A repetitive table top pulsed plasma device to study materials under intense fusion relevant pulses

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Materials for fusion reactors

The time of interaction, peak power and deposited energies on materials in inertial and magnetic confinement differ. However, the parameter defined as Q $t^{1/2}$ (with Q the power flux and t the time of interaction with the material), known as damage factor F, reach values as high as ≥ 7×10^3 ($Wcm^{-2}\ s^{1/2}$) for both, ELM´s in ITER divertor and in the first wall in a typical direct drive target [1]. For similar F values, similar thermomechanical effects are produced. These thermomechanical effects, are the results of heat, ion-matter interactions resulting in defect production. Thus, the determination of the materials damage threshold is an important issue to study different materials for plasma-facing components of nuclear fusion reactors.

The dense plasma focus (DPF) produce a pinch plasma and is a pulsed source of radiation and particles as x-rays, ion and electron beams, neutron bursts [2], plasma shocks [3] and plasma jets [4]. DPF discharges are being used as pulsed radiation sources to explore applications, for both industrial and to other sciences. For instance, in non- destructive analysis, pulsed x-rays and neutron imaging, and as non-radioactive sources for field application, as well as in material [5] and nanoscience, and recently in biological research [6]. In addition, the dense plasma focus (DPF) has the distinctive feature that is a self-scale kind of z-pinch [7].

1. J. Alvarez et al. Fusion Engineering and Design 86, 1762–1765 (2011)
2. L. Soto, Plasma Phys. and Control. Fusion 47, A361 (2005)
3. L. Soto et al., Phys. Plasmas, 21, 122703, (2014)
4. C. Pavez et al., Phys. Plasmas, 22, 040705 (2015)
5. M. J. Inestrosa-Izurieta et al., Nuclear Fusion 55, 093011 (2015)
6. J. Jain et al., AIP Advances, 7, 085121, (2017)
7. L. Soto et al., Plasma Sources Sci. and Technol. 19, 055017 (2010)
7. D. Zanelli et al., 19th ICPP, Vancouver, Canada, June 2018.

Damage factor

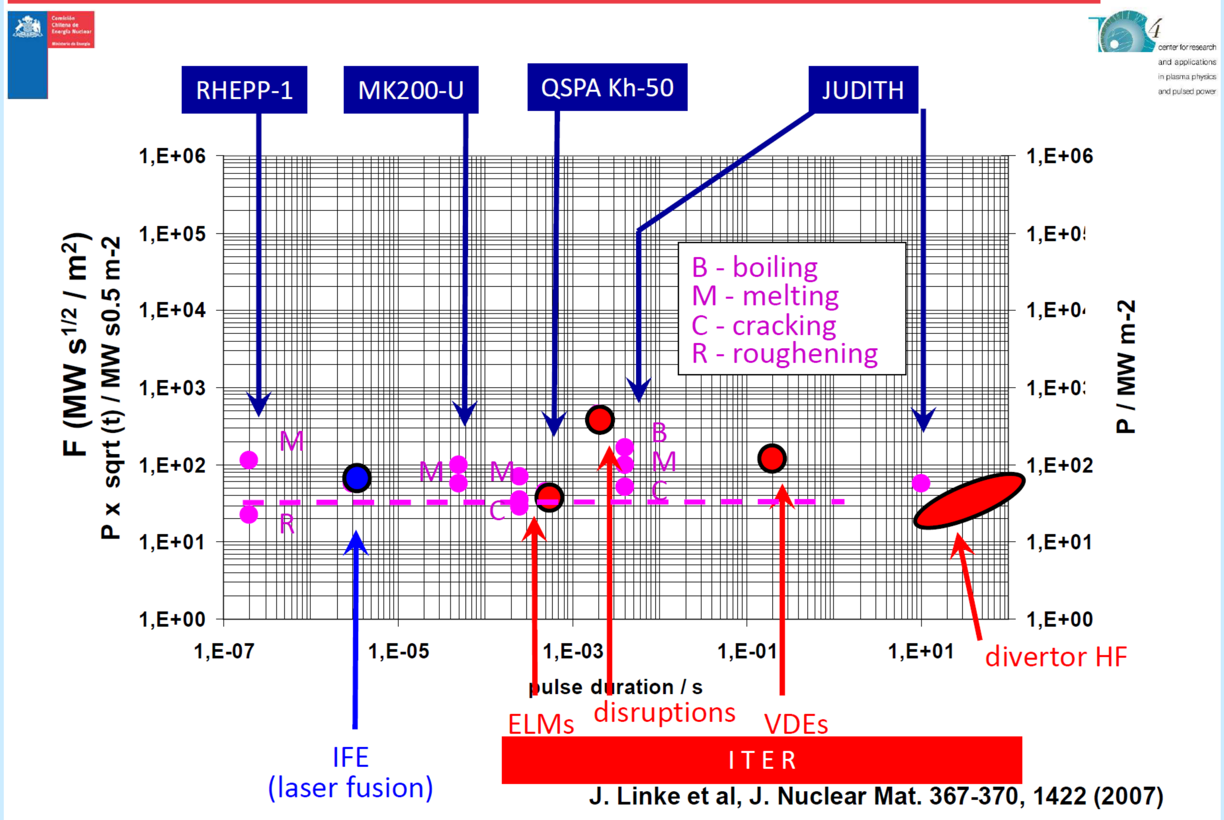
$$F \sim q\cdot\tau^{1/2} = E/S\tau^{1/2}$$

q: power flux, τ: interaction time, S: interaction area

The damage factor F, is an empirical parameter that has been recognized that a good measure of the damage in an irradiated sample. In fact, it has observed that radiation sources producing high power flux q with a short time interaction τ on a specific material, have the similar thermomechanical effects if the material is irradiated with a source with less q and longer τ, if in both situation the damage factor F has the same value.

For a theoretical explanation of the damage factor, see:

"A model for defect formation in materials exposed to radiation", S. Davis, F. González-Cataldo, G. Gutiérrez, G. Avaria, B. Bora, J. Jain, L. Soto, C. Pavez, and L. Soto, Matter and Radiation at Extremes **6**, 015902 (2021); https://doi.org/10.1063/5.0030158



J. Linke et al, J. Nuclear Mat. 367-370, 1422 (2007)

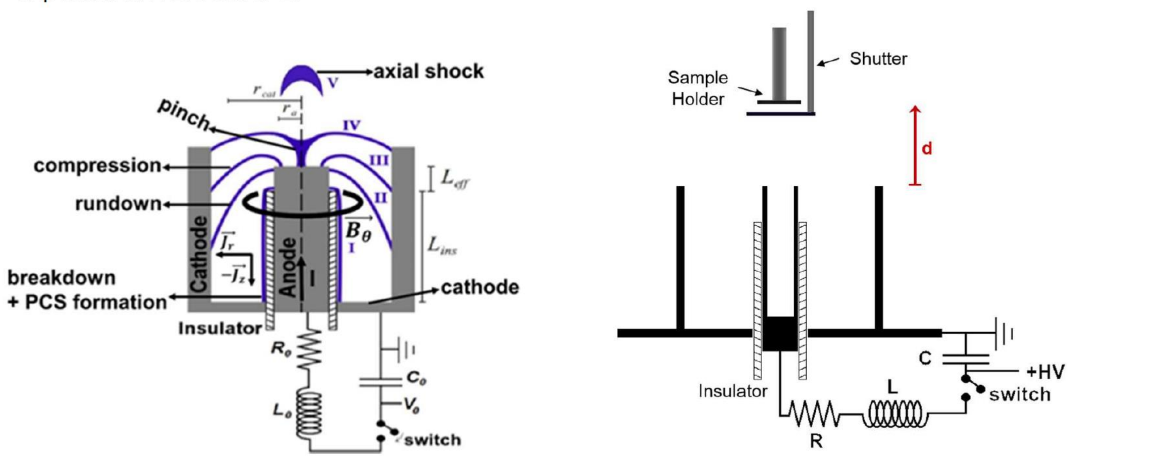
Motivation

Plasma guns, accelerators and others large facilities are currently used to mimic the irradiation conditions that PFM have to withstand in a nuclear fusion reactor . These devices produce a few shots per day with low repetition rate.

On this frame, a table top plasma source is highly desirable to reproduce the equivalent irradiation conditions to test PFM for fusion reactors.

Previous work on effects of pulsed radiation on materials of interest for nuclear fusion reactors

3 plasma focus devices (2kJ, 400J, 2J) were used to irradiate materials under equivalent condition than the expected in ITER and IFE.



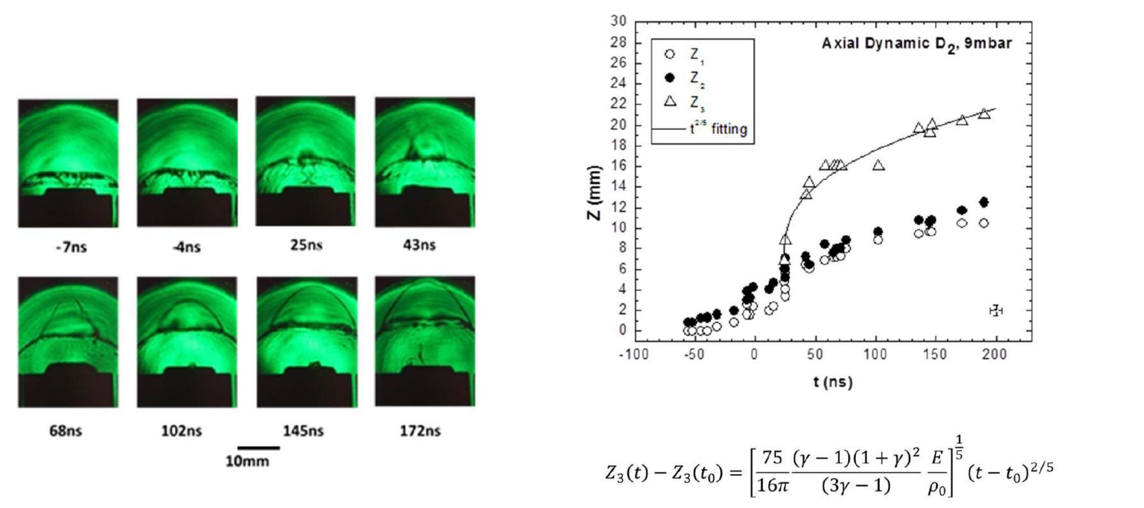
Damage factor: F ~ q·τ½ = E/Sτ½

q: power flux, τ: interaction time, S: interaction area

Plasma bursts after the pinch

Previous studies did not pay atention after the pinch disruptions

PF- 400J **D_2 9mbar**



L. Soto, C. Pavez, J. Moreno, M. J. Inestrosa, F. Veloso, G. Gutierrez, J. Vergara, F. Castillo, A. Clausse, H. Bruzzone and L. Delgado-Aparicio, Physics of Plasmas 21, 122703 (2014)

Damage Factor produced by Plasma bursts after the pinch

PF- 400J

Total mass inside the bubble, m: ~ total pinch mass

(the pinch is ejected trough Z2, creating so the bubble)

The pinch density was previously measured using pulsed interferometry, thus the total pinch mass is **m ~ 1.5×10^{-10} kg**

C. Pavez and L. Soto, Physica Scripta T131, 014030 (2008)

Energy of the axial ejected plasma: ½ mv²

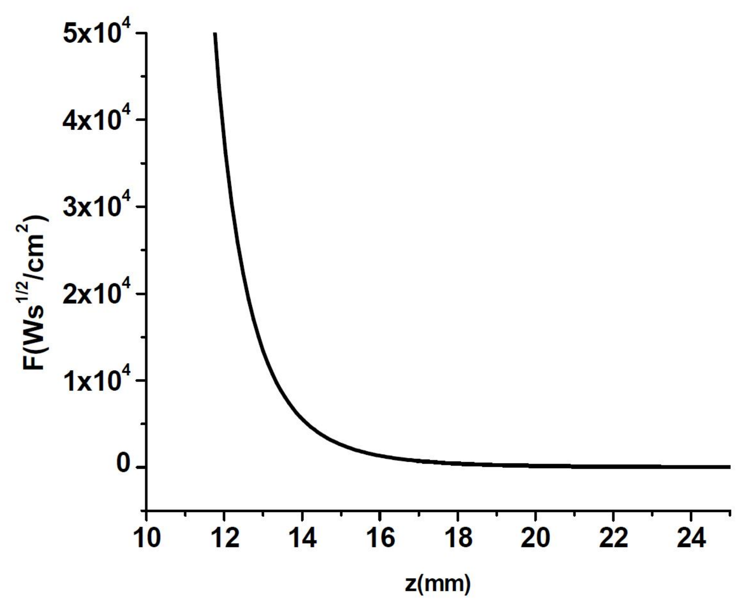
Length of the ejected mass: ~ pinch length, L = 5.6 mm

Time of interaction, τ ~ L / v

Interaction area, S, is measured from images of irradiated samples

Tunable Damage Factor

PF-400J



Expected Damage in Fusion Reactor

ITER:

$$F \sim q\cdot\tau^{1/2} \sim 10^8 (W/m^2)\ s^{1/2} = 10^4 (W/cm^2)\ s^{1/2}$$

at 0.5 – 1 Hz , 10^3 pulses

IFE:

$$F \sim q\cdot\tau^{1/2} \sim 10^4 (W/cm^2)\ s^{1/2}$$

at 10 Hz

PF-400J:

$$F \sim q\cdot\tau^{1/2} \sim 10^3 - 10^5 (W/cm^2)\ s^{1/2}$$

at 0.05 Hz

6 order of magnitud in energy translates in only 1 order of magnitude in damage factor

damage factor, $F \sim q\cdot\tau^{1/2} \propto \tau^{1/2} \propto a^{1/2} \propto (E^{1/3})^{1/2}$

The damage factor F scale with the energy device as $F \propto E^{1/6}$

PF, 1MJ	**F**
PF, 1kJ	**~ 1/3 F**
PF, 100J	**~ 1/5 F**
PF, 10J	**~ 1/7 F**
PF, 1J	**~ 1/10 F**

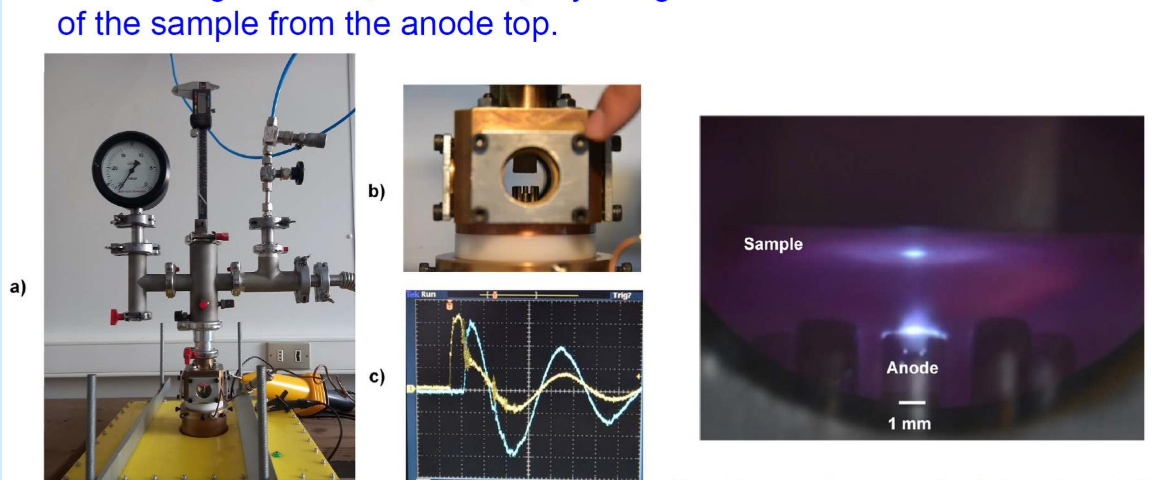
Roughly speaking

The damage factor for the PF-1000 (1MJ) at Poland is only 3.65 times greater than the damage factor for the PF- 400J (400J) at Chile.

L. Soto et al, in preparation

Plasma focus PF-2J with tuneable damage factor F

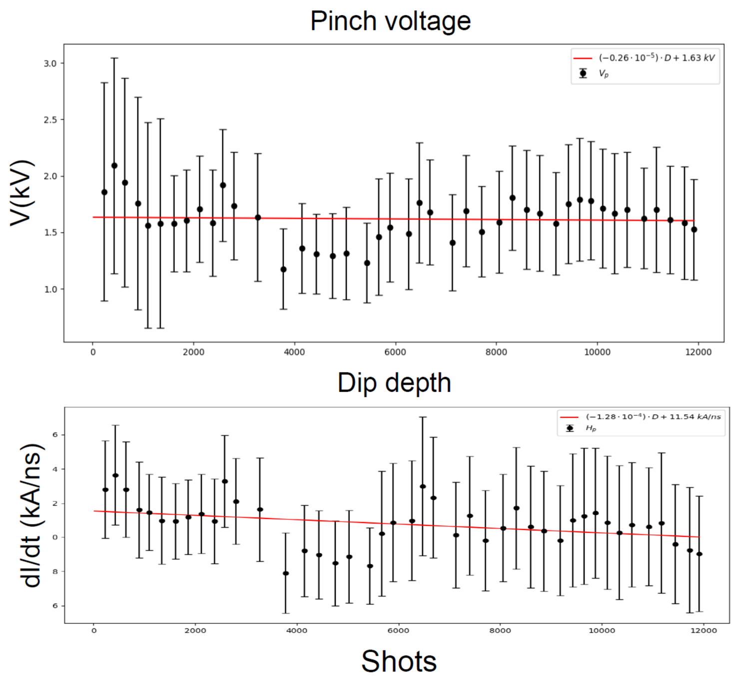
The damage factor F, is tune in, adjusting the distance of the sample from the anode top.



a) The whole device, including the X, Y, Z positions for materials samples. In the axis Z is a micro positioner. b) Discharge chamber details, cathode bars and anode at center. Over the anode is the sample holder that is axially adjusted. c) Electrical signals, voltage and current derivative for a discharge in hydrogen at 6 mbar.

Time integrated photograph of a single discharge in the PF-2J. It can see plasma on the top of the anode (anode diameter 2.2mm). Also a bright spot it can see in the sample located over de anode due to the axial plasma shock interacting with the sample.

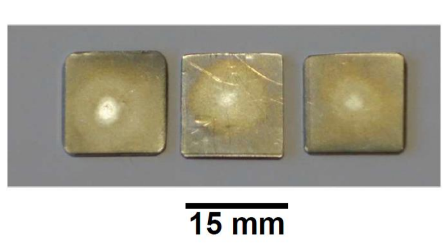
Performance analysis from electrical signals

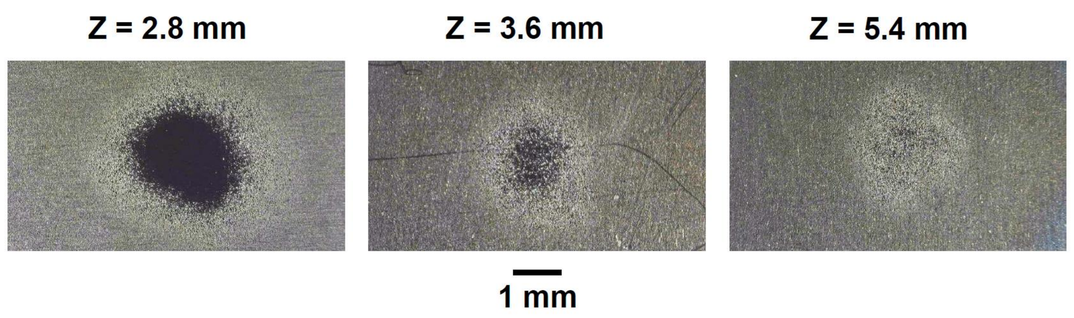


The life cycle for the pinch plasma voltage and for the depth in the current derivative signal is more than 1×10^4 without changes in the voltage pinch and with a decrease of 10% in the depth dip of the current derivative.

Plasma focus PF-2J with tuneable damage factor F

AISI 304 **100 shots** **0.1 Hz**



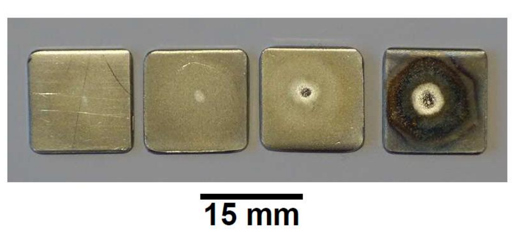


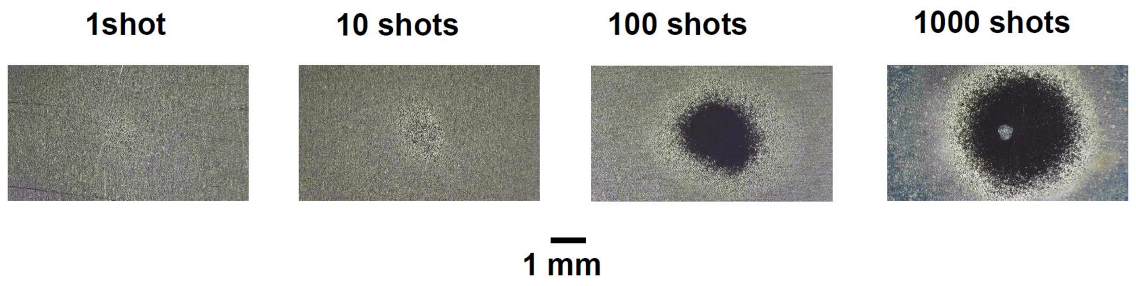
$F\sim10^4 (W/cm^2)\ s^{1/2}$ — $F\sim10^3 (W/cm^2)\ s^{1/2}$ — $F\sim10^2 (W/cm^2)\ s^{1/2}$

Plasma focus PF-2J with tuneable damage factor F

AISI 304 **Z = 2.8 mm** **0.1 Hz**

$F\sim10^4 (W/cm^2)\ s^{1/2}$





Conclusions

- A very small PF devices working at only 2J was designed constructed and tested as a tunable damage factor irradiator.
- Thousands shots are possible to obtain in 5 hours using the PF-2J at 0.1Hz
- A better calibration of the damage factor for plasma focus devices is required. The determination of the irradiation area is critical and also the radial dependence of the power flux on the sample.

Acknowledgments

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