CRLS

Center for Relativistic Laser Science

Relativistic Laser Science Research

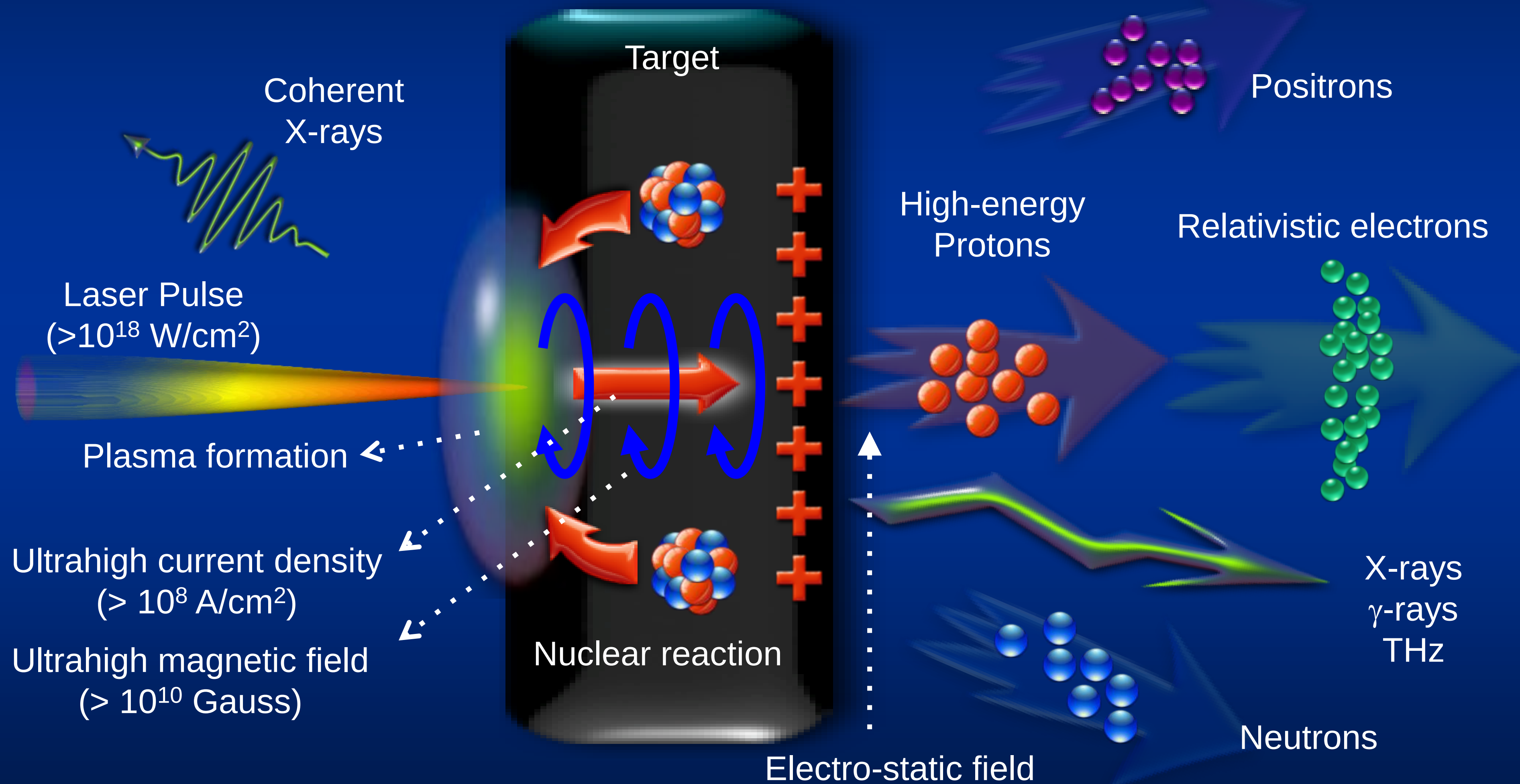
Chang Hee Nam

Institute for Basic Science &

Gwangju Institute of Science and Technology

Relativistic Laser Science

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



Overview

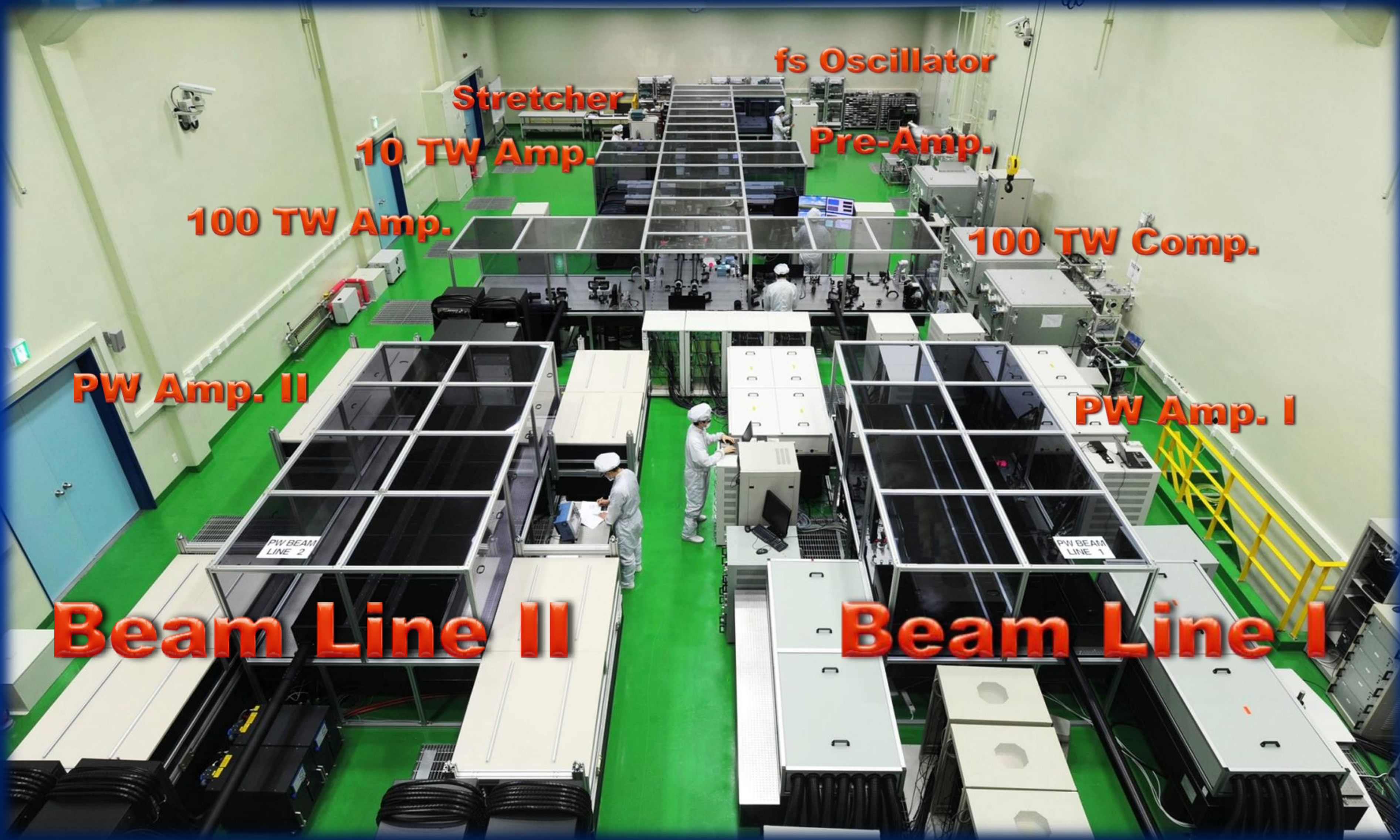
1. Femtosecond PW laser system
2. Relativistic Laser Science
    A. Laser electron acceleration
    B. High energy proton generation
    C. Relativistic harmonic generation

IBS Center for Relativistic Laser Science

GIST Ultrashort Quantum Beam Facility (PI: Prof. J. Lee)

- 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

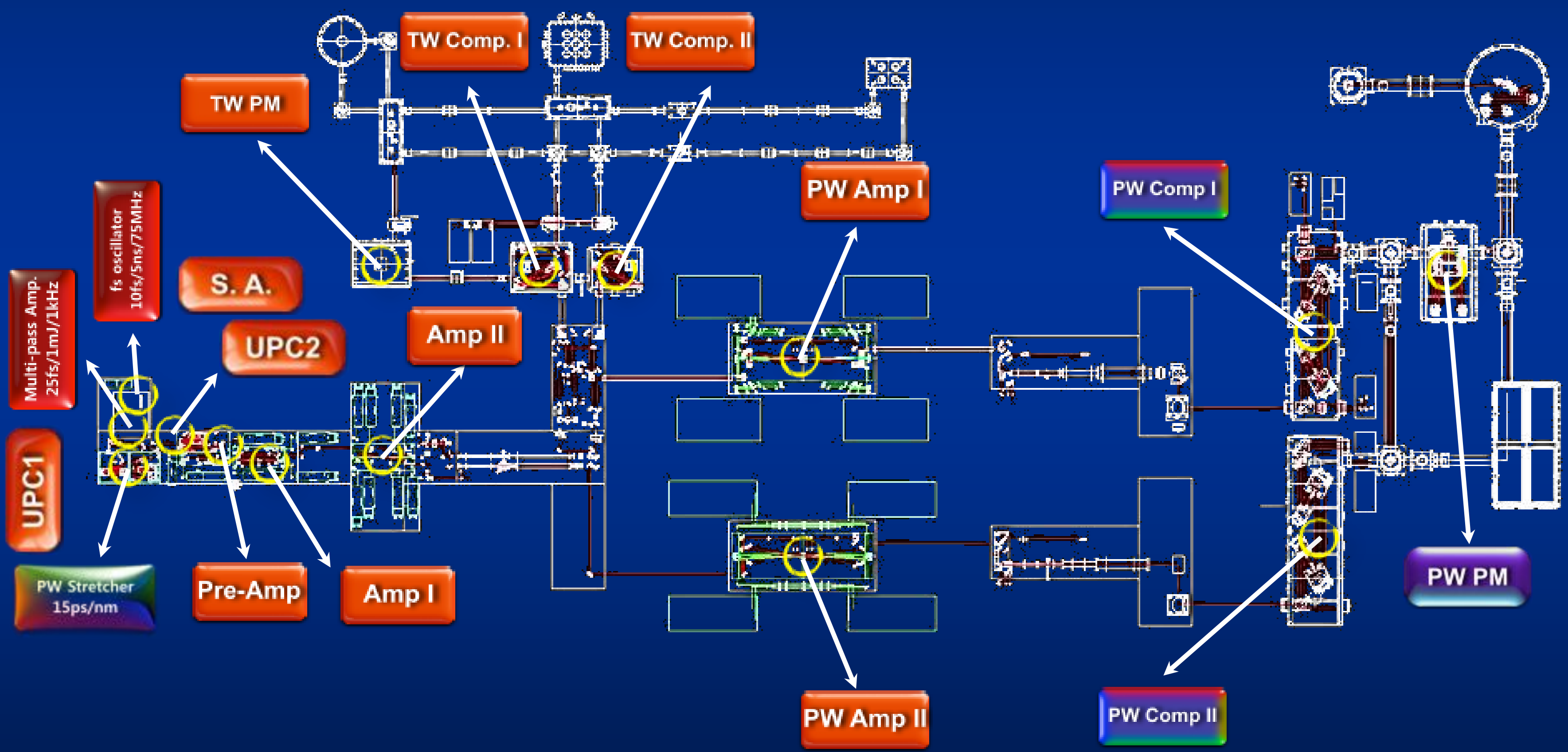
PW Ti:Sapphire Laser



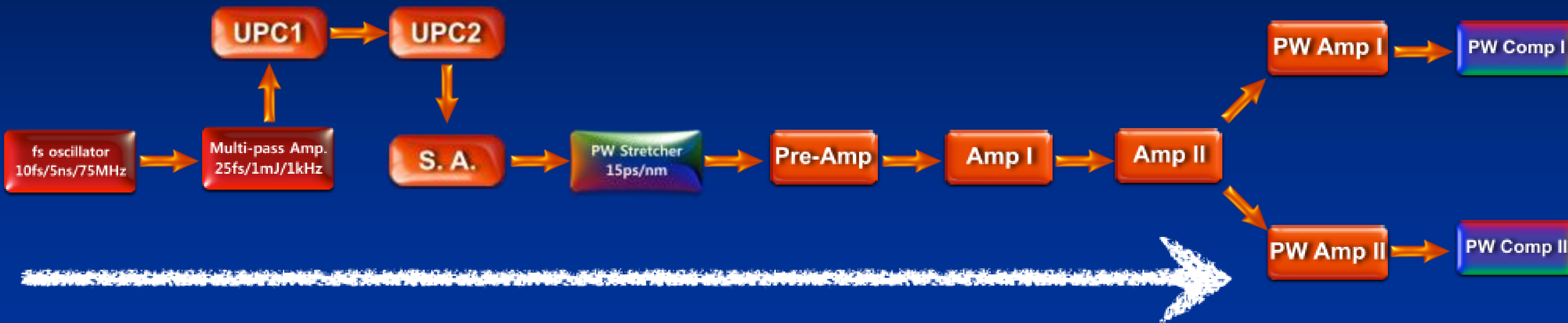
PW Laser Beamline I & II

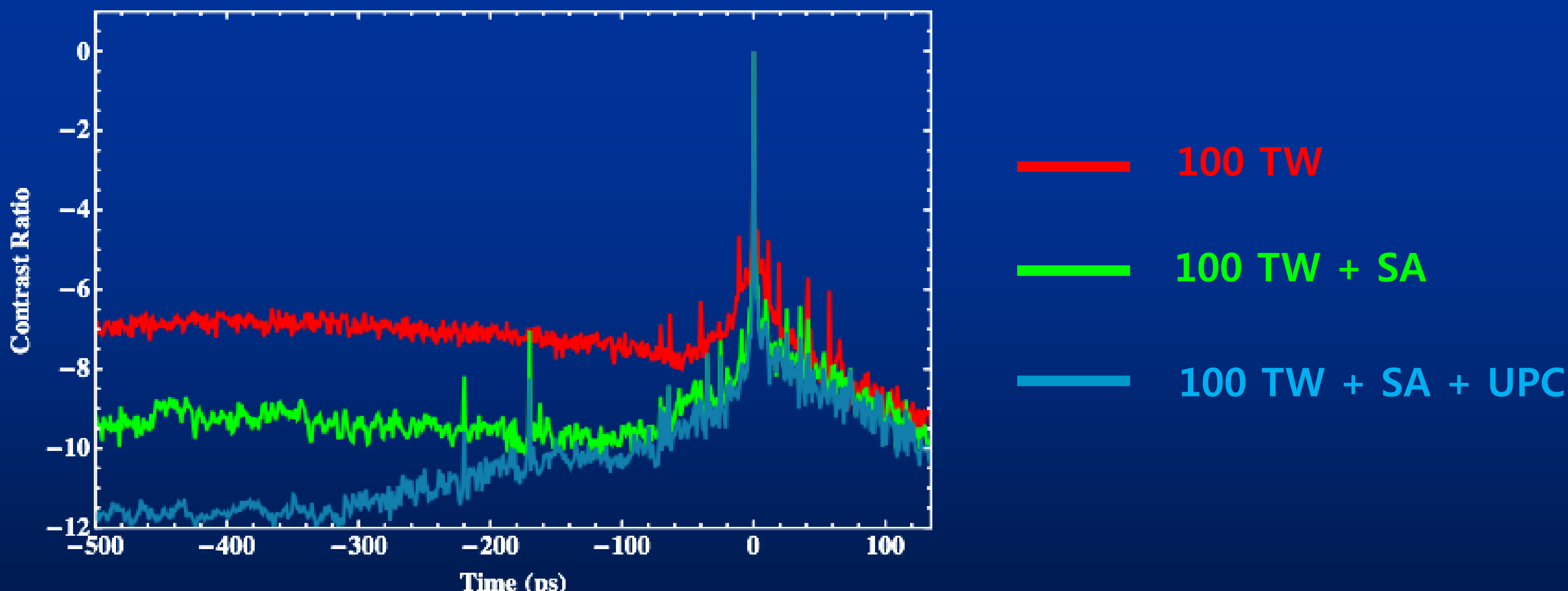
Before 2009

2012

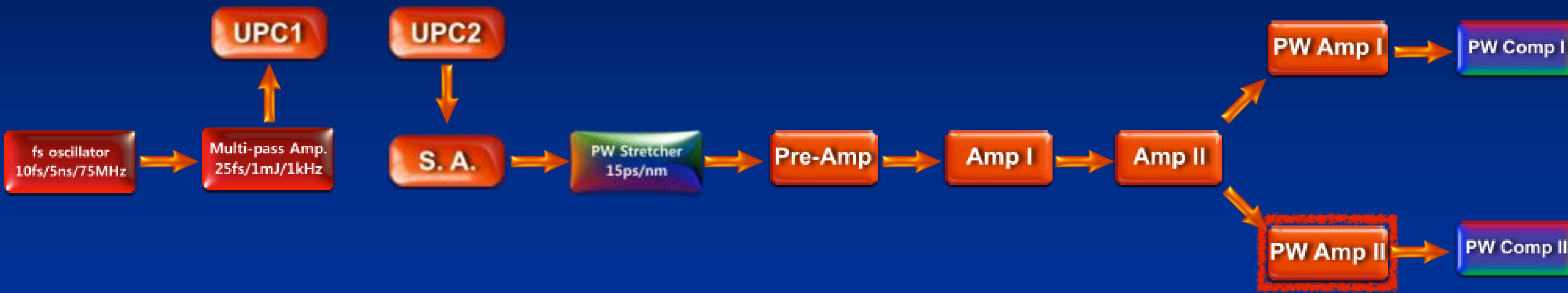


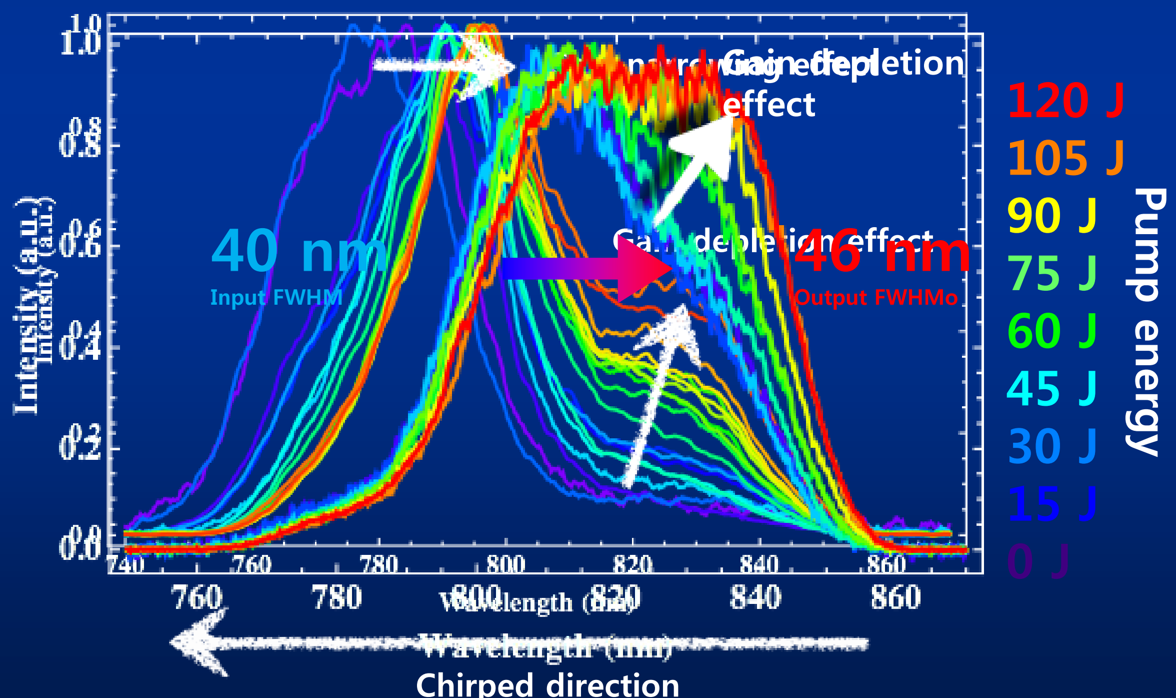
Contrast Ratio





Amplification in PW Amplifier

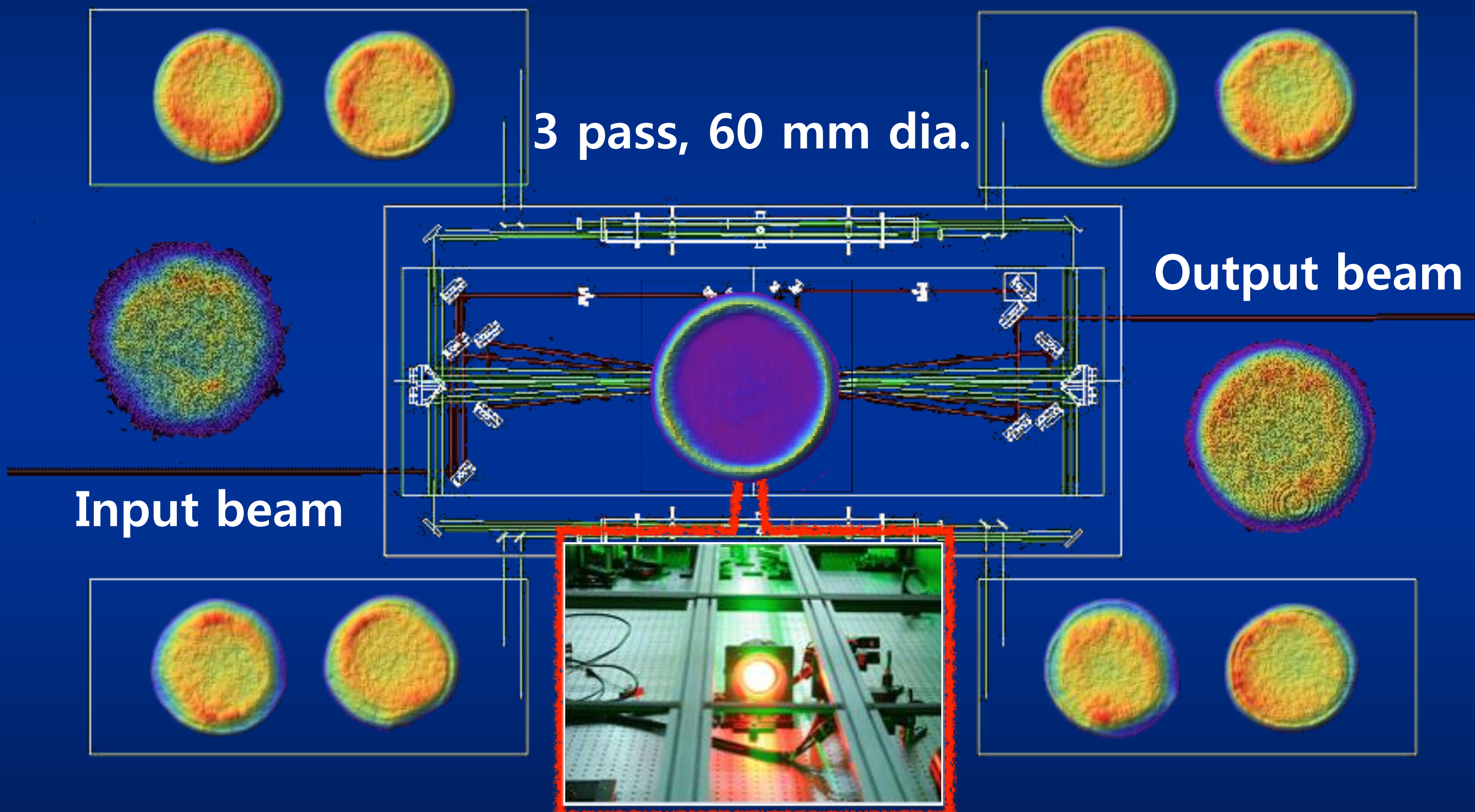




Beam Uniformity in PW Amplifier II

30J Nd:glass Pump Laser 1

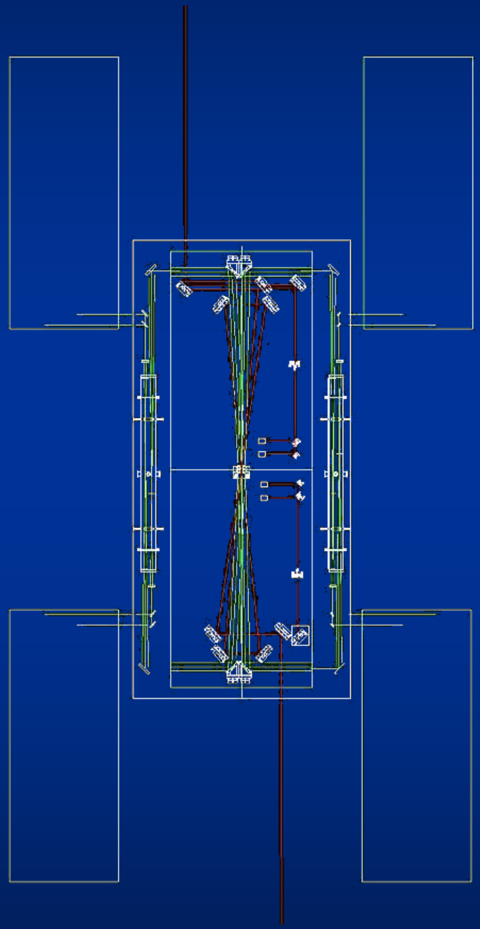
30J Nd:glass Pump Laser 2

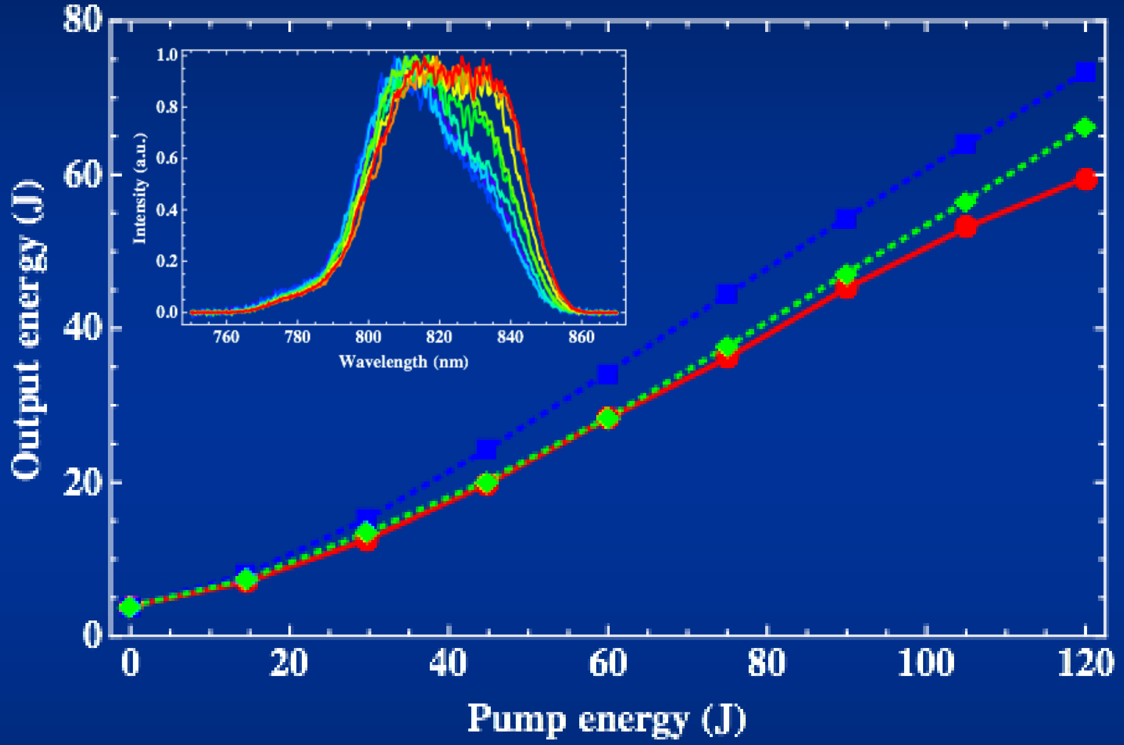


30J Nd:glass Pump Laser 3

30J Nd:glass Pump Laser 4

PW Amplifier II: Output Energy vs Pumping energy

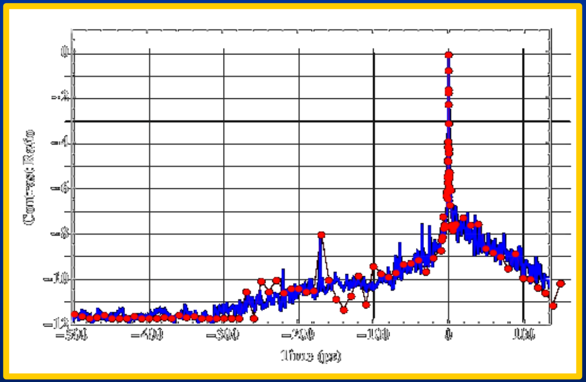




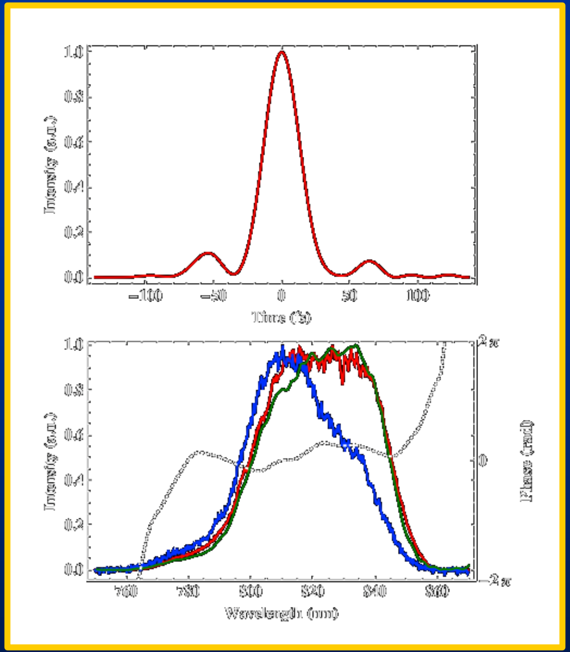
Measured output energy
2D F-N simulation
1D F-N simulation

High contrast, 30 fs, 1.5 PW Laser

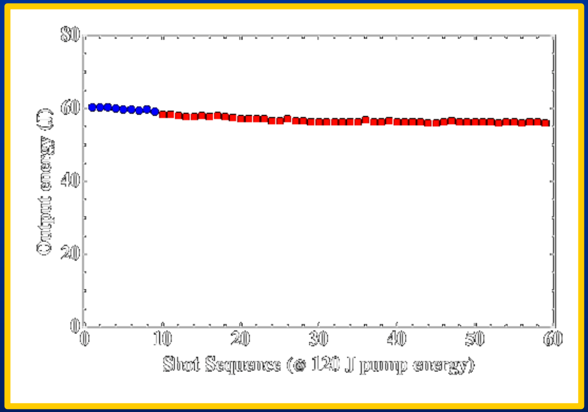
High contrast



30 fs



1.5 PW



World-wide PW Laser Facilities

10 PW OPCPA
ELI/Czech (2016)

1.5 PW Ti:sapphire
APRI/Korea

1.5 PW Nd:glass
LLNL/USA (1999)

World's Highest!
in 2012

0.5 PW Ti:Sapphire
RAL/UK (2008)

1.16 PW Ti:sapphire
IOP/China (2011)

0.85 PW Ti:sapphire
APRC/Japan (2003)

1. Femtosecond PW laser system

2. Relativistic Laser Science

   A. Laser electron acceleration

   B. High energy proton generation

   C. Relativistic harmonic generation

Relativistic Laser-Matter Interactions

- ***Exploration of Relativistic Laser-Matter Interactions***
  - **Basic Relativistic LMI Physics**

    Relativistic self-focusing, relativistic flying mirror, relativistic transparency

    Giga-Gauss DC Magnetic Field Generation
  - **Mono-energetic Particle Acceleration**

    Mono-energetic electron acceleration by LWFA

    High-energy proton generation by TNSA and RPA
  - **High Energy Photon Generation**

    γ-ray generation through Betatron radiation and Inverse Compton Scattering (ICS)

- ***Attosecond Science***
  - **Attosecond light sources**

    High harmonic generation from gaseous atoms

    High harmonic generation from solid materials
  - **Ultrafast atomic and molecular dynamics**

Relativistic Laser Intensities

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 $a_0 = 1$, $v = 0.75c$. For $a_0 > 1$, relativistic.

Intensity for relativistic electron:
(Relativistic regime)

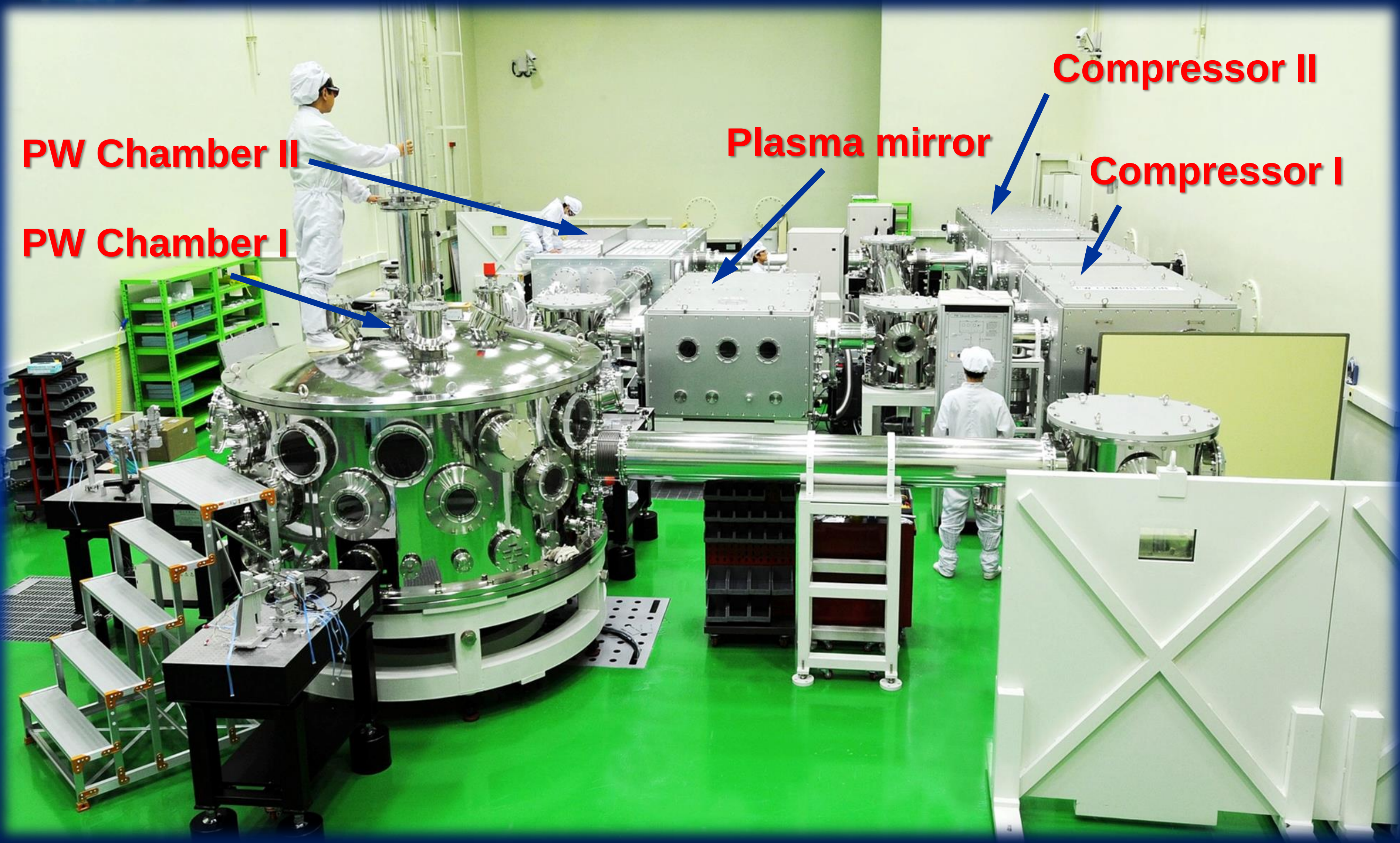
$$I_{\mathrm{Re}} \approx \frac{1.4\times 10^{18}}{\left(\lambda^2\right)_{\mu m}} a_0^{\,2} \text{ W/cm}^2$$

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

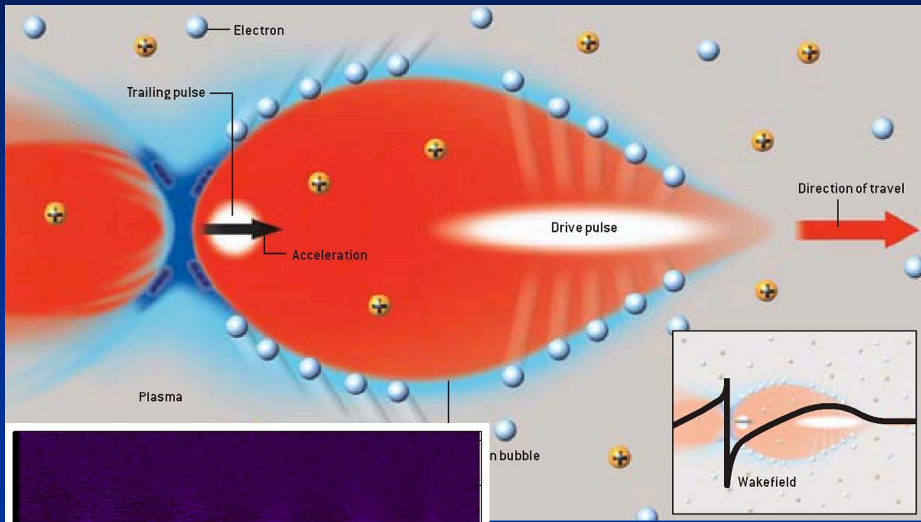
Intensity for relativistic proton:
(Ultra-relativistic regime)

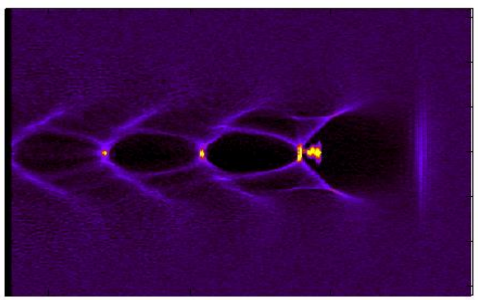
$$I_{Rp} \approx \frac{4.5\times 10^{24}}{\left(\lambda^2\right)_{\mu m}} \text{ W/cm}^2$$

PW Laser Experimental Area



Laser Wake Field Electron Acceleration





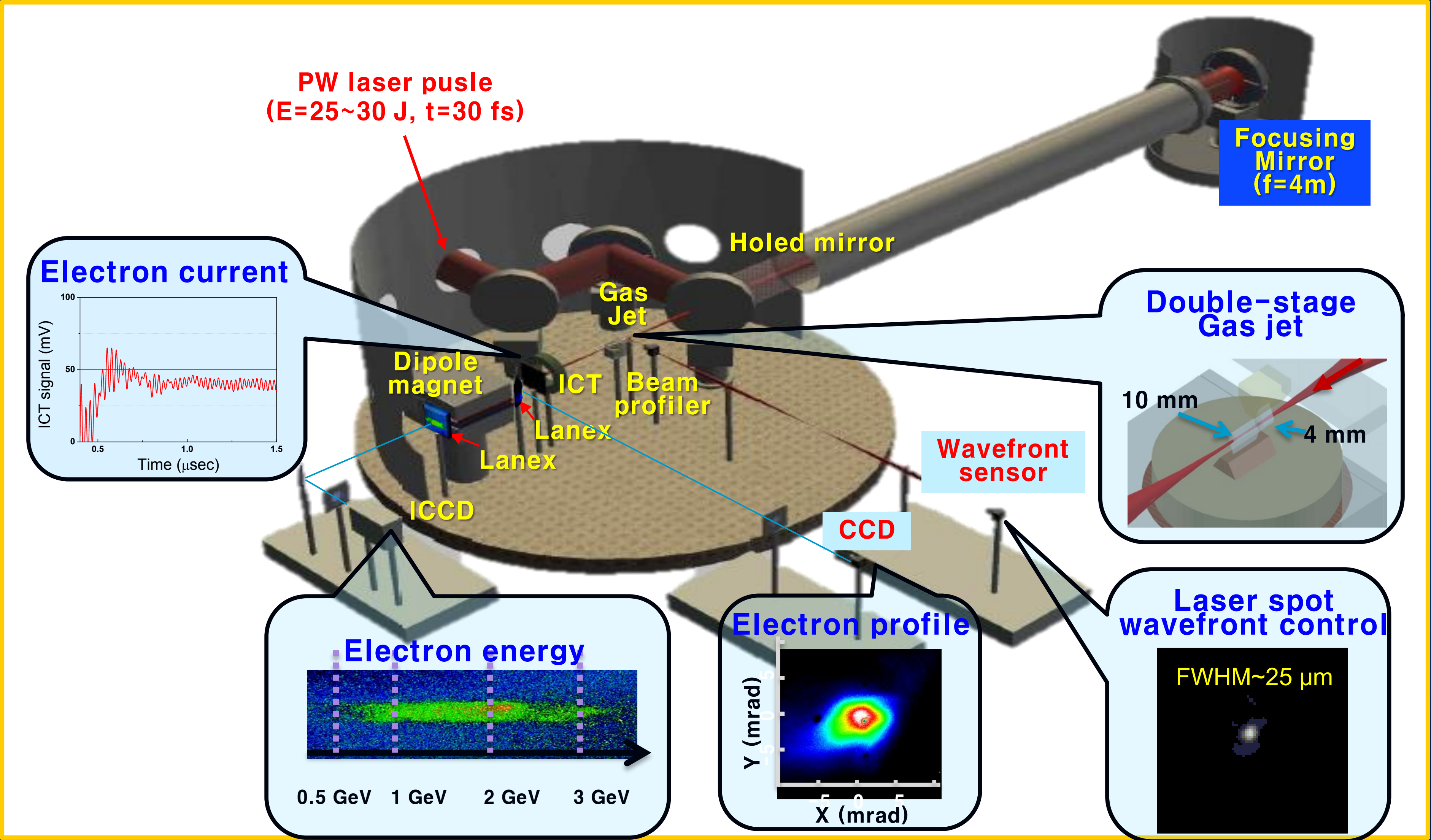
nderomotive force
intense laser pulse
e original position
→ Electron plasma wave created
→ Acceleration of an injected electron bunch by the plasma wave

Huge acceleration field of LWFA > 100 GeV/m

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

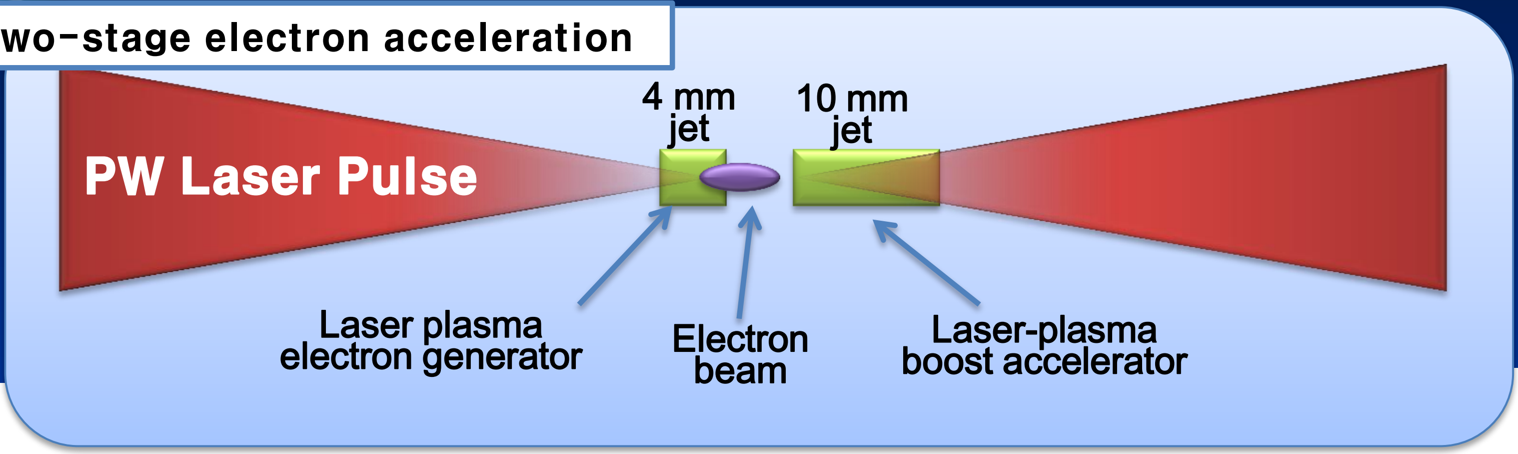
Acceleration by plasma wave
~ Surfing to the wave in sea

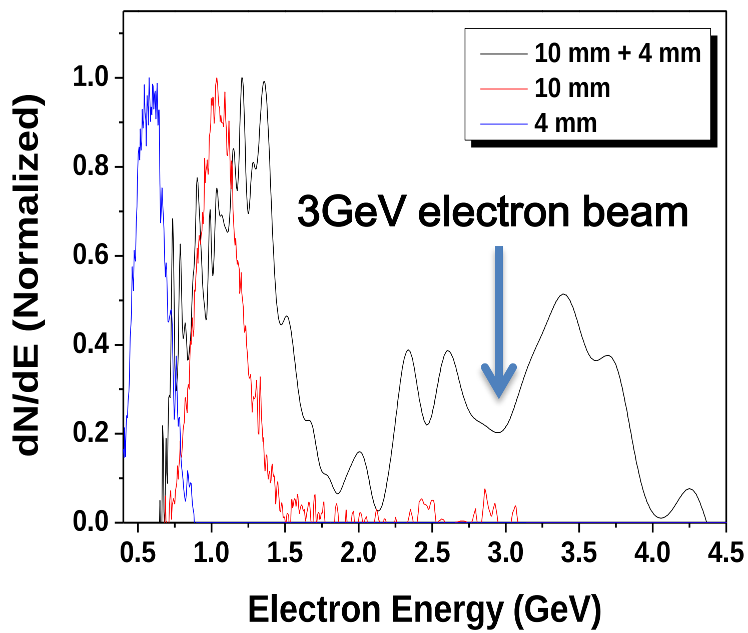
Electron Acceleration using PW Laser Pulses

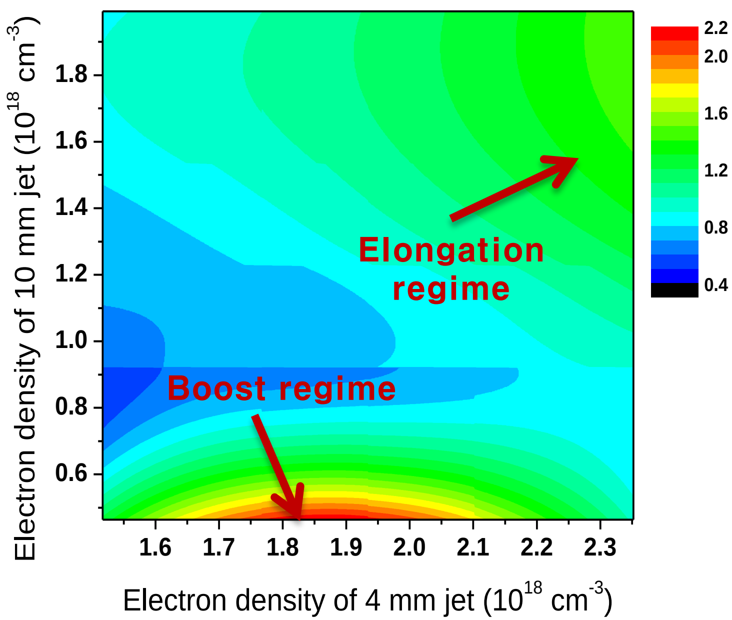


Multi-GeV electron Beam using PW Laser Pulses

Two-stage electron acceleration





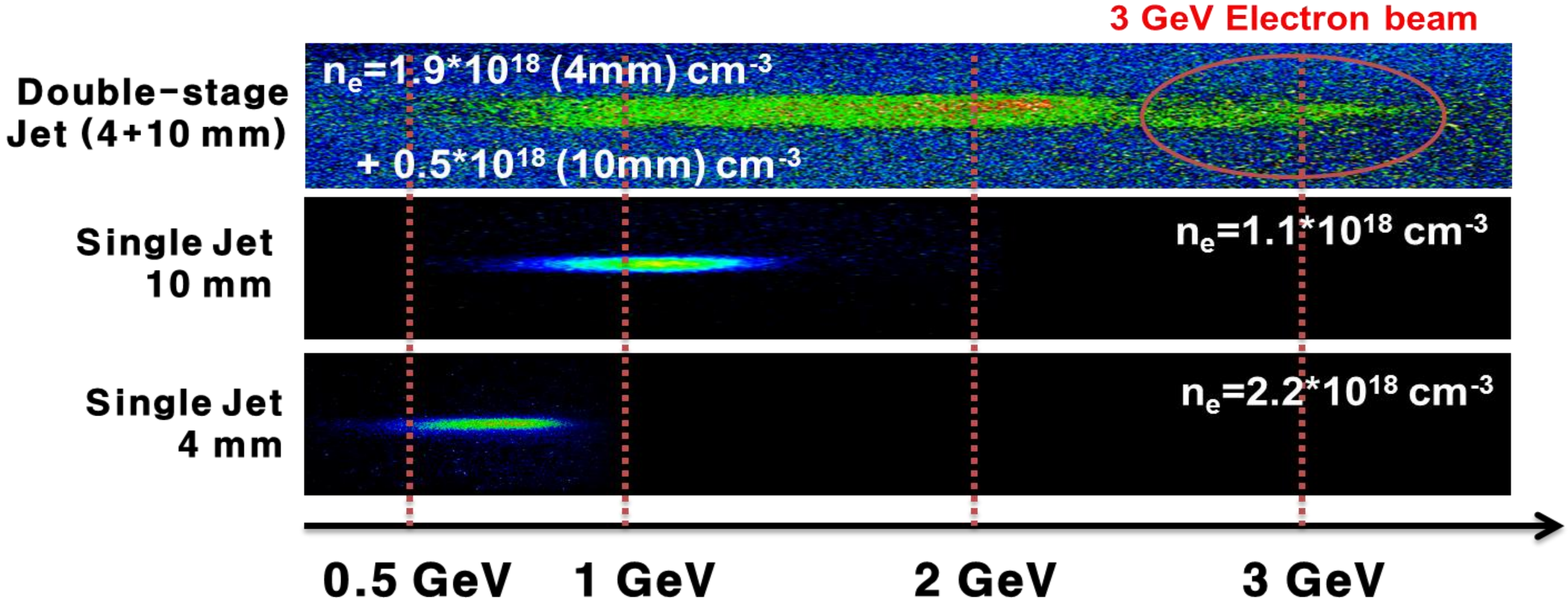


Multi-GeV E-beam Generation

Self-Injection with Long Depletion and Dephasing Lengths

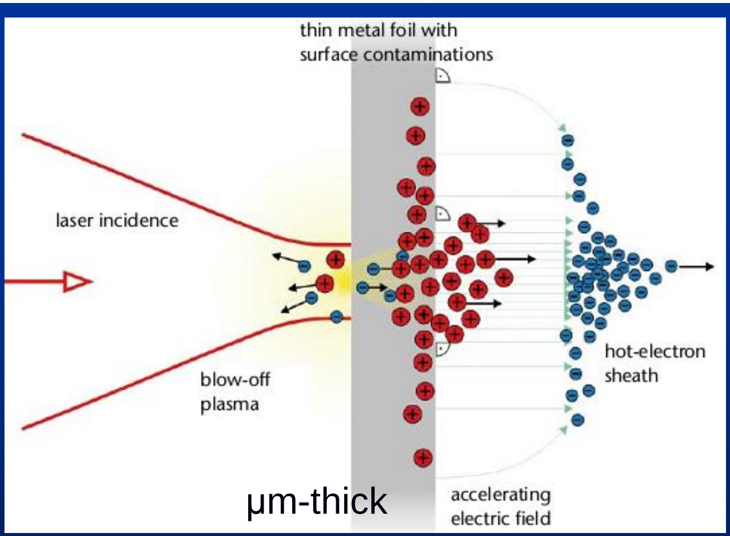
- Pumping energy 22–25 J on target with 60 fs pulse duration
- 4 mm, 10 mm, elongated supersonic He gas jet
- Laser Intensity = 3 x 10^{19} W/cm^2 (a_0 = 3.7)

Electron energy spectrum

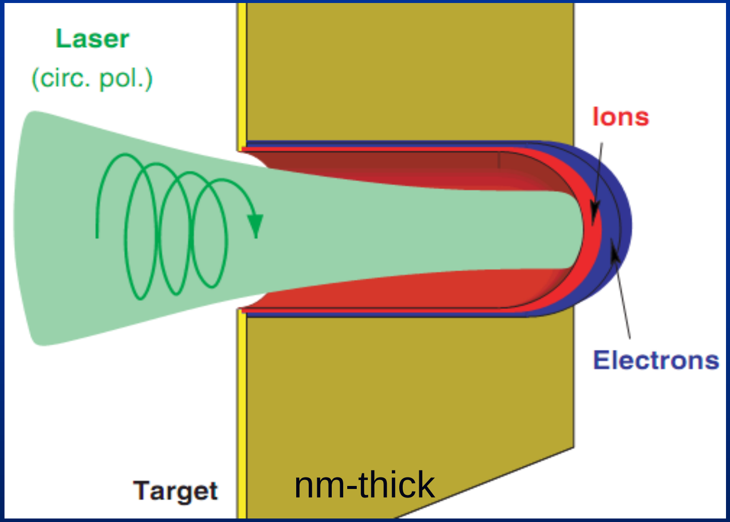


Generation of Energetic Protons

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	$E_{ion} \propto I$

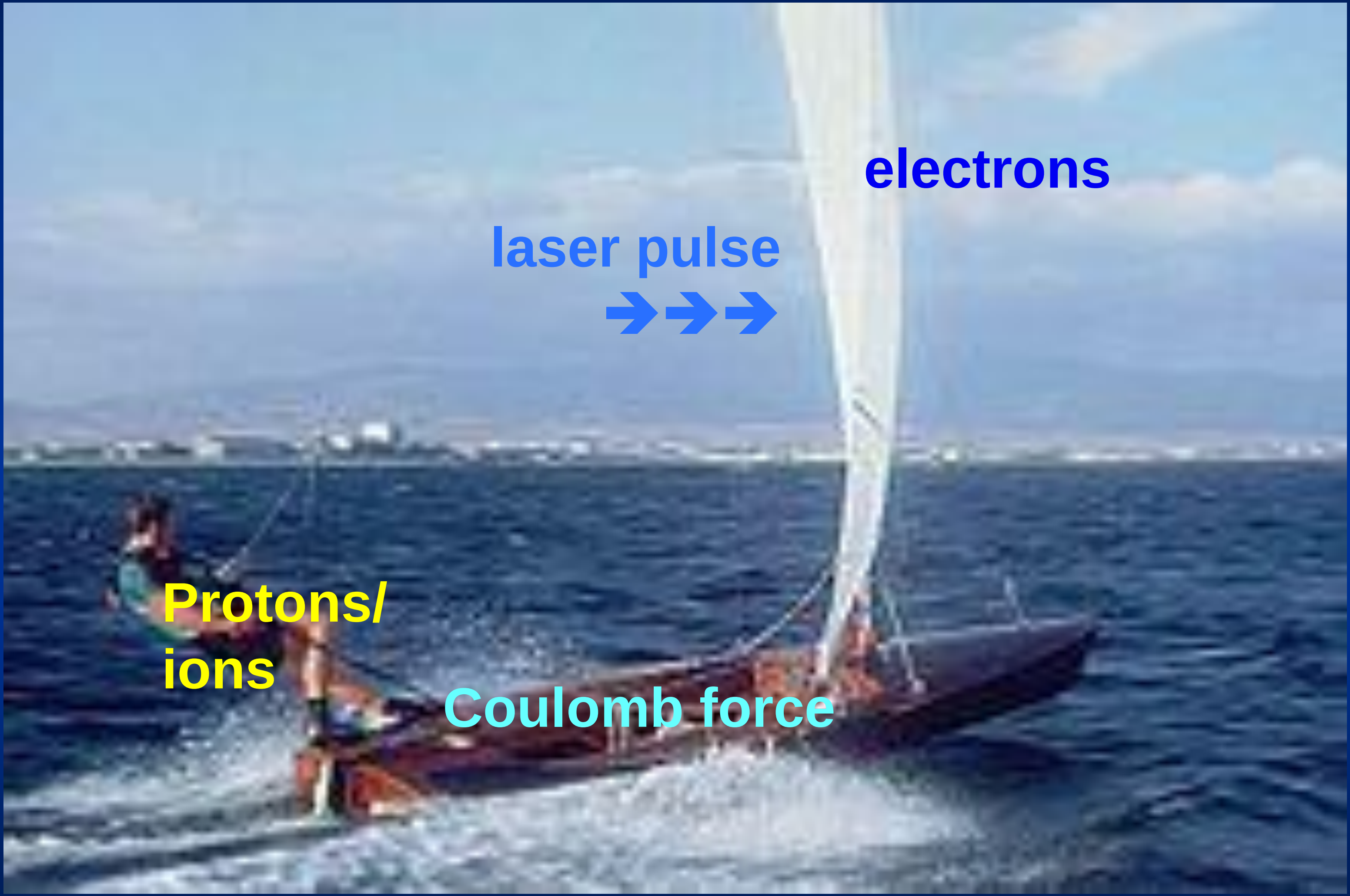


Laser, not penetrating the target, heats electrons, which drag protons after penetrating the target.



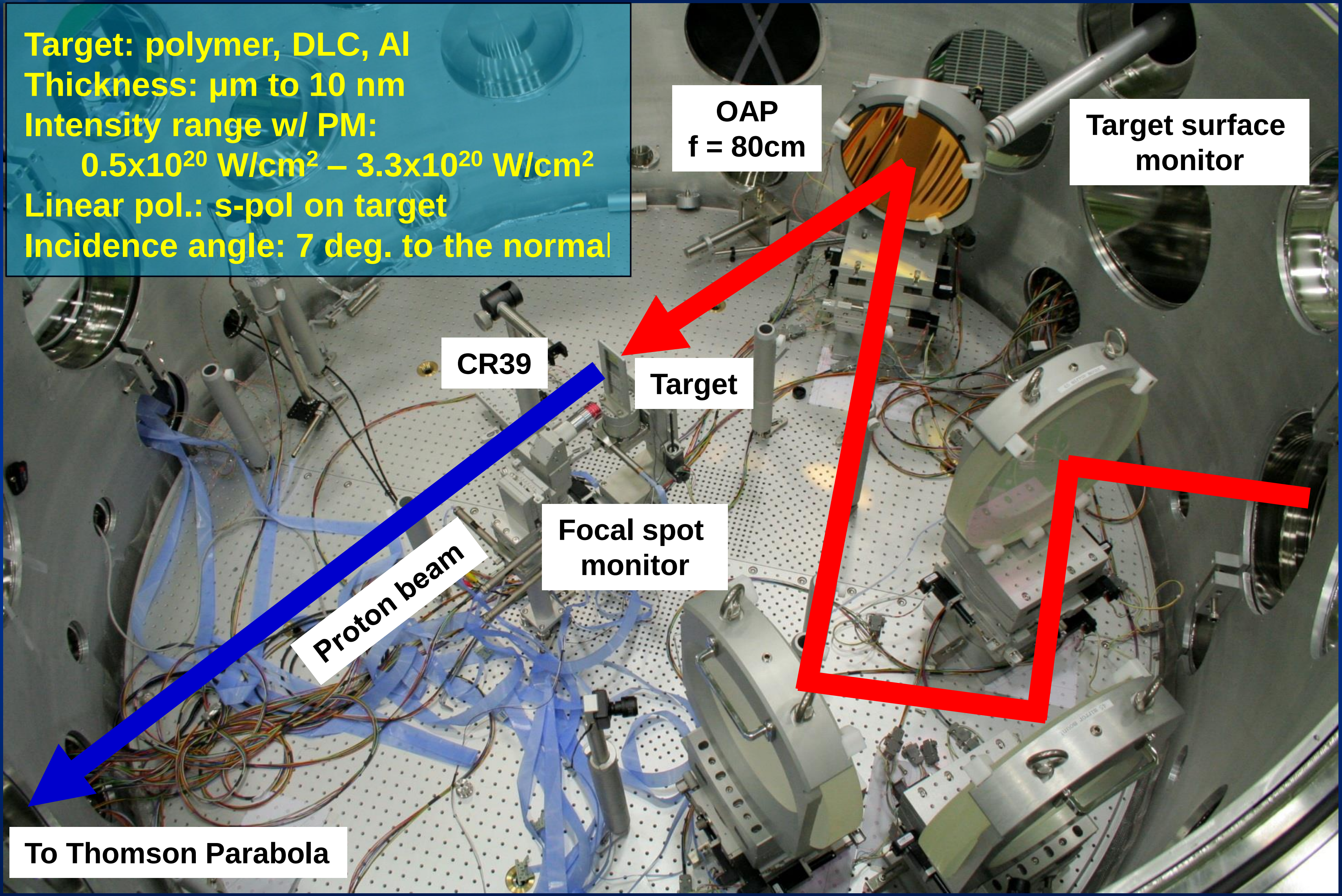
Laser pulse pushes electrons as a whole, which drag the protons.

Radiation Pressure Acceleration: Light Sail

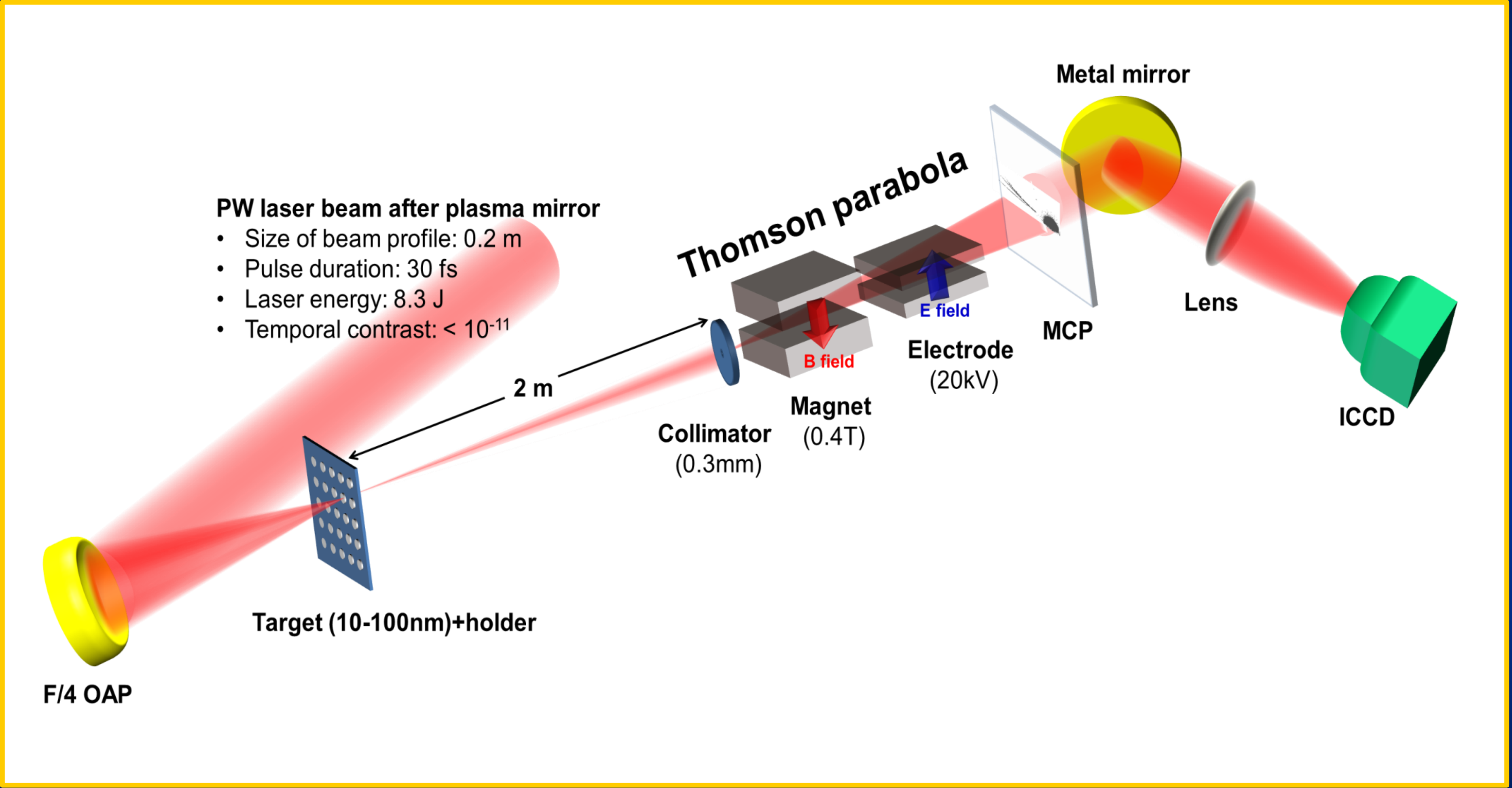


PW Target chamber for proton experiment

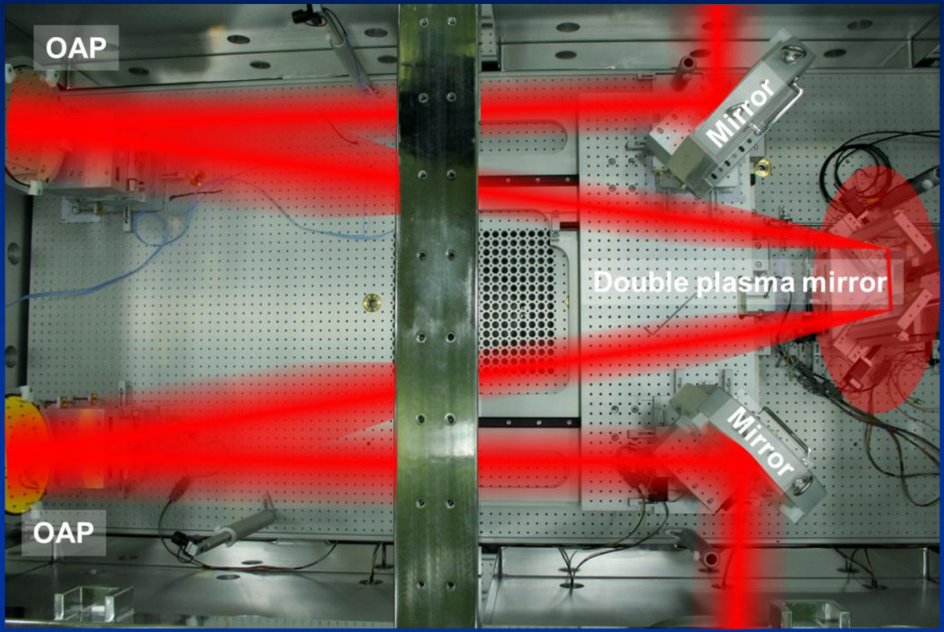
Target: polymer, DLC, Al
Thickness: μm to 10 nm
Intensity range w/ PM:
0.5×10^{20} W/cm^2 – 3.3×10^{20} W/cm^2
Linear pol.: s-pol on target
Incidence angle: 7 deg. to the normal

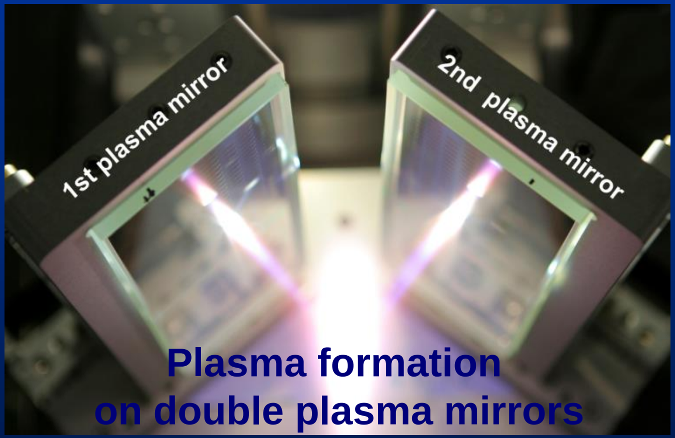


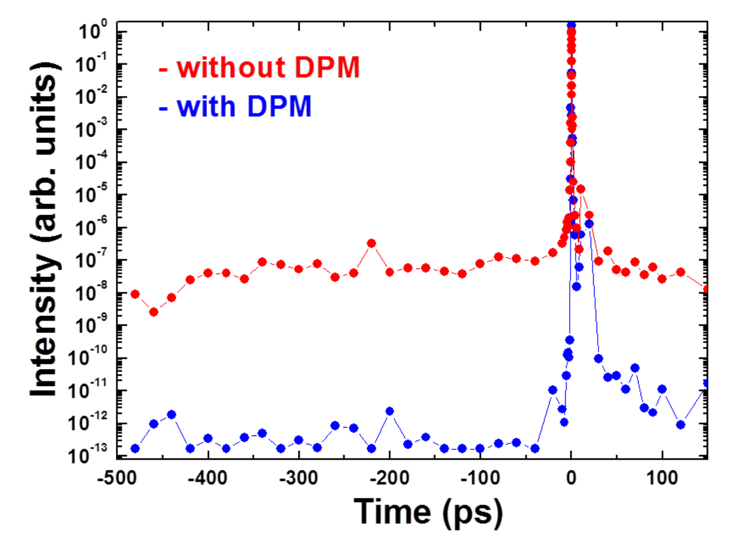
Target and Thomson parabola



PW Plasma mirror: contrast enhancement





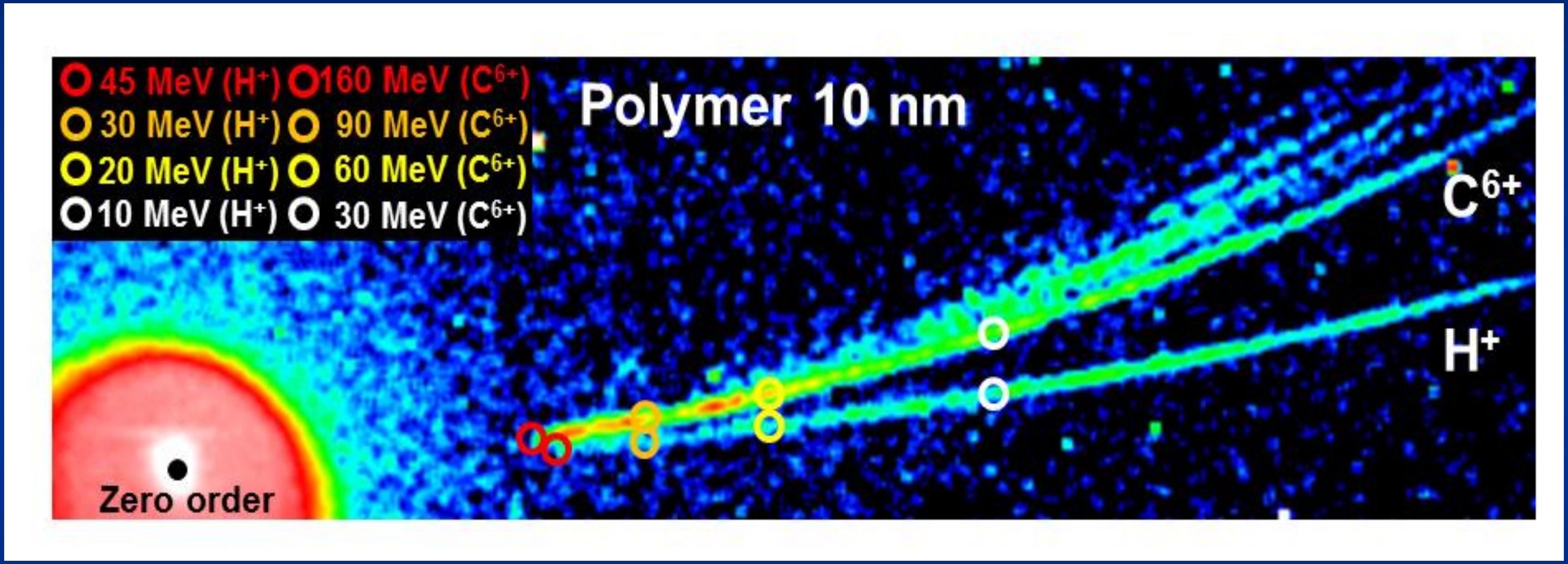


Temporal profiles measured with
a third-order cross correlator.

Contrast 10^{-8} (w/o PM) -> 10^{-12} (w/ PM)
Contrast enhancement: 10^{4}

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

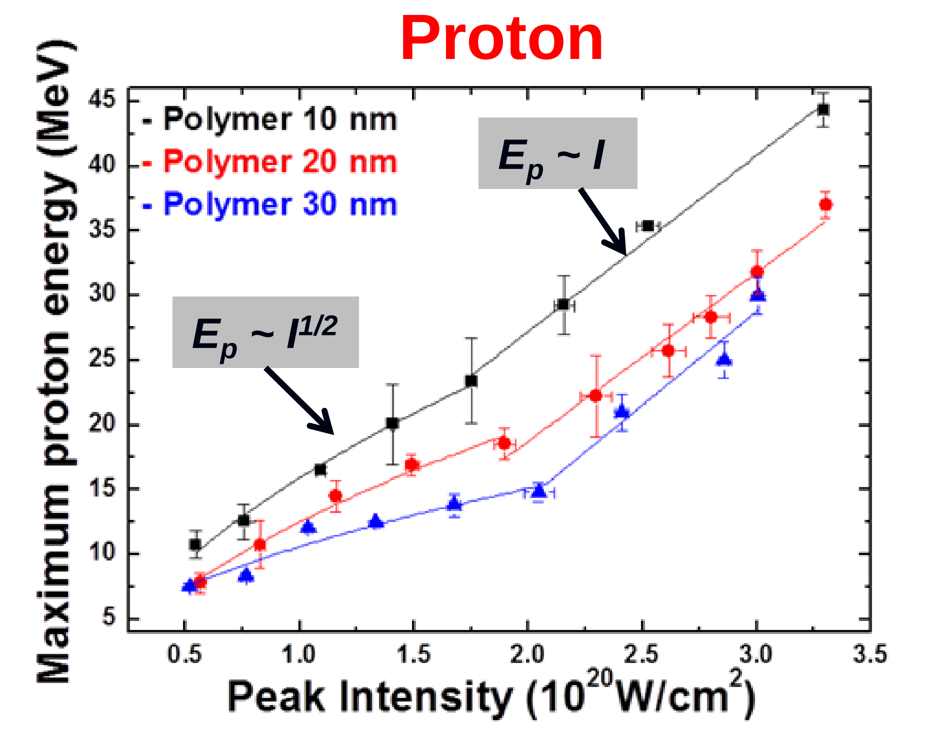
Energy spectra of protons and carbon ions obtained from a 10-nm-thick polymer target irradiated with $I = 3.3 \times 10^{20}$ W/cm^2.

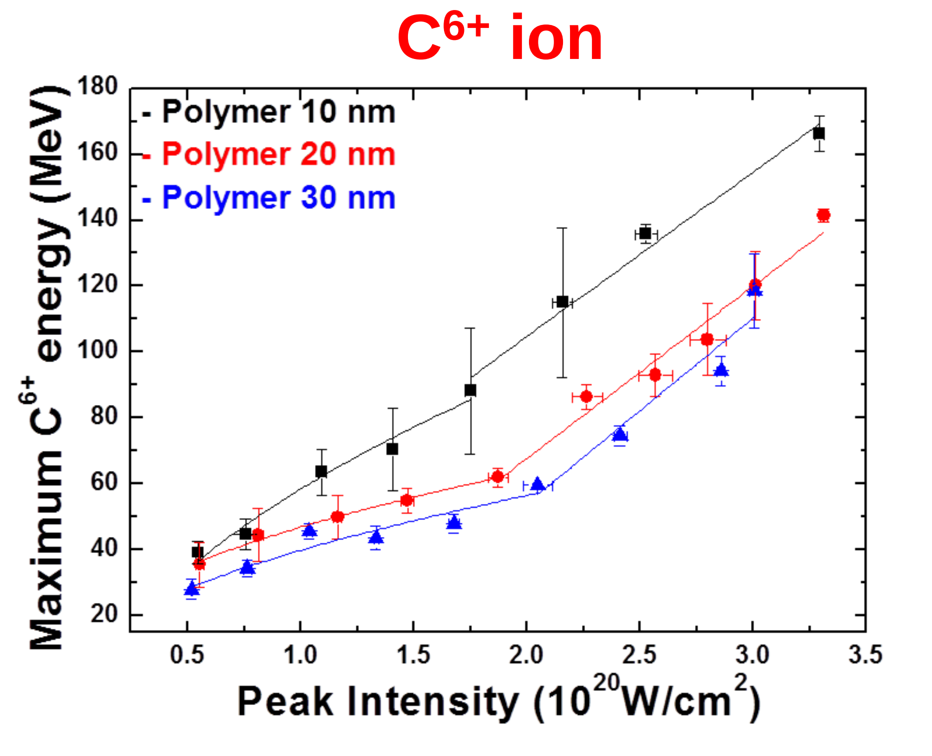


The proton energy of 45 MeV is highest among those obtained with high-power Ti:Sapphire lasers.

Proton Generation using PW Pulses

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





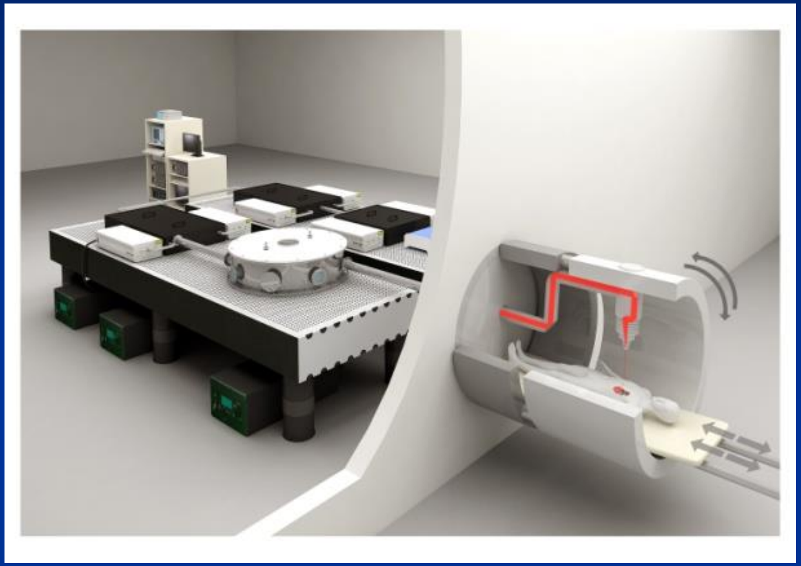
45 MeV @ 3.3×10^{20} W/cm^2 (linear polarization)

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

Proton/hadron oncology

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

Proton/ion acceleration
using cyclotron/synchrotron



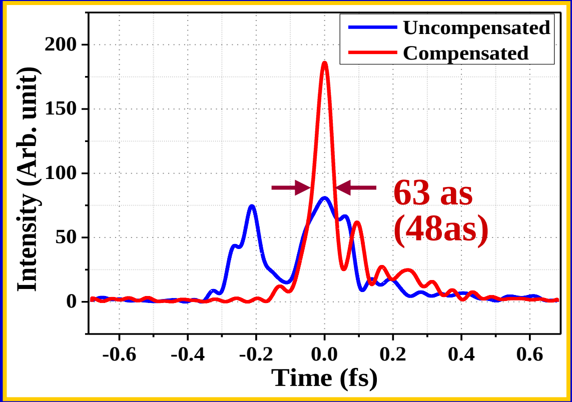
Particle acceleration
using a table top laser

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.

CRLS

Attosecond Science

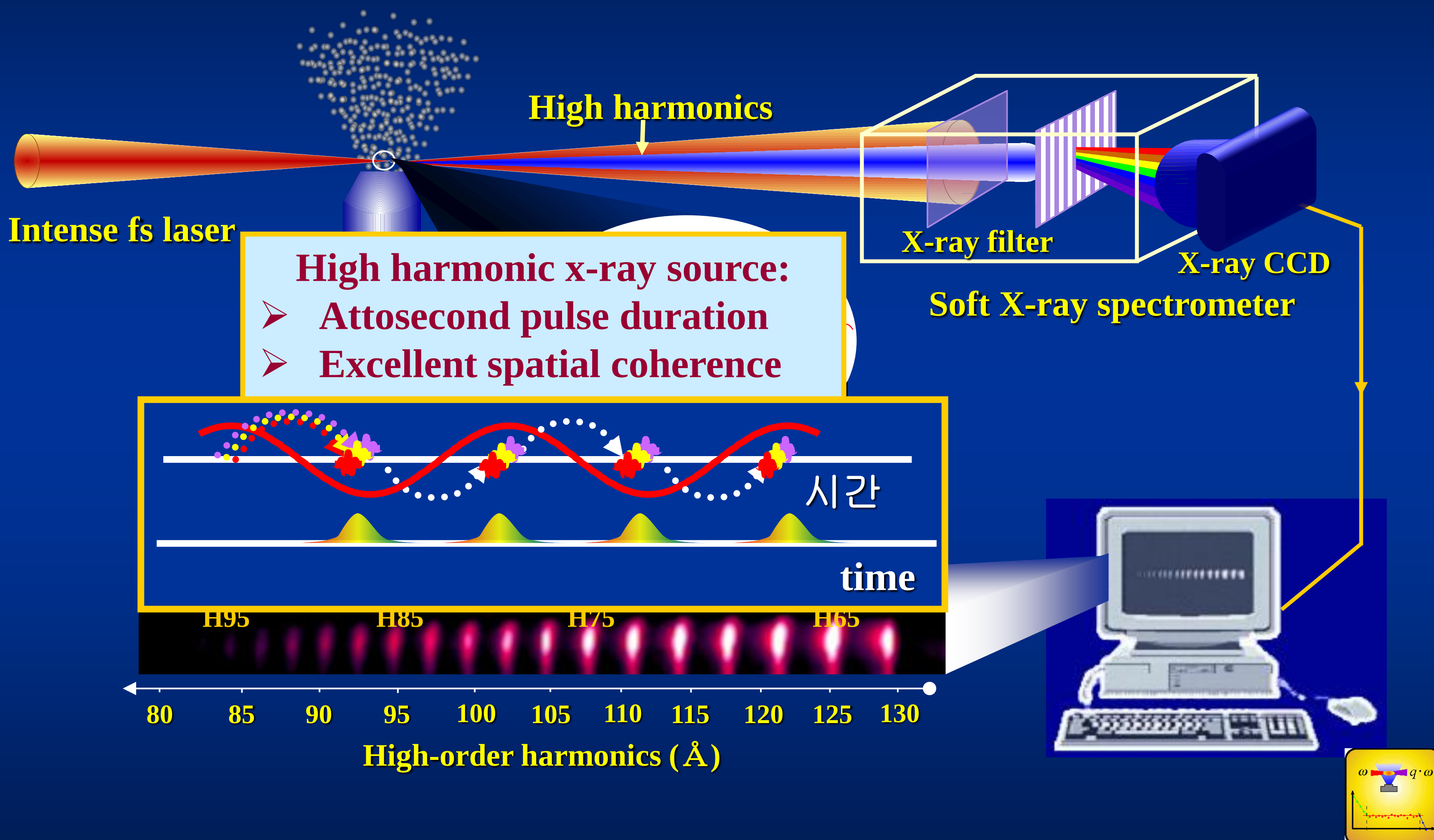
- *Exploration of Attosecond Science*
  - **Development of Attosecond (as) Photon Sources**
    High-harmonic generation (HHG) from gaseous targets – He, Ne, Ar, Xe
    HHG from solid targets in the relativistic regime
  - **Characterization of Attosecond Pulses**
    Autocorrelation in the as time-scale
    Cross-correlation methods – RABITT, CRAB
  - **Ultrafast Dynamics in Matter**
    Photoionization of valence & innershell electrons
    Dynamics of doubly excited states in atoms & molecules
    Ultrafast dynamics in nano-structures and solids



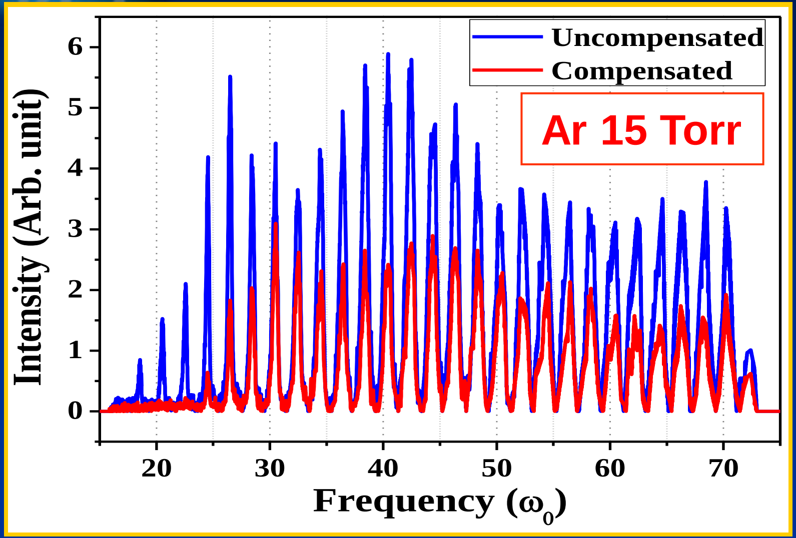
- *Development of Shorter Wavelength Harmonic Sources*
  - **Water-window (2.3 – 4.4 nm) and beyond**
    1.6 keV (0.8 nm) harmonics from Ne driven by 3.8-um laser (VUT/JILA)
  - **For sub-as or zeptosecond pulses**
    For Δt = 1 as, ΔE ~ 600 eV. => HHG in the hard x-ray region

ibs GIST

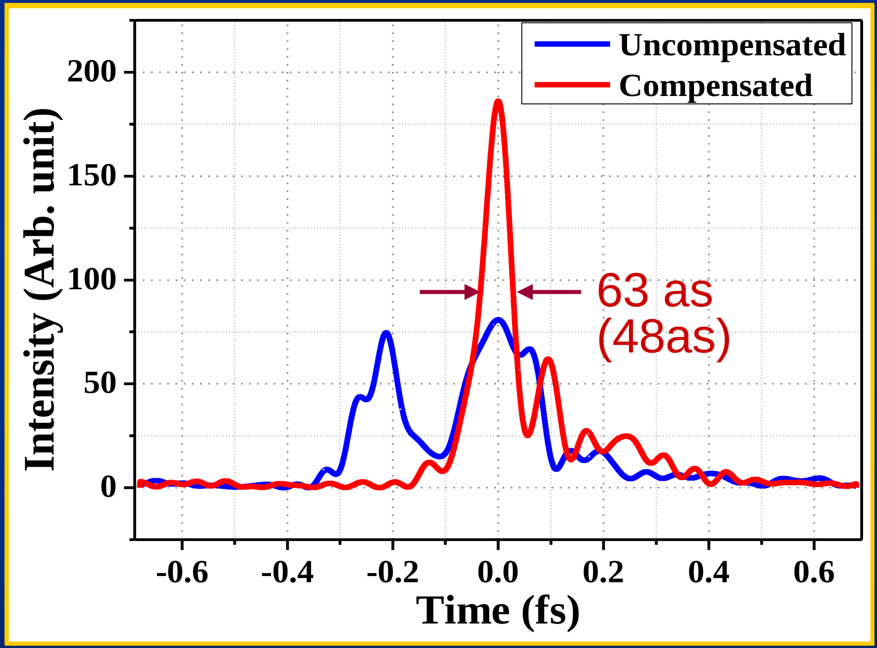
High Harmonic Generation Process

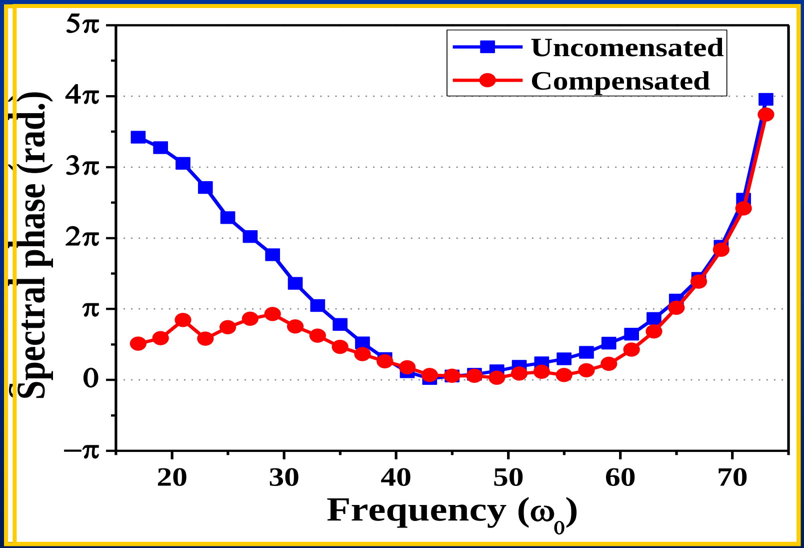


Compensation of atto chirp by material dispersion



Harmonic generation from Ne
Atto chirp compensation in Ar

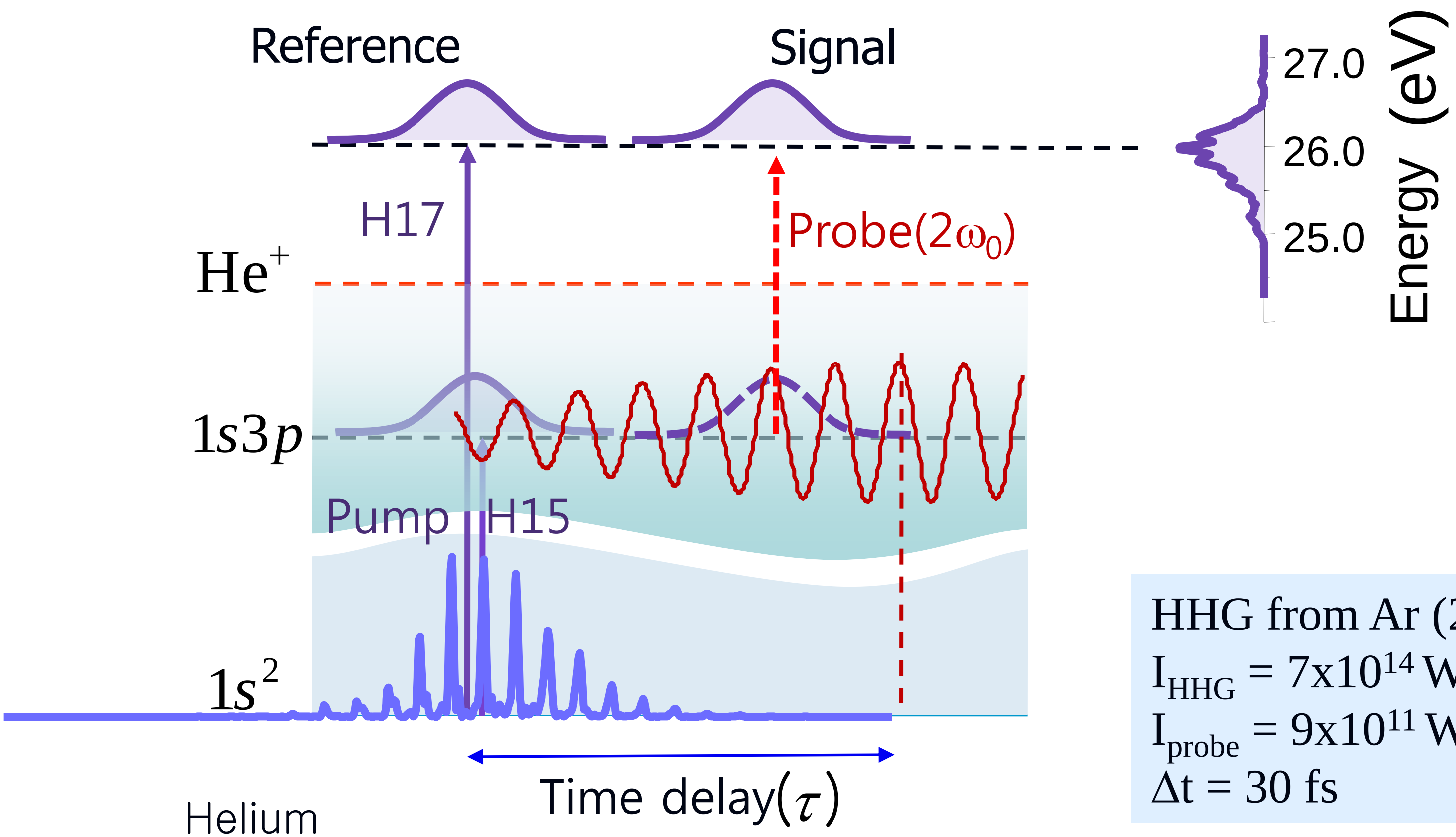




D. H. Ko et al., New J. Phys. 12, 063008 (2010)

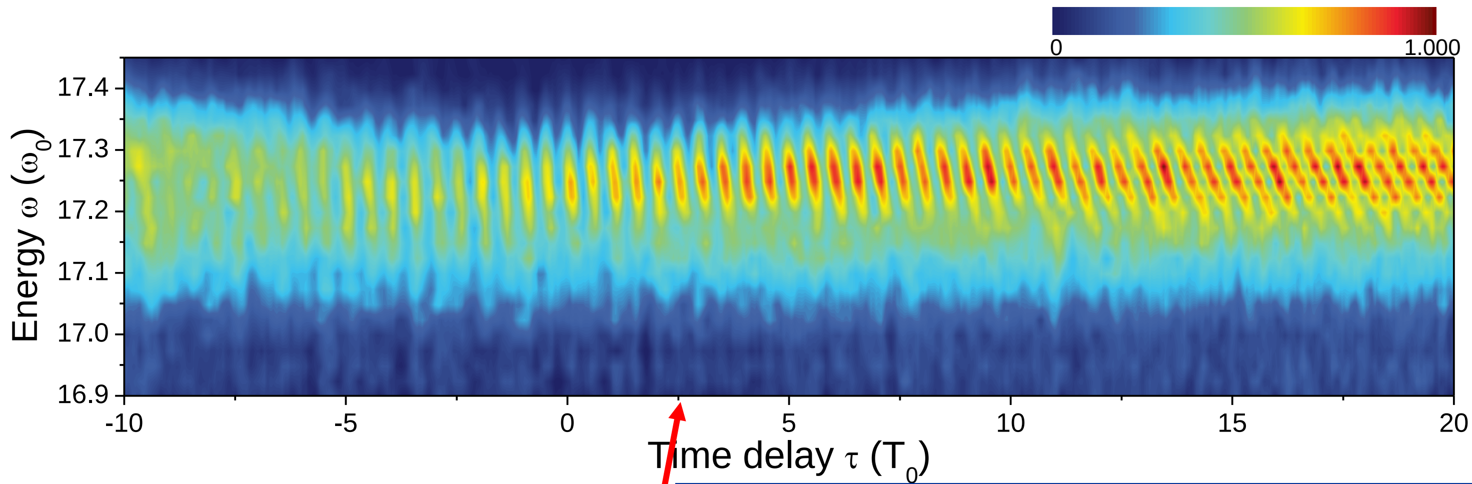
Photoionization dynamics of He

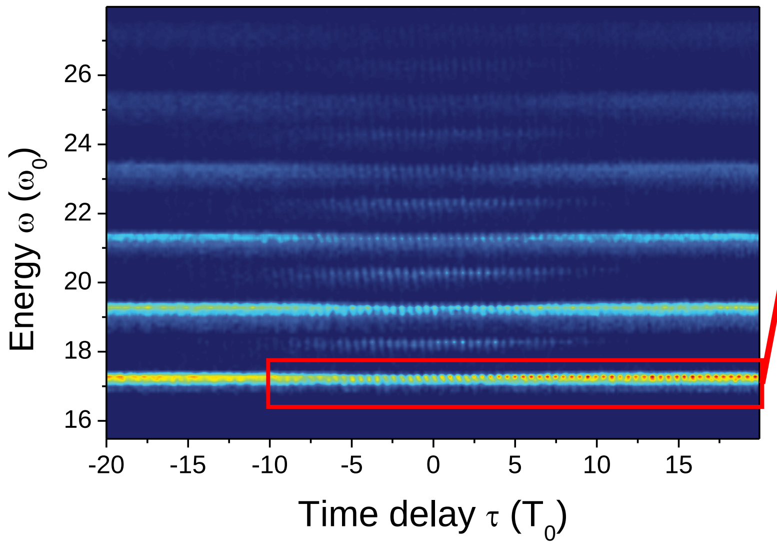
Investigation of attosecond photoionization dynamics with high-harmonic pulses



HHG from Ar (20 Torr)
I_{HHG} = 7x10^{14} W/cm^2
I_{probe} = 9x10^{11} W/cm^2
Δt = 30 fs

Measured interferogram in photoelectron spectra





SI signal with electron wave packets

$$S(\omega,\tau)=\left|c_R\right|^2+\left|c_S\right|^2+2\,\mathrm{Re}\left[c_R c_S^*\right]$$

The reference wave should be known!

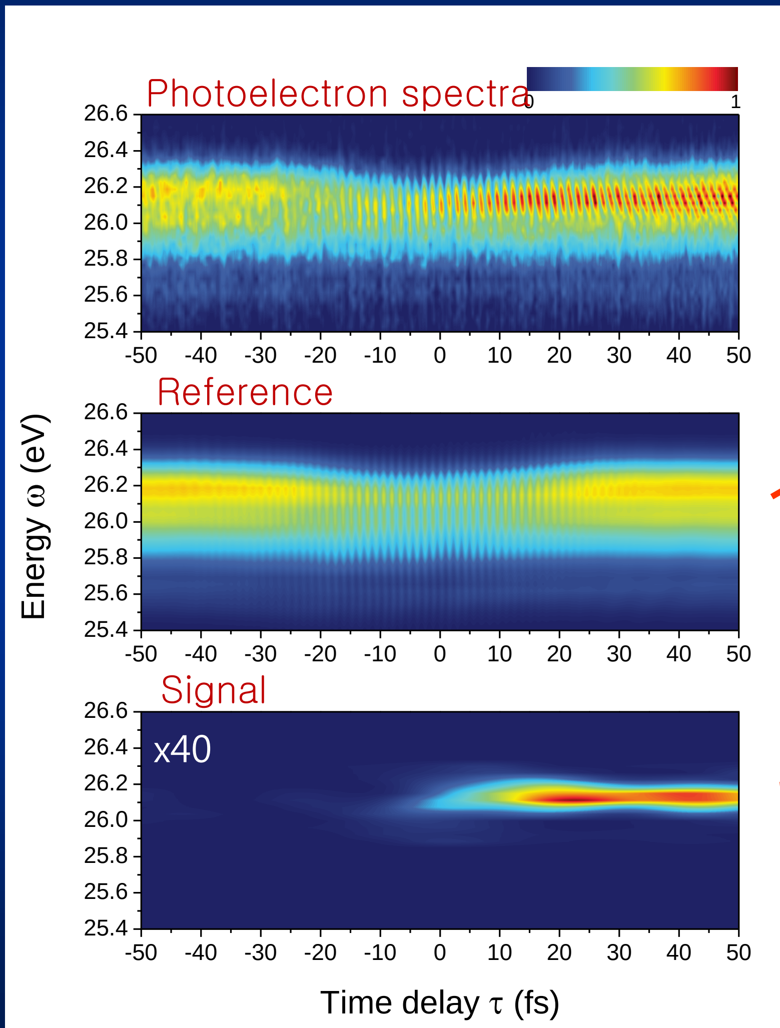
→C_R can be measured by the CRAB analysis.

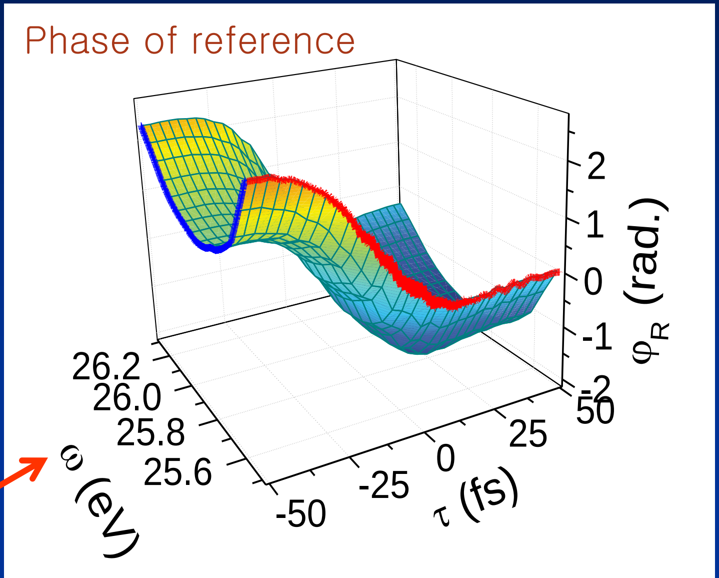
HHG: Ar 20 torr, 7×10^{14}W/cm^2

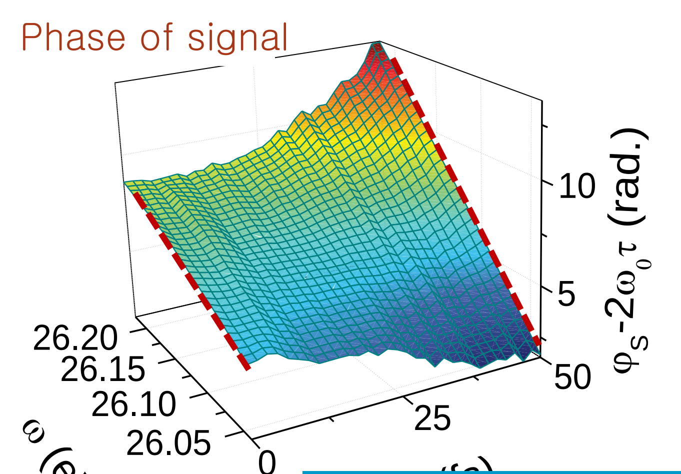
IR$_{probe}$: 9×10^{11}/cm^2

Reconstruction of signal electron wave packet

$$\underline{b(\omega,\tau)} = \underline{|b_R|}^2 + |b_S|^2 + 2\,\mathrm{Re}\left[\underline{b_R} b_S^*\right]$$







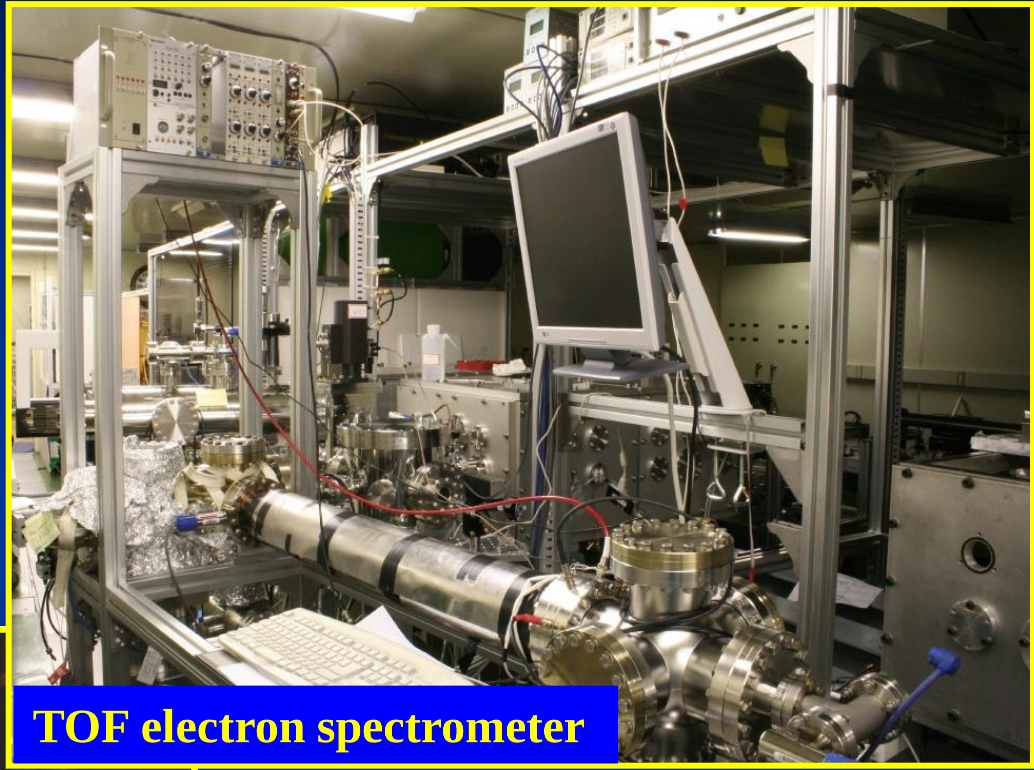
GD tells when electrons are ejected

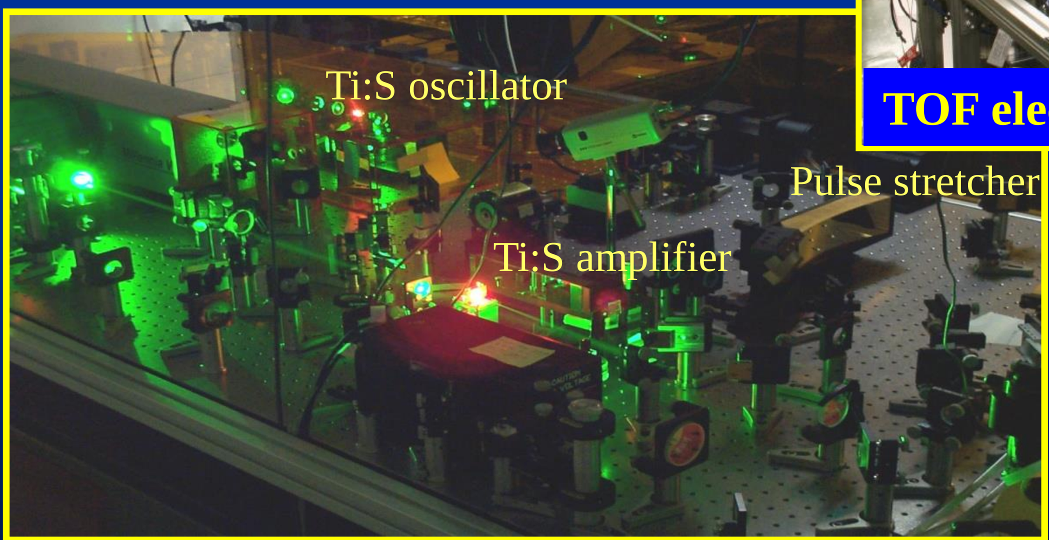
K. T. Kim, Phys. Rev. Lett. **108**, 093001 (2012)

Attosecond Science Research at CXRC

Attosecond science research

- Nonadiabatic blueshift, PRL'99
- Coherent control of HHG, PRL'01
- Two-color HHG, PRL'05, APL'08
- Atto chirp compensation, PRL'07
- Ultrafast photoionization, PRL'12
- 63-as pulse generation, NJP'11
- FROG CRAB method, NJP'11

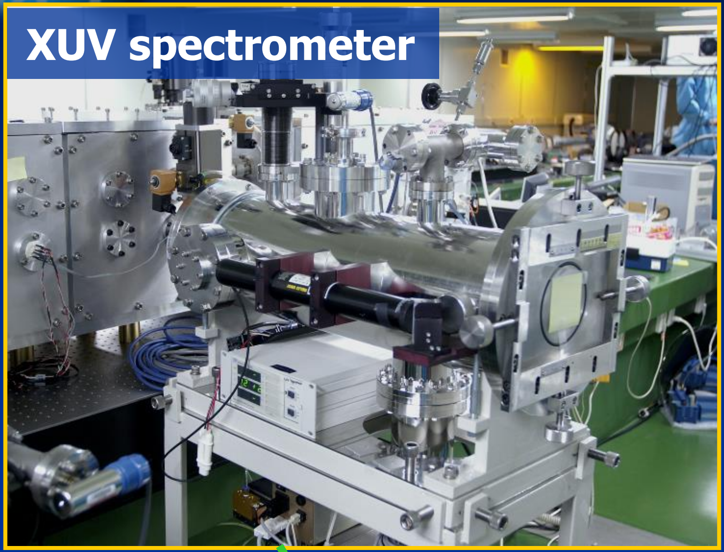


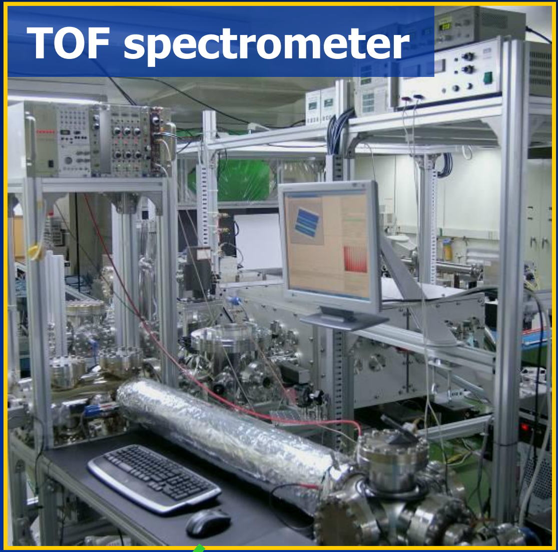


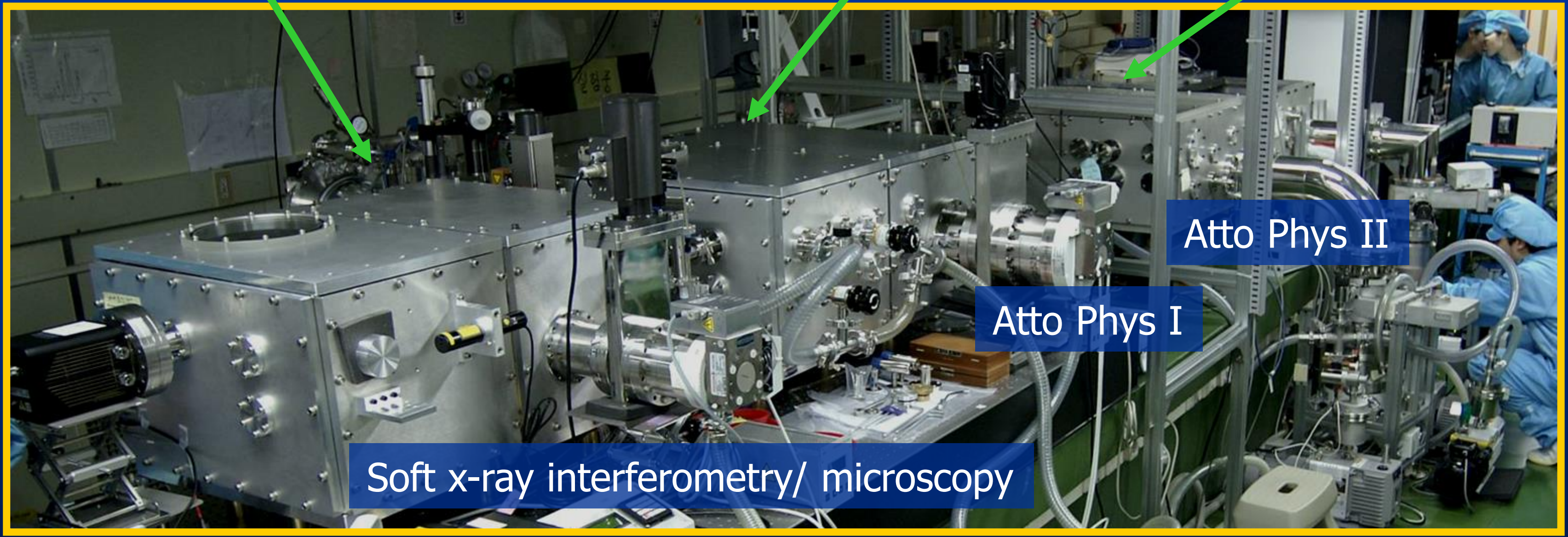
Advanced femtosecond laser tech

- Long wavelength injection, JOSA B'99
- 3.7-fs, 0.3 TW laser @ 1 kHz, OL'09
- Direct CEP locking, OEx'05,'07,'08,'10

Experimental Facility at CXRC

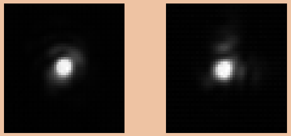




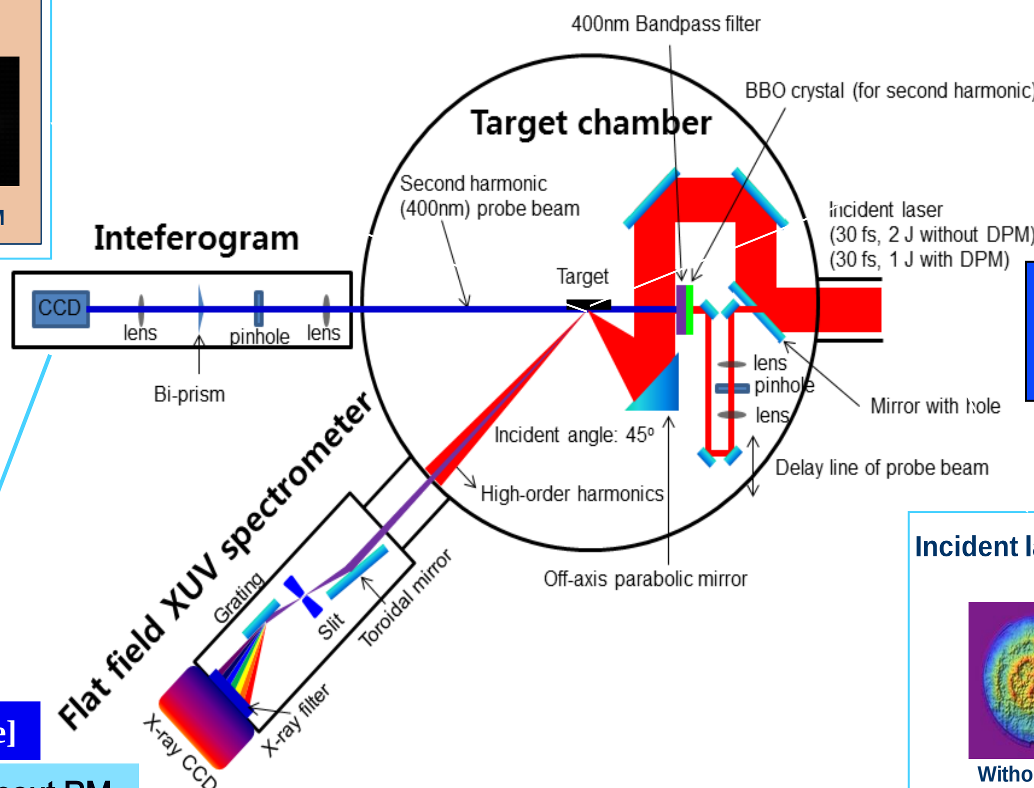


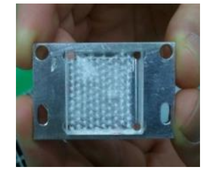
Relativistic High Harmonic Generation

Focal spot image



without DPM   with DPM

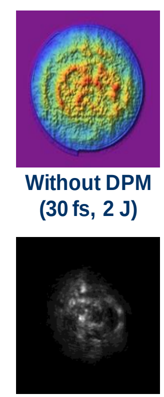




(SiO_2 Bulk)

On target :
$I = 9 \times 10^{19}$ W/cm^2 (w/o DPM)
$I = 4.5 \times 10^{19}$ W/cm^2 (w/ DPM)

Incident laser beam

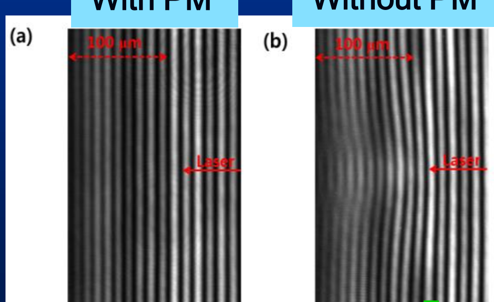


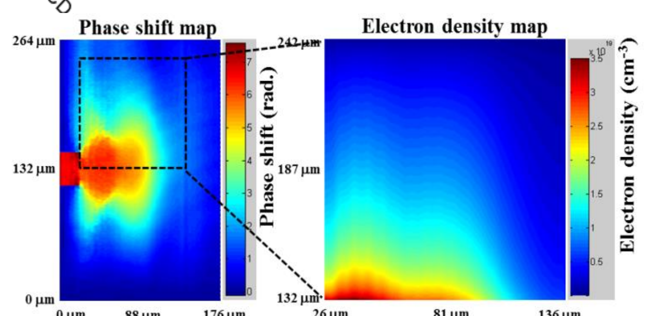
Without DPM (30 fs, 2 J)

With DPM (30 fs, 1 J)

[50ps before main pulse]

With PM   Without PM



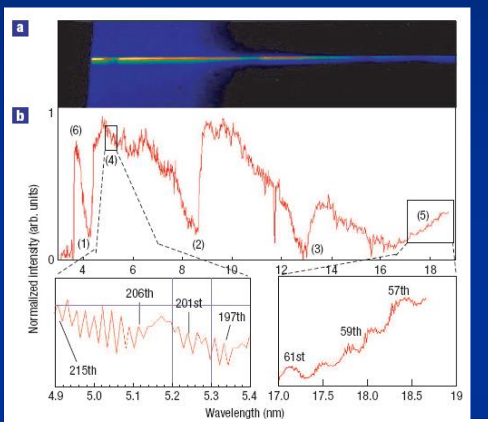


RHHG: relativistic oscillating mirror (ROM)

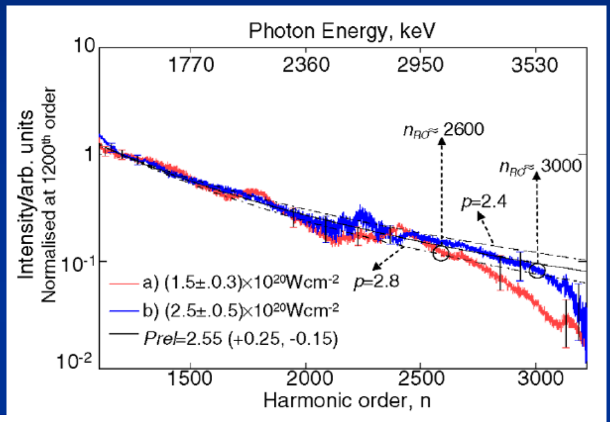
High intensity (>10^{18} W/cm^2) and high temporal contrast (>10^{-10})

Vulcan sub-ps petawatt Nd:glass laser

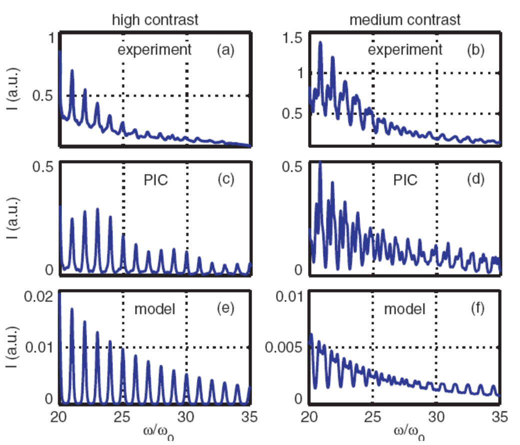
Arcturus 100 TW Ti:sapphire laser



Nature Physics 2, 456 (2006)



PRL 99, 085001 (2007)



PRL 106, 0185002 (2011)

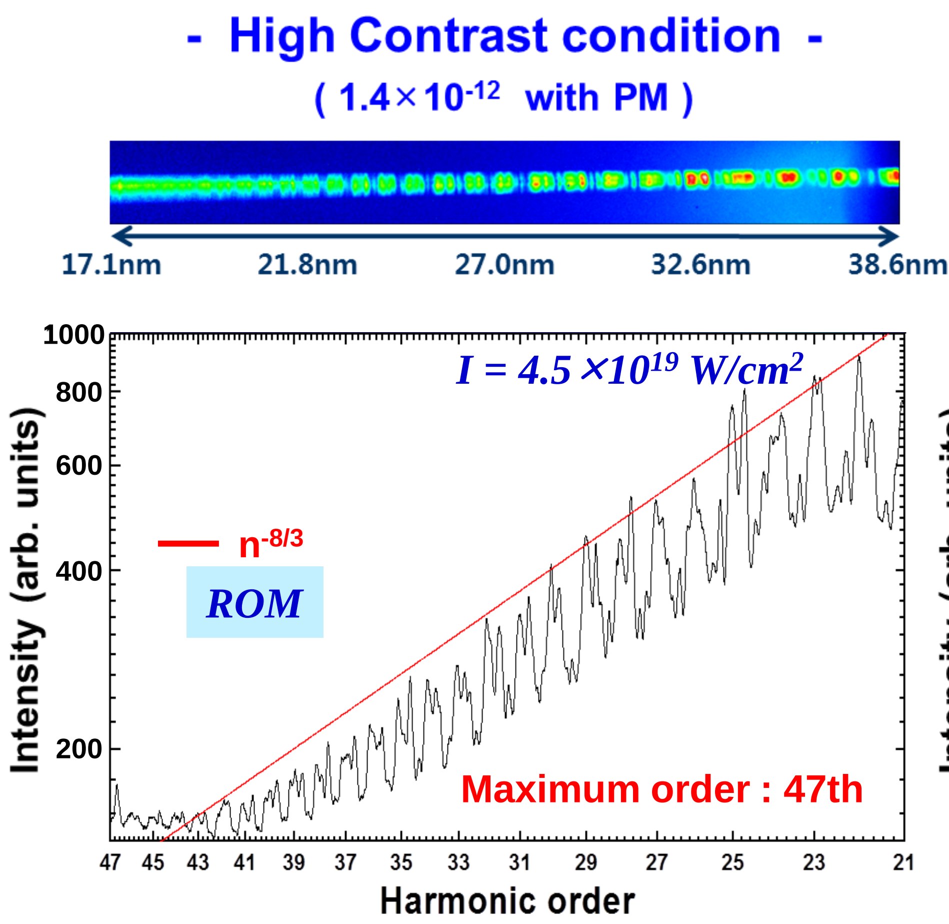
Multi-keV RHHG
Low repetition rate (1 shot/hr)

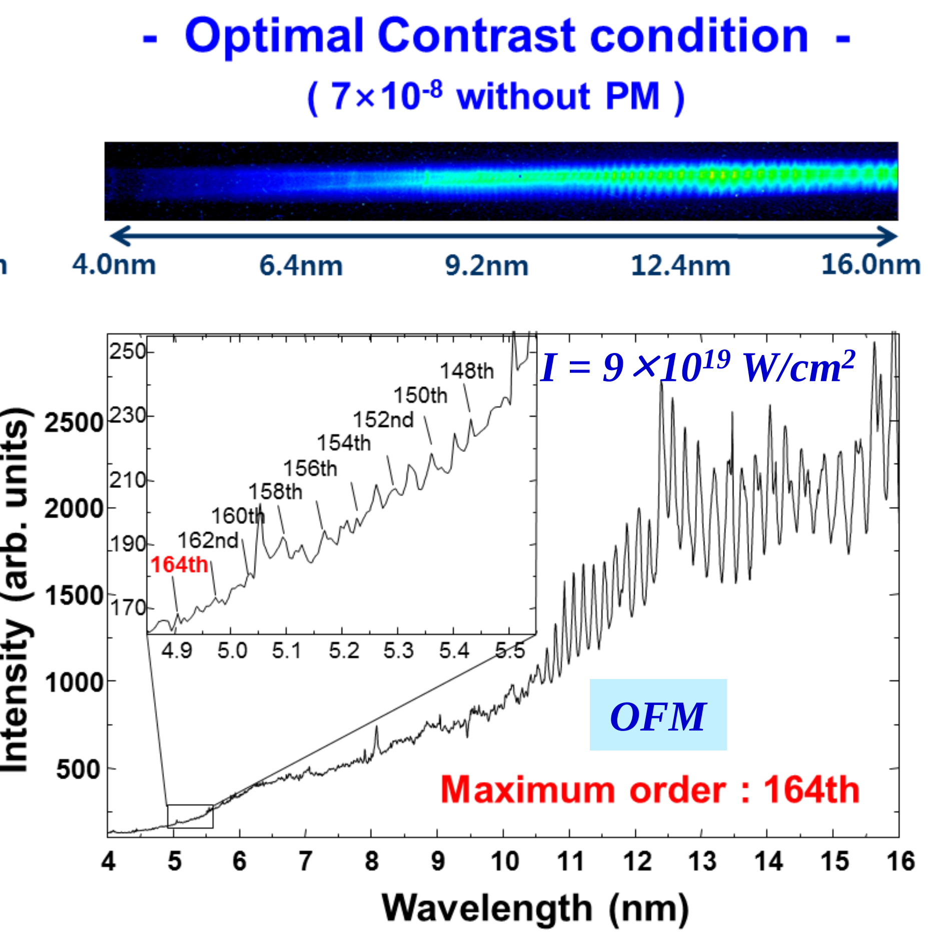
High repetition rate (10 Hz)
Low-order harmonics (~35^{th} , ~23nm)

high intensity (>10^{18}W/cm^2) but low contrast (~10^{-7})
-> RHHG using self-induced *oscillatory flying mirror (OFM)*

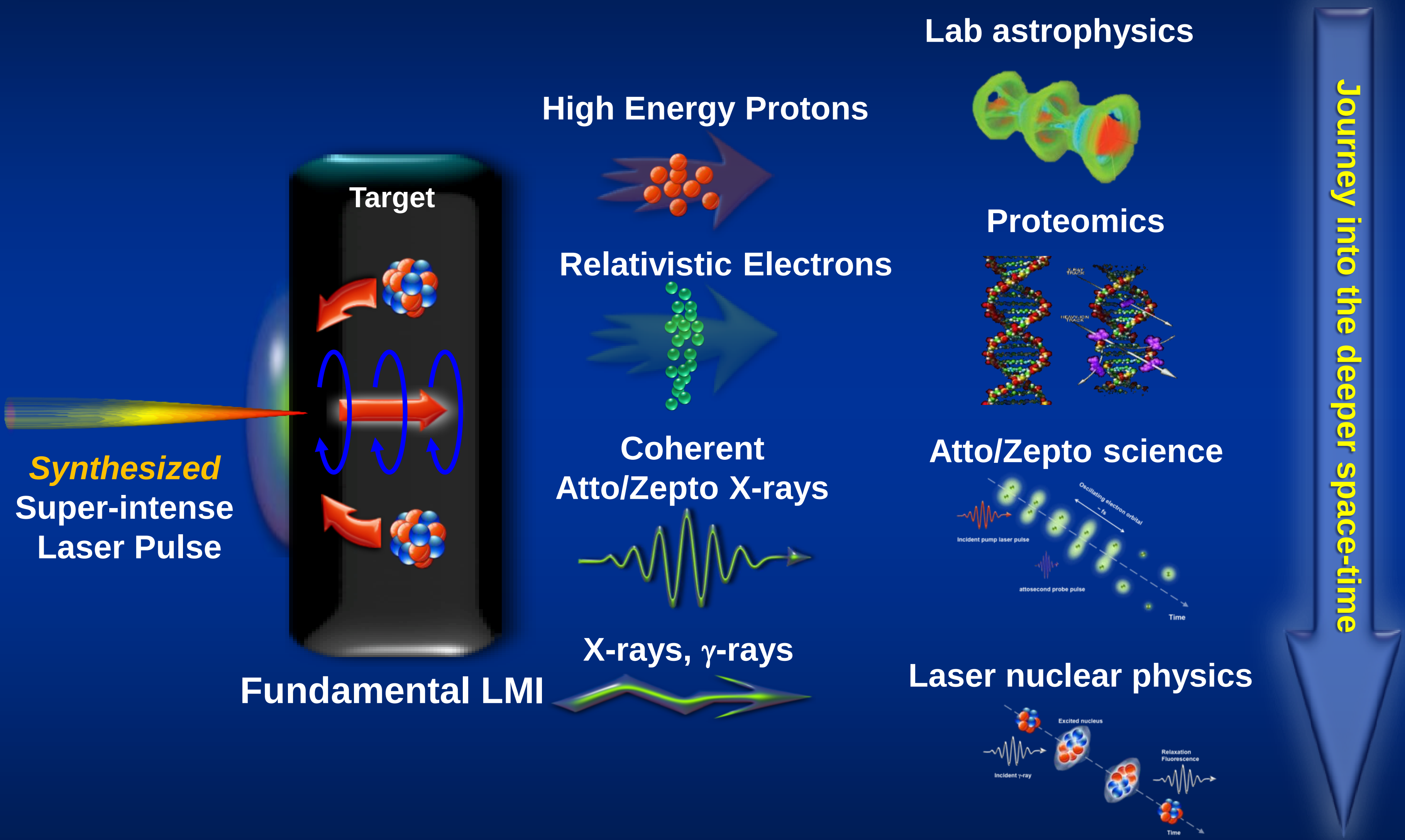
RHHG: Contrast Ratio

Significant Extension of Relativistic Harmonics with <100 fs Pulses





Research Overview



Exploration of Relativistic Laser-Matter Interactions using Super-intense Laser Pulses

Harnessing laser science at relativistic conditions

"Matter under extreme environments"

"New horizon in time & space"

"Discovery of novel physical processes"

Leading Laser Lab in the World