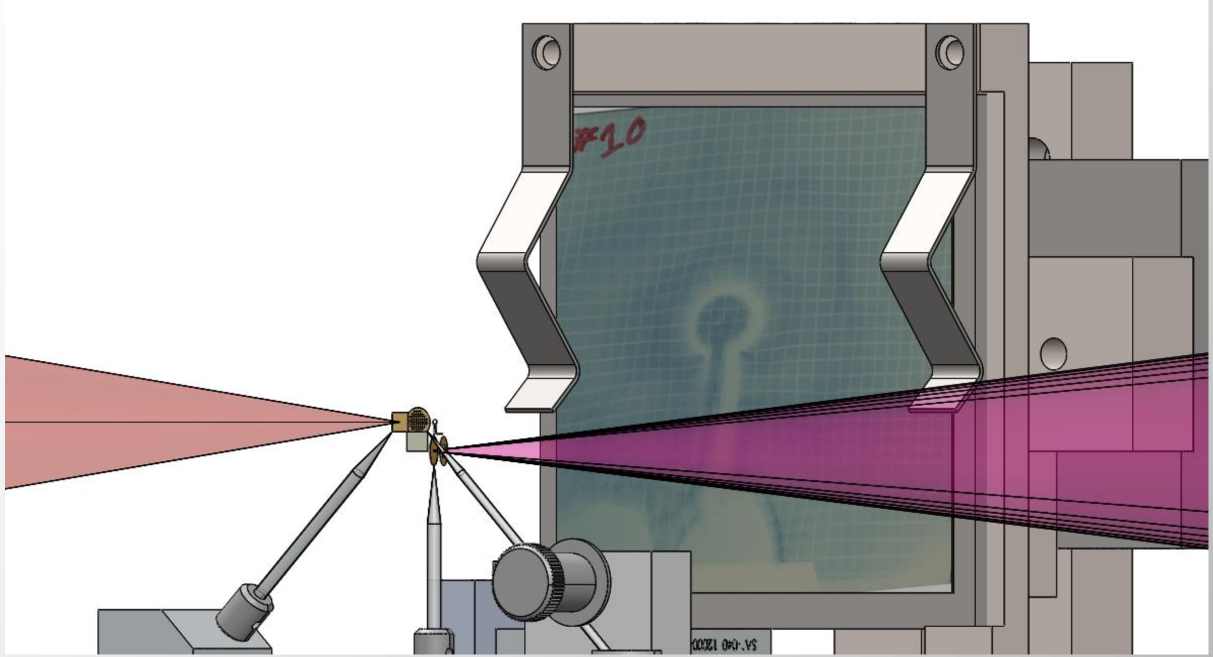
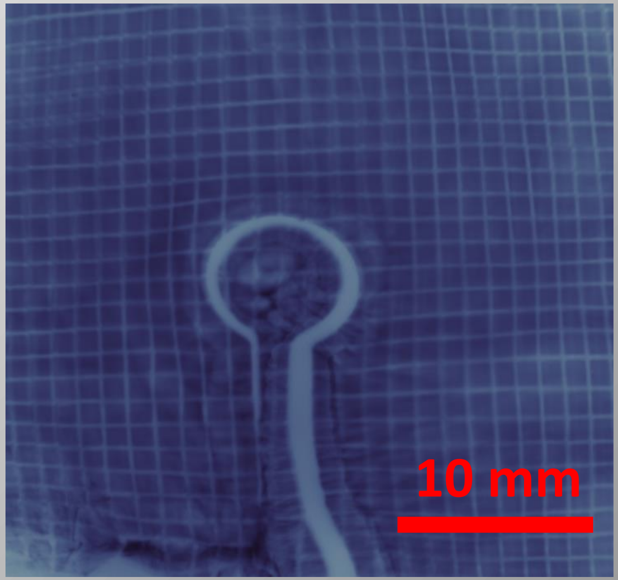
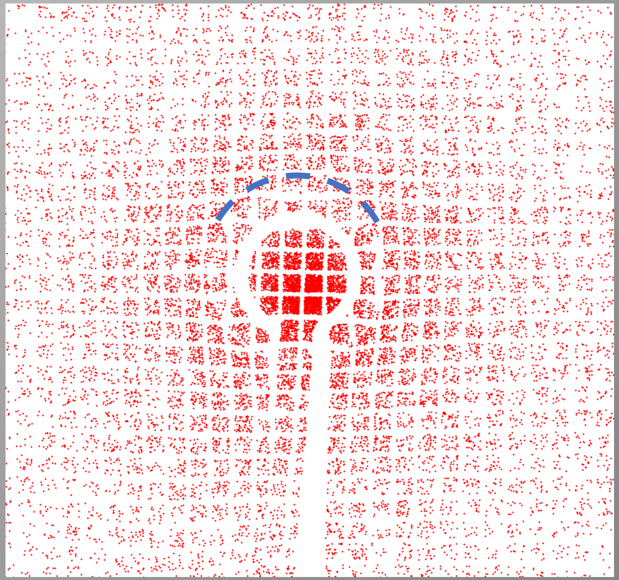
Laser-driven quasi-static magnetic fields for magnetized high energy-density experiments







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ECLIM 2022

September 21 – Frascati, Italy

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- L. Gremillet

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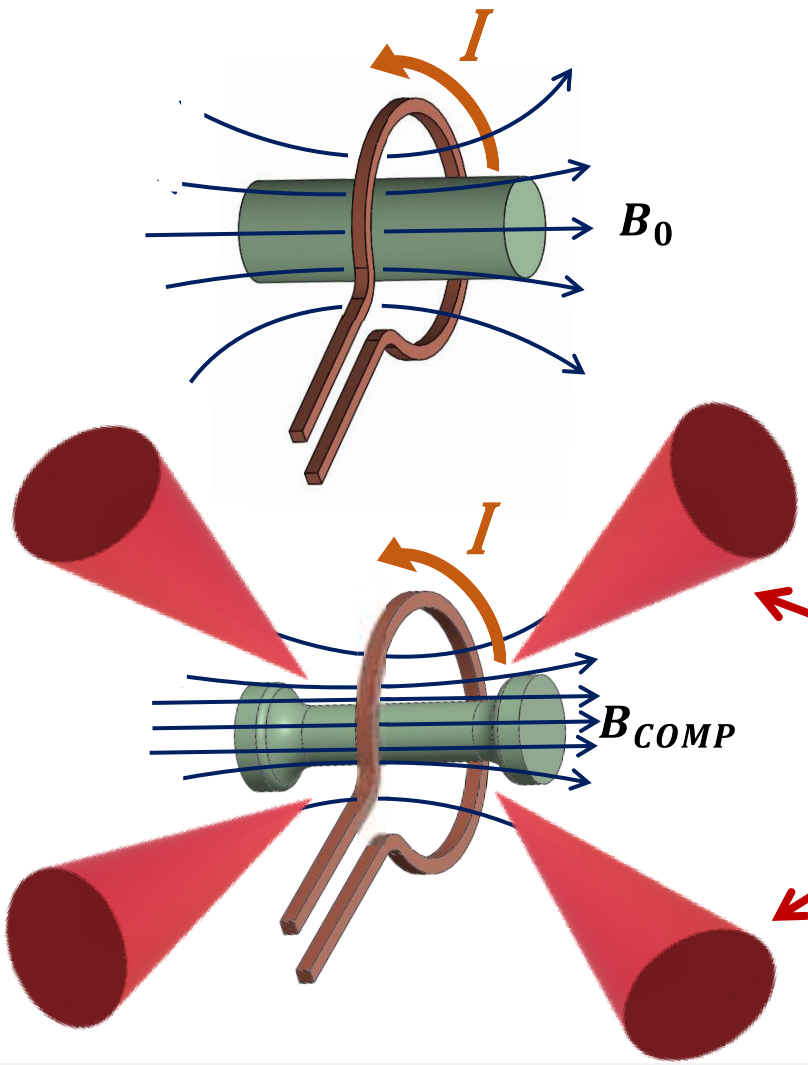
Magnetized implosions

In-flow B-field compression



Laser beams for implosion

1) Soaking of seed B-field into the target

2) B-field amplified by advection with the imploding target

$$\frac{\partial \vec{B}}{\partial t} \approx \frac{\eta}{\mu_0} \Delta \vec{B} + \vec{\nabla} \times \left(\vec{u} \times \vec{B}\right)$$

Magnetic Reynolds number

$$R_m = \frac{\tau_d}{\tau_i}$$

Magnetic diffusion time

$$\tau_d = \mu_0 R_0^2 / \eta$$

Implosion time

$$\tau_i = R_0 / v_{imp}$$

$R_m \sim 200$
for LMJ drive conditions

$$\frac{B_{comp}}{B_0} = \left(\frac{R_0}{R}\right)^{2(1-1/R_m)} \rightarrow \left(\frac{R_0}{R}\right)^2$$

$B/B_0 \sim 500$ previously demonstrated at OMEGA with 15 kJ laser drive

*Hohenberger *et al.*, Phys. Plasmas **19**, 056306 (2012)

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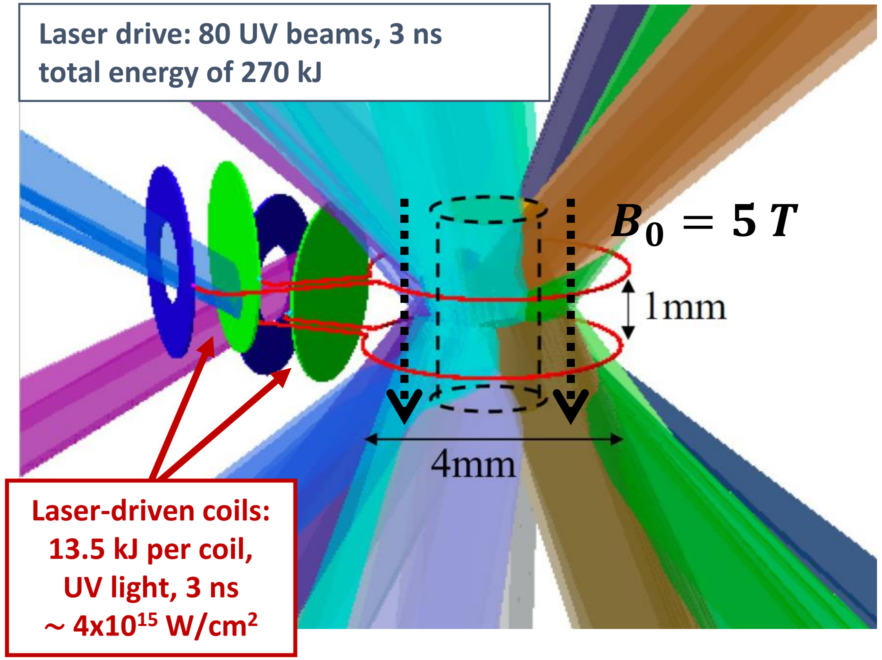
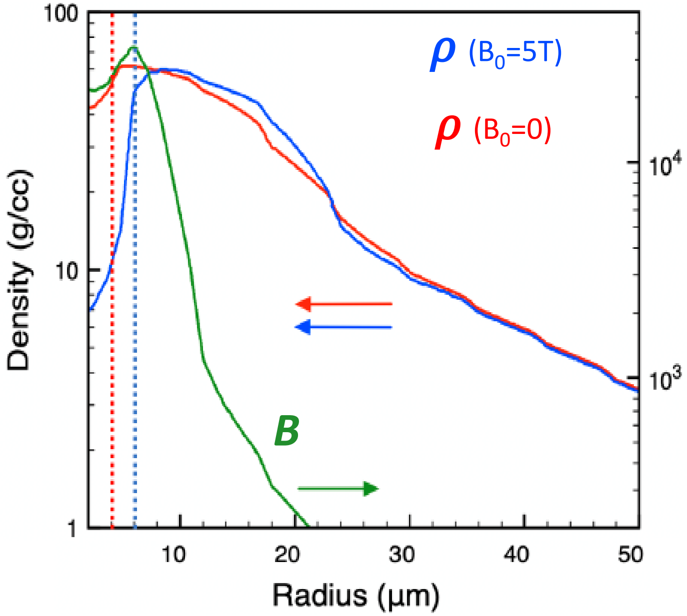
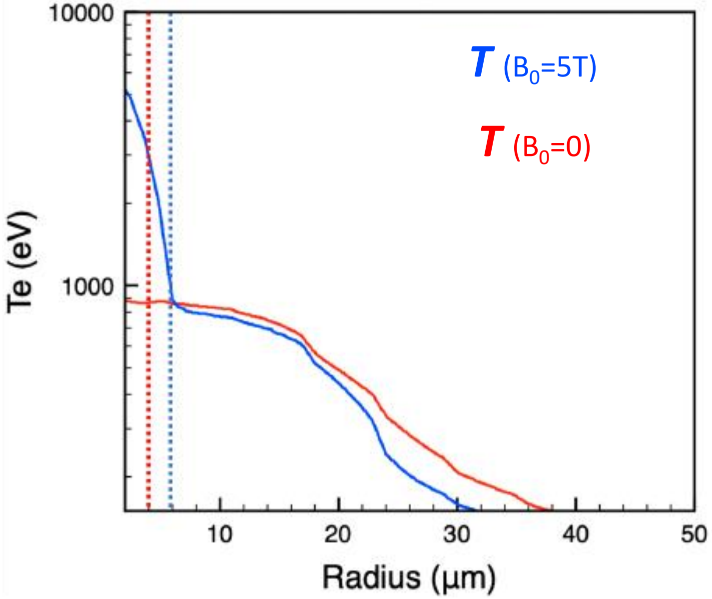
LMJ platform



Pérez-Callejo *et al.*, Phys. Rev. E **106**, 035206 (2022)

Extended-MHD (Gorgon) predictions for the stagnated plasma





- **High B-fields** (10 kT can be reached departing from a relatively low seed B-field) **grant access to an unexplored MHD regime**

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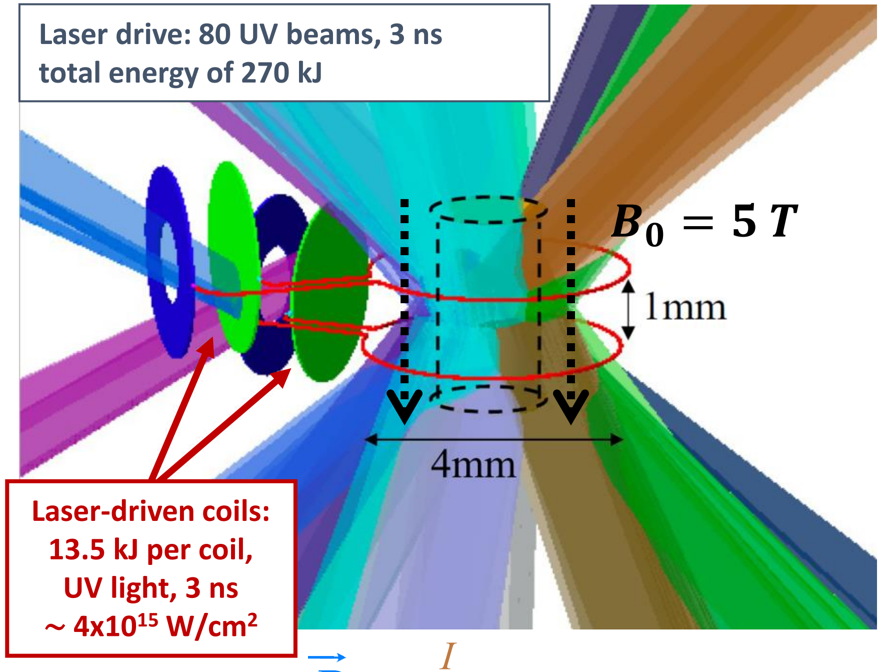
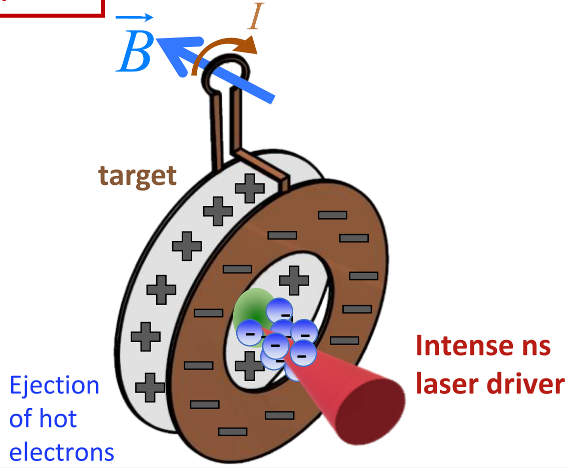
Why to use coils in the LMJ platform?





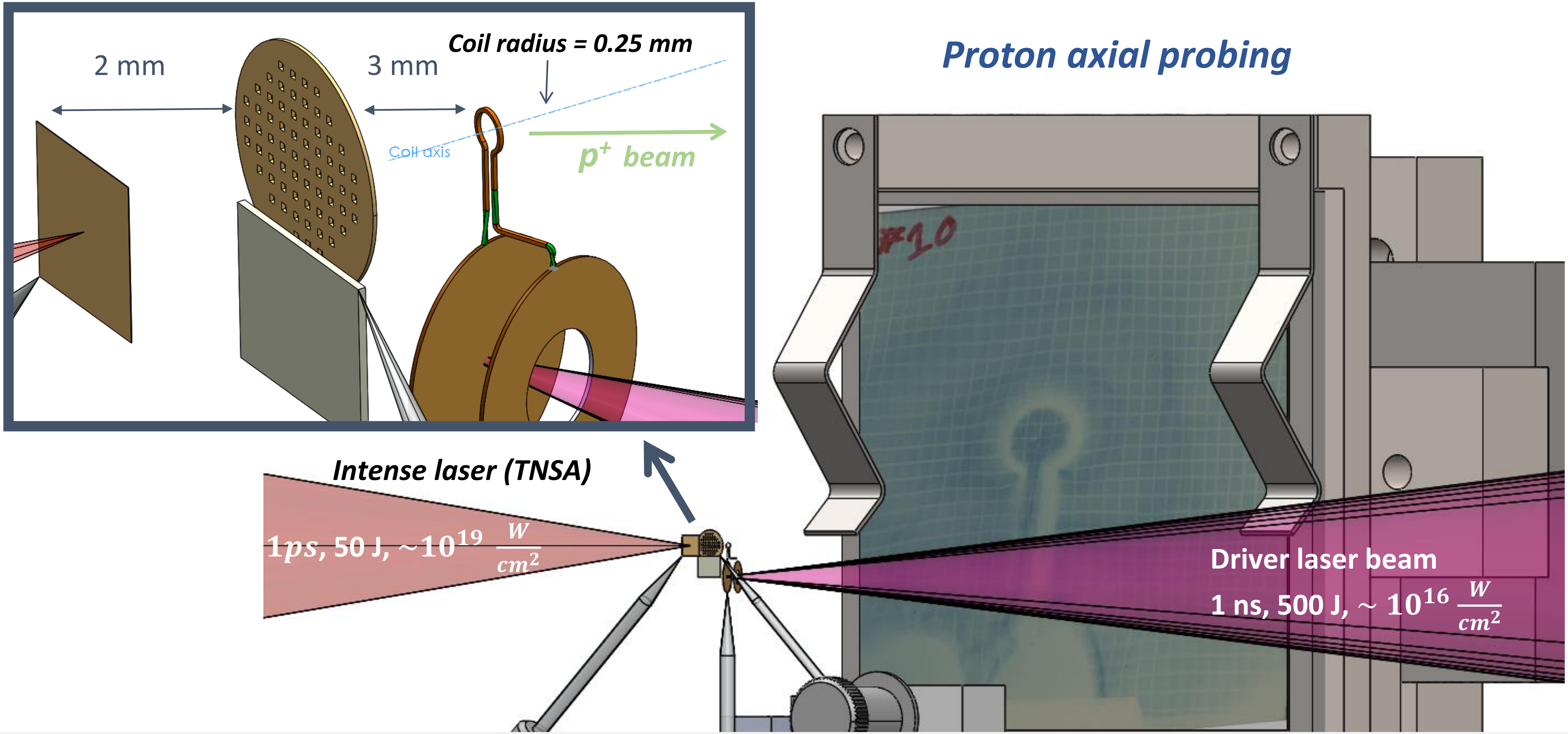
- There is not an external pulsed power coil system at present in LMJ and probably during the next 5 years
- The laser driven coils don't block the line of sight for other diagnostics of the experiment

Prediction validation:

- ➢ *Several kJ energy and 3ω light is a new regime for the laser driven coils.*
- ➢ We performed some promising first tests at LULI and Omega facilities but in general this regime is not accessible in facilities smaller than LMJ.

LDCs in 1ω light and sub-kJ energies (LULI, May 2021)

Proton axial probing



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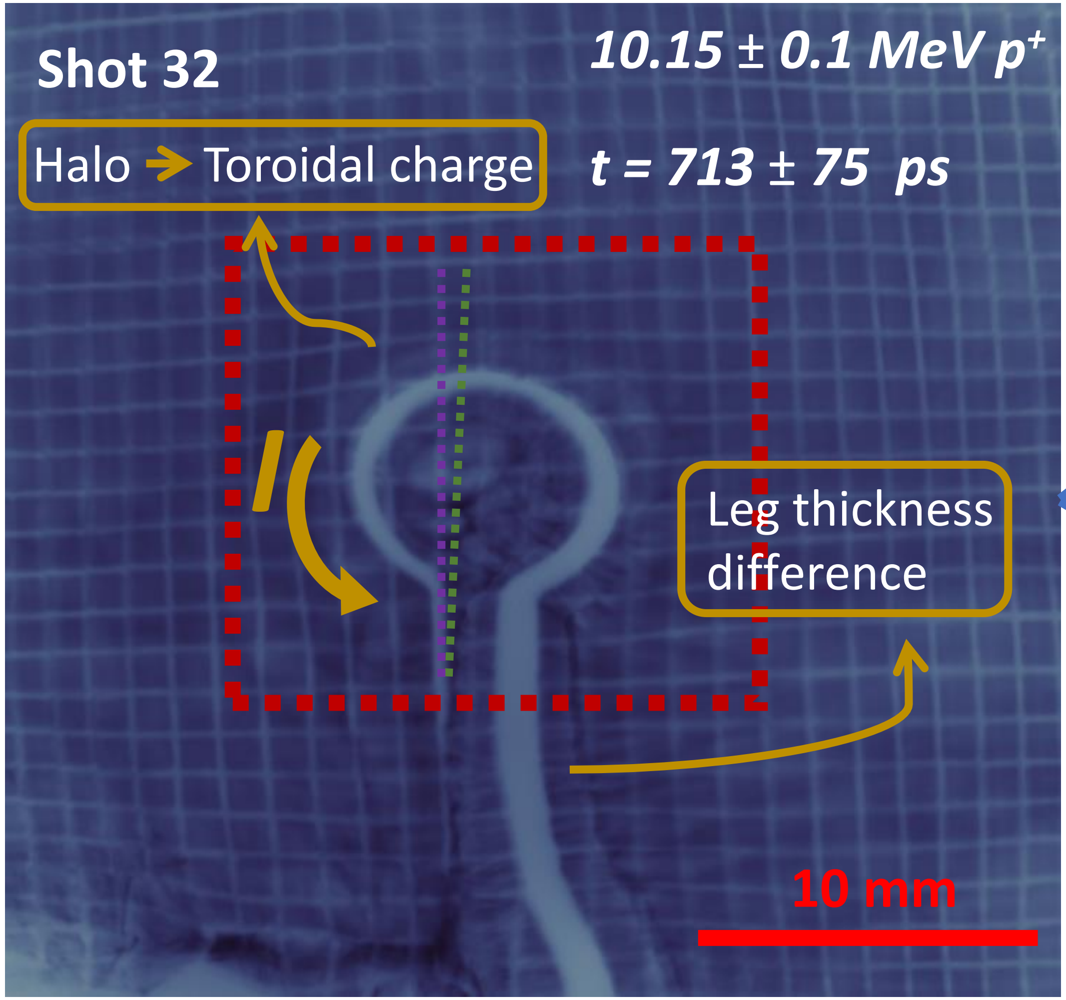
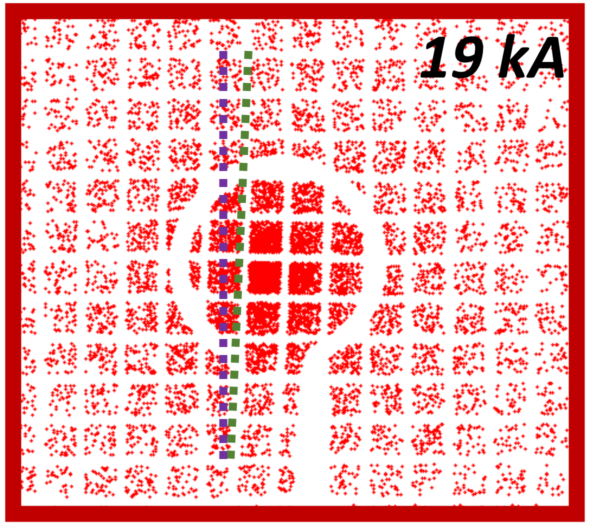
Typical results from axial proton probing

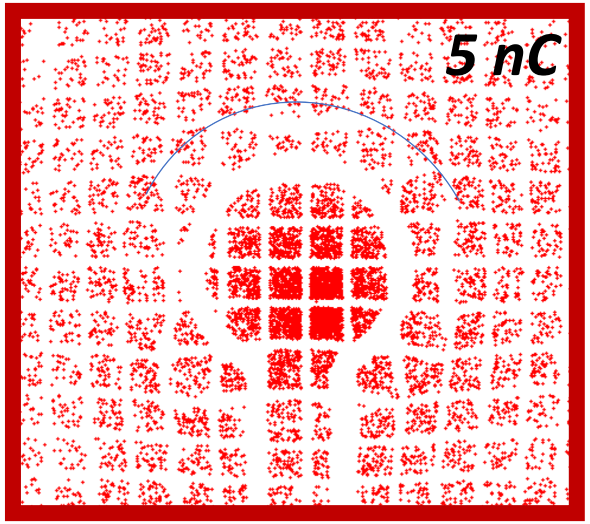


At LULI :
0.5 kJ, 1 ns IR laser at 5×10^{15} W/cm^2
L = 3.7 nH, coil radius = 250 µm

Only currents



Only static charges



PAFIN test-particle simulations *

* M. Ehret, Master Proposal, Universite de Bordeaux, 10.13140 (2015)

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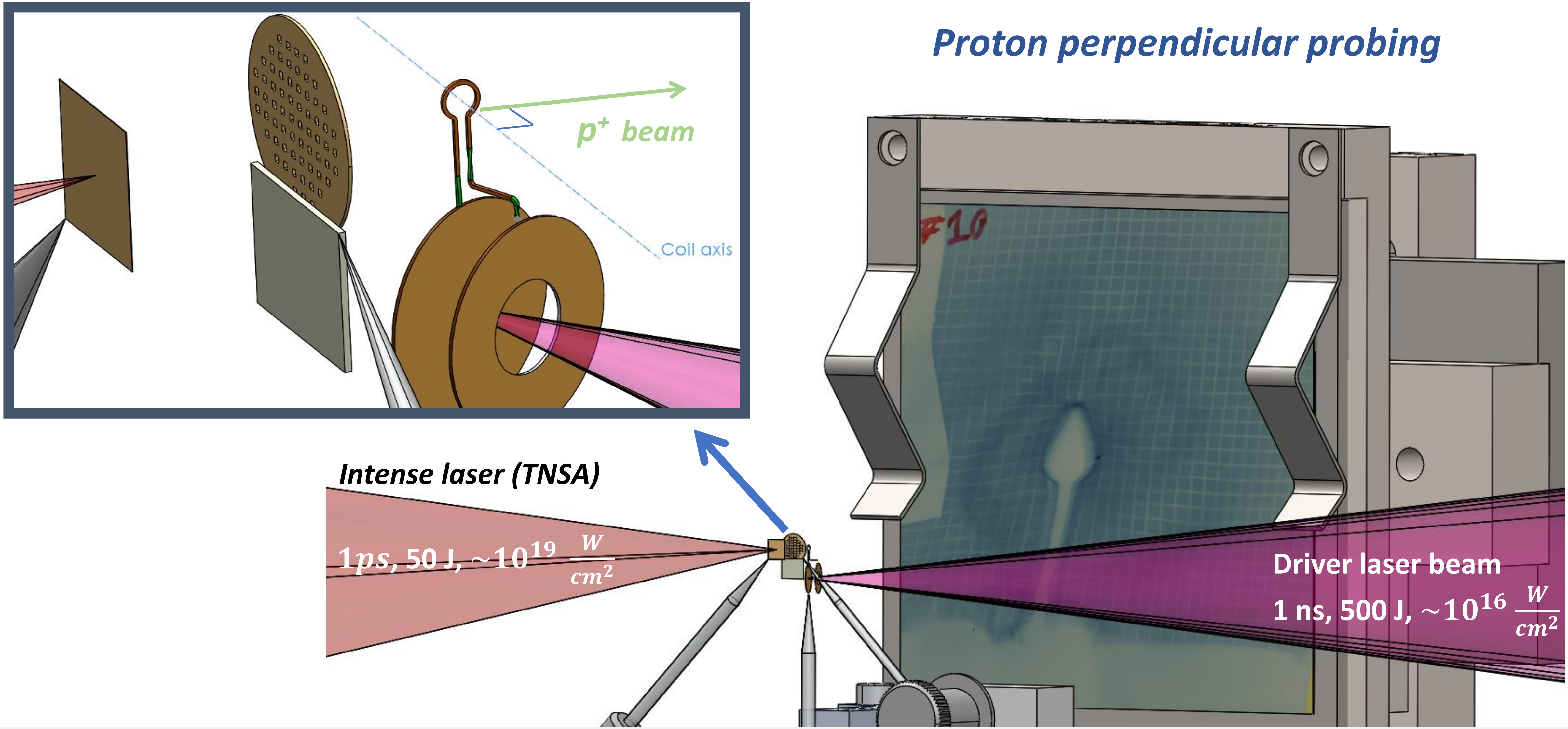
LDCs in 1ω light and sub-kJ energies (LULI, May 2021)



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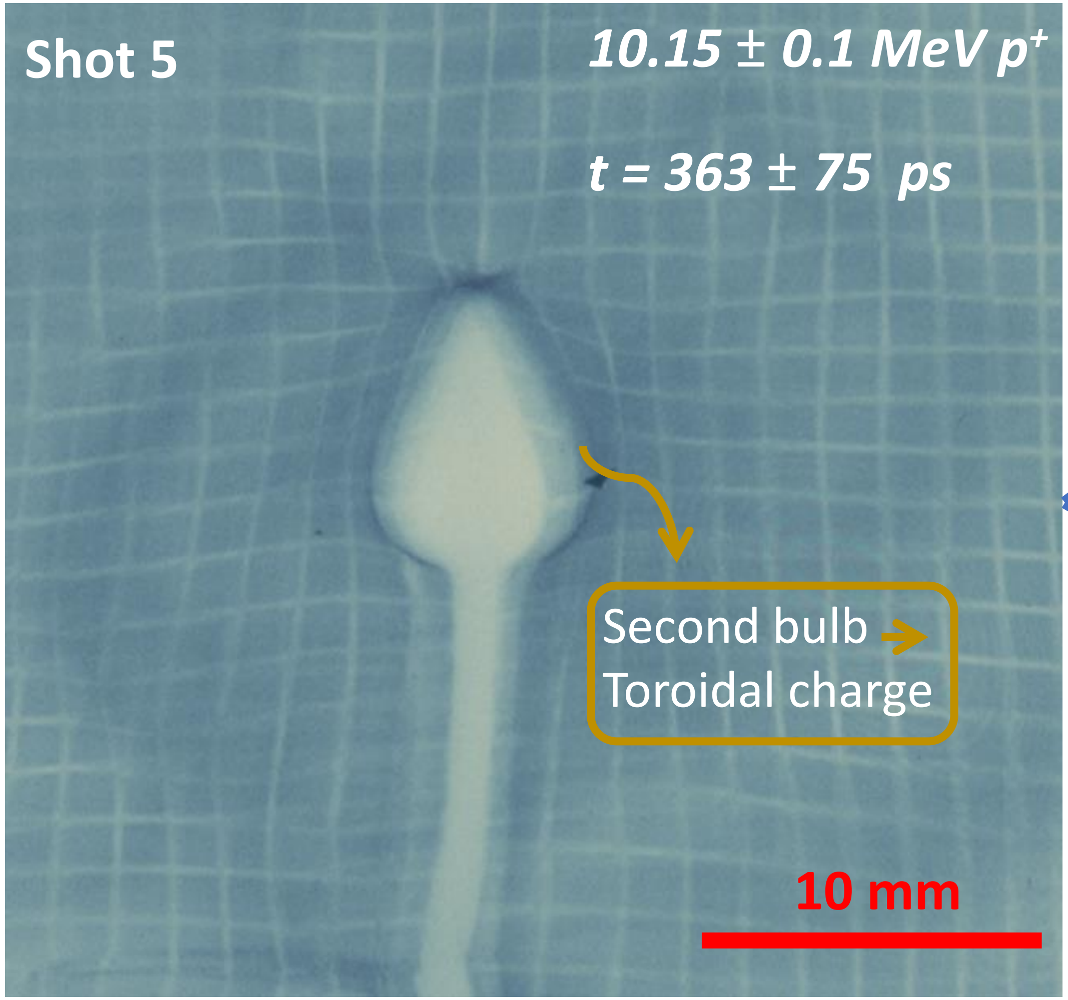
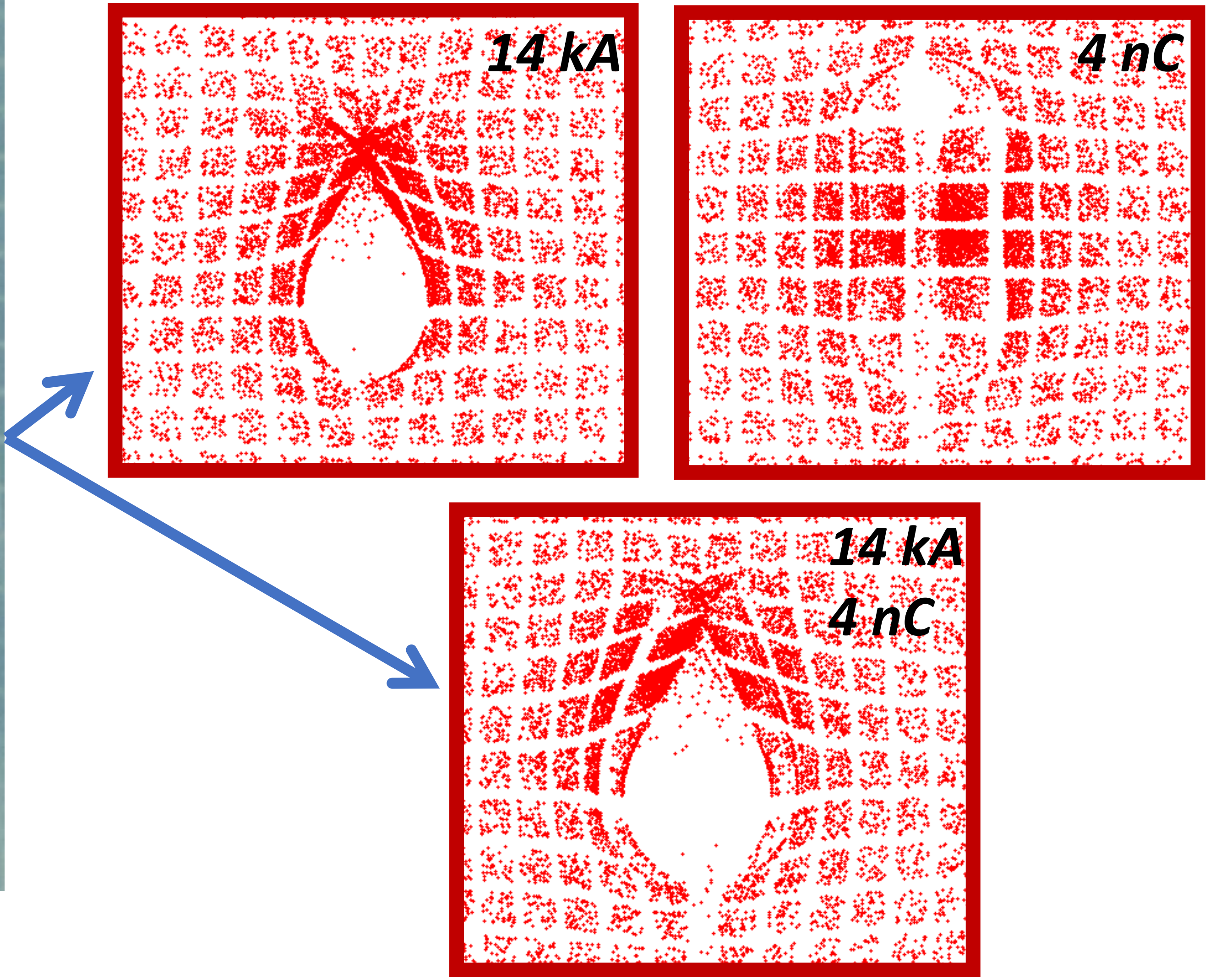
Typical results from perpendicular proton probing



Only currents *Only static charges*



At LULI :

0.5 kJ, 1 ns IR laser at 5×10^{15} W/cm^2

L = 3.7 nH, coil radius = 250 µm

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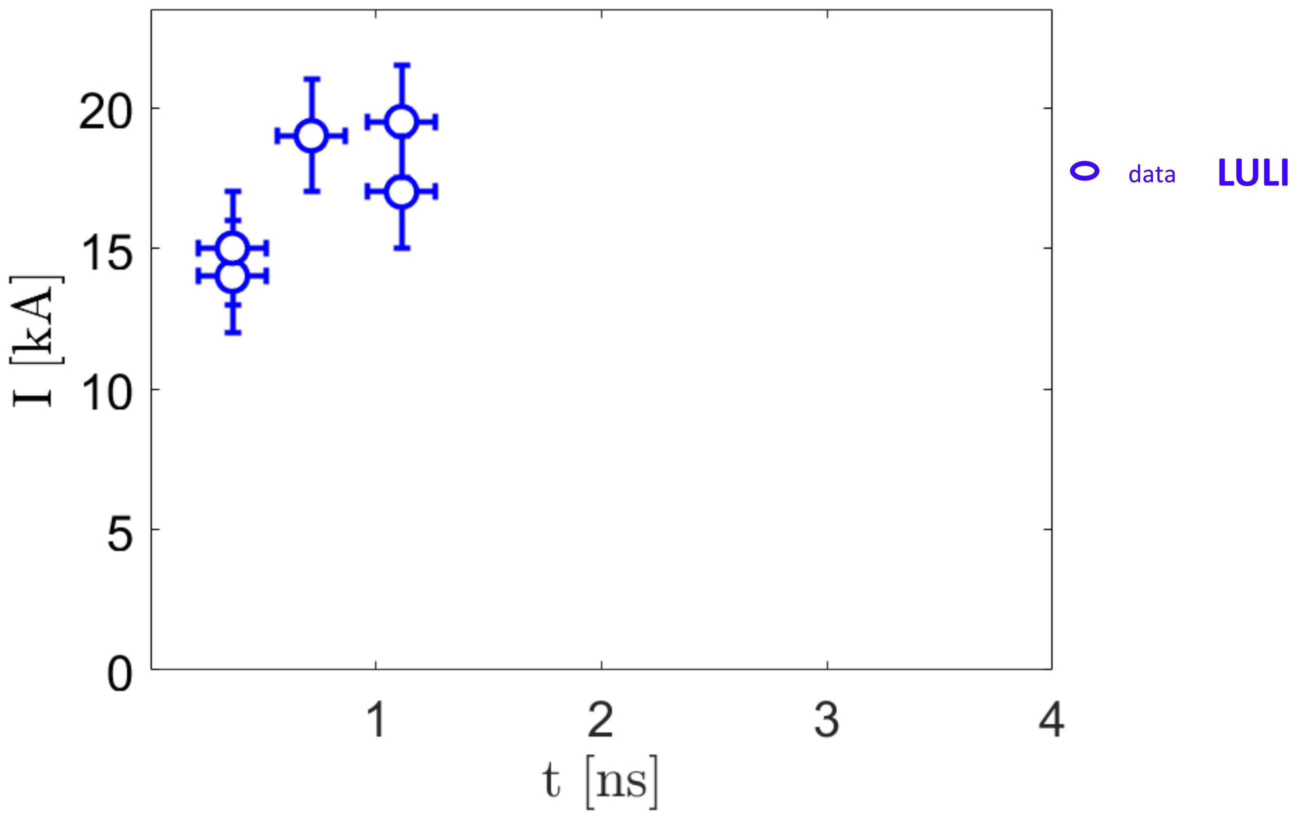
LULI experimental results



Target	***Laser***			
Inductance **L** [nH]	Pulse duration $\boldsymbol{\tau}$ [ns]	Energy [kJ]	Wavelength $\boldsymbol{\lambda}$ [μm]	Irradiance $\mathbf{I\lambda^2}$ [W $cm^{-2}\mu m^2$]
3.7	1	0.5	1.053 (ω_0)	$6x10^{15}$

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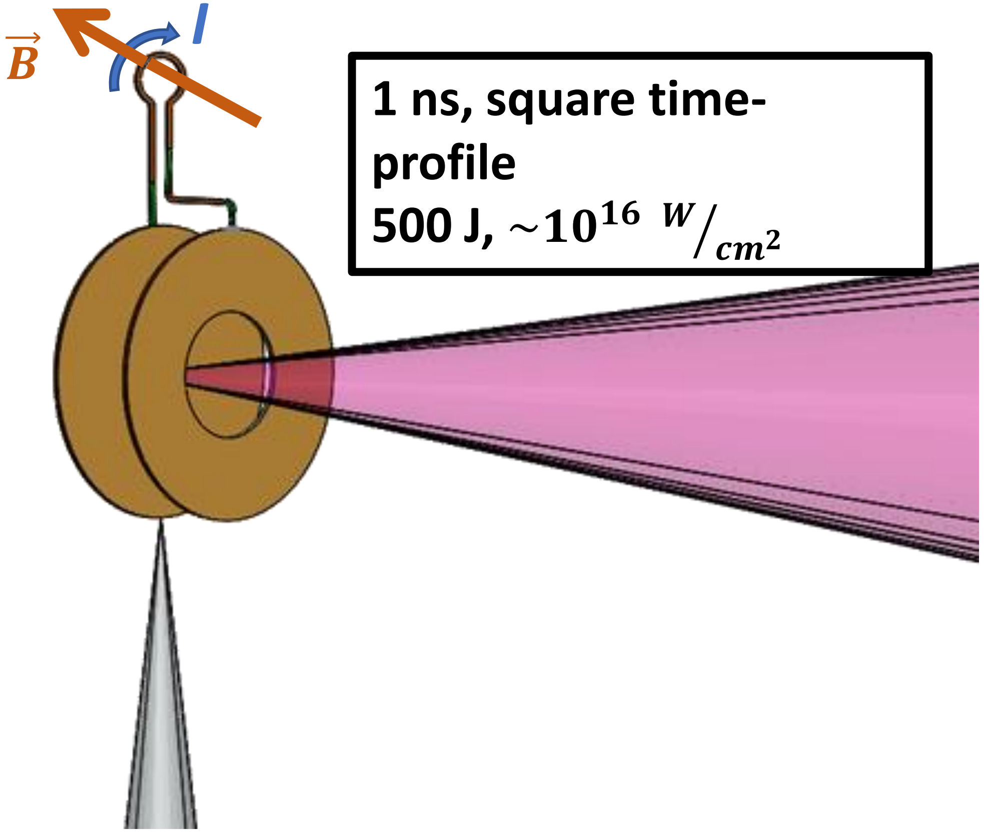
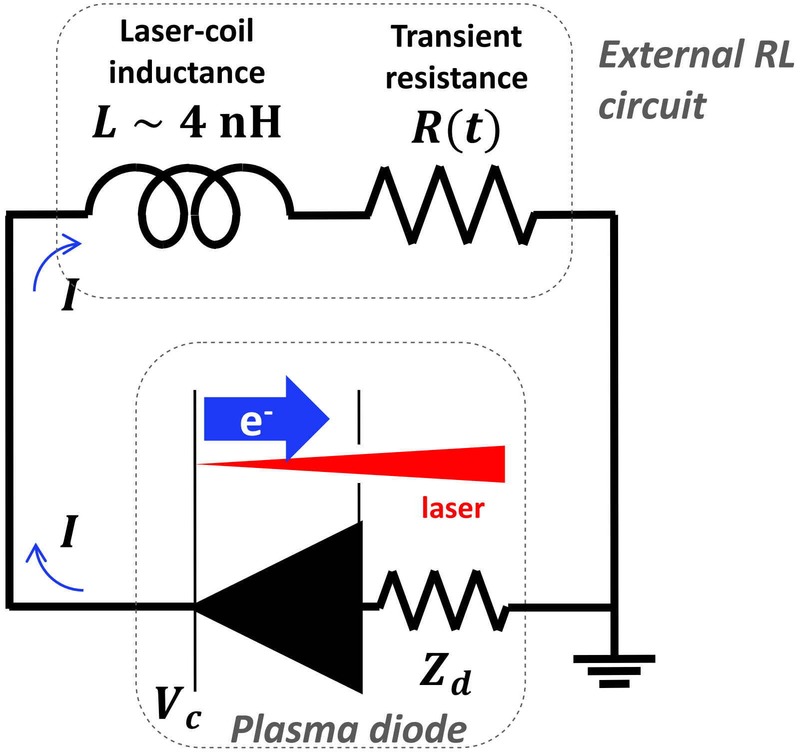
Modeling B-field generation in laser driven coils



1 ns, square time-profile
500 J, $\sim 10^{16}\ W/cm^2$

$$V_c = L\frac{dI}{dt} + \left(Z_d + R(t)\right)I$$



Scaling laws for hot electron temperature:

$$T_h = 9(I_{las}\lambda_{las}^2)^{0.25}\ \text{KeV}, \qquad \text{if } \ 10^{14} < I_{las}\lambda_{las}^2 < 10^{16}\,\frac{\text{W}\,\mu m^2}{\text{cm}^2}$$

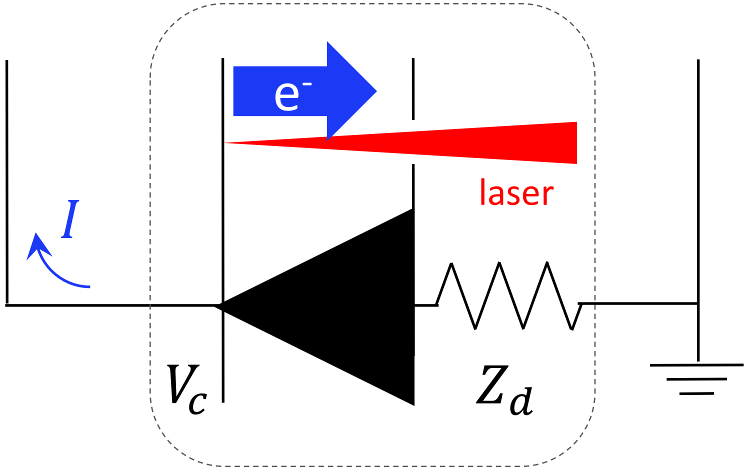
$$T_h = 12(I_{las}\lambda_{las}^2)^{0.42}\ \text{KeV}\,, \qquad \text{if } \ I_{las}\lambda_{las}^2 \geq 10^{16}\,\frac{\text{W}\,\mu m^2}{\text{cm}^2}$$

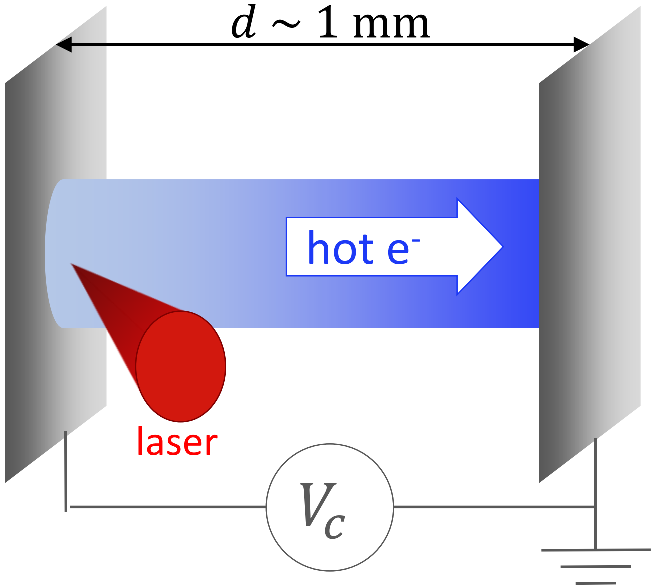
Forslund et al, Phys. Rev. Lett. **39**, 284 (1977)
Estabrook et al, Phys. Rev. Lett. **40**, 42 (1978)

Tikhonchuk *et al.*, Phys. Rev. E **96**, 023202 (2017)
Williams et al, J. Appl. Phys. 127, 083302 (2020)

Diode current limited by space charge

Plasma diode

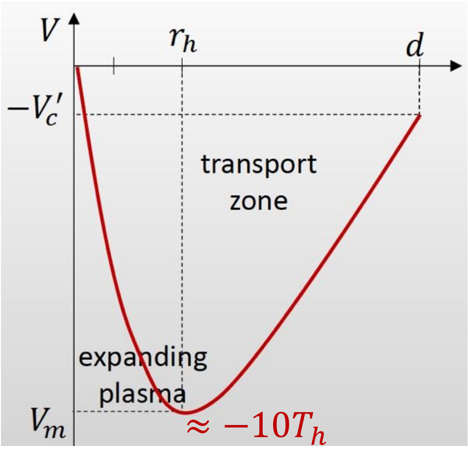




→ Laser maintains a voltage and drives a current across the gap

$$I_d = I_0 \exp(-eV_c/T_h)$$

i) $t < {}^{d}/_{v_i} \sim 200$ ps : Space charge limits **electron current in vacuum**



Tikhonchuk *et al.*, Phys. Rev. E **96**, 023202 (2017)
Williams et al, J. Appl. Phys. 127, 083302 (2020)

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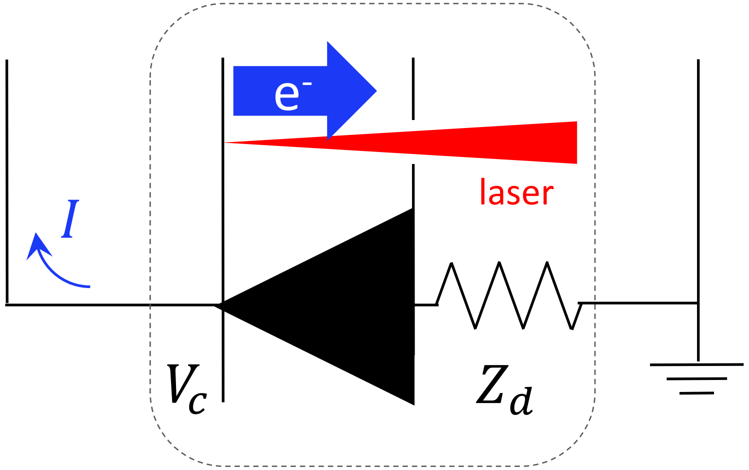
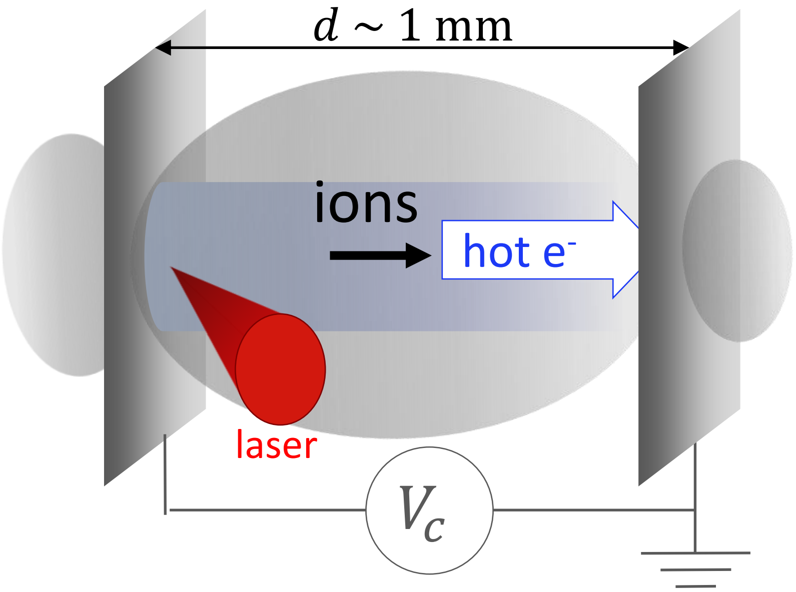
Diode current limited by space charge

Plasma diode



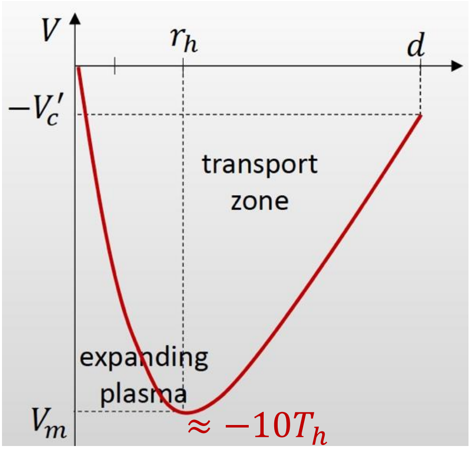


→ Laser maintains a voltage and drives a current across the gap

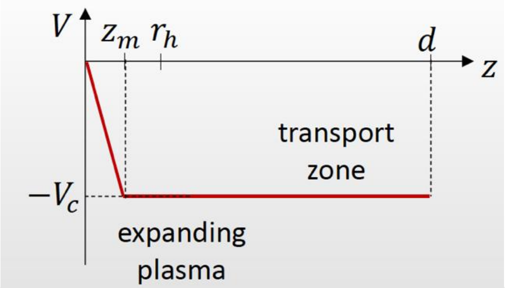
$$I_d = I_0 \exp(-eV_c/T_h)$$

→ **Ion inertia determines two regimes for the laser-driven diode**

i) $t < {}^{d}/_{v_i} \sim 200$ ps : Space charge limits **electron current in vacuum**



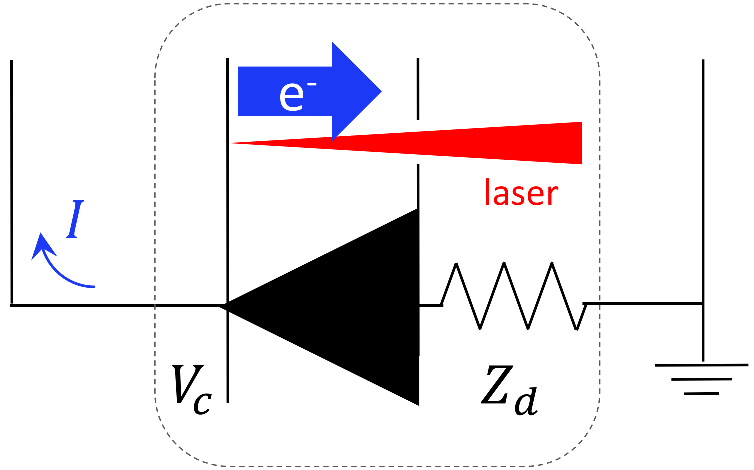
ii) $t > {}^{d}/_{v_i}$: Ion expansion allows stationary **electron current in quasi-neutral plasma**

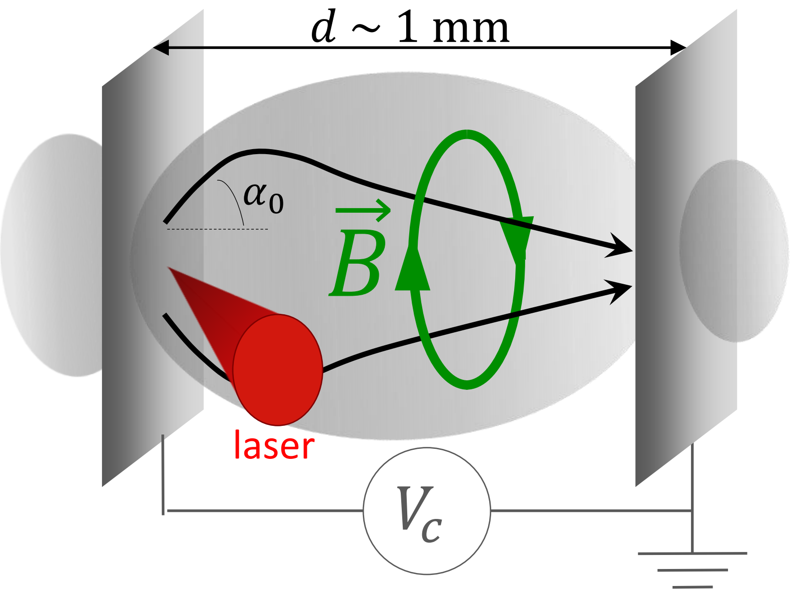


Tikhonchuk *et al.*, Phys. Rev. E **96**, 023202 (2017)
Williams et al, J. Appl. Phys. 127, 083302 (2020)

Diode current also limited by self-consistent magnetization

Plasma diode





Limits for the diode current :

- **Magnetization limit** at low voltage

$$I_m \approx \frac{V_c}{Z_d} \qquad \text{with} \quad Z_d = \sqrt{\frac{\mu_0}{\epsilon_0}} \frac{\lambda_{Dh} d}{\pi r_p^2}$$

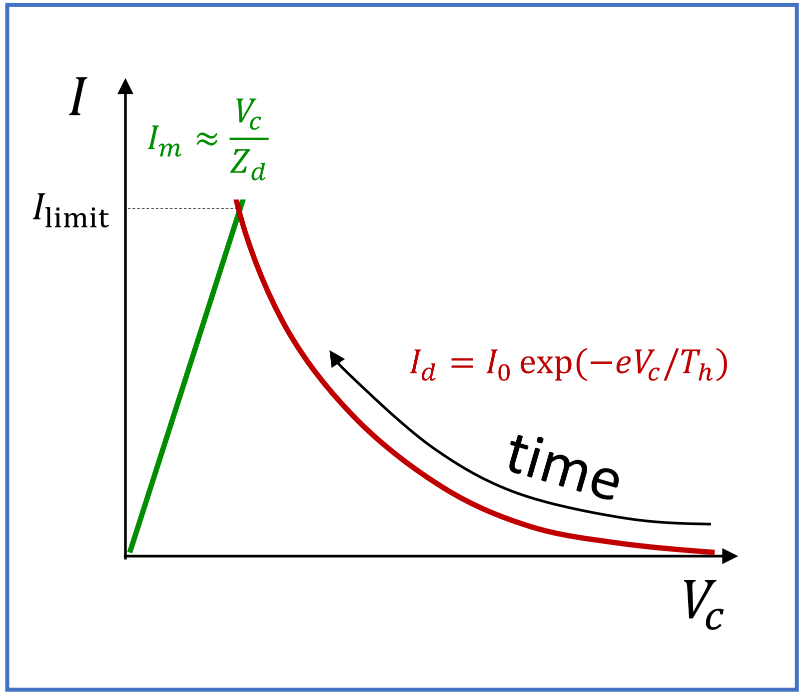
When current-carrying electrons don't pinch before the anode

- **Space-charge limit** at high voltage

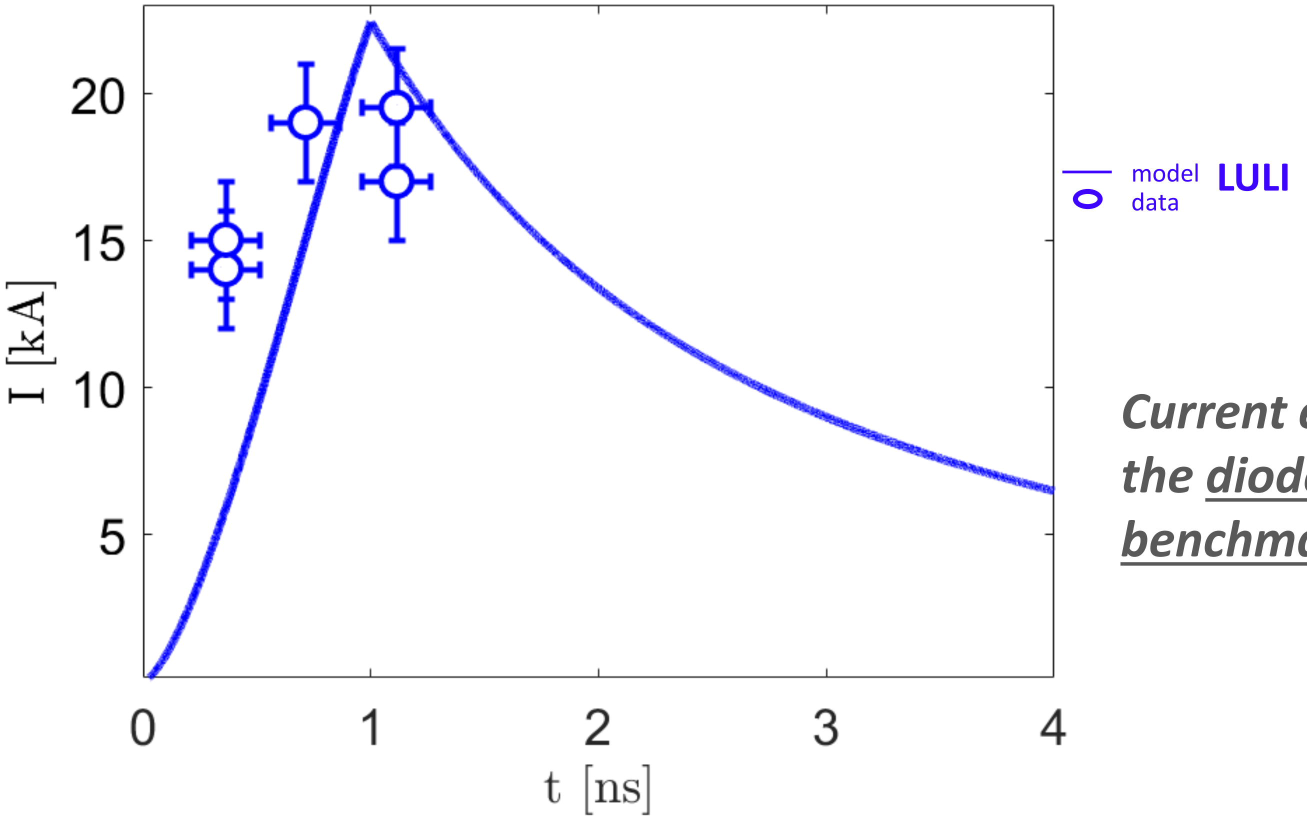
$$I_d = I_0 \exp(-eV_c/T_h)$$

Plasma compensates the charge of current-carrying electrons

Current-voltage characteristic of the laser-driven diode



LULI experimental results and modeling

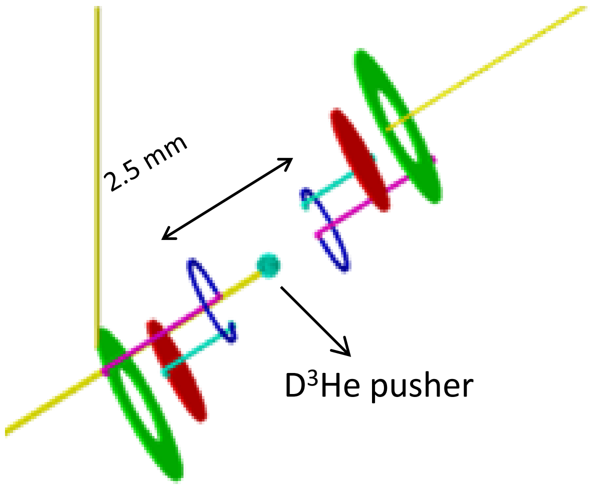


Target			*Laser*	
Inductance **L** [nH]	Pulse duration τ [ns]	Energy [kJ]	Wavelength λ [µm]	Irradiance $I\lambda^2$ [W cm^{-2}µm^2]
3.7	1	0.5	1.053 (ω_0)	6x10^{15}

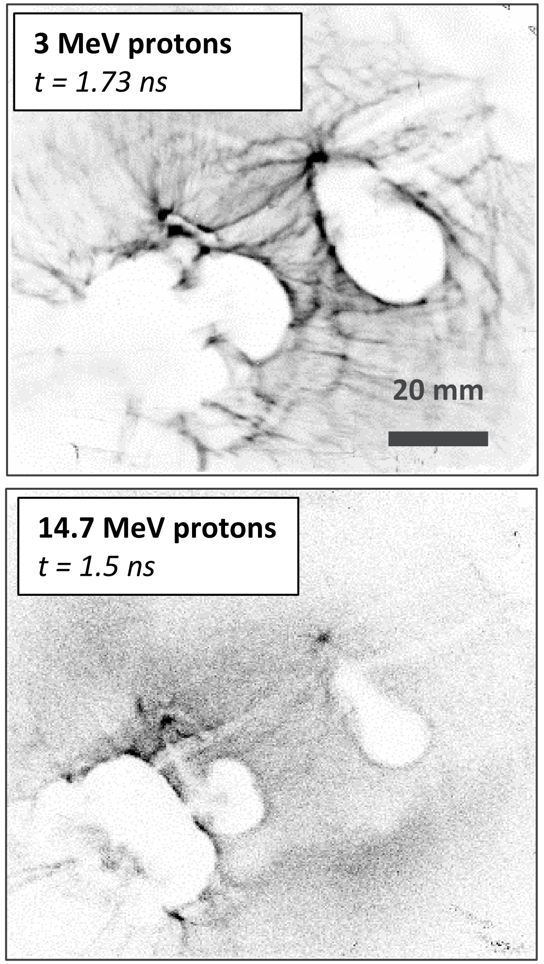
Current evolution in laser-driven coils from the <u>diode-source model</u> *(curves)* ***and recent <u>benchmarking data</u>*** *(symbols)*

LDCs in 3ω light and several kJ energies (Omega, 2021)

Coil radius
a = 750 µm

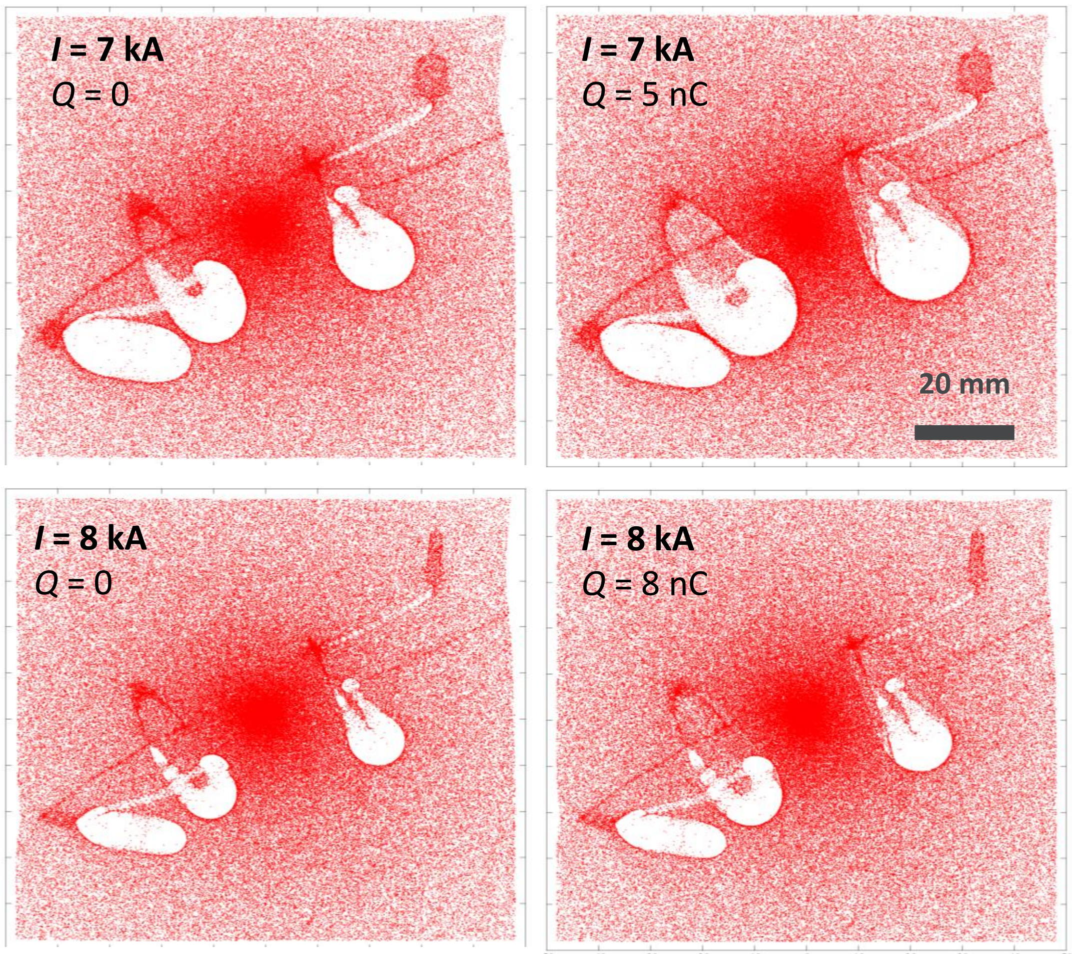


Deflectometry data



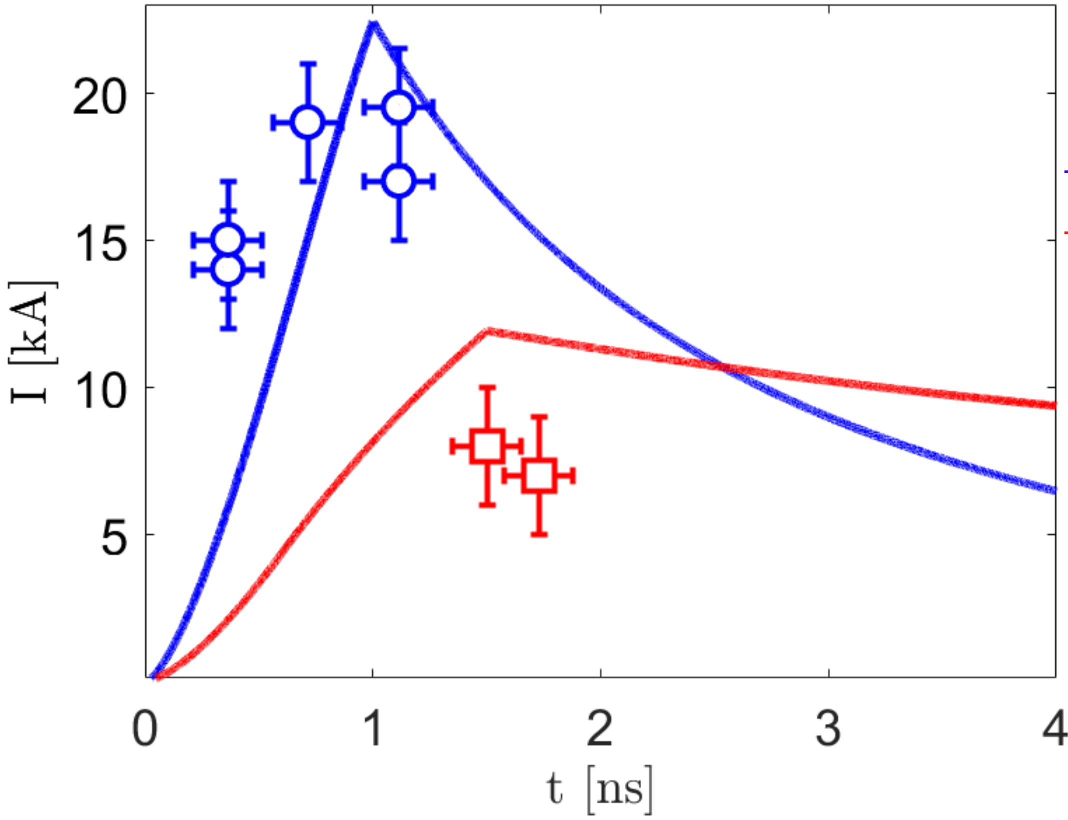
Synthetic deflectometry

Only currents | *Currents and charges*



* M. Ehret, Master Proposal, Universite de Bordeaux, 10.13140 (2015)

Omega experimental results and modeling



	Target	*Laser*			
	Inductance **L** [nH]	Pulse duration τ [ns]	Energy [kJ]	Wavelength **λ** [μm]	Irradiance **Iλ²** [W cm^{-2}μm^2]
model (curve) / data (o) **LULI**	3.7	1	0.5	1.053 (ω_0)	6x10^{15}
model (curve) / data (□) **OMEGA**	6.5	1.5	2	0.351 ($3\omega_0$)	1.2x10^{15}

***Current evolution in laser-driven coils from the diode-source model** (curves) **and recent benchmarking data** (symbols)*

😔 UV laser drive $\Rightarrow T_h \propto I_L \lambda_L^2 \searrow$

😔 Geometrical constraints $\Rightarrow L \nearrow$

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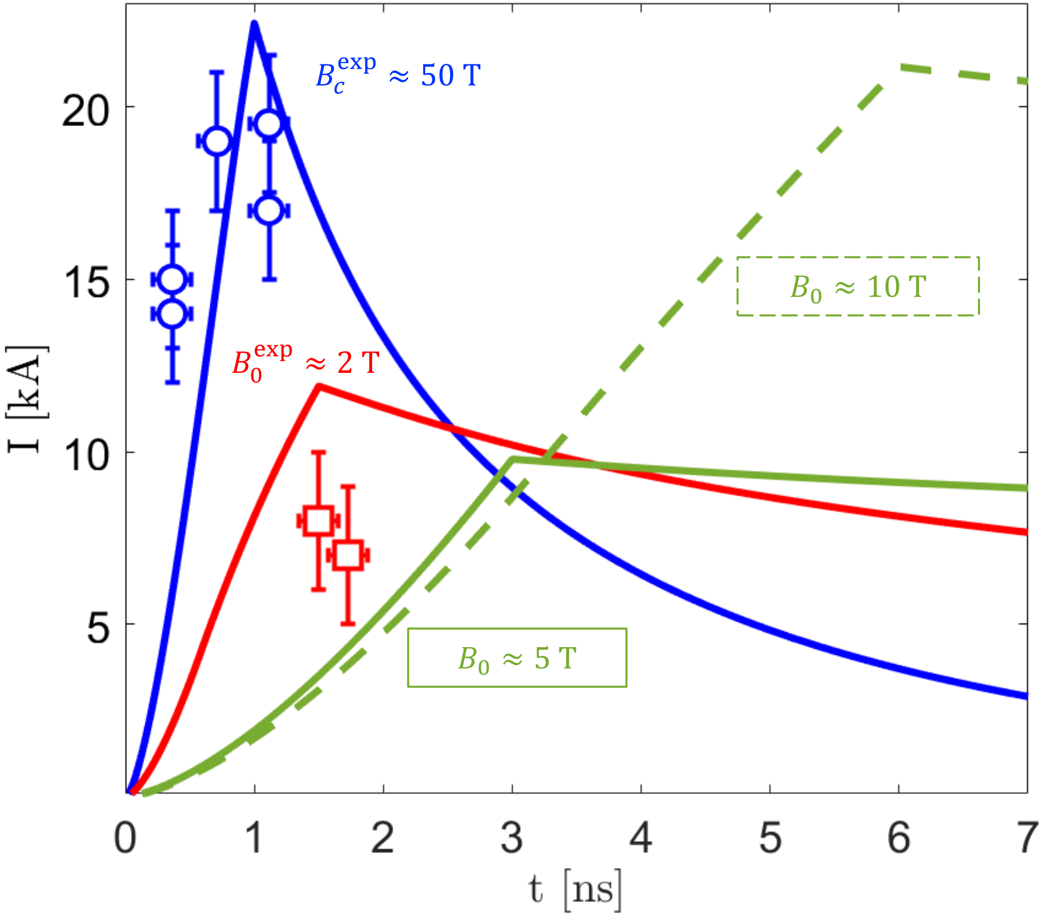
Summary and Conclusions



	Target	Laser			
	Inductance **L** [nH]	Pulse duration ***τ*** [ns]	Energy [kJ]	Wavelength **λ** [μm]	Irradiance **Iλ²** [W cm⁻²μm²]
model / data **LULI**	3.7	1	0.5	1.053 (ω_0)	$6\text{x}10^{15}$
model / data **OMEGA**	6.5	1.5	2	0.351 ($3\omega_0$)	$1.2\text{x}10^{15}$
model **LMJ**	13	3 and 6	13.5	0.351 ($3\omega_0$)	$5\text{x}10^{14}$ and $2.5\text{x}10^{14}$

→ In facilities without external pulsed power, laser-driven coils (LDC) are an **alternative to magnetize laser-plasma experiments** in an open-geometry for lasers and diagnostic access, with small production of debris

→ **Use of LDC in ns and large-scale experiments is more challenging** (larger volumes, lower fields, B-field pulse comparable to the physics time-scale)

- Adapt laser drive duration to target inductance
- Harsh conditions linked to laser-target interaction and generated plasma need specific care

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Thank you !

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