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Foam target experiments with the PF-1000 plasma focus facility

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Abstract. This paper describes experiments on foam liners performed with the PF-1000 plasma focus facility. A streak camera has been used to observe interaction of a hydrogen plasma current sheath with a cylindrical foam target. It is shown that a thin foam liner can be uniformly imploded by a plasma focus current sheath.

PACS. 52.55.Ez Z-Pinch, theta pinch, plasma focus and other pinch devices

1 Introduction

Using a powerful plasma focus (PF) generator as a driver of a staged plasma foam liner opens new possibilities for research in high-energy-density physics. In the experiment described, a well-formed plasma focus current sheath strikes a low-mass foam liner designed previously for the "Angara" (TRINITI) double implosion program [1]. In order to get liner implosion speeds in excess of 1 cm/μs with condenser bank energies below 1 MJ one must employ liners whose mass is less than 0.1 g, which implies very thin solid liners (bubbles) or gaseous liners (gas puffs). The current sheath interaction with bubble or gas liners was already investigated and is described elsewhere [2–4]. Unfortunately, the production of uniform bubbles at very low pressures ($p < 10$ Torr) is connected with many inconveniences (pollution of the discharge chamber) whereas the use of gas puffs produces only low-density liners. It is for these reasons that the use of foam as a base material for liners has been attempted. The high-energy plasma focus current sheath, accelerated during some microseconds in a coaxial accelerator, delivers its kinetic, thermal and magnetic energy to a cylindrical liner positioned on the accelerator top in a rather short period of time ($\sim$ 100 ns). The PF current sheath is made to arrive at the liner when the current $I \sim I_{\max}$ and, therefore, the liner is immediately driven by the maximum magnetic pressure by $(\frac{B^2}{8\pi})_{\max}$. In fact the plasma drive transforms a slow condenser bank into a fast one. A further advantage of the plasma drive is that the foam is uniformly preionized and consequently the pinch current is uniformly distributed on the periphery of the foam cylinder —a situation which is not encountered when a high-voltage bank is directly switched on to a foam load. Investigation of the phenomena taking place during the process of the plasma focus current sheath interaction with the foam liner was the main goal of our experiment. The parameters of our experiments are far from the optimum ones and we hope, in the future, to go to much higher PF currents, better liner geometry and more incisive diagnostics.

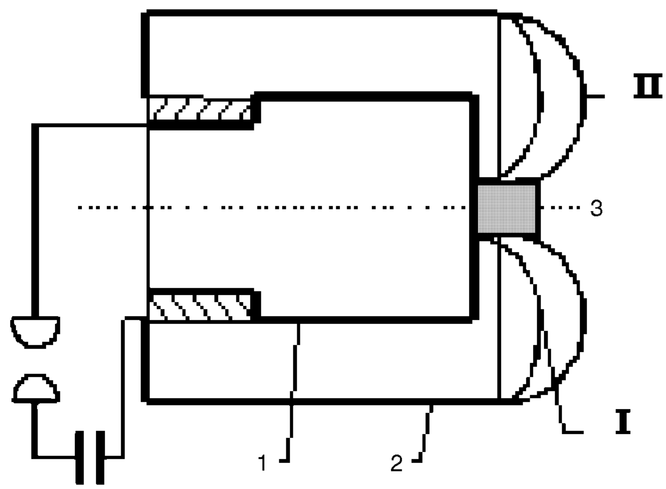

Fig. 1. Schematic illustration of the Plasma Focus liner configuration. 1. PF inner electrode (anode); 2. PF outer electrode (cathode); 3. position of foam liners (type a or b); I, II different positions of the current sheath.

2 Experimental scheme and diagnostics

A schematic diagram of the megajoule plasma focus machine with the foam liner attached to the inner electrode end is shown in Figure 1. The liners were produced from agar gel (1.5 mg of agar in 1 g of water was

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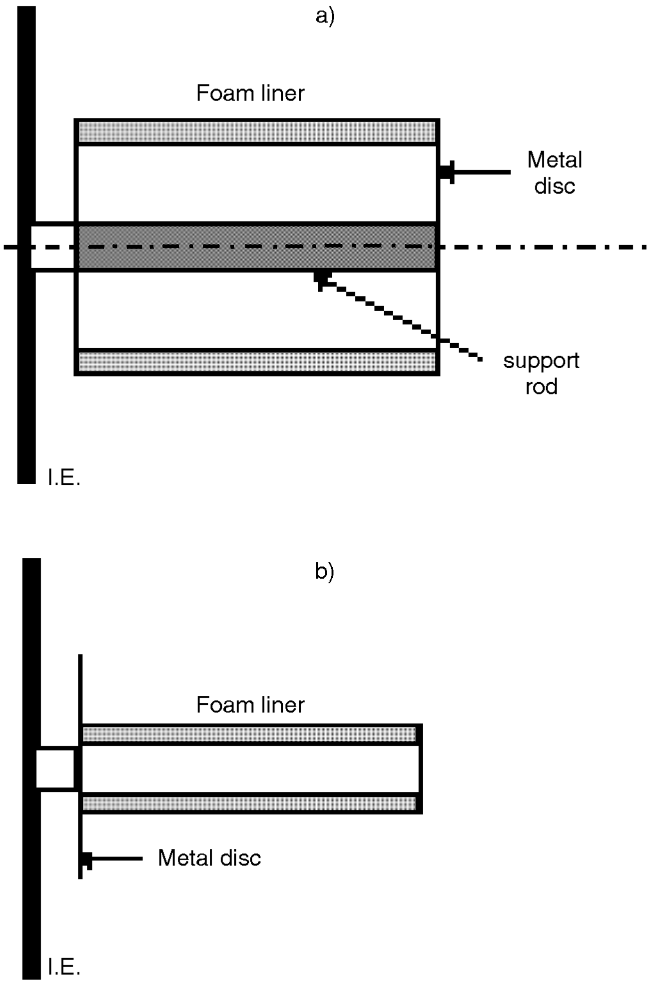

Fig. 2. Schematic illustration of the types of liner used in the experiment. (a) linear density 200 μg/cm, diameter 20 mm, length 15 mm. (b) linear density 280 μg/cm, diameter 5.4 mm, length 20 mm. IE is the top of the inner electrode.

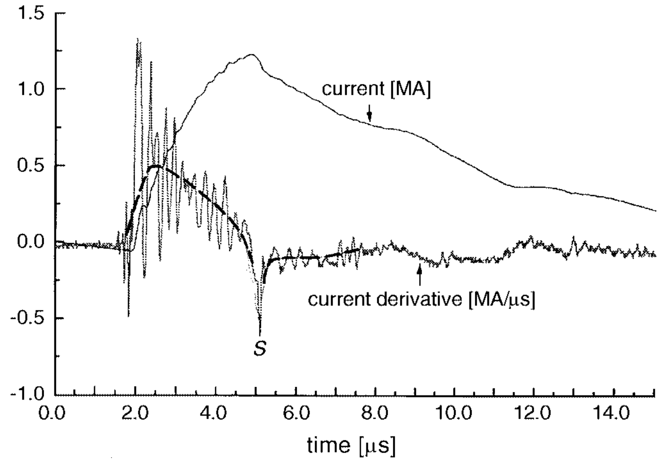

Fig. 3. Typical electrical signals (shot 1313). The mean value of dI/dt is indicated by the hatched curve. The singularity S marks the SP and liner collapse.

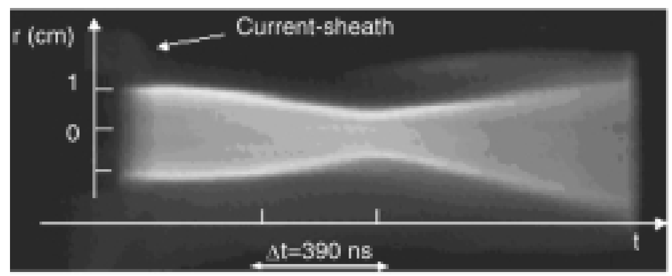

Fig. 4. Streak photograph of the plasma sheath PS imploding on the liner type "a". The radial slit was in the midplane of the liner (streak duration 2 μs), the arrow indicates the trace of the SP.

used). Extremely thin cylinders were manufactured from frozen agar gel ($\rho = 2 \cdot 10^{-3}\,\mathrm{g/cm^3}$) by vacuum drying method [5]. Two kinds of liners were prepared for the experiment (Fig. 2), some with a diameter of 20 mm (a liner mass density of 200 μg/cm —type "a") and others with a diameter of 5.4 mm (250–280 μg/cm —type "b").

The PF-1000 plasma focus facility was equipped with a 100 mm diameter inner electrode and a 150 mm diameter outer electrode, both made of 330 mm long copper tubes. The system was energized by a 1000 μF condenser bank charged up to 25 kV. The plasma focus was operated at a H_2 filling pressure $p = 5.9$ Torr. At this pressure the current sheath strikes the liner when $I \sim I_{\max}$. A total discharge current with amplitude above 1 MA and rise time 4–5 μs was determined using a Rogowski coil. The current derivative dI/dt and voltage $V(t)$ signals were measured by means of probes. Current sheath and liner dynamics were investigated using a streak camera sensitive to visible light through a radial slit centered in the middle of the liner. The quantum energy of the soft X-ray emission was roughly estimated on the basis of pictures taken with a time-integrated pinhole camera equipped with two pinholes covered with 10 and 25 μm Be foils, respectively. The signals from the Rogowski coil and hard X-rays were registered by means of Tektronix 2430A and THS-700 oscilloscopes and synchronized with the dI/dt and $V(t)$ wave forms.

3 Experimental results

Typical electrical signals, *i.e.* the discharge current derivative $\frac{\mathrm{d}I}{\mathrm{d}t}$ ($\frac{\mathrm{MA}}{\mu\mathrm{s}}$) and discharge current I(MA) are shown in Figure 3. The maximum current has been obtained from the current oscillogram by noting the time at which the singularity occurs in the waveforms. The singularity is characteristic of the occurrence of a rapid compression process. The measured maximum total current reaches a value of about 1.2 MA. We observed the outer edge of foam plasma which started to expand at the moment of current sheath arrival at the liner surface (type "a"); 100 ns later the foam liner reached a diameter of 22 mm; after that it imploded on the support rod with a mean velocity of $v_{\mathrm{L}} \simeq 2 \cdot 10^6$ cm s^{-1}. After this implosion the liner plasma

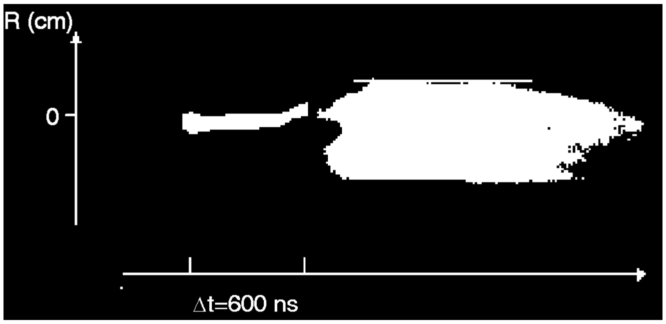

Fig. 5. Streak photograph of the plasma sheath imploding on the liner type "b". The radial slit was in the midplane of the liner (streak duration 2 μs).

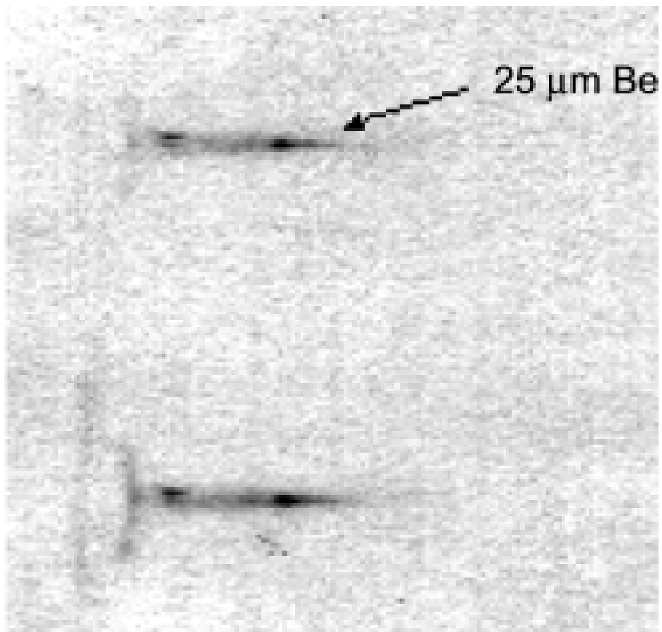

Fig. 6. Time-integrated soft X-ray camera picture (10 μm, 25 μm, Be filter).

was reflected from the insulating rod with almost the same velocity (Fig. 4).

The visible surface of the 5.4 mm diameter liner (type "b") was not subject to any significant compression or expansion within the period of 600 ns after the plasma sheath struck the liner surface (Fig. 5). Nevertheless, a pretty shaped plasma column (2 mm in diameter and 10 mm long) with a 1 mm diameter core was observed with the X-ray pinhole camera (Fig. 6). No "hot spots" are visible in the picture presented in Figure 6.

Emission in the energy range 0.1–1 keV originated probably from more heated regions of the plasma column. These regions are visible in the pinhole camera photos taken with the 10 μm Be filter (Fig. 6). This picture shows that the 5.4 mm diameter liner was constricted by pinch effect. The hot plasma core with a diameter of 1 mm is almost as long as the whole foam liner. The picture taken with the streak camera revealed a plasma corona which was localized within a diameter of 3–4 mm (Fig. 5).

4 Conclusion

The preliminary results of the first experiments on the plasma focus interaction with a foam liner seem to be encouraging. A homogeneous foam plasma liner without any filamentations was produced as a result of this interaction.

An azimuthally uniform implosion of the liner mass was observed, following the impact of a uniformly distributed current sheath on the foam cylinder (Fig. 4).

It was also observed that the foam liner did not expand dramatically during the process of interaction, an effect predicted for a sandwich liner [6] and described approximately in Appendix A. It follows from the considerations of Appendix B that the efficiency of the liner is low ($\eta < 4\%$). In the future we shall try to operate with larger-diameter foam cylinders, closing the top of the outer electrode and using better the potentialities of our bank (the $I_{\max}$ should go up to 3 MA).

Appendix A: Liner-thickness during implosion

We shall assume that after the impact of the snow plough (SP) on the foam liner the kinetic energy of the SP is transformed mainly into the thermal energy of the foam, *i.e.*

$$\frac{1}{2}M_{\rm sp}v_{\rm sp}^2 = \frac{1}{2}\left(\alpha + 3Z_{\rm L}\right)kT_{\rm L}N_{\rm L}, \tag{A.1}$$

where $M_{\rm sp}$ and $v_{\rm sp}$ are the SP surface mass density and speed of the SP, respectively. $N_{\rm L}, T_{\rm L}$ are the ion surface density and temperature after the SP impact. $Z_{\rm L}$ is the degree ionization and α the degrees of freedom of the liner ions.

The $T_{\rm L}$ immediately after the impact will be

$$T_{\rm L} = \frac{\rho\cdot\Delta R\cdot v_{\rm sp}^2}{\left(\alpha+3Z_{\rm L}\right)kN_{\rm L}}, \tag{A.2}$$

where ρ is the density of the PF filling gas and ΔR the effective distance over which the SP collected its mass $M_{\rm sp}$ before the impact. But

$$v_{\rm sp}^2 \simeq \frac{B_\phi^2}{8\pi\rho},\quad B_\phi = \frac{0.2I}{R},\quad N_{\rm L} = 0.6\cdot10^{24}\frac{\rho_{\rm f}\delta_{\rm f}}{\langle A_{\rm f}\rangle},$$

where $\rho_{\rm f}$ is the foam density, $\langle A_{\rm f}\rangle$ the average atom mass of the foam, I the axial current (A) and $\delta_{\rm f}$ the initial liner thickness. We get for $T_{\rm L}$

$$T_{\rm L} \cong 1.8\cdot10^{-11}\left(\frac{I}{R}\right)^2\frac{\langle A_{\rm f}\rangle}{\alpha+3Z_{\rm L}}\frac{\Delta R}{\delta_{\rm f}}\rho_{\rm f}^{-1}. \tag{A.3}$$

Ex.: $\frac{I}{R} = 10^6$, $\frac{\langle A_{\rm f}\rangle}{\alpha+3Z_{\rm L}} = 1$, $\rho_{\rm f} = 2\cdot10^{-2}$, $\delta_{\rm f} = 10^{-1}$, $\Delta R = 5$, we get $T_{\rm L} = 4.8\cdot10^4$ [K].

The foam liner will be, therefore, ionized and heated and consequently it will expand until it is again compressed by the $\frac{B_\phi^2}{8\pi}$ pressure.

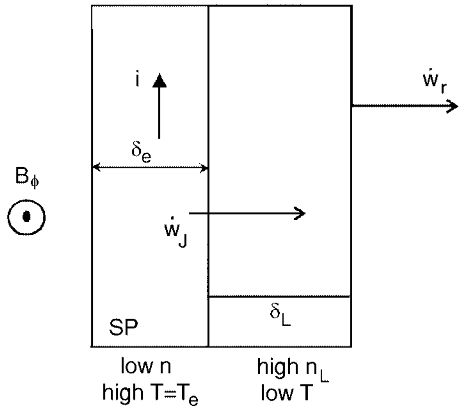

Fig. 7. A sketch of the energy transfer from snow plough to the liner plasma. We assume that in equilibrium $\dot{w}_{\rm J}$ is fully transformed into $\dot{w}_{\rm r}$.

In the absence of energy input (Joule heating) and energy losses (radiation), the liner plasma will settle into a Haley thickness δ which follows from

$$\frac{B_\varphi^2}{8_\pi} = (1+Z_{\rm L})\frac{N_{\rm L}}{\delta}kT\,, \tag{A.4}$$

where $\frac{T}{T_{\rm L}} = \left(\frac{\delta_{\rm f}}{\delta}\right)^{\frac{2}{3}}$. Using all the previous relations we get

$$\frac{\delta}{\delta_{\rm f}} \cong 3.86\left(\frac{\Delta R}{\delta_{\rm f}}\right)^{\frac{3}{5}}\cdot\left(\frac{1+Z_{\rm L}}{\alpha+3Z_{\rm L}}\right)^{\frac{3}{5}} \tag{A.5}$$

independent of $\rho_{\rm f}$ and $\frac{I}{R}$. Obviously $\delta > \delta_{\rm f}$.

However, one can hope that owing to radiation loss the liner will collapse to $\delta_{\rm L} < \delta_{\rm f}$ provided the characteristic time of this collapse is smaller than the time of the liner implosion. This final $\delta_{\rm L}$ is determined by the Joule heat input $\dot{w}_{\rm J}$ from the hot current carrying layer, into the cooler dense foam plasma liner. We shall assume that all $\dot{w}_{\rm J}$ is fully transferred from SP to L and have (per cm^2 of the liner surface, see also Fig. 7).

$$\dot{w}_{\rm J} = 10^7 i^2\rho_{\rm e}\delta_{\rm e}^{-1}\,, \tag{A.6}$$

$$\dot{w}_{\rm r} = 2\sigma_{\rm SB}T^4\left[1-\exp\left(-2\kappa\delta_{\rm L}\right)\right]\,, \tag{A.7}$$

where $i^2 = 10^2\frac{1+Z}{2\pi}\frac{n_{\rm L}}{\delta_{\rm L}}kT$, $\rho_{\rm e} \simeq 2\cdot 10^4\frac{\ln\Lambda}{T_{\rm e}^{3/2}}\cdot Z$, $\kappa\delta_{\rm L} = 10^{-23}\frac{N_{\rm L}^2}{\delta_{\rm L}}\cdot T^{-7/2}$, κ being the opacity of the liner plasma.

For small $\delta_{\rm L}$ we have in most cases $\kappa\delta_{\rm L} > 1$ and the radiation is almost that of a black body. Putting $\ln\Lambda = 3$, $Z = 2$ and setting $\dot{w}_{\rm J} = \dot{w}_{\rm r}$ we get for the equilibrium liner temperature

$$T_{\rm L} \simeq 3.2\left(\frac{N_{\rm L}}{\delta_{\rm L}\cdot\delta_{\rm e}}\right)^{1/3}\cdot T_{\rm e}^{-1/2}\,. \tag{A.8}$$

Ex.: for $N_{\rm L} = 10^{20}$, $\delta = \frac{1}{2}\delta_{\rm e} = 0.1$ and $T_{\rm e} = 10^6$ (K) we get $T = 7.8$ (eV). The final thickness δ is obtained from equation (A.4) which gives

$$\delta_{\rm L} \simeq 10^{-16}\left(1+Z_{\rm L}\right)N_{\rm L}\left(\frac{I}{R}\right)^{-2}\cdot T_{\rm L}\,. \tag{A.9}$$

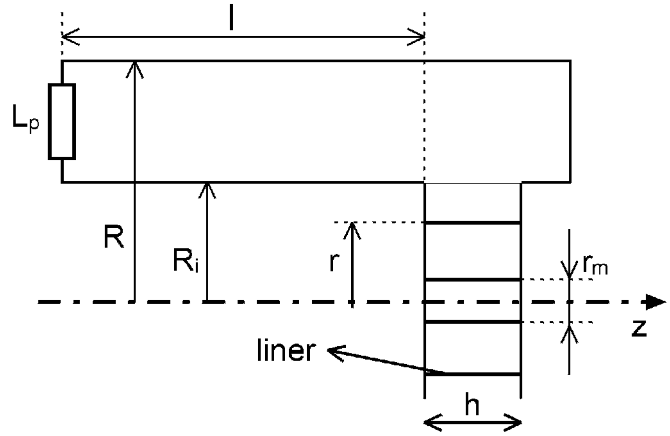

Fig. 8. The geometry of the system in which the liner is driven by $I \sim I_{\rm max} \sim$ const.

For the above example $\delta_{\rm L} = 240$ μm and, therefore, $\delta_{\rm L}$ is smaller than $\delta_{\rm f}$, suggesting that the liner density can be higher than the original foam density.

Appendix B: The efficiency of the plasma drive

Let us assume that the current I reaches its maximum at the moment of contact between the SP and the liner and that during the liner implosion $I \simeq$ const. The latter is approximately true provided the inductance L of the liner is much smaller than that of the rest of the system and provided the time of implosion is much shorter than the quarter period of the bank. The situation is schematically depicted in Figure 8. The kinetic energy of the liner at its maximum implosion (before it is decelerated compressing a target) is

$$\frac{1}{2}M_{\rm L}v_{\rm L}^2 = 10^7\cdot\frac{1}{2}\Delta L\cdot I^2 \quad [{\rm ergs, H, A}]\,, \tag{A.10}$$

where $\Delta L = 2\cdot 10^{-9}h\ln(\frac{r}{r_m})$.

It follows that $v_{\rm L}$ is

$$v_{\rm L} = I\sqrt{\frac{\Delta L}{M_{\rm L}}} = 0.141\cdot I\sqrt{\frac{\ln\dfrac{r}{r_m}}{M_0}}\,. \tag{A.11}$$

Ex.: in our experiment $\ln\frac{r}{r_m} \simeq 1.4$, $I \simeq 1.2$ MA, and $M_{\rm L} = h\cdot M_0 \simeq 0.025$ g and, therefore, $v_{\rm L} \simeq 2(\frac{\rm cm}{\mu s})$, which agrees well with the measured value.

The efficiency of energy conversion can be expressed as

$$\eta = \frac{\frac{1}{2}M_{\rm L}v_{\rm L}^2\cdot 10^{-7}}{\epsilon\cdot\frac{1}{2}\left(L_1+L_2\right)I^2+\frac{1}{2}L_{\rm p}I^2}\,, \tag{A.12}$$

where $L_1 = 2\cdot 10^{-9}\cdot h\cdot\ln\frac{R}{r}$, $L_2 = 2\cdot 10^{-9}\cdot l\cdot\ln\frac{R}{R_i}$, $L_{\rm p}$ is the remaining circuit inductance and $\epsilon \simeq 2$ represents energy dissipated in snow-ploughing.

The above can be written as

$$\eta = \frac{\Delta L}{\epsilon\,(L_1 + L_2) + L_\mathrm{p}} = \\ = \frac{h \cdot \ln \frac{r}{r_m}}{\epsilon \cdot l \left(\frac{h}{l} \ln \frac{R}{r} + \ln \frac{R}{R_i} \right) + \frac{1}{2} 10^9 \cdot L_\mathrm{p}} \,. \quad \text{(A.13)}$$

Ex.: for $\ln \frac{r}{r_m} = 1.5$, $\epsilon = 2$, $\frac{h}{l} = 0.1$, $\ln \frac{R}{r} = 2$, $\ln \frac{R}{R_i} = 0.5$, $L_\mathrm{p} = 100$ [nH], $h = 2.5$ [cm] we get $\eta = 4.4\%$. Obviously in order to get a high η we must try to get a high $\frac{r}{r_m}$ and h and r as high as possible.

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