The Concept of Plasma Focus driven Fusion-Fission Hybrid Reactors

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Outline

- Brief introduction about Chile, lithium and Chilean Nuclear Energy Commission.
- What is a Plasma Focus device.
- Fu-Fi hybrid nuclear reactors. Background facts.
- The concept of Plasma Focus driven fusion-fission hybrid reactors.
- Remarks and conclusions.

South America
Chile

P^{2}mc

Lithium brines in Chile, Bolivia and Argentina

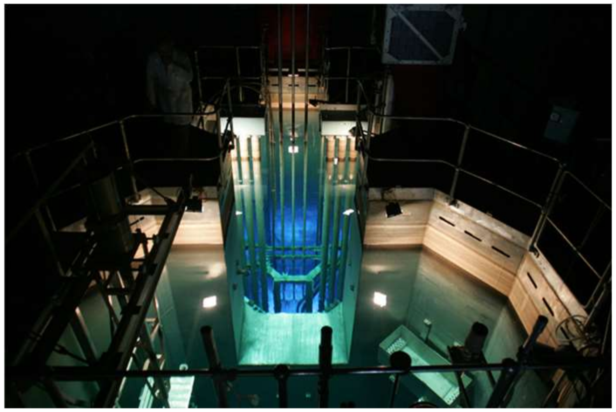
World lithium brines reserves

85% in South America
39% in Chile

Atacama, Chile

lithium carbonate

Main facilities at the Chilean Nuclear Energy Commission

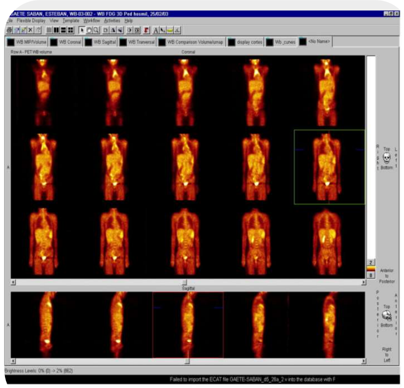


6 MW FISSION REACTOR

- Radioisotopes for medicine

CICLOTRÓN

-Flúor 18-FDG
-Flúor 18-NaF



FUEL ASSEMBLY PLANT

Plasma Physics and Nuclear Fusion at the Chilean Nuclear Energy Commission

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- **Plasma physics related with thermonuclear fusion in Z-pinches:**
  - Stability in gas embedded Z-pinch at MA currents
  - Plasma foci: increasing the plasma energy density in order to increase the thermonuclear neutron yield.
- **Miniaturization of Plasma Focus devices:**
  - Nanoflashes of radiation from miniaturized devices.
  - Scaling studies
- **Other pinch configuration:**
  - Wires arrays
- **Effects of pulsed radiation on materials**
  - First wall materials for fusion reactors
- **Effects of pulsed radiation on biological objects**
  - Cancer treatment
- **Low temperature plasmas (RF and continuous discharges)**
  - Plasma Torch for materials environment applications
  - Plasma needles for biomedicine applications
  - Scaling studies
- **Theoretical studies**
  - Statistical mechanics in non canonical systems
- **Main diagnostics:**
  - Electrical signals
  - Visible plasma images, ICCD, 4ns to 100ns gated frame
  - Optical Refractive diagnostics, Nd-YAG laser: 8ns, 1J; 170ps, 100mJ
  - Neutrons detecton (in particular low yield pulses)
  - X-rays detection (with spatial en temporal resolution
  - Ions detection
  - Espectroscopy (visible, VUV and soft X- rays)
  - UHV radiation detection and analysis
  - Material characterization

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Plasma Physics and Nuclear Fusion at the Chilean Nuclear Energy Commission

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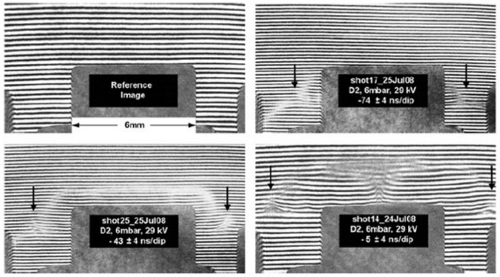
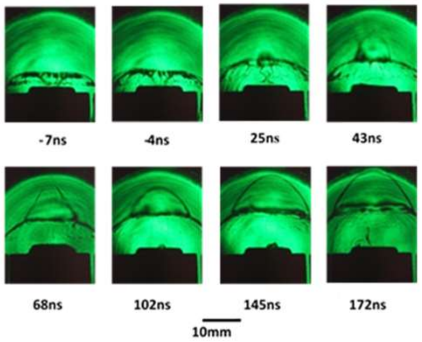
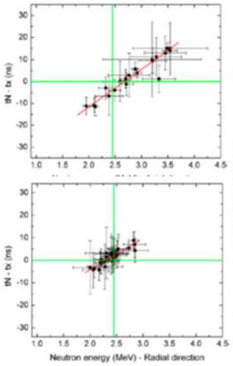
Basic Physics



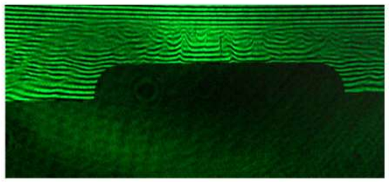
Toroidal singularity



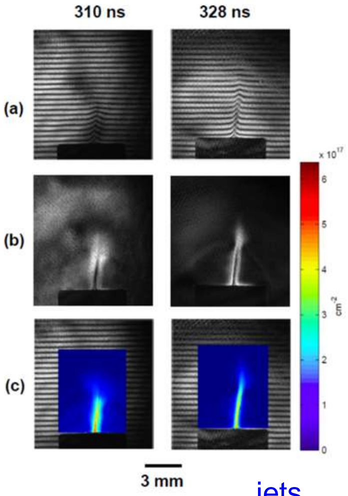
shocks



neutron energy distribution

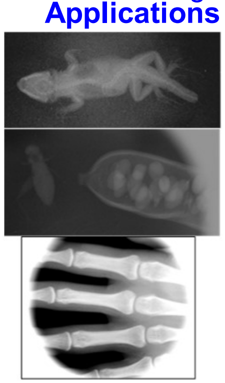


fillaments

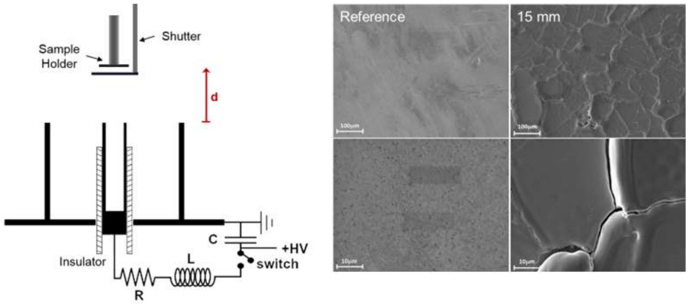


jets

Applications

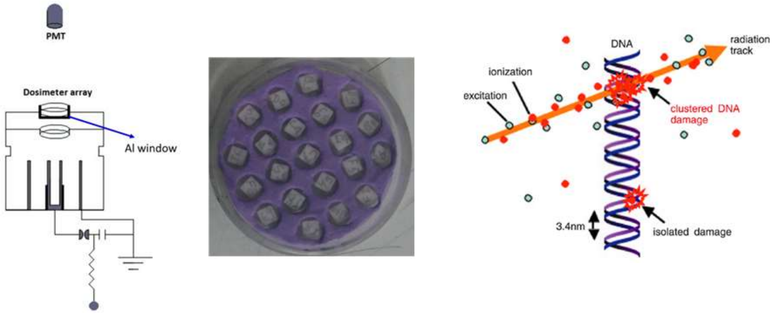


Pulsed x-ray and neuron sources



Effects on materials for 1st wall of nuclear fusion reactors

Plasma torch 20kW and microtorch 2 milliwats for materials and matter proccesing



Effects of pulsed radiation in life matter

Pulsed plasma thruster for nanosatelites

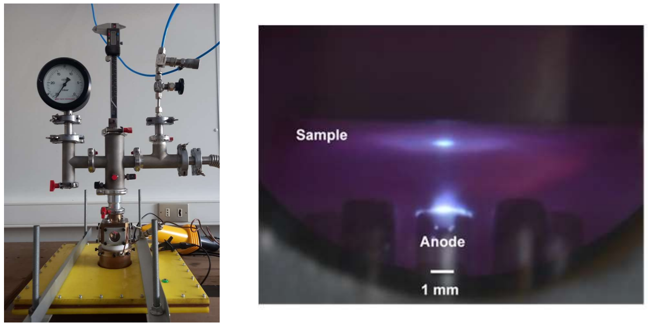


Table top plasma focus with tuneable damage factor F

Relevant publications

- “Transient Electrical Discharge in Small Devices” (Invited paper, ICPP 2000 and APS Plasma Division 2000), Leopoldo Soto, Andrey Esaulov, José Moreno, Patricio Silva, Gustavo Sylvester, Marcelo Zambra, Andrey Nazarenko, and Alejandro Clausse. Physics of Plasma 8, 2572 (2001).
- “A Plasma Focus Driven by a Capacitor Bank of Tens of Joules” Patricio Silva, Leopoldo Soto, José Moreno, Gustavo Sylvester, Marcelo Zambra, Luis Altamirano, Horacio Bruzzone, Alejandro Clausse, and César Moreno, Review of Scientific Instruments 73, 2583 (2002).
- “Neutron Emission from a Fast Plasma Focus of 400 Joules”, P. Silva, J. Moreno, L. Soto, L. Birstein, R. Mayer, W. Kies, Applied Physics Letters 83, 3269 (2003)
- “Pinch evidence in a fast and small plasma focus of only tens of joules”, P. Silva, L. Soto, W. Kies and J. Moreno, Plasma Sources Science and Technology 13, 329 (2004).
- “Dense transient pinches and pulsed power technology. Research and applications using medium and small devices” Leopoldo Soto, Cristian Pavez, Jose Moreno, Miguel Cárdenas, Ariel Tarifeño, Patricio Silva, Marcelo Zambra, Luis Huerta, Jorge Ramos, Rodrigo Escobar, Claudio Tenreiro, Miguel Lagos, Cesar Retamal, J. Luis Giordano and Luis Altamirano (Invited paper, XII Latin American Workshop on Plasma Physics), Physica Scripta T131, 014031 (2008)
- “System for measurements of low yield neutron pulses from D-D fusion reactions based upon a ^{3}He proportional counter”, J. Moreno, L. Birstein, R. Mayer, P. Silva, L. Soto, Meas. Sci. and Technol. 19, 087002 (2008)
- “Demonstration of neutron production in a table top pinch plasma focus device operated at only tens of joules”. Leopoldo Soto, Patricio Silva, José Moreno Moreno, Marcelo Zambra, Walter Kies, Roberto E. Mayer, Alejandro Clausse, Luis Altamirano, Cristian Pavez, and Luis Huerta J. Phys. D: App. Phys. 41, 205215 (2008).
- "Motion of a red blood cell in interference filed", Luis Alfredo Viera, Ignacio Lira, Leopoldo Soto, and Cristian Pavez, Optics Communications 282, 64 (2009)
- “Nanofocus: ultra-miniature dense pinch plasma focus device with submillimetric anode operating at 0.1J”, Leopoldo Soto, Cristian Pavez, José Moreno, Mario Barbaglia, and Alejandro Clausse, Plasma Sources Sci. and Technol. 18, 015007 (2008)
- “Experimental study of the hard x-ray emissions in a Plasma Focus of hundreds of Joules", Mario Barbaglia, Horacio Bruzzone, H. Acuña, Leopoldo Soto and Alejandro Clausse, Plasma Physics and Controlled Fusion 51, 045001 (2009).
- “Numerical experiments on plasma focus neutron yield versus pressure compared with laboratory experiments”, S. Lee, S. H. Saw, L. Soto, S. V. Springham, S. P. Moo, Plasma Physics and Controlled Fusion 51, 075006 (2009).
- “Experimental results on hard x-ray energy emitted by a low energy plasma focus device: a radiographic image analysis”, M. Zambra, P. Silva, M. Moreno, C. Pavez and L. Soto, Plasma Physics Controlled Fusion 51, 125003 (2009)
- “Demonstration of x-ray Emission from an ultraminiature pinch plasma focus discharge operating at 0.1 J. Nanofocus”, Cristian Pavez and Leopoldo Soto, IEEE Trans. Plasma Science, 38, 1132 (2010).
- “Studies on scalability and scaling laws for the plasma focus: similarities and differences in devices from 1MJ to 0.1J”, Leopoldo Soto, Cristian Pavez, Ariel Tarifeño, José Moreno and Felipe Veloso, Plasma Sources Sci. and Technol. 19, 055017 (2010).
- “Dynamics and Density Measurements in a Small Plasma Focus of Tens of Joules Emitting Neutrons”, Ariel Tarifeño, Cristian Pavez, José Moreno and Leopoldo Soto, IEEE Trans. Plasma Science, 39, 756 (2011)
- “Dependence of hard x-ray emissions with the charging pressure in a small Plasma Focus” M. Barbaglia, L. Soto and A. Clausse, Journal of Fusion Energy 31, 105 (2012). (DOI 10.1007/s10894-011-9455).
- “Toroidal high-density singularities in a small Plasma Focus”, Federico Casanova, Ariel Tarifeño-Saldivia, Felipe Veloso, Cristian Pavez, Leopoldo Soto and Alejandro Clausse, Journal of Fusion Energy 31, 279 (2012). (DOI 10.1007/s10894-011-9469-1)
- “Correlations among neutron yield and dynamical discharge characteristics obtained from electrical signals in a 400 joules plasma focus”, Felipe Veloso, Cristian Pavez, Jose Moreno, Victor Galaz, Marcelo Zambra and Leopoldo Soto, Journal of Fusion Energy 31, 30-37 (2012). (DOI 10.1007/s10894-011-9429-9)
- “Modelling of the internal dynamics and density in a tens of joules plasma focus device”, Ariel Marquez, José Gonzalez, Ariel Tarifeño-Saldivia, Cristian Pavez, Leopoldo Soto y Alejandro Clausse, Physics of Plasmas 19, 012703 (2012)
- “Non-intrusive plasma diagnostics for measuring sheath kinematics in plasma focus discharges”, Felipe Veloso, José Moreno, Ariel Tarifeño-Saldivia, Cristian Pavez, Marcelo Zambra and Leopoldo Soto, Meas. Sci. And Technol. 23, 087002 (2012)
- “Plasma sheath kinematics and some implications on the modeling of very low energy plasma focus”, Felipe Veloso, José Moreno, Ariel Tarifeño-Saldivia, Cristian Pavez, Marcelo Zambra and Leopoldo Soto, Plasma Phys. and Control. Fusion. 54, 095007 (2012)
- “Potentiality of a small and fast dense plasma focus as hard x-ray source for radiographic applications”, C Pavez, J. Pedreros, M Zambra, F Veloso, J Moreno, A Tarifeño-Saldivia and L. Soto, Plasma Phys. and Control. Fusion. 54 105018 (2012).
- “Statistical characterization of the reproducibility of neutron emission of small plasma focus devices” Ariel Tarifeño-Saldivia and Leopoldo Soto, Physics of Plasmas 19, 092512 (2012)
- “Digital interferometry applied to transient dense plasmas”, Cristian Pavez, José Pedreros, Carlos Curín, Gonzalo Muñoz, and Leopoldo Soto, IEEE Trans. Plasma Science 40, 3384 (2012)
- “Drive parameter of neutron-optimized dense plasma foci”, Daniel Klir and Leopoldo Soto, IEEE Trans. Plasma Science 40, 3273 (2012)
- “Electrical behavior of an ultralow-energy plasma focus”, M. O. Barbaglia, H. Bruzzone, H. N. Acuña, L. Soto and A. Clausse, IEEE Trans. Plasma Sci. 42, 138 (2014)
- “Calibration methodology for proportional counters applied to yield measurements of a neutron burst”, A. Tarifeño-Saldivia, R. E. Mayer, C. Pavez and L. Soto, Rev. Sci. Instrum. 85, 013502 (2014)
- “Observation of the partial reheating of the metallic vapor during the wire explosion process for nanoparticle synthesis”, B. Bora, S. S. Kausik, C. S. Wong, O. H. Chin, S. L. Yap, and L. Soto, Applied Physics Letters 104, 223108 (2014)
- “Filamentary structures in dense plasma focus: current filaments or vortex filaments”, Leopoldo Soto, Cristian Pavez, Fermin Castillo, Felipe Veloso, José Moreno, and S. K. H. Auluck, Physics of Plasmas 21, 072702 (2014)
- “Influence of finite geometrical asymmetry of the electrodes in capacitively coupled radio frequency plasma”, B. Bora and L. Soto, Physics of Plasmas 21, 083509 (2014)
- “Effects of gas chamber geometry and gas flow on the neutron production in a fast plasma focus neutron source”, A. Tarifeño-Saldivia and L. Soto, Plasma Physics and Controlled Fusion 56, 125013 (2014).
- “Characterization of the axial plasma shock in a table top plasma focus after the pinch and its possible application to testing materials for fusion reactors”. L. Soto, C. Pavez, J. Moreno, M. J. Inestrosa-Izurieta, F. Veloso, G. Gutiérrez, J. Vergara, A. Clausse, H. Bruzzone, F. Castillo, and L. F. Delgado-Aparicio, Physics of Plasma 21, 122703 (2014)

Relevant publications

- “Feasibility study of a hybrid subcritical fission system driven by Plasma-Focus fusion neutrons”, Alejandro Clausse, Leopoldo Soto, Carlos Friedli and Luis Altamirano, Annals of Nuclear Energy 78, 10-14 (2015)
- “Influence of the Anode Length on the Neutron Emission of a 50 J Plasma Focus: Modeling and Experiment”, Alejandro Clausse, Leopoldo Soto, and Ariel Tarifeño-Saldivia, IEEE Trans. Plasma Sci. 43, 629 (2015)
- “Neutron energy distribution and temporal correlations with hard X-ray emission from a hundred of joules plasma focus devices”, J. Moreno, F. Veloso, C. Pavez, A. Tarifeño-Saldivia, D. Klir, and L. Soto, Plasma Phys. Control. Fusion 57, 035008 (2015)
- “Observations of plasma jets in a table top plasma focus discharge” C. Pavez, J. Pedreros, A. Tarifeño Saldivia and L. Soto, Physics of Plasmas 22, 040705 (2015)
- “Morphological and structural effects on tungsten targets produced by fusion plasma pulses from a table top plasma focus” M.J. Inestrosa-Izurieta, E. Ramos-Moore and L. Soto, Nuclear Fusion 55, 093011 (2015)
- “Evidence of nuclear fusion neutrons in an extremely small plasma focus device operating at 0.1 Joules”, Leopoldo Soto, Cristian Pavéz, José Moreno, Luis Altamirano, Luis Huerta, Mario Barbaglia, Alejandro Clausse, and Roberto E. Mayer, Physics of Plasmas 24, 082703 (2017)
- “Hundred joules plasma focus device as a potential pulsed source for in vitro cancer cell irradiation”, J. Jain, J. Moreno, R. Andaur, R. Armisen, D. Morales, K. Marcelain, G. Avaria, B. Bora, S. Davis, C. Pavez, and L. Soto, AIP Advances 7, 085121 (2017);
- “Electromagnetic Burst Measurement System Based on Low Cost UHF Dipole Antenna” Ismael Escalona, Gonzalo Avaria, Marcos Díaz, Jorge Ardila-Rey, José Moreno, Cristian Pavez and Leopoldo Soto, Energies 10, 1415 (2017)
- “Observation and interpretation of neutron origin prior to hard x-rays and pinch in a hundred joules plasma focus device”, J. Jain, J Moreno, D Morales, S Davis, B Bora, G Avaria, M J Inestrosa-Izurieta and L Soto, Laser and Particle Beams 35, 656 (2017)
- “Understanding the Ti film deposition process of a plasma focus by an experimental design”, Inestrosa-Izurieta, J. Moreno, S. Davis and L. Soto, AIP Advances 7, 105026 (2017)
- “Electrical and Optical Characterization of Plasma Needle to be Used for Biomedical Applications”, B. Bora, A. Aguilera, J. Moreno, J. Jain, C. Pavez, G. Avaria, M.J. Inestrosa-Izurieta, S Davis and L. Soto, Plasma Medicine 7, 417 (2017)
- “Development, Characterizations and Applications of a Hand Touchable DC Plasma Needle for Bio-Medical Investigation”, B. Bora, A. Aguilera, J. Jain, G. Avaria, J. Moreno, and L. Soto, IEEE Trans. Plasma Science 46, 1768 (2018)
- “Differential miRNA expression profiling reveals miR-205-3p to be a potential radiosensitizer for low- dose ionizing radiation in DLD-1 cells”, Rodrigo Andaur, Julio C. Tapia, José Moreno, Leopoldo Soto, Ricardo Armisen and Katherine Marcelain, Oncotarget 9, 26387 (2018)
- “Energetics X-ray Burst Observation in the Collapse of a X-pinch Conducted in a Small Capacitive Generator of Low Impedance”. C. Pavez, A. Sepúlveda, N. Cabrini, J. Pedreros, G. Avaria, P. San Martin, and L. Soto, IEEE Transactions on Plasma Science 46, 3829 (2018) https://doi.org/10.1109/TPS.2018.2876283
- “A Methodology for the Digital Reconstruction of an Interferogram, a Schlieren Image, or a Shadowgram from a Single Digital Holographic Recording”. C. Pavez, J. Pedreros, G. Avaria, B. Bora, J. Moreno, and L. Soto. Review of Scientific Instruments, 89, 123103 (2018); https://doi.org/10.1063/1.5023388
- “Hard X-ray emission detection using deep learning analysis of the radiated UHF electromagnetic signal from a Plasma Focus discharge”, G. Avaria, J. Ardila-Rey, S. Davis, L. Orellana, B. Cevallos, C. Pavez and L. Soto, IEEE Access 7, 74899 (2019), https://doi.org/10.1109/ACCESS.2019.2921288
- “Single-particle velocity distributions of collisionless, steady-state plasmas must follow Superstatistics”, Sergio Davis, Gonzalo Avaria, Biswajit Bora, Jalaj Jain, José Moreno, Cristian Pavez, Leopoldo Soto; Physical Review E 100, 023205 (2019);
- “On the Relationship Between the Electromagnetic Burst and Inductive Sensor Measurement of a Pulsed Plasma Accelerator” L. Orellana, J. Ardilla-Rey, G. Avaria, M. A. Diaz, C. Pavez, R. Schurch, and L. Soto, IEEE Access 7, 133043 (2019)
- “Experimental evidence of more than one ions acceleration mechanisms in plasma focus device: Observations and interpretations”, Jalaj Jain, José Moreno, Sergio Davis, Biswajit Bora, Cristian Pavez, Gonzalo Avaria, and Leopoldo Soto, Physics of Plasmas 26, 103105 (2019)
- “Experimental measurements of high-energy photons in X-rays pulses emitted from a hundred joules plasma focus device and its interpretations”, J Jain, J Moreno, S Davis, B Bora, C Pavez, G Avaria, L Soto, Results in Physics 16, 102915 (2020)
- “Materials studies for inertial fusion devices using pulsed plasma shocks from a repetitive table top plasma focus device”, L. Soto, C. Pavez, S. Davis, IAEA-TECDOC-1911 (2020).
- “A model for defect formation in materials exposed to radiation”, Sergio Davis, Felipe González-Cataldo, Gonzalo Gutiérrez, Gonzalo Avaria, Biswajit Bora, Jalaj Jain, José Moreno, Cristian Pavez, and Leopoldo Soto, Matter and Radiation at Extremes 6, 015902 (2021); https://doi.org/10.1063/5.0030158
- “A Repetitive Tabletop Pulsed Plasma Device to Study Materials under Intense Fusion Relevant Pulses”, Leopoldo Soto, Daniel Zanelli, Jalaj Jain , Cristian Pavez, José Moreno, Biswajit Bora, and Sergio Davis, 27 IAEA Fusion Energy Conference 2020, Virtual, May 10-15, 2021
- “Influence of electrode geometry on x-ray emission, plasma inductance, voltage, and current derivative signals obtained from a plasma focus device”, Jalaj Jain, Jose Moreno, Biswajit Bora, and Leopoldo Soto, Results in Physics 23, 104016 (2021);
- “Hyper-radiosensitivity in tumor cells following exposure to low dose pulsed x-rays emitted from a kilojoule plasma focus device”, Jalaj Jain, Hector Araya, Jose Moreno, Sergio Davis, Rodrigo Andaur, Biswajit Bora, Cristian Pavez, Katherine Marcelain, Leopoldo Soto, Journal of Applied Physics 130, 164902 (2021); https://doi.org/10.1063/5.0060710
- “Update on the Scientific Status of the Plasma Focus”, Sunil Auluck, Pavel Kubes, Marian Paduch, Marek J Sadowski, Vyacheslav I Krauz, Sing Lee, Leopoldo Soto, Marek Scholz, Ryszard Miklaszewski, Hellmut Schmidt, Alexander Blagoev, Maurizio Samuelli, Yeow Sing Seng, Stuart Victor Springham, Alireza Talebitaher, Cristian Pavez, Mohammad Akel, Seong Ling Yap, Rishi Verma, Karel Kolacek, Paul Lee Choon Keat, Rajdeep S Rawat, Ali Abdou, Guixin Zhang, Tõnu Laas, Plasma 4, 450-669 (2021)

The plasma focus discharge

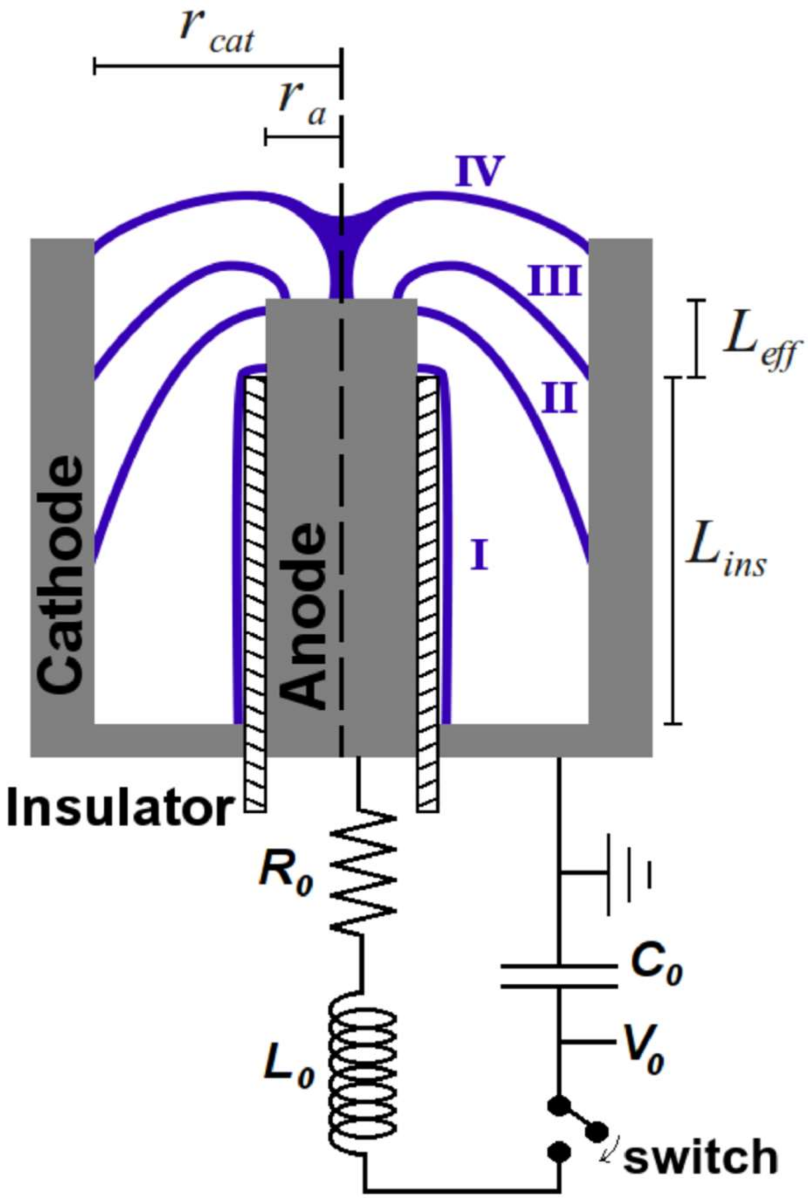
The Mather Plasma Focus (PF) is a transient electrical discharge produced in arranged coaxial electrodes, separated by an insulator, and driven typically by a capacitive pulsed power generator, which is controlled by a spark-gap switch.

(I) The discharge starts over the insulator.

(II) The Lorentz force pushes the plasma sheet to move axially.

(III) and then to move radially.

(IV) Finally the sheet collapses to form a dense column of plasma (pinch). During these stage, when operating with deuterium, hard X-rays and neutron are generated.



The plasma focus discharge

$E \sim 0.1J - MJ$

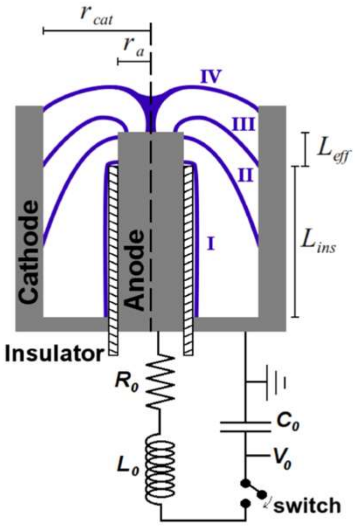
$I \sim 100kA - 1MA$

$t_p \sim 1ns - 100ns$

$Y_n \alpha E^2$

$Y_n \alpha I^{3.3\text{-}4.7}$

$n \sim 10^{25}\ m^{-3}$



- The plasma focus has the special feature that is a self-scale kind of z-pinch. For devices in the energy range 1MJ to 0.1J of stored energy optimized for neutron emission:
  - axial rundown velocity and radial compression velocity has practically the same value, being $4x10^4$ m/s to $1x10^5$ m/s and $1x10^5$ m/s to $2x10^5$ m/s respectively
  - same ion plasma density in the pinch in the order of 10^{24} m^{-3} to 10^{25} m^{-3}
  - same magnetic field in the pinch edge of order of 10 to 20 T
  - same Alfvén estimated to be above $1x10^5$ m/s
  - same temperature ~ 0.5 to 1keV.

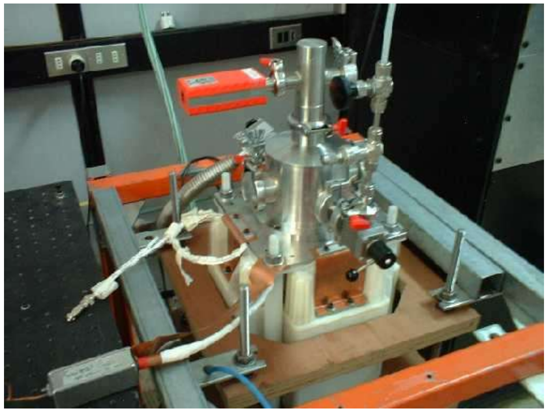
L. Soto et al., Plasma Sources Sci. Technol. 19,055017 (2010).

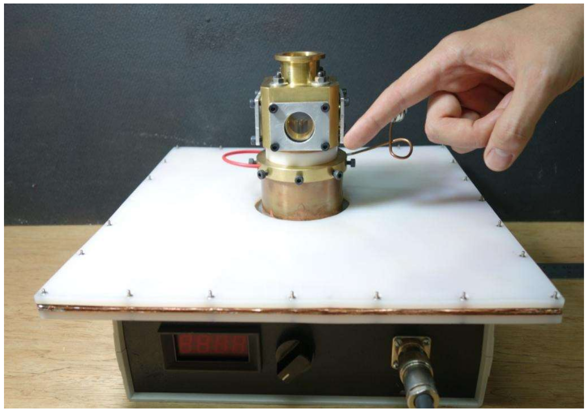
- Axial plasma shocks from table top plasma focus produce the same damage factor in materials than the expected in ITER and IFE.

L. Soto et al., Physics of Plasmas 21, 122703 (2014)
M. J. Inestrosa Izurieta et al., Nuclear Fusion 55, 093011 (2015)
S. Davis et al., Matter and Radiation at Extremes 6, 015902 (2021)

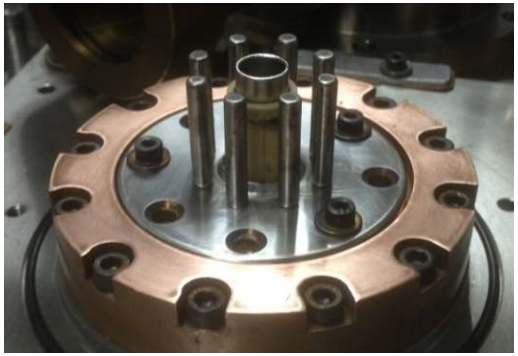
PF devices at CCHEN

kJ and under kJ

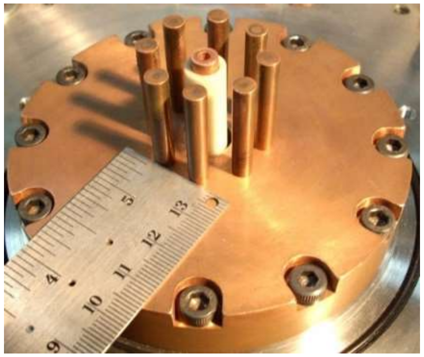




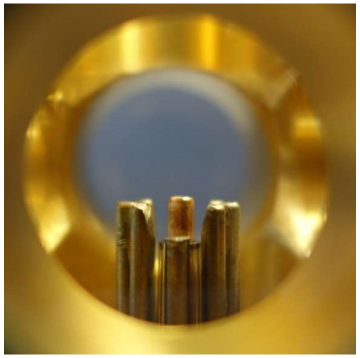
PF-2kJ, 180kA



PF-400J, 130kA



PF-50J, 60kA



PF-2J, 15kA

PF- SPEED 2
187kJ, 4MA

The Concept of Plasma Focus driven Fusion-Fission Hybrid Reactors

Fu-Fi hybrid nuclear reactors. Background facts

- The concept of Fusion-Fission Hybrid Reactor involves a subcritical fission reactor driven by the neutrons generated in a nuclear-fusion device
- It was proposed already in the 1950s. Thus, the concept taken up in the 1970s (Hans Bethe 1979).
- Then interest declined, due to lack of economic incentive rather than technical difficulties.
- But it has increased over the last two decades because of its possible use in energy production, whether with uranium 235 or "breeding" uranium 233 from thorium, and also for the destruction of radioactive waste.

Central Idea and Feasibility

- Concept: surrounding a source of neutrons produced by fusion, with fissile material, so that it would function as a sub-critical reactor.
- Synthesis of the fission reactor. For safety and control it is usual to limit the effective multiplication factor at most to about 0.95 in thermal reactors, which greatly limits the amplification factor. This limit was overcome with the concept of a cascade reactor introduced at the beginning of the fifties, being still sub-critical the reaction.
- There is still no general consensus on which would be the optimum fusion device that can be used as neutron source to feed the subcritical cascades. There are energetic, economic, and geometrical constraints which should be considered and balanced; but recent theoretical studies suggest that simplicity and volume would be the key concepts. Among the possible candidates to comply with these requirements, Plasma Focus (PF) devices have emerged as a very interesting alternative, bringing about the concept of Plasma-Focus driven Fusion-Fission Hybrid Reactors (PF-FFHR).

Central Idea and Feasibility

- There are a few studies that entertained the idea of using a PF device as the seed of neutrons for a hybrid fusion–fission system (Gribkov and Tyagunov, 1983; Zoita and Lungu, 2001). Those studies analyzed the simplest array of a single subcritical region hosting a PF device, concluding that, achieving break-even conditions would require energies as high as 10 MJ capable of deliver currents of 20 MA in 1 μs to produce pulses of 10^{18} neutrons. Alas, that sort of figure is out of the range of the current technology. In effect, although since their invention 50 years ago several projects were carried out to push higher the upper energy limit of PF facilities, the neutron production ceases to increase beyond 1 MJ (Nukulin and Polukhin, 2007; Lee, 2009).

Our approach

Details in A. Clausse, L. Soto, C. Friedli and L. Altamirano "Feasibility study of a hybrid subcritical fission system driven by Plasma-Focus fusion neutrons", Annals of Nuclear Energy 78, 10-14 (2015)

- In this work our approach consists in a "Cascade Fission Nuclear Reactor Maintained by Fusion Neutrons from a Central Plasma Focus (PF)"
- The analysis starts from the model of a two-stage cascade presented by Barzilov et al. (1996), which is here specified for a spherical geometry, deriving a set of equations to assess the neutronic amplification in terms of the geometric parameters.
- The occurrence of optimum configurations is determined here for two spherical fission blankets, varying the size of each region while keeping constant the total volume of the system.

Cascade Fission Nuclear Reactor Maintained by Fusion Neutrons from a Central Plasma Focus (PF)

- It consists of two multiplicative sections whose coupling is not symmetrical, so that neutrons produced in the first section easily penetrate the second while those produced in the second have little effect on the first (see Figures 1 and 2)
- Selective absorption and geometric arrangement are used to approach the ideal cascade (in which the feedback from the region 2 is null). And the design of section 1 generates faster neutrons, that can reach the 2, where they are multiplied and, being greater its moderation there, they become more thermal. But these hardly reach the region 1 through an absorbent of the thermal. On the other hand, figure 1 shows how the geometry also collaborates in this.
- A sustained oscillatory regime is produced by a periodic train of neutron pulses from the central PF, amplified in the two fission sections, each treated, as already said, analytically and numerically with diffusion equations of a single neutron-group, and corroborated the results with Monte Carlo calculations.

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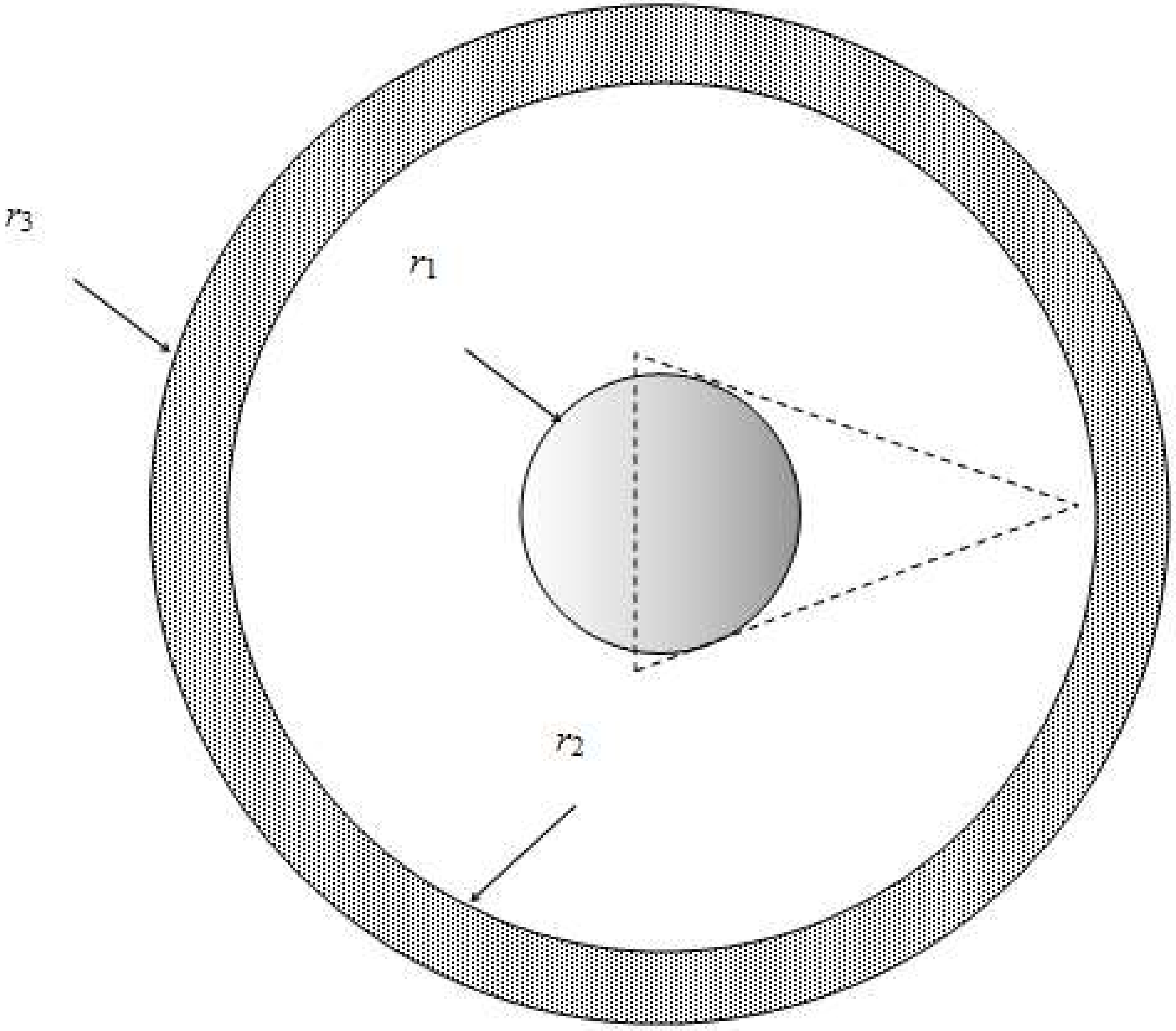

Figure 1. Spherical cascade diagram consisting of a central multiplicative core surrounded by a multiplicative spherical shell.

Neutron-monogroup equations, both prompt and delayed, governing the density C(x, t) of the precursor atoms and that of neutrons n(x, t)

$$\frac{\partial n}{\partial t} - Dv\,\nabla^2 n = -\Sigma_a v\,n + (1-\beta)\,\bar{\upsilon}\,\Sigma_f v\,n + \lambda C + S$$

$$\frac{\partial C}{\partial t} = -\lambda C + \beta\bar{\upsilon}\,\Sigma_f v n$$

The spatial distribution of neutrons is described with the Helmholtz equation:

$$\nabla^2 n + B^2 n = 0$$

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Analytical results for the cascade, from the neutron-monogroup model and the geometric configuration of the hybrid system

Analytical expressions are obtained for the amplification factor M, the asymmetry ε and the coupling c, which have been defined, respectively, by:

$$M = \frac{F_1 + F_2}{S_1 + S_2} \qquad \varepsilon = \frac{S_1}{S_1 + S_2} \qquad c = \frac{\left(\frac{1}{p_1} - \frac{k_{\infty 1}}{k}\right)\left(\frac{1}{p_2} - \frac{k_{\infty 2}}{k}\right)}{\left(\frac{1}{p_1} - 1\right)\left(\frac{1}{p_2} - 1\right)}$$

In these relationships:

- M is the total number of fission neutrons per neutron inserted by the sources.
- F_1 and F_2 are the number of fission neutrons produced in regions 1 and 2, respectively.
- S_1 and S_2 are the densities of the neutrons that enter per second in 1 and 2, respectively.
- p_1 and p_2 are the probabilities that neutrons *will NOT come out* from 1 and 2, respectively.
- k, $k_{\infty 1}$, and $k_{\infty 2}$ are the total effective, and the infinite multiplication factors of regions 1 and 2, respectively.

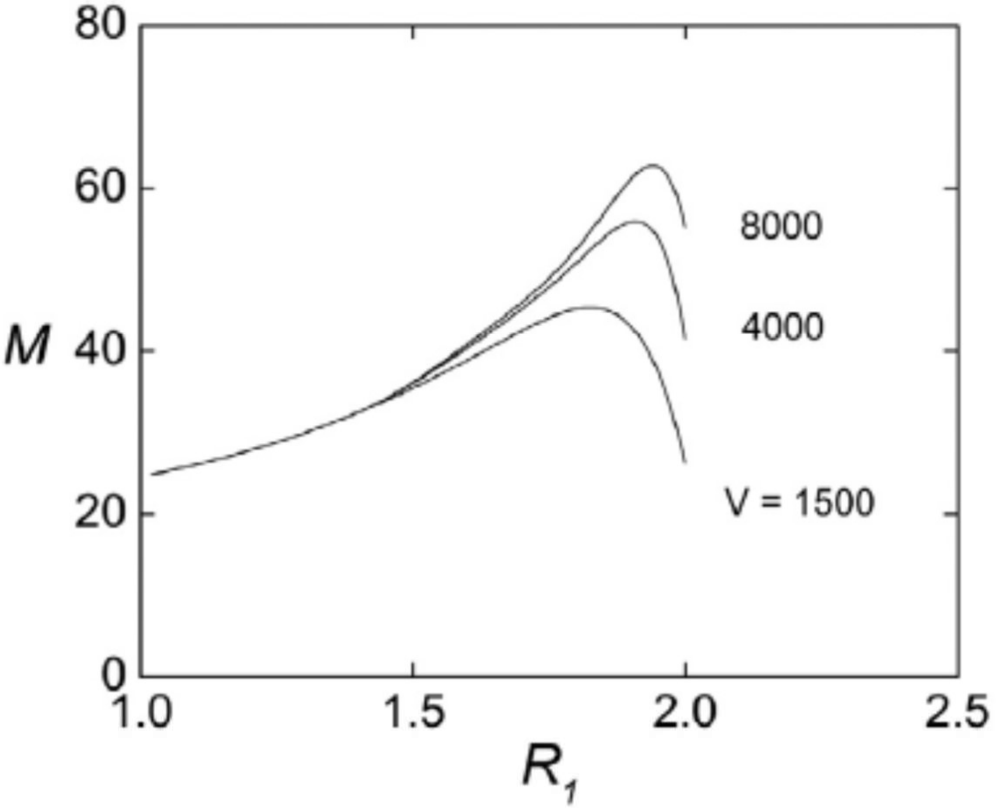


Fig. 2. Amplification factor of the spherical cascade for different volumes of 8%-enriched Uranium ($k_\infty = 1.18$) calculated with the analytical approximation given by Eqs. (12)–(14). All dimensions are given in units of the diffusion length times π. The effective multiplication factor of the whole system is in all cases $k = 0.95$.

Corroboration using the code Monte Carlo MNCP5

- The analytical results were corroborated with the Monte Carlo code MCNP5.
- Effective multiplication factors k = 0.95 and k_∞ = 1.18 (also k_∞ = 2), and spherical symmetry.
- Metallic uranium with enrichment of 8%.
- 14.1 MeV neutron point source, which simulates D-T PF.
- Figures 3, 4 and 5 show some of the results.
- A conservative PF energy value for "break-even", was obtained, namely, $E_{PF} \sim 4000$ kJ / M.

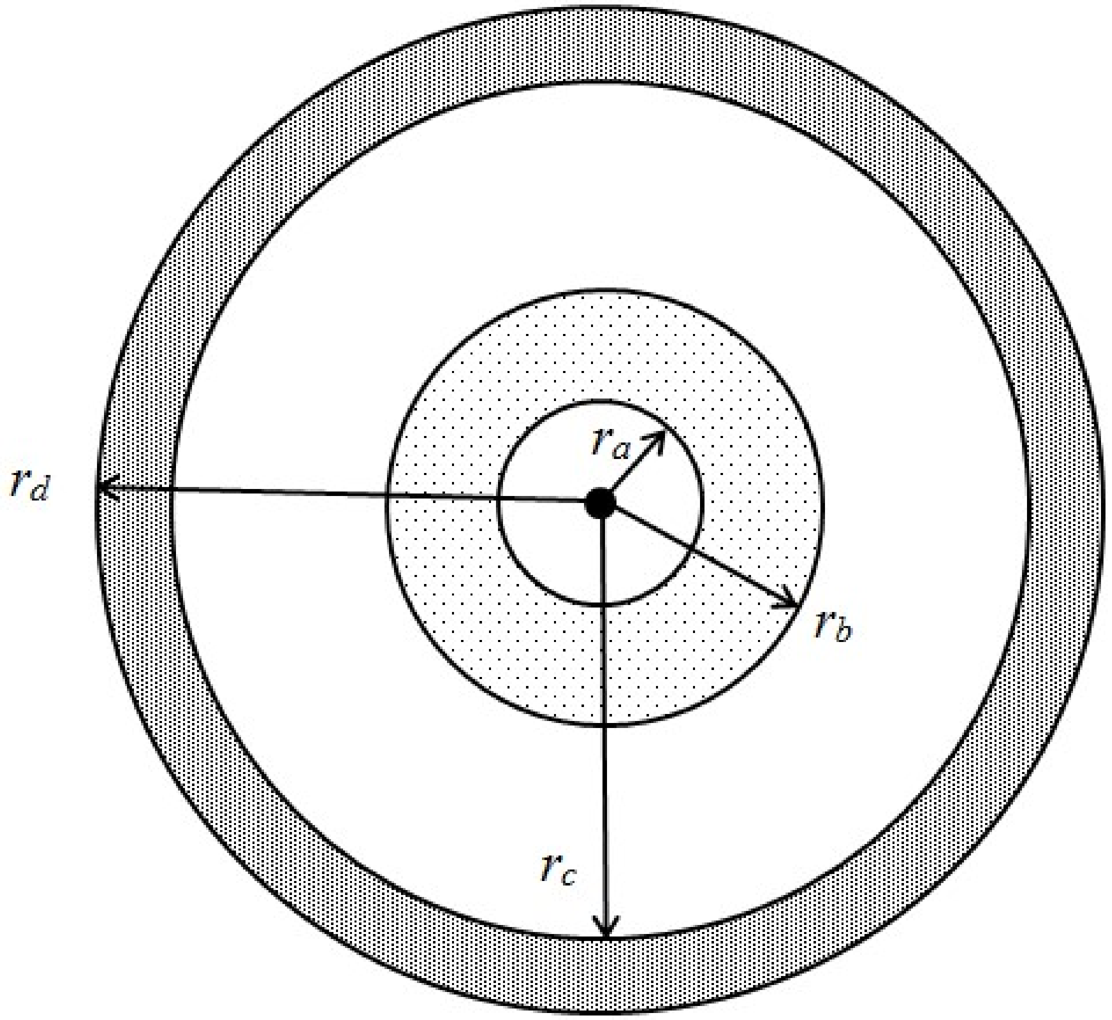


Figure 2. Configuration of the spherical cascade used in the Monte Carlo calculations.

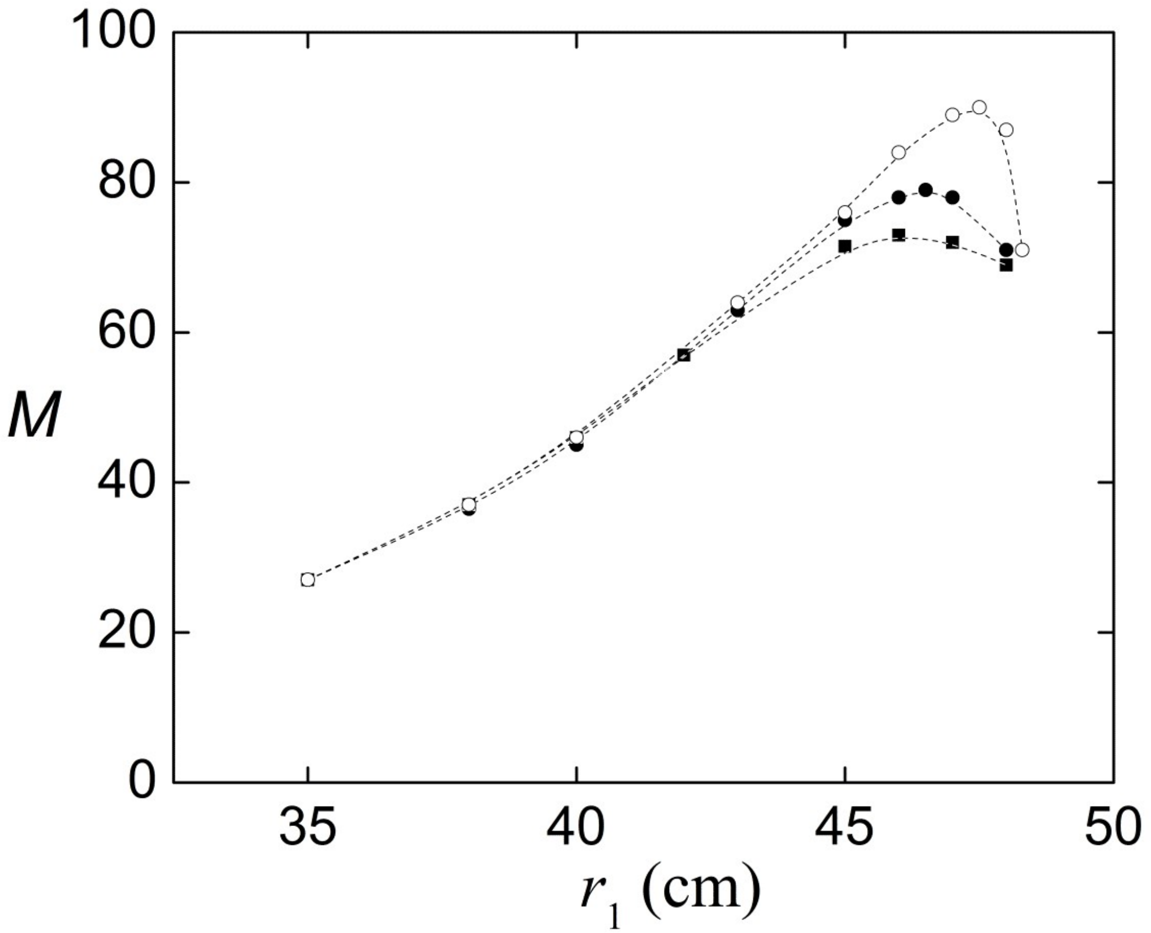
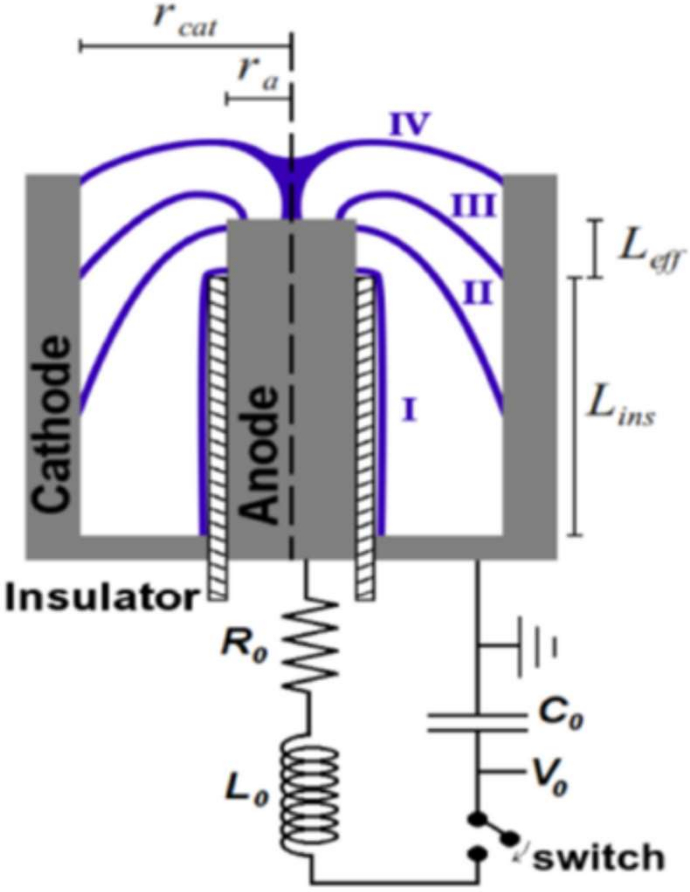


Figure 3: Monte Carlo results for the amplification coefficient *M* in spherical cascade of volumes: 4.2 m^3 (■), 11.3 m^3 (●) and 22.6 m^3 (○). Effective multiplication factor *k* = 0.95 and radius r_a = 20 cm from the center of the PF to the limit of the vacuum surrounding it (see Fig. 2).

Neutron pulses due to Fusion in Central Plasma Focus

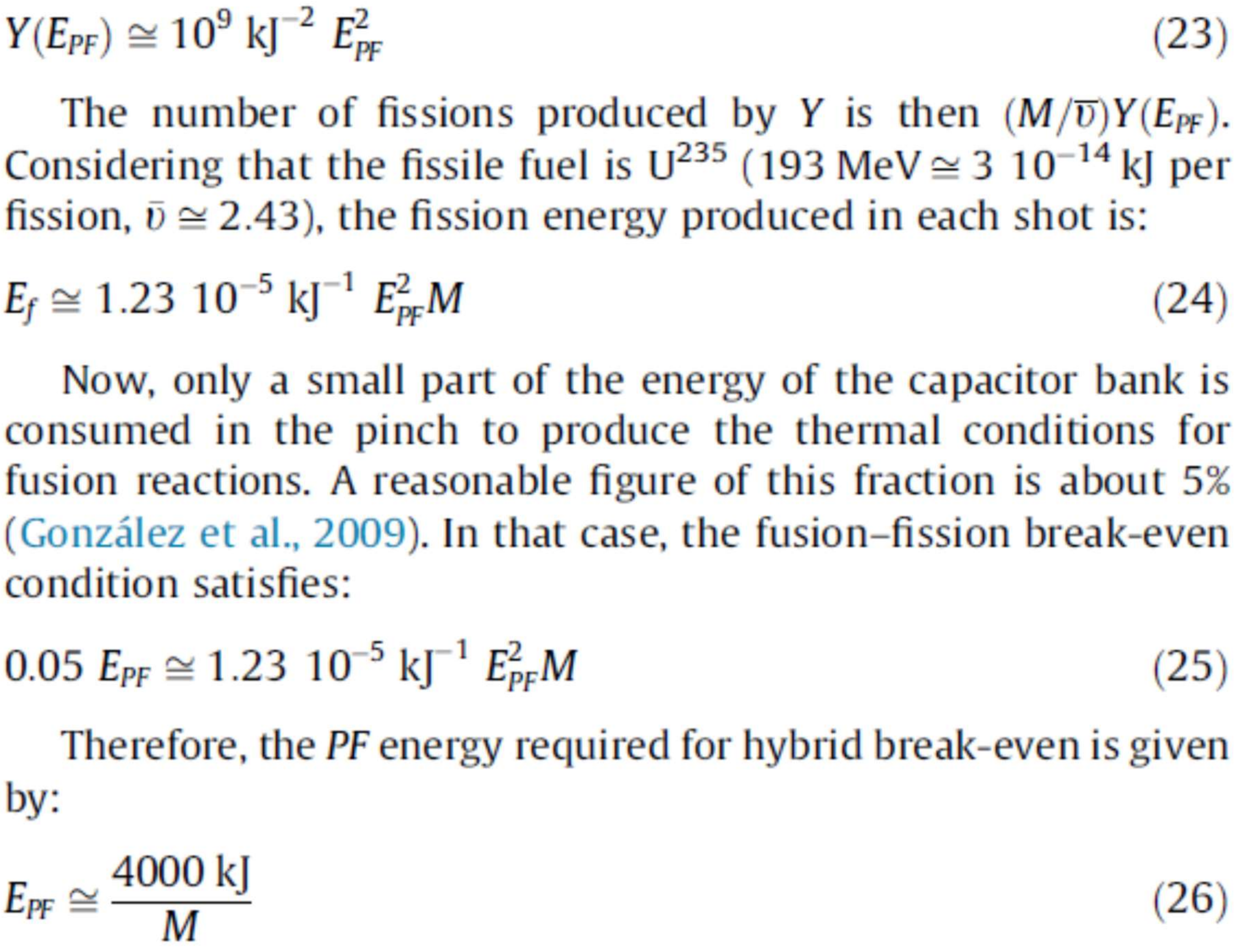


D-D : $Y \sim 10^7 E^2$

D-T : $Y \sim 10^9 E^2$

Y: neutron yield per pulse

E: bank energy for the PF, in kJ



$$Y(E_{PF}) \cong 10^9 \text{ kJ}^{-2} \, E_{PF}^2 \tag{23}$$

The number of fissions produced by Y is then $(M/\overline{\upsilon})Y(E_{PF})$. Considering that the fissile fuel is U^{235} (193 MeV $\cong 3\ 10^{-14}$ kJ per fission, $\bar{\upsilon} \cong 2.43$), the fission energy produced in each shot is:

$$E_f \cong 1.23\ 10^{-5} \text{ kJ}^{-1} \, E_{PF}^2 M \tag{24}$$

Now, only a small part of the energy of the capacitor bank is consumed in the pinch to produce the thermal conditions for fusion reactions. A reasonable figure of this fraction is about 5% (González et al., 2009). In that case, the fusion–fission break-even condition satisfies:

$$0.05\, E_{PF} \cong 1.23\ 10^{-5} \text{ kJ}^{-1} \, E_{PF}^2 M \tag{25}$$

Therefore, the *PF* energy required for hybrid break-even is given by:

$$E_{PF} \cong \frac{4000 \text{ kJ}}{M} \tag{26}$$

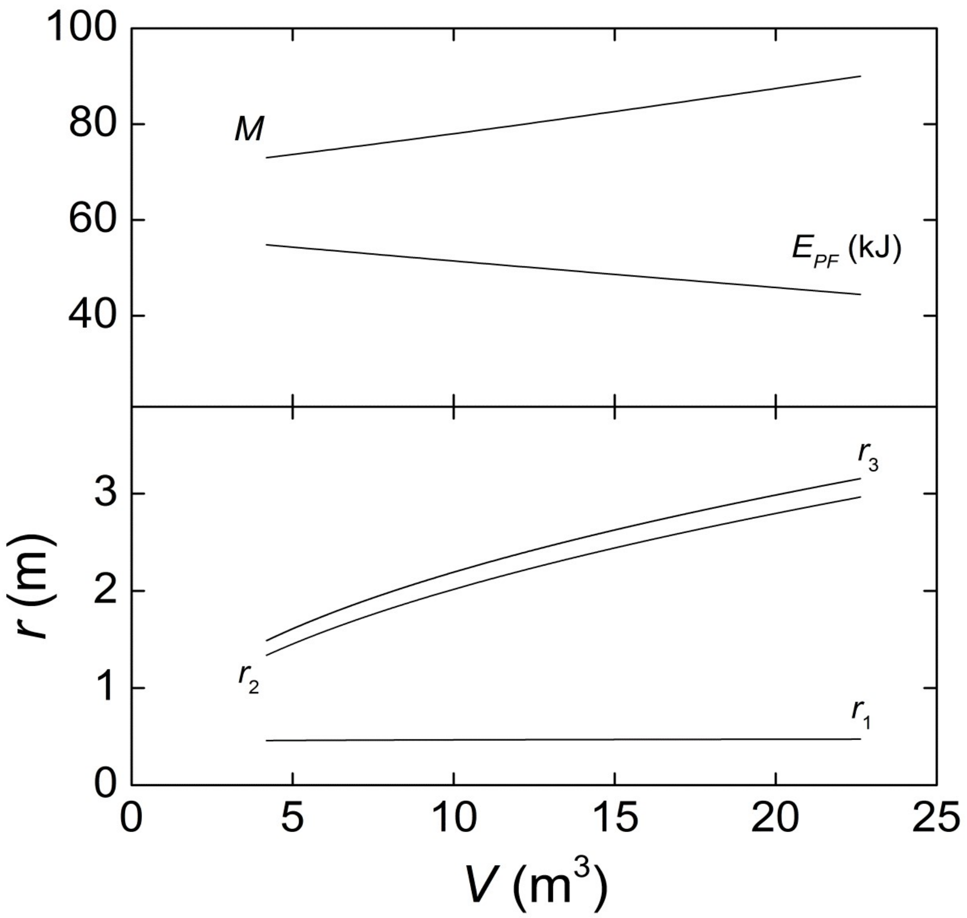


Figure 4. Optimal amplification factor, PF energy for "break-even" and geometric parameters of the spherical cascade as functions of the volume of 8%-enriched Uranium, calculated with MCNP.

Considering an optimal value of the total number of fission neutrons per neutron inserted by the sources, M ~ 80,

From the relation;

$$E_{PF} \cong \frac{4000\ \text{kJ}}{M} \quad ,$$

the energy of the Plasma Focus required for break-even in the optimum spherical configurations for the range of volumes considered in the MCNP calculations is about 50 kJ, which is within the range provided by the current technology.

Moreover, the reactor external radius is about 2 m, which is also a feasible figure.

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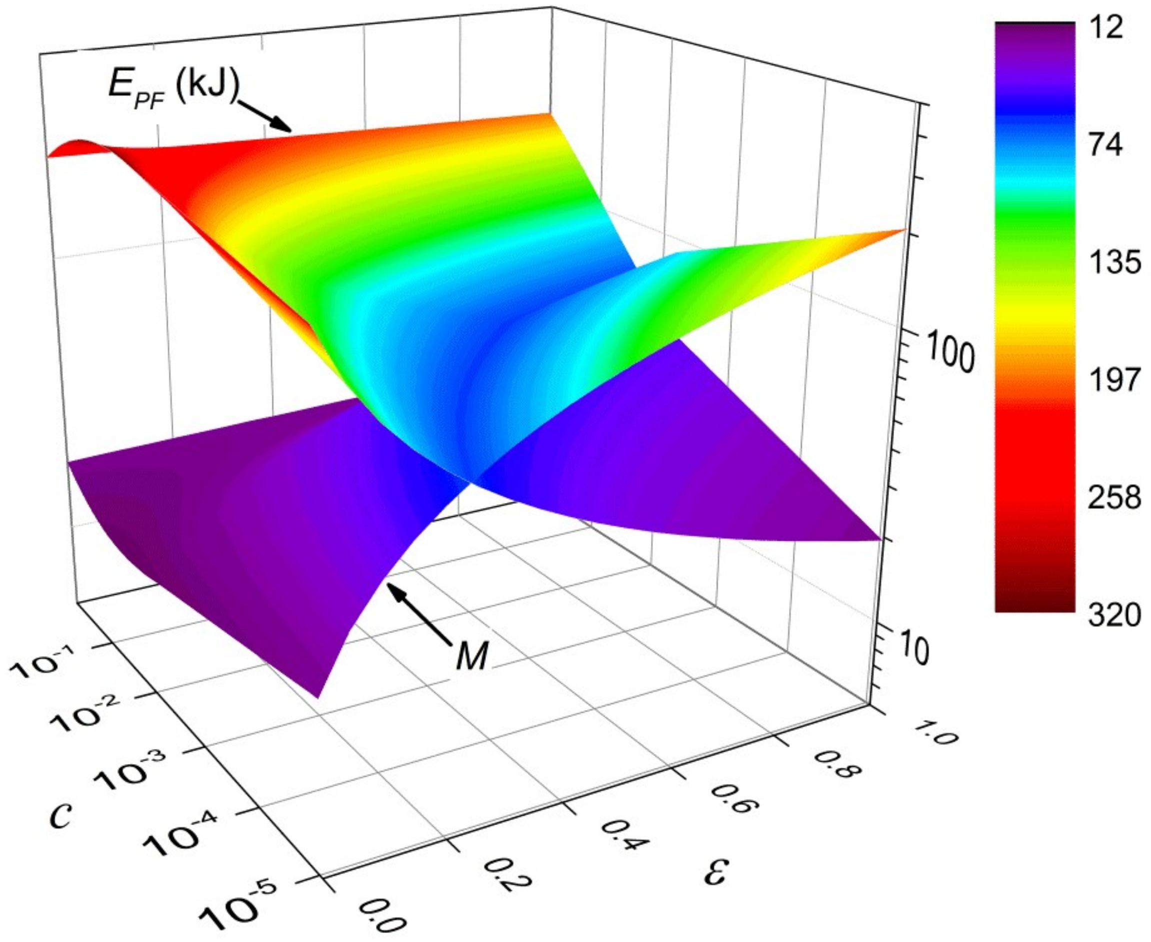

Figure 5. Amplification coefficient *M* and energy E_{PF} of the plasma focus at the break-even equilibrium point in the case of $k_1 = k_2 = k$ sub-critical cascade ($k_\infty = 2$, $k = 0.95$)

Conclusions

- The feasibility of a hybrid fusion–fission system consisting of a two-stage spherical subcritical cascade driven by a Dense Plasma Focus was studied.
- An analytical model based on the one-group neutron diffusion equation was developed to estimate the amplification achieved per source's neutron knowing the neutronic parameters of each region. The conditions for energy break-even for this hybrid concept were assessed. It was found that in principle the concept is feasible given the current Plasma-Focus technology (PF of tens of kJ).
- The results were corroborated by means of Monte Carlo calculations and a design chart was produced for assessing the optimum configuration of the spherical cascade to achieve different levels of neutron amplification.

Conclusions

- The energy of the Plasma Focus required for break-even in the optimum spherical configurations for the range of volumes considered in the MCNP is about 50 kJ, which is within the range provided by the current technology. Moreover, the reactor external radius is about 2 m, which is also a feasible figure.
- The present novel analysis of PF-driven two-region reactors is valuable regarding that the technology of PF neutron sources, in spite of its limited neutron yield, is currently more advanced than their counterparts based in inertial fusion.
- The remaining challenge is to increase the discharge rate of PF devices of tens of kJ in order to achieve reasonable power outputs.

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Thank you for your attention

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