the Bell Jar

Vacuum Technique and Related Topics for the Educator & Amateur Investigator

Notes from the Vacuum Shack No. 2 January 2020

A Revival for the Silvering of Optics?

There was an interesting article about two amateur astronomers in the January 2020 issue of *Sky & Telescope* magazine. One had to get his 28 inch mirror recoated but winced at the quoted price of $2000. The other lost his local coating house. Faced with the expense and risk of shipping their precious mirrors, each decided to try silvering.

Home silvering kits are available at low cost from Angel Gilding (angelgilding.com). With careful preparation, the process is fairly straightforward. If it doesn't work first time, try again. The cost of the coating materials is around $10 to $20. While silver coatings are more reflective than aluminum, tarnishing is the big issue. A coating will generally have to be redone after about a year. The same company also sells a protective overcoat (Angel Guard) that does an excellent job of protecting the silver film without degrading the figure of the mirror.

Coaxial Plasma Accelerators: the Dense Plasma Focus and Impulse Plasma Deposition - An Opportunity for Amateurs?

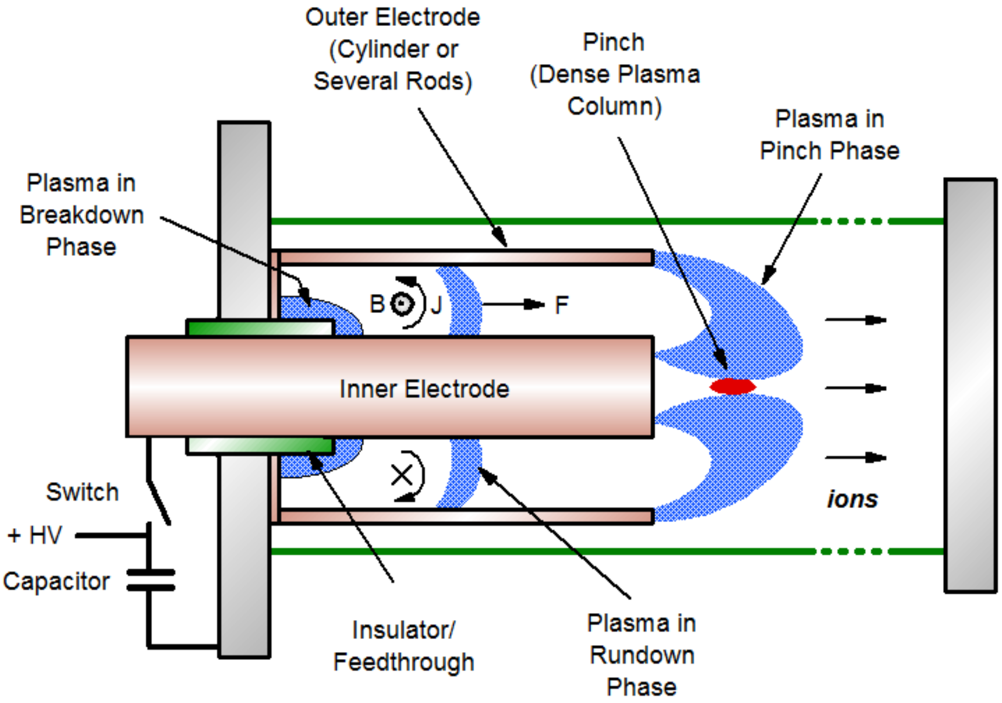
Overview

One of my longstanding interests is in the area of coaxial plasma accelerators. These are basically linear motors where the driven member is the plasma. It would be a cousin to the rail gun but in a coaxial geometry.

A specific configuration of the coaxial accelerator is the dense plasma focus (DPF) where the parameters are optimized to produce a dense pinch at the muzzle end of the device, adjacent to and in line with the center electrode. The basic geometries were established independently by Filippov and Mather in the early 1960s. Primarily used for the production of neutrons via the D-D fusion reaction, coaxial accelerators have also been used to produce x-rays and high velocity plasmas for film deposition and surface modification applications.

The figure on the next page depicts a coaxial plasma focus device and its stages of operation. The key features are a central anode electrode and a larger cylindrical electrode. The two are insulated from each other by means of a glass or ceramic insulating sleeve that is positioned at the base of the central electrode. With the device under vacuum, when the capacitor is discharged there will be a breakdown across the insulator as the plasma is being formed. From this initial liftoff from the insulator, the **J** x **B** Lorentz force that is generated between the electrodes causes the plasma to accelerate away from the backwall and toward the open end.

In a DPF device, the elements are designed such that the peak current occurs when the plasma sheet reaches the muzzle. Here the axially accelerated plasma enters the pinch phase where radial forces cause the plasma to constrict to a small pinch region. The constriction occurs at a much faster speed than the axial phase because the constricting current creates a much higher magnetic field,



The DPF as a Teaching and Research Tool

A small version of the DPF became “standardized” as a plasma education and research tool in the 1985-1986 timeframe. This was largely due to the efforts of Prof. Sing Lee of the University of Malaya and Walter Shearer of the United Nations University (UNU). The resulting program was called the UNU/International Center for Theoretical Physics Plasma Fusion Facility or UNU/ICTP PFF. A specific goal was to define a platform for the study of plasma physics that could be replicated at relatively low cost. Today, representative DPF devices are located at institutions around the world.

One starting point of the program was the glow discharge which has applications in numerous industrial processes. The plasma arc would be an important offshoot. Moving to higher temperatures and densities, devices such as the electromagnetic shock tube or linear Z-pinch are typical examples. The latter can produce high temperatures but, at least in small sizes, is not an efficient producer of neutrons.

This pretty much cleared the field for the DPF. The following are points taken from reference [1], *Twelve Years of UNU/ICTP PFF - A Review*:

> It is an excellent device for teaching plasma dynamics and thermodynamics besides being a rich source for a variety of plasma phenomena including soft x-rays and plasma nuclear fusion. The plasma focus is superior to both the electromagnetic shock tube and the linear Z-pinch in its range of plasma parameters. It combines the essential mechanisms of both devices in such a properly sequenced manner that all the features of both devices, and others including fusion, may be demonstrated in one single simple low cost device.
>
> The plasma focus needs only the same power supply, control electronics and basic diagnostic requirements as required by the simple Z-pinch. It needs a much cheaper vacuum system with only rotary pump requirement. Yet it produces more intense plasma phenomena including copious x-rays, relativistic electron beam (REB) and fusion neutrons, all in one small easily packaged facility.
>
> The Plasma Focus is a compact powerful pulsed source of multi-radiation. Even a small table-top sized 3 kJ plasma focus produces an intense burst of radiation with extremely high powers. For example when operated in neon, the x-ray emission power peaks at 10^9 watts over a period of nanoseconds. When operated in deuterium the fusion neutron burst produces rates of neutron typically 10^{15} neutrons per second over burst durations of tens of nanoseconds. The emission comes from a point source making these devices among the most powerful laboratory pulsed radiation sources in the world. These sources are plasma-based.

The 10^{15} neutrons per second is impressive but the important figure is neutrons per shot where the shot (or pulse) only lasts a matter of nanoseconds and the charging cycle is much longer – usually many seconds or even minutes. The important figure is the yield per shot. It turns out that yield per shot is roughly related to the square of the capacitor energy i.e. $N \sim E^2$. A 1 kJ DPF will produce about 10^7 neutrons per pulse. The UNU/ICTP 3.3 kJ device has a yield of about 10^8 neutrons per shot and, at the upper end of the scale, a large 1 MJ DPF will produce around 10^{13} neutrons per shot.

With regard to operating pressure, Lee [2] points out:

> The pinch phase is very intense because it starts at a very large current (typically 500 kA) and at a relatively small radius (typically 1 cm). Thus the operating pressure may be relatively high (10 Torr in D_2 for a plasma focus against 0.1 Torr or less for a pinch). The increased density and temperature more than compensates for the reduced volume in terms of the neutron yield....

For those who are interested in learning more about the UNU/ICTP PFF program, please visit the site of the Institute for Plasma Focus Studies at https://plasmafocus.net/ Also visit https://plasmafocus.net/IPFS/courses.htm and examine the courses and materials for self study.

Going Small

A fair amount of work has gone on with scaling the DPF to smaller sizes. Although the neutron yields are smaller, the reduced size of the capacitors makes the device more amenable to higher repetition rates. Such devices can be used in the field for neutron activation and the like.

Verma [3] describes a miniature plasma focus (MPF) with energy just under 240 J. He points out that the neutron yield for a "useful" device is on the order of 10^7 to 10^{10} neutrons/sec. Since the MPF is only capable of 10^3 to 10^6 neutrons/sec. it is necessary to operate the device at a high repetition rate. His 3rd device operates at 10 Hz resulting in a yield of 1.4 x 10^7 neutrons per second, i.e. ten shots with about a 100 ms charge time per shot within each 1 second period.

Clausse, *et al*. [4] have described a 50 J focus in a study of the effect of anode length. The capacitor bank consisted of 4 units of 40 nF. The peak yield was on the order of 10^4 neutrons per pulse.

The Author's DPF - The Mini-F

At some point in the past couple of decades I began acquiring the components for a small DPF. The heart of the unit is a Sangamo 59 µF, 10 kV capacitor. The design, as it stood in the 2012 timeframe, is described at http://www.belljar.net/mini_f.htm

I sent the basic information and dimensioned sketches to Prof. Sing Lee in early 2012. He had developed a modeling tool (Excel based) and ran the model. Here is his response:

> I ran your planned PF on the Lee Model code using the following parameters:
> - Bank: L_0=90 nH (estimated from your geometry) C_0=59 µF, r_0=4 mOhm (~0.1 of $(L_oC_o)^{0.5}$)
> - Tube: a=1cm; b=3 cm (which are about what I would take using my rule-of-thumb; also very similar to what you have in your drawing)
> - z_0=18 cm (in order to reach a peak speed of ~9cm/µs at ~time of peak current which takes ~3.6µs for your bank parameters.
> - Operation: V=10kV pressure = 4 Torr gas = Deuterium
>
> You will have a peak current of 185kA, axial phase ending at 3.1 µs (axial phase ending a little before 'natural peak current; can increase pressure to 5 Torr if you like) neutron yield of just over 10^7 D-D neutrons (our experience with such Type 2 plasma focus i.e. one with relatively high L_0, is that actual neutron yield could be 2-5 time this value for good shots). Radial dynamics and temperatures (gross column basis) also given in the figures.

The web page has some additional information and a link to Prof. Lee's model for the unit.

Impulse Plasma Deposition

My work on the Mini-F is, at least for the moment, suspended. My priorities are to continue the refinement and tests of my pseudospark electron source and also to finish the construction of a coaxial accelerator that is optimized for impulse plasma deposition (IPD).

In 1999, *the Bell Jar* had an article *Materials Modification with the Coaxial Plasma Gun: Using high speed pulsed plasmas to alter surface characteristics and to implant adherent coatings*. This article is currently available in the *Second Five Years* compilation. I have also extracted the pages and these are available at http://belljar.net/supplements/tbj_734_coaxial.pdf. Much of the content is based on patents by Ouderkirk (3M Corp.) and others. Work has continued on the use of DPF for materials work and there is a fairly extensive literature.

I'd sort of forgotten about this until I ran across some relatively recent papers by Prof. Krzysztof Zdunek of the Warsaw University of Technology and his team on what they call Impulse Plasma Deposition or IPD. A good place to start is his 2007 IPD review paper [5]. Basically, IPD uses a coaxial accelerator that is operated a relatively low voltage (as compared to the DPF) and high capacitance (e.g. 2 kV and 200 µF). In other words, it is not optimized for the creation of a dense pinch and is thus simpler in some aspects. From the abstract:

> Plasma is generated with the frequency of 10^{-1} – 10 Hz. The life time of plasma in each impulse is of order of 10^{-4} s. During the discharge of condensers individual plasmoids are being accelerated in the coaxial generator by the Ampere force to the speed of the order of 10^4 m s^{-1} and directed to the substrate. The substrate is nonheated from any external heat source prior, during and after the plasma process. Experiments showed that the nucleation of phases takes place on ions of plasma and layer is constituted by the limited coalescence of the subnano- or nano particles on the substrate surface. Layers of DLC, c-BN, oxides, interstitial phases and complex metallic alloys with nano- or amorphous/nano-crystalline structure are produced with the use of IPD. In 1989 the IPD method was implemented to the industry for deposition of TiN layers on cutting tools.

I contacted Prof. Zdunek and quickly received replies from him and members of the team. He provided a bit of history:

> An interesting detail related to IPD is its genesis. It was developed as an original solution, as the only effective way to create a diamond synthesis environment (in the form of coatings) from graphite (a source of carbon vapours) or hydrocarbons. According to our concept, diamond nucleation occurs homogeneously in the plasma itself on carbon ions. The formation of sp^3 hybrid bonds is conditioned by the efficiency of energy exchange between plasma electrons and carbon clusters. This exchange occurs through inelastic collisions of the particles in the plasma and is the most effective in high-energy non-equilibrium plasma. Such plasma can only be generated in pulses using a capacitor as a source of electric energy. The very short plasma lifetime promotes the freezing of excited states, and therefore promotes the "diamond" phase composition of the condensate produced on any substrate as a film deposited on it. The substrate does not have to be

> electrically polarized and heated. We used the IPD in the early eighties of the last century to produce DLC coatings with a high sp^3 content. Later the IPD was used to produce coatings for other super-hard and high-melting materials. It has been implemented in the Polish machine industry for the production of coatings on cutting tools. The IPD was 30 years ahead of the known High Power Impulse Magnetron Sputtering (HPIMS) method developed in 2010. The IPD, however, still has unique advantages not available with HPIMS.

My apparatus is under construction and will use an available 3 kV 300 µF capacitor. The chamber materials are primarily comprised of ISO 63 components.

The chamber pressure requirements also vary from those of the DPF. From the reference:

> In the IPD method, typically, the pressure of a few tens of Pa is selected so that the free path of the particle movements is smaller than the characteristic dimensions of the vacuum chamber. If this is so, the plasma reaching the substrate contains predominantly clusters. If however this pressure is so low that the particle free path exceeds the characteristic dimensions, the dispersion of the particles will increase and, on reaching the substrate, the plasma contains predominantly the atomic fraction. Therefore, depending on the pressure of the plasma-generating gas that prevails during the growth of the layer on the substrate, the predominating growth mechanism may be "classical" (atomic dispersion, nucleation of the substrate, layer grows through the growth of the nuclei) or so-called "cluster-type", the latter consisting of limited coalescence of clusters that are delivered to the substrate together with the impulse plasma. Thanks to the "cluster-type" mechanism of the IPD growth, it is easy to produce nano-crystalline layers with or almost without nano-pores (depending on the plasma process parameters)

I'll be starting off simply with copper deposition at a pressure of 20 Pa.

Summary –Plasma Accelerators, the Dense Plasma Focus and the Amateur

While I could well be wrong, I am not aware of any amateur work with devices of this type (I'd love to be proven otherwise). The most obvious community that might have an interest would be the amateurs that are working on D-D fusion using the Farnsworth-Hirsch type inertial electrostatic confinement (IEC) "Fusor." It would seem that the DPF would be the logical extension for those fusioneers that have conquered the IEC and are looking for something that provides a somewhat different set of challenges.

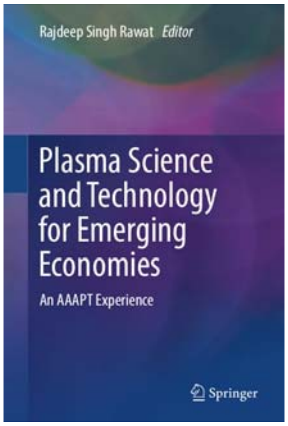
I checked with Richard Hull and he did note that one of the group's members has made a linear pinch device that does produce measurable neutrons. Mark Rowley's device, the Columbus-1, is described at https://fusor.net/board/viewtopic.php?f=15&t=13073. It has a 25 kV capacitor that stores 4375 J. Test pressures have ranged from 100 to 425 mTorr of D_2.

Other experimenters might be more interested in some other characteristics of the DPF such as x-ray or high energy ion beam production. And some might like to pursue the IPD type device.

References

1. S.P.Moo, C.S.Wong, A.C.Chew, *Twelve Years of UNU/ICTP PFF - A Review*, ICTP Preprint IC/98/231, October 1998. On line at https://plasmafocus.net/IPFS/otherpapers/12YrsUnuIctpPFFReviewMonograph.pdf
2. S. Lee, *Technology of a small plasma focus*, in *Small Plasma Experiments II*, S. Lee and Paulo H. Sakanska (Eds.), World Scientific, 1990, pg.144,
3. Rishi Verma, *Construction and Optimization of Low Energy (< 240J) Miniature Repetitive Plasma Focus Neutron Source*, A thesis submitted to the National Institute of Education Nanyang Technological University in fulfillment of the requirement for the degree of Doctor of Philosophy 2010. On line at https://www.plasmafocus.net/IPFS/phdtheses/PhD2010VermaRishi.pdf
4. Alejandro Clausse, Leopoldo Soto Norambuena and Ariel Tarifeño, *Influence of the Anode Length on the Neutron Emission of a 50 J Plasma Focus: Modeling and Experiment*, IEEE Transactions on Plasma Science, Vol. 43, No. 2, February 2015. (Available via Academia.edu)
5. Krzysztof Zdunek, *Concept, techniques, deposition mechanism of impulse plasma deposition — A short review*, Surface & Coatings Technology 201 (2007) 4813 – 4816. (Available via Acedemia.edu)

Plasma Science and Technology for Emerging Economies – An AAAPT Experience
Rajdeep Singh Rawat (Ed.), Springer Nature, 2017



Prof. Lee brought this book to my attention. AAAPT stands for the Asian African Association for Plasma Training. The book begins with an overview of the AAAPT, history, members and impact. There are several chapters on DPF including modeling, diagnostics and applications in materials processing, Other chapters cover Tokamak experiments, RF plasmas and applications, cold atmospheric plasmas and their application in medicine, the dielectric barrier discharge and other topics. The book is well written and has excellent photographs and drawings.

Chapter 9, *Cost-Effective Plasma Experiments for Developing Countries* is a very interesting chapter for the educator or experimenter. It starts with simple line frequency glow discharges with various topics including the use of the Langmuir probe, the modification of biomedical materials and a couple of simple dielectric barrier reactors. The chapter concludes with some more advanced topics. A section on atmospheric plasma jets includes information on construction, diagnostics and applications such as the synthesis of nanoparticles. There is a section on a small vacuum spark device for producing x-rays and a wire explosion system that is based on the vacuum spark apparatus.

Articles of Possible Interest in *Vacuum Coating & Technology* Magazine

Anyone that has read the *Bell Jar* or the various tutorials on the web site will be familiar with my chart that shows the various devices that are used to create and measure vacuum and then the various applications. That chart has gone through a number of updates over the years. The most recent update was in 2015 where I incorporated it in a pair of articles in *Vacuum Coating & Technology* magazine. For the January 2020 issue I have written a related article. This one is more like an out-of-order introduction to the other two. As a result, there's some necessary duplication. Perhaps someday I will pull it all together in a single article.

Articles may be accessed at http://vtcmag.com/. Scroll to the bottom of the page to the back issue selection box. I've listed these articles in the suggested order of reading:

January 2020
Some Properties of Vacuum from Atmosphere to UHV
This article is addressed to those who are curious about why the environment at 1 Torr is different from that at 1 milliTorr or 10^{-8} Torr.

June and July 2015
Creating, Measuring and Using Vacuum: How They All Fit Together (in two parts)
These articles discuss the operating pressures for various pumps and vacuum gauges along with the pressure ranges that are appropriate for many processes and other applications.

Ongoing Projects

This is just a list of the more significant projects that are ongoing here.

- Complete documentation for the basic vacuum trainer. This is described on my education page.
- An optical emission spectroscopy set up using a Penning cell and an emission spectrometer.from Vernier Software & Technology.
- A simple PID pressure controller.
- Complete next round of upgrades for the pseudospark electron source (see below).
- Assembly and testing of an impulse plasma deposition (IPD) system.
- Resume work on my Mini-F DPF.

Next Month - Update on my Pseudospark Electron Source

"In the late 1950s Jens Christiansen worked on parallel plate avalanche counters for nuclear physics experiments. Near the Paschen minimum, anomalous sparks at the edge zones of these counters resulted in erratic failures. Twenty years later he reestablished the research in this almost forgotten effect." [Quote from K. Frank and J. Christiansen, IEEE Trans. Plasma Sci. 17, 748, (1989)].

In 1979, J. Christiansen and C. Shultheiss published a paper *Production of high current particle beams by low pressure spark discharges*, in Z. Phys. A 290, 35 (1979). In this paper, a low pressure fast discharge phenomenon between a hollow cathode and an anode is described and named as pseudospark.

A minimal pseudospark device consists of two parallel plates, each with a small (typically 2-5 mm) aperture and separated by an insulator. Behind the cathode plate is a hollow cathode where the discharge initiates. The device works on the left hand side of the Paschen curve, i.e. where decreasing pressure results in a higher breakdown voltage. Additional electrodes may be added to increase the breakdown voltage. The charging circuit of a pseudospark device generally consists of a small high voltage capacitor and dc power supply. The hollow cathode may incorporate a trigger mechanism or rely on self breakdown. Typical operating pressures are in the range on 100 - 500 mTorr.

The pseudospark device has two primary modes of operations. The first is an initial high voltage hollow cathode discharge that produces a high brightness beam of electrons with energy approaching the supply voltage. This may proceed to a lower energy high current discharge.

Pseudospark devices are now available as high current, fast switching alternatives to thyratrons, ignitrons and spark gaps. In addition, pseudospark devices are used as sources of electrons to pump other devices and for use in specialized thin film deposition processes.

My device, as it currently stands, is shown in the photo above and is configured as an electron source. It has 7 anodes (6 floating) with 4 mm apertures. Although it can be electrically triggered, I generally let it free run (pressure set at the desired breakdown voltage). Below the pseudospark source is a small experiment chamber that was fabricated from the shell of a cold trap.

I have tested the unit to a voltage of about 80 kV but I generally operate it between 30 and 60 kV.

Immediate improvements include replacement of the electrodes and the addition of a dielectric beam guide. I also need to add some simple diagnostics.

Your Projects

The 10 volumes of the printed *Bell Jar* had a high proportion of reader projects. If you are working on something that is vacuum related that may be of interest to others, please contact me.

That’s it for this month.

Steve