Verso le macchine per la Fusione Fredda (Toward Cold Fusion Devices)

Presentation · February 2021

DOI: 10.13140/RG.2.2.31545.90720

12 authors, including:

Francesco Celani
INFN - Istituto Nazionale di Fisica Nucleare

Giorgio Vassallo
Università degli Studi di Palermo

Enrico Purchi
Ministero dell'Istruzione, dell'Università e della Ricerca

Ricerca di frontiera per l'energia nucleare sostenibile.
Le tecnologie più innovative per la produzione di energia decarbonizzata.

Verso le macchine per la Fusione Fredda

(Toward Cold Fusion Devices)

Dott. Francesco Celani

Ricercatore Associato INFN-LNF; Vice-President ISCMNS; Member of the Steering Board of the European Project "CleanHME".

C. Lorenzetti(1), G. Vassallo(1,3), E. Purchi(1), S. Fiorilla(1), S. Cupellini(1), M. Nakamura(1), P. Cerreoni(1), R. Burri(1), P. Boccanera(1), A. Spallone(1,2,4), E. F. Marano(1).

(1) ISCMNS_L1, Intern. Soc. of Condensed Matter Nuclear Science, Via Cavour 26, 03013 Ferentino-IT; (2) EU Project H2020: CleanHME; (3) DIDI, Univ. of Palermo, 90128 Palermo (PA)-IT; (4) Istituto Nazionale di Fisica Nucleare, Via E. Fermi 40, 00044 Frascati (RM)-IT

This is a presentation held at the Committee on Nuclear Research and Innovative Reactors of the "Order of Engineers of the Province of Rome" on February the 9th 2021. It summarizes the main findings in the field of "Cold Fusion" occurred in the last 31 years with a focus to the research conducted at INFN-LNF. With respect to previous similar presentations, this time we have preferred using the original denomination, well aware that the term "Cold Fusion" does not provide an exhaustive denomination for a much ampler phenomenology, where fusion may only be one among several of the possible manifestations. This presentation includes some information on the most successful experiments from 1989, and quickly moves to those of the authors. In that respect, much emphasis is given to the role on non-equilibrium conditions such as those able to promote a flux of active species (deuterium or protium) in active mediums. The use of electric pulses is described from the first electrolytic experiments with palladium in 1994, to the most recent evolutions with nickel-copper alloys in gas phase.

This work has received funding from the European Union's Horizon2020 Framework Programme under grant agreement no 951974.

Webinar. Ordine degli Ingegneri della Provincia di Roma, Piazza della Repubblica 59, 00185 Roma-Italia.

09 Febbraio 2021.

Ricerca di frontiera per l'energia nucleare sostenibile.
Le tecnologie più innovative per la produzione di energia decarbonizzata.

Verso le macchine per la Fusione Fredda

(Toward Cold Fusion Devices)

Dott. Francesco Celani

Ricercatore Associato INFN-LNF; Vice-President ISCMNS; Member of the Steering Board of the European Project "*CleanHME*".

This work has received funding from the European Union's Horizon2020 Framework Programme under grant agreement no 951974.

Webinar. Ordine degli Ingegneri della Provincia di Roma, Piazza della Repubblica 59, 00185 Roma-Italia.

09 Febbraio 2021.

OUTLINE

- **An historical introduction to Cold Fusion experiments[1] and the most relevant results obtained to date around the world.**

- **The role of flux of active species (Deuterium, Hydrogen) through the lattice of certain metals.**

- **The most recent procedures to obtain Anomalous Heat Effects (AHE) at INFN-LNF and some background on microsecond pulsing techniques:**

  a) The beginning in 1994 with plates and straight Palladium wires at low temperature (<100 °C) in liquid D_2O or gaseous Deuterium atmosphere
  b) The most recent experiments with Constantan[2] wires in a coaxial coiled geometry[3] in Hydrogen and or Deuterium[4] atmosphere at High Temperatures (up to 900 °C).

---

[1] Cold fusion was the name adopted in 1989; after 2010 LENR acronym was used instead, Low Energy Nuclear Reactions to include a variety of experimental findings not always fitting with a "Cold Fusion" reaction.
[2] Cu-Ni-Mn alloy, low cost material.
[3] comprised of a counter-electrode.
[4] pure or mixed with Ar, Xe.

- The Coaxial Coiled wire geometry with counter-electrode: the use of multiple effects enabled by strong electric pulses and related electromagnetic effects.

- A similitude of operations with Otto-Benz engine.

- Conclusions.

The beginning, from 1989, to the most recent "Cold Fusion" evolutions.

- **The announcements made, separately, by Fleischmann-Pons (excess energy during electrolysis of D_2O using Pd cathode) and S. Jones (neutron emission in similar experiments, based on Ti cathode) on March 23, 1989 at Universities of Salt Lake City and Provo (USA), after some initial enthusiasm, became the source of heavy discussions and controversy.**

- **The main issues were the poor reproducibility of the experiments, and extremely low signature of the expected nuclear ashes, in sharp contrast with the expectations from a typical two-body physics at high energy at low pressure, as following:**

  - **D+D → Tritium+proton ➔ Energy=4.0 MeV, Probability= 50%**
  - **D+D → ^{3}He+neutron ➔ Energy=3.3 MeV, Probability= 50%**
  - **D+D → ^{4}He+gamma ➔ Energy=24 MeV, Probability= 10^{-5}%**

In relation to safety, for instance, to get just 1 W of excess energy by DD fusion, 0.85 *10^{12} neutrons per second have to be emitted on average: a "dose" considered close to lethal one for humans.

The Key Point of Cold Fusion:

The "Cold Fusion[5]" is very different from

Hot Fusion (hundreds of Millions of °C), operated in almost vacuum.

Gas pressure in a usual Tokamak is, typically, just $5*10^{-6}$ Atm, i.e. $1.3*10^{14}$ Atoms/cc

"Cold Fusion" may occur even at NTP, due to possible lattice effects.

***1 Mole=$6.02*10^{23}$ atoms* (Avogrado's number)**

Usually Ti, Ni, Pd and their alloys absorb macroscopic amounts of Hydrogen or Deuterium.

Given their mean density (g/cm^3) and mean atomic mass, respectively 4.5, 48; 8.9, 59; 12.0, 106, it results that the number of atoms/cm^3, according to the formula N= Avogadro number/(Atomic mass/density), are:

- **Ti =>$6.02*10^{23}$ /(48/4.5)= $5.64*10^{22}$;**
- **Ni =>$6.02*10^{23}$/(59/8.9)= $9.08*10^{22}$;**
- **Pd =>$6.02*10^{23}$/(106/12)= $6.82*10^{22}$.**

---

[5] We are using Cold Fusion original terminology for didactic purposes, despite there is not yet a consensus on which specific process or processes are occurring. The authors believe in a process featuring multiple reactions, among which fusion, though not necessarily the predominant nor the most common in all experimental conditions.

- **In other words, the density of active specie (H, D) inside an appropriate lattice M[6], is more than 8 orders of magnitude (10^8) larger with respect to a Tokamak reactor operating in steady state conditions[7].**

- **The highly dense states of H or D in the metal lattice, and their non-equilibrium. Is this the pivot of Cold Fusion?**

[6] **Assuming an H/M ratio 0.5-0.9**

[7] **during "operations" can reach locally pressure up to 10^5 times higher, i.e. few bars**

Fig.1 Scheme of the first "Cold Fusion" cell, shown by M. Fleischmann and S. Pons: March 23, 1989. Power measured using the isoperibolic methods (techniques which are experimentally very simple, but mathematically rather complex).

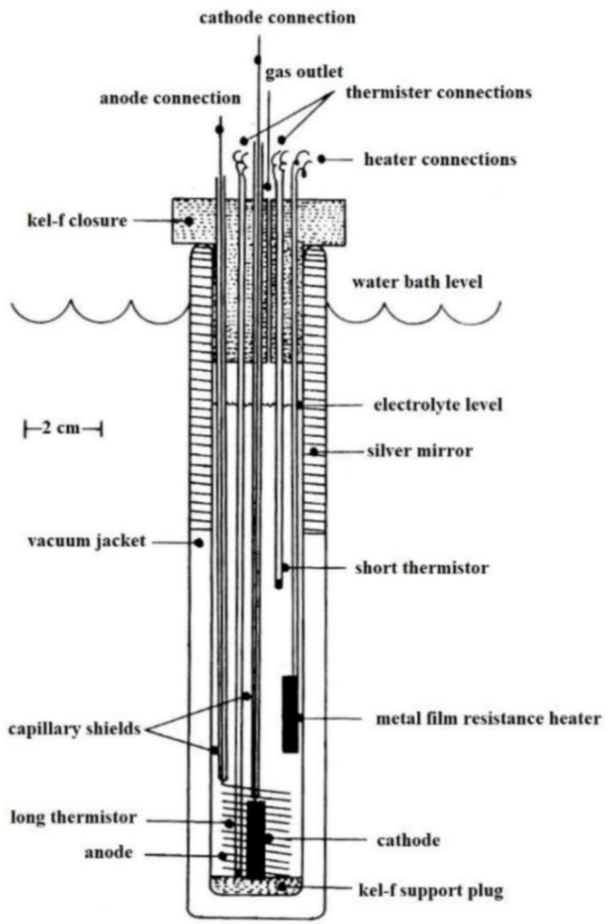
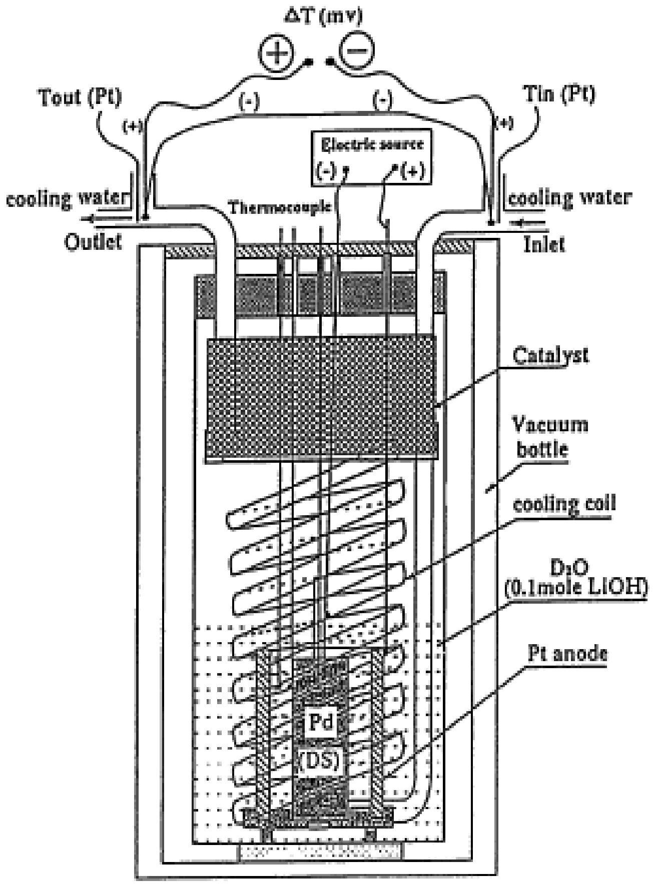


Fig. 2, 3. Two, well known, reactors: left developed by Mike Mc Kubre (Stanford Research Institute International, SRII, USA); right Double Structure Cathode (DSC), developed by Yoshiaki Arata (Osaka University, Japan). This second design contains Pd black (a material consisting of nanometric powders) inside the Pd vessel.



a

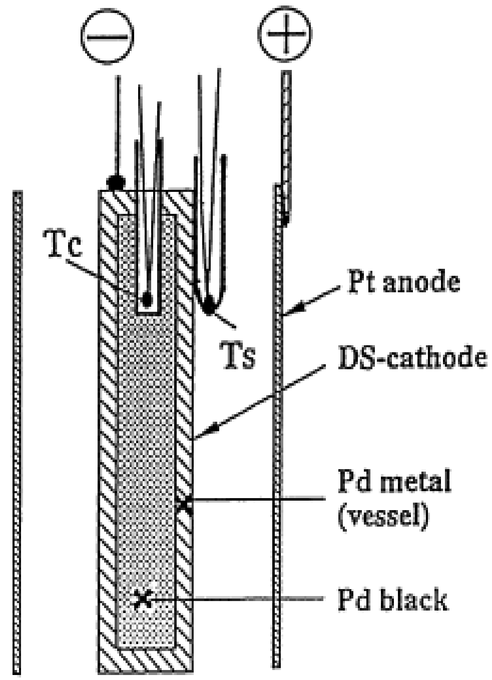


Fig.4. Results from one of the typical experiments using D_2O electrolyte compared with H_2O, off line. (Pd electrode, 0.1 mole LiOH). The occurrence of excess heat ONLY when a threshold in current density (J) was exceeded, is the most relevant point (i.e. J=250 mA/cm^2 of cathode surface). The excess power increased almost linearly with the current density up to a maximum of 700 mA/cm^2: above this value, the excess heat drops because of excessive deuterium bubbles. These measurements were made by flow calorimetry **(a technique which is complex to implement, but convenient for the analysis of the results). This experiment was made by M. Mc. Kubre (1992).**

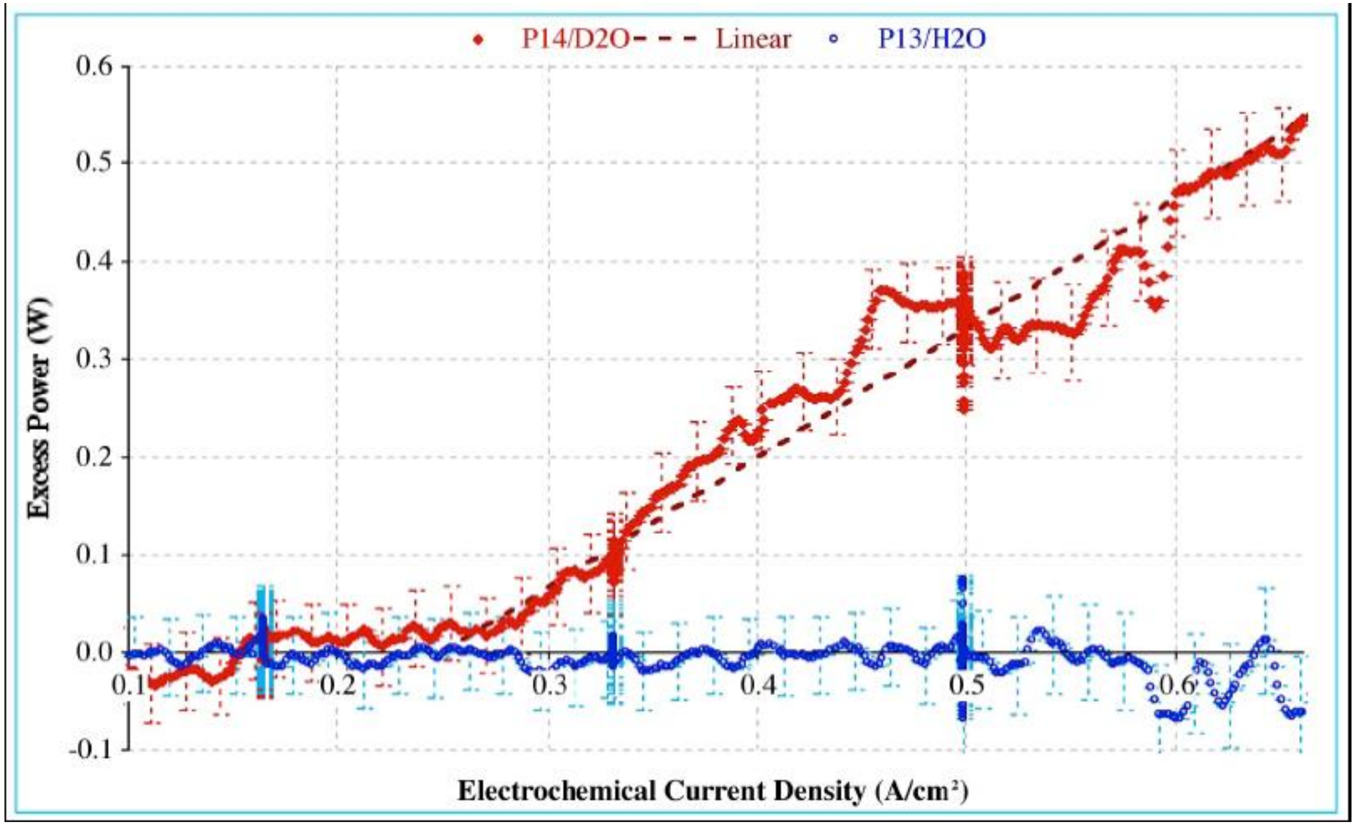
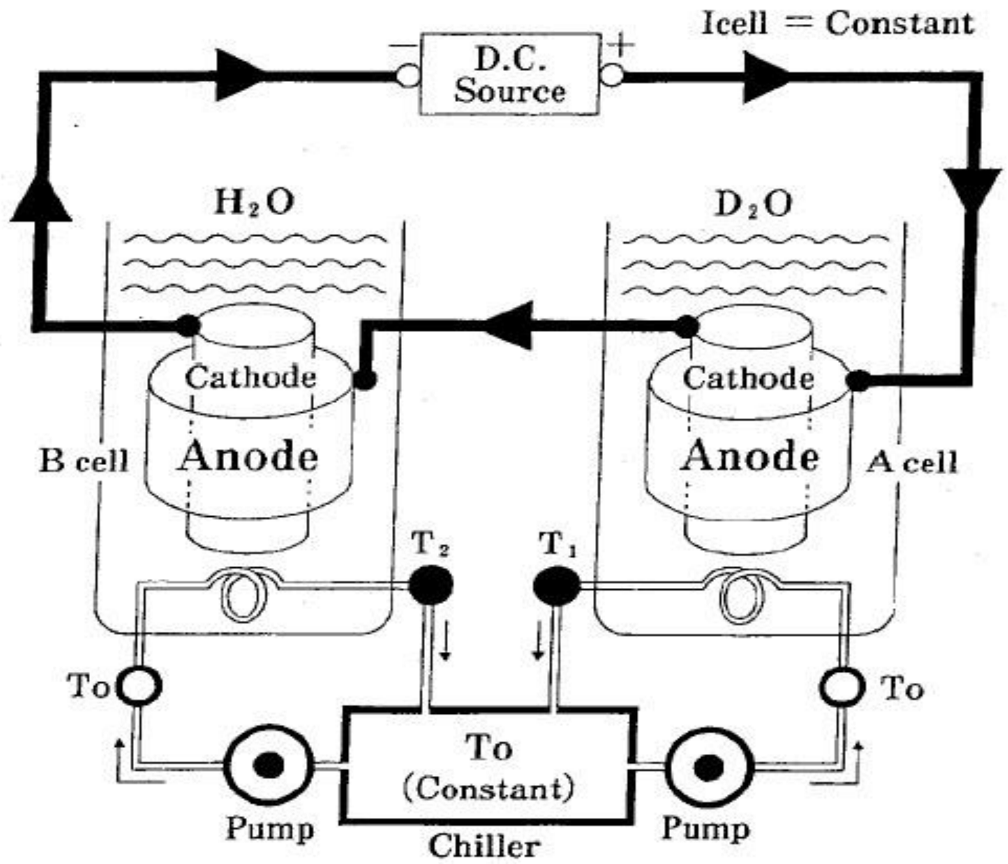


Fig. 5. One of the few experiments featuring a direct comparison $D_2O \Leftrightarrow H_2O$, on line.



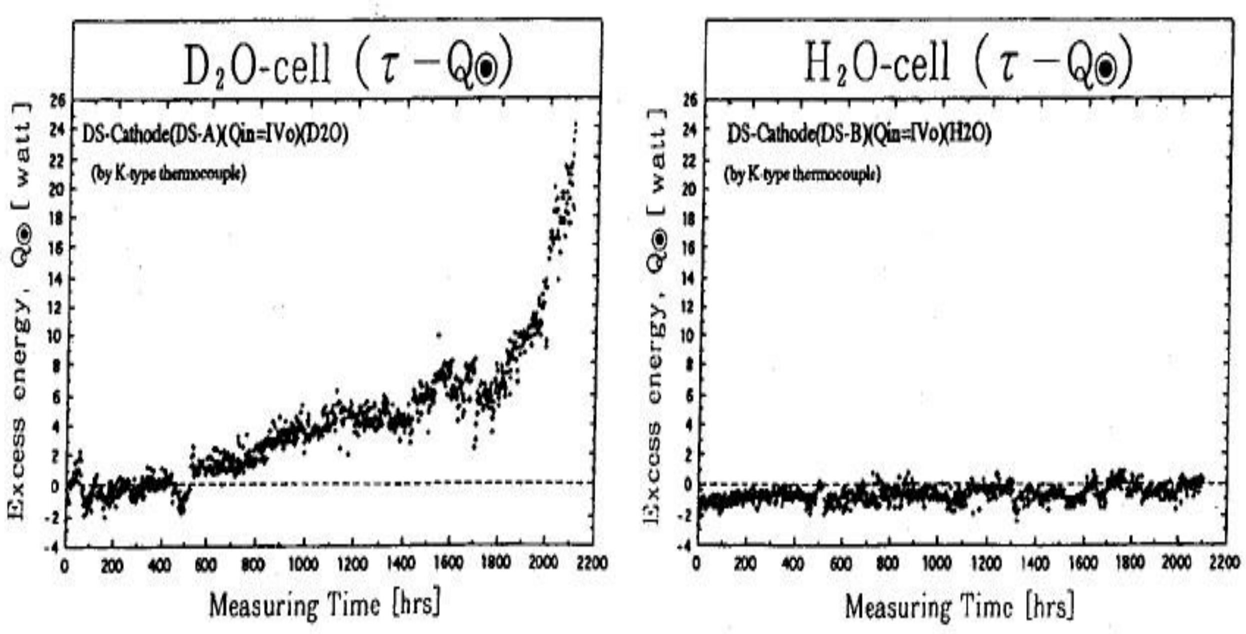
Main results of electrolysis experiment performed using DSC (Double Structure Cathode) geometry:

long time-lag needed before AHE occurrence.

When using a D_2O solution as in Fig. 6 (left), the time needed for the occurrence of excess heat is over 30 days. Also, excess heat "jumps" after 75 days. After 90 days approximately, the experiment has to be stopped because of the excessive pressure inside the DSC (a Pd tube containing Pd powder). At this point in time the excess heat was noteworthy (24 W).

This experiment demonstrates the importance even of a modest deuterium flux within the Pd lattice.

Fig.7. (right) Nothing relevant occurs with the control cell, based on a H_2O solution.

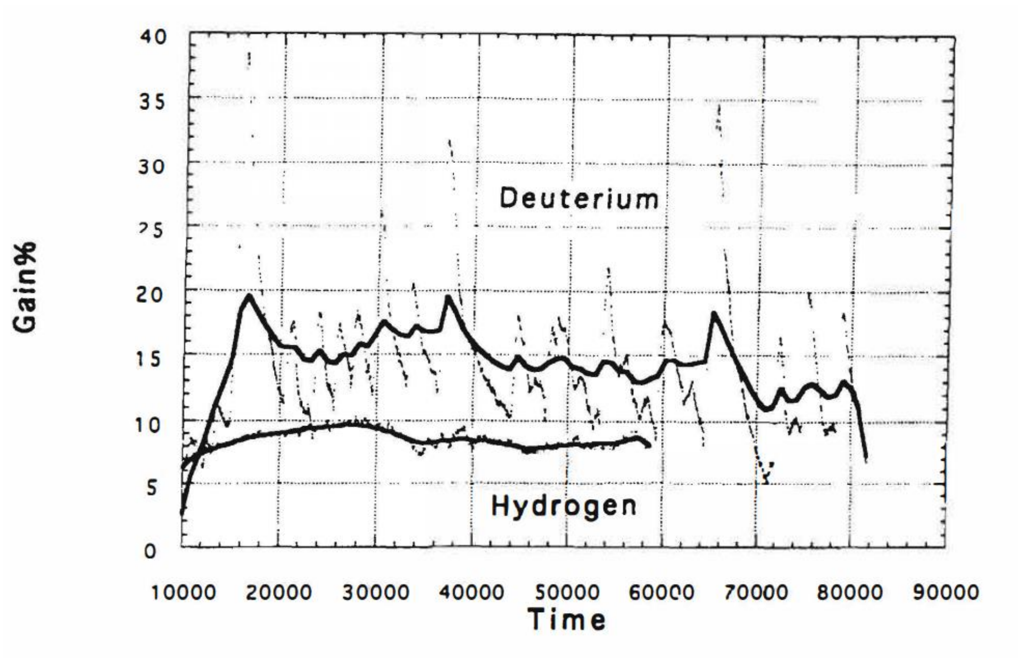


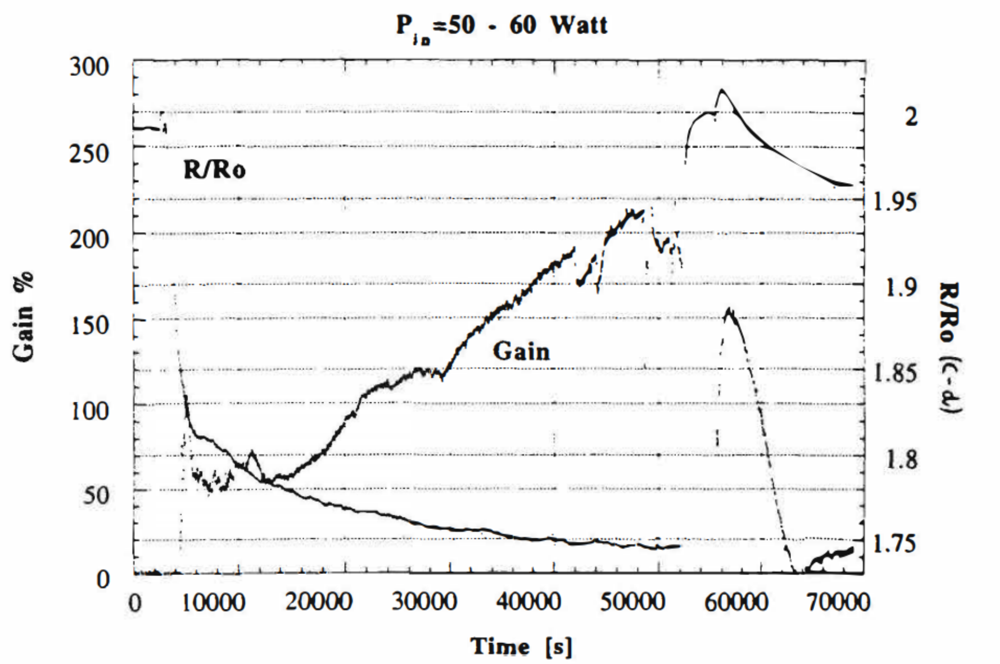
Experiment at INFN-LNF: thin wires, alloy ($Pd_{97}Y_{0.03}$), comparison H_2O<--> D_2O, off line. Pulsing procedures.

Fig. 8. Comparison of AHE using $Pd_{97}Y_3$ wires in D_2O and H_2O solutions, using pulsed power conditions (see Fig. 6 in the document reported), and measured using flow calorimetry. We assume that in these conditions a longitudinal flux of Deuterium occurs.

After 6 cycles of loading-deloading, the AHE, in the case of H_2O solution, went down to 3%. A small value but not neglectable considering the 1% accuracy of the calorimeter calibrated with a resistive heater.

Experiments of F. Celani's group Italy, presented at the "ICCF6", Sapporo-Japan, October 13-18, 1996.





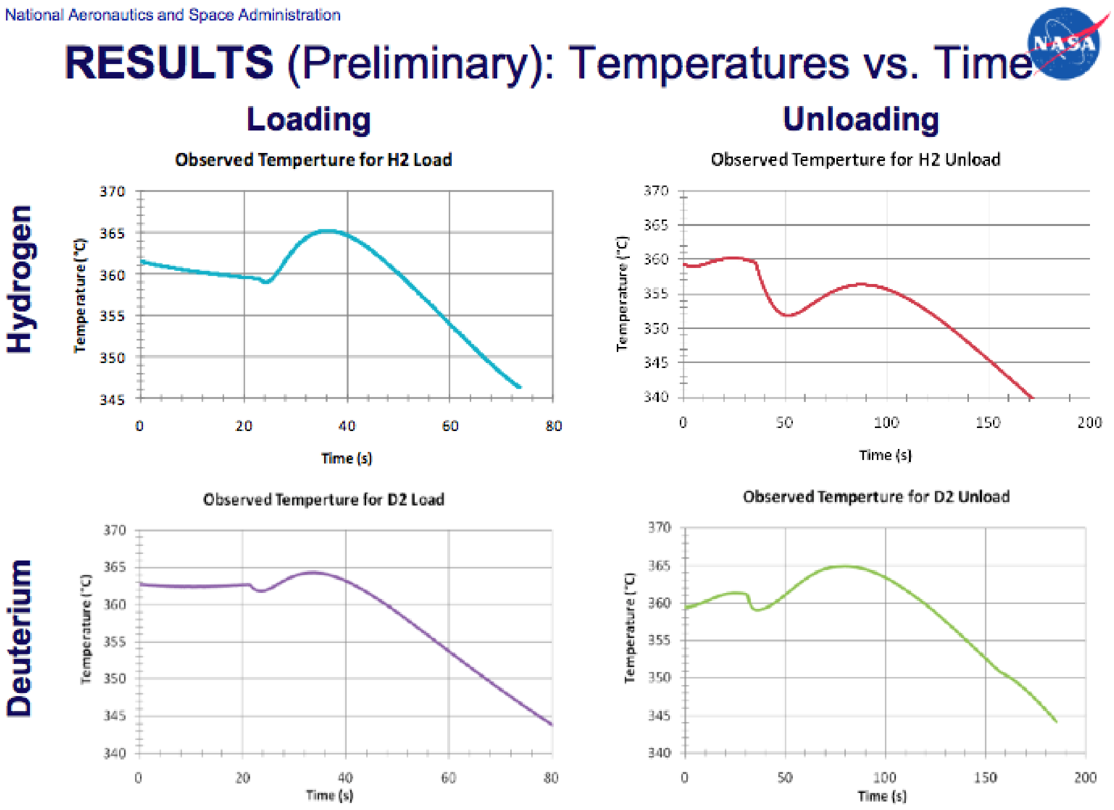
A short history of cross-correlations among non-equilibrium, Deuterium flux and anomalous effects.

1) The First report dates back to April 1989 (2 weeks only after the 23 March 1989 announcement of M. Fleischman-S. Pons, S. Jones) some "anomalous effect" occurred, in our electrolytic systems, during non-equilibrium states only[8].

2) On December 1989 at NASA, Gustave Carl Fralick, demonstrated experimentally that it is possible to get measurable "excess heat" flowing gaseous Deuterium through a thin-wall Pd tube, at about 320 °C, by large pressure gradients. The key point being the anomalous heat that occurs in both loading and unloading regimes. As self-calibration the experiment was repeated, very-short time later, using Hydrogen. These results kept "confidential" for several years until the experiment was repeated, with improved instrumentations, by himself and other "independent" Collaborators in 2011 and made public soon afterward. Results were qualitatively similar to 1989 experiment.

[8] This was reported during the Workshop held at the "Ettore Majorana Research Center for Nuclear Physics", Erice-Italy. Author: F. Celani. Mentioned by Nature.

Fig. 9) Data from the replication of Fralick experiments at NASA in 2011 using Pd thin wall tube at about 360 °C. These results are qualitatively similar to old one made by the same in 1989. There is a clear evidence of *anomalous heat occurrence during both loading and unloading* of deuterium with respect to Hydrogen.



1) **Around 1991 Mike Mc Kubre demonstrated that the anomalous heat, in electrolytic systems (D_2O, Pd), depends on the product among the atomic concentration *D of Deuterium stored* inside a proper Pd rod (M), i.e. D/M, (D minus a proper threshold, about 0.85) and the intensity of the flux of fresh Deuterium going through its surface.**

2) **Around 1995, Yoshiaki Arata demonstrated the possibility to get an extremely high pressure (up to 3000 bar), inside a hollow Pd electrode featuring a specific geometry[9]. He obtained excess energy during the long-lasting dynamic stages when the Deuterium was flowing through the Pd wall of the vessel. He reached an internal pressure limited only by the vessel mechanical resistance. In this experiment, a self-calibration was performed using H_2 instead of D_2. Replications at SRII included also the successful detection of ^3He.**

3) **We can anticipate that the generation of Anomalous Heat Effects (AHE)*,* occurs in our experiments during both loading or unloading phases, analogously to Fralick's experiments at NASA.**
We have been observing the same behavior with Constantan at high temperature (600-800 °C).

---

[9] **called DSC, a tubular palladium vessel containing Pd nano-powders.**

The path to obtain AHE by gas loading, after over 31 years of experiments[10].

a) At the beginning, it is essential to load an appropriate material[11] (Pd, Ti, Ni, alloys) with the active species (H_2, D_2,..);

b) Induce non-equilibrium conditions[12] in the loaded materials through: thermal or concentration gradients, flow of charged species, phase transitions, voltage stimulation, others;

c) We observed experimentally that the "interaction" of the active gas with the gas-loaded material, must be as strong and fast as possible. The active specie FLUX seems to be the main parameter governing AHE. This flux however needs to be enabled by an external energy input;

d) For us the demonstration of the role played by FLUX came only after a deep analysis of more than 80 experiments (reported on JCMNS in July 2020);

---

[10] These are conclusions based both on the general consensus of the LENR community, and our own experiments.

[11] This is a commons experience, reported in almost all LENR experiments;

[12] Based on our experience from 1989, later-on "common sense";

e) New procedures will be needed in the future to minimize the electric energy input needed to enable non-equilibrium of the gas loaded active material[13,14].

A convenient approach is the use of powerful electric pulses, similarly to the experiments carried out at INFN-LNF in 1994-1998.

f) The use of optimized electric pulses to sustain non-equilibrium conditions (via electromigration, localized impulsive heating, plasma discharges in the gas) is major line of development at INFN-LNF.

[13] This non-equilibrium may mediate electromigration in the bulk of Constantan, or additional surface phenomena.
[14] Constantan wires comprise a submicrometric textured surface.

The major obstacles to the exploitation of the AHE effect

- **From the very beginning of our investigations, we have observed that anomalous effects associated to cold-fusion[15] after an initial rise and a plateau phase tend to vanish over time,**

- **AHE[16] for instance, is generally associated to transient states and need continuous stimuli to prevent its decline. In that respect our group has identified certain procedures able to provide stimuli for AHE occurrence:**
    - temperature gradients,
    - pressure gradients,
    - electric stimuli[17] seem the most practical.

[15] Thermal effects or nuclear signatures
[16] Anomalous heat effect
[17] e.g. electromigration using thin wires

- **Over the last years we have focused in particular on:**

  a) **Use of thermal gradients (knots, *Capuchin knots*);**

  b) **Stimulation of the surface of Hydrogen loaded materials by the combined effect of a counter-electrode and high voltages;**

  c) **changes in the pressures:**

  d) **low pressures, *Richardson, electron plasma,* effective for short time;**

  e) **moderate-high pressures, Paschen/DBD, Hydrogen plasma, effective for long time operation.**

The role of localized thermal large gradients

- **The presence of thermal and/or chemical gradients has been stressed as being of relevance, especially when considering the noteworthy effect of knots[18] on AHE.**

- **Attempts to further increase AHE focused on the introduction of different types of knots, leading to the choice of the *"Capuchin"* type and, later, the *"advanced Capuchin knot"*.**

- ***The knot design, specially Capuchin one, as shown in Fig. 10, leads indeed to very hot spots along the wire at very short distances: features three areas characterized by a temperature delta up to several hundred degrees (e.g. 600→800→1000 °C in the photo shown, bottom of Fig. 10).***

- **Flux is induced by very large, localized, thermal gradients: peculiar of Capuchin knot geometry when heated by DC.**

  a) **Advantage: no extra energy needed to promote flux and then AHE.**
  b) **Drawback: excessive stress on the wire which tends to break.**

[18] introduced by our group in 2015

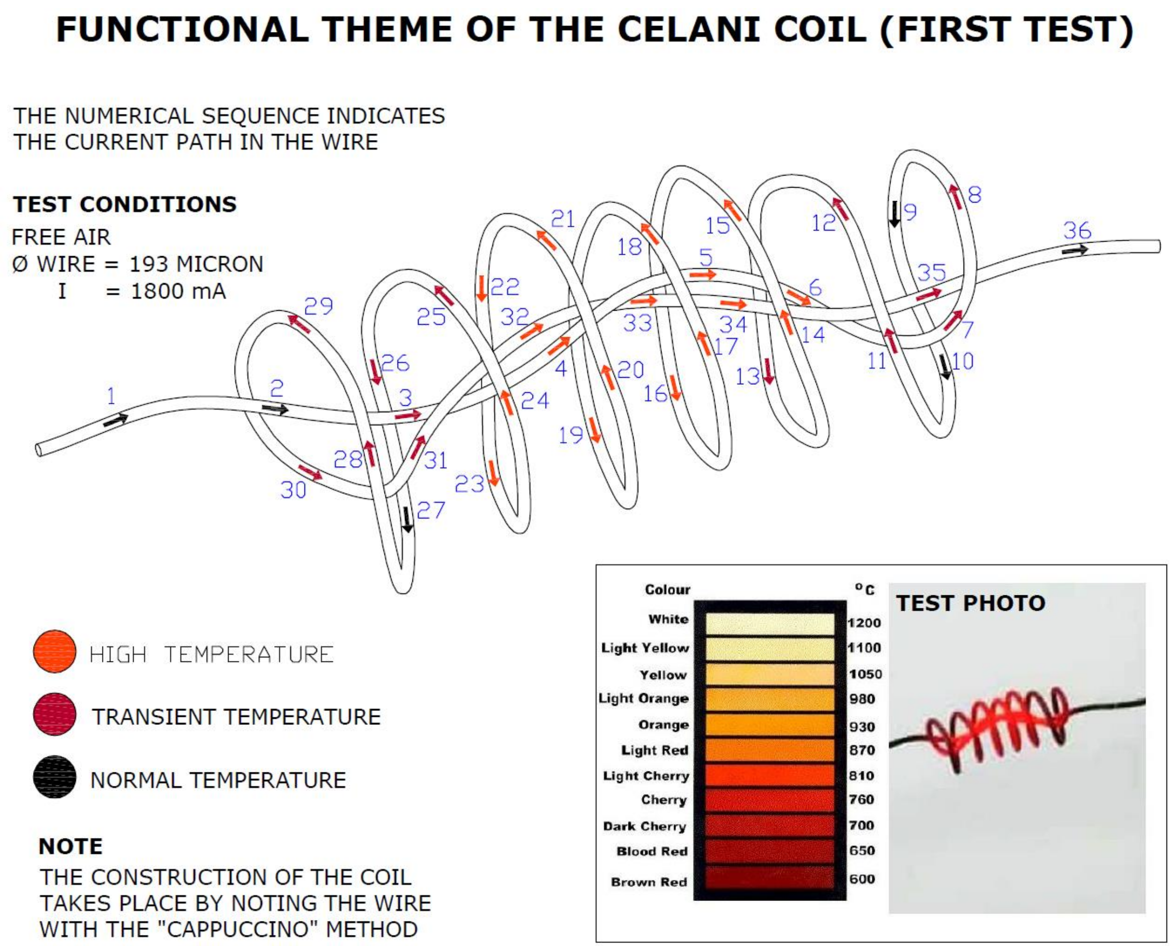


Fig. 10. Photo, I=1900 mA DC, of a piece of Constantan wire having a diameter of 193 µm. Capuchin knots with 8 turns. Temperatures estimated by color. At darkest area T<600°C; at external helicoidal section T at about 800 °C; at inmost section, linear, up to 1000 °C in some points. Distances are few mm.

Overall key aspects

The Cold Fusion (LENR) reaction needs *controlled* NON-Equilibrium:

These are NOT spontaneous but stimulated reactions.

The electrical stimulation is the simplest procedure to be adopted.

We MUST minimize the energy added to the system and maximize the excess power.

The origin of the "pulse" approach.

(More details are available at DOI: 10.13140/RG.2.2.27524.45449)

In 1994 electric pulses, transversal and partially longitudinal, were pioneered by us in low temperature experiments, i.e. electrolytic environments, on plates and later-on wires (with longitudinal component self-increased because geometrical effects) made of Palladium and its alloys.

- **The use of pulses aimed, mainly, at enhancing the effects of Electromigration of deuterium or protium. Moreover, pulses are source of strong NON-EQUILIBRIUM to the system.**

- **The whole program of the time considered, apart the well-known[19] Electromigration effects of protium, even the potential occurrence of "Coherence" as per Giuliano Preparata's model (about 1995).**

---

[19] **since 1928, Alfred Coehn**

- **Such experiments considered only DC condition: maximizing V/cm ratio, in the case of Cohen experiments; the whole voltage drop along the wire, in the case of Preparata's experiments (under the strict condition to get "*coherence*" of the whole wire).**

- **The results were object of several publications.**

- **Notwithstanding Palladium is expensive, and shows various limitations: its brittleness, in particular, negatively affects experiments with wires and their duration.**

- **In the last two decades the work shifted from the initial study of Palladium based systems[20]; to Nickel (2002) and its alloys (since 2011), pure and/or covered by other elements, usually multilayer structures.**

Initially only electrolytic experiments, after 2002 high temperature gaseous experiments in D_2, H_2, or their mixtures with Ar. First tests with pure Ni, coated also by $Th(NO_3)_4$ and "liquid glass", multilayers structure.

- **Constantan ($Cu_{55}Ni_{44}Mn_1$) is much cheaper[21] than Palladium, withstands continuously temperatures as high as 900 °C and shows AHE activity both with deuterium and hydrogen.**

- **In fact, since 2011 hot Constantan wires became the focus of several experiments that leveraged on the unique set of properties of this alloy:**
  1) **Its Low cost;**
  2) **Its remarkable capability to absorb hydrogen (T>150 °C, few bar of pressure) and keep it also at high temperatures (700 °C);**
  3) **A high resilience in harsh experimental conditions.**

[21] Currently 3 orders of magnitude cheaper.

Heated Constantan shows occurrence of anomalous AHE if a series of conditions are met:

A) Sufficiently high temperatures and large thermal gradients along the wire;

B) The surface is roughened and coated with Low Work-Function (LWF) oxides;

C) Presence of a flux of atomic or ionised, deuterium or protium.

In short, *non-equilibrium conditions are compulsory to observe the occurrence of thermal anomalous effects, likewise to Pd based experiments.*

- **The critical point, for a practical application of thermal anomalous affects, is the need to minimize the extra energy added to the system in order to stimulate the "non-equilibrium":**
  - **The ultimate goal being a useful power gain.**

- **The evolution of the experimental set up with Constantan wires, from the point of view of electrical connections, is shown in Fig. 11.**

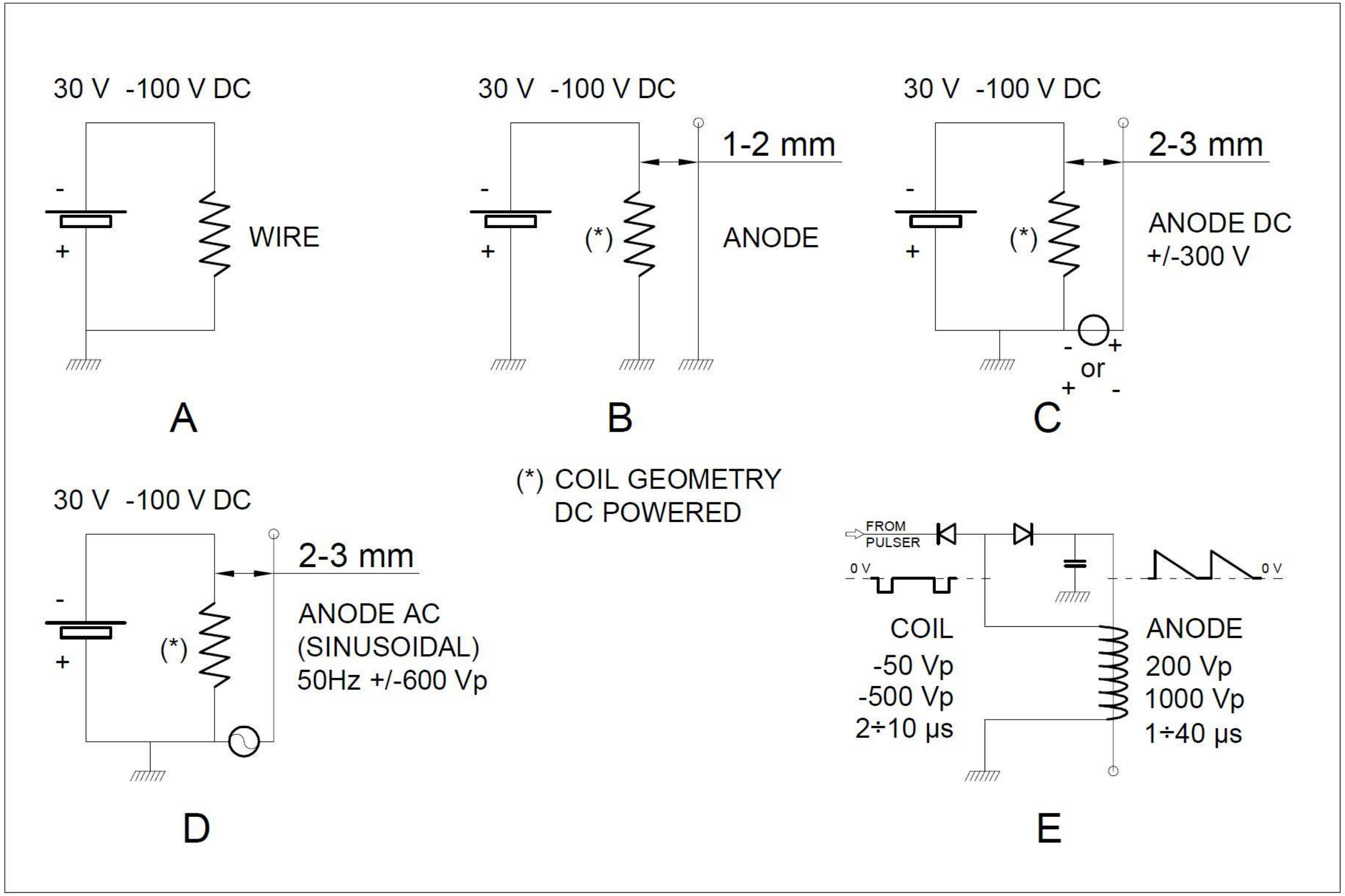


Fig.11. Overview of the evolution of our experimental set-up from the point of view of electrical connections: 2011 (A, the simplest), the previous tested (D) and reported at ICCF22, ending with (E) discussed in this report. i.e. work in progress.

Reactor's core geometry

On the base of the strong experimental evidence that non-equilibrium conditions are essential to obtain AHE, a new geometry of the reactor core was designed.

The wire is arranged for an optimal utilization of the pulses and their electromagnetic effects:

1. **High-Power longitudinal negative pulses impulsively over-heat the surface of the wire causing a boil-off of electrons thanks to the Richardson effect. The "skin effect", due to HF of pulses, helps to increase the temperature at the porous *surface* of the wire[22].**

---

1. [22] **The wire features a submicrometrically porous/textured surface of conductive and non-conductive oxides. The conduction mechanism is likely to happen through percolative-paths among multilayers of LWF oxides comprised of iron (a magnetic material).**

2. **Afterward a self-generating High Voltage-Low Power positive pulse. It is used both for accelerating the electrons toward the anode (Child-Langmuir effect) and induce the breakdown of the active gas (Paschen/DBD effects) among the cathode (Constantan wire) and the anode (iron tube on which the insulated Constantan wire is coiled).**

- **The pressure in the reactor has a key role for effects in 1) and 2) and an optimization is necessary.**

The "in-situ" pulse generation takes advantage of the short distance among the Constantan coil (that generates the positive pulse) and the iron core anode. This approach enables an effective energy transfer from extremely fast pulses, thus reducing the unwanted problematics of: impedance mismatching, parasite capacitive effects.

- **In addition, this allows to have a sequence, of thermal pulses able to increase electron emission when the temperature is appropriate for Richardson effect of the Low Work Function (LWF) materials coating of the wire.**

- All together are starting points for an impulsive electro-migration, apart huge phonon effects (to be explored in the near future), with diffusion speed of Hydrogen increased just because higher temperatures, in presence of also a dielectric barrier discharge (or Paschen breakdown).

In conclusion, the reactor is based on a coiled coaxial structure (made by a porous Constantan wire comprising LWF oxides on its surface) with an inner core used as counter electrode[23].

The concept was introduced during ICCF22 Conference (8-13 September, 2019), Fig. 12 A, B.

The iron core acts as an anode enabling various operating regimes instrumental for the "non-equilibrium" of Constantan wires:

1. **Richardson operation mode: electrons are emitted by Thermionic effect, specially from localized points (hot spot). The anode is almost disconnected: low voltage in respect to cathode, also movement of electrons at surface are at low values (Child-Langmuir: current flowing depends on voltage as per $V^{1.5}$).**

   2; 3. Child Langmuir activated; Paschen/Dielectric Barrier Discharge modes. If the voltage of applied pulses and pressure are appropriate, also a gas breakdown occurs. Several experiments have provided evidence that in these conditions the highest and longer lasting AHE can be obtained.

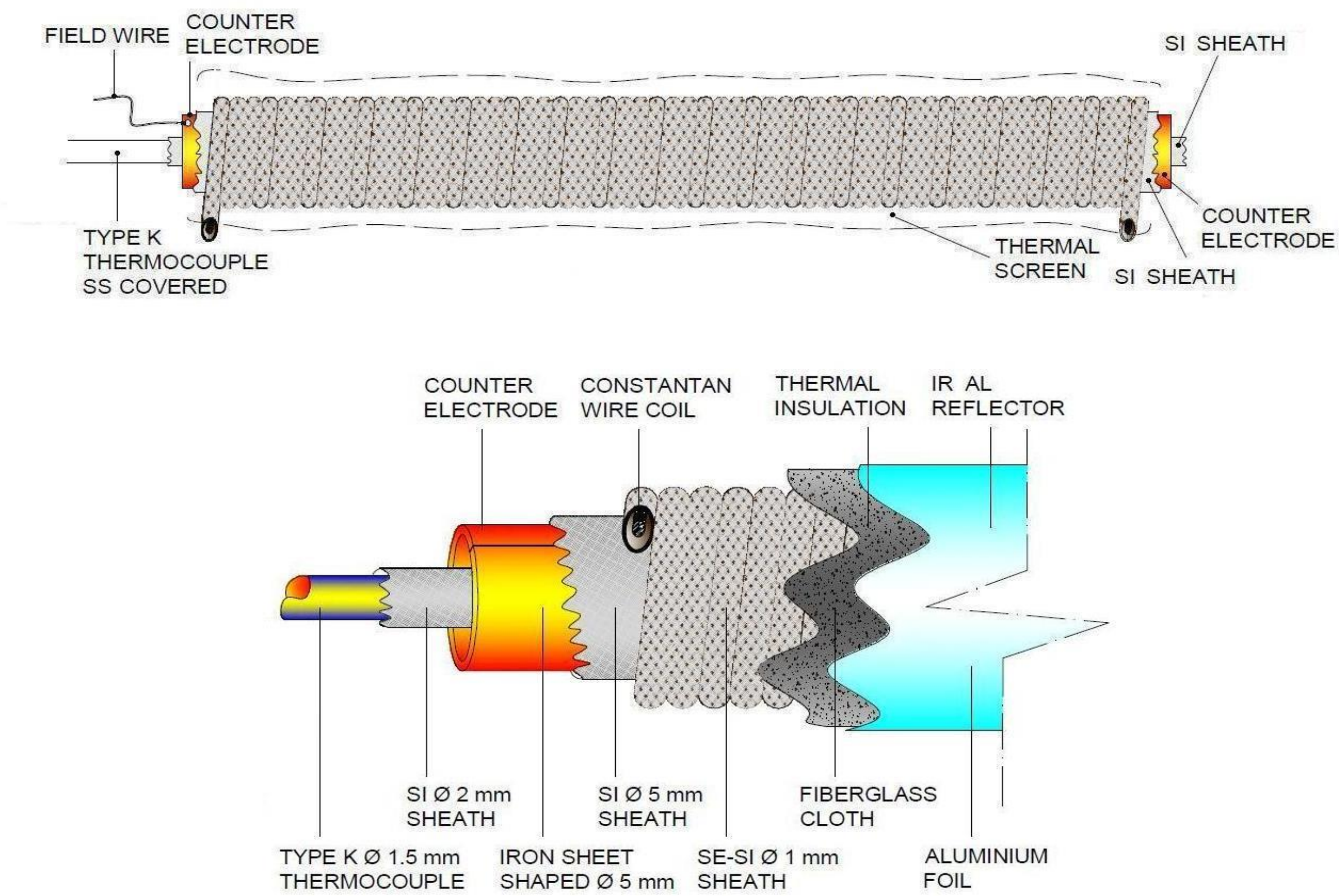


Fig. 12A. Scheme of the coaxial coil with its inner Fe counter-electrode. A coil has usually 75 turns.

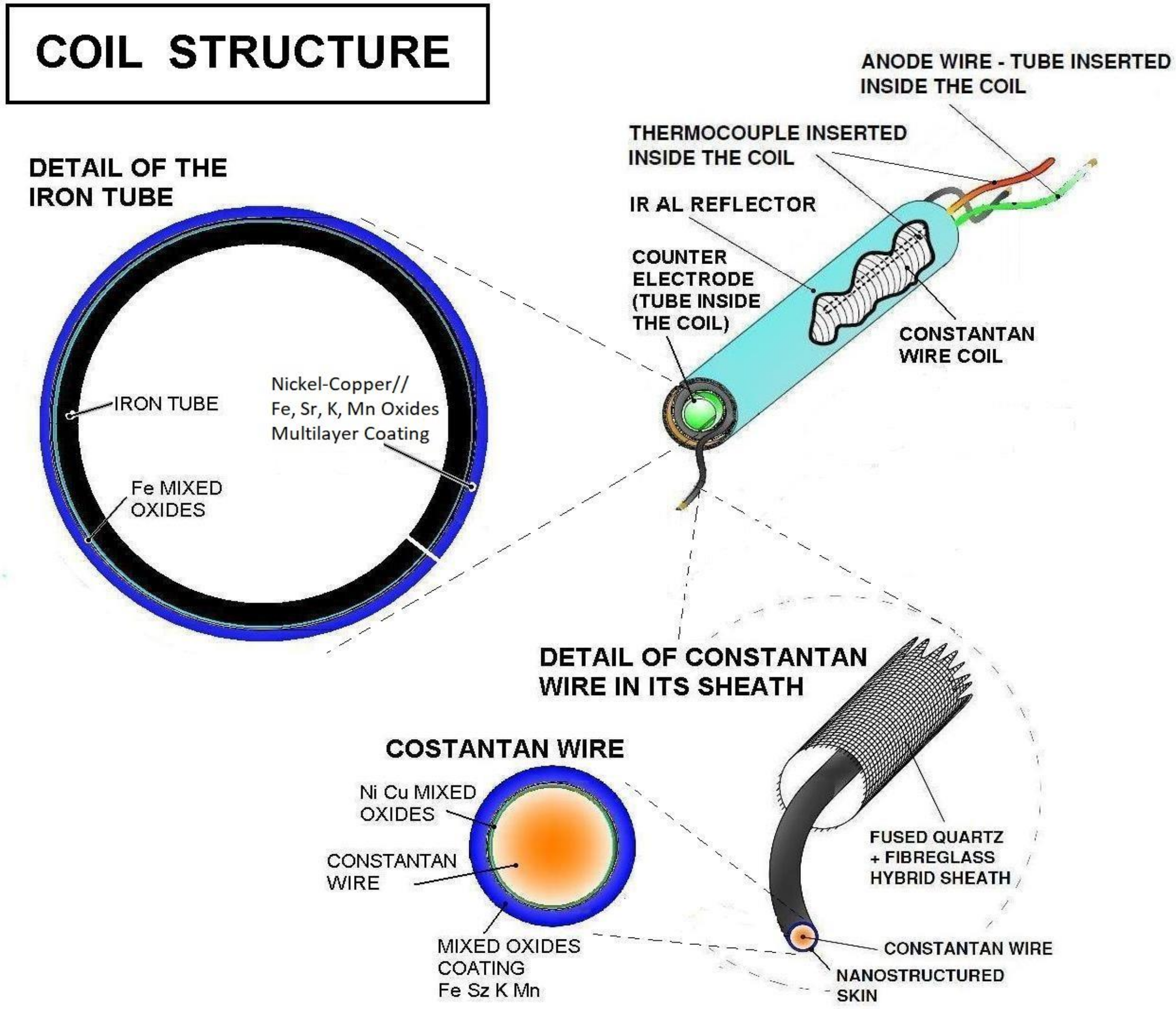


Fig.12B. Overview of the coil assembly comprised of a multilayer coating of LWF oxides; high temperature insulating hybrid glass-(AlO_2-SiO_2) sheaths; and an external IR reflector.

With respect to the circuitry used in previous experiments [4] (ICCF22), the following upgrade was made:

in addition to a DC power supply, used to heat the wire close to the operating temperatures (600-700 °C), a pulsed power supply was connected in parallel.

A) **The pulsed voltage-current, is expected to reach rather large peak values. For instance, using a test coil at NTP (i.e. in free air and room temperature), up to 13600 V*A (mean values of about 11000 V*A), duration 10 μs, were "injected" by the power supply without signs of damage (details in Fig. 14)**

B) **Considering the energy transferred on each pulse (110 mJ), the weight of wire (1.5 g), the Cp of Constantan (0.39 J/g*K) and supposing adiabatic conditions (i.e. negligible thermal conduction), the temperature increase, in the bulk of the wire, is probably less than 1 °C. However the overall energy provided by each pulse, although low on average, when localised at the surface due to electrical skin effect (due to fast rise time of the pulse) and "pointed" sub-micrometric structures on the surface, may increase the temperature at the surface of the wire of some orders of magnitude (hence up to few hundred degrees).**

C) The pulse duration can be varied from 0.5 to 10 μs. The measured current equilibrium time is about 2 μs when using:

A1) our "reference test coil" (l=160 cm; turns=75; Φ=350 μm; R_series=9 Ohm; L=1.8 μH);

A2) our capacitive discharge pulser (Fig. 13).

Main effect is due to the time constant of the coil itself. The repetition rate (RR), at high powers, can be varied up to over 1000 Hz using the reference test coil: it is limited by the maximum steady state power that can be applied to the wire (about 120 W). The measured intrinsic limit of RR, with short pulses duration and low-power, is as large as 30 kHz with proper setting of the pulser.

D) Resuming: the pulsed power supply cause, for each pulse injected:

D1) possibly, instantaneous temperature increasing of *some points* at the wire surface (thin layer), estimated up to 100 °C;

D2) extremely large electro-migration values, in the order of 2-3 V/cm, for the whole wire.

E) Moreover, because the coil geometry has intrinsically magnetic proprieties, we *take advantages of the extra-voltage that arises when the current pulse is ended abruptly.* Considering the inductance of the coil (about 1.8 μH), the typical peak current applied to the coil (50 A), and the time of current opening (about 80 ns), it is possible to get an over-voltage as large as 1100 V. *This voltage is then sent to a "peak detector" circuit (D7 and C4 in Fig. 13) that collects it and sends it back to the counter electrode[24] (iron tube core).*

F) One of key parameter for "in-phase" operations, i.e. the delay from the end of powerful Richardson regime and the time to get the High Voltage (to start the Paschen/DBD regime), was measured to be <100 ns. Such value is proper for our purposes.

This can nearly be considered an "additional" in-situ pulser.

G) Very recently we overcome the main limitation of using the "inductive opening extra voltage procedure" to generate, *in-situ*, High Voltage. Considering the well-known formula of V=L*(dI/dt), there is a complete correlation among the "wished" peak voltage (usually as high as possible, apart uncontrolled short-circuitry issues) and the intrinsic characteristic of the coil, included the peak current that can be managed safely, i.e. without catastrophic failures. In other words, we added a new specific circuitry (named VVB, i-e. Variable Voltage Booster), as shown in Fig. 13. In such a way the inter-dependence of the conditions between the end of the coil and the value of current applied was reduced *from 100% to about 20-30%,* increasing the possibility to can tailor the operating conditions to what really needed, *especially from the point of view of longer operation times without damages of the reactor's core*.

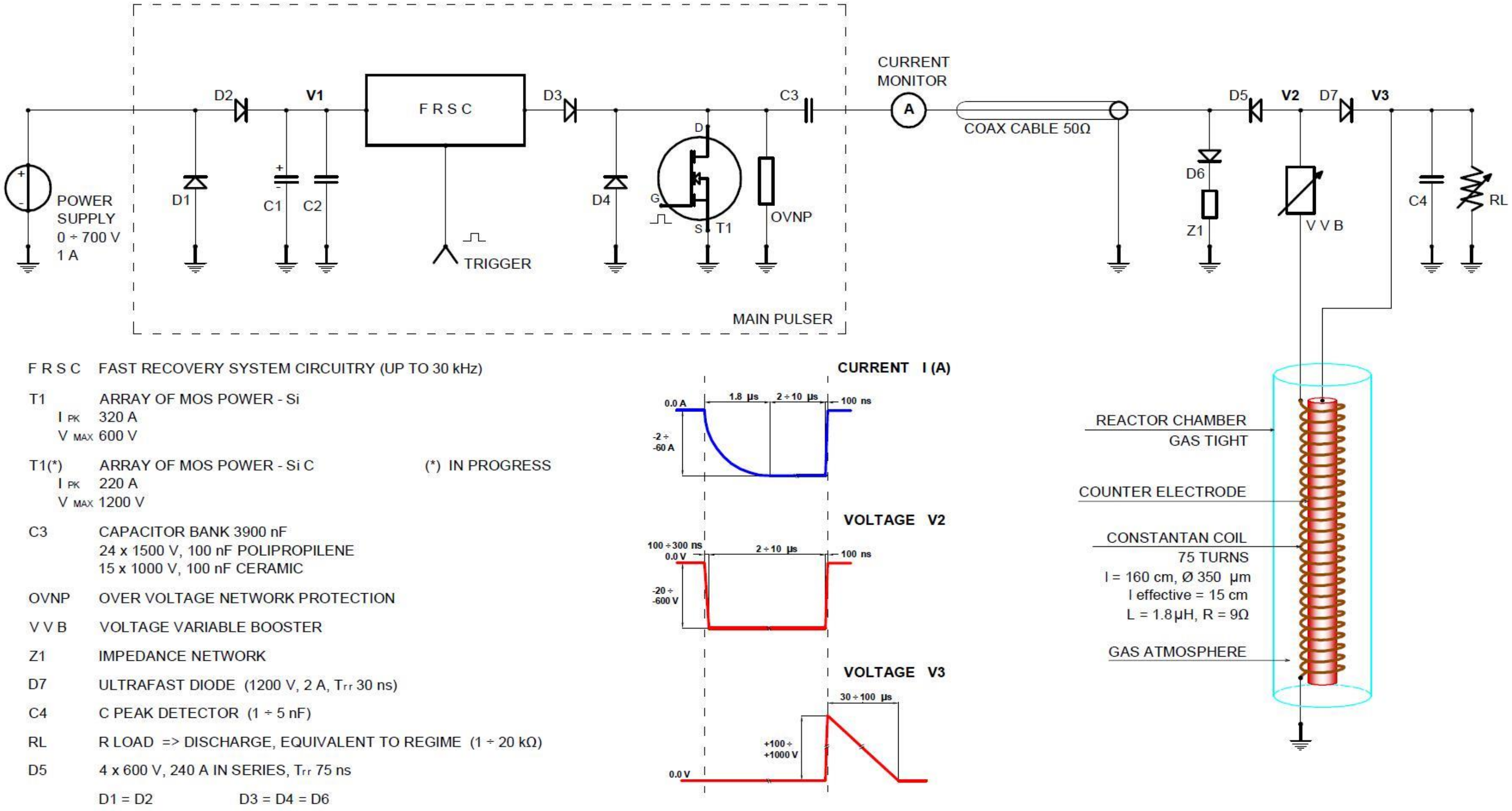


Fig. 13. Scheme of the assembly used to get negative high power pulses from the pulser (V2, I, up to 500 V, 50 A, 2-10 µs duration) and positive high voltage pulsed (V3, up to 1000 V). The pulse duration/fall is determined by the discharge mode along the electrodes (i.e. DBD and/or Paschen).

Operating principles[26]

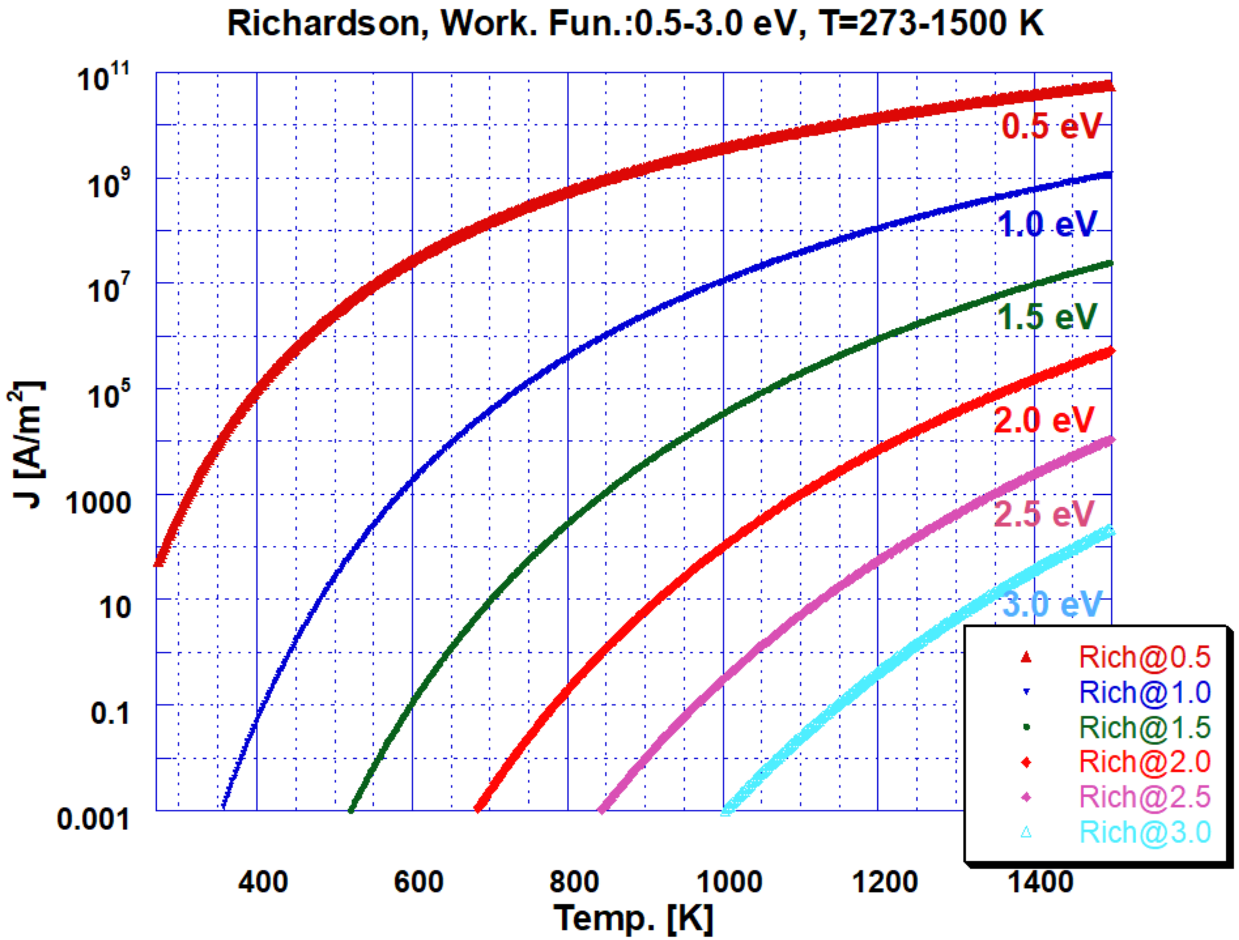
Fig. 14. Snapshot: Waveforms with Vdc=400 V for a Coil made of a 350 µm thick, 160 cm long wire. Pulse duration is 10 µs. Voltage (100 V/div), in red; Current (10 A/div) at the end=32 A, in blue. Pw in green, scale factor 4 → 4 kV*A /div.; peak power at 2 µs= 13.6 kV*A. The current rise time is about 2 µs (0→100 %). The HV at V3 is about 400 V, similar to excitation, without activation of VVB.

The reactor operating procedure is based on the application of various concurrent stimuli that were associated to AHE occurrence in previous experiments.

The pulsed power supply and reactor assembly allows in particular to optimize the timing of the stimuli producing the non-equilibrium conditions. These are a consequence of the following effects:

- **The Richardson effect occurs at high temperatures and allows a continuous flow of electrons from the surface of a material. In our case, the emission of electrons is increased at relatively low temperature thanks to a coating of low work-function oxides. The dependence of current density on temperature and work-function of material surface is shown in Fig. 15. With the LWF materials from us adopted, the usual values are 1-9--2.3 eV.**

Fig. 14A. Value of High Voltage, red colour, in the case of VVB activation. With only 100 Vdc, equivalent to a maximum current flowing of 8 A, the peak HV is 430 V. The *"efficiency" was increased 4 times*.



Electrons are emitted following the **Richardson law** for the thermionic emission at reduced pressure:

$$J = AT^2 e^{-\frac{W}{kT}}$$

Where:

J is the current density emitted (A/m^2)

T is the emitter temperature (K)

W is the work function (eV)

k is the Boltzmann constant (J/K)

A is a constant (in the simplest form of the law)

In our experiments, the current follows a trend analogous to the **Child-Langmuir law:**

$$B * S * \frac{V^{1.5}}{d^2}$$

where B is a constant, S is Anode surface, V voltage among Anode and Cathode, d their distance

Fig.15. Dependence of density of electron emission (A/m^2) on Temperature (273-1500 K) and Work Function (0.5—3.0 eV).

- **Child–Langmuir law. The electrons that "boil-off" at the surface of hot material at low gas pressures, can be accelerated/expelled when a counter electrode with a certain voltage is positioned at a sufficiently close distance from the material surface. The current intensity depends as $V^{1.5}$.**

- **DBD or Paschen gas breakdown. The current of the discharge depends on the distance among electrodes, pressure and the type of gas. Figure 16 shows this dependence for a typical Paschen discharge, while Figure 17 shows schematically the occurrence of a DBD discharge on the surface of the wires, and possible effects on electron density.**

- **With reference to the Paschen discharge curves, Fig. 16; we would highlight that the use of the LWF oxides coating on the wires, and of a Thoriated Tungsten (multiple wires) close to the reactor wall, allows to significantly reduce the breakdown voltage because γ emission. In the experiments of 2019 we collected evidence confirming that the Thoriated Tungsten is a useful enabler of Paschen discharges also in our experimental setup.**

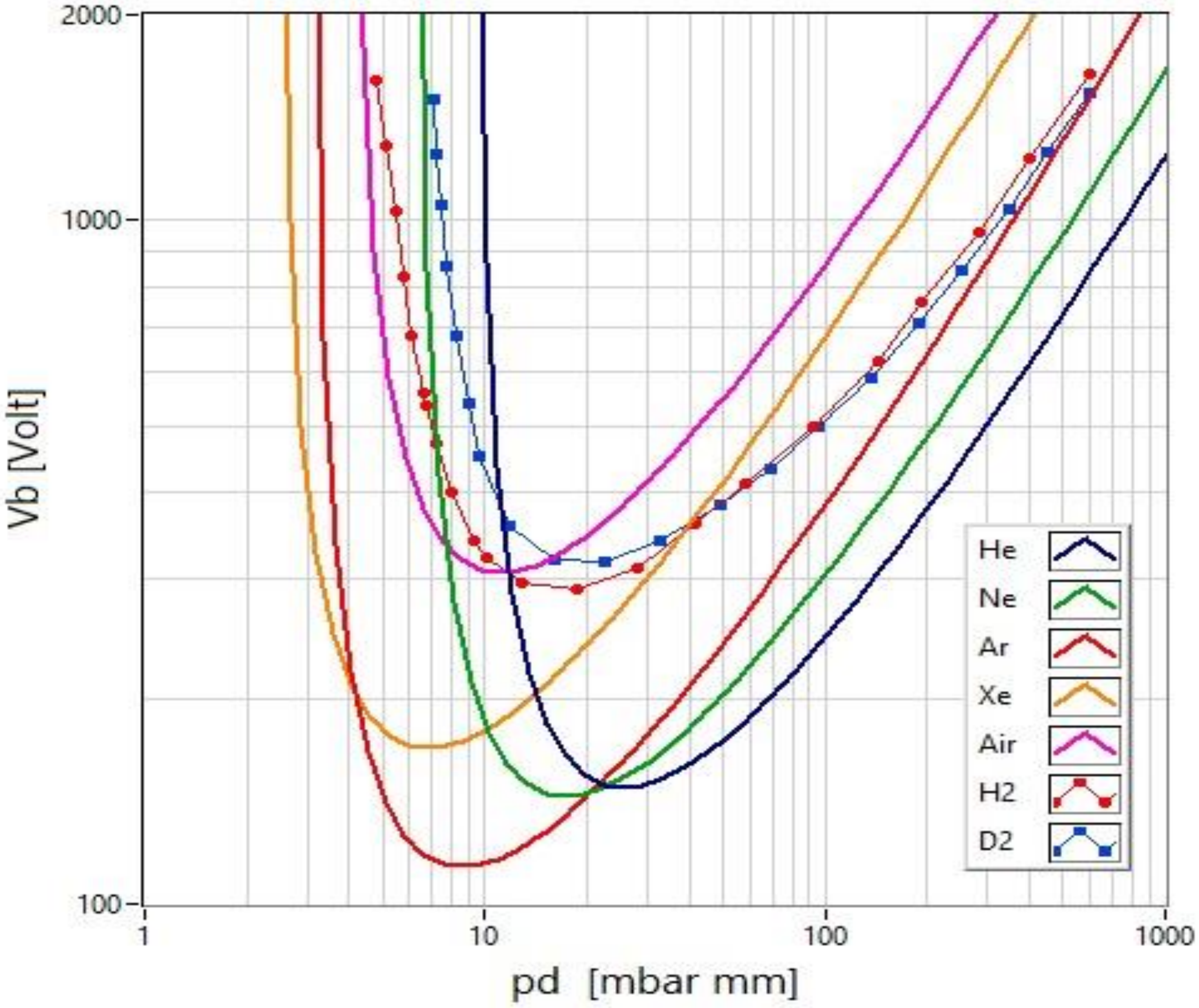


Figure 16. Direct current breakdown tension (Vb) of several gases versus pressure and distance between electrodes (p*d). The addition of Ar to D_2 clearly enables discharges at a lower voltage.

A similarity of pulsed coil reactor with an Otto engine

The Otto-Benz engine working principle may offer an intuitive comparison with the process steps of the new power supply and reactor core design.

The specific arrangements of the circuitry, with its steps and their timing, remembers indeed the functioning of an Otto engine, where a spark-plug ignites a petrol-air mixture via an electric high voltage discharge. Similarly:

- ***The high-power long pulse (up to 10 μs), increases the temperature of low work-function oxides in some specific points: initiates electrons emission. This step is "comparable" to an almost adiabatic compression of air-petrol mixture. The ignition step of a spark-plug corresponds instead to the ionization of the active gas among Constantan and counter-electrode.***

Conclusions: Richardson-Paschen/DBD stimulation "mode"

- **The proposed new setup and process, apart the required optimizations and adaptations, is based on the previous experience with Palladium wires, both in electrolytic and gas-phase experiments.**

- **The energy gain, using thin and long wires of Palladium, ranged between 15 and 30% while some experiments showed values as large as 250%, although for short times.**

- **The main drawback was the frequent break of the wires, due to an excessive brittleness of Pd after absorption of Deuterium.**

- **Moreover, the overall experiments duration was limited to few hours when highest energy gains were observed.**

- **The ionization in gas-phase systems by electric discharges was reported by our group at ICCF22, but has not been explored to the full potential, that is instead the focus of the new proposed experimental setup.**

- **The coaxial coiled Constantan set-up, preliminarily evaluated in experiments performed on June-September 2019, showed clearly that AHE occurs mostly due "non-equilibrium" in the wires.**

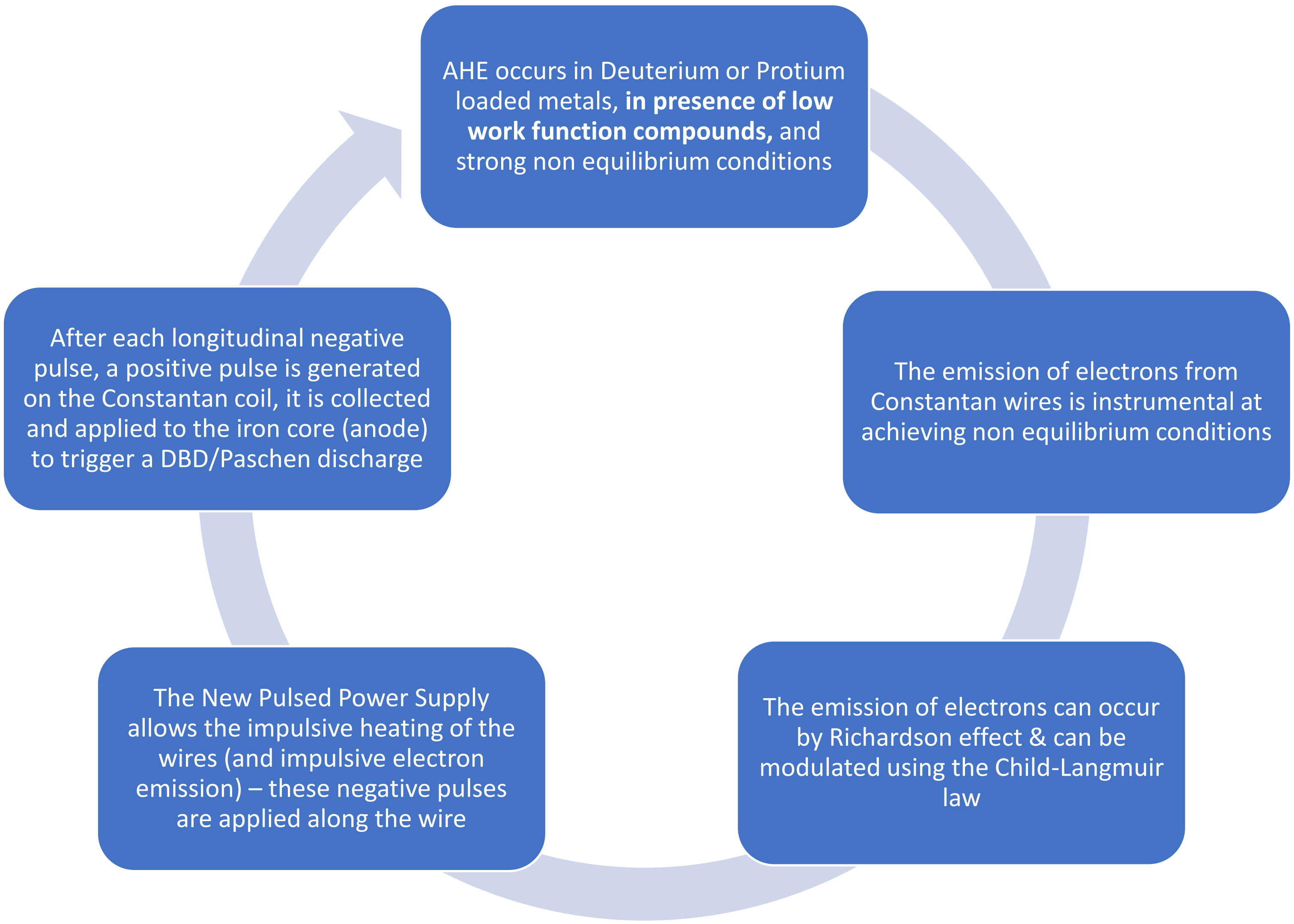
- **This was proved already applying a mild 50 Hz sinusoidal excitation (voltage up to + - 600 Vpk at the counter-electrode).**

- **The new proposed setup is leveraging on the experience built since 1994 with high power pulses, and on a long series (since 2011) of experiments with *Constantan, a very robust alloy that proved to withstand various experimental conditions and temperatures as high as 900 °C for several days.***

- **We are confident that the proposed setup, comprised of a multistep pulse excitation, may turn to be a significant step toward a practical application of LENR-AHE technologies.**

- **The first results from the experimental setup object of this preliminary proposal are expected in Q2-Q3 2021**

A Graphic Summary of the Current Experimental Process



Acknowledgements

We are indebted to a Metallurgical Company in the **North-Eastern part of Italy (NEMC)**, which since 2011 provided some financial support and performed key experiments in their own Laboratories (with their Scientist and Technicians). In fact, a fully independent cross-check of our most critical experiments was useful to increase the confidence on reported results.

Since 2017 we initiated a multiple collaboration with **NEMC** and **SIGI-Favier** (Italy-France), to design an original hybrid sheath obtained by crossing glass and Alumina–Quartz fibres, (these sheaths are used for the electric insulation of the wires). These original sheaths can continuously operate up to 1200 °C and, thanks to a tailored geometry, may adsorb significant amounts of Atomic Hydrogen[27].

We thank **"Franco Corradi S.A.S."** Company (Rho, Milan) as they provided some high performance thin alumina tubes used for heavy-duty test up to 1100 °C.

Special thanks to the Scientists involved in the CleanHME European project, chaired by Konrad Czerski (Szczecin University, Poland). In particular, for the fruitful collaboration with Prof. Bo Hoistad and Collaborators (Uppsala University, Sweden) as well as with Dr. Andras Kowacs from the Company Broadbit.

This work has received funding from the European Union's Horizon2020 Framework Programme under grant agreement no 951974.

[27] Some types of glass, such as those used in our original sheaths, are able to adsorb atomic hydrogen at their surface, but not the molecular as discovered by I. Langmuir in 1928. Glass is also a "buffer" of LWF elements.