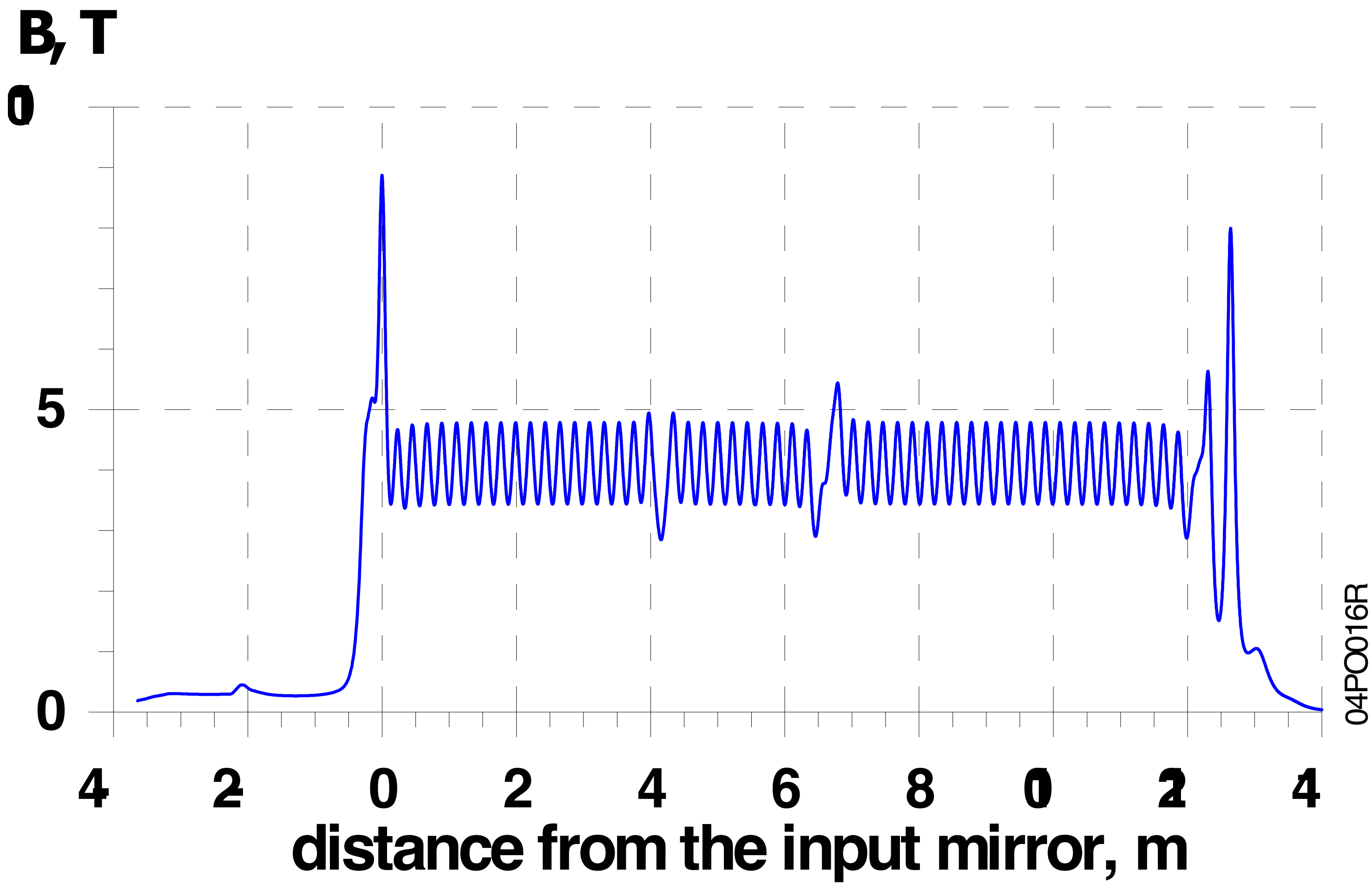
<u>Plasma</u>
- length ~12 m
- density~10^{14}- 10^{16} cm^{-3}
- T_e ~1-4 keV
- T_i ~ 2 keV

GOL-3 multi-mirror trap



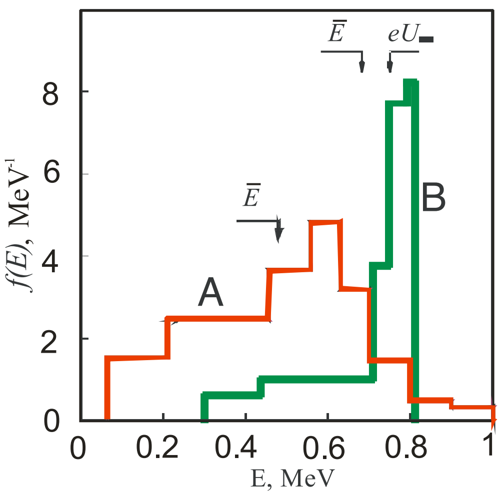
GOL-3 multi mirror trap

Plasma is confined in a solenoid with corrugated (multi-mirror) field, which comprises 55 cells with B_{max}/B_{min}= 4.8/3.2 T



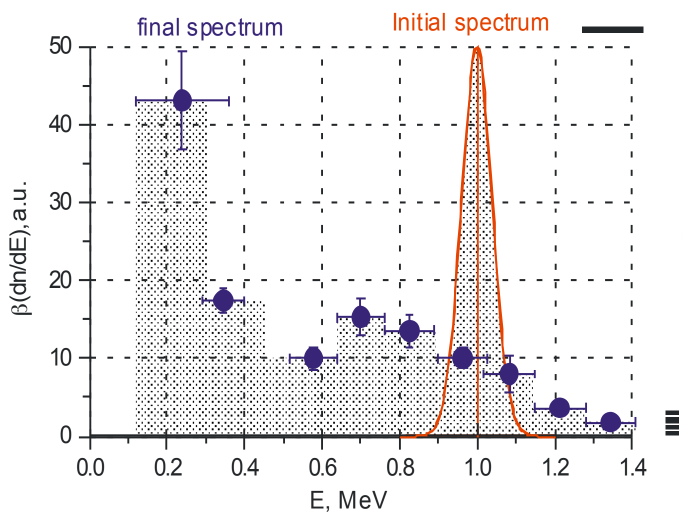
ENERGY SPECTRUM OF ELECTRONS AT THE EXIT OF THE GOL-3 FACILITY

1990



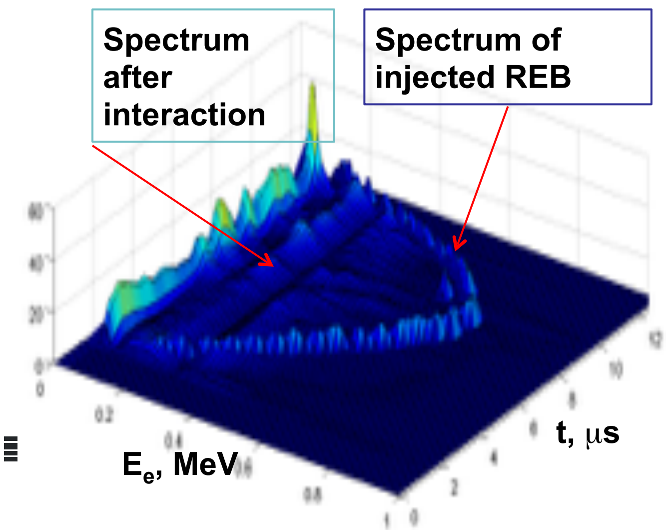
Multifoil analyser
GOL-3-I
Homogeneous magnetic field
Beam injection through the anode foil:
E_e=0.7MeV
B- injection in vacuum
A -injection in plasma

2001



Magnetic spectrometer
GOL-3-II
Homogeneous magnetic field
Beam injection without anode foil
E_e=1MeV
Injection in plasma

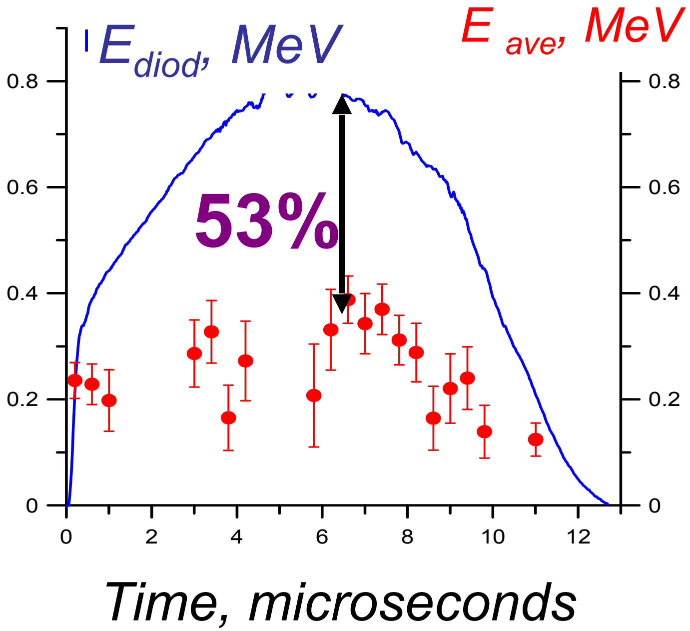
2008



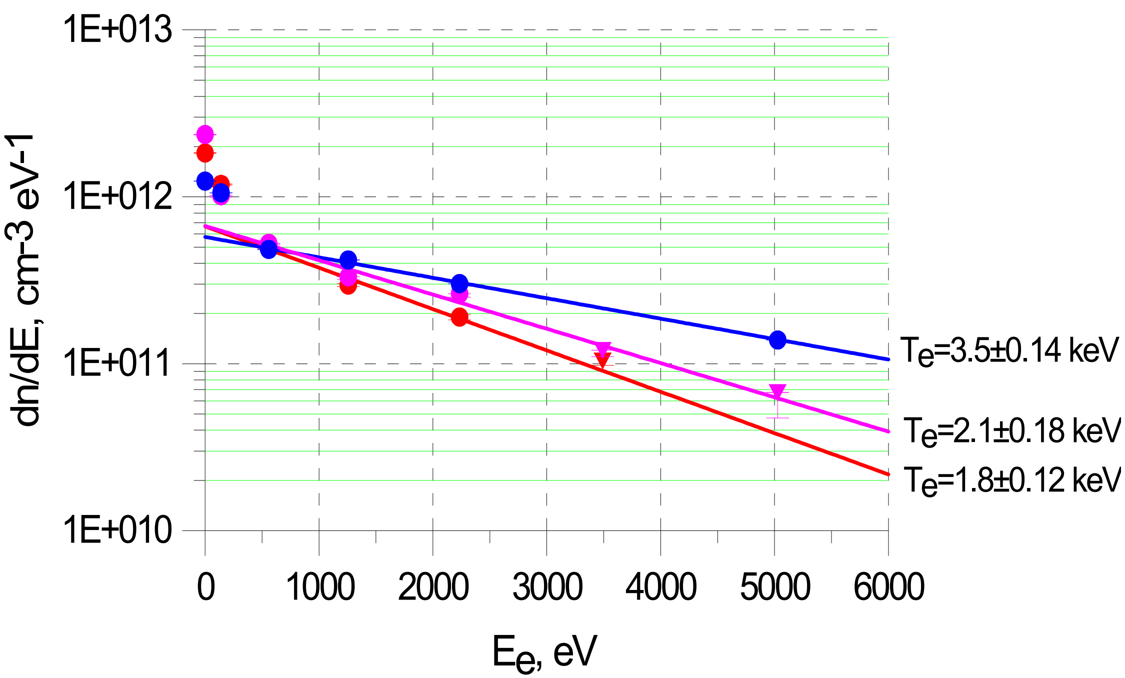
Multifoil analyser
GOL-3-II
Corrugated magnetic field
Beam injection without anode foil:
E_e=0.7MeV
Injection in plasma
t=2-8μs

Collective E-beam relaxation and heating of plasma electrons

Beam spectrum analyzer



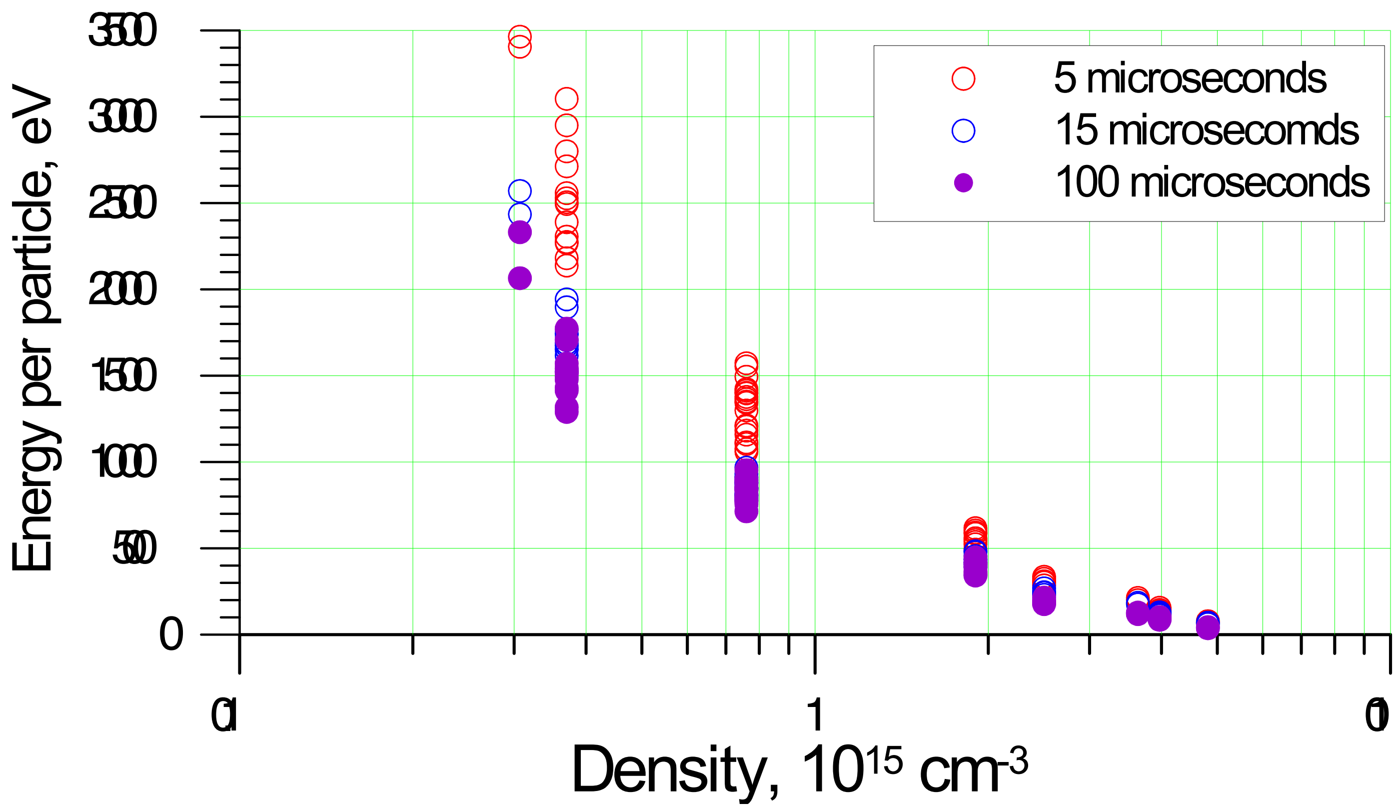
Thomson scattering spectra
t=6μs after the beam start, $n_p=4x10^{14}cm^{-3}$



Result: microsecond REB with small angular spread can be used for effective heating of plasma electrons in multi-mirror trap

Plasma heating

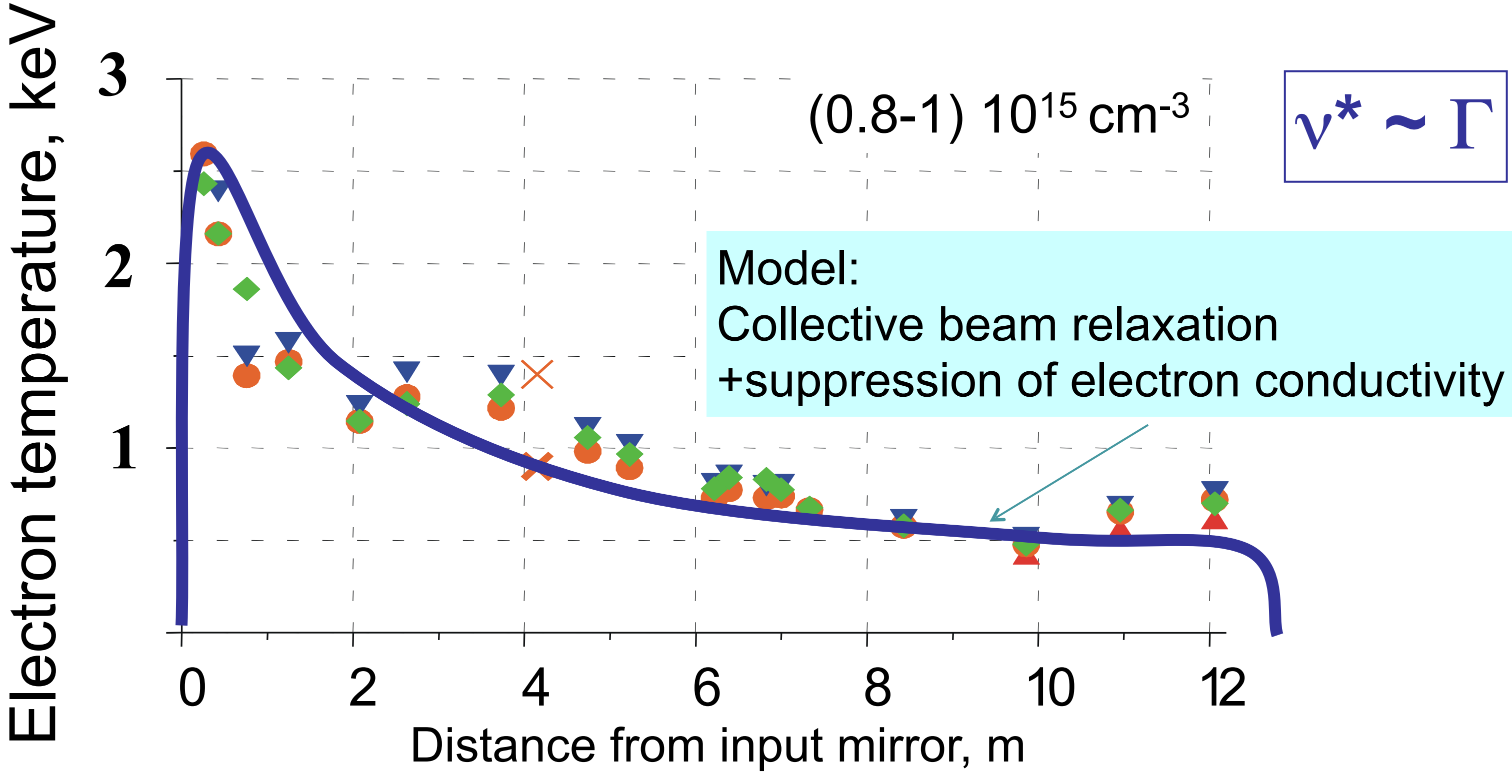
Average particle energy in heated plasma on its initial density at the same beam current density ~2kA/cm^2



Result: the dependence of energy per particle on plasma density for heating plasma by microsecond beam is close to the one obtained for 100ns REB

Suppression of axial electron heat flux

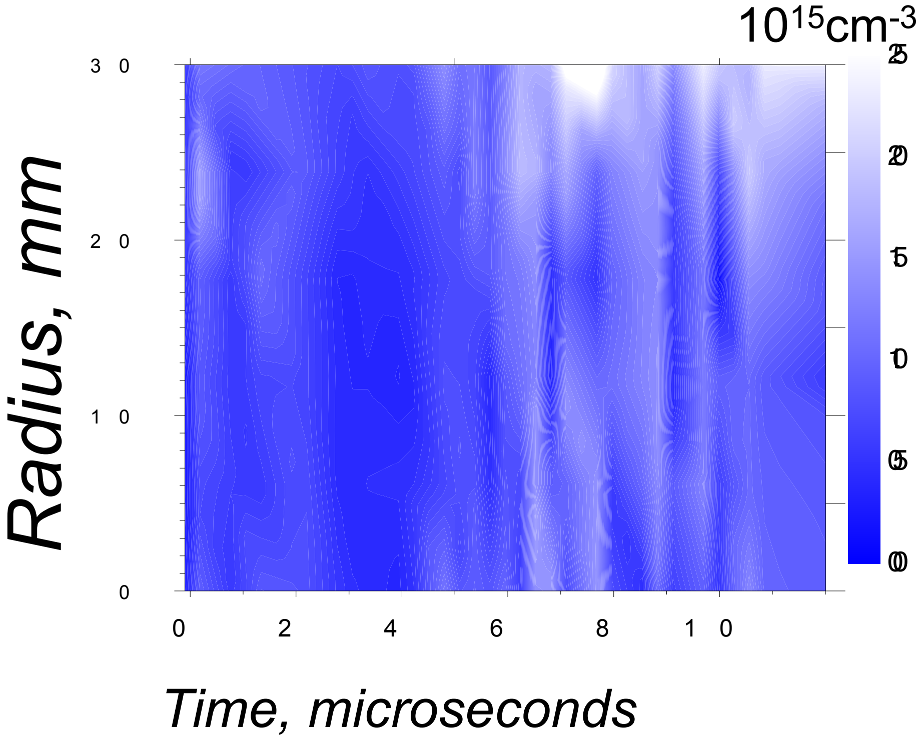
Diamagnetism and Thomson scattering data, comparison with theory



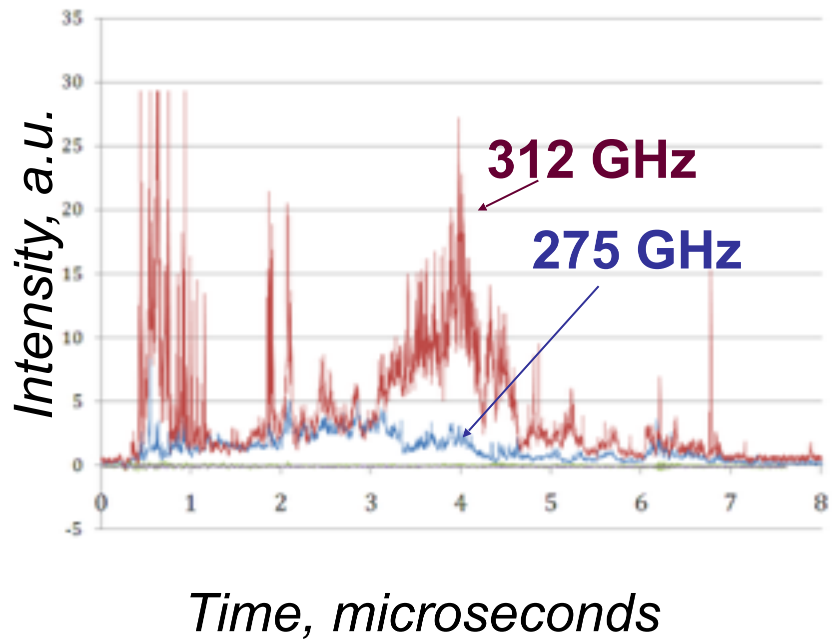
Discrepancy: at such electron temperatures the plasma cooling time should be << 1μs, hence at the known rate of heating such temperatures are unreachable. It means that some additional scattering of electrons suppresses electron thermal conductivity. The best candidate is fluctuations of plasma density produced by the developed Langmuir turbulence. In accordance with observed temperature gradients the collisional frequency should be multiplied by factor ~1000 that makes it close to the increment of two-stream instability. The model based on anomalous collision frequency $\nu^* = \Gamma$, well describes the temporal and space behavior of the electron temperature in the trap.

Collective e-beam relaxation leads to strong density fluctuations

Thomson scattering:
Density profile (shot-by-shot)



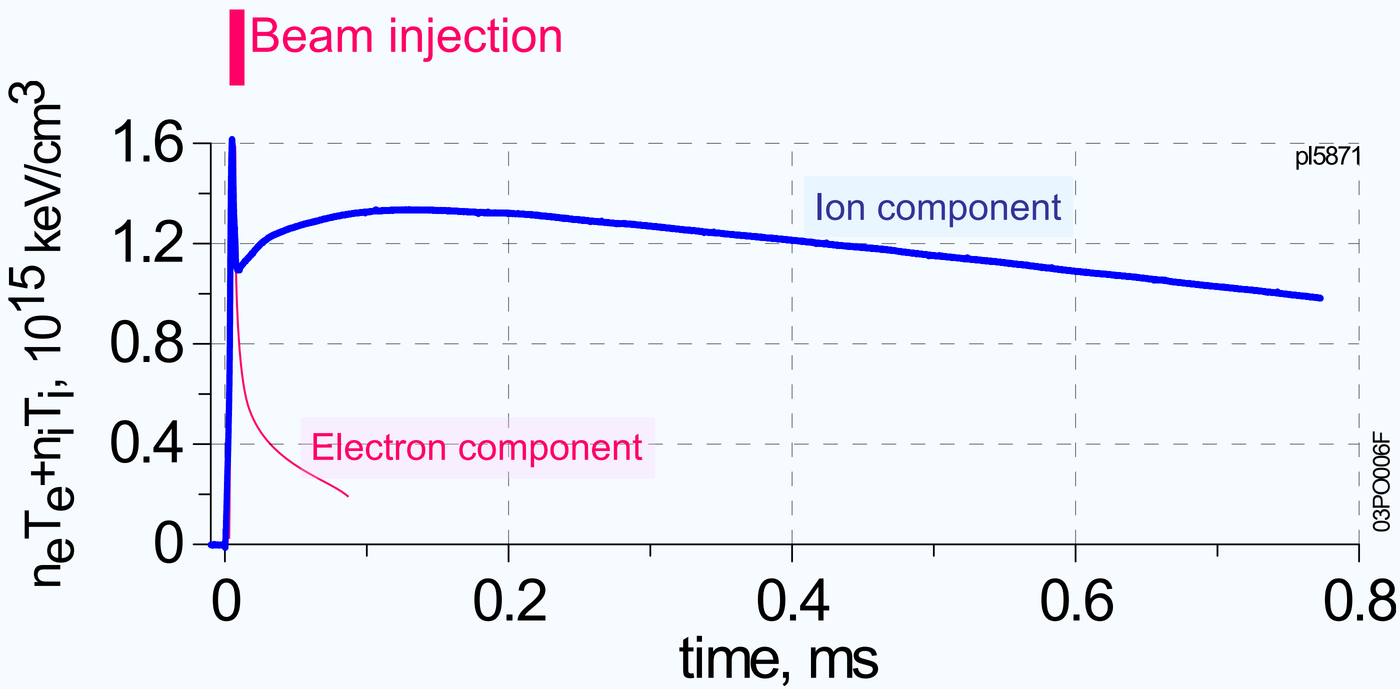
Sub-mm emission near double plasma frequency



Plasma density fluctuations are responsible for suppression of axial heat transport. Radial losses of energy are negligible

Plasma heating

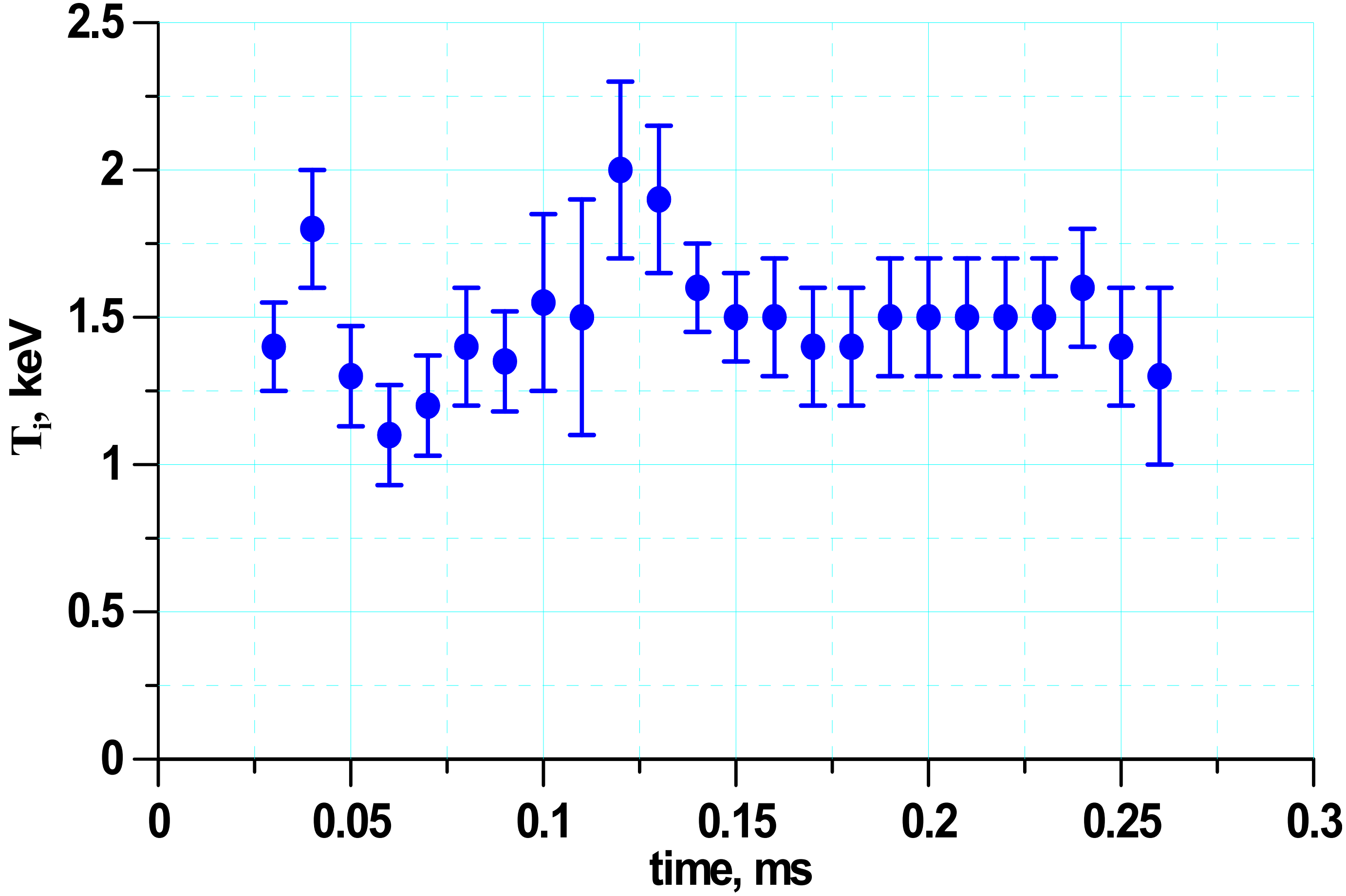
Result of plasma pressure measurements in multi-mirror trap.
($1.5\ 10^{15} cm^{-3}$), z=2.08 m



The part of the beam energy during the beam pulse is transferred to the plasma electrons. After the end of beam T_e drops quickly with τ~15μs but T_i is increasing up to 0.1ms. From simple estimates the electrons cannot heat the ions by collisions during this time. What is the mechanism for so fast ion heating ?

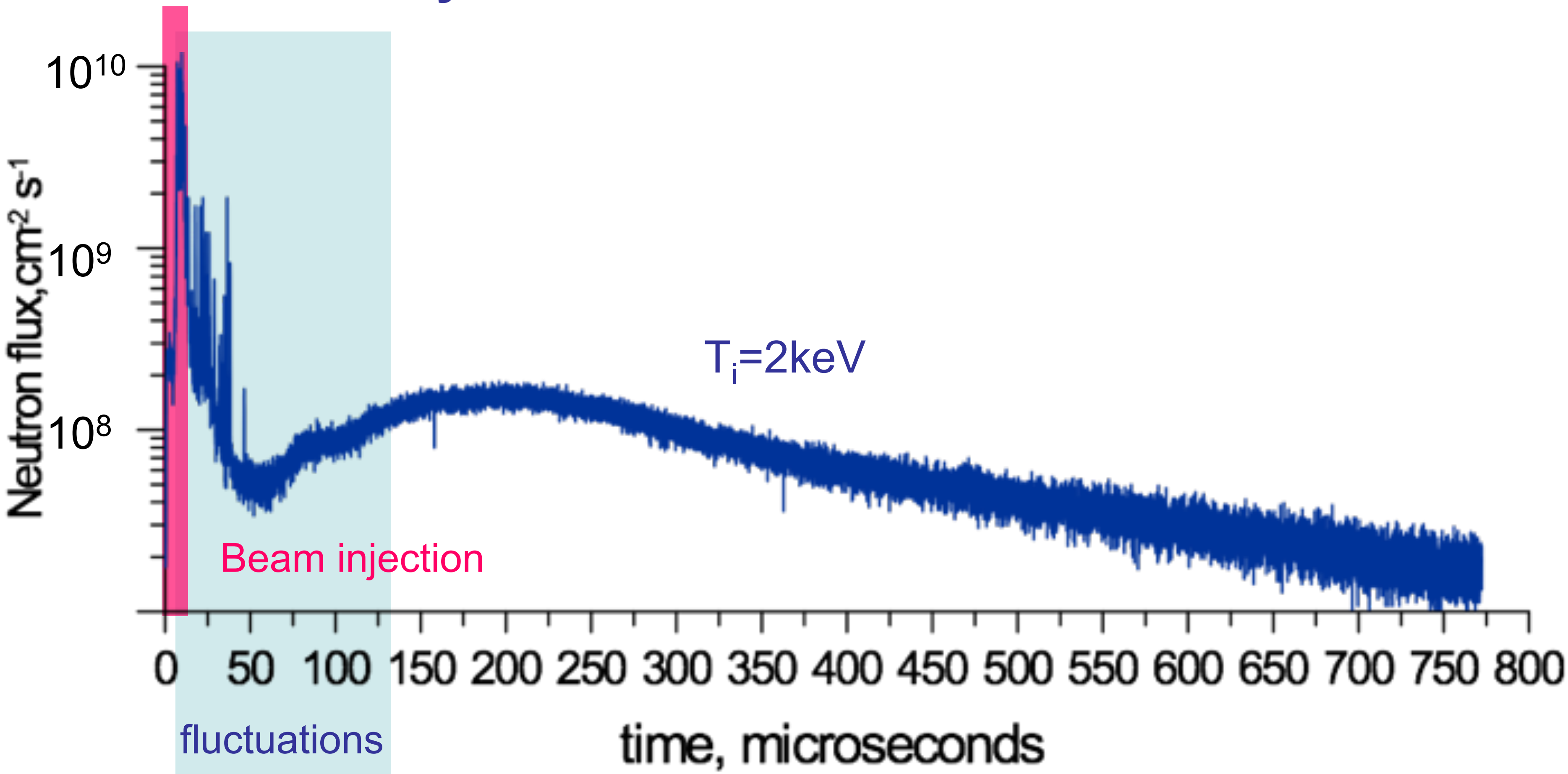
Fast ion heating in multi mirror trap

Temporal variation of ion temperature measured via Doppler broadening of D_a spectral line .
Initial plasma density - $0.3 \cdot 10^{21}$ m^{-3}.



Fast ion heating in multi mirror trap

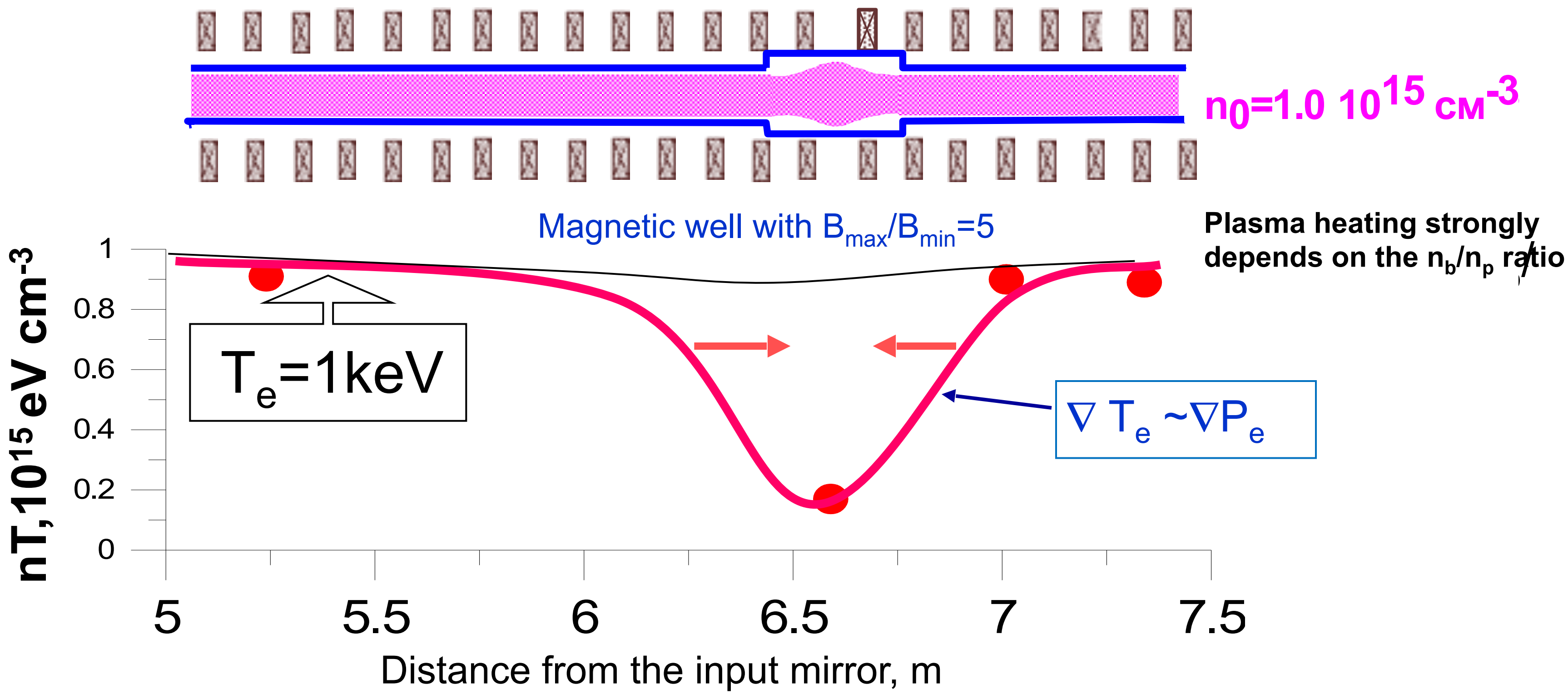
Intensity of DD neutron emission from cell



- In the fluctuation stage, the ion component acquires energy (mainly a longitudinal one) due to the effect of fast ion heating in the multi mirror trap.
- After thermalization of ions the transverse energy of ions increases and then drops due to the losses

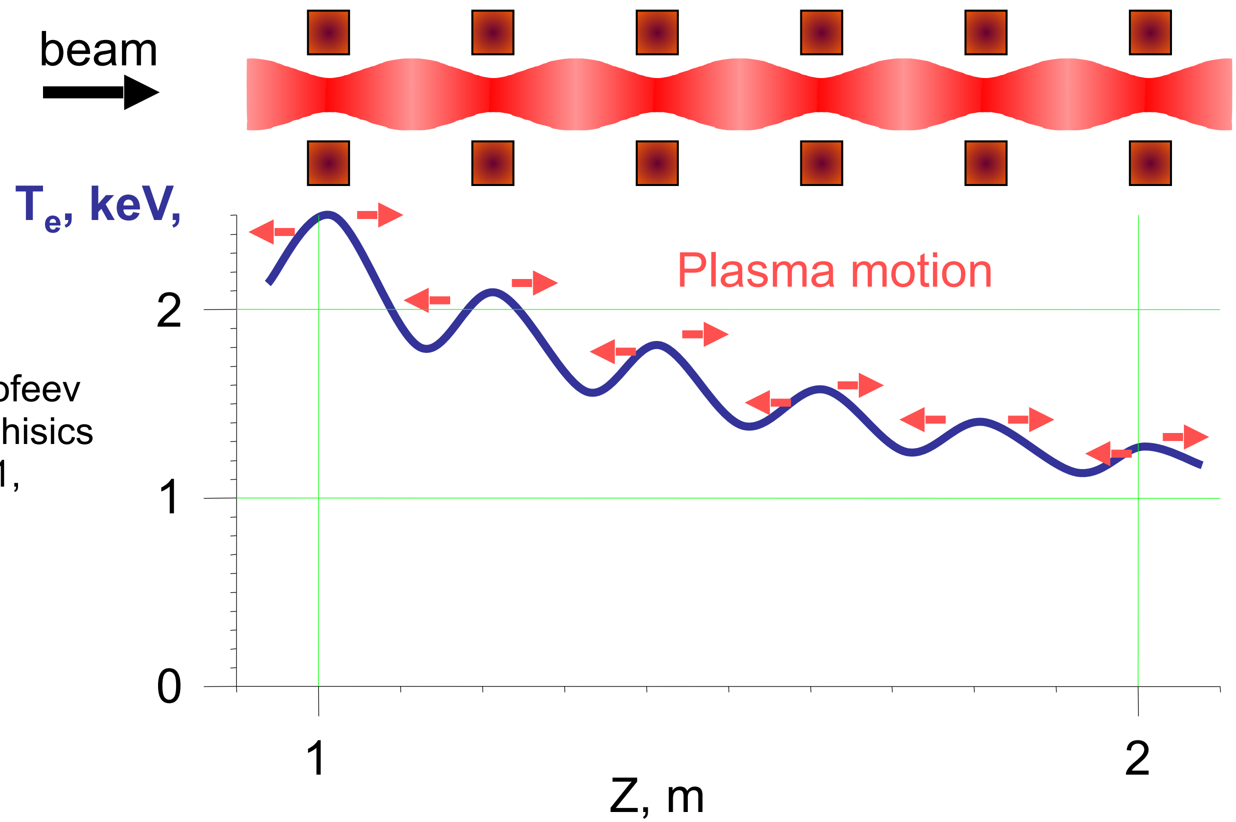
Suppression of electron thermal conductivity (experiment with magnetic well)

This experiment is a key for understanding the effect of fast ion heating



- The non-uniform electron pressure produces a longitudinal ambipolar electric field, which accelerates the plasma ions on both sides of the magnetic well toward the central plane of the cell, where the counter-propagating plasma flows collide.
- The kinetic energy of the directed ion motion is transformed into their thermal energy.
- Efficiency of this heating mechanism is higher than that determined by binary electron–ion collisions.

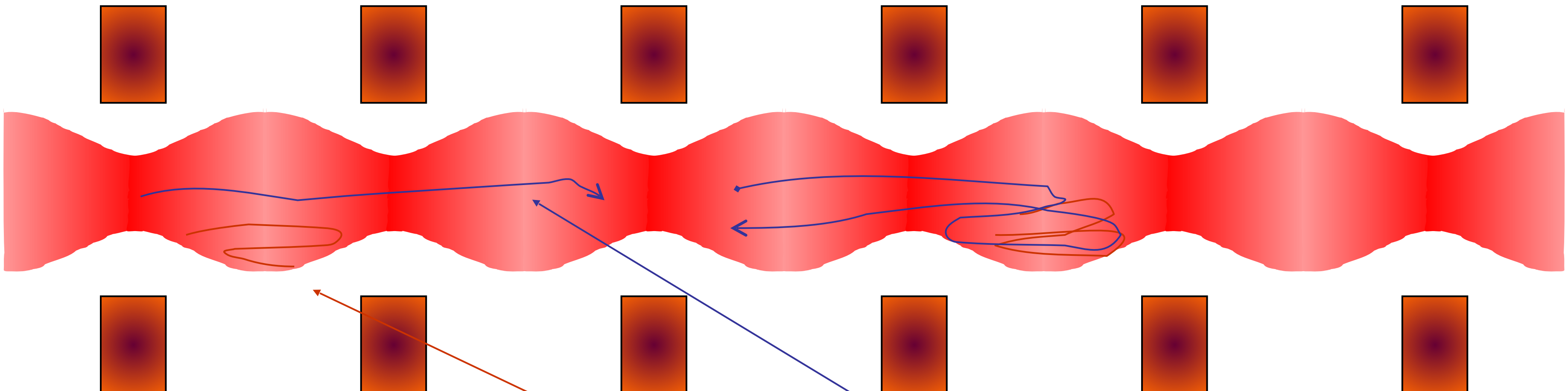
Fast ion heating in multi mirror trap



Theory: A.V.Timofeev and K.V.Lotov, Phisics of plasmas, **13**, 1, (2006).

- The beam energy deposition is non uniform along the system. It results in high pressure gradients inside mirror cells along the magnetic field and macroscopic motion of the plasma. These gradients determine two kinds of plasma motion: local - inside each cell and global one - along the system.
- Both these kinds lead to fast energy transfer from the electron to ions that is much faster than due to binary collisions. As a result, electron and ion plasma temperatures up to 2-4 keV at density ~10^{15} cm^{-3} are achieved.

Effects of ion dynamics in multi-mirror trap on plasma confinement



There are two sorts of ions in the multi-mirror trap: "trapped" and 'transiting"

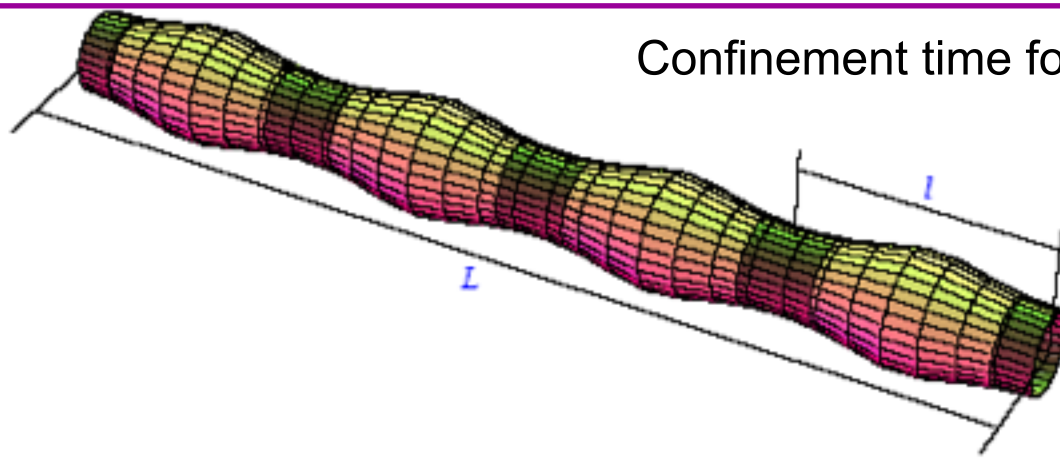
Due to collisions 'transiting" ion will be trapped in one of the cells. When after a few oscillations it again becomes transiting, the direction of its motion changes randomly with respect to the its initial direction. **It means a slow diffusional decay of plasma!**

$$\boxed{\tau \sim R^2 \frac{L^2}{\lambda_i V_{Ti}} = R^2 \frac{L}{\lambda_i} \tau_0}$$

~10²

$$R = \frac{B_{max}}{B_{min}} \qquad \tau_0 \sim \frac{L}{V_{T_i}}$$

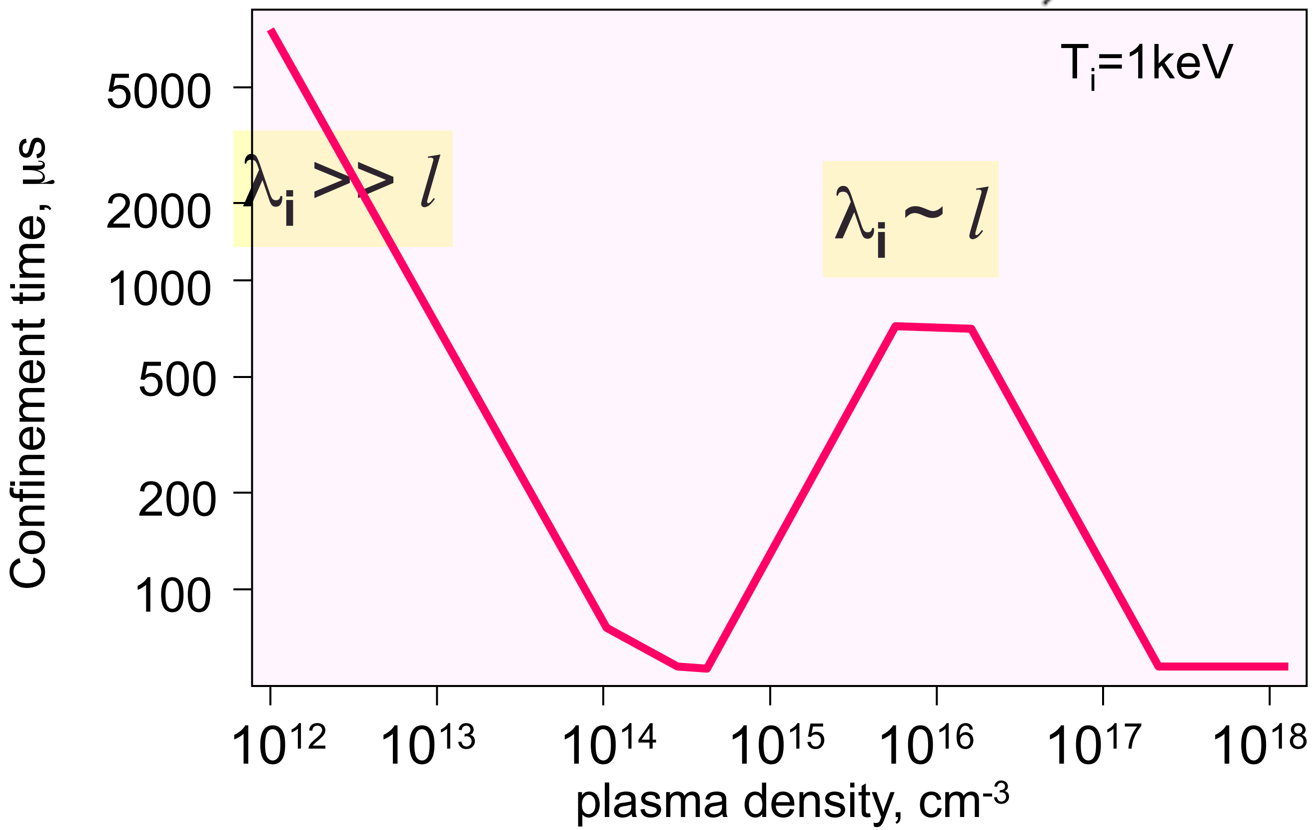
Multi mirror plasma confinement



Confinement time for conditions of GOL-3

$R=1.5$

$L/l=55$



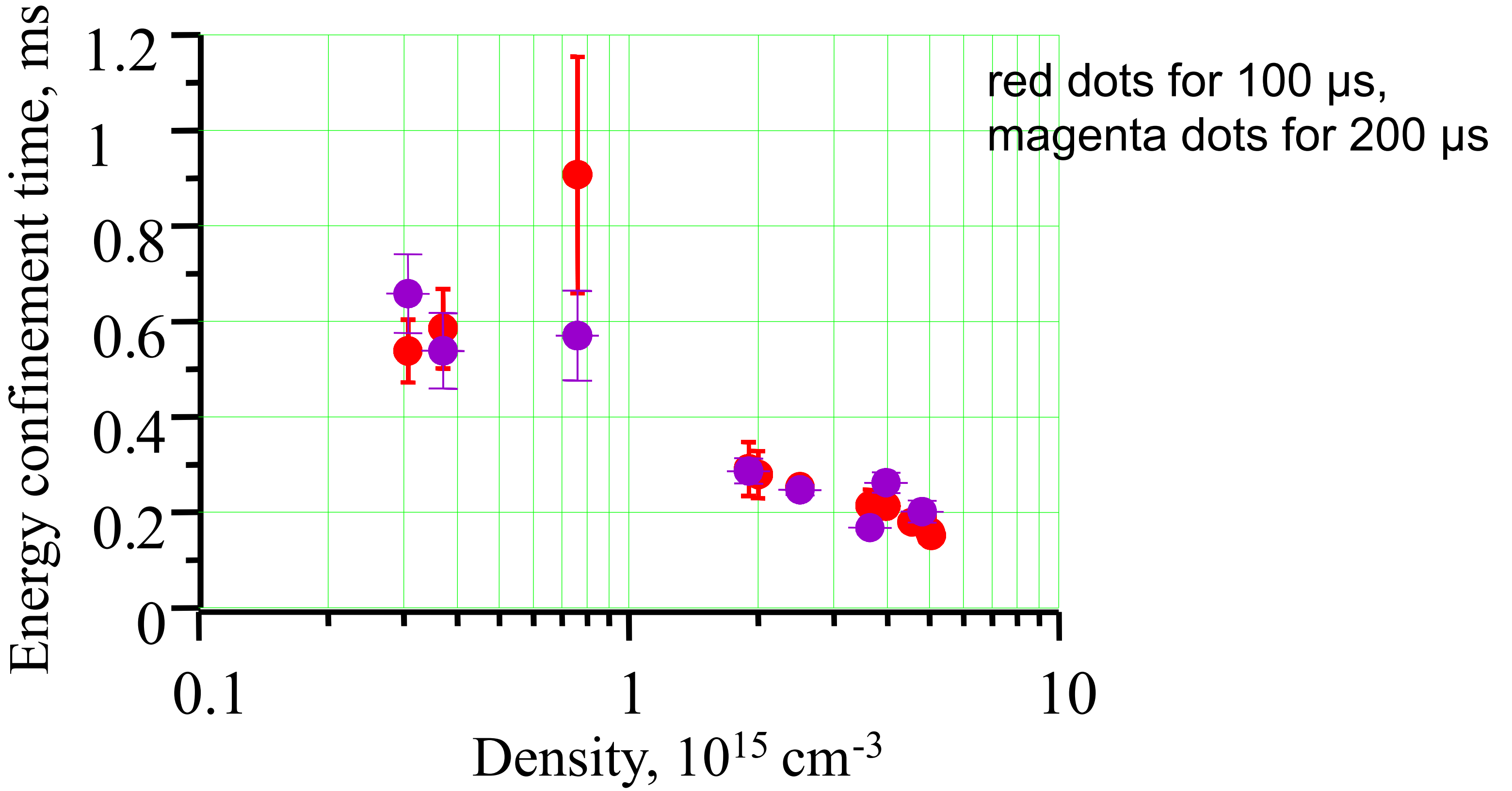
$\tau \sim \tau_0 L/l$

$\tau_0 \sim \frac{L}{V_T}$

Theory: I.A. Kotelnikov, Fusion Science and Technology, 51, N 2T, p. 186 (2007)

Plasma confinement

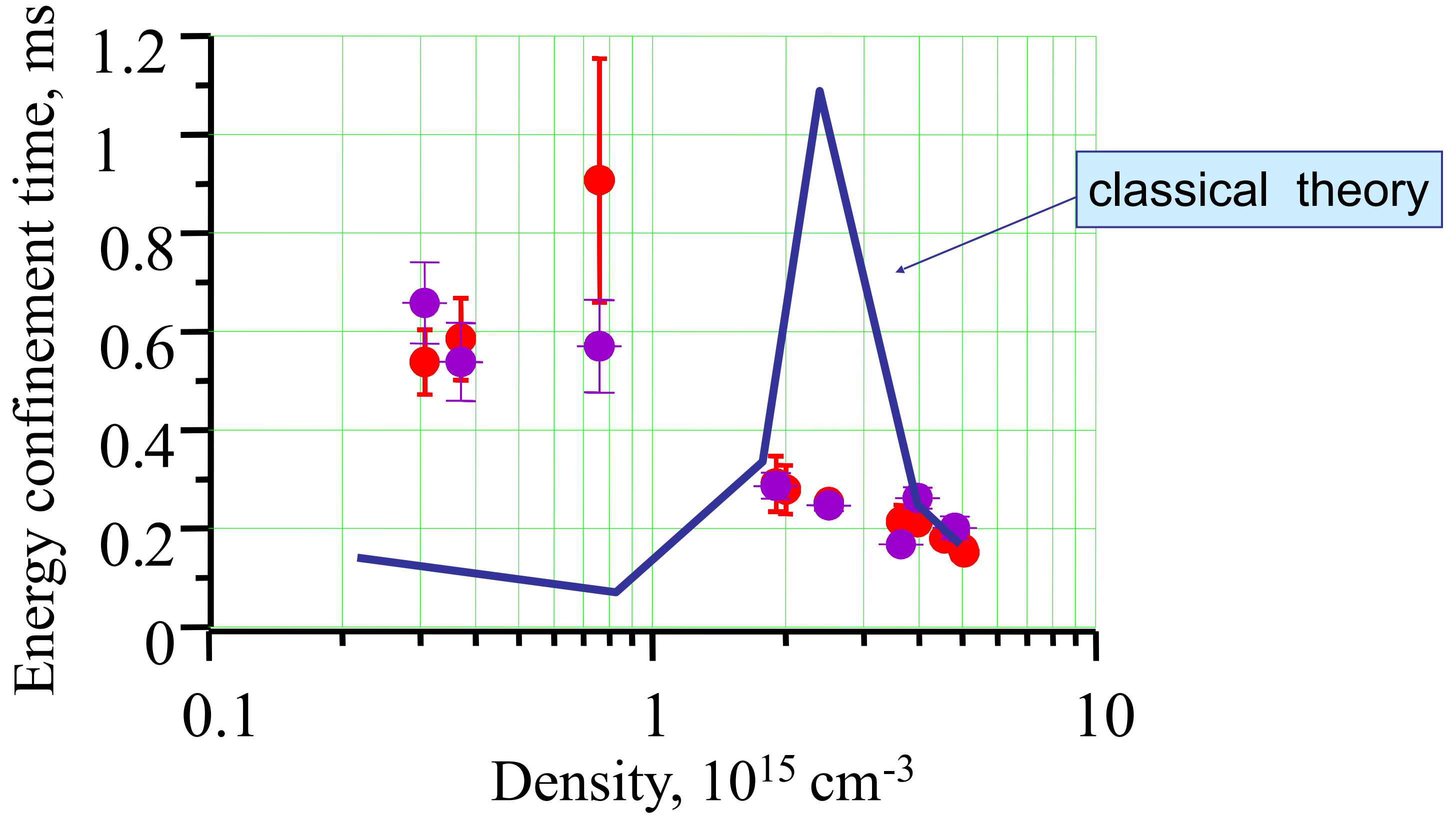
Dependence of global energy confinement time on plasma density



Comparison of data with the theory prediction for classical binary collisions indicates that energy confinement time agrees well with the theory,

Plasma confinement

Density dependence of global energy confinement time



Comparison of data with the theory prediction for classical binary collisions indicates that energy confinement time agrees well with the theory, but optimal density for the longer confinement regime is shifted to the lower density.

Plasma confinement

Increased energy confinement time in the multi mirror trap GOL-3 (~1ms) corresponds to theory predictions but it is achieved at much lower density, than predicted.

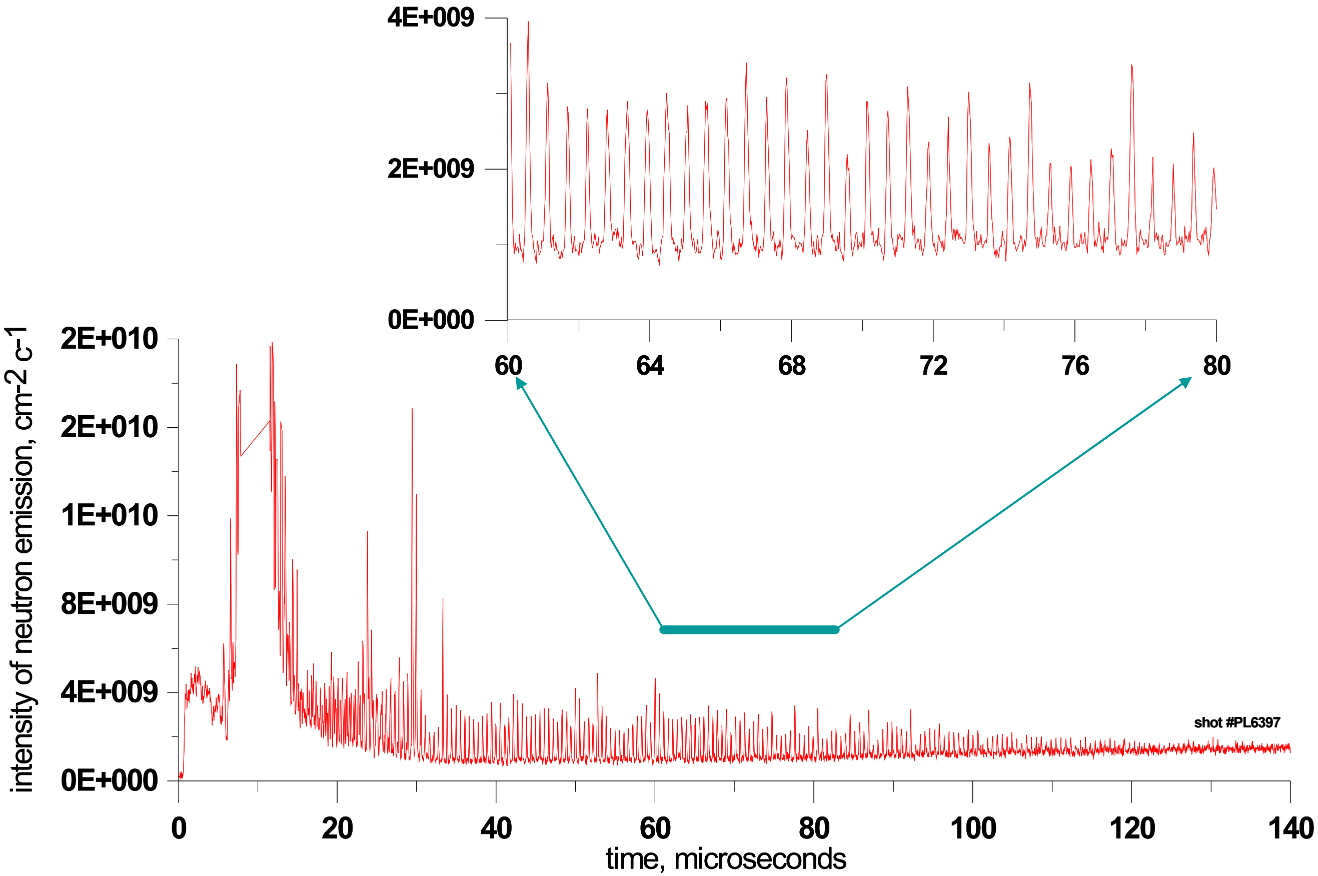
Good confinement indicates that effective collision frequency in the plasma exceeds the classical value by a factor of few tens.

This fact is beneficial for multi-mirror-trap-based fusion reactor concept.

Possible mechanism of the longitudinal confinement improvement is excitation of bounce-oscillations in cells.

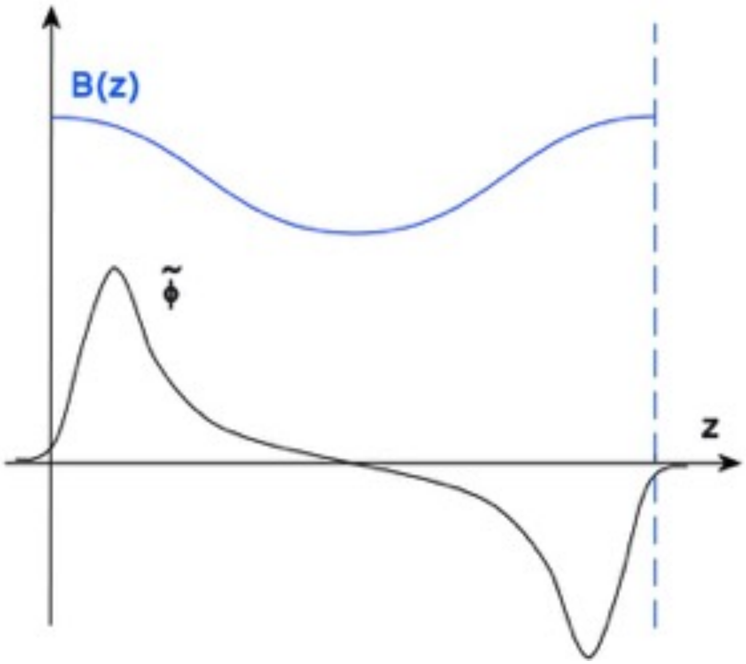
Bounce oscillations of fast ions in separate cells

Periodic oscillation of neutron emission observed in the experiments



Oscillations confirm the excitation of bounce oscillations of ions in cells of multi mirror trap

Bounce oscillations of fast ions in separate cells



$$\omega \sim \frac{C_s}{l}$$, C_s is a sound velocity

Perturbations of density is odd and are peaked near reflection points of resonant ions.

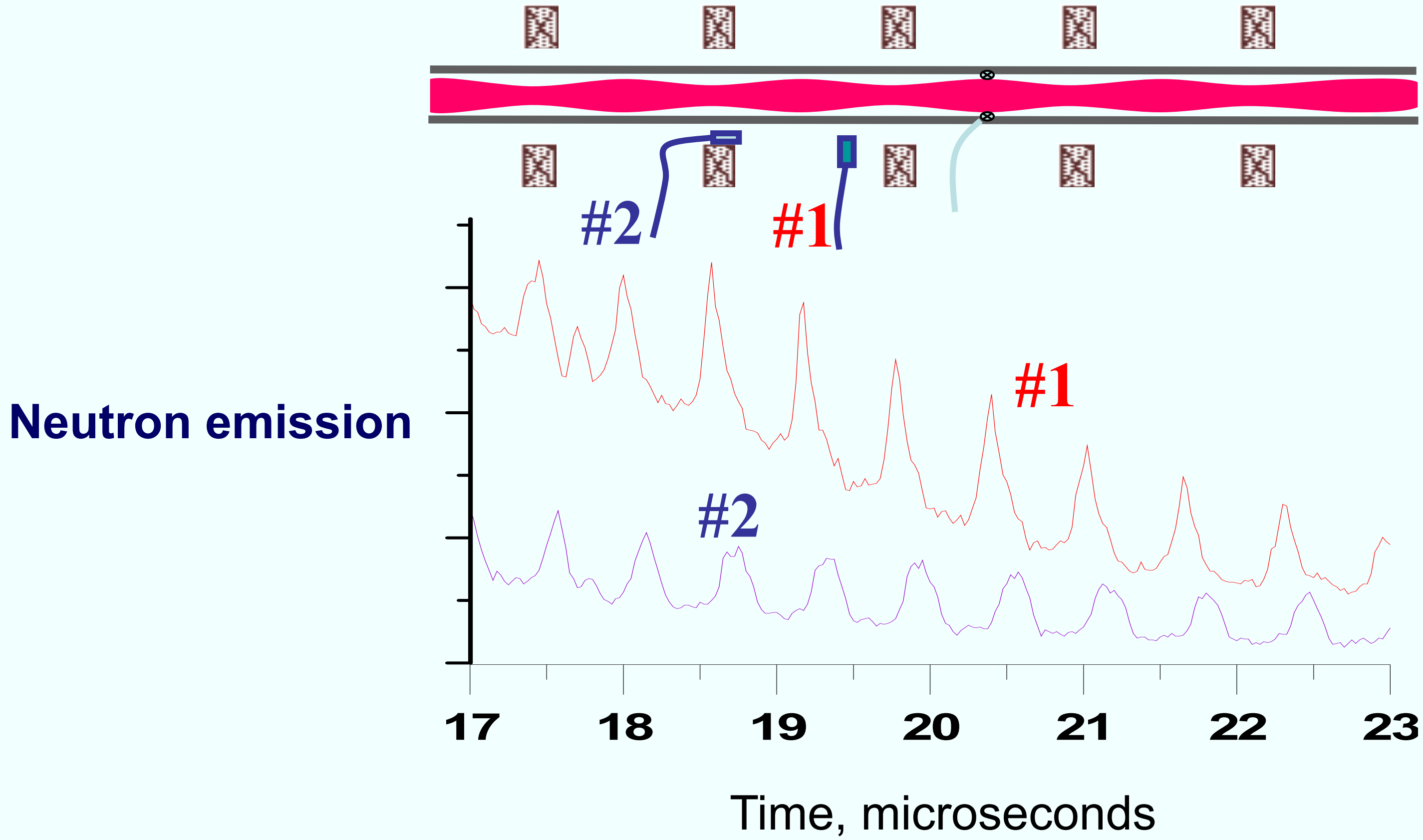
- The plasma motion in the axial direction through the multi-mirror system excites the bounce oscillations inside *separate cells*. Period of oscillations agrees well with the predicted period for bounce oscillations.
- These oscillations induce effective scattering of “transiting” ions, therefore the plasma confinements in the multi mirror system improves and the maximum of lifetime is shifted to the lower density.

Theory: A.D. Beklemishev, Fusion Science and Technology, 51, N 2T, p. 186 (2007)

Bounce oscillations of fast ions in separate cells

Theory predicts phase shift of DD neutrons splashes along cell

Two local neutron detectors was placed near maximum of the magnetic field in one cell



Phase shift of neutron emission in separate cell of the trap was observed.

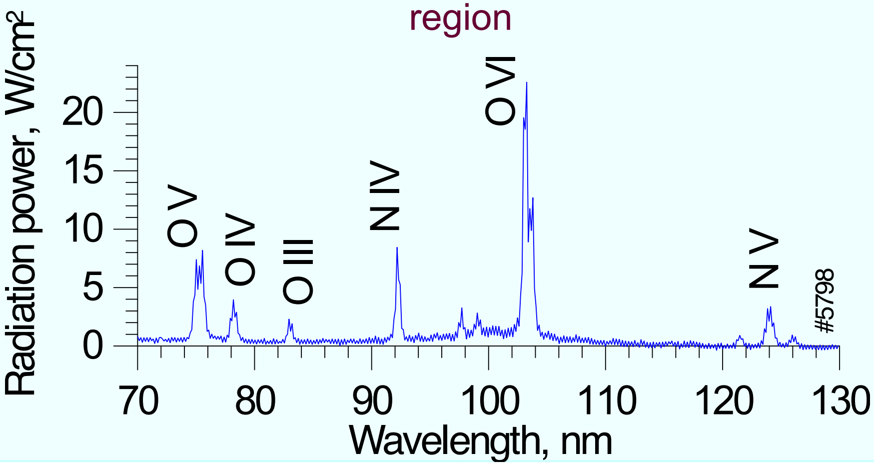
Plasma confinement

Good confinement indicates that effective collision frequency in the plasma exceeds the classical value by a factor of few tens.

Special measurements of an effective charge of plasma have shown that such scattering may not be provided with scattering on impurity ions.

Measurements of transverse loses and Z_{eff}

Power of plasma radiation in VUV spectral region

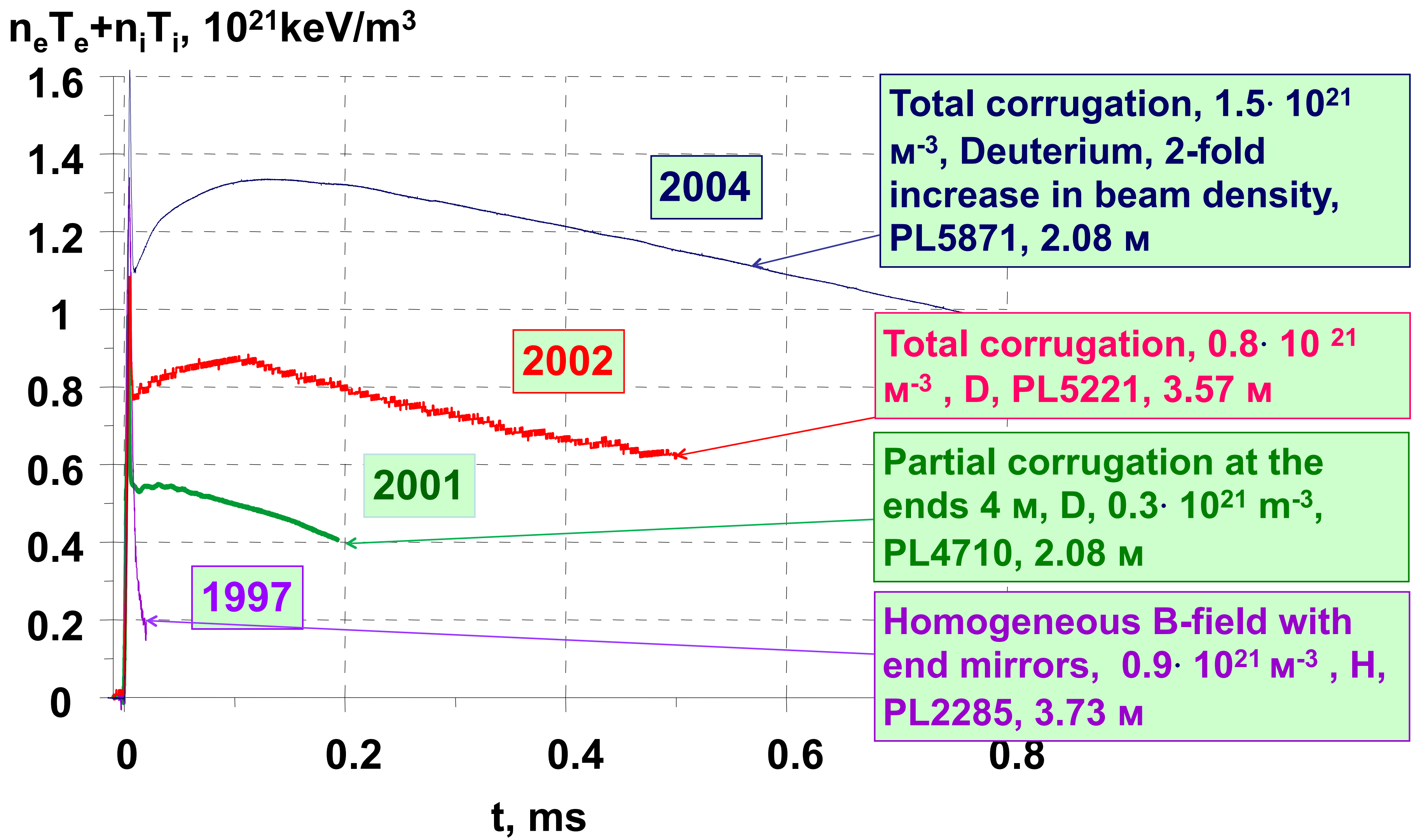


Impurity concentration is equal
$n_O=10^{12}$ cm^{-3} $n_C=2x10^{12}$ cm^{-3}

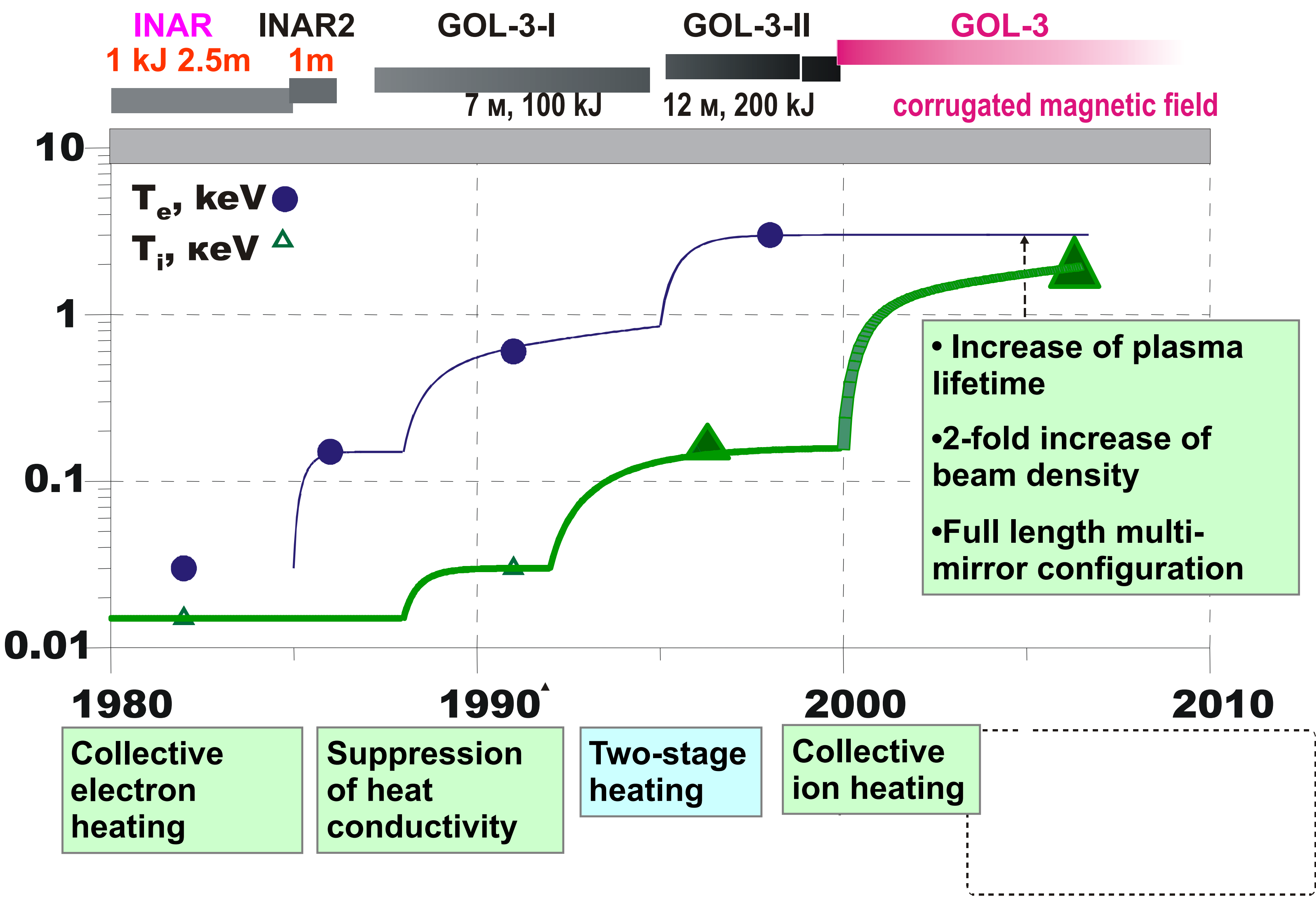
Z_{eff}=1,2 – 1,6

PROGRESS IN PLASMA PARAMETERS of GOL-3

Plasma diamagnetic signals (transverse plasma pressure) for various magnetic configurations



TIME DIAGRAM OF REACHED PLASMA TEMPERATURE



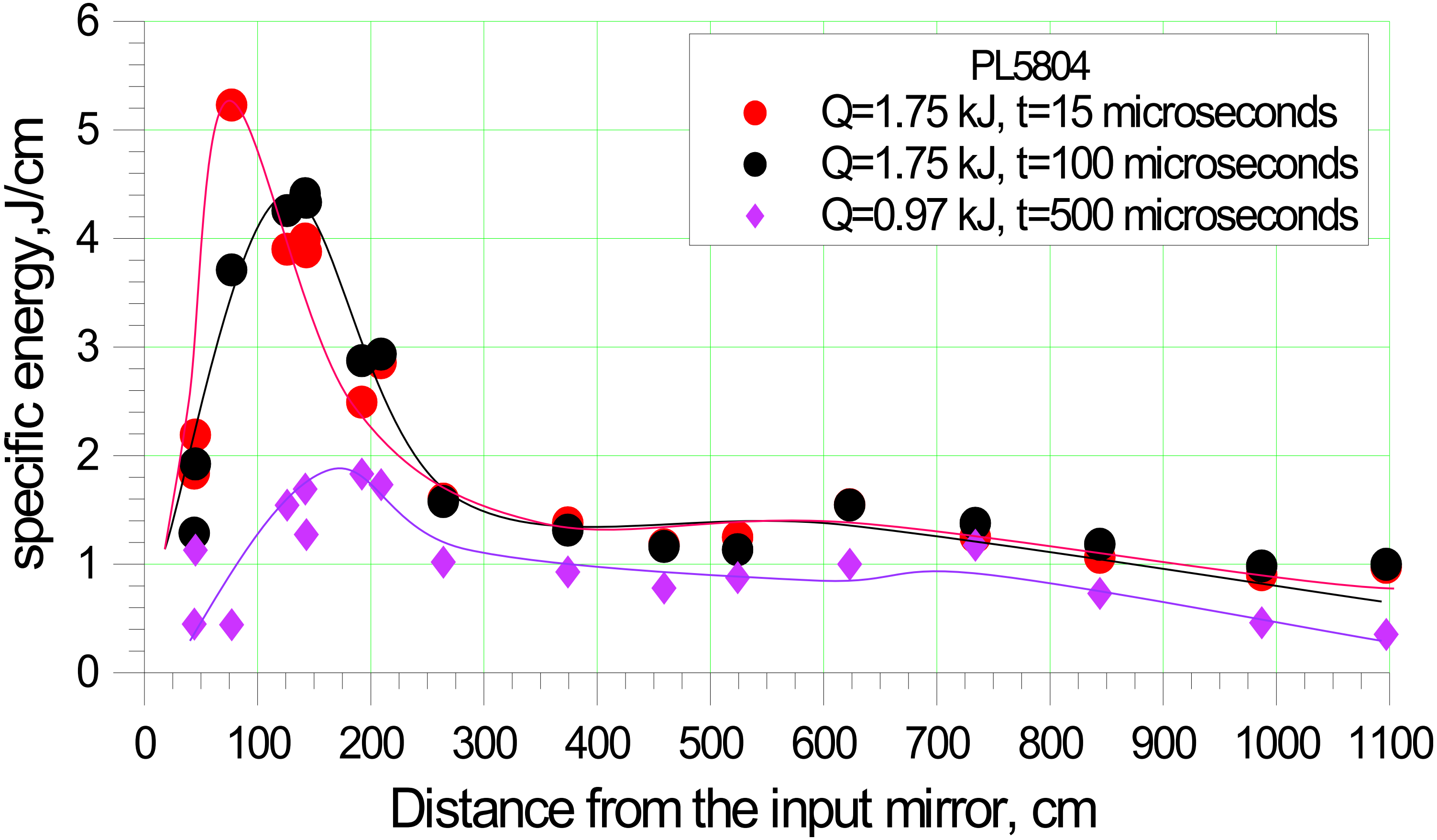
Summary

- Conditions for stable beam transport in the preliminary plasma of multi-mirror trap have been found.
- Practically all the characteristic features of the beam-plasma interaction investigated in the experiments with 100ns REBs have been registered in the experiments with microsecond beams.
- New collective effects: suppression of electron conductivity, fast ion heating, MHD stabilization and self-organized confinement due to bounce instability are discovered in the experiments on heating plasma by REB in a multi-mirror trap.
- In the result of collective (turbulent) effects sub fusion plasma parameters (electron temperature ~2-4 keV at $n_p \sim 4 \cdot 10^{14}$ cm^{-3}, ion temperature up to ~2 keV at $n_p \sim 10^{15}$ cm^{-3}, energy confinement time ~1 ms) are reached in the GOL-3 facility.


Thank you…

Plasma confinement

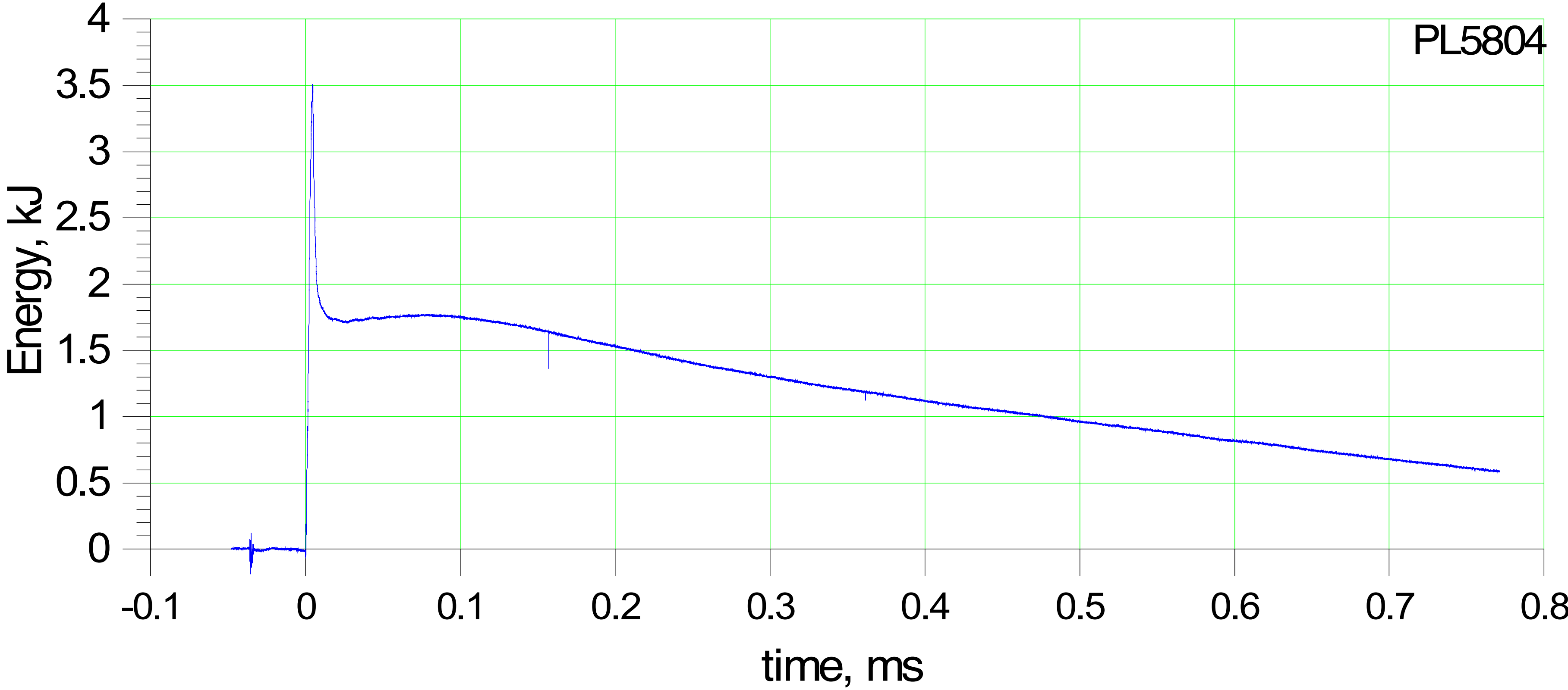
Axial distribution of plasma energy at different time moment.



Slow motion of plasma along the multi-mirror trap due to the gradient of pressure is observed. Especially it is appreciable on distances of 1-3 meters from an input mirror where pressure of plasma is increases.

Plasma confinement

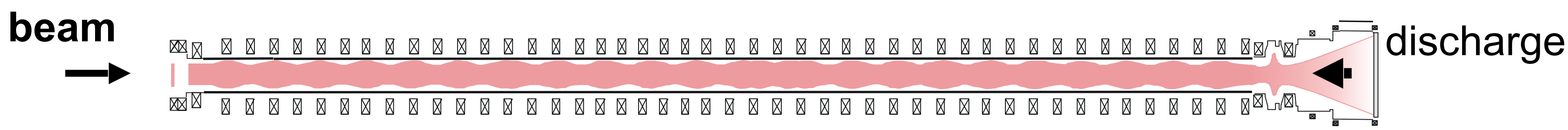
Confinement of full energy in multi-mirror trap

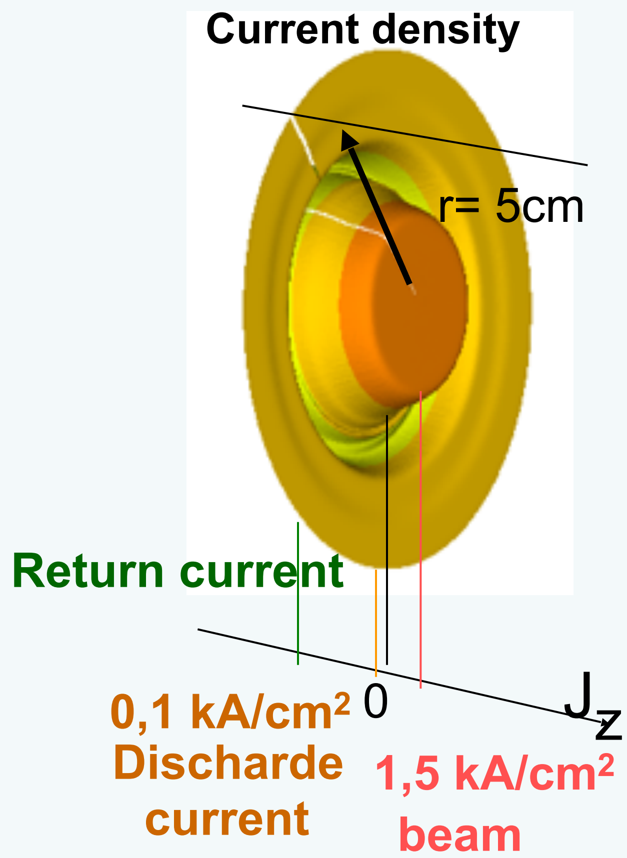


Energy stored in plasma with density of 8×10^{14} cm^{-3}. Confinement time is ~1ms.

Stable operation regimes of the multi mirror trap GOL-3

Plasma in multi mirror trap is MHD-unstable. Special efforts are need to stabilize plasma. Magnetic shear is used for this aim.





Radial profile of local current density is created by three main sources.

external:

- current electron beam
- current of the preliminary linear discharge

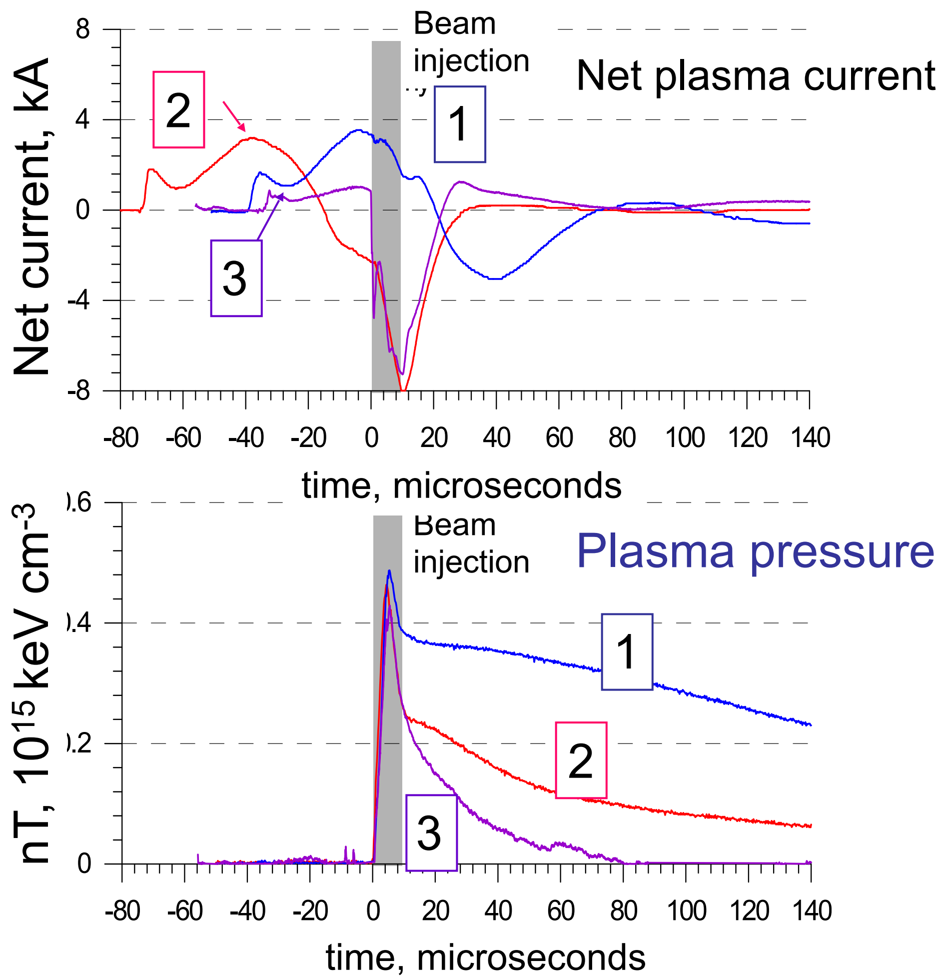
Internal:

- return current to the beam generator.

Result:

Helical structure of the magnetic field with shear is formed

Stable operation regimes of the multi mirror trap GOL-3



1 **Stable regime**

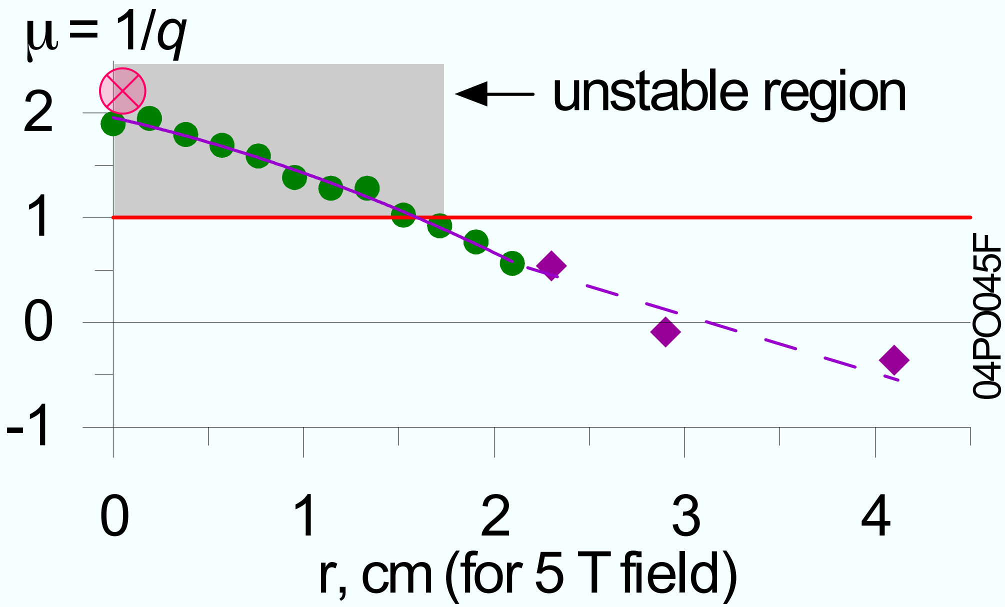
2
3 **Unstable regime**

The stable regime of plasma is reached if discharge current value exceeds 3 kA and is directed opposite to the beam current.
In the GOL-3 conditions the magnetic shear was shown to be the important factor for good plasma confinement.

Stable operation regimes of the multi mirror trap GOL-3

Results of measurements of rotary transformation factor $\mu = \frac{1}{q} = \frac{LB_\phi}{2\pi rB_z}$

Stable regime



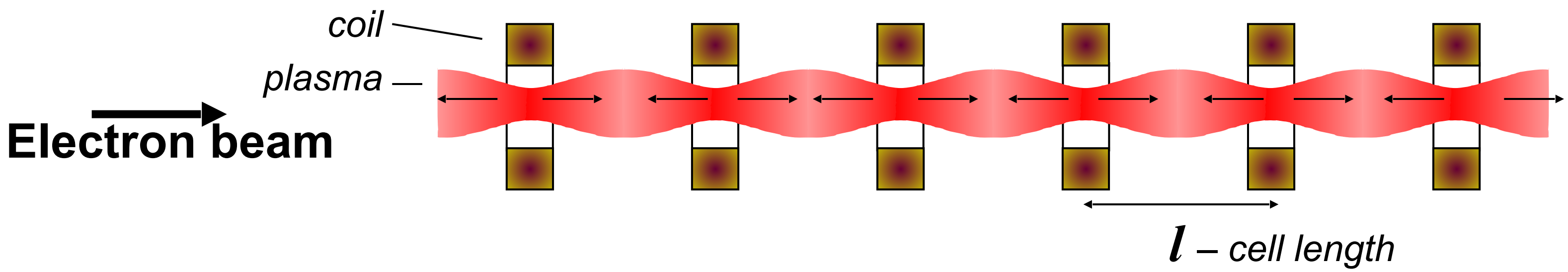
μ is of different sign in the center and at the edge of the plasma

dots- X-ray footprint, cross-current density on exit, rectangles-currents measurements on entrance.

Radial structure of currents results in sheared magnetic field, which can stabilize some MHD modes in the multimirror trap
Plasma in the shaded area is unstable in respect to inner modes.

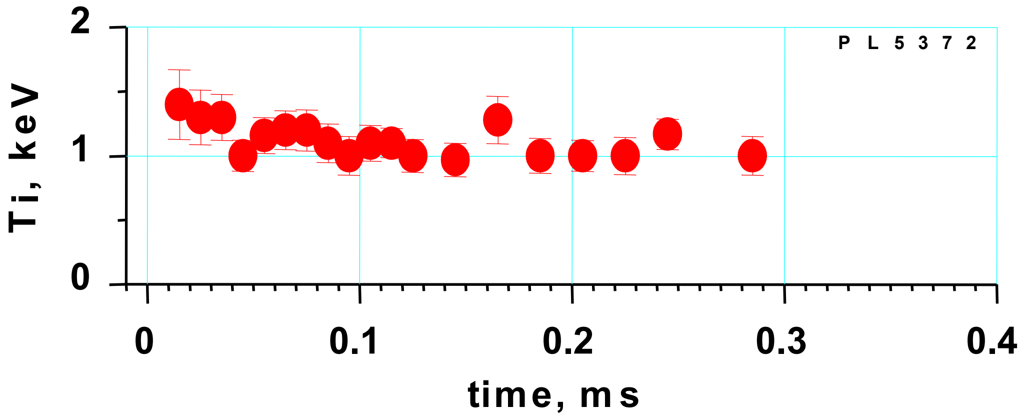
Plasma as a whole is stable

Effect of fast ion heating in multi-mirror trap



• nonuniform plasma heating (which depends on the n_b/n_p ratio, i.e. on the local magnetic field);

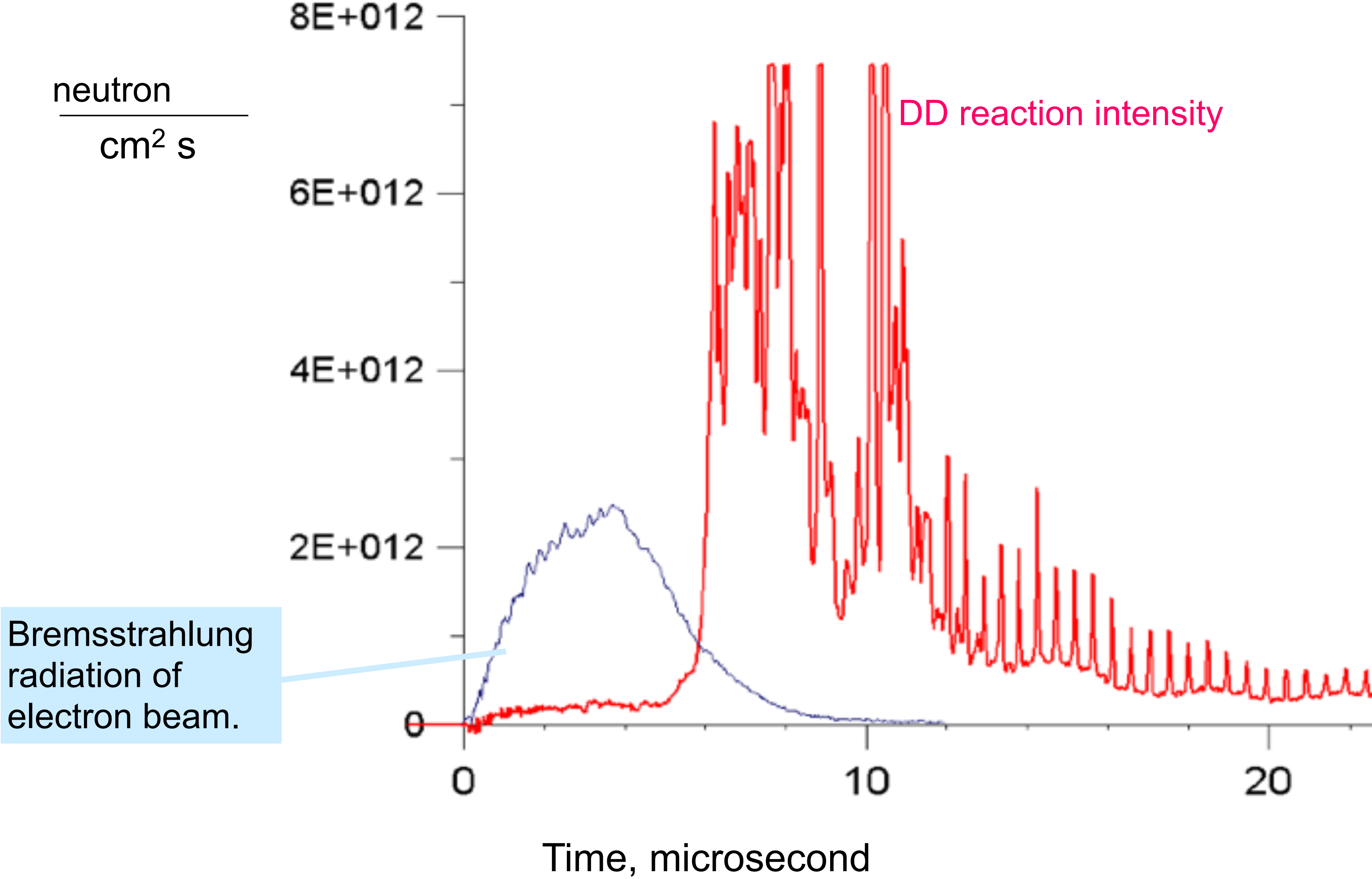
•collective acceleration of plasma flows from the high-field part of corrugation cells to cell's 'bottom';



$3.5 \pm 0.5 \times 10^{14}$ cm^{-3}

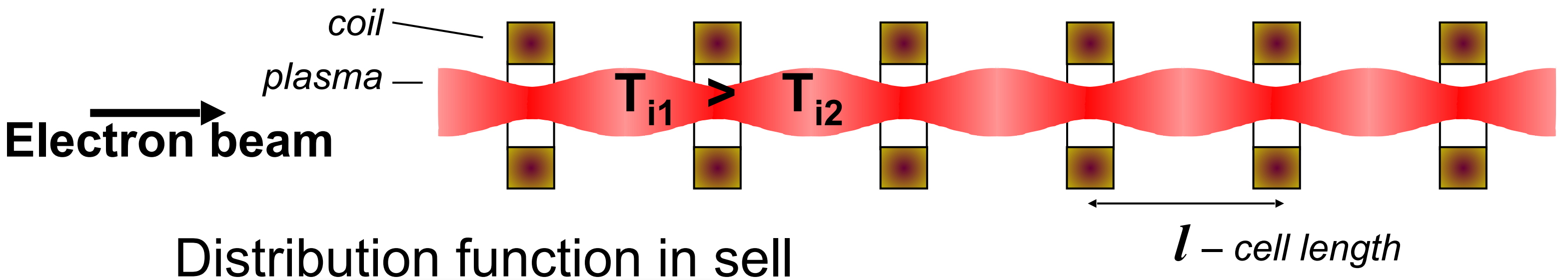
Strong density and ion velocity modulation in cells of the trap.

Effect of fast ion heating in multi-mirror trap

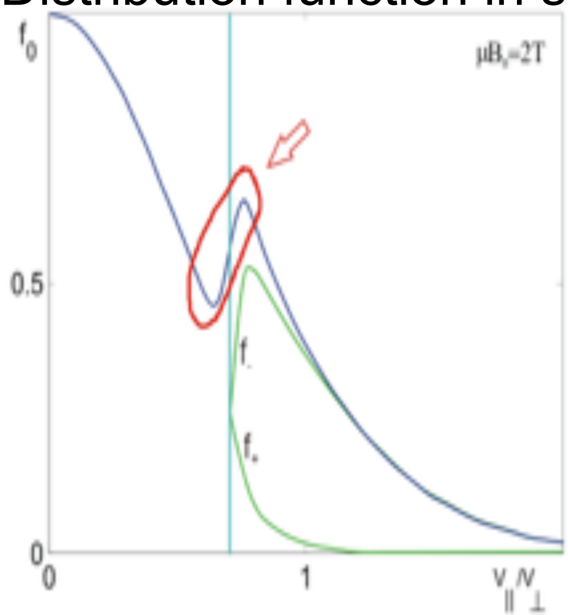


Excitation of plasma density oscillations in the cells on the confinement stage

Ion temperature has axial gradient



Distribution function in sell



Hot flow through a cold cell

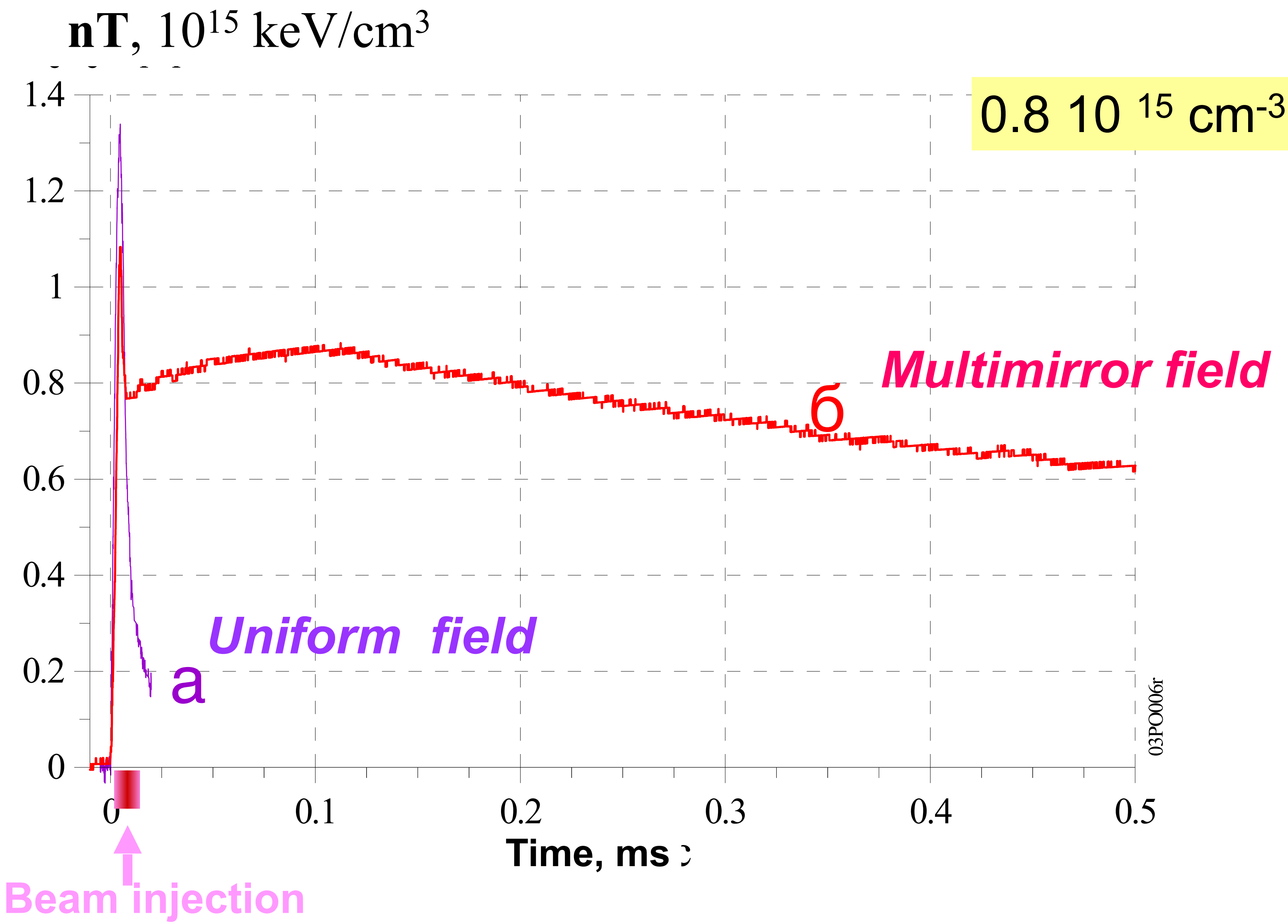
Bounce Instability:

$$\omega \sim \frac{V_{T_i}}{l} \propto \sqrt{T_i}$$

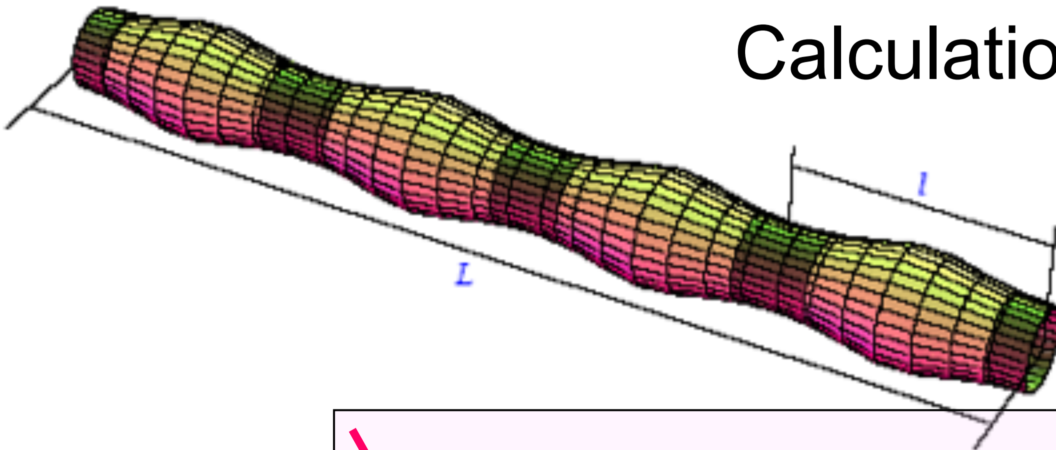
Excited oscillations cause enhanced scattering of transit ions – plasma axial flow slows down

Weakly passing ions are scattered in one cell: $\lambda_{i\,eff} \sim l$

Confinement in GOL-3



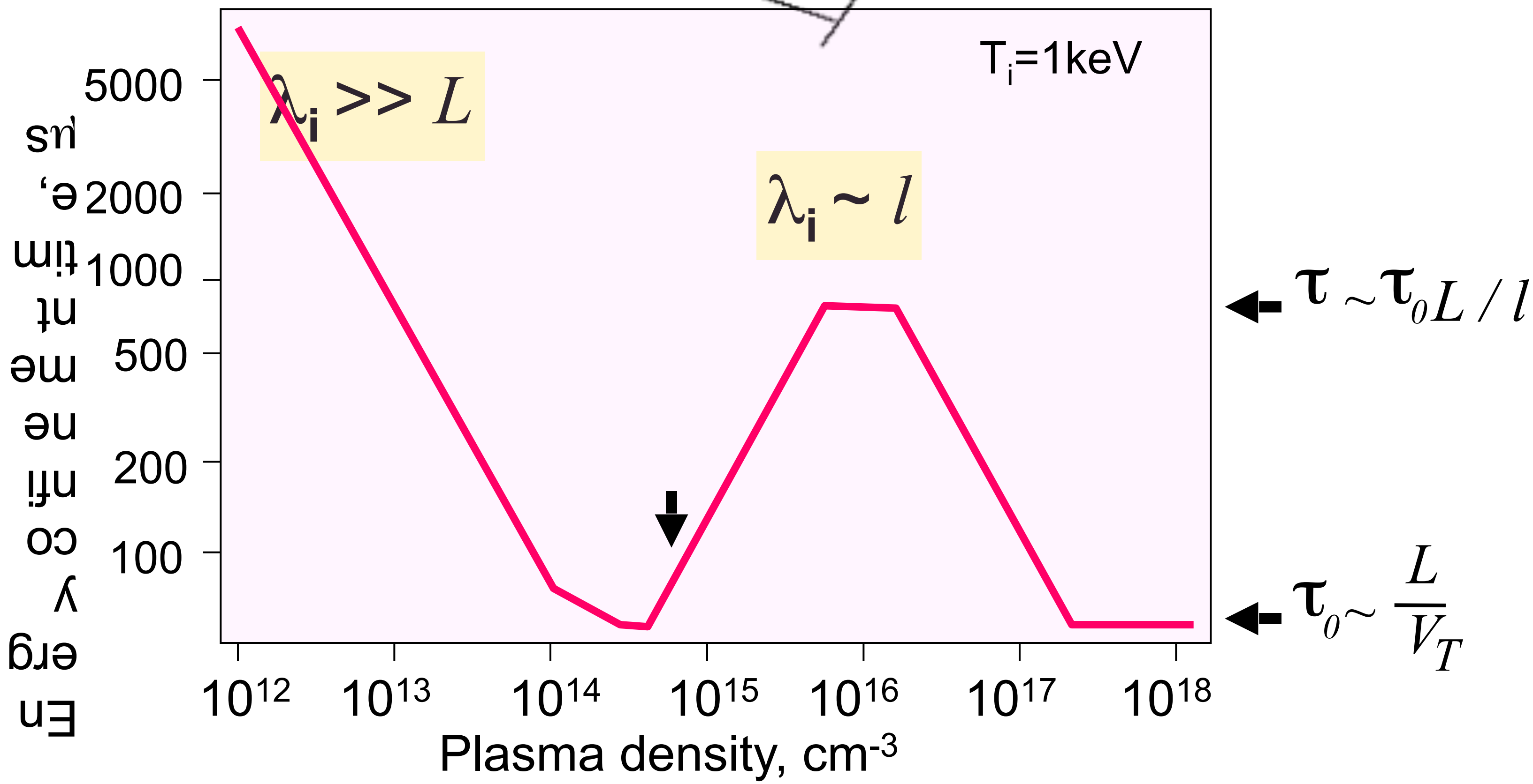
Confinement in GOL-3



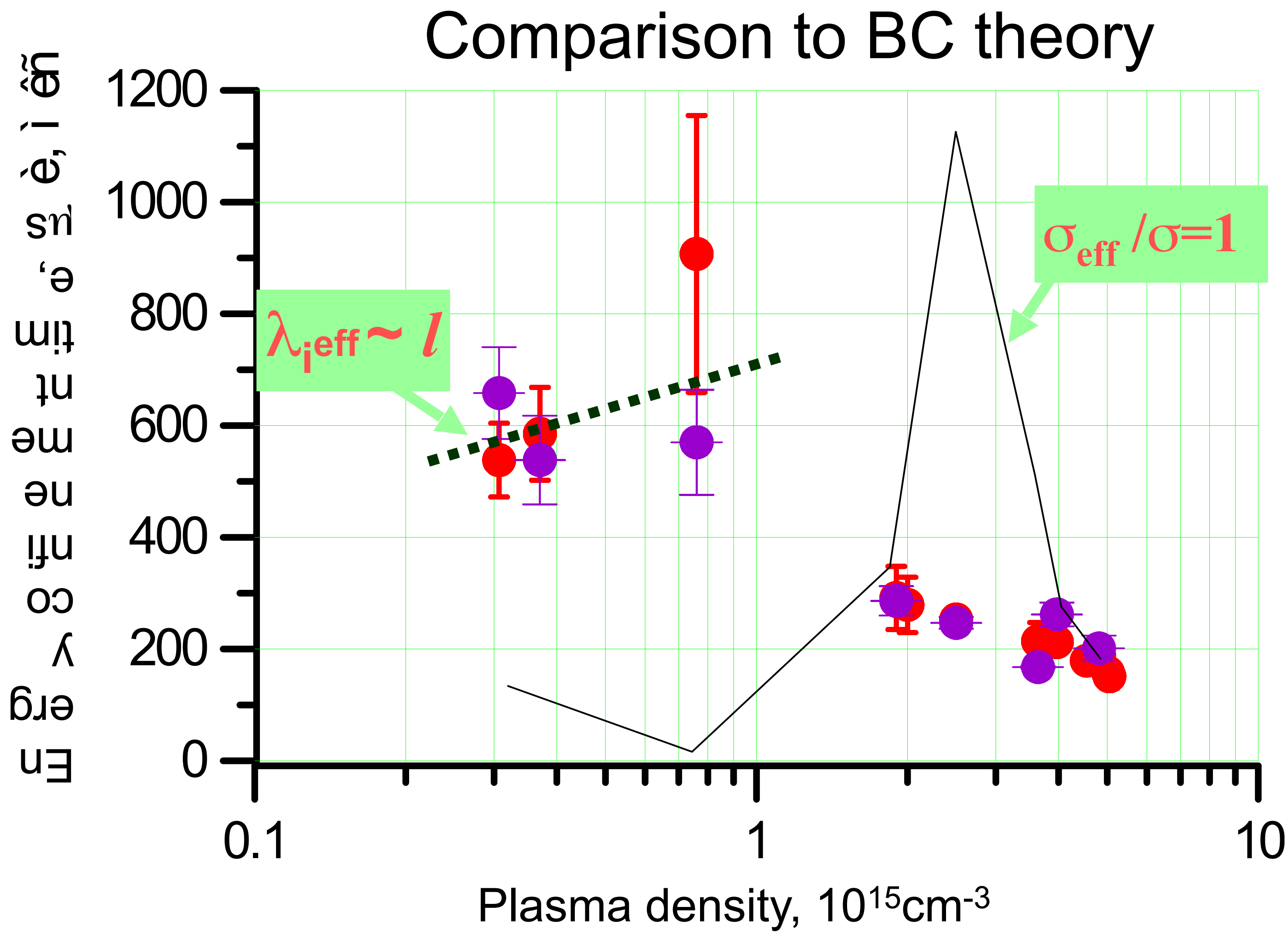
Calculation with BC theory

$R=1.5$

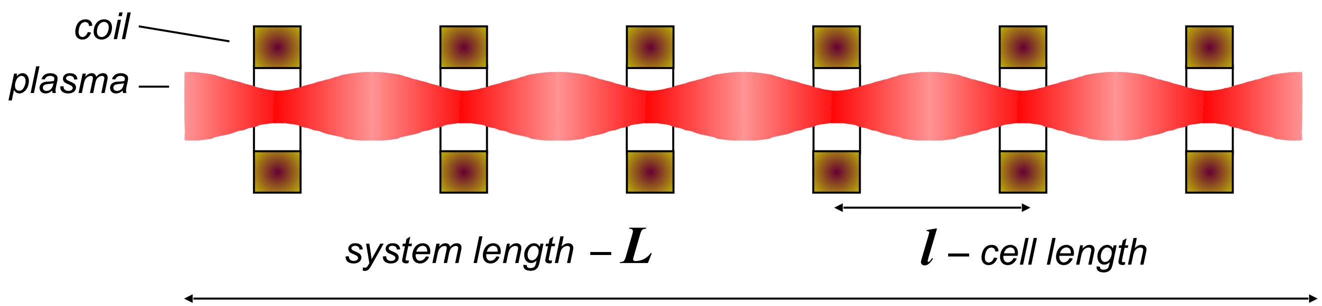
$L\,/\,l=55$



Plasma confinement



Basic Ideas + new paradigm



- The plasma density should be high: free path length λ is much less than system length L

Do not need: $\lambda_* \sim l$ automatically !!!

Rough estimate of the confinement time (BC Theory):

$$\boxed{\tau \sim R^2 \frac{L^2}{\lambda_i V_{Ti}} = R^2 \frac{L}{\lambda_i} \tau_0}$$

BC theory:

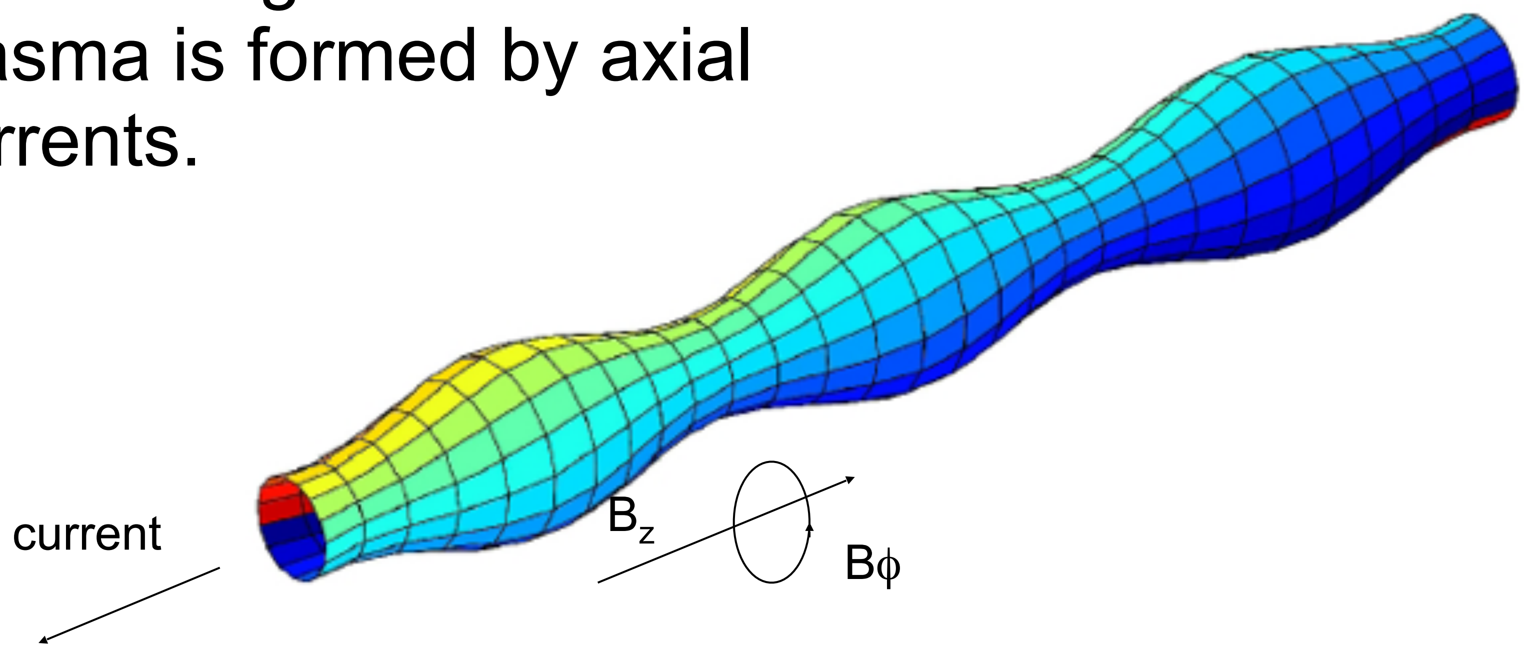
$$\tau \propto R^2 \frac{L^2 n}{T^{5/2}}$$

$\lambda_* \sim l$:

$$\tau \propto \frac{L^2}{l\, T^{1/2}}$$

Global plasma stabilization in GOL-3 is achieved by control of the magnetic shear.

Helical magnetic field in plasma is formed by axial currents.



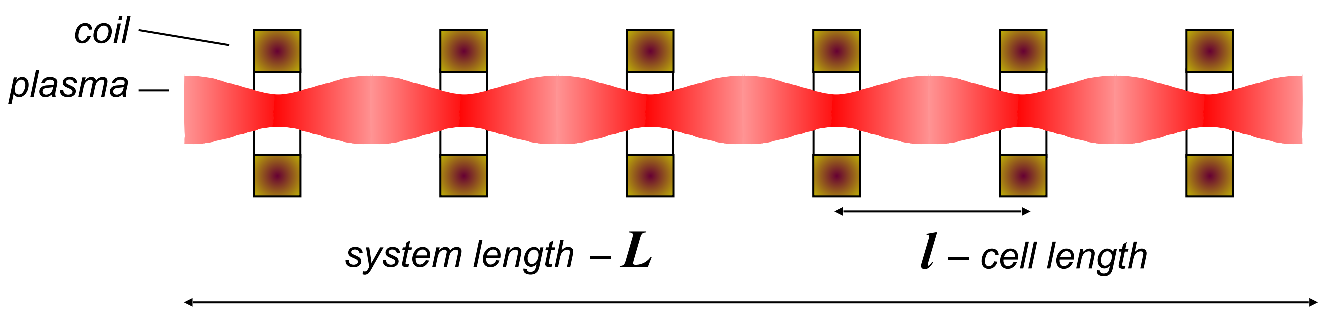
· Magnetic shear is important factor for achievement of stable operation regimes and good plasma confinement in GOL-3.

Computations show:

•tearing-like instability could exist inside the plasma column

•MHD stability will be realized at fusion reactor parameters as well

Basic Ideas



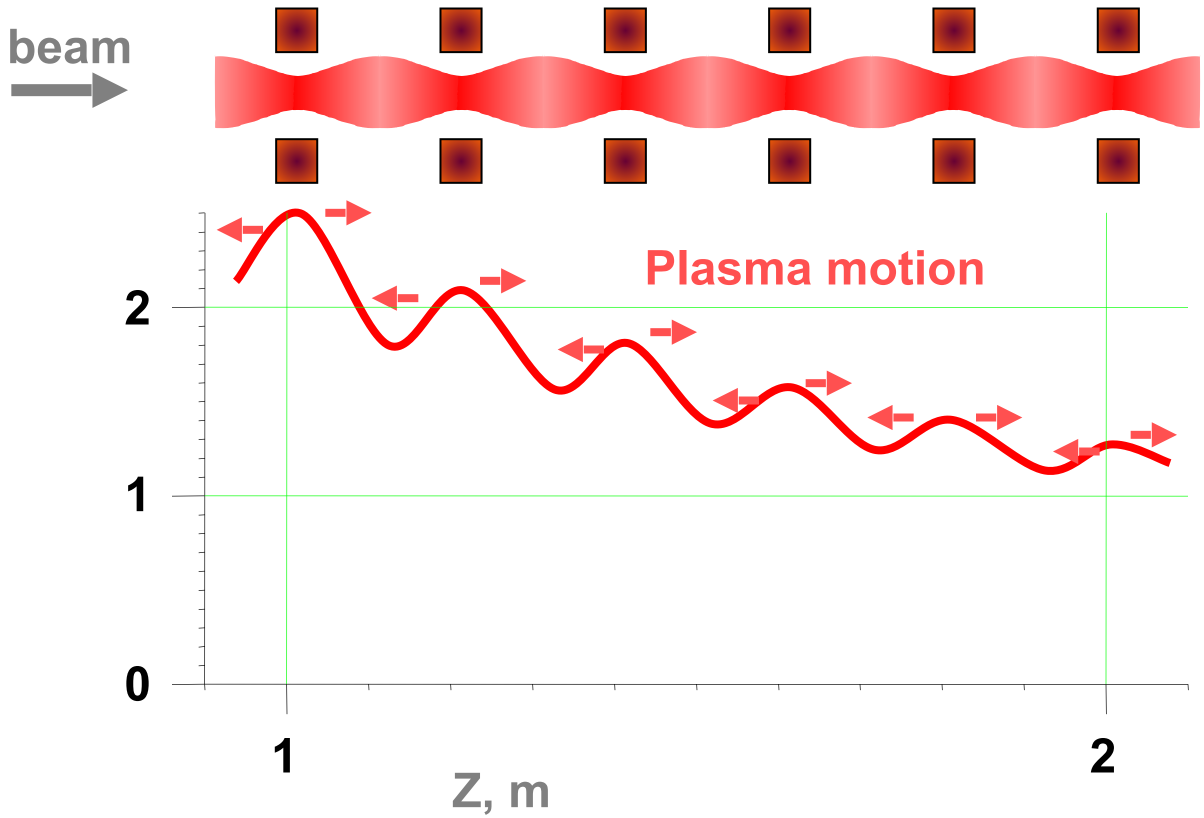
- The plasma density should be high: free path length λ is much less than system length L
- Due to collisions “transiting” ion will be trapped into some corrugation cell.
- After a few oscillations it leaves the cell in random direction. It is a diffusive-like expansion!
- Rough estimate of the confinement time:

$$\boxed{\tau \sim R^2 \frac{L^2}{\lambda_i V_{Ti}} = R^2 \frac{L}{\lambda_i} \tau_0}$$

where $R = B_{max}/B_{min}$ is mirror ratio and $\tau_0 = L/v_{Ti}$ is plasma lifetime in a simple solenoid

Figure of merit $R^2 \frac{L}{\lambda_i}$ can be done large enough for competitive fusion reactor system!

FAST ION HEATING



Nonuniform electron pressure produces longitudinal ambipolar electric field which accelerates the plasma ions. After collisions of expanding clouds the kinetic energy is transferred to thermal energy of the ions .
As a result, ion temperature up to 2keV at density ~10^{15} cm^{-3} is achieved.