Challenging tasks in laser wakefield acceleration with PW lasers

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Relativistic Laser Intensities

Atomic field strength: $E_B = \frac{e}{r_B^2} \approx 5.1\times10^9 \text{ V/cm};\quad I_B = \frac{cE_B^2}{8\pi} \approx 3.5\times10^{16} \text{ W/cm}^2$

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

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

Intensity for relativistic electron:
(Relativistic regime)

$$I_{\text{Re}} \approx \frac{1.4\times10^{18}}{\left(\lambda^2\right)_{\mu m}} a_0{}^2 \text{ W/cm}^2$$

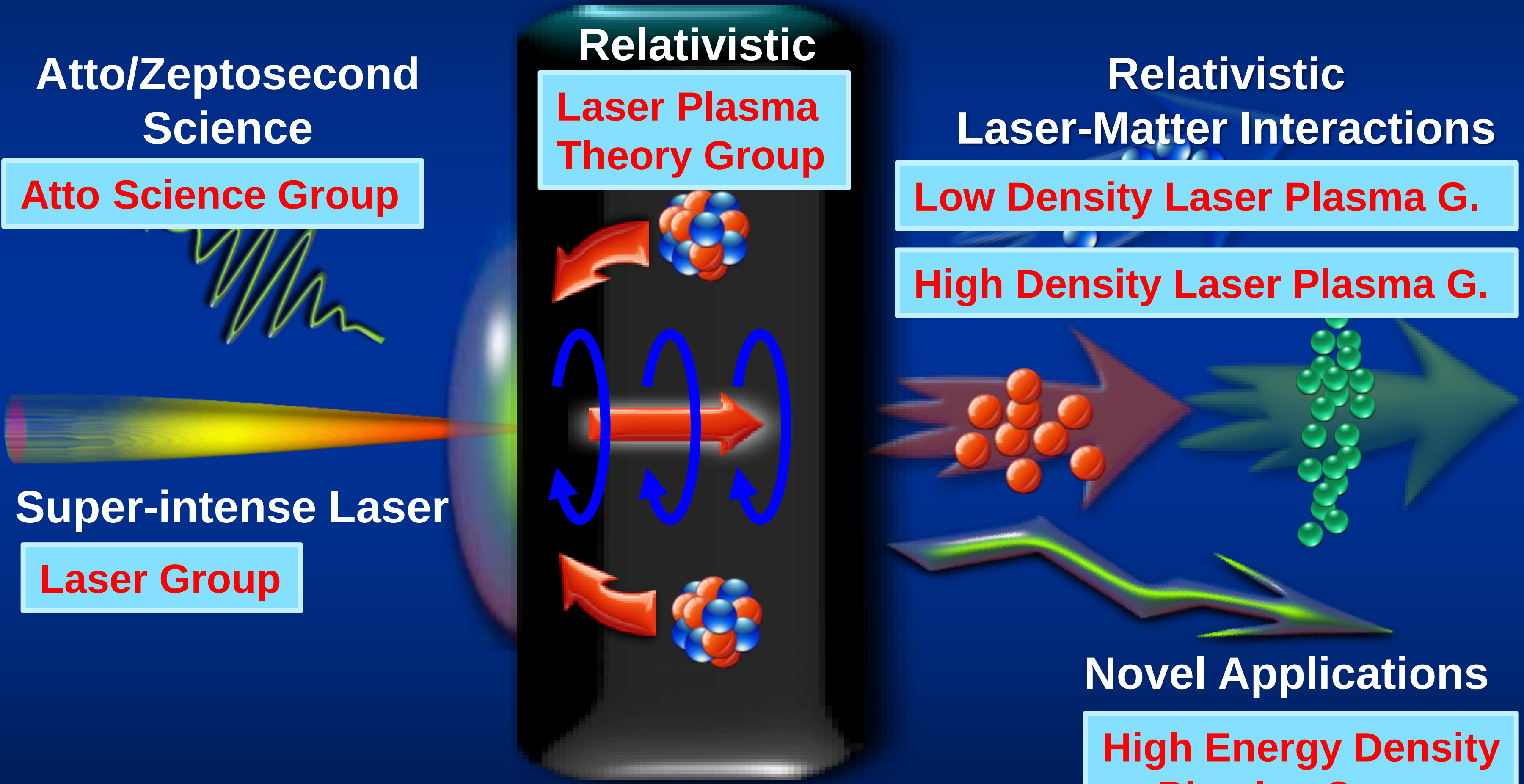
For $a_0 = \frac{M_p}{m_e} = 1800$, ultra-relativistic.

Intensity for relativistic proton:
(Ultra-relativistic regime)

$$I_{Rp} \approx \frac{4.5\times10^{24}}{\left(\lambda^2\right)_{\mu m}} \text{ W/cm}^2$$

Research Groups at CoReLS, Inst for Basic Science

Exploration of Relativistic Laser-Matter Interactions using Ultra-high Intensity Lasers



Atto/Zeptosecond Science

Atto Science Group

Super-intense Laser

Laser Group

Relativistic

Laser Plasma Theory Group

Relativistic Laser-Matter Interactions

Low Density Laser Plasma G.

High Density Laser Plasma G.

Novel Applications

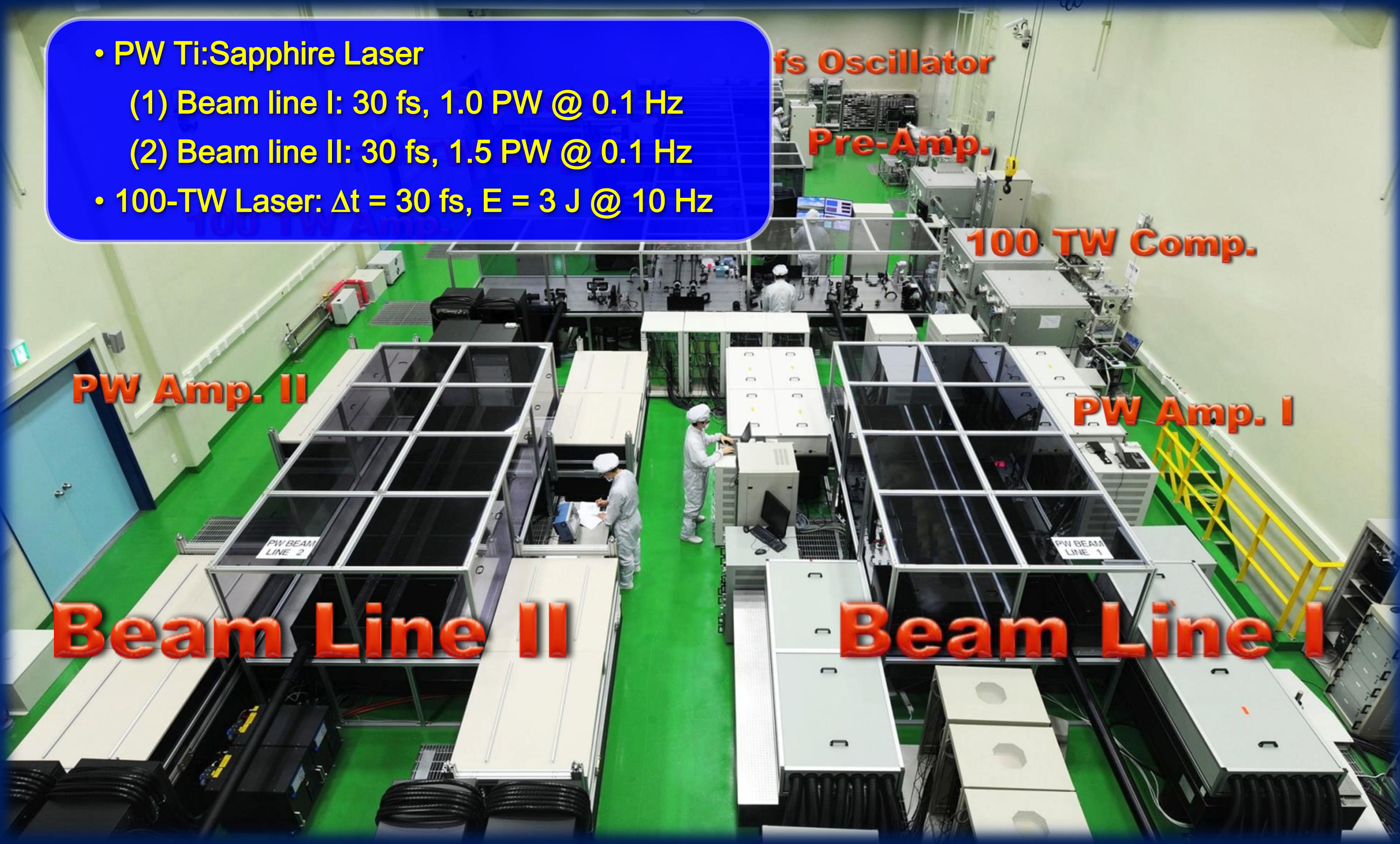
High Energy Density Physics Group

Overview

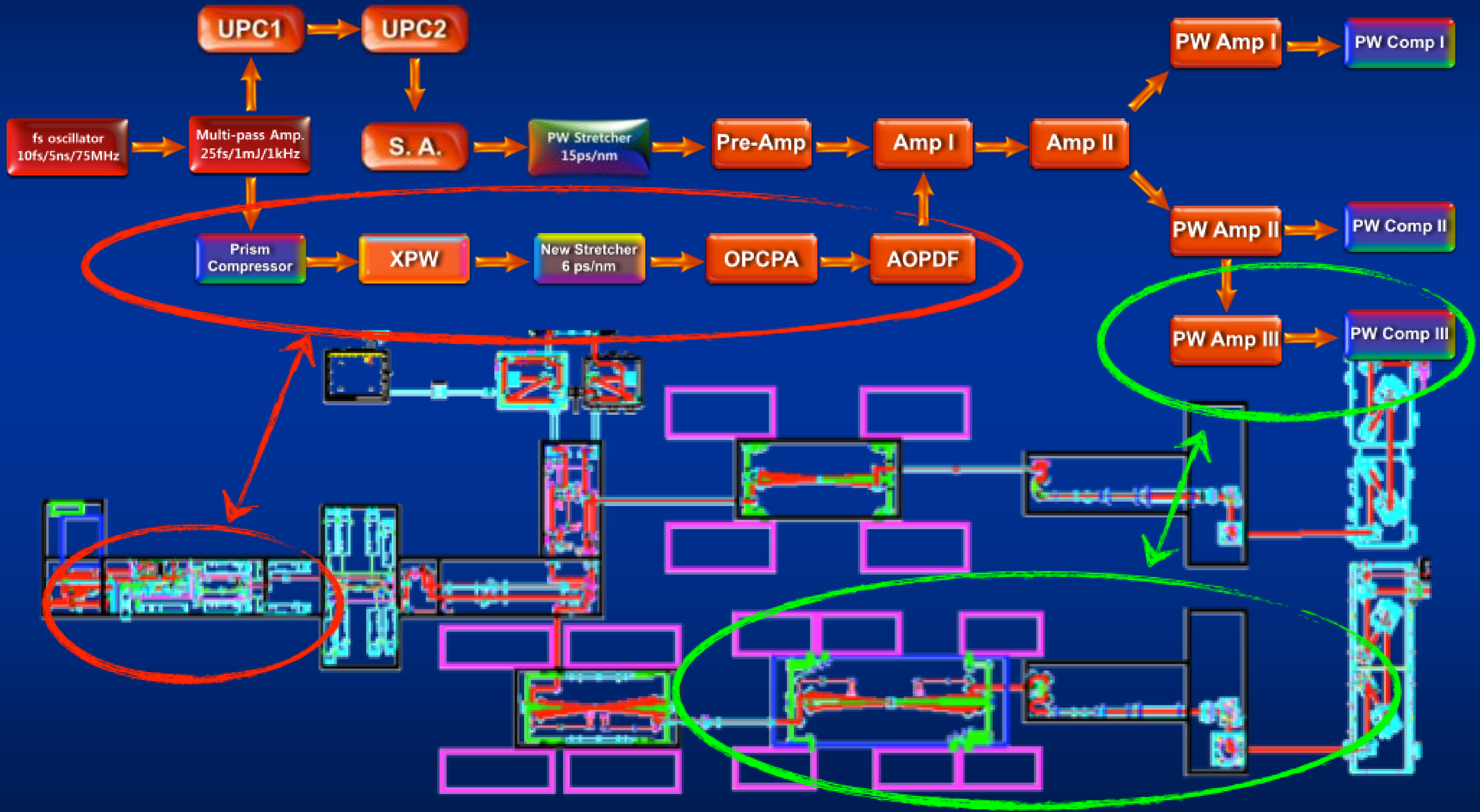
1. **PW Ti:sapphire laser**
2. **Laser wakefield electron acceleration**
   - **A. LWFA with PW lasers**
   - **B. Compton backscattering – MeV γ-ray**

PW Ti:Sapphire Laser at CoReLS

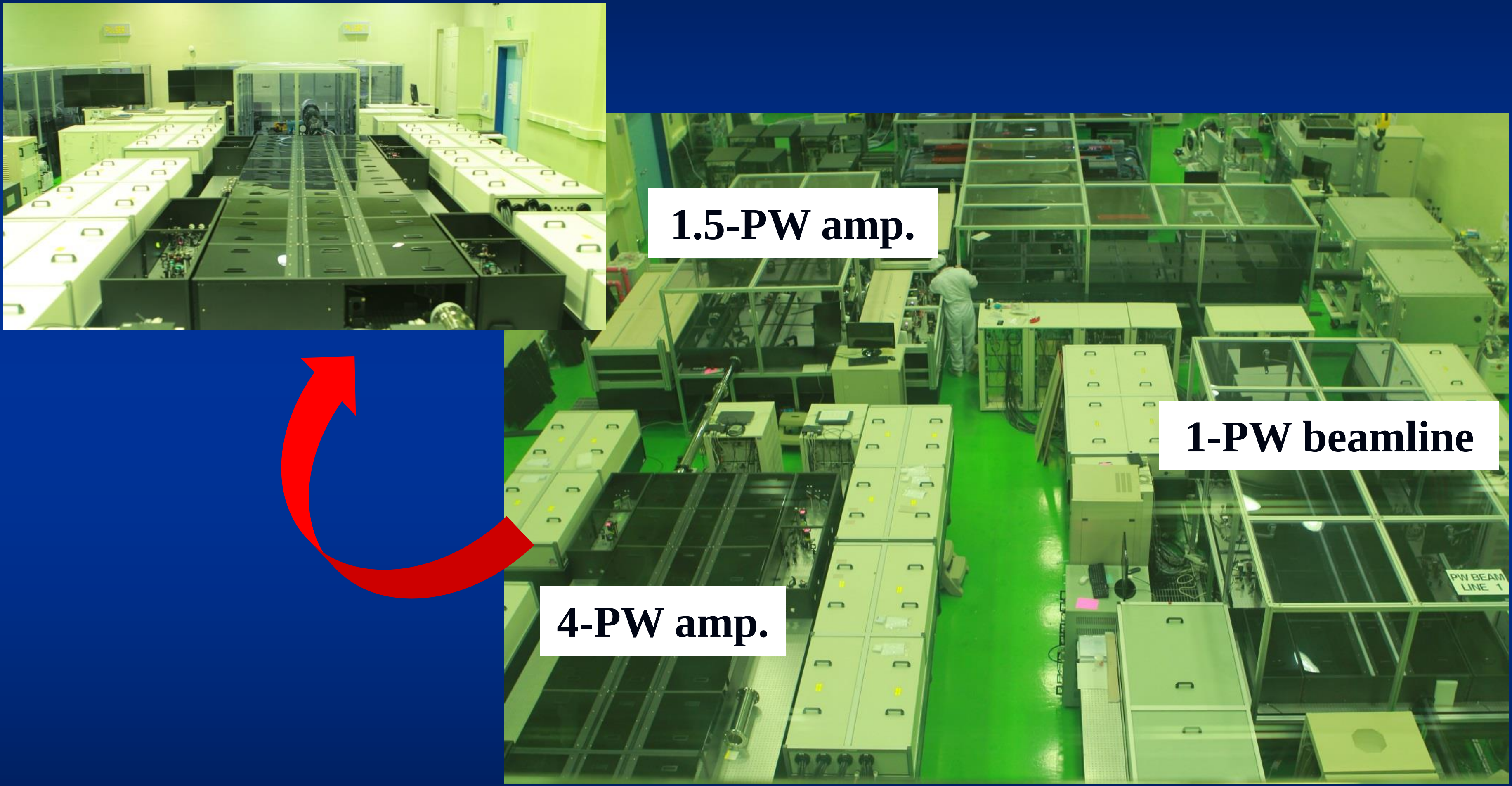
- PW Ti:Sapphire Laser
  - (1) Beam line I: 30 fs, 1.0 PW @ 0.1 Hz
  - (2) Beam line II: 30 fs, 1.5 PW @ 0.1 Hz
- 100-TW Laser: Δt = 30 fs, E = 3 J @ 10 Hz



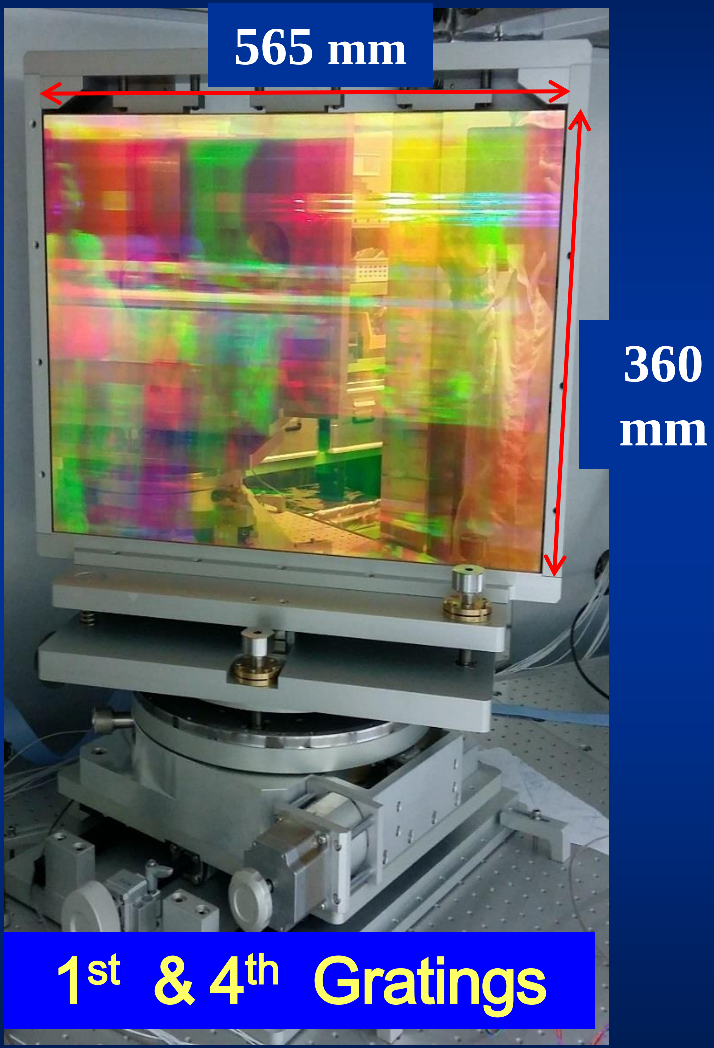
Upgrade: High Contrast, 20 fs, 4 PW Laser



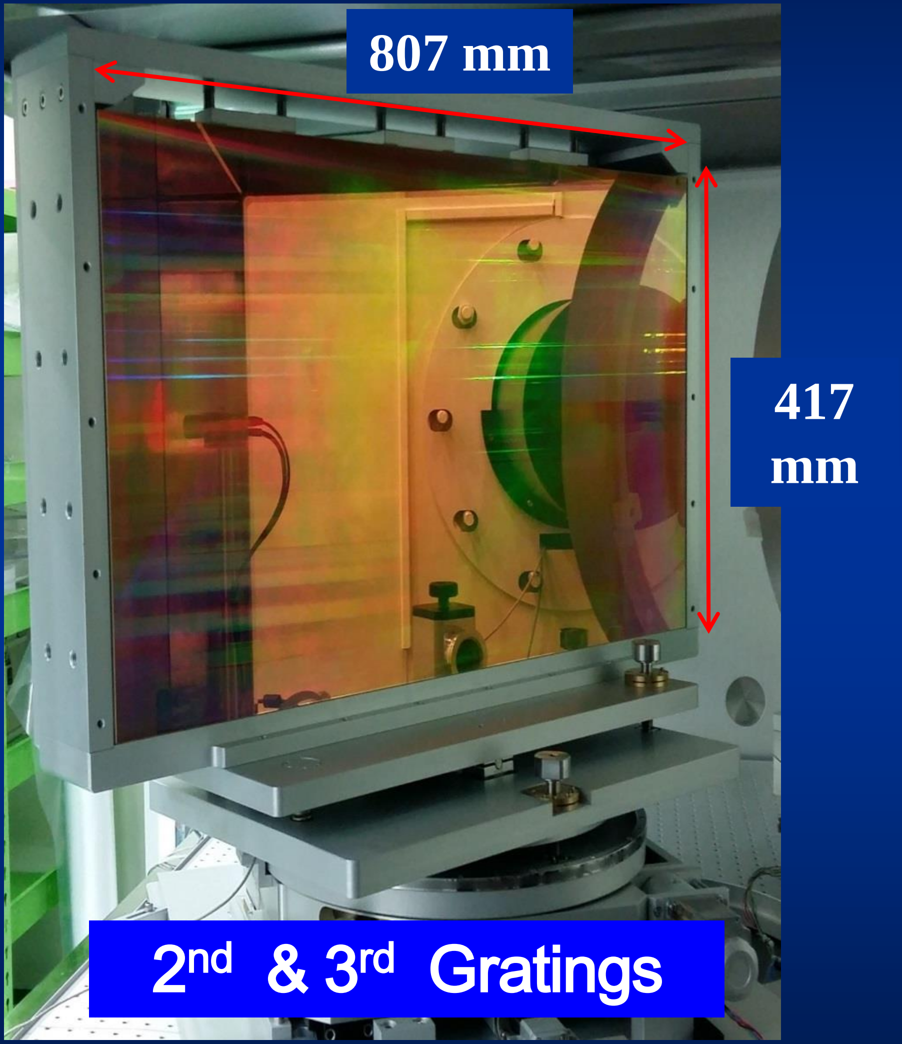
Installation of 4-PW amplifier



Pulse Compression Gratings



1st & 4th Gratings

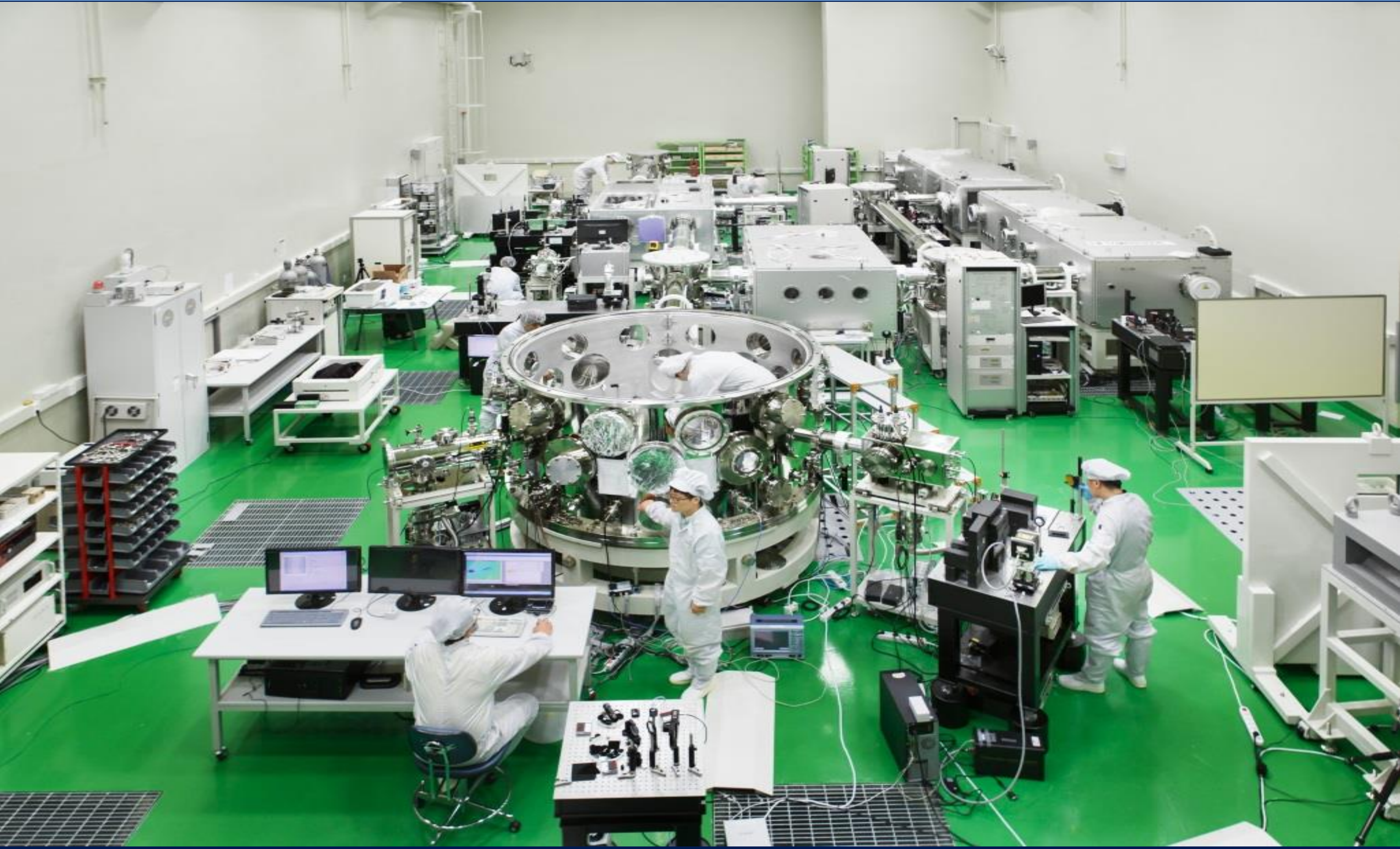


2nd & 3rd Gratings

1. PW Ti:Sapphire laser

2. Laser wakefield electron acceleration
    A. LWFA with PW lasers – 10 GeV e^- beam
    B. Compton backscattering – MeV γ-ray

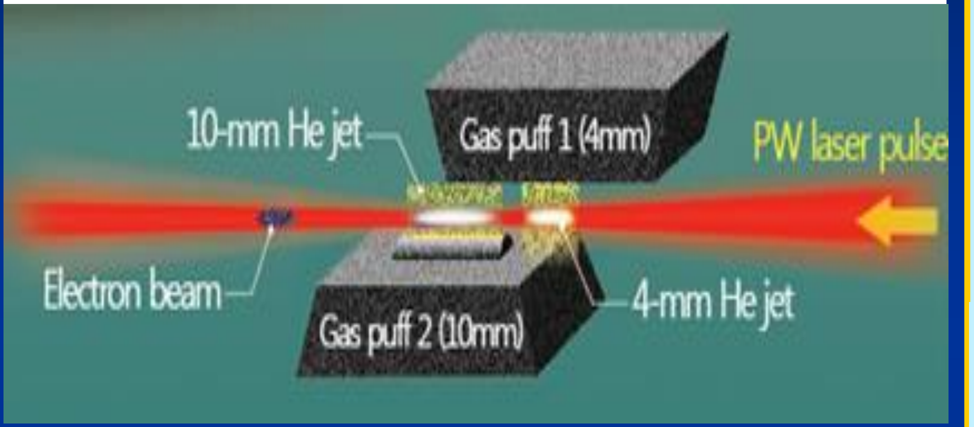
PW Laser Experimental Area



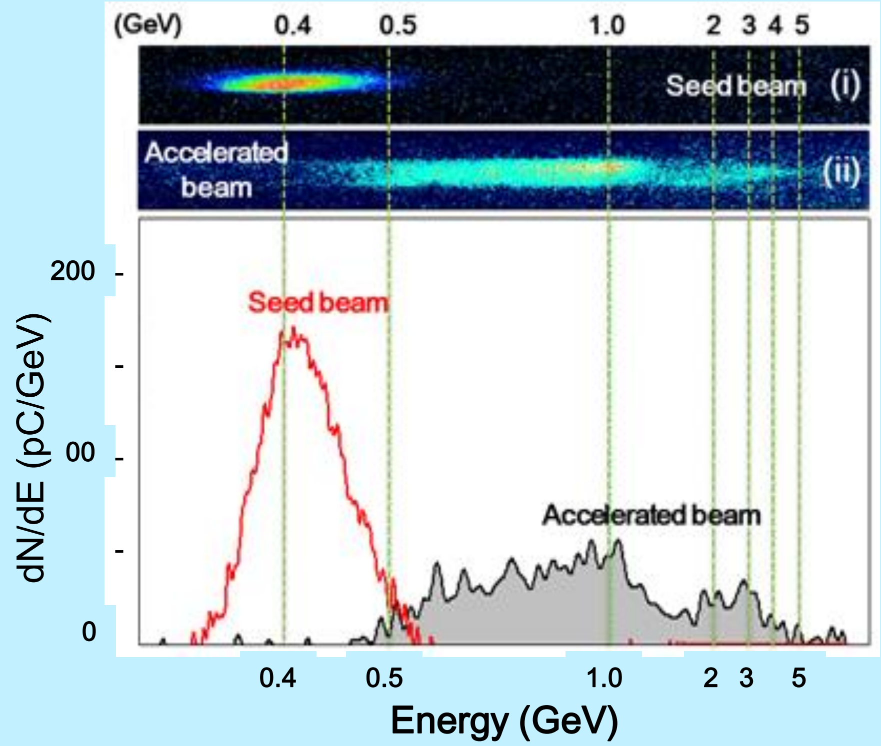
Multi-GeV e-Beam Generation with Dual Gas Jets

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)



Electron energy spectrum



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)

HT Kim et al., PRL (2013)

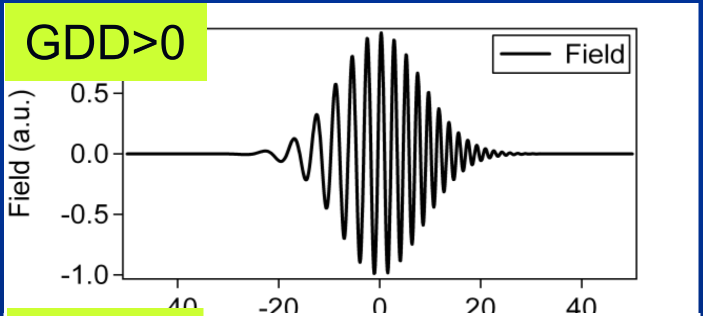
Coherent Control of Laser-Matter Interactions

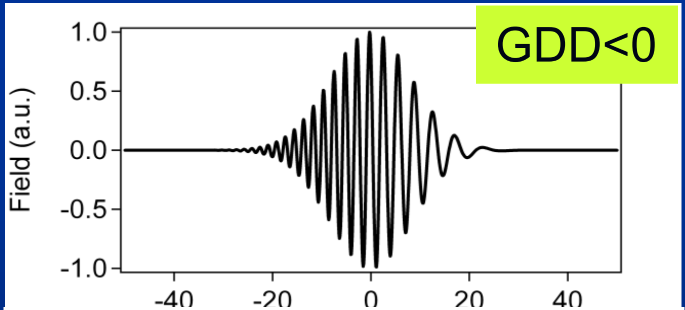
spectral phase:

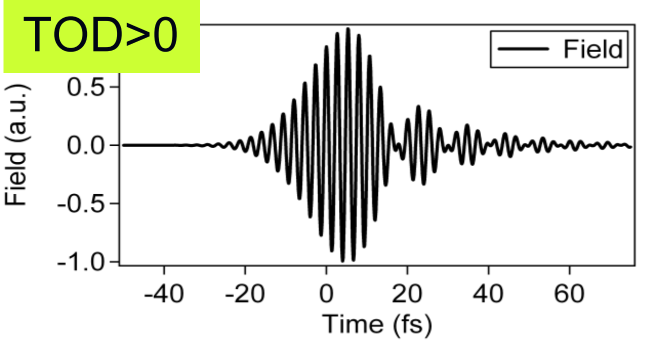
$$\boxed{\varphi(\omega) = \varphi_0 + \varphi_1 \frac{\omega-\omega_0}{1!} + \varphi_2 \frac{(\omega-\omega_0)^2}{2!} + \varphi_3 \frac{(\omega-\omega_0)^3}{3!} + \ldots}$$

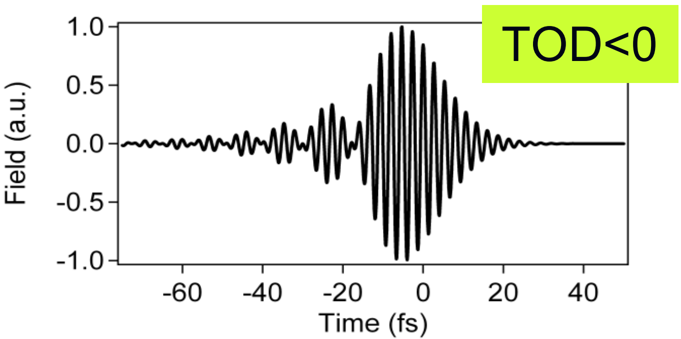
where $\varphi_2 = \left.\frac{d^2\varphi}{d\omega^2}\right|_{\omega=\omega_0}$ = group-delay dispersion (GDD) = linear chirp ,

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

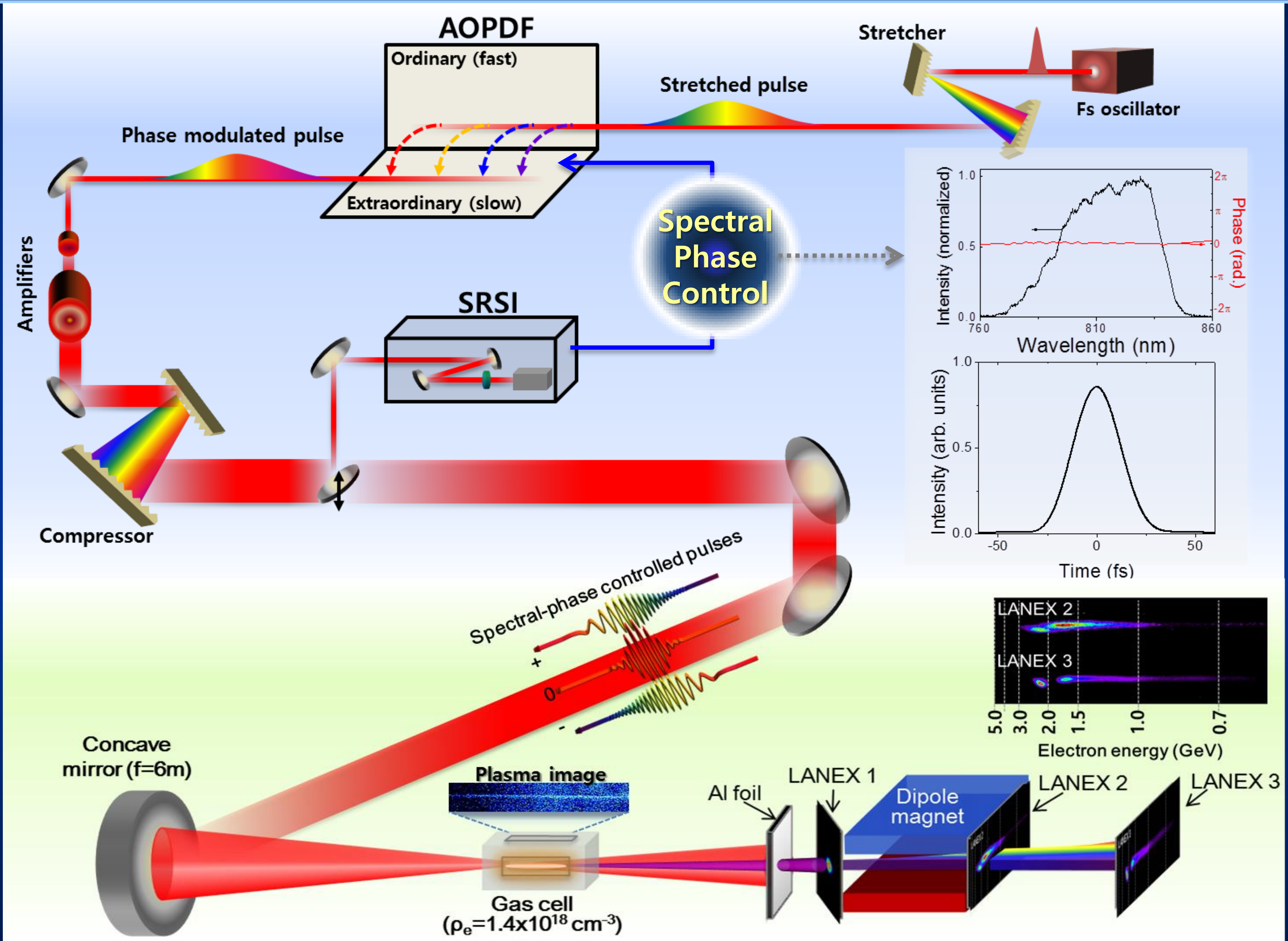








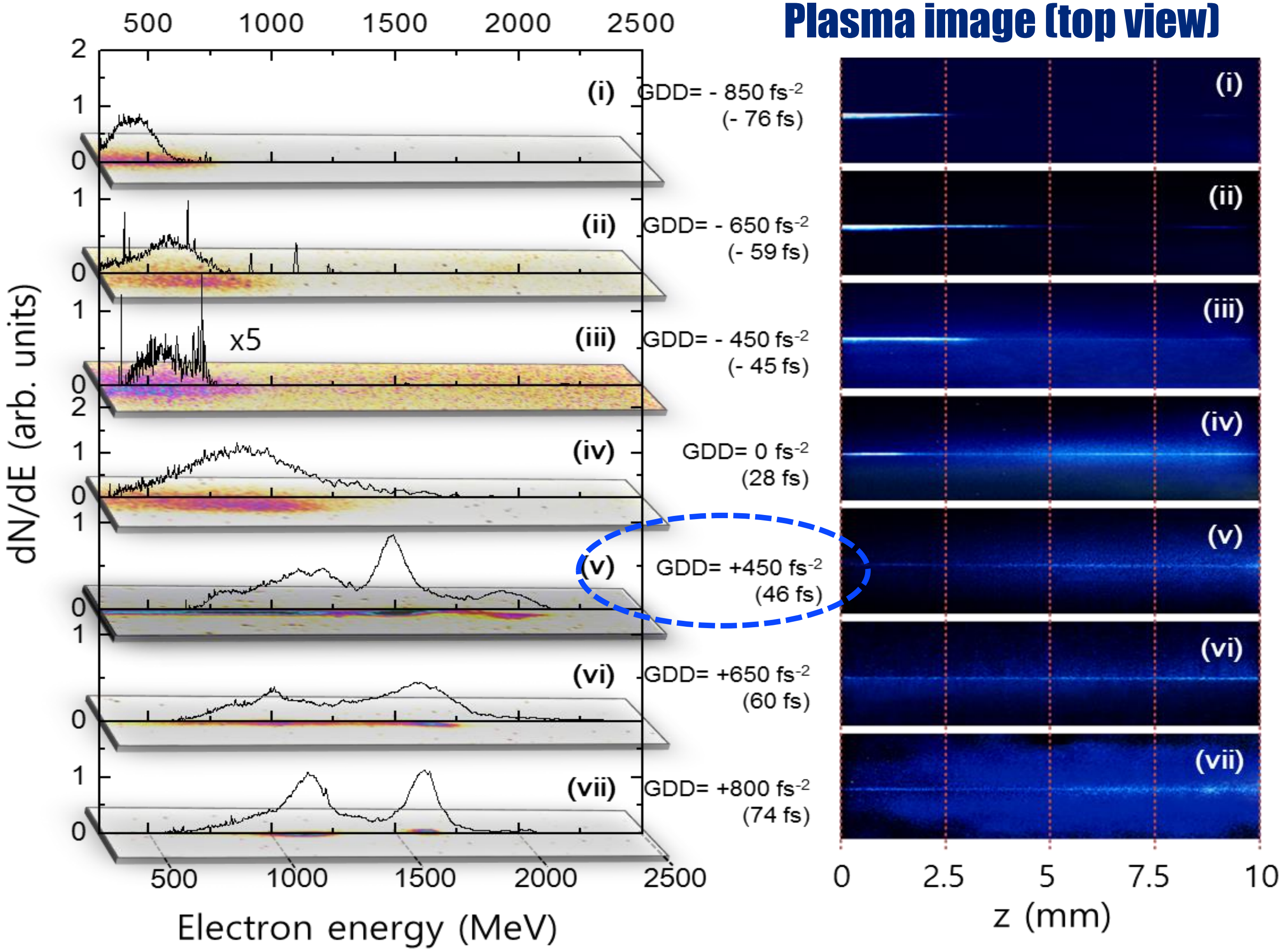
LWFA with chirp-controlled PW laser pulses



Control of spectral phase: GDD

26 J on target, focal spot ~ 35 micron, $N_e = 1.4\times10^{18}\ \mathrm{cm^{-3}}$, 10 mm cell length

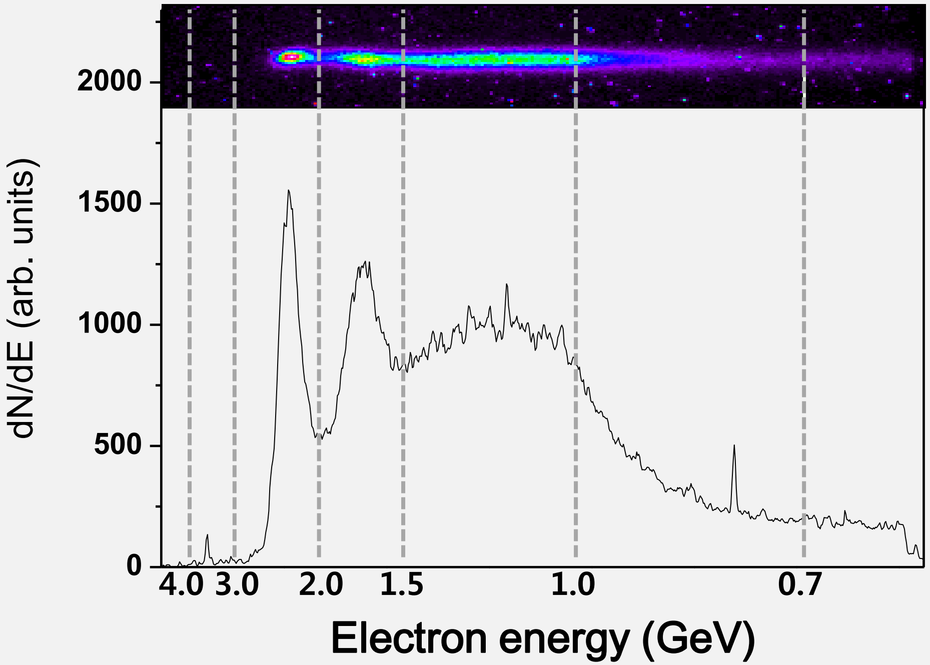
Plasma image (top view)



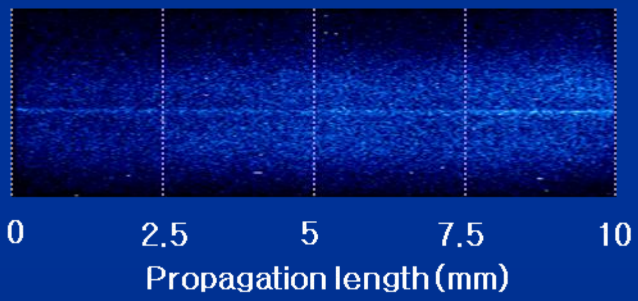
Electrons over 2 GeV from a 10-mm gas cell

Gas cell length = 10 mm
Positively chirped 61 fs
Intensity = 2×10^{19} W/cm^2 (a_0=3)

Electron energy spectrum



Top view (Thomson scattering)



Smooth propagation over the whole medium length of 10 mm

Electron energy > 2 GeV

All-Optical Compton Experiments

- **Laser Compton γ-ray production** via interaction of **GeV e-beam** with a laser beam of **10^{18} - 10^{22} W/cm^2**

  Compton backscattering: $e^- + \omega_0 \rightarrow e^- + \gamma$

  - MeV-Gamma beams useful for photo-nuclear physics

  Nonlinear Compton Scattering: $e^- + n\omega_0 \rightarrow e^- + \gamma$

  - Measuring radiation reaction effects

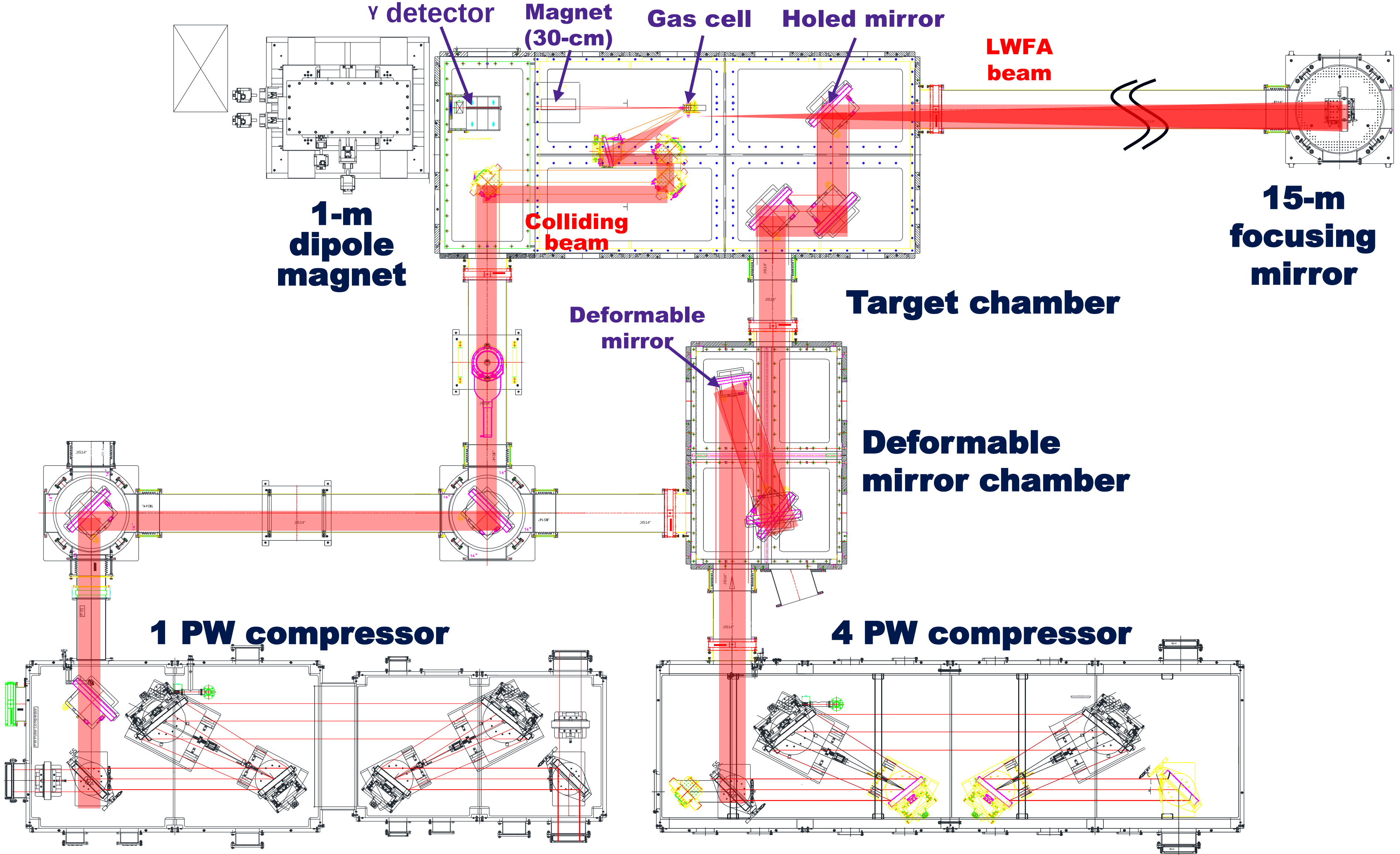
    Energy loss and radiation damping (cooling) of the electron beam

  - Assessing QED
  - Electron-positron pair creation: $\gamma + n\omega_0 \rightarrow e^- + e^+$

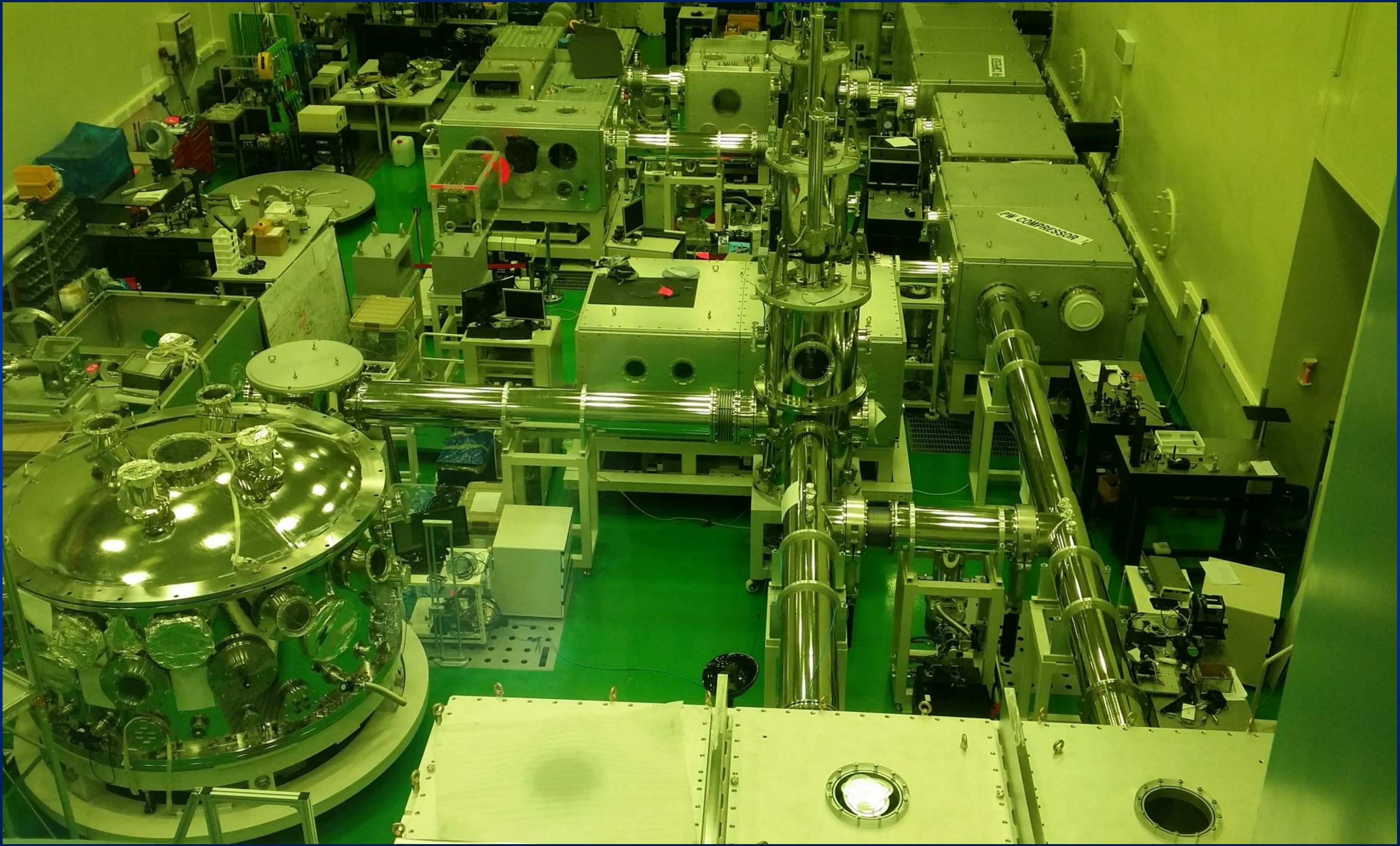
    Only one experiment with 46.6 GeV linac e-beam and $a_0 = 0.36$

    D.L. Burke et al., Phys. Rev. Lett. 79, 1626 (1997)

Optical Layout for LWFA with the 4 PW laser



PW Laser Experimental Area ('16. 3.)



Challenging Tasks

1. **Coherent control of LWFA**

   Propagation calculation of chirped PW laser pulses in gas

2. **Radiation reaction**

   Observable laser intensity

   Transition from classical to quantum processes

3. **γ-ray production from Compton backscattering**

   nonlinear Compton scattering: $e^- + n\omega_0 \rightarrow e^- + \gamma$

4. **Pair production from photon-photon interaction:**

   Breit-Wheeler process: $\gamma + n\omega_0 \rightarrow e^- + e^+$

Summary

1. Two PW laser beamlines, 1 PW and 1.5 PW at 30 fs, at CoReLS of IBS are operational for research on high field science. One beamline is being upgraded to 4 PW.
2. Laser wakefield acceleration has been explored. With the two-stage acceleration 3-GeV electron beam was generated. Using the coherent control of LWFA process with PW laser pulses monoenergetic electron beam over 2 GeV was stably produced from a 1- cm gas cell.
3. After the 4 PW laser upgrade we are expecting to achieve electron beams over 10 GeV.
4. Compton backscattering of PW laser pulses with multi-GeV electron beam are being prepared for 10’s MeV γ-ray production. Radiation reaction and pair production will be examined.