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EDITORIAL

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Whence Z-pinches? A personal view

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N. R. Pereira[a)]

AFFILIATIONS

Ecopulse, Inc., Springfield, Virginia 22152, USA

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[a)]**Author to whom correspondence should be addressed:** ninorpereira@gmail.com. **URL:** http://www.ecopulse.com

ABSTRACT

The first Dense Z-Pinch (DZP) conference, in 1984, marked an attempt to use then-modern pulsed power with a Z-pinch to work toward thermonuclear fusion energy. This 11th DZP conference in China is a good time to look back, to comment on progress since, and to project forward. What follows is a personal perspective: scattered comments from a sympathetic outsider and one-time participant. In these 35 years, Z-pinch theory has evolved from little more than cartoons to fully 3D MHD computer simulations, measurements have gone from mostly time- and spatially integrated diagnostics to monochromatic imaging, highly resolved x-ray spectroscopy, and active laser probing. Large pulsed power generators now drive x-ray-producing Z-pinches that are powerful enough for many applications; thermonuclear fusion may work single-shot in the future.

I. INTRODUCTION

Thermonuclear fusion burst onto the scene in the early 1950s with almost unlimited explosive power, and, ever since, thermonuclear fusion has been thought of as a potentially unlimited supply of energy: fission became useful as an energy source almost overnight, so why not fusion? A linear Z-pinch was an early attempt to create a fusion-relevant plasma in the laboratory. The microsecond-long pulsed power available at the time did indeed produce neutrons that proved a nuclear reaction. Fusion energy seemed right around the corner, and the world's nuclear powers tried to make this happen by themselves.[1]

As is now well known, instabilities in the linear Z-pinch give some ions enough energy to overcome the multi-keV Coulomb barrier between two deuterium (D) or tritium (T) nuclei. A few energetic ions can then participate in an exothermic nuclear reaction, but the resulting energy is much less than the energy that the vast majority of these energetic ions lose to the plasma. Thermonuclear fusion demands constant recycling of the energy so that the DT mixture remains full of energetic ions, that is, it is a DT plasma.

Once the nuclear powers with thermonuclear energy programs realized that they could not achieve quick success on their own, they decided to share their research in what is now known as magnetic fusion energy, with ever-increasing cooperation between the actors. The hope is to create a stable DT plasma with thermonuclear parameters as in the ITER tokamak, a joint project between many nations that should become operational three-quarters of a century after the initial attempts with the Z-pinch. Thermonuclear fusion research with the available pulsed power continued in the dense plasma focus; the practitioners hoped that instabilities could somehow be dealt with: either suppressed or otherwise used to good advantage.

An alternative, inertial confinement fusion (ICF), joined the party in the 1970s. ICF tries to achieve thermonuclear conditions by compressing a small DT sphere from all sides with a short pulse of power, from x-rays or otherwise: the aim is for inertia to keep the DT plasma dense enough for sufficiently long to produce appreciable energy. A quite recent development is magnetized liner inertial fusion (MagLIF), which attempts to compress a preheated plasma inside an imploding Z-pinch shell, wherein the magnetic field keeps heat loss to the outside within limits.

What Z-pinches do depends ultimately on the available pulsed power. Typically, this is a short (~100 ns or less), high-voltage (~0.1–1 MV or higher), and high-current (~0.1–10 MA and higher) electrical discharge. In the UK, the technology came largely from J. C (Charlie) Martin[2] and his co-workers, and in the USA through his group's cooperation with Sandia National Laboratories (SNL) and other organizations. Comparable developments went on elsewhere.

Figure 1 was shown various times at the conference. It is an overview of the history of pulsed power, illustrated by focusing on SNL. The purple line on the left suggests a linear progress in Pulserad-like generators. The square symbol represents Aurora, a stack of four Pulserads in a square (although not at SNL). They use a high-voltage Marx generator followed by an oil-filled Blumlein capacitor, a technology that is now superseded by inductive adders as in Hermes-III. These give shorter,

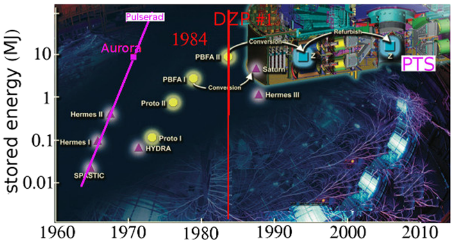

FIG. 1. Advances in pulsed power illustrated with the machines at Sandia National Laboratory (SNL).

more desirable pulses ideal for demanding radiography and to mimic multi-MeV ionizing radiation from nuclear explosions.

These γ-ray pulses are far off the right side in Fig. 2, where high-intensity pulses can be made with a simple space-charge-limited vacuum diode with an impedance $Z = V/I \sim 10\ \Omega$ or so. Around 0.3 MeV, electrons can still produce powerful enough bremsstrahlung, but the vacuum diode must be more sophisticated, with $Z \lesssim 0.1$–$1\ \Omega$ and with pulsed power to match. At SNL, these low-impedance generators include the Proto machines (yellow dots in Fig. 1).

An electron in a space-charge-limited diode converts its energy into radiation only once, with an efficiency $\eta \sim V^{2-3}$ or so, which makes it impossible to get powerful enough x-ray pulses below ~100 keV with a vacuum diode. Instead, the electrons must continually regain their energy so that they can make radiation multiple times; that is, there must be a plasma. The plasma can come from a powerful laser (NIF in Fig. 2), but this conference is about Z-pinch plasmas. The most powerful radiating Z-pinch is made with Z, marked in both Figs. 1 and 2.

Very little material is required to suppress space change: the charge $Q = -I\tau = -0.1$ C carried by an $I \sim 1$ MA pulse over $\tau \sim 100$ ns is the same as ~1 μg of any material has in its electrons. The art of the Z-pinch is, then, to have the discharge start through some material that connects the electrodes electrically, in some clever way that makes the best use of the electrical energy available in the pulse to optimize the intended output. This is very difficult when the discharge can have only a small amount of material: it could be blown off an insulator, injected as a gas, or put in as thin wires. Figure 3 illustrates some of these geometries.

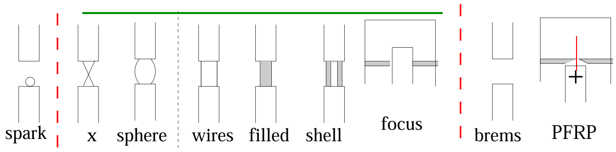

FIG. 3. Initial state of Z-pinches that are subjects at the DZP conference.

All of these initial conditions eventually end up with the diode material becoming a hot plasma. Heating is in part instantaneous Ohmic heating VI, where $V = IR$ (and defines the resistance R). Often the larger power source is conversion of kinetic energy stored in an implosion into heat; the voltage is then inductive ($V = I\,dL/dt$) and corresponds to the power needed to fill the diode with magnetic energy.

Naively, the highest density, and most powerful radiation, should occur along an axis of cylindrical symmetry, but this is not always the case. Implosions are highly unstable: with a nominally ideal, cylindrically symmetric initial condition, a Z-pinch may radiate softer x-rays from an ideal plasma cylinder as in Fig. 4, all the while radiating harder x-rays from isolated bright spots. Asymmetry along the axis may put the bright spot at a preferred location, as in the X-pinch or spherical pinch. Untangling all this makes the Z-pinch and its variants so interesting.

Radiating Z-pinches are tightly bound up with pulsed power. Besides the generators at SNL mentioned in Fig. 1, a pioneering machine since the 1970s is the ~1 MA Gamble II at the Naval Research Laboratory (NRL). Other multi-MA machines include Double Eagle at PI (now part of L3Harris), which is the sole survivor of Z-pinch work within the US Department of Defense (DOD), and Russia's Angara-V. All these were built before the first Dense Z-Pinch (DZP) conference. Now there are MA-class machines at universities, such as MAGPIE at Imperial College London (IC), COBRA at Cornell University, and MAIZE at the University of Michigan. The University of Nevada, Reno recently lost funding to maintain its Zebra facility. More recent (2010) is China's Primary Test Stand (PTS), now renamed Jutong-1 (Jutong, 巨龙, translates to Giant Dragon): it looks similar to Angara-V, but has slightly higher peak current ($I_p \sim 8$ MA), comparable to that at SNL: it has been added to Fig. 1.

For thermonuclear fusion, the temperature T in a DT plasma must reach close to 10 keV, the density n must be large enough, and it must remain so for enough time τ: one (Lawson-like) parameter is $nT\tau$ (as in Fig. 10: tokamaks want $nT\tau \simeq 10^{21}$–10^{22} keV s/m^3). For x-ray production, the x-ray output depends on the atomic number Z of

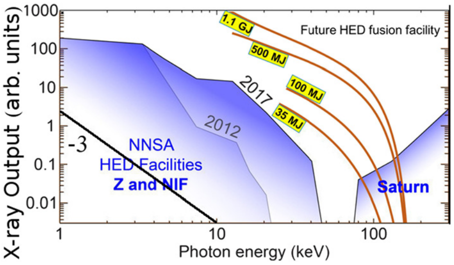

FIG. 2. Progress in the radiation per pulse achievable with Z or NIF from 2012 to 2017. A future fusion facility would produce substantial radiation in the difficult region around ~60 keV.

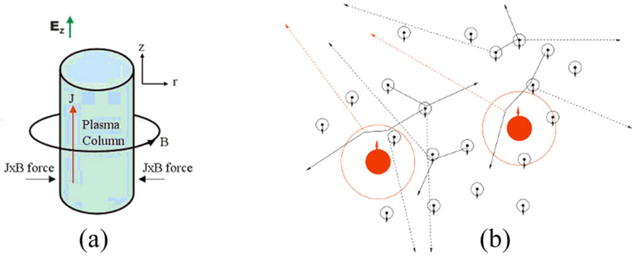

FIG. 4. (a) An idealized Z-pinch in early modeling. (b) On a microscale, the plasma is made up of electrons and different kinds of ions that interact with photons.

the plasma (see, e.g., Sec. III in Ref. 3): not only must the electrons be hot enough to ionize the atoms of the plasma to a helium-like ionization state (the binding energy for K-shell electrons in an atom with atomic number Z is ~0.01 × Z^2 keV), but the ionized plasma must remain together for some time as well.

The shaded areas in Fig. 2 illustrate the x-ray output Y per pulse as a function of some characteristic photon energy that can be achieved nowadays. On the left side are the Z-pinches on Z at SNL and the laser facility NIF [at the Lawrence Livermore National Laboratory (LLNL)]. The straight lines suggest a power law $Y \propto (h\nu)^n$ as a function of a nominal photon energy $h\nu$, with $n \simeq -2/3$ for x-rays up to argon ($Z = 18$, at ~3 keV), $n \simeq -3$ up to stainless steel ($Z \simeq 26$, at ~7 keV), and less regular toward krypton ($Z = 36$, at ~13 keV) and above (more details can be found in Ref. 3). On the right side, the bremsstrahlung at Saturn has the opposite scaling, with $n \sim 3$ above 150 keV.

In between the plasma radiators on the left and bremsstrahlung on the right of Fig. 2 is a bucket-shaped intermediate region where the output is too low for the graph. "Filling the bucket" with photons is an ongoing challenge for a laboratory x-ray source. One approach is through thermonuclear fusion. The orange lines in Fig. 2 give the x-ray output that should accompany ICF explosions, for the indicated energies per pulse. Even for the lowest (35 MJ) output in fusion energy, the corresponding x-rays completely cover the bucket, and even more so for the larger outputs. How to make good use of these x-rays despite the damage from the explosion is a problem that will have to be solved eventually.

In the USA, the Department of Energy (DOE) funds research aimed at thermonuclear fusion, and much research on pulsed radiation as well. The DOD deals with x-rays only, for which it sponsors research at government laboratories such as NRL, at private companies like PI (or L3Harris), and at universities. On this softer Z-pinch side of Fig. 2, the x-ray outputs are now large enough to fulfill the requirements, so further work is not so urgent.

The vagaries in Z-pinch research are typical of applied work: irrespective of whether some stated goal is reached or abandoned, the focus of interest can shift, as is reflected in Fig. 1. ICF was an original goal for SNL's PBFA machines (just as for LLNL's NIF). First, electron beams would compress DT pellets, later on protons would do it, and then lithium ion beams would overcome the problems associated with protons. Each of these approaches ran into its own difficulties, and the research went on to the next stage. PBFA-II became Z when the x-ray power output from a sophisticated multiwire tungsten Z-pinch seemed to be large enough to implode ICF pellets in much the same way as pursued elsewhere with lasers.

SNL's present ICF direction is magnetized inertial fusion (MagLIF),[4] in which a preheated plasma is compressed as in a Z-pinch. Sandia's work with the Z-machine, and with its refurbished successor, now also named Z, is a principal inspiration for Z-pinch research all over the world, including at US universities: two oral presentations at this DZP Conference deal with MagLIF.[5,6]

Building and operating large pulsed power generators is expensive and time-consuming, and so is research with them. Hence, many smaller pulsed power generators that can still create relevant plasmas are important in Z-pinch research, and are quite productive: the diagnostics from plasmas made by smaller machines are just as challenging to interpret as those from the massive facilities. Already mentioned are the ~1 MA generators at IC in the UK and at Cornell and the University of Michigan in the USA; similar research goes on at the University of California, San Diego (UCSD) in the USA, in Russia, China, Israel, and elsewhere. Still smaller machines make interesting plasmas as well, in, for example, Chile, Singapore, and Japan. Besides suggesting intellectual challenges, the larger laboratories motivate research at the smaller sites by personal contacts among students and scientists, and through funding for aspiring students and their eventual employment.

This paper reinterprets the talk that I gave at the 11th DZP conference. It is a personal view of the field in which I was active early on and of which I later became a sympathetic observer from the outside. I apologize upfront for any misconceptions I may have, for selecting my favorite topics over yours, and for freely taking information I deemed reliable from the web: distressingly many pitches for fusion are misleading nonsense.

II. WHERE DOES THE DZP CONFERENCE FIT IN?

When a small, specialized, and growing field of research exceeds a certain size, it deserves a small, specialized conference for practitioners in the field to get together, learn about what is going on elsewhere, comment on each other's work, and get to know each other so that off-site communication becomes less of a hurdle. They complement the larger meetings with their many parallel sessions, where a smaller field can get drowned out. Z-pinches for radiation and fusion remain topics at the annual plasma conferences such as the APS-DPP (Division of Plasma Physics) conference and its analogues elsewhere, at the IEEE-ICOPS (Plasma Science), and the IEEE-PPS (Pulsed Power).

Z-pinches reached this point in the mid 1980s, when pulsed radiation production with Z-pinches blossomed in the open. The DZP conference was modeled on the BEAMS conference, which dealt with pulsed-power-driven particle beams and their applications, including ICF and radiation from vacuum diodes as on the right side of Fig. 2, but less with the atomic physics and radiation hydrodynamics that are essential to gain insight into x-ray-producing Z-pinches.

As the interest in a technical field changes and possibly decreases, its specialized conference may have to adapt: BEAMS did this by combining with DZP in 2002 in Albuquerque, NM, USA, and most recently in 2018 with the East Asia Pulsed Power Conference in Changsha, China. The DZP may well have to adapt in a similar way, since pulsed radiation production with Z-pinches is no longer so compelling, and funding for the topic may decrease.

A. The first DZP1984: "Dense Z-Pinches for fusion"

NRL's John Sethian organized the first International Conference on Dense Z-Pinches, DZP1984, in Alexandria, VA, USA, with a clear purpose in mind. In the introduction to the proceedings, he states, essentially:

> . . . this meeting is singularly dedicated towards attempts to develop the Z-pinch into a source of thermonuclear energy. At first glance a renewed attempt with Z-pinches seems futile: dense Z-pinches have generated 14 MeV neutrons since the earliest days of fusion. However, recent advances in pulsed power suggest that Z-pinch fusion is still in its infancy. Fusion reactor concepts based on the elegant and simple Z-pinch seem much more attractive than magnetic confinement or other schemes.

Indeed, one such reactor concept was presented at that first DZP.

The High Density Z-Pinch (HDZP) program at Los Alamos National Laboratory (LANL) is an example of the thinking at the time. It envisions a stable DT pinch as in Fig. 4, in force (Bennett, $T \propto I^2$) equilibrium as resistive heating increases the plasma temperature. The current must then increase in time along the so-called Haines–Hammel curve, named for the scientists who derived it independently at IC and LANL. Initially, the heating power is larger than the power lost in bremsstrahlung, but as the current increases, heating and cooling become equal; this happens at the Pease–Braginskiĭ current $I_{PB} \simeq 1.4$ MA. In this concept, the Z-pinch could not be in equilibrium for $I > I_{PB}$. Instead, something dramatic would happen when the current exceeded I_{PB}: the pinch was thought to have to contract radially, to some higher density and temperature where thermonuclear fusion might occur: radiation collapse.

As it turns out, in deuterium, pinches do not collapse like this, but collapse-like micropinches can occur when the atomic number Z is larger and atomic transitions make the radiation much stronger than bremsstrahlung.

This first DZP helped NRL to explore Z-pinch fusion, first with a pinch that was thought to remain stable inside a capillary, and eventually with a cryogenic deuterium wire. The resulting pinches indeed seemed stable and produced neutrons, but they turned out not to be thermonuclear: the deuterium core remained solid and cold while a low-density, low-resistance plasma outside carried the current. Plasmas blown off from wire or metal when it carries a high surface current remain a problem today, on the one hand because they are not easy to model properly and on the other because they are difficult to deal with experimentally.

The NRL machine vanished, but the LANL machine resurfaced as Zebra at the University of Nevada, Reno (UNR), where it was very productive (as in Fig. 7). MAGPIE at IC did not achieve fusion either, but did much excellent research on Z-pinches. Right now, it supports research on astrophysical plasmas.[7–9]

Despite the failure to produce fusion energy with a Z-pinch that started off DZPs, thermonuclear fusion research keeps going in part because of its enormous payoff, "The Final Solution to the World's Energy Problem." Its lack of success so far may disappoint, but is not so bad: overcoming obstacles needs plasma physicists who remain gainfully employed.

B. The second DZP1989: Add x-rays and Soviet scientists

In the USA in the 1980s, President Reagan's Star Wars initiative imagined military applications for intense beams of protons, electrons, and all kinds of photons from microwaves to hard x-rays. All needed similar pulsed power, but different front ends. By then, Z-pinches had shown ever-larger radiation outputs (but still much lower than in Fig. 2; see Ref. 3), diagnostics had become better, and numerical models for radiation hydrodynamics started to have some connection with reality. All these are good topics for a specialized scientific meeting, which is why Norman Rostoker, then at the University of California, took the initiative for an International Conference on Z-Pinches. Grafting this second DZP onto Sethian's first gave the conference additional heft, although the continuity is somewhat contrived.

During the Cold War, the USA and the Soviet Union (USSR) had been in respectful competition on such research, with occasional technical exchange visits by prominent scientists, including Norman Rostoker to the USSR and Leonid Rudakov to the USA. Perestroika in the late 1980s and American money made it possible for seven Soviet scientists to attend the second DZP conference.

This conference was very successful. Attendance was about one-third non-US, and hence truly international. The attendees decided to continue with DZPs on a quadrennial schedule, rotating between the locations where most Z-pinch research occurred: the USA, the UK, Continental Europe, and the USSR. In analogy to the BEAMS conference, a Governing Board would consist of previous Conference Chairs. The scientific emphasis would tilt to the front end, where a small change can make a large difference. Some are sketched in Fig. 3. Those for Z-pinches are below the green bar. The X-pinch and spherical pinch on the left intend to concentrate energy into a small spot. The three middle ones are the most common; the dense plasma focus is to the right.

C. The third DZP1993 and later ones

Malcolm Haines organized the third conference in London, UK. As before, Continental Europe, the UK, and the USA were well represented. Many scientists with backgrounds in the USSR came too, some now from Russia and many with affiliations elsewhere (including S. I. Braginskiĭ). He and R. S. Pease, both of I_{PB} fame, inaugurated IC's newly built MAGPIE generator. In retrospect, this conference may have been a high point for DZPs: defense-relevant research had not yet decreased and visas for scientists to travel to the USA had not yet become so uncertain.

The effects of the world political climate continued to be seen at the DZP. Instead of the next meeting being in the USSR, DZP1997 moved to Vancouver, Canada so that the conference remained visibly international. Fewer attendees with Soviet pedigrees came from Russia than from elsewhere, since many had joined foreign institutions, where some were already key figures in Z-pinch research. Leonid Rudakov, now in the USA, alerted the attendees to 1800-vintage pulsed power,[10,11] built because "…smaller machines can not get what you want…" and evaluated for its military potential,[12] just as is the case at present.

One prominent attendee was R. S. Pease, who by now had retired as Director of the UK's thermonuclear fusion research efforts. In his keynote address, he confessed to being disappointed with the progress in fusion: in about 1975, he had expected to have thermonuclear energy by now. Another was Lu Ming-fang (Chinese Academy of Sciences), the first scientist from China to attend a DZP, who discussed work on a small plasma focus.

In the decade after the end of the Cold War, sometime in the early 1990s, the military's interest in particle beams and x-ray pulses dwindled. In contrast, success with ICF-relevant quasi-blackbody radiation from multiwire tungsten Z-pinches at SNL had spurred an upgrade of Z to ZR. To match this upgrade, the next DZP conference was delayed by one year and combined with BEAMS. This joint conference had 12 attendees from China: three of them organized the present DZP (J.-J. Deng, N. Ding, and C. Ning). Their papers now included research on large pulsed power generators built in China.

On the technical level, each subsequent conference testified to the increased power of computers, from the quality of the visuals in the presentations to the increasing physics content in numerical modeling. Likewise, diagnostics became ever more powerful. Progress in the field is best seen from the reviews that appear periodically, some in connection with a DZP and others with other conferences. The most extensive, that by Haines,[13] reflects a prominent Z-pinch scientist's lifelong activity in and contributions to the field, Another comprehensive review is that by Giuliani and Commisso,[3] with up-to-date data.

One thing that is remarkable is the continuously increasing prominence of Chinese scientists at the DZP. One exception is DZP2008, when US visa problems prevented their attendance. Bureaucratic problems happen in reverse as well: US Government rules prevented US Government scientists coming to China for this 11th DZP, much to their chagrin.

III. PROGRESS IN THEORY

This personal account does not intend to review the technical progress, which is better done by the papers in Table I. Instead, as at the conference, I mention only a few issues that plagued Z-pinches back then and continue to do so now.

The Z-pinch cartoon on the left in Fig. 4 is a cylindrically symmetric, axially uniform plasma fluid, with its pressure in equilibrium with the magnetic field outside a boundary $R(z) = R_0$. The total current $J = \int_0^R dr\, 2\pi r\, j_z(r,z)$ is along the axis, and the current density $j_z(r,z)$ is assumed to be so as well. Such a plasma is unstable in many ways: it can flow along the axis with radial symmetry (or pinch, $m = 0$), flow sideways (or kink, $m = 1$), and even concentrate current in local channels when its resistance decreases with temperature. It allows analytical expressions such as the Bennett relation

$$\frac{\mu_0 J^2}{4\pi} = 2NkT \times (\text{dimensionless factors}), \tag{1}$$

which applies to a hydrogen pinch with equal electron and ion densities $n_e(r) = n_i(r) = n$, thermal equilibrium $T_e = T_i = T$, and other simplifying assumptions. $N = \pi R^2 n$ is the line density. The dimensionless factors depend on the simplifying assumptions: a plasma with Z-times ionized ions has $Z\times$ more electrons than ions, and the factor is $(1 + Z)/2$.

TABLE I. A selection of Z-pinch-relevant summaries.

Title or topic	Reference
X-rays from Z-pinches…[a]	40
Plasma points and radiative collapse…	41
Scientific status of plasma focus research	42
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The physics of fast Z pinches	44
The past, present, and future of Z pinches	45
A review of the dense Z-pinch[b]	13
Magnetically driven implosions for ICF at SNL	46
…Z-pinch as an X-ray and neutron source…	3
Characterizing the plasmas of dense Z-pinches	47
X-pinch I, II, III	48
…wire array Z-pinch and dynamic hohlraum…	49

[a] Old, but can serve as an introduction.
[b] The most extensive account.

Adding power equilibrium gives another analytical relation, the Pease–Braginskiĭ current

$$I_{PB} \simeq \frac{I_A}{\sqrt{\alpha}} \times \ln\Lambda \times (\text{dimensionless factors}) \simeq 1.4\,\text{MA}, \tag{2}$$

in the form from Ref. 14. The numerical value is for a hydrogen plasma. Here, the Alfvén current $I_A = ec/r_e \simeq 17$ kA is a fundamental current scale that contains only standard constants: $r_e = e^2/4\pi\epsilon_0 mc^2$ is the classical electron radius. The plasma comes in only through a numerical factor $\ln\Lambda$, which is often $\simeq 7$ for fusion plasmas. An approximately constant value of 1.4 MA for I_{PB} irrespective of pinch geometry (and only weakly dependent on the plasma, through $\ln\Lambda$) suggests that I_{PB} expresses something fundamental, and indeed it does: the fine structure constant $\alpha = e^2/2\epsilon_0 hc$ comes in because the collisions that put power into the plasma are responsible for the bremsstrahlung as well. The fine structure constant α that is a factor in I_{PB} is fundamental to bremsstrahlung-producing collisions and comes from the ratio of the relevant cross sections.

At the start of an electrical pulse, the pinch in Fig. 4 cannot exist. Early on, a fast pulse might flow within a thin boundary layer on such a pinch, but a fast pulse implies high voltage (across a high inductance such as a wire), and the cathode can emit electrons. These carry some current outside the wire through the vacuum[15] before magnetic insulation sets in. How the current penetrates into the plasma is, I think, not well understood. Even when the initial state is made to be cylindrically symmetric, the discharge may not agree in its actual structure.[16] Fortunately, many complicated phenomena can be avoided or suppressed in practice without having to understand them to a scientist's satisfaction.

Unlike the featureless fluid plasma in Fig. 4(a), on the microscale in Fig. 4(b), the plasma is shown with its individual particles (for a higher-Z plasma). It has many free electrons (black), and ions (red) that are only partially ionized. The free electrons move rapidly in all directions with thermal-like energies: the radial electric field that keeps them inside the sharp border implies some minute net positive charge. The outside electrons can then $\mathbf{E} \times \mathbf{B}$-drift in the axial direction. Elastic, energy-conserving collisions maintain a thermal distribution unless the electrons lose too much energy by inelastic, ionizing collisions. The final result is a photon that may escape from the plasma, or ionize further and random-walk its way to the outside. Current inside the plasma corresponds to a slow drift of the electrons and ions in opposite directions: any strong enough magnetic field makes the electrons move partly or completely along a circle, a gyromotion not shown in this cartoon.

For such higher atomic number plasmas, atomic radiation is more intense than bremsstrahlung. One consequence is the dimensionless factor in Eq. (2), which is less than unity and makes I_{PB} less than for hydrogen.[14] Analytical investigations such as these are rare nowadays (but see Ref. 17, for a laser-produced plasma), but can still provide insight.

The present approach is largely numerical. The ever-increasing capabilities of computers allow the codes to include more phenomena and treat these more accurately; ever-better computer graphics and even movies give seductive images that range from misleading to insightful.

Figure 5 is one such frame from a computation with the MHD code Gorgon of an 8-wire Z-pinch implosion. At this time, the low-density plasma blown off the wires is already in the center, while the wires themselves are too massive to have moved yet. At the conference, I had intended to comment on the nice graphics, and on the code's validity for the situation. Two-dimensional symmetry is almost unavoidable, but is the low-density plasma still collisional as needed for MHD? And what about energy loss by radiation? This early computation may have had such issues, but by now they may be taken care of: Gorgon's principal developer Jerry Chittenden described their ongoing work on the code in his invited talk,[18] including some of the physics that I had (mistakenly) thought to be absent. Wire blow-off and what to do about it came up at the conference a lot, in four oral papers by Chinese scientists and in a few posters.

The x-rays emitted by Z-pinches are usually estimated in collisional radiative equilibrium (CRE), where Maxwellian electrons are locally in thermal equilibrium with the different ion species as these radiate away the plasma's energy, and the radiation itself spreads the energy throughout the plasma, nonlocally. The atomic physics is now well enough known for a code on the web (FLYCHK[20,21]) to give good estimates for a uniform plasma's average ionization, which ionization states the ions are in, and the x-ray spectrum the plasma emits, all as functions of a single temperature and density. To do this for all the plasma states the Z-pinch goes through as it implodes is only possible with additional approximations, including some to the CRE model itself. Another talk at the conference[22] discusses x-rays and spectroscopy of such plasmas in much more detail.

The approximations can be done in many ways that are compared regularly in the biennial Non-Local Thermodynamic Equilibrium (NLTE) workshops. Figure 6 shows the ratio between Li-like satellite lines and the He-α line as a function of the plasma temperature for one test case at the 10th NLTE workshop:[23] it is a neon plasma with electron density $n_e = 10^{19}/\text{cm}^3$ as might happen in a Ne Z-pinch. The more extensive models (thick dark lines) agree with each other within a factor of two; simpler, faster models that might be good for including in MHD codes still agree more or less. Integrated results, such as average ionization or radiated power, do better.

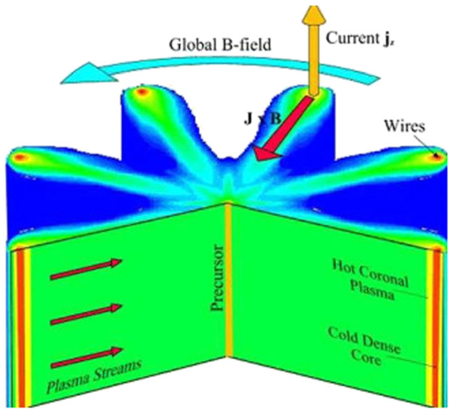


FIG. 5. Gorgon simulation of an 8-wire Z-pinch,[19] performed with an older version than that presented at the conference.[18]

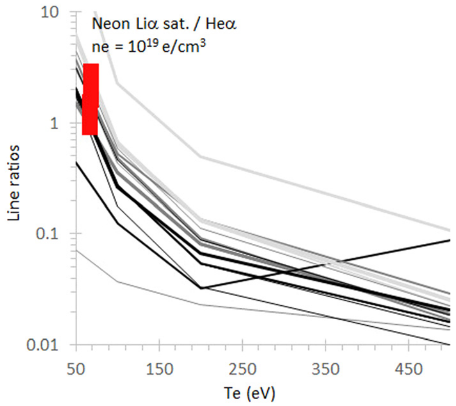


FIG. 6. A temperature-sensitive line ratio in Ne computed at the NLTE workshop.[23]

At the conference, I illustrated one approximation to CRE with my favorite example: non-Maxwellian electrons. Every x-ray that leaves the plasma implies at least one inelastic collision wherein an energetic electron loses the corresponding energy. Getting that energy back takes multiple Coulomb collisions. With inelastic collisions taken into account, in one computation,[24] the electron energy distribution has fewer energetic electrons than a Maxwellian with the same temperature. As a result, the line ratio in Fig. 6 changes by half an order of magnitude, as illustrated by the red bar. Such a change serves to remind us that less obvious effects, perhaps a boundary or some deviation from detailed equilibrium as in this computation, might influence the CRE model results. Indeed, a test for time dependence (on another sample problem) was part of NLTE-10.

Exploring plasma physics with abridged models remains useful: a particle-in-cell (PIC) computation at the conference[25] dealt with the plasma oscillations that should occur in the low-density edge plasma, where the MHD approximation is invalid owing to there being too few collisions. Discrepancies may reflect unsatisfied assumptions in the modeling, such as too simple an atomic model or a dense spot within the plasma that is too small to stop the faster electrons. Modeling all the different stages is particularly difficult when the plasma is at its most interesting, with strong spatial gradients as in the X-pinch.[26] So far, Z-pinch research lacks the support needed to develop comprehensive codes such as those available for laser-driven radiating and ICF plasmas (see, e.g., Ref. 27).

Despite the approximations in the models, radiation-MHD computations of Z-pinches do produce x-ray spectra that may result in credible numbers for the plasma parameters. Despite the inevitable shortcomings, the modeling effort itself is essential for Z-pinch research: how else to give our sponsors the numbers they want, and to satisfy our desire to know what goes on in the plasma from ever-improving diagnostics?

IV. PROGRESS IN MEASUREMENTS

In reality, an imploded plasma is not a uniform cylinder as in Fig. 4 or in time-averaged images of XUV radiation. The time- and spatially resolved density in Fig. 7 gives a more realistic image. The

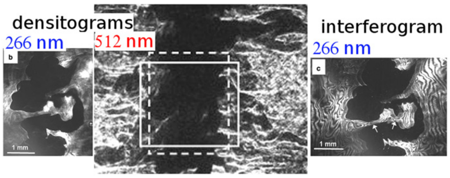


FIG. 7. Densitograms of the same Al wire plasma obtained with two laser wavelengths, and one corresponding interferogram. Reprinted with permission from Ivanov *et al.*, Phys. Rev. Lett. **107**, 165002 (2011). Copyright 2011 American Physical Society.[29]

center panel is a shadowgraph of an Al pinch, obtained with 512 nm light from a short-pulse laser. The dark ≃2 mm diameter column is overdense plasma that the light cannot go through. The panels on the sides indicate fourfold-denser plasma, taken at 266 nm: to the left is the density, to the right the density with additional information from interferometry. The fourfold-denser plasma has a complicated kink-like structure, with a less-dense region across the middle. Gorgon's MHD model indeed gives a similar kink, but this kink is not clear in the lower-density plasma in the center panel. The underdense plasma on the outside has a complicated structure that is hard to understand and easy to ignore.

Pulsed lasers can give spatially and time-resolved images of the current density as described recently in this journal,[28] and, together with complementary diagnostics, gives a more complete picture of the Z-pinch. Its internal structure is usually more complicated in x-ray images with harder or monochromatic x-rays, but invisible with softer x-rays. Reproducing all this information with computations is a real challenge.

I could have picked any number of excellent x-ray spectroscopy diagnostics to illustrate what can be done with x-rays. The one I showed was the time-resolved Doppler shift of an Mg impurity's He-α line in an Al wire implosion, which finds the implosion velocity of the material that makes the x-rays.[30] I omit that discussion here: it is best admired in the original publication.

V. WHERE MIGHT Z-PINCH RESEARCH GO?

In academia, scientific interest in a particular topic may well keep an individual researcher occupied for their entire career, but in an applied and policy-sensitive field such as radiative Z-pinches, the direction and most importantly the funding come from some government agency. Thermonuclear fusion is sometimes supported by rich individuals or private organizations, investors who accept that most research does not pay off but hope that they are the lucky ones to grab a "unicorn," the single exception that makes up for all the failures. While unusual in a scientific paper, I found it appropriate to comment on these matters at a DZP conference.

I briefly mentioned the multiwire Z-pinch identified with Tom Sanford and others at SNL. In papers starting with Ref. 31 (see also Ref. 13), they showed that carefully initiating a wire Z-pinch with tens or even hundreds of wires gives ever-shorter x-ray pulses, with the same total energy and higher power. As a consequence, SNL's research changed surprisingly quickly from ion beams to Z-pinches, as marked by PBFA-II's conversion to Z in Fig. 1.

Changes in research direction may have less happy outcomes. At the meeting, I mentioned one in radiation and one in fusion.

A. The saga of decade

Nuclear explosions result in giant plasmas that radiate short, powerful x-ray pulses over the entire photon spectrum up to many MeV. Governments that worry about nuclear weapons would want to have laboratory sources that are similar. When such concerns recede, research in this direction may then lose its urgency, as happened with Z-pinches. A painful transition period with ever-decreasing funding then leaves all kinds of interesting science abandoned and equipment repurposed.

When MeV-type x-ray pulses seemed important in the USA in the 1960s and 1970s, a 10 MV pulsed power machine with 1 MA peak current such as Aurora could be built. Its ~10 MJ capacitor bank is shown in Fig. 8(a). However, softer x-rays were needed too, as in Fig. 2: the red "Z" in the middle of Fig. 8(a) indicates the flange left over from an attempt back then to make these on the cheap, with a Z-pinch driven by a low-impedance transition with Aurora's capacitor bank as the energy source. This failed. With additional money, some of the parts from this attempt ended up in Phoenix, which achieved I_p ~ 3 MA and did well with Z-pinches. In pulsed power, as elsewhere, you get what you pay for.

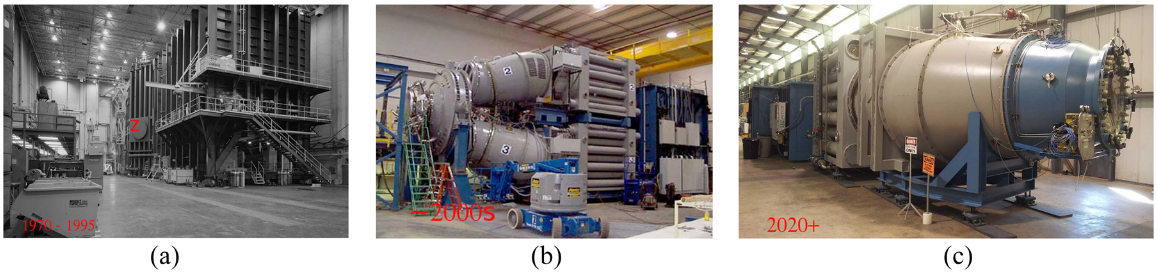
A few decades later, the lesson had been forgotten, as is illustrated by Figs. 8(b) and 8(c). By that time, a requirement document[32] stated (paraphrased): "The 1992 underground test moratorium leaves nuclear weapons effects testing to the radiation from Z-pinches. Therefore, the Department of Defense (DOD) should develop a Z-pinch with a peak current of 100 MA that is affordable to the DOD." The key word "affordable" here is ominous: the best option technically may be superseded by money. In this particular case, money would appear to be saved if any such facility were operated by the organization that needed it rather than the experts that built it.

The eventual choice became to first try for 10× more bremsstrahlung, on the right side in Fig. 2, hence the name Decade. As was done for Aurora, the lower-cost pulsed power option chosen for this machine was verified first by building only one-quarter of the final machine. Once everything worked properly years later, money had become still tighter. Now one-quarter of the original output seemed sufficient, and the machine was left as Decade-Quad.

While the original ~100 MA peak current seemed infeasible, with a high-current machine like Decade-Quad in the right place already, the most affordable path toward the highest I_p seemed to be to add a Z-pinch option. Figure 8(b) is Decade-Quad in its Z-pinch configuration.

Decade-Quad's Z-pinch encountered the usual technical setbacks, in part resulting from a nontechnical issue: Decade-Quad's location lacked technical people with the attitude needed for pulsed power and scientific staff with the expertise. Eventually, Decade-Quad's Z-pinch did achieve its promised output, but by that time the program had already been canceled because the need for a more powerful Z-pinch had receded.

As with Phoenix, some of the hardware lives on. One-quarter of Decade-Quad is now Charger-1, seen in Fig. 8(c). It should drive a neutron-producing Z-pinch, a central component in a conceptual pulsed fission–fusion propulsion system (PuFF).[33] Even if this project seems far-fetched, in its new role, Charger-1 may well become just as successful as the Zebra machine at the University of Nevada, Reno (UNR) has been after its earlier unsuccessful fusion run at LANL.



(a) (b) (c)

FIG. 8. Three fateful pulsed power generators: (a) Aurora; (b) Decade-Quad in its Z-pinch configuration; (c) the Decade module that survives as Charger-1. For a scale, identify the stairs in (a) and (b).

B. Thermonuclear fusion: Still at the end of the rainbow

Hope springs eternal, and paper is patient. Figure 9 shows the maximum neutron yield Y per unit length achieved in a Z-pinch as a function of peak current.[3] The most recent data[34] are not included here, and earlier neutron-producing DPF machines are off the bottom of this graph. The lower green line is for deuterium, and the upper red line is the ~100× larger yield inferred from nuclear reactions with energetic ions. To this figure, I have added the largest yield from NIF I knew about (it may be more now), a (black) trend line for a ~50× larger output that might come from a deuterium–tritium (DT) mixture instead of pure D_2, and ticked the 50 MA peak current expected for a future machine[35] in China. For its design peak current $I_p \sim 50$ MA, it might produce 1 MJ/cm in thermonuclear energy according to the trend line $Y_{\text{neutrons}} \sim I_p^{3.5}$, a prediction just as uncertain as the Chinese symbol for happiness on top is large. Still, anywhere close to 1 MJ in thermonuclear energy in the laboratory counts as a fantastic success, the pulsed power analogue of travel to the Moon or Mars is for the space program.

In my talk, I expressed my admiration for those who manage to obtain funding for speculative attempts to develop thermonuclear fusion commercially, especially when they sell an explosion to do it when experience so far shows how difficult that would be. Right now, the record is ~0.05 MJ in thermonuclear energy, with a ~10 MJ discharge. In a high-value application such as x-ray simulation, which demands months of preparation before and months of analysis after each experiment, single-shot fusion is completely acceptable despite its expense.

It is perfectly possible to get useful energy from repeated explosions, but this works best when the hardware survives: in a car, each cylinder produces up to 1 kJ per explosion, at 100 Hz. For a 100 MW Z-pinch fusion that makes ~100 MJ thermonuclear energy per pulse each second, with a comparable amount to drive the explosion, hardware cannot survive: one tank of gasoline has ~1 GJ in energy. Admirable efforts[36] in this direction could still have financial payoff when the technology can be sold for another purpose.[37] Companies that pursue fusion commercially all have nice websites that remind me of the Emperor's New Clothes.[38]

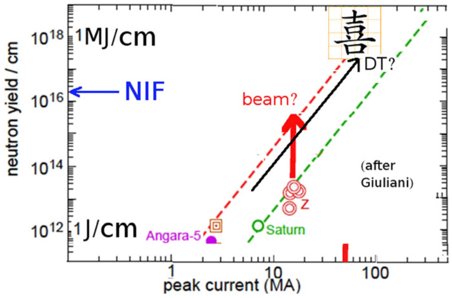


FIG. 9. Neutron yields per centimeter in D_2 pinches: achieved and extrapolated. After Ref. 3.

Perhaps for reasons similar to the above, the US Government funds thermonuclear energy only for those efforts that have some additional payoff. Figure 10 shows the present status, from one of the recent reports of an ARPA-E ALPHA program that no longer supports Z-pinch fusion. It gives the Lawson-like triple-product criterion most relevant to tokamaks, with the latest numbers for some other fusion attempts. The farthest along is the new Chinese tokamak EAST, which recently reported $nT\tau \simeq 500 \times 10^{20}$ keV s/m^3, offscale. The NIF laser at LLNL and MagLIF at SNL are put on the same scale, even though the comparison is not quite appropriate. MagLIF's performance predicted for 50 MA is essentially the same as in Fig. 9.

Achieving a megajoule-class thermonuclear explosion by ICF, on a pulsed power machine with a Z-pinch or with a laser, is a worthy and also a reasonably achievable goal: NIF has reportedly reached 30% of the threshold for ignition.[39] I would like to be alive when a 100 MJ thermonuclear explosion in the laboratory can be done once in a few months, at ~10^{-6} Hz, and when the energy problem has been solved with cheaper alternatives than fusion can be. As already mentioned, R. S. Pease was too optimistic when he expected fusion energy within 20 years in 1975, but I like to think that I am realistic.

Hopefully, governments in the USA and elsewhere will continue to support research on high-energy-density plasmas, including those in Z-pinches. The scientific and technical challenges are more than

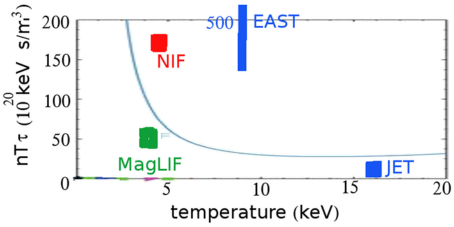


FIG. 10. Triple-product fusion parameter $nT\tau$ for different fusion devices.

sufficient to keep a scientist interested and to attract students to plasma physics. The desire to fill the bucket in Fig. 2 may help motivate funding for fusion with other arguments than intellectual curiosity. In addition, the matter is complicated enough for different groups in various countries to cooperate, as they do with tokamaks.

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