Experiments with “Thin” Electron Beam at GOL-3


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Outline of the Talk

1. Introduction

2. Relaxation of the thin electron beam in the plasma

3. Heating of the plasma and of non-ionized deuterium

4. Stabilization of the beam

5. Summary
Motivation of This Activity

GOL-3 experiments are encouraging for a fusion prospects of such systems. Several new physical effects were found which benefit confinement.

- Future multiple-mirror reactor must be a steady-state system.
- The relevant physics and technology is to be developed.
- Feasible reactor will have moderate power of the electron beam:
  
  tens GW $\rightarrow$ tens MW  \hspace{1cm} (dictated by economics)

- Development of fusion technology: long-pulse electron beams.
- Development of physics in a new domain of parameter space at the existing device:
  - lower specific parameters of the electron beam,
  - smaller physical size (radius) of the beam-heated zone $\rightarrow$ this paper
Experiments with decreased radius of the electron beam in the plasma:

• Theory and most of experiments deal with a large plasma ( $\Omega >> 2\pi c/\omega_p$ ) → will the beam-plasma interaction change at comparable spatial scales?

• Up to date axial heat losses were prevailing. Smaller beam size worsens ratio of the plasma volume to its surface → will transverse losses dominate?

• The beam current creates highly sheared magnetic field due to turbulent plasma resistance in the beam-heated zone. This benefits confinement of axisymmetric plasma, but is dangerous due to large axial currents which make a $q < 1$ plasma. → will this stabilization by the magnetic shear work for a lower beam current?

• Current GOL-3 system strictly prohibits experiments with the beam injection into a neutral gas (100% disruptions with a heavy damage to in-vacuum components). → Low beam current will make such experiments possible.

• Some plasma diagnostics benefit from smaller beam size (geometry of ports).
**Multiple-Mirror Trap GOL-3**

### Magnetic Field
- **multiple-mirror**
- 52 mirror cells
- 4.8/3.2 T (max/min)

### Electron Beam
- Energy ~0.8 MeV
- Current <20 kA
- Duration ~12 μs
- Diameter 4 cm @ 3.2 T
- Energy ~ 0.12 MJ

### Plasma
- Length ~12 m
- $n \sim 10^{20-10^{22}} \text{ m}^{-3}$
- $T \sim 1 \text{ keV}$
- Lifetime ~0.5 ms

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**«Standard» regime**

Thomson NBI sheet beam diode U-2 generator of the electron beam corrugated magnetic field exit unit solenoid

**B, T**

**axial coordinate, m**
“Thin Beam” Configuration at GOL-3

Two regimes of the beam injection

Initial uncompressed beam
- $75 \times 3.5 \text{ cm}^2$
- $E = 0.8 \text{ MeV}$
- $I = 30 \text{ kA}$
- $\tau = 9 \div 12 \mu\text{s}$

Vacuum chamber $\Ø 100 \text{ mm}$
Limiters and foreplasma $\Ø 80 \text{ mm}$

«thick» (or standard)
- $\Ø 4 \text{ cm}$
- $j \sim 1 \text{ kA/cm}^2$
- $Q \sim 7 \text{ kJ}$

«thin»
- $\Ø 1.3 \text{ cm}$
- $j \sim 1 \text{ kA/cm}^2$
- $Q \sim 7 \text{ kJ}$

Hot core plasma becomes much smaller than the cold edge plasma $\Rightarrow$ thin beam.

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Three different initial conditions of the experiment:

- the beam injection into vacuum at \(~3\cdot10^{-3}\) Pa residual pressure;
- the beam injection into neutral deuterium at shown density profile;
- the beam injection into a low-temperature preliminary plasma.

Gas-puffing technology enables producing a nonuniform density profile along the solenoid;
three valves are in operation;
typical \(n_{\text{max}} = (2\div8)\cdot10^{20} \text{ m}^{-3}\)
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Net Plasma Current

Injection into the neutral gas
Net current corresponds to the beam current

Injection into the plasma
The beam current is screened by the plasma
The beam current counters the discharge one

Note: a special low-current shot is shown. Standard shots are of 1.5-2 kA, but measurements are impossible due to emerging plasma currents which heavily distort the waveform.

Waveforms of 8 Rogowski coils at different coordinates are shown.
Efficiency of the Beam Relaxation

Dynamics of the mean energy of the beam electrons after passing the plasma

- At the beam injection into the vacuum the mean electron energy is \(~90\%\) of the initial one \(\rightarrow\) some beam-plasma interaction exists due to gas in compression area.
- Decrease of the mean energy reaches \(~50\%\) at the beam injection into the plasma.
- Analyzer signals are continuous and last for the expected period at the beam injection into vacuum.
- At the beam injection into the gas or into the plasma, the waveforms experience simultaneous breaks and recoveries that may evidence large beam displacement.
Plasma Emission at $2\omega_p$

Process: non-linear merging of two Langmuir plasmons with emission of $2\omega_p$ photon

\[ f = 250\div410 \text{ GHz}, 4 \text{ spectral channels} \]

fragment of two microwave waveforms is it an evidence of localized emission?

PL9406

cathode voltage

diamagnetism

microwaves 312 GHz
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The profile consists of a decreasing “pedestal” and two “hot spots” at ~0.8 and ~2 m. Slight differences in the regime lead to slightly different axial pressure profile. The “hot spots” are the features of the beam relaxation in the nonuniform plasma. Large spread of measurements at 0.8-2.1 m is due to displacements of the peaks.

\[ Q_{\text{dia}} = 450 \text{ J} \]

\[ n_{\text{max}} = (3\div4)\cdot10^{20} \text{ m}^{-3} \]

*the green line was drawn by hand for convenience only!*
Plasma Heating: Diamagnetism

- Beam-heated area is 10% of the standard one
- Waveforms for 3 different locations are shown

• The plasma heating by the thin beam is as good as before.
• Slight differences in the regime lead to slightly different axial pressure profile.
Neutron Emission from D-D Reaction

Blue: reference standard regime, shot PL8626
Red: thin beam, shot PL9142

The signals are normalized for the beam area

- All earlier observed at GOL-3 features of neutron emission are reproducing.
- Decay time at the confinement stage is good → at least the hottest zone is stable.
• If the energy stays within the formal beam flux tube, then $\beta_{\text{vac}} \approx 30\div35\% (!)$
• If the energy spreads to farther radii, the beta value is lower.
• Origin of this pressure: is there a lot of trapped fast electrons?
• Position of this pressure peak along the axis is easily controllable by axial density profile.
Thomson Scattering Data

- Diagnostics is located at Z = 415 cm (far from the hottest zone)
- Two radial points: 0 and 6 mm

Three observed cases:
- \( \langle E \rangle_{\text{center}} > \langle E \rangle_{\text{edge}} \)
- \( \langle E \rangle_{\text{center}} \sim \langle E \rangle_{\text{edge}} \)
- \( \langle E \rangle_{\text{center}} < \langle E \rangle_{\text{edge}} \)

- Electron distribution function is non-Maxwellian.
- Hot core displacement comparable to its radius is observed.

\[ \text{PL9059} \]
\[ \langle E \rangle \sim 400 \text{ eV center} \]
\[ \langle E \rangle \sim 100 \text{ eV edge} \]
Beam Injection Into Neutral Deuterium

- At the injection into the gas the beam relaxation efficiency is ~30%, i.e. about the half of the plasma case.
- Final plasma energy is also ~50% of the plasma case.
- The plasma size is wider than the expected beam diameter.

Profile of OV line at 76.0 nm

Density increment at 10 μs after the beam start (NBI data)

- Excursions of the beam are detected (VUV, NBI, Thomson).
- The beam cross-section is close to the expected one (better than to a factor of 1.5)
- After the beam shot the plasma emerges anywhere within the vacuum chamber.
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Stabilization of the Beam

Some possible reasons for the beam instability:
- decompensation by current density, $(q < 1$ within the beam cross-section);
- beam asymmetry at the input into the plasma;
- asymmetry of the return plasma current.

Possible ways of stabilization:
- improve freezing of the magnetic field into the beam receiver;
- improve plasma conductivity near the beam receiver for more uniform return current.

Technology:
- puffing of a heavy gas near the exit receiver.
Beam Footprint at the End Receiver

X-ray images of the beam footprint

1 μs frame

Asymmetry of the footprint at different Krypton puffing

\[ n_{Kr} = 1.5 \cdot 10^{21} \text{ m}^{-3} \]
Improvement of Stability is Statistical

Statistics for the net energy lost to the wall during the shot (probability distribution)

- good shots can be found in both regimes;
- no catastrophic events with Kr;
- improvement is statistical but valuable;
- losses to the wall are comparable with peak plasma energy; what does this mean combined with good confinement?

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Main results from GOL-3 experiments with the thin beam are the following:

• the measured beam relaxation efficiency reaches ~50%;
• the beam relaxation in the plasma is twice better than in the gas;
• transient events of $2\omega_p$ emission with ~10 ns duration are detected;
• in general diamagnetic energy content is consistent with the decreased
  beam cross-section, the confinement is good in best shots;
• electron distribution function is non-Maxwellian one, it should be studied
  better in the “hot spots”;
• radial excursions of the beam are detected;
• in the gas shots the plasma emerges anywhere in the vacuum chamber;
• stabilization by the gas-puffing statistically works.
Thank You!