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 $10\mu$s 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.


   M. Andrews, J. Bsura, H.H.Fleischmann, and N. Rostoker

3. “Propagation of High Current Relativistic Electron Beams”
   D.A. Hammer and N. Rostoker,

4. “Relativistic Electron Beam Neutralization in a Dense Magnetized Plasma”
   K.R.Chu and N. Rostoker
Beam-plasma interaction experiments with 100 ns REBs

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 $10^{14}$ to $10^{16}$ cm$^{-3}$
Diameter- 6 cm
Length – 240 cm
Magnetic field – 1-4 T
$n_b/n_p$ – $10^{-4}$ – $10^{-1}$
Beam current neutralization by return plasma current \( t=7\text{ns} \) after the beam start (INAR)

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

**Experimental conditions:**

- Beam current – 10 kA,
- duration – 70 \text{ns}
- diameter – 2 cm
  \( n_b = 5\times10^{11} \text{ cm}^{-3} \)
- Plasma diameter – 8 cm


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

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

Arzhannikov A.V. et al.  

Arzhannikov A.V. et al.  

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

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)

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

Beam parameters:
- Electron energy \( \sim 0.6 \text{MeV} \)
- Particle density \(-3-5 \times 10^{11} \text{cm}^{-3}\)
- Beam diameter \(-1.8 \text{cm}\)
- \(n_b/n_p - 3-5 \times 10^{-4}\)

Plasma parameters:
- Density \(-1-2 \times 10^{15} \text{cm}^{-3}\)
- \(T_e - 20-60 \text{ eV}\)
- Length \(-240 \text{ cm}\)
- Magnetic field \(-2.5 \text{ T}\)
- \(\omega_{pe}/\omega_{ce} = 5/1\)
Measurements of Langmuir oscillation spectrums at GOL-M device

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

Spectrum along the line $k_\parallel \frac{V_b}{\omega_{pe}} = 1$

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

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 $2 \times 10^{14}$ 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 $n_b \sim 10^{11} - 10^{12}$ cm$^{-3}$ can transfer substantial part ($\sim 0.4$) of its energy to a plasma with density $n_p \sim 10^{15} - 10^{16}$ 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, \( \Phi_{\text{cathode}} \sim 20\text{cm} \)
- Beam parameters: \( E_e \sim 1\text{MeV}, I_b \sim 50\text{kA}, \tau \sim 5\mu\text{s}, Q \sim 100\text{kJ} \), \( \Phi_{\text{beam}} \sim 3-4\text{cm}, j_b=1-2\text{kA/cm}^2 \)

**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: \( E_e \sim 1\text{MeV}, I_b \sim 50\text{kA}, \tau \sim 10-14\mu\text{s}, Q_{\text{ribbon beam}} \sim 400\text{kJ} \), in magnetic field \( B=4\text{T} \) \( \Phi_{\text{beam}} \sim 4\text{cm} \), \( j_b=1-2\text{kA/cm}^2 \), \( Q_{\text{compressed beam}} \sim 250\text{kJ} \)

**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, \( \Phi_{\text{cathode}} \sim 20\text{cm} \). Beam parameters: \( E_e \sim 1\text{MeV}, I_b \sim 40\text{kA}, \tau \sim 5-7\mu\text{s} \). In magnetic field \( B=5\text{T} \) \( \Phi_{\text{beam}} \sim 4\text{cm} \), \( j_b=1-3\text{kA/cm}^2 \), \( Q \sim 100\text{kJ} \),
Layout of the U-2 accelerator

Two modes of operation

Ribbon beam
140x3.5cm
$E_e=1\text{MeV}$
$I_b=50\text{kA}$
$\tau_b=8\mu\text{s}$
$Q_b=0.4\text{MJ}$
Circular beam
$\phi=6\text{cm}$
$j=1\text{ kA/cm}^2$
$Q_b=0.2\text{MJ}$

Dense ribbon beam
75x3.5cm
$E_e=1\text{MeV}$
$I_b=30\text{kA}$
$\tau_b=9\div12\mu\text{s}$
$Q_b=0.25\text{MJ}$
Circular beam
$\phi=4\text{cm}$
$j=2\text{ kA/cm}^2$
$Q_b=0.15\text{MJ}$

Beam imprint on entrance limiter
Beam imprint after compression system without limiter
Beam Energy Content on Charging Voltage

- Hatching -140 cm cathode markers - 70 cm cathode
- Energy content in capacitors
- Beam in diode
- Ribbon beam in channel
- Compressed circular beam

Elongation of beam pulse
Optimization of switching delay

Square of charging voltage

Q, kJ
Electron beam generator U-2

Ribbon beam diode with beam compression system

Solenoid with multi-mirror magnetic field

Magnetic field
- multi-mirror
- 55 cells
- 4.8/3.2 T

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

Plasma
- length ~12 m
- density ~10^{14} - 10^{16} cm^{-3}
- T_e ~1-4 keV
- T_i ~ 2 keV
GOL-3 multi-mirror trap
Plasma is confined in a solenoid with corrugated (multi-mirror) field, which comprises 55 cells with $B_{\text{max}}/B_{\text{min}} = 4.8/3.2$ T.
ENERGY SPECTRUM OF ELECTRONS AT THE EXIT OF THE GOL-3 FACILITY

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

**Magnetic spectrometer**
GOL-3-II
Homogeneous magnetic field
Beam injection without anode foil
$E_e=1 \text{MeV}$
Injection in plasma

**Multifoil analyser**
GOL-3-II
Corrugated magnetic field
Beam injection without anode foil: $E_e=0.7 \text{MeV}$
Injection in plasma
$t=2-8 \mu s$
Collective E-beam relaxation and heating of plasma electrons

Beam spectrum analyzer

Thomson scattering spectra
t=6μs after the beam start, \( n_p = 4 \times 10^{14} \text{cm}^{-3} \)

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
Discrepancy: at such electron temperatures the plasma cooling time should be $<< 1\mu s$, 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 $\sim 1000$ 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 \times 10^{15} \text{cm}^{-3}), z=2.08 \text{ 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 $\tau \sim 15 \mu s$ 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?
Temporal variation of ion temperature measured via Doppler broadening of $D_a$ spectral line.

Initial plasma density - $0.3 \cdot 10^{21} \text{ m}^{-3}$. 

The graph shows the variation of ion temperature ($T_i$, keV) over time (time, ms) with error bars indicating uncertainty. The data points are shown along with error bars, indicating the spread of data points.
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

\[ n_0 = 1.0 \times 10^{15} \text{ cm}^{-3} \]

\[ T_e = 1 \text{ keV} \]

- 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

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 \(\sim 10^{15}\) 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!

\[
\tau \sim R^2 \frac{L^2}{\lambda_i V_{Ti}} = R^2 \frac{L}{\lambda_i} \tau_0 \sim 10^2
\]

\[
R = \frac{B_{\text{max}}}{B_{\text{min}}} \quad \tau_0 \sim \frac{L}{V_{Ti}}
\]
Multi mirror plasma confinement

Confinement time for conditions of GOL-3

\[ R = 1.5 \]
\[ \frac{L}{l} = 55 \]

\[ \lambda_i \gg l \]
\[ \lambda_i \sim l \]

\[ \tau \sim \tau_0 \frac{L}{l} \]
\[ \tau_0 \sim \frac{L}{V_T} \]

Confinement time, \( \mu s \)

Plasma density, \( \text{cm}^{-3} \)

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

\[ \omega \sim \frac{C_s}{l} \]

\( C_s \) is a sound velocity

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

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

Neutron emission

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 $Z_{\text{eff}}$**

Impurity concentration is equal

$n_O = 10^{12} \text{ cm}^{-3}$  \hspace{1cm} $n_C = 2 \times 10^{12} \text{ cm}^{-3}$

$Z_{\text{eff}} = 1.2 - 1.6$
PROGRESS IN PLASMA PARAMETERS of GOL-3
Plasma diamagnetic signals (transverse plasma pressure)
for various magnetic configurations

\[ n_e T_e + n_i T_i, \ 10^{21} \text{keV/m}^3 \]

- **2004**
  - Total corrugation, \(1.5 \cdot 10^{21} \text{m}^{-3}\), Deuterium, 2-fold increase in beam density, PL5871, 2.08 m

- **2002**
  - Total corrugation, \(0.8 \cdot 10^{21} \text{m}^{-3}\), D, PL5221, 3.57 m

- **2001**
  - Partial corrugation at the ends 4 m, D, \(0.3 \cdot 10^{21} \text{m}^{-3}\), PL4710, 2.08 m

- **1997**
  - Homogeneous B-field with end mirrors, \(0.9 \cdot 10^{21} \text{m}^{-3}\), H, PL2285, 3.73 m
TIME DIAGRAM OF REACHED PLASMA TEMPERATURE

- Increase of plasma lifetime
- 2-fold increase of beam density
- Full length multi-mirror configuration

INAR 1 kJ 2.5m 1m
INAR2
GOL-3-I 7 m, 100 kJ
GOL-3-II 12 m, 200 kJ
GOL-3 corrugated magnetic field

$T_e$, keV ○
$T_i$, keV △

1980
Collective electron heating

1990
Suppression of heat conductivity

2000
Two-stage heating

2010
Collective ion heating
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 $\sim$2-4 keV at $n_p$ $\sim$4·$10^{14}$ cm$^{-3}$, ion temperature up to $\sim$2 keV at $n_p$ $\sim$10$^{15}$ cm$^{-3}$, energy confinement time $\sim$1 ms) are reached in the GOL-3 facility.
Thank you...
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.
Energy stored in plasma with density of $8 \times 10^{14}$ cm$^{-3}$. Confinement time is $\sim 1$ ms.
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.
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

\[ \mu = \frac{1}{q} \]

unstable region

\[ \mu \text{ is of different sign in the center and at the edge of the plasma} \]

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';

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

Strong density and ion velocity modulation in cells of the trap.
Effect of fast ion heating in multi-mirror trap

Bremsstrahlung radiation of electron beam.

DD reaction intensity

neutron/cm² s
Excitation of plasma density oscillations in the cells on the confinement stage

Ion temperature has axial gradient

Electron beam

Distribution function in sell

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: \( \lambda_{\text{eff}} \sim l \)
Confinement in GOL-3

\[ nT, 10^{15} \text{ keV/cm}^3 \]

Time, ms

Uniform field

Multimirror field

Beam injection

0.8 \(10^{15}\) cm\(^{-3}\)
Confinement in GOL-3

Calculation with BC theory

\[ R = 1.5 \]
\[ \frac{L}{l} = 55 \]

\[ \lambda_i \gg L \]
\[ \lambda_i \sim l \]

\[ \tau \sim \tau_0 \frac{L}{l} \]
\[ \tau_0 \sim \frac{L}{V_T} \]
**Plasma confinement**

Comparison to BC theory

Plasma density, $10^{15} \text{cm}^{-3}$

$\lambda_{\text{eff}} \sim l$

$\sigma_{\text{eff}} / \sigma = 1$
Basic Ideas + new paradigm

- The plasma density should be high: free path length $\lambda$ is much less than system length $L$.

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

Rough estimate of the confinement time (BC Theory):

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

**BC theory:**

$$
\tau \propto R^2 \frac{L^2 n}{T^{5/2}} \quad \lambda_* \sim l : \quad \tau \propto \frac{L^2}{l T^{1/2}}
$$
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 $\lambda$ 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:

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

where $R = \frac{B_{\text{max}}}{B_{\text{min}}}$ is mirror ratio and $\tau_0 = \frac{L}{v_{Ti}}$ 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!
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 2 keV at density $\sim 10^{15}$ cm$^{-3}$ is achieved.