Relativistic Laser Plasma Explored with PW lasers at CoReLS

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IBS Center for Relativistic Laser Science

- **PW Ti:Sapphire Laser**
  - **(1) Beamline I: 20 fs, 1 PW @ 0.1 Hz**
  - **(2) Beamline II: 20 fs, 4 PW @ 0.1 Hz**
- **150-TW Laser: Δt = 25 fs @ 5 Hz**

Overview

1. Femtosecond PW Laser

2. Relativistic Plasma

A. Achieved laser intensity > 10^{22} W/cm^2

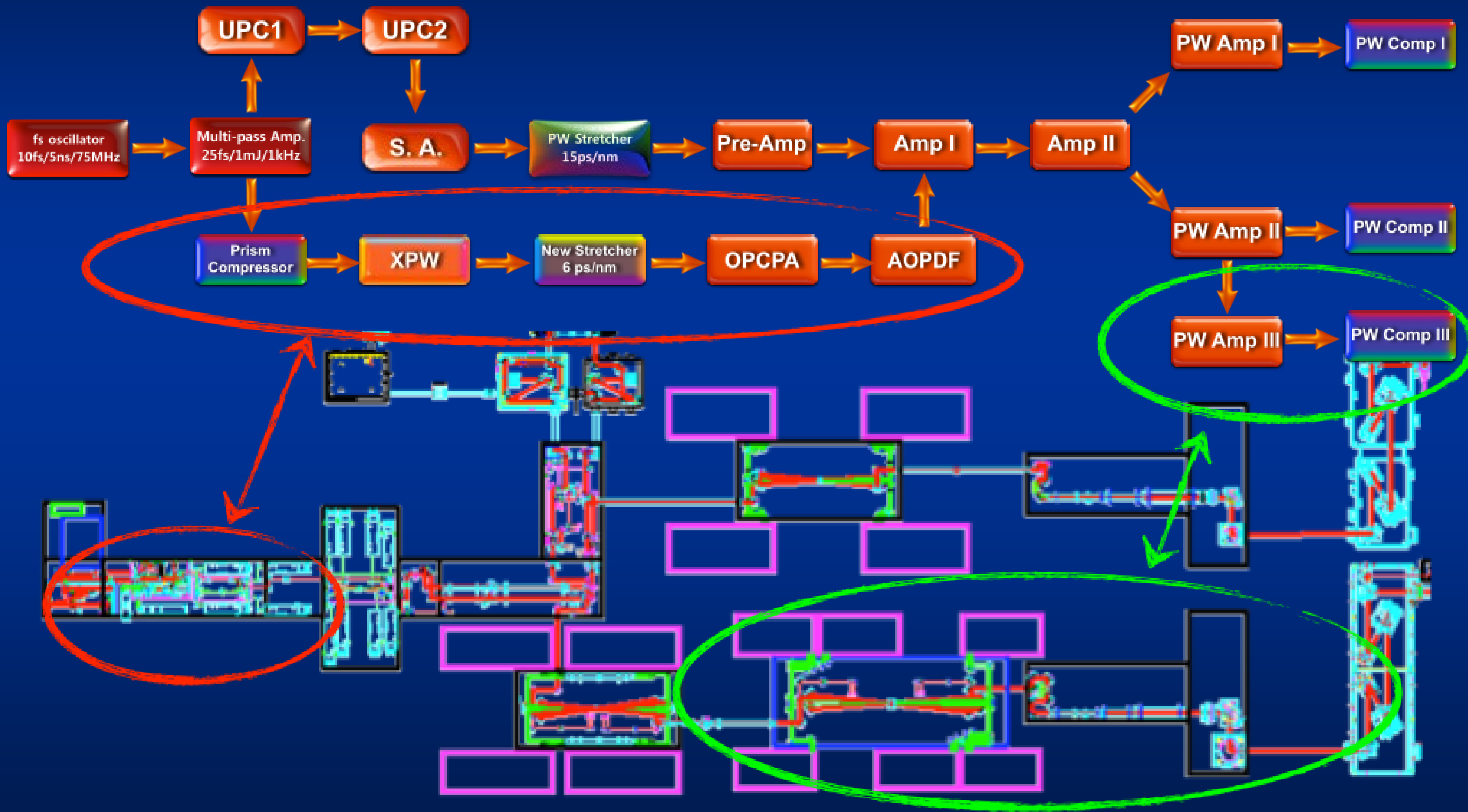
B. High energy proton generation

3. Strong Field QED

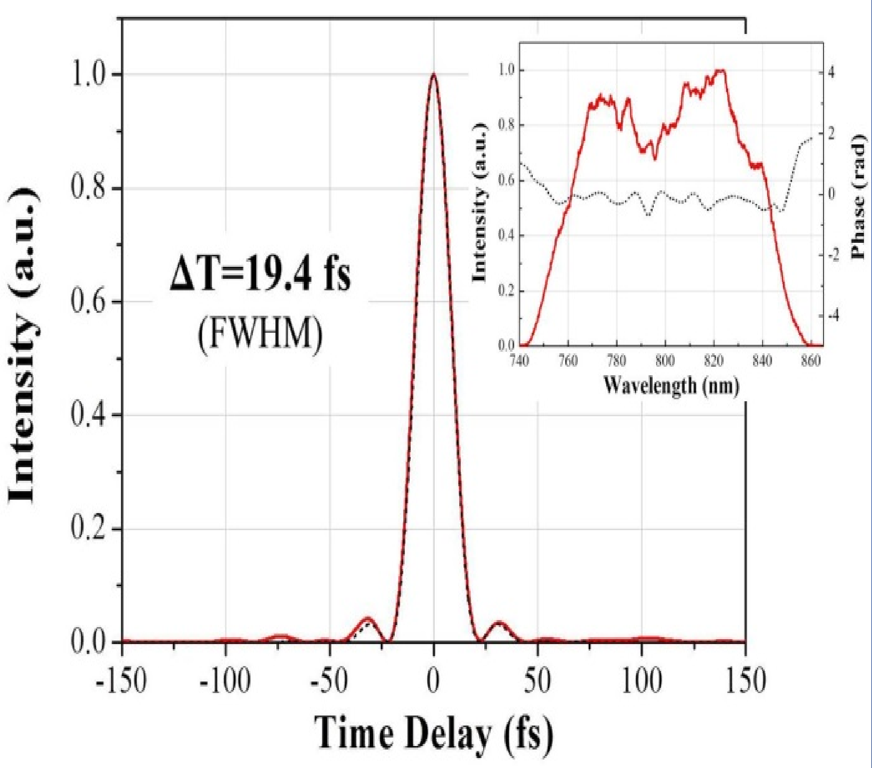
A. Multi-GeV electron acceleration

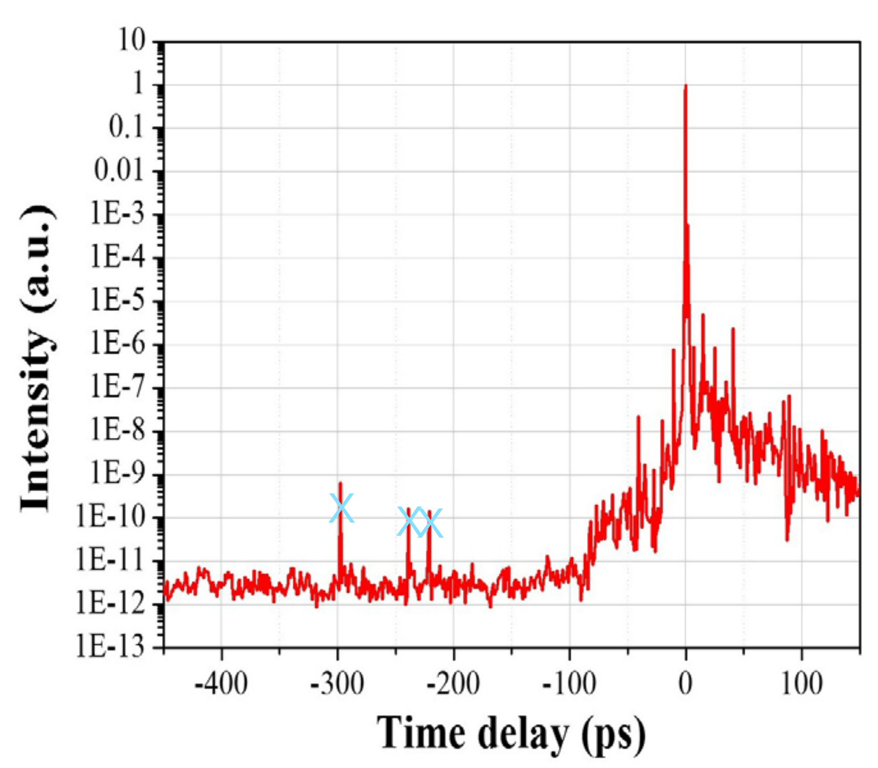
B. Nonlinear Compton Scattering

Upgrade: High Contrast, 20 fs, 4 PW Laser



Temporal Profile and Contrast of 4 PW Laser





83J, 19.4fs, 4.2PW!

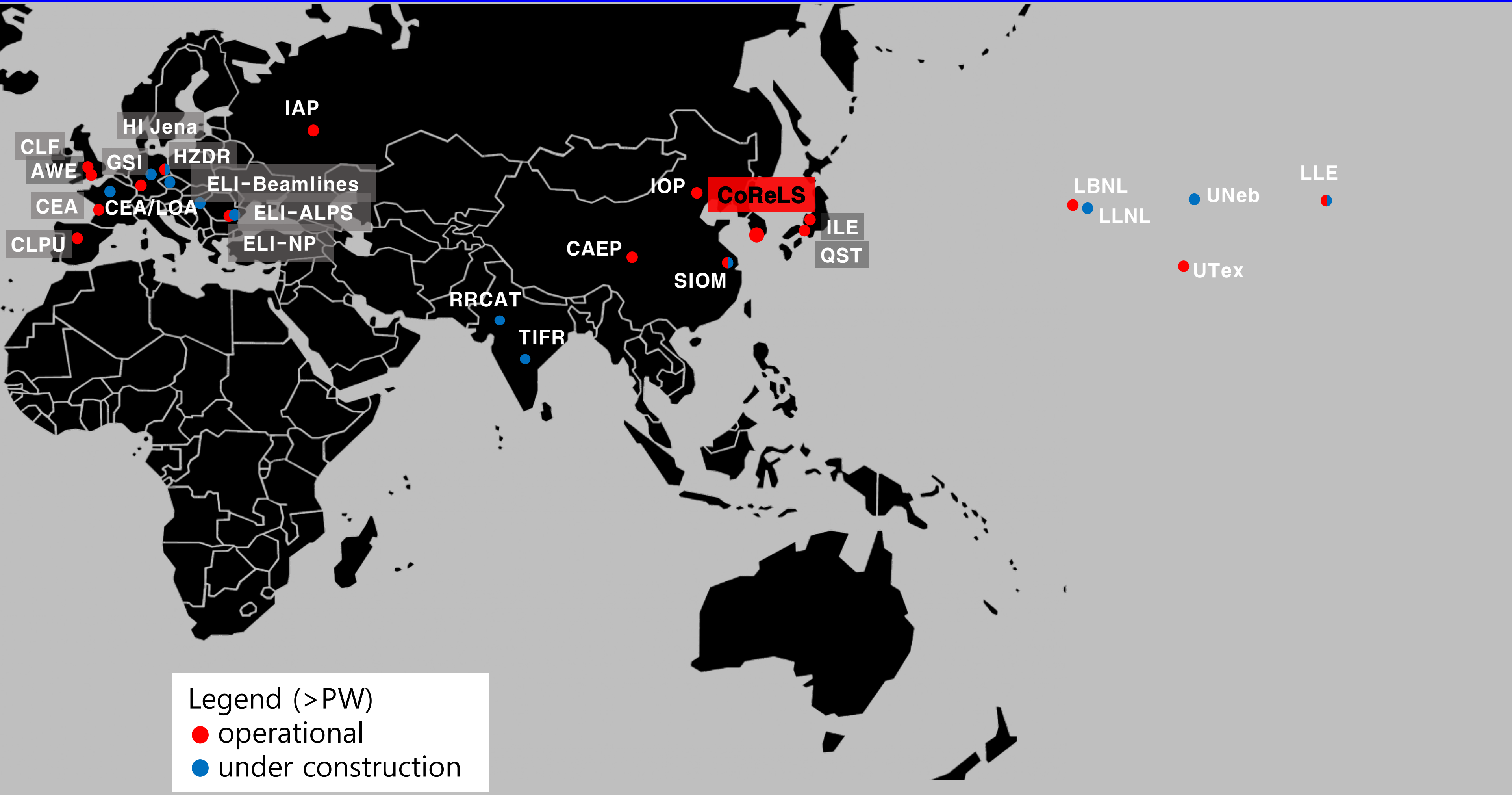
ibs CoReLS Center for Relativistic Laser Science

Sung et al., Opt. Lett. (2017)

GIST

CoReLS PW laser: 1 PW + 4 PW Beamlines

Worldwide PW Lasers



Referred by http://smashinghub.com/vector-world-map-collection.htm

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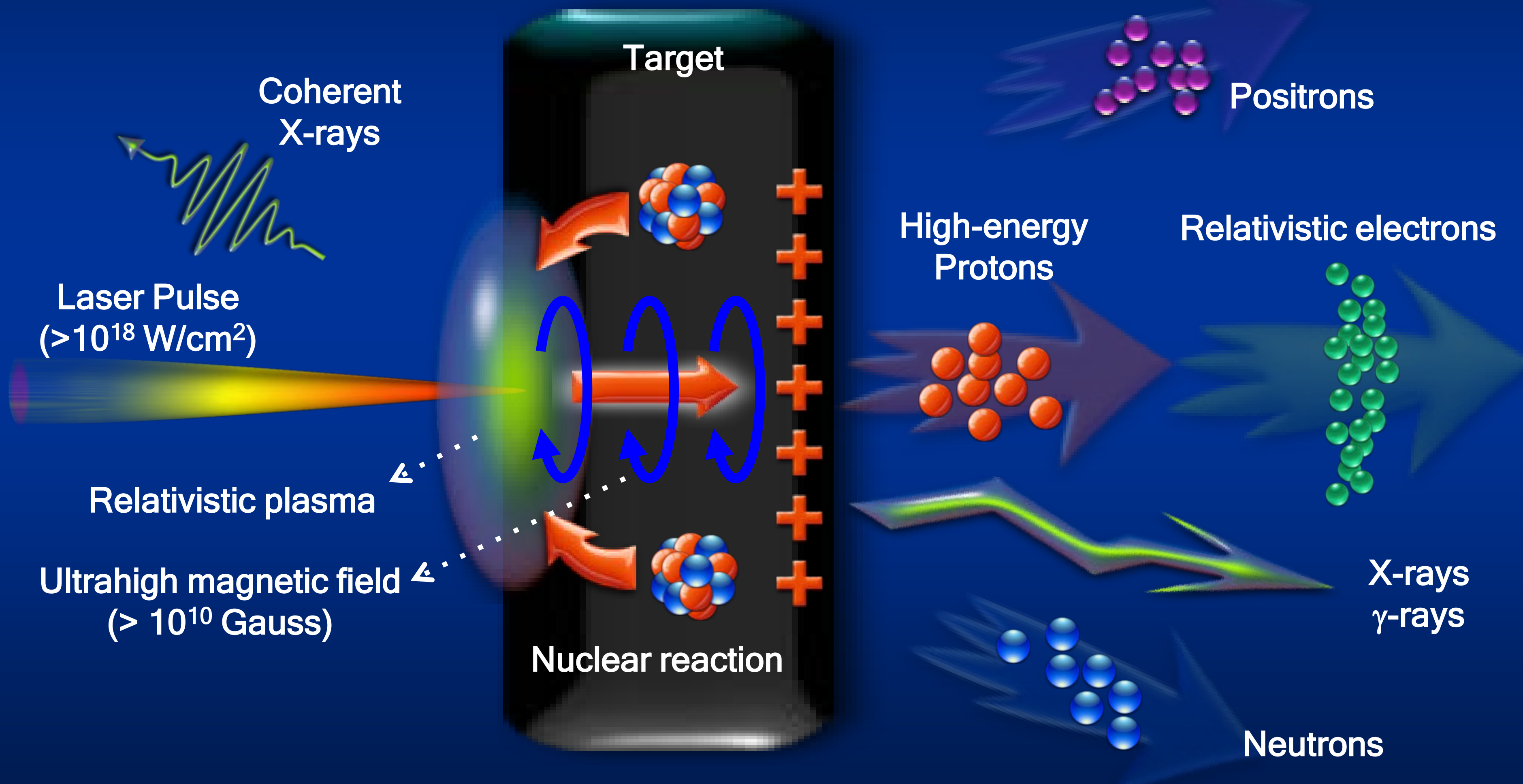
Relativistic Laser Science

Laser-Matter Interactions and Related Phenomena Explored at Relativistic Laser Intensity



Relativistic Laser Intensity

Atomic field strength: $E_B = \dfrac{e}{r_B^2} \approx 5.1\times 10^9$ V/cm; $I_B = \dfrac{cE_B^2}{8\pi} \approx 3.5\times 10^{16}$ W/cm^2

$$a_0 \equiv \frac{v_{NR}}{c} = \frac{eE_0}{m_e\omega_0 c} = \frac{eA_0}{m_e c^2} = \frac{\text{speed of nonrelativistically oscillating electron}}{\text{speed of light}}$$

When $a_0 = 1$, $v = 0.7c$. For $a_0 > 1$, relativistic.

Intensity for relativistic electron:
(Relativistic regime)

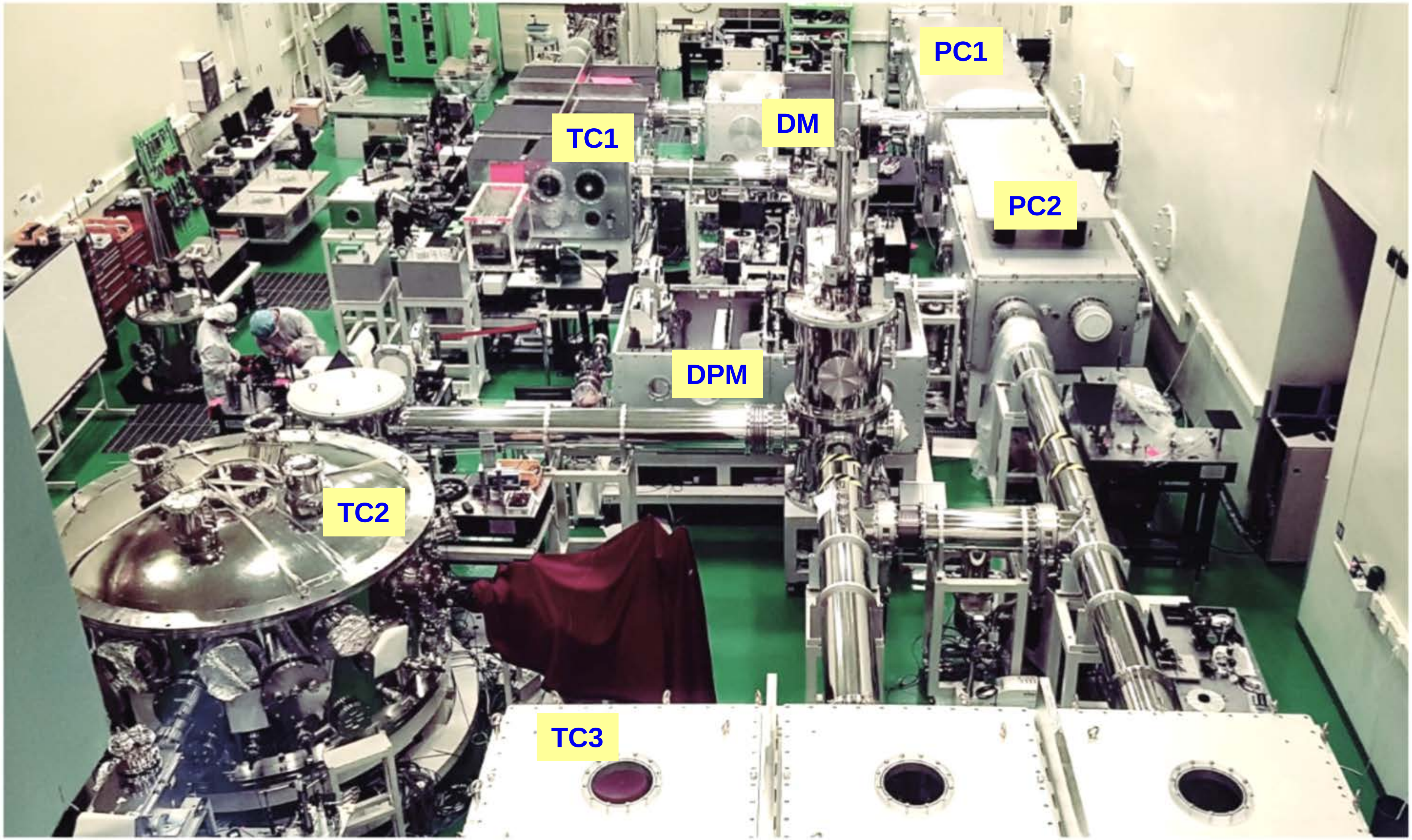
$$I_{\mathrm{Re}} \approx \frac{1.4\times 10^{18}}{\left(\lambda^2\right)_{\mu m}} a_0^{\,2} \ \text{W/cm}^2$$

For $a_0 = \dfrac{M_p}{m_e} = 1800$, ultra-relativistic.

Intensity for relativistic proton:
(Ultra-relativistic regime)

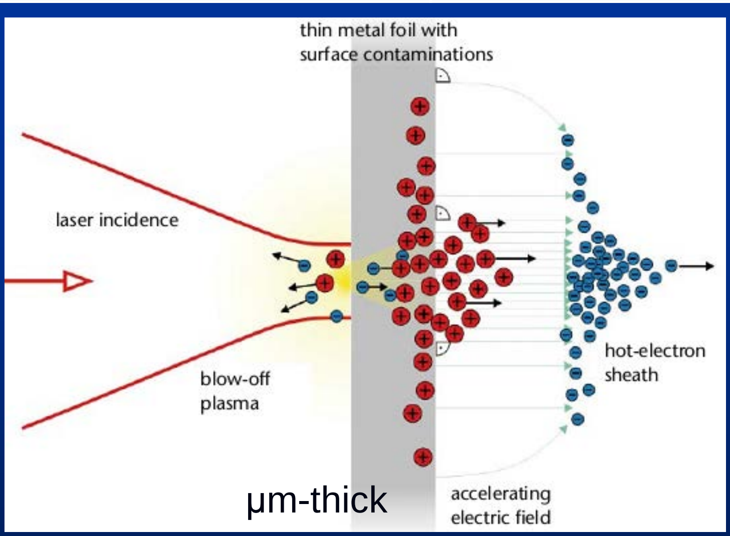
$$I_{Rp} \approx \frac{4.5\times 10^{24}}{\left(\lambda^2\right)_{\mu m}} \ \text{W/cm}^2$$

PW Laser Experimental Area

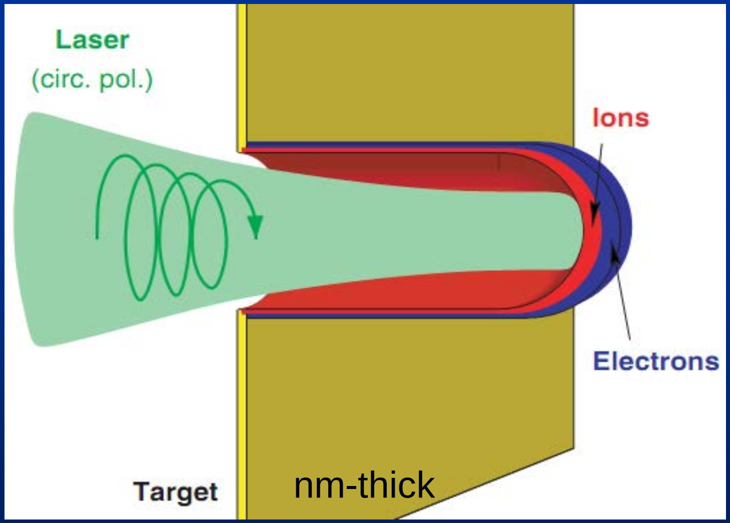


Laser Proton/Ion Acceleration

Acceleration mechanism	laser	Target thickness	Characteristics	Energy scaling
TNSA (Target normal sheath acceleration)	I>10^{18} W/cm^2 Linear pol.	~μm	Broad spectrum, thermal electrons	$E_{ion} \propto I^{1/2}$
RPA (Radiation pressure acceleration)	I>10^{20} W/cm^2 Linear pol. Circular pol.	~nm	Quasi-monoenergetic, collective electrons	$E_{ion} \propto I^2$



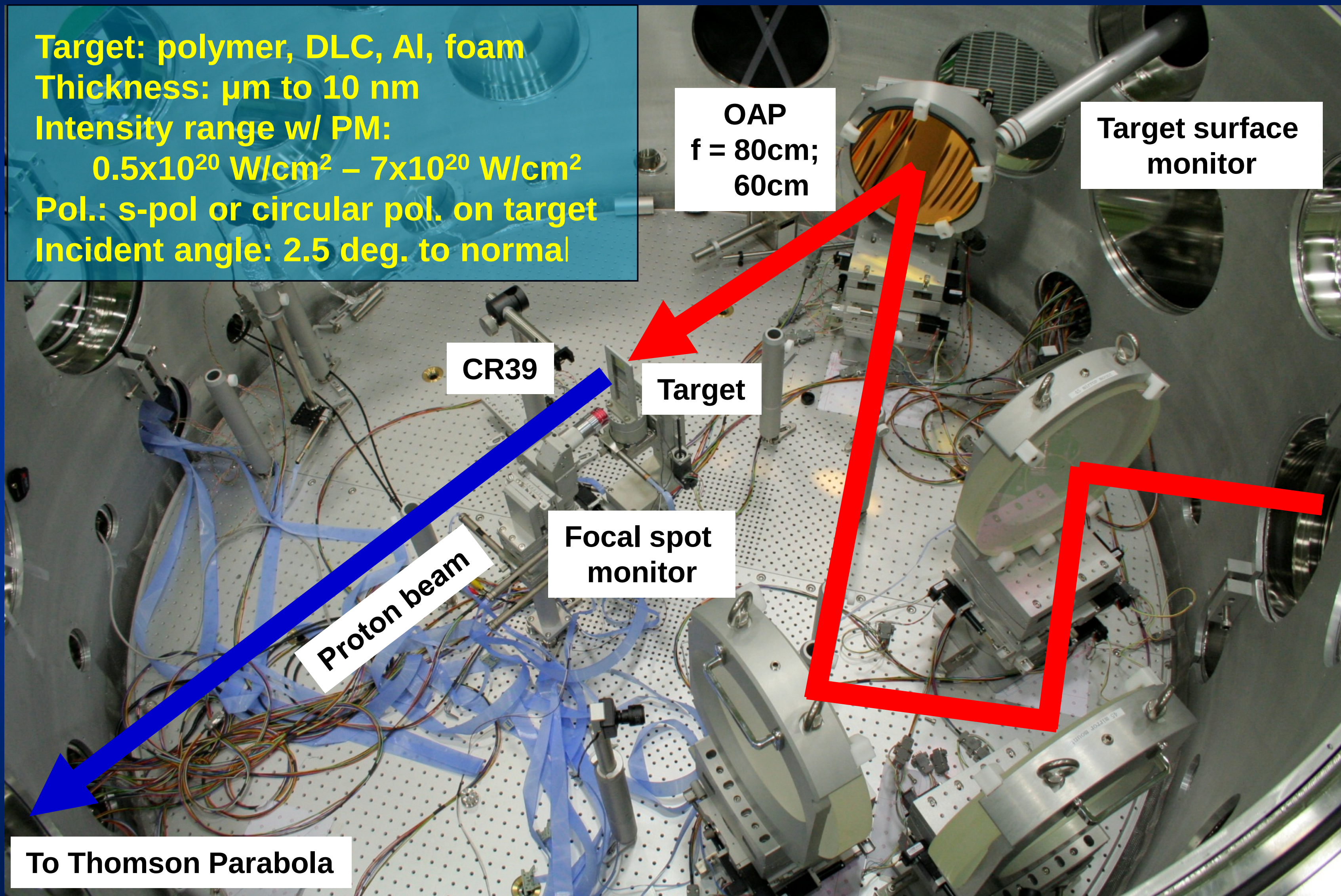
Laser, not penetrating the target, heats electrons, which drag protons after penetrating the target.



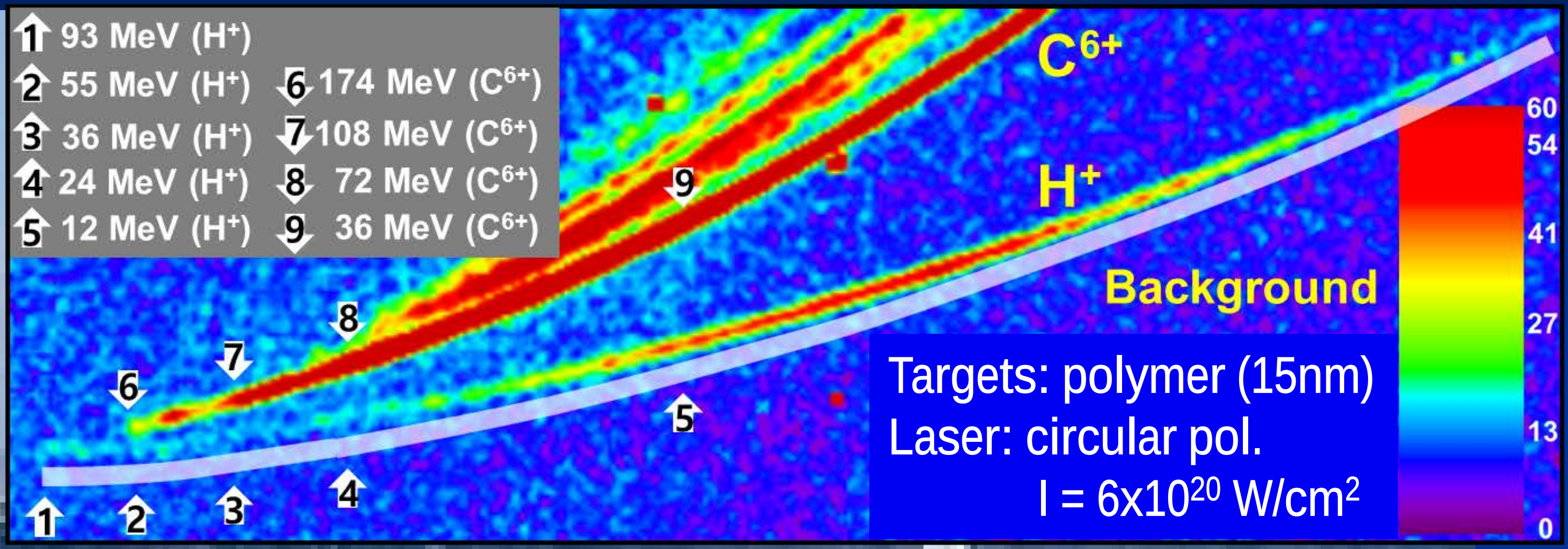
Laser pulse pushes electrons as a whole, which drag protons.

PW Target chamber for proton experiment

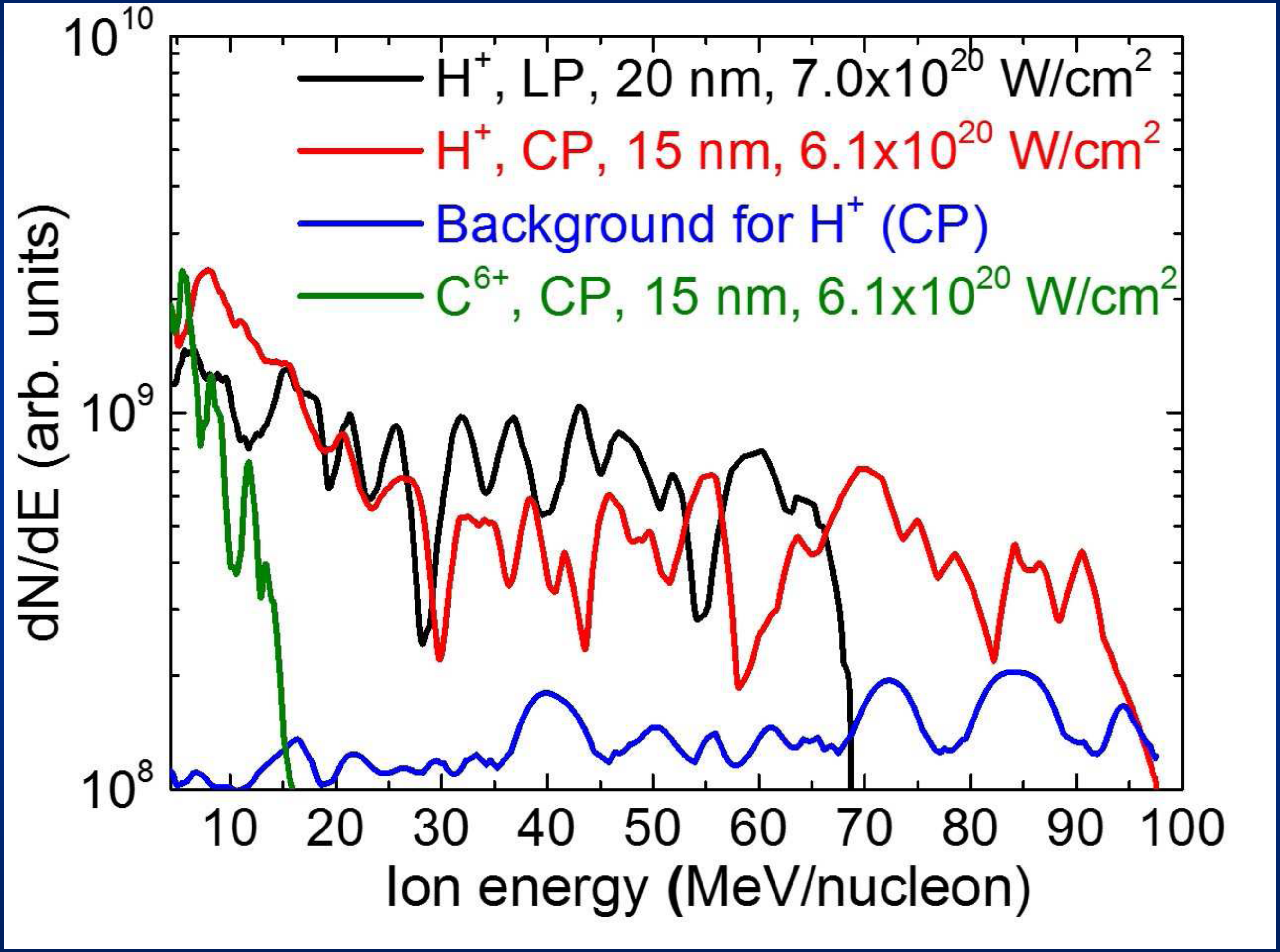
Target: polymer, DLC, Al, foam
Thickness: μm to 10 nm
Intensity range w/ PM:
0.5×10^{20} W/cm^2 – 7×10^{20} W/cm^2
Pol.: s-pol or circular pol. on target
Incident angle: 2.5 deg. to normal



Radiation Pressure Acceleration: Light Sail



Proton energy spectra for CP and LP cases



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Strong Field QED

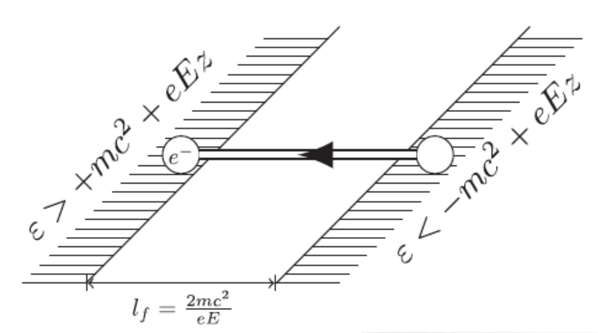
Schwinger field (E_S) for nonlinear optics in vacuum

Field-driven pair production over $\lambdabar_C$ in vacuum

$$eE_S\lambdabar_C = m_e c^2 \text{ where } \lambdabar_C = \frac{\hbar}{m_e c} = 3.9 \times 10^{-11}\ \mathrm{cm}$$

$E_S = \frac{m_e^2 c^3}{e\hbar} = 1.3 \times 10^{16}\ \mathrm{V/cm}$: Schwinger limit

$I_S = 2 \times 10^{29}\ \mathrm{W/cm^2}$: the corresponding laser intensity



χ_e: characteristic parameter for strong–field QED

Field-driven pair production over $\lambdabar_C$ with field ($F_{\mu\nu}$) and electron (p_μ)

$$\chi_e = \frac{1}{m_e c^2}\frac{\lambdabar_C}{c}\sqrt{\left(\frac{e}{m_e}F_{\mu\nu}p^\nu\right)^2} = \frac{E_{\text{proper}}}{E_S}$$

$\Rightarrow 2\gamma E/E_S$ for a counterpropagating relativistic electron

Pair production when $\chi_e \gtrsim 1$

For a rest electron, $I \sim I_S = 2 \times 10^{29}\ \mathrm{W/cm^2}$ for $\chi_e = 1$

For a 5-GeV electron, $I \sim 10^{-8} I_S = 2 \times 10^{21}\ \mathrm{W/cm^2}$ for $\chi_e = 1$

Strong Field QED: All Optical Compton Experiment

- **Laser Compton γ-ray production** from the scattering of a PW laser pulse with multi-**GeV e-beam**
  - **Compton backscattering**: $e^- + \omega_0 \rightarrow e^- + \gamma$

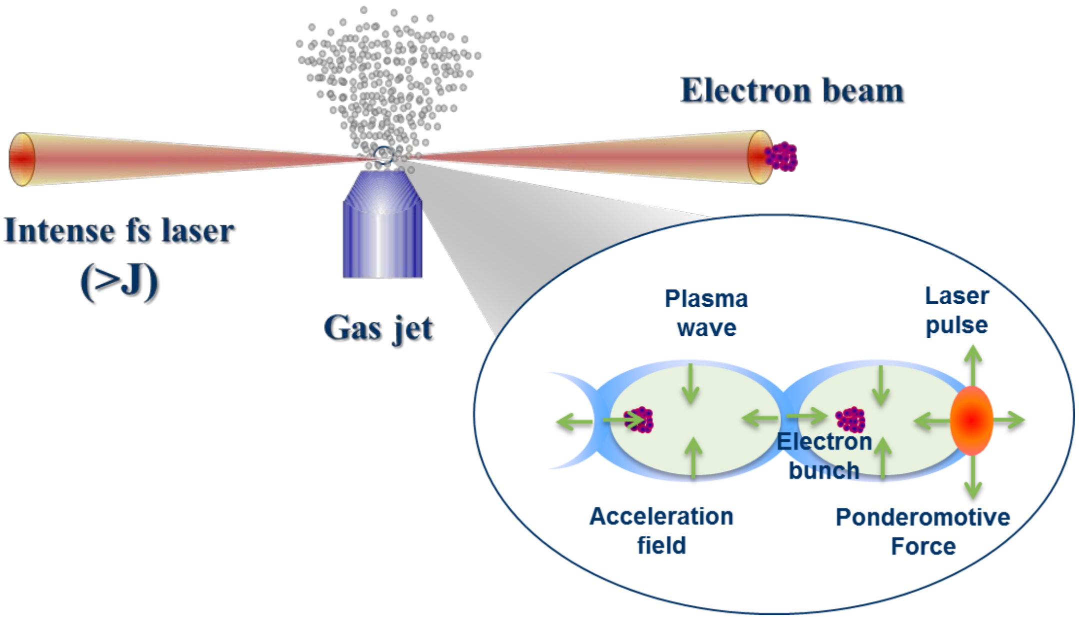
    MeV-Gamma beams useful for photo-nuclear physics
  - **Nonlinear Compton Scattering**: $e^- + n\omega_0 \rightarrow e^- + \gamma$
  - Measurement of **radiation reaction** effects

    Energy loss and radiation damping (cooling) of GeV e^--beam
  - Breit-Wheeler pair creation**:** $\gamma + n\omega_0 \rightarrow e^- + e^+$

    Only one experiment with 46 GeV linac e-beam and $a_0 = 0.36$

    D.L. Burke et al., Phys. Rev. Lett. **79**, 1626 (1997)
  - Assessing strong field QED theories

Laser Wakefield Electron Acceleration



Wake waves by ship

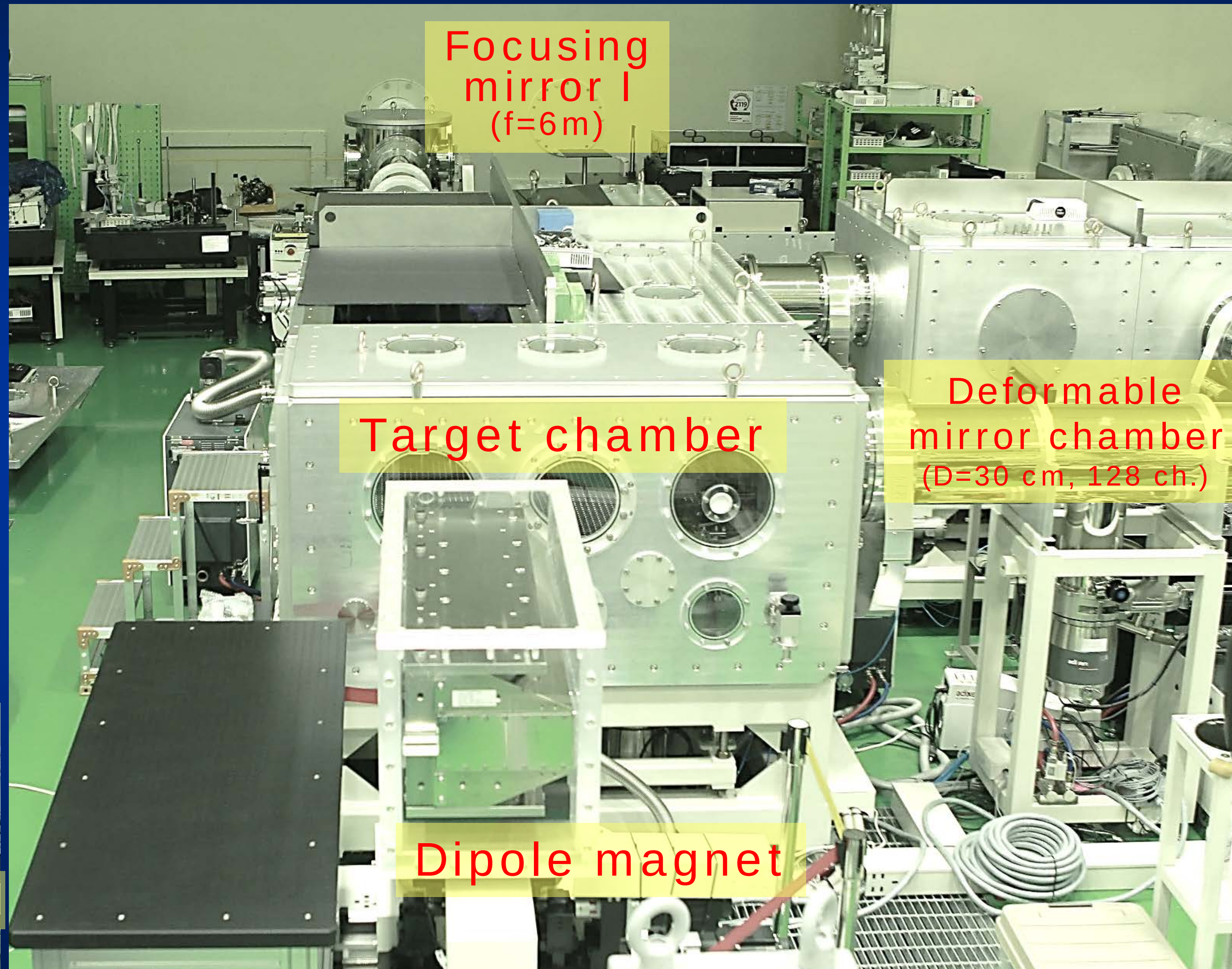
Surfing to the wave

LWFA (2D PIC)

Electrons pushed out by ponderomotive force
and pulled back by the Coulomb force by ions
→ Creation of electron plasma wave
→ Acceleration of an injected electron bunch
by the plasma wave

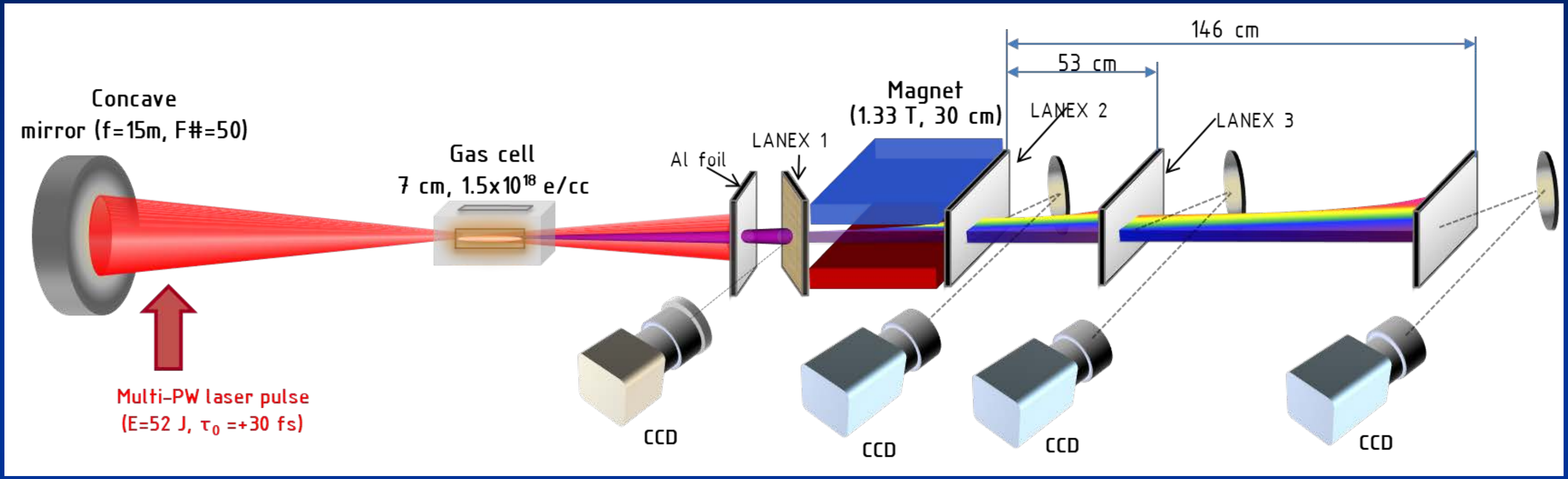
Huge acceleration field
> 100 GeV / m

Target chamber for LWFA with 4 PW laser

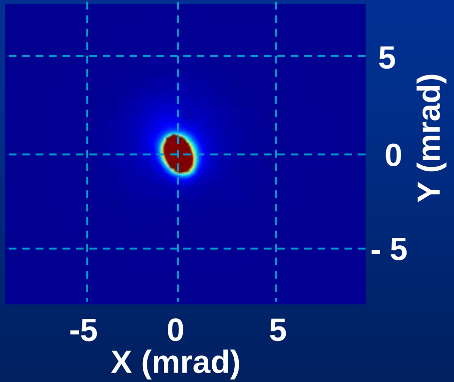


Electron acceleration with a multi-PW laser

Laser parameters: 52 J, + 30 fs (GDD +350 fs^{-2}), I ≈ 4 x 10^{19} W/cm^2 (a_0 ≈ 4.5)
Medium: He mixed with 1% Ne; 7-cm gas cell; N_e ≈ 1.5 x 10^{18} cm^{-3}

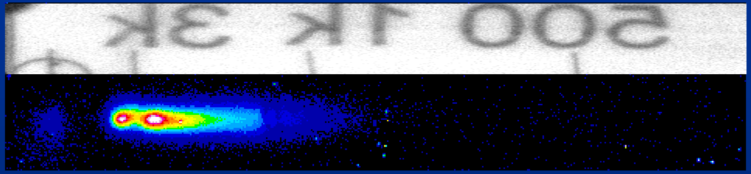


LANEX 1 (profile)

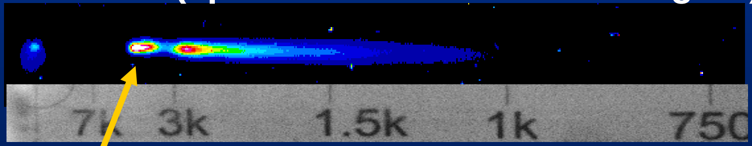


Deeply saturated;
Divergence < 2 mrad

LANEX 2 (spectrum at the end of magnet)

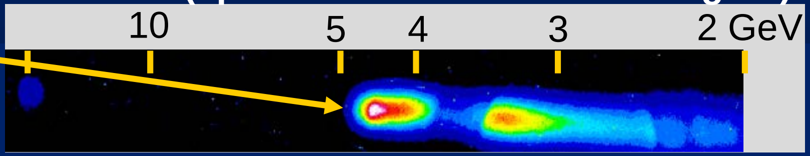


LANEX 3 (spectrum at 53 cm from magnet)



E_{max} ≈ 4.5 GeV

LANEX 4 (spectrum at 146 cm from magnet)



Strong field QED: All-optical Compton scattering

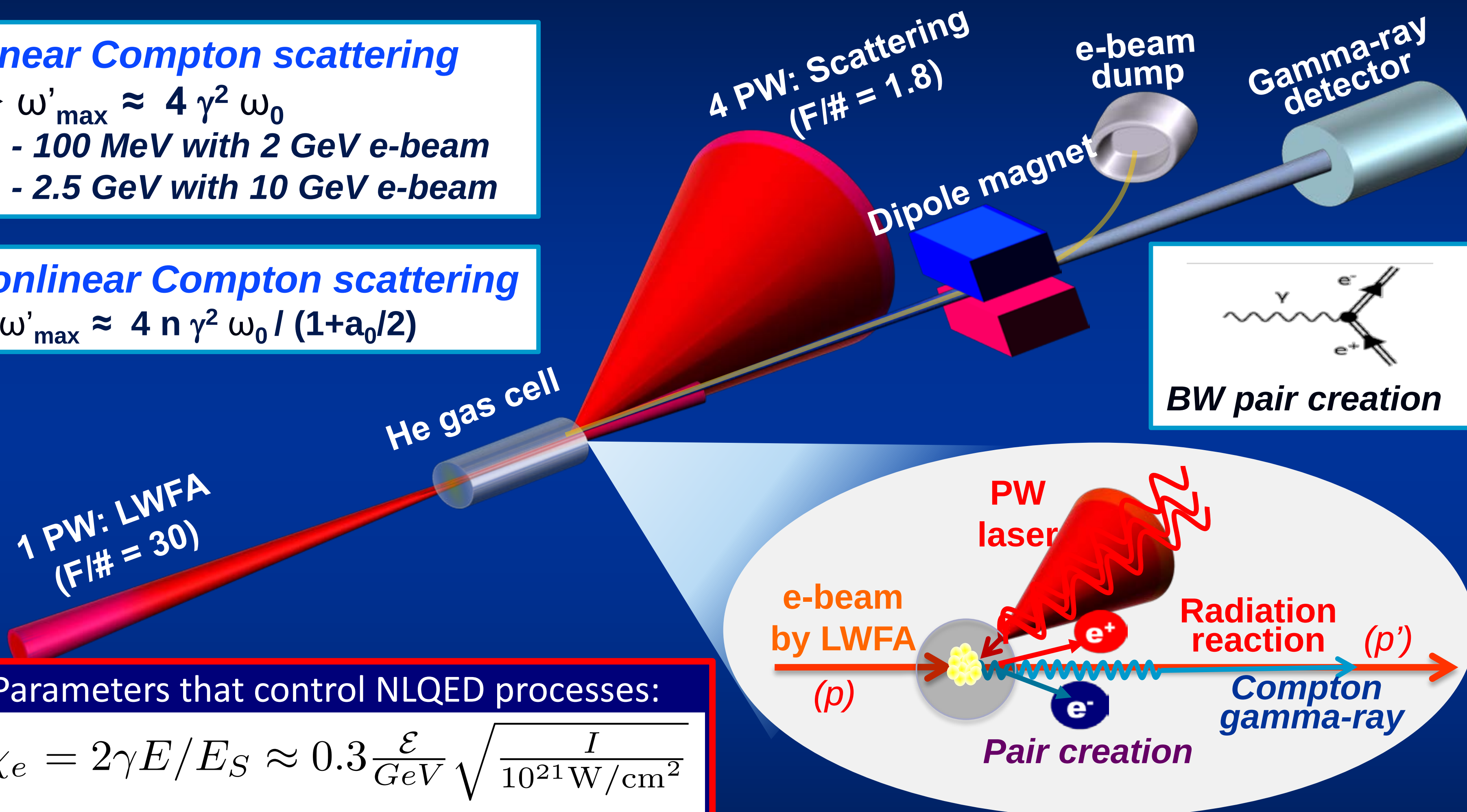
Linear Compton scattering

▶ $\omega'_{max} \approx 4\gamma^2\omega_0$

- *100 MeV with 2 GeV e-beam*
- *2.5 GeV with 10 GeV e-beam*

Nonlinear Compton scattering

▶ $\omega'_{max} \approx 4n\gamma^2\omega_0/(1+a_0/2)$

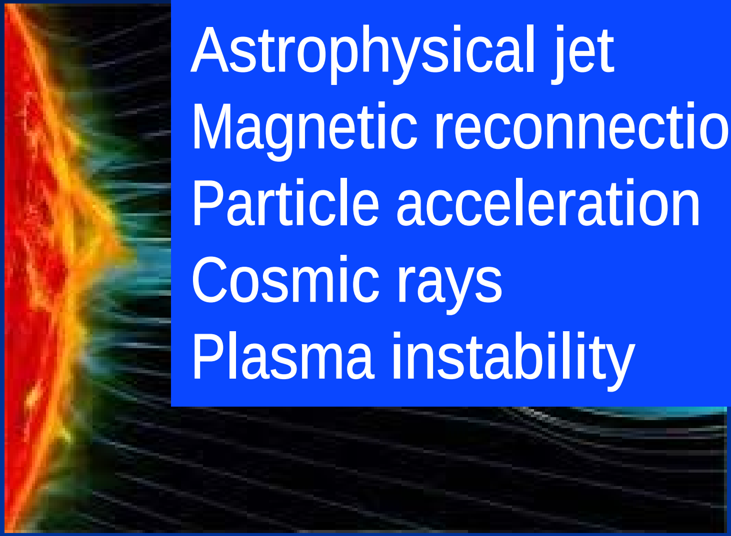


Parameters that control NLQED processes:

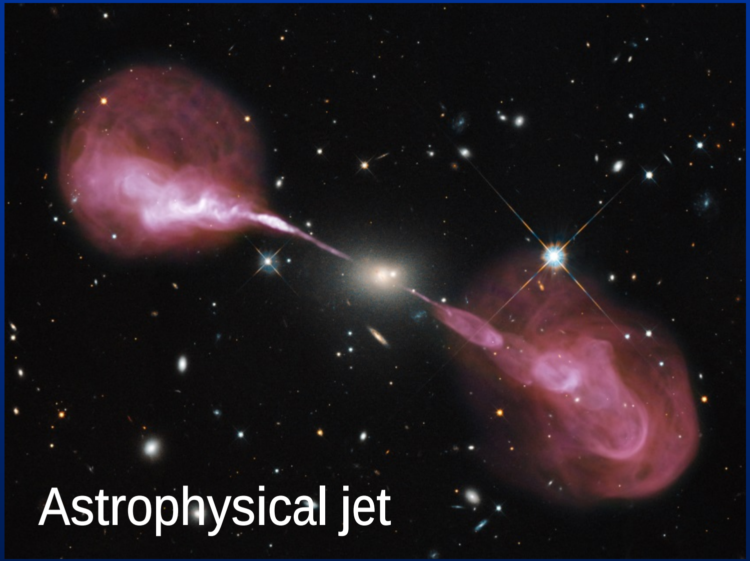
$$\chi_e = 2\gamma E/E_S \approx 0.3\frac{\mathcal{E}}{GeV}\sqrt{\frac{I}{10^{21}\,\mathrm{W/cm^2}}}$$

$$\chi_\gamma \approx \frac{\hbar\omega}{m_e c^2}\frac{E}{E_s}$$

Laboratory Astrophysics



- Astrophysical jet
- Magnetic reconnection
- Particle acceleration
- Cosmic rays
- Plasma instability



Summary

1. CoReLS of IBS operates two PW laser beamlines, 1 PW and 4 PW at 20 fs, for research on high field science.
2. After finishing the upgrade to 4 PW, a series of commissioning experiments have been performed in 2017. The laser intensity achieved was as high as 5×10^{22} W/cm^2. In the laser-driven proton acceleration protons with energy over 90 MeV was obtained with an ultrathin polymer target.
3. As a part of strong field QED research, Compton backscattering of a PW laser pulse with a multi-GeV electron beam is being prepared for 10's MeV γ-ray production; nonlinear Compton scattering, radiation reaction, and Breit-Wheeler pair production processes will be explored.