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U.S. DEPARTMENT OF
ENERGY

Laser Channeling and Electron Filamentation in Near-Critical Density Plasma

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JAI
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Outline

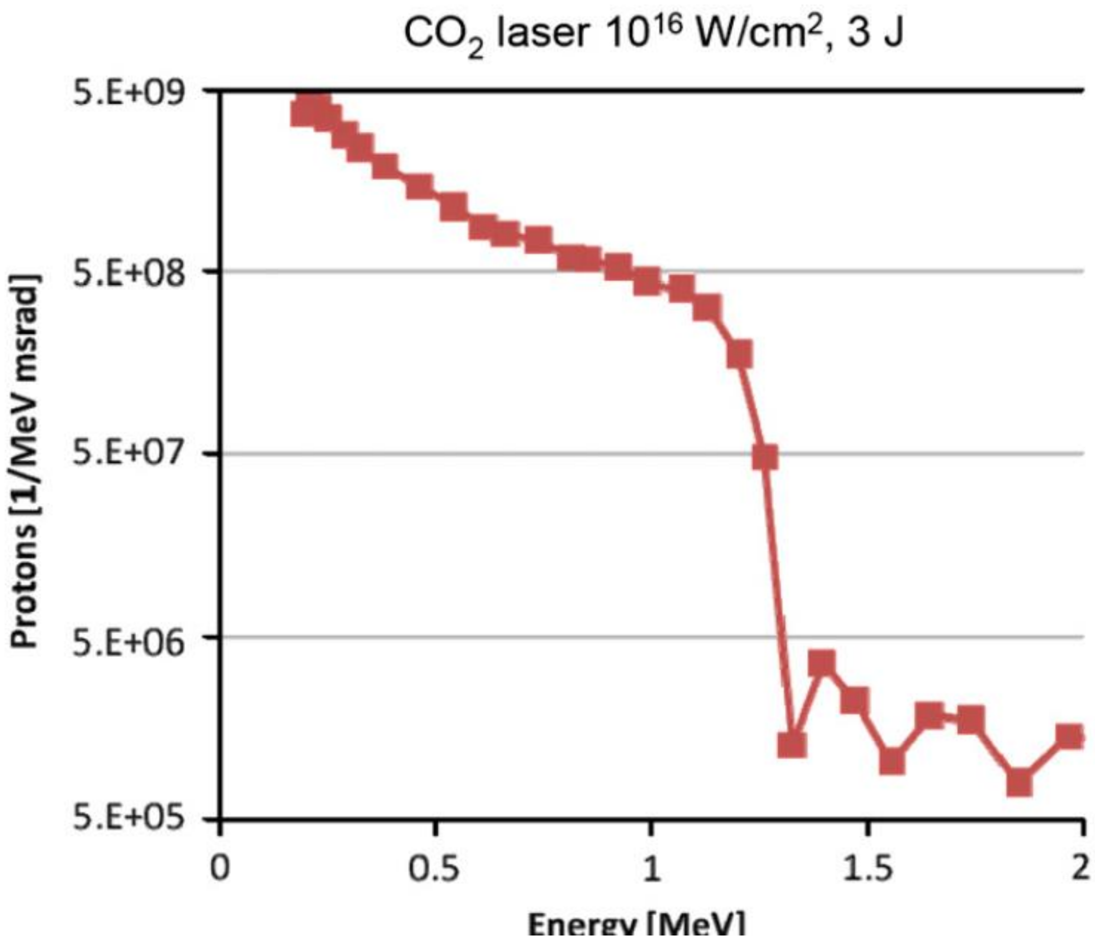
- Benefits from longer wavelengths for studies of laser-plasma interactions at near critical density
- Hole boring and shock waves
- Probing current filamentation instability
- Laser channeling

Benefits from longer wavelengths: $a_0 \sim \lambda$

a_0 scales favorably with wavelength

$$a_0 = \frac{eE_0}{m_e c} \cdot \frac{\lambda}{2\pi c}$$

- As the result, TNSA demonstrated with 10^{16} W/cm^2 at 10 μm is the same as with 10^{18} W/cm^2 solid state laser.
- This means also that 10-μm CO_2 laser of the same power and energy as 1-μm laser can produce 100x more TNSA ions.

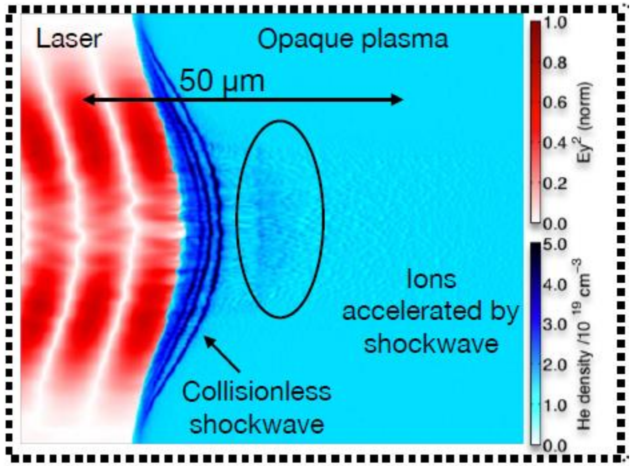


I.V. Pogorelsky et al. / Nuclear Instruments and Methods in Physics Research A 620 (2010) 67

Benefits from longer wavelengths: $n_{cr} \sim \lambda^{-2}$

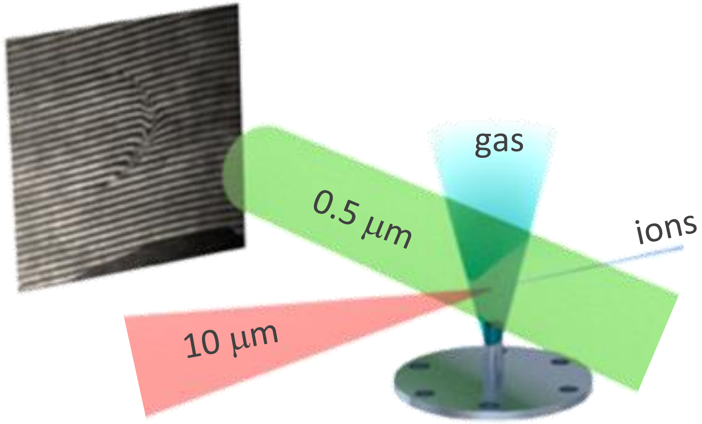
$$n_c = \gamma \frac{\epsilon_0 m_e}{e^2} \cdot \frac{4\pi^2 c^2}{\lambda^2}$$

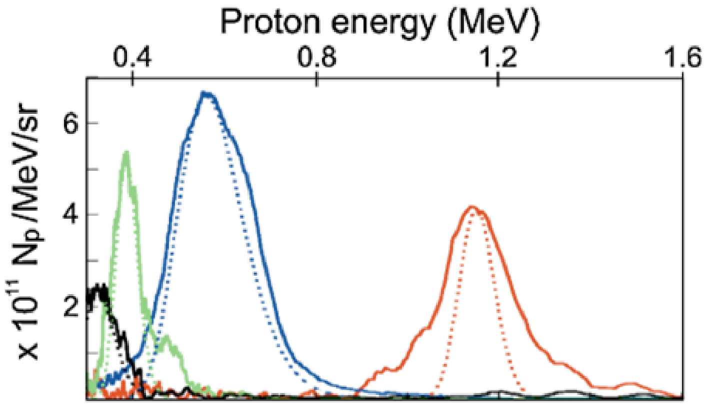
- Critical density of a plasma scales favorably with wavelength opening access to new acceleration mechanisms such as radiation pressure acceleration in gases.



- Shock wave acceleration

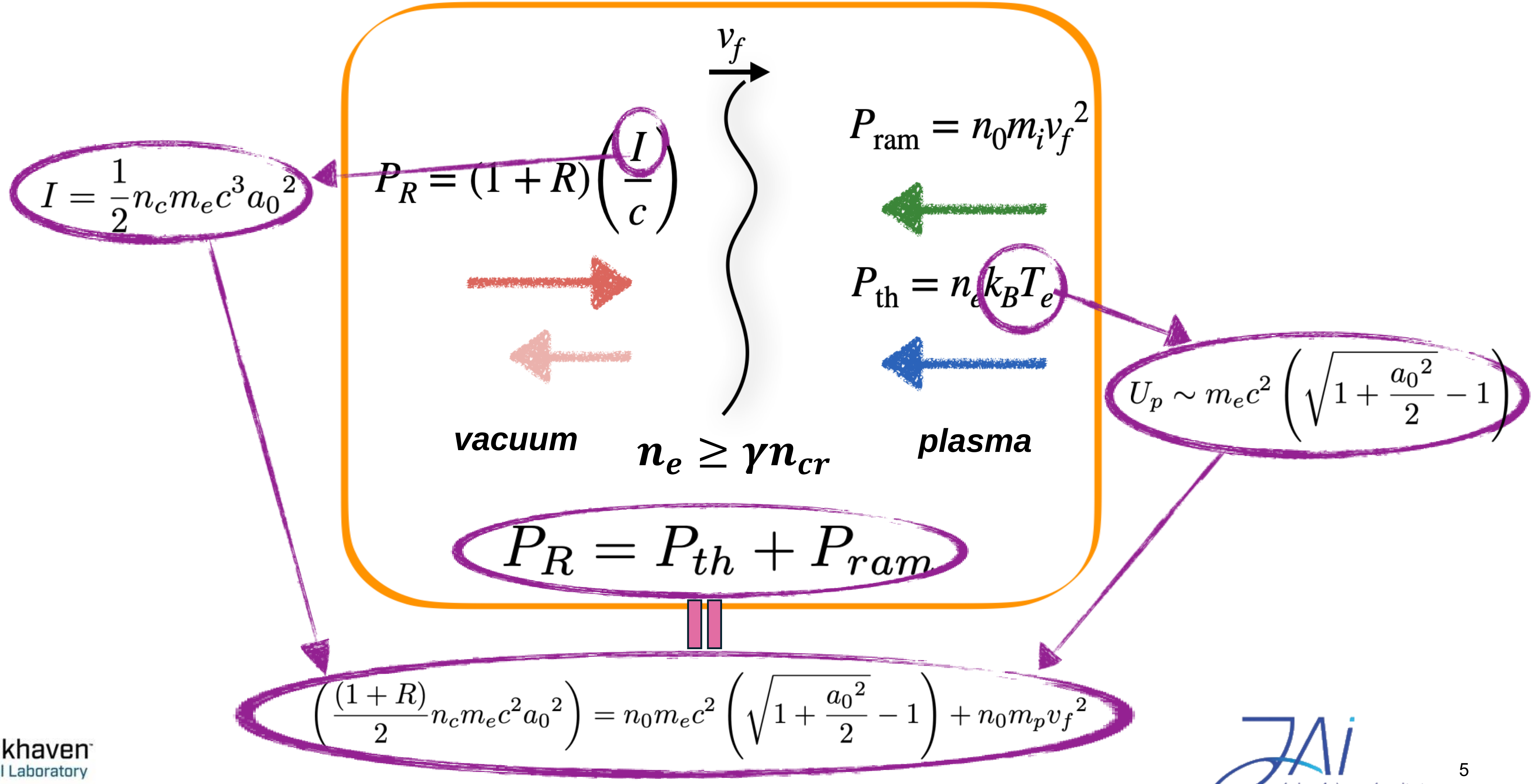
- Optical interferometry





- Monoenergetic ion beams

Radiation Pressure Driven Acceleration



v_f

$$P_R = (1+R)\left(\frac{I}{c}\right)$$

$$I = \frac{1}{2} n_c m_e c^3 {a_0}^2$$

$$P_{\text{ram}} = n_0 m_i {v_f}^2$$

$$P_{\text{th}} = n_e k_B T_e$$

$$U_p \sim m_e c^2 \left(\sqrt{1 + \frac{{a_0}^2}{2}} - 1\right)$$

vacuum

$n_e \geq \gamma n_{cr}$

plasma

$$P_R = P_{th} + P_{ram}$$

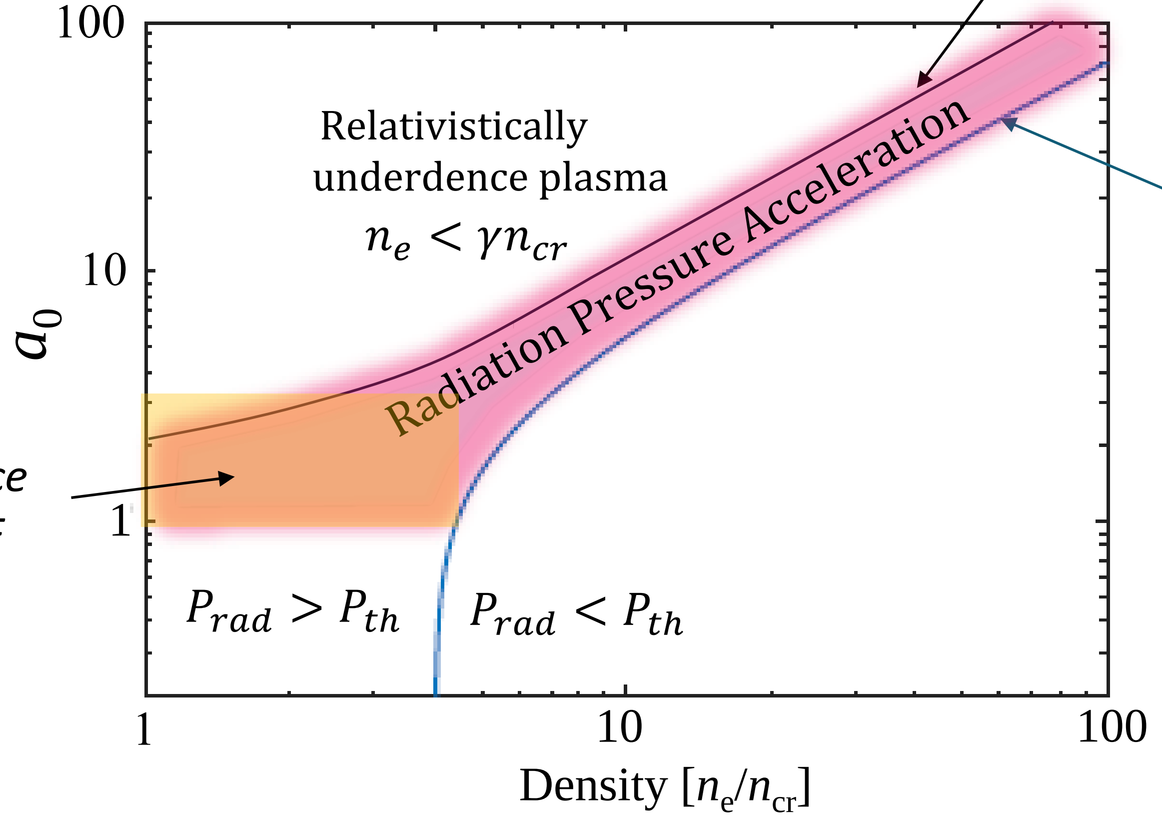
$$\left(\frac{(1+R)}{2} n_c m_e c^2 {a_0}^2\right) = n_0 m_e c^2 \left(\sqrt{1 + \frac{{a_0}^2}{2}} - 1\right) + n_0 m_p {v_f}^2$$

Parameter space for RPA

Another boundary condition due to plasma transparency:

$$n_e = \gamma n_{cr}$$

with $\gamma = \sqrt{1 + a_0^2/2}$ $\Longrightarrow$ $\boxed{a_0 = \sqrt{\frac{4n_e^2}{n_{cr}^2} - 1}}$



Parameter space explored at ATF so far

$$\boxed{a_0 = \sqrt{\frac{n_e^2}{2n_{cr}^2} - \frac{2n_e}{n_{cr}}}}$$

$$\Uparrow$$

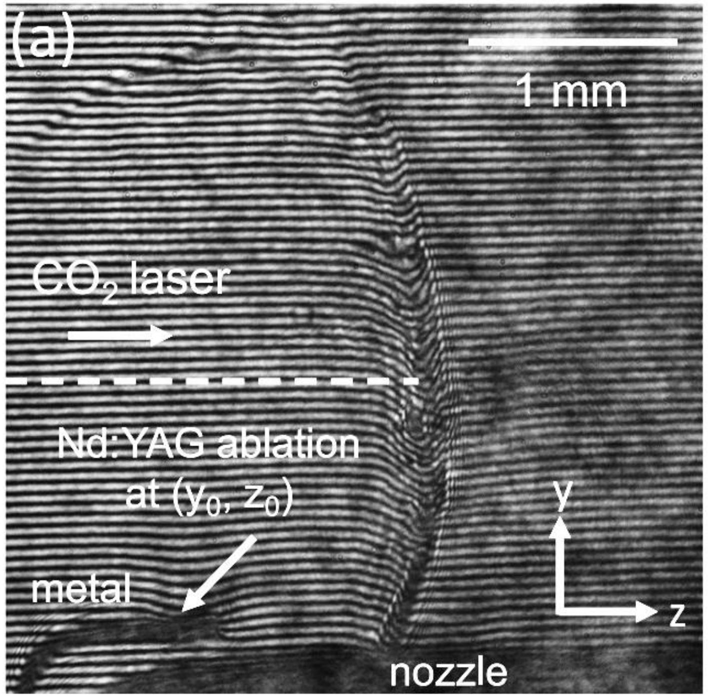
$$\frac{n}{n_{cr}} = \frac{a_0^2}{\sqrt{1 + a_0^2/2} - 1}$$

Separation line between radiation pressure and thermal pressure dominated regimes: $P_{rad} = P_{th}$

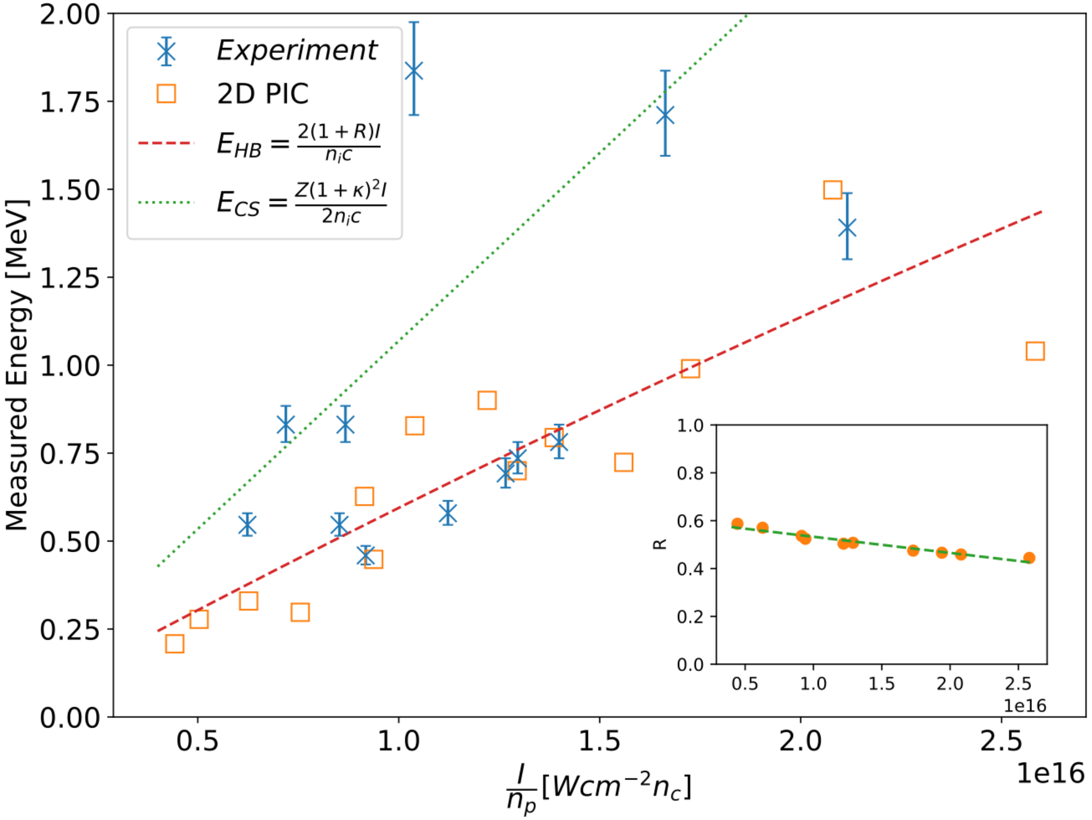
$$\left(\frac{(1+R)}{2} n_c m_e c^2 {a_0}^2\right) = n_0 m_e c^2 \left(\sqrt{1 + \frac{{a_0}^2}{2}} - 1\right) + n_0 m_p {v_f}^2$$

Current status of proton acceleration at ATF

Chen+, Phys. Plasmas 30, 053106 (2023)



a_0 ~ 1- 2.5 n_i ~ (1-4) n_{cr}



Ettlinger+
(in preparation)

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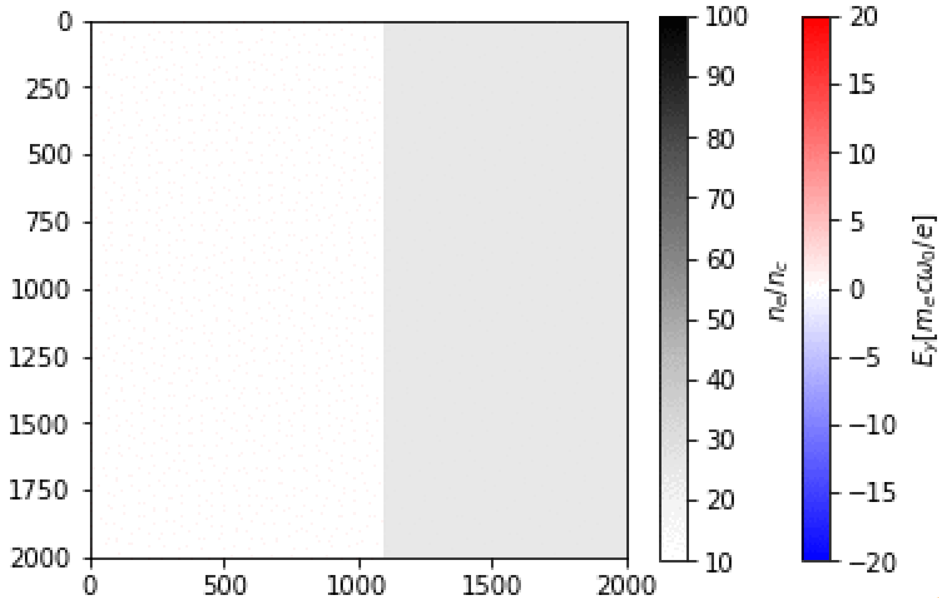
Radiation Pressure Driven Acceleration

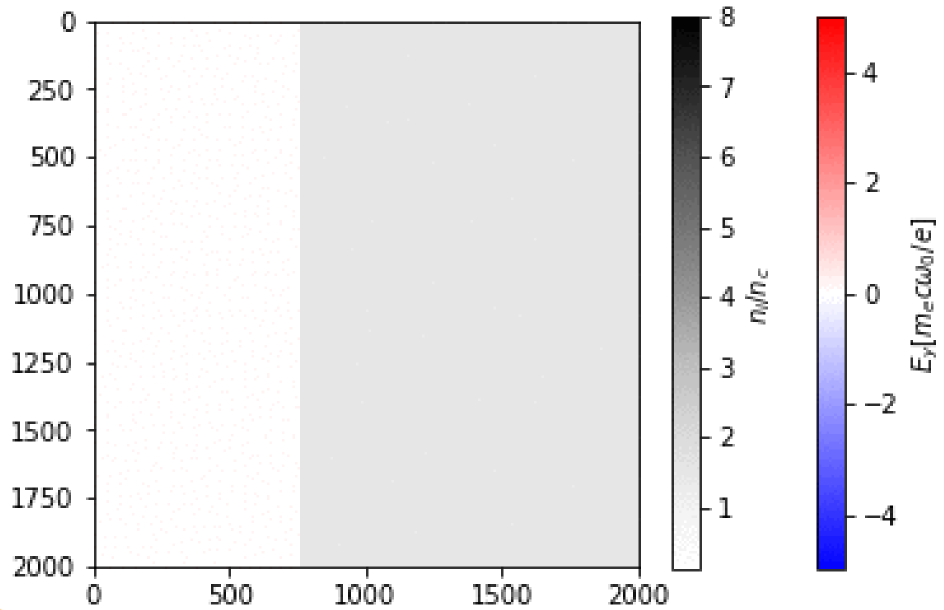
Radiation pressure dominant - hole boring radiation pressure acceleration

$$E_i = \frac{2(1+R)I}{n_i c}$$



Closer to hermal pressure dominant - possible to form a collisionless shock structure, accelerating ions

$$E_{SN} = \frac{Z(1+\kappa)I}{2 n_i c}$$



$$v_b = \sqrt{\frac{I_L}{n_i m_i c}}$$

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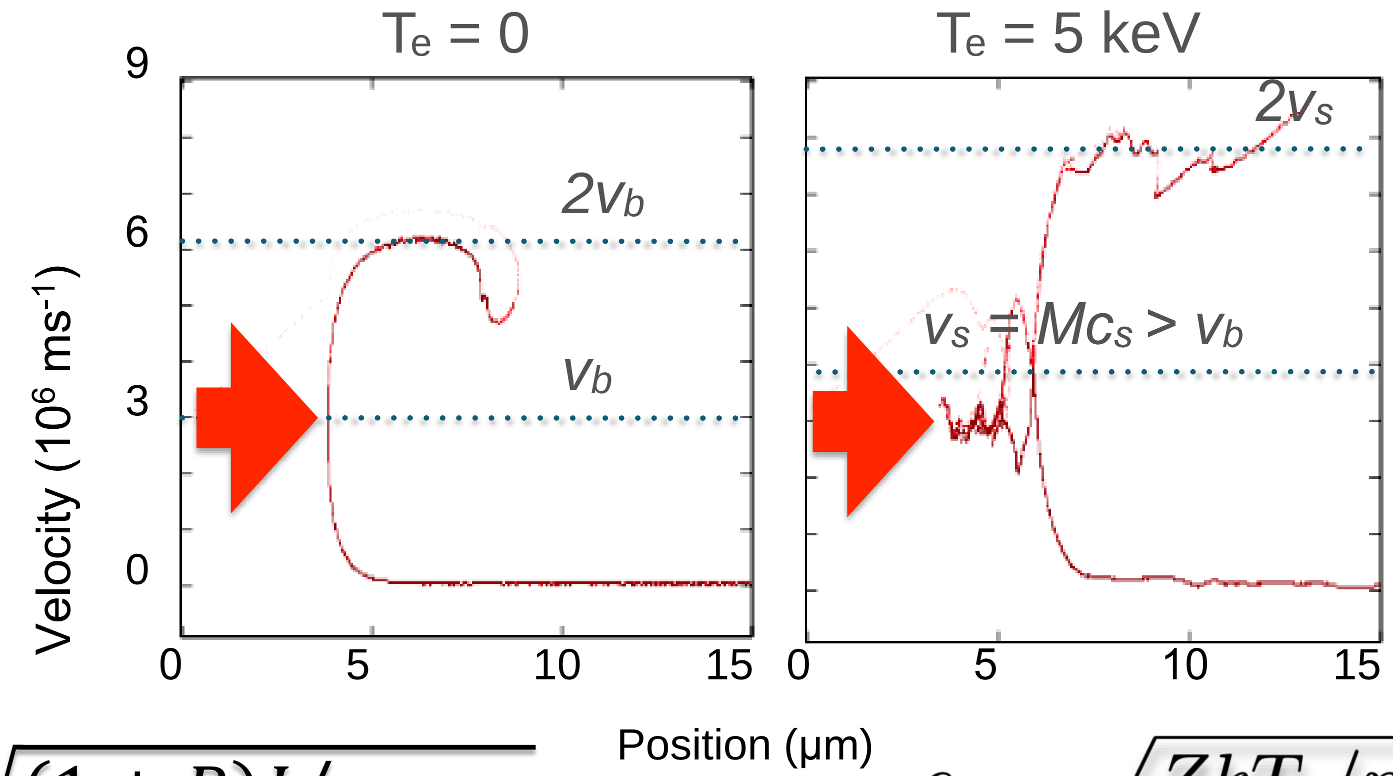
Hole boring and shock regimes



$$v_b = \sqrt{(1+R)I/cn_0m_i}$$

$$c_s = \sqrt{ZkT_e/m_i}$$

How can we experimentally access relevant physics for ion generation?

Near-IR	~3 fs	~1 µm	~10^{21} cm^{-3}
	Too short	*Too small*	*Too dense*

These scales are difficult to access experimentally

☹

Collisionless laser plasmas can be defined using reference frequency:

Time	*Length*	*Density*
$\tilde{t} = \omega_L t$	$\tilde{x} = \frac{\omega_L}{c} x$	$\tilde{n} = \frac{n}{n_{cr}} \propto \frac{1}{\omega_L^2} n$

LongWave-IR

$$\underbrace{\text{~30 fs} \qquad \text{~10 µm}}_{\textit{Easier to resolve experimentally}} \qquad \text{~}10^{19}\ \text{cm}^{-3}$$

Convenient for optical probing

😃

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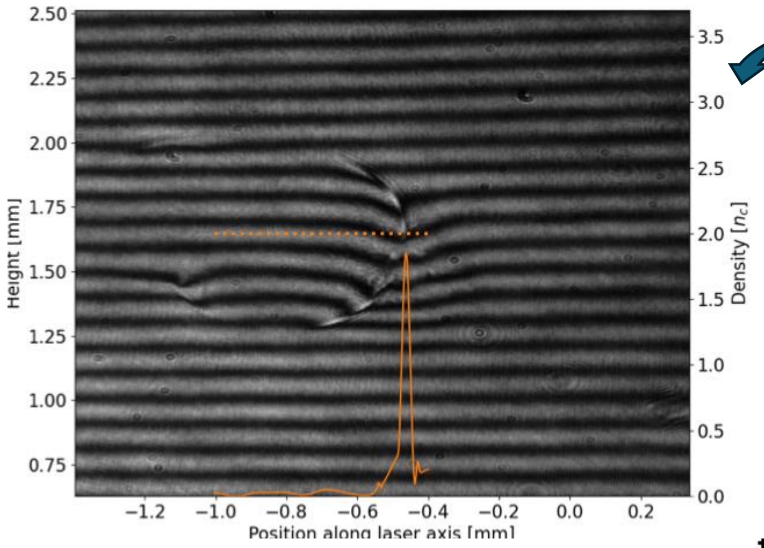
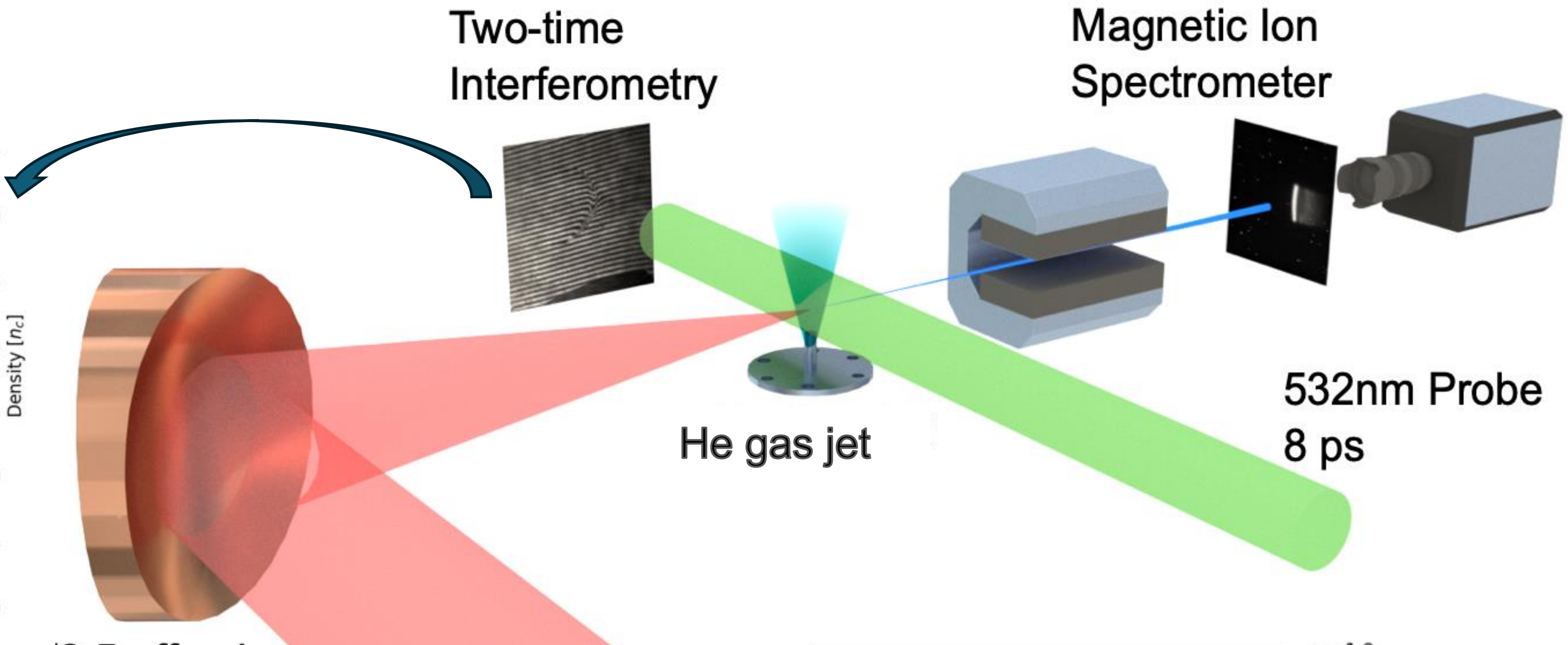
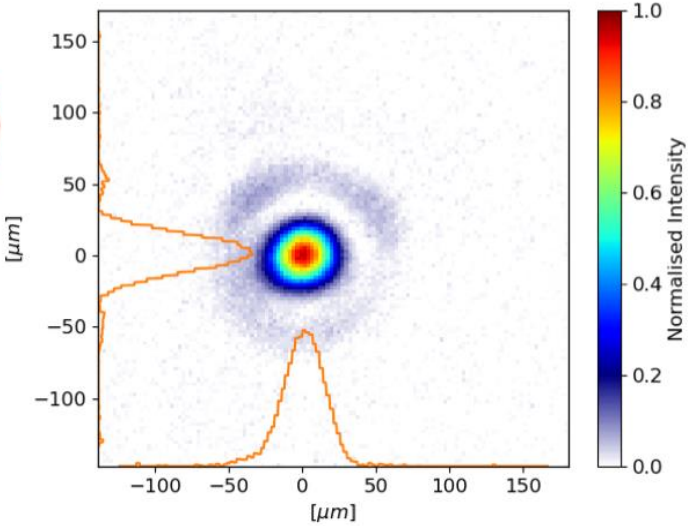
Case study 1: Probing current filamentation instability





5 J, 3 ps, 10 µm CO_2 laser
50 µm focal spot
5×10^{16} W/cm^2 on target
a_0 ~ 2



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Observed filamentation beyond critical surface

- Current Filamentation Instability
- CFI growth rate:

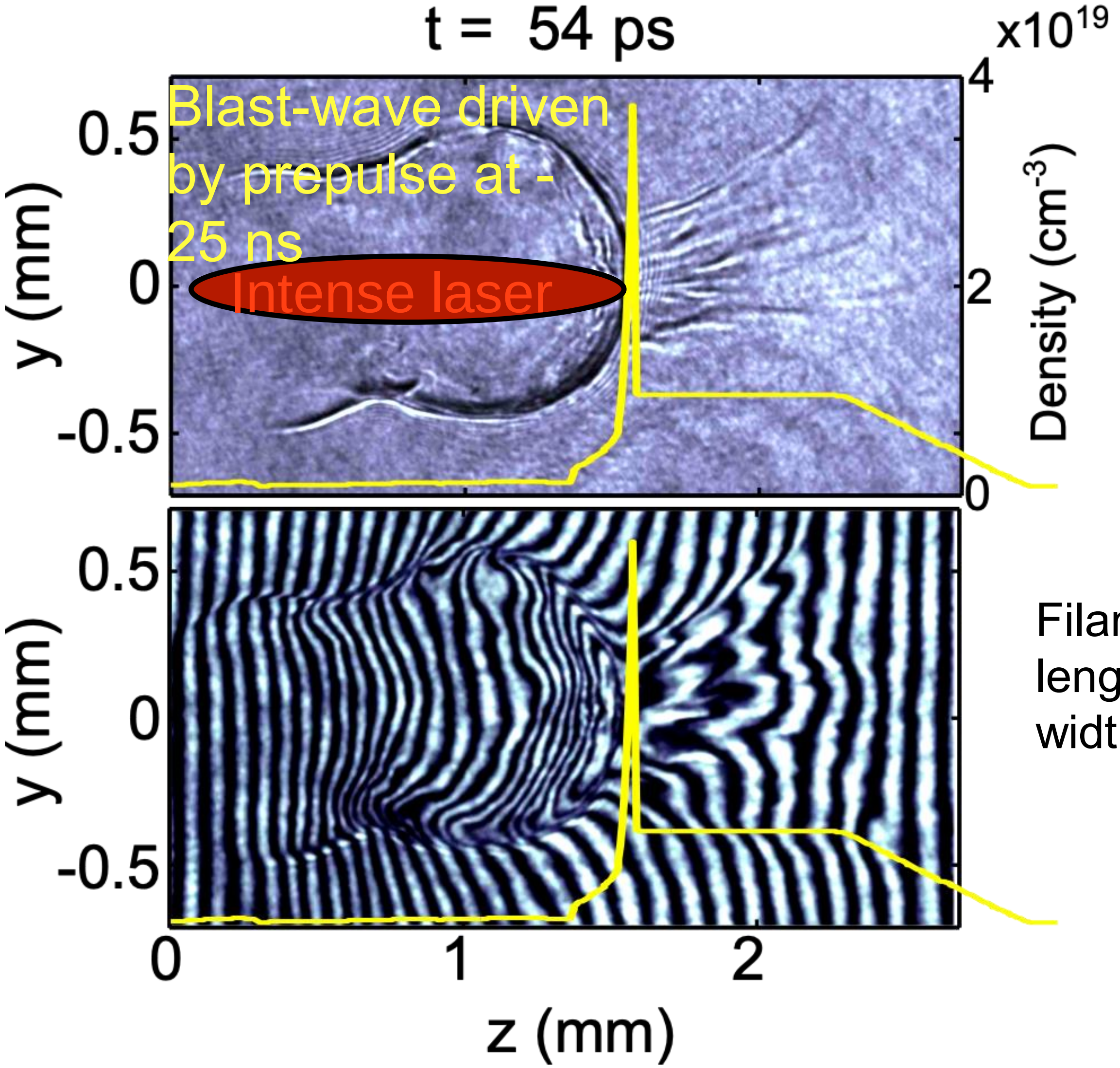
$$\delta_{fil} \sim \omega_p \beta_b \sqrt{\frac{\alpha}{\gamma_b}} \approx \omega_l \sqrt{\alpha}$$

where $\alpha = \frac{n_b}{n_c} \approx 0.1$

- Filament width and period

$$\lambda_{fil} \approx 2\pi \frac{c}{\omega_p} \approx 10\mu\text{m}$$

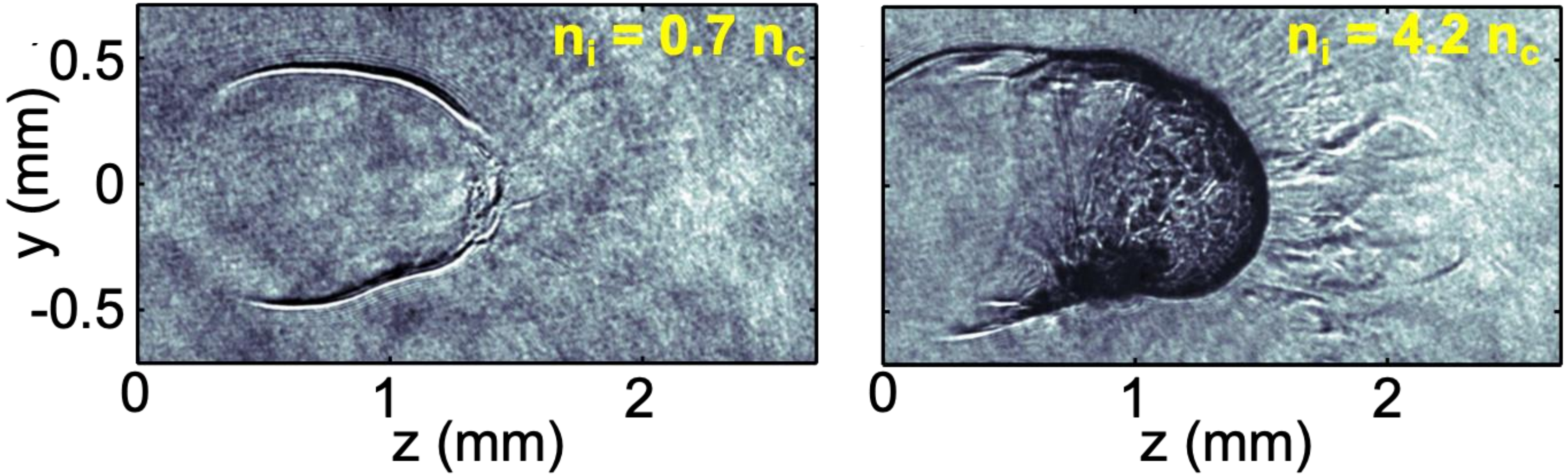
He plasma, 1 n_c



Filaments length ~ 800 μm, width ~ 10 μm

Transverse filament size reduces with increasing density

t = 54 ps



- At lower density, no filaments generated
  - Density too low and laser penetrates through blast wave with no localized energy deposition
- At highest density, filaments penetrate not as far
  - at $n_i = 4.2\ n_{cr}$, ~ 400 μm (800 μm @1.1 n_{cr})
  - Transverse filament size smaller for higher density

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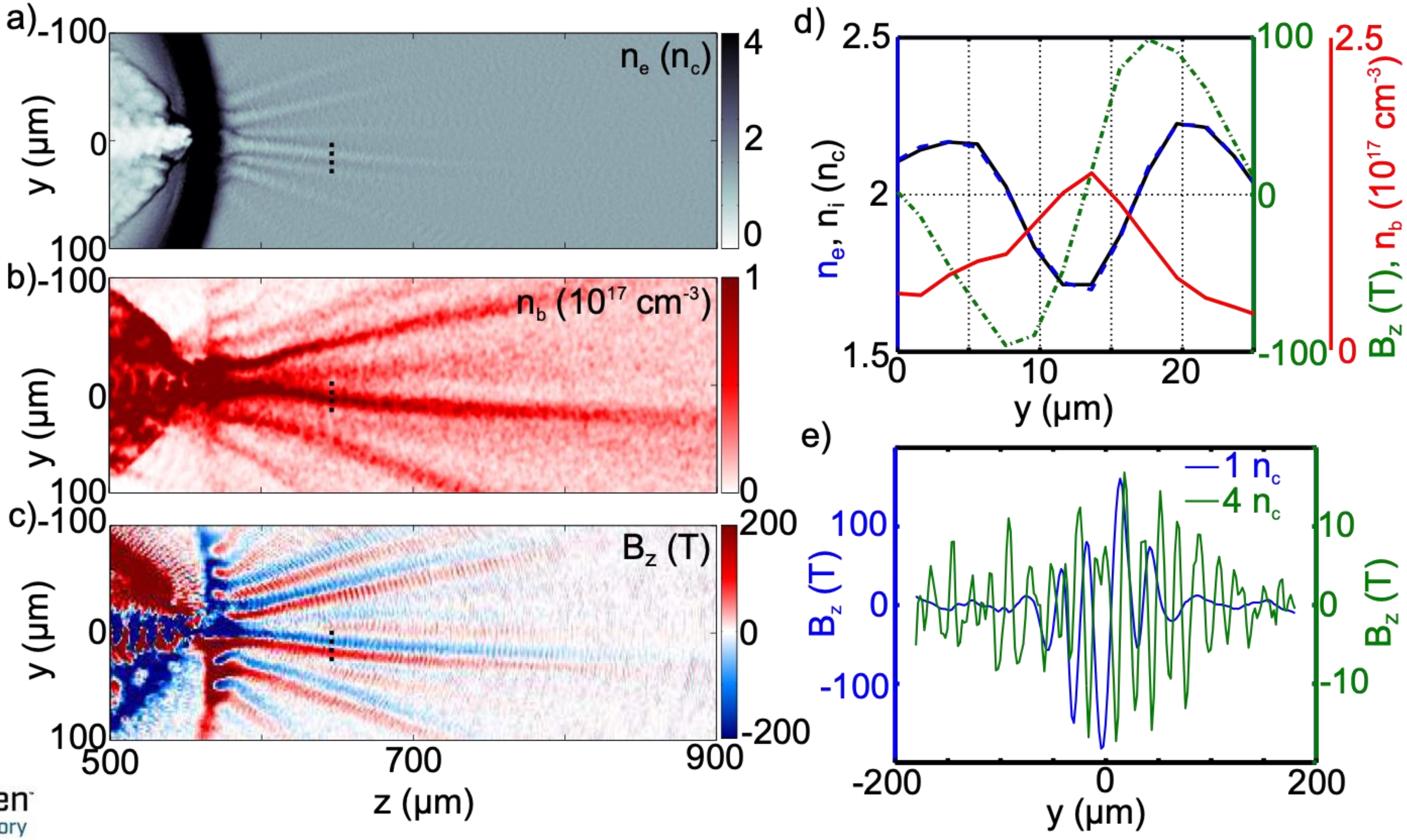
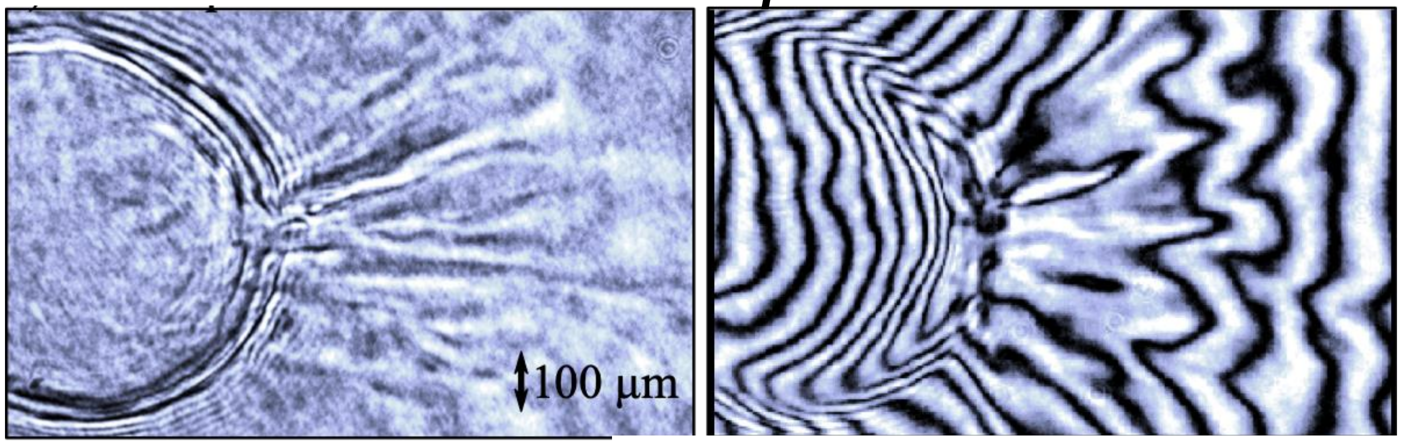
2DPIC shows the generation of current filamentation instability

Using the output from hydrodynamic simulations of blast wave:

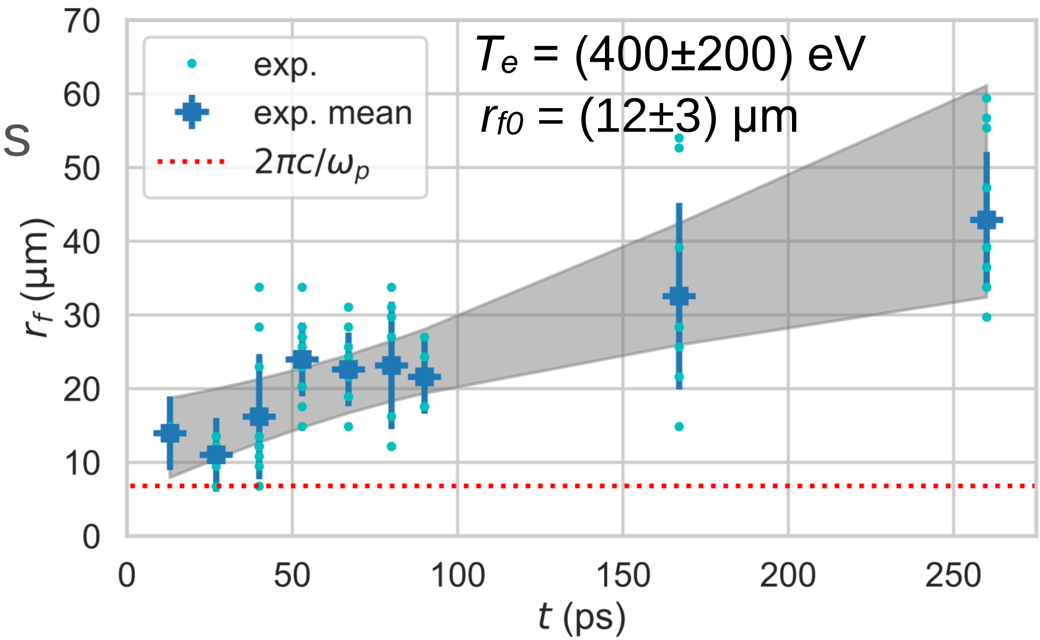


Filaments are seen expanding in time long after end of LPI

t = 260 ps



- Filament diameter increases in time after LPI
- Expansion depends on background T_e ~ *400 eV* (c_S~ 1.5 x 10^5 m/s)
- He ions observed up to 1 MeV (> 10^7 m/s);



T_e = (400±200) eV

r_{f0} = (12±3) µm

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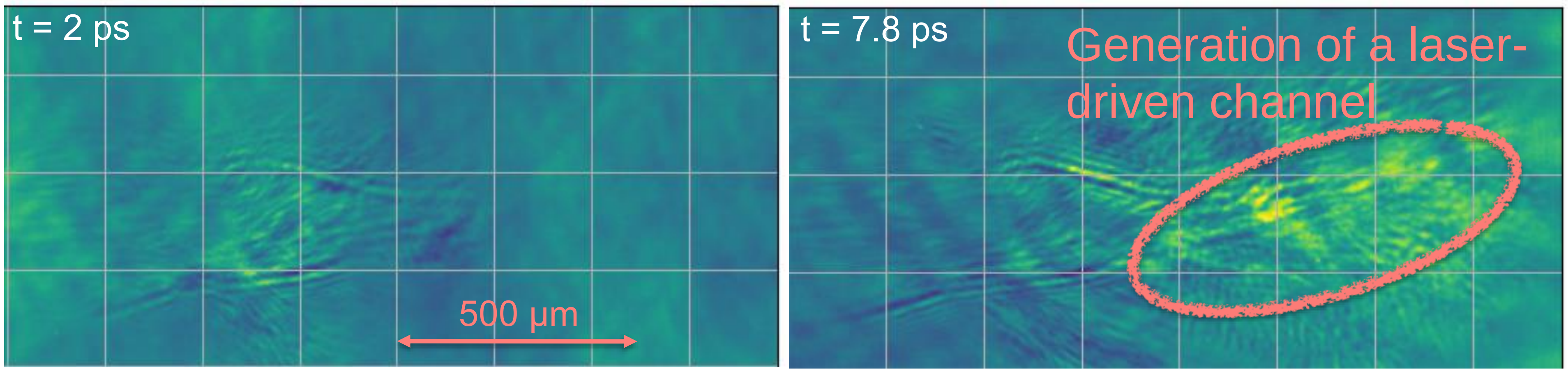
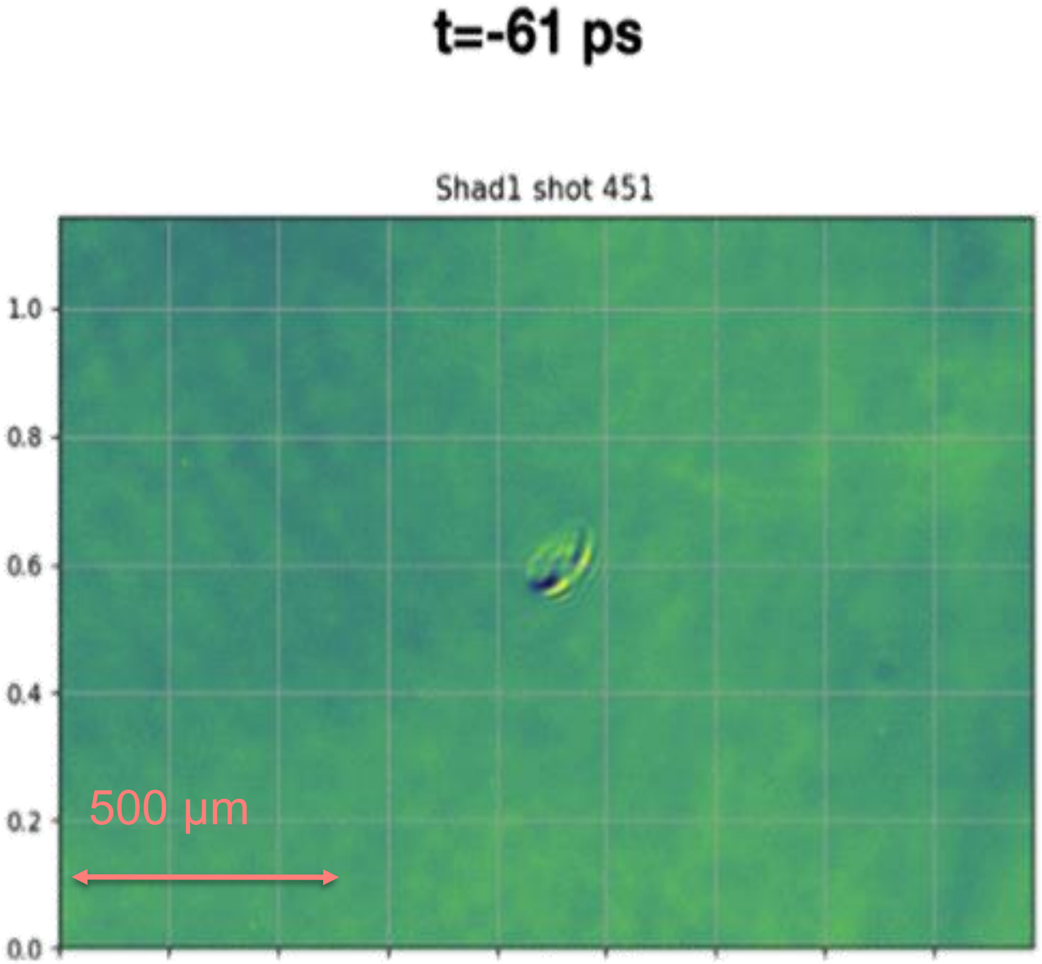
Case study 2: Investigation of channeling in near critical density plasma

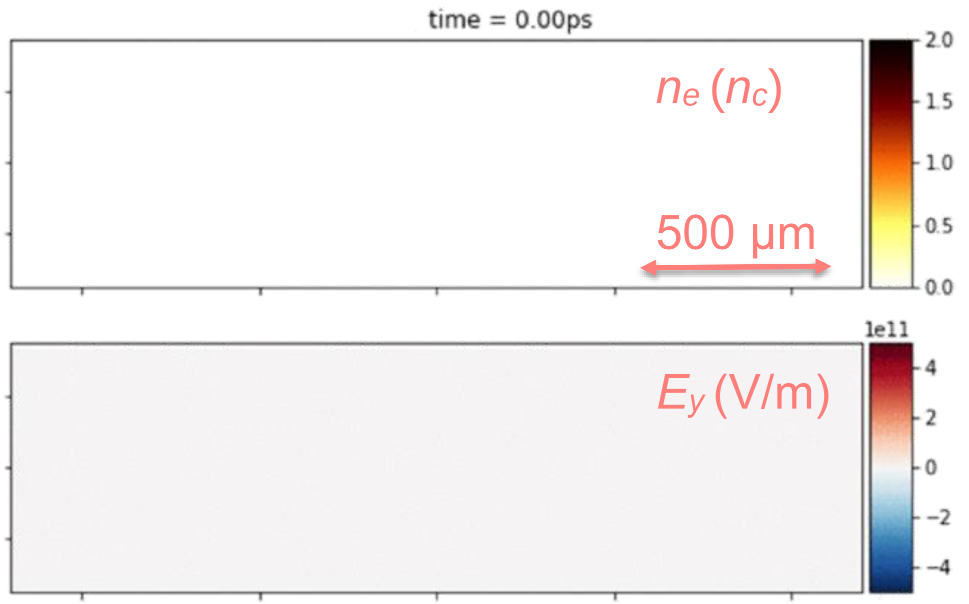
Shadowgraphy at two times from the same shot:

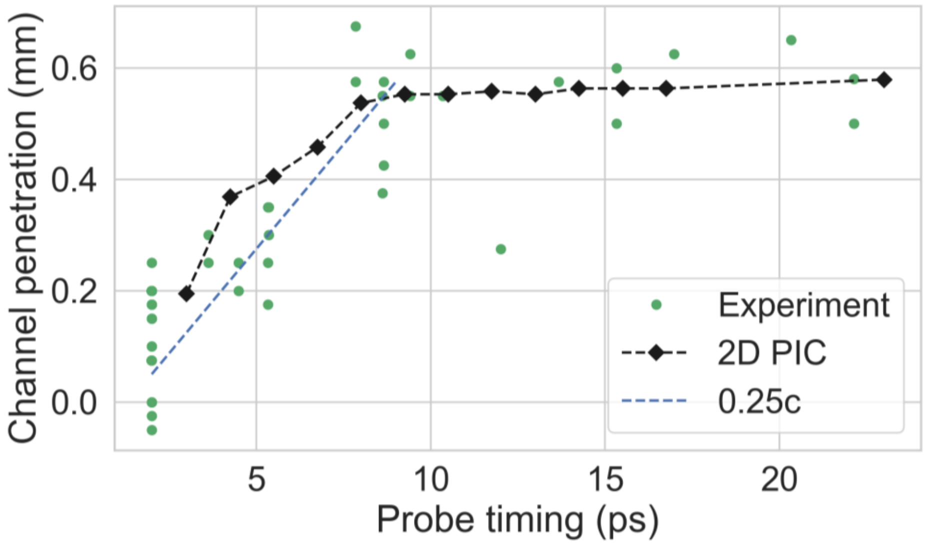


~1 n_{cr} hydrogen plasma

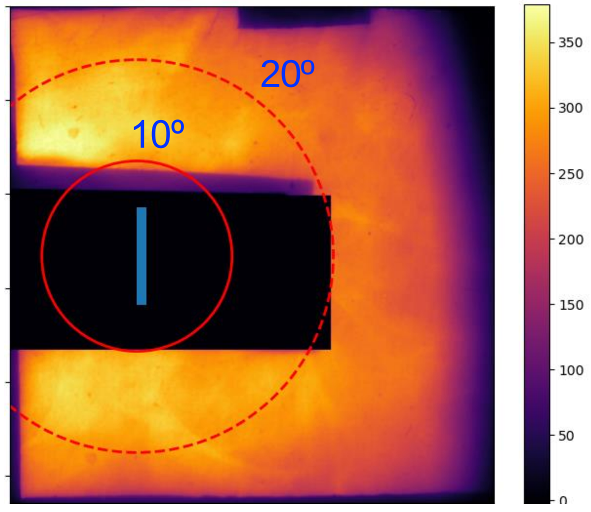
We measure temporal evolution of channel formation

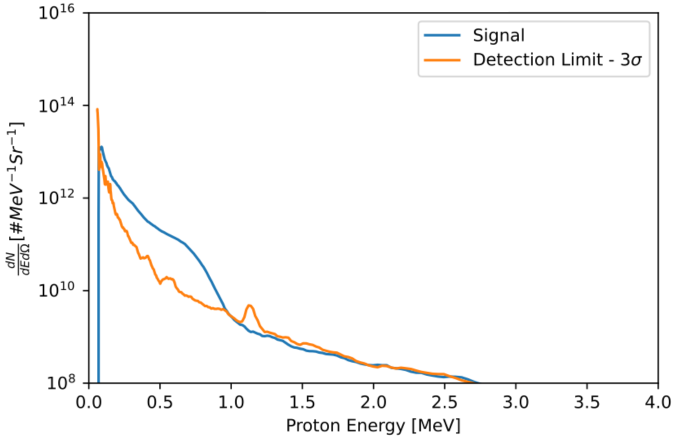


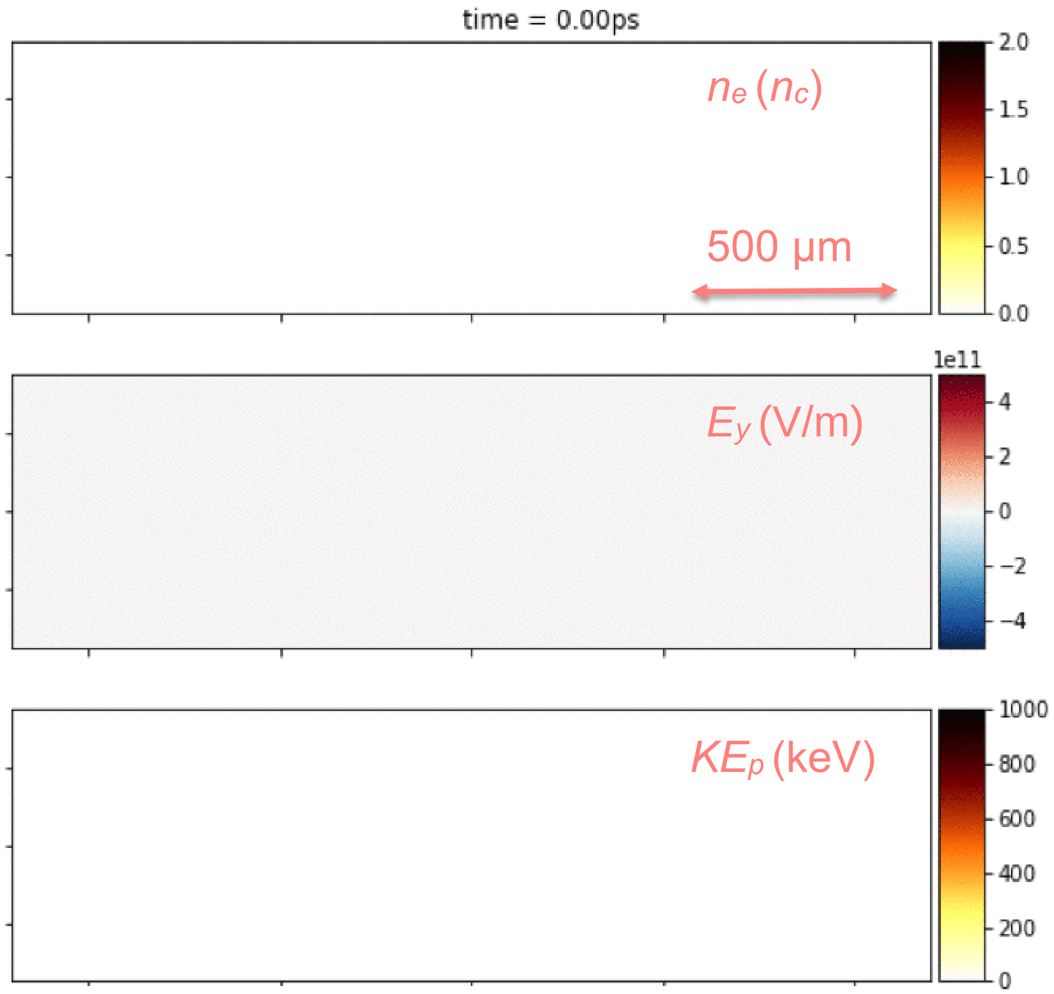




Ions also unexpectedly generated from channeling regime







Low energy, broadband ions generated from sheath acceleration at the rear of the plasma

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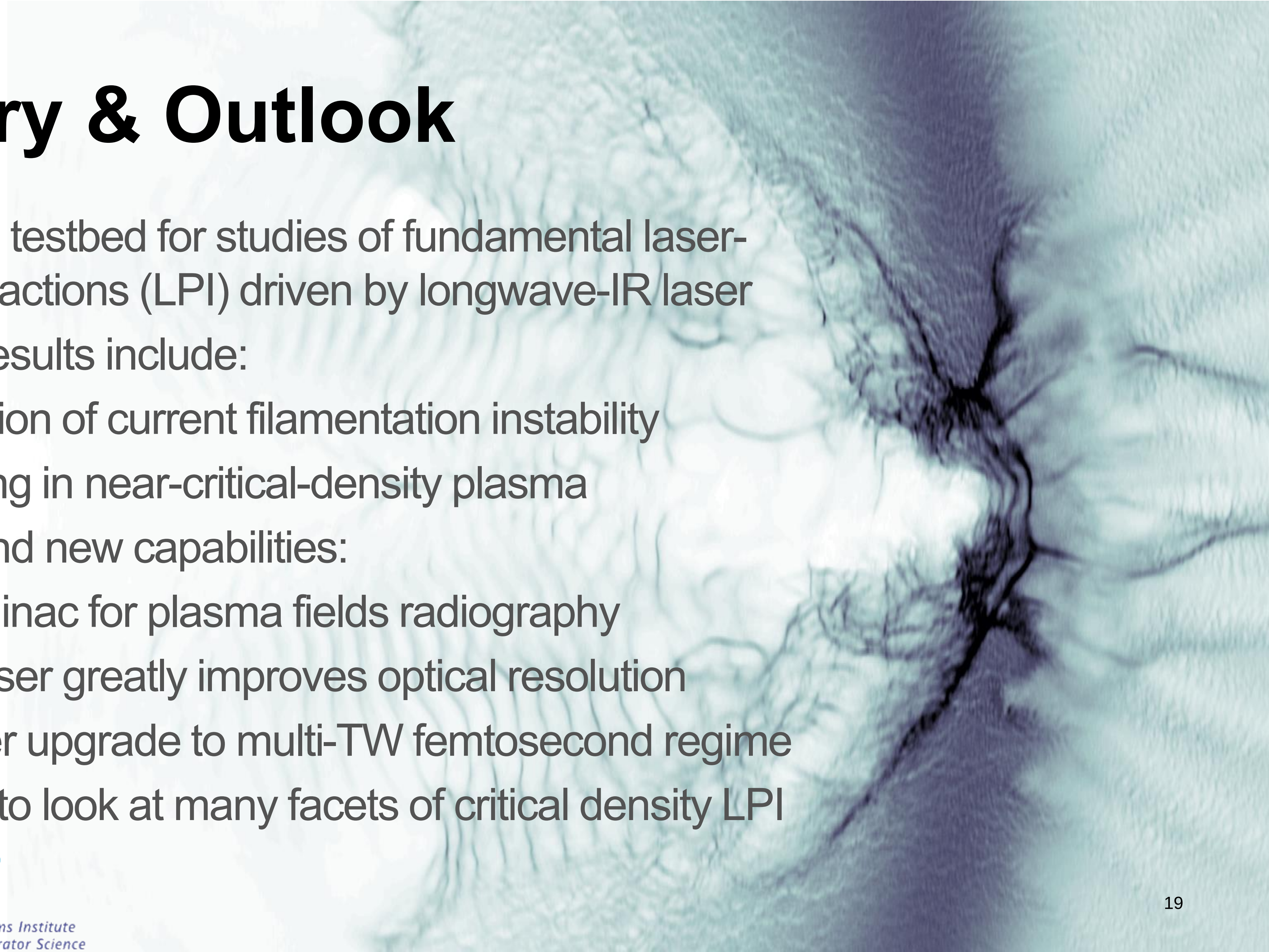
Summary & Outlook



- ATF offers a testbed for studies of fundamental laser-plasma interactions (LPI) driven by longwave-IR laser
- Presented results include:
  - Investigation of current filamentation instability
  - Channeling in near-critical-density plasma
- Additional and new capabilities:
  - electron linac for plasma fields radiography
  - fs Ti:S laser greatly improves optical resolution
  - CO_2 laser upgrade to multi-TW femtosecond regime
- Possibilities to look at many facets of critical density LPI