Studies on the Applicability of Slit Metal Vessels in Fast Theta-Pinch Discharges

A. Eberhagen

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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Abstract

The applicability of slit metal vessles for fast magnetic plasma compression was experimentally investigated. The results were encouraging for small diameter vessels when the time needed for plasma compression was not significantly longer than the time for the development of the limiting shortcircuiting arcs across the slit gaps. Applicability of large diameter slit metal vessels was only achieved after superposition of magnetic bias fields. The limiting effects were identified and the condition for the necessary bias field is presented.

It is shown further that satisfactory efficiencies of shockwave heating in slit metal vessels can be achieved only if apart from superposition of bias fields the widths of the metal strips is reduced to the order of centimeter.

With the increase in size and energy of fast magnetic compression experiments an urgent need rises for suitable discharge vessels for plasma confinement. Such vessels have to fulfill, among others, the following requirements:

i) Their fabrication must be technically simple, robust and acceptably cheap even for complicated forms with narrow tolerances

ii) They must be sufficiently resistant against the particle influx and the thermal and radiation load from the plasma

iii) They must permit sufficiently short risetimes (< 0.1 usec) of the electromagnetic fields produced inside for an effective compressional plasma heating.

For small and moderate size experiments these requirements can be satisfactorily met by quartz and ceramic vessels commonly used at present. In future larger experiments, however, severe difficulties are to be expected with these materials. Requirement i), e.g., becomes increasingly unrealistic and the expenditures for such vessels would be unreasonably high. In addition, the risk becomes intolerable that with such dielectric material vessels ruptures will cause unjustifiably long breaks in the experimental program.

The question, raised in requirement ii), for the maximum admissable thermal load capacity of various wall materials has already been extensively studied in 1958 at Aldermaston and Harwell (1) - (4) and in Los Alamos (5). The results pointed quite generally at the superiority of metals over dielectrics. Apart from these more favourable properties, metals are also generally less affected by radiation damages than insulators and, furthermore, due to their better heat conductivity they permit higher wall loads of energy influx from the plasma because effective cooling is possible.

It follows from these facts that metals must be considered the first choice as wall materials and the question arises as to the applicability of metal vessels in fast high-energy discharges. With respect to requirement iii), however, the apparent conflict to be resolved is between the desired good thermal conductivity of the metals on the one hand and their unwanted high electric conductivity on the other which does not permit sufficiently short risetimes of the electromagnetic fields inside the vessels.

Simple estimates show that this cannot be achieved with fully closed metal vessels, as impracticably thin walls would result. Apparently the simplest way to eliminate this difficulty is to interrupt the metal walls properly by insulated slits. This principle had already been applied to some extent in the Culham Zeta-experiment (1), (2). It was specifically investigated in Los Alamos (1970) by Phillips et al. (6) for a fast Z-pinch experiment and by Naraghi (1974) in Tehran (7) for a theta pinch. Highly subdivided aluminium walls were used in both cases with slit distances of about a millimeter or less (Naraghi: 1.4 mm and Phillips: 0.25 mm). Insulation between the individual aluminium blades was achieved by anodizing their adjacent flat surfaces. The vessels withstood induced electric field strengths of up to about 1 kVolt/cm (Z pinch) and 150 Volt/cm (theta pinch), respectively, and the discharges produced inside developed essentially the same features as in all-dielectric tubes.

It was the object of our investigations to establish the limits of the applicability of properly slit-metal vessels in fast compression experiments. We intended to identify the limiting factors involved in order to arrive eventually at less highly subdivided metal walls as quoted before, which were thought to be impractical in all but simplest configurations.

The studies were performed in two different experimental regimes of fast compressional plasma heating: They were started with rather conventional data for vessel diameter (Ø = 8.5 cm) and filling pressure (p_o = 5 - 50 mTorr), but they were also extended to more topical values (Ø = 40 cm, $p_o \leqslant$ 5 mTorr). We shall try to collect in this report all relevant results and experiences gained in the course of the investigations together with the associated discussions and considerations.

Small Vessel Diameter (Ø = 8.5 cm)

The investigations were begun on a small theta-pinch apparatus with the following characteristic data:

Bank energy:	15 kJoule
B_{max} (with crowbar):	28 kGauss

$(dB/dt)_{max}$:	23 kGauss/μsec
$U_{o,\ bank}$	36 kVolt
U_{coil} :	15 kVolt
Coil length :	20 cm
Coil diameter :	10.5 cm

With this equipment plasma temperatures of 30 - 100 eV and densities in the 10^{16} - 10^{17} cm^{-3} range were produced depending on the deuterium filling pressure which was varied between p_o = 5 - 50 mTorr. The discharge vessel was constructed as indicated in fig. 1 (8), (9):

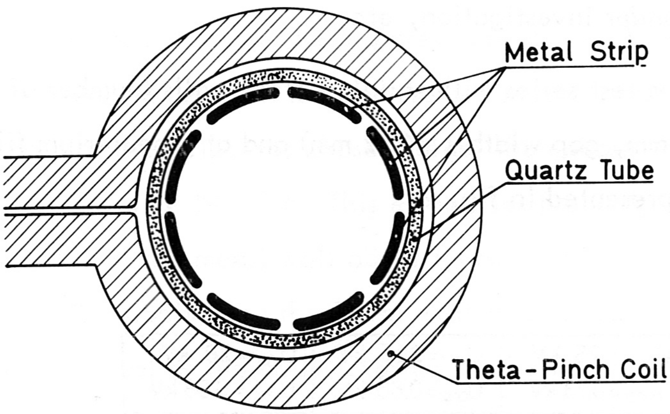

Fig. 1 Schematic of the Slit Metal Vessels

Bare metal strips were fixed to the inner surface of a quartz tube, which served as the vacuum chamber. They protruded 10 - 15 cm out of the coil ends where they were kept in position by mounting them on insulating rings ($\varnothing_{vessel}$ = 8.5 cm). The strips were arranged parallel to the magnetic theta-pinch field. Their number (1 - 22), thickness (1.5 - 5.0 mm) and the gaps between them (s = 1.5 - 8.5 mm) were varied in the course of the experiments. The strips were degreased thoroughly with ether, but no further cleaning process, chemical or mechanical, was applied. The metals selected for the present studies were aluminium, brass and stainless steel.

The operational procedure in the experiments was the following: The deuterium gas was preionized either by an rf-cable and a subsequent 0.4 kJoule theta-discharge, or, at lower filling pressures, by a 1 kJoule Z pinch (120 kV). Then the 15 kJoule main bank was fired. Its charging voltage, and the corresponding voltage difference induced across the strip gaps, was varied from shot to shot to find the limiting voltage at which arcing across the gaps was just avoided. This critical voltage could be identified rather clearly with help of the diagnostics which consisted of:

... side-on and end-on framing and smear pictures

... diamagnetic signals from two axial positions

... photomultiplier signals from spectral lines characteristic of the metal under investigation, etc..

An example of such a test series with stainless steel walls (number of strips N = 12, strip shickness: 1.5 mm, gap width s = 2.2 mm) and at a deuterium filling pressure of p_o = 50 mTorr is presented in fig. 2.

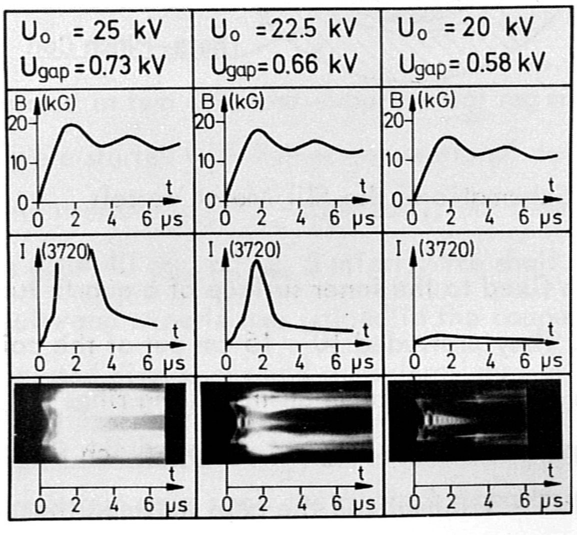

Fig. 2 Example of a test series for the determination of the critical field strength in slit metal vessels

Here are shown for three different charging voltages of the bank:

a) the time variation of the magnetic field in the coil

b) the multiplier signal of the ion resonance line at 3720 Å in end-on observation

c) the relevant end-on smear pictures.

In this instance the critical charging voltage obviously is 20 kVolt corresponding to an induced critical field strength in the gaps of $E_c = U_{gap} / s = 2.7$ kVolt/cm. In this selected example 90% of the inner vessel surface was covered by metal; in other instances up to 99% was covered and the critical field, E_c, was observed to be as high as 20 kVolt/cm. Below this critical figure the theta-pinch discharges developed very much in the same way as in a dielectric vessel, at least as long as the number of slits was not too much reduced. At lower filling pressures ($p_o \lesssim 15$ mTorr) narrow plasma bridges sometimes occurred between the compressed plasma and the center of each strip when the width of the strips was chosen larger than about the vessel radius, i.e. when the number of the slits: $N \lesssim 6$. This effect was probably caused by z-components of the current induced in the metal wall about its two ends by the theta-pinch, as it could be eliminated by subdividing the metal wall in z-direction and limiting the length of the vessel to that of the coil. Coating of the inner metal vessel surface with glass, however, had no influence on this effect. There was also some indication that the plasma temperature produced in the metal vessels was slightly lower (typically 30 eV, density 3×10^{17} cm^{-3}) than in quartz vessels alone (typically 50 eV, density 2×10^{17} cm^{-3}). It is conceivable that this was due to a stronger cooling of the plasma through the coil ends in the case of the metal vessel, which was protruding 10 - 15 cm out of both these ends. It might be added that with the interpretation given these two disadvantages found for linear metal vessels should disappear in toroidal geometry.

In the course of the investigations a variety of observations and results were obtained, which cannot each be presented here in detail. Some more general experiences and conclusions, however, shall be listed:

i) All metal strip vessels revealed a conditioning effect immediately after their introduction inside the vacuum chamber. It always took some ten to twenty discharges until the critical voltage had settled to a figure fairly constant from discharge to discharge.

ii) The most important condition to reach maximum critical voltages is: The preioinized plasma necessarily present in the vicinity of the gaps ought to be as rarefied as possible whenever large electric fields are induced, e.g. at the beginning of the discharge.

Consequences from this general rule are:

a) Successive ringing of the theta-preionization before discharging the main bank must be avoided. This was done by using thyrites in the preioinization circuit and thereby cancelling all half-cycles except the first two.

b) The critical voltages can be increased considerably by a small theta-pinch prepulse which "gently" removes the plasma from the gap and wall region before the high electric fields are subsequently applied.

c) The situation becomes difficult with respect to arcing when antiparallel magnetic fields are to be superimposed to the generated plasma, since in this case the plasma expands temporarily onto the walls just at the time when the induced fields are high. But again the danger of arcing across the gaps can be considerably reduced by application of a proper single theta-pinch prepulse, which just achieves field-reversal on the plasma boundary and shifts this boundary off the wall before the main bank is fired.

Next some figures shall be presented on the limits of the applicability of uncoated slit metal vessels in fast compression experiments. These critical field strengths at the gaps before arcing occurred refer to discharges without any magnetic field superimposed, no prepulse applied before the main discharge and with the theta- and Z-pinch preionization, respectively, cancelled after 1 - 2 half-cycles. In the other respects the experimental conditions were as mentioned before, i.e. in particular:

... vessel diameter $\varnothing$ = 8.5 cm

... deuterium filling pressures p_o = 5 - 50 mTorr

... strip number N = 1 - 22

... gap width s = 1.5 - 8.5 mm

... strip thickness - equal to twice the radius of curvature of the metal surface at the gaps : 1.5 - 5.0 mm

... strip metals: aluminium, brass, stainless steel.

Within the limits of this range of investigation all the individual results obtained might be summarized by the simple emperical formula:

$$E_c \cdot (p_o \cdot s)^{\alpha} = K = \text{const.}$$

where: E_c (kV/cm) = U_c/s

U_c (kV) = critical voltage across the gaps before arcing occurred

s (cm) = gap width

p_o (mTorr) = deuterium filling pressure.

The validity of this representation may be judged from fig. 3:

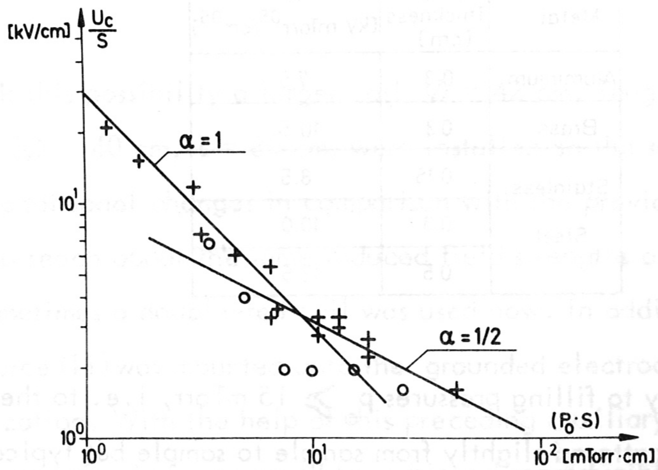

Fig. 3 $E_c \cdot (p_o \cdot s)$ relationship for stainless steel vessels

Here are indicated, as one example, by crosses (+) the experimental results for slit stainless steel vessels with strip thicknesses of 3 mm, but filling pressures, slit numbers and gap widths varied between the limits mentioned. It can be seen from the diagram that the exponential α exhibits an additional slight dependency on the filling pressure p_o: The experimental points establish $\alpha = 1/2$ for $p_o \geqslant 15$ mTorr, whereas for lower filling pressures $\alpha = 1$ is indicated.

Insertion of insulators into the gaps, whether flat or sunk, had only little effect on the critical field strengths in the cases of glass, ceramics or protolin. Only with some commercial materials, e.g. plexiglass or trovidur, were partially reduced critical fields, E_c, found, possibly due to the occurrance of sliding sparks. Corresponding results for plexiglass in the gaps are indicated in fig. 3 by open circles (o) (10).

Experimental values for the constant K in the given emperical formula are listed in the following table:

$$\frac{U_c}{s} \cdot (P_o \times s)^{\alpha} = E_c \cdot (P_o \times s)^{\alpha} = K = \text{const.}$$

Filling Pressure : $P_o \geqslant 15$ mTorr: $\alpha \approx 0.5$

Metal	Strip Thickness [cm]	K [kV·mTorr$^{0.5}$/cm$^{0.5}$]
Aluminium	0.3	7.5
Brass	0.3	10.5
Stainless Steel	0.15	8.5
	0.3	10.0
	0.5	12.5

These figures apply to filling pressures $p_o \geqslant 15$ mTorr, i.e. to the exponential $\alpha = 1/2$. They scattered slightly from sample to sample but typically did not deviate from the average value given by more than 15%. According to the table stainless steel is clearly better suited as wall material than aluminium. The table indicates further that weaker curvatures of the metal surface at the gaps reduced the tendency of arcing.

A compact vessel with slit stainless steel walls was finally constructed with the experience gained. It had two slits of 5 mm width and with glass as insulator. It was surrounded by protolin for mechanical rigidity and vacuum tightness. With this prototype the applicability of small diameter slit metal vessels in fast theta-pinches was demonstrated at filling pressures about 5 mTorr according to expectation.

Large Vessel Diameter (Ø = 40 cm)

Although the experience with slit metal vessels was very promising, so far, the important question was still open of how these favourable results extrapolate to even lower filling pressures and hence to larger vessel radii. The empirical formula obtained before indicated a still better behaviour of slit metal vessels in very low density fast compression experiments. On the other hand the possibility was to be recognized, that with the small vessel radius and the fast risetime of the magnetic field the plasma compression might have been almost completed ($t_{compr} \approx 3 - 4 \times 10^{-7}$ sec at $p_o \lesssim 10$ mTorr) before arcs across the gaps were sufficiently developed.

Anticipation of such a time-scale for the arc formation would imply that in large diameter slit metal vessels the driving magnetic field would be excluded from the interior of the vessel by the shortcircuiting arcs during the very early stages of the plasma compression.

In order to check this possibility a larger coil (Ø = 42 cm, length L = 80 cm) and discharge vessel (Ø = 40 cm, L = 80 cm) were installed on the same theta-pinch apparatus. Two additional changes in comparison with the previous experiment were made: In order to reach about the same induced field strengths of $\approx$ 400 Volt/cm in both cases sometimes a double-fed coil was used now. In addition a sliding-spark UV-radiation source (11) was mounted onto the grounded electrode of the 120 kV Z-pinch preionization. With the help of this preceding auxiliary preionization a homogeneously preionized plasma could be achieved reproducibly for filling pressures $p_o \geqslant 1$ mTorr. For the slit metal vessels henceforth only stainless steel was used because of its superior behaviour in the former tests.

The experiments with these large diameter slit metal vessels indeed persistantly revealed the impediment of the fast plasma compression by shortcircuiting arcs across the gaps even at the lowest possible filling pressures and slit numbers as high as N = 32. This adverse result could not be changed by any modification in the shaping of the slit region.

To pursue the question of the applicability of slit metal vessels in fast compression experiments further it then appeared necessary to get more insight into the spatial and temporal distribution of the currents within and in the vicinity of the metal walls before and after the occurrance of shortcircuiting arcs.

For this purpose the diagnostics applied were extended by (12):

... magnetic probes to measure the radial distribution of the magnetic field inside the vessel

... a specially developed pair of compensated B_z-field probes introduced axially on both sides of the metal wall and at equal axial and azimuthal position for measuring the current induced within the wall during the discharge. This pair of probes was 20 cm long for achieving information sufficiently well averaged in the axial direction and had a time response of better than 4×10^{-8} sec.

Both these sets of magnetic probes were shifted to different azimuthal positions along the metal wall in the course of the measurements.

Together with the earlier diagnostics was shown with help of these probes:
As can be recognized from fig. 4, trace a, the shortcircuiting arcs across the gaps occurred at about 150 - 200 nsec after the start of the main discharge. They developed sufficiently within about 100 nsec to exclude the driving magnetic field completely from the interior of the vessel. The magnetic field inside the slit metal tube thus became constant after about 250 - 300 nsec, see fig. 4, trace b.

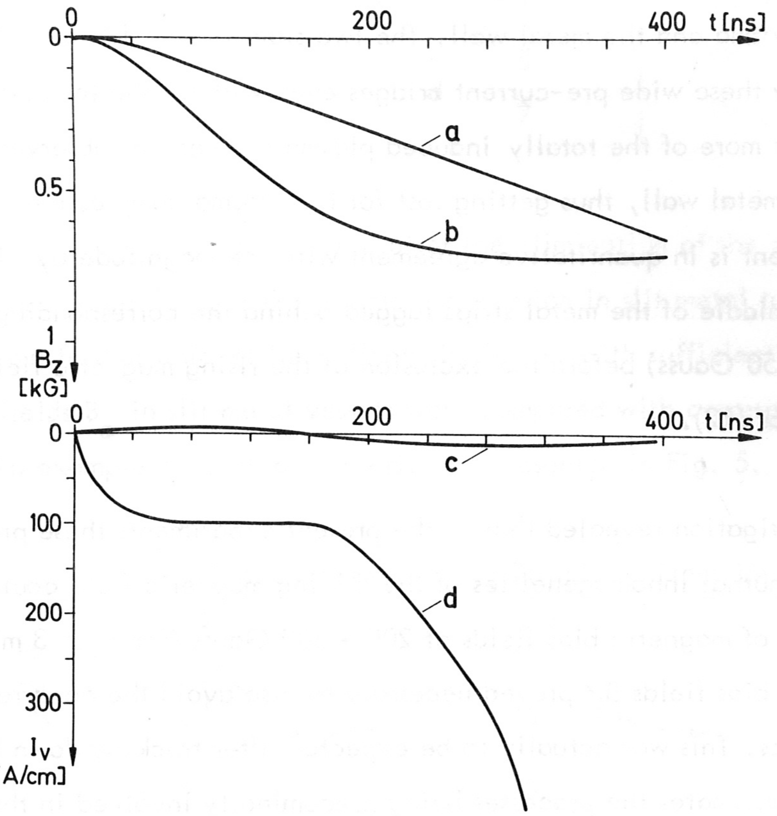

Fig. 4 Magnetic field B_z in front of and the current I_v within the wall of large slit metal vessels during the early phases of theta-pinch discharges (12)
trace a: B_z at the inner wall surface without plasma
trace b: B_z at the inner wall surface with plasma (p_o = 3 mTorr)
trace c: Wall current I_v without plasma (reference line after compensation for evaluation)
trace d: Wall current I_v with plasma (p_o = 3 mTorr)

But even before these arcs were limiting the applicability of the slit metal vessels, a current was flowing already within the metal wall, see fig. 4, trace d. This so-called pre-current appeared immediately after the start of the discharge. It increased azimuthally from about 20 Amps per cm (length in z-direction) in the close vicinity of the slits, to about 100 - 140 Amp/cm measured in the middle of the 30 cm wide metal strips (slit number N = 4). In combination with calculations of the potential distribution in front of the inner vessel surface (12), this pre-current could be identified as azimuthally distributed radial currents between the initial pre-ionization plasma and the metal wall. The two sides of the slits are electrically connected by these wide pre-current bridges even without shortcircuiting arcs occurring. Up to 30% or more of the totally induced plasma current was observed to flow in this way via the metal wall, thus getting lost for the plasma compression. The magnitude of this pre-current is in quantitative agreement with the magnitude by which the magnetic field at the middle of the metal strips lagged behind the corresponding values within the slits (120 - 150 Gauss) before the exclusion of the rising magnetic field by short-circuiting arcs (12).

Further investigation revealed that in the present experiments these pre-currents together with the azimuthal inhomogeneities of the driving magnetic field could be removed by superposition of magnetic bias fields of 200 - 300 Gauss (for p_o = 3 mTorr). Incidentally about similar bias fields B_o proved necessary to also avoid the occurrence of the short-circuiting arcs. This was actually to be expected after tracking down by various discussions and estimates the processes being predominatly involved in the formation of the shortcircuiting arcs (12). According to these considerations locally evaporated anode material, produced and ionized by electrons from the cathode side of the slit is of importance here. In order to prevent these electrons from reaching the opposite side of the slit gap the amplitudes of their paracycloidal drift orbits:

$$a = \frac{m_e \cdot E_{gap}}{e \cdot B_o^2} \qquad \text{with: } E_{gap} = E_{ind} \cdot \frac{2\pi r_o}{N \cdot s} \quad (r_o = \text{vessel radius})$$

had to be adjusted smaller than the slit width s by superimposing correspondingly large magnetic bias fields B_o. The measurements verified indeed that the following bias fields B_o were necessary for avoiding the shortcircuiting arcs:

$$B_o > \frac{1}{s}\left(\frac{2\pi m_e}{e} \cdot \frac{E_{ind} \cdot r_o}{N}\right)^{1/2} \cdot f(p_o) \approx \frac{6}{s(cm)}\left(\frac{E_{ind}(V/cm) \cdot r_o(cm)}{N}\right)^{1/2} f(p_o) \ (\text{Gauss})$$

where $f(p_o)$ was about unity at small filling pressures p_o but it increased rapidly at $p_o > 5$ mTorr

p_o (mTorr)	$f(p_o)$
2	$\approx$ 0.7
3	$\approx$ 1.0
5	$\approx$ 1.3
7	$\approx$ 2.7

Finally, in order to check whether or not after the elimination of the shortcircuiting arcs and the pre-current bridges the plasma compression in slit metal tubes was still impeded by some further unidentified effects discharges with sufficiently large superimposed bias fields B_o in slit metal vessels were compared with corresponding ones in glass tubes. An example of such a comparison is presented in Fig. 5.

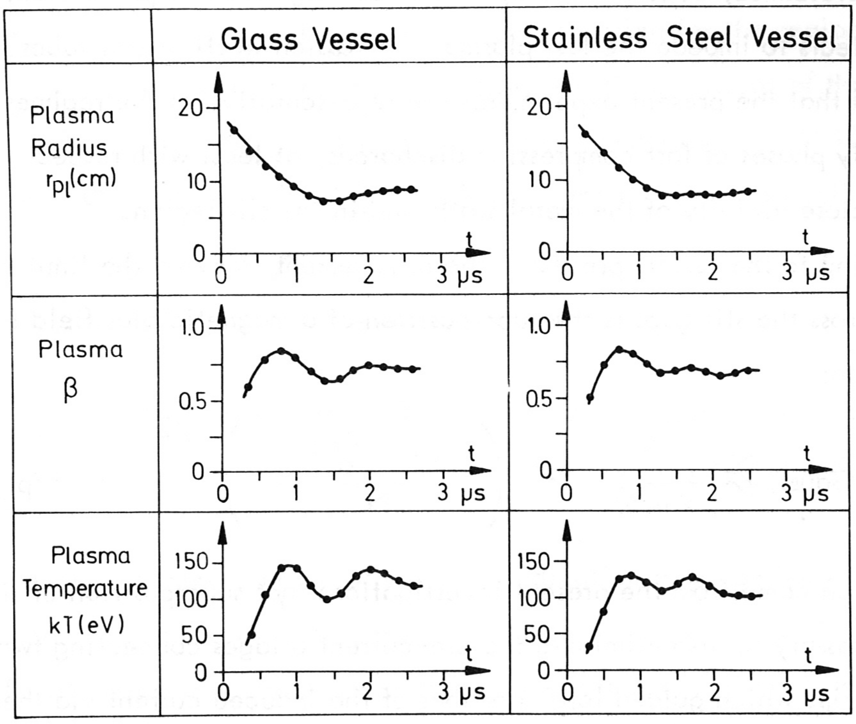

Fig. 5: Comparison of plasma parameters achieved in a glass vessel and in a slit metal vessel (p_o = 2 mTorr, B_o = 300 Gauss, N = 32, s = 3 mm, E_{gap} = 4700 V/cm)

Only minor effects of the metal walls on the plasma parameters are indicated here during and after the compression. The plasma temperature and ß are reduced slightly and the compression itself is not quite as pronouned. On the other hand, the necessary bias field B_o did not result in an exceedingly small ß-value in the presented case (N = 32, i.e. strip width $\approx$ 4 cm!). This indicates that the magnetic bias fields, B_o, necessary for avoiding arcing across the gaps might be tolerable for fast plasma compression in slit metal vessels.

Scaling of the Applicability of Large Slit Metal Vessels

The latter expectation, however, needs a closer examination before more general statements can be done on the applicability of slit metal vessels, particularly with larger diamters. It will be presumed for the following discussions that according to the results presented, e.g. in Fig. 5, shortcircuiting arcs and pre-current bridges are the only effects to impede the fast plasma compression in slit metal tubes. It will also be assumed that the present experiments are representative of the regimes considered for the early phases of fast compression discharges, at least with respect to the situation in the close vicinity of the metal walls and in the slit region.
According to the results presented the requirement to avoid the limiting shortcircuiting arcs across the slit gaps is the superposition of a magnetic bias field B_o with the condition:

$$B_o\ (\text{Gauss}) \gtrsim \frac{6}{s\ (\text{cm})} \cdot \left(\frac{E_{ind} \cdot r_o(\text{cm})}{N} \right)^{1/2} \cdot f\ (p_o)$$

Indication came from the present investigations that superposition of similar bias fields was necessary to also eliminate the pre-current bridges connecting two neighbouring metal strips which guided large portions of the induced current via the metal wall rather than the plasma in front of it. For later discussions, the condition involved here is to be made more precise. Calculation on the azimuthal distribution of the radial electric field strength in front of the inner vessel surface (12) had shown a fairly linear increase of this quantity from $E_r = 0$ at the middle of each metal strip (azimuthal angle $\theta = 0$) to $E_r = \frac{U_{gap}}{2\Delta}$ at positions very close to the slits ($\theta = \pi/N$), when Δ was the distance between the metal surface and the edge of a conductive plasma assumed in front of it ($\Delta \ll r_o$). Letting Δ be the screening distance of the radial electric field E_r, i.e. $\Delta = \lambda_{Debeye,\ wall}$, the pre-current flowing in the middle of the metal strip can be estimated from:

$$I_{pc} = \sigma_{wall} \int_{\theta=0}^{\theta=\pi/N} E_r(\theta) \cdot r_o \, d\theta = \left(\frac{\sigma}{\lambda_{Deb}}\right)_{wall} \frac{\pi}{4} r_o \frac{U_{gap}}{N} = \frac{\pi}{2}^2 \left(\frac{\sigma}{\lambda_{Debye}}\right)_{wall} \cdot \frac{E_{ind} \cdot r_o^2}{N^2}$$

when: σ_{wall} = plasma conductivity in front of the wall

$\frac{N \cdot U_{gap}}{2\pi r_o} = E_{ind} \equiv$: Electric field strength induced inside the vessel by the rising magnetic field

Using experimental figures for I_{pc}, E_{ind}, N, r_o, and assuming for the region of width $\Delta = \lambda_{Debye,\ wall}$ in front of the metal surface, elastic collisions of the electrons with neutrals $[\nu_{eo} = n_o \cdot \sigma_{eo} \cdot (kT_e/m_e)^{1/2}$, neutral density $n_o \approx 10^{14}$ (cm^{-3}) for $p_o \approx$ 2mTorr, $\sigma_{eo} \approx 10^{-15}$(cm^2)] to vastly exceed the Coulomb collisions $[\nu_{eo} \gg \nu_{ei} \approx 3 \cdot 10^{-6} \cdot \Lambda \cdot n_e \cdot (kT_e)^{-3/2}$, $(kT_e)_{wall} \approx 0.05$ (eV)] results in $n_{e,\ wall} \approx 10^6$ (cm^{-3}) and correspondingly:

$\lambda_{Debye,\ wall} \approx 0.2 \text{ cm} \ll \lambda_{eo} \equiv$: mean free path of electrons in the close vicinity of the wall.

Despite the crudeness of these considerations, the indication may, perhaps, be accepted that the radial electric fields in front of the metal wall surface act over distances of the order of millimeters and that the electrons move rather collisionless within this region. By analogous arguments as before for the slit region, electrons entering this sheath will then be prevented from falling onto the metal surface if magnetic bias fields

$$B_o^* > \frac{6}{\sqrt{2}\,\Delta} \left(\frac{E_{ind}(\text{V/cm}) \cdot r_o\ (\text{cm})}{N}\right)^{1/2} \qquad \text{(Gauss)}$$

are applied. Except for the experimental factor f (p_o) both criteria for B_o are about identical in practice as long as $s \approx \sqrt{2}\,\Delta$ and both are of the order of a millimeter.

The factor $\sqrt{2}$ in B_o^* enters as the maximum potential difference between wall and plasma is only $U_{gap}/2$.

Shortcircuiting arcs and pre-current bridges thus can be indeed avoided in slit metal tubes by superimposed bias fields B_o determined by the same condition:

$$B_o\,(\text{Gauss}) > \frac{6}{d(\text{cm})}\left(\frac{E_{ind}\,(\text{V/cm})\cdot r_o(\text{cm})}{N}\right)^{1/2}\cdot f(p_o)$$

with d to be the smaller length of slit width s or ($\sqrt{2}\cdot\lambda_{\text{Debye, wall}}$)

This result simplifies the determination of the limits of the applicability of slit metal vessels in fast compression experiments. For this aim theta-pinch discharges will be considered with superimposed bias fields B_o according to the foregoing condition and with a sinoidal increase of the driving magnetic field $B_{ao}\cdot\sin(\omega t)$.
The total magnetic field:

$$B(t) = B_o + B_{ao}\sin(\omega t)$$

is thought to be kept constant ("crowbarred") after the moment of first maximum compression, i.e. shockwave-heating is referred to here only.
For the calculations the snow-plough model was applied:

$$2\pi r\left[\frac{B(t)^2}{2\mu_0}-\frac{B_o^2}{2\mu_0}\left(\frac{r_o}{r}\right)^4\right] = -\pi\cdot\rho_0\frac{d}{dt}\left[(r_o^2-r^2)\frac{dr}{dt}\right]$$

which is reduced to

$$x\left[b+\sin(\alpha\tau)\right]^2 - b^2\cdot x^{-3} = -\frac{d}{d\tau}\left[(1-x^2)\frac{dx}{d\tau}\right]$$

with help of the abbreviations:

$$x = \frac{r}{r_o}\;;\quad b = \frac{B_o}{B_{ao}} = b\left(E_{ind}, \frac{r_o}{N}, (\omega\cdot r_o)\right)$$

$$\tau = \frac{t}{t_{Alfv}}\;;\quad t_{Alfv} = \left(\frac{\mu_0\,\rho_0\,r_o^2}{B_{ao}^2}\right)^{1/2}$$

$$\alpha = \omega\cdot t_{Alfv} = 19.3\left(\frac{\omega\cdot r_o}{10^7}\right)^2\cdot\frac{(\mu_i\cdot P_0)^{1/2}}{E_{ind}}\;;\quad \mu_i = \frac{m_{ion}}{m_{proton}}$$

$$\omega = \omega(\sec^{-1})\;;\quad r_o = r_o(cm)\;;\quad P_0 = P_0(mTorr)\;;\quad E = E(V/cm)$$

and considering here: $\left(\frac{\omega \cdot r_o}{10^7}\right) = 20 \frac{E_{ind}}{B_{ao}(Gauss)}$

This equation was evaluated for the parameter range: $0.03 \leq \alpha \leq 1$; $b \leq 0.3$

The final plasma particle energy after thermalization was:

$$\mathcal{E} = 0.905 \cdot \frac{A}{\alpha} \cdot \frac{E_{ind}\,(V/cm)}{(p_o\,(mTorr)/\mu_i)^{1/2}} \qquad (eV)$$

with: $A = A(\alpha, b) = \left[(1 - x^2) \cdot (dx/dt)^2\right]_{max}$ to be deduced from the numerical calculations.

For judgement about the optimum achievable efficiency of shockwave-heating in slit metal vessels with the presence of the minimum necessary superimposed magnetic bias fields one may inspect the pertaining ratio: $\mathcal{E}$ (eV)/E_{ind} (V/cm) as a function of the induced electric field applied.

In Fig. 6 corresponding plots are presented for various ratios of (r_o/N). The inverse of this quantity is a measure for the

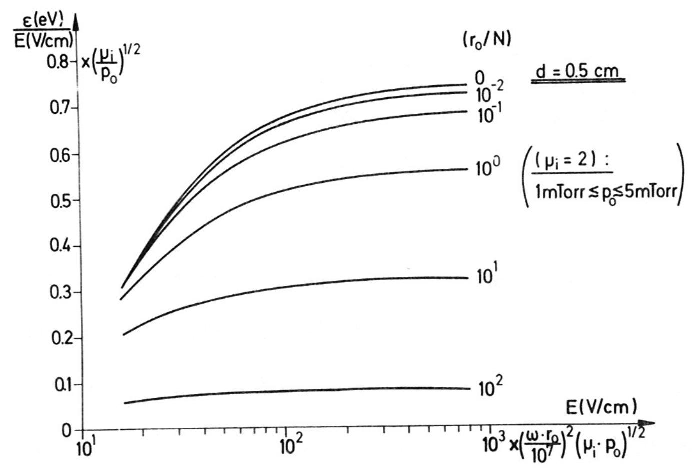

Fig. 6: Optimum achievable efficiency ($\mathcal{E}$/E) of shockwave-heating in large slit metal vessels at varying subdivision of the wall $(r_o/N)^{-1}$ (d=5mm, 1 mTorr $\leq p_o \leq$ 5 mTorr for μ_i = 2)

subdivision of the metal wall and accordingly $(r_o/N) = 0$ corresponds to a completely dielectric tube. The plots presented are valid for d = 0.5 cm (either slit width s or $(\sqrt{2}\,\lambda_{Debye,\ wall}$, see before) and apply to filling pressures p_o: 1 mTorr $\leq p_o \leq$ 5 mTorr if deuterium gas ($\mu_i = 2$) is considered. Apart from this validity range, the abscissa may also be adapted for different values of $(\omega \cdot r_o)$ in the experiment.

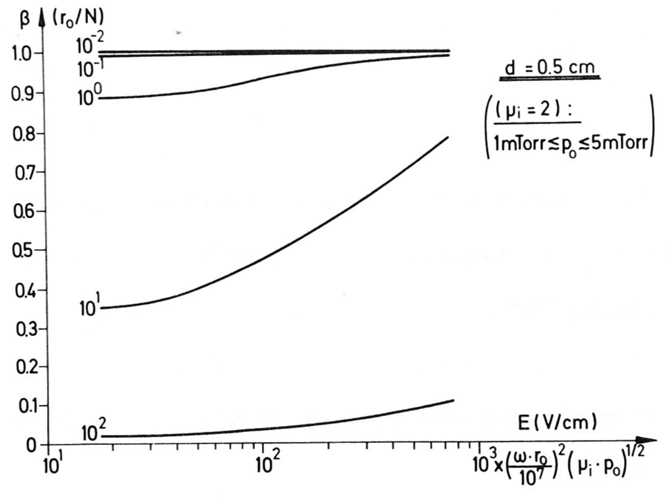

Fig. 7: Maximum achievable ß-values by shockwave heating in large slit metal vessels at varying subdivision of the wall $(r_o/N)^{-1}$ (d = 5 mm, 1 mTorr $\leq p_o \leq$ 5 mTorr for $\mu_i = 2$)

In Fig. 7 corresponding curves for the maximum achievable ß-values are displayed pertaining to the merely shockwave heated plasmas after the radial bouncing. It should be specifically recalled, however, that these results originate from snow-plough model calculations with sharp compressional fronts. This may infer too optimistic ß-values particularly at the low filling pressures considered here.

This argument certainly also holds for the optimum achievable efficiency presented in Fig. 6. Considering further an adequate safety factor to be indispensable in practical use (e.g. bias field $\approx 2 \cdot B_o$) the conclusion may be drawn from the presented results that for safe application of large slit metal vessels in fast compression experiments the

subdivision of the wall ought to be determined by: $(r_o(cm)/N) < 1$, if not too much of the potentialities of shockwave heating is to be abandoned.
By this requirement, however, the widths of the individual metal strips $w = 2\pi r_o/N$ are to be reduced to the order of a centimeter. For practical widths of the isolated slits of several millimeters the insulating material then would constitute a considerable fraction of the total wall surface material. This may still be tolerable in some large diameter compression experiments, but it makes the application of large slit metal vessels problematic when fusion-like plasma conditions are to be achieved by fast compression heating.

Summary

The applicability of slit metal vessels for fast magnetic compression was experimentally investigated on a 15 kJoule theta-pinch apparatus. The results were encouraging for small diameter slit metal discharge vessels (Ø = 8,5 cm), in which the time for the development of the limiting shortcircuiting arcs across the slit gaps is not significantly shorter than the time needed for the shockwave compression of the plasma. The scaling laws for the limiting E_{gap}-fields as function of pressure, gap width and wall material are presented.
These favourable results could not be reproduced with large diameter slit metal vessels (Ø = 40 cm). Detailed investigation revealed that the time for the development of the shortcircuiting arcs is about 200 nsec. In addition to these arcs wide current bridges were identified which connected two neighbouring metal strips and which were independent of the appearance of arcs. Appreciable portions of the induced currents were guided via the metal wall by these current bridges rather than via the plasma in front of it. It was established that both these limiting effects are eliminated simultaneously by the superposition of a magnetic bias field B_o. The necessary condition for B_o is presented. With such bias fields applied, in both cases the fast plasma compression discharge in slit metal vessels and in glass tubes differed only insignificantly.
Closer inspection was done of the restricting effects from the indispensable bias field B_o on the plasma parameters achieved in the fast shockwave heating. Numerical snow-plough model calculations revealed that despite the benefits obtained from the superposition of B_o, the metal vessel must be highly subdivided and the widths of the metal strips

limited to the order of centimeters to avoid wasting too much of the efficiency of the shockwave heating. In this case, however, the insulating material separating the individual metal strips constitutes a considerable fraction of the wall.

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