The Z machine: Over two billion degrees!
Malcolm Haines' paper

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The title of Malcolm Haines' paper is "*Ion Viscous Heating in a Magnetohydrodynamically Unstable Z Pinch **at Over 2×10^9 Kelvin***".

2×10^9 K = 2 billion K = **3.6 billion °F**

In fact in this experiment, the maximum temperature has reached 3.7 billion K (6.6 billion °F), well *over* the announced 2 billion Kelvin.

An introduction for non-scientists:

Some readers ask if these ion temperatures rising above two billion K were *really* measured at the end of 2005. The answer is yes. A disconcerting phenomenon was however noticed in 1998 and in 2004 in plasma compression experiments made with the Z machine, but then without a precise measurement of the real temperature. These experiments involved various protocols. For example, when the "round birdcage" (the *wire-array liner*) imploded, a gas puff was injected in the middle and was consequently constricted. The X-rays radiation allowed to directly measure the temperature. A plasma is a "two-species mix": the ions (heavy) and the electrons (light). Inside an "iron plasma", i.e. in "ionized iron", iron nucleii are 50'000 times heavier than electrons (a nucleus is made of "nucleons" having about the same mass: protons and neutrons. An electron is 1850 times lighter than a proton).

There are also these "two species" inside a neon tube: neon ions (which however keep some of their electron cloud around them) and free electrons. When the tube is powered on, its ionized gas is a non-equilibrium "two-temperature" plasma, where the gas keeps cool (you can touch the tube) but where the "electron gas" is a lot hotter, about 10'000 K. Why cannot you feel that high temperature with your hands? Because electrons are too small to transmit their heat. However they have enough energy to stimulate, through collisions, the fluorescent coating which recovers the interior of the tube. It is why these devices are called *fluorescent lamps*. The fluorescence is the ability to absorb some electromagnetic radiation then give it out in another frequency, visible. Thus the fluorescein for example absorbs solar radiation then emits green light. Nylon shirts can absorb UV radiation and emit in the visible spectrum (it is the "black light" in nightclubs), etc. The white coating in fluorescent lamps is bombarded by electrons which have energies in the UV-range. But these electrons, hitting the coating material, cause a visible emission, because this coating is made of a special compound intended to produce light looking like the natural visible light. But it is not perfect and that's why you feel the fluorescent light is a bit "strange".

What is important to remember is that some matter states can have "two temperatures". The reason is that the electric field inside the tube, created by the voltage applied on electrodes, transmits its energy uppermost to electrons, which then retrocede it through encounters with ions. But since the energy transport between an electron gas and a ion gas is inefficient, the difference between their own temperature can be very large. This fact is partly due to the rarefied medium (low-pressure gas). If the pressure is increased with some leak, this non-equilibrium state immediately disappears. Strongly coupled to ions, the electron gas cools down quickly. Then these "less-agitated" electrons (the absolute gas temperature relates to the thermal velocity of its particles) go back on atoms which deionize, become neutral again.

The experiment in the Z machine led to an odd situation. There are two species:

- The electron gas
- The ion gas (in steel, mainly positively charged iron nucleii)

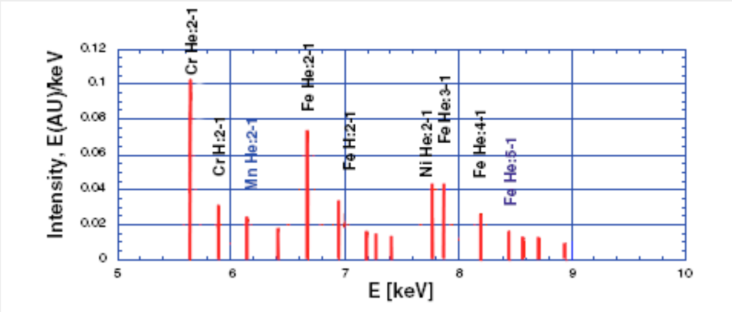
When people, from 1998, tried to report their measurements, they only could access the electron temperature by measuring X-ray radiation. Why is the main radiation source due to the electron gas in these experiments? Because a powerful magnetic field wraps the plasma. When the electrons launched at 40'000 km/s (90 million mph) enter this powerful magnetic area, they curl, they whorl in a helical path. Then they "shout", they emit an X-ray "braking radiation" called *Bremsstrahlung* (from German *Bremsen* "to brake" and *Strahlung* "radiation"). Experimenters previously measured the temperatures upon this effect, which indicates only the *electron* temperature: about 35 million K (63 million °F).

But thanks to appropriate formulas (the "Bennett relation") when they tried to evaluate the *ion* temperature required to counterbalance the huge "magnetic pressure" pushing around the plasma, they discovered it had to be considerably higher than the electron temperature. Since 1998, whatever the experiments this large gap between the two species temperatures was more and more obvious. High ion temperatures had to be there in order for the plasma to not be instantaneoulsy crushed under the fantastic magnetic pressure upon it. We see the calculation already suggested a non-equilibrium state (at thermodynamic equilibrium, all species in a gas have the same temperature) with the ion gas hotter than the electron gas, thus an *inverted* non-equilibrium state in comparison to what is classically known in plasma physics.

In order to understand that strange behavior, the Z team wanted to make direct measurements. First, they measured the diameter of the pinch, the compressed plasma at stagnation on axis, and they even drew a 7-point curve giving the evolution of this diameter through time. A minimum value was reached at 1.5 to 2 millimeters (0.05 to 0.08 inches) then the pinch started to dilate.

Next they wanted ot get iron ion temperatures. To do this, they used the classical method of spectral line broadening. Each nucleus (as the atoms and molecules) indeed emits radiation with its proper spectrum presenting specific lines.

If the medium is relatively cold, these lines are thin:



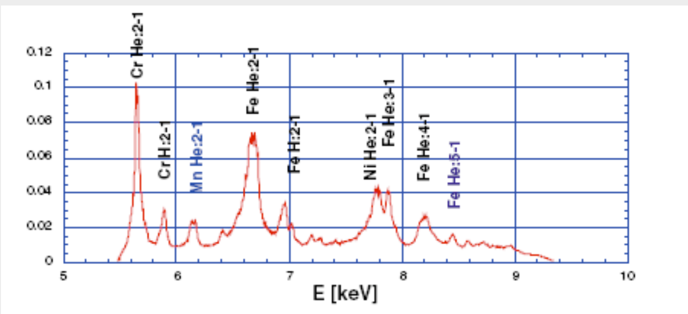
Emission spectrum of "relatively cold" stainless steel (100'000 K)
Chromium lines (the first on the left) then manganese, iron and nickel.
In that steel, carbon represents 0.15 % of the compound and its lines are not visible.

These lines correspond to electron stimulations. Electrons orbit around their nucleus, on well defined, precise orbits, for reasons relying on quantum mechanics (the orbital quantification). An additional energy coming from any indifferent source can cause a "transition", i.e. excited electrons jumping on a higher orbital level. There is no need to show complicated formulas to explain this idea. You know that to place charges with a mass M onto Earth orbit, you need a powerful rocket. And the higher the orbit, the biggest the rocket. So an additional energy dropping on the atom makes an electron jump to a "higher" orbit. But it does not stay there a long time (there is a lifetime for such an excited state) and it falls again towards the nucleus in a few nanoseconds, onto a lower orbit. Doing this, it looses some energy which is emited as a photon, whose energy is equal to the difference between the two energy levels of the transition. Hence this emission spectrum, with "lines".

An atom such as iron owns 26 electrons. They can all do an orbit change then lower again, not inevitably on their initial orbit. Hence a spectrum made of various lines. Some are higher than others. What is this height? It is the power emitted with the frequency. Some transitions are more probable than others, so those are more frequent and contribute mainly to the radiation. On the above picture we can see that for stainless steel with a temperature between 58'000 Kelvin (5 electronvolts) and 116'000 K (10 eV) the strongest emission comes from a chromium line. The manganese line is smaller. At such temperatures atoms are very "stripped", with many unbound electrons. How many? I have not presently a book here to answer that question, but this escape is progressive. The energy required to strip all electrons of an iron atom (its nucleus has 26 positive charges) down to the last one can be calculated.

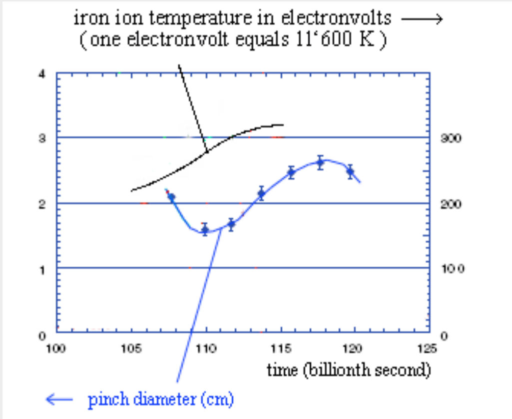
What was measured in Sandia's experiments relates to an energizing/de-energizing spectrum of electrons which stayed around their nucleus.

The line broadening is due to the Doppler effect, for that matter it is called "Doppler broadening".



Spectrum of the same material, heated to billion degrees. Doppler broadening.

The frequency corresponding to a specific orbital jump (a line) is higher if the atom approaches the observer, and lower when it goes away (redshift). Thus the thermal agitation *broadens the lines*. The measures, reliable, confirmed these high ion temperature values, in billion degrees (**between 2.66 and 3.7 billion Kelvin, i.e. between 4.8 and 6.6 billion °F!**).



Results of Sandia's Z machine, May 2005.
In black, the ion temperature rising. In blue, the diamater of the plasma.
Along abcisssa: time in nanoseconds (one nanosecond is one billionth second)

That temperature leap is not an event among others. It is a big scientific discovery, which will likely have tremendous consequencies on our civilization.

First, ions are a hundred times hotter than electrons. Until now it was the only possible explanation, but this time it has been directly measured, in repeatable experiments. Moreover this ion temperature *grows through time*. At last, the energy radiated by the electron gas, as X-rays, is 3 to 4 times higher than the kinetic energy of the incoming steel rods, from the liner, when they are constricted on axis.

Haines and is coauthors tried in their paper to elucidate this enigma. Where could that energy come from?

When the Z machine is powered on, the energy distributes under several foms. There is the thermal energy of the plasma, which relates to the addition of the kinetic energies of all its components (mainly the kinetic energy of iron ions). But there is also another energy, more difficult to understand: the *magnetic energy*, warping around the plasma constricted on axis. Haines therefore suggested some "MHD instabilities" could appear, allowing the plasma to harness some of this energy. He agrees in his paper that this theory is in embryonic stages, and that idea did not lead to any "simulation". His conclusion just tells it would not be impossible that heating could be caused by this suggested phenomenon. By the way he shows the encounter coupling between electrons and ions is weak, which explains the delay of the X-ray radiation. The phenomenon starts to heat the ions, which transmit some energy to the electron gas, which then strongly become emisive (by *Bremsstrahlung*). But these measures (4 points) show *the iron ion gas keeps heating*. The maximum temperature is visibly not reached. However the (measured) iron ion temperature reaches 3.7 billion Kelvin (6.6 billion °F)! This is 37 times the temperature a tokamak such as ITER could ever reach (100 millions Kelvin).

Chris Deeney said such a weird result compelled him to redo several times the experiment and measurements, to be sure. You can note the paper title says "*Over two billion Kelvin*". Logically, these researchers would have adverted the maximum value: 3.7 billion Kelvin. Perhaps they did not want to hurtle too much in front of the huge result obtained.

We must remind that lithium-hydrogen fusion can be ignited with 500 million Kelvin, giving helium and no neutron (aneutronic fusion). With 1 billion Kelvin we have another "clean fusion", i.e. without radioactivity nor nuclear waste: hydrogen-boron fusion. What could we do with 3.7 billion Kelvin, or even more? If the ion temperature continues to grow, logically even higher temperatures could be reached.

One comment. In these experiments the electric current delivered in the Z machine (18 to 20 million amperes) cannot be endlessly sustained. It is a discharge: the current rises through time, reaches a maximum then decreases. In the Z machine that electric pulse lasts 100 billionth second. Another aspect: if Haines is right, the magnetic field warping the plasma contains a very high energy. So if the current is sustained for some time, the magnetic fields keeps feeding the plasma, increasing its ionic temperature. Thus these 3.7 billion Kelvin do not reach a ceiling and nobody knows how much the temperature shall climb in such a device.

The first concrete realization of these experiments could be a "clean pure fusion" power plant, with lithium-hydrogen (lithium is present worldwide in oceans, natural brines and igneous rocks (its price is currently US$ 0.06 per gram) or hydrogen-boron (crystalline boron cost about US$ 5 per gram and amorphous boron cost about US$ 2 per gram). It would be the Golden Age, from an energy point of view. But also its counterpart… cheap pure fusion weapons: H-bombs without their polluting A-bomb ignitor, for everyone.

A supernova reaches 10 billion Kelvin. Through fusion reactions it creates all atoms of the Mendeleev periodic table (and their radioactive isotopes, with different lifetimes). If a "boosted" Z machine can one day reach 10 billion Kelvin, the highest temperature made in the universe would be created in lab. This leap forward embodies a drastic change in nuclar physics and our physics in general.

Until now we settled for "embers". This next step really represents the invention of the nuclear fire.

Thereafter the introduction of the paper from Haines, Deeney *et al.*:

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Ion Viscous Heating in a Magnetohydrodynamically Unstable *Z* Pinch at Over 2×10^9 Kelvin

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Pulsed power driven metallic wire-array *Z* pinches are the most powerful and efficient laboratory x-ray sources. Furthermore, under certain conditions the soft x-ray energy radiated in a 5 ns pulse at stagnation can exceed the estimated kinetic energy of the radial implosion phase by a factor of 3 to 4. A theoretical model is developed here to explain this, allowing the rapid conversion of magnetic energy to a very high ion temperature plasma through the generation of fine scale, fast-growing $m = 0$ interchange MHD instabilities at stagnation. These saturate nonlinearly and provide associated ion viscous heating. Next the ion energy is transferred by equipartition to the electrons and thus to soft x-ray radiation. Recent time-resolved iron spectra at Sandia confirm an ion temperature T_i of over 200 keV (2×10^9 degrees), as predicted by theory. These are believed to be record temperatures for a magnetically confined plasma.

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There has been some difficulty in understanding how the radiated energy in a wire-array *Z* pinch implosion could be up to 4 times the kinetic energy [1–4], and also how the plasma pressure could be sufficient to balance the magnetic pressure at stagnation if the ion and electron temperatures were equal. In fact, theoretically the excess magnetic pressure should continue to compress the plasma leading to a radiative collapse. Some theories [5,6] have been devel- not appear to be significant at the time of the main 5 ns FWHM soft x-ray radiation pulse where mainly long wave-length $m = 0$ modes can be and are observed. There is evidence from other wire-array experiments [8] that not all the mass and perhaps not all the current arrives on axis to the main pinch but resides in the trailing mass arising from axially nonuniform erosion and ablation of the wire cores. However, while we assume that 30% of the initial mass is

In the abstract we can read "*the soft x-ray energy radiated in a 5 ns pulse at stagnation* ***can exceed the estimated kinetic energy of the radial implosion phase by a factor of 3 to 4***".

Haines and his coauthors start to remind the basic problem: How the radiated energy emitted by the plasma can outrun and reach 3 to 4 times the incoming kinetic energy? This "kinetic energy" is simply the energy delivered by the velocity of the compressed plasma rods. It is the sum 1/2 mV^2 of all metal atoms radially launched against the others on axis. When they finish their accelerated run alltogether, at stagnation on axis, this kinetic energy is transformed into thermal energy. But when data is analysed, it cannot produce such great radiation. So this additional energy must come from elsewhere. Haines thinks about the magnetic field. How about that?

Let us consider a wire-array liner (made of 240 wires). When an electric current passes through a wire, its azimuthal magnetic field intensity can be calculated. Each wire undergoes an eletromagnetic force (the Lorentz force) J×B. It is easy to show that the force is the same as if it was created by a field coming from a linear electrical conductor on axis, where all the current would circulate (in Sandia's Z machine: about 20 million amperes).

This method also allows to calculate the exterior magnetic field around the liner, with a hypothesis: the field is considered as created by wires of infinite length (which of course is not the case). Therefore this gives only some orders of magnitude. A *magnetic pressure* is associated with the magnetic field. It can be noted in Newton per square meter but also in Joule per cubic meter. The magnetic pressure is an energy density, per unit volume. It is evaluated by an infinite linear electrical conductor.

$$B = \frac{\mu_o I}{2 \pi r} \qquad p_m = \frac{B^2}{2 \mu_o} = \frac{\mu_o I^2}{8 \pi^2 r^2}$$

This way to calculate the magnetic field can be taken as a first approximation near the liner, so the magnetic energy can be calculated between a cylinder of radius r and a cylinder of radius dr:

$$dE = \frac{\mu_o \pi I^2 h}{4 \pi^2 r} dr$$

r_{min} is the pinch minimal radius. Of course, integrating this value to infinite would be a nonsense, since it is valid only for infinite linear conductors. But we can write:

$$E = \int_{r_{min}}^{\dots} \frac{\mu_o I^2 h}{4 \pi^2 r} dr = \frac{\mu_o I^2 h}{4 \pi^2} [Log\, r]_{r_{min}}^{\dots}$$

We see the more the atoms package is near the system axis, the highest the energy is, in the form of magnetic pressure. Haines sees there the energy being likely the source of increased ion temperature. Ions have indeed already converted their kinetic energy into thermal energy. If V is the radial ion velocity at impact (stagnation) the thermal velocity can be evaluated:

$$\frac{1}{2} m V^2 = \frac{3}{2} k T \quad \text{with} \quad k = 1,38\,10^{-23} \quad (\text{Boltzmann Constant})$$

Using this formula implies that the "iron ion gas" is "thermalized", that it acquired a Maxwell-Boltzmann velocity distribution. But as Haines shows farther, the relaxation time for such a medium is very short.

τ_{ii} , relaxation time in the ion medium: 37 picoseconds ("ion-ion collision time", Haines)

The energy coupling with the electron gas is also weak. Furthemore the redistributed energy can only be a kinetic energy (thermal energy of ion-electron collisions). So this simple formula would be valid, but only if we suppose the ion gas is not fed by another energy source, and we will se farther it is the case.

That said, with a speed of 1000 km/s just before stagnation, we would get those 2 billion Kelvin. When does the imploding liner leave the "separated wires" configuration to become a real "plasma corona"? The paper does not specify it. With a liner having a 4 cm radius and a 100 ns implosion time, we can calculate that the minimal mean radial velocity is 400 km/s. An iron atom weights 9×10^{-26} kg. If this radial speed truely represents the ion velocity at impact, it would generate 348 million Kelvin. But this is only an *average* velocity. When the differential equation of movement is written, we get a spectacular acceleration near finish, a "final sprint". The fact the discharge has not a constant electric current must also be taken into account. Its current rises through time. Hence:

$$r'' = -\frac{\mu_o \left[I(t) \right]^2}{2 \pi M r}$$

M is the liner mass per meter. We see the acceleration is increased at the end of the discharge. The speed soars near the end. Haines writes:

> There has been some difficulty in understanding how the radiated energy in a wire-array Z pinch implosion could be up to 4 times the kinetic energy [1– 4], and also how the plasma pressure could be sufficient to balance the magnetic pressure at stagnation if the ion and electron temperatures were equal. In fact, theoretically the excess magnetic pressure should continue to compress the plasma leading to a radiative collapse. Some theories [5,6] have been developed to explain the additional heating, but neither of these have addressed the pressure imbalance.

Quick look to the references:

[1] C. Deeney *et al.*, Phys. Rev. E 56, 5945 (1997).
[2] C. Deeney *et al.*, Phys. Plasmas 6, 3576 (1999).
[3] J. P. Apruzese *et al.*, Phys. Plasmas 8, 3799 (2001).
[4] C. A. Coverdale *et al.*, Phys. Rev. Lett. 88, 065001 (2002).
[5] L. I. Rudakov and R. N. Sudan, Phys. Rep. 283, 253 (1997).
[6] A. L. Velikovich, J. Davis, J.W. Thornhill, J. L. Giuliani, Jr., L. I. Rudakov, and C. Deeney, Phys. Plasmas 7, 3265 (2000).

The reference [1] goes back to 1997. Therefore as from that time, this unexplained phenomenon was already noticed. Deeney is the director of Z experiments. I did not read the cited papers. If a reader can send me these PDF by email I would peruse them and give additional comments.

Let's jump directly to conlusion:

> In conclusion, it appears that short wavelength m = 0 MHD instabilities at stagnation in low mass implosions provide fast viscous heating of ions to record temperatures of over 200 keV. Such temperatures have been measured, the energy coming from conversion of magnetic energy on a 5 ns time scale. The ions heat the electrons which immediately radiate the energy. Furthermore, the broadened spectral lines arising from the high ion temperature will permit a greater radiative power to occur due to decreased opacities. The proposed mechanism provides a plausible explanation of several phenomena of fundamental importance to Z pinch dynamics including pressure balance at stagnation, the absence of radiative collapse, the significant excess of x-ray radiation.

The equation (1) in Haines' paper is quoted as the "Bennet relation" which goes back to 1934 (called forth in the reference [1]). We can restore it here. The Bennet relation simply tells the magnetic pressure equals the pressure inside the plasma. We gave the magnetic pressure previously. The total pressure in the plasma is the sum of all partial pressures constituted by (k is the Boltzmann constant):

- the electron gas $n_e\,k\,T_e$
- the ion gas $n_i\,k\,T_i$

If Z is the ionization level:

$$n_e = Z\,n_i$$

Besides if those temperatures are expressed in electronvolts (eV) and not in Kelvin anymore, with:

$$k\,T = e\,V$$

then the pressure in the plasma is written:

$$n_i\, e\, (T_i + Z\, T_e)$$

We see the second member appearing in the Bennet relation. Previously we established:

$$B = \frac{\mu_o I}{2 \pi r} \qquad p_m = \frac{B^2}{2 \mu_o} = \frac{\mu_o I^2}{8 \pi^2 r^2}$$

r is then the minimum radius of the plasma compressed on axis (the pinch at stagnation). The Bennet relation introduces a number of ions per meter N_i in the liner.

$$\frac{\mu_o I^2}{8 \pi^2 r^2} = p_i + p_e \quad (partial\ pressures) \ = n_i k T_i + n_e k T_e = n_i k (T_i + Z T_e)$$

$$\frac{\mu_o I^2}{\pi} = 8 r^2 n_i e (T_i + Z T_e) \quad if\ temperatures\ are\ in\ eV$$

$$n_i = \frac{N_i}{\pi r^2} \quad where\ r\ is\ the\ plasma\ radius$$

Which gives (Bennet, 1934):

$$\mu_o I^2 = 8 \pi N_i e (T_i + Z T_e)$$

This expression is noteworthy because the radius of the compressed plasma does not intervene. Why?

When the plasma gets thinner, the magnetic pressure upon it grows like the inverse square of its radius. But ion density is also increased the same way. This counterbalances that. Which is indeed odd is the great difference between the ion and electron temperatures does not relate to the final radius of the plasma neither, which could be as small on axis as we would want. We have a differential equation giving the evolution of the plasma radius r through time:

$$r'' = - \frac{\mu_o [I(t)]^2}{2 \pi M r}$$

The curves can be calculated (only if the electric current rising law I(t) is known, which is an "entry" of the problem. A Z machine should have a linear rising). The r down grade intensifies. I mean that the implosion velocity increases when r decreases. When r is zero, the implosion velocity would become infinite. But we forgot one thing when we wrote this equation: the pressure force opposed to implosion, which would have to be taken into account. That said, the problem is more complicated than it seems. The pressure which counterbalances the implosion depends on the ion temperature. But we cannot model it because, according to Haines, its growth depends on a phenomenon we do not know how to consider: plasma heating by MHD micro-instabilities.

Conclusion: one has to know to stop when a model cannot take all involved parameters into account. We have the formula:

$$\frac{1}{2} m V^2 = \frac{3}{2} k T \quad with \quad k = 1,38\, 10^{-23} \quad (Boltzmann\ Constant)$$

but we do not know the ion velocity V at the end of implosion. Introducing an average speed (liner radius on implosion time) has little signification since the speed quickly grows at the end of the implosion.

Haines then refers to a particular Z machine test, shot Z1141, where the liner mass per meter was 450 mg of stainless steel wires (4.5×10^{-5} kg/m) organized into two concentric coronas. The outer liner had a 55 mm diameter, having the double of the inner's mass which had a 27.5 mm diameter.

A bit farther Haines uses a value of Ni (number of ions per meter) equal to 3.41×10^{20}. The mass of an iron atom is 9×10^{-26} kg. If I divide 4.5×10^{-5} kg/m by that mass, I get 5×10^{20} ions per meter. But haines states while imploding, 30 % of the mass is "lost on its way". So we find thereabouts his number.

He indicates electron temperatures measurements gives 3 keV at stagnation, i.e. 35 million Kelvin. He specifies the electric current has srisen to 18 mega-amperes in 100 nanoseconds. He estimates 30 % of the matter is "lost on its way", so 70 % reaches axis. This ratio is reported in all sudies on wire-array z-pinches. While wire collapse, they "evaporate" like degasing comets. They leave plasma trails in their wake, whose mass can be 30 to 50 % of the initial wire mass.

With $N_i = 3.41\times10^{20}$ ions per meter and Z = 26 (iron), let's apply the Bennet relation with the electric charge $e = 1.6\times10^{-19}$ (Coulomb)

$\mu_o = 4 \pi \times 10^{-7}$ MKSA

Let us calculate $(T_i + Z T_e)$:

$$T_i + Z\,T_e = \frac{4\,\pi\,10^{-7}\,(1.8\,10^7)^2}{1.6\,10^{-19}\,8\,\pi\,3.41\,10^{20}} = 296.920\,eV = 296\,keV$$

which corresponds to **3.44 billion Kelvin** **(6.2 billion °F)**. When the diameter of the compressed plasma reaches its minimum (see the curve) the ion temperature is measured at 270 keV, i.e. 3.12 billion Kelvin. Considering the error margin this harmony is quite noticeable.

How to evaluate the ion temperature in such an experiment (J.P. Petit - June 27, 2006)

Let's write with details the differential equation giving the liner motion dynamics under the influence of a radial electromagnetic force. The magnetic field, created by a wire conductor curtain arranged as a cylinder, is similar to a magnetic field generated by one wire on axis in which all electric current would pass through. Hence:

$$B(r) = \frac{\mu_o\,I}{2\,\pi\,r}$$

There are n wires. An electric current I/n runs through each wire. It is subject to a Lorentz force, per unit length:

$$\frac{I}{\pi\,n}\,B = \frac{\mu_o\,I^2}{2\,\pi\,n\,r}$$

Let's call M the mass per unit length of the liner. As long as the wire is not vaporized, the differential equation is get writing:

$$\frac{M}{n}\frac{d^2\,r}{d\,t^2} = -\frac{\mu_o\,I^2}{2\,\pi\,n\,r} \quad thus \quad r'' = -\frac{\mu_o\,I^2}{2\,\pi\,r\,M}$$

where I depends of time, by the way. But it is a piece of data in the differential equation.

Let's now replace a wire by a metal vapor. More precisely, let's replace all wires by a plasma cylinder, a pinch. An electric current I still circulates through it. On the surface we can calculate the magnetic field B, with the same formula. But we can also add a pressure force, which tends to stop the implosion. This is the ion pressure:

$$p_i = n_i\,k\,T_i$$

But we are not master of it since it depends on the energy transmited to ions, in a misunderstood way, through MHD micro-instabilities according to Haines. We have the Lorentz force acting on each "wire" or each plasma area corresponding to the sector $2\pi/n$ it occupied previously. The pressure force acting on this sector per unit lenght is:

$$p_i\,\frac{2\pi\,r}{n}$$

I can write the differential equation of motion:

$$\frac{M}{n}\,r'' = -\frac{\mu_o\,I^2}{2\,\pi\,n\,r} + n_i\,k\,T_i\,\frac{2\,\pi\,r}{n}$$

We get:

$$n_i = \frac{N_i}{\pi\,r^2}$$

introducing in equation :

$$r'' = -\frac{\mu_o\,I^2}{2\,M\,r} + \frac{2\,N_i\,k\,T_i}{M\,r}$$

As we do not know how to give the evolution of temperature through time, since it depends on that added exterior energy, we cannot go much farther. We can nevertheless try to evaluate the ion emperature when the acceleration and r" are equal to zero, at stagnation. Thus we get:

$$T_i = \frac{\mu_o\,I^2}{4\,\pi\,N_i\,k} = \frac{4\,\pi\,10^{-7}\,(1.8\,10^7)^2}{4\,\pi \times 3.41\,10^{20} \times 1.38\,10^{-23}} = 6.88\,10^9\,K$$

We see the ion temperature (it is just an order of magnitude in a rough calculation) at stagnation condition depends on the square total current I^2 and grows when ions per meter decreases. So for the same liner mass and geometry one should use heavier atoms, or as suggested by a former military engineer, for example gold, ductile and easy to model, in addition four times heavier than stainless steel. With a gold wire-array in Sandia's Z-machine we could perhaps reach ten billion Kelvin.

But all parameters would have to be under control, that is to say if we knew "why it worked". The sublimation rate can play a key role. The slower it is, the longer the material will stay as an axisymmetric liner made of individual wires. If the sublimation rate of gold is too fast, it would be a worse choice than stainless steel. But it should be tested. And systems with greater electric currents should be tested too. In 2008, what will be the temperature given by ZR (Z Refurbished) with its 27 million amperes in less then 100 nanoseconds, instead of 18 million amperes in the current Z machine? Logically the ion temperature should increase again. Maybe 5 billion Kelvin?

Let's see the Bennet relation again. In Sandia's experiment, the measured electron temperature T_e (according to X-rays) is 3 keV. With Z = 26 we have:

$$Z\,T_e = 78$$

Therefore the pressure is not due to the electron gas... So in order to counterbalance the magnetic pressure (Bennet relation) only the ion pressure remains. But in order for the ions to do this, they would have to heat at 219 keV or... 2.54 billion Kelvin! Indeed:

$$T_i + 78 \text{ (measured)} = 296$$

And that's not all. Before these experiments, Z men tested some "gas puff" injections in the middle of the wire-array liner just before its implosion.

> However, the same pressure balance discrepancy arises in gas puff Z pinch implosions [9] in which the density and temperature profiles have actually been measured at stagnation, but which also have a hitherto unexplained high measured ion temperature of 36 keV.
>
> [9] K. L. Wong et al., Phys. Rev. Lett. 80, 2334 (1998).

Then again, if a reader could send me the PDF of ref. [9] I would analyze it closely.

Haines rules out the resistive heating, the simple Joule effect Gerold Yonas primarily thought about. For example he indicates that to heat a pinch where radius is 2 mm at 3 keV (3.4 million Kelvin) *8 microseconds* are required!

He sees the surrounding magnetic field as the only possible energy source. He then invokes ion heating *via* MHD instabilities having very short wavelengths, followed by an equipartition, i.e. electron gas heating through ion-electron collisions. Finally energy would be emitted by those electrons (by Bremsstrahlung or braking radiation, i.e. by interaction of their velocity with the magnetic field).

What is exposed thereafter refers to the nature of those MHD micro-instabilities. Then the energy equation is:

$$\rho \frac{c_A^2}{a}(c_A^2 + c_S^2) = \frac{3}{2} k (T_i - T_e)\, n_e\, \nu_{eq}$$

k is the Boltzmann constant and ν_{eq} the collision frequency. C_A is the Alfvén speed and C_s the speed of sound. a is the minimal diameter of the plasma. But Haines writes this equation otherwise, setting the temperatures in electronvolts and replacing the collision frequency by its self-inverse, the mean free path time or "equipartition time" τ_{eq}

$$\rho \frac{c_A^2}{a}(c_A^2 + c_S^2) = \frac{3}{2} e (T_i - T_e)\, n_e \frac{1}{\tau_{eq}}$$

In comparison to other non-equilibrium plasmas, for example the fluorescent tube in your kitchen, you can see this time the ion temperature is higher than the electron temperature (it is the opposite in the fluorescent lamp: hot electron gas and cold neon). It is an "inverted non-equilibrium state". Thereafter the classical equation for a non-equilibrium plasma like in a simple fluorescent lamp:

$$\frac{J^2}{\sigma} = \frac{3}{2}\frac{2 m_e}{m_i} e (Te - Ti)\, n_e \frac{1}{\tau_{eq}}$$

The first member represents the electron gas heating by Joule effect. J is the current density vector, and σ the electrical conductivity. The term on the right can be read as follows: The denominator is the mean free path time τ_{eq} in the gas, which inverse is the the collision frequency ν_{eq}. When an electron encounters an ion, it transmit its energy with difficulty, and a coefficient appears in the equation, the mass ratio:

$$\frac{2 m_e}{m_i}$$

But when an ion collides with an electron, the energy transfer efficiency is 100 %. So that's why the mass ratio coefficient disappears in Haines' equation (more exactly, its value is 1). Haines then appeals the classical electron-ion collision frequency formula. The plasma has Coulomb collisions. We find the electron-ion collision cross section in the following expression, classical in kinetic theory of gases:

$$\frac{1}{\tau_{eq}} = \frac{8\sqrt{2\pi m_e} e^{5/2}}{3m_i(4\pi\varepsilon_0)^2} \frac{Z^2 n_i \ell n \Lambda_{ei}}{T_e^{3/2}}$$

The part concerning the birth of MHD instabilities is quite rough, in particular because Haines says the Hall parameter for ions is greater than one.

$$\textit{Hall parameter of ions:} \qquad \beta_i = \frac{Z\,e\,B}{m_i\,v_{ii}} = \Omega_i\,\tau_{ii}$$

The ion-ion collision frequency steps in the problem. Yonas told me in 2006 that "*Haines' theory well explains this non-equilibrium state*" but I am not as convinced as him. Haines' explanation stays in embryonic stages, recaps in a score of lines. He assumes such instabilities would affect ions and cause a viscous heating.

The reader presumably asks what are exactly those instablities and how they appear. Heat dissipation by Joule effect is, per unit volume:

$$\frac{J^2}{\sigma}$$

The considered instabilities create a turbulence in the current density. Current lines squeeze in, then open out, squeeze again, with wavelengths Haines estimates in microns or ten or so microns. They are micro-instabilities. If the current density is locally increased, it pairs with a higher magnetic field, and *vice versa*. It is therefore an electromagnetic turbulence, typical effect of pinches. Those turbulences are also found in lightning bolts. A flash of lightning does not last a long time, but pictures taken of this phenomenon show plasma droplets in single file. There the gas (the air) is not completely ionized. When a pinch starts in the discharge, the current density rises, and the electron temperature as well. The lightning bolt is an electric arc, an electrostatic breakdown which produces an electric discharge in a gas and a consecutive plasma. The involved mechanisms are complicated. The constricted current lines have locally an increased electric current, which provokes an increased heating by Joule effect. So the plasma strand dilates, etc…

The micro-instabilities Haines suggested are "cousins" of those instabilities. Micro-pinches would occur. The local value of the current density would increase, so subsequently the magnetic field and the magnetic pressure, and this growth accentuates the pinch. It is the basis of plasma self-instability, of the electromagnetic turbulence. Then a whole bunch of things can happen, but they could only be theorized through specific calculation, which Haines did not do. The least we can say is the medium is complex. Let's assume, before instabilities start to heat ions in the plasma, that both electron and ion temperatures are equal, for example 20 million Kelvin. A pinch happens. So electron temperature increase. Does this make new unbound, free electrons? That hinges upon the "characteristic ionization time". There again data, calculation, etc. But contrary to the classical electrothermal instability, that instability impacts the ion gas and not electrons, through "viscosity". Physically those pinches "shake" the ions radially.

To firm up details, the elecric current in a plasma is due to an electron current and not an ion current. The plasma is linked to metal elecrodes. When the pinch occurs there is a reinforcement of the magnetic field, so the Lorentz force J×B is increased. This force especially acts at first upon electrons, which transmit this impulsion to ions through collisions. The constricted "tangle" of electron current lines creates a radial electric field which then pulls the ions. Inside this instability there is a micro-turbulence phenomenon impacting the electron gas, which itself transmits the jolts to the ion gas.

Then Haines writes the energy equation relating to the ion gas, introducing in the first member the viscous heating effect due to these instabilities:

$$\rho\frac{c_A^2}{a}(c_A^2 + c_S^2) = \frac{3}{2}e(T_i - T_e)\,n_e\,\frac{1}{\tau_{eq}}$$

The characteristic time in the second member denominator is the mean free path time of ions, induced by electron-ion collisions. Thus it is the "equipartition time", the characteristic time for two different temperatures to equalize (electron and ion temperatures). Haines tells it is "approximately 5 ns".

Note the ratio (m_i / m_e) is involved in the equipartition time. The longer it is, the less ion and electron gases are coupled. For iron ions this ratio is:

$$\textit{iron ion mass}\ \frac{\textit{proton mass}}{\textit{electron mass}} = 55.8\ \frac{1.67\,10^{-27}}{0.9\,10^{-30}} = 55.8\ 1850 = 103.000$$

A question could arise: can the velocity distribution function be viewed as Maxwellian in the ion medium? Haines thinks so, and gives the value of the characteristic thermalization relaxation time τ_{ii} which would be 37 picoseconds. Since that time is short comparatively to the equipartition time, Haines infers the ion gas is thermalized, Maxwellian. He then makes use of the formula above, with wavelengths he chooses. Thus he says the MHD micro-instabilities wavelengths measure between a hundredth and a tenth of a millimeter.

$$(T_i - T_e) = 2.1 \times 10^{36}\frac{al^3 T_e^{3/2} A^{1/2}}{Z^3 N_i^{5/2} \ell n \Lambda_{ei}} \qquad (5)$$

In this expression, **A** is the atomic weight of iron (55.8), **a** is the minimal diameter of the pinch, and **I** is the electric current circulating through the plasma (we do not talk about a wire-array liner anymore: the wires are transformed into a constricted plasma).

The key sentence is:

> Thus for stagnated Z pinches where τ_{eq} is significantly longer than a / c_A the ion temperature will greatly exceed the electron temperature.

Going back to the experiment refered as a touchstone, Haines decides to take the diameter of the stagnated plasma as 3.6 mm. With such a value he gets a result "consistent with T_i of 219 keV" (2.5 billion Kelvin). He recalls the Saturn experiment (ref. [3]) where the same factor 3 to 4 was theoretically found between the ion thermal energy and the kinetic energy of the pinch, but then without a direct ion temperature measurement. The difference is nowadays experimenters have access to such measures, thereafter detailed.

That said:

> Indeed, without this artificial fix no codes have been able to model these large array diameter experiments. 2D and 3D simulations of wire-array implosions in general [9] require, as input parameters, the wavelength and initial amplitude of modes and a value of the resistivity of the "vacuum", defined as where the plasma density falls below a given value. In addition, no simulation currently includes ion viscosity (let alone the full stress tensor) or a fine enough mesh to model the short wavelength instabilities proposed here. Often an ad hoc procedure is used to prevent radiative collapse.

rambling which relativize a bit the explanation of ion heating by an interacion with the surrounding magnetic field.

The ion temperature has been measured by lines Doppler broadening, moreover through time by using a LiF crystal spectrometer located at 6.64 meters from pinch. Please read Haines' paper for technical precisions pertaining to this spectrometer. Hereunder the emission spectrum:

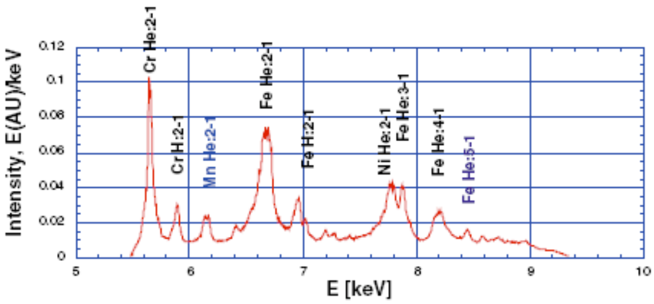


FIG. 1 (color). *K*-shell emission lines from the stainless-steel plasma of Z1141. In addition to the dominating Cr and Fe lines, Mn and Ni are apparent. Ion temperatures were obtained from emission lines with reduced opacity: Fe He-δ at 8.49 keV and Mn He-α at 6.18 keV.

In the stainless-steel plasma from shot Z1141, we find chromium and iron lines dominating, and also manganese and nickel lines. The temperature is evaluated with iron at line 8.49 keV and manganese at line 6.18 keV. Measures of these lines, albeit weaker, are less susceptible to opacity effects.

The paper farther vouches for the reliability of the temperature measurements, the error margin being estimated to 35 keV. In the following chart, the evolution of temperature, radiated power and pinch diameter through time:

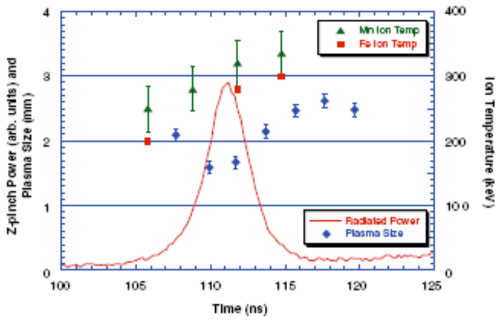


FIG. 3 (color). Measurements of ion temperature, plasma size, and radiated power as a function of time. The plasma size reached a minimum 1 to 2 ns before the x-ray output peaked, and enlarged from this time up to 2.5 mm. The ion temperature rose from 230 to 320 keV. The calculated 0D kinetic energy was reached 7 ns after the peak output. After this time 500 kJ was emitted by the plasma.

The reader could notice that error margin bars, relating to the (three) iron ion temperatures, are not indicated on the graph. But in the paper we can read:

An error of 35 keV is assigned to the temperature measurements based on uncertainty in measuring linewidths.

The authors just forgot to draw them. They are six persons, so either only one writes the paper and the others cosign, or everyone writes its part. However that may be, we can add these error bars on the chart ourselves (in red):

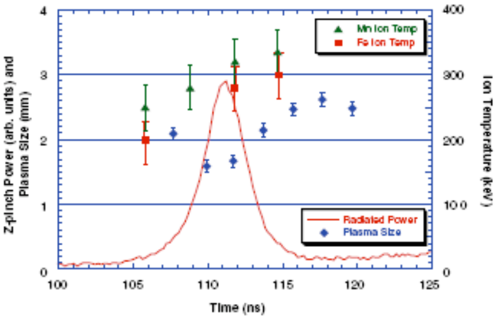


FIG. 3 (color). Measurements of ion temperature, plasma size, and radiated power as a function of time. The plasma size reached a minimum 1 to 2 ns before the x-ray output peaked, and enlarged from this time up to 2.5 mm. The ion temperature rose from 230 to 320 keV. The calculated 0D kinetic energy was reached 7 ns after the peak output. After this time 500 kJ was emitted by the plasma.

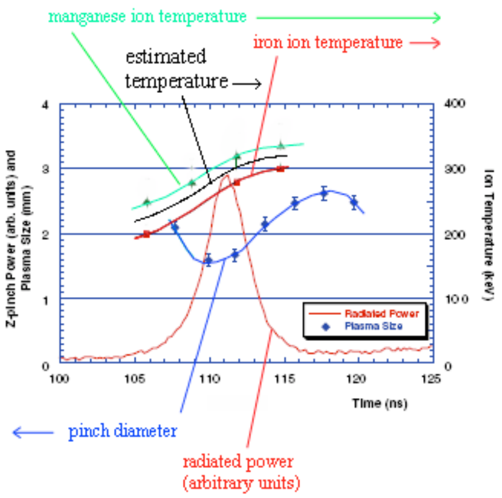
The measure points for iron ions overlap the error interval for manganese ions, and *vice versa*. In the chart the iron ion temperature dots rise from 200 to 300 keV and the dots for manganese ions rise from 250 to 330 keV. But since the measures mix together and without considering -deservedly- a temperature gap between the two populations of iron and manganese ions, the authors give the intermediate values from 230 keV (2.66 billion Kelvin) to 320 keV (3.7 billion Kelvin). They are well "over 2×10^9 Kelvin" and the difference is quite sizeable since the maximum value reaches 3.7×10^9 Kelvin. Moreover we do not know if what is shown is the real maximum value. When you look at the curve you can see a higher temperature could be possible if the dots in the following 5 ns had also been measured and reported. If the increasing temperature has a sustained evolution as it seems on the curve before its slump, the maximum temperature reached could not be "2 billion" as advertised but… 4 billion Kelvin (keep in mind supernovæ produce 10 billion Kelvin).

Logically, if the temperatures have been measured with good reliability as it is stated in the paper, the authors should have titled "*A temperature of 3.7 billion Kelvin has been reached*" adding "*record holder*". This value is even included in the interval taking into account the error margins. But they settled for "*over two billion Kelvin*". Why such a… shyness? In addition notice that:

- With 500 million Kelvin, say hello to clean nuclear fusion with hydrogen and lithium (p–$_7$Li)
- With 1 billion Kelvin: another aneutronic fusion with hydrogen and boron (p–$_{11}$B)
- With 4 billion… what? (specialized nuclear physicists should have the answer)
- If the temperature of 10 billion K is reached one day, then all nuclear synthesis reactions become possible, allowing to create all atoms of the Mendeleev table, i.e. all the range of Genesis.

Call me God…

Same chart, adding evolution curves of temperatures through time (in black the mean temperature, with the values kept in the paper):



We see the plasma diameter decreases to a minimum value before t = 110 ns. X-rays are radiated during 5 ns. Note max temperature values: 300 keV (3.94 billion Kelvin) for manganese ions.

NB - The Bennet relation:

$$\mu_o I^2 = 8 \pi N_i (T_i + Z T_e)$$

gives (see previously) 2.5 billion Kelvin for iron. This calculation relates to shot Z1141 (18 million amperes, 450 mg liner) as the figure 1. But analysis and data presented in the paper refer to three shots (Z1141, Z1137 and Z1386).

My comment:

Read again the title of Haines' paper: "**over 2×10^9 Kelvin**". While such systems reached one million or one million and a half Kelvin in preceding years, then two million Kelvin and more, suddenly the machine speeds up out of control, giving *billions* degrees. Some readers could be surprised not to see any carbon emission line. But (wikipedia) there is very few carbon in austenitic stainless steel (less than 0.15 %):

> ***Steel* on Wikipedia**:
>
> Steel is a metal alloy whose major component is iron, *with carbon being the primary alloying material.* Carbon acts as a hardening agent, preventing iron atoms, which are naturally arranged in a crystal lattice, from sliding past one another. Varying the amount of carbon and its distribution in the alloy controls qualities such as the hardness, elasticity, ductility, and tensile strength of the resulting steel. Steel with increased carbon content can be made harder and stronger than iron, but is also more brittle. *One classical definition is that steels are iron–carbon alloys with up to 2.1 percent carbon by weight;* alloys with higher carbon content than this are known as cast iron. Steel is also to be distinguished from wrought iron *with little or no carbon*. It is common today to talk about 'the iron and steel industry' as if it were a single thing; it is today, but historically they were separate products.
>
> ***Stainless steel:***
>
> In metallurgy, *stainless steel is defined as a ferrous alloy with* a *minimum of 10.5% chromium* content.
>
> Austenitic stainless steels comprise over 70% of total stainless steel production. They contain a maximum of 0.15% carbon, a minimum of 16% chromium and sufficient nickel and/or manganese to retain an austenitic structure at all temperatures from the cryogenic region to the melting point of the alloy.

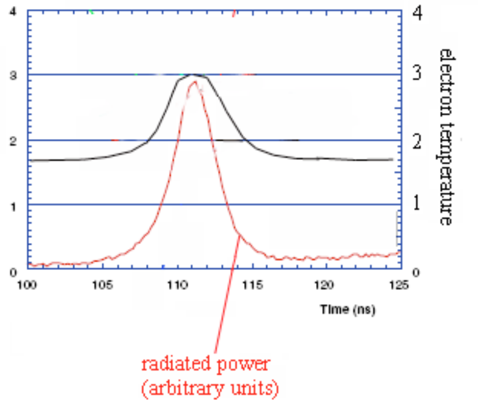
We drew the two temperature curves for the iron ion and the manganese ion gases, which seem different. But on the one hand the error range for manganese overlaps the iron ion temperature, so these two temperatures could be really similar. On the other hand the manganese ion, even though its electric charge is near iron's (25 vs 26), is two times lighter (30 vs 58); so if some MHD micro-instabilities occurs, those two gases could present a low (12 %) non-equilibrium effect with two different temperatures.

Haines: the plasma diameter reaches its minimal value (1.5 mm) 2 nanoseconds before the maximal X-ray radiation. He estimates that when this maximum is reached, the density and the "equipartition" would be at their maximum (I would rather say the "tendency" towards equipartition).

Let's try to make these curves "talk". What happens?

We have four points for temperature. One is eliminated for iron (the second) due to a problem while measuring. This small number is only apparent because the equipment can measure no only such temperatures but also their evolution in time, on a billionth of a second scale, which is extraordinary. That said we do not know the values before t = 105 ns and after t = 115 ns.

The text tells electron temperature in plasma reached 3 keV (35 millions Kelvin) at stagnation. That means when the electron temperature reaches this maximum, it will never be able to grow higher than a hundredth of the maximal ion temperature. Since the radiated power rises as a strong pulse, one has to suppose it was much less before t = 105 ns. We feel the temperature collapses quickly, by a factor of 9, around 115 ns. But the Stefan–Boltzmann law states the radiated energy varies like the fourth power of the temperature. So the decrease is actually directly proportional to the fourth root of 9, i.e. 1.73. Which sets T_e from 3 to 1.68 keV. I draw the curve in black:



In black, the electron temperature variation. In red, the radiated power variation (Stefan–Boltzmann law)

But at t = 105 ns, ions are already heated (T_i ~ 200 keV). Therefore the heating mechanism, to elucidate, acts *before* stagnation, before the plasma reaches its minimum radius at t = 110 ns.

In broad outline: the plasma implodes. Without the special extra energy phenomenon, to elucidate (but which Haines thinks being a magnetic energy transformation into heat), the plasma would entirely implode, if the ion temperature was equal to the electron temperature (less than 20 million Kelvin before t = 105 secondes).

But ions are fed by this special added contribution. The ion temperature grows. The ion-electron gases coupling takes place during the "characteristic equipartition time" τ_{eq} which Haines calculated to 5 ns. So the electron temperature rising time tallies with this number (107 to 112 ns).

Haines says the ion heating phenomenon suffices to counterbalance the magnetic pressure and that stagnation conditions are really reached, because the characteristic variation rate of the plasma radius is only 15 % of ion thermal velocity. We can valuate iron ion thermal velocity between minimum and maximum measured temperatures.

$$\langle V_i \rangle = \sqrt{\frac{3kT_i}{m_i}} \qquad m_{iron} = 55.8 \times 1.67\, e^{-27} = 9.68\, 10^{-26}\ k$$

$$k = 1.38\, e^{-23} \qquad \langle V_i \rangle = 70433 \sqrt{T_i\,(keV)}$$

- For the minimum temperature, 230 keV or 2.66 billion Kelvin: $< V_i >$ = 1066 km/s
- For the maximum temperature, 320 keV or 3.7 billion Kelvin: $< V_i >$ = 1258 km/s

Haines compares these values to the plasma expansion rate, saying it represents about 15% of ion thermal velocity. Whatever the manner to evaluate it taking dots on the curve, it stays lower than thermal velocity, which seems to indicate the pressure inside the plasma counterbalances the magnetic pressure.

After that, the plasma diameter starts to grow again. Why? Because the ion keeps heating. One could try to calculate this expansion.

One thing I do not understand for now remains: why does the electron temperature decrease, since the electron gas would still receive energy from the ion gas which keeps heating (at least in the time range available to us)?

A precision: what is the thermal velocity in the electron gas at 3 keV (35 billion Kelvin).

$$< V_e > = \sqrt{\frac{3kT_e}{m_e}} = \sqrt{\frac{3 \times 1.38\ 10^{-23}\ 3.5 10^7}{0.9\ 10^{-30}}} = 40\,000\ km/s$$

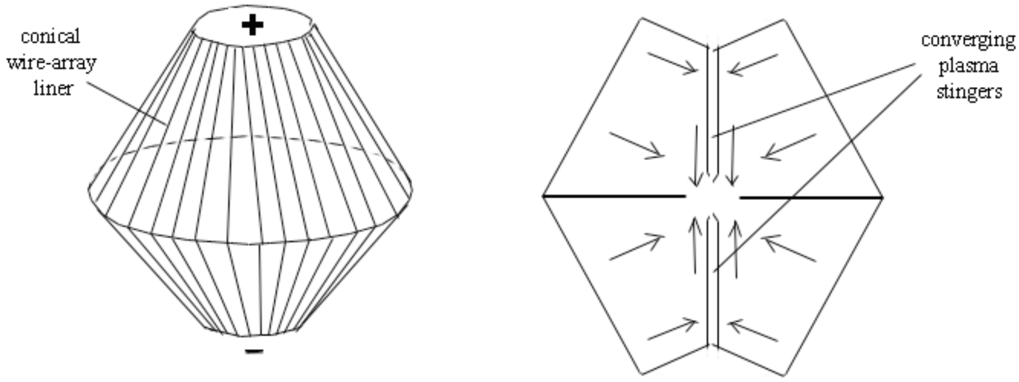
Let's suppose we could shoot 18 million amperes in a plasma pinch of 1.5 millimeter diameter. What would be the magnetic field value, in contact with the plasma, and its corresponding magnetic pressure? (of course we make the assumption of an infinite conductor)

$$I = 1{,}8\ 10^7\ A \qquad \mu_o = 4\pi\ 10^{-7} \qquad r = 7{,}5\ 10^{-4}\ m$$

$$B = \frac{\mu_o I}{2\pi r} = 4500\ teslas \qquad p_m = \frac{B^2}{2\mu_o} = 9\ 10^{12}\ pascals\ or\ 90\ megabars$$

June 27, 2006. An interesting idea:

In another file devoted to other MHD devices (explosively pumped flux compressors) inspired by Russian equipment from the 50's, we demonstrated the working principle of the MC-1 generator. Thereafter some people experimented some liners not cylindrical anymore, but conical. They gave a "shaped charge" effect. The liner mass gathers on axis and generates a high-speed plasma stinger. I recall velocities of about 80 km/s. But we could also imagine Z machines with conical wire-array liners too, in order to produce the same shaped charge effect. We could imagine various geometries. MHD is really the hang-out for the most creative solutions. See below a mounting with two truncated cones linked from their base. If plasma stingers would form and collide, we should even get higher temperatures.



For now we cannot do anything but this sketch. Some simulations could be undertaken, and of course, experiments.

July 16, 2006. What is the Hall parameter $\beta_i = \Omega_i \tau_{ii}$ for ions?

Haines says in his paper that the Hall parameter of ions is greater than one. That parameter is the ratio between the gyrofrequency and the collision frequency. According to Haines the ion collision frequency is essentially a ion-ion collision frequency. Its inverse, the relaxation time τ_{ii} is given as 37 picoseconds. Which gives the colision frequency:

$$\nu_{ii} = 3 \times 10^{10}$$

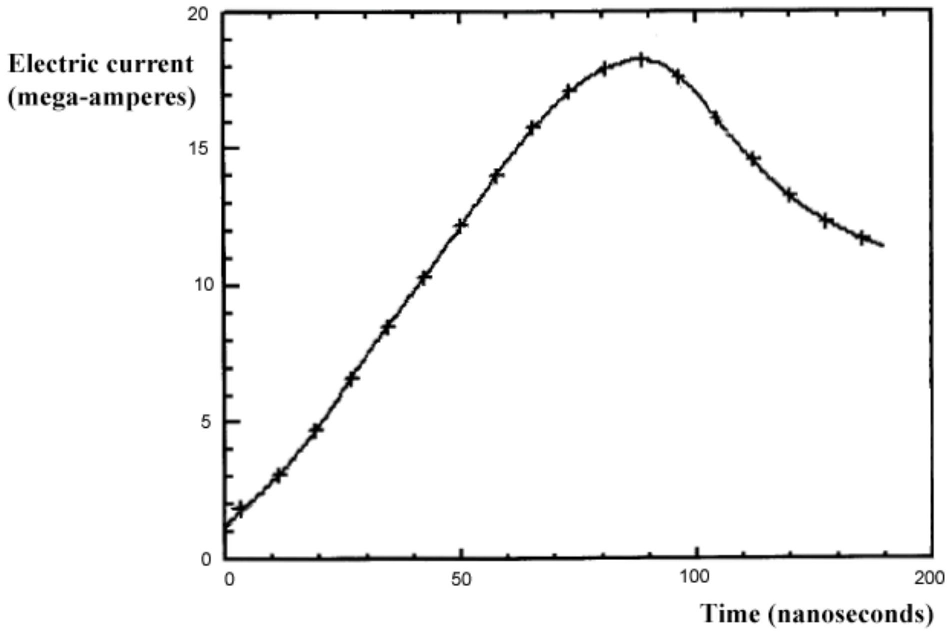
The gyrofrequency is:

$$\Omega_i = \frac{e\,B}{m_i} = \frac{1.6\ 10^{-19}\ 4500}{9.3\ 10^{-26}} = 7.74\ 10^{9}$$

Which gives $\boldsymbol{\beta_i}$ **= 0.258** for the Hall parameter. I don't find it greater than one… Maybe I did something wrong?

Appended data - source: Radiation Ablation gap closure calculations for Z and ZR

The characteristic evolution curve of the current discharge in the Z machine:



It is the brevity of the current rising (less than one hundred nanoseconds) which allowed to reach such temperatures in Sandia's Z machine. Indeed the steel wire sublimation was slower than predicted. Thus the wire-array liner could endure its structure during implosion, keeping its axisymmetry, which disappear when it tranforms into a plasma curtain, because then it squirms under the influence of MHD instabilities. Before wire-array liners, when liners were plain cylinders they badly distorted while imploding, into something close to what would occur if you tried to crush a paper cylinder in your hand. I think the CEG pulsed power team in France, with their Sphinx, did not understand that this parameter was critical (see for example this paper presented at 14th SHCE (Symposium On High Current Electronics) in Tomsk by September 2006. Minimum rising time: 800 nanoseconds). Yonas confirmed this to me by email in 2006.

Jean-Pierre Petit
www.mhdprospects.com
