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

GOL-3

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.

OS-2010: A.V.Burdakov, Tuesday, 11:10

- Future multiple-mirror reactor **must** be a steady-state system.
- The relevant physics and technology is to be developed.

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- Feasible reactor will have moderate power of the electron beam:

tens GW $\rightarrow$ tens MW *(dictated by economics)*

- Development of fusion technology: long-pulse electron beams.

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- Development of physics in a new domain of parameter space *at the existing device*:

- lower specific parameters of the electron beam,

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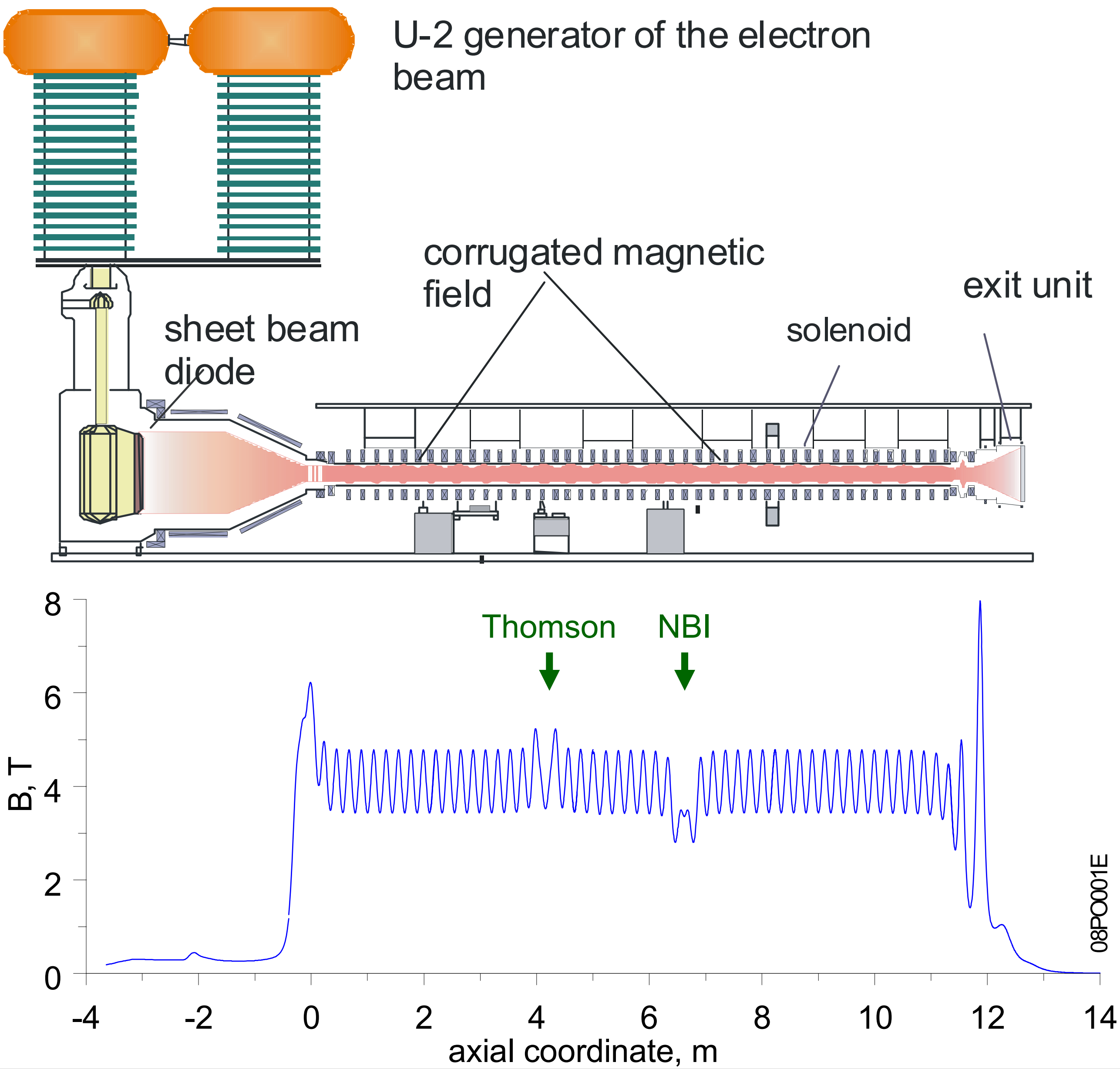
- smaller physical size (radius) of the beam-heated zone → this paper

Physical Problems for a Thin Beam

Experiments with decreased radius of the electron beam in the plasma:

- Theory and most of experiments deal with a large plasma ($Ø >> 2\pi c/\omega_p$) → 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



«Standard» regime

Magnetic Field

- multiple-mirror
- 52 mirror cells
- 4.8/3.2 T (max/min)

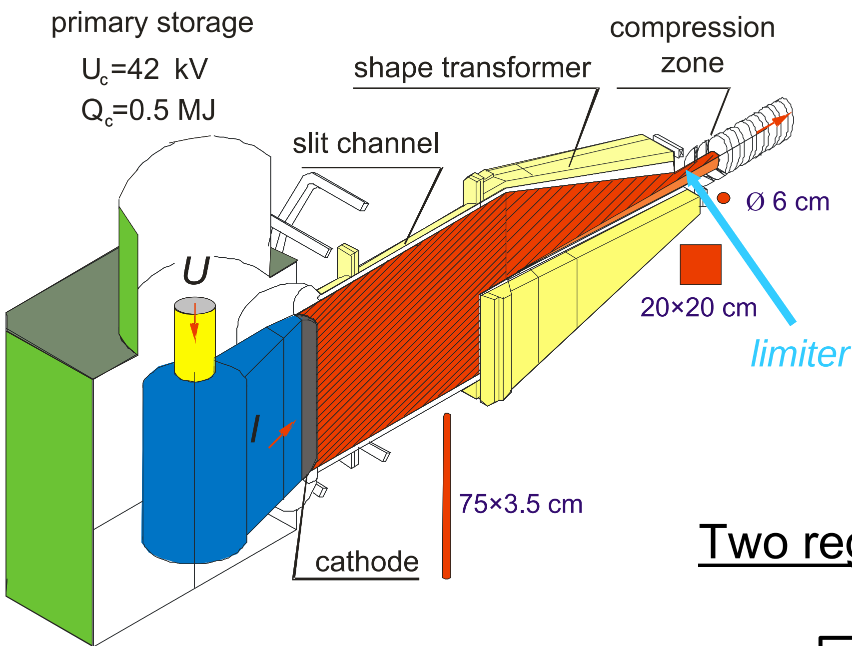
Electron Beam

- 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 ~ 10^{20}-10^{22} m^{-3}
- T ~ 1 keV
- Lifetime ~0.5 ms

“Thin Beam” Configuration at GOL-3



Initial uncompressed beam

75×3.5 cm^2

E = 0.8 MeV

I = 30 kA

τ = 9÷12 μs

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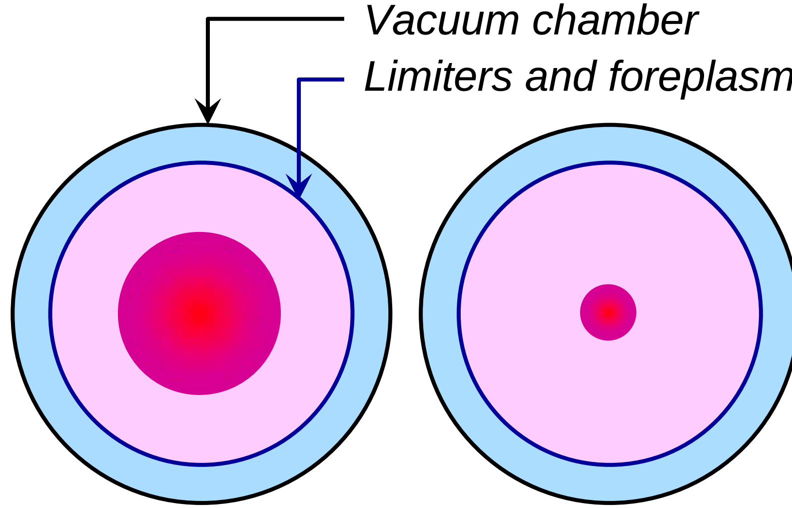
Two regimes of the beam injection

Vacuum chamber *Ø 100 mm*

Limiters and foreplasma *Ø 80 mm*



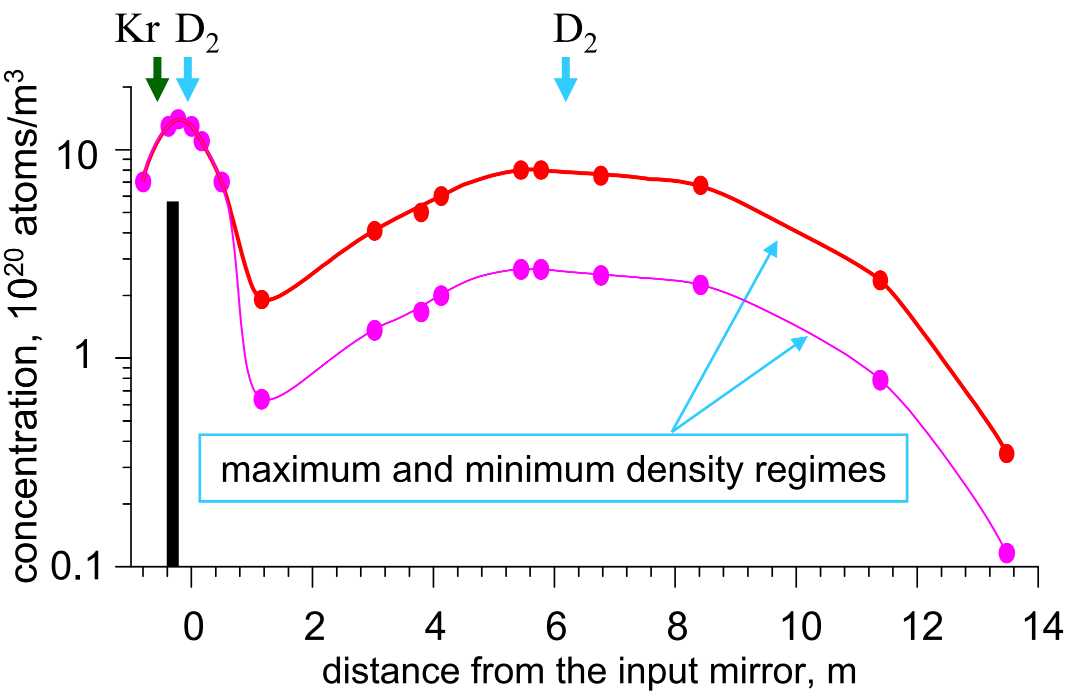
«thick»
(or standard)
∅ 4 cm

«thin»
∅ 1.3 cm
j ~ 1 kA/cm^2
Q ~ 7 kJ

Hot core plasma becomes much smaller than the cold edge plasma ⇒ **thin beam**.

Conditions in Confinement Zone

Initial gas density distribution



gas-puffing technology enables producing a nonuniform density profile along the solenoid;

three valves are in operation;

typical n_{max} = $(2÷8)·10^{20}$ m^{-3}

Three different initial conditions of the experiment:

- the beam injection into vacuum at ~$3·10^{-3}$ Pa residual pressure;
- the beam injection into neutral deuterium at shown density profile;
- the beam injection into a low-temperature preliminary plasma.

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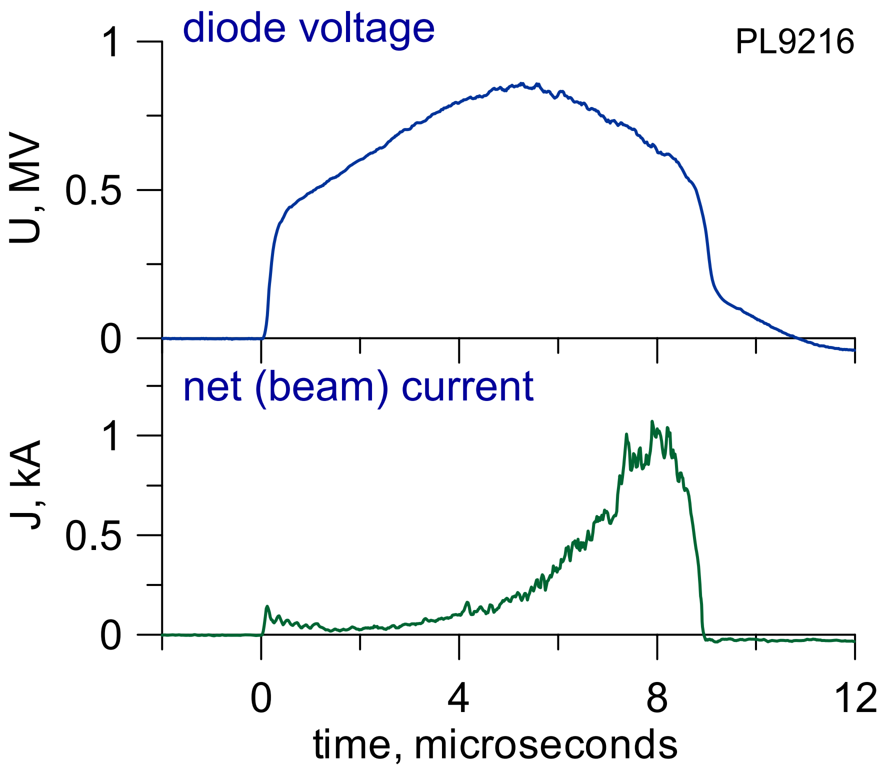
Net Plasma Current

injection into the neutral gas

net current corresponds to the beam current

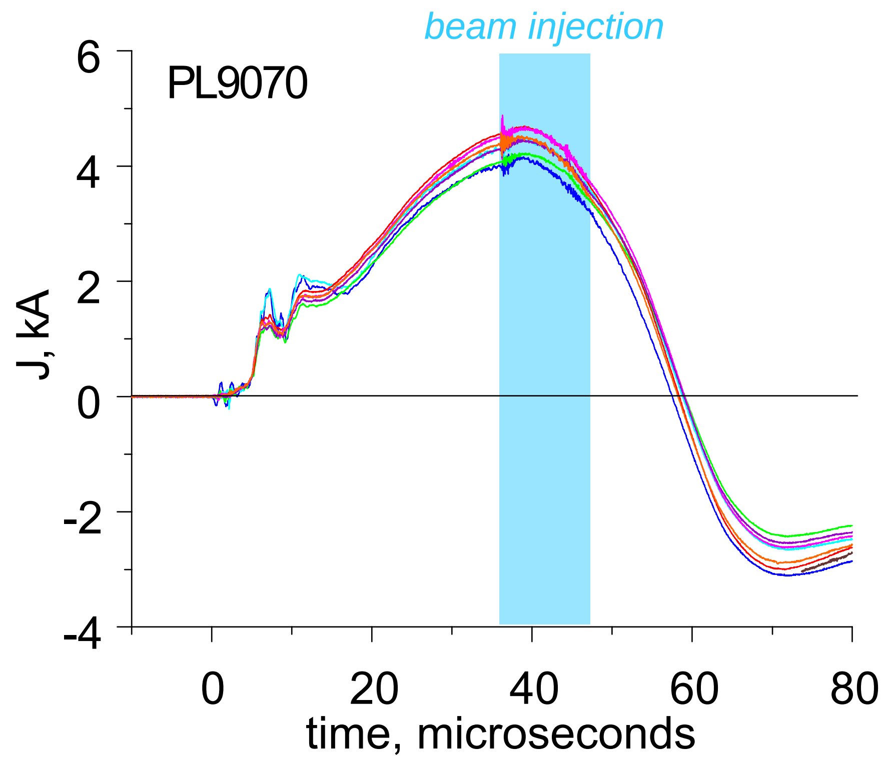


Note: a special low-current shot is shown. Standard shots are of 1.5-2 kA, but measurements are impossible due to emerging plasma currents which heavily distort the waveform.

injection into the plasma

the beam current is screened by the plasma

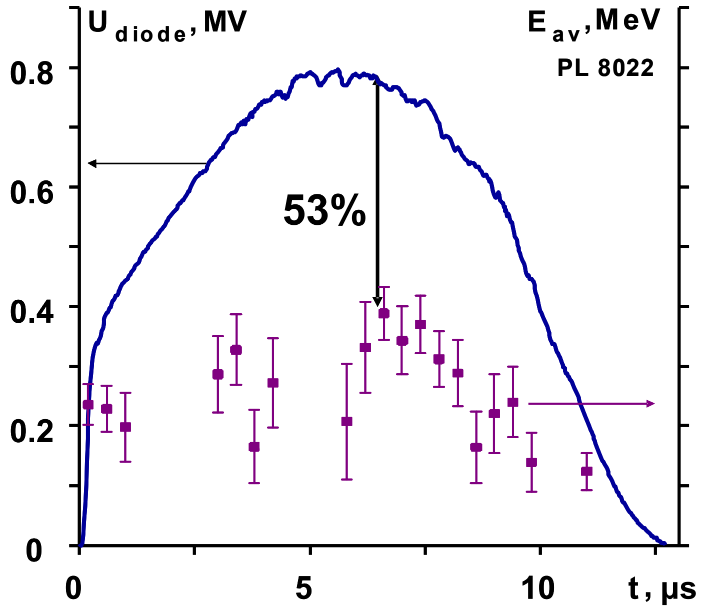
the beam current counters the discharge one



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



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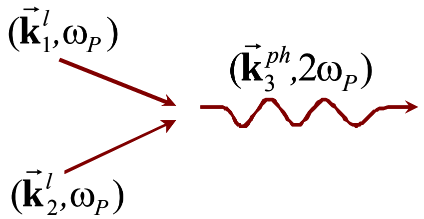
- At the beam injection into the vacuum the mean electron energy is ~90% of the initial one → some beam-plasma interaction exists due to gas in compression area.
- Decrease of the mean energy reaches ~50% at the beam injection into the plasma.
- Analyzer signals are continuous and last for the expected 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.

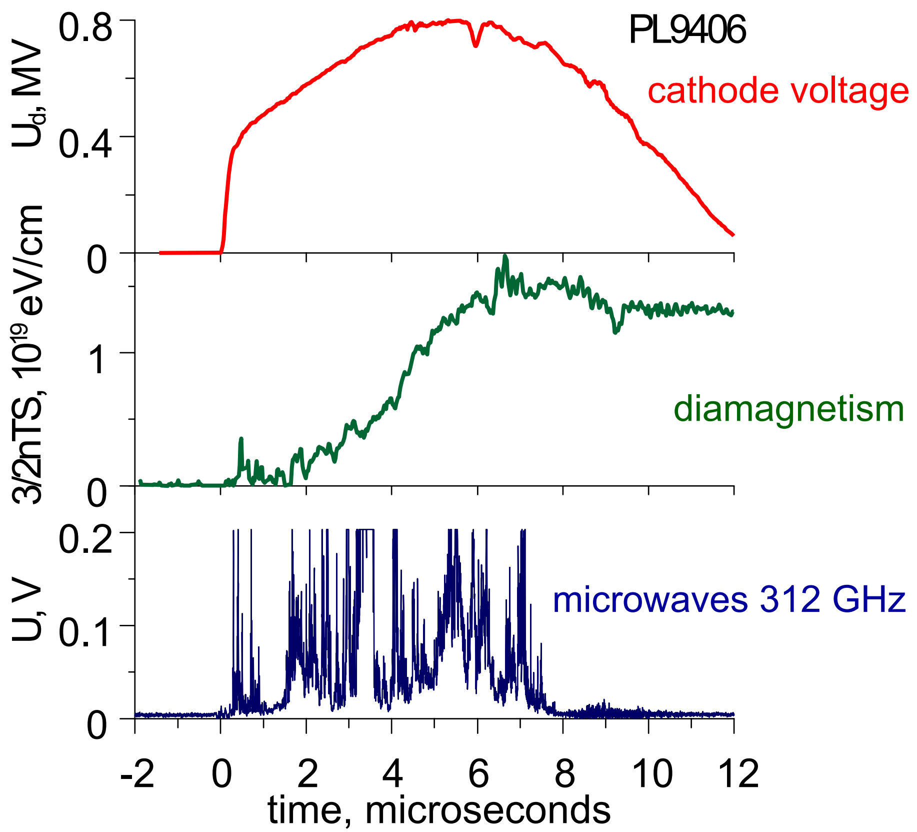
Plasma Emission at $2\omega_p$

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



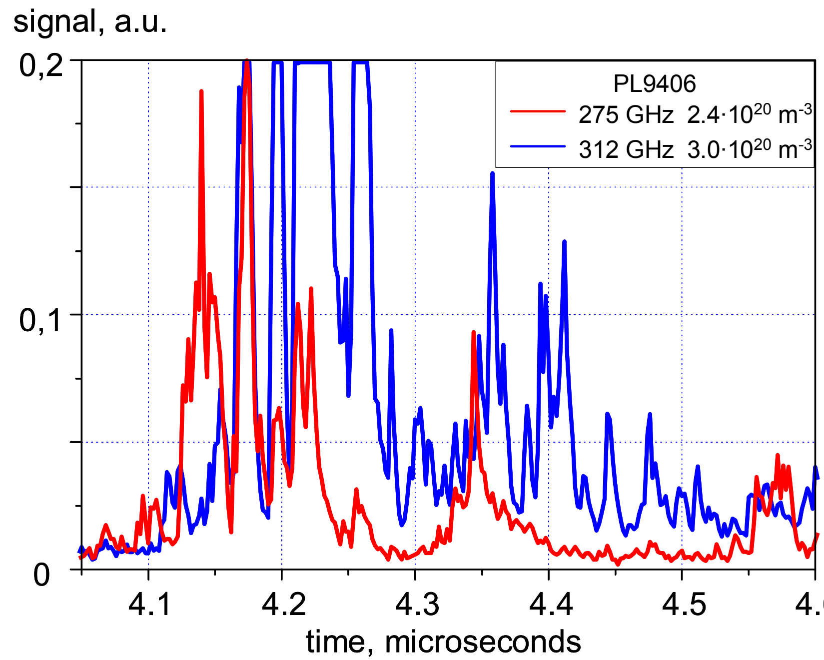
f = 250÷410 GHz, 4 spectral channels

OS-2010: A.V.Arzhannikov, Tuesday, 12:25



fragment of two microwave waveforms

is it an evidence of localized emission?



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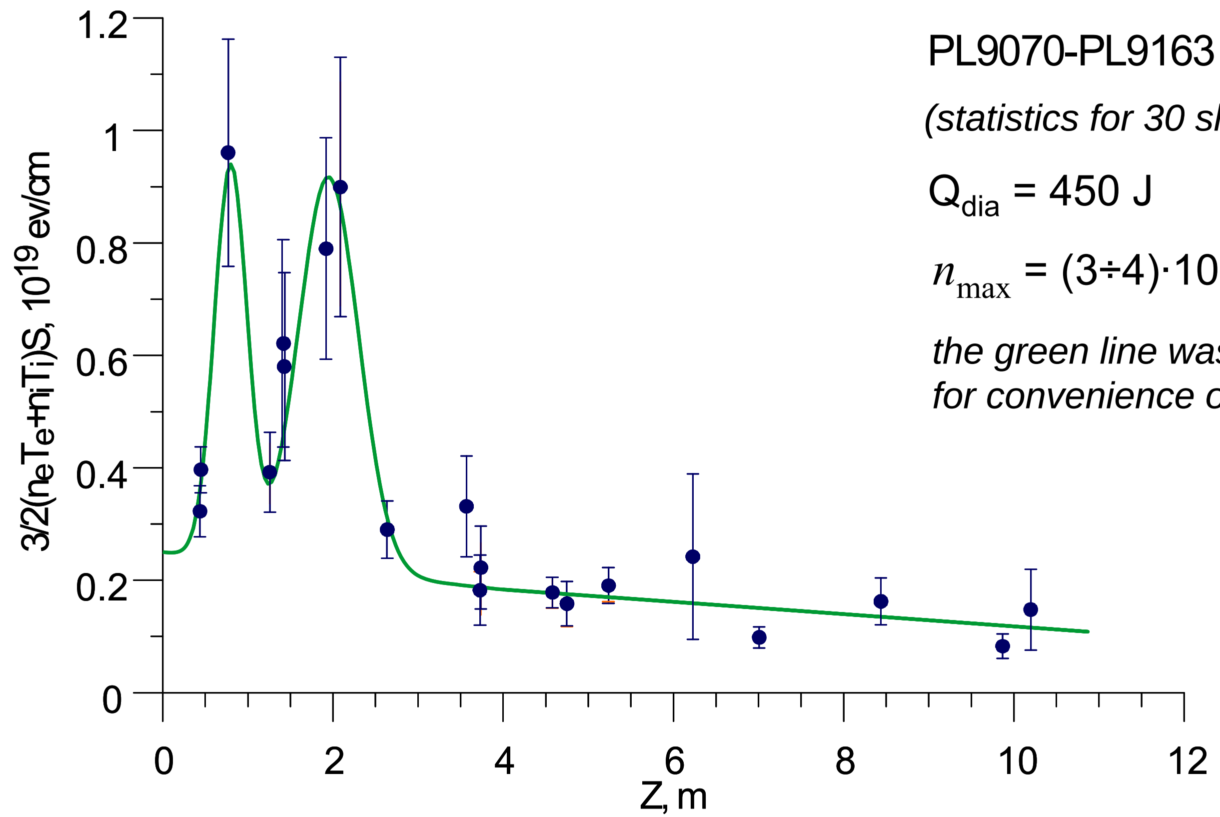
Profile of Diamagnetic Pressure



PL9070-PL9163

(statistics for 30 shots is shown)

Q_{dia} = 450 J

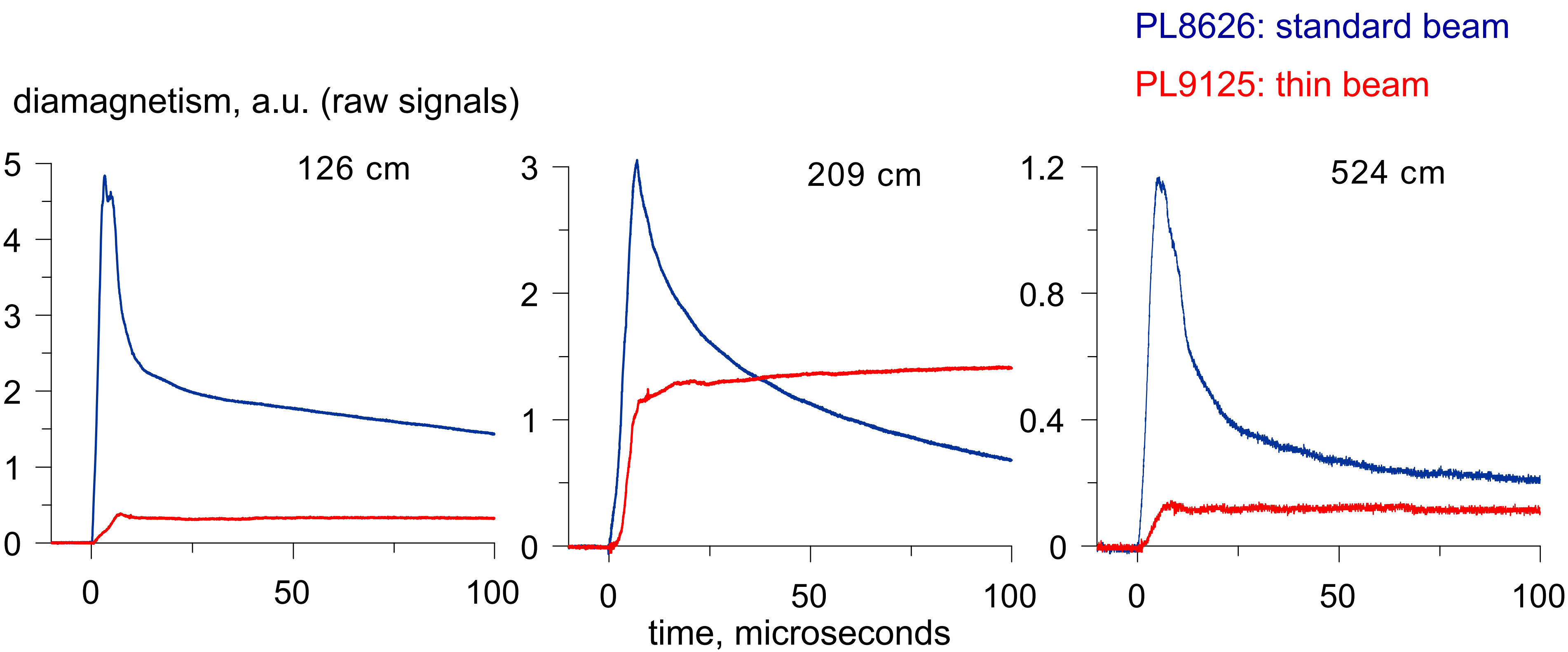
n_{max} = (3÷4)·10^{20} m^{-3}

the green line was drawn by hand for convenience only !

- 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.

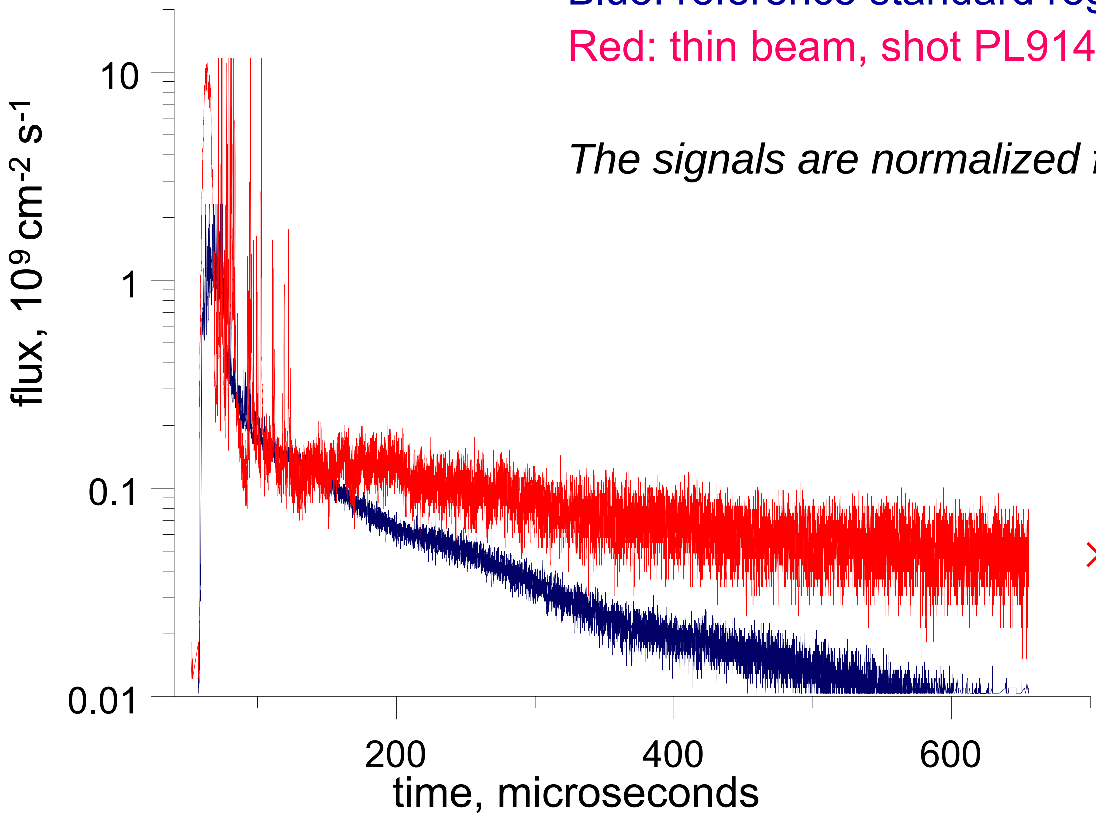
Plasma Heating: Diamagnetism

- 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

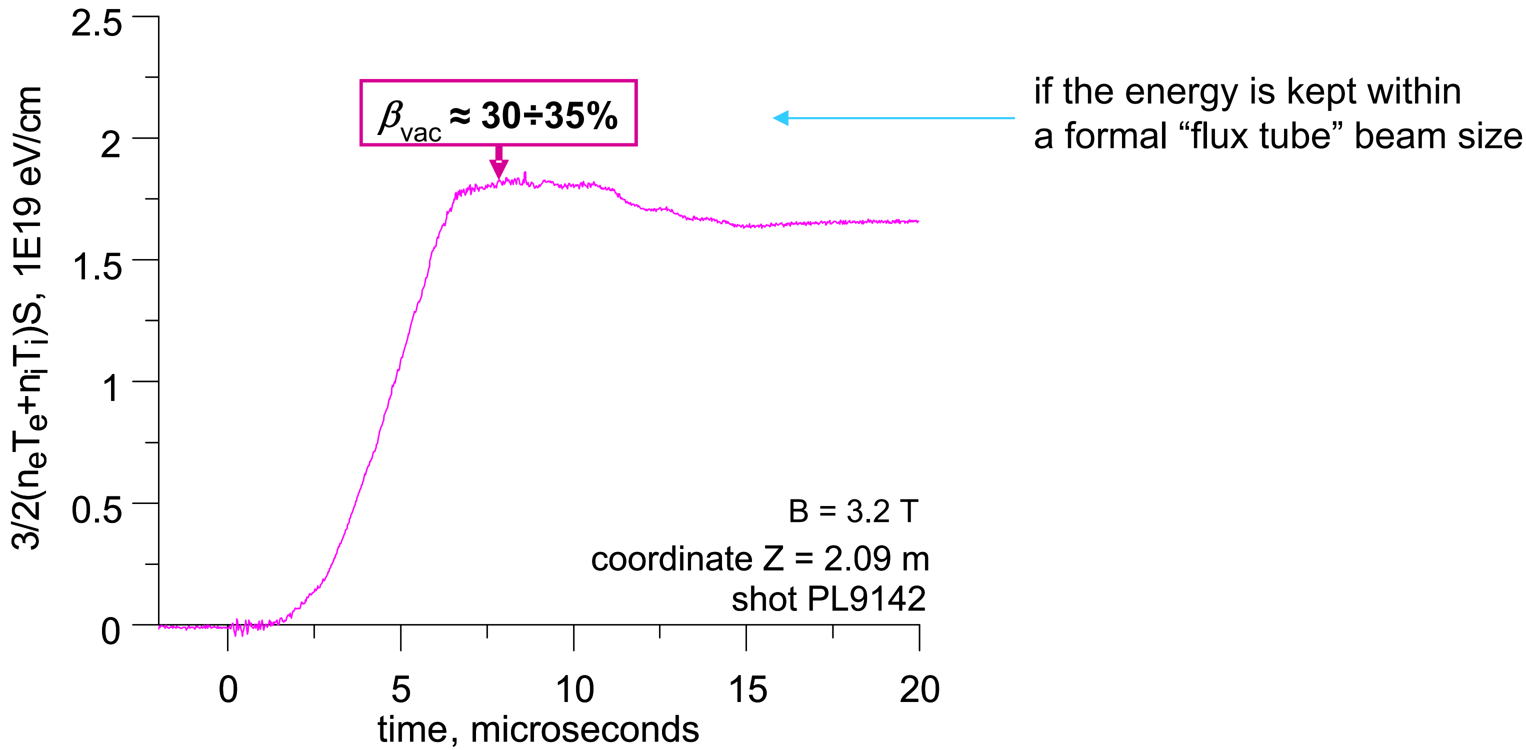
Red: thin beam, shot PL9142

The signals are normalized for the beam area

$\times 10 = S_{thick} / S_{thin}$

- 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.

Peak Plasma Pressure



- If the energy stays within the formal beam flux tube, then $\beta_{vac} \approx 30÷35\%$ (!)
- 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

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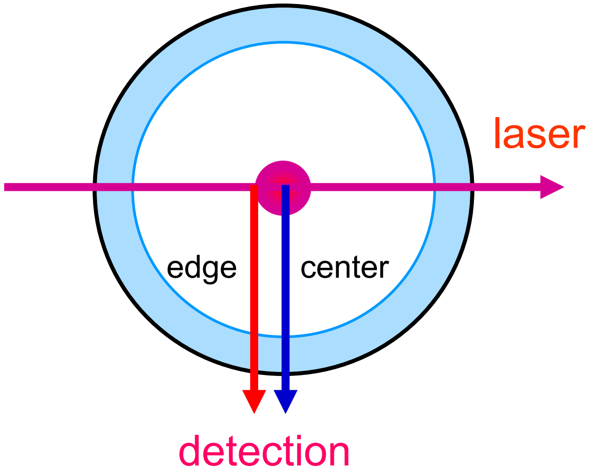
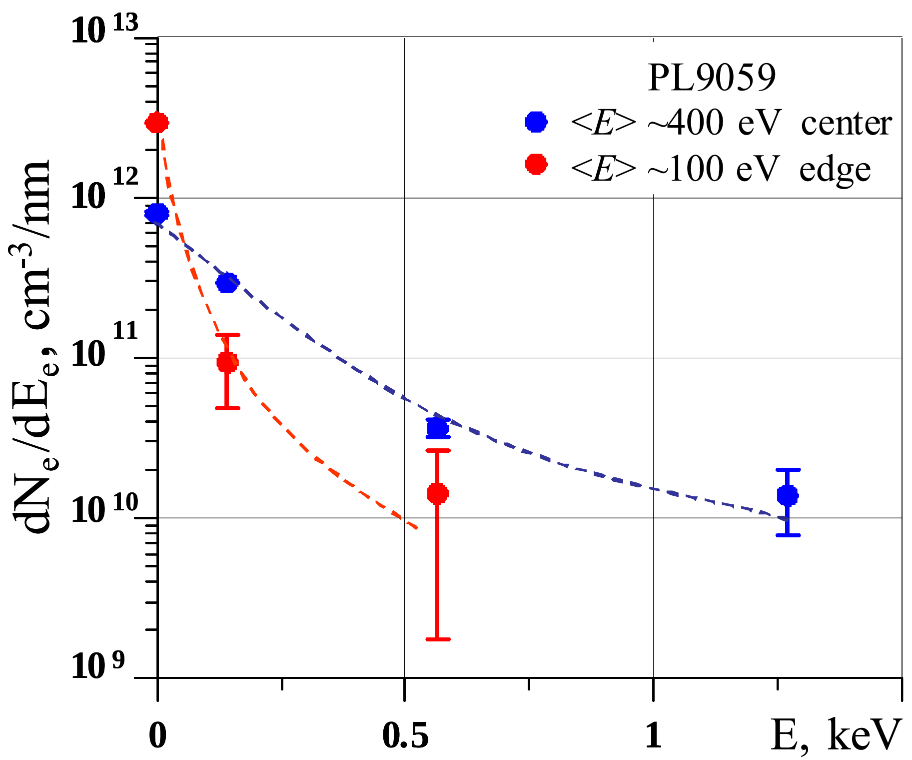


Three observed cases:

- $\langle E \rangle_{center} > \langle E \rangle_{edge}$
- $\langle E \rangle_{center} \sim \langle E \rangle_{edge}$
- $\langle E \rangle_{center} < \langle E \rangle_{edge}$



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

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.

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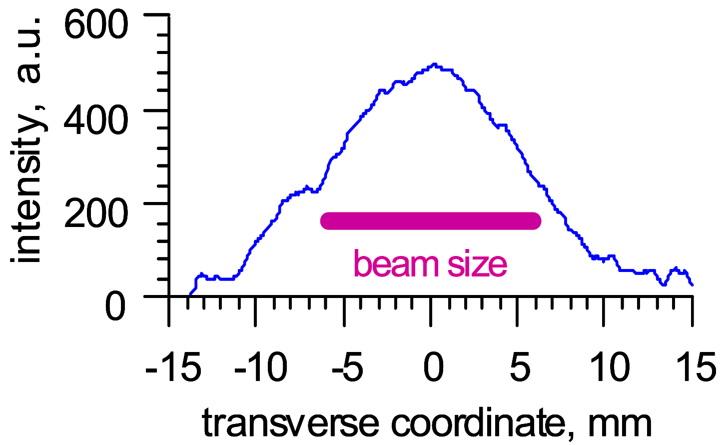
- Final plasma energy is also ~50% of the plasma case.
- The plasma size is wider than the expected beam diameter.

Profile of OV line at 76,0 nm



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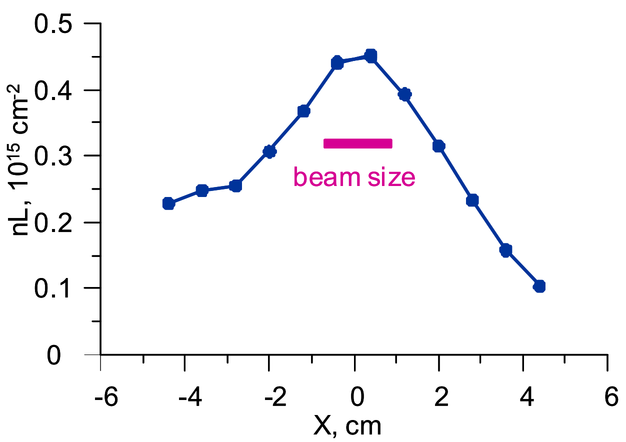
Density increment at 10 μs after the beam start (*NBI data*)



- 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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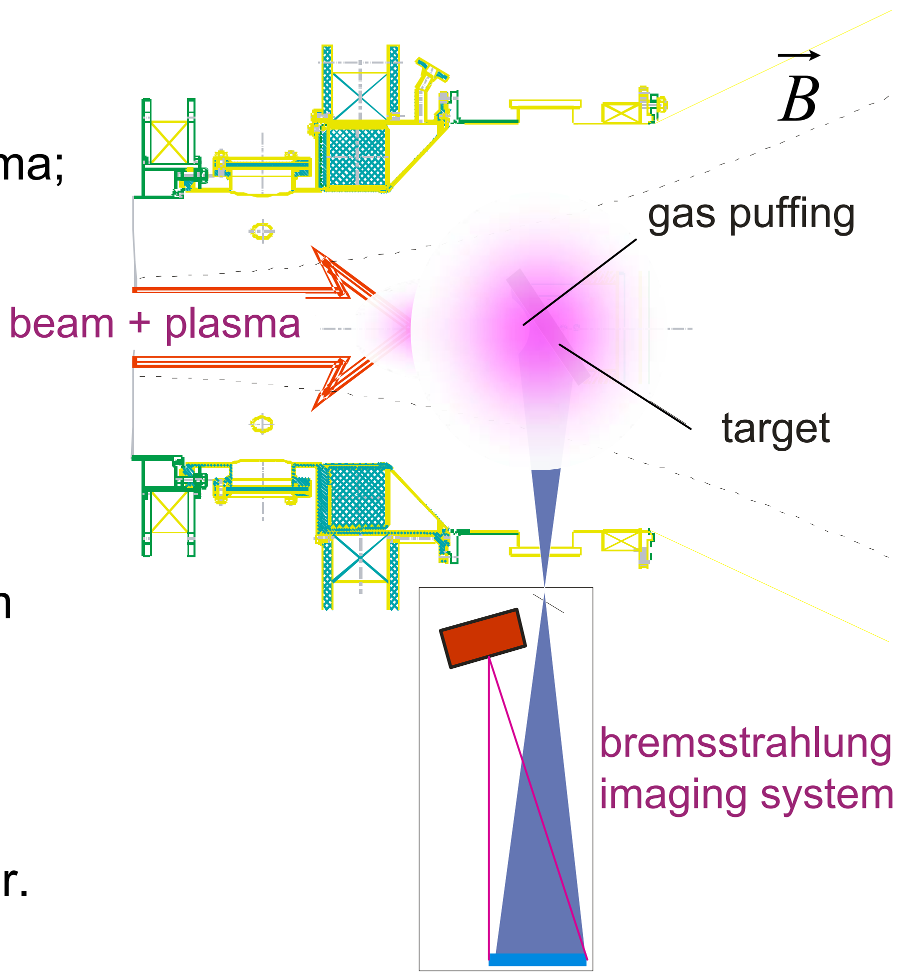
Stabilization of the Beam

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 frozening 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.

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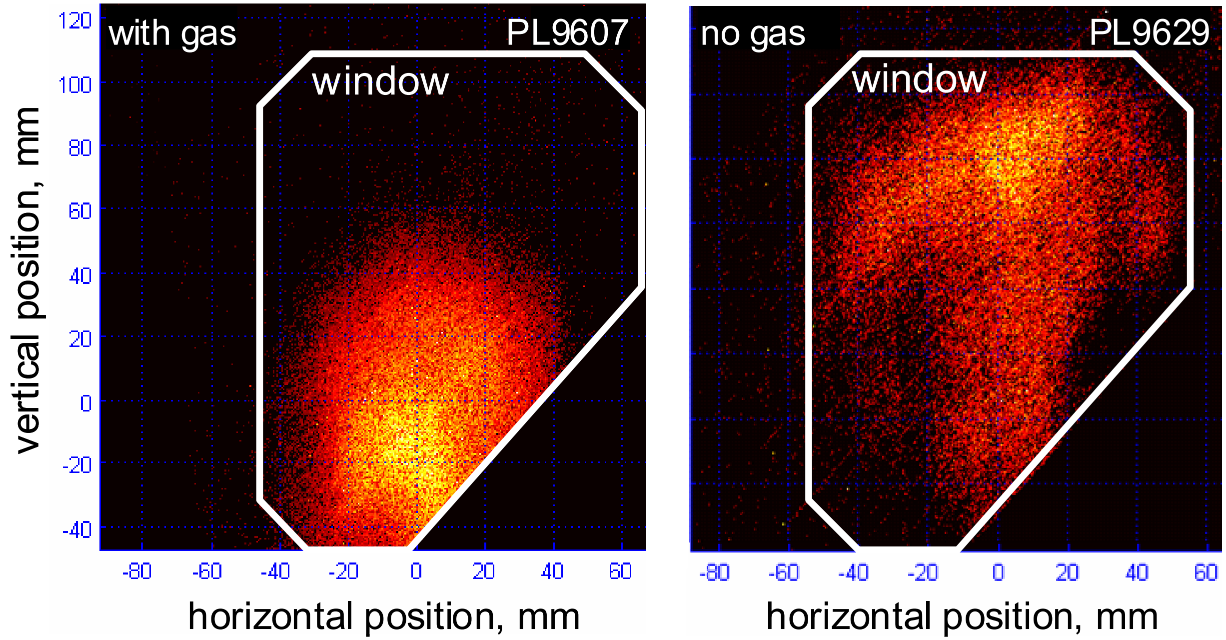
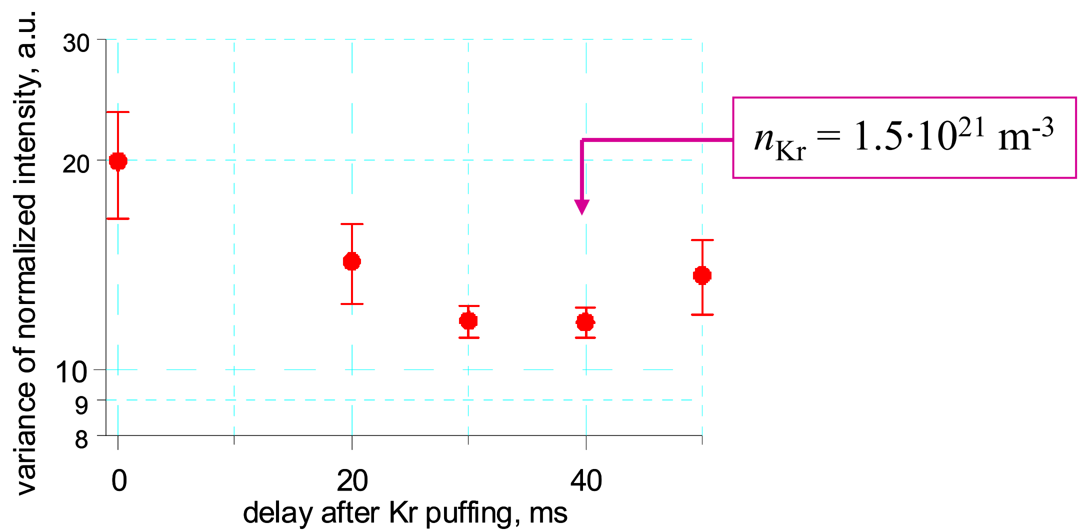
Beam Footprint at the End Receiver

X-ray images
of the beam footprint

1 μs frame



Asymmetry of the footprint
at different Krypton puffing

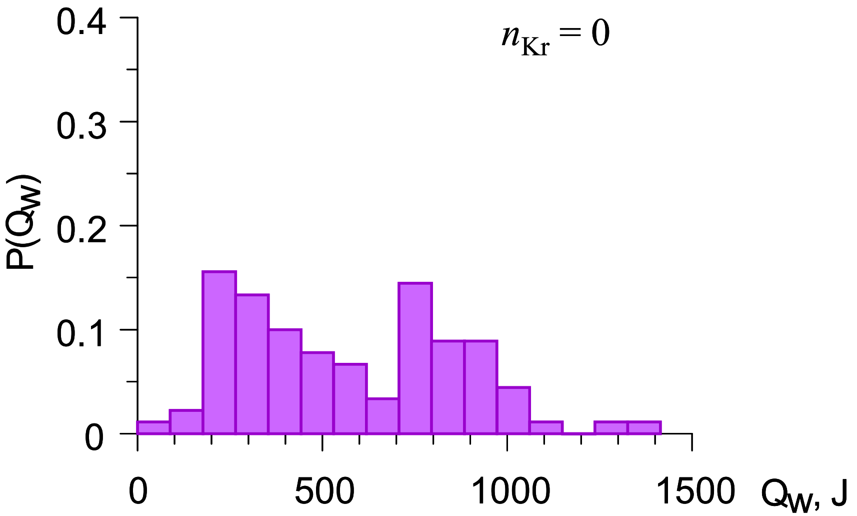


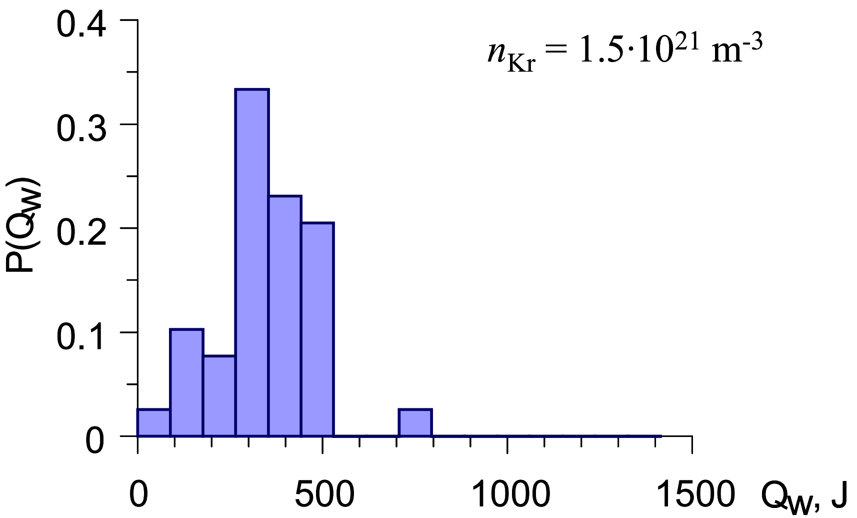
Improvement of Stability is Statistical

<u>Statistics for the net energy lost to the wall during the shot</u>
(probability distribution)

no gas puffing →

$n_{Kr} = 1.5 \cdot 10^{21}$ m^{-3} →





- 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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Summary

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.

The Really Last Slide

Thank You !