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Dose-current discharge correlation analysis in a Mather type Plasma Focus device for medical applications

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A B S T R A C T

In a Plasma Focus device the plasma collapses into the pinch where it reaches thermonuclear conditions for a few tens of nanoseconds, becoming a multi-radiation source. The nature of the radiation generated depends on the gas filling the chamber and the device working parameters. The self-collimated electron beam generated in the backward direction with respect to the plasma motion is one of the main radiation sources of interest also for medical applications. The electron beam may be guided against a high Z material target to produce an X-ray beam. This technique offers an ultra-high dose rate source of X-rays, able to deliver during the pinch a massive dose (up to 1 Gy per discharge for the PFMA-3 test device), as measured with EBT3 Gafchromic©film tissue equivalent dosimeters. Given the stochastic behavior of the discharge process, a reliable on-line estimate of the dose-delivered is a very challenging task, in some way preventing a systematic application as a potentially interesting therapy device. This work presents an approach to linking the dose registered by the EBT3 Gafchromic©films with the information contained in the signal recorded during the current discharge process. Processing the signal with the Wigner-Ville distribution, a spectrogram was obtained, displaying the information on intensity at various frequency scales, identifying the band of frequencies representative of the pinch events and define some patterns correlated with the dose.

1. Introduction

As is well known, a Plasma Focus (PF) is a pulsed power device able to confine the plasma produced in a discharge phenomenon in a small region, in the so called ‘pinch’ event, through electromagnetic acceleration of a current sheet (Sumini, 2006). When the plasma is in the pinch status, it can reach thermonuclear pressures and energy densities; in such conditions it acts as emitter of several kinds of radiation like thermal bremsstrahlung X-rays, ion and electron beams and of any kind of products allowed by the nuclear reactions that could possibly take place in that environment (Lee and Saw, 2011). The underlying physics of this peculiar class of devices is still debated and it is safe to say that it is not yet well understood. The pinch phenomenon is extremely fast (a few tens of nanoseconds) and it is believed to be highly non linear with respect to the control parameters and chaotic. These combined characteristics make the study of the whole phenomenon quite difficult. In the past, some efforts have been put in finding a way to predict the neutron yield from D-D or D-T fusion reactions coming from a PF pinch by considering its constructional and operational parameters, like the capacitor's bank energy, the chamber pressure and the operating voltage (Patran, 2005). Recently, the PF technology has been proposed as a viable fast X-ray source: the electron beam emitted from inside the pinch can be used to produce X-rays via the interaction with a suitable target (Tartari (2004), Ceccolini (2012); Sumini (2015)). The main unsolved issue with this technology is that, under very similar operating conditions, the radiation yield and spectrum can vary at every discharge: this is particularly true for the spectrum of the electrons emitted from the pinch. The scope of this work is to study the characteristics of the current signal registered from the PF circuit of an experimental Mather type device actually operated in our laboratory, the PFMA-3 (Plasma Focus for Medical Applications #3) and to extrapolate some features that can be correlated with the dose delivered to a stack of Gafchromic©films to be considered as tissue equivalent (Ceccolini (2012a), Ceccolini (2012b)). Starting from a quite high number of recorded shots, the current signals have been processed using high-

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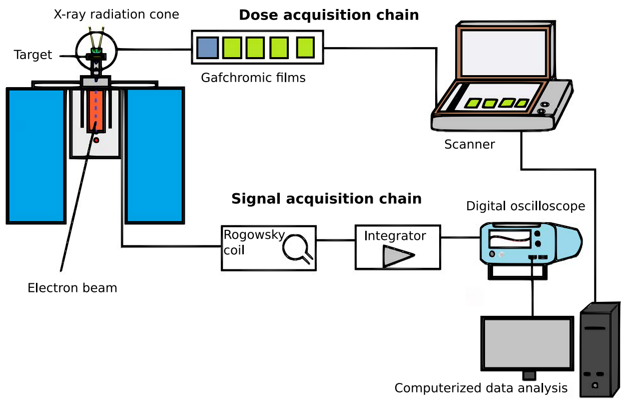

Fig. 1. Scheme of the actual setup for dose analysis.

pass filters in order to highlight their fine structure. The Wigner-Ville distribution function (Cohen, 1989) has been computed for each filtered signal to obtain its time-frequency representation. This work is intended as a step towards the identification of a set of parameters that can help predict with some degree of accuracy the behavior of a PF when operated as an X-ray source.

2. The Mather type PFMA-3 and the acquisition apparatus

The PFMA-3 has been built in order to be operated as an X-ray source (Sumini, 2015) for cell culture irradiation. This device does not use the pinch thermal bremsstrahlung X-rays but instead exploits the electrons accelerated during the radiative phase, thanks to the hollow inner electrode. The electrons are channeled through an extraction tube and subsequently directed on a brass foil target (the actual setup is shown in Fig. 1 and the device main parameters are reported in Table 1) leading to X-ray production. Currently the PFMA-3 is used as a low energy radiation source for evaluating the biological effect of the high dose rate radiation delivered and compared to a traditional X-ray tube. The whole electron bunch is of the order of 0.1 mC and has a spectrum that ranges up to 300 keV with a leading fraction between 50 and 80 keV. The spectrum of the X-rays produced by conversion in the target has its bulk in the 30–60 keV interval. From dimensional considerations as well as experimental evidence, the pinch lifetime of the plasma focus machines has been found to be related to the anode radius (Lee and Saw (2011), Patran (2005)). Considering the PFMA-3 inner anode external radius of 60 mm then the pinch time can be roughly estimated the to be between the 20 ns and 50 ns. The set up used to measure the current signal requires a Rogowski coil with a built in integrator circuit linked to a Tektronix DPO4032.

The pressure inside the chamber is measured with a Pirani gauge coupled with a digital controller with a sensitivity of 10^{-2} mBar. The pressure tends to rise slightly after every discharge, this is probably due to degassing of the electrodes and to copper particles ablated by the plasma sheet and then dispersed inside the internal atmosphere. The pressure rise rate is quite unpredictable and the pressure variation $\triangle P$ has been observed to vary from a minimum of 10^{-2} mBar to a maximum of $2.0 \cdot 10^{-2}$ mBar. Another aspect to be considered is that the target is an alpha-brass foil of 50 µm of thickness that undergoes significant thermomechanical stress and surface etching at every discharge: the life expectancy for a target is in the order of $\simeq 10 \div 20$ discharges, and

Table 1
PFMA-3 Technical Data.

Maximum Current	200–250 kA
Operating Pressure	0.5 mBar N_2
Total Capacitance	22.3 µF
Capacitor's Energy	3 kJ
Operating Voltage	18 kV

the effect of this damage on electron conversion should be taken into account. The electron beam is rather well collimated, but still retains a small angular distribution that varies slightly at every discharge. The dose delivered in a pinch time was measured using EBT3 Gafchromic© films, scanned using a consumer grade digital scanner and then read using the proprietary sw Picodose©. For a selected region the mean gray-level and its standard deviation was computed. Those values are converted from gray-level to dose using a fourth grade polynomial calibration curve, considering the standard deviation as the uncertainty on the measurement, obtaining values up to 1 Gy in a pinch time (shot). The EBT3 films irradiated with the PFMA-3 present also some degree of spatial anisotropy, resulting from the small X-ray source beam cross section, the close proximity of the dosimeters and the statistical anisotropy of the primary electron bunch (Ceccolini, 2012).

3. Signal analysis methodology

The plasma pinch spatial extension is of the order of a few microns, and the electron maximum energy is in the hundreds of keV, as explained in Section 2. These values lead to the conclusion that the accelerating field is ranging from some dozens of MV/m up to a hundred MV/m. Such field can only exists for a very short time and should leave a mark in the current signal. There is some support to the idea that the plasma resistivity can be considered negligible compared to the whole circuit resistivity during the whole PF operation (Lee and Serban, 1996) and this fast perturbation is believed to be associated with a very localized inductance variation of the electrical system that is related to the various plasma phenomena. The signal analysis technique utilized in this work aims at finding the trace of the aforementioned process inside the current signal from the PF. It is well known that the short circuit plasma focus equation for the current as a function of time is:

$$I(t) = \frac{V_0}{wL} exp(-\xi t) sin(wt) \quad (1)$$

where $\xi = \frac{R_0}{2L}$, $w = \frac{1}{\sqrt{LC_0}}$, C_0 describes the capacitor bank and L is the total inductance of the PF equivalent circuit. The underlying evolution of the current during operation is essentially the one described by Eq. (1); in coincidence with the signal peak, there is a sudden drop in the current (explained by the well established snow plow model) followed by a fast, small scale perturbation (Frignani, 2007). If any useful information about the pinch exists, then this short portion of the current signal is the best candidate for a direct search. It should be noted that the perturbation frequency is roughly two orders of magnitude smaller that the PF short circuit frequency: this simple consideration leads to the idea that the signal can be filtered to point out the relevant details without significantly altering them thanks to the fact that the PF frequency is known. This operation can be carried out with a physical filter circuit or by well established digital signals processing techniques. The latter option was chosen for this work, the filtering procedure used involving basic Fourier analysis of time series. In short the signal is Fourier transformed via a simple Coolidge-Tukey FFT algorithm, the resulting spectrum is then weighted using a custom high-pass filter that dampens heavily every coefficient that is associated with a frequency equal or less than the one of the PF circuit, then the resulting spectrum is back-transformed (Semmlow and Griffel, 2014). Different filters have been proposed and tested, the one chosen for the PF at study is a high pass with exponential damping with filter gain till the threshold frequency (7.5 MHz) equal to 0 and the stop-band frequency at 0.5 MHz, very close to the PMFA-3 calculated frequency of 0.55 MHz. The mathematical structure of the filter is the following:

$$I(f) = 1 \quad if\ f \geq f_{threshold} \quad (2)$$

$$I(f) = exp\left(-\frac{A}{f}\right) \quad if\ f < f_{threshold} \quad (3)$$