

# CALCULATION OF THE INDUCTANCE OF PLASMA COLUMN AT PF-1000 DEVICE WITH ASSUMED CURRENT DISTRIBUTION

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**ABSTRACT.** Processed data is taken from the D–D fusion reaction experiments on PF-1000 at IFPILM Warsaw, operating with 2 MA,  $10^{11}$  neutron yield, using interferometry, temporal resolved neutron diagnostics, magnetic probe diagnostics and X-ray diagnostics. The inductance is calculated under two different circumstances: with the known distribution function determined by the magnetic probe signal, and with the border of the plasma column determined from interferograms using Matlab. The inductance of the whole column is calculated using the formula for the inductance of a coaxial cylinder.

**KEYWORDS:** nuclear fusion, plasma focus, pinch, inductance, diagnostics, Matlab.

## 1. INTRODUCTION

Interferometry is a method for visualizing plasma and for obtaining some information about its structure and density. It has been used to measure plasma with density above  $10^{23} \text{ m}^{-3}$  in various PF devices [9, 1].

The PF-1000 plasma focus device, located at IP-PLM in Warsaw, has recently been operating with 2 MA with  $10^{11}$  neutron yield [7]. Interferometry, neutron diagnostics, hard X-ray diagnostics, and magnetic probes diagnostics [5] are used, along with measurements of current, its time-derivative and voltage with nanosecond resolution. BC408 scintillators and Hamatsu photomultipliers are used for temporal resolved hard X-ray and neutron diagnostics. They are positioned side-on (7 m) and in the upstream direction ( $7 \div 84$  m). Counters with activated silver are used for total neutron yield estimation [4].

The magnetic probes are induction-type probes customized specifically for the PF-1000 device. They are located at the face of the anode, 1.3 cm and 4 cm from the axis, as shown in Fig. 1. They register the temporal derivative of the azimuthal magnetic field at the anode front, and this enables the current density to be determined. An example of a signal from the probe in 1.3 cm is shown in Fig. 2. The  $y$  axis was adjusted to have a maximum value of 1 for better evaluation. Its scale is therefore arbitrary. The value  $x = 0$  represents the time of the maximum soft X-ray signal. This applies to all figures in this paper, unless otherwise stated.

The interferometer at PF-1000 was designed and installed at IPPLM in Warsaw. The beam from the Nd:YLF EKSPLA SL300 series laser, operating on second harmonic wavelength 527 nm with pulse length below 1 ns, is divided into 16 mutually delayed beams. The time step between the beams alternates between 10 ns and 20 ns [10]. Interferograms are created which show us the time-evolution of the pinch

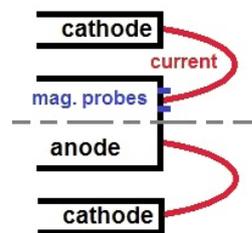


FIGURE 1. Schematic of the experimental setup.

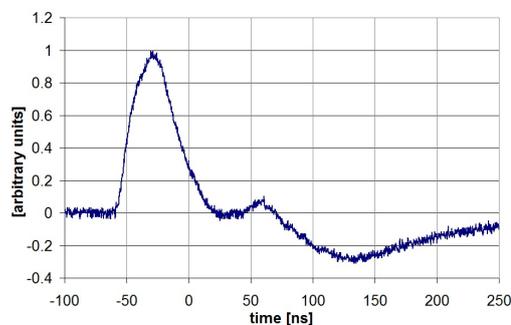


FIGURE 2. Signal from the magnetic probe in radial position 1.3 cm from the axis of the anode. Shot No. 9367.

over the course of 220 ns in one shot [10]. With these, we can correlate the time-evolution of the pinch dynamics with the neutron and X-ray emission [8, 6].

Interferometry is a path-integrated technique, so a method based on Abel transformation is used for axial symmetry [2]. More accurate unsymmetrical densitograms are then created using a method presented in [3]. An example of a densitogram of this type is shown in Fig. 3.

The aim of this work is to use two different calculations of the inductance of the plasma column for two temporal intervals. The first calculation is based on detecting the borders of the plasma after the implosion,

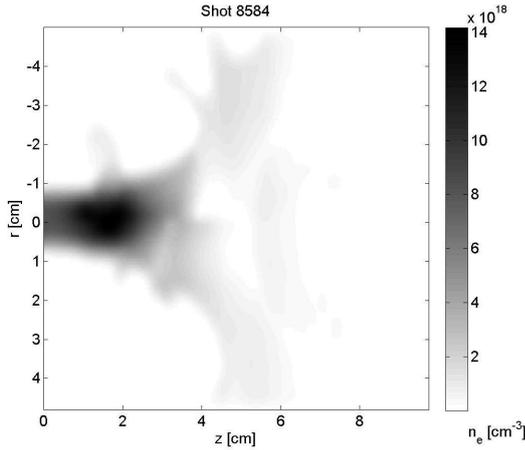


FIGURE 3. Asymmetrical densitogram of shot No. 8584.

and the second calculation is based on estimating the current distribution from the magnetic probe data during the implosion.

## 2. CALCULATIONS

### 2.1. CURRENT FLOWS ALONG THE BORDER OF THE DENSE PLASMA COLUMN

For the calculation of the inductance, we presume that after the implosion the mean value of the current flows along a thin layer on the surface of the dense plasma column.

The application detects the borders of the plasma by finding the threshold value of the density. The search algorithm searches for the first and last pixel with this threshold value in each column of pixels. These two values are designated the upper and lower border of the plasma for the current pixel column. With known position of the borders, we can determine the radius  $r$  of the plasma column. The formula for determining the threshold density was

$$D = D_{lm}[k_1 + k_2(1 - D_{lm}/D_{max})] \quad [\text{cm}^{-3}], \quad (1)$$

where  $D_{lm}$  is the maximum density in the current column of pixels,  $D_{max}$  is the maximum density in the whole shot, and  $k_1$  and  $k_2$  are constants. These constants are set for the borders to follow the places where we see a sharp rise or drop in plasma density. We need to set them experimentally for each shot, because each shot has its own special density ratios. For shot 9013, the values were determined  $k_1 = 0.23$  and  $k_2 = 0.65$ . The detected borders of the plasma column are shown in Fig. 4.

The formula for the inductance  $L$  of a coaxial cylinder is used,

$$\sum_1^n \Delta L = \sum_1^n \left( \Delta l \frac{\mu}{2\pi} \ln \frac{R}{r} \right) \quad [H], \quad (2)$$

with length of the pixel in meters  $\Delta l$ ,  $\mu$  is the magnetic constant ( $4\pi \times 10^{-7}$  H/m),  $r$  is the inner radius determined by the detected borders of the plasma,

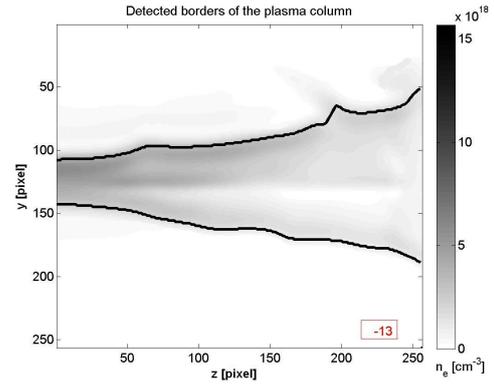


FIGURE 4. Detected borders in the densitogram of shot No. 9013,  $t = -13$  ns (relative to the time of the maximum pinch).

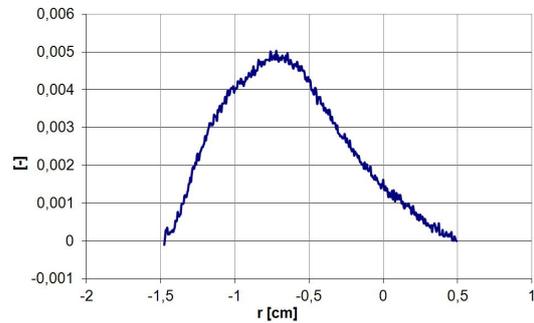


FIGURE 5. Distribution function of the current flow at the time of pinch for shot No. 9367;  $x = 0$  represents the position of the magnetic probe, positive values are towards the center of the anode.

$R$  is the radius of the outer electrodes (15 cm), and  $n$  is the number of the pixel columns in the current picture.

The application calculates the inductance of each column of pixels and adds them up to get the inductance of the whole column. When this process is used for every densitogram in the shot, the time resolved inductance is obtained.

### 2.2. CURRENT FLOWS DISTRIBUTED

The magnetic probe signal was registered near the anode face in temporal scale dependence. To obtain the radial distribution of the current during the implosion, we use the formula

$$s = vt \quad [\text{m}], \quad (3)$$

where  $s$  is length,  $v$  is implosion velocity and  $t$  represents time. We used implosion velocity  $2.5 \times 10^5$  m/s with relative uncertainty of 20% calculated from the positional differences of the plasma border at the same  $z$ -coordinates in the succeeding interferograms.

The signal is then truncated to contain only the region of the first peak, where the magnetic probe is not yet damaged by the high-temperature plasma. The values of this signal are adjusted so that the sum

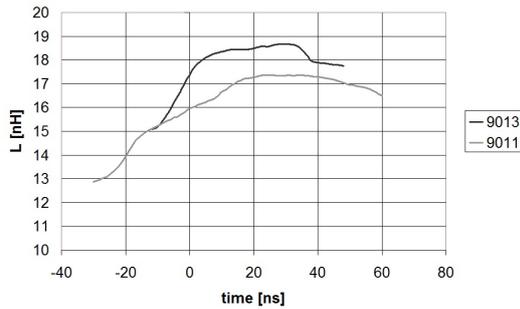


FIGURE 6. Inductance of shots No. 9011 and No. 9013 using plasma border detection.

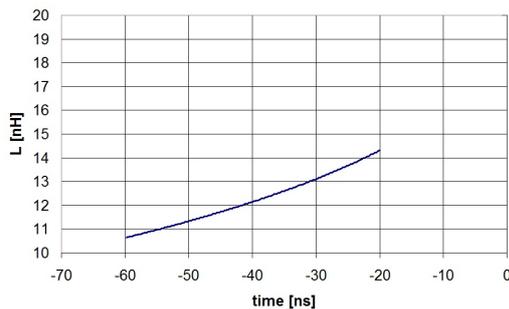


FIGURE 7. Inductance of shot No. 9367 using the current distribution.

of the signal equals 1. Thus it does not have physical units. The acquired function, shown in Fig. 5, is used as a distribution function of the current flow.

We assume the same radial distribution of the current for all axial positions toward the boundary.

With the known distribution function of the current, Eq. 2 can be used again. In this case,  $r$  is the current layer diameter and  $R$  is again the radius of the electrodes (15 cm).

The inductance is calculated for each current layer, i.e. row of pixels. It is multiplied by the corresponding value of the distribution function, and added up to get the inductance of the whole plasma column. The time-resolved inductance is acquired by applying this process for every nanosecond in the shot.

### 3. RESULTS

The results of the border detection method are shown in Fig. 6 for shots No. 9011 and No. 9013. A similar slow increase in inductance from 15 nH at  $-10$  ns to 18 nH at  $40 \div 50$  ns was also observed in other shots. Later the inductance slowly decreases.

The result of the calculation based on the current distribution measured by the magnetic probes for shot No. 9367 is shown in Fig. 7. The differences between the results for other shots were below an uncertainty value of 20 %.

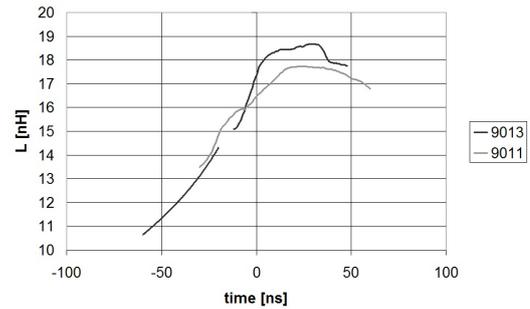


FIGURE 8. Comparison of the resulting inductances for two calculations for shots No. 9011 and No. 9013.

### 4. CONCLUSIONS

The inductance of the plasma column has been estimated from shots No. 9011, 9013 and 9367.

Each of the calculations can be used only at certain times, specified by the limitations of the diagnostic methods.

This plasma border detection method can be used only when we have interferometric data for the times after the implosion phase. For shot No. 9011, the time was from  $-30$  ns to  $60$  ns, and for shot No. 9013 the time was from  $-12$  ns to  $48$  ns.

The current distribution can be used only during the time of the implosion. The distribution is similar for different shots, so the conclusions about the temporal evolution of the inductance can be generalized with uncertainty of 20 %.

According to the magnetic probe method, most of the current flows about 1 cm above the border of the dense plasma column during the implosion phase falls towards the plasma column during the stagnation phase, and could even sink into the plasma later during the expansion.

The composition of the two calculations, see Fig. 8, shows that there is a connection between them in the intersection region.

This shows that the assumption made in the plasma border method – that the mean value of the current flows along a thin layer of the plasma column – can be taken as valid, at least after the implosion phase.

### ACKNOWLEDGEMENTS

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