Technical challenges in laser assisted proton-Boron fusion

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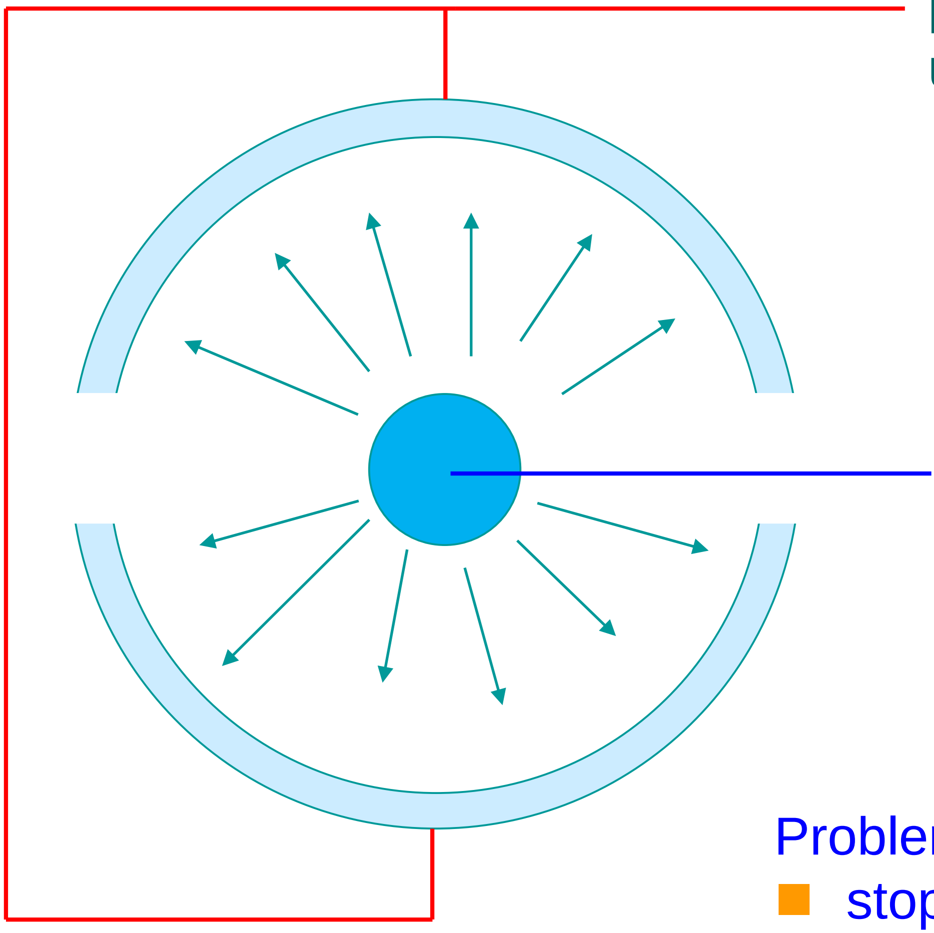
Advantages of proton-boron fusion

$$^{1}p + {}^{11}B + 0.6\text{MeV} \longrightarrow 3\ {}^{4}He + 8.7\text{MeV}$$

- Both reactants and products are not radioactive
- Much less neutron to damage the container
- Boron is abundant on earth
- The products are charged particles, easy to stop and convert to heat.

side reaction (1/1000): $^{11}B + {}^{4}He \rightarrow {}^{14}N + n + 157\ \text{keV}$

Converting directly to electric energy?



Problems:

- stopping range of alpha particle
- short circuit by electrons

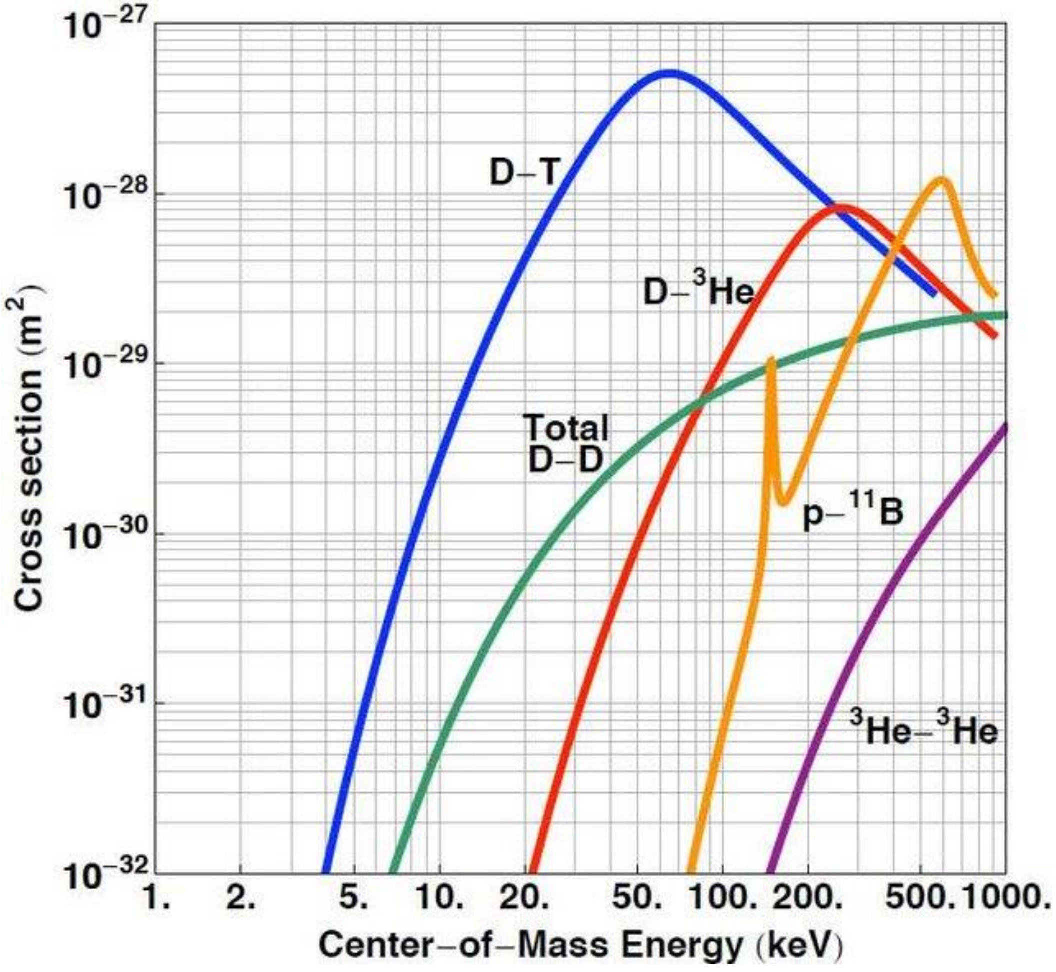
Disadvantages of proton-boron fusion

$$^{1}p + {}^{11}B + 0.6\text{MeV} \longrightarrow 3\ {}^{4}He + 8.7\text{MeV}$$

- The required collisional energy is ten times larger than D-T fusion
- The cross section is four times smaller than D-T fusion
- Bound electrons of boron dissipate most of the proton energy

Not suitable for the Tokamak reactor!

Disadvantages of proton-boron fusion



Can we accelerate proton to induce p-B fusion?

- Accelerating proton to 0.6 MeV is not difficult, but electrons must be expelled before the protons can get through effectively.
- It is difficult to expel electrons because the Coulomb force is very strong, and the expelled electrons return quickly.
- Protons will be scattered by the boron nucleus and leave the path of laser beam. Strong magnetic field is needed for confinement.

The problem of stopping range vs. mean free path

p-B fusion cross section
at 0.6 MeV

mean free path
for fusion

$$L = 1/(n\sigma) = 7 \text{ cm}$$

density of solid boron

electronic stopping range for 0.6-MeV proton = $6\ \mu\text{m}$

https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

Assisting proton-boron fusion

ARTICLE

Received 24 Jan 2013 | Accepted 27 Aug 2013 | Published 8 Oct 2013

DOI: 10.1038/ncomms3506

Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

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$$^{1}p + {}^{11}B + 0.6\,\mathrm{MeV} \longrightarrow 3\,{}^{4}He + 8.7\,\mathrm{MeV}$$

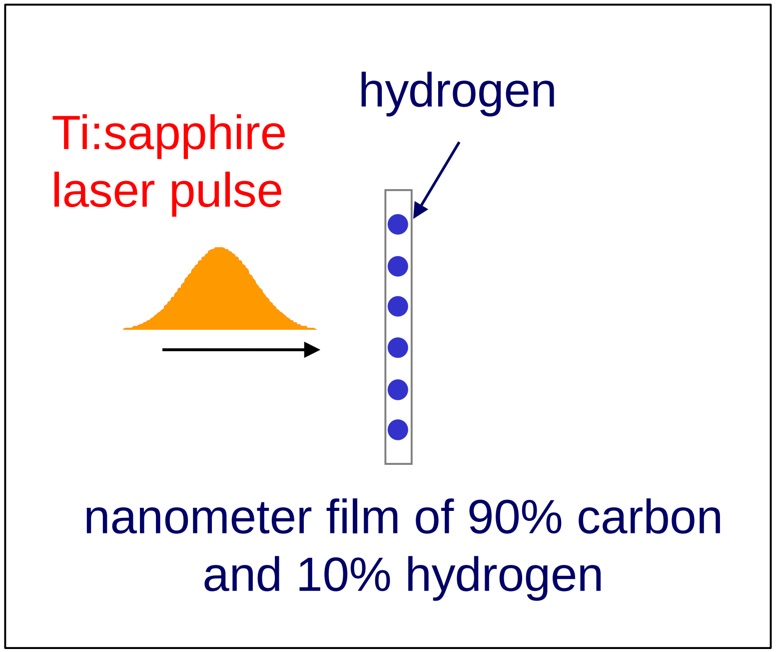
The advent of high-intensity-pulsed laser technology enables the generation of extreme states of matter under conditions that are far from thermal equilibrium. This in turn could enable different approaches to generating energy from nuclear fusion. Relaxing the equilibrium requirement could widen the range of isotopes used in fusion fuels permitting cleaner and less hazardous reactions that do not produce high-energy neutrons. Here we propose and implement a means to drive fusion reactions between protons and boron-11 nuclei by colliding a laser-accelerated proton beam with a laser-generated boron plasma. We report proton-boron reaction rates that are orders of magnitude higher than those reported previously. Beyond fusion, our approach demonstrates a new means for exploring low-energy nuclear reactions such as those that occur in astrophysical plasmas and related environments.

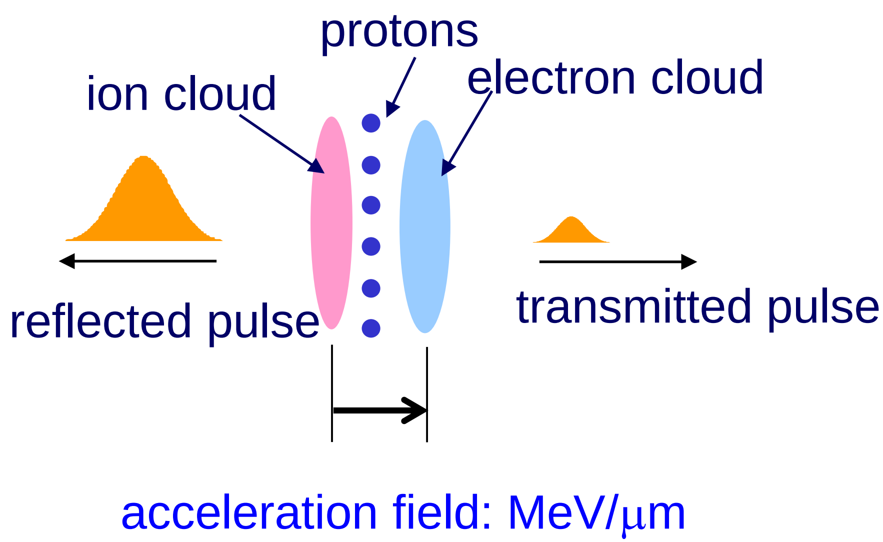
How pulsed laser can help

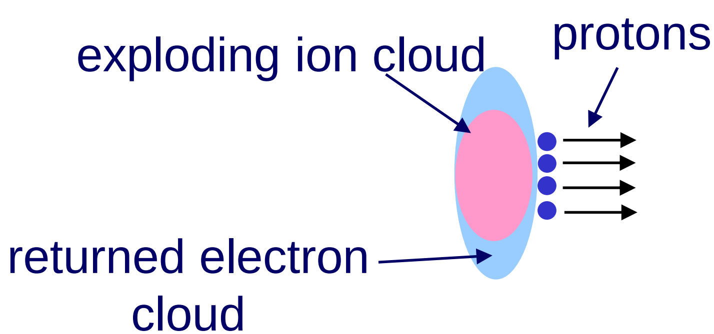
$$^{1}p + ^{11}B + 0.6\,MeV \longrightarrow 3\ ^{4}He + 8.7\,MeV$$

- Accelerating protons in ultrashort pulse mode
- Ionizing boron atoms and expel electrons synchronously
- Generating strong magnetic field synchronously for proton confinement

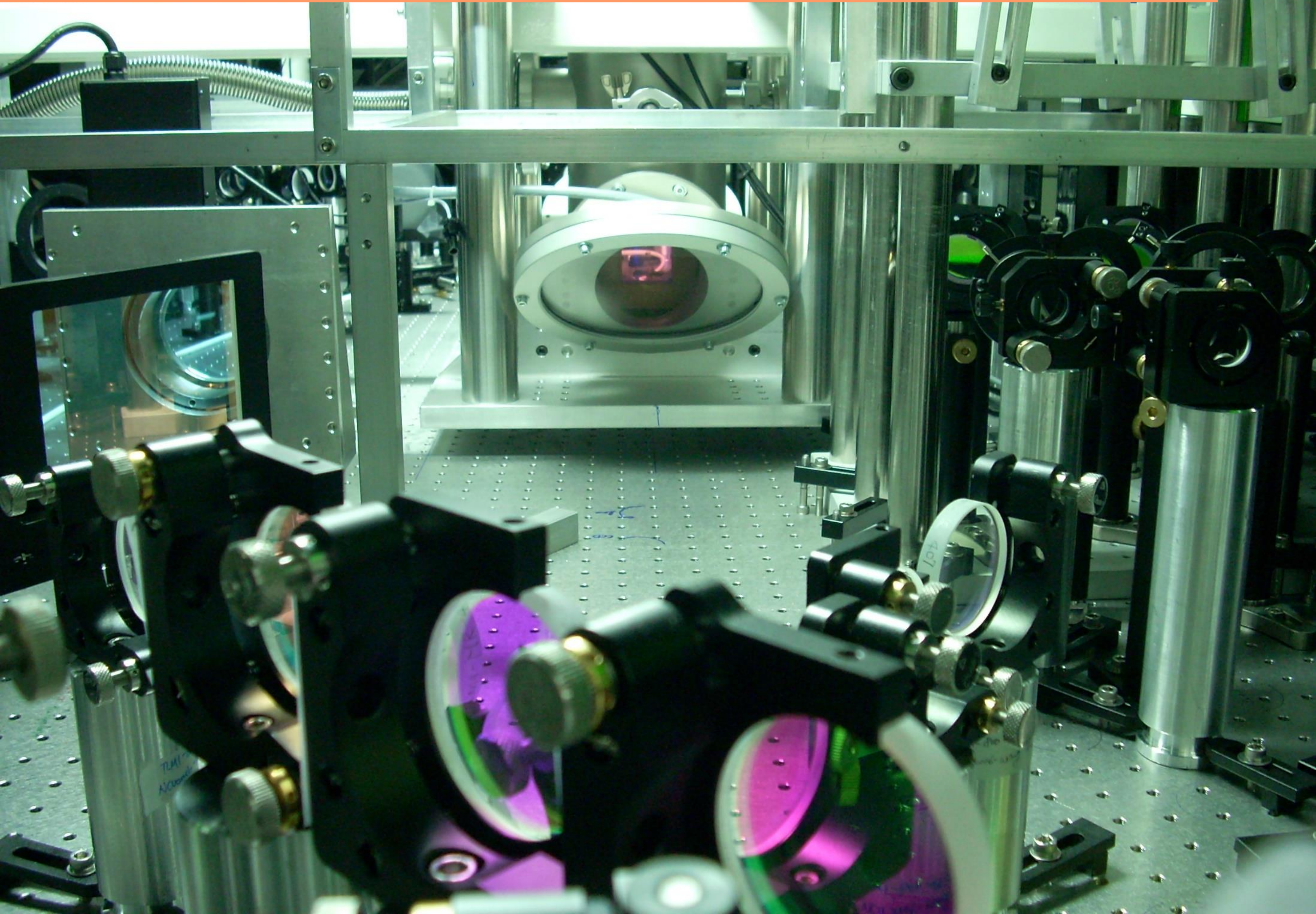
A scheme of laser-driven proton accelerator





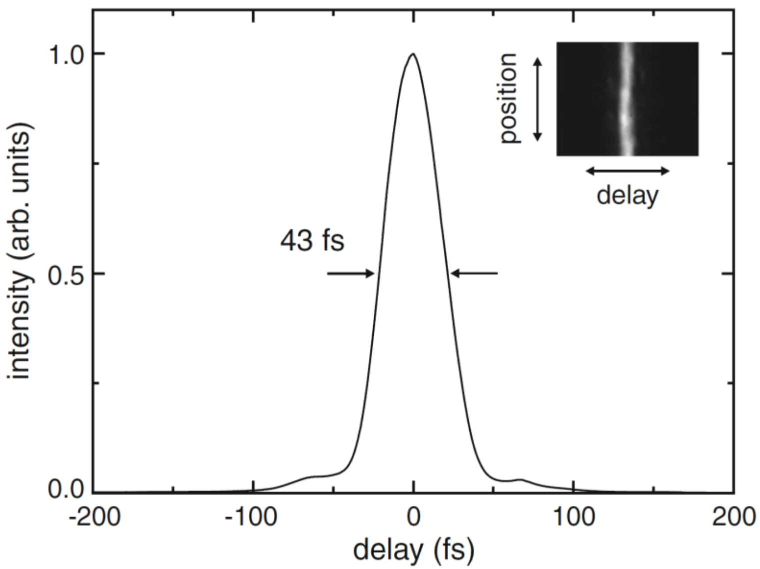


100-TW final stage amplifier at Nat'l Central Univ.



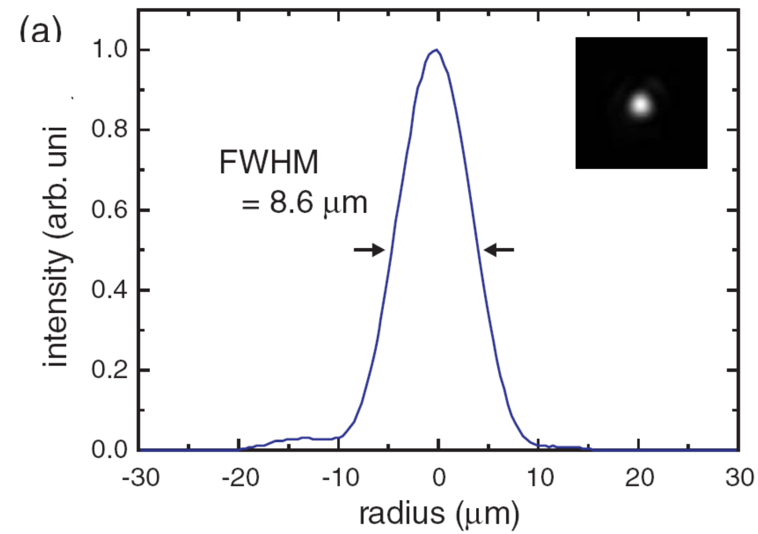
Compressed and focused pulse

autocorrelation trace



corresponding to a pulse duration of 30 fs

camera lineout



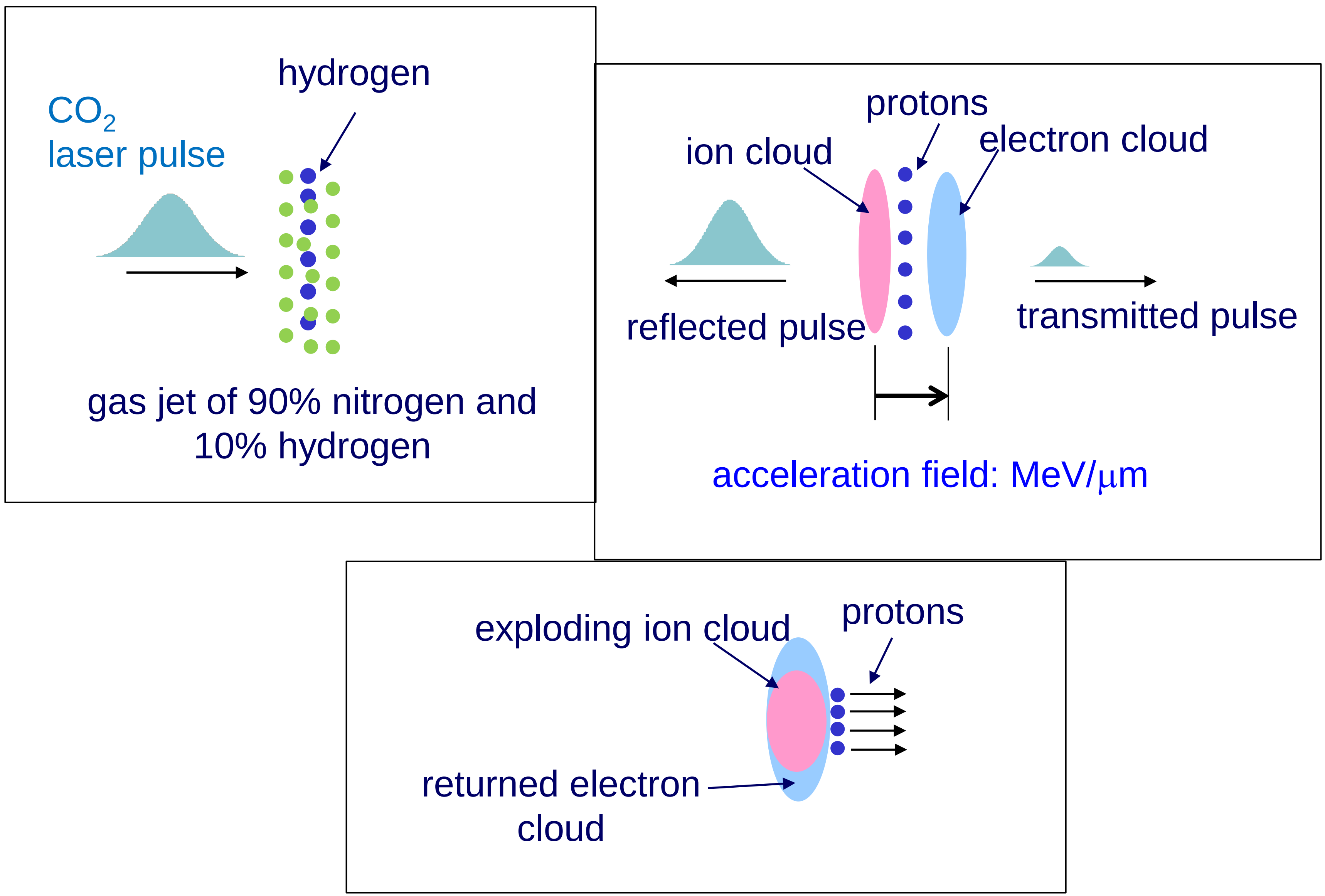
If adaptive mirrors are used, it is possible to focus down to 1-μm diameter.

Appl. Phys. B **117**, 1189 (2014)

100-TW laser focused to 10-μm diameter

- peak intensity: 10^{20} W/cm^2 (sunshine at noon = 0.1 W/cm^2)
- electric field: 3.2×10^{13} V/m (50× Coulomb field in hydrogen)
- magnetic field: 1.1×10^{5} T (2B× earth surface magnetic field)
- optical pressure: 6.7×10^{10} bar (1/4× center of the Sun)
- plasma temperature: 10^{7} K (center of the Sun)
- energy density: 10^{9} J/cm^3 (B83 H-bomb, 1.2 MT of TNT)

A scheme of laser-driven proton accelerator



Ponderomotive force for free electrons

$$\mathbf{a} = -\frac{e\mathbf{E}}{m}$$ nonrelativistic, ignoring $\frac{\mathbf{v}}{c} \times \mathbf{B}$

electron displacement $$\mathbf{x} = \frac{e\mathbf{E}}{m\omega^2}$$

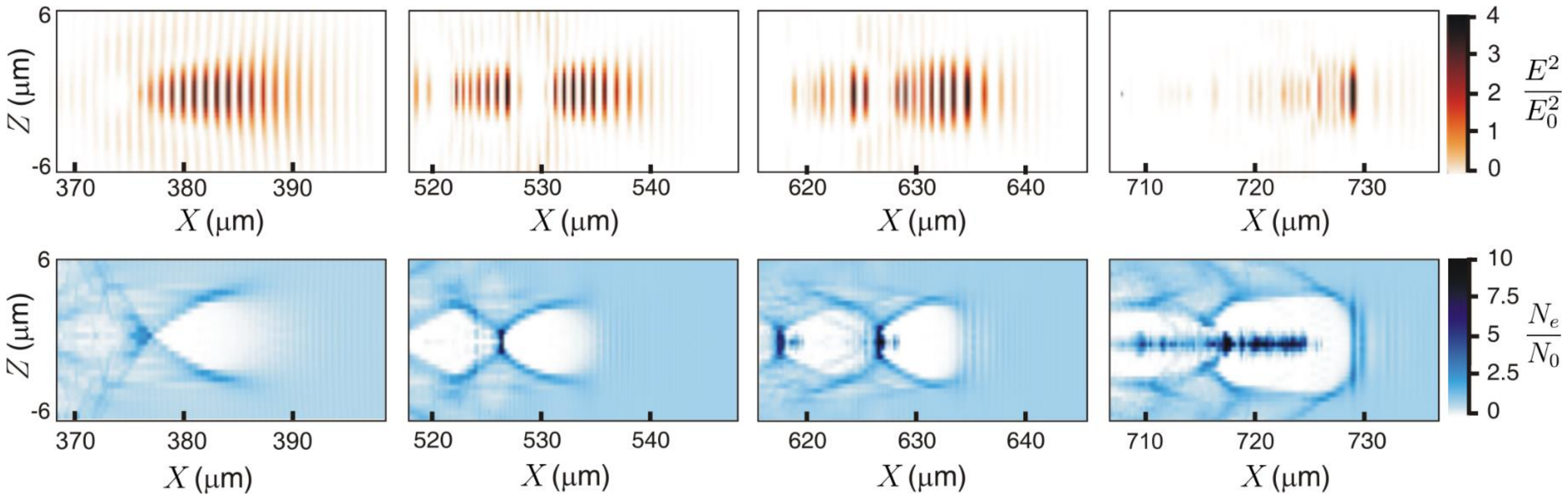
dipole moment $$\mathbf{p} = -\frac{e^2\mathbf{E}}{m\omega^2}$$

ponderomotive force $$\mathbf{F}_p = (\mathbf{p} \cdot \nabla)\mathbf{E} = -\frac{e^2}{2m\omega^2}\nabla(\mathbf{E} \cdot \mathbf{E})$$

An intense laser pulse expels electrons with a ponderomotive force of ~GeV/cm.

Accelerating electrons in a nonlinear wake

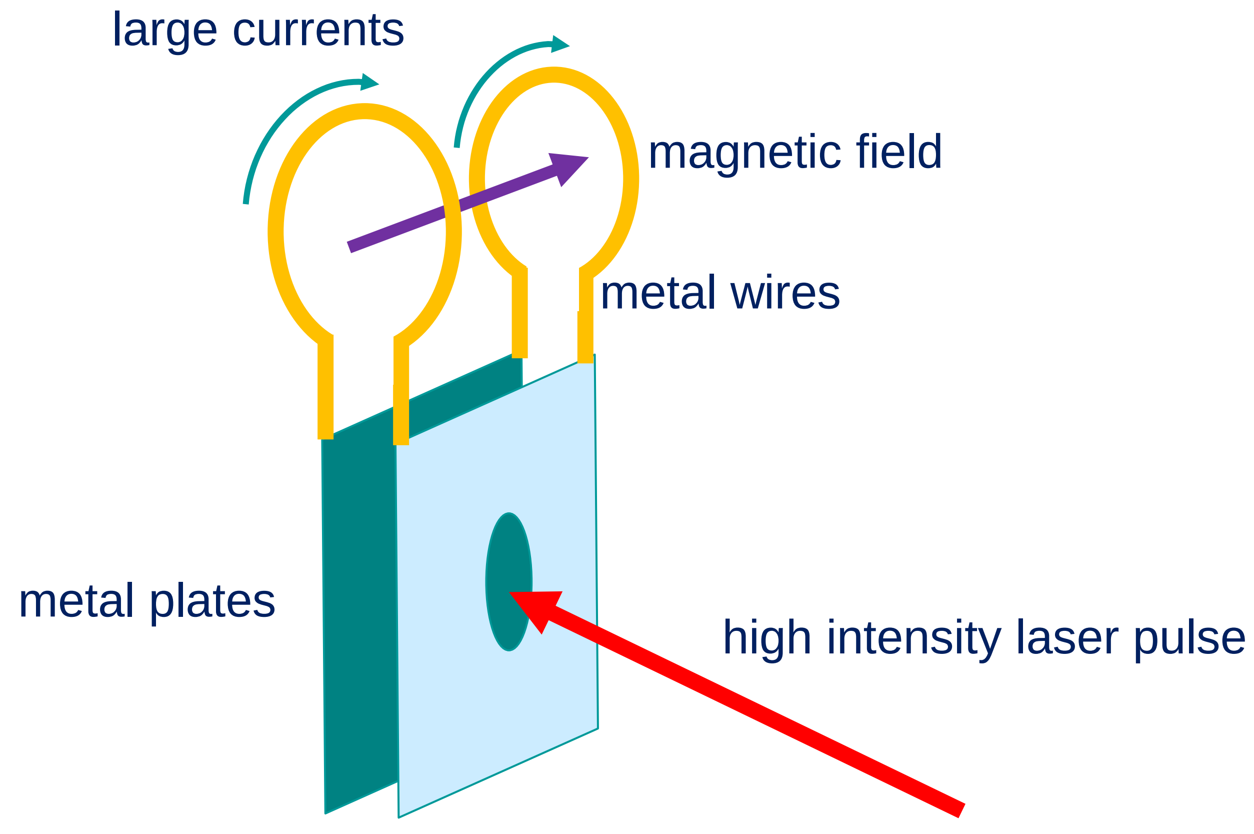
evolution of laser pulse



evolution of electron density

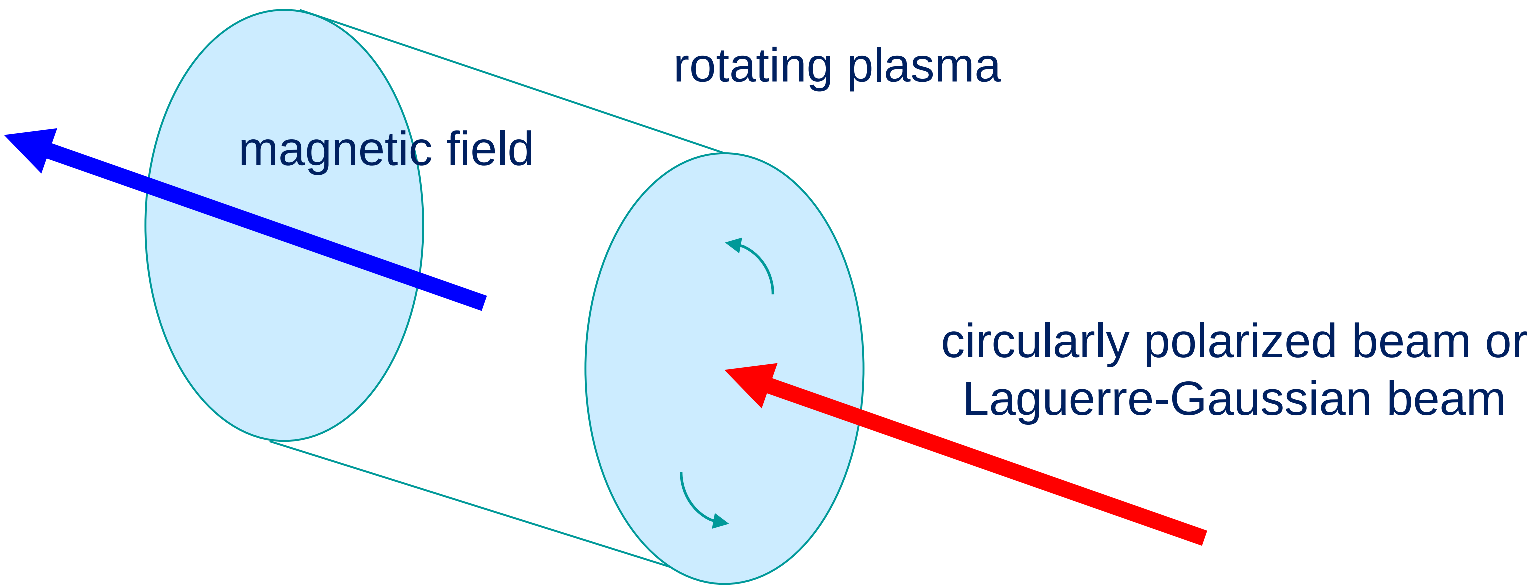
- After nonlinear propagation, the laser pulse becomes spatially self-focused and temporally compressed.
- The ponderomotive force expels electrons, resulting in a positively charged cavity following laser pulse.
- The electric field at the rear edge of the cavity is ~3×10^{11} V/m.

Generating kilotesla magnetic field?



Scientific Reports **3**,1170 (2013)

Transferring angular momentum from laser to plasma



10^4 T is required to limit the Larmor radius to 10 μm for 0.6-MeV protons.

Energy balance sheet

energy gain from p-B fusion = 8.7/0.6 = 14.5

efficiency of CO_2 laser ≈ 0.01

key problem

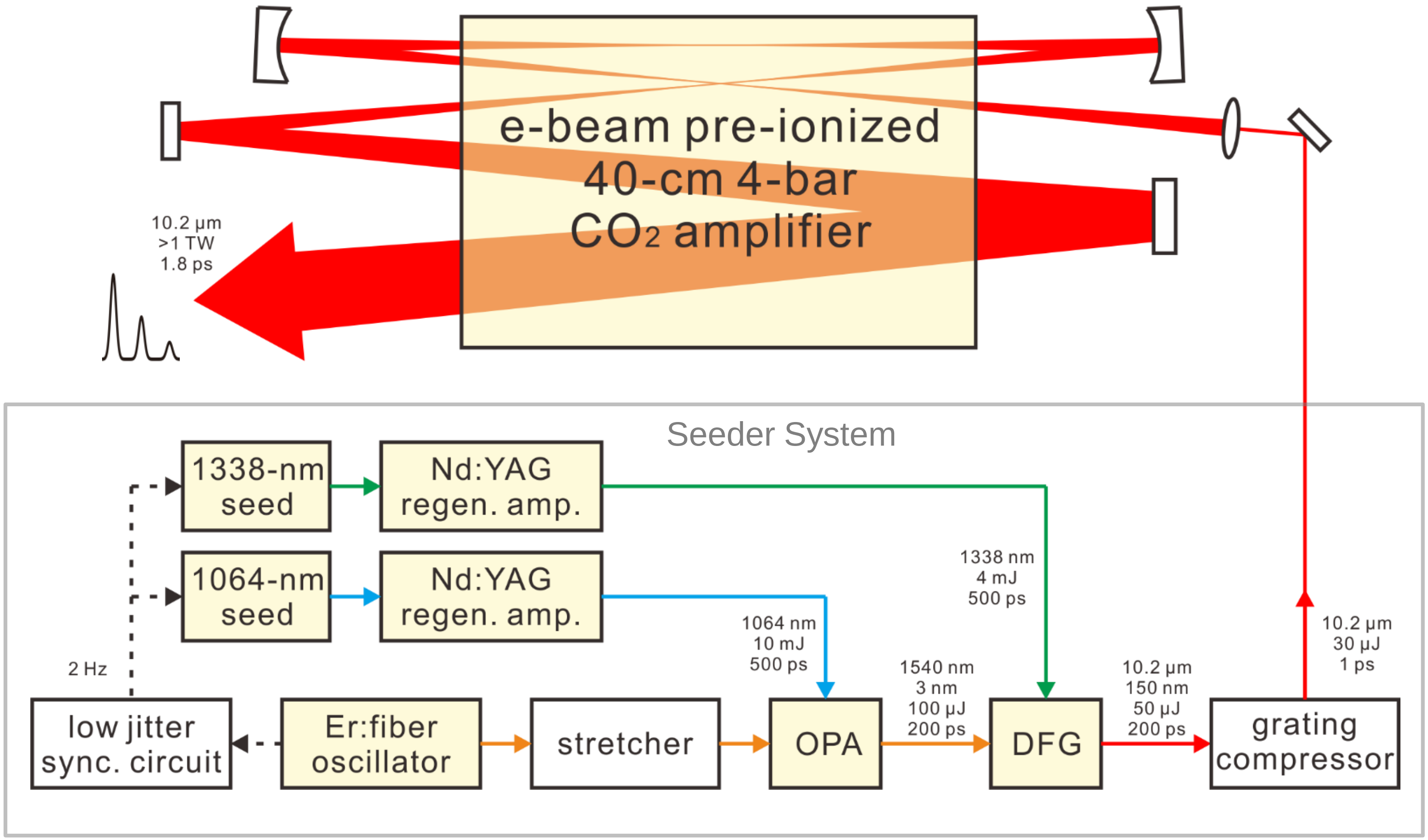
efficiency of laser proton accelerator ≈ 0.01

total energy gain ≈ 0.0015

without including the energy cost for magnetic field generation.

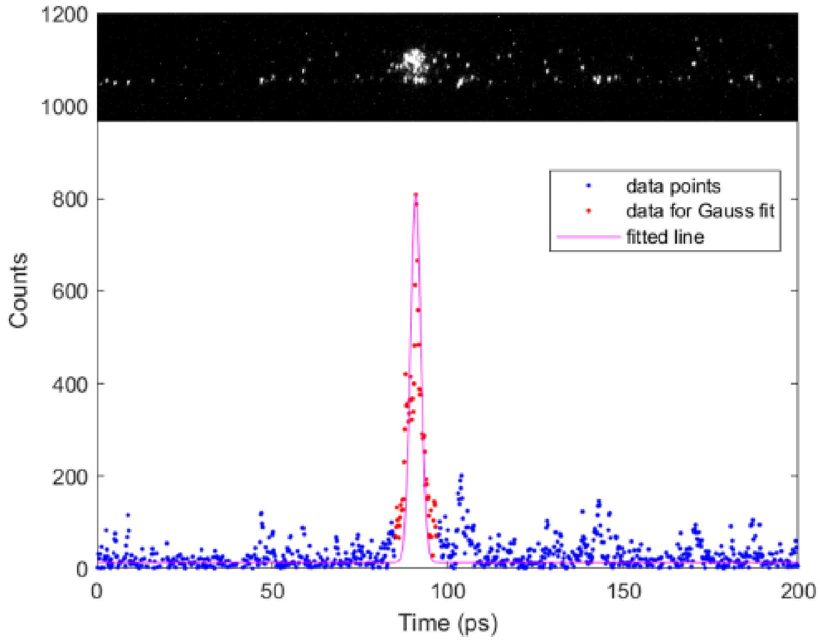
The NSTC energy strategic project

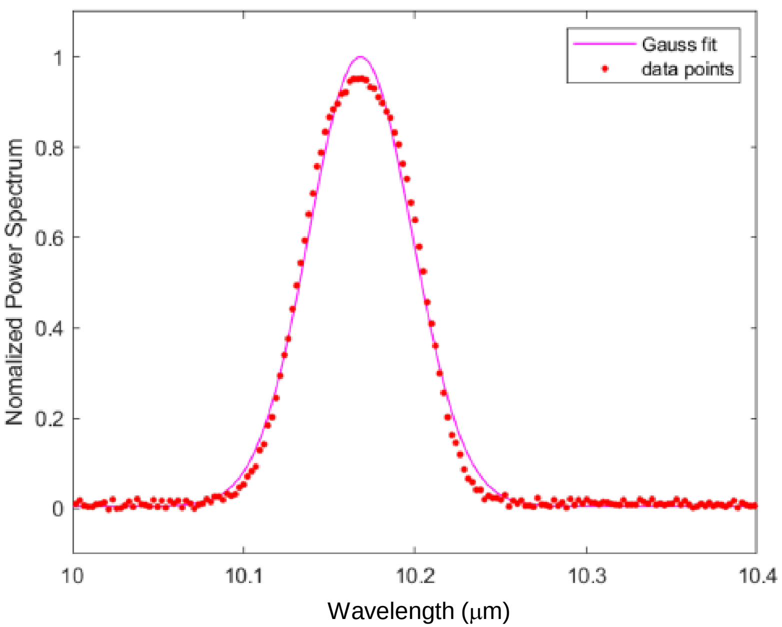
The proposed TW CO_2 laser system

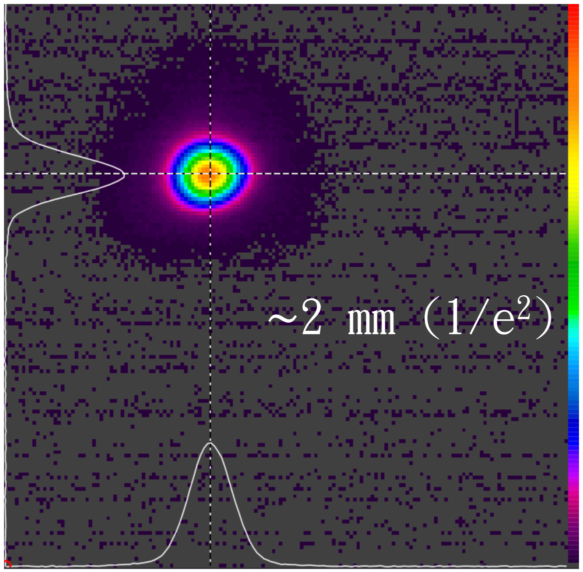


Peak intensity of >5 GW/cm^2 can be achieved by focusing the beam to 60-µm diameter (FWHM).

The CO_2 laser seed pulse







central wavelength: 10.17 μm

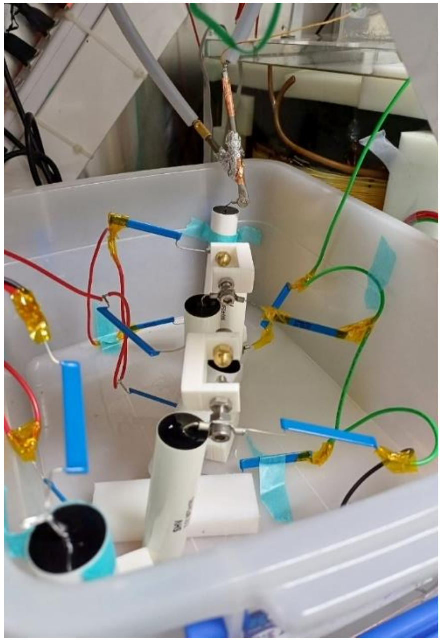
spectral bandwidth: 70 nm (FWHM)

pulse duration: < 3 ps

pulse energy: 60 μJ

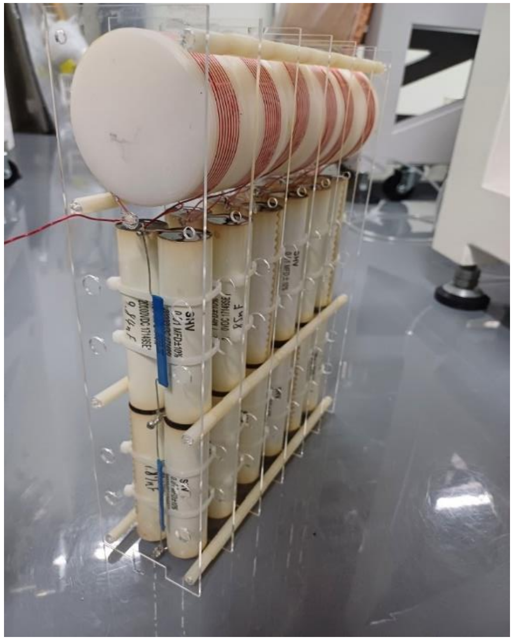
energy stability: 3% rms

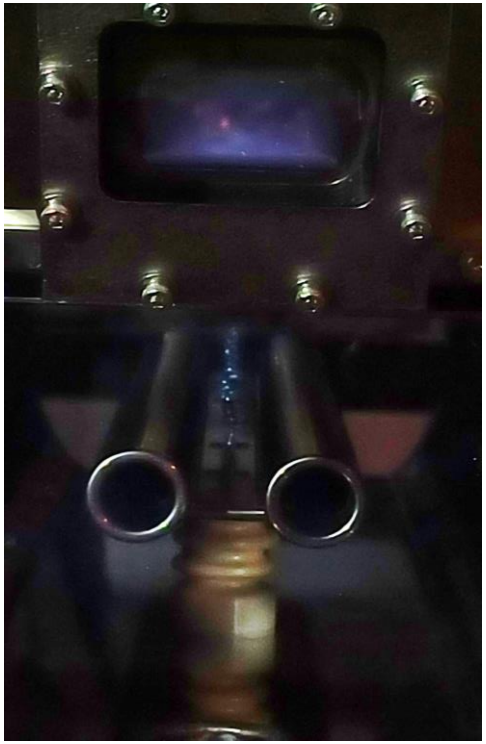
The CO_2 laser amplifier (under construction)



6-stage Marx generator

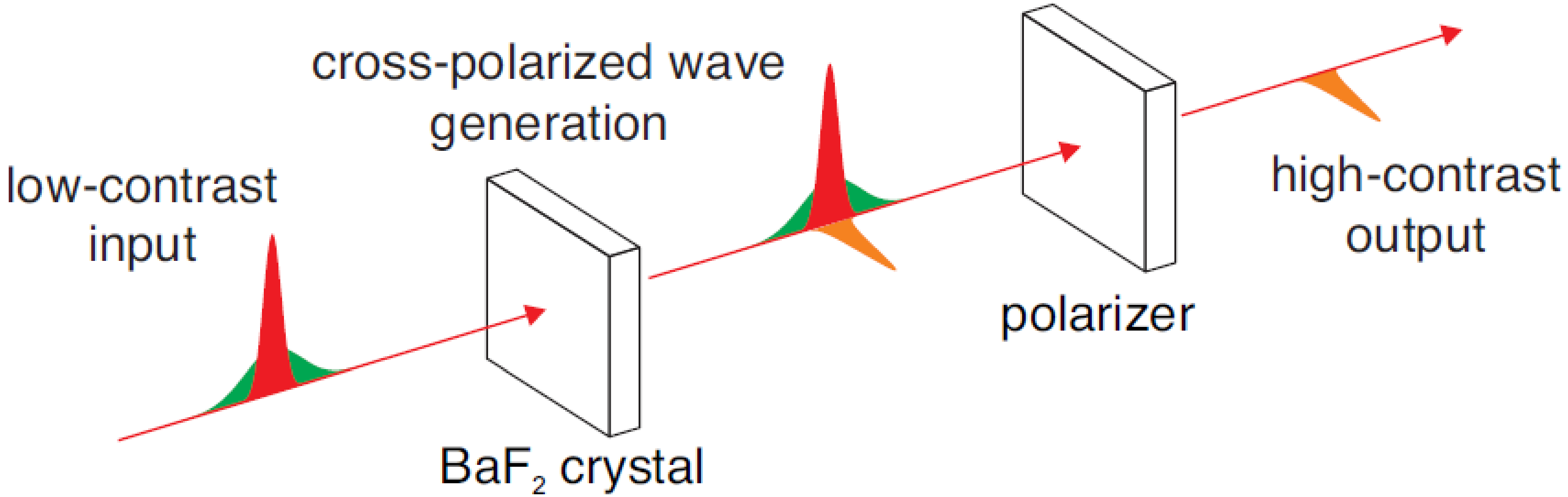
6-stage pulse-forming network



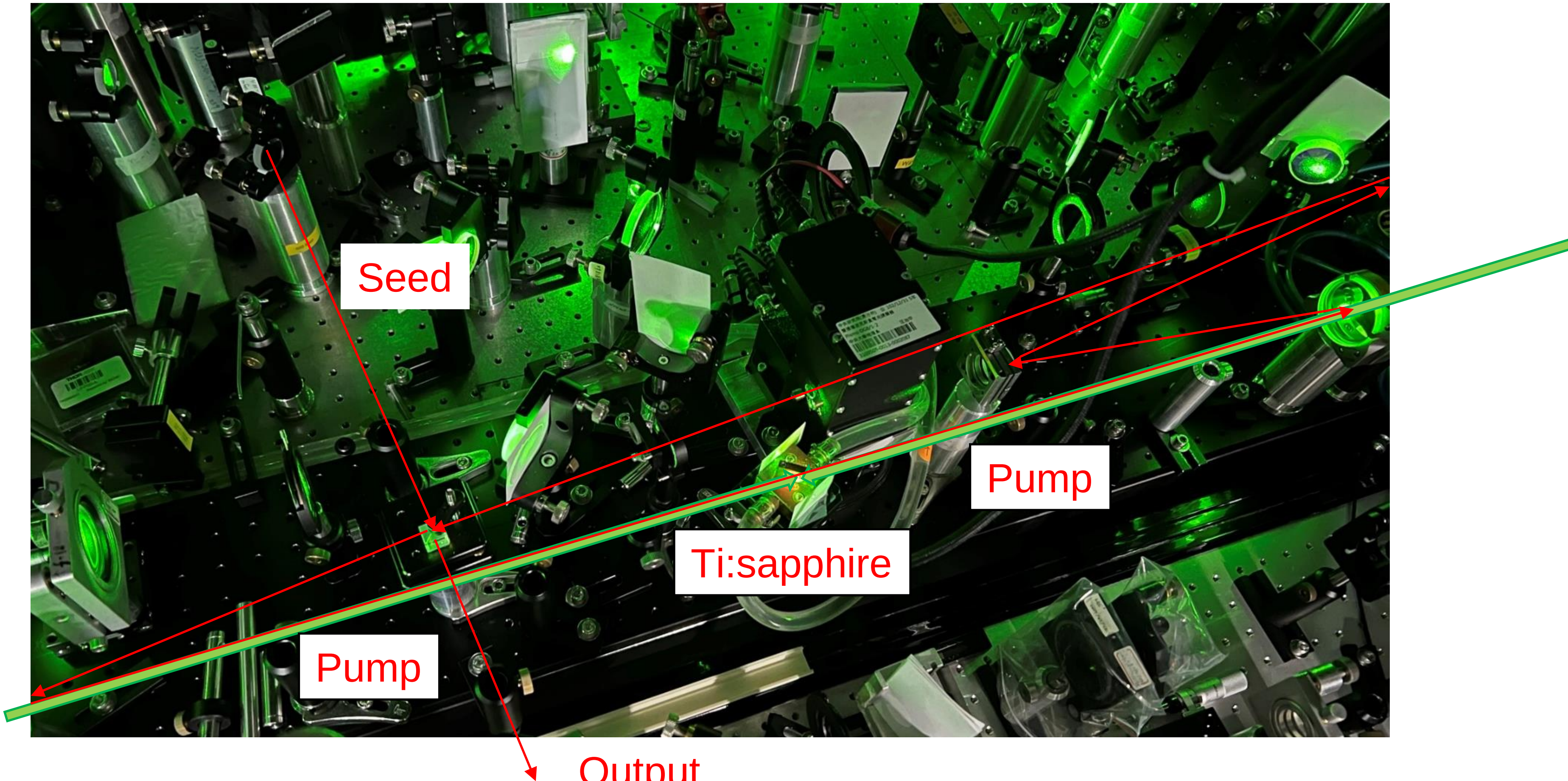


Purplish light from N_2 ionized by electrons emitted from a cold cathode.

Enhancing pulse contrast by nonlinear optics

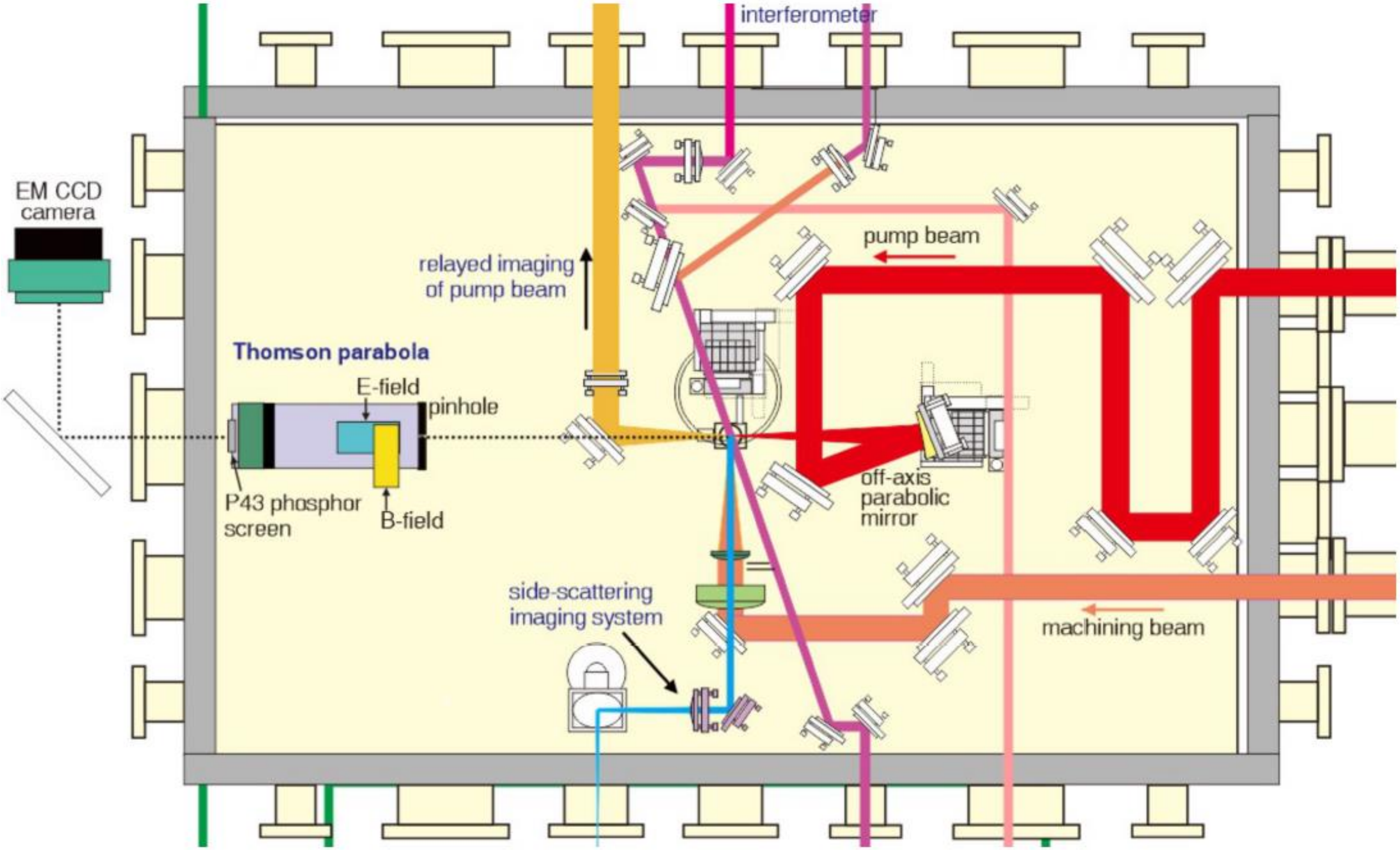


A ring regenerative amplifier built for double CPA



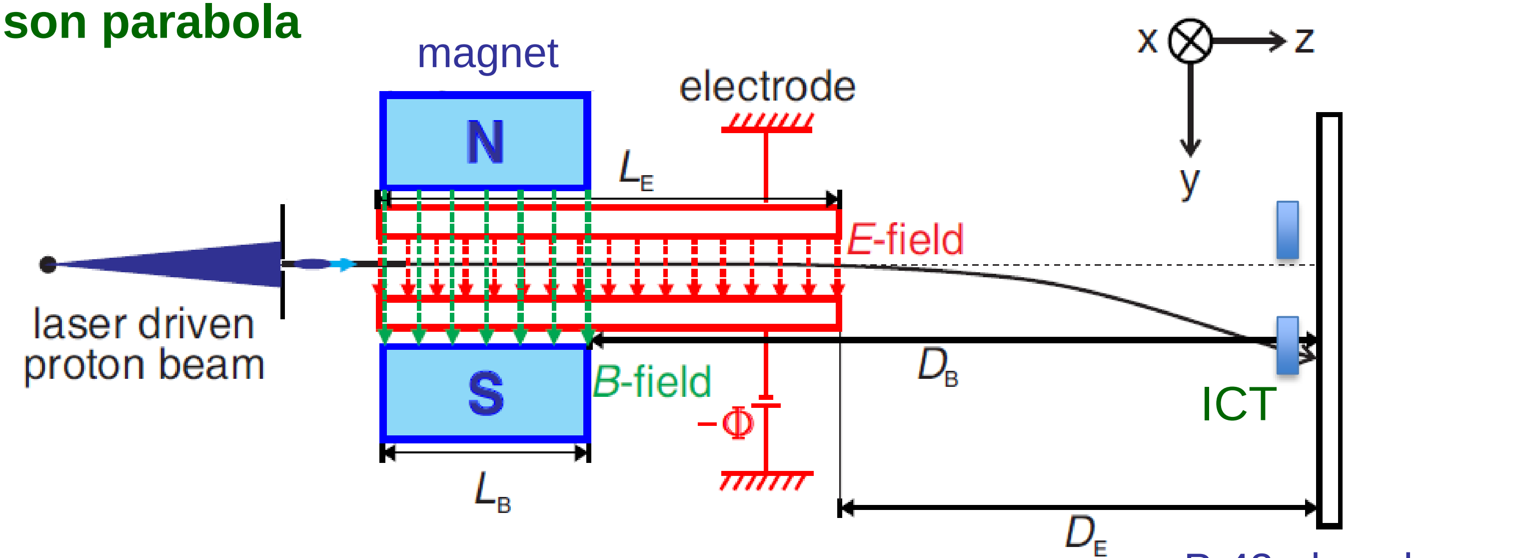
A high-contrast ring regenerative amplifier (1.2 mJ, 1.5% fluctuation) has been constructed, which will be incorporated into the 100-TW laser system.

Experimental setup for laser proton acceleration



Proton beam diagnosis

Thomson parabola



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

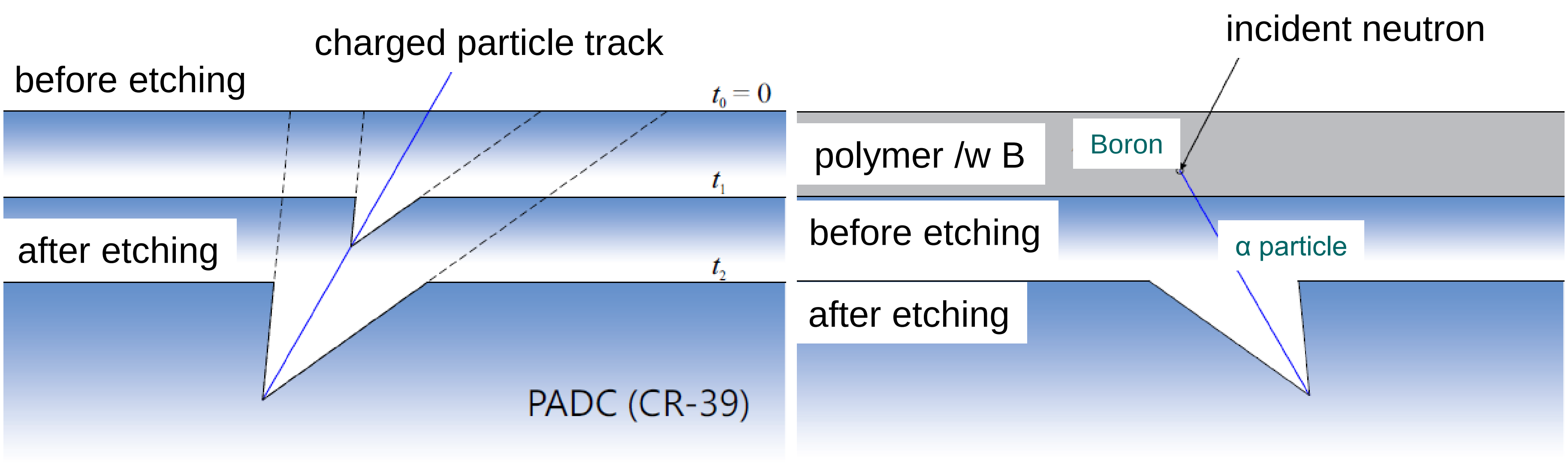
$$x = \frac{qB}{mv} L_B \left(\frac{L_B}{2} + D_B\right),$$

$$y = \frac{qE}{mv^2} L_E \left(\frac{L_E}{2} + D_E\right)$$

Thomson parabola is for measuring proton energy spectrum. Absolute proton number can be measured by using CR-39 plate and integrating current transformer (ICT).

Diagnosis of p-B fusion products

- p-B fusion products: proton, α particle, neutron
- Diagnosis: track analysis of etched CR-39



charged particle (proton, α particle) detection

neutron detection

Thank you for your attention