Research Article

Electromagnetic Excitation of Coaxially-Coiled Constantan Wires by High-Power, High-Voltage, Microsecond Pulses

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Abstract

This paper is mostly based on our presentation given at the 23rd International Conference on Condensed Matter Nuclear Science (ICCF23) held at Xiamen University (XMU)-PRC on June 9-11, 2021. Upon the suggestion of the Conference Organizers, we added a detailed explanation of our procedures; moreover, we included the latest results and data from our recently published papers. In the framework of LENR-AHE (Low Energy Nuclear Reaction - Anomalous Heat Effects) studies, since 2021, we have been focused on innovative, low-cost materials instead of the usual, precious metal palladium. We found that the Cu-Ni alloy, known as Constantan (also used for J-type thermocouple construction), has the peculiarity of being able to easily dissociate H_2 (or D_2) from molecular to an atomic state. While the catalytic feature appears at a rather low temperature (150 °C), Constantan is also able to store atomic hydrogen within its lattice and/or at surfaces, up to temperature of 700-800 °C, and in a wide range of pressures. Thanks to our long experience (since 1994) with wires, we designed various experiments that take advantage of such specific shapes, namely in terms of electromigration of absorbed and adsorbed H, under a suitable longitudinal electric field (0.4-2.5 V/cm), DC and/or pulsed. In 1995 we got noticeable results using Pd wires in electrolytic environments (D_2O) at mild temperatures (40-60 °C). Later on, in some experiments, we used even gaseous environments at high temperatures (up to 700-800 °C). The main problem of Pd was its

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large brittleness after H or D absorption. Moreover, we experimentally reconfirmed that one of the key conditions to induce AHE is the "*flux*" of H moving inside its lattice (longitudinal) or through the surface (transversal). Pioneers of transversal flux were G. C. Fralick-NASA [1]; M. McKubre-SRI [2]; Y. Iwamura-Mitsubishi [3], [4], [5]; Y. Arata-Osaka Univ [6]; F. Celani-INFN [7]. We focused mainly on *longitudinal flux* (following also the theoretical models developed by G. Preparata-Milan Univ. [8], although some of our unconventional electrolytic experiments (1995-1998) had both. In any case, apart from the initial state (the situation of intrinsic hydrogen concentration gradients), the flux needs external energy to be continuously activated. Based on our own experiences since April 1989, AHE are due to *non-equilibrium conditions*, i.e., they need continuous stimulation, usually energy consuming, apart from some specific (but delicate) geometric set-ups (such as the *Capuchin knot*, which we began testing in 2018, in some of our geometric arrangements where local thermal gradients were extremely large: > 100 °C/mm). Recently, we developed an unconventional geometry of the electrode we aimed to use, and at almost the same time, longitudinal and transversal flux at high temperatures in gaseous environments: our goal was to minimize extra energy added, to maximize the AHE and keep it operative for as long as possible. We report here on procedures to enable flux by high power electric pulsing with both related problematics and peculiar advantages, some unexpected. The core of the reactor is arranged as a *reversed coaxial coil* with inner electrode made by a Fe tube, which we described beginning in 2019 at ICCF22.

Keywords: H_2-induced LENR-AHE, H_2 electromigration, High power electric pulses, Hydrogen flux, Memory effect

1. Introduction

This paper summarizes the presentation given at the 23rd International Conference on Condensed Matter Nuclear Science (ICCF23 at the Xiamen University (XMU)-PRC on June 9-11, 2021). This presentation was given via web-conference due to Covid-19 limitations. We are obliged to highlight that this paper is rather complex due to the exploitation of techniques coming from different and distant fields of science.

We report some preliminary results on the electromagnetic field stimulation of LENR phenomena in coated Constantan wires in a hydrogen atmosphere. In particular, the use of microsecond longitudinal current/voltage pulses triggers the occurrence of modest anomalous heat effects (AHE). Speculatively, the phenomenon is mediated by large non-equilibrium conditions and the electro-migration of active species in the Constantan wires. This stimulation technique seems to induce an *activation* of the material, and its effects on AHE remain noticeable for long times, even after pulse stimuli are ceased. The preliminary findings reported in this presentation confirm earlier experiments with the same technique already studied, by us during the nineties, in electrolytic experiments using Pd wires [7].

2. TOPICS

- Introduction to the current-voltage pulse approach[1] in the study of anomalies in hydrogen and/or deuterium-metal systems. From the initial electrolytic near room temperature experiments with LiOD-D_2O and palladium [7] to (present) gas phase experiments with Constantan up to 900 °C [9].
- Overview of the techniques explored from 2018 to induce AHE (Anomalous Heat Effects) at different temperatures, pressures, voltages, and the exploitation of electron emission as a tool for non-equilibrium conditions[2].
- Stimuli based on the Richardson effect and space charge modulation (Child-Langmuir law [10]).
- Use of Dielectric Barrier (DBD) or Paschen discharges.
- The correlation between AHE occurrence and electron emission mediated by: Richardson effect, Child-Langmuir effect, Paschen discharges.

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[1]The use of pulse had been pioneered at INFN in 1994, other authors have explored similar approaches since then [36] [38].
[2]The authors have clear evidence that LENR phenomena tend to occur only in presence of non-equilibrium conditions.

- Modified Constantan wires heated with direct current (DC) in the presence of a transversal mild excitation (a few milliamps, ±600 V, 50 Hz sinusoidal): recent advances, on the reactor design based on coaxial cathode-anode wire geometry[3], and related operating conditions [9]. Further progress was as follows:
  - A) Description of the latest high power, fast rise-time, pulse excitation approach to induce a large instantaneous flux of active species across interfaces[4] of the materials:
    - A1. longitudinal electromigration and surface high current density (skin effect included but with its effective role to be fully quantified).
    - A2. some preliminary evidence of the surface activation of the wires by a plasma of hydrogen-noble gas mixtures.
  - B) Some experimental results and next steps: advantages and drawbacks of nickel alloy field excitation.

3. Introduction to Current-Voltage Pulse Approach [9]

The use of longitudinal/transversal current/voltage pulses as LENR stimuli was pioneered by our group at INFN beginning in 1994. The original implementation was conducted in electrolytic experiments comprised of palladium-yttrium alloys (specially developed for us by the precious metal company, Tanaka K. K. in Japan). The use of pulses aimed, mainly, at enhancing the electromigration of deuterium or protium. Moreover, pulses were already considered as the enabler of strong non-equilibrium conditions. The whole program, since 1995, started with the study of electromigration of protium[5] isotopes and its effects on LENR occurrence, and with the investigation of the potential occurrence of "*Coherence*" phenomena as per Giuliano Preparata's model [8]. See **Annex A.**

In short, the so-called electromigration effect is controlled by the amplitude of the voltage drop divided by the length (V/cm). Usual values are on the order of 0.05-1 V/cm. In the case of Preparata's effect, in some specific conditions of "coherence", the effect depends on the TOTAL voltage along the wire. His advantage is evident, mainly by a large reduction of power dissipated. The main drawback is the extreme difficulty of achieving such conditions. As a practical matter, it is quite difficult to obtain Coherence for wire lengths over 10-20 cm, at least in our experimental tests since about 1994. Moreover, we observed that over such length some unusual phenomena, like increased conductivity, almost disappear or were difficult to detect. A possible reason is some unpredictable over-accumulation of impurities in specific points along the wire, due to electromigration itself. In other words, this could be a self-limiting phenomenon.

The electromigration effect was experimentally discovered by M. Gerardin in 1861 [11] and studied later by Alfred Cohen *et al*. in 1929 [12], among others.

After an initial study of the effect of direct current, our focus shifted to the use of powerful microsecond pulses.

This program enabled us to compare the effect of direct current and pulsed stimuli and resulted in various publications.

Already at that time it became clear that palladium did not have much future in *practical applications*, due to both its high cost and brittleness upon H or D absorption. The lack of robustness had a negative impact on every experiment with thin wires[6] which were prone to break very easily. Afterward, and beginning in the early 2000's, the work shifted from the investigation of a palladium-based systems to simpler, and cheaper, DC experiments with nickel (2002) and later with its alloys (since 2011). In 2011 we started the investigation of Constantan ($Cu_{55}Ni_{44}Mn_1$) due to its low cost and the capability to withstand temperatures as high as 900°C. Moreover, this alloy shows AHE activity using both

[3]Presented at ICCF22, 8-13 Sept. 2019, Assisi-Italy.
[4]Surface or bulk interfaces.
[5]The study of proton electromigration was pioneered by Alfred Cohen [12]-Germany.
[6]The best geometry to maximize and observe electromigration, or coherence, phenomena.

deuterium and hydrogen gases, although frequently we found "transition time" of AHE when changing gas (typically H_2, D_2) and the AHE vanished and/or was even negative in respect to the calibrations (usually by He gas).

In other words, the unique set of properties of this alloy can be summarized as follows:

- Low cost.
- Its noteworthy capability to dissociate H_2, D_2 molecules to the atomic state H, D, and their absorption from 150 °C up to about 700 °C [13].
- High robustness in harsh experimental conditions.
- Once "activated", a Constantan wire heated by a large direct current shows the occurrence of AHE, provided that the temperature is sufficiently high. However, the wire "activation" remains the most difficult task to achieve.

We have been able to detect a modest AHE, with satisfactory reproducibility (i.e., of academic interest only, at least at the moment), when the following conditions are met:

- Sufficiently high temperatures and large thermal gradients along the wire. We tested such effects developing the so-called "Capuchin knot" geometry. Anyway, although this is a very promising approach to minimizing added external energy, it was difficult to perform because of several practical geometric constraints. In the end, we were forced to quit, even though it is in principle an excellent approach.
- The surface is rough, being micro-structured, or better, nano-structured, and coated with Low Work Function (LWF) stable oxides [14], [15], [16];
- A flux of atomic or ionized deuterium or protium is induced in the wire.

In short, *non-equilibrium conditions*, enabled by various physical-chemical techniques, are compulsory to produce excess heat and possibly other effects, similarly to the better/deeper studied Pd-based systems.

4. Overview of the Techniques Explored

The critical parameters for a practical application of Anomalous Heat Effects (AHE), are:

(1) Establishing a reliable and simple procedure to "activate" and keep stable over time the metal (or alloy) where AHE occurs.
(2) Finding a process to "renew-refresh" in-situ the material, counteracting the "aging and deactivation" that almost always occurs. By the way, such "negative" behavior is like the well-known deactivation of Fe, Ni, Cu, Mn, K based catalysts used in chemical processes.
(3) Minimizing the extra power used to stimulate the "non-equilibrium" conditions needed for AHE occurrence.

In Fig. 1 we summarize the technical solutions adopted over time to obtain conditions for AHE occurrence with surface-modified Constantan wires.

The main degrees of freedom of the experimental set-up wires are:

a) core geometry.
b) wire diameter.
c) pressure and gas mixture recipe (H_2, D_2 or their mixtures with noble gases, mainly Ar).
d) maximum peak voltage allowable between the Constantan wire cathode and the tubular anode.
e) temperature.

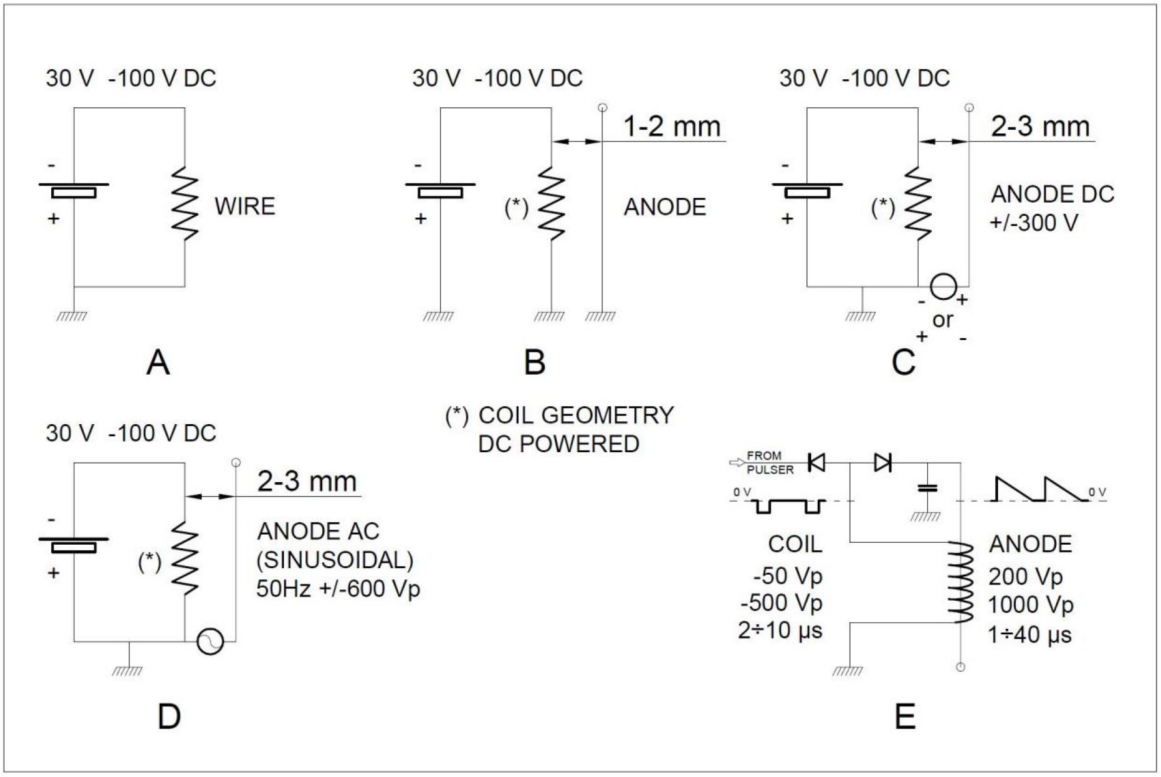


Figure 1. Different wire arrangements used to enable an increasingly more effective field stimulation in the last decade (2011–2021), starting from the simplest A in 2011, to the more elaborated E (2020–2021).

Background: reactor core geometry:

a) On the basis of the strong experimental evidence that non-equilibrium conditions are essential to obtain AHE, a new geometry of the reactor core was designed.
b) The wire is arranged to fully exploit the power of pulses and their electromagnetic effects, as follows:
   b.1) First, high-power longitudinal negative pulses over-heat mainly the wire surface. This is due to combined effects to get a large skin effect with: very fast-rise time and short pulse duration; magnetic material at the surface. The skin depth is given by the well-known simplified formula:

$$\delta = (\rho / (\pi * \nu * \mu_r * \mu_o))^{0.5} .$$

In this formula: δ is the skin-depth of the current injected; ν is the frequency in Hz; μ_r is relative magnetic permeability of the conductor; μ_o is the magnetic permeability of free space ($4\pi*10^{-7}$ H/m). Although the virgin Constantan ($Cu_{55}Ni_{44}Mn_1$) we usually used (IsabellenHutte-Germany) is not magnetic, we very often *measured* at room temperature magnetic behavior after prolonged current treatments at high temperatures ($> 800°C$) needed for the oxidation, to get spongy surfaces, and the addition of relatively large value of Fe. In fact, the LWF mixture is made by: Sr=10, Fe=10; K=1, Mn=1. This liquid mixture is "painted" several times over the Constantan wire surface by intermediated high temperature

cycles. We recall the unique ability of Constantan to dissociate H_2 to H is quite constant even in the large relative range of composition of Cu/Ni from 80/20 to 20/80. Regarding the possibility of demagnetizing Fe (because the temperature was close to the Curie temperature of 768 °C), we recall that the stationary temperature of the wire, before pulsing, is on the order of 500-700 °C: measured by the K type thermometer put inside the Fe counter electrode.
In fact, although very promising, the effectiveness of the skin effect is difficult to assess precisely with the setup used: this should be further investigated in the future.

This results in the "boiling-off" of the electrons emitted by Low Work Function material covering the sponge Constantan wire due to the Richardson effect: apart from the "help" by the instantaneous skin effect, at least when the repetition rate of pulses (also considering gas composition-pressure) is large enough to keep the mean wire temperature suitable for such electron emissions.

b.2) Second, self-generated High Voltage-Low Current positive pulse. Such pulse is sent to the Fe counter-electrode tube (Fig. 2A) on which the Constantan wire is wound in the shape of a compact coil, having a high value of inductance L. By elementary considerations of electrodynamics (e.g., Faraday-Neumann law and very fast rise-time, <100 ns at the end of the input pulse) a high voltage with opposite polarity to the main is generated (Fig. 8, red color curve). The value of peak voltage is related to the variation of current (I) over time (t) as: $V=-L*dI/dt$. It is used, depending on the pressures, both to accelerate the electrons toward the anode (Child-Langmuir effect) and/or to induce the breakdown of the active gas (Paschen/Dielectric Barrier Discharge effects). The diameter of the Constantan-Fe counter electrode is typically <1 mm because the glassy sheath is thin. The glass insulation sheath covering Fe is micrometric porous. It fills the volume between the cathode (Constantan wire) and the anode (Fe tube on which the insulated Constantan wire is coiled).

c) The "in-situ" pulse generation leverages on the short distance between the negative Constantan coil (that generates the positive pulse at the end of the input pulse) and the Fe core anode. This approach enables an effective energy transfer from extremely fast pulses, thus reducing the unwanted problematics of: impedance mismatching, parasitic capacitive effects. The complex circuit is a suitable compromise among values of inductance and storage capacitor (C2 in Fig. 3). Anyway, because of large variations of operating points and "aging effects" no attempts were made to tune by C2. Its value was selected mainly in respect to maximum voltage allowed before uncontrolled short circuits could happen, although circuitry (based on Zener diodes and other ancillary circuitry, not shown in Fig. 3 for simplicity) was used to prevent further damage arising from overvoltage situations.
d) In addition, this allows us to have a sequence of thermal pulses able to increase electron emission when the temperature is appropriate for the Richardson effect of the Low Work Function (LWF) materials (multilayered mixture of Sr, Fe, K, Mn) coating the wire. The multilayer structure in LENR was pioneered by Yasuhiro Iwamura-Japan [3], [4], [5], since 1998 (at that time at Mitsubishi Heavy Industries, Yokohama). Since 1998, although the layers used by Iwamura were much thinner, we used simple chemical paint procedures. We tried to have some control of the coating thickness by varying the concentration of the solution (which was usually quite low). Obviously, by our simple procedure, the control of the thickness is less accurate and reproducible compared to the sophisticated one adopted by Iwamura.
e) Together, these are the starting points for longitudinal impulsive electromigration, with even diffusion speed of hydrogen increased because of higher temperatures.
f) Moreover, if suitable conditions of gas pressure and voltage are reached, as shown in Fig. 5, it is possible to enter the Paschen regime that can allow both increased non-equilibrium condition and renewing surface of

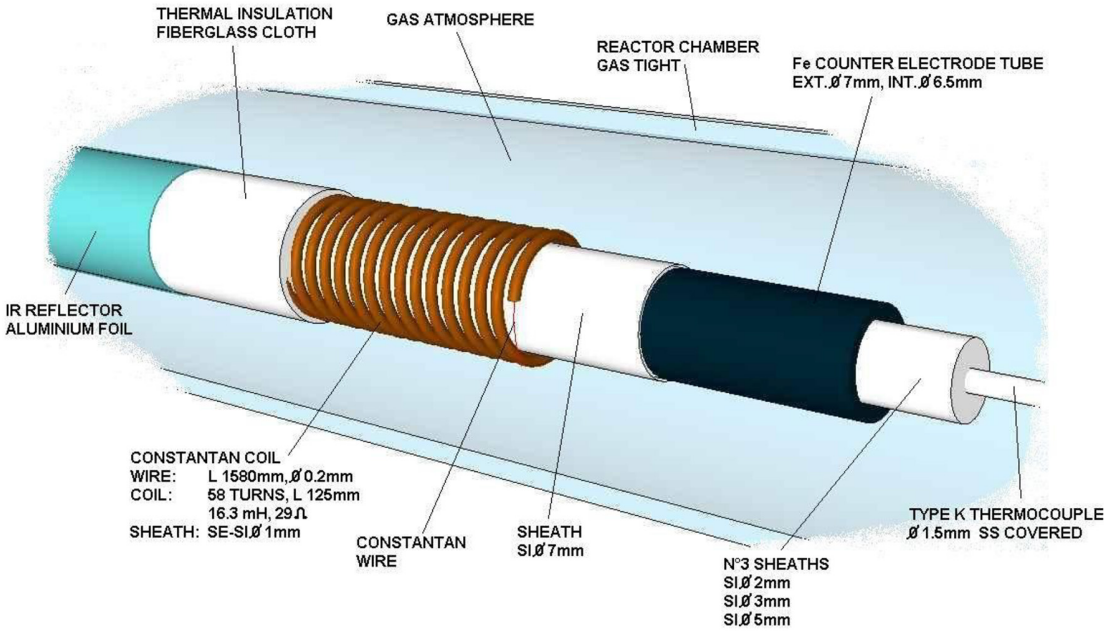


Figure 2. Schematic of the coaxial coil with its inner Fe counter-electrode. The wire, length of 158 cm, is arranged as a coil with a typical length of 12-14 cm. The coil usually had 75 turns; recently reduced to about 50 (i.e., with a larger diameter) because of problems with HV insulation. The sheath on Constantan wire is a fabric made of two kinds of main materials: a) SE, a glass similar to the composition of a tungsten light bulb, with a maximum operating temperature of 700 °C, and unusual atomic hydrogen surface adsorption; b) SI, a mixture of Al_2O_3 and SiO_2, with a maximum operating temperature of 1200 °C; c) SE-SI, a mesh of SE and SI (produced under our specific request by SIGI-Favier Company).

constantan wires (if sintered). We think that the Paschen regime, because it acts each time on different localized points of the wire, is able to promote "fresh" surfaces just by electric erosion. The main drawback is that if the erosion is excessively strong in localized points, the wire will break. *This is still now an open problem*. DBD regime is possible in condition far from the optimal Paschen one, as qualitatively shown in Fig. 6.

g) In conclusion, the reactor is based on a coiled coaxial structure (made of sponge Constantan wire with surface coated by LWF materials) with the inner core used as a counter electrode. Its schematic and key details are shown in Fig. 2A, 2B.

We recall that the unusual property of SE glass was discovered in 1928, by chance, by Nobel Laureate Irving Langmuir. In that case, the atomic hydrogen was produced by tungsten wires at low pressure and very high temperature (2700–3200 °C): research related to the development/optimization of incandescent light bulbs [37]. In our case, the operating temperature is only 200–800 °C, thanks to the unusual property of hydrogen dissociation by Ni-Cu alloys (from 20/80 up-to 80/20 relative composition).

The system was organized to be quite versatile, allowing it to enter several chemical-physics regimes: Richardson, Child-Langmuir, Paschen, DBD. Such regimes are activated just by changing gas pressure and anode-cathode voltage. The cathode, put along the geometric center of the coil, is just the iron tube as shown in Fig. 2A.

1) Richardson operation mode: electrons are emitted by LWF materials covering the Constantan wire by a simple thermionic effect. The anode is almost disconnected (or grounded by high impedance): low voltage in respect to the cathode, also movement of electrons at surface are at low values, just "boiling off" at the surface.

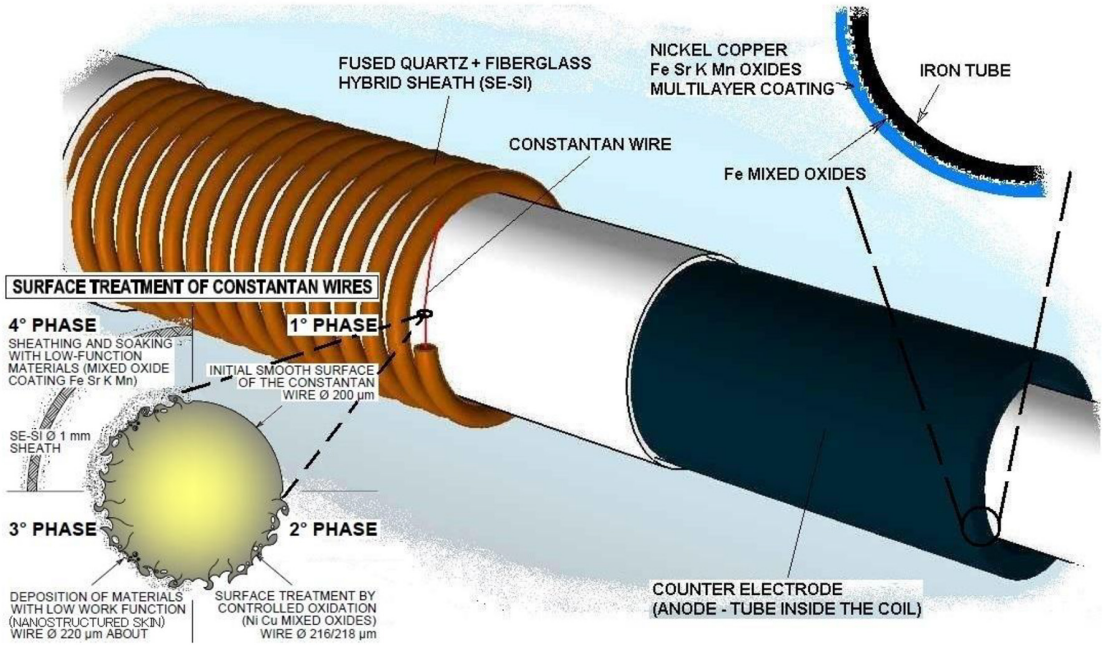


Figure 2B. Overview of the coil assembly: multilayer coating of LWF oxides; high temperature insulating hybrid glass (Al_2O_3-SiO_2) porous sheaths; external IR reflector. The structure of the wire has 3 main multilayer sections: a) inner with pure Constantan ($Cu_{55}Ni_{44}Mn_1$), "true bulk" about 190 µm diameter after oxidation procedures; b) external with mixed Cu_x-Ni_y composition oxidized to create sponge structures; c) sponge structures filled by Sr, Fe, K, Mn mixed oxides. Because of uncontrolled leakage during the coil conditioning with sheaths inserted, some amounts of mixed oxides (even Cu-Ni) could cover the Fe surface. The several steps for wire constructions, and related details, are described in the insert named: phase $1°, 2°, 3°, 4°$.

2) When gas pressure is low enough ($\ll$ 1 mbar) it is possible to activate a "Child-Langmuir" regime that allows boiling electrons to flow toward the anode with current density that depends on voltage as $V^{1.5}$, according to the literature [17] in parallel plate geometry.
3) Paschen/Dielectric Barrier Discharge modes: if the voltage of applied pulses and pressure are suitable, a gas breakdown occurs. This regime, we believe, is the most suitable to generate AHE because the hydrogen atoms stored inside the sponge surface of Constantan are forced to go through the surface. Previous experiments, shown at ICCF22, provided evidence that in these conditions (2&3) the highest and longest lasting AHE can be obtained. Anyway, as pointed out several times, we were not able to "control" the intrinsic spark regime for a long enough time (days or weeks) in a reliable way, suitable to develop practical applications.

5. Latest High Power, Fast Rise-Time, Pulse Excitation Approach

A) To continue, for each pulse injected, impulses cause the following effects:
- As clearly shown in Fig. 2A, there is a K type stainless-steel (SS) covered thermocouple at the inner core of the reactor. As a consequence, the temperature reported is lower than the real wire temperature. In respect to instantaneous overheating of the thin-skin wire's surface it is *estimated*, by considering the conditions of the largest injected power for each pulse (4.5 kW peak, about 4 kW mean), with a rise

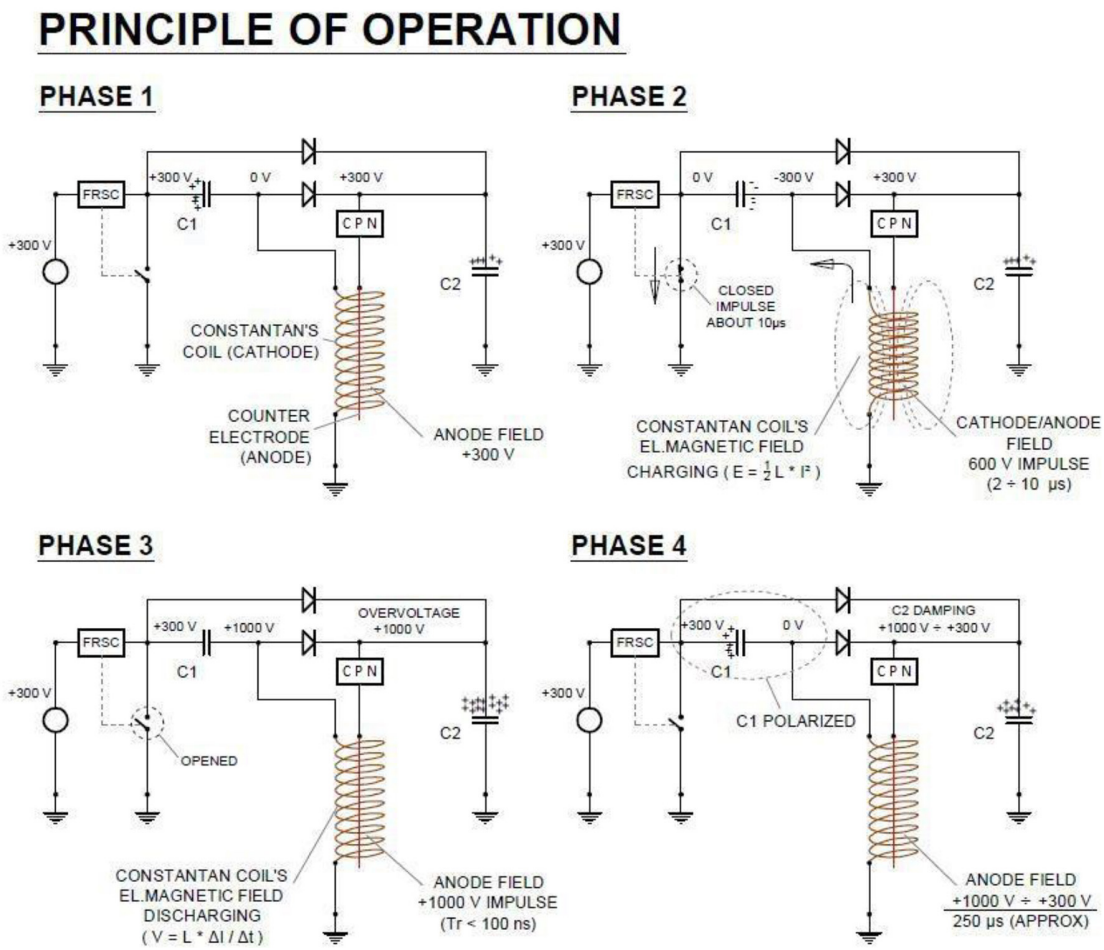
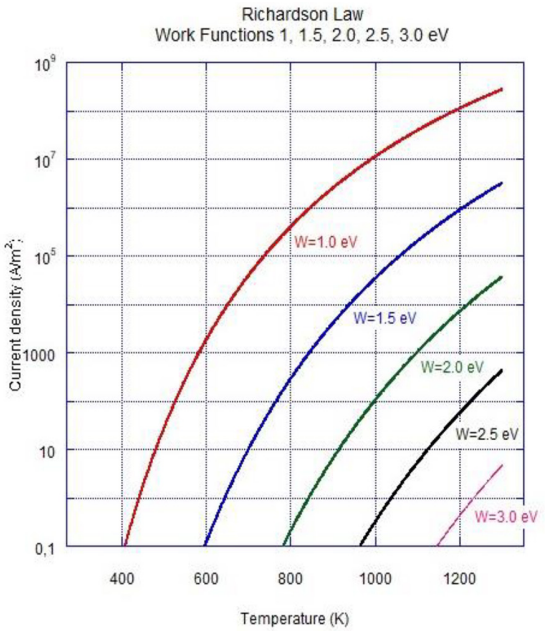


Figure 3. Schematic of the pulser with main auxiliary circuits, depicted as a "black box".Pulse duration/fall at Fe counter-electrode is determined by the discharge mode along the electrode itself (i.e., DBD, Paschen): it is dependent on the kind of gas, pressure, and inter-electrode distance. The term **FRSC** means: Fast Recovering Synchronized Charging. The (unusual) circuitry was developed by us since 1994. The aim is to operate at quite high repetition rate (up to 30 kHz in some cases) at high energetic efficiency, without using the usual inductance-resistance network. It decouples the main switch from the power supply, in the figure at +300 V, during the time of power switching conditions. The term **CPN** means: Controlled Peak power Network. It was introduced to reduce excessive power injected to the Fe tube (the counter electrode) that is connected, by surrounding gas, to the main coil. Anyway, up to now, the practical results by using the present CPN circuitry were not satisfactory enough for long term (days or weeks) operation: the thin Constantan wire (Φ=200 μm) frequently failed catastrophically.

time of a few microseconds and skin depth of a few micrometers, that the maximum peak temperature increasing could reach large values (several tens of degree Celsius) in respect to the stationary one (500-700 °C), depending on the operating conditions of pulses and insulation. Although the temperature increase apparently is not very large (some tens of degrees Celsius), it could be quite effective in electron emission phenomena recalling the exponential nature of it toward temperature (Richardson law, Fig. 4 and formula therein).



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)

k is Boltzmann's constant

W is the work function (eV)

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

Figure 4. Calculated dependence of density of electron emission J (A/m^2) on Temperature (273–1500 K) and Work Function (1.0–3.0 eV), according to the Richardson law. Because of specific treatments at the wire surface, which is sponge-like, the effective surface is about 100 times larger (based on SEM observations): in the case of our 200 μm diameter, 158 cm long wire, it increases from 10^{-3} to 10^{-1} m^2. With W = 2 eV, J is 10^1 A/m^2 at 730 °C and jumps to 10^3 A/m^2 at 980 °C. J depends largely on both temperature and work function.

- Extremely large electro-migration "driving force" values, on the order of 1.5-2.5 V/cm, as measured by a 100 MHz digital oscilloscope during pulse conditions. Sometimes an analog oscilloscope was also used, 200 MHz BW, for cross-check purposes. The data were consistent.

B) At the start of a voltage pulse only the Richardson effect is present. It takes less than 100 ns to reach a voltage level sufficient to start the Paschen/DBD regime.

6. Operating Principle

The reactor operating procedure is based on the application of various concurrent stimuli that were associated with AHE occurrence in previous experiments (like the ones presented at ICCF22).

The "new" pulsed power supply and reactor assembly allows us in particular to optimize the timing of the stimuli producing the non-equilibrium conditions. As anticipated, these are consequences of the following effects:

6.1. Richardson Effect

The Richardson effect and its formulation (Fig. 4) occurs at high temperatures. It allows a continuous emission of electrons from the surface of any material. In our case, the emission of electrons is large even at relatively low temperature thanks to a coating of Low Work Function oxides (1.9-2.3 eV).

From the Richardson law equation [18] (shown in Fig. 4), it is evident that values of *W as low as possible* are needed to avoid operating temperatures excessively large (over 1000°C). In our experiments we used mainly SrO, K doped

(at 10% concentration), to have a value of W close to 2 eV. All the wire pretreatments processes (i.e., repeated surface oxidation <–> reduction steps to get submicrometric sponge-like surfaces, i.e., large effective area) and multiple chemical coatings (multilayers procedure), are homemade.

6.2. Child-Langmuir Law

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

In detail:

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

Where:

- J is the Current density,
- B is a constant,
- S is Anode surface,
- V is Voltage among Anode and Cathode,
- d is Anode-Cathode distance.

We point out that the Child-Langmuir regime was used only in some specific conditioning procedures of the wire: sometimes we verified, under vacuum, the relationship between voltage applied and measured current density. Anyway, in our experimental conditions (which are not conventional!), the measured value of the exponent was 1.3-1.4, not 1.5. The reduction is due to two main effects: coaxial geometry (instead of flat parallel plates), and the presence of a porous sheath instead of a void gap.

6.3. Dielectric Barrier Discharges (DBD) or Paschen Gas Breakdown

The current of the discharge depends on the distance between the electrodes, the pressure, and the type of gas. Figure 5 shows this dependence for a typical Paschen discharge, while Fig. 6 shows, schematically, the occurrence of a DBD discharge on the surface of the wires, and possible effects on electron density (due to the Maxwell-Wagner-Sillars effect at the interface of materials featuring different dielectric constants).

With reference to the Paschen discharge curves (Fig. 5) we would highlight that the use of the LWF oxides coating on the wires, and of thoriated tungsten ($WTh_{5\%}$, bundle of 2 mm diameter long rods, inside a SS airtight thin-wall tube) very close to the glass reactor external wall, allows some reduction of the breakdown voltage because of γ emissions. In the experiments of 2019, we collected evidence confirming that the thoriated tungsten is a useful, safe and simple, enabler of Paschen discharges also in our experimental set-up, especially in the optimal Paschen regime. The experiment with $WTh_{5\%}$ were based on previous, specific tests where we observed the behavior of high voltage induced current by oscilloscope. Tests made mainly in DC conditions up to +2 kV at Fe counter-electrode. The main result was that using the $WTh_{5\%}$ the number of the discharges increased and were more regular (i.e., less "violent").

7. Recent Results Using Pulsed Power

- Since March 2021 the main improvements made to the pulser, to "match" the unusual needs of coiled coaxial core (magnetic materials both at the wire surface (Fe_xO_y) and at the inner section (Fe tube)), were satisfactory for the planned heavy-duty test. The pulser was designed according to the principles of "capacitive discharge"

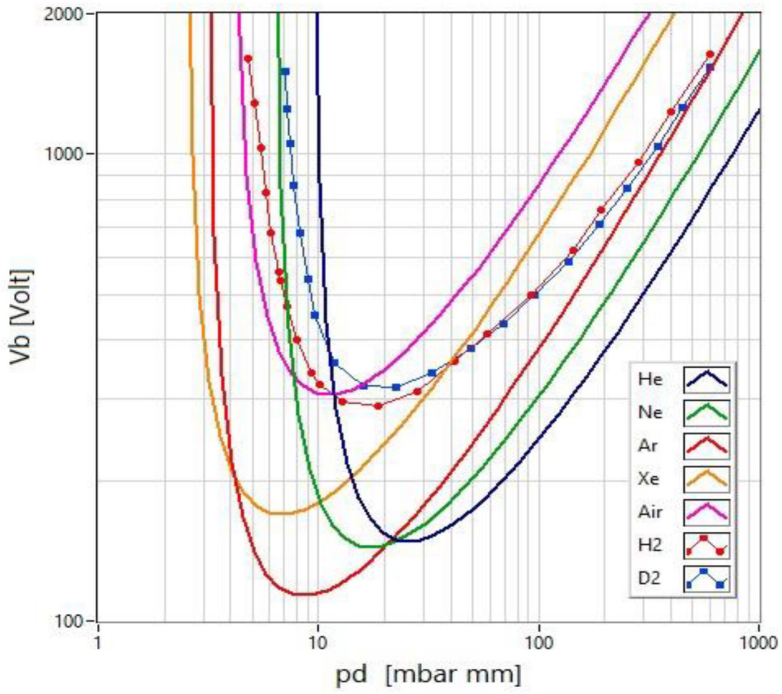


Figure 5. Direct current breakdown tension (Vb) of several gases as a function of the product of pressure and distance between electrodes (p*d). The addition of Ar (pure Ar has the lowest value of Vb, about 120 V) to H_2 or D_2 clearly enables discharges at lower voltages. Moreover, He could be very useful at higher pressures.

and is characterized by an unusual (proprietary) high energy-transfer efficiency, even at quite large repetition rates (up to 30 kHz; specific circuitry labelled as FRSC in Fig. 3), as shortly described in the explanations of the figure.

- In particular, the new unconventional procedure to generate useful (i.e., under control) high voltage at the end of the main power pulse was tested for long times without failure of electronics, even in the most severe operating conditions *($\Delta V/\Delta t$ on the order of* 5-10 *kV/*μs, up to 2500 Hz of the present repetition rate, typical pulse duration of 10 μs).
- Moreover, thanks to the performance at very high frequency of the main high-power switch adopted (based on SiC technology), the commutation losses were kept low, thus increasing the *overall efficiency of the pulser (close to 90%), and its long-term robustness*.
- Due to some experimental observations, we were prompted to increase the highest operating repetition-rate from 1 kHz up to 2.5 kHz. Even in this case, except the time spent to modify the pulser design, we did not observe damage to the circuitry and/or to the Constantan wire. Upcoming tests are planned to investigate higher pulse rates and reduced pulse duration (currently 10 μs) thus reaching the overall mean input power up to 100-130 W.
- Up to now, the "useful" maximum peak power applied to the Constantan wire (l=158 cm, Φ=200 μm, weight about 450 mg) was over 4500 VA, i.e., over 10 kVA/g of material. The overall time duration of the pulse was kept, for now, at 10 μs. We have indications, based on previous short-duration tests, that it could be possible to

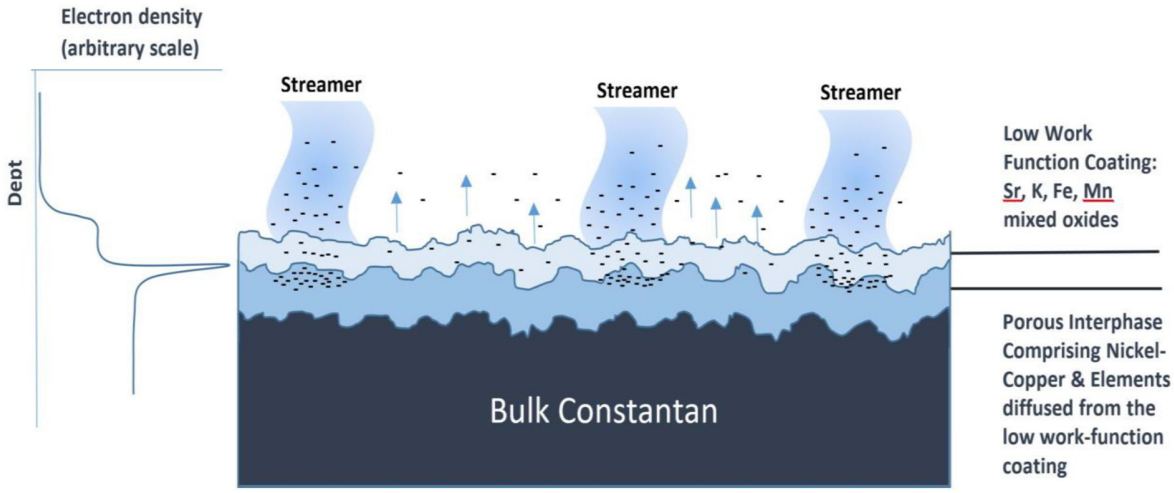


Figure 6. Schematic drawing of electron behaviour during a negative unipolar pulse. The occurrence of destructive discharges is prevented by the low conductivity coating on the Constantan wires as well as by the porous dielectric sheaths. The range of voltage-frequency used during the experiments enables the production of a mild filamentary discharge [19].

increase by 30% the peak power currently used by increasing the operating voltage of the main power supply (now at 400 V).

- It is important to highlight that the effective mean power is about 80% of the peak power due to inductive effects of the coil, that comprises a magnetic core (rise-time of the pulse is limited by the value of L/R). Also, we recall that the extra voltage of the opening switch that we used to generate high voltage has the following expression V=−L*di/dt. Therefore, a sufficiently high value of inductance is needed due to the intrinsic limits of the speed of the main switch adopted (SiC technology), featuring a fall time on the order 50-100 ns at the maximum peak current used (on the order of 12 A in the present experiments).
- The electromigration effect by itself, and local heating of the wire by longitudinal current flowing, to provide mean power up to about 95 W, was successful: no damage even after 60 h of continuous operations at 2.5 kHz repetition rate. The measured mean inner coil temperature was close to 600 °C: temperature as measured by the axial thermocouple. The temperature of the Constantan must be higher. To rule out the possibility of RFI during the pulse, we abruptly disconnected the pulse and observed a temperature decrease. It was regular (i.e., exponential-like decreasing, with no jumps). When we adopted H_2 gas largely enriched by Ar (i.e., *Ar*/H_2=*84/16)*, we reduced the gasses thermal conductivity to the cold side (i.e., the room temperature), just thanks to the lower thermal conductivity of Ar (about 7 times lower compared to H_2). As a consequence, the internal temperatures were much higher: it increased by 50-150 °C.
- The *SIMPLE* glass reactor, in the present work just the dissipation type (thermal equilibrium time <30 minutes), worked well for our purposes and it was even possible to make sufficiently accurate thermometry using several "blanks" (sometimes quite complete: Ar, He, Xe, air, at different pressures, usually: vacuum; He, Ar at about 0.1 and 3 bar). We used only 2 K-type thermocouples (max temperature 1200 °C), SS covered (external body grounded to minimize possible RF interference) and electrically insulated. The first thermocouple, Fig. 2A, was put into the center of the coil (T_int.) inside the Fe counter-electrode (tube geometry); the second at the external wall (T_ext.) of the borosilicate glass reactor (3 mm thick; tested for high temperature

and pressure operations): the same type used since 2011 in our experiments. We note that, thanks to several blanks and using the T_ext values as the key parameter, the thermometry is almost equivalent to calorimetry for the purposes of the present experiments. Fully blank tests (i.e., with several different gases) were made from time-to-time, for a cross check of the whole system. The usual standard blanks were made using He gas because its thermal conductivity is the closest to H_2. *In the case of pulse conditions, the blank test are the values of temperatures measured under H_2 in DC conditions*. So, the values of AHE could be under-estimated. The power applied were 5, 10, 15, 20, . . . i.e., steps of 5 W, up to 60 W; and later steps 10 W up to 120 W.

- The reference temperature is the room temperature, air conditioned and continuously measured. The thermocouple, at the 3 mm thick glass (type 3.3 Schott-Duran) surface, is attached by a quite complex procedure as follows: A) at first, the glass is covered by twin layers of 40 μm thick Al foil, 2 cm $\times$ 3 cm. It is used because it has the local mean value of temperature, and to avoid potential IR interference from (possibly) the localized hottest area of the inner core of the reactor toward the tip of thermocouple (positioned at the center of 2 x 3 cm foil); B) the thermocouple is covered by 4 layers of the same kind of Al described before, with the same dimensions; C) the side of Al toward ambient is covered by a high thermal insulation material, 1 cm thick, to avoid abrupt interference from localized ambient temperatures; D) the whole assembly is elastically pushed toward the glass tube by 2 independent springs that circumvent the tube. In future experiments we plan to make further improvements related to temperature measurements.
- At present we are not able to evaluate potential "aging" due to material degradation. In fact, the experiments ends when the wire breaks, therefore it is not possible to perform a control run at the end of the experiment (i.e., with helium). In any case, due to the fact that various regimes of operation are associated with different values of AHE, we can make a self-check of the system even after several weeks of operation: the operative operating points that do not give AHE results, or give poor results, are all quite similar, (and all are similar to a "blank" run).
- In the near future, once we obtain enough satisfactory results as a whole, we will move to a usual air-flow calorimeter (equilibrium time about 4–6 hours), operating in the Frascati Laboratory (e.g., our ICCF22 paper, published by JCMNS 33, 2020, pg. 1-28). So, we will be able to evaluate the *absolute value* of AHE, if any, and not only relative to blank experiments (which are supposed to be the "zero").
- All the tests at sufficiently *high pressure (several bars, i.e., far from the Paschen regime*) of gas (He, H_2, Ar-H_2) used were successful. Also, tests under dynamic vacuum were successful. In short, there were no catastrophic failures of the wire, and we detected measurable values of AHE as described below. In other words, the 200 μm thick wire is able to withstand *longitudinal* current as large as 12 A for pulse duration of 10 μs and repetition rate up to 2.5 kHz. As reference, in free-air, the maximum DC current recommended by the Constantan's manufacturer (IsabellenHütte-Germany) is 2.34 A: at that current the surface overheating (in respect to NTP conditions) is 600 °C with a related surface power load of 13.6 W/cm^2. We experienced that, at such wire's surface temperature (620°C), no oxidation occurred during a 24 h test in free air, using a virgin wire (as provided by the producer).
- When we tried to enter into the Paschen/DBD regime, i.e., lowering the pressure step-by step (from 4-5 bar down to 0.1 bar, or lower), under high voltage pulsed situations at the Fe thick counter-electrode (about 1000 V), we experienced several catastrophic failures of the coils. Anyway, such unwanted effect was expected: Paschen/DBD discharges are always highly localized. Breakdown occurs first at a particular point and all the energy is dissipated on that point. It is destructive for small wires, which is not surprising. We made some counter-measures to reduce such problems, but they are not yet sufficient, as detailed later.
- As anticipated, we did not observe catastrophic failures when operating in a full dynamic vacuum (up to mean power on the order of 50-60 W, measured inner temperatures close to 900 °C). We adopted the procedure of first making a vacuum (dynamic) and after giving High Pulsed Power. About pumping, a usual 2-stage rotary

is enough: a TMP type is not necessary. We just needed to pay attention to minimize contamination by oil vapour.

- The most probable reason for breaking, according to our visual observations, were localized high voltage (about 1000 V peak) discharges (i.e., like a hot-spot). Calculated peak power, supposing 1 μs of time to transfer the energy, was on the order of $2.5*10^3$ W/pulse.
- The simplest explanation is that the Paschen regime is excessively "severe" to the thin wire used (Φ=200 μm) in our present experimental conditions. We are aware that sparks (arcs) are locally destructive to all metallic surfaces: because of such intrinsic effects, innovative solutions are needed. Work is in progress.
- Up to now we changed 5 coils. We even made changes to the geometric construction details, but they were, so far, not enough to solve the problems.
- Even the addition of some current protection network, shown as the CPN black box in Fig. 3, to limit the "long duration" (>>1 μs) current flowing between the electrodes, was not fully effective. The CPN was simply based on a RC network in parallel: at short times (i.e., high frequency), the impedance of the capacitor is low, so enough current is allowed to be transferred to obtain the high positive voltage planned. Anyway, the procedure was not enough to solve the problem for a long-enough time of operation (at least 30 minutes, i.e., the equilibrium time of the system). In some experiments it was really a big problem. Deeper analysis of damaged sheaths is necessary: future specific work is planned.
- Waiting for some new idea/devices/circuitry to make the electric field more homogeneous among the electrodes (i.e., to avoid a localized hot-spot), we deeply studied the effect of electromigration by itself, neglecting, for now, the other very important effects we were looking for: Paschen/DBD; Richardson with related Child-Langmuir NOT under usual high vacuum but even at 10-50 mbar of pressure. At such intermediate pressures there is some coexistence with the Paschen curve, scientifically interesting but at present out of our control. Anyway, the amount of data collected are not enough to allow the building of a proper plot.
- We began our in-depth analysis because in our older experiments (1994-1998), when we used only pulsed electromigration, with plates at the beginning, and later wires, in an electrolytic environment at about 1 bar of pressure, Pd-Pt or Pd-Ni electrodes. In these experiments we observed some AHE in specific operating conditions of: electrolytic conductivity/composition, pulse duration, repetition-rate, power injected. Some information about this research is scattered among several Conference/Workshop/Meetings papers of that time period, although no systematic final study, was performed.
- In the recent tests some of the operating conditions are even more "intense" in comparison with old ones, with Pd based material, so the probabilities to observe something "strange/useful" are increased.
- Figure 7 shows the pulse regime typical values of Voltage, Current, Power applied in experiments at high mean power (>90 W). Voltage, (100 V/div., in red), Current (2 A/div., in blue) Power (800 V*A/div., in green) applied to the Cathode, time scale 1 μs/div. Gas pressure, mixture Ar/H_2 (84/16): about 4 bar at RT, 5.2 bar at HT. The maximum temperature measured inside the wire coil (by the axial thermocouple T_in) was about 580°C.
- Figure 8 is similar to Fig. 7 for operating conditions. It shows the high voltage (in red, 200 V/div) applied to the anode, maximum value about +1060 V. As reference, the current (in blue) but with time scale of 2 μs/div, produces some evolution of peak voltage versus time. The reference value of voltage did not start from 0 V but from a higher value, about +400 V (i.e., the value of main power supply at the test): deliberately *applied,* by suitable auxiliary circuitry (shown in Fig. 3)*, to get pre-ionization of the gas mixture (see Paschen curve, Fig. 5)* in the case of future suitable gas pressure reduction.

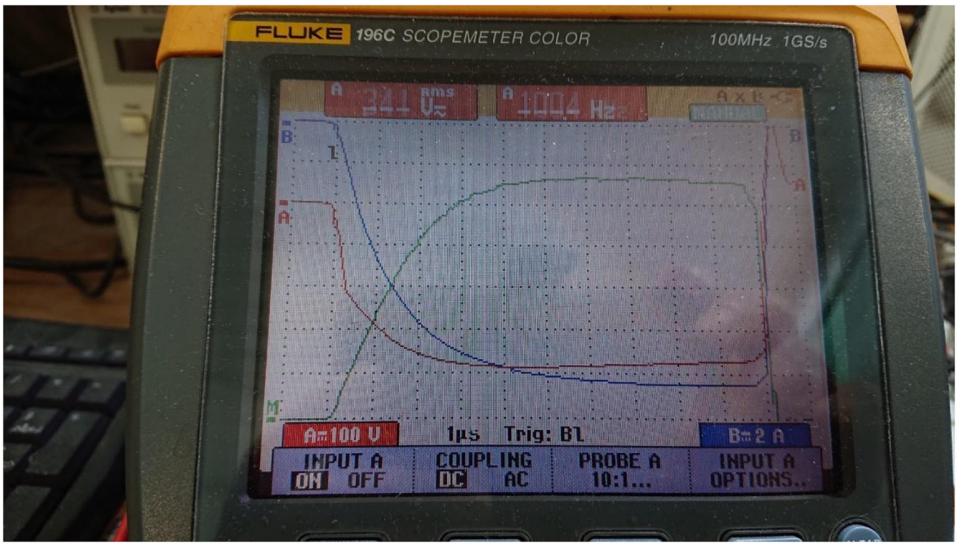


Figure 7. Snapshot of Voltage (red color, 100 V/div, maximum value −380 V), Current (blue color, 2 A/div, maximum value −12.4 A), Power (green color, scale factor 4, 800 W/div, maximum value 4500 W) of a typical high-power pulse. Time scale is 1 μs/div. The repetition rate was the highest up to now used (2.5 kHz). As previously reported, the progressive buildup of the negative current at the beginning of the pulse is due to the L/R ratio of the wire (added with auxiliary coil, not shown for simplicity in Fig. 1 or 3), in contrast to the very rapid extinction made possible by the SiC circuitry shown in Fig. 3.

8. Main Results

The main details are shown under the figure captions, as shown in Fig. 9, Fig. 9A, Fig. 10, Fig. 11, Fig. 12.

Figures 9 and 9A show the difference between the external glass temperature (T_ext) and the reference temperature (T_ref=room temperature) as a function of the input power. In red we have the DC calibration curve obtained by 4^{th} order polynomial fitting, based on 20 measurements (i.e., starting from 0, each power step is as low as 5 W up to 60 W, and later on 10 W up to 120 W with an added intermediate measurement at 105 W). In the case of pulsing, made 8 measurements. Power varied changing the main power supply, shown (as an example) at +300 V in Fig. 3, from +50 V up to +400 V, step 50, for each repetition rate adopted (1.0, 1.5, 2.0, 2.5 kHz). In total we made 32 measurements for each combination of gas composition. Anyway, for simplicity we reported only measurements using concentrated H_2 at a few bars of pressure.

Fig. 9A is just the same figure at low power, to make observation of details easier.

Figures 9 and 9A together show the measurements in the DC and pulse regime, with pulse peak power varying from 64 W to 4640 W, changing the main power supply from +50 V up to +400 V. The *repetition rate,* from 1 kHz to 2.5 kHz, affects the *mean power*. The power is displayed on the X-axis as equivalent DC heating power.

In other words, in Fig. 9 and 9A we have the same core, the same atmosphere (H_2) and similar pressures as shown in both the DC calibration (data fitted with equation shown) and several temperatures/equivalent power by pulsing procedures. Fitting for pulsing conditions are performed but not reported for simplicity. Anyway, the R quality-factor of fitting was always >0.9999.

Observing the green color curve in Fig. 7, we have to consider that the mean power is lower than peak power shown because of the time needed to reach the flat regime (to be specific, about 3.5 μs). Moreover, the nominal duty-cycle

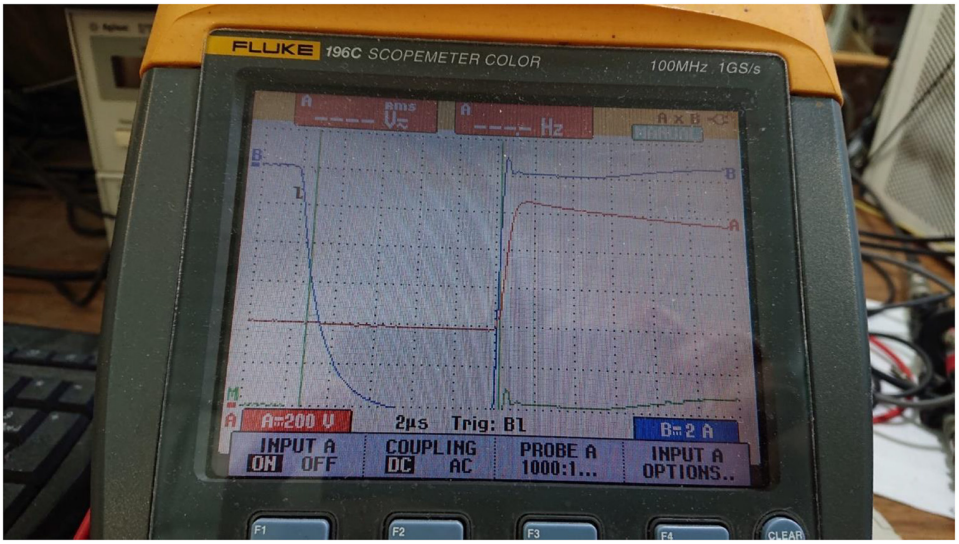


Figure 8. Snapshot of the peak voltage at the counter electrode (red colour, 200 V/div, maximum value +1060 V). Shown also, as reference, the current applied (blue colour, 2 A/div). The large positive voltage is due to the "opening circuit phase" of the pulse. It is extremely fast because combined effects of both overall electronic arrangements and intrinsic fall time performance of SiC switch used at our operating point (<<100 ns).

(supposing ideal rectangular pulses with rise/fall times close to zero ns), with the present pulse width (10 μs), were: 1%, 1.5%, 2%, 2.5%.

The power input is just what is observed for each pulse, using the 100 MHz oscilloscope (Fluke Mod. 96 C), with in-phase power (green color) multiplied by the repetition rate. We made several snapshots of the pulses, noted them, and determined their mean value.

The accuracy of measurements in the procedure was ensured as follows:

a) First we calibrated the system using an array of 8 non-inductive resistors (Wishay model RCH25, each 220 Ohm, TEMPCO 150 ppm/°C), with high power (25 W each) connected in parallel. Nominal maximum power is 200 W: used at 100 W. Moreover, the array was fan cooled to keep temperature variations as low as possible. The value of final resistance (nominal 27.5 Ohm) is close to the value of the wire used, i.e., l=158 cm, Φ=200 μm. The value of resistance was measured, in DC conditions, by V-I procedures (accuracy better than 0.1%) up to the maximum power of 200 W.
b) The measurements were repeated, under pulsed conditions, at a mean power of 100 W by the scope. Each measurement was mediated by 64 individual measurements (one of the mathematical functions of the scope). No detectable differences happened between DC and pulsed conditions. We recall that, for the kind of resistor used, under 10 μs of single pulse duration, the safety overload factor is as large as 30 kW in comparison to nominal 25 W in DC condition.
c) The evaluations of measurements, by scope, i.e., power injected as shown in Fig. 7, were made by 3 independent researchers.
d) Considering the several cross checks performed, and routinely repeated, we estimated the overall accuracy to be on the order of 1%.

Anyway, the input power, apart from initial times (about 5 minutes) from changing power, is quite constant.

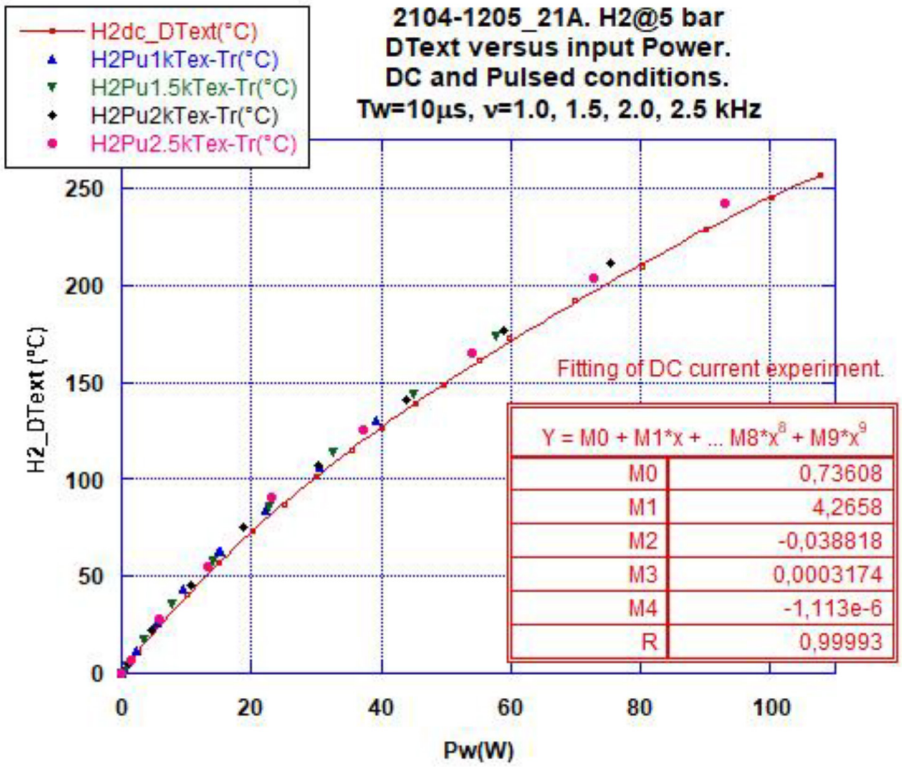


Figure 9. Behaviour of temperature difference, at reactor glass wall, changing the Pw from DC to pulsed. In the case of DC (20 measurements in total, including values at 0, 105, 110, 120 W) is shown. The curve is a 4° order polynomial. Part of the full range of measurements performed is shown, up to about 105 W. The fitting of data has a R value very close to 1 (➔0.99993).

We suppose that AHE in the DC regime is negligible and therefore the greater temperature increment in the pulse regime is due to only AHE triggered by the pulse activation mode. We have obtained graphs in Fig. 10 and Fig. 11 that show directly the AHE variation versus the equivalent DC heating power, for 4 different pulse repetition rate values and 8 values of peak power pulse.

To calculate AHE we used the formula AHE=((ΔText–ΔTdc)/ΔTdc)*Pw, valid only for low AHE values. Then, it is possible to consider a thermal exchange coefficient K constant such that ΔTdc=K*Pw and ΔText≈K*(Pw+AHE). We specify that ΔText means ΔT under pulse regime. Actually, K decreases as temperature increases because of thermal losses, resulting in some *underestimation* of AHE value.

The obtained measurements are very conservative, as partially anticipated, for the following reasons:

1. We suppose that AHE obtained in DC regime has a value of zero, as referred to similar curves obtained with He as thermal exchange gas, although we have often observed AHE>0 even in such conditions, i.e., AHE_H2>AHE_He.
2. We recall that, after suitable activation cycles, the AHE measured in DC conditions under hydrogen is larger in respect to helium gas, as reported in our ICCF22 paper.

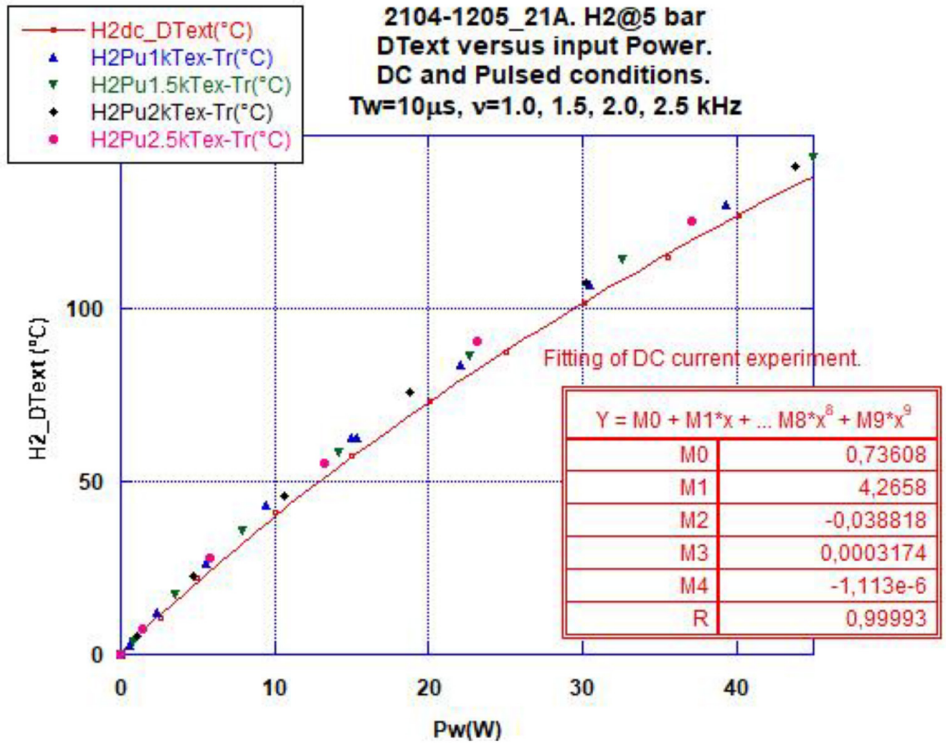


Figure 9A. Same measurement as Fig. 9 but at lower power (0-45 W) for an easier evaluation at low power regions. In the plots the terms DText and Tex-Tr have the same meaning, i.e., temperature difference in respect to room temperature. Different names from previous experiments are used in the plot just for historical reasons. In the case of DC measurements, the reactor wall temperature is shown as DText (i.e., T_wall reactor-T_room). In the case of pulsing it is explicitly quoted as T_reactor-T_room.

3. The formula used inherently gives AHE values less than real values because we assume there is no increment of thermal losses as temperature increases. For example, in Fig. 9 the AHE seen by graphical evaluation is over 6.7 W, while the same using the formula it is just 3.7 W. Moreover, at the maximum power of pulsing, it is about 9 W.

- At the end of Fig. 12 the unexpected beneficial effect of HPPP (High Peak Power Pulse) is shown. HPPP is discussed in our publications since 1993 experiments [20], [21], [22], [7]). The design of current pulser shares several features with the original one, nevertheless it has been improved in some specific respects. In fact, the original device was conceived for an electrolytic system where a very high current was needed (for instance in the case of plate electrode geometry, a current up to 150 A and a peak voltage up to 200 V; typical duration was 1-3 μs). Now, using thin wires in a gas system, we need instead a maximum current of about -20 A, a maximum voltage of -500 V, and an extra positive voltage up to $+1200$ V, $+1$ A. Anyway, in our paper, for simplicity, we reported in detail only results with maximum current of -12 A and voltage of -400 V. The sequence of events in the case of the present experiment are shown in Fig. 3, phases 1➔4.

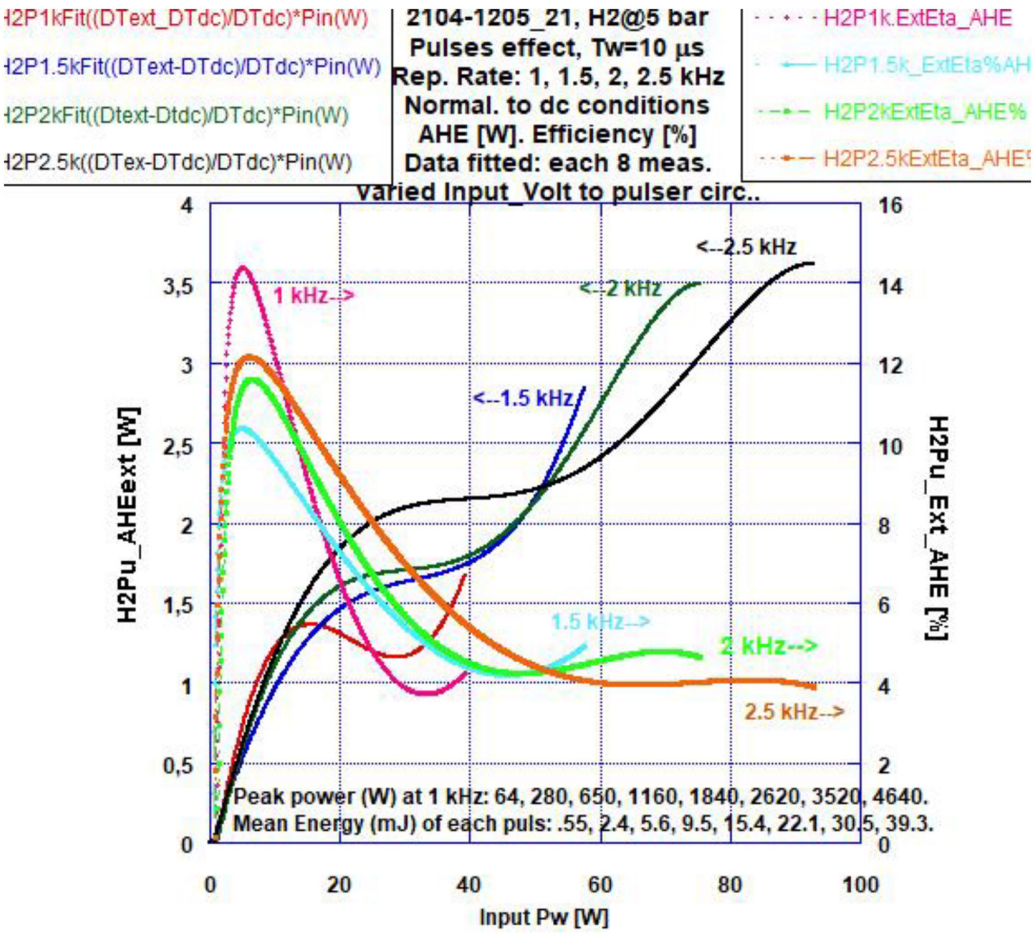


Figure 10. Only the electromigration effect is shown; H_2 at 100%, 5 bars. Plot of percent of AHE changing the peak power pulses (explored 8 values, 64→4640 W, detailed at the foot of the figure) and repetition rate (4 values: 1, 1.5, 2, 2.5 kHz). Data is normalized at the same input power in DC conditions. AHE values on the left scale (W) and relative values on the right scale (%). We observed that while the absolute input power increases the efficiency tends to a flat value of about 4-5%. In the data shown it is not possible to show each data points because calculations are based on *fitting* of the calibrations (i.e., under DC measurements) and the values of exact input power can be different (up to few watts) from the effective one.

*Regarding the value of the mean energy of each pulse, for the sake of comparison, we recall that the typical energy needed to ignite the gasoline-air mixture in an Otto-Benz engine is on the order of 20-160 mJ, depending on the gasoline/air ratio and the compression ratio. Moreover, the total time of ignition is on the order of some milliseconds. In our case, we have energy up to 40 mJ and time of pulse of only 10 µs. In other words, the energy involved is over 100 times more concentrated in respect to time. The drawback is large stress to the thin wire.

- To prove such beneficial effectiveness, we made specific tests by changing the gas mixture composition (H_2➔H_2/Ar 60/40➔H_2/Ar 16/84). The typical pressures were in the range of 3-5 bars, apart from specific, explorative tests at different (low) pressures. We even de-loaded the wire from the hydrogen stored in the bulk, as much as possible, by vacuum treatments.

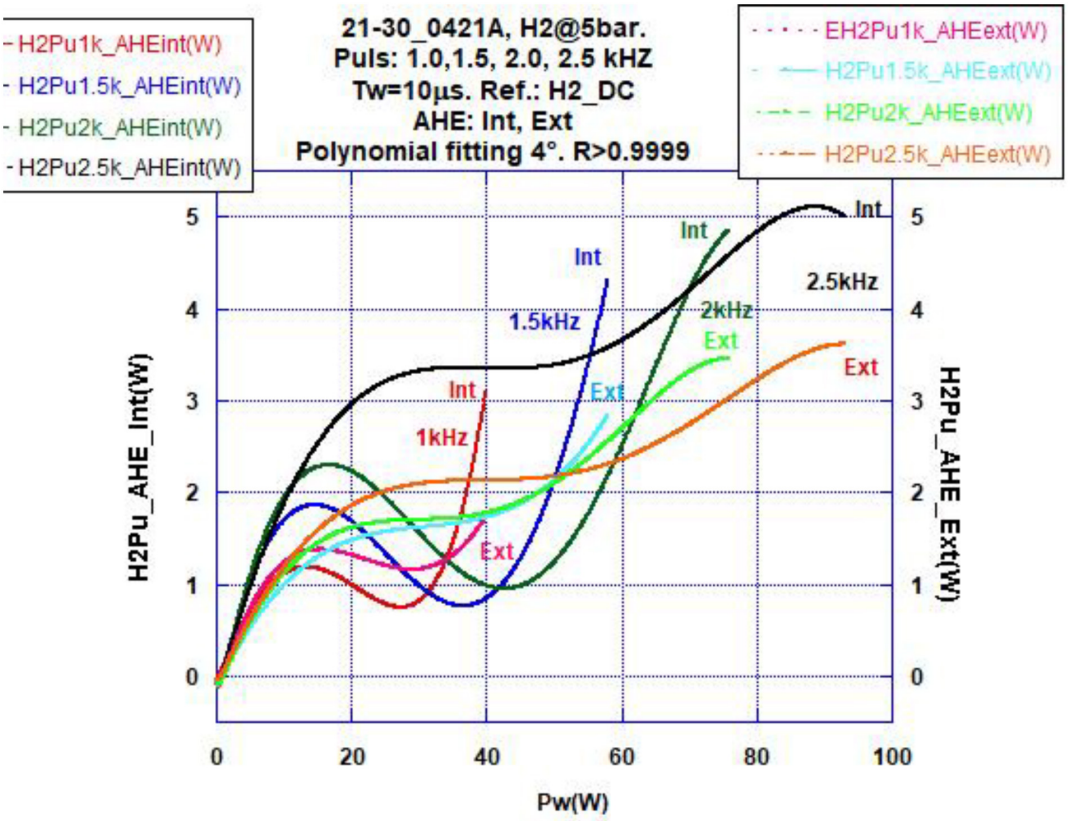


Figure 11. Only Electromigration effect; H_2 at 100%, 5 bars. Plot of absolute AHE. The values of AHE external are the same of Fig. 10, left side. Comparison between internal and external AHE, calculated with the same procedures and considering the DC condition as blank. We observed that the internal one is always higher than the external one. We guessed that some of the energy coming out from the coil is not fully converted to temperature increase through the gas and thick glass wall. We observed by oscilloscope quite large HF signal coming out to the environment. The shapes of HF signals are quite irregular and chaotic, so they can be used only as starting points for future improvements to the apparatus. In conclusion, such observation suggest that in the next experiments we should modify the reactor geometry to recover energy that is otherwise not included in the computation and lost.

- Restoring of the initial "good conditions", at the moment has only been partially achieved. We just guess that, in the de-loading procedures (mainly by vacuum at high temperatures and long times) severe sintering occurred at the surfaces of the submicrometric, useful, "active" location that are the main places where AHE is generated. The "*active Site*" model (but with different explanations) was pointed out by Edmund Storms and Mitchell Swartz, both in the USA, among others. Further experiments are needed to validate these statements more deeply.
- We recall that in our project, one of the roles of the mixed *plasma* of Ar and H_2, meant for the Paschen/DBD regimes, was to "reactivate" surfaces that went inactive because of spontaneous, severe "aging effects". This work is in progress.

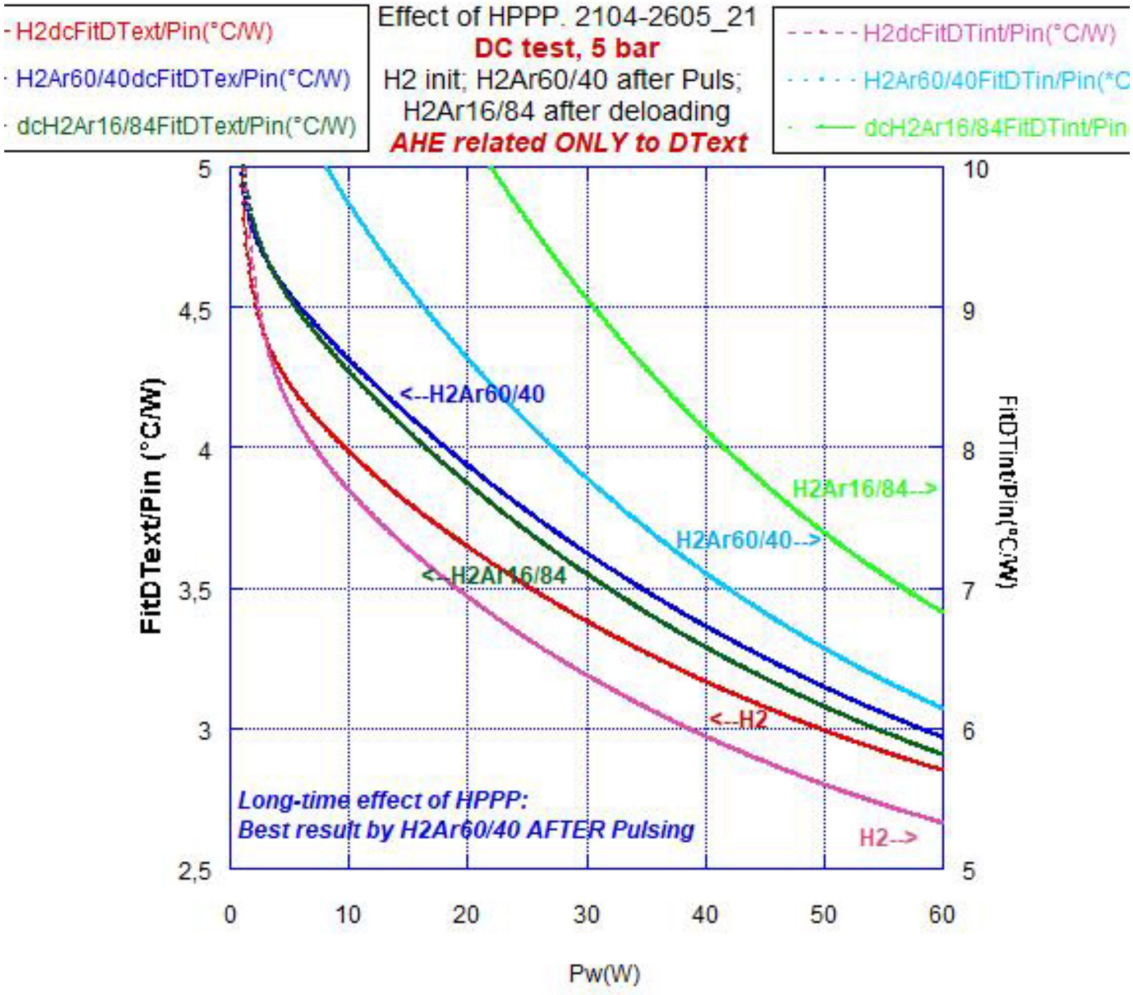


Figure 12. An unexpected, useful effect after HPPP (High Peak Power Pulse) treatments are applied, over $2*10^7$ pulses at 10 kVA/g. Shown is the ratio of DT/Pwin (°C/W) versus input power. Vertical left-side: DT_ext; Vertical right-side: DT_int.

- We recall also that in our old experiments, with Pd (1994-1998), we observed some "useful" *memory effects* by long-time pulsing but we have never analyzed the phenomena deeply enough.
- Several similarities among the behaviors of Pd-D and Constantan-H are observed. We guess that other pure materials or alloys may exist (with suitable amounts of hydrogen or deuterium stored at the surface or into the bulk) that can produce AHE in the right conditions, hopefully at higher levels than the present one.

All the measurements reported are in DC conditions: the calibration curve is the usual in H_2 in DC at the beginning of the specific experiment (26 April 2021), before pulsing.

Regarding the values of DT_int (right side of the curve), it is necessary to consider that, *because of the lower thermal conductivity of Ar in respect to H_2, the mixture H_2/Ar=16/84 has the largest values of DT_Int/Pin but lower in respect to the DT_Ext/Pin at H2/Ar=60/40*. ***Anyway, results are always better than with pure H_2 at the beginning of the experiment.***

Over time we made 3 long main tests, detailed as follows:

- 1st test with H_2 only in DC conditions (**reference**, pink and red colors). The tests, with power up to 61 W, were made *BEFORE* applying the pulse mode, i.e., at the beginning of the experiment (April 21-26, 2021). The plot is the ratio of DT/Pin, so it is not necessary to have the zero values shown but only their trend for comparison purposes.
- 2nd test after pulses on H_2. R/Ro decreased from 1.000 to 0.820 (i.e., H absorbed into the bulk of the Constantan); R/Ro measurement performed by V/I procedures with I at low intensities, <200 mA, to avoid self-heating. Later on, the gas composition was changed from H_2 at 100% concentration to H_2/Ar=60/40. Increased both external (blue color) and internal (sky-blue color) temperatures, the last one expected because lower thermal conductivity of Ar/H_2 mixtures.
- 3rd test: We de-loaded the previously adsorbed H_2 as much as possible (R/Ro, went from 0.820 back to 0.969). After further vacuum cleaning, the gas composition was changed to H_2/Ar=16/84. Results: the internal temperature (light green) increased largely because of the lower gas conductivity (as expected); the external temperature (green curve) DECREASED in respect to 60/40 composition. Anyway, the results were still *better than the initial reference*. This is a clear demonstration of HPPP: it "activated" the material, most probably in the inner bulk of Constantan. We have evidence that with our procedure it was not possible to FULLY de-load the wire from the most inner locations of the lattice. In other words, the activation seems quite stable for long times (weeks): ***the target was achieved.***
- Again, we remind the reader that all the experiments in pulsed condition are normalized in DC under H_2. As a consequence, the AHE values could be underestimated.

We guess that, at least in these specific experiments, devoted to study bulk properties, that the "movement", or more accurately termed the flux of atomic hydrogen, even at low concentrations, has a key role in AHE production. Further work is necessary to reinforce this hypothesis.

- For this specific experiment we were able to observe the beneficial effect, after pulsing, for only a few days because the wire was destroyed some hours after last experiment: a heavy-duty test (which was planned long before it was done). Anyway, after also reconsidering previous experiments, we *estimate* that the time of beneficial effect of pulsing to be on the order of 1 week.

9. Conclusions

(1) It was experimentally demonstrated that the "old" beneficial effects of HPPP, discovered by us starting in 1994 with the very costly Pd system (Pd has recently cost about 75 €/g), *can be "transferred" also to the low cost Constantan alloy (about 20 €/kg)*.

(2) The pulsing procedure, by itself, can induce some AHE, which is stable over time. *The effect seems to behave positive feedback over the temperature range we have explored up to now (maximum about 600 °C, pure H_2). We expect further advantages at temperatures over 700 °C (by using Ar-H_2 mixtures at low pressures), where the Richardson regime is further enhanced*.

(3) Moreover, we have found, just by chance, a procedure to "*activate*" our specific Constantan wires, allowing them to produce AHE when other conditions (gas, high temperature, sponge surface covered by LWF materials, thermal gradients, ...) are fulfilled.

(4) The activation was found to be stable enough to be beneficial also in DC conditions, even after several days after ending the pulsing.
(5) From a theoretical point of view, one of the most interesting hypotheses on the origin of anomalous heat is based on the active role of Nickel-Copper alloys in the decomposition of molecular hydrogen and in the catalysis of Ultra-Dense Hydrogen (UDH) formation, according to Leif Holmlid's (Univ. Goteborg-SE) models and experiments [23]. In the case of Holmlid's experiments, non-equilibrium conditions were applied, mainly, by intense Laser pulses (see also: [24] for the interpretation of the results from a very innovative although complex, point of view). We hope to soon overcome the problems of catastrophic coil destruction and to can use at fully the possibilities given by the combined effects of Richardson, Child-Langmuir, Paschen/DBD, Skin, from the point of view of increasing the values of AHE measured up to now.
(6) In conclusions, only a few of the possibilities we explored to induce and increase the AHE were realized because of several technical constraints. We hope that the "indications" given by us can be used by other researchers active in the field.

Annex A.

Brief theoretical description of the Coherence processes underlying LENRs and the Preparata's effect.

In this annex we give a short description of the fundamental concepts of the theory of the *electrodynamic coherence* developed in the 90's by Giuliano Preparata [8], which describes the coherence processes in the context of quantum electrodynamics in condensed matter.

According to this theoretical view, in a metal hydride a reorganization of the quantum vacuum of QED takes place caused by the self-interaction of the charges of the deuterons through the radiative electromagnetic field when they overcome a *concentration threshold*, causing the spontaneous formation inside the metal of a large number of *coherence domains* (CD) each consisting of roughly 10^{11} deuteron and described by a single quantum state. These coherence domains have typical dimensions on the order of 1-10 μm and their thermodynamic stability is guaranteed by the fact that the deuteron belonging to the domain acquire an energy gap on the order of 1 eV per deuton, thus guaranteeing the existence of such states for temperatures up to the melting temperature of metals.

The existence of such coherence domains has recently been theoretically studied also by other authors [25], who independently confirmed the existence of the states.

The interest in these states stems from the fact that:

1. In the scattering processes between coherent states the transition cross sections are proportional to the square of the number of particles that constitute them, differently from what happens for the incoherent processes which are proportional to the number of particles. Consequently, processes that would be totally negligible in the incoherent case are amplified by a factor 10^{11} and may become predominant.
2. The kinematics of such processes is substantially different from that of processes involving a small number of particles (single particle processes).
3. The involvement of coherent states in LENR processes is supported by the experimental evidence of the suppression of highly energetic particles (T, p, ^{3}He, n), typical of the well-known nuclear processes occurring in a vacuum.
4. The dynamics of interaction of the coherent processes allows the distribution of the energy associated with a nuclear-type reaction to a very large number of deuterons ($\sim 10^{11}$), explaining in a natural way the absence of highly energetic reaction products.

5. Since the coherent states are in thermodynamic equilibrium with the incoherent fraction of the deuterons, the excess energy acquired by the nuclear reactions by the final coherent states can be efficiently transferred to the incoherent fraction in the form of heat.

We note in passing that the described features of the coherent interactions provide a natural explanation of the long-standing Huizenga three miracles [26].

The coherent nature of the deuteron plasma confined inside the metal produces the so-called *Preparata effect* that can be advantageously exploited to obtain enhanced deuterium loading of thin hydride wires when subjected to a longitudinal electric potential.

A quantum system, whose dynamics is described by a unique wave function, is able to "see" the electrostatic potential applied to a palladium wire as a chemical potential that confines the D+s in the lattice, thus increasing the achievable concentration (Preparata's effect) [27]. The theory applies equally well for Constantan. This effect is analogous to the well-known Böhm-Aharonov effect [28] where the dynamics of a quantum system is affected by a change in the e.m. potential through a modification of the phase of the wave function. The chemical potential μ of H+ (D+) in a metal is thus shifted by the applied electric potential V(r) multiplied by the screened charge Z*e of the H+ (D+) in the metal

$$\mu[\mathrm{V}(r)] = \mu[0] + \mathrm{Z} * \mathrm{eV}(r) \tag{1}$$

In eq. (1) μ[0] is the chemical potential of the point 0 of the cathode where the electric potential is highest, so that V is the (negative) relative potential of the point r with respect to 0. The profile of the chemical potential μ is changed in such a way that the chemical potential in some regions of the cathode can fall below: a) the chemical potential μ_sol of the ions in solution, in the case of electrolytic loading; b) below μ_gas, in the case of gas loading. Consequently, an inflow of ions occurs in those regions.

The Preparata effect is most effective when it is possible to apply large electric potential differences across the cathode without inducing sizeable Joule heating that might spoil the pre-condition of the effect, i.e., the H+(D+) coherence. The optimal effect is expected when very thin cathodes whose resistance

$$\mathrm{R} = \rho \mathrm{l}/\mathrm{S} \tag{2}$$

is increased as much as possible by taking a large length (l) divided by a very small cross-section S; ρ is its resistivity. Since the expected height of the chemical potential barrier is a fraction of 1 eV and Z* has been estimated [29] as about 0.1, a voltage of about 10 V applied along the one-dimensional cathode should be sufficient to induce a massive inflow of ions increasing the loading by a factor 1.3-1.4 compared to a two or three dimensional cathode (plate or rod) exposed to the same electrolytic current density.

The intermediate voltages along the wire will decrease the chemical potential of the coherent state so that in the regions where the electric potential is lower, the loading will be favoured, resulting in a sort of confinement of the hydrogen inside the metal and the activation of AHEs in the more negative part of the wire.

The increasing factor of 1.3-1.4 can have huge effects regarding AHE production. In some experiments, made by Preparata's Team around 1999-2000 at ENEA-Frascati in collaboration with the LEDA Company, the effect was experimentally verified and more deeply analysed [30].

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Since 2017 we initiated collaborations with **NEMC** and **SIGI-Favier** (Italy-France), to design an original hybrid sheath obtained by crossing glass and Alumina–Quartz fibers. The 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, can adsorb significant amounts of Atomic Hydrogen. Moreover, the sheaths are porous, with holes of micrometric dimension: *one of the key aspects of our experimental set-up*.

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This time the work performed by the **Referee** (unknown) and the Editor of the Journal (**Jean Paul Biberian**) were the key factors to improve, largely, our original paper: not enough detailed to be understood by the typical reader, even expert in the (complex) field of LENR.

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Disclaimer

This work was written under the sole responsibility of the Authors and does not contain nor represent necessarily the opinion nor the position of the whole CleanHME European project.

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