EUROPEAN FUSION DEVELOPMENT AGREEMENT

Istituto di Fisica del Plasma "Piero Caldirola"
Consiglio Nazionale delle Ricerche

CONSIGLIO NAZIONALE DELLE RICERCHE

Electro-Optical Probe for Hypervelocity dust detection

Technical Report for EFDA task: WP09-PWI-03-01/CNR/PS-BS

M. De Angeli[1], G. Grosso[1], G. Gervasini[1], C. Castaldo[2], S. Ratynskaya[3], U. de Angelis[4], FTU team[2].

[1] Istituto di Fisica del Plasma-Associazione EURATOM-ENEA-CNR, Milan, Italy.
[2] ENEA-Frascati, Frascati, Italy.
[3] Royal Institute of Technology KTH, Stockholm, Sweden.
[4] Department of Physical Sciences, University of Naples and INFN Sezione di Napoli, Italy.

FP 10/02 June 2010

ISTITUTO DI FISICA DEL PLASMA
"Piero Caldirola"

Associazione EURATOM-ENEA-CNR

Via R. Cozzi 53 - 20125 Milano (Italy)

I. Introduction

Dust impact ionization effects, produced by hypervelocity (> a few km/s) micron sized particles, have been recently detected during tokamak plasma discharges [1-4]. Here we discuss the project of a specific diagnostic for such hypervelocity particles, impinging on plasma facing components at velocities higher than the velocity of the compressional waves in the target and projectile materials.

Such project is motivated by the importance of the erosion effects. The latter is about 1 nm s^{-1} as has been estimated from the rates of hypervelocity impacts and the damages produced on molybdenum probes during plasma discharges of the FTU tokamak.

The diagnostic is an electro-optical probe (EOP). It is based on the simultaneous detection of the charge released upon impacts (electrical detection), producing spikes of the order of a few tens mA in the ion saturation current collected by an electrostatic probe, and the light emission at a characteristic wavelength from the vaporized target material, collected by optical fibers looking at the probe tip (optical detection). This allows to discriminate events (spikes of the ion saturation current) due to plasma fluctuations, which are not accompanied by line emission, as well as events due to arcs, which are characterised by current spikes of larger amplitude (> 1 A). In the following sections of the report we discuss the feasibility of the project (Section II) , the scheme of the electric and optical detectors and the mechanical design for the installation of the probe in a port of the FTU tokamak (Section III). Indication of the materials and the costs sustained under the EFDA priority support PWI 0301 is also provided.

II. EOP feasibility

A study of the EOP feasibility has been carried out under the baseline and the priority EFDA support. The expected electric and optical signals have been compared to the plasma background noises.

From the results of previous experiments on FTU, it has been found that a few tens mA spikes produced by dust impacts can be easily distinguished from the background currents (considering both their average values and the fluctuations), if the ADC sampling rate is of the order of 0.5 MHz, for a probe surface area of about 0.3 cm^2 exposed in SOL plasma with density $n_e \leq 5\ 10^{17}\ m^{-3}$ and temperature $T_i \approx T_e \leq 5$ eV. Lower amplitude current fluctuations might be identified as due to impact events if simultaneous occurrence of light flashes is observed.

To evaluate the intensity of light emission a simple self-consistent modeling of the expanding vapour cloud has been developed. It has been found reasonable to assume that the largest impact craters (with diameter of the order of 100 μm) observed on the molybdenum probe tip in the FTU experiments do correspond to the largest spikes of the ion saturation current; in addition, the initial radii of the molybdenum vapour clouds produced by the dust impacts on the probe are of the order of the diameter of such craters. Based on experimental results on the expanding vapour clouds produced by the impacts [5-6] it has been also assumed that local thermal equilibrium (LTE) conditions at the target vaporisation temperature T_v are verified during the first phase of the cloud expansion, namely within an interval $\Delta t_o \approx 100$ ns after the impact. During such interval, the ionization is assumed negligible. The clouds expand at a velocity $V_{exp} \approx 3\ C_s$ as expected for typical explosive phenomena. As the clouds expand the ionization increases and the electron impact ionization due to the surrounding plasma, which is assumed negligible during the interval Δt_o, is expected to be more and more effective, so that the vapour clouds will be fully ionised. Therefore, the number of the neutrals N_v initially produced can be assumed equal to the total number of the elementary charges (10^{13}) collected by the electrostatic probe. The initial number density n_{vo} of the clouds with 100 μm radii and 10^{13} atoms is therefore of the order of 10^{24} cm^{-3}.

Tungsten has been chosen as a probe tip material, because it is not intrinsic in FTU, and W line emission at 401 nm from the impact vapour cloud cannot be confused with other line emission in FTU. It is assumed that the initial density of the W vapour cloud produced by hypervelocity impacts is of the order of 10^{24} cm^{-3} as expected for molybdenum targets.

Consistently with the above assumptions it can be shown that, for a tungsten cloud of $N_v \approx 10^{12} - 10^{13}$ atoms, with temperature $T_v \approx 0.5$ eV, formed by a dust impact with initial number density $n_{vo} \approx 10^{24}$ cm^{-3}, and expanding at velocity $V_{exp} \approx 3\ C_s$ in a background plasma with $n_e \leq 5\ 10^{17}$ m^{-3} and $T_i \approx T_e \leq 5$ eV, the following statements hold during an interval $\Delta t_o \approx 100$ ns after the impact:

i) The characteristic rate of the expansion $\nu_e = V_{exp}/r_v$, where r_v is the radius of the cloud, is much lower than the typical rate of the neutral collisions $\nu_c = n_v\ \sigma_v\ V_{th}$, where $\sigma_w > \pi(2\ r_a)^2$ is the cross section for neutral collisions at thermal velocity V_{th} and r_a is the atomic radius;

ii) The fractions of ionised (index i) and excited (index ex) atoms by electron are, respectively, less than 0.08 % and less than 1 %, as follows from the respective frequencies $\nu_{i,ex} = n_e\ \sigma_{i,ex}\ V_{th,e}$ and the cross sections $\sigma_i \approx 1.5\ 10^{-19}$ m^2 [7], $\sigma_{ex} \approx 2\ 10^{-18}$ m^2 [8].

iii) Therefore, the conditions for LTE are verified, and the ionised fraction of the atoms from Saha's equation is less than 15%, so that the population of the atomic levels is expected to follow the Boltzmann distribution as in vacuum experiments [5-6].

In the later stage of expansion, the LTE hypothesis is no more valid, and electron impact ionization due to the surrounding plasma fully ionizes the vapour cloud within a few tens μs.

Therefore, the photon rate S_{pq} due to p->q transitions can be evaluated by the simple expression

$S_{pq} = N_v\ (g_p/g_q)\ \exp(-E_{pq}/T_v)\ A_{pq}$ where $g_{p,q}$ are the degeneracies of the p,q states, E_{pq} is the energy of the transition and A_{pq} is the transition strength.

For W line emission at 401 nm, $g_p = 9$, $g_q = 7$, $E_{pq} \approx 3$ eV, $A_{pq} \approx 1.63\ 10^7$ s^{-1}. At a collection optic with surface area $A_c \approx 3 \times 10^{-7}$ m^2, located at a distance $d \approx 1$ cm from the probe tip, the expected number of photons collected during Δt_o, for $N_v = 10^{12} - 10^{13}$, is $N_{ph} \approx 10^6 - 10^7$

This value has been compared with the photons emitted in the wavelength range 401±1 nm by the background plasma. The main source of such noise is the Bremsstrahlung radiation. The wavelength range for the evaluation has been chosen considering the use of an interference filter with 2 nm FWHM. The power spectral density for Bremsstrahlung emission is given by

$$P_\omega = -\frac{4\sqrt{2}}{3\sqrt{\pi}} n_e^2 r_e^3 \frac{(m_e c^2)^{3/2}}{(k_B T_e)^{1/2}} Z_{eff} E_i(-w_m)$$

where r_e is the classical radius of the electron, E_i is the exponential integral and $w_m = (1/2)(\hbar\omega/3k_B T_e)^2$. Parabolic profiles of density and temperature in the main plasma and exponential decay in SOL are assumed to evaluate the Bremsstrahlung emission inside the cone of sight of the diagnostics by a numerical code. The following values of density and temperature at the wall (W), at the last magnetic surface (L) and at the centre (C) were used:

$N_W = 1\text{-}3\ 10^{17}\ m^{-3}$, $n_L = 3\text{-}5\ 10^{18}\ m^{-3}$, $n_C = 5\text{-}7\ 10^{19}\ m^{-3}$,
$T_W = 1\text{-}3$ eV , $T_L = 20\text{-}50$ eV , $T_C = 1\text{-}3$ keV.
As a result, less than 10^3 photons due to Bremsstrahlung emission are expected on the fiber, for 25° opening angle of the cone of sight. The line emission due to hypervelocity impacts can be distinguished from the noise provided the time gate for optical data acquisition is of the order of 100 ns.
We note that the electrical signal (probe current) exhibits features on much longer times scales than the expected optical signal. Namely, waiting time of such events is of the order of 10 ms, and the duration of current spikes is of the order of several tens μs. That implies that for electrical signal sampling frequency of 500 kHz is sufficient.
All the probe materials to be used for EOP (W, AISI 304, polyimide, ceramic insulator, Si of the optical fiber) are fully compatible with FTU operations.

II. EOP design

The scheme of the EOP, concerning the detection of the current spikes produced by hypervelocity impacts is reported in Fig. 1 below.

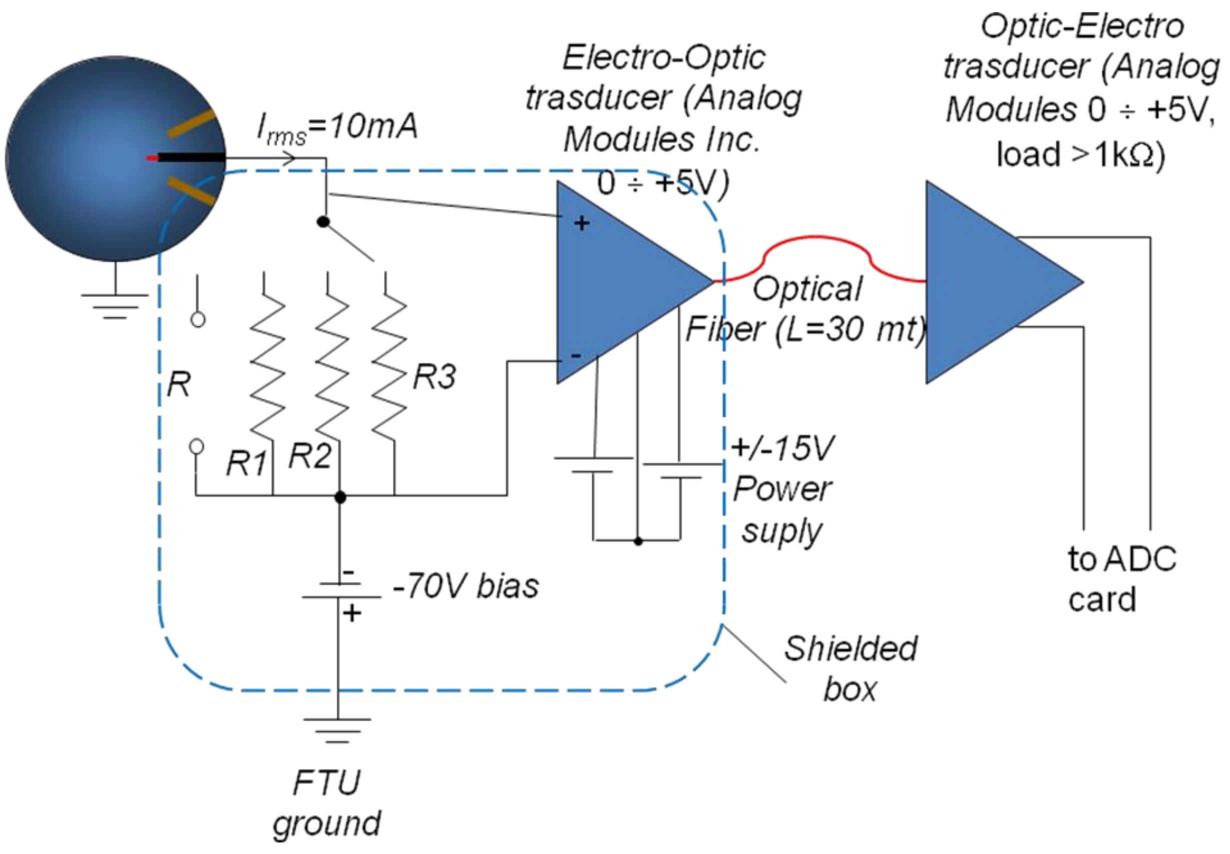

Figure 1. Scheme of the EOP probe for hypervelocity impacts detection (charge released)

It can be seen that a shielded box, for signal acquisition in the FTU hall, and a signal transmission by electro-optic transducers have been adopted to avoid any electrical noise from the FTU environment. The ADC card (with sampling rate ≥ 0.5 MS/s) has to be triggered by a signal based on the FTU interlock plasma signal.

The scheme of the EOP, concerning the detection of the line emission produced by hypervelocity impacts is reported in Fig. 2 below.

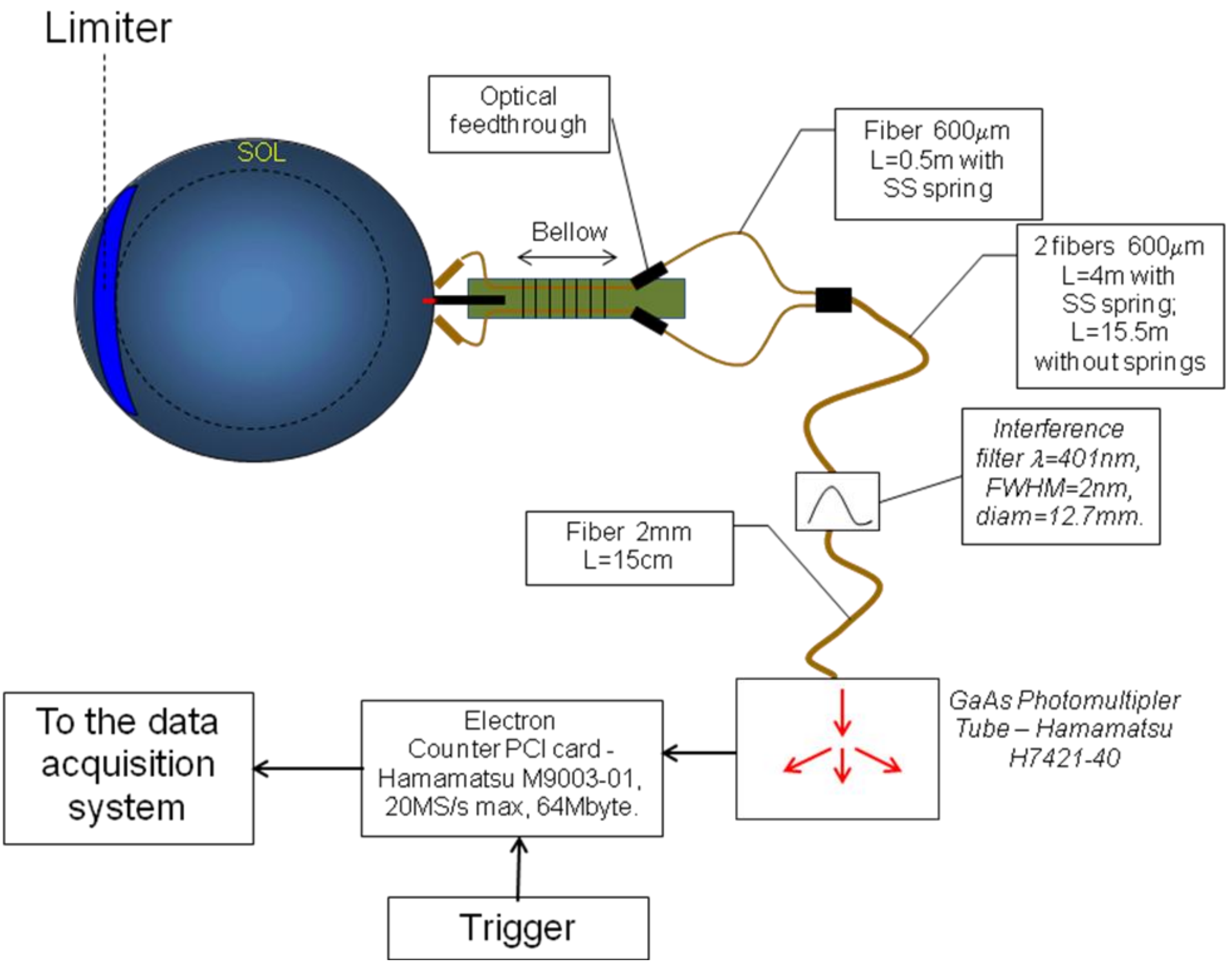

Figure 2. Scheme of the EOP probe for hypervelocity impacts detection (optical line emission).

The trigger of the electron counter must be aligned within 1-2 μs with the trigger of the ADC card, used for the detection of current spikes.

The mechanical design of the probe installed in port 5 of FTU is shown in Fig. 3, while the details of the head are reported in Fig. 4.

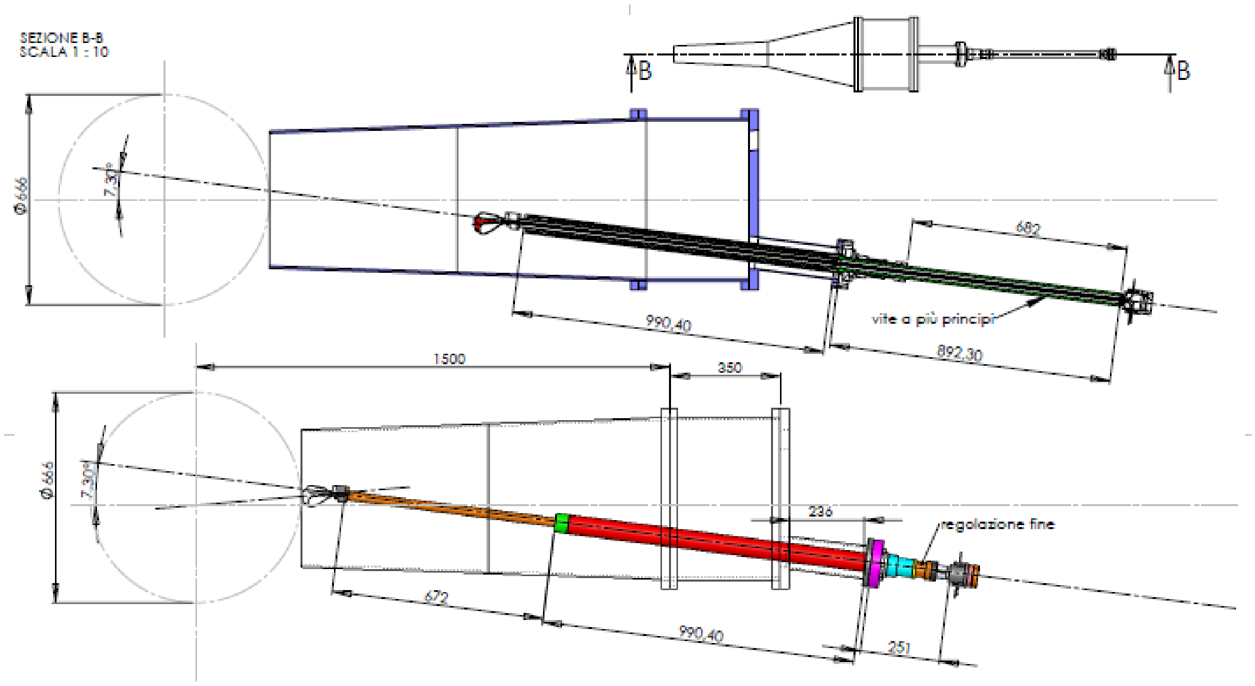

Figure 3. Mechanical design of the EOP with cross-sectional view of the port and vacuum chamber. The lengths are in mm. "Vite a più principi" indicates a screw with two or more threads. "Regolazione fine" means fine regulation screw.

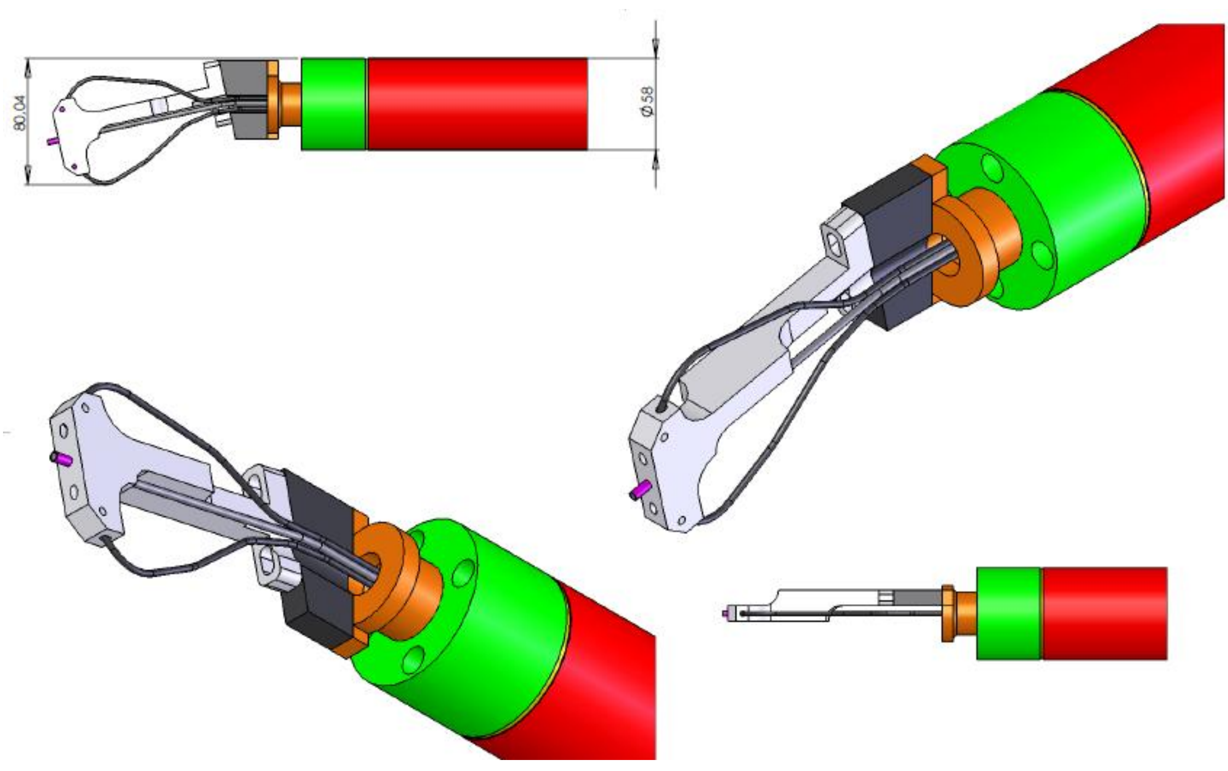

Figure 4. Details of the EOP head. The lengths are in mm.

III. Financial support from EFDA

The items listed in table 1 have been bought within the EFDA priority support.

Item:	Price:
Resistors, power supply, the "Analog Module" devices, and resistors for the electric detection system for current spikes (see Fig. 1).	2087 Euro
Fiber optics with connections and SS springs, fiber optic splitter, PMT case, special fiber optics and connectors compatible with high vacuum environments, optics (i.e. gredlens) for the optical detection system (see Fig. 2).	4440 Euro
Optical and electrical vacuum to air feedthrough.	2138 Euro
Total	8665 Euro

References

[1] C. Castaldo, S. Ratynskaia, V. Pericoli et al., Nuclear Fusion **47**, L5 (2007).
[2] S. Ratynskaia S, C. Castaldo, K. Rypdal K et al., Nuclear Fusion **48**, 015006 (2008).
[3] G. E. Morfill et al., New Journ. Phys. **11** 113041 (2009).
[4] S. Ratynskaia, H. Bergsaker et al., Nuclear Fusion **48**, 122001 (2009).
[5] S. Sujita, et al J. Geophys . Res. **103** E8 (1998) 427.
[6] S. Sujita, et al J. Geophys . Res. , **108** E12 (2003) 514.
[7] I. Beigman, et al. PPCF **49** (2007) 1833.
[8] Yu. M. Smirnov, High Temperature **47** (2009) 17.