Time-varying inductance measurements in the PF1000 Plasma-Focus device

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Abstract

The time varying inductance of the system plasma-electrodes in a large Plasma Focus device (PF1000) is experimentally determined from voltage and current-time derivative signals for several shots performed at the same conditions (2.4 mbar D_2, 24 kV), and using these results, the voltage drop on the pinch column is also evaluated as a function of the time. The values of these voltage drops exceed 100 kV in all the shots.

Introduction

The time varying inductance $L_p(t)$ of the system formed by the coaxial electrodes and the plasma current sheet (CS) bridging them in Plasma Focus (PF) discharges has been calculated using measured values of $V(t)$, the voltage at the breach end of the electrodes and dI/dt, the time derivative of the current circulating in the system originally by Mather (Mather 1968) on a 13 kJ PF device in Los Alamos. Later on, $L_p(t)$ was also evaluated in smaller energy devices (Bruzzone 2006a, Bures 2011, Veloso 2011) and this physical magnitude was used for estimating other relevant parameters of the device operation, like the voltage on the pinch column, and the energy delivered to the pinch during its formation (Bruzzone 2008, Barbaglia 2009, Bruzzone 2013). The purpose of this paper is to extend this procedure for a large energy device, the PF1000 operating at the International Center for Dense Magnetized Plasmas (ICDMP) located in Warsaw, Poland, using measurements performed during an experimental campaign conducted in 2013, in order to confirm that the technique can be extended to large PF devices and also to gain better information on the PF1000 device, namely, the values of the voltage drop on the pinch plasma column.

Experimental set up and primary results

The parameters of the PF1000 configuration used in this work have been given elsewhere (see for instance Kubes 2012). The electrodes geometry is particularly relevant for our purposes, and it consists of an inner electrode 23 cm in diameter, surrounded by 12 tubes, 8.2 cm in diameter symmetrically located with their centers on a 38.5 cm from the anode axis. The length of both electrodes is 48 cm.

Around 23 shots were performed at the same pressure (2.4 mbar, D_2) and at a bank voltage of 24 kV, recording among other features *V(t)* and *dI/dt* in all of these shots. As an example, Fig. 1 show typical traces of *V(t)* and *dI/dt*.

Analysis of the results and assessment of $L_p(t)$

The start of the Rogowski signal is chosen as reference time, $t = 0$, indicating that the total circuit resistance, including that of the plasma CS bridging the coaxial electrodes, is dropping down to values of the order of $(L_o/C_o)^{1/2}$, with L_o being the system fixed inductance and C_o the bank capacitance. However, it is worth noting that *V(t)* must start before $t = 0$, due to the fact that the breakdown within the electrodes requires some amount of time for the electric field between them to reach its pressure-dependent breakdown value, after which certain additional time interval is needed for building up an adequate electron density value (more precisely, an appropriate ratio of electron density to neutrals density) to achieve the required plasma resistivity value (Bruzzone et al. 2006b). In Fig. 2, a time expanded view of the signals given in Fig. 1 is shown to illustrate this situation. The damped oscillations present during this portion of the signals are similar to those recorded in the device Speed 2 (Kiess 1986), having generally relative higher-frequency and smaller amplitudes in almost all PF devices. Those damped oscillations are not relevant for the purpose of this work and will not be commented here.

As discussed in Bruzzone et al (2006b), the evaluation of $L_p(t)$ requires the validity of the equivalent circuit equation:

$$V(t) = \frac{d}{dt}\left[L_o' + L_p(t)I(t)\right] \qquad (1)$$

where L_o' is a constant external inductance due to connections and *I*(*t*) is the electrical current. This equation can be used whenever the resistive component of the forming CS becomes sufficiently small compared with the other impedances in the circuit. Let t_o be the time at which this condition holds, which certainly occurs after the first *dI/dt* peak is attained, provided that its amplitude is equal or close to V_o/L_o (V_o is the charging voltage). Then, for $t > t_o$:

$$L_p(t) + L_0' = \frac{\int_{t_o}^{t} V(t)\,dt + \left[L_0' + L_p(t_o)\right] I(t_o)}{I(t)} \qquad (2)$$

In practice, in order to perform this calculation using the measured *dI/dt* and *V(t)* signals, two critical parameters should be determined. Firstly, the value of t_o should be chosen near to the first maximum of *dI/dt.* Secondly, the value of $L_o' + L_p\left(t_o\right)$ should be determined such that the resulting $L_p(t)$ starts nearly constant, that is, $\left. dL_p \middle/ dt \right|_{t=0} = 0$. The latter can be usually performed by trial and error. The physical reason for this condition is that the CS requires a certain amount of time for detaching from the insulator, *i.e.* the lift-off time, hence the initial values of the plasma inductance are expected to be nearly constant. Actually, since the CS formation always occurs at the insulator surface when the device operates properly, the initial inductance should be similar in all shots, even under different operating conditions, like filling pressure or charging voltage. Furthermore, this initial value should be consistent with an educated assessment based on geometrical considerations or what an appropriate short circuit measurement yields. It is recommended to verify always if the latter is satisfied. L_o' has not been measured yet in the PF1000 device, but this is not a serious problem for our purposes as it will be seen in what follows.

After the initial plateau, L_p is expected to increase rather smoothly and almost linearly (coaxial traveling stage) up to a value at which there is a sudden increment in its slope, associated with the emergence of the CS from the coaxial electrodes. The difference between L_p at this particular time and $L_o' + L_p\left(t_o\right)$ should be roughly equal to the total inductance of the electrode´s system and also substantially independent of the charging voltage and filling pressure, p_o. In devices with small inner-electrode radius, this time usually coincides with the beginning of the *dI/dt* dip associated to the focus or pinch stage. However, in large-radius devices, like PF1000, this is not the case because due to the relatively large cathode radius, an intermediate radial convergence stage occurs before the formation of the pinch column.

Figure 3 shows a plot of the resulting $L_p(t)$ calculated by applying Eq. (2) to the signals recorded in one of the shots. The measured *V(t)* signal is also plotted for comparison purposes. It can be seen that L_p starts at approximately 22 nH and changes its slope at approximately 53 nH. Afterwards the inductance keeps rising smoothly up to a certain time, t_c, that coincides with the start of a peak in *V(t),* which is the pinch commencement. The pinch can be recognized by a strong increase in L_p for some 200 ns, followed by a slower growing.

Figures 4 show plots of L_p for three additional shots performed in the same conditions. It can be seen that the initial values are essentially constant and practically coincident, and the same is observed for the value at which the first noticeable change of slope occurs. The initial value of L_p is in agreement with a rough geometrical estimation of the fixed inductance due to connections in this part of the device. The additional increment up to the first change of slope ($L_p \sim 30$ nH) agrees with the inductance of the whole length of the coaxial gun, taking into account that the return current flowing in the relatively large diameter tubes forming the cathode probably flows in the part of the tubes nearer to the anode. Hence, these results can be trusted as reasonable measurements of the system CS electrodes inductance in this device.

The determination of L_p(t) together with Eq. (1) can be used to assess the voltage applied to the plasma column, $V_p(t)$, associated with the pinch stage. Actually, for $t > t_c$ and defining $L'_p(t)$ such that $L_p(t) = L_p(t_c) + L'_p(t)$, equation (1) can be written as

$$V(t) = L_p(t_c)\frac{dI}{dt} + \frac{d}{dt}\left[L'_p(t)I(t)\right] \qquad (3)$$

The second term of Eq. (3) is the inductive voltage drop on the plasma column, $V_p(t)$, therefore, for $t > t_c$

$$V_p(t) = V(t) - L_p(t_c)\frac{dI}{dt} \qquad (4)$$

It should be noted that within this time interval, dI/dt is negative, so that V_p is larger than V. Also, this inductive voltage drop occurs mainly in the regions of the converging current sheet and plasma column in which a current density flows, that is, in the external boundary of the plasma structure. Figure 5 shows the plots of $V_p(t)$ for the complete set of shots performed. It can be seen that the peak values of V_p are in the hundreds of kV range. It should be stressed that the main contribution to this value is due to the term proportional to dI/dt. The shot to shot time fluctuation in the occurrence of the peaks is due to the time fluctuation of the pinch formation, typical of PF devices.

Final remarks and conclusions

The evaluation of the time varying inductance of the CS electrodes system in the PF1000 device using measured values of the V and dI/dt yields values which are in good agreement with what is expected from a single traveling CS, bridging the electrodes and carrying all the discharge current, agreeing with the behavior reported for several smaller PF devices. These results strongly suggest that the hypothesis of alternative current paths in the operation of PF devices, while perhaps valid in some particular devices and eventually in a certain range of operating conditions (Bruzzone et al. 1993), cannot be considered a general phenomenon. It is also worthwhile to stress that, the evaluation of the voltage $V_p(t)$ applied to the plasma column yields values which agree with the observed properties of the hard X-ray emission in these devices, without requiring unusual electron acceleration mechanisms.

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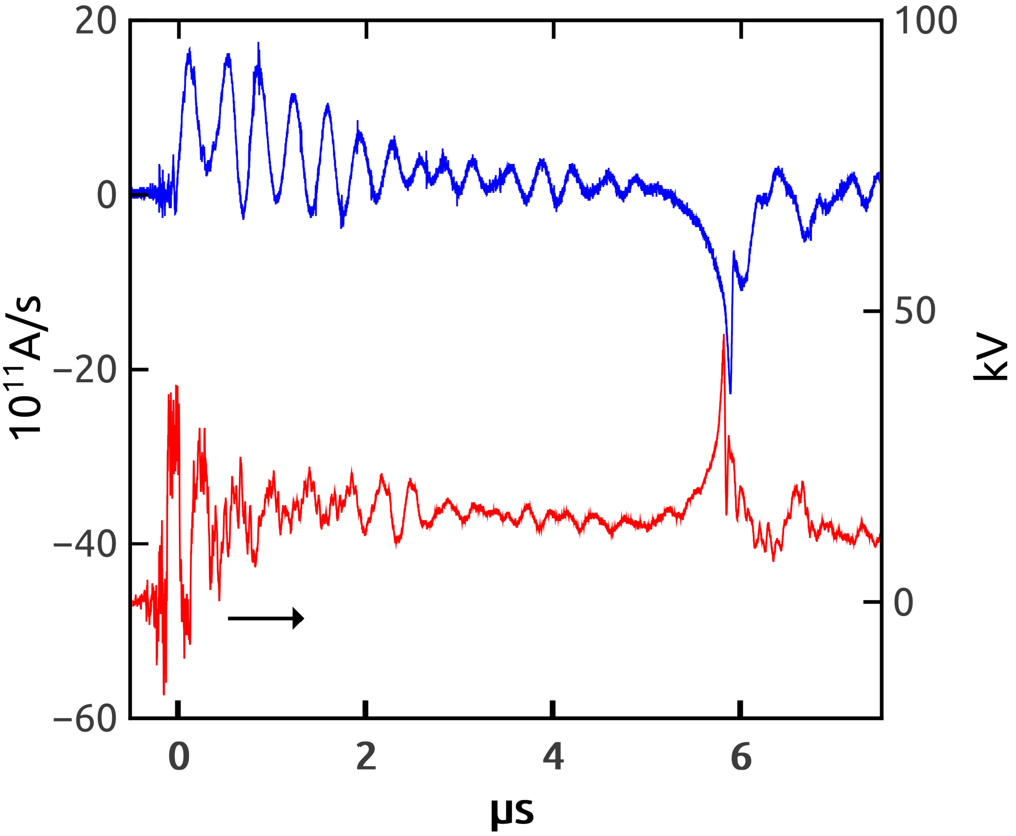

Figure 1: Typical current derivative (up) and voltage (down) signals from the PF1000 device charging the capacitor bank at 24kV. The discharge vessel was filled with 2.4 mbar of D_2.

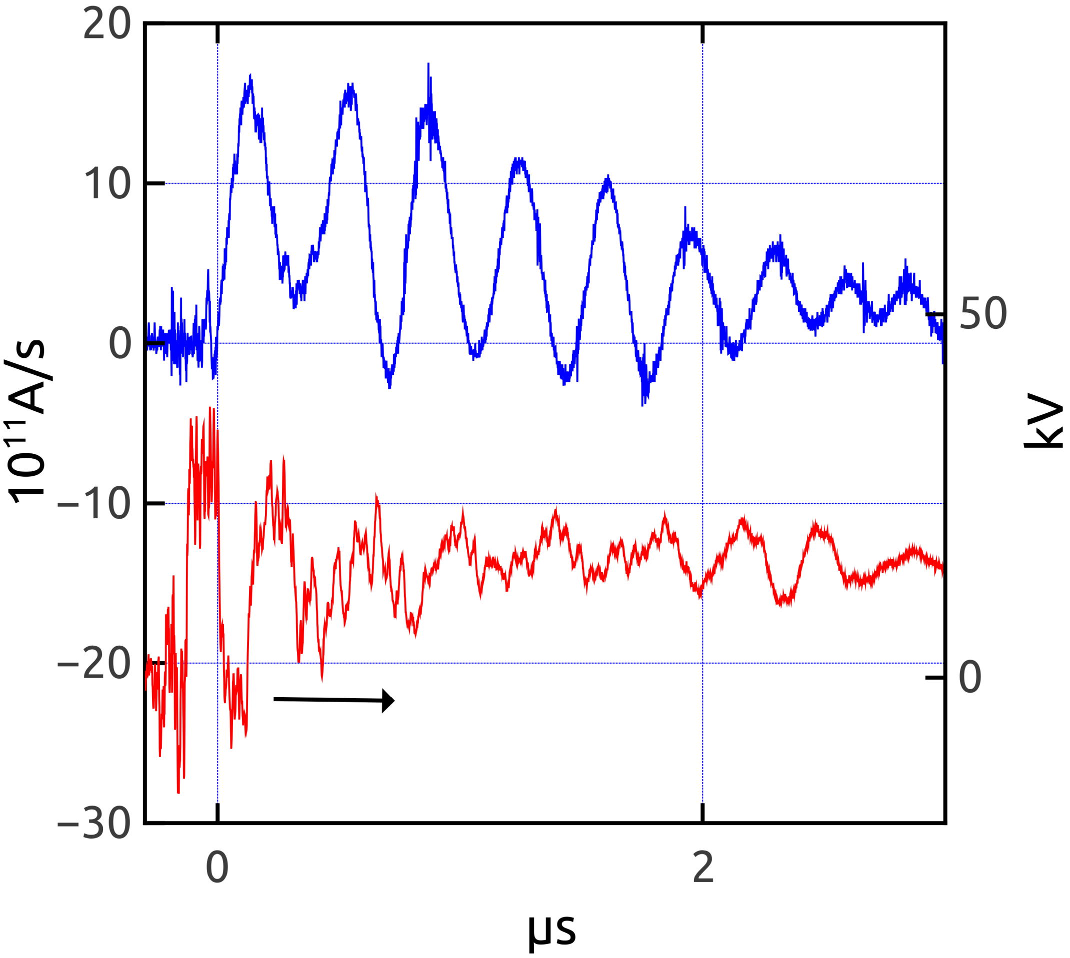

Figure 2: Expanded view of the initial part of the data shown in Figure 1

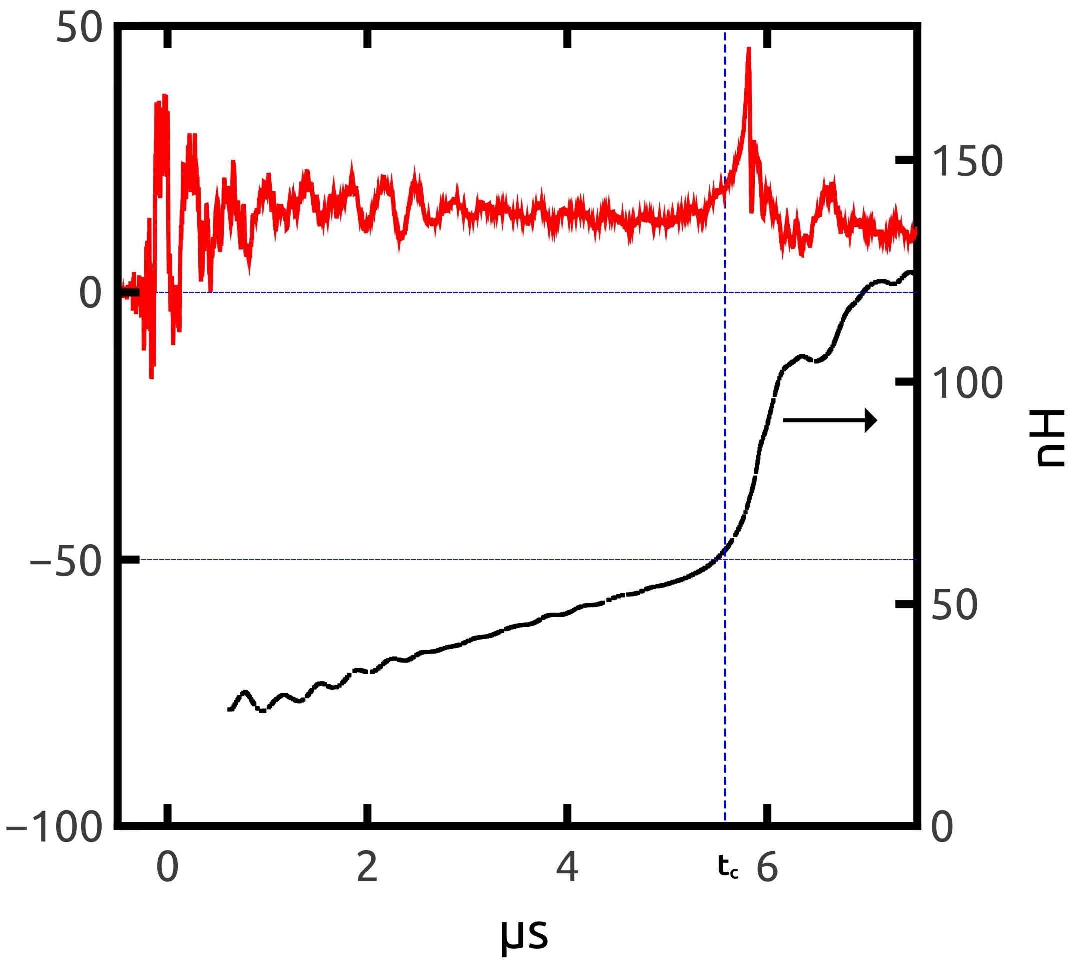

Figure 3: Anode voltage signal, $V(t)$ and calculated $L_p(t)$ for one shot at 24kV, 2.4 mbar of D_2.

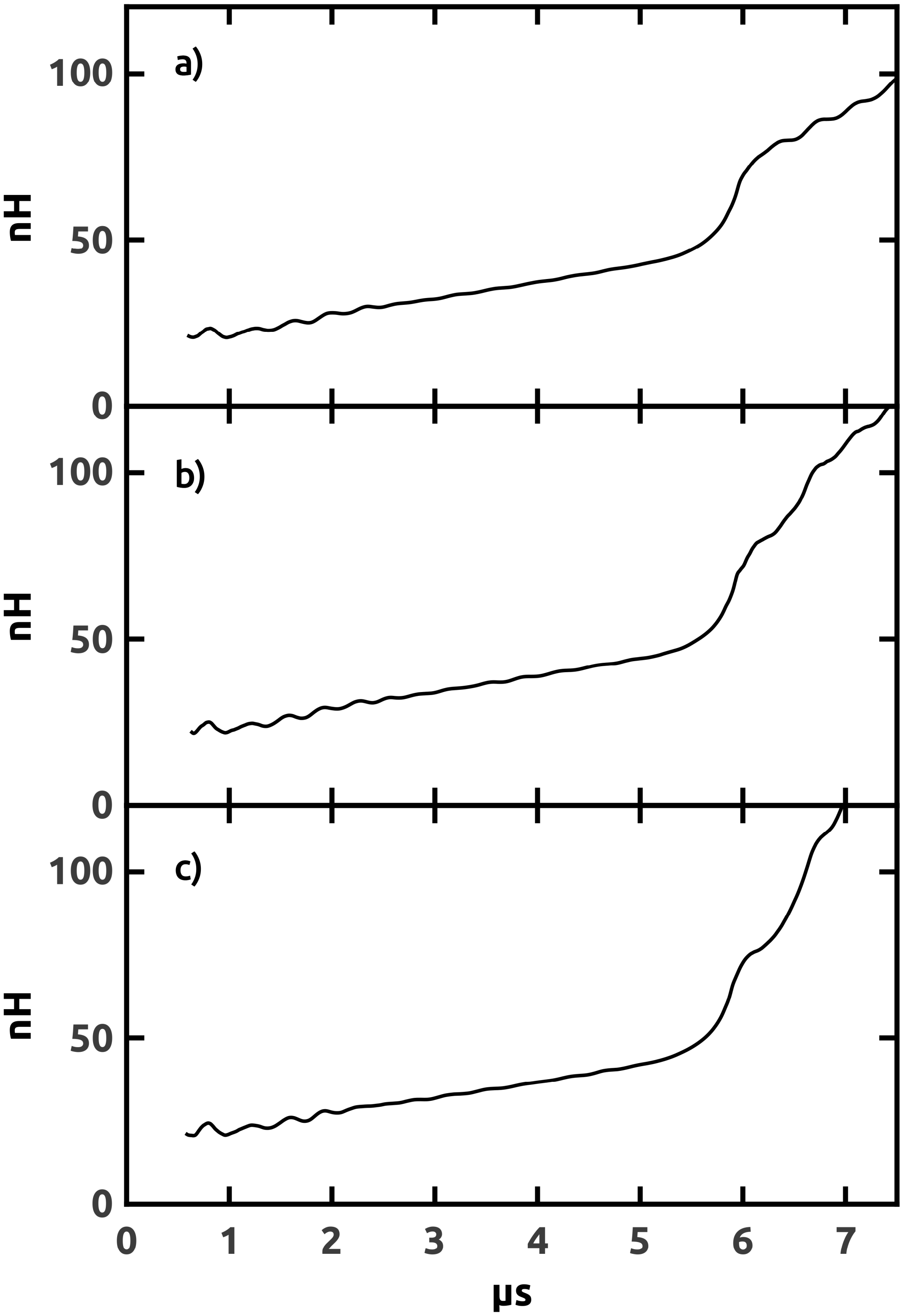
a)
b)
c)
nH
nH
nH
0
50
100
0
50
100
0
50
100
0
1
2
3
4
5
6
7
µs

Figure 4: Current sheet inductance as a function of time calculated for discharges at 24kV, 2.4 mbar of D_2

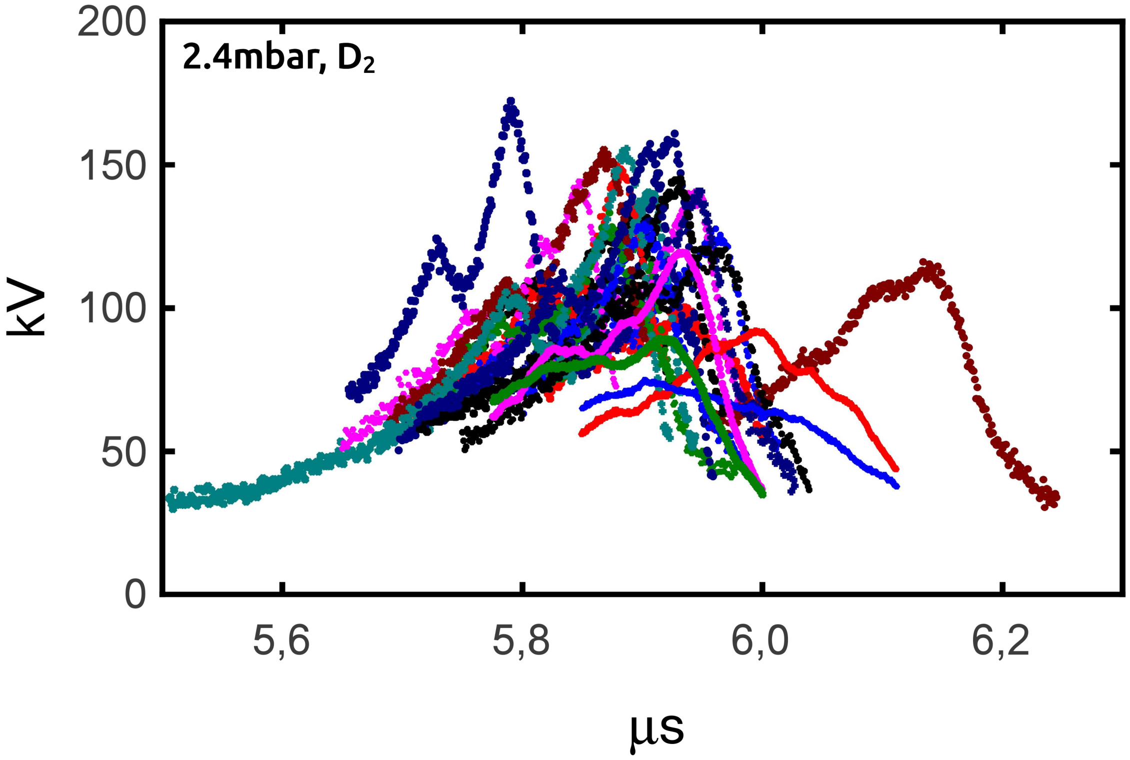

Figure 5: Pinch voltage as a function of time for 23 discharges at 24kV filling the vessel at 2.4 mbar of D_2