Relativistic Laser Science Explored with PW Lasers at CoReLS

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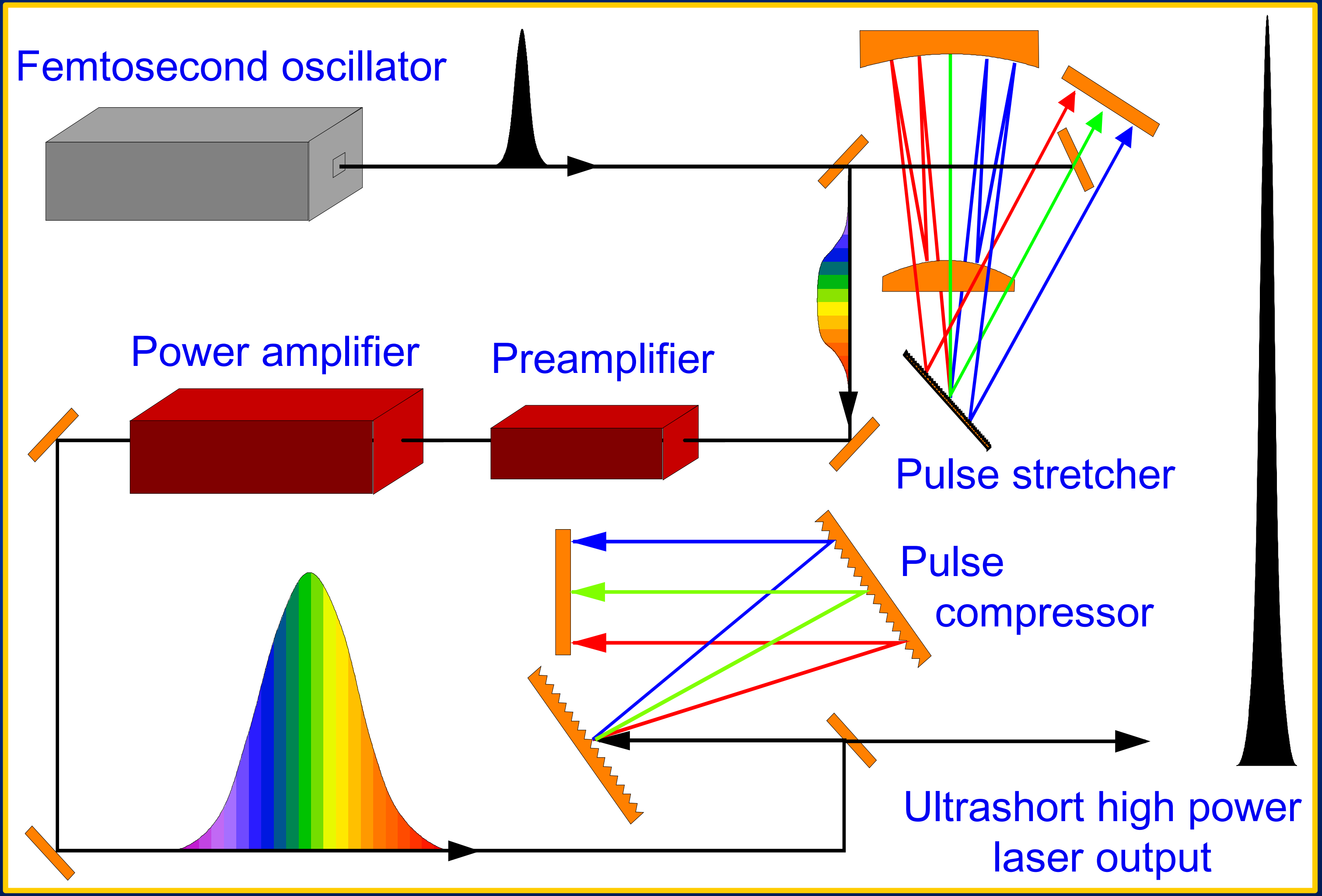
Overview

1. Femtosecond PW Laser
2. Relativistic Laser Science
   A. Laser electron acceleration
   B. High energy proton generation
3. Laser Upgrade: 4 PW Laser

High Power Femtosecond Laser: Basic Principle

Chirped-Pulse Amplification (CPA) Technique

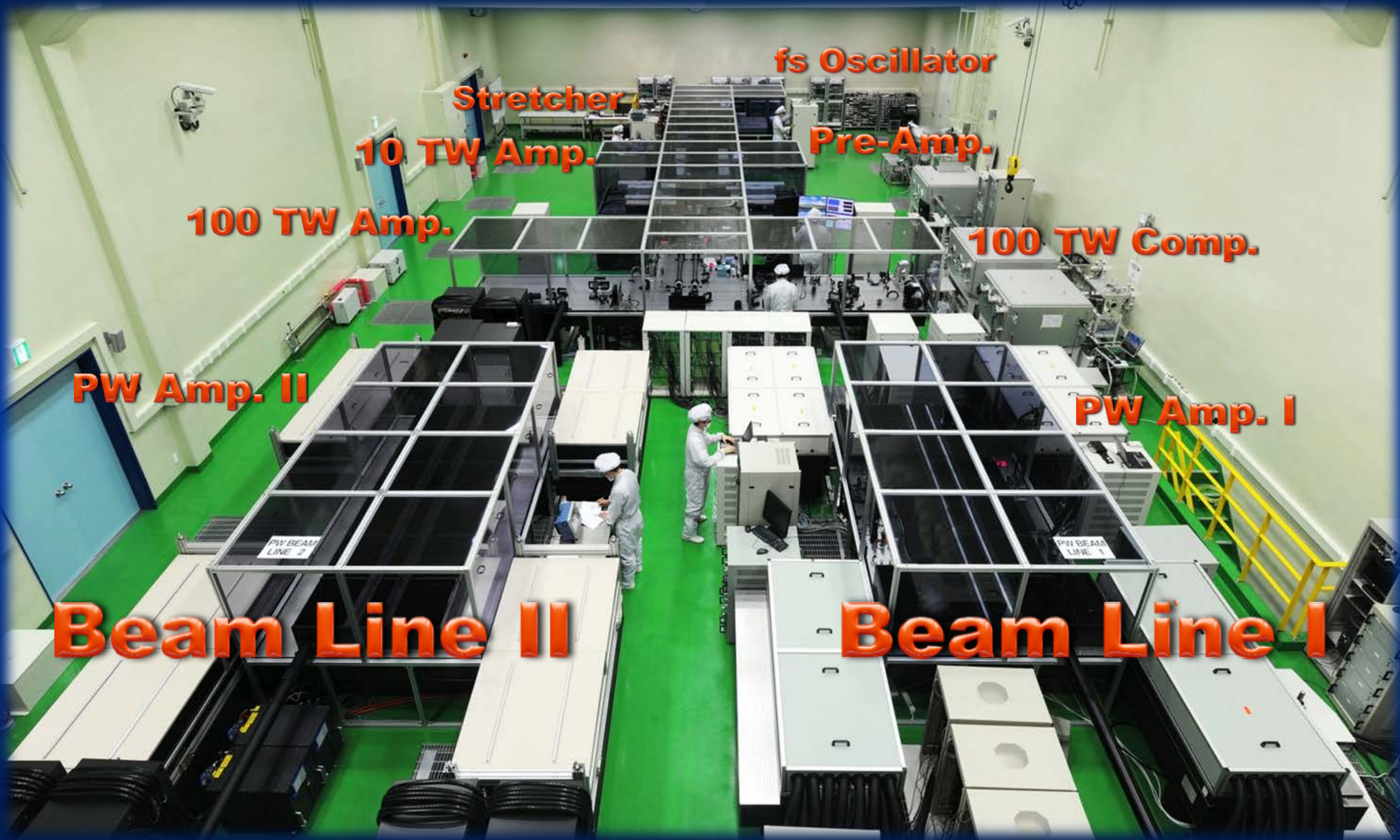


IBS Center for Relativistic Laser Science

GIST Ultrashort Quantum Beam Facility

- PW Ti:Sapphire Laser
  - (1) Beam line I: 30 fs, 1 PW @ 0.1 Hz
  - (2) Beam line II: 20 fs, 4 PW @ 0.1 Hz
- 100-TW Laser: Δt = 25 fs, E = 3 J @ 5 Hz

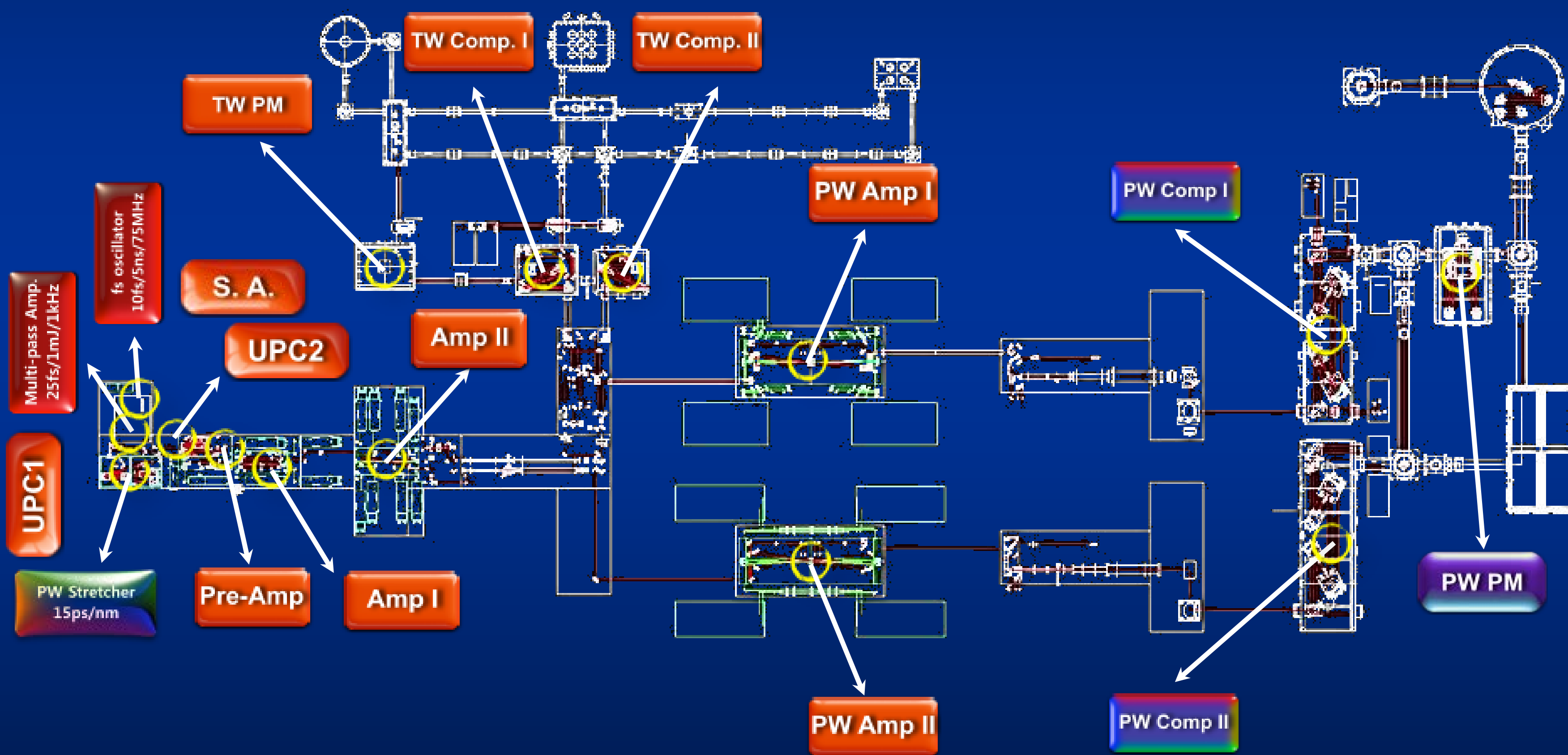
PW Ti:Sapphire Laser



PW Laser Beamline I & II

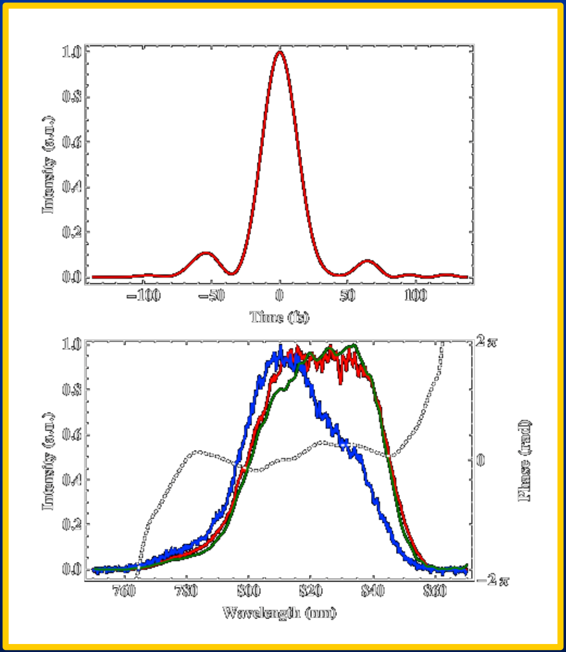
Before 2009

2012

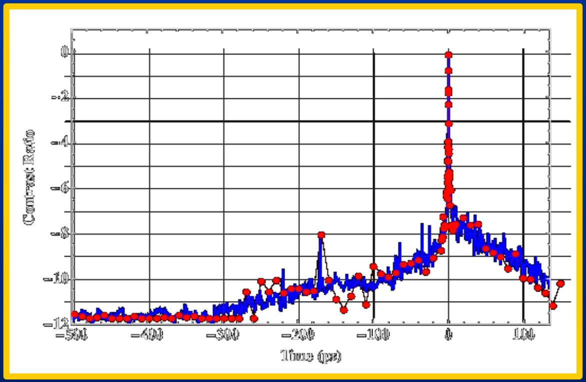


High contrast, 30 fs, 1.5 PW Laser

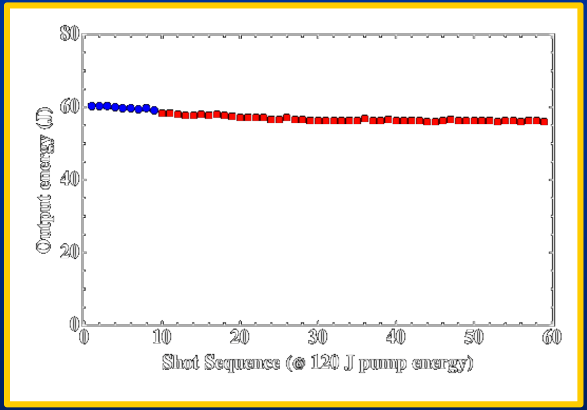
30 fs



High contrast



1.5 PW



1. Femtosecond PW Laser

2. Relativistic Laser Science

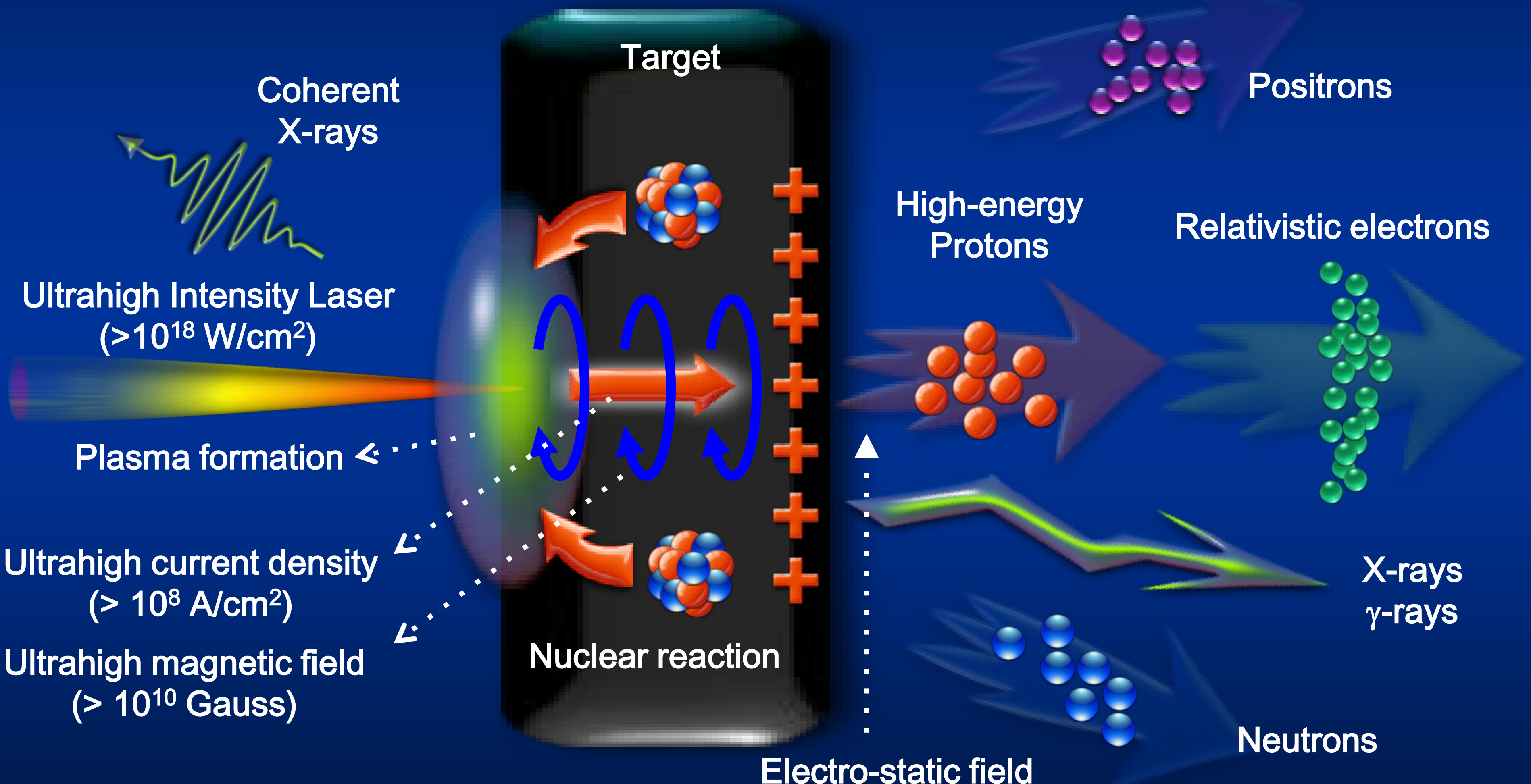
   A. Laser electron acceleration

   B. High energy proton generation

3. Laser Upgrade: 4 PW Laser

Relativistic Laser Science

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



Relativistic Laser Intensity

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

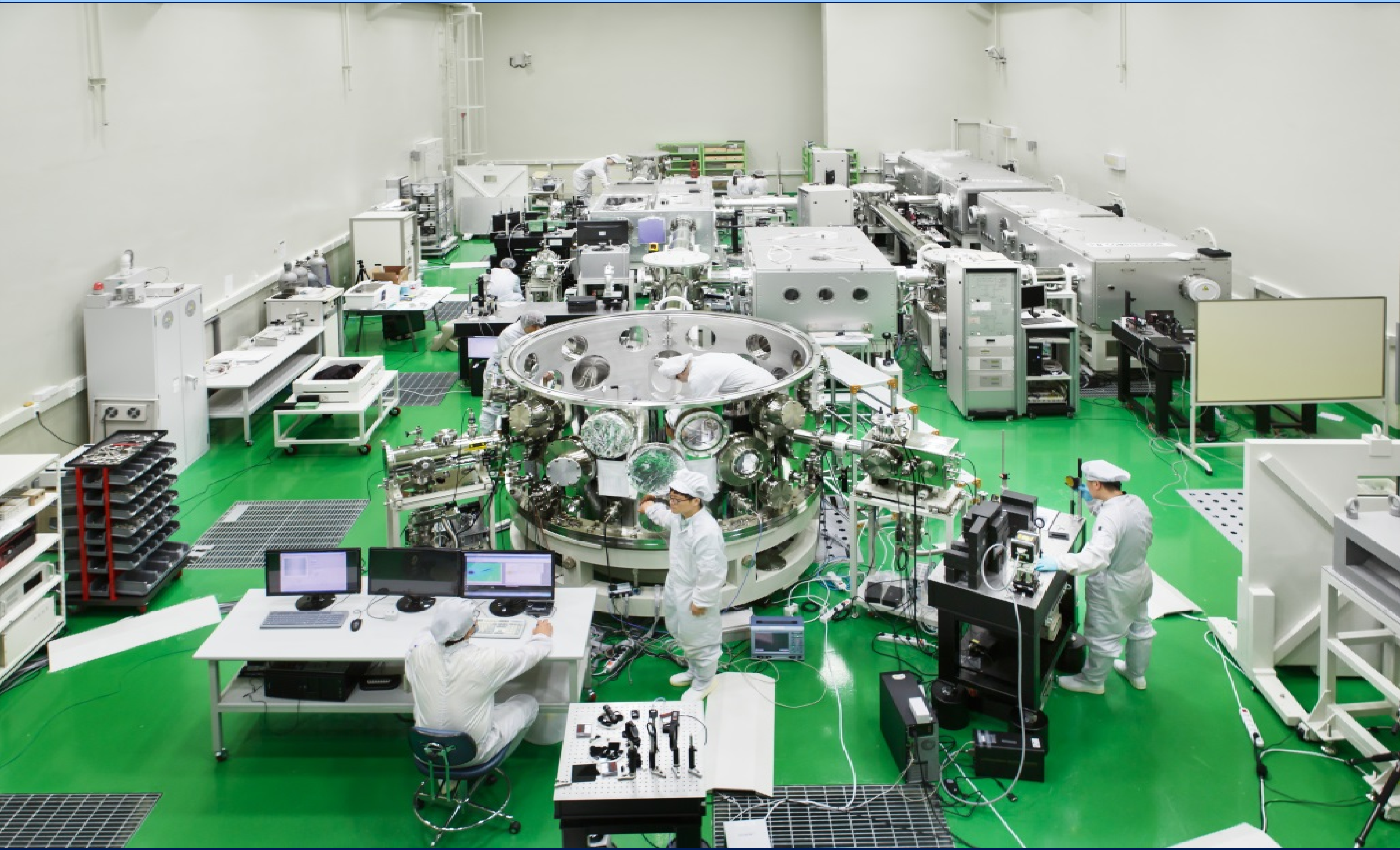
$$I_{\text{Re}} \approx \frac{1.4 \times 10^{18}}{\left(\lambda^2\right)_{\mu m}} a_0^{\,2} \ \text{W/cm}^2$$

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

Intensity for relativistic proton:
(Ultra-relativistic regime)

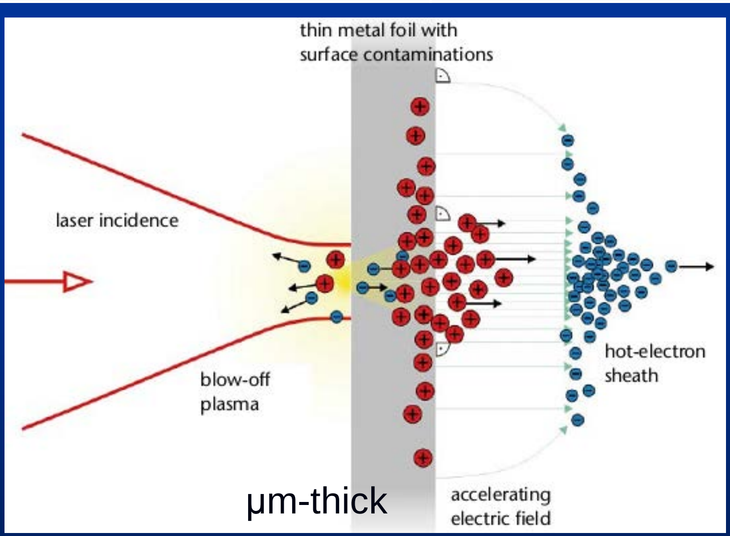
$$I_{Rp} \approx \frac{4.5 \times 10^{24}}{\left(\lambda^2\right)_{\mu m}} \ \text{W/cm}^2$$

PW Laser Experimental Area

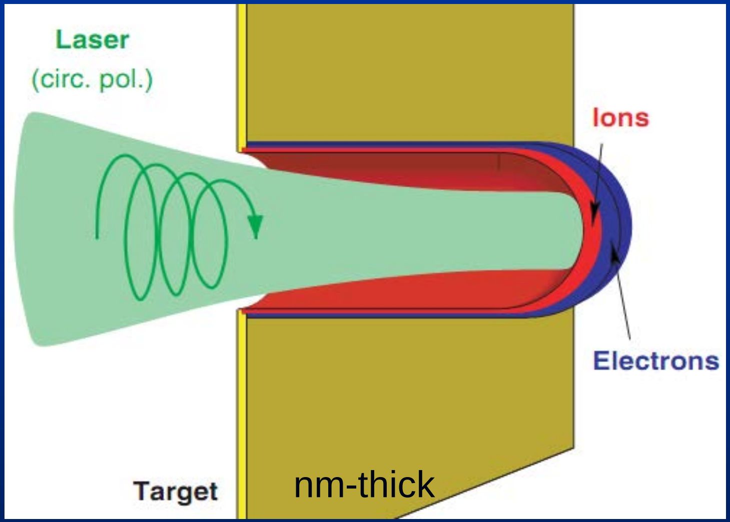


Laser Proton/Ion Acceleration

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	$E_{ion} \propto I^2$



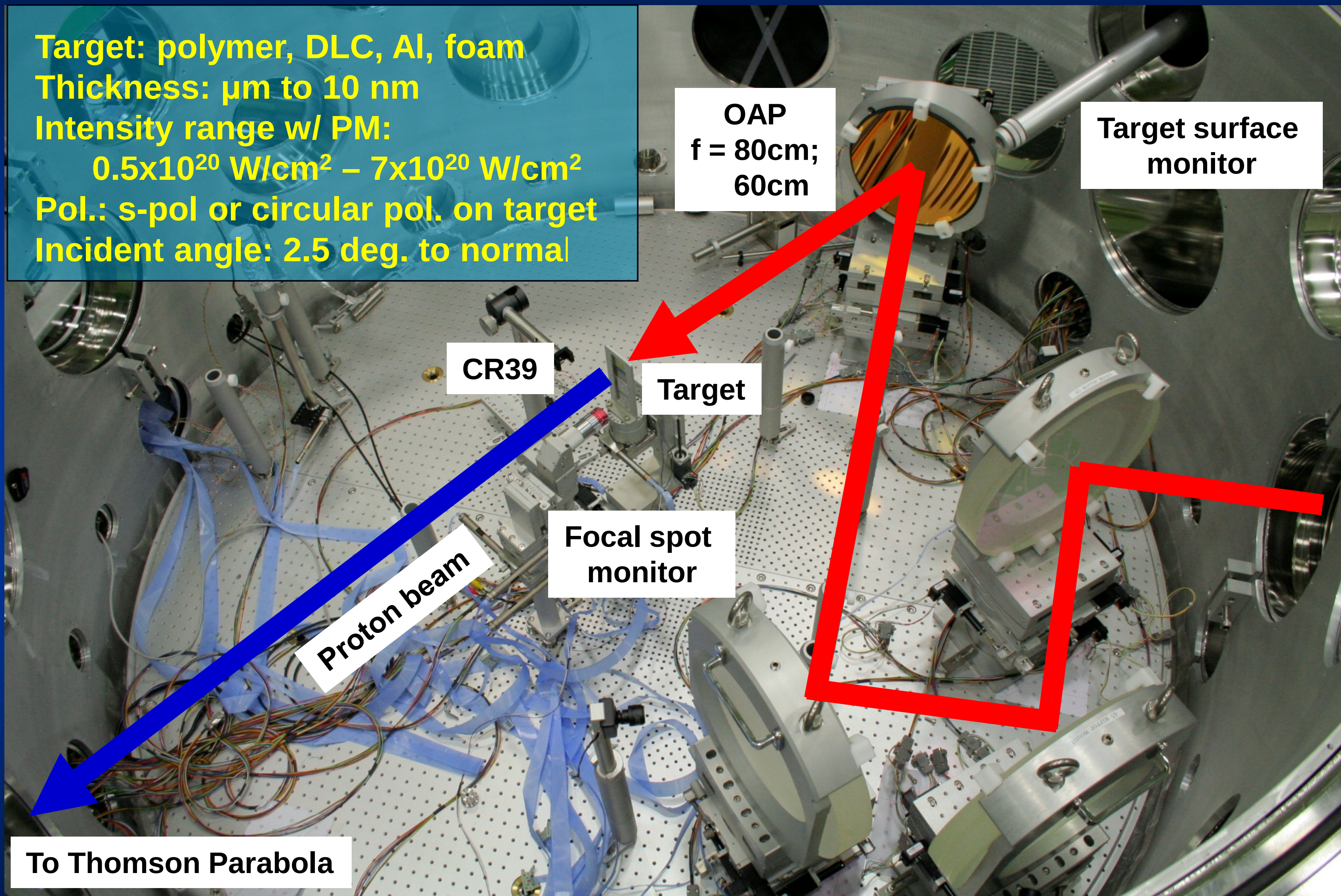
Laser, not penetrating the target, heats electrons, which drag protons after penetrating the target.



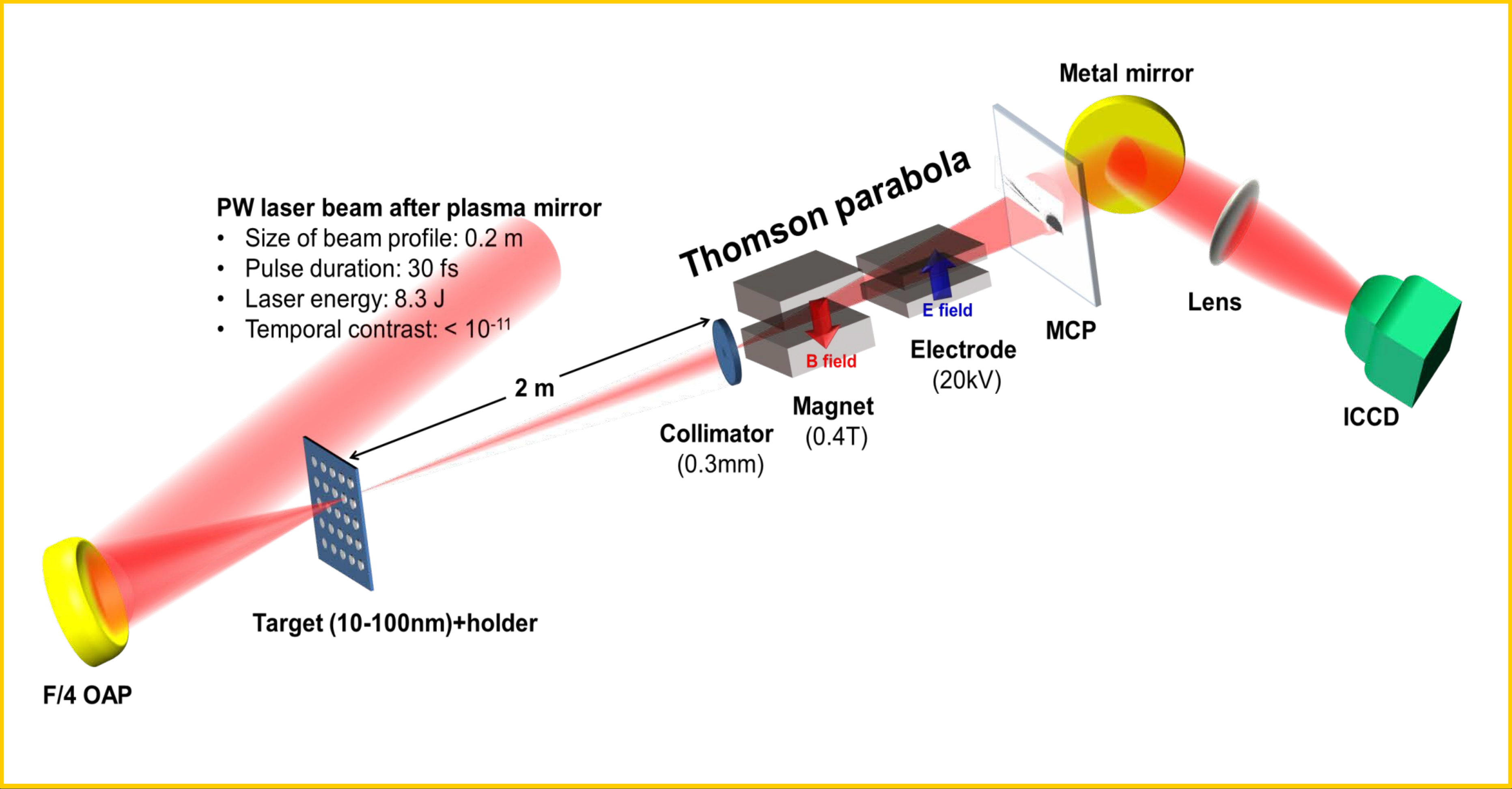
Laser pulse pushes electrons as a whole, which drag protons.

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

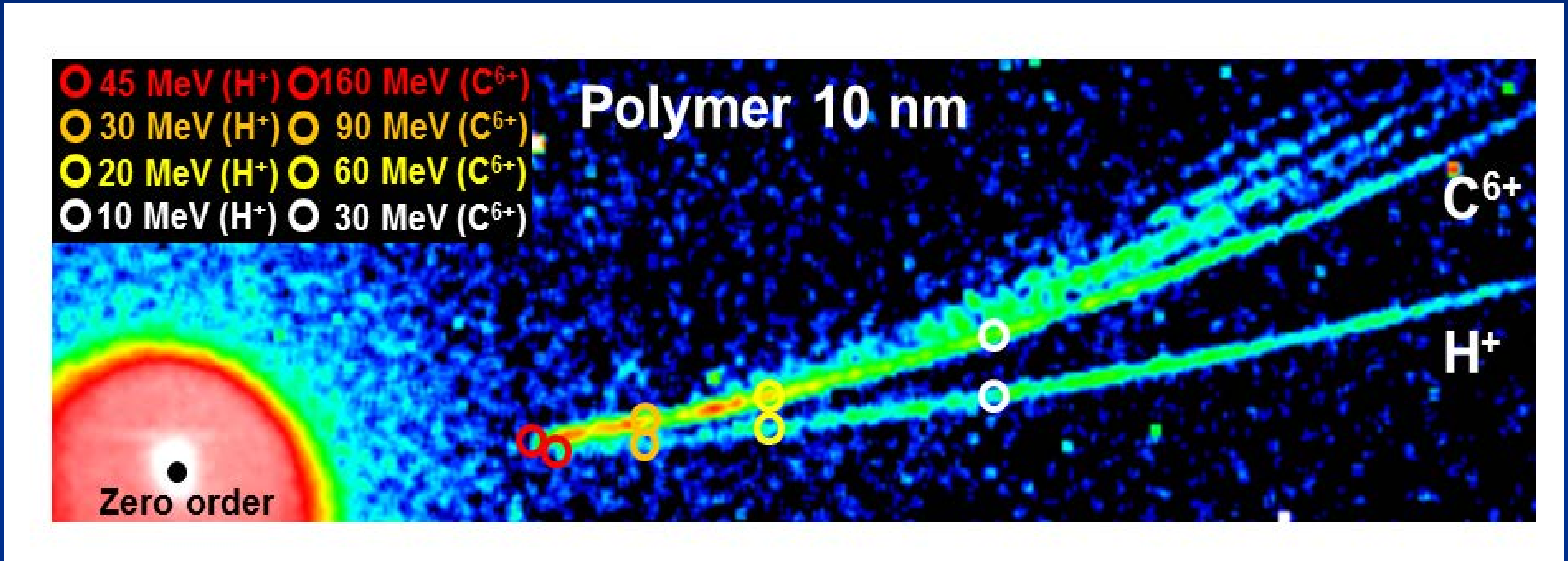


Target and Thomson parabola



Proton and C^{6+} measured with Thomson parabola

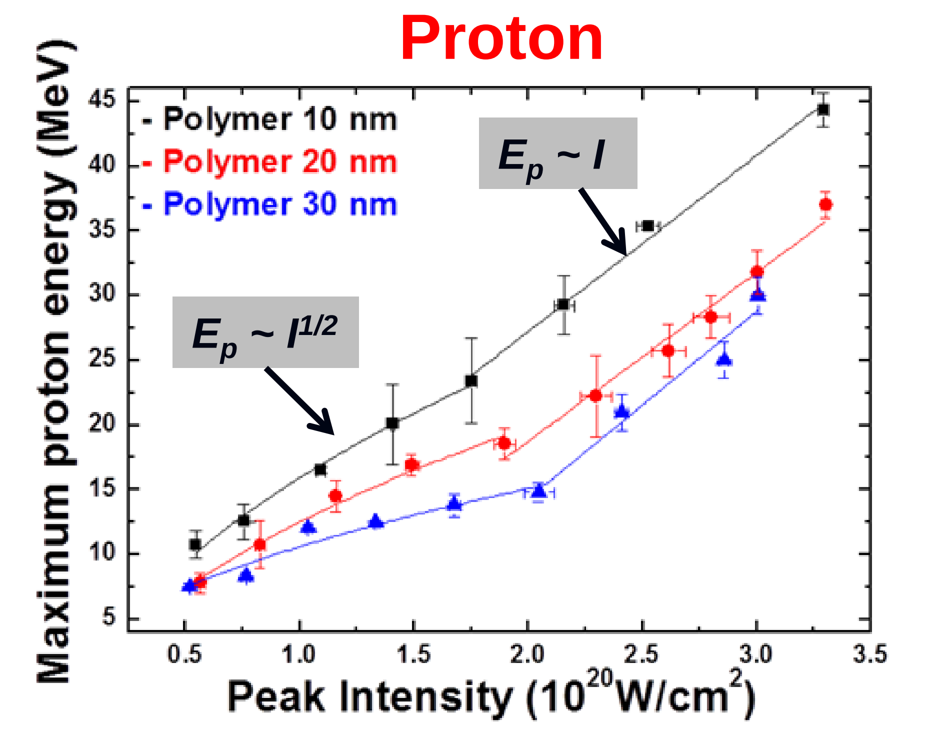
Target: 10-nm-thick polymer
Laser intensity: 3.3 × 10^{20} W/cm^2.

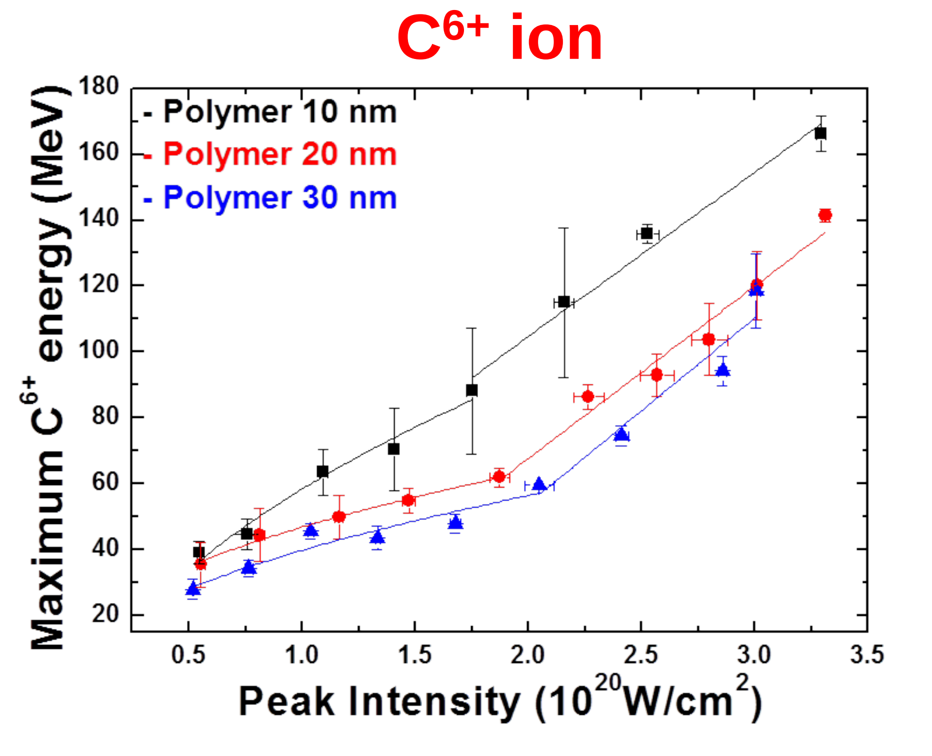


Proton energy: 45 MeV

Proton Generation using LP PW Pulses

Intensity scaling from ~ $I^{1/2}$ to ~ I ⇨ Transition from TNSA to RPA

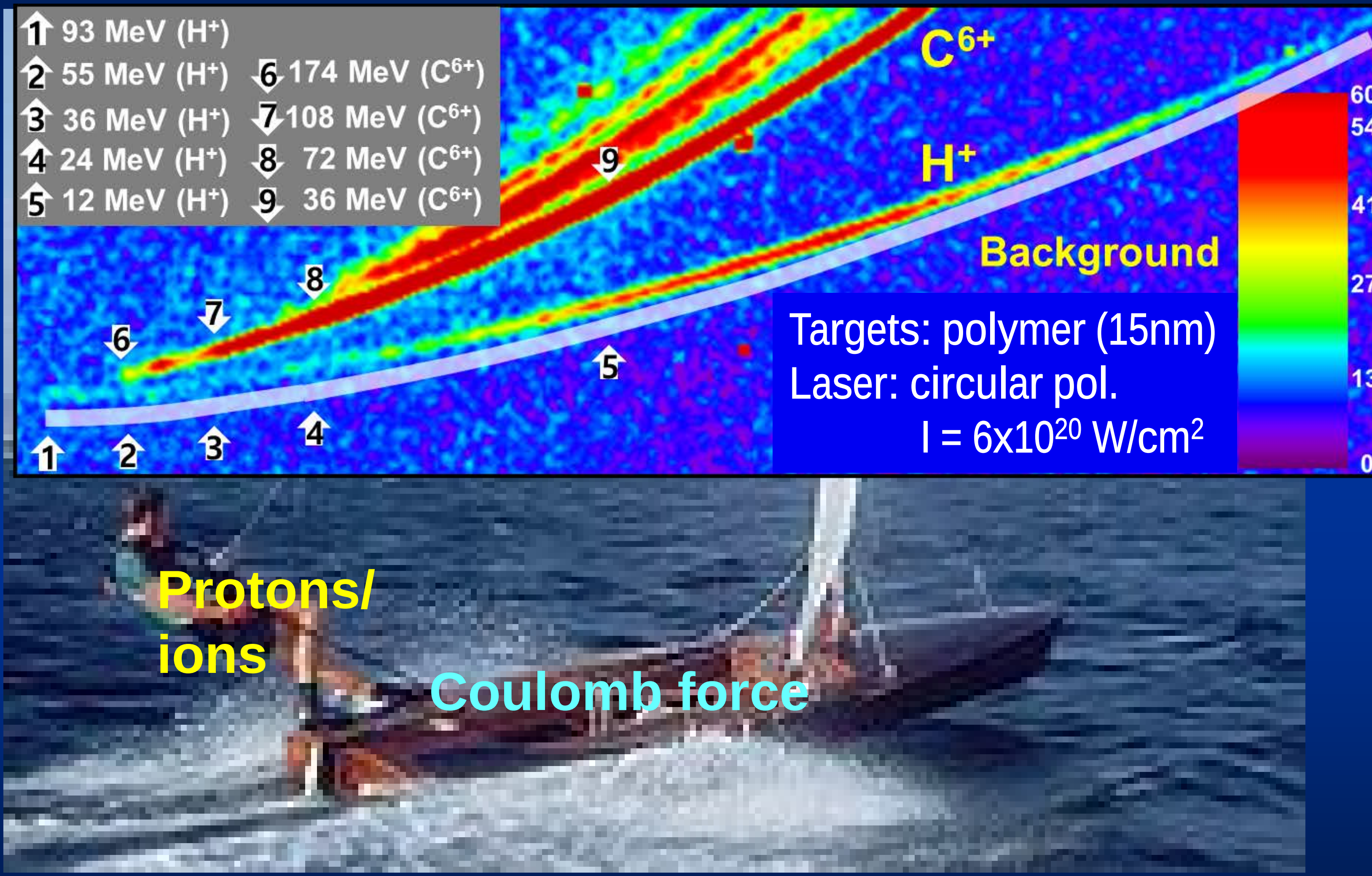




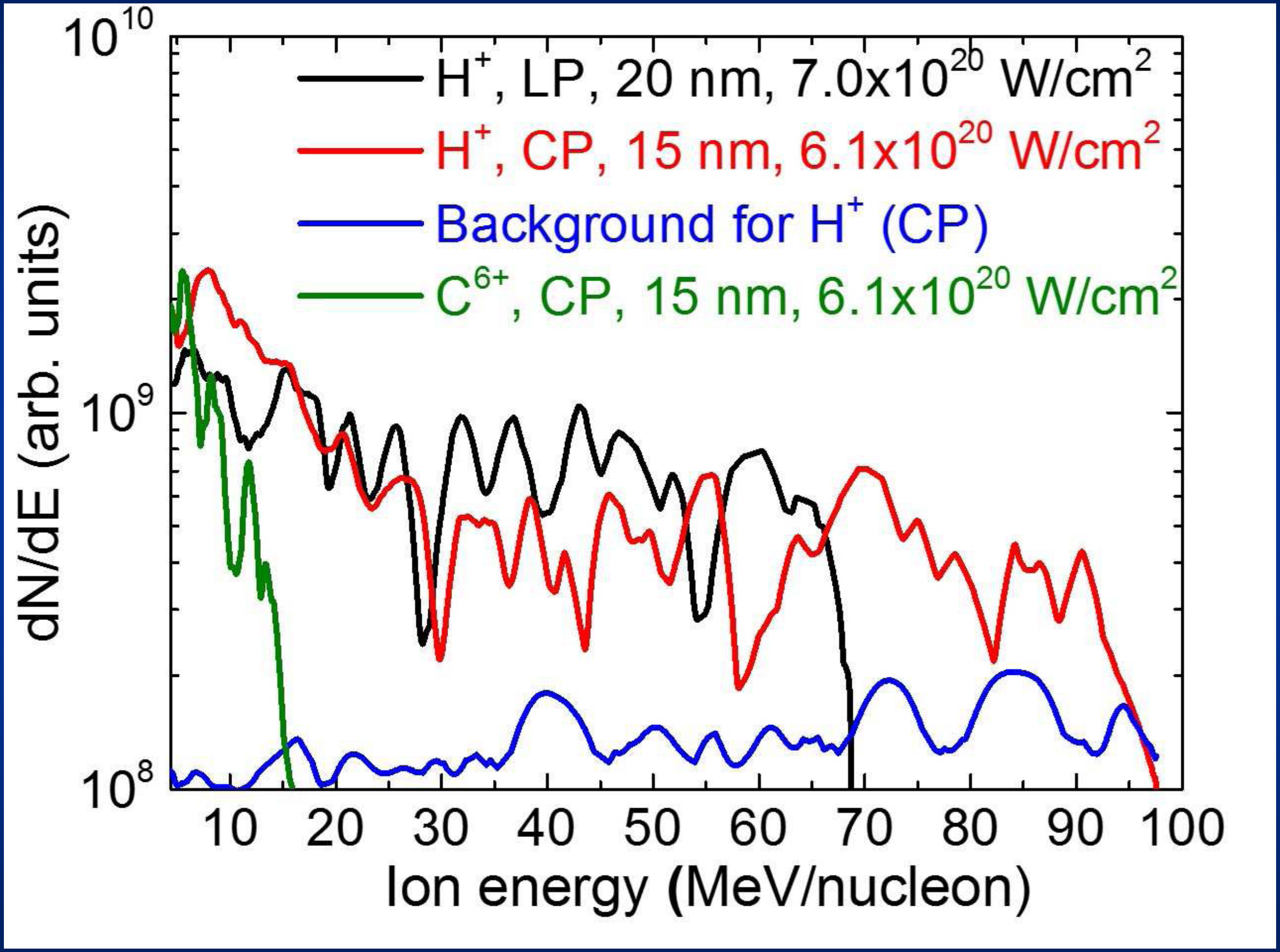
45 MeV @ 3.3×10^{20} W/cm^2
(linear polarization)

165 MeV @ 3.3×10^{20} W/cm^2
(linear polarization)

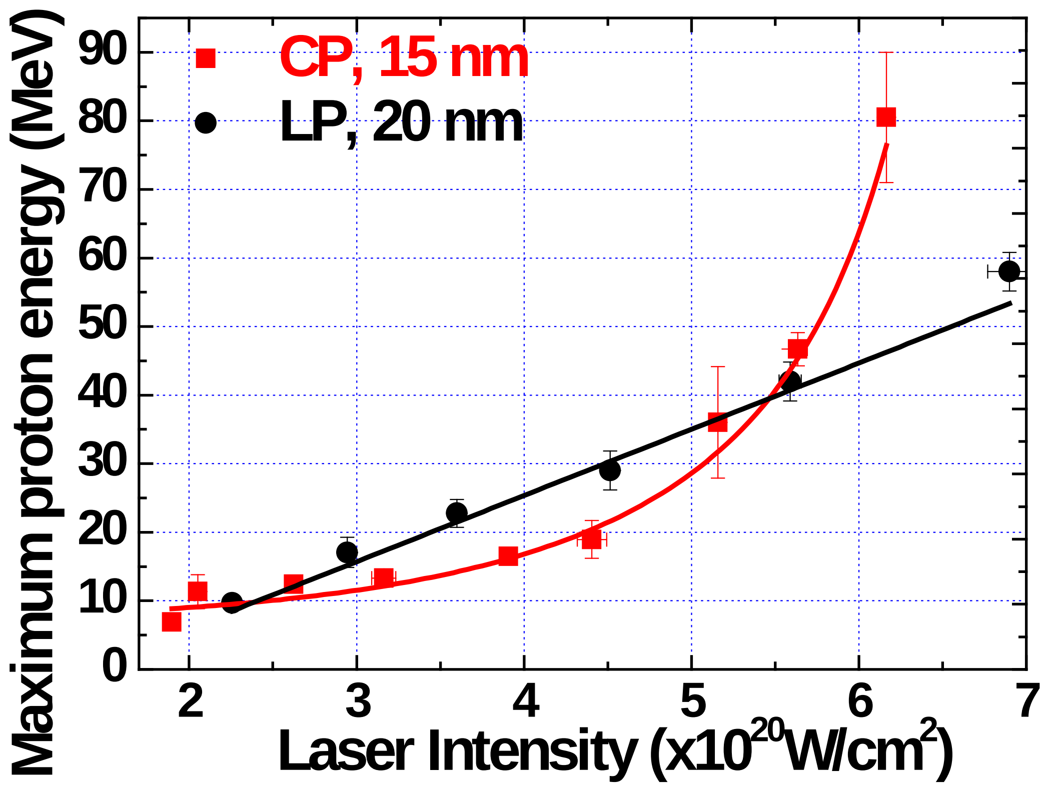
Radiation Pressure Acceleration: Light Sail



Proton energy spectra for CP and LP cases



Scaling of maximum proton energy to laser intensity



CP: Quadratic scaling
LP: Linear scaling

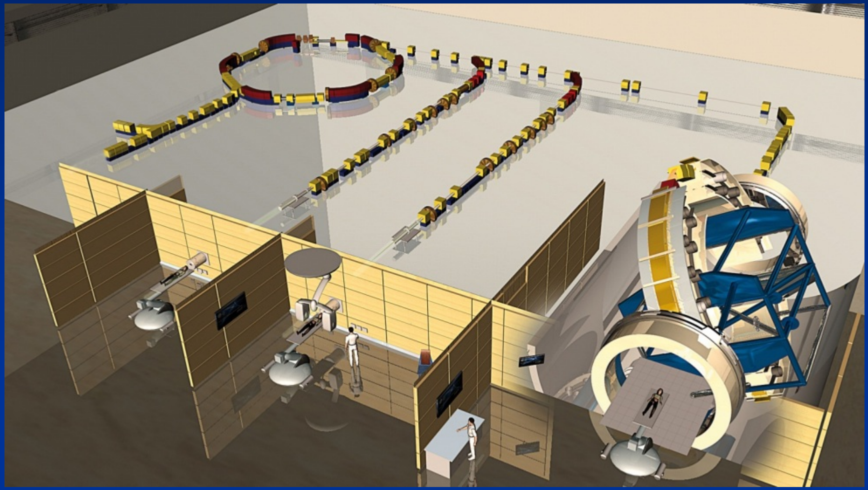
Outperformance of the CP case over the LP

Clear difference between LP and CP cases confirms the favorable role of CP laser pulses in RPA

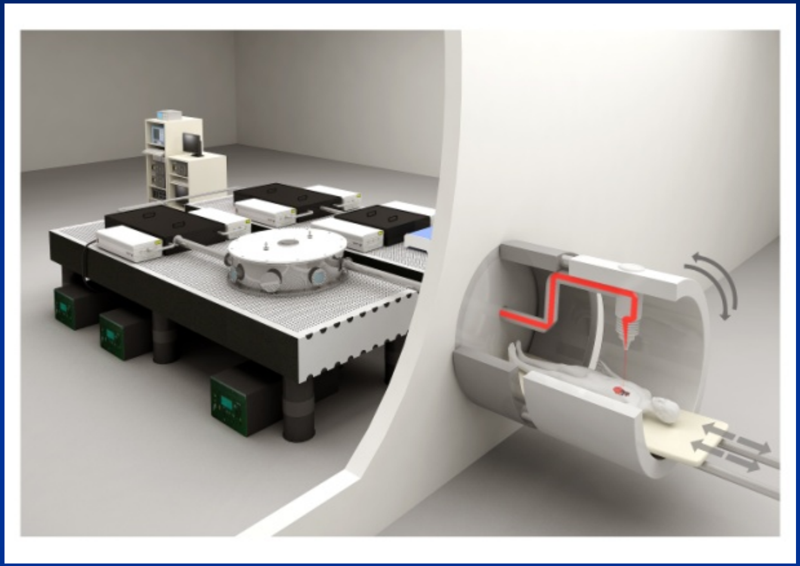
IJ. Kim et al., PoP 23 (2016)

Proton/hadron oncology

The feasibility of proton & heavy ion therapy using a table top laser facility



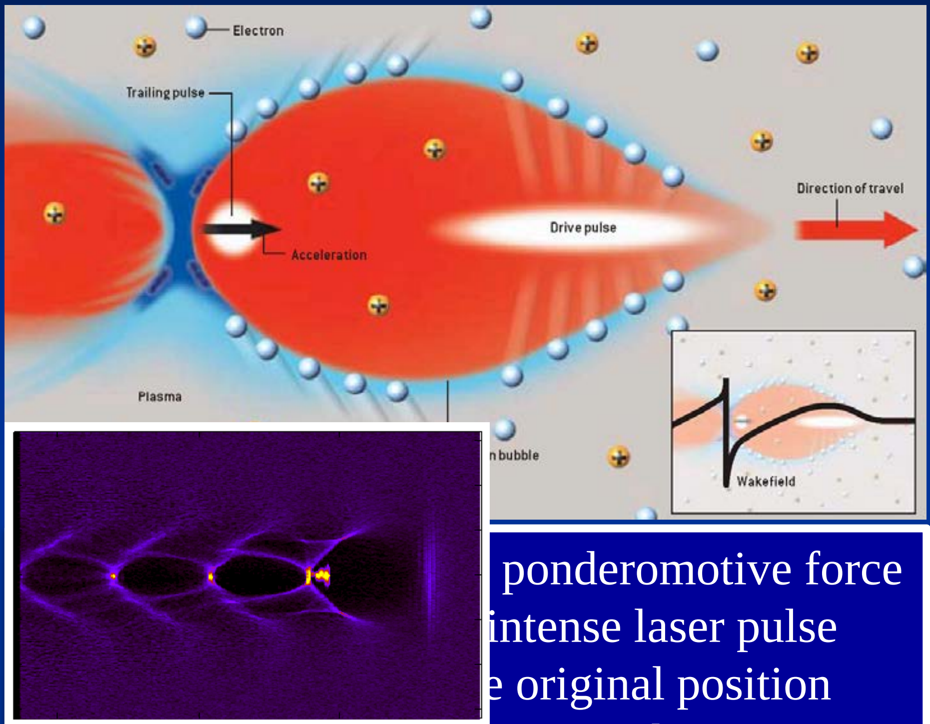
Proton/ion acceleration
using cyclotron/synchrotron



Particle acceleration
using a table top laser

Proton beam therapy has a physical advantage over gamma ray and x-rays when it comes to dosage deposition in healthy tissues. The energy can be very precisely controlled to place the Bragg peak within a tumor or other tissues targeted to receive the radiation dose. Because the energy deposition of protons is localized, healthy tissues beyond the target receive very little radiation.

Laser Wakefield Electron Acceleration



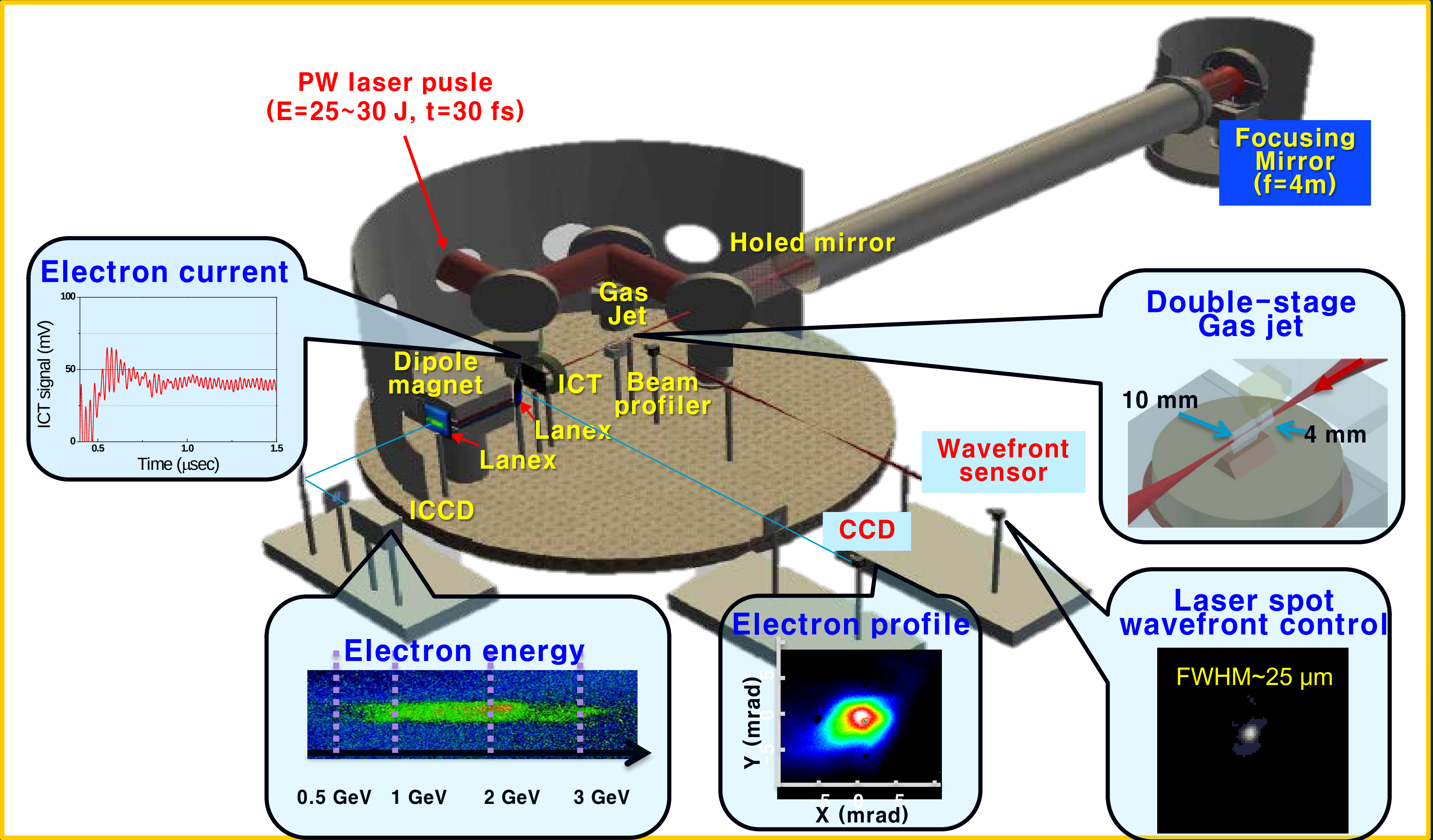
ponderomotive force
intense laser pulse
e original position
→ Electron plasma wave created
→ Acceleration of an injected electron bunch by the plasma wave

Huge acceleration field of LWFA > 100 GeV/m

Plasma wave by a laser pulse ~ Waves by a ship in sea

Acceleration by plasma wave ~ Surfing to the wave in sea

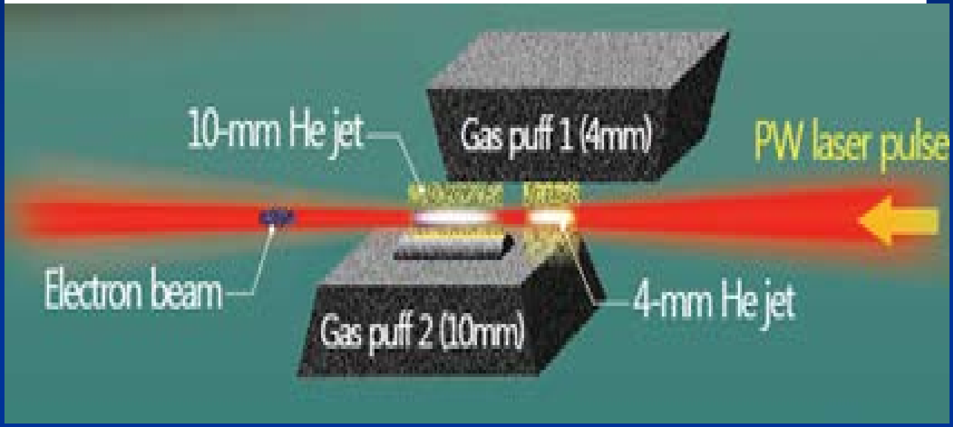
Electron Acceleration using a PW Laser



Multi-GeV e-Beam Generation with Dual Gas Jets

Double-stage Gas jet

$d_e = 2 \times 10^{18}\ cm^{-3}$ (4 mm) ; $d_e = 0.7 \times 10^{18}\ cm^{-3}$ (10 mm)

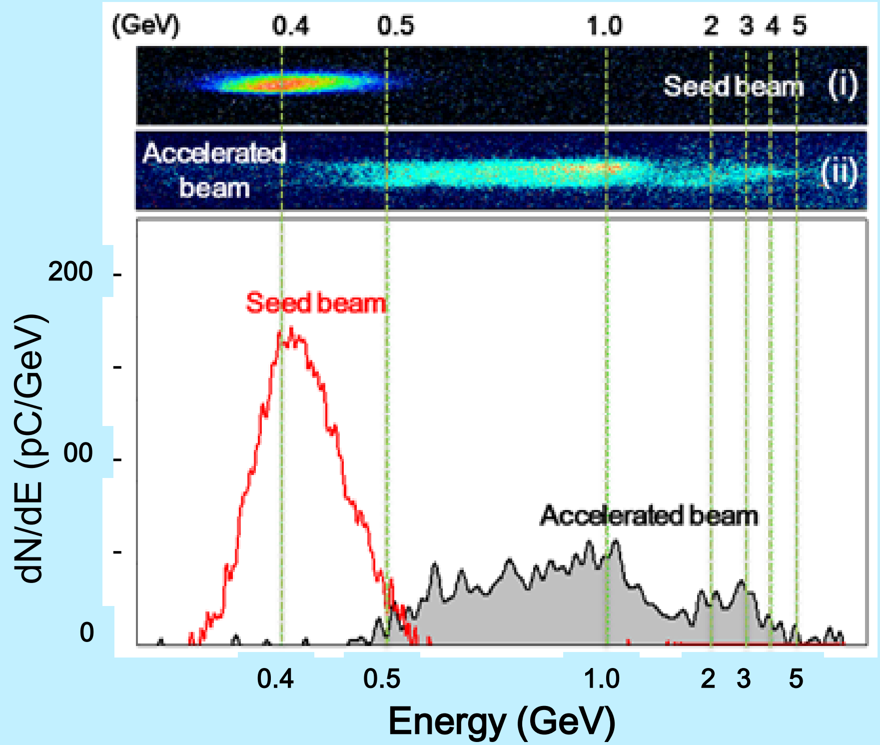


High-energy electron beam (>400 MeV) injected to the second gas jet

→ Investigation on multi-jet configuration with high energy electron injection

Charge of electron beam (4+10 mm):
~ 80 pC (> 0.5 GeV), ~10 pC (> 2 GeV)

Electron energy spectrum



HT Kim et al., PRL (2013)

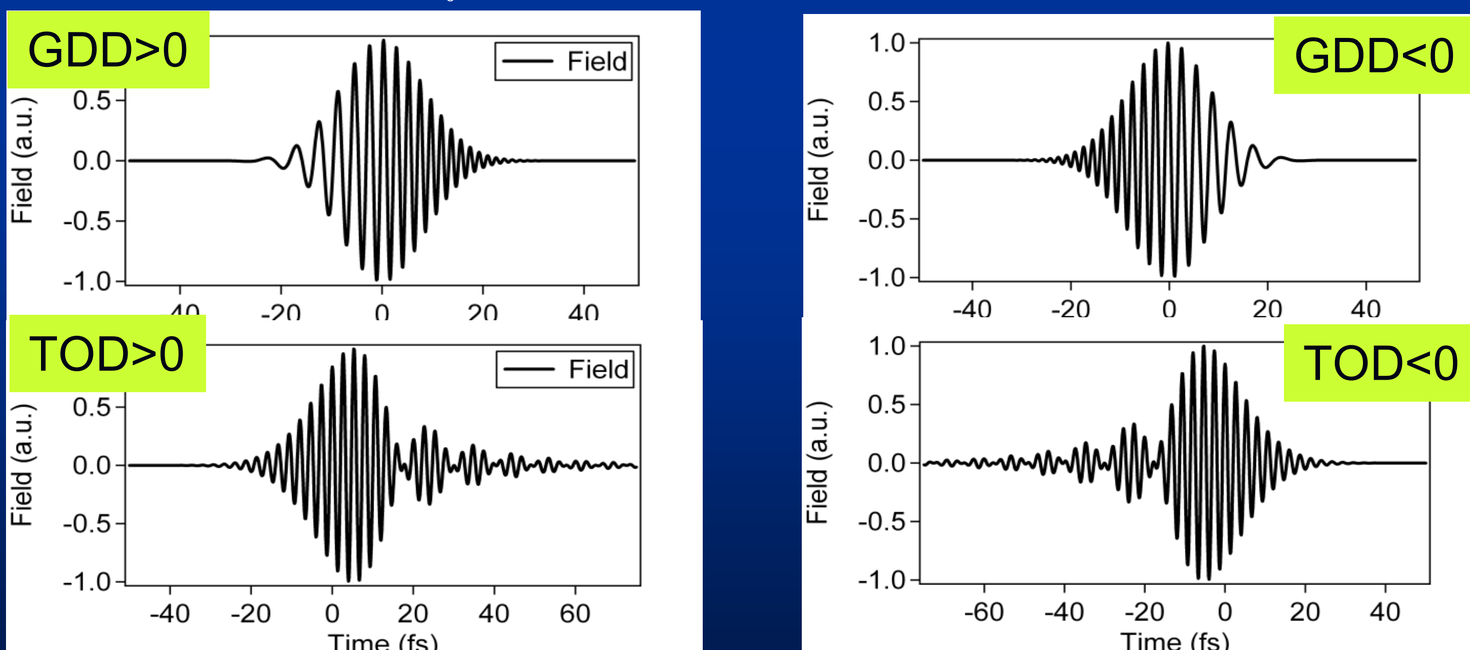
Coherent Control of Laser-Matter Interactions

spectral phase:

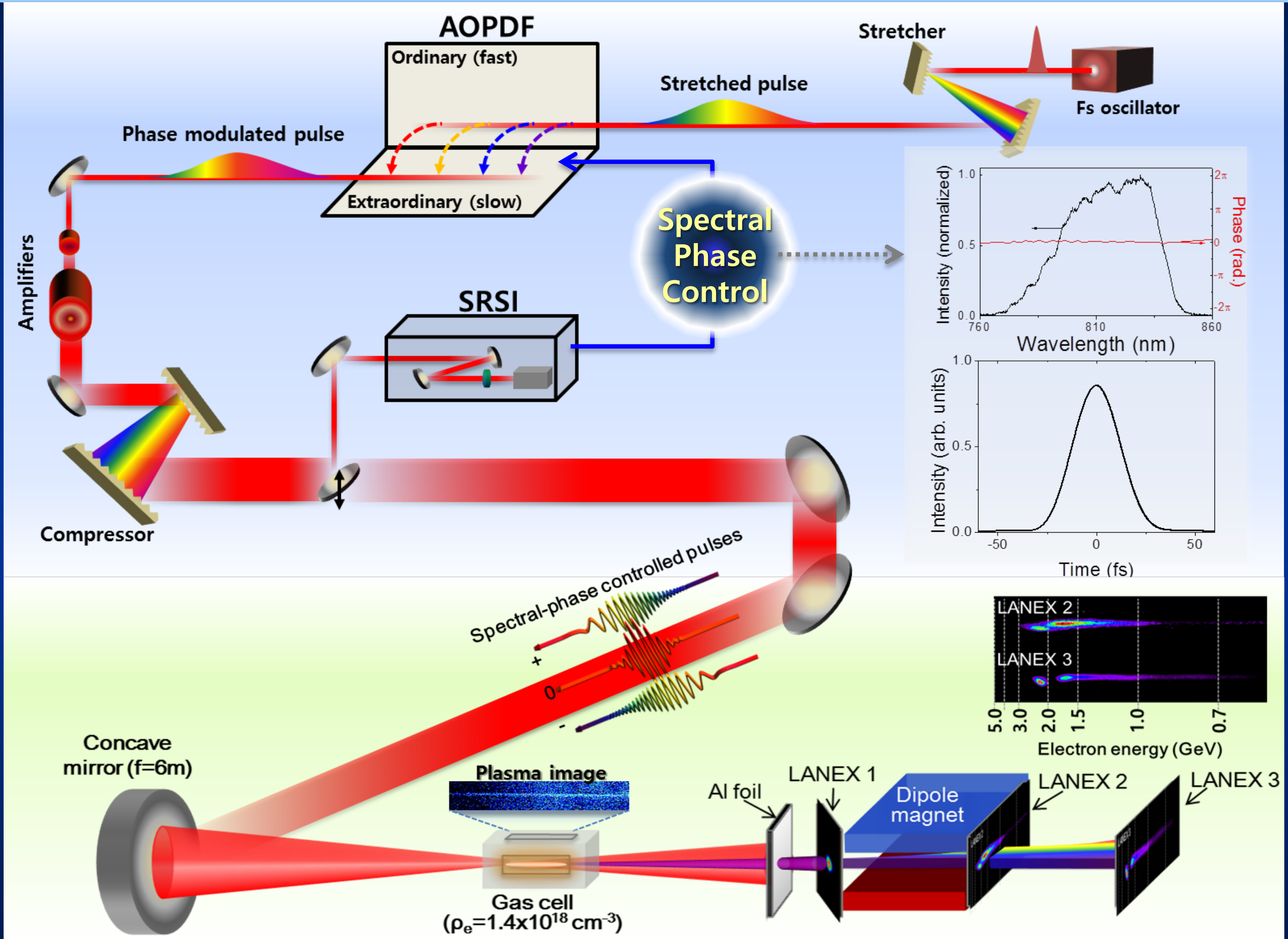
$$\varphi(\omega) = \varphi_0 + \varphi_1 \frac{\omega - \omega_0}{1!} + \varphi_2 \frac{(\omega - \omega_0)^2}{2!} + \varphi_3 \frac{(\omega - \omega_0)^3}{3!} + \ldots$$

where $\varphi_2 = \left.\frac{d^2\varphi}{d\omega^2}\right|_{\omega=\omega_0}$ = group-delay dispersion (GDD) = linear chirp ,

$\varphi_3 = \left.\frac{d^3\varphi}{d\omega^3}\right|_{\omega=\omega_0}$ = 3rd –order spectral phase (TOD) = quadratic chirp

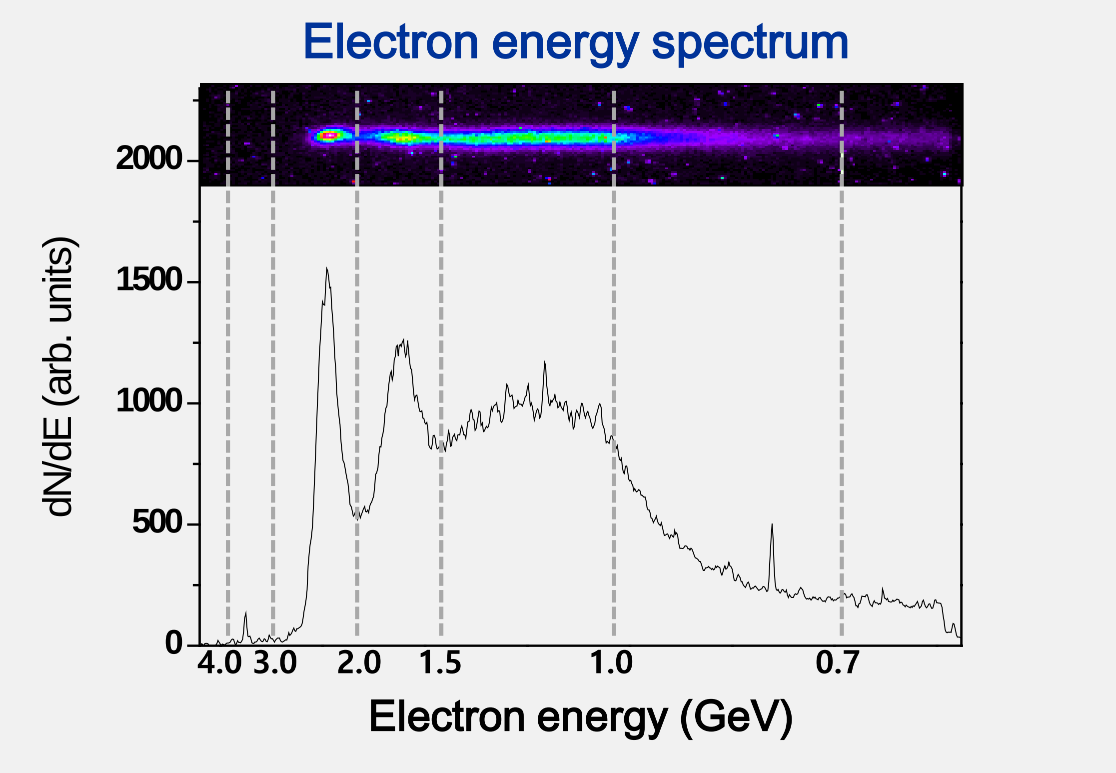


Coherent Control of LWFA



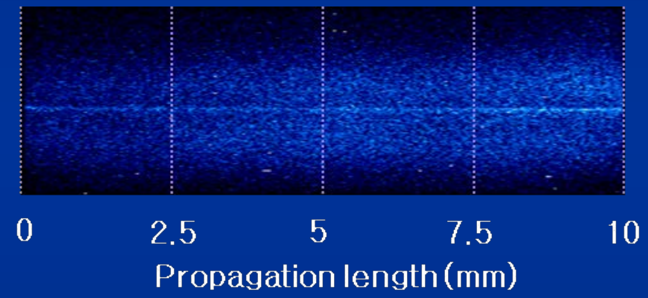
Electrons over 2 GeV from a 1-cm gas cell

Gas cell length = 10 mm
Positively chirped 61 fs
Intensity = 2×10^{19} W/cm^2 (a_0=3.1)



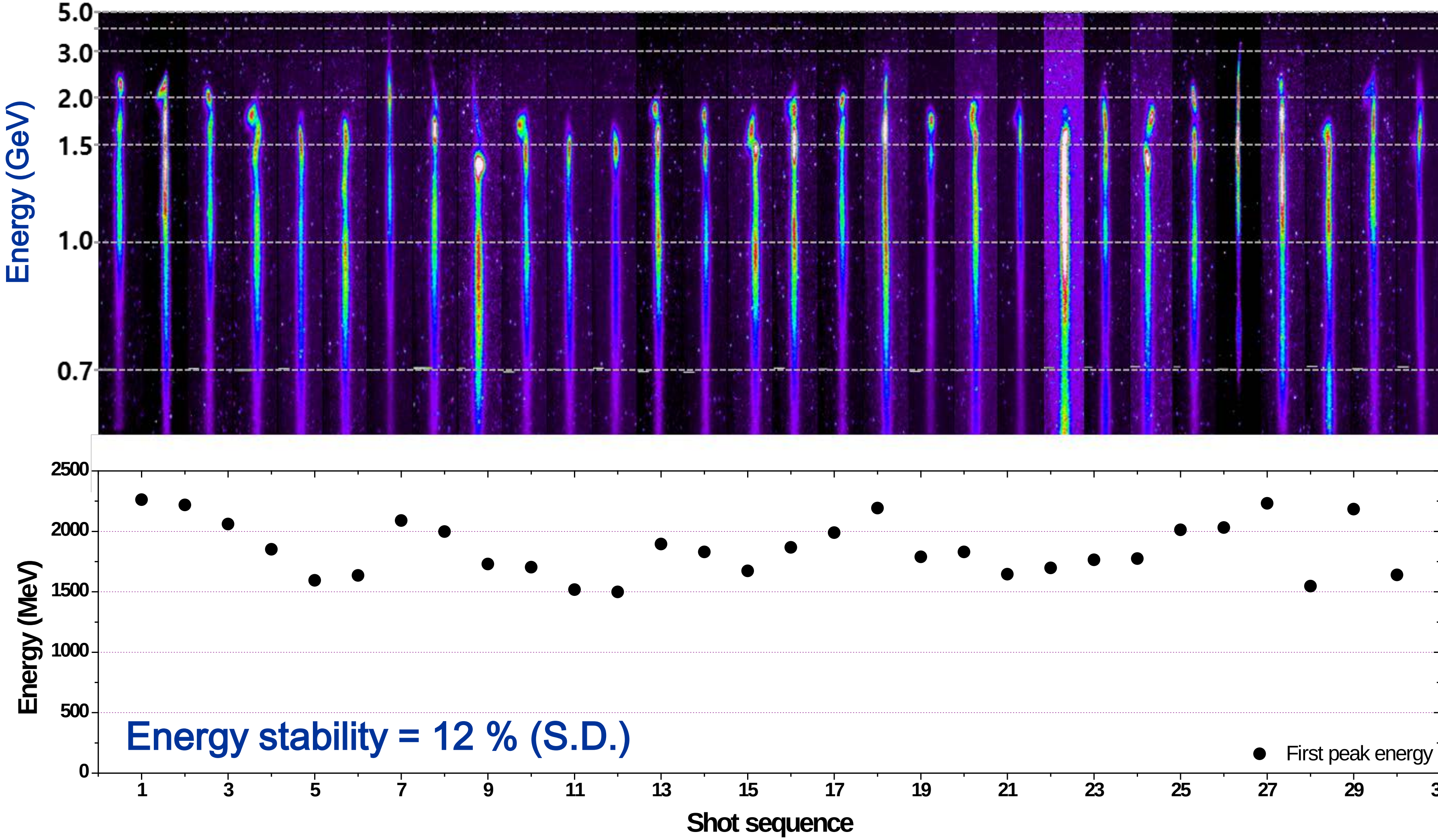
Electron energy > 2 GeV

Top view (Thomson scattering)



Smooth propagation over the whole medium length of 10 mm

Stability of electron beam from a single gas cell (30 shots)

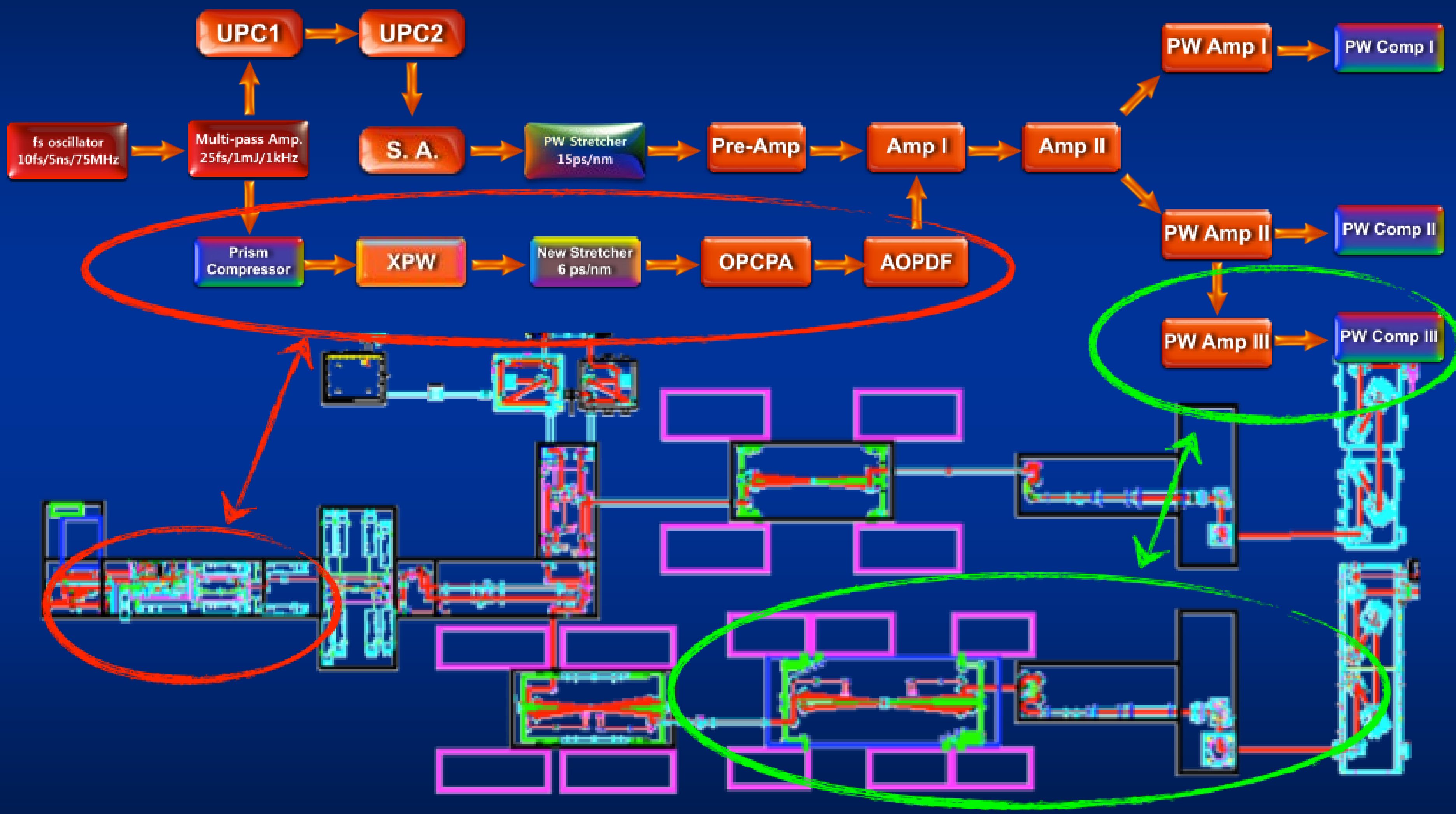


1. Femtosecond PW Laser

2. Relativistic Laser Science

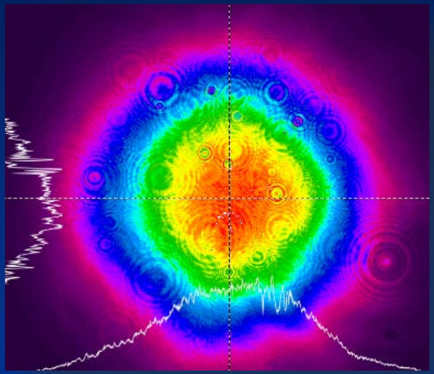
3. Laser Upgrade: 4 PW Laser

Upgrade: High Contrast, 20 fs, 4 PW Laser

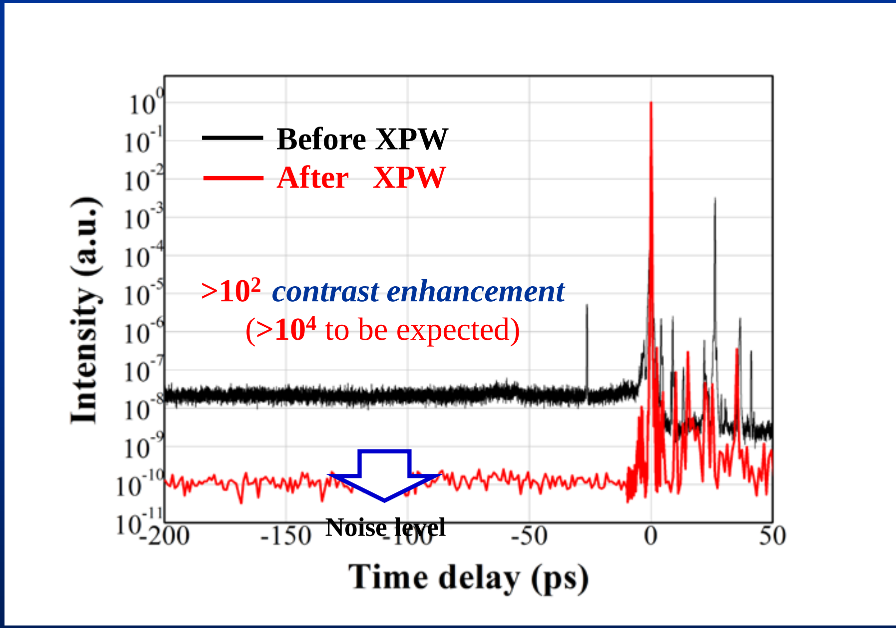


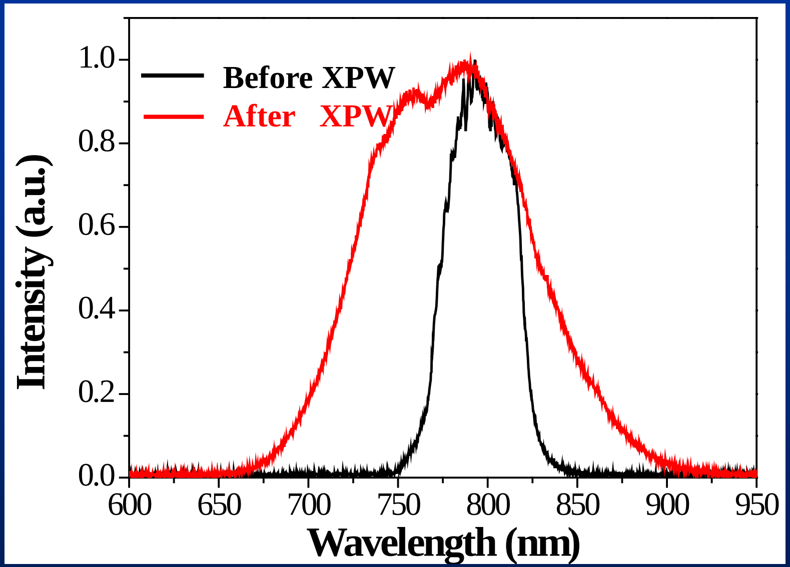
High contrast, broadband seed pulse with XPW

- Input pulse: 3 mJ, 25 fs
- Hollow fiber: 250-µm core, 20-cm long
- Energy after BaF_2 XPW: 500 µJ (16 %)

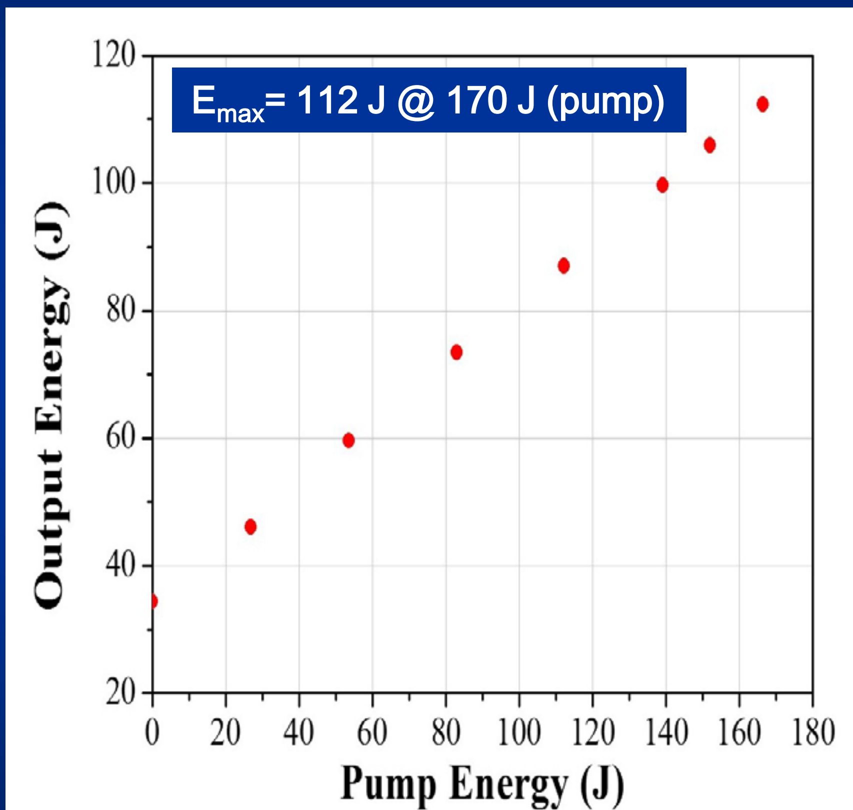


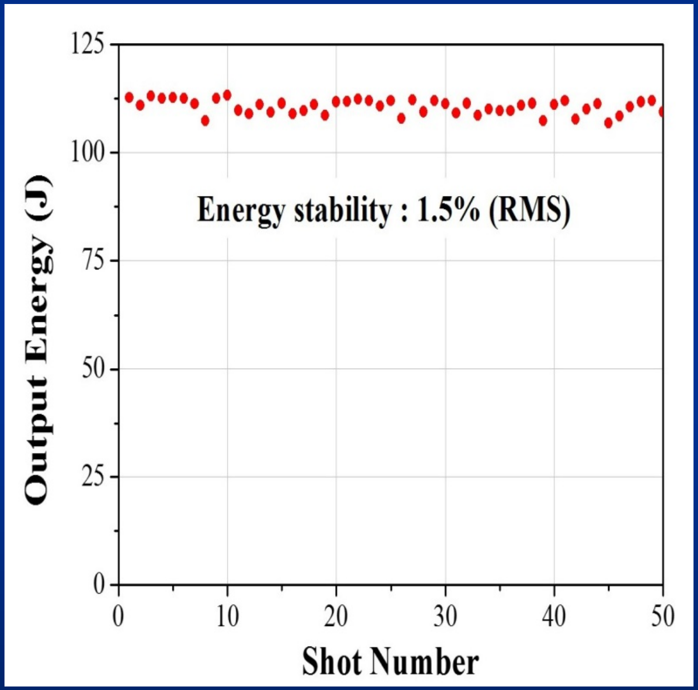
Beam profile after XPW



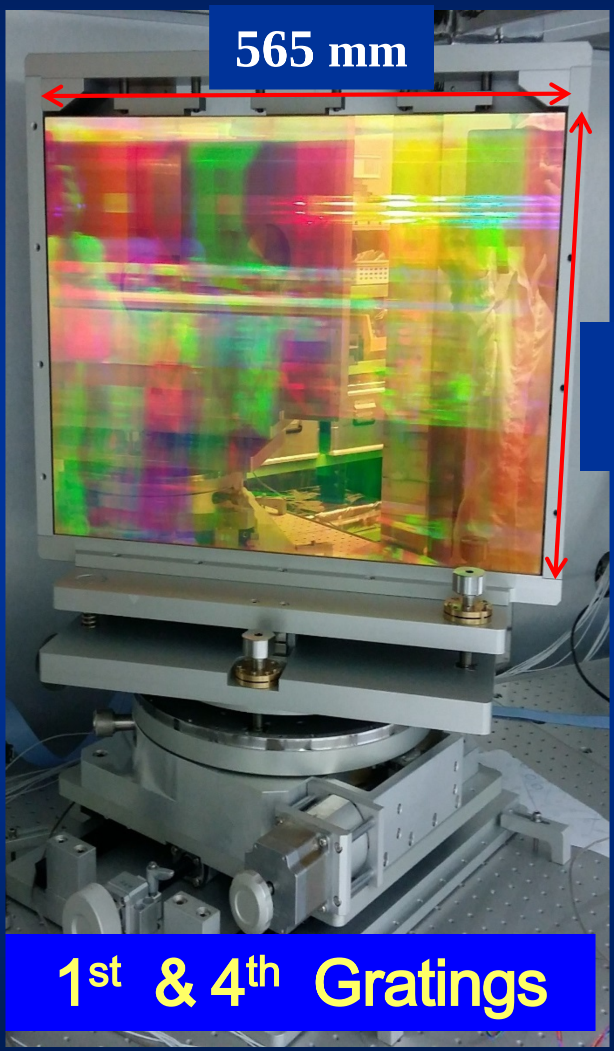


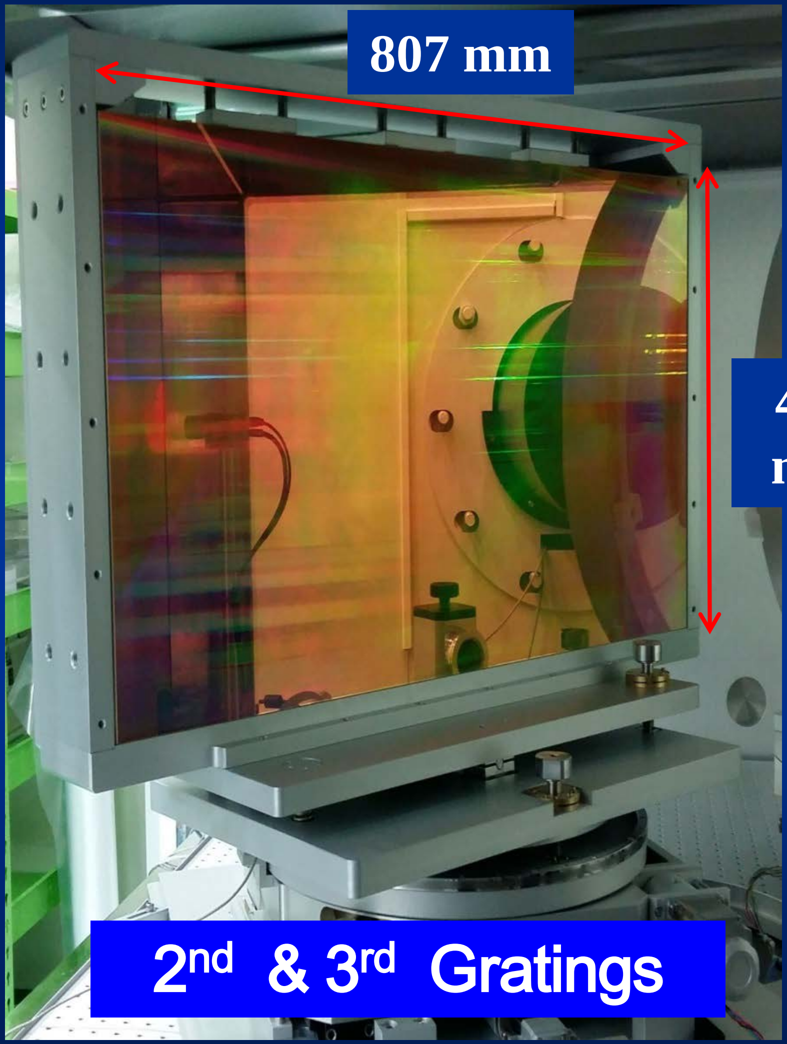
Energy and Stability of Final Booster Amplifier



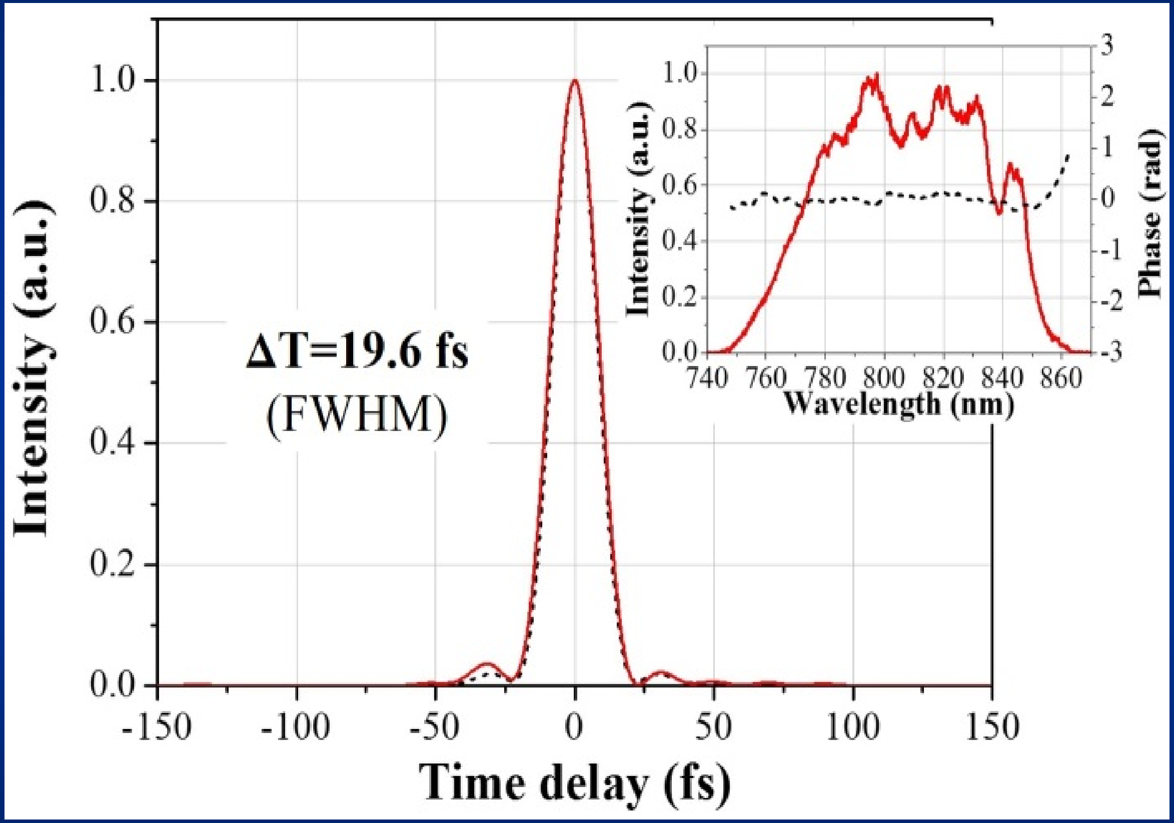


Pulse Compression Gratings

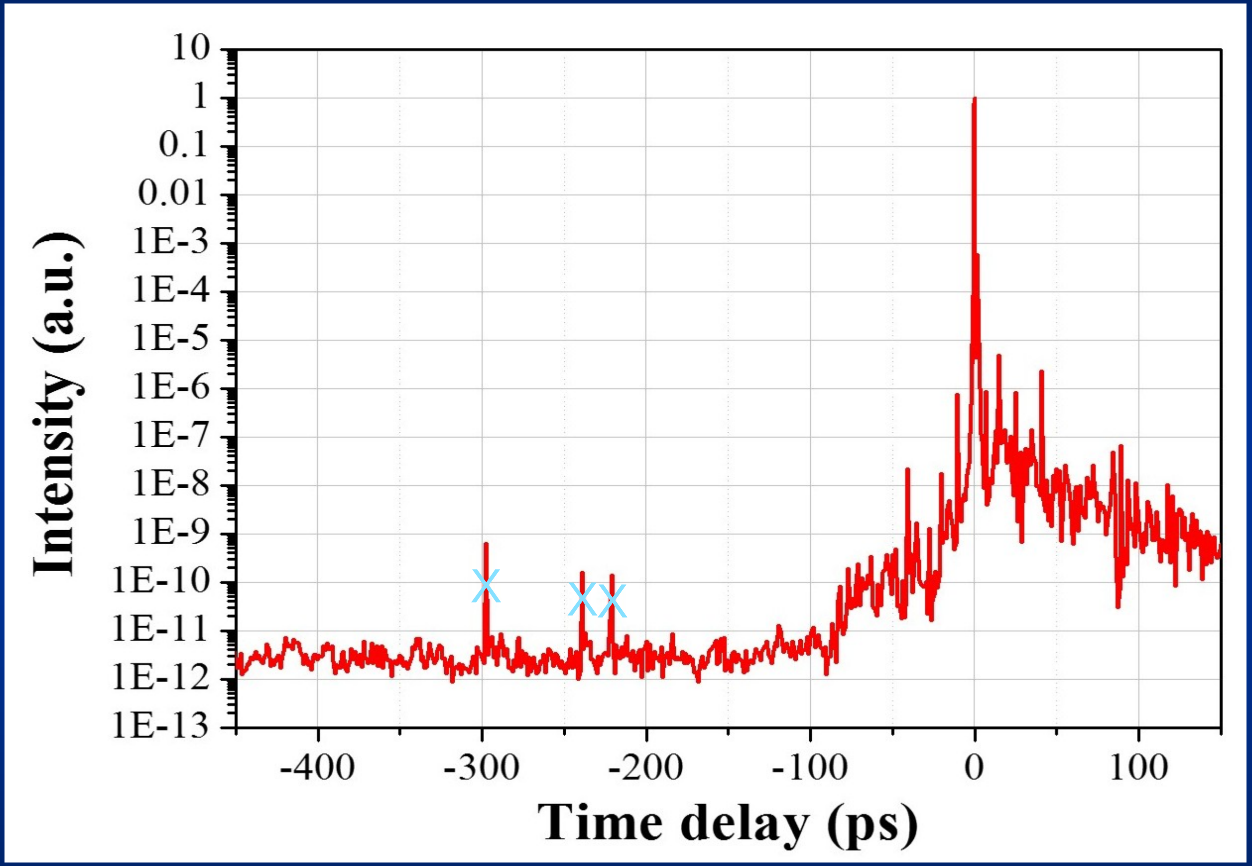




Temporal Profile of 4 PW Laser

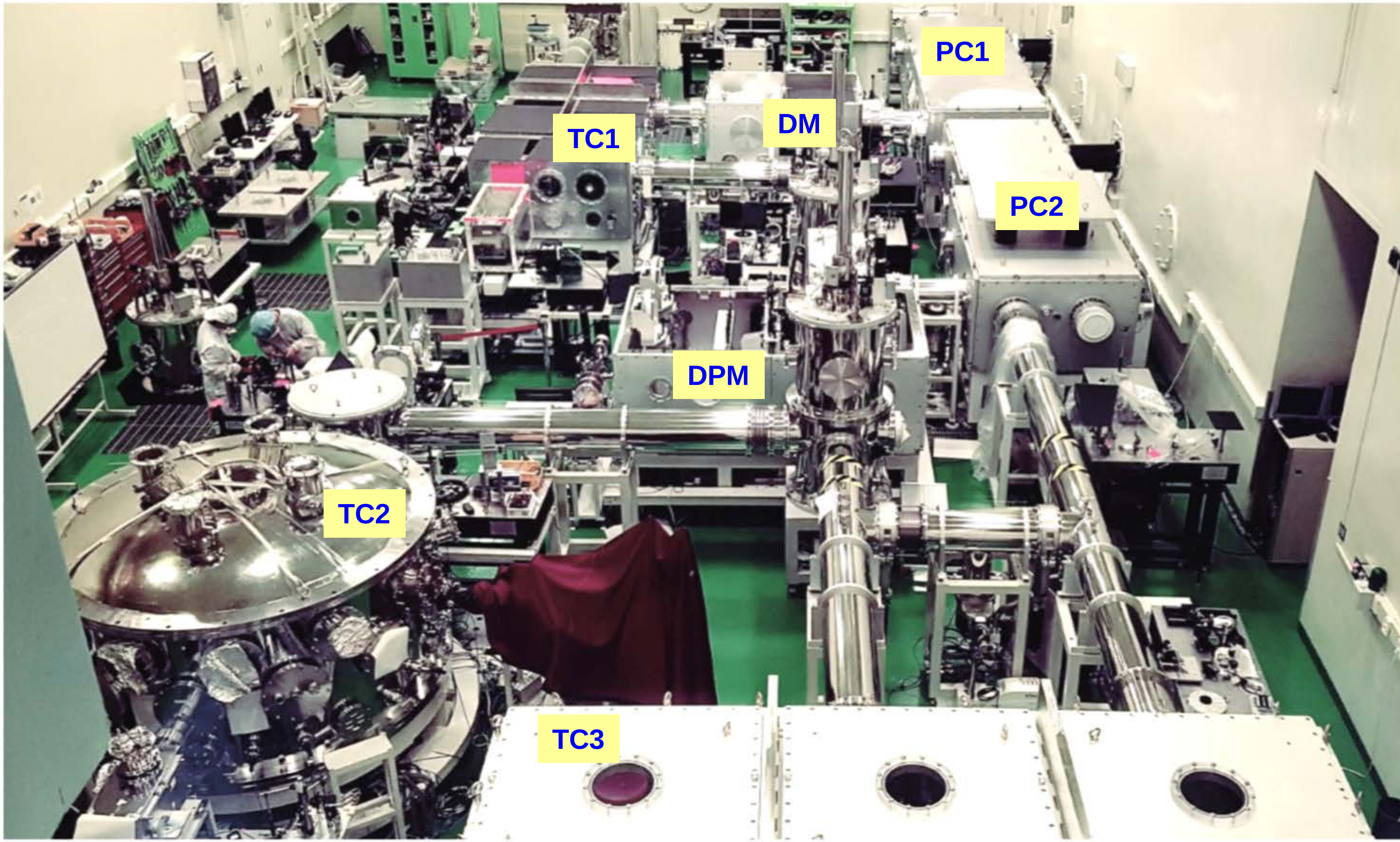


Contrast of 4 PW Laser Pulses



CoReLS PW laser: 1 PW + 4 PW Beamlines

PW Laser Experimental Area



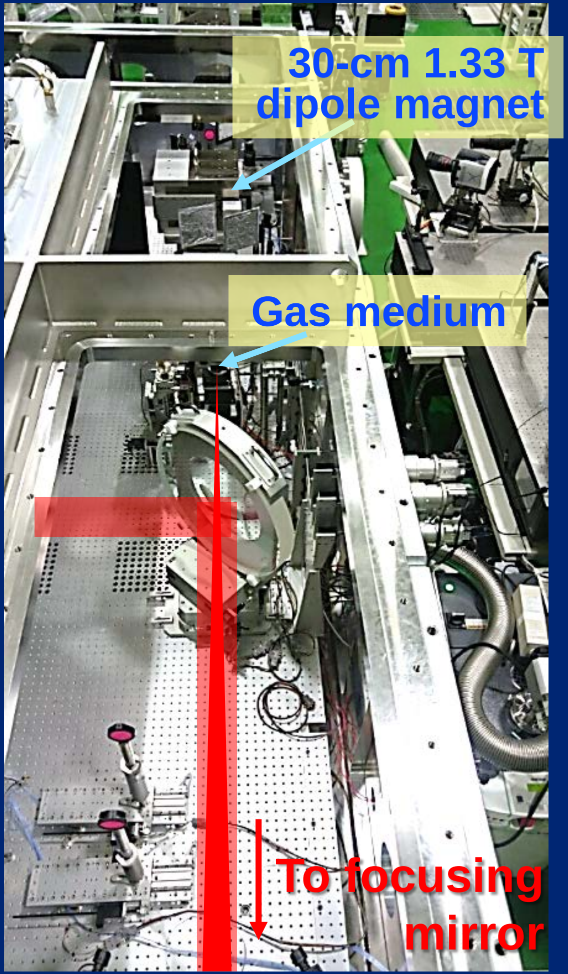
Strategy for 10 GeV LWFA

- **Injection control**
  - Two stage approach: Gas jet + gas cell
    >> Guided flow to minimize the mixing between two media

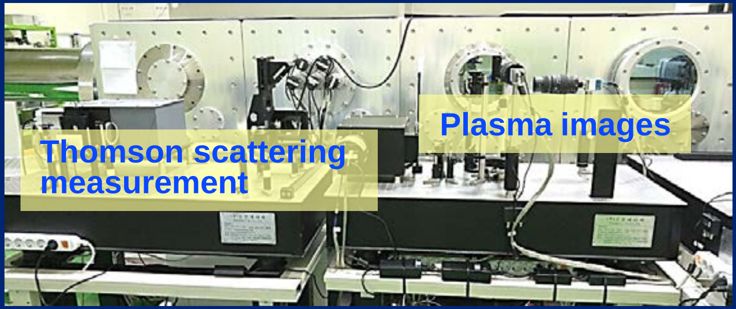
- **Laser guiding**
  - Capillary - limitation in laser input energy
  - Self-guiding to be tested, but not easy for 20-cm length.
  - Laser guiding using a ns laser focused by an axicon lens or by using prepulse of a pump laser itself.
    >> Hydrodynamic analysis of guiding structure

- **Acceleration control**
  - Control of LWFA by manipulating spectral & spatial phase of laser (Dazzler & Wizzler system + large deformable mirror)
  - Quasi phase matching by modulating the density profile
  - Two-color LWFA

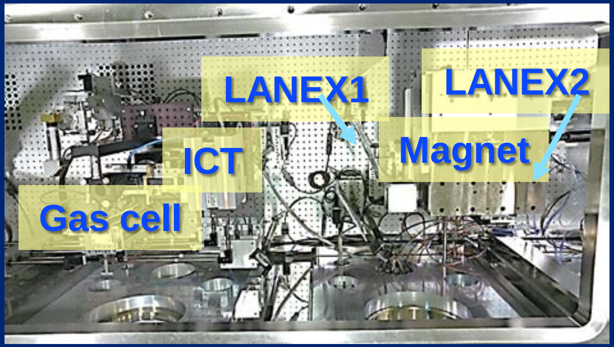
Preparation for LWFA experiment using 4 PW laser pulses



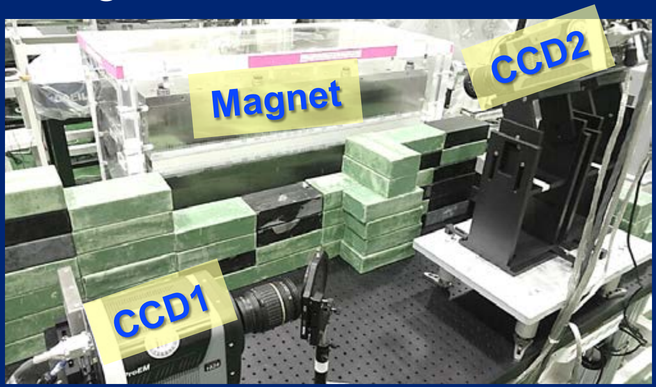
Target chamber



Plasma diagnostics



Electron beam diagnostics in chamber



1-m long variable-gap magnet

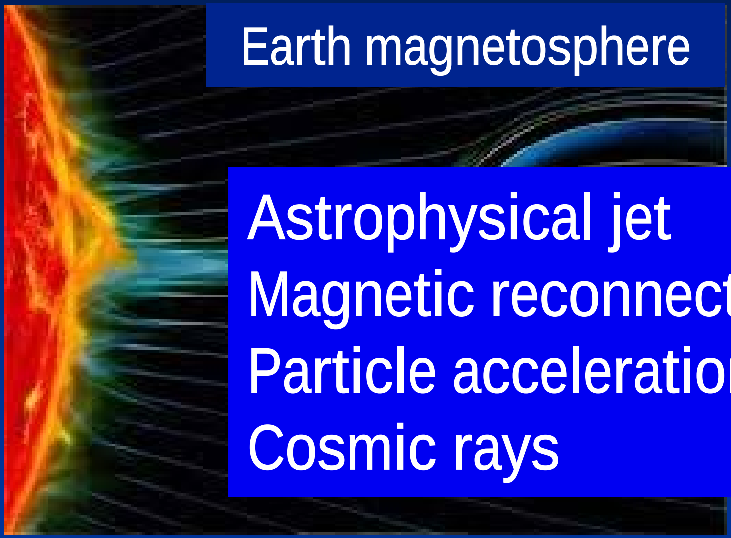
All-Optical Compton Experiments

- **Laser Compton γ-ray production** via interaction of **GeV e-beam** with **10^{18} - 10^{22} W/cm^2** laser field
  - **Compton backscattering**: $e^- + \omega_0 \rightarrow e^- + \gamma$
    - MeV-Gamma beams useful for photo-nuclear physics

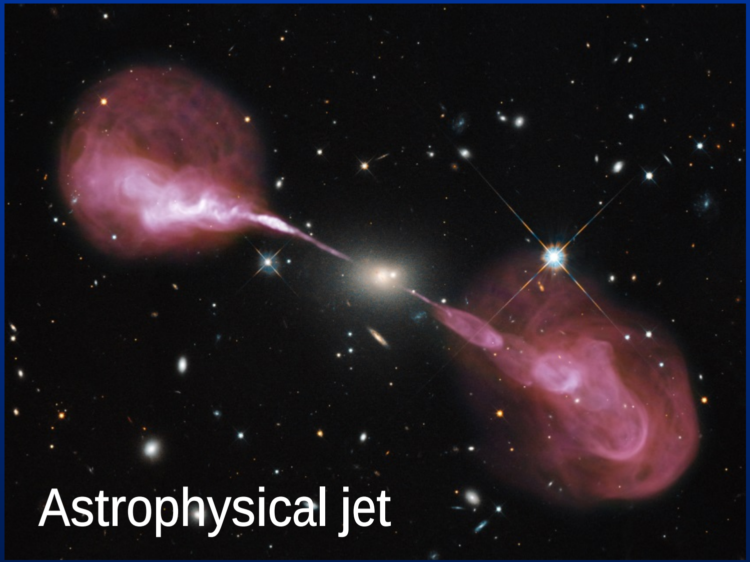
$$\omega'_{max} \approx 4\gamma^2 \omega_0 \approx 90\text{ MeV with 2 GeV e-beam}$$

  - **Nonlinear Compton Scattering**: $e^- + n\omega_0 \rightarrow e^- + \gamma$
    - Measuring radiation reaction effects
      Energy loss and radiation damping (cooling) of the electron beam
    - Investigating strong field QED effects
    - Electron-positron pair creation (B-W): $\gamma + n\omega_0 \rightarrow e^- + e^+$
      Only one experiment with 46.6 GeV linac e-beam and $a_0 = 0.36$
      D.L. Burke et al., Phys. Rev. Lett. **79**, 1626 (1997)

Laboratory Astrophysics



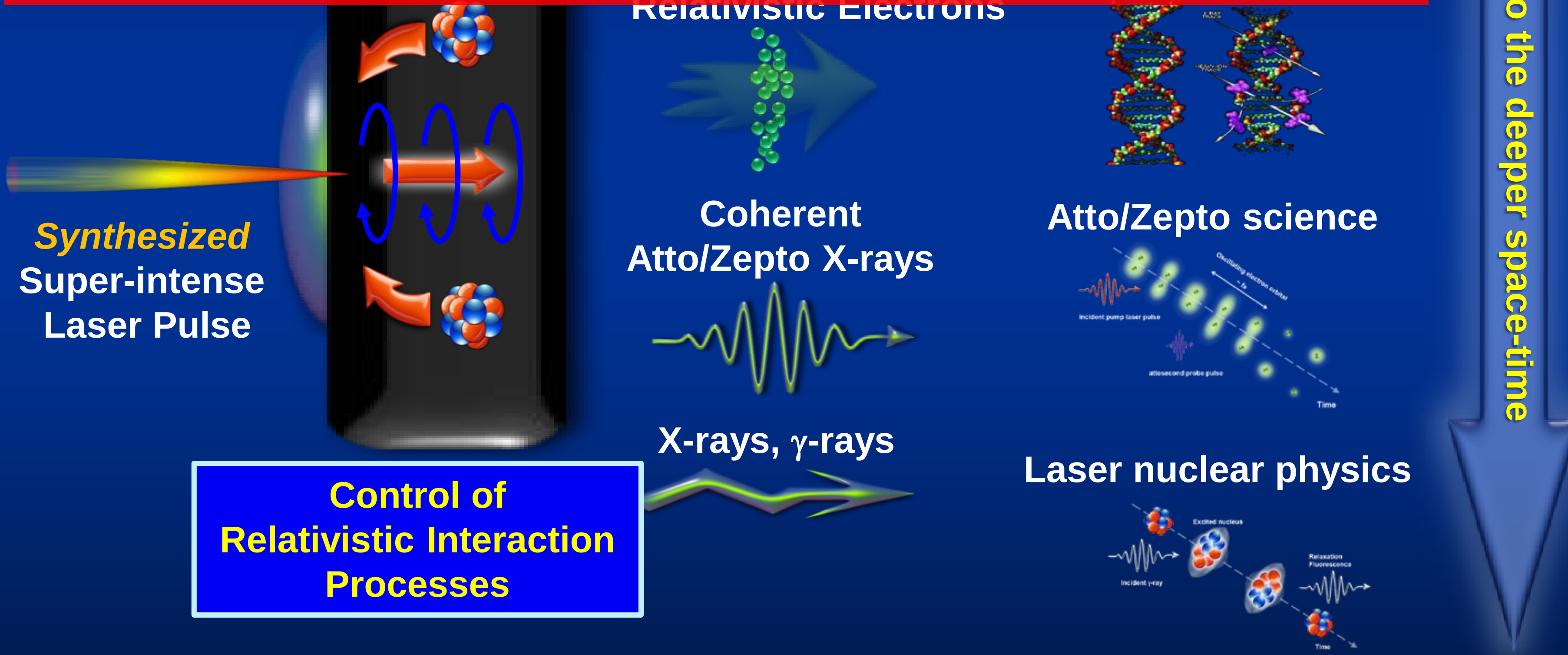
- Astrophysical jet
- Magnetic reconnection
- Particle acceleration
- Cosmic rays



Research Overview

Leading Laser Lab in the World

Exploration of Relativistic Laser-Matter Interactions using Super-intense Laser Pulses, especially with 1 PW + 4 PW Lasers



LPAW (Laser Plasma Accelerator Workshop)

IBS conference on laser plasma accelerators

Venue: Jeju Island, Korea
Dates: Aug. 27 – Sep. 1, 2017

http://ibs-conference.org/2017/lpa/