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Report

FAST HIGH VOLTAGE Z-PREIONIZATION OF A MEGAJOULE THETA PINCH

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by

A.A. NEWTON

ABSTRACT

The impurities in theta pinch plasmas are found to originate from the interaction of the pre-ionized plasma with the tube wall when the theta pinch bank is switched on. An improved pre-ionizer is described which reduces the concentration of oxygen in the final plasma by minimising the wall contact in the early stages. The conditions necessary for increased purity result in less efficient magnetic compression of the plasma.

Various Z-preionization schemes are compared by observing their effect on the diamagnetism of the final plasma.

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1. INTRODUCTION

Pre-ionization for Megajoule theta pinches is by the use of low energy discharges with either axial or induced azimuthal currents.

At Culham Laboratory(1), General Electric(2) and the Institut für Plasmaphysik, Garching(3) z-pinches are used with currents in the range 10-20 kA, flowing for times such as 3-10 μsec, between electrodes well clear of the main coil. The impurity in the theta pinch plasma is oxygen at concentrations from 1 to 3% and the degree of ionization achieved is typically 10 to 30% with a capability of operating at pressures down to 10 mtorr.

The fast theta pinch connected directly into the main coil and ringing at 300 kc/s, was chosen by the groups at Los Alamos(4) and N.R.L.(5). Again oxygen is the main impurity but at significantly lower levels of about 0.1%. Complete ionization is achieved but operation in the case of the latter group is restricted to a lowest pressure of 30 mtorr. A full summary of these results is listed in Table I.

TABLE I

Summary of Pre-ionization Circuits used in Megajoule Theta Pinches at September, 1965

	Type	Peak Current	Current Duration	Degree of Ionization α	Main Theta Pinch Impurity	Main Theta Pinch Electric Field	Tube Material
Culham	Z	14 kA	5 μsec	$\sim$ 0.3	1.5 ± 0.5% Oxygen	400 V cm^{-1}	Silica
G.E.	Z	18 kA	3 μsec	?	1% Oxygen + Carbon	600 V cm^{-1}	Silica
Garching	Z	20 kA	10 μsec	0.1 to 0.2	3% Oxygen	500 V cm^{-1}	Silica
		Peak Field	Ringing Frequency				
Los Alamos	θ	9 kG	330 kc/s	$\sim$ 1.0	< 0.1% Oxygen	1100 V cm^{-1}	Alumina
N.R.L.	θ	1.2 kG	300 kc/s	$\sim$ 1.0	0.1 to 0.15% Oxygen	200 V cm^{-1}	Silica

Recently the Group at Garching have published details of a fast high voltage system used with the Isar Megajoule experiment(6). The plasma purity improved by an order of magnitude to give an oxygen content of 0.3% at 10 mtorr. A similar circuit was quickly assembled at Culham to repeat the work of the Garching team and explore the physics of rapid high voltage pre-ionization. This report summarises the investigations and makes comparisons with previous experiments(1,7).

2. DESCRIPTION OF PRE-IONIZATION CIRCUIT

The fast high voltage system employed a three stage Marx generator giving an output voltage of 120 kV. Current flowed for 0.85 μsec reaching a peak value of 10 kA and overswing was suppressed with a thyrite non-linear resistor. A preliminary discharge using 10 nF capacity at 40 kV through 100 Ω was necessary to establish finite conductivity in the plasma and prevent the full Marx output (doubled to 240 kV) flashing externally across the discharge tube.

The energy fed into the discharge tube can be determined(8) from the measured voltage V across the tube and the current I where

$$W(t) = \int_0^t VI\,dt. \qquad \ldots (1)$$

From the measured electrical energy input of 7 joules the degree of ionization, α, must have been less than or equal to 14%.

3. PLASMA DYNAMICS

The radial behaviour of the plasma with the 120 kV pre-ionizer has been traced with an image converter streak camera. At 20 mtorr pressure there was a rapid implosion pinching at 0.6 μsec, then a luminous region could be seen across the whole tube diameter which slowly compressed to 0.7 of the tube area at current zero. Thereafter the plasma expanded so as to reach the discharge tube walls at about 4 μsec.

Application of snowplough theory(9) to the measured implosion time indicates that of the order of 6% of the gas is involved in the first rapid implosion. The second slow luminous front evidently contains more of the initial gas filling.

4. EFFECTS ON THE THETA PINCH

Further investigations used the Culham Megajoule theta pinch to determine the effect of pre-ionization conditions on the final plasma. In particular a study of how the impurity and energy density are affected by varying the delay, Δt, between switching on the pre-ionizing circuit and applying the main bank. Observations at 0.86 MJ (36 kV) and 20 mtorr are presented in the following subsections.

Impurities

Earlier work with a time shuttered grazing incidence spectrograph sensitive to wavelengths between 10 and 200 Å, revealed oxygen, ionized to OVII and OVIII, as the most abundant impurity(10). The concentration was determined by adding known amounts of this contaminant and monitoring peak intensities of OII and OIII lines from the pinched plasma at visible and ultraviolet wavelengths. In all cases the line intensity increased linearly with added oxygen and the intrinsic level was found by extrapolation to zero intensity(1).

The pre-ionizing discharge contained $\lesssim$ 0.05% oxygen impurity. When the theta pinch was applied the impurity level rose considerably. The level of oxygen line intensity depended on Δt, rising by an order of magnitude as Δt was raised from 1 μsec to 3 μsec

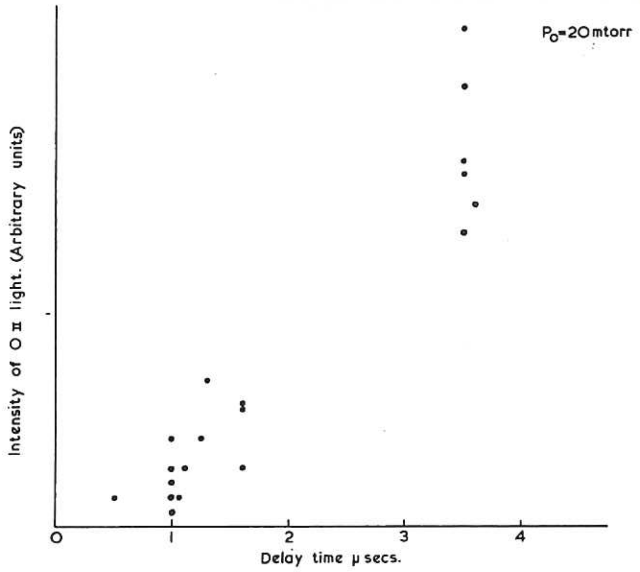

Fig. 1 (CLM-R62)
Intensity of oxygen line radiation vs delay time between pre-ionization and theta pinch

(see Fig. 1). Calibration at the shorter delay showed the residual impurity content to be 0.15 ± 0.05%.

Using a coronal model for the excitation of OVII and OVIII lines and a semi-empirical excitation rate$^{(11)}$ suggests that 0.15% oxygen in the above states radiates 6×10^{11} erg cm^{-3} sec^{-1} at $n_e = 10^{17} cm^{-3}$ and $T_e = 300$ eV, a rate some 20 times that of pure hydrogen bremsstrahlung. The corresponding radiation cooling time of the final compressed high-β can be shown to be ~ 250 μsec.

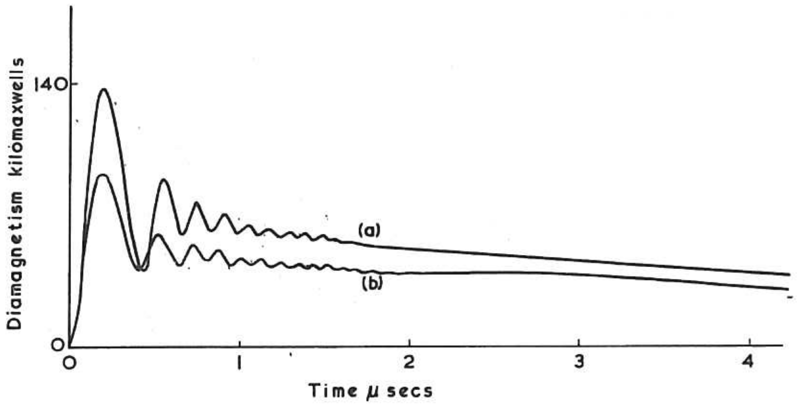

Fig. 2 (CLM-R62)
Plasma diamagnetism at 20 mtorr. (a) Pre-ionization to theta pinch delay 3.5 μsec (b) Delay 1.4 μsec

Peak Diamagnetism

An established technique for determining many plasma properties is the observation of the plasma diamagnetism$^{(1,7,12)}$. From tracings of typical diamagnetic waveforms shown in Fig. 2 we see that a peak signal is reached at about 0.2 μsec. A minimum occurs at 0.4 μsec corresponding to the first pinch and subsequent regular decaying oscillations are a hydromagnetic radial motion excited by the implosion(13).

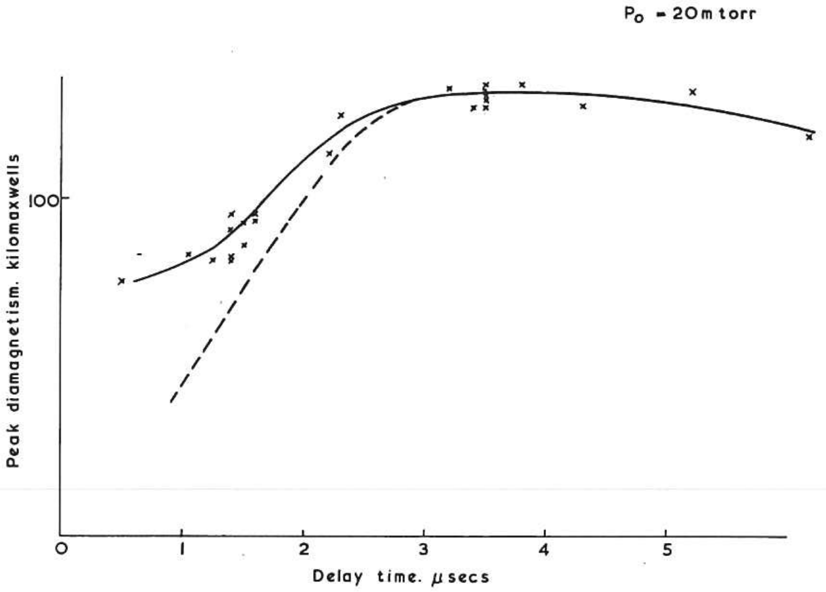

Fig. 3 (CLM-R62)
Variation of peak diamagnetism with delay time between pre-ionization and theta pinch

The variation of the first diamagnetic peak, $\hat{S}$, with delay time Δt is shown in Fig.3, where measurements of individual discharges are plotted as points and the form of $\hat{S}(\Delta t)$ suggested by the solid line. As Δt increases from 1 μsec to 3.5 μsec $\hat{S}$ rises to a broad maximum and falls slowly with larger values of Δt.

An interpretation of the peak amplitude has been developed in an earlier paper on the implosion of partially ionized theta pinches(7). The peak occurs when the plasma has imploded one fifth of the initial radius and assuming zero trapped flux it has been shown that

$$\hat{S} = A M_0^{1/4} B_0^{1/2} f(\log \alpha)^{1/4} . \qquad \ldots (2)$$

The function f is weakly dependent on α and $f^{1/4}$ may be taken as unity. Also the dependence on the line mass, M_0, is small so that for constant rate of rise of magnetic field, $\dot{B}_0$, equation (2) leads simply to

$$\hat{S} \ \alpha \ A$$

where A is the initial plasma area. In the previous work(7) the pre-ionized plasma filled the tube and accurate numerical agreement was obtained with $A = A_T$ the tube internal area. The same agreement is obtained with the present results at the peak of $\hat{S}(\Delta t)$ but at earlier times, where the pre-ionization plasma is pinched, $A < A_T$ and $\hat{S}$ is a measure of this area. From Δt = 1 to 3.5 μsec the form of $\hat{S}$ agrees qualitatively with the photographed plasma area.

Radial Hydromagnetic Oscillations

Radial oscillations, excited by the theta pinch implosion, are readily detected by measuring the plasma diamagnetism and can be used as a measure of plasma line mass $M^{(13)}$. The frequency is given by

$$\nu = \frac{g}{4\pi}\,\frac{B}{\sqrt{M}} \qquad \ldots (3)$$

where g is a correction factor depending on the radial density profile and can be taken as 2.2 for practical purposes(14). Provided M is constant with time its value may quickly and accurately be determined by counting the number of oscillations N^* between two times t_1, t_2, i.e.,

$$M = \left\{ \frac{g}{4\pi N^*} \int_{t_1}^{t_2} B \, dt \right\}^2$$

The results are summarised in Table II in terms of M/M_0 where M is the line mass calculated from the pressure of gas filling the tube. The difference between the pure and impure cases with high voltage pre-ionization ($\Delta t = 1.0, 3.5$ μsec) is accounted for by the change in oxygen concentration, with 0.73 ± 0.10 of the filling gas trapped in both cases.

TABLE II

Summary of Theta Pinch Plasma Properties

	High Voltage Pre-ionizer				40 kV Pre-ionizers
Delay time Δt (μsec)	3.5	1.1	1.1	1.1	3.5 - 10
Pressure (mtorr)	20	20	8	5	20
M/M_0	0.83 ± 0.11	0.73 ± 0.10	0.7 ± 0.15	?	1.00 ± 0.07
Diamagnetism at 2 μsec (kilomaxwells)	46	35	21	16	46
Relative Total Temperature	1.00 ± 0.15	0.87 ± 0.14	1.35	(1.6)	0.84 ± 0.06
Oxygen content (%)	~ 1.5	0.15 ± 0.1	-	-	⩾ 1.5 ± 0.5

The effects of partial ionization on mass collection, measured from the first diamagnetic peak, have been investigated by the author and others(7) who established a connection between α and $\hat{S}^4$. An estimate of α is obtained by using the relation between $\hat{S}$ and M (see equation 2) under conditions where A can be taken as a constant i.e.

$$\left(\frac{\hat{S}}{\hat{S}(\alpha = 1)} \right)^4 = \frac{M}{M_0} = f(\log \alpha)$$

From the experimental data of reference (7) an $M/M_0 = 0.73 \pm 0.10$ is given by an $\alpha = 16 \pm 3\%$. This degree of ionization is quite consistent with $\alpha < 14\%$ from energy considerations and $\alpha > 6\%$ from the pre-ionizer pinch dynamics.

Plasma Energy

Estimates of the total temperature, that is the sum of ion and electron temperatures, can be made from the diamagnetism at some later time when the oscillations have decayed but before particle or energy loss has occurred, say at 2 μsec.

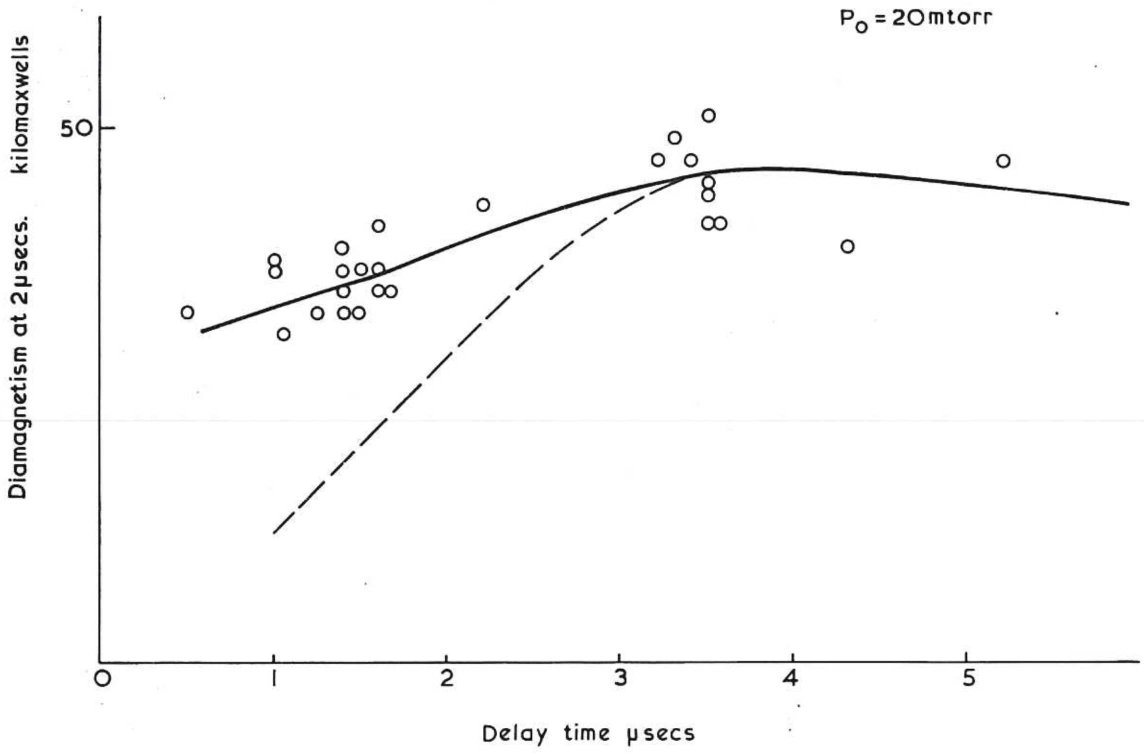

Fig. 4 (CLM-R62)
Variation of diamagnetism at 2 μsec with delay time between pre-ionization and theta pinch

The variation of S(2 μsec) with Δt is shown in Fig.4 where experimental points are plotted and a full line drawn showing the general trend. The behaviour is similar to that of $\hat{S}$ (see Fig.3) rising to a flat maximum of 46 kilomaxwells at Δt = 3.5 μsec. In the pure condition (Δt = 1 μsec) the diamagnetism was lowered to 35 kilomaxwells.

Diamagnetism, line density and total temperature are all related by pressure balance on a model of radially uniform plasma by

$$8\pi k\ NT = SB\left(1 + \frac{\varphi}{S + \varphi}\right) \qquad \ldots (4)$$

The bracket containing φ, the trapped flux, always lies between 1 and 2 but φ is likely to be small from previous investigations at high pressures showing

$$\varphi \propto p_0^{3/2}$$

and predicting φ = 5 ± 2 kilomaxwells at 20 mtorr(15). In these cases the factor could thus be expected to make ~10% difference in the absolute value of T and since the variation of φ with pre-ionizer is not known we have assumed φ = 0 to find comparative values of T.

Calculations of T, in relative units using the line density from the radial oscillations are quoted in the summary Table II. At short delay times the plasma was less energetic and this is to be expected since the shock heating compresses the plasma from a smaller initial area.

5. EFFECTS AT LOWER PRESSURES

The reductions in impurity, and diamagnetism and inefficient mass trapping described in the previous sections were also apparent at 8 mtorr starting pressure. When the plasma energy analysis is repeated (see Table II) a 55% increase in total temperature over that at 20 mtorr is found.

At 5 mtorr, the character of the diamagnetism was changed there being no clearly defined first minimum of diamagnetism and no radial oscillations, suggesting that the implosion was heavily damped. An energetic plasma was obtained but without a knowledge of M no assessment of temperature is possible. The value of T in brackets in Table III is reached assuming $M/M_0 = 0.7$.

6. COMPARISON WITH EARLIER PRE-IONIZATION SYSTEMS

Our early pre-ionizer circuits were based on a five element artificial transmission line of 1 Ω at 40 kV(1). On small discharge tubes 2.7 μsec pulses of 20 kA were generated with a series terminating resistor, but on the Megajoule machine, because of the high plasma impedance, it was necessary to raise the series resistor to 2.6 Ω to limit the current duration so forfeiting the transmission line properties. The theta pinch results reported at the Culham Conference were obtained with this system.

In an attempt to reduce the current duration the above bank was cut to just the first element of the line and the series resistor trimmed to 1.9 Ω. The current was reduced and the energy input halved. The energy input measurement showed that both 40 kV systems delivered about or more than the minimum 50 joules required to dissociate and ionize a gas filling at 20 mtorr pressure. The electrical characteristics of all three systems are summarised in Table III.

TABLE III

Details of Pre-ionization Systems used at Culham

	Voltage	Capacity	Energy	Series Resistor	Peak Current	Current Duration	Energy fed into Discharge Tube
Marx Generator	120 kV	0.033 μF	240J	3000Ω to 1.5Ω	10 kA	0.85μsec	7J
Five element transmission line	40 kV	1.0 μF	800J	2.6Ω	14 kA	5.6μsec	80J
One element of transmission line	40 kV	0.2 μF	160J	1.9Ω	10 kA	1.9μsec	40J

With the 0.2 μF 40 kV pre-ionizer the implosion time of 1.0 μsec was more consistent with that expected on snowplough models for full gas collection. Unsymmetrical expansion was frequently seen and may originate from kink instabilities. The mean expansion velocity was 2 cm μsec^{-1} implying an ion temperature of about 4 eV and the plasma returned to the wall 3-4 μsec from the start of the current even if the latter was prolonged by use of the full transmission line. The pre-ionizing discharges also contained ~ 0.05% oxygen and when the theta pinch was fired with Δt = 3.5 to 10 μsec the concentration rose to 1.5 ± 0.5%. This level could be reduced to about 0.8 to 1% by choosing Δt = 1 μsec, but substantial axial currents were still flowing when the theta pinch was fired.

The variation of plasma diamagnetism with Δt, followed the pattern found with the high voltage pre-ionizer. However both $\hat{S}$ and S(2 μsec), shown by the dotted lines in Figs.3 and 4, fell to low values with Δt small, confirming the camera observations of a greater degree of compression in the pre-ionization pinch. Comparison of the expected line mass M/M_0 = 1.12 ± 0.04, including the contribution due to oxygen impurity, to the observed M/M_0 = 1.00 ± 1.07 indicates a more efficient collection of particles.

When the relative total temperatures derived from the absolute diamagnetic signal are examined one finds that within experimental error there is no dependence on the choice of pre-ionizer (see Table II). The less efficient magnetic compression heating, concomitant with high purity and depending on a smaller initial plasma area, is offset by the energy being distributed between fewer particles.

Pressures down to 10 mtorr were accessible for experiment with the low voltage pre-ionization but the diamagnetic behaviour was irreproducible at this lowest pressure with an average value of S(2 μsec) = 15 kilomaxwells. This contrasted with the performance of the high voltage system where the same diamagnetic level was more reproducibly attained at half the pressure.

7. GRAZING INCIDENCE SPECTROSCOPY

The technique mentioned on page 2 to determine the species of highly ionized impurities by recording their spectral lines also detects a continuous spectrum from the plasma in the region 10-200 Å. The wavelength of maximum intensity λ_m enables one to estimate the electron temperature(10) since

$$\lambda_m \approx \frac{hc}{2kT_e}$$

The observed λ_m occurs in the neighbourhood of 30 Å. When pre-ionization conditions were changed at 20 mtorr the position of λ_m was unaltered to within a few per cent suggesting no change in the electron temperature. This observation is quite consistent with the small change in temperature estimated from the diamagnetic waveforms.

8. CONCLUSIONS

The production of theta pinch plasma with very low impurity concentration has been achieved and the source of impurities identified as contact between the plasma and the wall. Unfortunately the need to prevent the plasma touching the wall is in conflict with the optimum heating of the plasma by magnetic compression. The effects of inefficient shock heating and poor mass trapping in the pure condition tend to cancel each other so that the final temperatures are unchanged.

The measurements of energy input, implosion time and mass trapping all indicate that the particular high voltage system studied produces a level of ionization of about 10%. In principle this weakness can be eliminated by an improved first stage of ionization.

9. ACKNOWLEDGEMENTS

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