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Polari-interferometric diagnostics of pulsed plasmas - recent interferometric results from PALS experiment

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Plan:

1. Introduction.

- **Fundamentals of the interferometric and polarimetric measurements in plasmas**
- **Limitations of the polari-interferometric methods**

2. Review of experimental diagnostic system and investigations results.

- **Plasma-focus**
- **Laser-produced plasma**
- **PALS experiment**

3. Conclusions.

Fundamentals of the interferometric and polarimetric measurements in plasma

Simultaneously application for plasma diagnostic of:

- **inteferometry**
- **polarimetry**
- and **shadowgraphy**

enables to determine:

electron density and **magnetic field** in plasma.

Only this way the information about magnetic field, and density **distribution** can be obtained **simultaneously in all regions** of the investigated plasma with good spatial and temporary resoultion

In the case of a **homogeneous and highly ionized plasma** the interferometric measurements enables determining of the electron density on the basis of a EMW phase shift:

$$\delta = \frac{1}{\lambda}\int_0^L (1-N)\,dl \cong 4.46\cdot 10^{-14}\,\lambda \int_0^L n_e\,dl$$

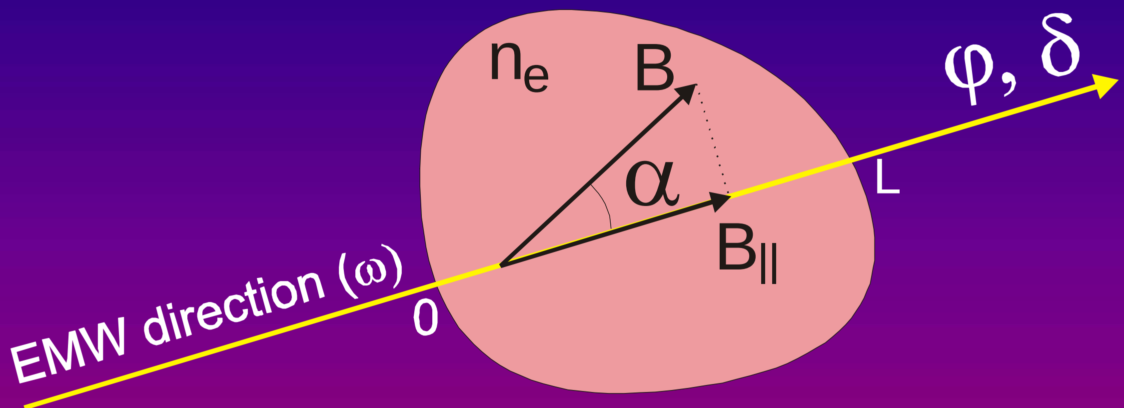
Homogeneous and highly ionized plasma:

$$N \cong 1 - 4.46\cdot 10^{-14}\,\lambda^2 n_e$$

N - the refractive index

n_e - the electron density component

If the EMW propagation in the plasma is „quasilongitudional”:



the polarization-p

Conditions for „quasilongitudinality”:

$$\varphi \cong 2.62 \cdot 10^{-17} \lambda^2 \int_0^L n_e B_{||} dl$$

$$u = \frac{\omega_P^{\ 2}}{\omega^2};$$

$$V = \frac{\omega_B^{\ 2}}{\omega^2}$$

$$s = \frac{\nu}{\omega}$$

are fulfiled with satisfactory accuracy when:

u<<1, v<<1 and s<<1

where: $B_{||}$ - the avarage magnetic induction in Gs.

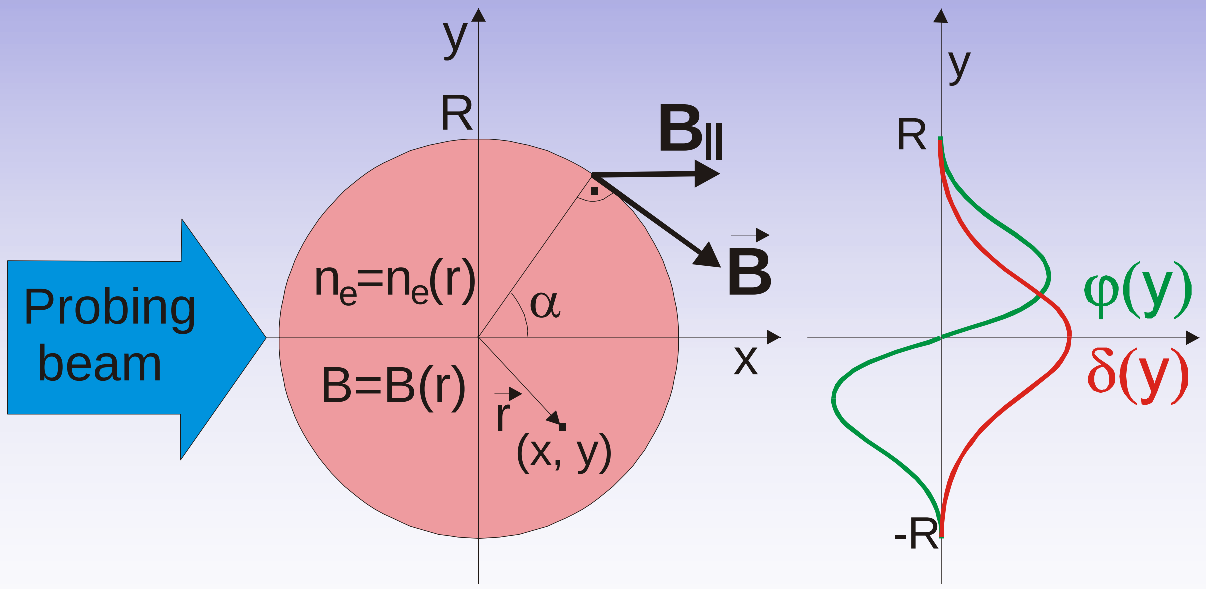
If measurements of φ and δ are made simultaneously it is possible to determine the average magnetic induction along the probing direction L:

$$\overline{B}_{\parallel} = \frac{\int_0^L n_e B_{\parallel} dl}{\int_0^L n_e dl} \approx \frac{1.70 \cdot 10^3}{\lambda} \cdot \frac{\varphi}{\delta} \qquad [MGs]$$

Note that no information on the symetry of the object is necessary to determine $\overline{B}_{\parallel}$

Determination of the magnetic field spatial distribution

In the case of the **axial symmetry** in the plasma
it is possible to reconstruct not only the average MF projection,
but also the entire distribution of the vector B(r).



$$B_{\|} = B\cos\alpha$$

In a cylindrical coordinate frame:

$$\varphi(y) = 5.24 \cdot 10^{-17} \lambda^2 \int_y^R \frac{B(r) n_e(r) y dr}{\sqrt{r^2 - y^2}}$$

$$\delta(y) = 8.92 \cdot 10^{-14} \lambda \int_y^R \frac{n_e(r) r dr}{\sqrt{r^2 - y^2}}$$

Expressions for φ(y) and δ(y) can be reduced to a form an integral Abel equation:

The solution of AE – Abel inversion and can be written in two forms:

$$f(r) = -\frac{1}{\pi} \int_r^1 \frac{\frac{dS}{dy} dy}{\sqrt{y^2 - r^2}}$$

or

$$f(r) = -\frac{1}{\pi r} \frac{d}{dr} \int_r^1 \frac{S(y) y dy}{\sqrt{y^2 - r^2}}$$

After transition to the Abel equation one obtains:

for φ(y)

$$f_B(r) = 2.62 \cdot 10^{-17} \lambda^2 R \left(\frac{B(r) n_e(r)}{r} \right)$$

$$S_B(y) = \frac{\varphi(y)}{y}$$

for δ(y)

$$f_n(r) = 4.46 \cdot 10^{-14} \lambda R n_e(r)$$

$$S_n(y) = \delta(y)$$

Finally we can obtain the expression for B (r) :

$$B(r) = 1.70 \cdot 10^{3} \frac{r}{\lambda} \cdot \frac{f_B(r)}{f_n(r)}$$

However, $f_B(r)$ and $f_n(r)$ can be only determined by means of special numerical methods

because the experimental functions $\varphi(y)$ and $\delta(y)$ are given in the form of measured values at many chosen points.

and

$f_n(r)$ on the basis of $\delta(y)$ (from inteferometric measurement)

Some limitatins of the polarimetric and interferometric measurements

Accuracy of $\varphi(y)$ and $\delta(y)$ determination depends on:

- **depolarization of the probing EMW**

- **influence of the plasma self-luminosity**

- **nonhomogeneity of the coross section of the probing beam**

Depolarization of the probing EMW

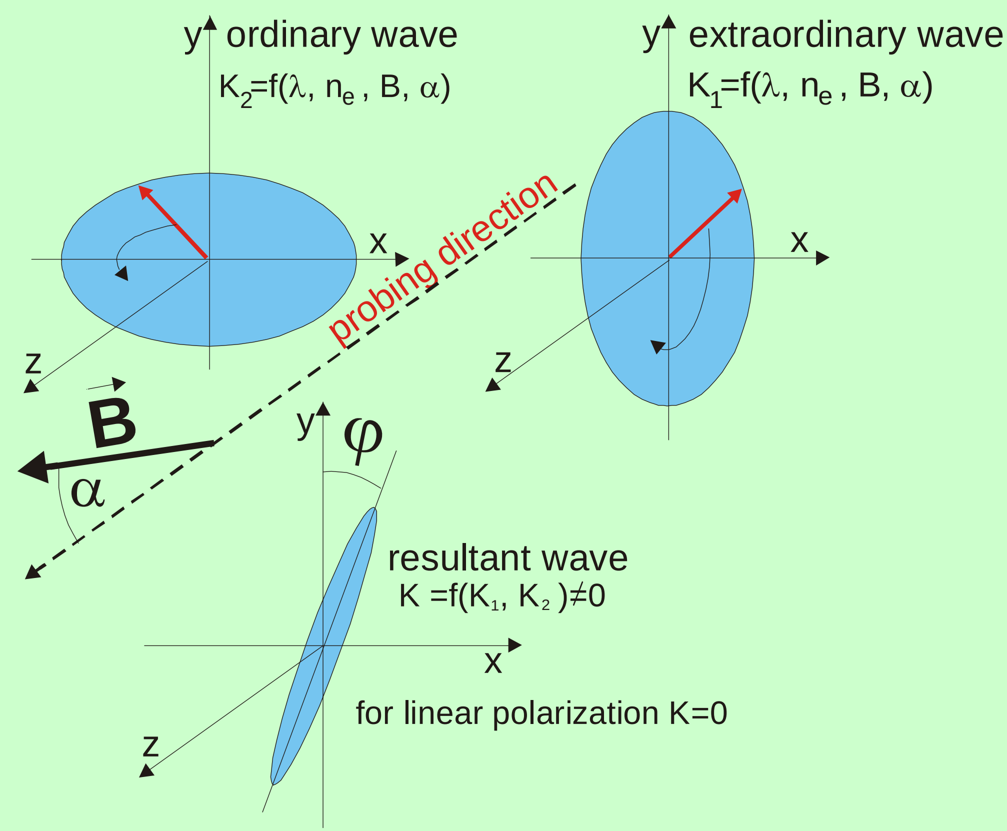
Depolarization of the linearly polarizerd EMW can be caused by :

- **N**onlongitudional propag
  of the EMW (ω) in relatio
  with:

$$K_{1,2} \cong - \frac{i\ldots}{u \sin^2 \alpha \pm \sqrt{u\ldots}}$$

the extraordinary (K_1) and
polarizations.

Inhomogeneities of the e
temprature in a plasma ca
rotation angle φ of the pr



Influence of the plasma self-luminosity

In real experiments it is imposible to avoid the plasma self-luminosity. Therfore the polar… …ut with initial turn-angle $\varphi_0(y)$ of …

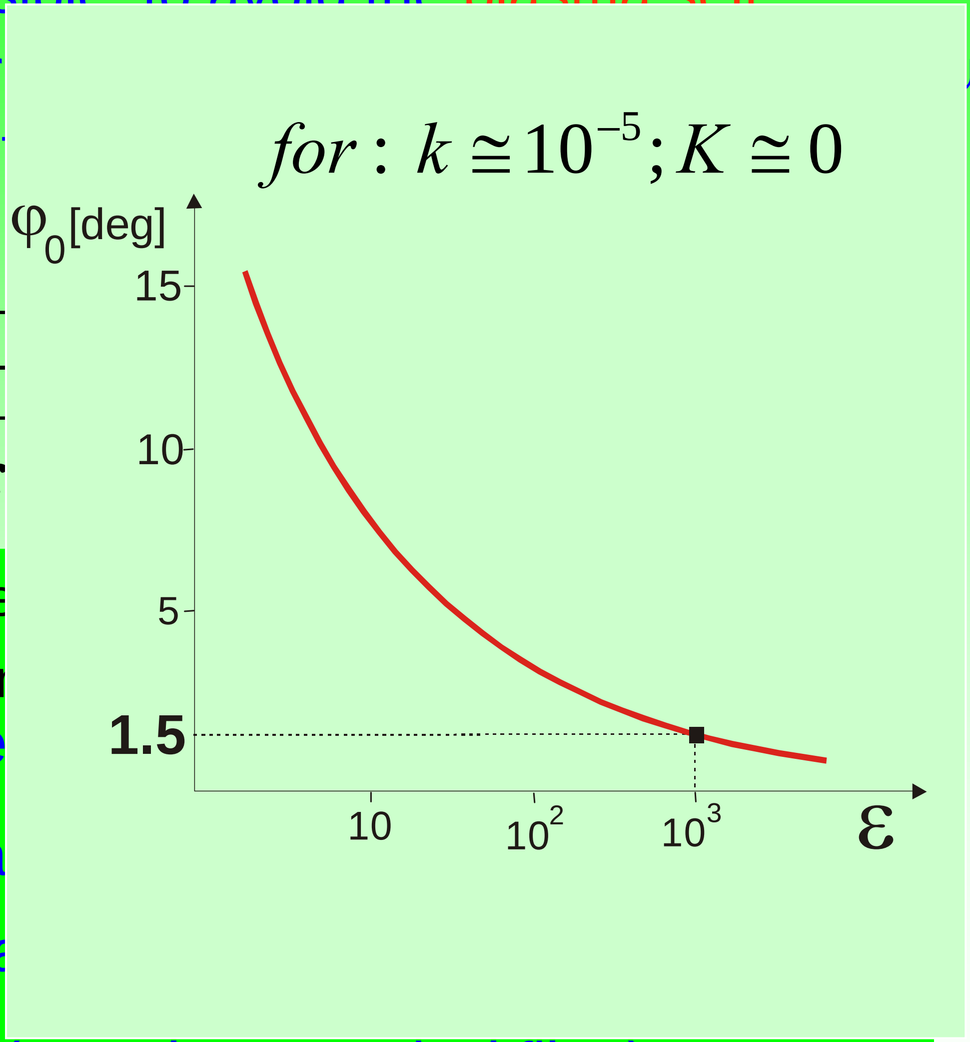
The optimal uncrossing angle …

$$\varphi_0 \cong arc\sin\sqrt{\frac{1\ldots}{2+\varepsilon\ldots}}$$

The p…

E_L- laser energy, E_p– ene…

K – polarization coefficie…



- narrow-band colour or inte…
- spatial filtering (by diaphra…
- use of detector with optima…
- use of high-speed shutter (e.g. electro-optical filter)
- and other methods

Nonhomogeneity of the coross section of the probing beam

The nonhomegeneous intensity distribution within the probing can cause some errors:

- in interpretation and determination of the position of interference fringes,
- in redout of the absoulute values of the FR angle ,

The influence of beam nonhomegeneity, refraction and absorption in plasma on the polaro-interferomeric results can be minimized by **three-channel registration** (recording simultaneously **polarogram**, **shadowgram** and **interferogram**,)

Methodology of polari-interferometric measurements is described in:

Farada'y- rotation method for magnetic field diagnostics in a laser plasma,

T. Pisarczyk, A. A. Rupasov, A. S. Sarkisov and A. S. Shikanov

Journal of soviet laser research, Vol. 11, No. 1, pp. 1-32 (1990).

Review of experimental diagnostic systems and investigations results.

Plasma-Focus

In relation to PF devices the polari-interferometric method was applied very rarely:

Magnetic field distributions are presented in paper:

Other papers: Contain only general results.

However,

information about spatial and temporal behaviour of magnetic field is an average result from many discharges.

As contrasted to mentioned paper thanks to the prepared special mathodology and apparatus we could obtain the precise magnetic field distributions from one shot.

Results of our investigation on te PF-360 device are presented in paper:

Diagnostic method for the magnetic field measurement in the plasma focus device

S. Czekaj, A. Kasperczuk, R. Miklaszewski, M. Paduch, T. Pisarczyk, and Z. Wereszczynski,

Plasma Phys. and Contr. Fusion, 31, No.4, pp. 587-594, 1989.

The polaro-interferometric system for measurement an azimutal magnetic field in the PF-360 device

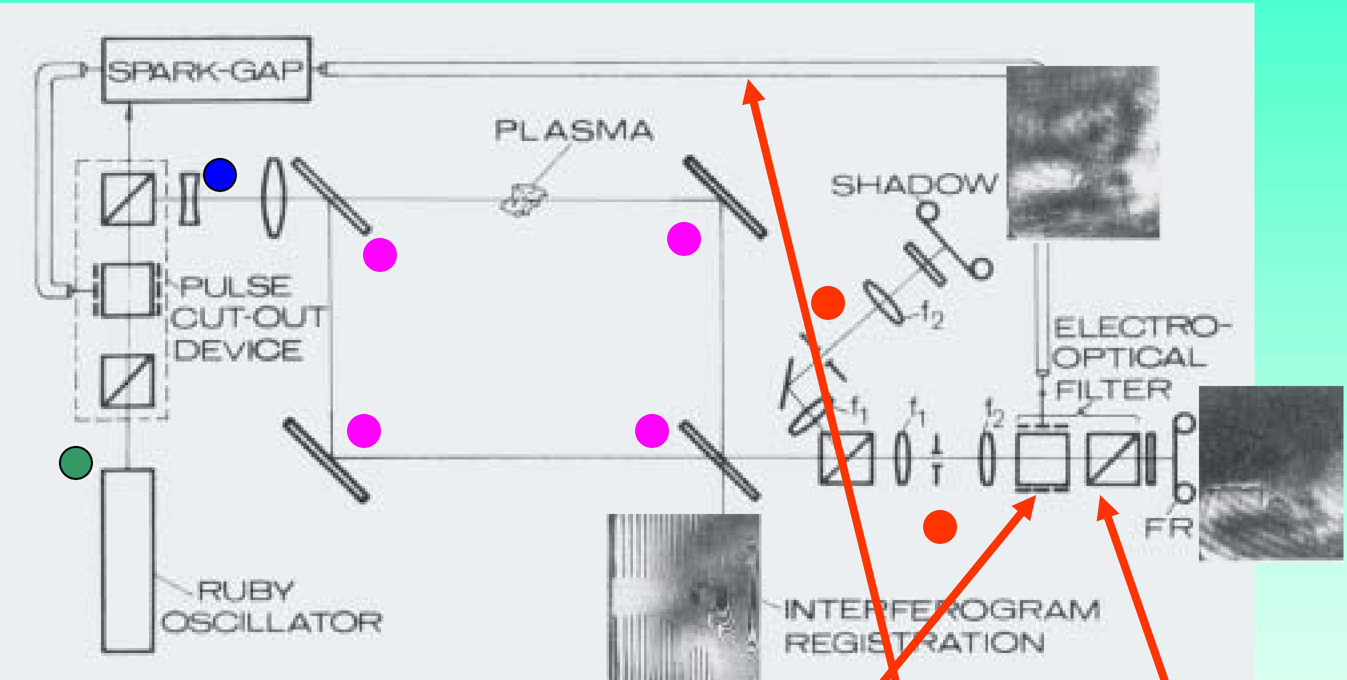
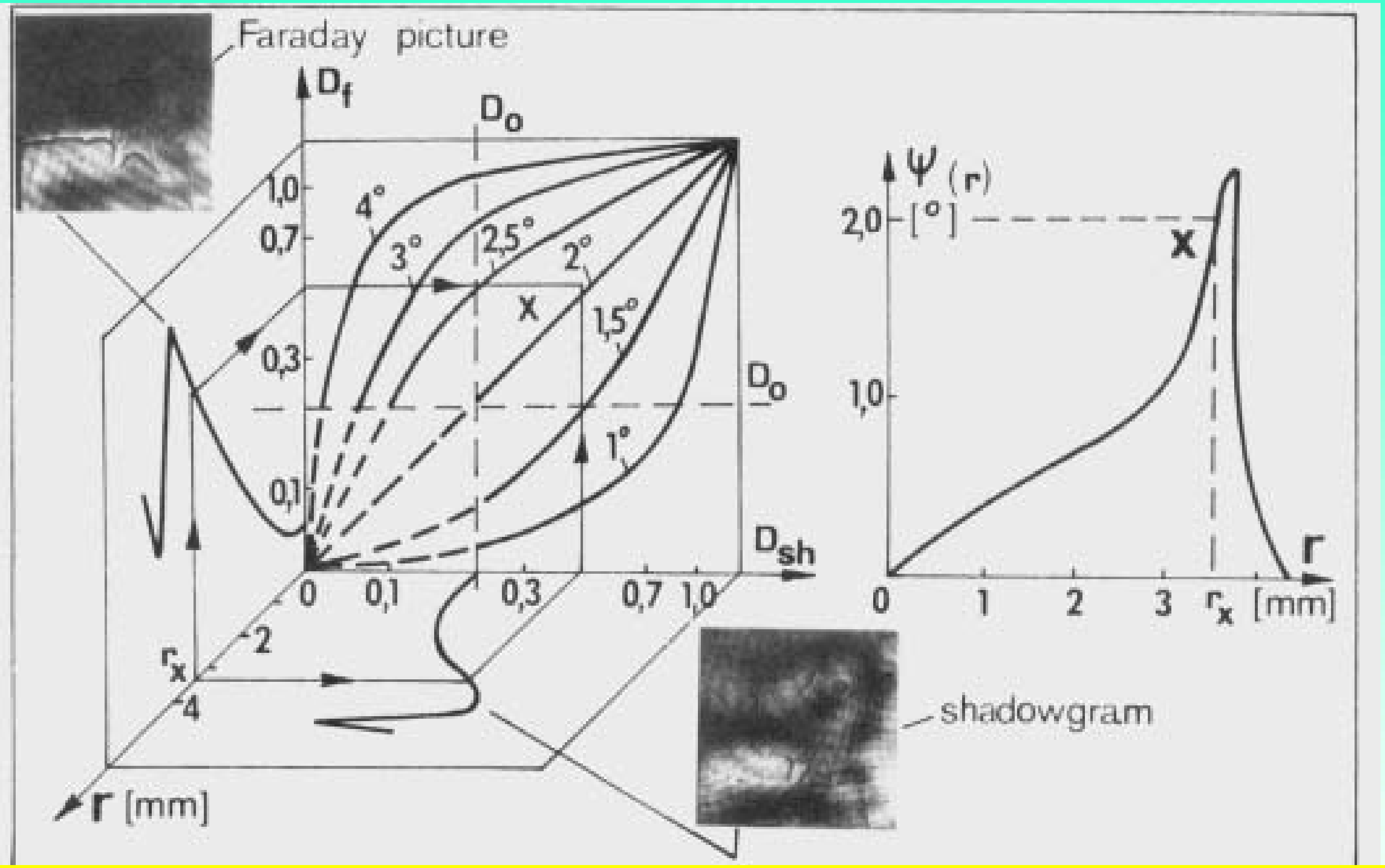


FIG. 1.—Experimental system for magnetic field measurements.

Polaro-interferometr enables the simultaneous registration of the polarogram, interferogram and shadowgram in selected moments of a plasma expansion.

The way to determine the polarization plane rotation angle



These curves were constructed by succesive exposures of the polarimeter by laser radiation of diffrent intensities for

This is why the absolute value of the FR angle in the plasma does not depend on the absolute intensity of radiation entering into the polarimeter.

In our experiment the error of FR readout does not excced of 5 angle minutes.

The measurements w
parameters:

- electrodes: 100/150 mm diameter
- voltage: 21 kV
- stored energy: about 60 kJ
- deuterium pressure 3 Torr
- maximum curent: about 1MA

The initia

The inpu
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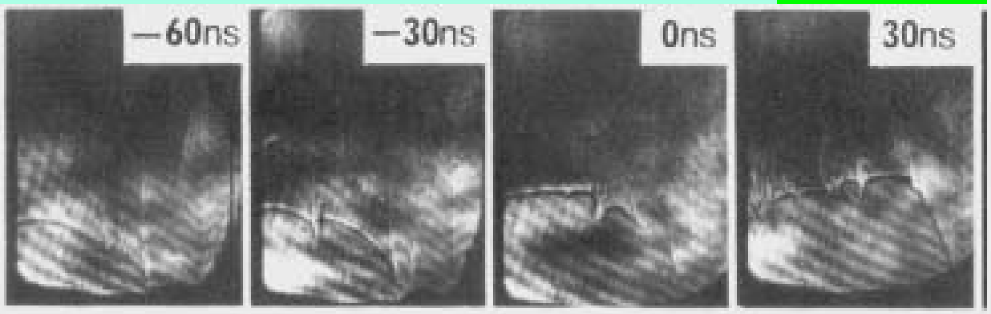
PF-pheno
t= -60 ns ... sponds

cm



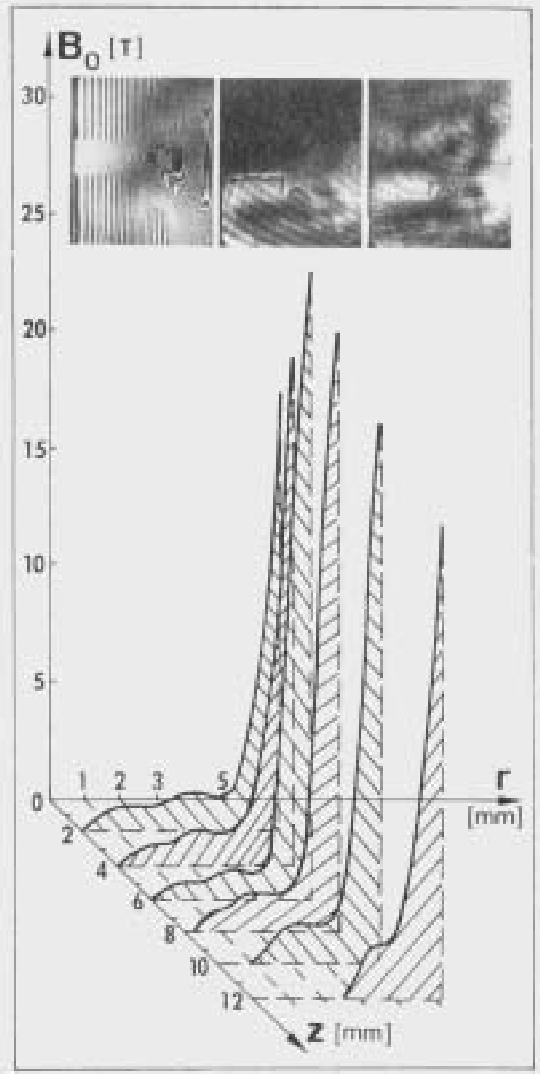
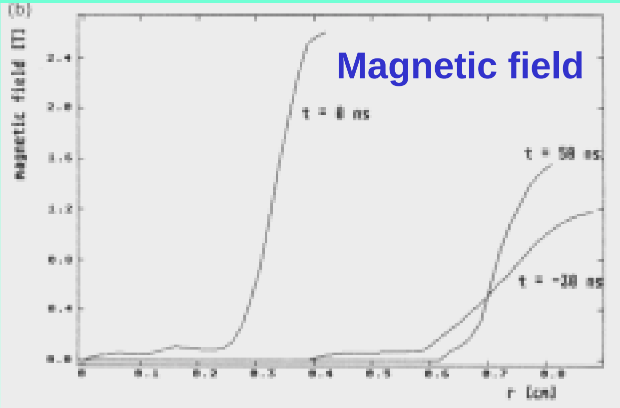


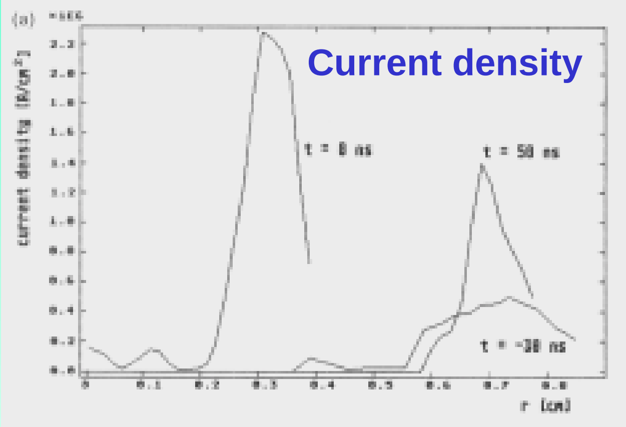
FIG. 4.—Magnetic field distribution in the pinch phase.

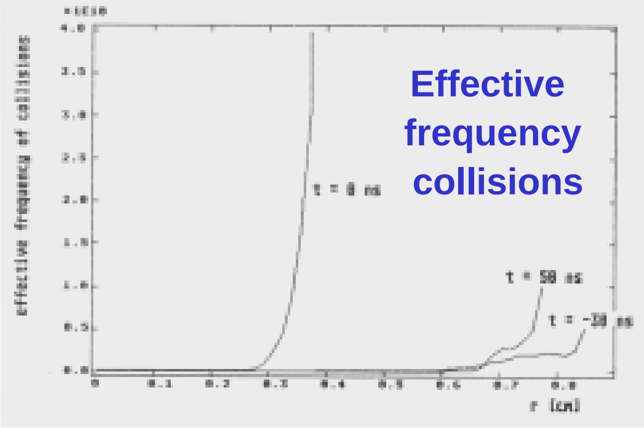
The asymetry of the intensity distribution on t
is caused by the initial turn-angle.
It is a confirmation of the azimutal direction of

Result of measurements

The electron density and FR angle distributions which were obtained in our experiment enables to determine the magnetic field and current density distributions and then to estimate the effective frequency of collisions.







Results analyse showed that a current-driven instability of plasma does not couse enhanced diffusion of the magnetic field up to the moment when the MHD m=0 instability of the plasma column is observed.

Some conclusions

- Presented apparatus and methodology have enabled, contrary to the mentioned paper, to obtain electron density and magnetic field distributions from one shot.

- Our measurements showed that only about 25% of current flows in the dense plasma sheath of the PF-360 device,

-This methodologhy was successfully employed by the author on the vacuum spark device in FIAN (Moscow):

Measurement of the space parameters in the micro-pinch discharge by Farada'y rotation method,

V. A. Veretennikov, A. E. Gurey, T. Pisarczyk, S. N. Poluhin, A. A. Rupasov, A. S. Sarkisov, O. G. Semenov and A. S. Shikanov

Plasma Physics (in Russian), Vol. 16, No. 7, pp. 818-822 (1990).

Laser produced plasma

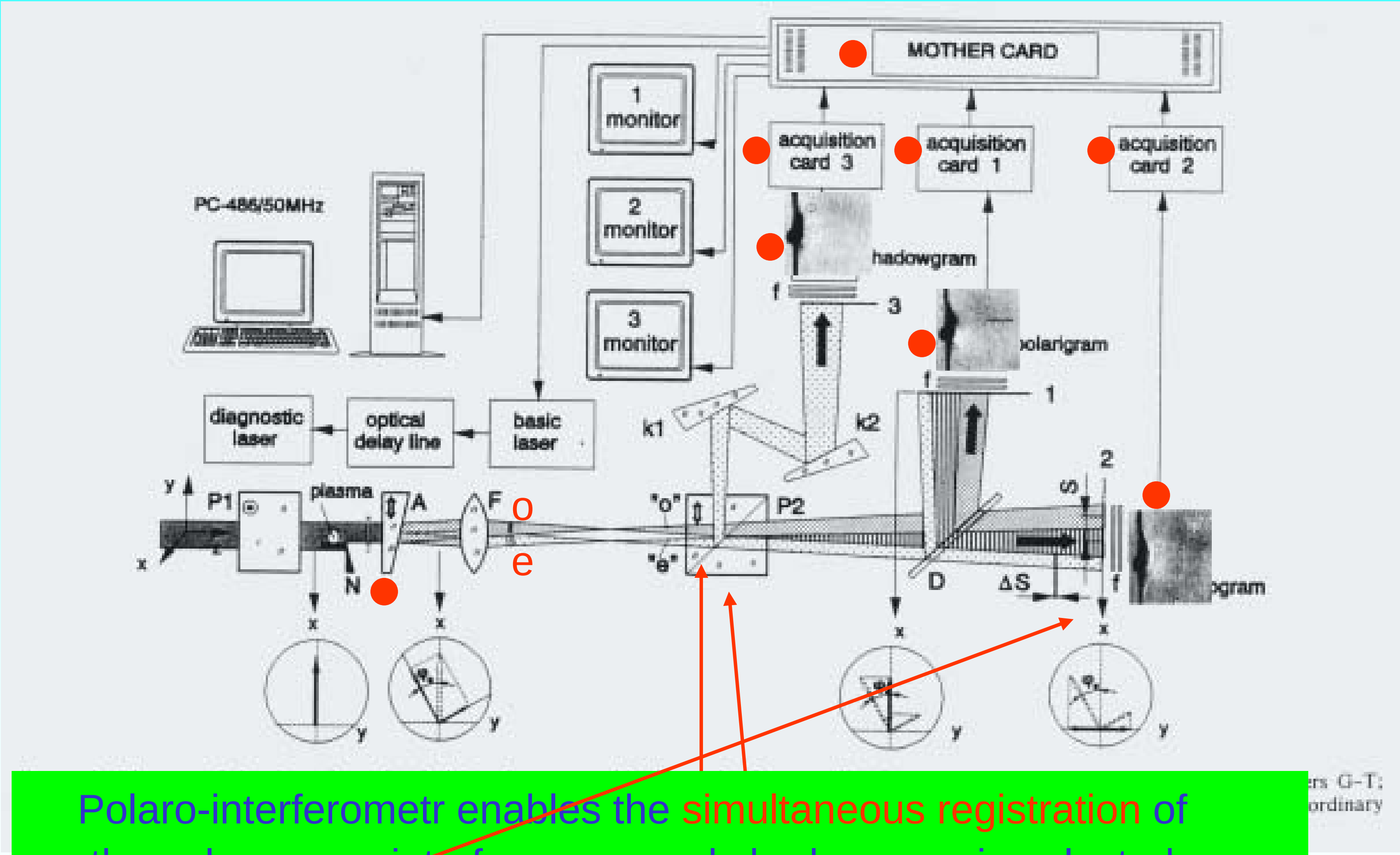
- Recording and investigation of spontenous magnetic field (SMF) in a laser plasma is very complicated experimental task.

- The main reasons are small spatial sizes of these fields (~100 μm) and high electron densities in the plasma regions in which SMF are generated.

- Another important factor is the short life time (~1ns) of SMF.

For a laser plasma investigation the three-channel polari-interferometer with automatic processing was elaborated within the project No. 8 8084 91/p02 of the Scientific Research Committee of Polish Government

The three-channel polari-interferometer for measurement of SMF in laser produced plasma



Polaro-interferometr enables the simultaneous registration of the polarogram, interferogram and shadowgram in selected moments of a plasma expansion.

Computer analyzis of plasma images

To analyze interferograms, polarograms and shodograms of plasma the special software was elaborated.

- „PRAZKI” procedure: for determination of phase shift distributions from interferograms,

- „ROTATOR” procedure: for determination of the rotation angle distributions of the polarization plane from polarograms and shadowgrms.

To calculate electron density and magnetic field distributions the „NETRAB”, „FATRAB” and „TRZYPE” procedures were prepared

Block diagram of software for computer image processing

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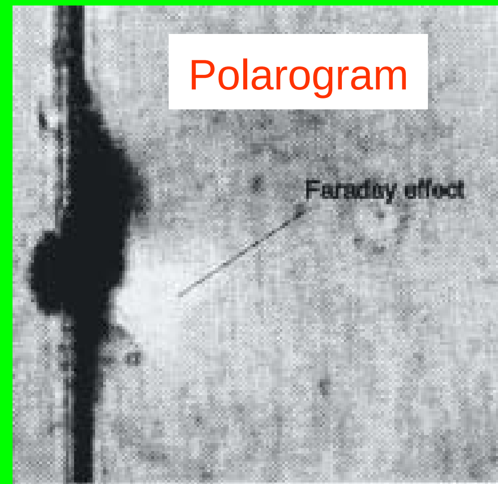
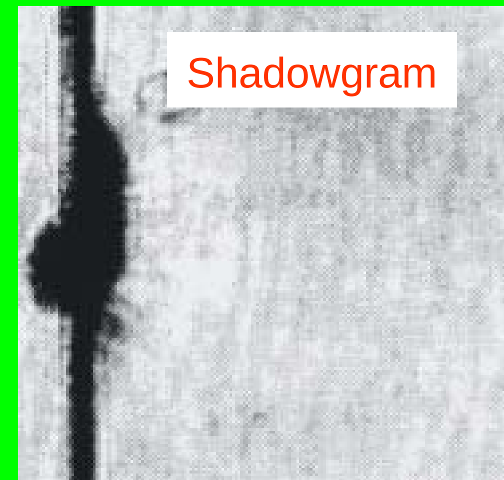




Distributions of the rotation angle of the polarization plane are calculated on the basis of polarograms and shadowgrams (ROTATOR procedure) by the formulas:

$$\varphi = arctg\left(\frac{(I-k_0)}{(1-k_0)}\right)^2 - \varphi_0, \quad I = \left(\frac{(k_0 + tg^2\varphi_0)}{(1+k_0 tg^2\varphi_0)}\right)\left(\frac{I_F}{I_{F_0}}\frac{I_{C_0}}{I_C}\right)$$

I_F, I_C - **intensities in the polarimetric and shadowgraphic channels, respectively**

I_{F_0}, I_{C_0} - **„background intensities”**

k_0 - **contrast of polarimeter**

This diagnistic system was used to measure the SMF of laser plasma on a four-channel Nd-laser system in IFPiLM.

- The plasma was heated by one beam with parameters:
□λ=1064 nm, output energy of 10 J, and pulse duration of 1 ns.

- The plasma was probed with the second harmonic of an Nd-laser (λ=532 nm) with a pulse duration of 0,7 ns and a delay of 1 ns relative to the maximum of the heating radiation.

- The target was an Al foil of 100 μm thick.

- The polarograms were obtained at initial rotation angle of the analyizing wedge of φ_0=1.5 degree.

The FR method was also successfully employed by the author on the **DELFIN laser system in FIAN (Moscow):**

Detection of spontaneous magnetic field in a laser plasma in the Delfin-1 device,

N. G. Basov, E. Wolowski, E. G. Gamalii, S. Denus, T. Pisarczyk A. A. Rupasov, A. S. Sarkisov, G. S. Sklizkov, V. T. Tikhonchuk, and A. S. Shikanov

JETP Lett. Vol. 45, No. 4, pp. 214-217 (1987).

Magnetic field distribution

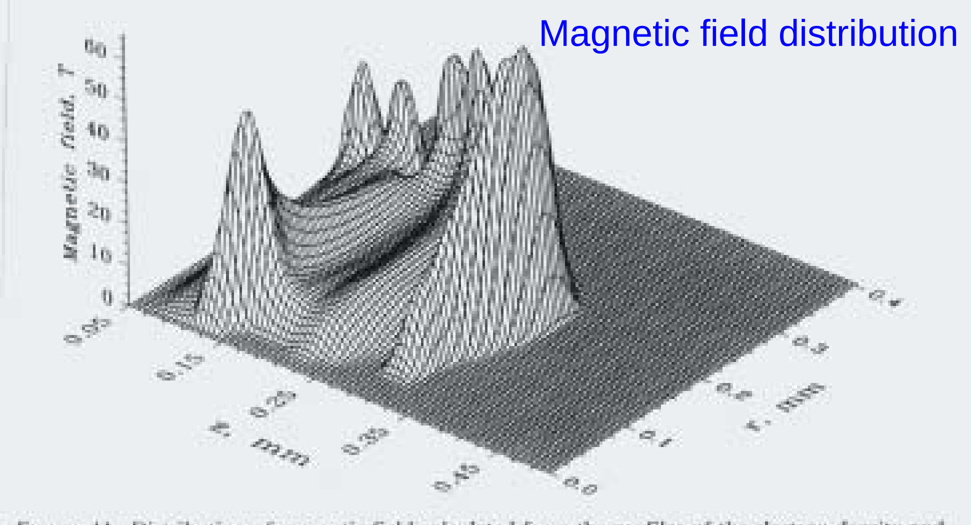


FIGURE 11. Distribution of magnetic field calculated from the profiles of the electron density and the rotation angle.

PALS experiment

- At present the polaro-interferometric system is used on the PALS experiment

- This research is carried on within the framework of the project PALS/013 (reg, no. HPRI-CT-1999-00053) which is suported by the 5th European Community.

- Main aims of experimental investigation are following:
  - optimization of laser ion sources
  - general investigations of plasma produced by high power lasers

Research on the PALS expriment are carried out by international team:

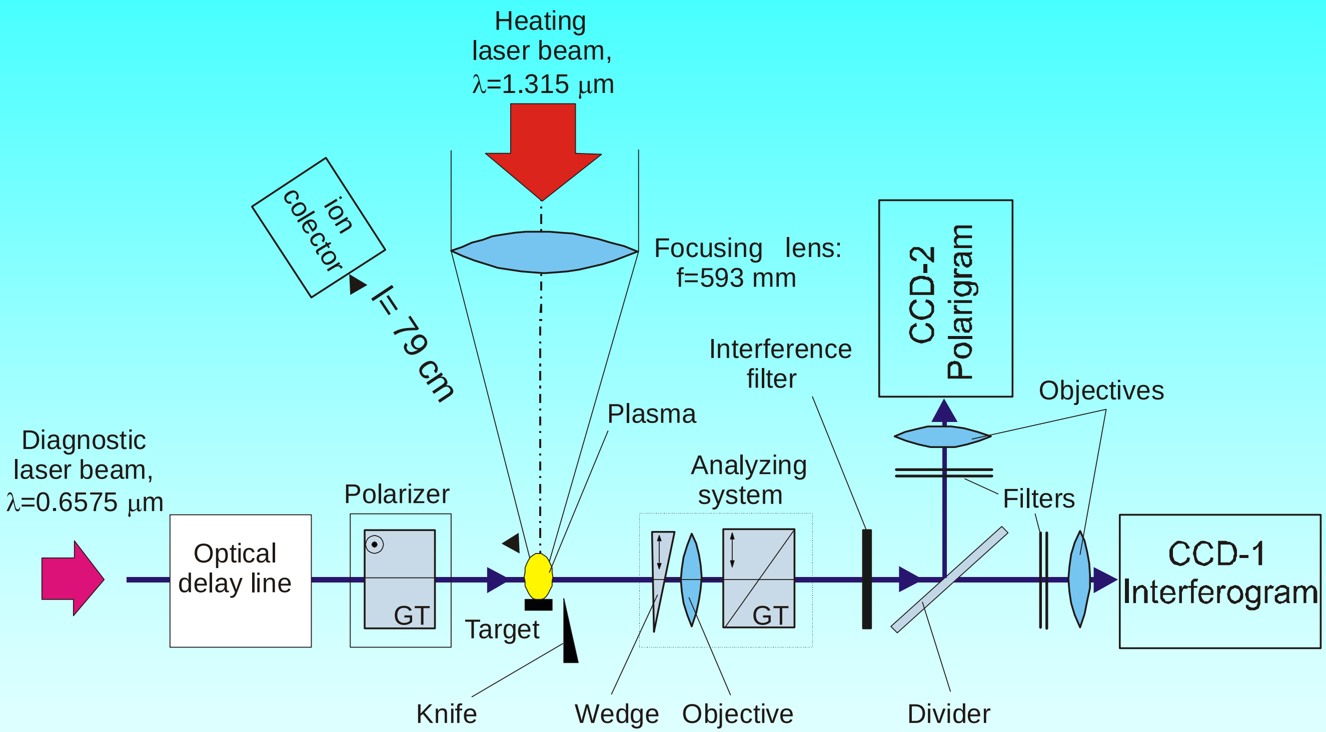
T. Pisarczyk, J. Badziak, A. Kasperczuk, P. Parys, J. Wolowski, E. Woryna
Institute of Plasma Physics and Laser Microfusion,
23 Hery St., 00-908 Warsaw 49, **Poland**

K. Jungwirth, B. Kralikova, J. Krasa, L. Laska, K. Masek, M. Pfeifer, K. Rohlena, J. Skala, J. Ullschmied
Joint Research Laboratory PALS of the Institute of Physics and Institute of Plasma Physics,
Acad. Sci. CR, Za Slovankou 3, 182 21 Praha 8, **Czech Republic**

M. Kalal
Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague,
Brehova 7, 115 19 Praha 1, **Czech Republic**

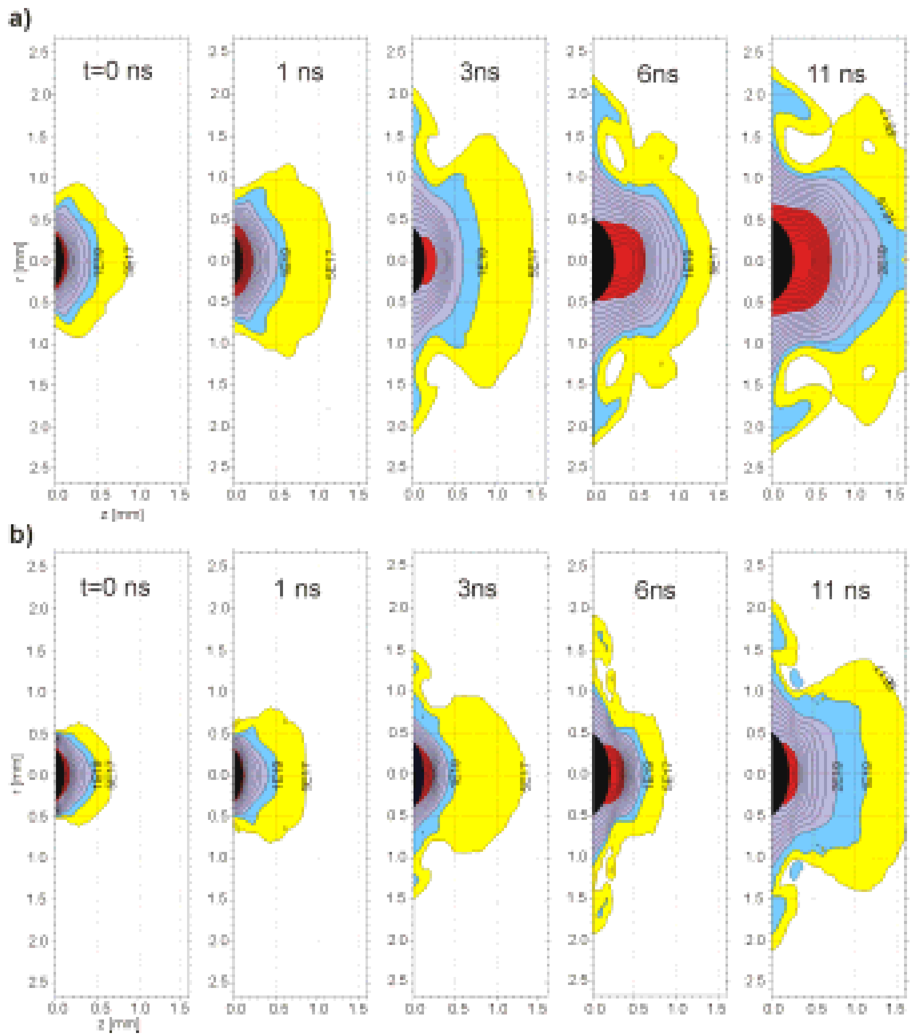
P. Pisarczyk
Institute of Computer Science, Warsaw University of Technology,
15/19 Nowowiejska St. 00-665 Warsaw, **Poland**

Polari-interferometer installed on the PALS experiment

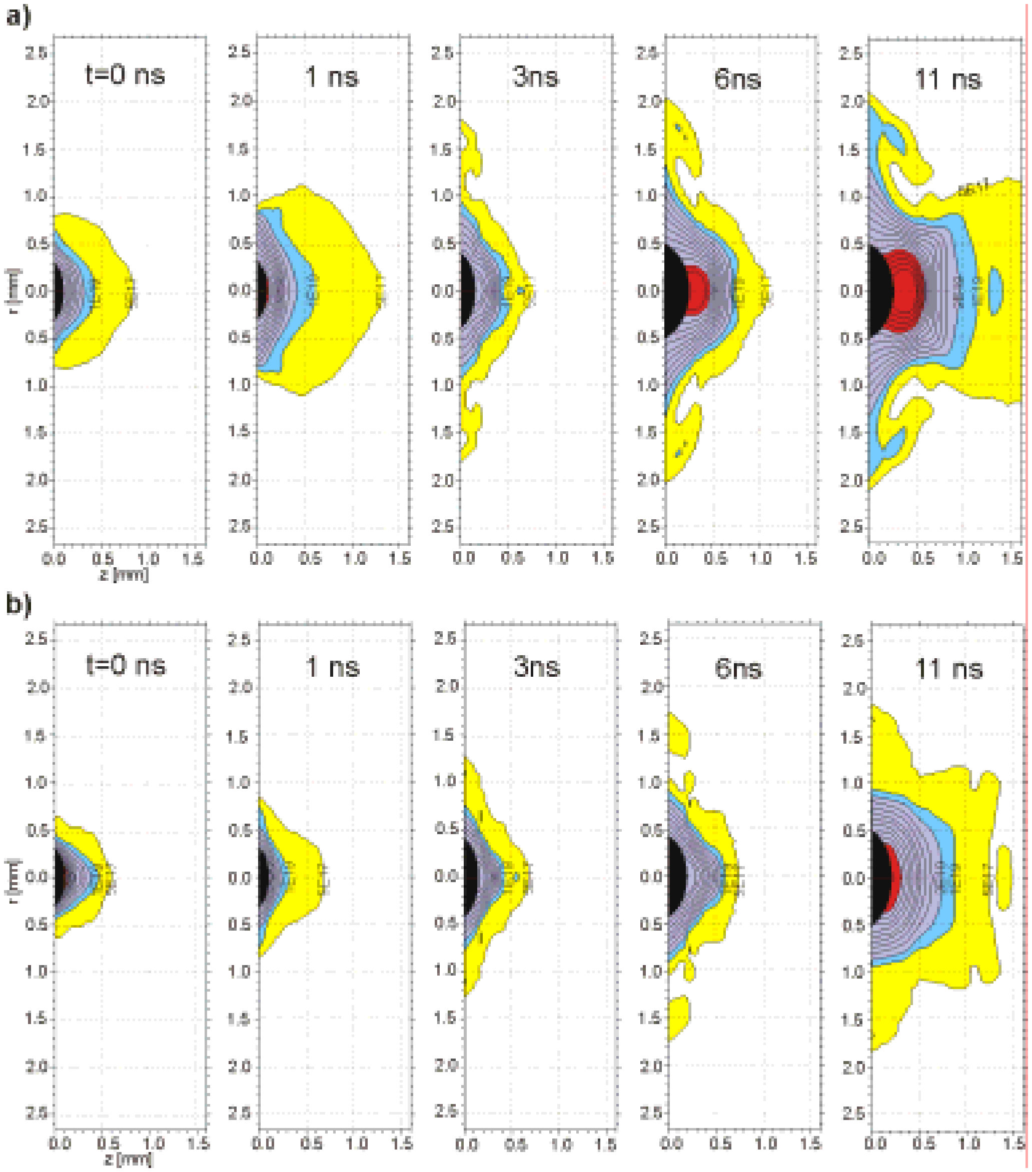


- The plasma was generated by iodine laser (from planar solid Al and Mo targets).
- Two laser energies of E=100 J and 600 J (τ=400 ps) were used.
- For acqusition of images CCD cameras of Pulnix TM-1300 type (1300x1300 pixels) with frame-grabber card (Matrox Meter-II/Multichannel) were applied.

Sequence of the electron density distributions for a massive Al targets: a) E=600 J and b) E=100 J



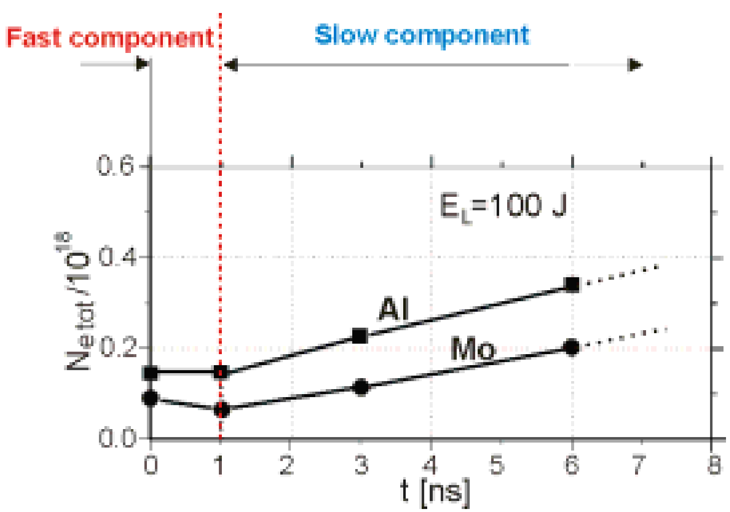
Sequence of the electron density distributions for a massive Mo targets: a) E=600 J and b) E=100 J

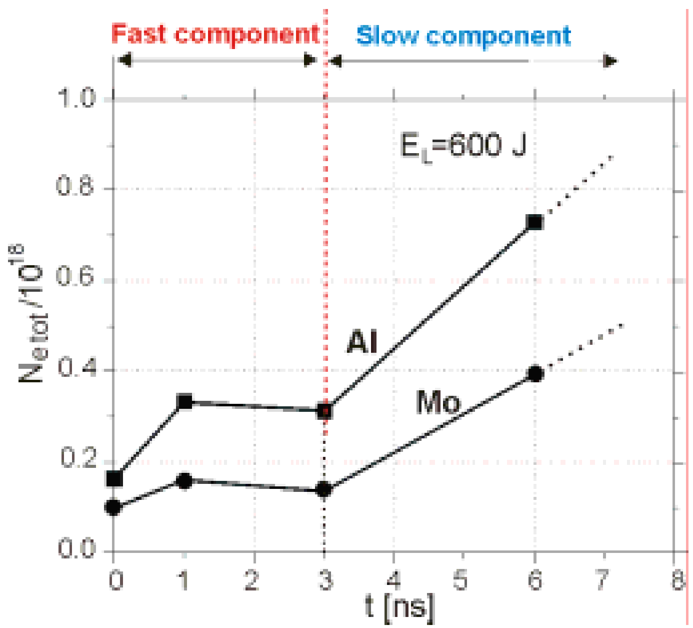


The analysis of interferometric results allowed us to distinguish two plasma components:

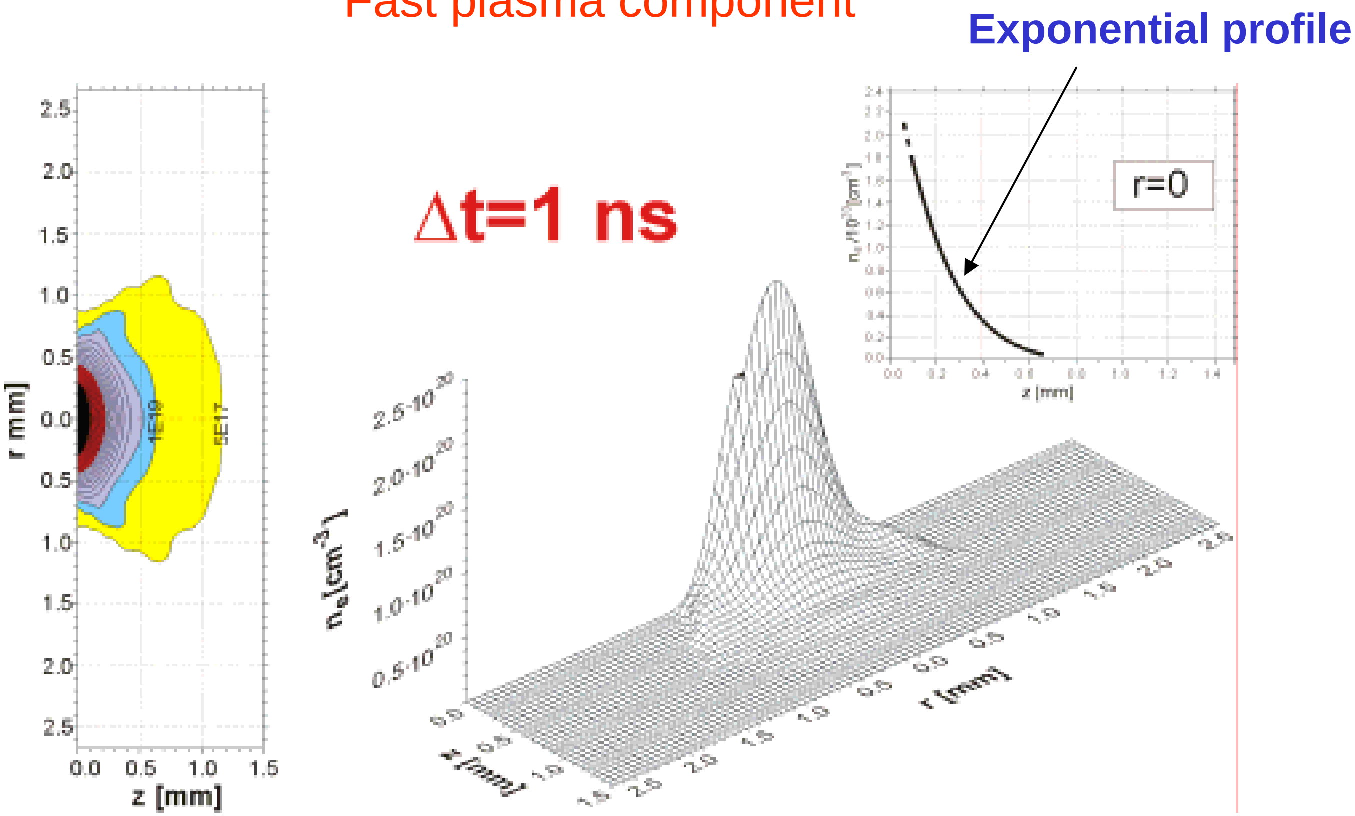
- a fast component appearing in the initial phase of the plasma expansion ($V_z \cong 10^8$ cm/s)
- a slow component, observed after the fast component disintegration ($V_z \cong 10^7$ cm/s)

The lifetime the fast component: for **E=100J – 1 ns** and for **E=600 J – 3 ns**





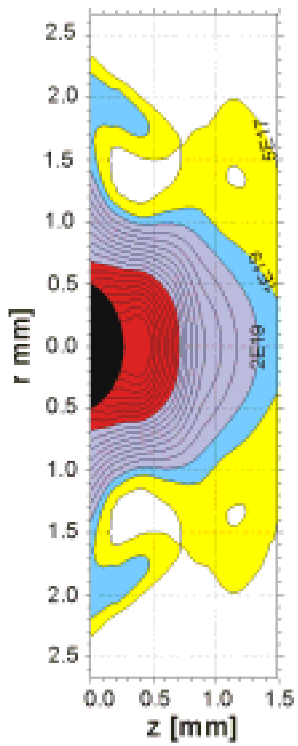
Fast plasma component

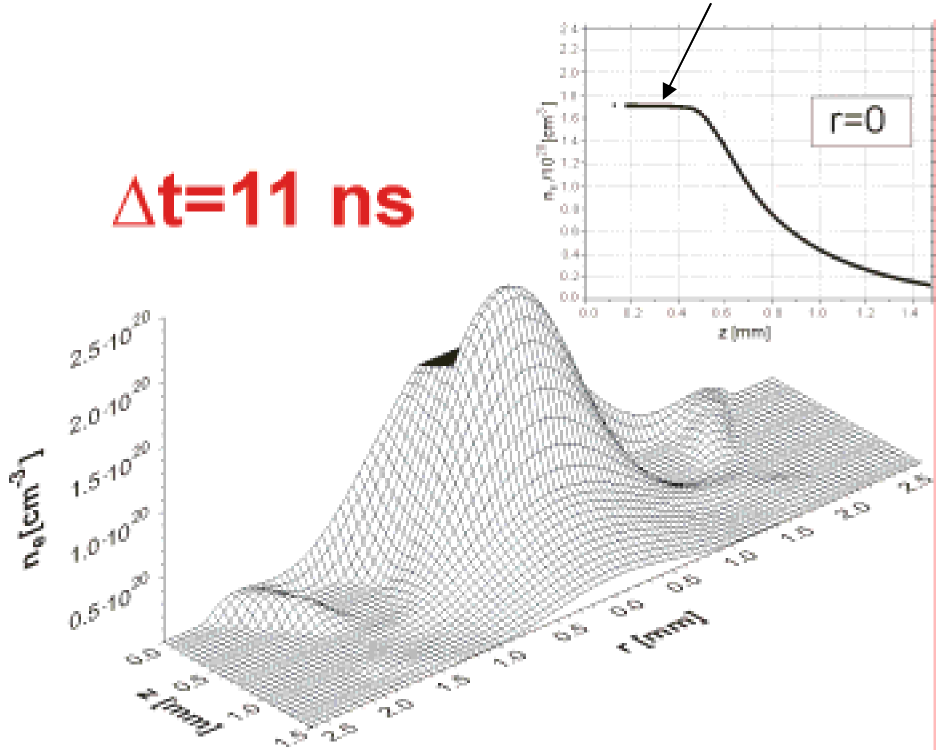


The fast plasma components corresponds to thermal plasma generated as a results of the target material ablation.

The electron density distribution becames flat in the vicinity of the target

Slow plasma component

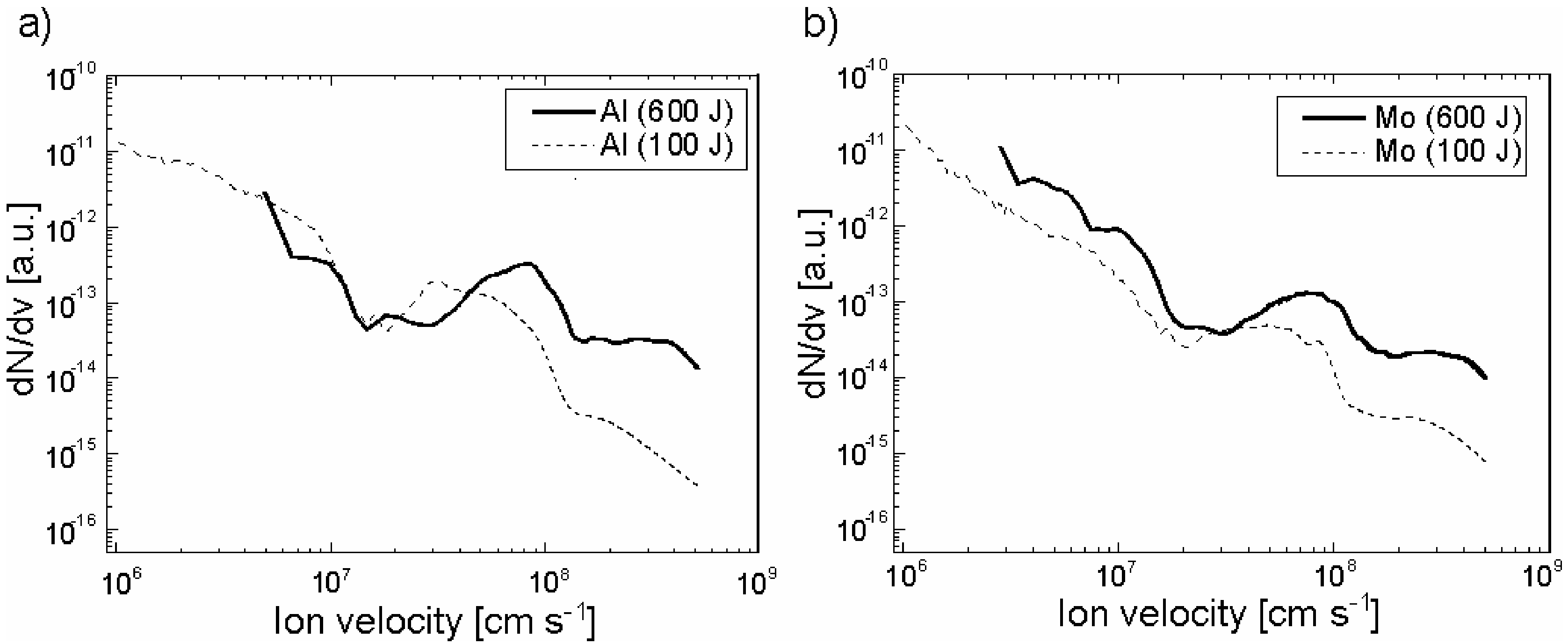




The slow plasma component originaties from a crater formed in the target due to secondary phenomena, such as shock wave, thermal conductivity, and XUV radiation

Together with
the interferometric measurements
the ion investigations
by means of the ion collector
(the time-of-flight technique)
were also carried out
in our experiments.

Examples of ion collector signals for Al (a) and Mo (b) plasmas generated by laser pulses with energies 100 J and 600 J.



The analysis of ion structure pulse allowed us to distinguish three ions group:

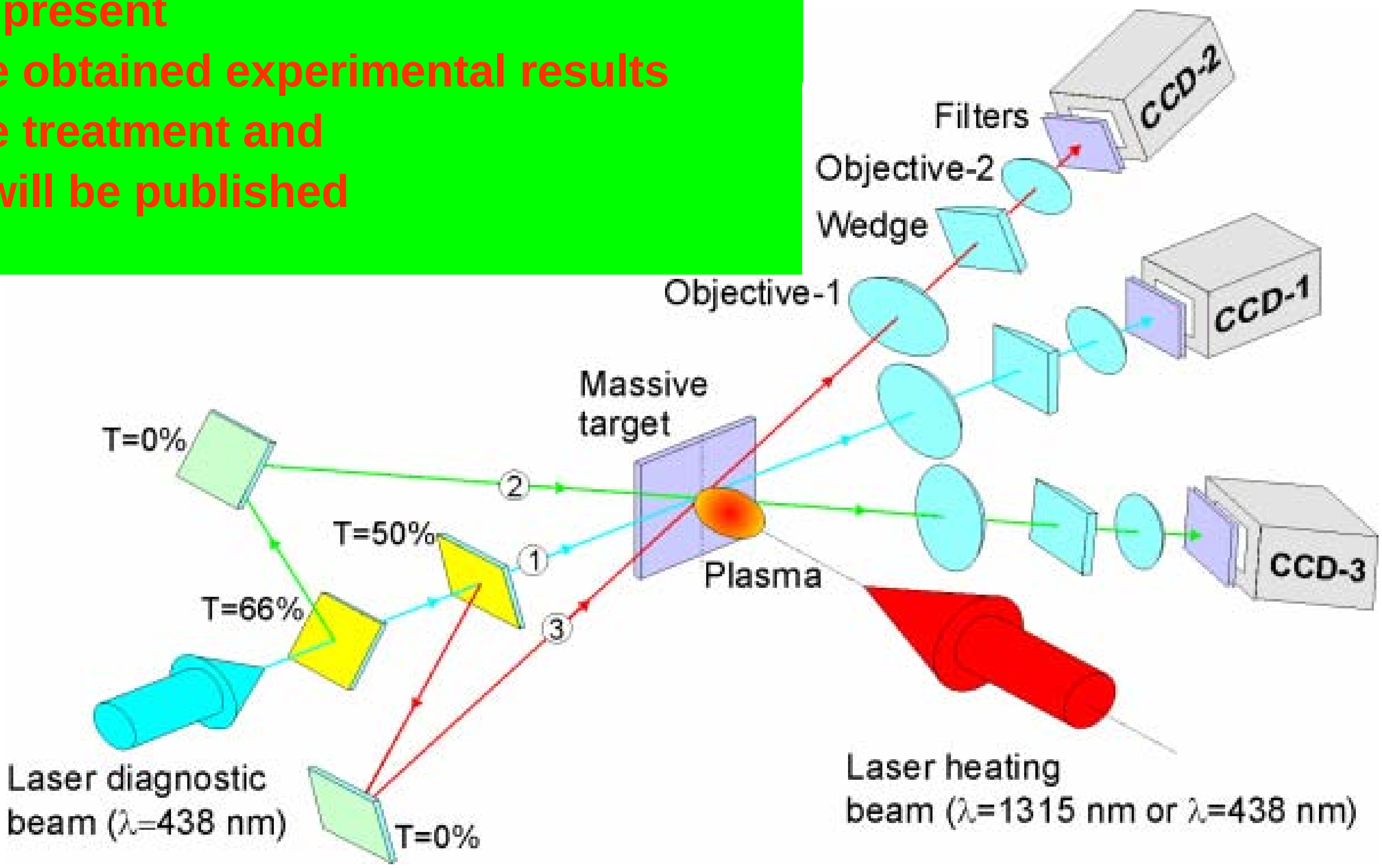
Slow ions group ($v_z<10^7$ cm/s):

- **The slow ions in the collector signal corresponds to the slow plasma component recorded by interferometry**

- **This group is produced by the secondary phenomena, such as shok wave, thermal conductivity, and irradiation of the target material by XUV radiation emitted from the hot plasma.**

Three frame optical system for registration of interferometic and shadowgraphic plasma images.

At present
the obtained experimental results
are treatment and
it will be published



Hitherto results of interferometric measurement are published in:

Interferometric investigation of an early stage of plasma expansion on the high-power laser system PALS,

A. Kasperczuk, M.Kalal, B. Kralikova, K. Masek, M. Pfeifer, P. Pisarczyk, T. Pisarczyk, K. Rohlena, J. Skala, J. Ullschmied,

Czechslovak Journal of Physics, Vol. 51, p.395 (2001)

Fast and slow plasma components produced by the PALS facility - comparison of interferometric and ion diagnostic measurements,

T. Pisarczyk, K. Jungwirth, J. Badziak, M. Kalal, A. Kasperczuk, B. Kralikova, J. Krasa, L. Laska, K. Masek, P. Parys, M. Pfeifer, P. Pisarczyk, K. Rohlena, J. Skala, J. Ullschmied, J. Wolowski, E. Woryna,

Czechslovak Journal of Physics (Suplement D), vol. 52, p. 310 (2002)

At present investigations of spontenous magnetic field on the PALS experiment are under preparation.

Conclusions:

- The polari-interferometric diagnostic is a very important diagnostic tool in the investigations of a hot and high density plasma

- The reason for that is:
  - complexity and high price of an interferometric diagnostic system,
  - the necessity of possession of indispensable soft-ware for the analysis and numerical treatment of interferometric pictures which enables to shorten the process of determining of electron density distribution in the investigated plasma,
  - competence and professional experience of scientific team in the analysis of the interferograms as well as their knowledge in the field of the investigated phenomena.

- This method was successfully employed by the authors in many plasma experiments:
  - in IFPiLM (on the PF-150 device and four channel laser system),
  - in Soltan INS in Swierk (on PF-360 device),
  - in Lebedev Phys. Inst. in Moscow (on the 213 channel laser system- Delfin and vacuum spark device)
  - in PALS experiment in Prague .

Determination of spatial electron density in great plasma focus device

- The use by the authors of the presented polari-interferometric system on a great plasma focus device has been practically imposible. This is mainly due to high refraction of the probing beam laser (ruby and Nd lasers).

- Since a refraction angle is proportional to λ^2 so this problem can be overcome by means of a laser with shorter wave length (i.e. UV and X-ray range).

- Because of a lack of such laser the authors have proposed a special method in order to determine spatial electron density distributions of plasma in the PF-1MJ device.

- The proposed method allowed us to obtain electron density distrubutions of plasma (in relative units) on the basis of a plasma images registered by means of an optical frame camera.

Physical bases of the presented method

The base of this method is a measurement of the spatial distribution of the plasma radiation intensity (I) in a very narrow optical range ($\Delta\lambda = 60$ A) by means of the electro-optical frame camera.

- It can be shown that t
  radiation in such narr

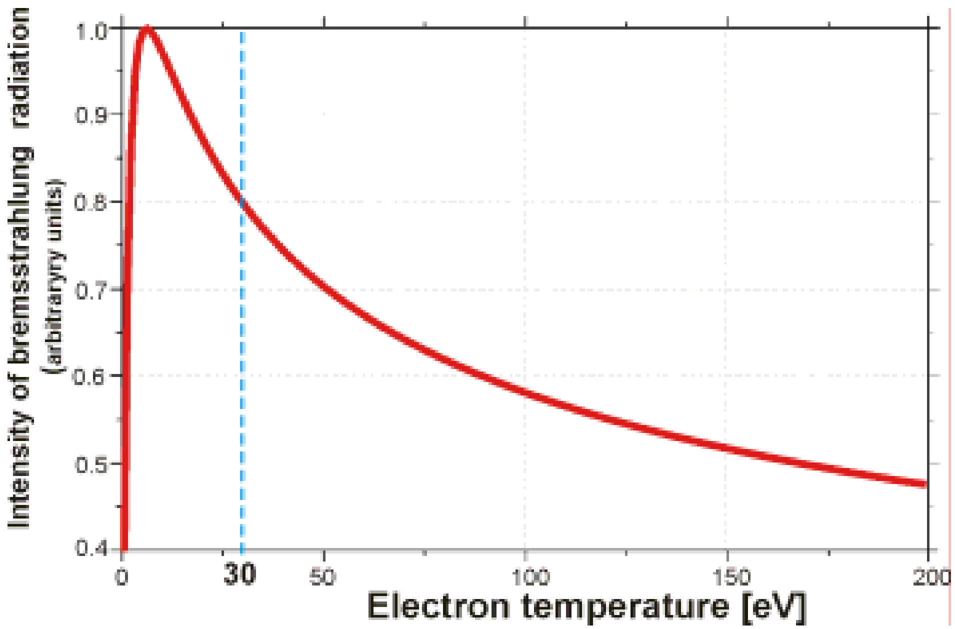
$$\varepsilon^{ff} \simeq 4.31\cdot 10^{-37}$$

Beam
splitter

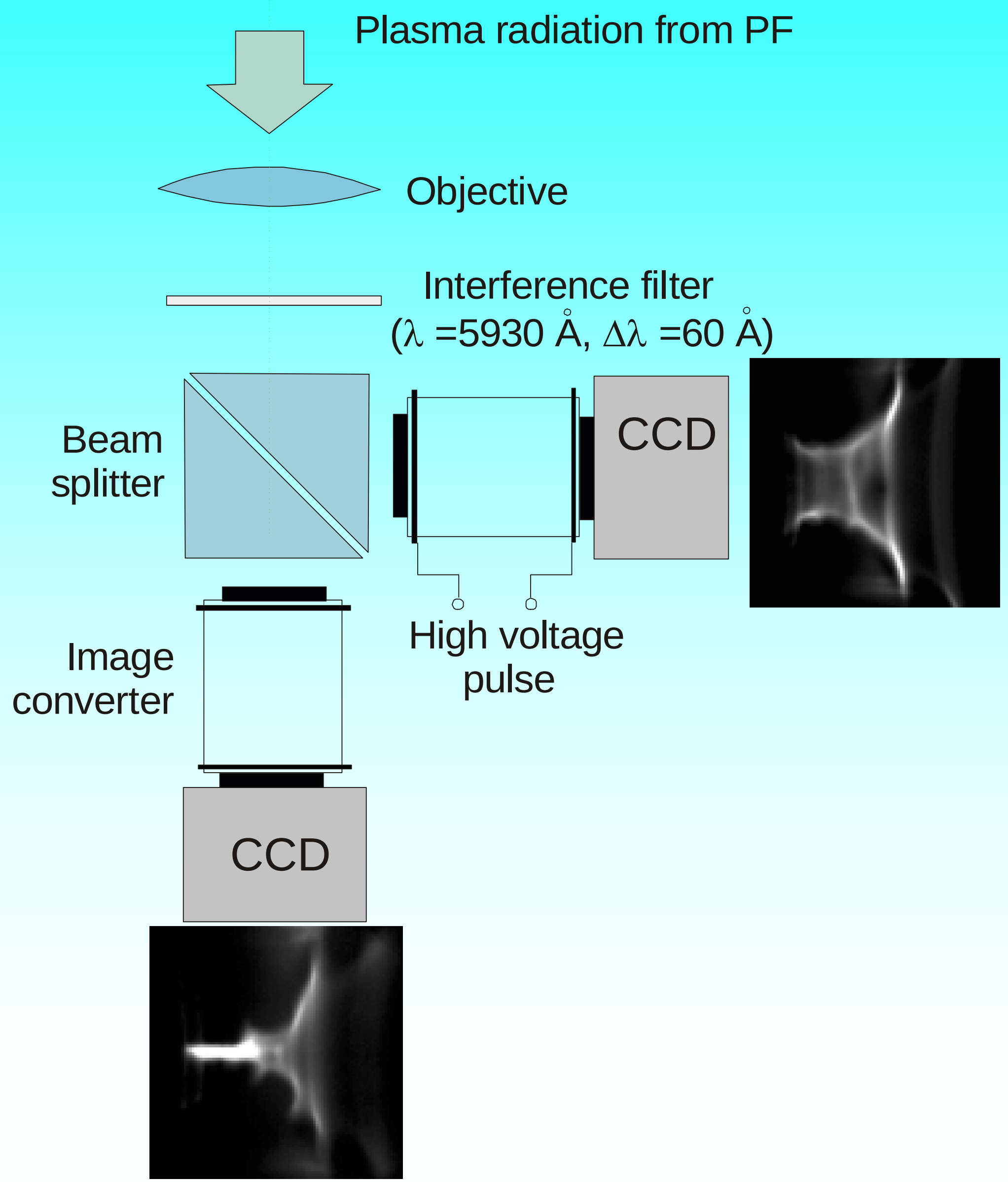
- If a photocatode of the
  recorded plasma radia
  so **I** is proportional to

Image
converte

For the temperature range being of interest (above 30 eV) the above formula shows weak influence the plasma electron temperature on ε^{ff}.



Having images of the plasma registered by means of the frame optical camera we can obtain the radiation intensity distribution I(y,z).



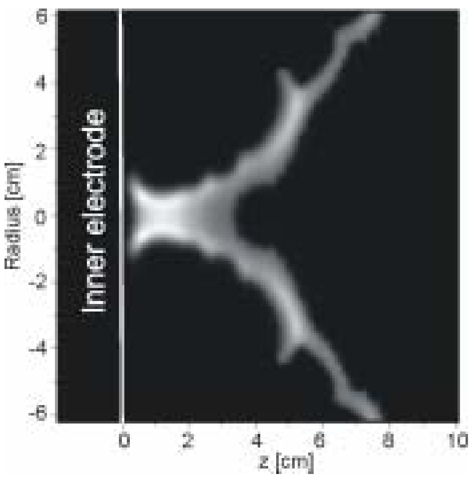
After the Abel transformation of I(y, z), the relative distribution of the plasma density n_e could be easily obtained:

$$n_e(r) = a\int_r^1 \frac{\frac{dI}{dy} r dy}{\sqrt{y^2 - r^2}} \quad for \quad z = const$$

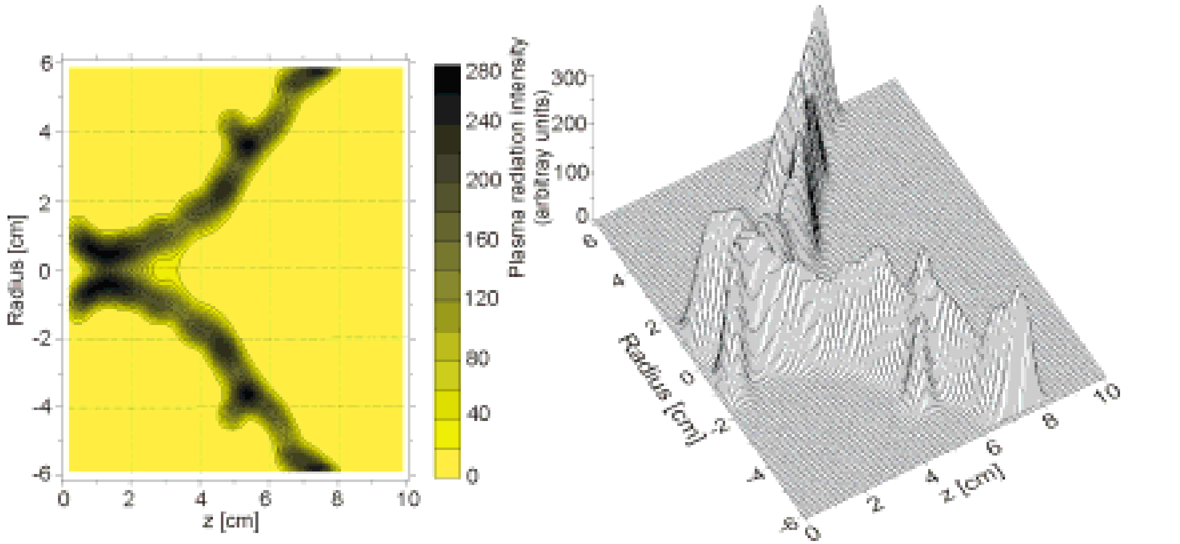
or

$$n_e(r) = b\frac{d}{dr}\int_r^1 \frac{I(y)ydy}{\sqrt{y^2 - r^2}}$$

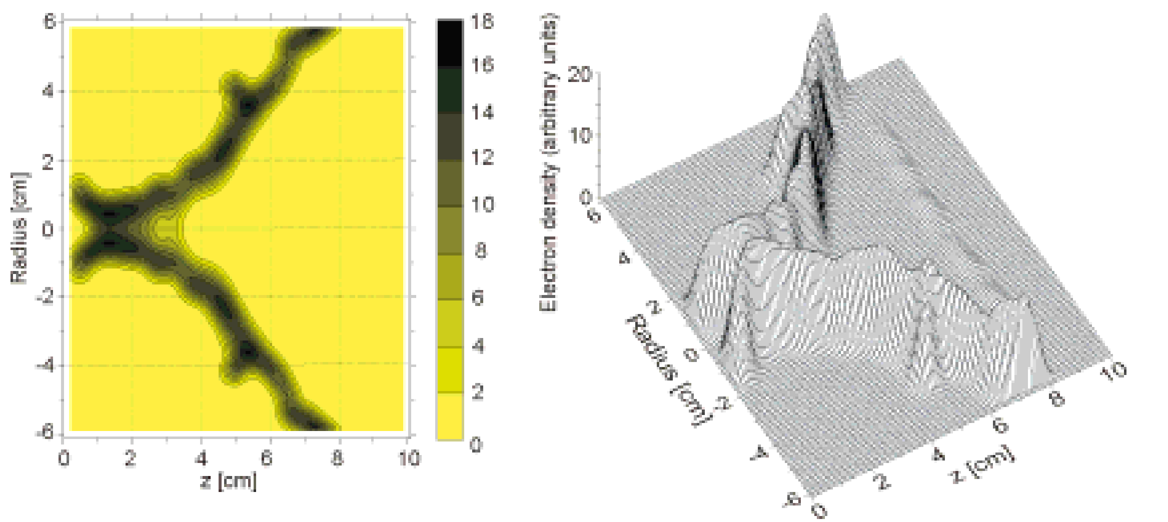
Plasma image from the electro-optical camera



The plasma radiation intensity distribution after the Abel transformation



The electron density distribution

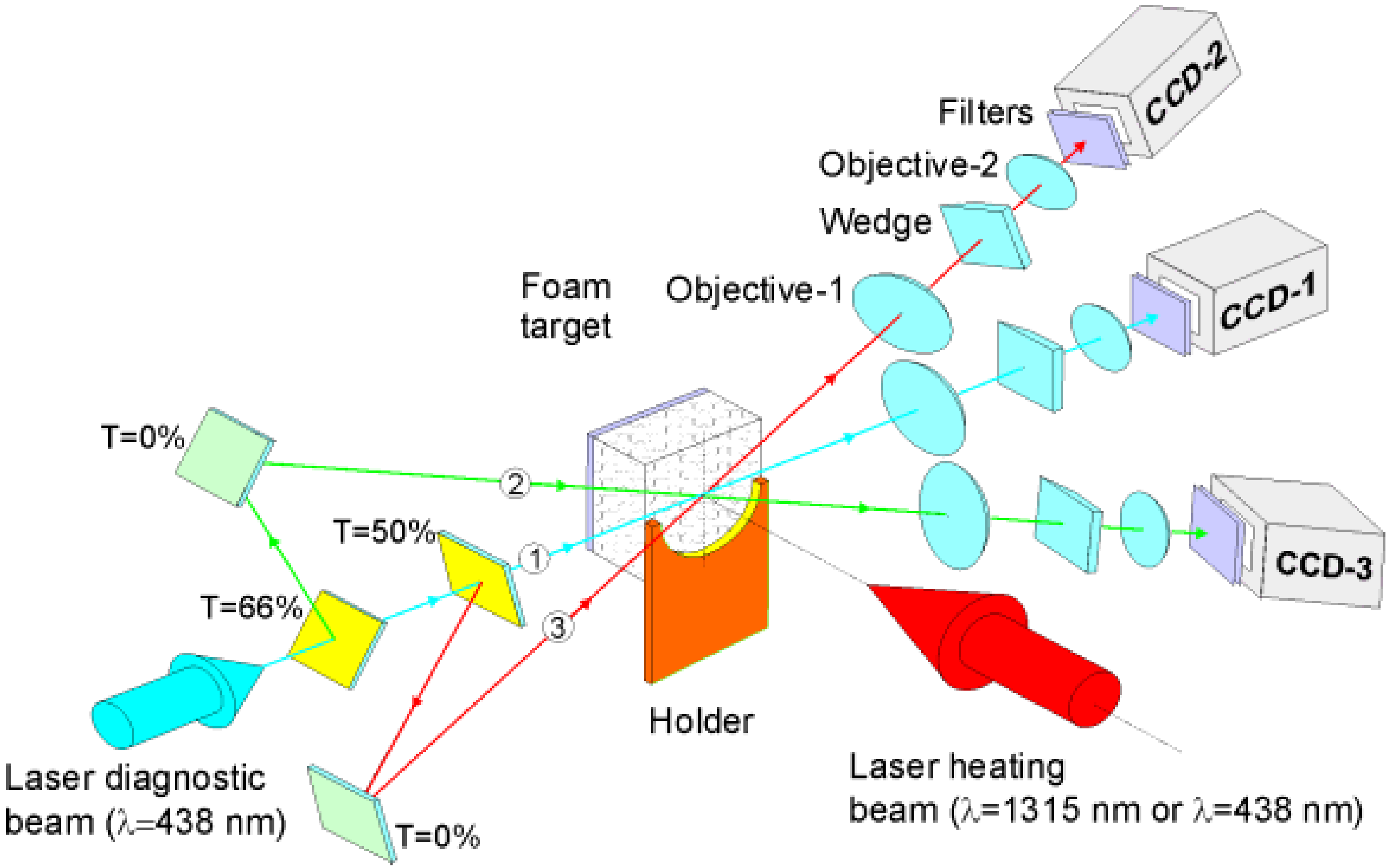


This method allowed us to determine the structure of the plasma sheath and the plasma column as well as plasma dislocation and deposition along the plasma sheath.

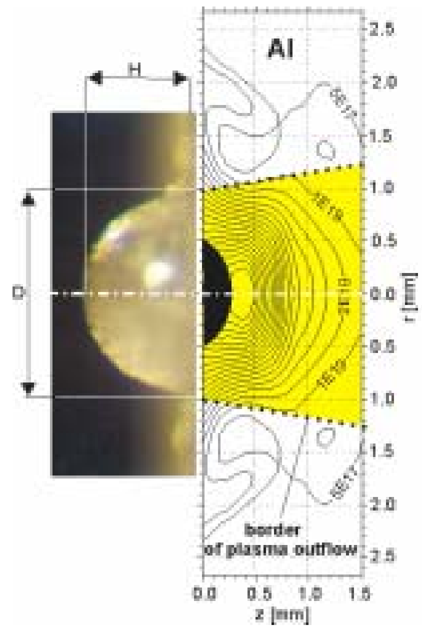
This method was elaborated by:

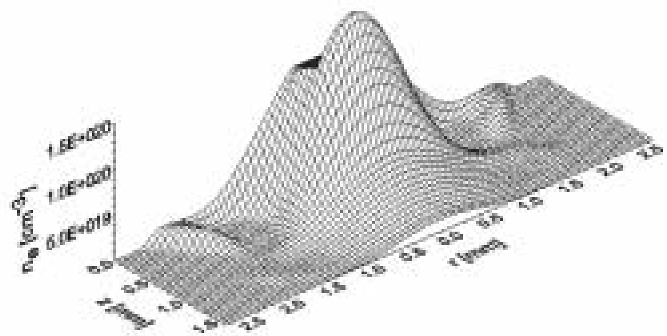
A method for the determonation of spatial electron density distribution in great Plasma–Focus devices

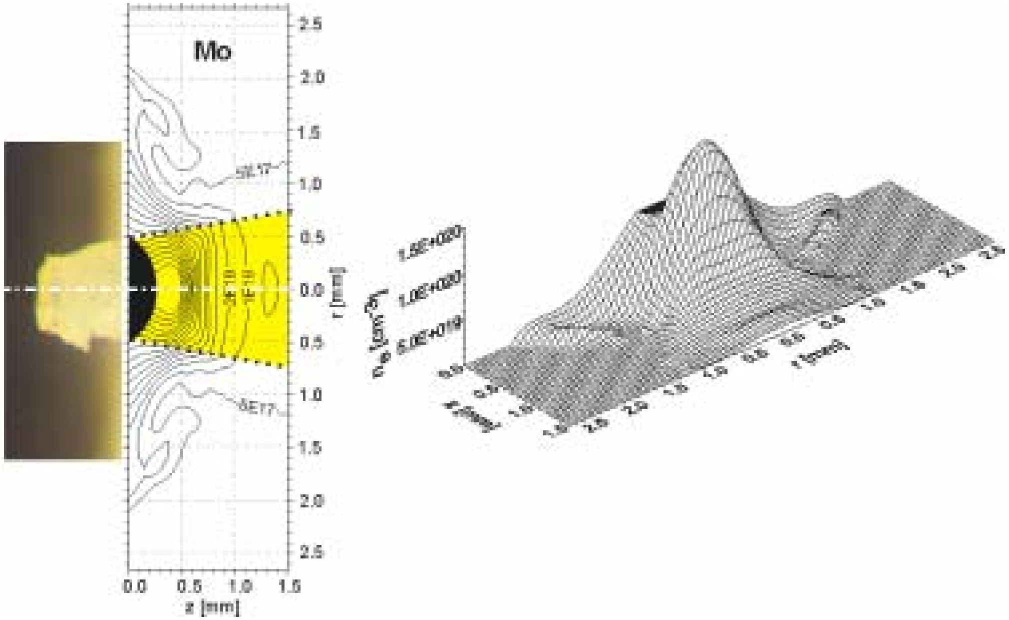
A. Kasperczuk, M. Paduch, T. Pisarczyk, and K. Tomaszewski, Nukleonika, **47,** No.4, pp. 23-26 (2002).



Filters
CCD-2
Objective-2
Wedge
Foam
target
Objective-1
CCD-1
T=0%
2
T=50%
1
CCD-3
T=66%
3
Holder
Laser diagnostic
beam (λ=438 nm)
T=0%
Laser heating
beam (λ=1315 nm or λ=438 nm)


H
D
Al
border
of plasma outflow
0.0 0.5 1.0 1.5
z [mm]
2.5
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
2.5
r [mm]


1.5E+020
1.0E+020
5.0E+019
0.0
r [mm]



Mo
5E17
5E17
r [mm]
z [mm]
0.0 0.5 1.0 1.5
2.5 2.0 1.5 1.0 0.5 0.0 0.5 1.0 1.5 2.0 2.5
1.5E+020
1.0E+020
5.0E+019
0.0
r [mm]

Ion velocity distributions calculated on the basis of the ion collector signals: a) for Al, and b) Mo target.