Dynamics of Plasma Channels for Reactor Transport

J. Hasegawa, T. Mawatari, and M. Ogawa

Tokyo Institute of Technology

Motivation and purposes

- Plasma-channel-based transport[1,2] recently attracts much attention because it potentially relaxes the requirements for beam quality and decreases the cost of driver accelerators.

- The dynamics of the plasma channel strongly depends on the properties of background gas, the amplitude and rise time of the discharge current, and so on. Moreover, the dynamics determines magnetic field distribution in the channel, which affects the beam transport and focusing properties.

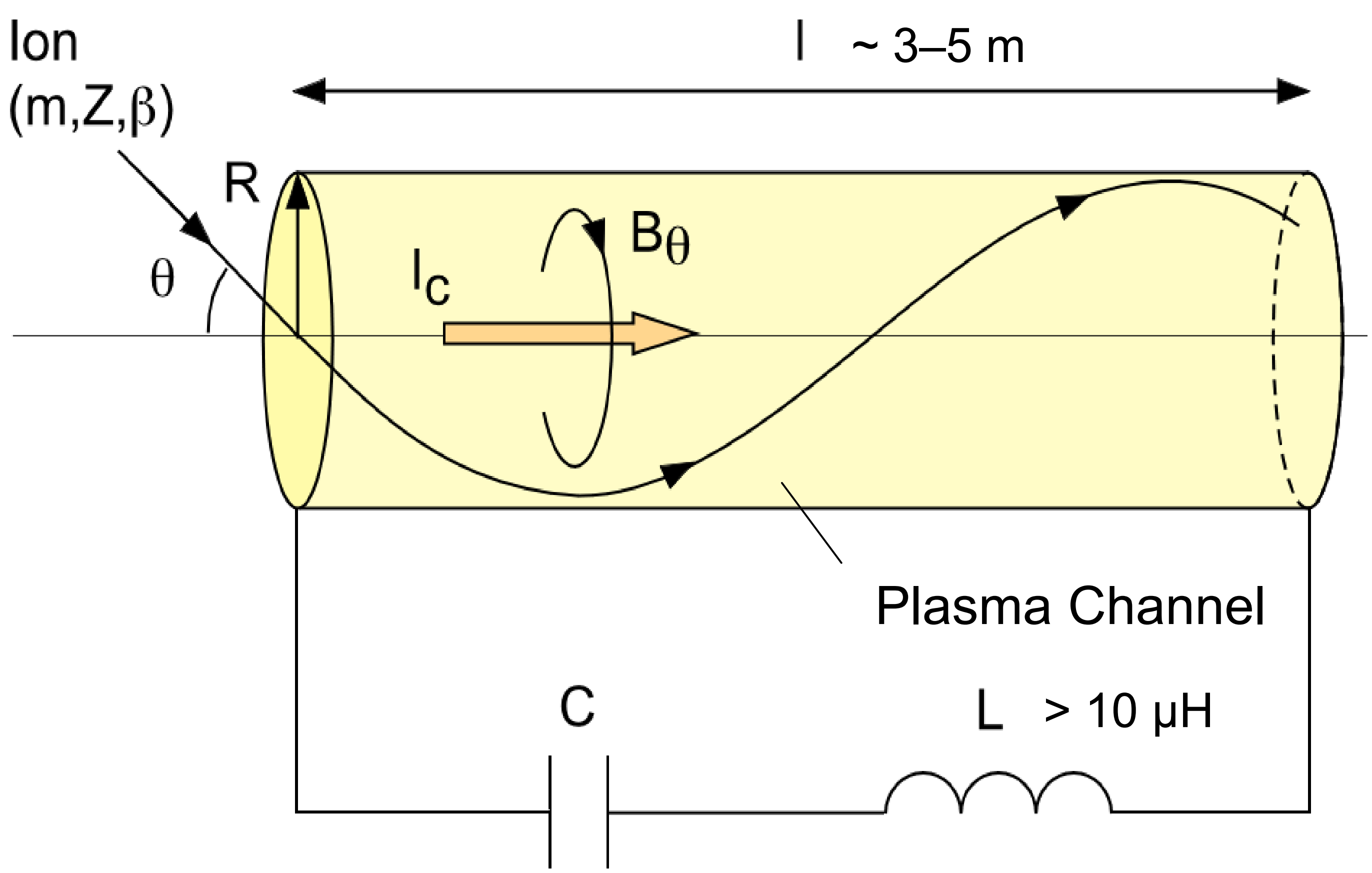
- To discuss the applicability of the plasma channel for chamber transport, design work taking into account plasma dynamics is also essential.

- The purpose of this study is to examine the realistic parameter range of the channel discharge and find the optimum conditions for beam transport from the results of the numerical calculations.

[1] S. Yu, et al, Nucl. Instr. and Meth. A 415 (1998) 174.

[2] D. R. Welch, et al, Phys. Plasma, 10 (2003) 2442.

An equivalent model of plasma channel



Estimation of discharge current for beam confinement

Beam density equilibrium:

$$\frac{n(r)}{n_0} = \exp\left[\int_0^r F(r')dr'/kT\right]$$

$$F(r) = -Ze\beta c B_\theta(r)$$

$$B_\theta(r) = \frac{\mu_0 I_c}{2\pi r}\frac{r^2}{R^2}$$

$$\frac{n(r)}{n_0} = \exp\left[-\frac{2\gamma m\beta^2 c^2}{kT}\frac{I_c}{I_A}\frac{r^2}{R^2}\right]$$

Beam Parameters

4.5-GeV Pb^{72+}

$\tau = 8$ ns

$\theta = 0.03$ rad

$R = 0.5$ cm

cf. D. R. Welch *et al*, Phys Plasmas, 10, 2442 (2003)

$$I_A = 4\pi\varepsilon_0 mc^3\beta\gamma/Ze$$
$$= 1.58\times 10^7 [\mathrm{A}]$$

$R \equiv 3\sigma$ (more than 99% of beam particles)

$$I_c = \frac{9kT}{4\gamma m\beta^2 c^2} I_A \approx \frac{9\theta^2}{4} I_A \approx 32[\mathrm{kA}]$$

$I_c \rightarrow 50$ kA

Conditions for beam neutralization

Space-charge neutralization:

$$n_e >> Zn_i = \frac{I_b / \pi r_b^2}{\beta c} \approx \underline{5 \times 10^{14} [\text{cm}^{-3}]}$$

$(> 0.015 \text{ Torr @ } 293 \text{ K})$

Beam-current neutralization:

$\tau_m = \pi \sigma r_b^2 / c^2$: Magnetic diffusion time

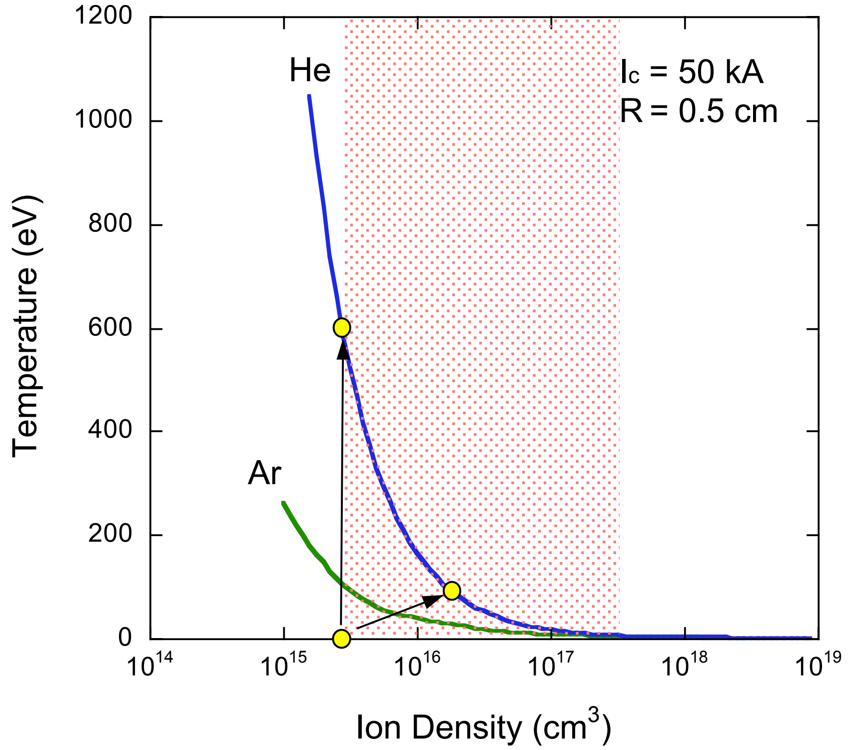
$$I_{net} = \frac{\tau}{\tau_m} I_b << I_d \Leftrightarrow \sigma >> \frac{\tau c^2 I_b}{\pi r_b^2 I_d} \approx 1 \times 10^{15} [\text{s}^{-1}]$$

$$\underline{T_e \geq 20Z - 100Z [\text{eV}]}$$

Lighter atoms seems to be suitable for background gas from a viewpoint of beam neutralization.

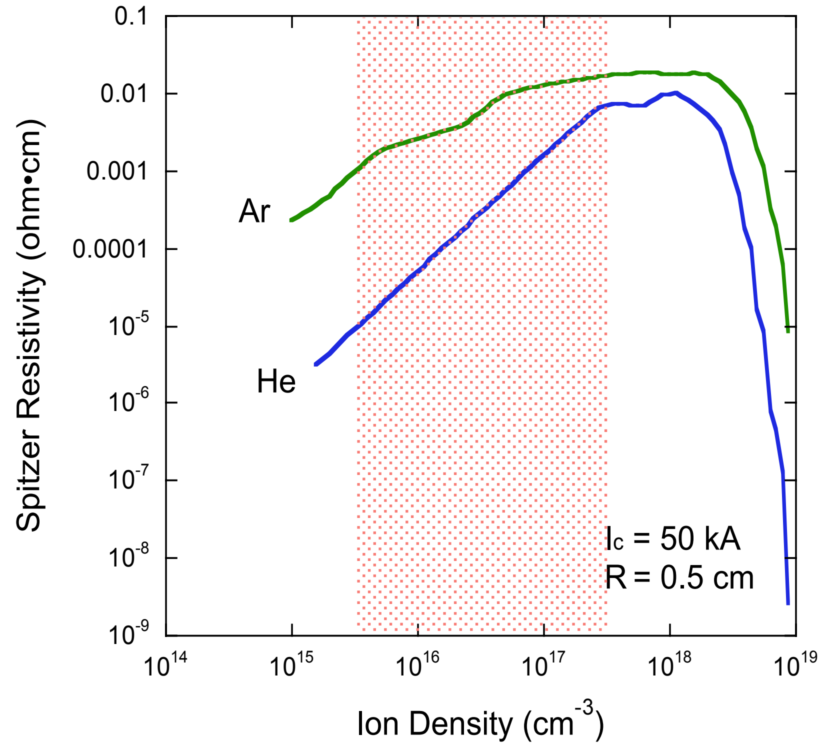
Bennett relation:

$$\frac{B^2}{2\mu_0} = (1+Z)nkT$$

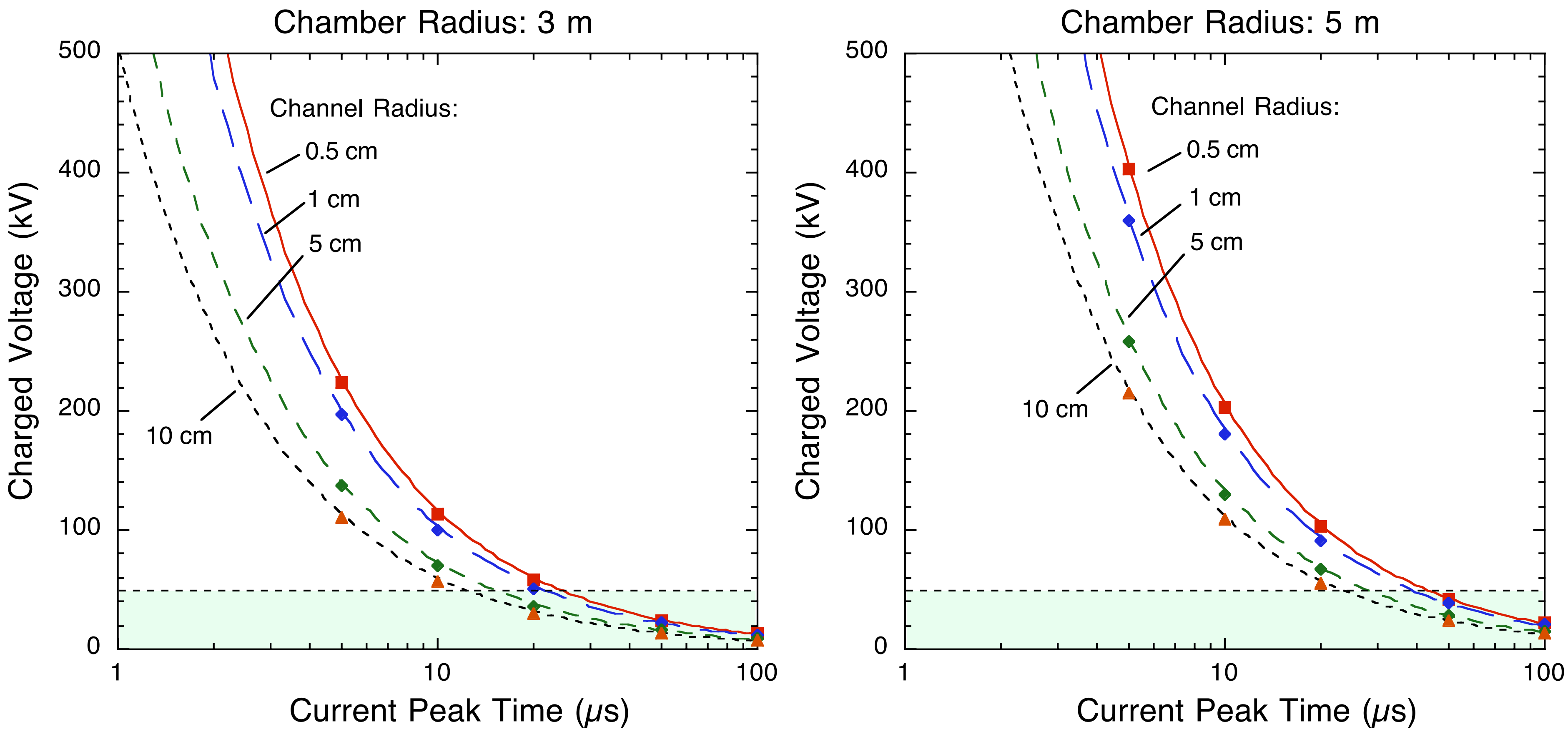


Spitzer resistivity:

$$\eta = 5.2\times10^{-3}\,\frac{Z\ln\Lambda}{T^{3/2}(\mathrm{eV})}(\Omega\cdot\mathrm{cm})$$



Large inductance of plasma channels requires high discharge voltage to achieve fast current rise times of ~50kA/μs.



Rise time of main discharge current must be longer than at least 10 μs to avoid unwanted breakdown in the reactor chamber.

Plasma pinch time was estimated using a snowplow model and set to be equal to current rise time to obtain relatively constant focusing fields.

Equation of motion:

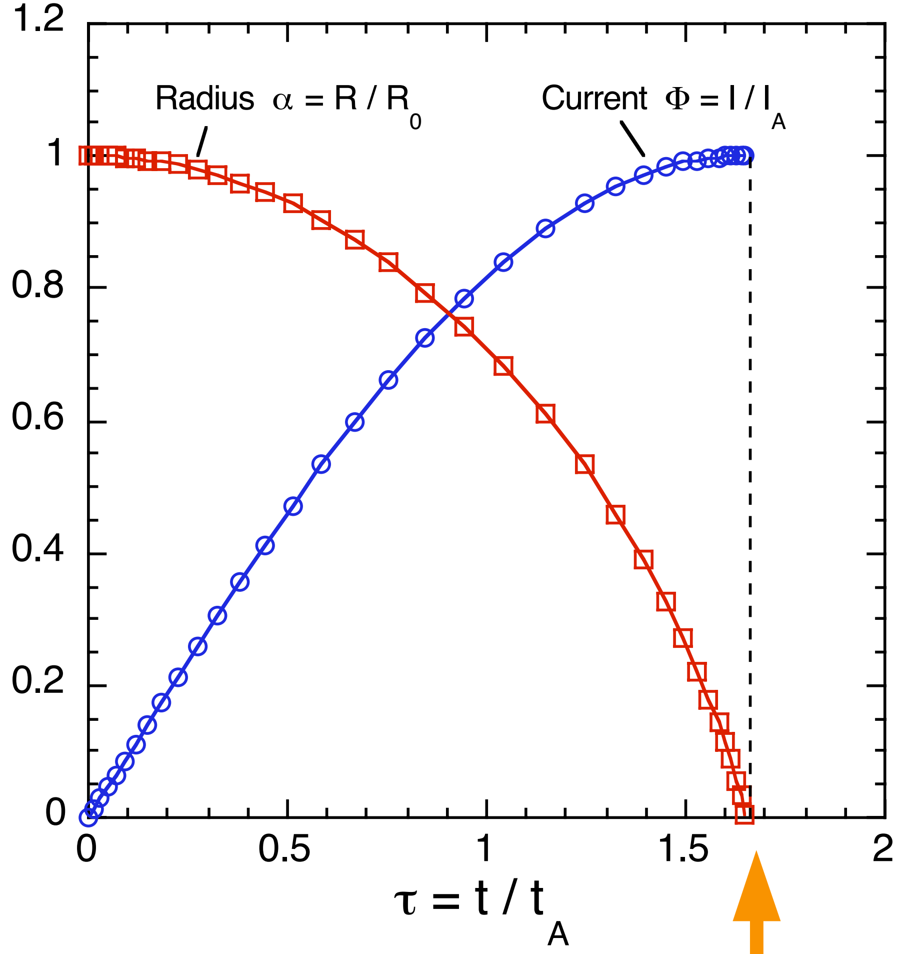
$$\frac{d}{d\tau}\left[(1-\mu\alpha^2)\frac{d\alpha}{d\tau}\right] = -\frac{\Phi^2}{\alpha}$$

$$\alpha(t) = R(t)/R_0, \tau = t/t_A, \mu = \frac{M}{M_s + M}$$

$$t_A = \frac{R_0}{v_A} = \frac{2\pi R_0}{I_{\max}}\left(\frac{\overline{\rho}}{\mu_0}\right)^{0.5}$$: Alfvén transit time

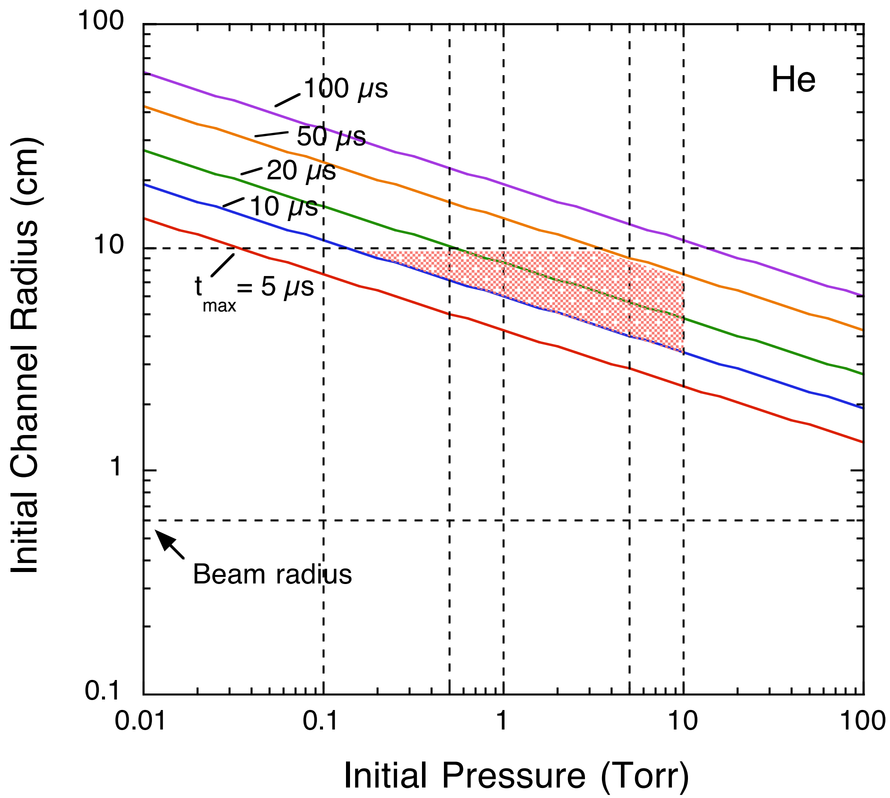
$$\Phi = \frac{I(\tau)}{I_{\max}} = \sin(\omega\tau)$$: Current waveform

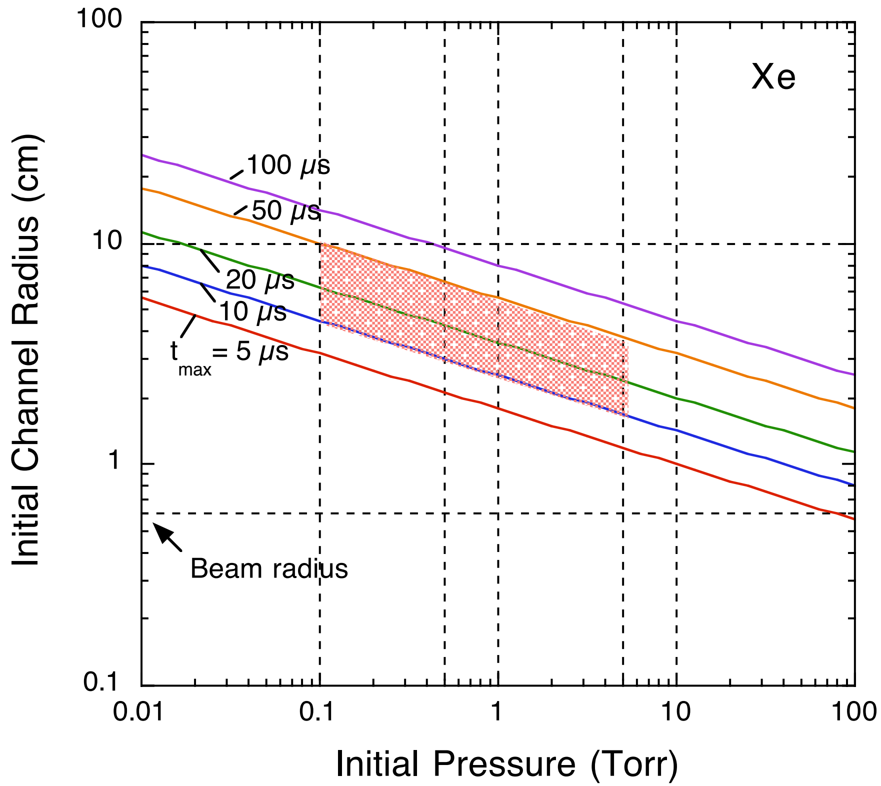
ω was chosen for $t_{\max} = t_{\text{pinch}}$



$t_{\text{pinch}} = 1.65 t_A$

Initial channel radiuses are determined by current rise times to obtain the maximum current at plasma pinch time.





$0.1\ \mathrm{Torr} \le p_0 \le 10\ \mathrm{Torr}$

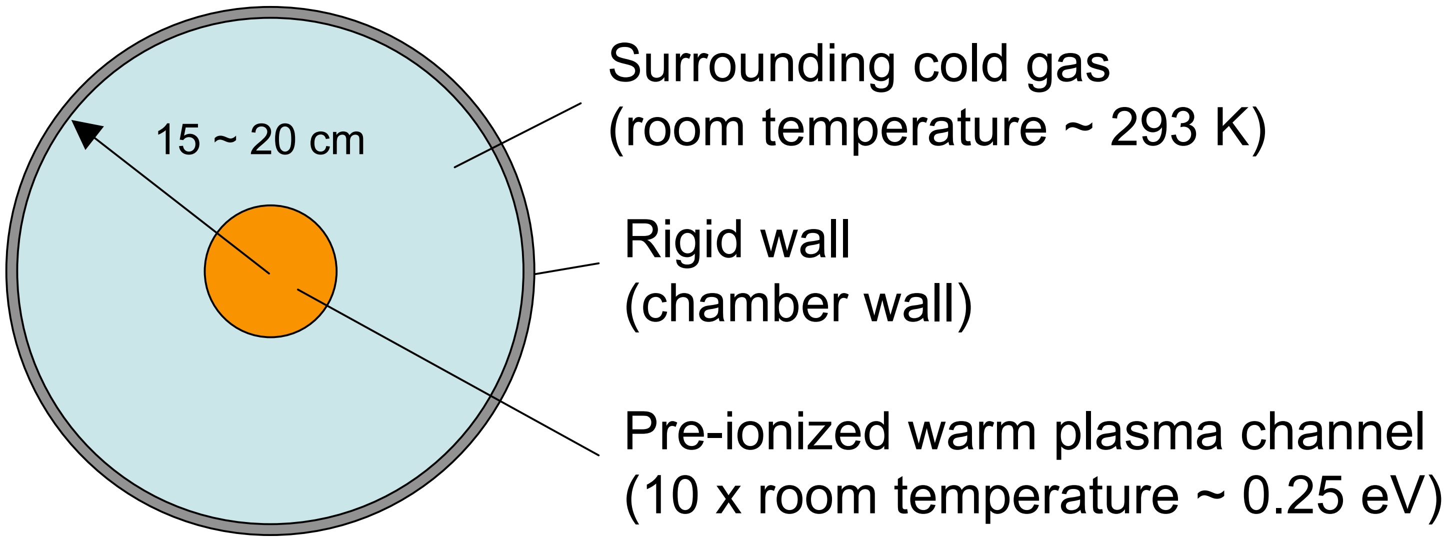
$0.5\ \mathrm{cm} \le R_0 \le 10\ \mathrm{cm}$

$10\ \mu s \le t_{max} \le 50\ \mu s$

A simulation model of plasma channels; pre-ionized warm plasma channels are surrounded by cold dense gas.

1D-MHD code MULTI-Z :

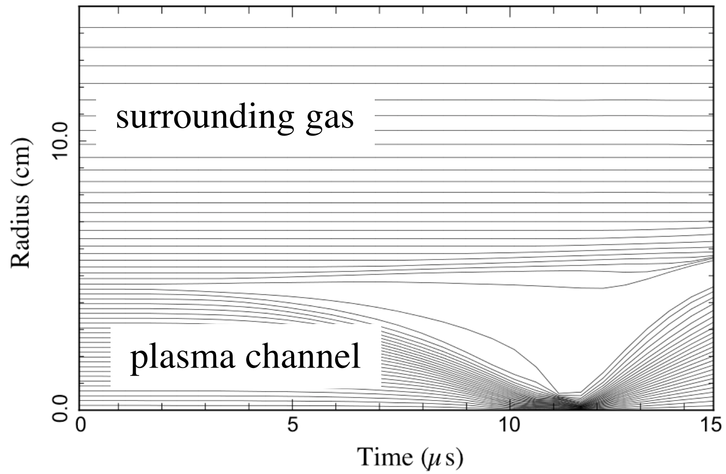
- One-fluid, two temperature model
- Radiation transport
- Sesame library for equation of state, opacity, mean ion charge

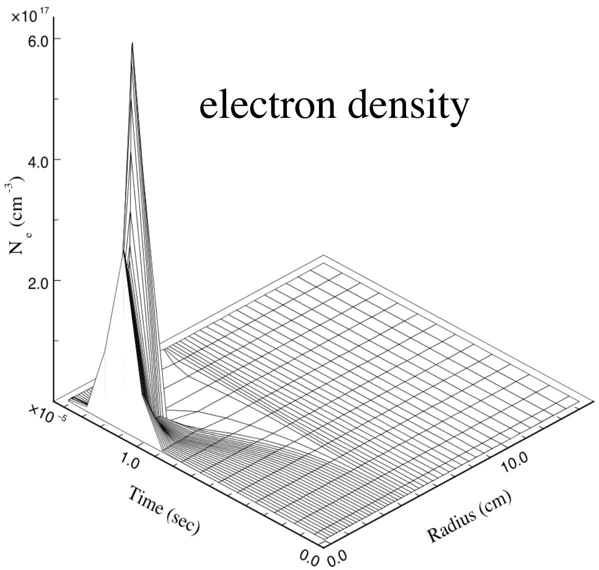


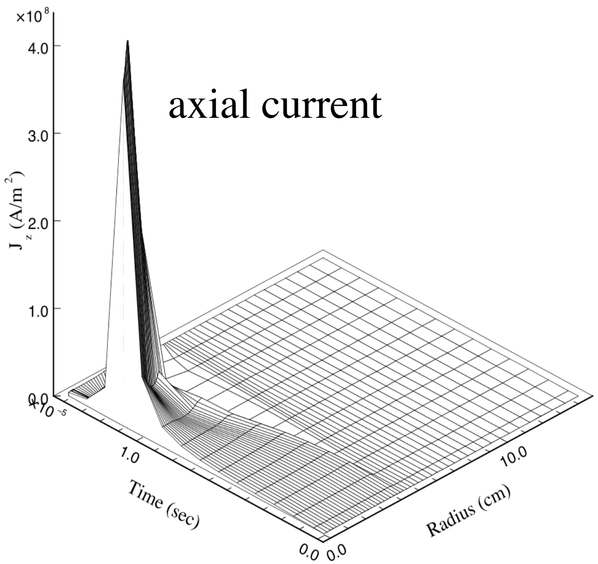
Initial density ratio between plasma channel and surrounding cold gas was set to 1 : 10.

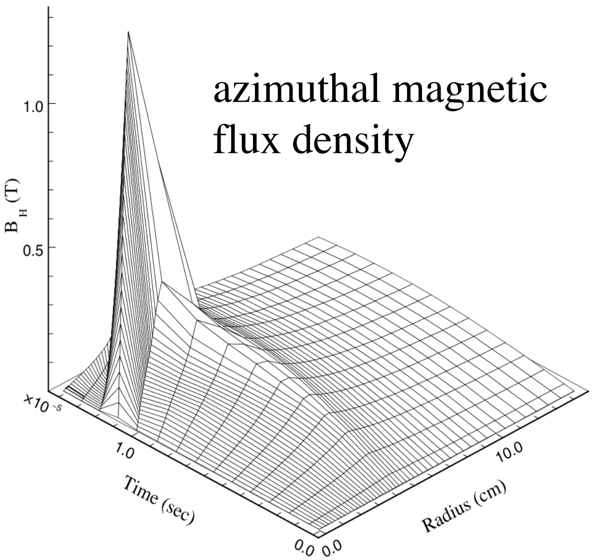
A typical result from MULTI-Z

Input parameters
Background gas: Xe
Initial Pressure : 0.1 Torr
Initial radius : 4.5 cm
Peak current : 50 kA at 10 μs



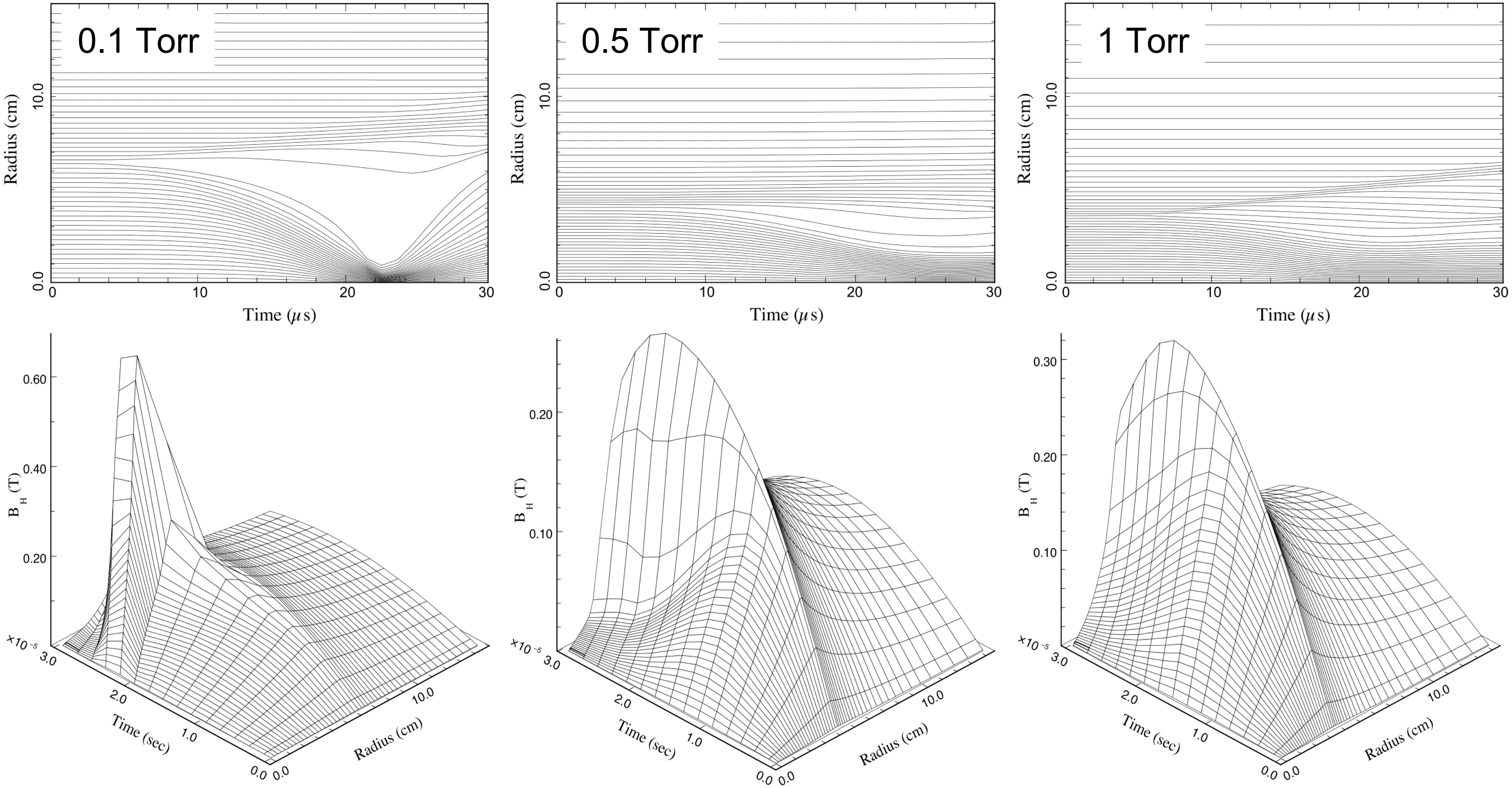






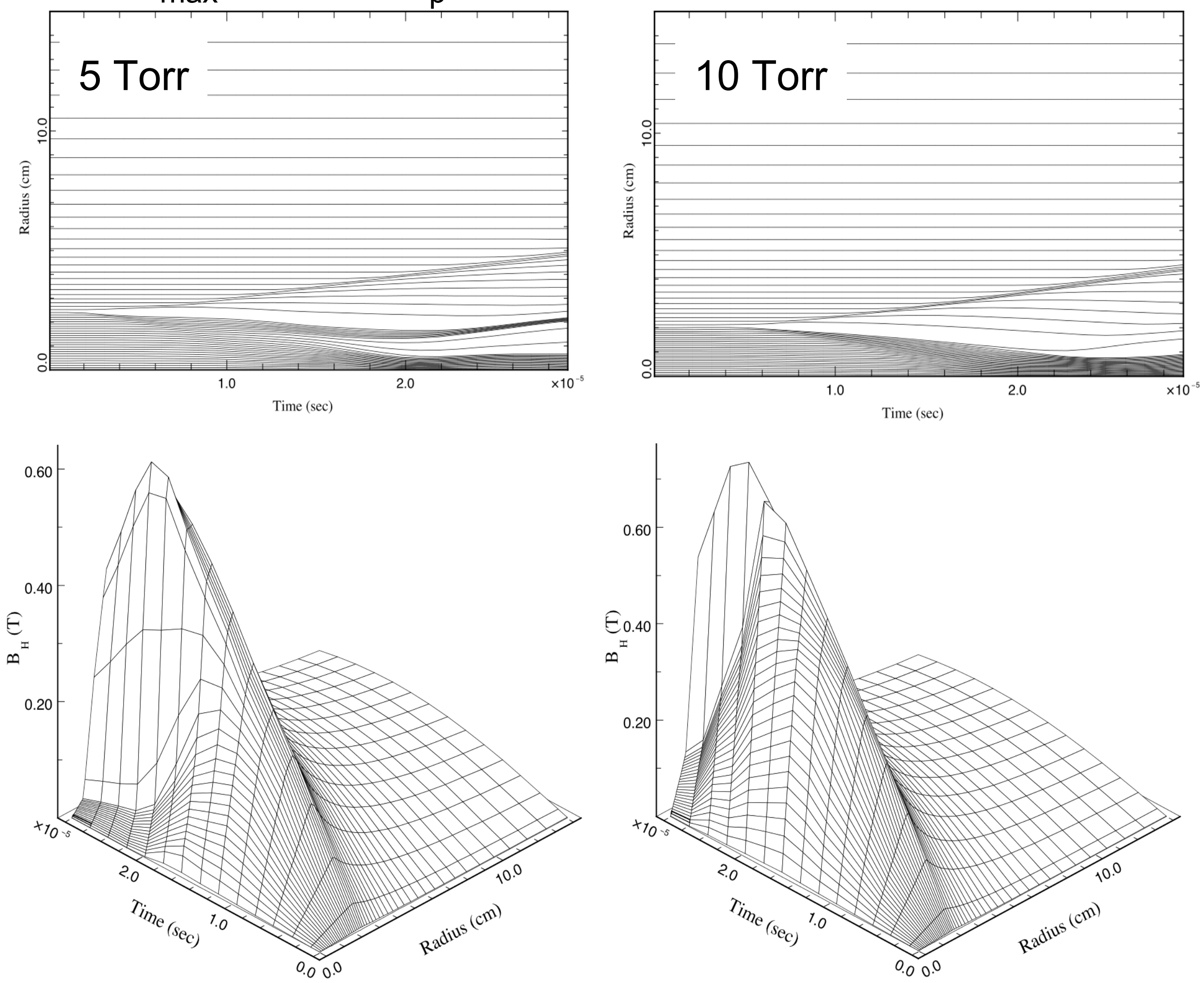
Dependence of magnetic field on initial background gas pressure.

Xe, I_{max} = 50 kA, t_{max} = 20 μs



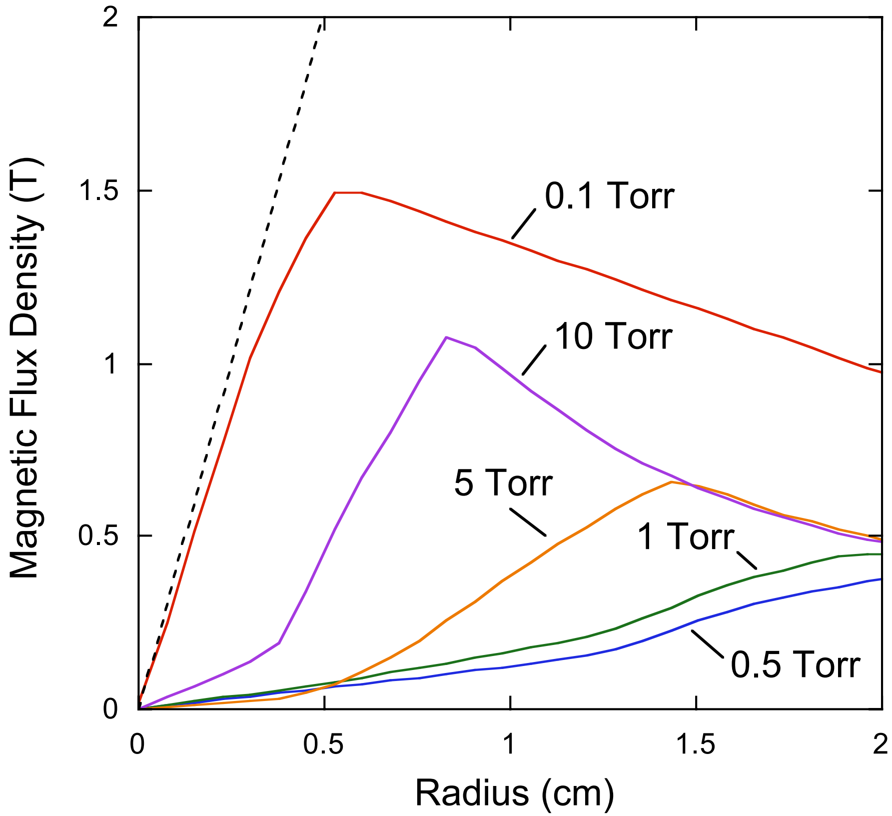
Dependence of magnetic field on initial background gas pressure. (continue)

Xe, I_{max} = 50 kA, t_p = 20 μs

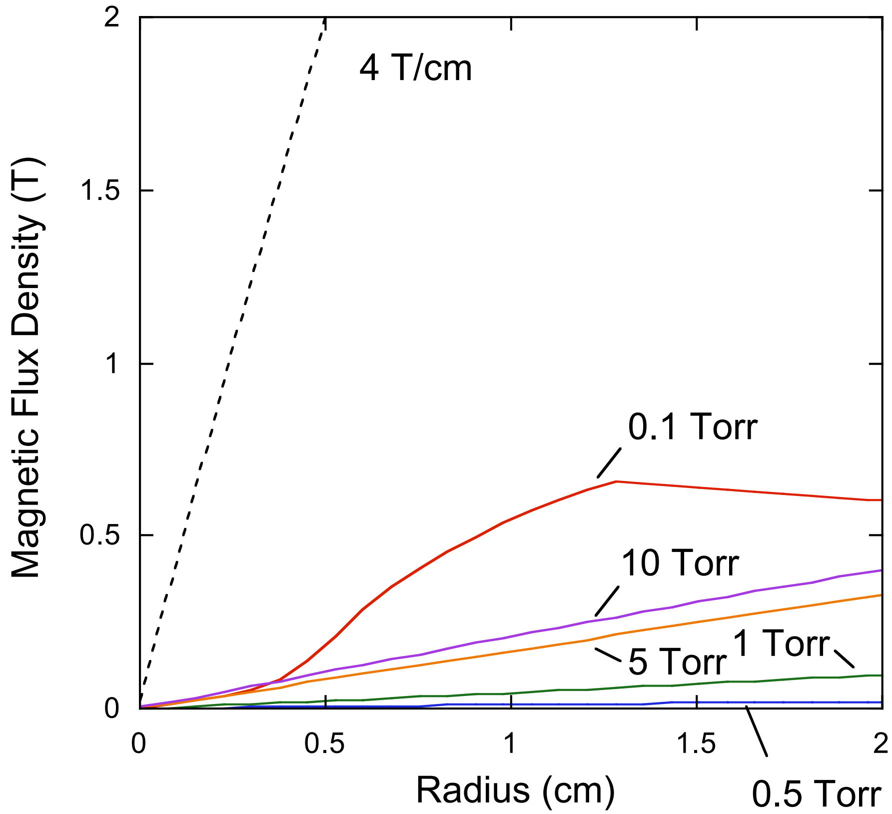


Dependence of magnetic field distribution on initial background gas pressure;

Xe, t_{max} = 10 μs

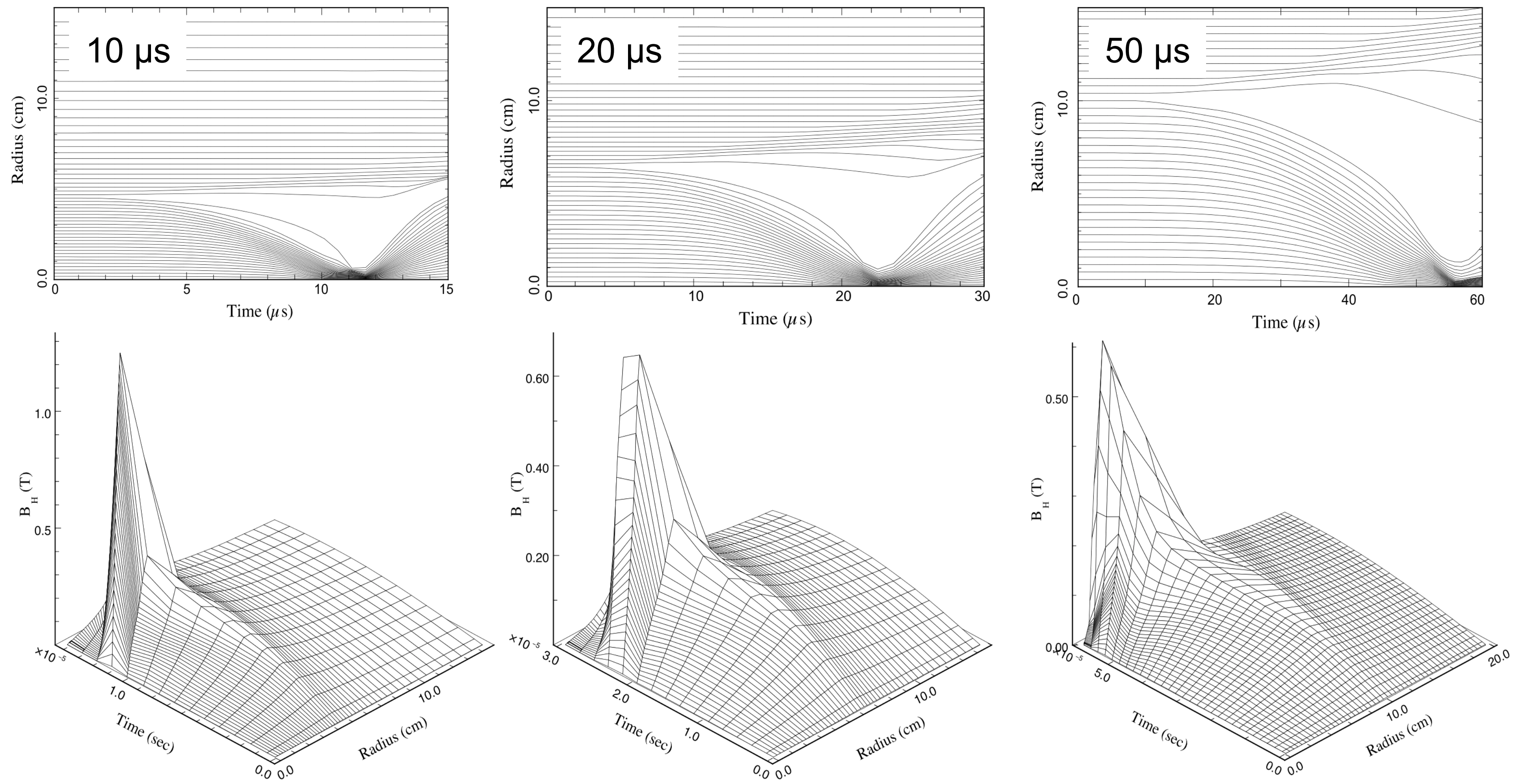


Xe, t_{max} = 50 μs

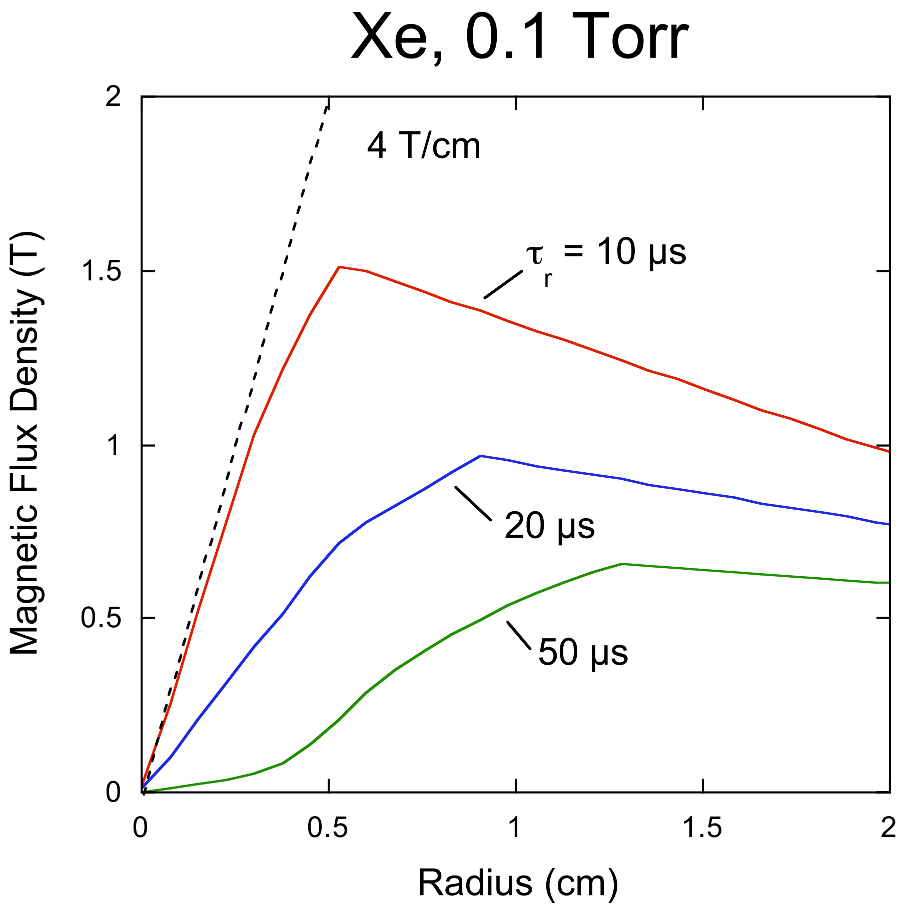


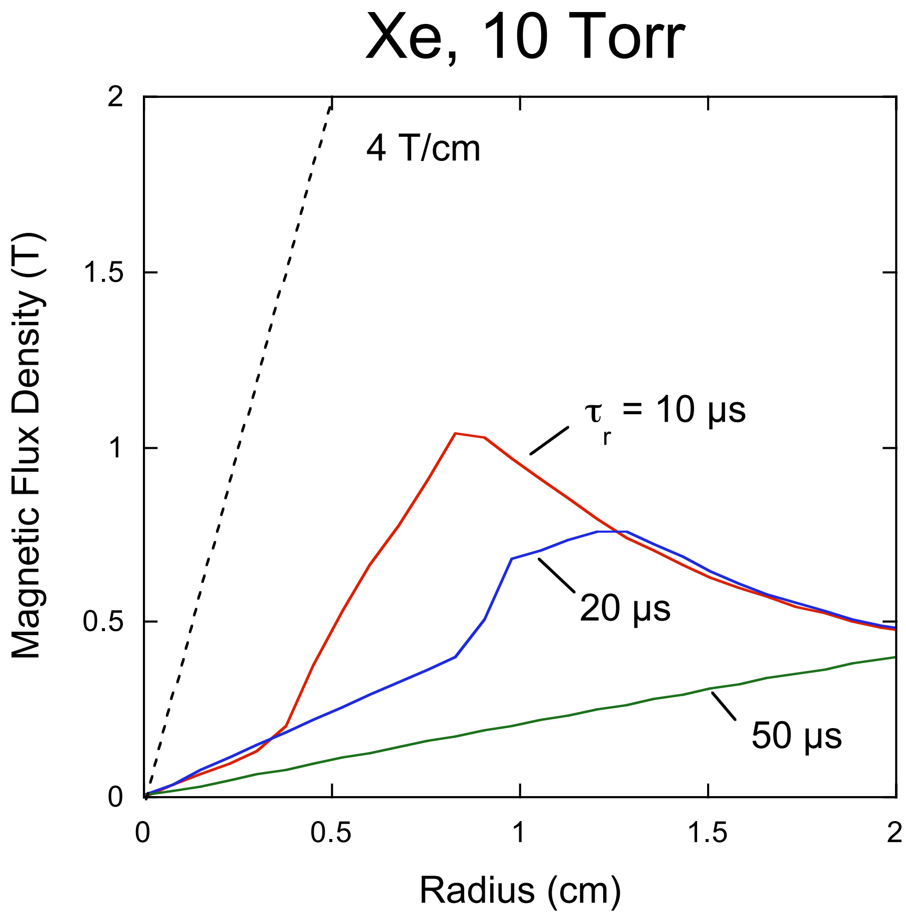
Dependence of magnetic field on current rise time; the field strength decreases with increasing current rise time.

Xe, I_{max} = 50 kA, P_0 = 0.1 Torr



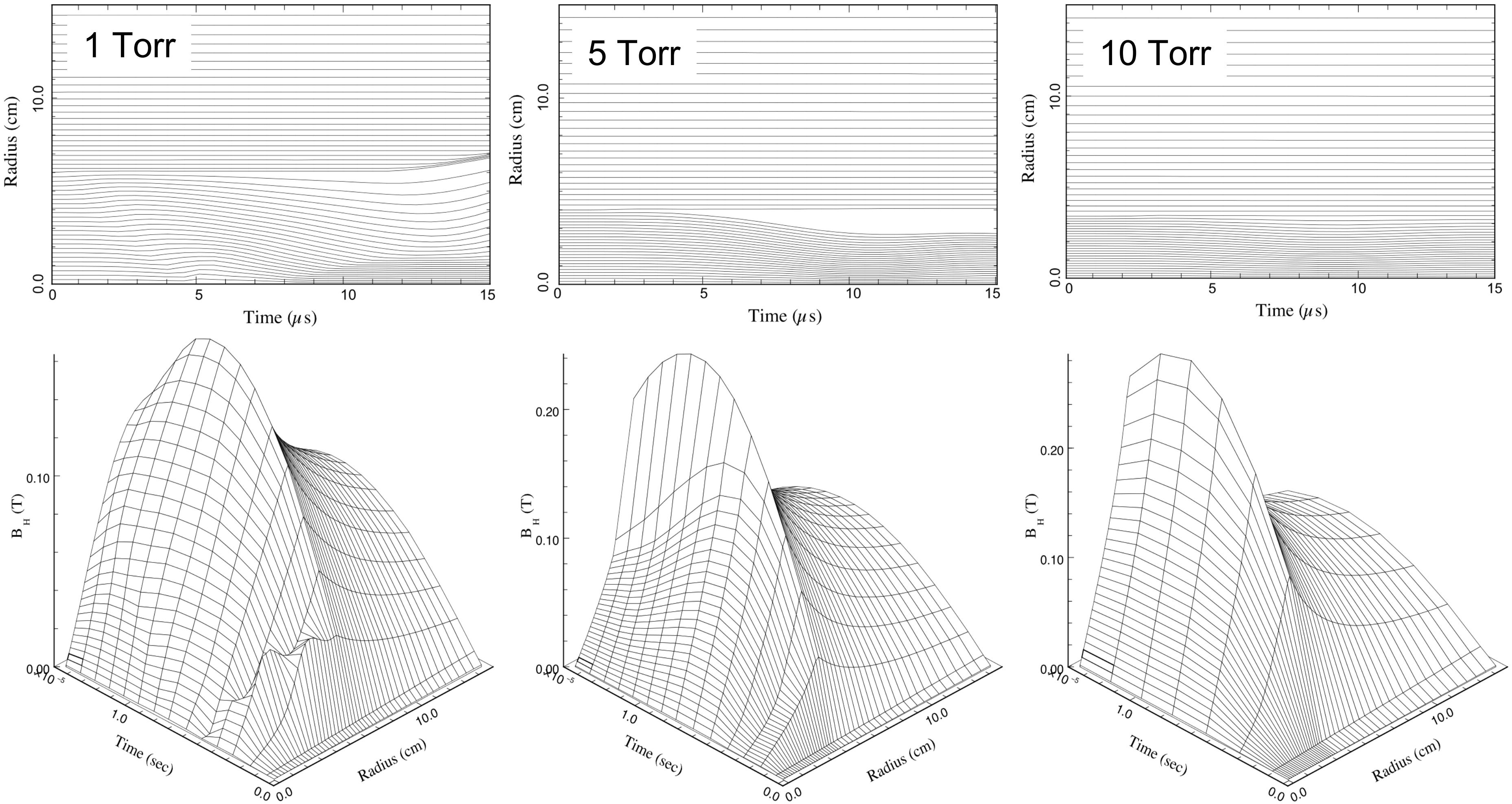
Dependence of magnetic field distribution on discharge current rise time; Faster rise time resulted in stronger magnetic focusing fields.



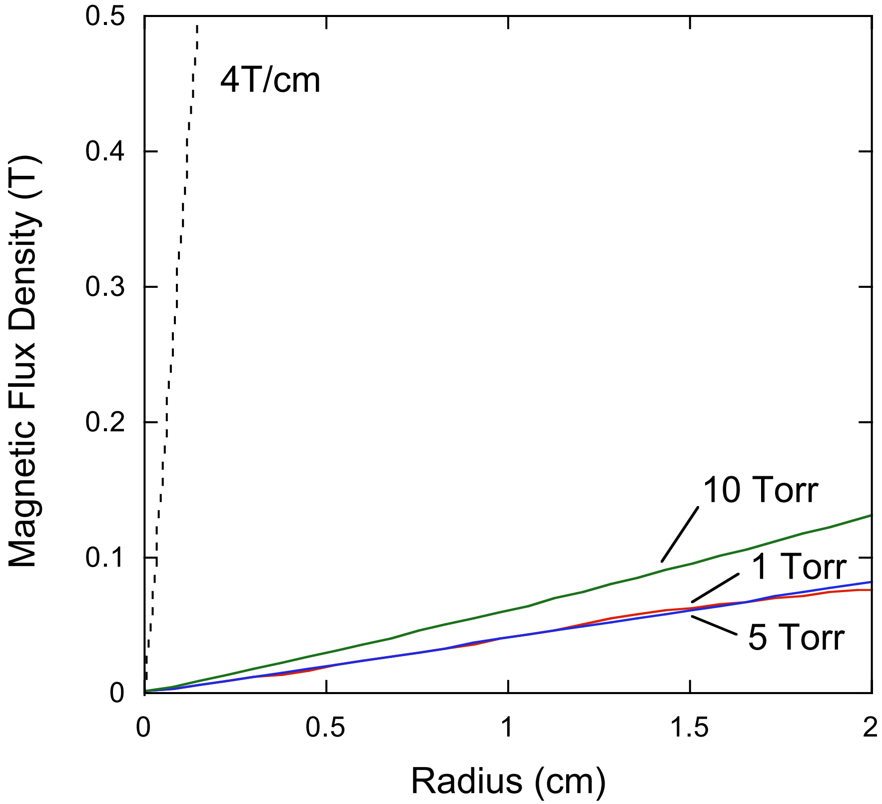


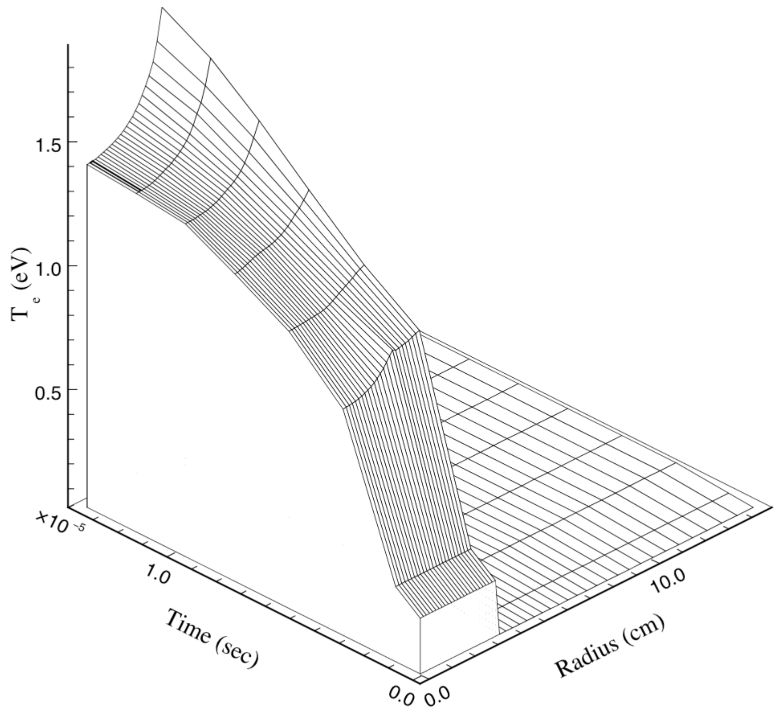
No strong pinch was observed in helium plasma channels because of a rapid increase in pressure due to ohmic heating.

He, I_{max} = 50 kA, t_{max} = 10 μs

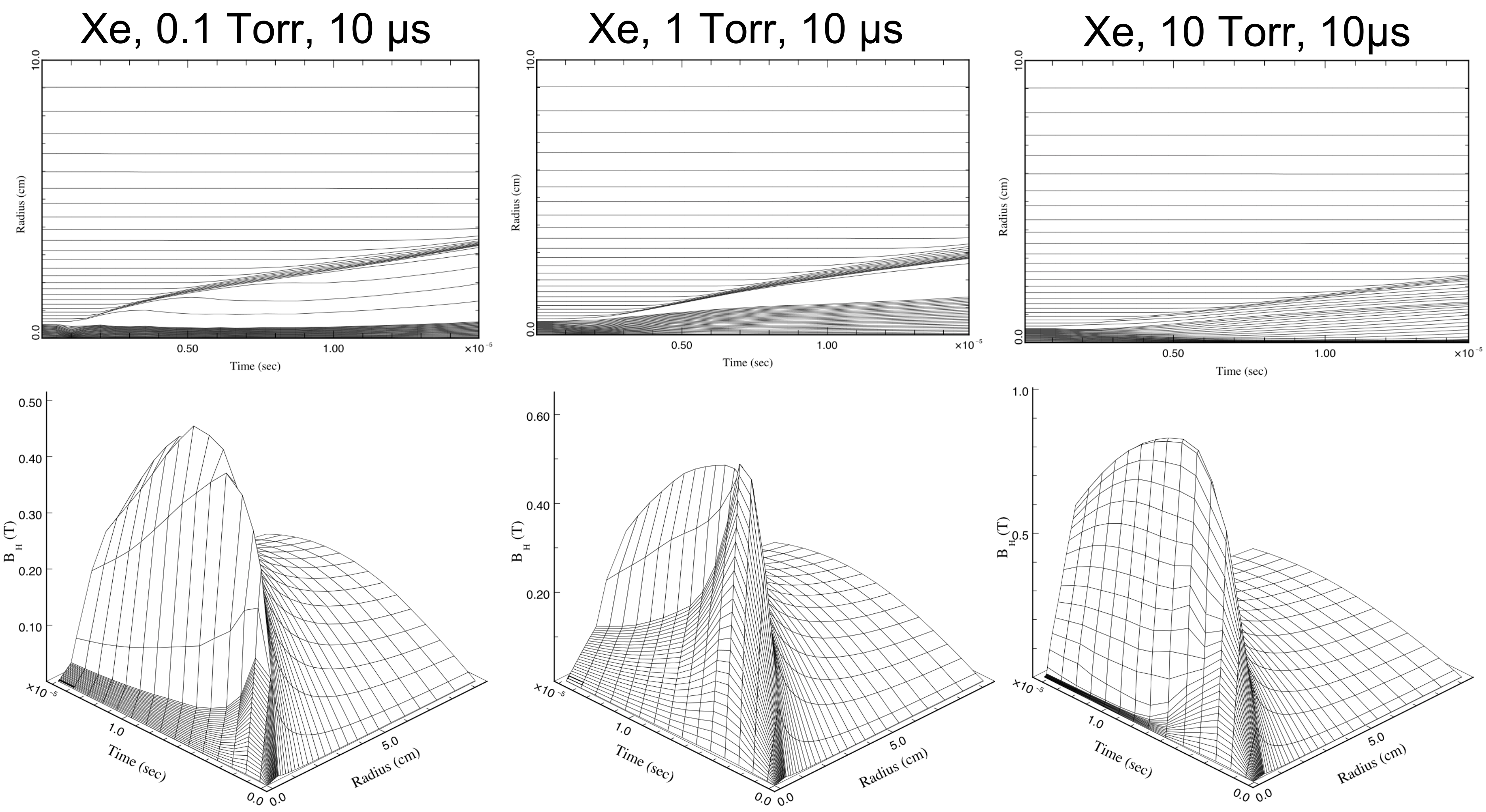


Helium channels could not produce enough focusing field. Plasma temperature was much lower than expected.

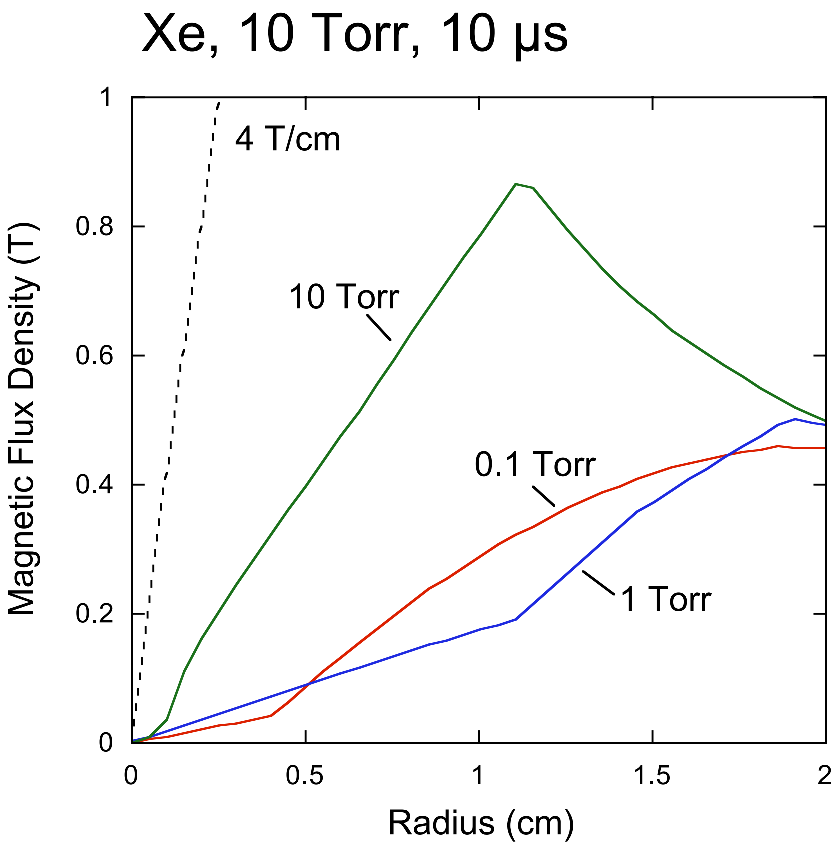


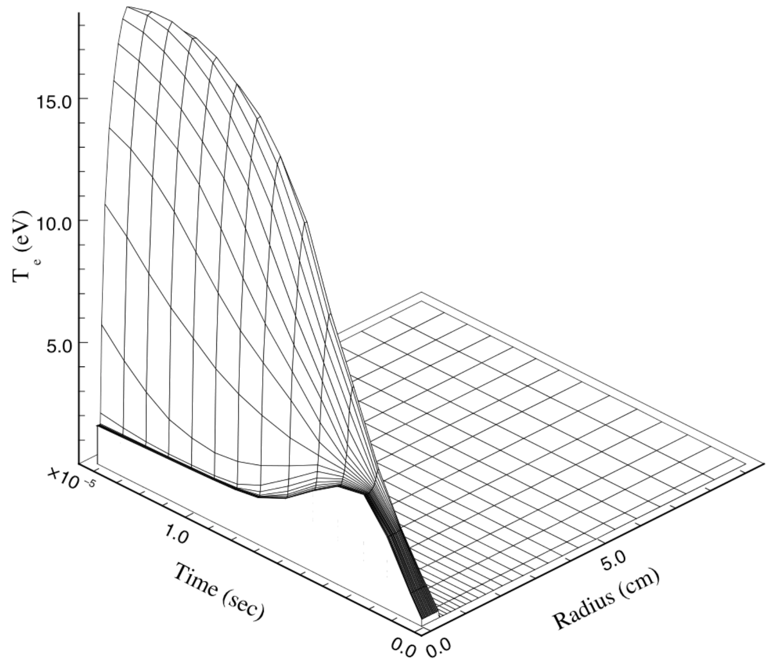


Non-pinch discharges starting with small initial radius of plasma column produced quasi-stable magnetic field.



Relatively strong field was obtained at higher background pressure. Higher plasma temperature was obtained, but only in the surface of the hot plasma channel.





Summary

- We examined operative ranges of xenon and helium plasma discharges in a fusion reactor by simple numerical methods.

- Helium plasma was suitable from a viewpoint of beam neutralization. However, helium plasma channels could not be imploded with long current rise times above 10 μs.

- By using a strong z-pinch, high magnetic focusing fields were available particularly at low background pressure. But, the time scale of the change in the plasma parameters was relatively short, which may be harmful for beam transportation.

- Discharges with initial high-current densities (small initial channel radius ~ 0.5 cm) also made strong and relatively stable focusing fields. This discharge mode could be second option for plasma channel.