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Testing of Carbon Materials for Fusion Applications on Linear Plasma Trap GOL-3

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Outline

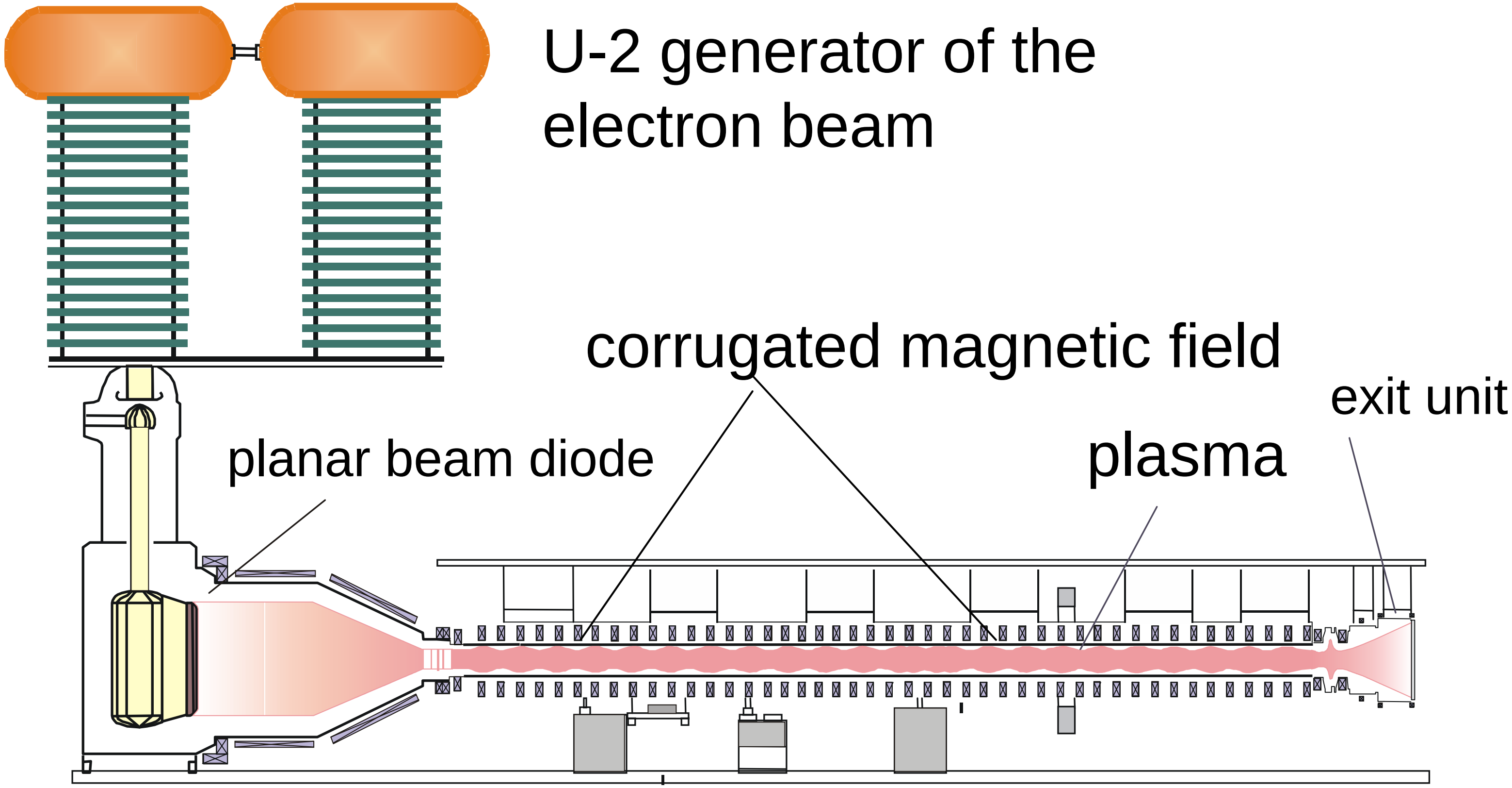
GOL-3 Facility

- Introduction and Summary

Plasma-wall interaction experiments at GOL-3

1. Erosion of fine grain high density graphite
2. Determination of destruction threshold
3. Long-range carbon migration
4. Investigation of carbon plasma transport along and across the magnetic field at long (~10m) distances

GOL-3 facility



The final aim of experiments carried out at the GOL-3 facility is development of a multi-mirror fusion reactor concept.

The main aims of the recent experiments were:
- **study of a mechanism of ion heating;**
- **study of multi-mirror confinement of a dense hot plasma;**

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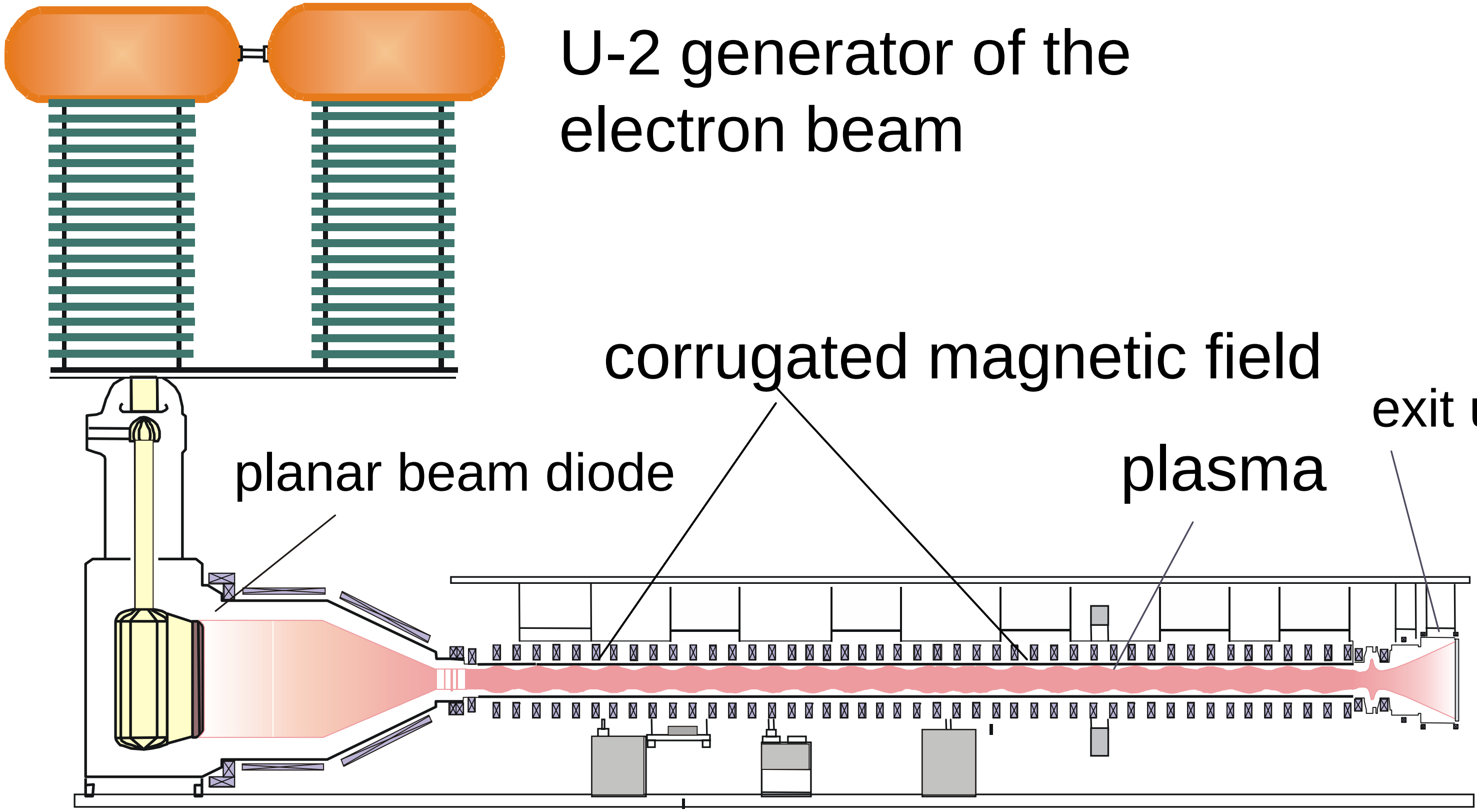
GOL-3 facility



Plasma	
Length	~ 12 m
Density	- 10^{20} - 10^{22} m^{-3}
Temperature	~ 1 keV

Magnetic field	
Solenoid	- 5 T
Mirrors	- 10 T
Capacity storage	- 20 MJ

Electron beam	
Energy	- 1 MeV
Current	- 50 kA
Energy content	- 0.3 MJ
Pulse duration	- 8 μs

GOL-3 facility

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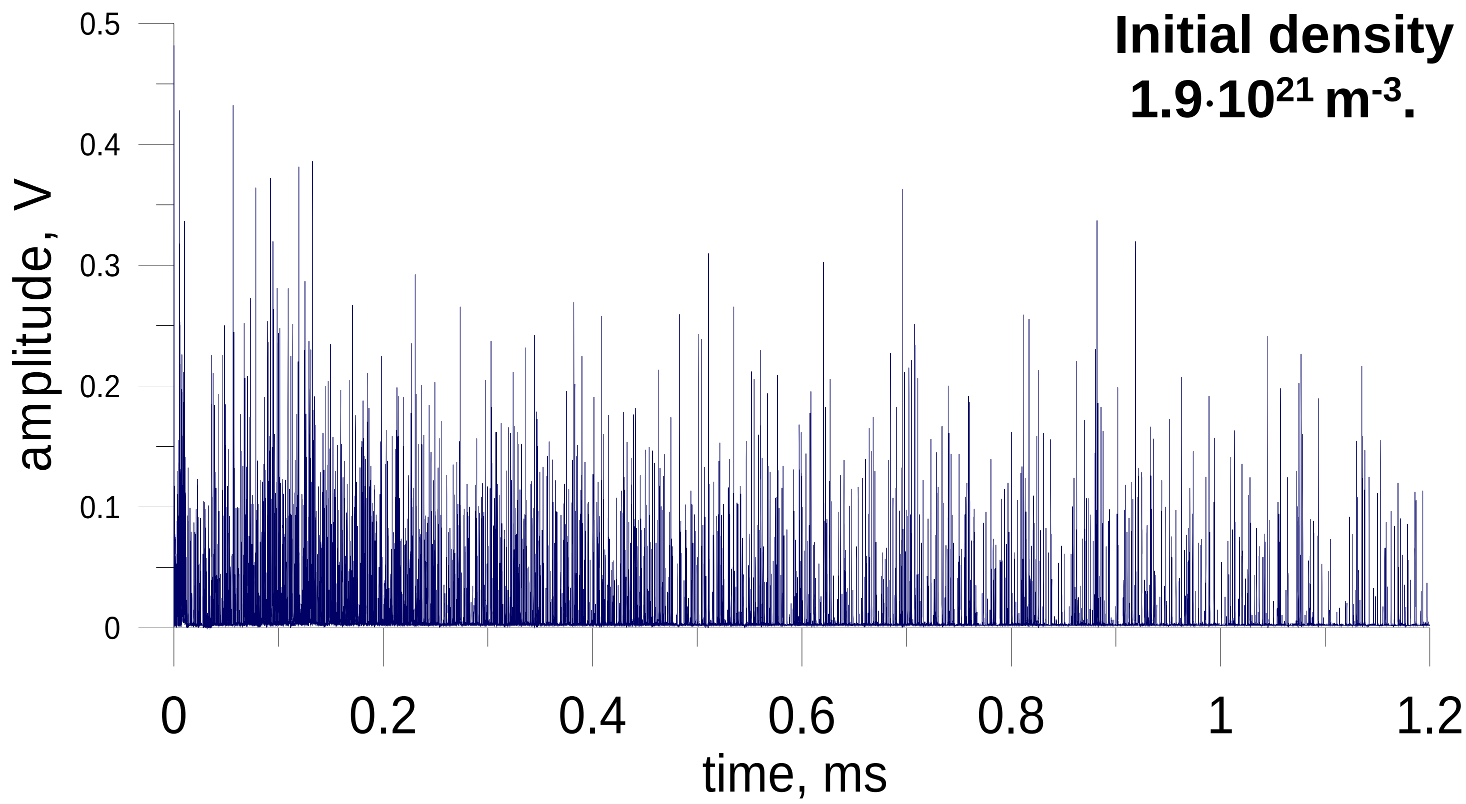
DD neutron generation

Waveforms of signal of digital PSD stilbene detector (Z=4.3 m).



The measured neutron source strength corresponds to an ion temperature of 1-2 keV and correlates with other ion diagnostics such as CX neutrals and Doppler broadening of the D-alpha line.

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Summary of the GOL-3 results

- ***Conditions for stable production and effective heating of plasma in the density range $(0.2 \div 6) \cdot 10^{21}$ m^{-3} are experimentally found.***

- ***Electron and ion plasma temperatures up to 2 keV at density ~10^{21} m^{-3} are achieved.***

- ***Macroscopical stability and long confinement of the dense plasma in multi-mirror system is obtained.***

- ***The value $n\tau_E$ ~ $(1.5 \div 3) \cdot 10^{18}$ m^{-3}s at ion temperature ~1 keV is attained.***

- ***Transition to full corrugation of the magnetic field and increase of specific parameters of heating E-beam results in considerable increase of plasma parameters in the multi-mirror trap GOL-3.***

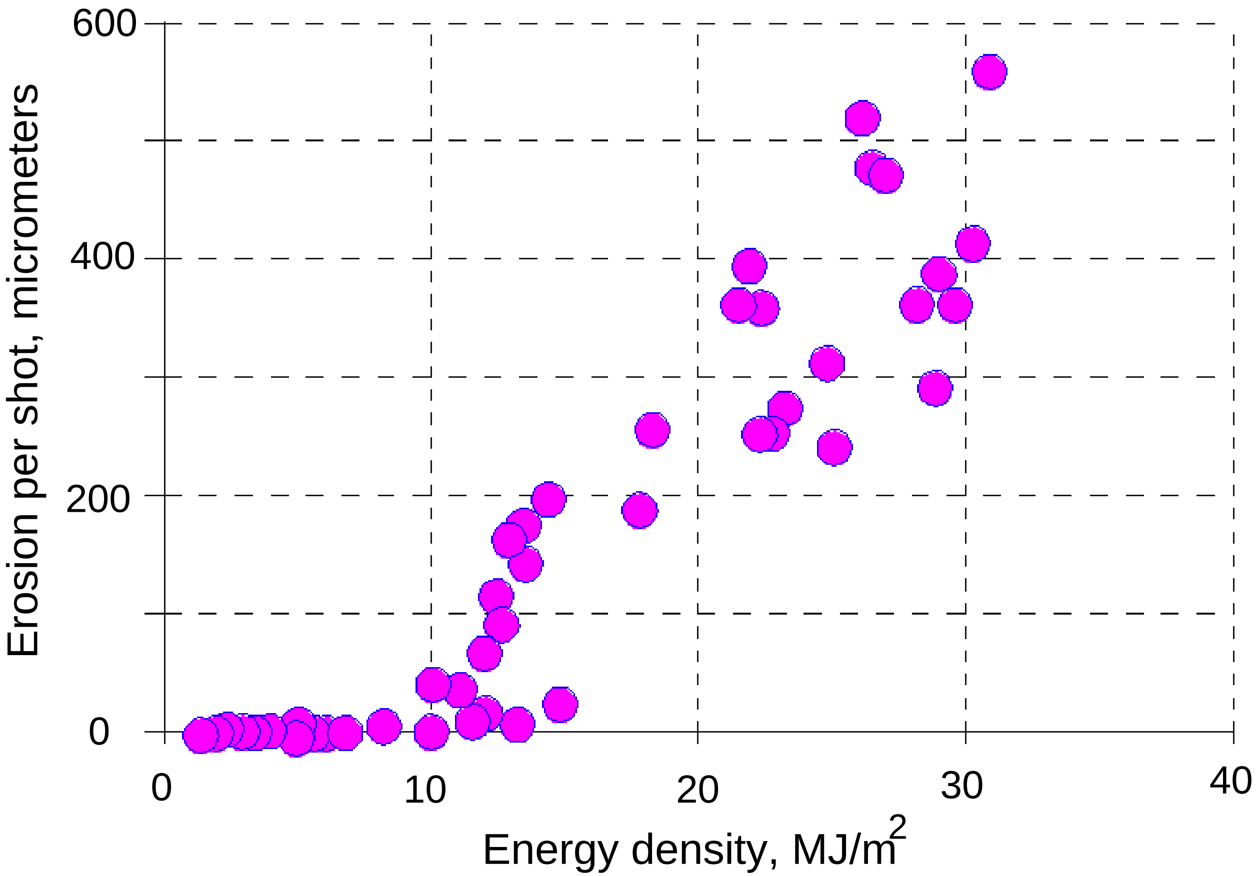
During the heating stage (~10 microseconds) the energy released at the target can be varied in the range of 0.5-50 MJ/m^2 (hot plasma electrons together with the electron beam).

Plasma-wall interaction experiments at the GOL-3

Aims of this activity:

- **Development of design solutions for GOL-3 plasma and beam dumps**
- **ITER-related studies of plasma-wall interaction**
  At present the problem is actual for the ITER tokamak, especially for disruptions and Edge Localized Modes (ELM) studies.

Erosion of fine grain high density graphite



Irradiation of the graphite target by a stream of the plasma hot electrons together with the relativistic electron beam leads to explosive (brittle) erosion of the graphite. The erosion depth of the graphite depends on the energy density and reaches 0.5-1 mm at 20-60 MJ/m^2.

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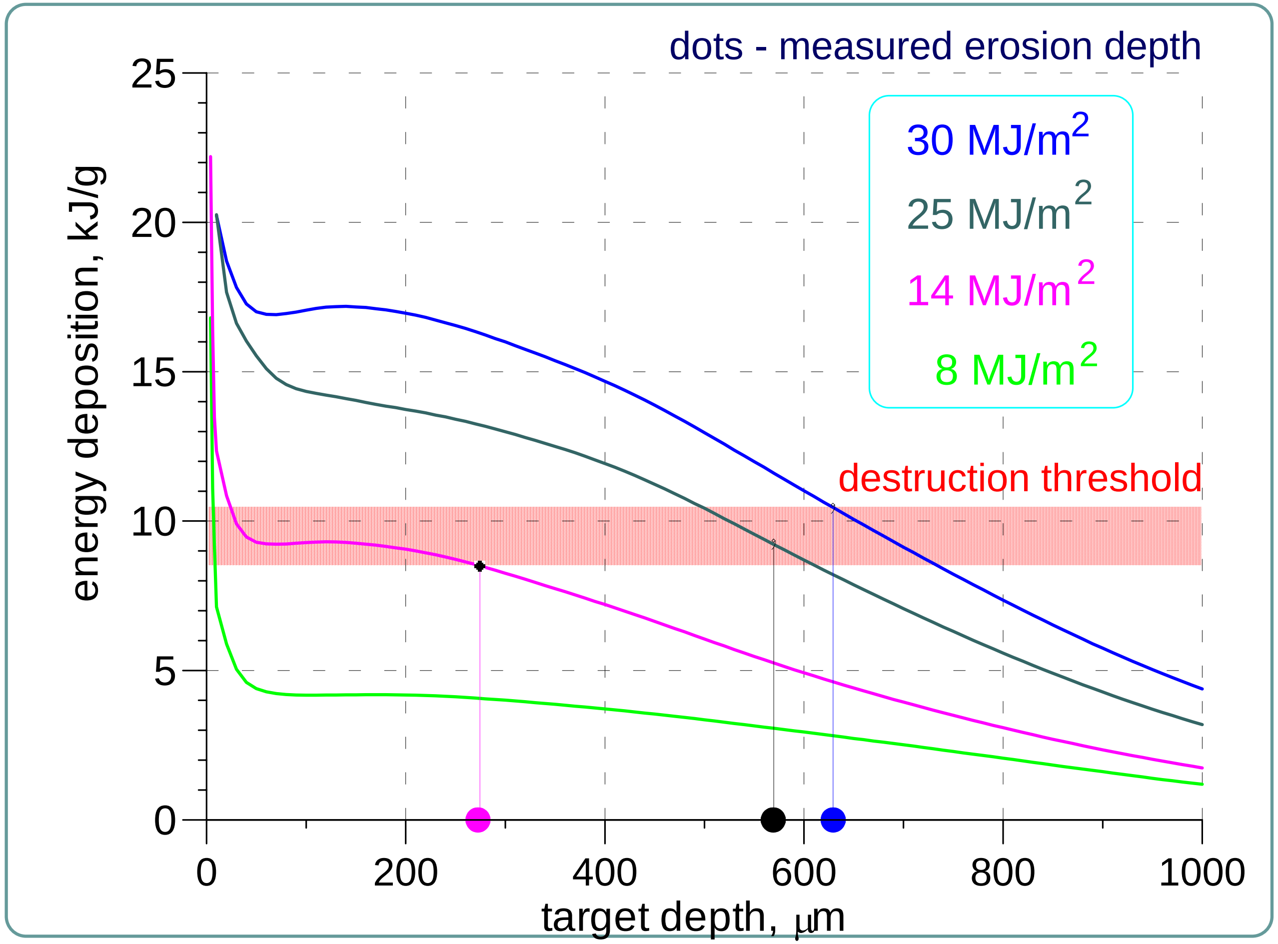
Determination of destruction threshold



The comparison of the depth dependence of the energy deposition with the graphite erosion observed in similar shots gives the graphite destruction threshold of 8-10 kJ/g.

This value is much less than the vaporisation enthalpy.

The high erosion observed at the interaction of powerful hot electron stream with targets cannot be explained by evaporation of target material.

The phenomenon of the explosive erosion can be explained by volumetric heating and phase transitions inside the material.

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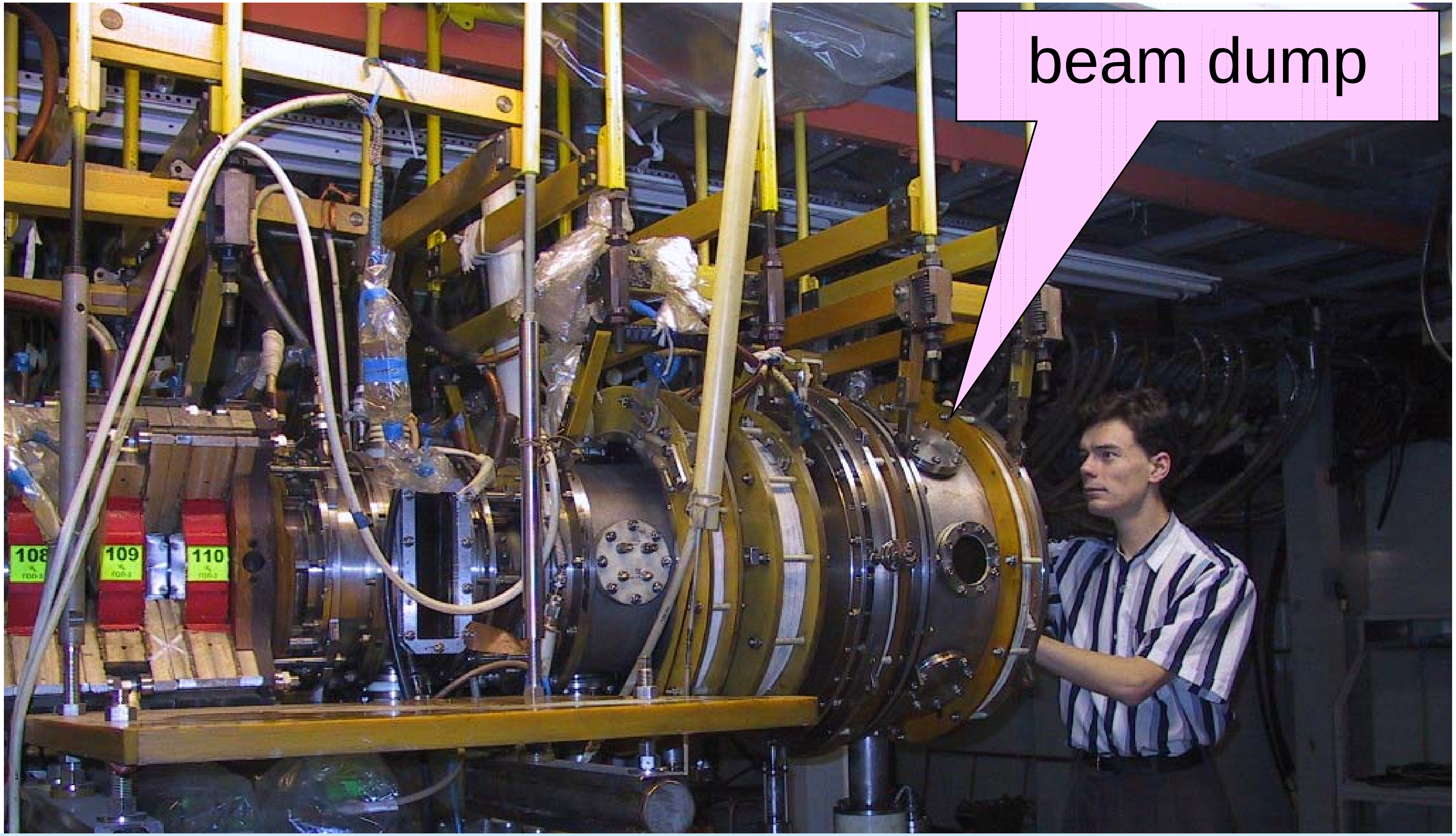
Long-range carbon migration



The conditions for long-lifetime operation of the graphite dump were found. It corresponds to energy density ~1 MJ/m^2 . Beam and plasma dump is in operation since 1999.

Solved problem: Large graphite erosion and vapor cloud feedback influence to plasma confinement

•***Problem to be solved: Carbon migration***

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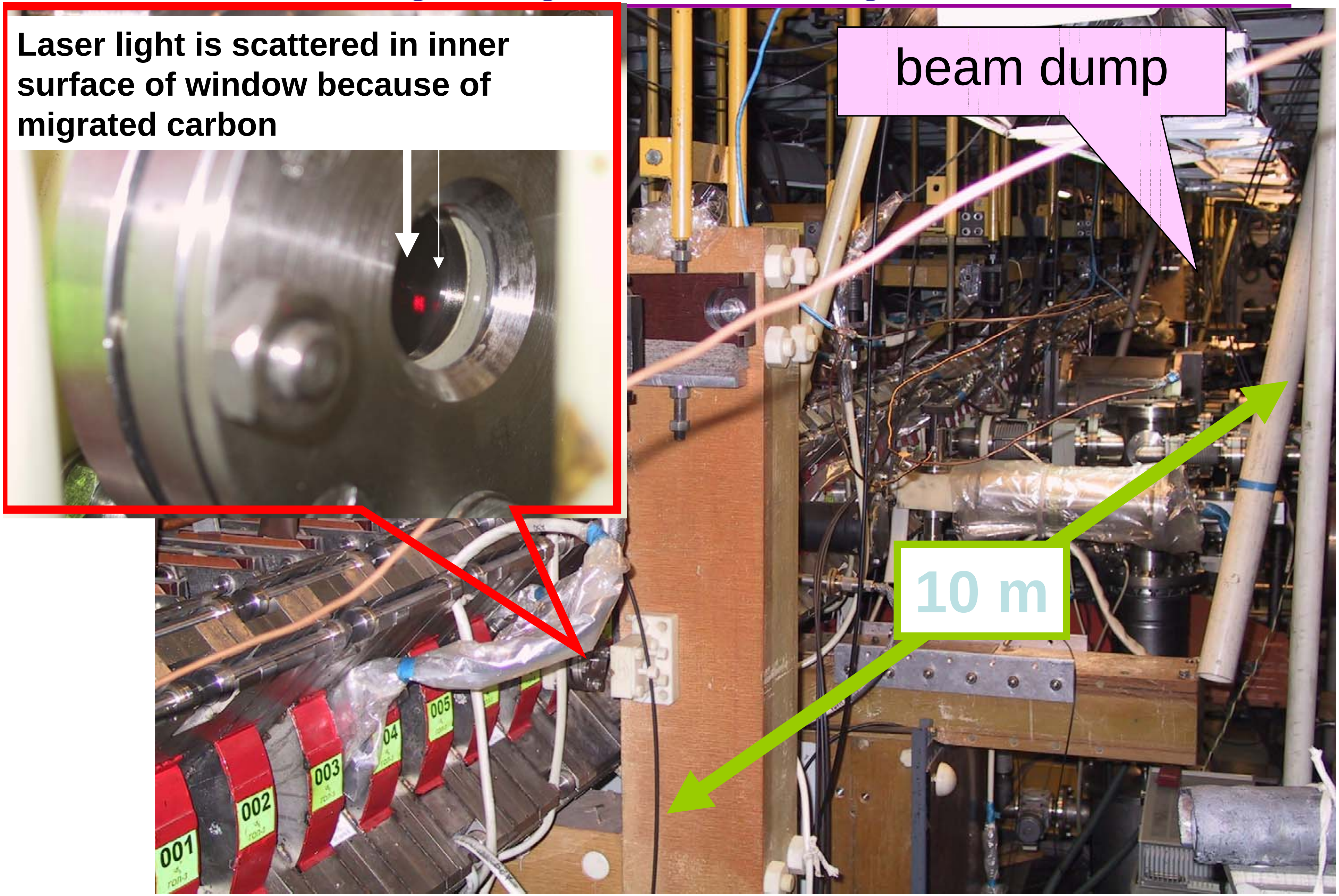
Long-range carbon migration



Re-deposited carbon layer

1 m distance from the graphite target

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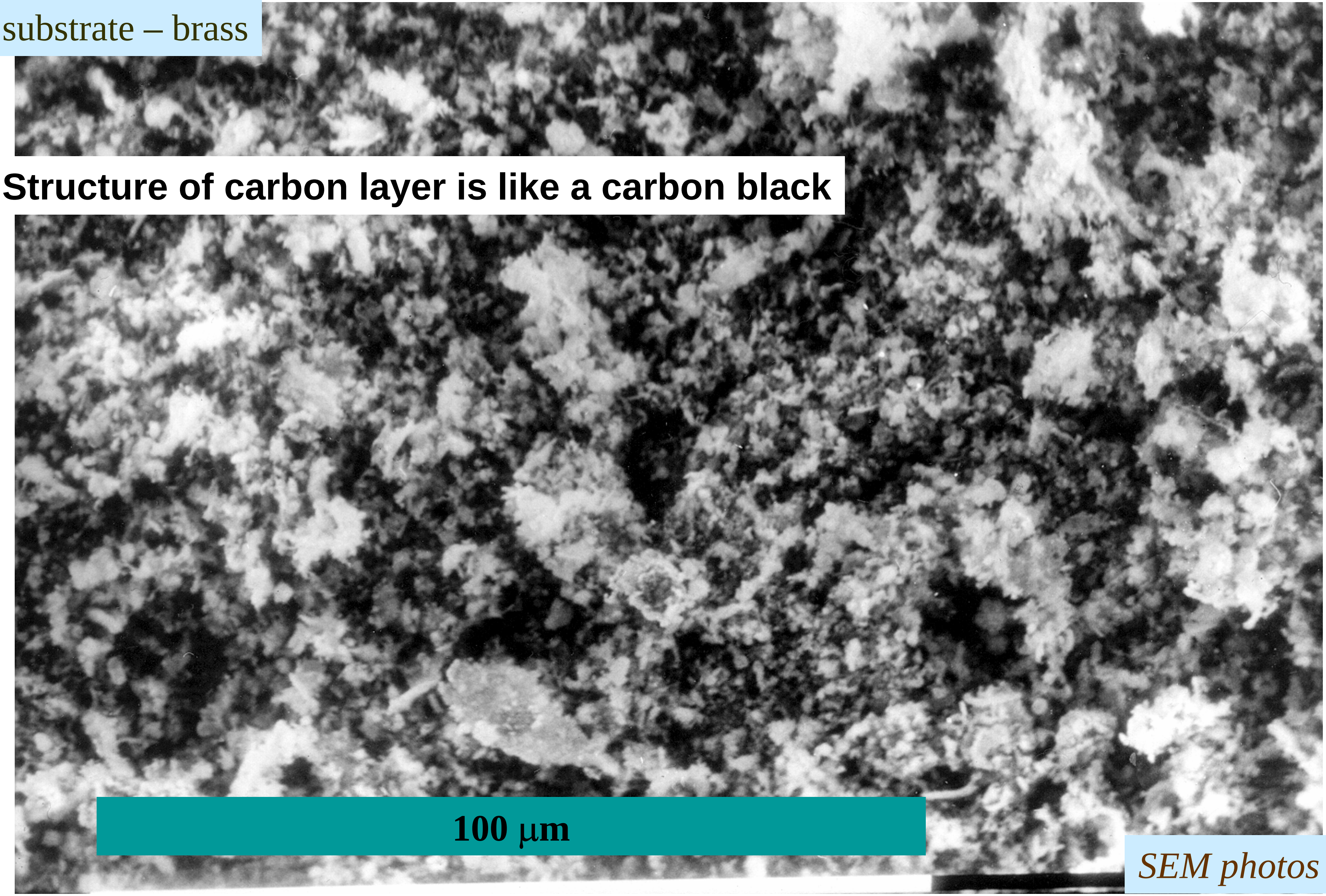
substrate – brass



Structure of carbon layer is like a carbon black

SEM photos

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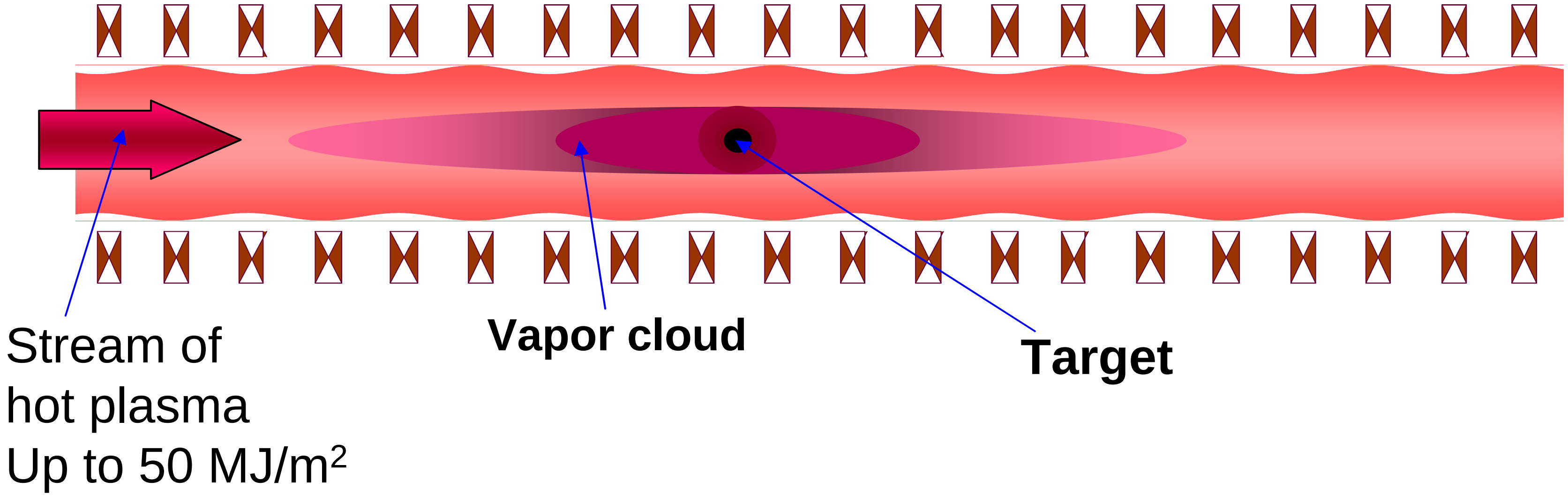
Carbon plasma transport along and across the magnetic field at long (~10m) distances

Idea of experiment:



A carbon pellet with diameter of 2 mm is placed in the center of vacuum chamber of the facility. In this experiment a pellet size exceeds the ranges of plasma particles in carbon therefore the processes of evaporation and formation of surface plasma are the same as in a thick solid target. The transverse size of the carbon jet is determined by a collisional expansion across the magnetic field near the target and diffusion of magnetically confined plasma.

Scenario of the experiment in GOL-3 facility

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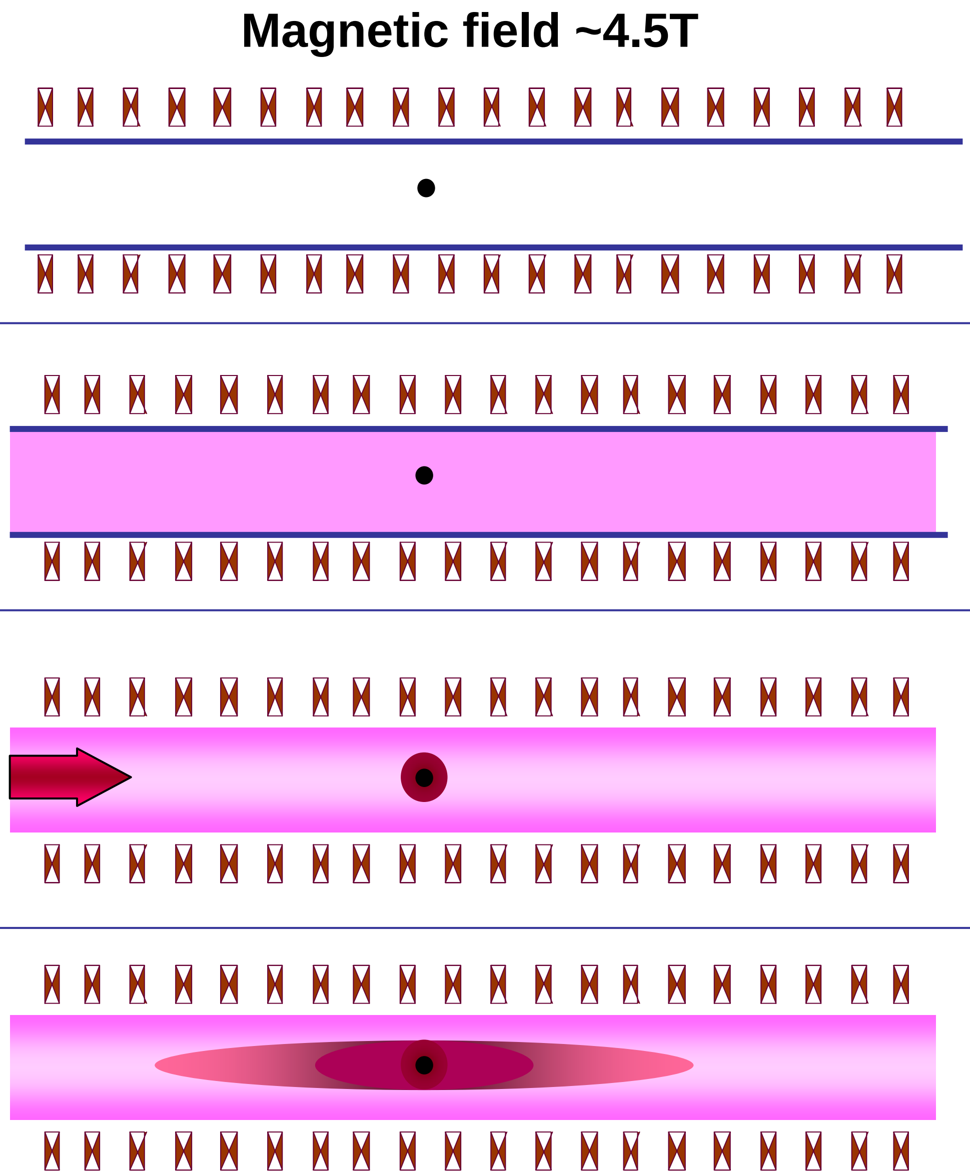

Target injection

Plasma creation

Plasma heating by REB
0.3-50 MJ/m^2

Simulation of ELM

Plasma confinement

Simulation of carbon expansion

Diagnostics for investigation of carbon cloud expansion

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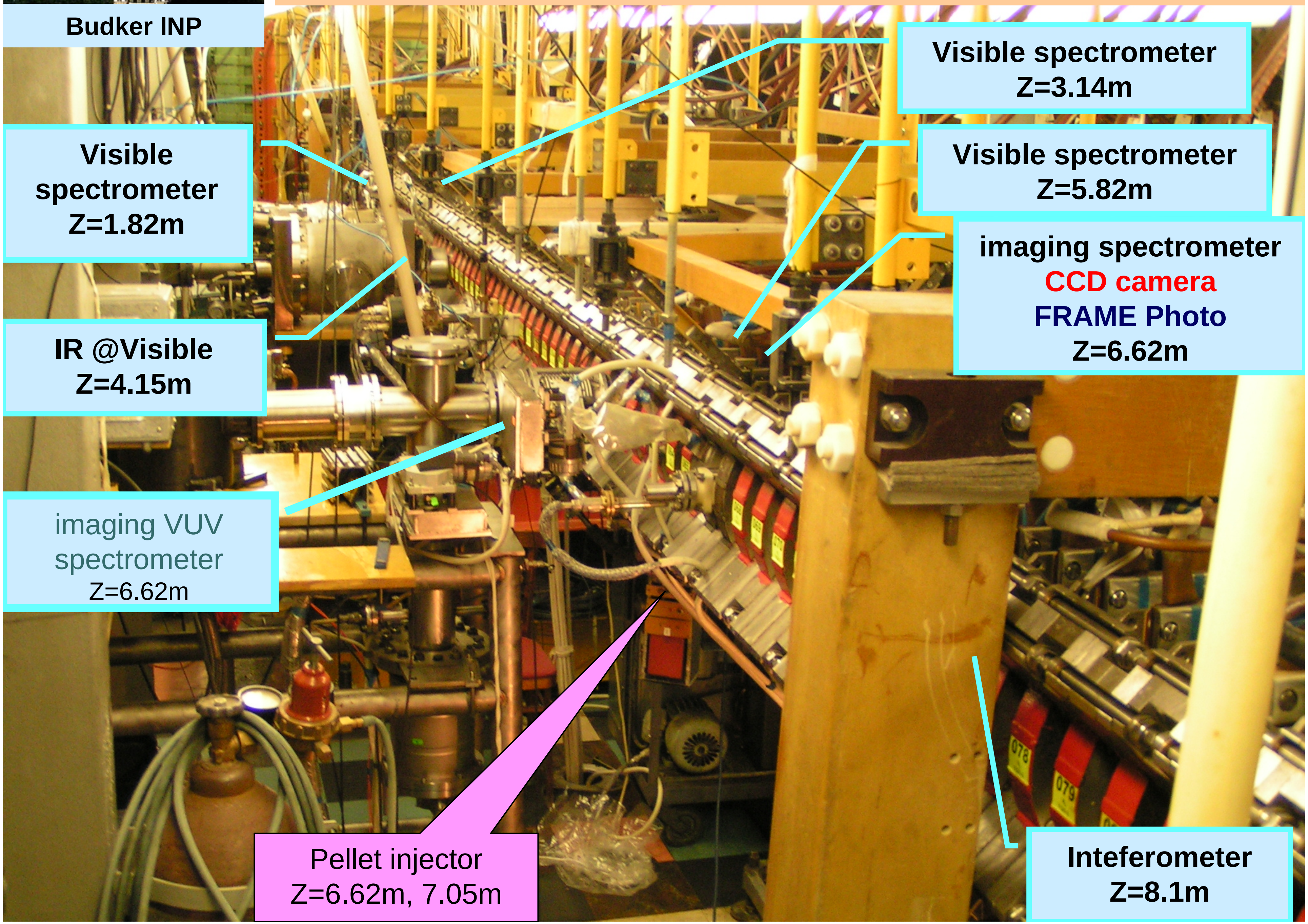
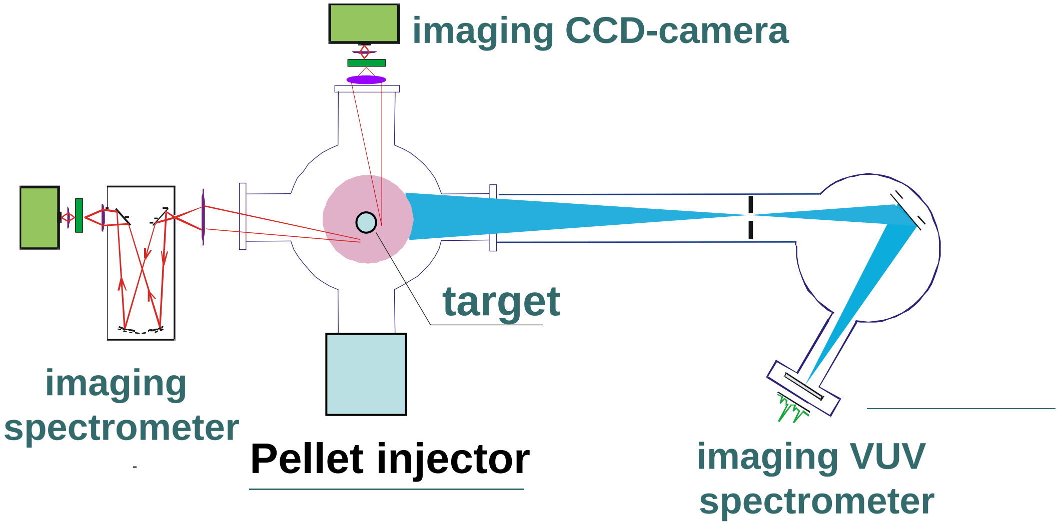


Carbon cloud creation and expansion



Arrangement of diagnostics for near-the –target measurements

Expansion of created carbon cloud is studied by absolutely calibrated diagnostics :

- CCD-camera with ICT for framing.
- Imaging spectrometer (380-680 nm). Gives spatial distribution of spectral lines intensity across magnetic field without time resolution.
- VUV spectrometer (50-400 nm) build on Seya–Namioka scheme. CCD-camera records spatial distribution of spectral lines intensity across magnetic field with time resolution.

[1] - V.T. Astrelin, et al. *Hot electron target interaction experiments at the GOL-3 facility* // Nuclear Fusion, Vol. 37, No.11, 1997, p.1541-1558.

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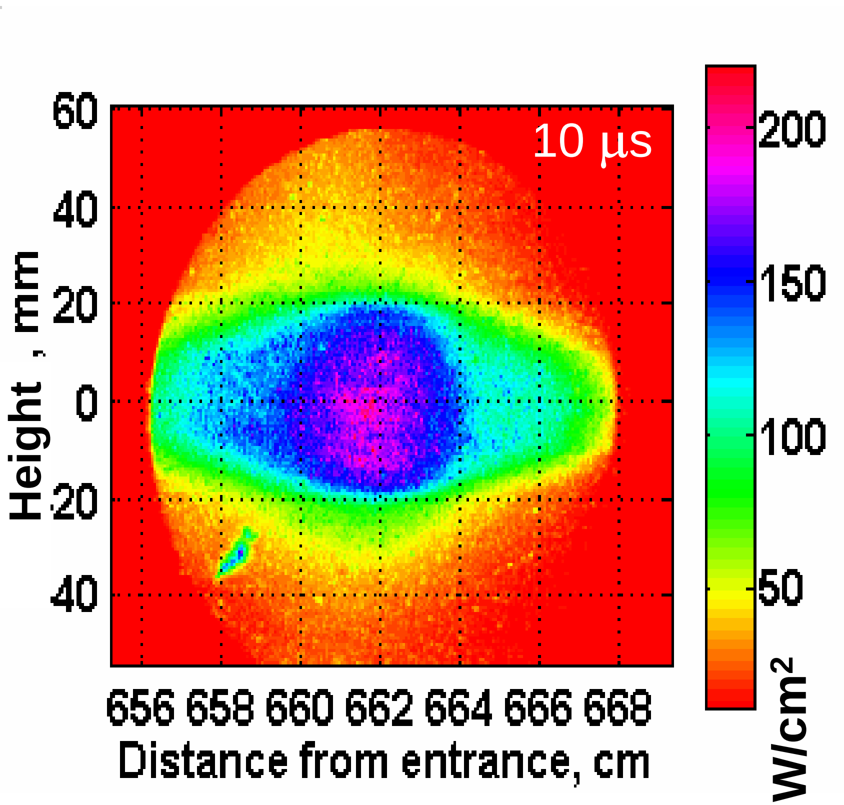
Carbon cloud creation and expansion



During e-beam heating stage a target surface blows up.

Formed carbon dust and gas cloud expands spherically and simultaneously is ionized by hot plasma electrons.

Prompt photo of carbon cloud at 10 μs, after beginning of e-beam injection.

Target is placed in the center.

Spherical carbon cloud is seen.

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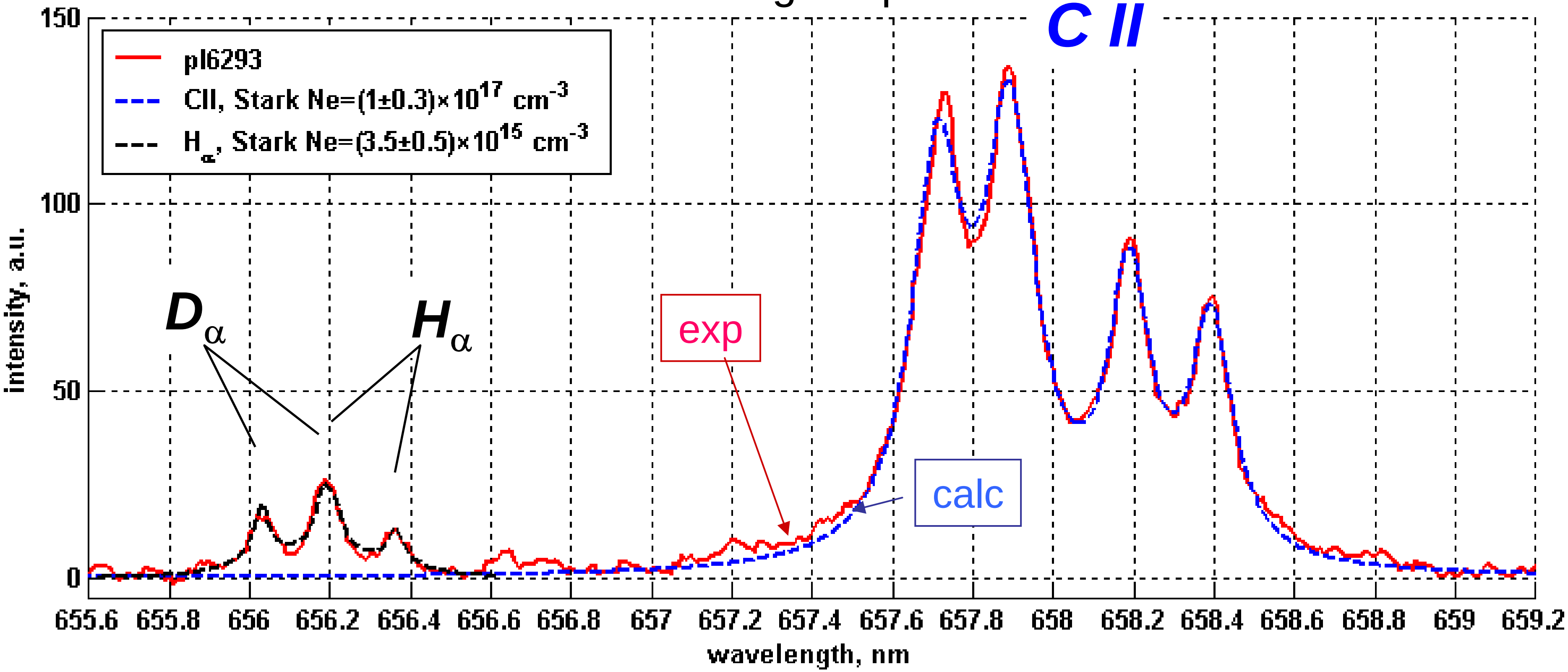
Profile of σ-components of H_α and *CII* lines near the target surface

Electron density in carbon cloud and in hydrogen corona was obtained from Stark broadening of spectral lines

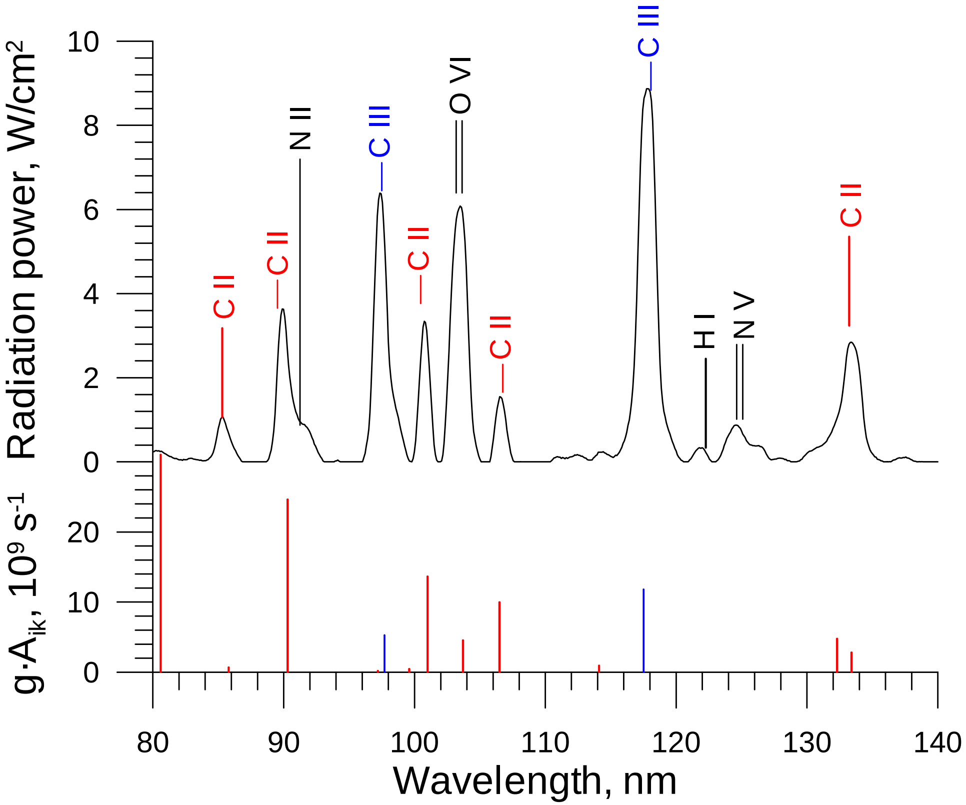


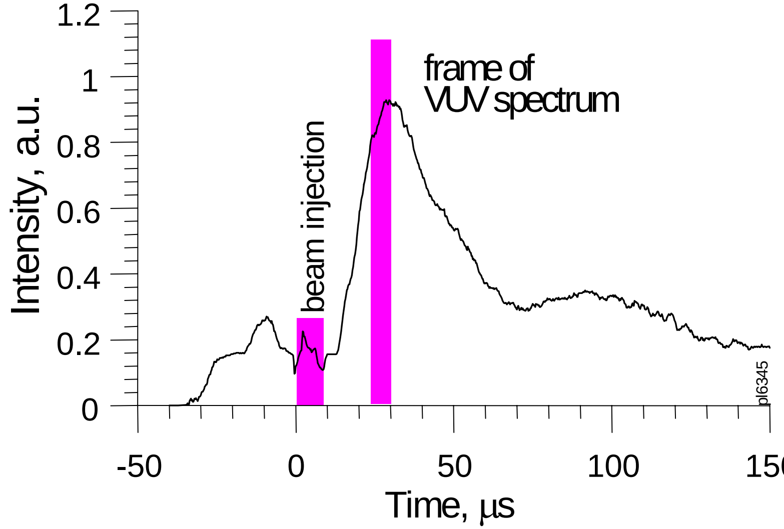
Averaged electron density in carbon target plasma near the target is 10^{17} cm^{-3}.

Averaged electron density on periphery of carbon target plasma (at the border of target plasma and hydrogen plasma) is $3{\cdot}10^{15}$ cm^{-3}.

Spectrum of VUV emission from expanded surface plasma

0. 4 m from target





Spectral lines of low-ionized carbon ions dominated in the spectrum

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Long-range carbon plasma expansion along the magnetic field.

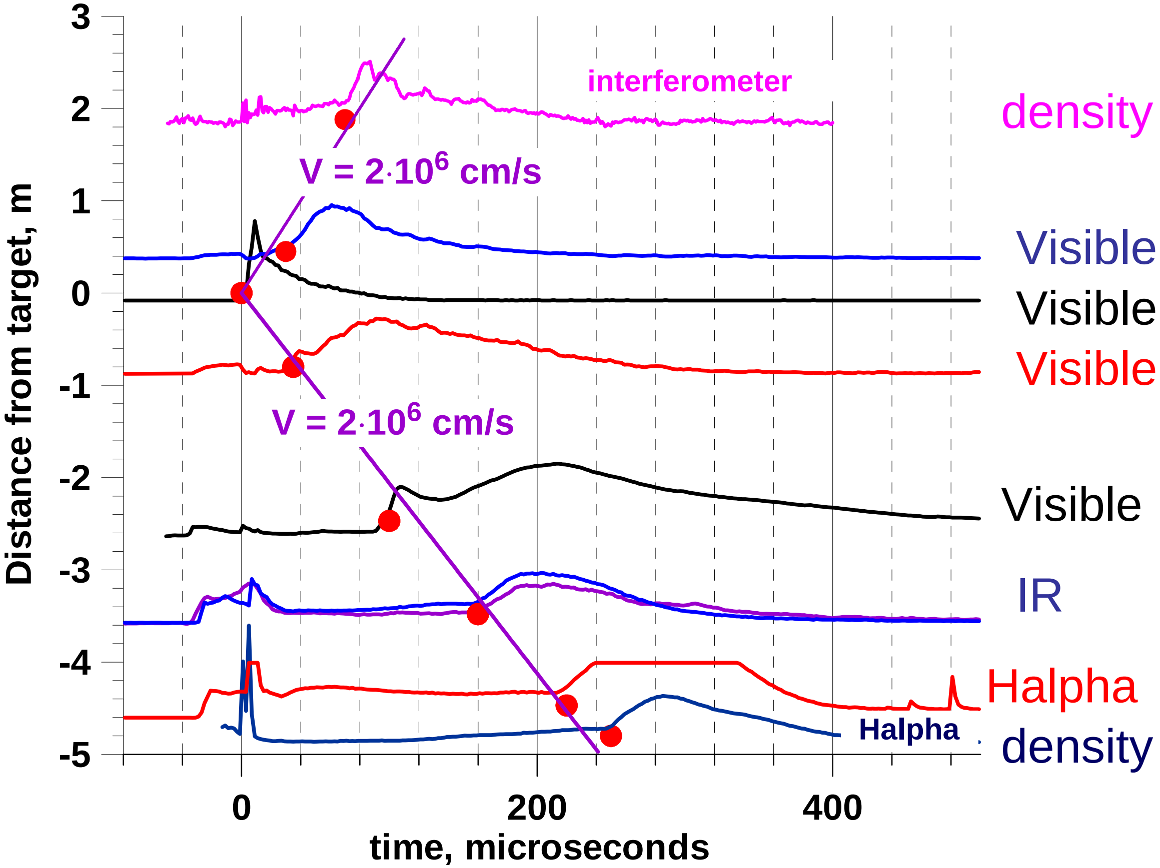

Figure shows measured on GOL-3 velocities of ~$2 \cdot 10^6$ cm/s.

Summary of GOL-3 results on plasma-wall interaction

Irradiation of the target by hot-electron plasma stream leads to explosive (brittle) erosion of the graphite and formation of vapor cloud mixed with dust.

Erosion depth of the graphite depends on energy density and reaches 0.5-1 mm for energy density of stream of fast electrons of 20-60 MJ/m^2.

Threshold of the volumetric destruction of the graphite (~10 kJ/g or ~4000 K) was determined.

Vapor layer consists of graphite dust, vapor cloud and plasma corona .

The conditions for long-lifetime operation of the graphite dump were found. It corresponds to energy density ~1 MJ/m2 .

Experiments for investigation of long-range carbon migration was carried out:

•Carbon plasma velocity measured at distances 0.8-4.5m from the pellet - 1÷2·10^6 cm/s corresponds to sound velocity of the plasma of 6-24 eV.
•Estimation of carbon plasma diffusion across the magnetic field confirms long range transport of the plasma: n_C~2 ÷10·10^{20} m^{-3} at the distance of 4.5m.

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Thank you!

Photo of carbon plasma