Stabilization of GeV Electron Beams by Coherent Control of LWFA Process

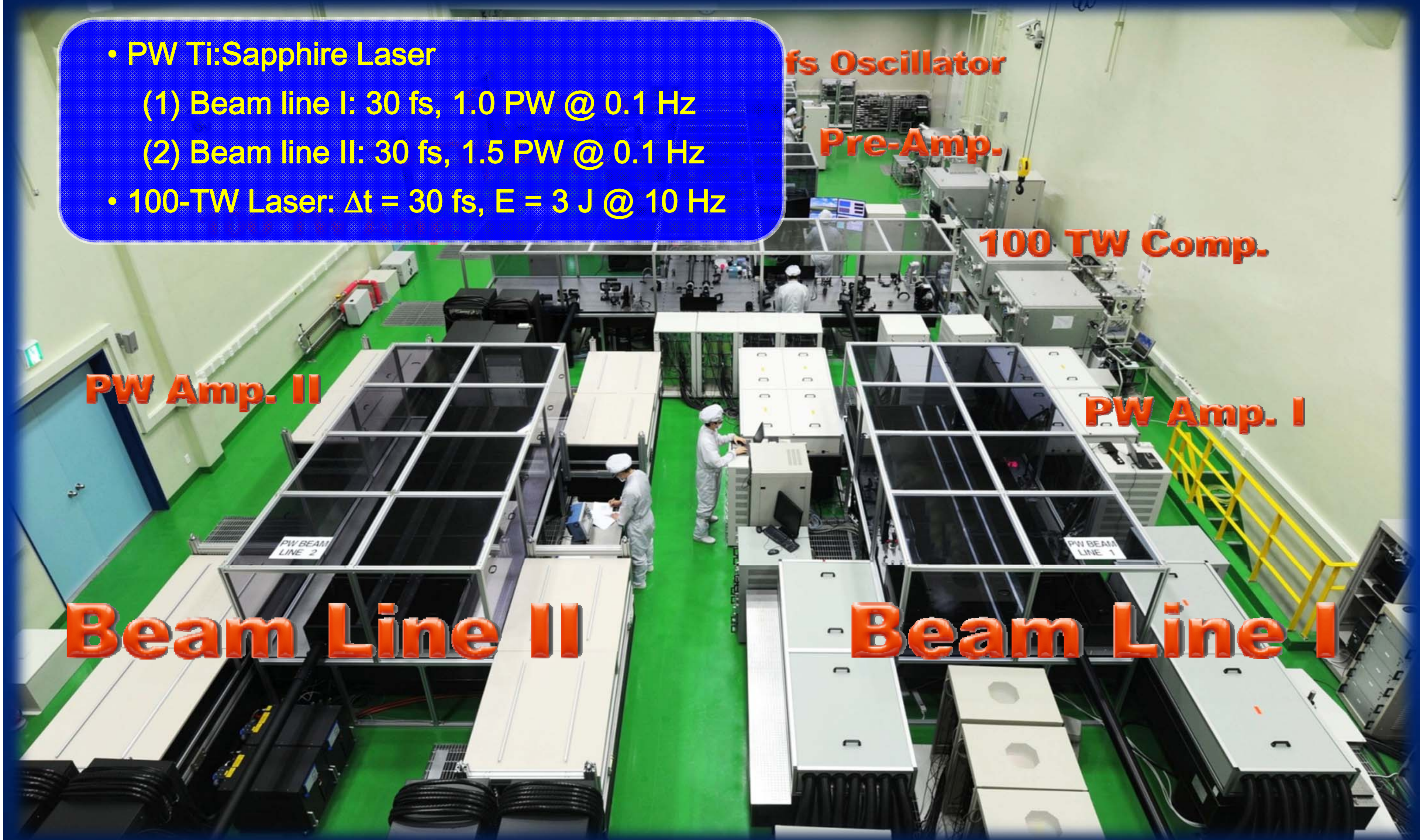
Hyung Taek Kim, Ki Hong Pae, V. B. Pathak, A. Lifschitz, F. Sylla, I Jong Kim, Seong Ku Lee, Jae Hee Sung, Hwang Woon Lee, E. Guillaume, C. Thaury, Kazuhisa Nakajima, J. Vieira, L. O. Silva, V. Malka, and Chang Hee Nam

IBS, Center for Relativistic Laser Science (Director Prof. Nam)
Ultrashort Quantum Beam Facility, APRI, GIST

Contents

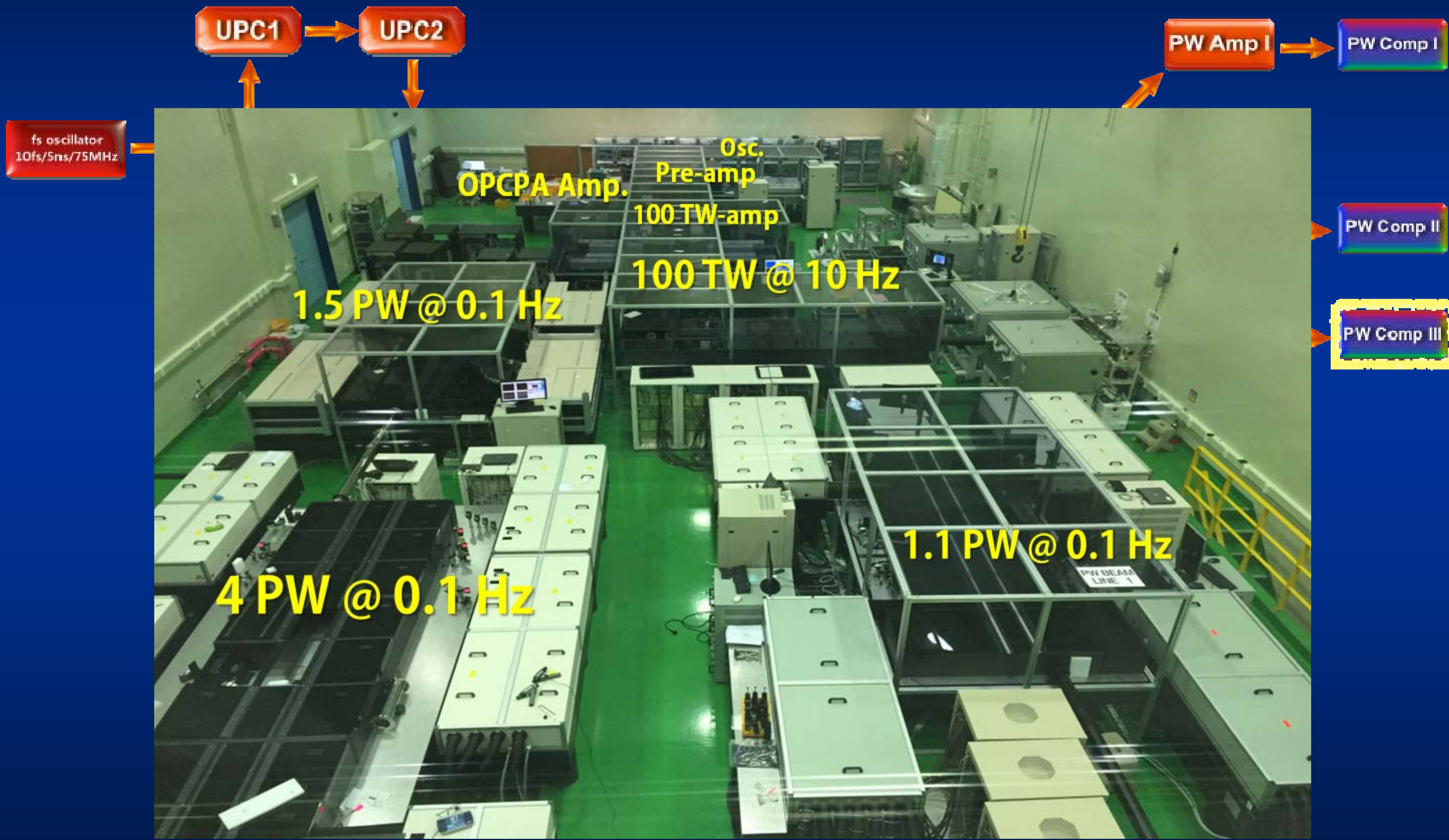
PW Ti:Sapphire Laser at CoReLS

- 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

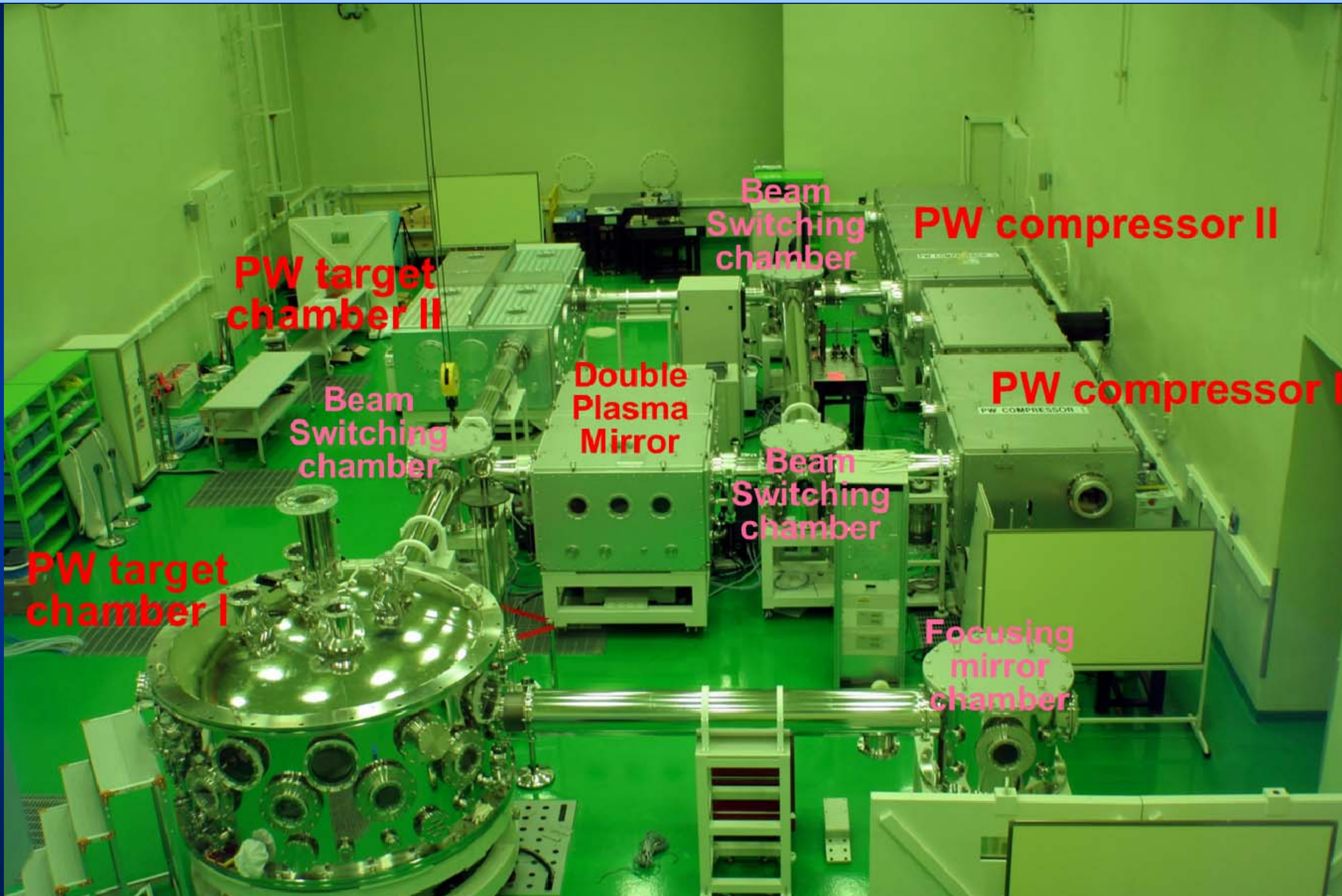


PW laser system

Laser upgrade (20 fs, 4 PW Ti:sapphire Laser)



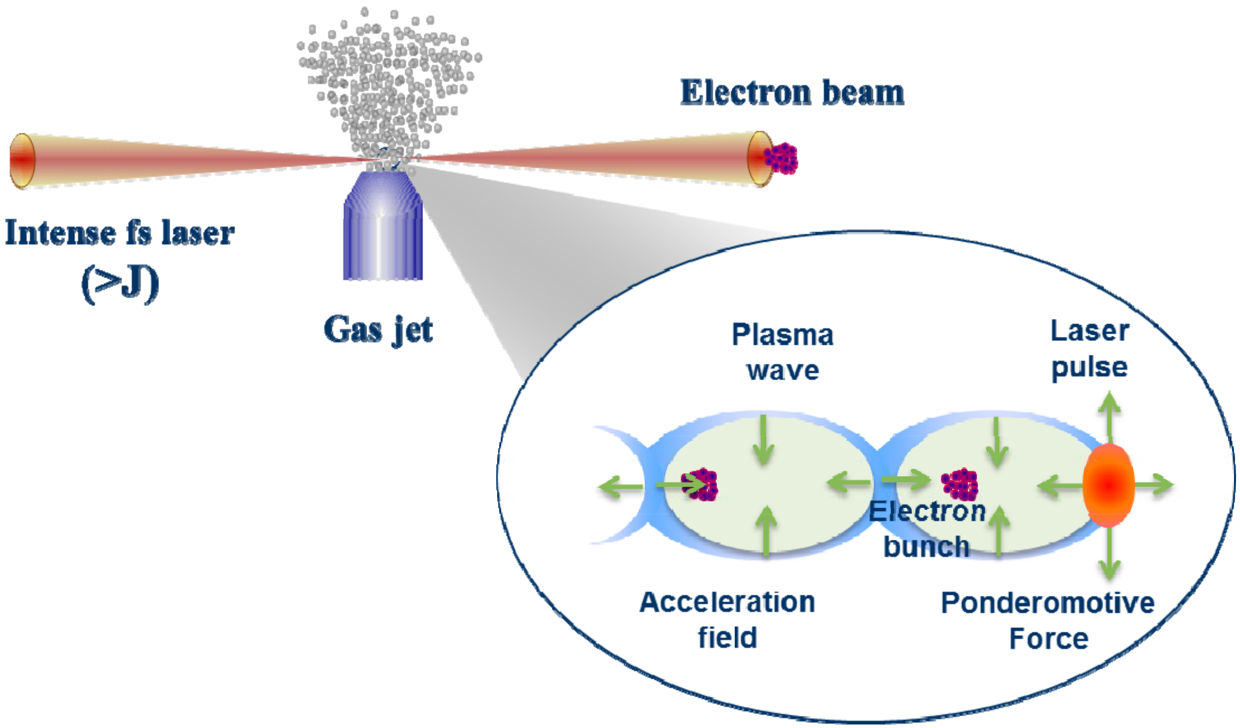
PW Laser Experimental Area



Control Room

Contents

Laser Wakefield Electron Acceleration



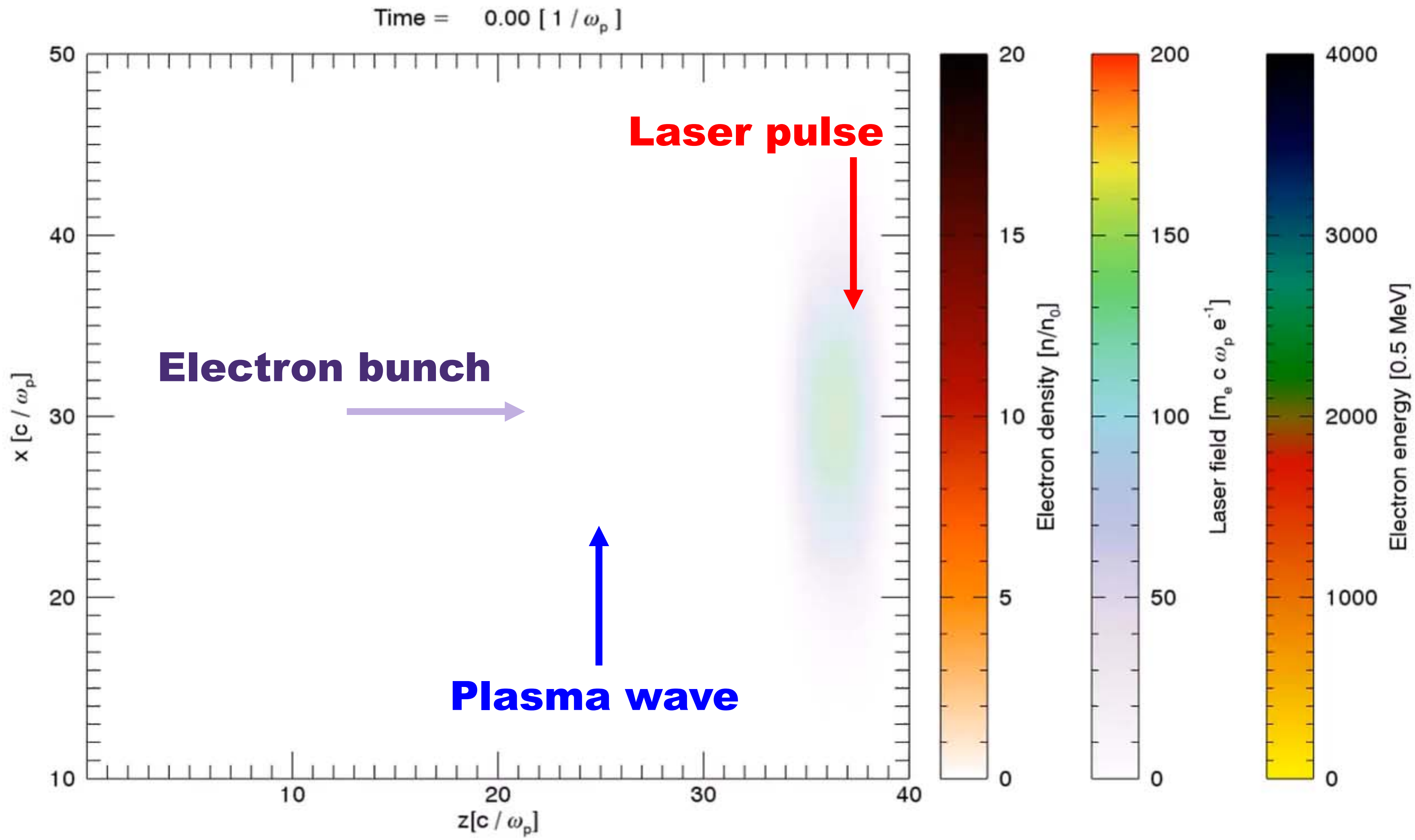
Plasma wave by laser pulse
~ Waves by ship in sea

Acceleration by plasma wave
~ Surfing to the wave in sea

Electrons pushed by ponderomotive force
→ Restoring to the original position
→ Electron plasma wave created
→ Injected electron bunch accelerated by the plasma wave

Huge acceleration field
> 100 GeV/m

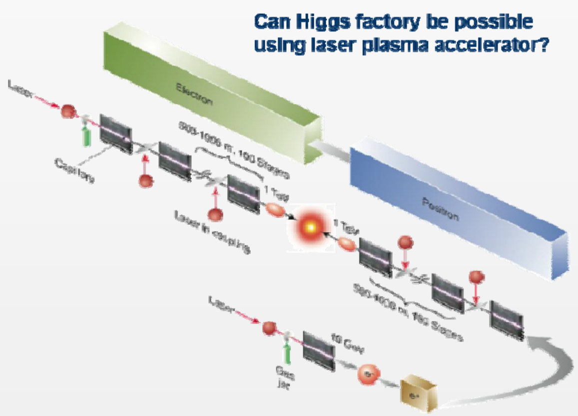
LWFA process (PIC simulation)



Motivation of LWFA research

Plasma accelerators 1000 x higher gradient than RF accelerator

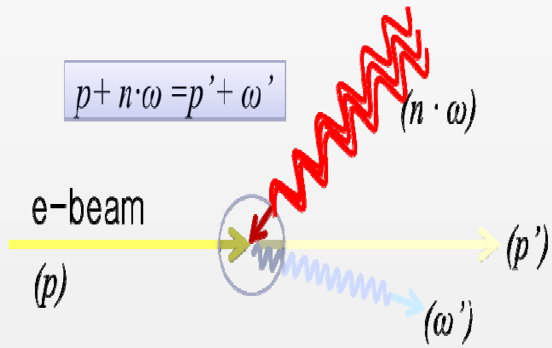
Next generation of linear collider



W.P. Leemans and E. Esarey, *Physics Today* **62**, 44 (2009).

100-GeV $e^- e^+$ collider

High energy high brightness photon sources



Nonlinear Compton scattering

Table-top linear accelerator for practical applications

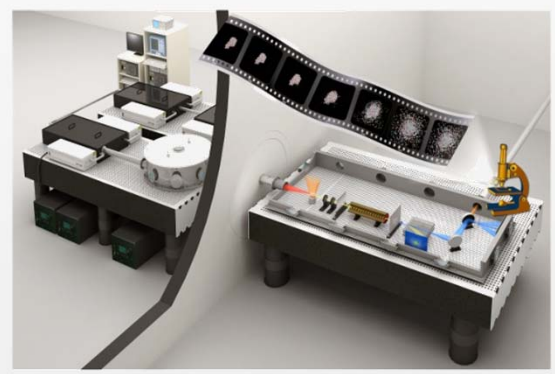
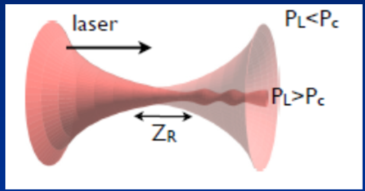


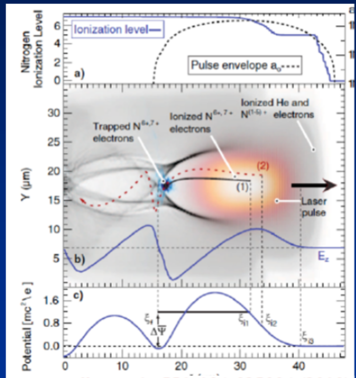
Table-top synchrotron source

LWFA can be a gate way to new physics

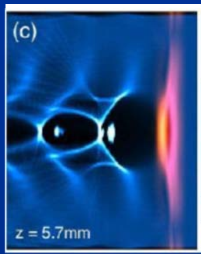
Issues in LWFA research

- ► **Electron bunch Injection**
  - Self injection
  - Injection by additional laser
  - Ionization injection
- ► **Laser propagation**
  - Relativistic self-focusing & channeling
  - Self steepening, pulse erosion, …
- ► **Acceleration process**
  - Dephasing & pump depletion
  - Beam loading effect
- ► **Radiation sources**
  - Betatron radiation
  - Inverse Compton scattering
- ► **Diagnostics on plasma dynamics**
- ► **Applications**





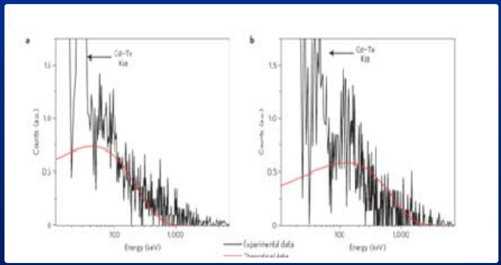
C. McGuffey et al., PRL 104, 025004 (2010)
A. Pak et al., PRL 104, 025003 (2010)



$$L_d \simeq \frac{c}{c - v_\phi} R \simeq \frac{2}{3}\frac{\omega_0^2}{\omega_p^2} R.$$

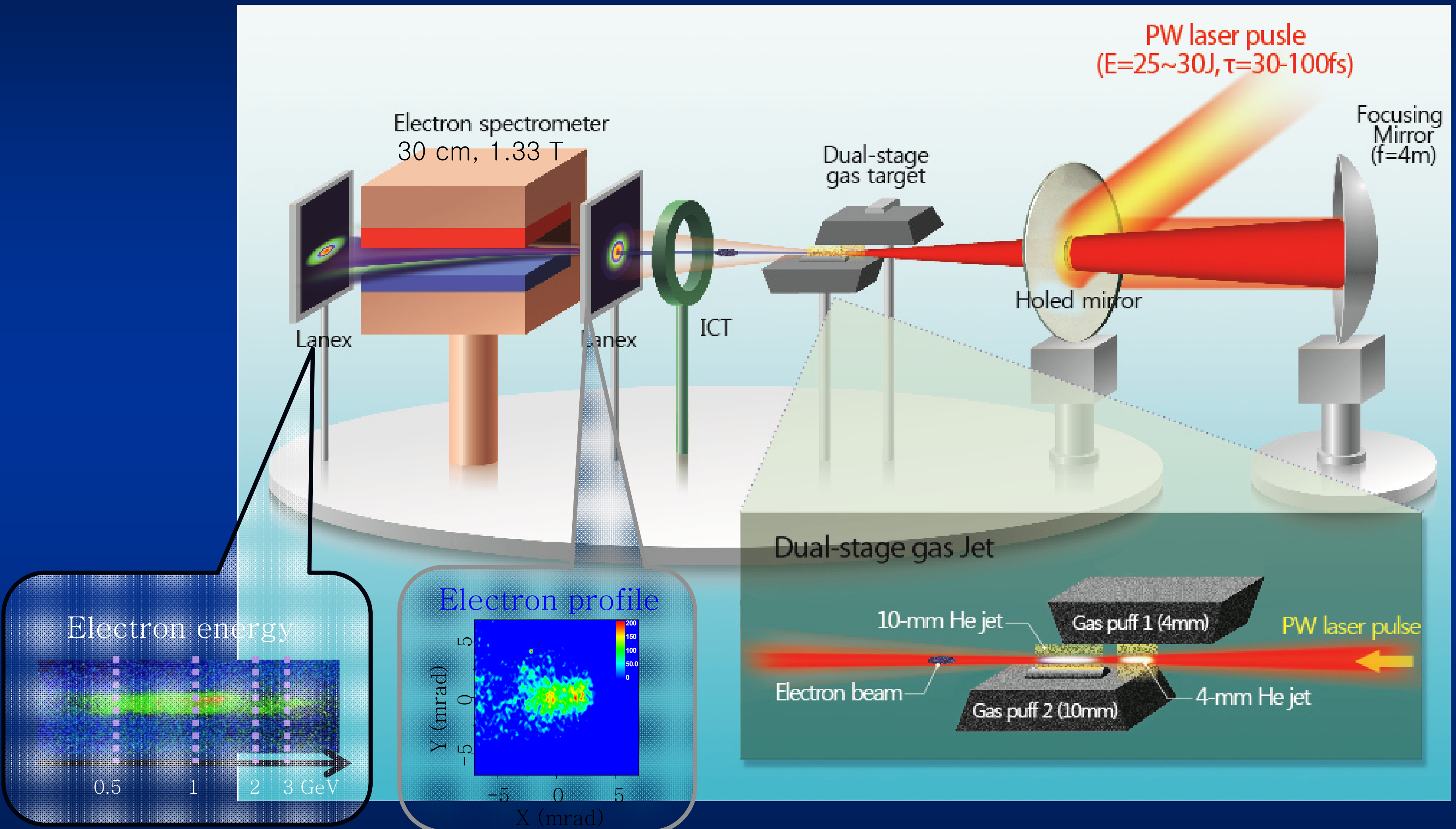
$$L_{etch} \simeq \frac{c}{v_{etch}} c\tau_{FWHM} \simeq \frac{\omega_p^2}{\omega_0^2} c\tau_{FWHM}.$$

W. LU *et al.*
Phys. Rev. ST Accel. Beams **10**, 061301 (2007)



Nature Physics 7, 867 (2011)

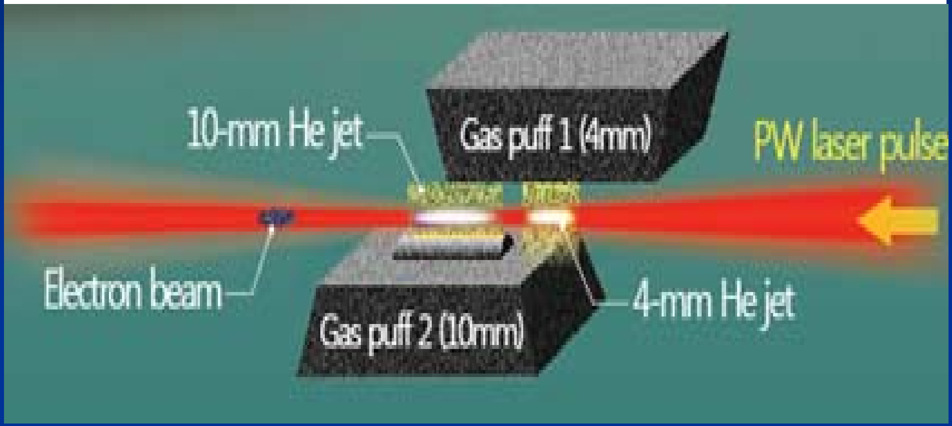
Dual-stage LWFA using PW laser pulse



Multi-GeV e-Beam Generation with Dual Gas Jets

Double-stage Gas jet

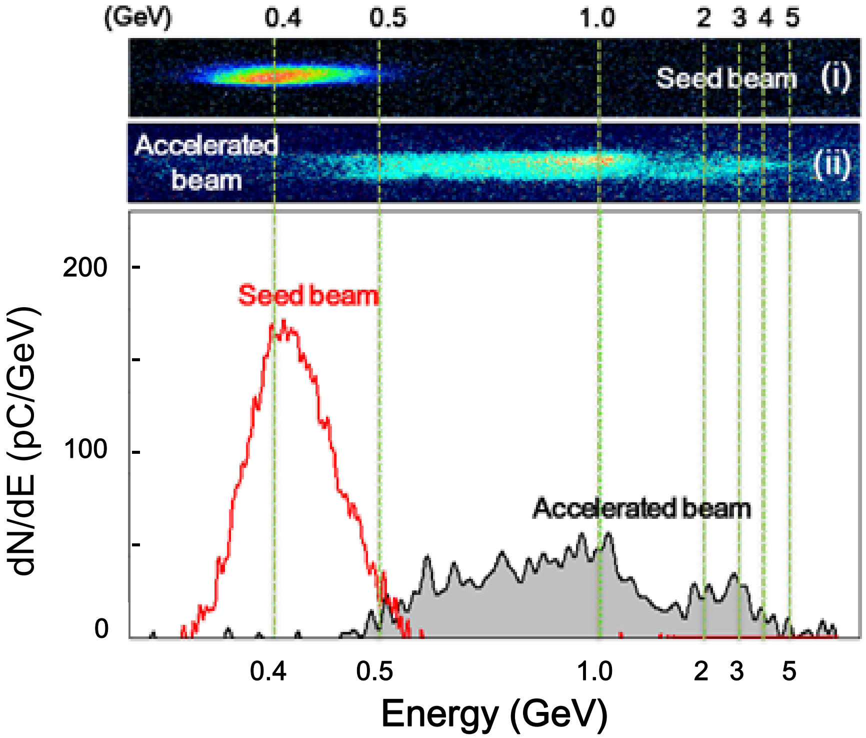
$d_e = 2.1 \times 10^{18}$ cm^{-3} (4 mm) ;$d_e = 0.7 \times 10^{18}$ cm^{-3} (10 mm)



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

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

Electron energy spectrum



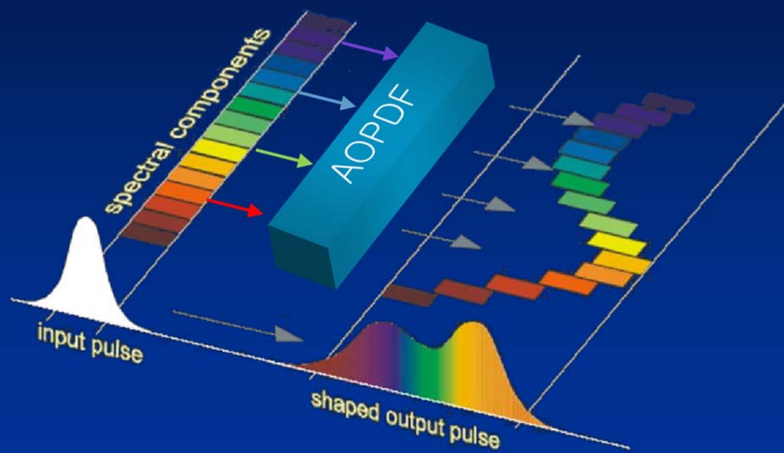
Charge of electron beam (4+10 mm):
~ 80 pC (> 0.5 GeV), ~10 pC (> 2 GeV)

HT Kim et al., PRL (2013)

ibs CoReLS GIST

Contents

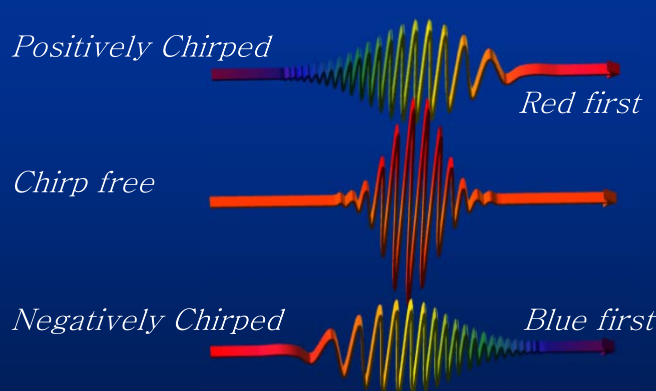
Concept of Coherent control



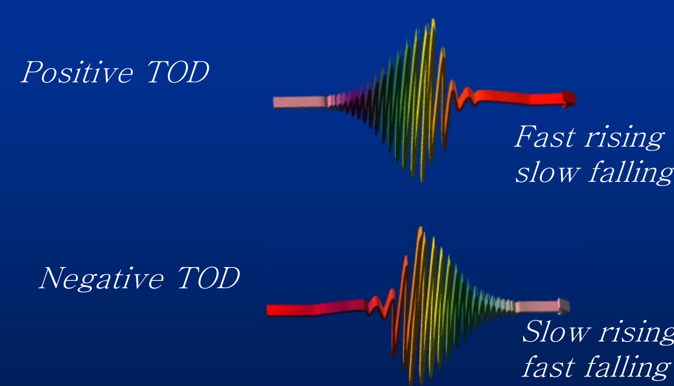
Control of interaction using spectral phase modification

$$\varphi(\omega) = \varphi(\omega_0) + \frac{\partial\varphi(\omega_0)}{\partial\omega}(\omega - \omega_0) + \frac{1}{2}\frac{\partial^2\varphi(\omega_0)}{\partial\omega^2}(\omega - \omega_0)^2 + \frac{1}{6}\frac{\partial^3\varphi(\omega_0)}{\partial\omega^3}(\omega - \omega_0)^3 \ldots$$

$\frac{\partial^2\varphi(\omega_0)}{\partial\omega^2}$: Group delay dispersion (Linear chirp, symmetric broadening)

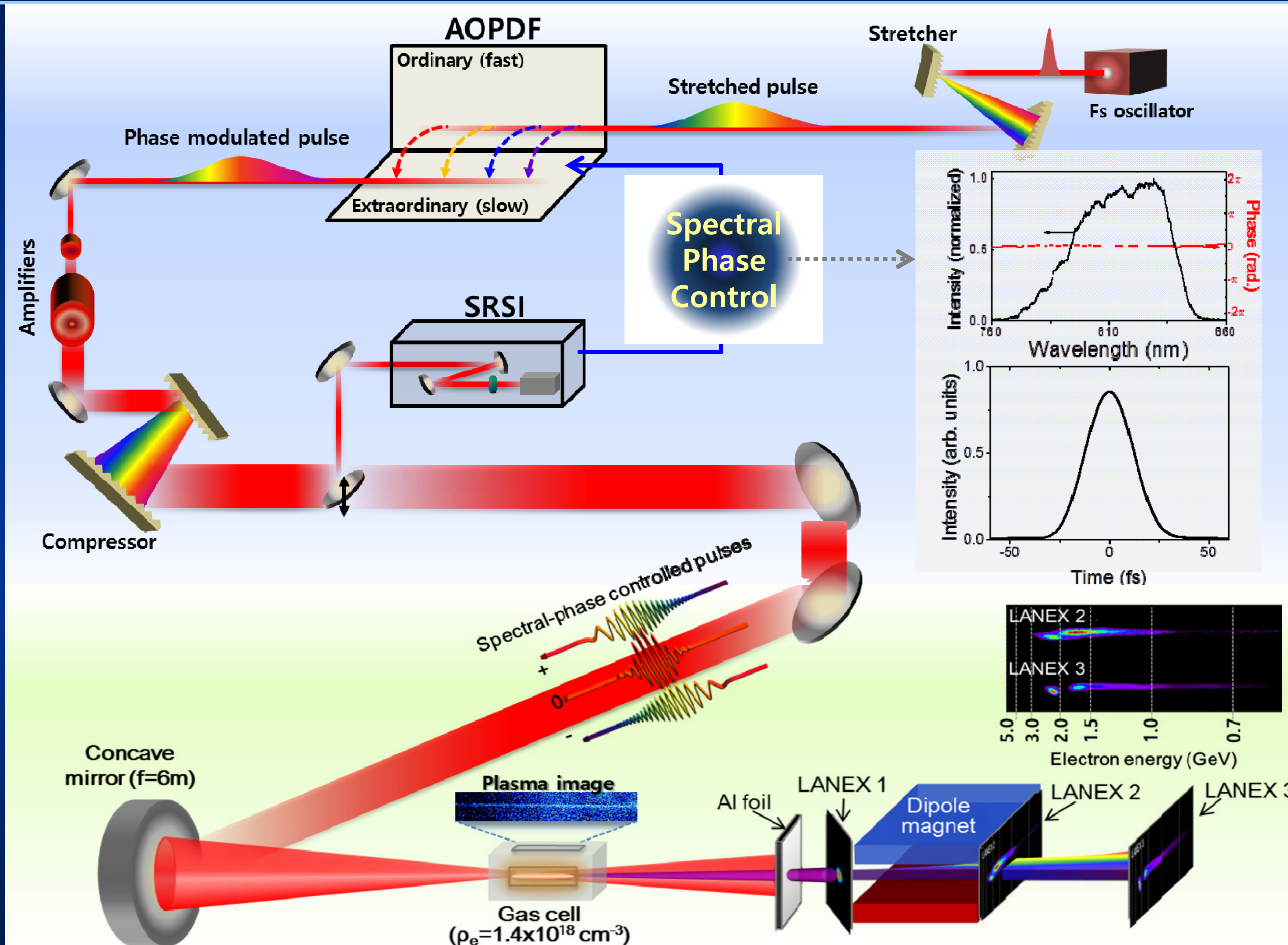


$\frac{\partial^3\varphi(\omega_0)}{\partial\omega^3}$: Third-order dispersion (Quadratic chirp, asymmetric profile)



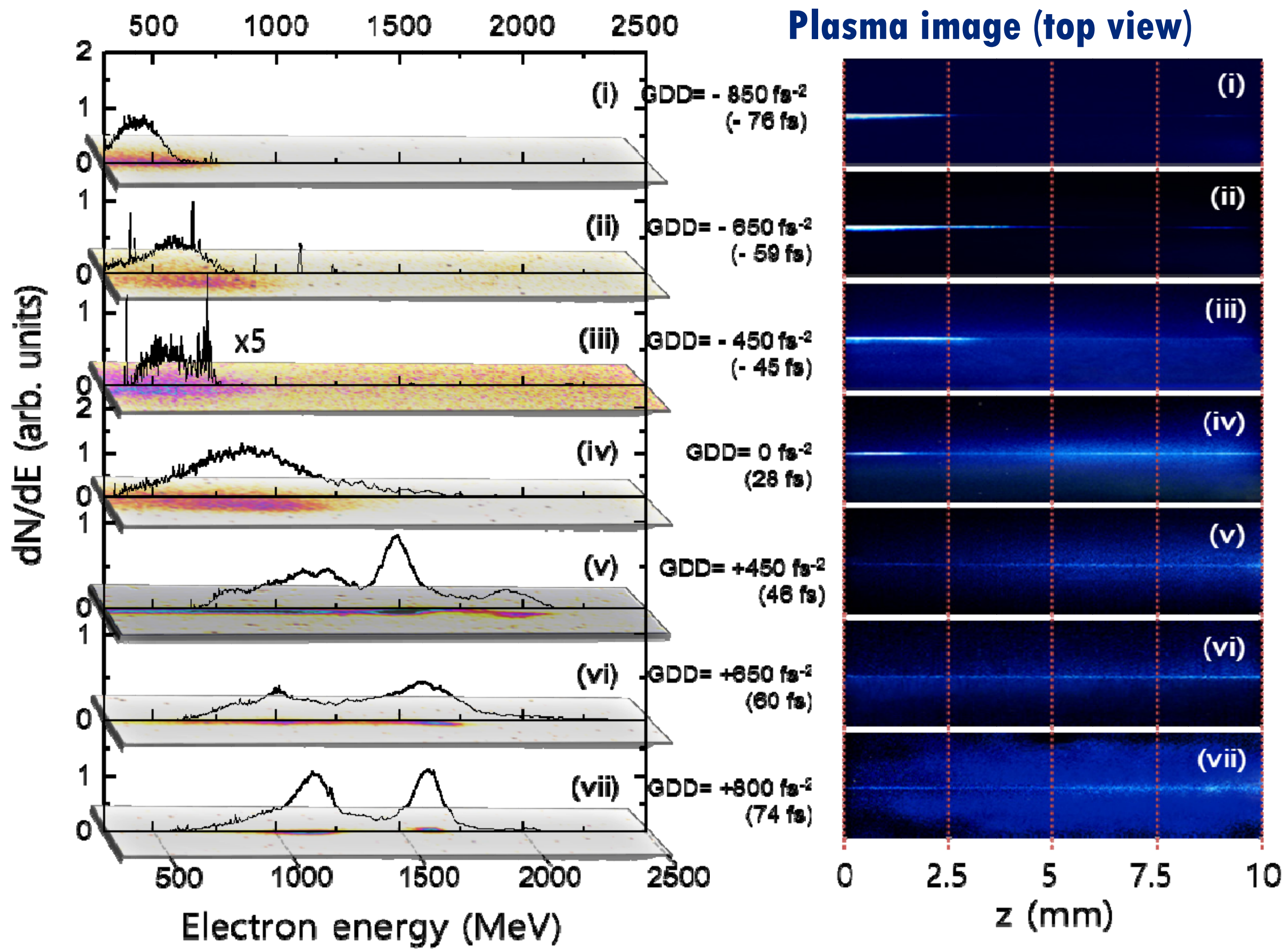
Experiments of Collaboration with LOA (V. Malka, A. Lifschitz et al.) & SourceLab (F. Sylla)

Coherent control of LWFA



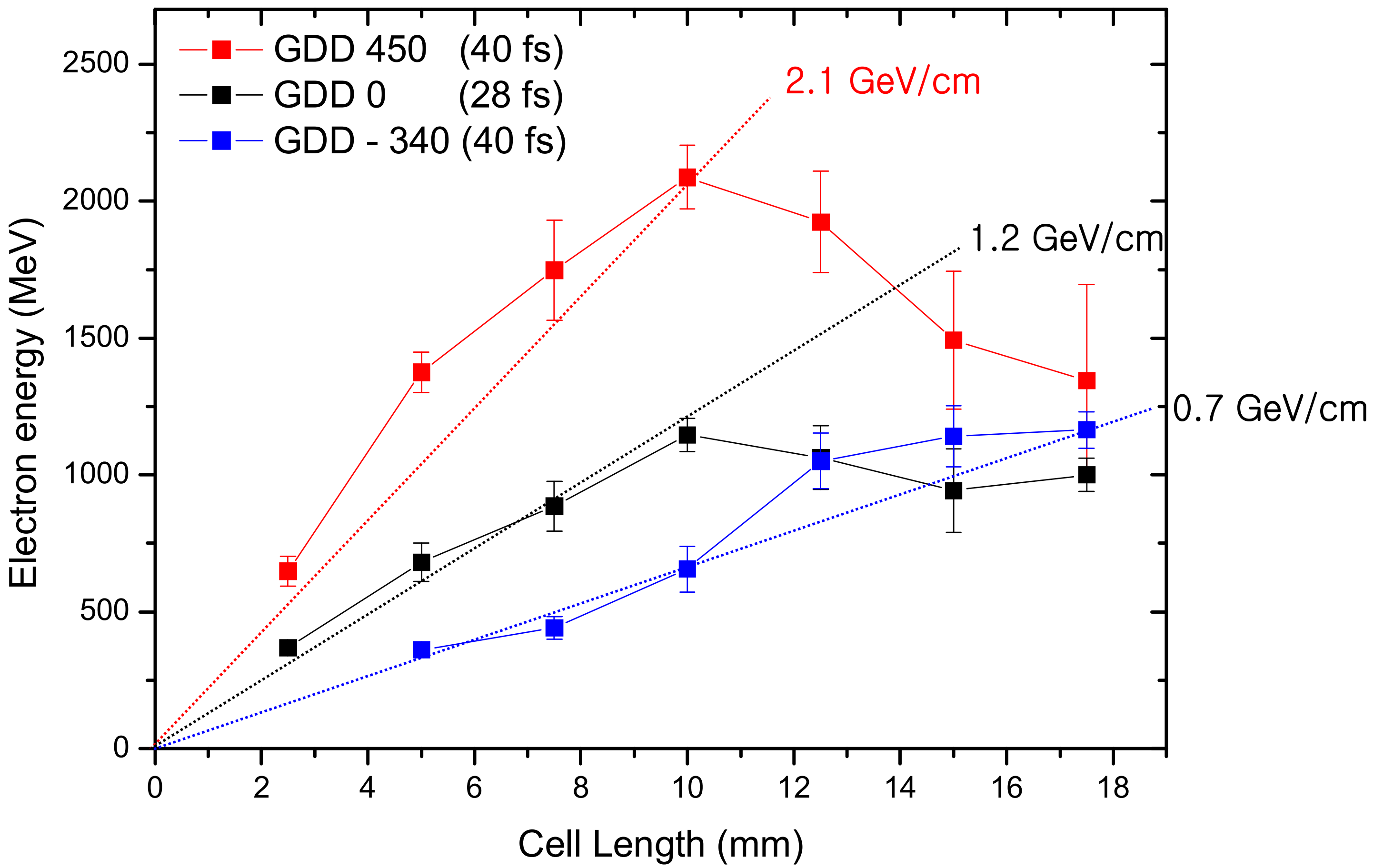
Control of spectral phase: GDD

26 J on target, focal spot ~ 35 micron, Ne ~ 1.4×10^{18} /cc, 10 mm cell length



Different acceleration gradient with changing GDD

26 J on target, focal spot ~ 35 micron, Ne ~ 1.4x10^{18} /cc, 10 mm cell length

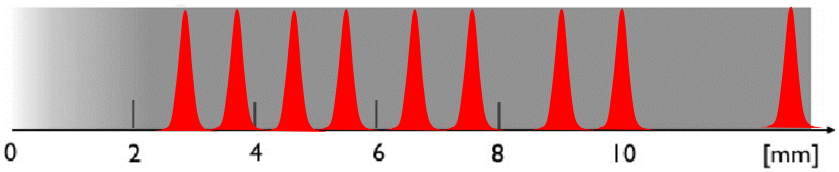


Significant enhancement of acceleration gradient by applying positive chirped PW laser pulses.

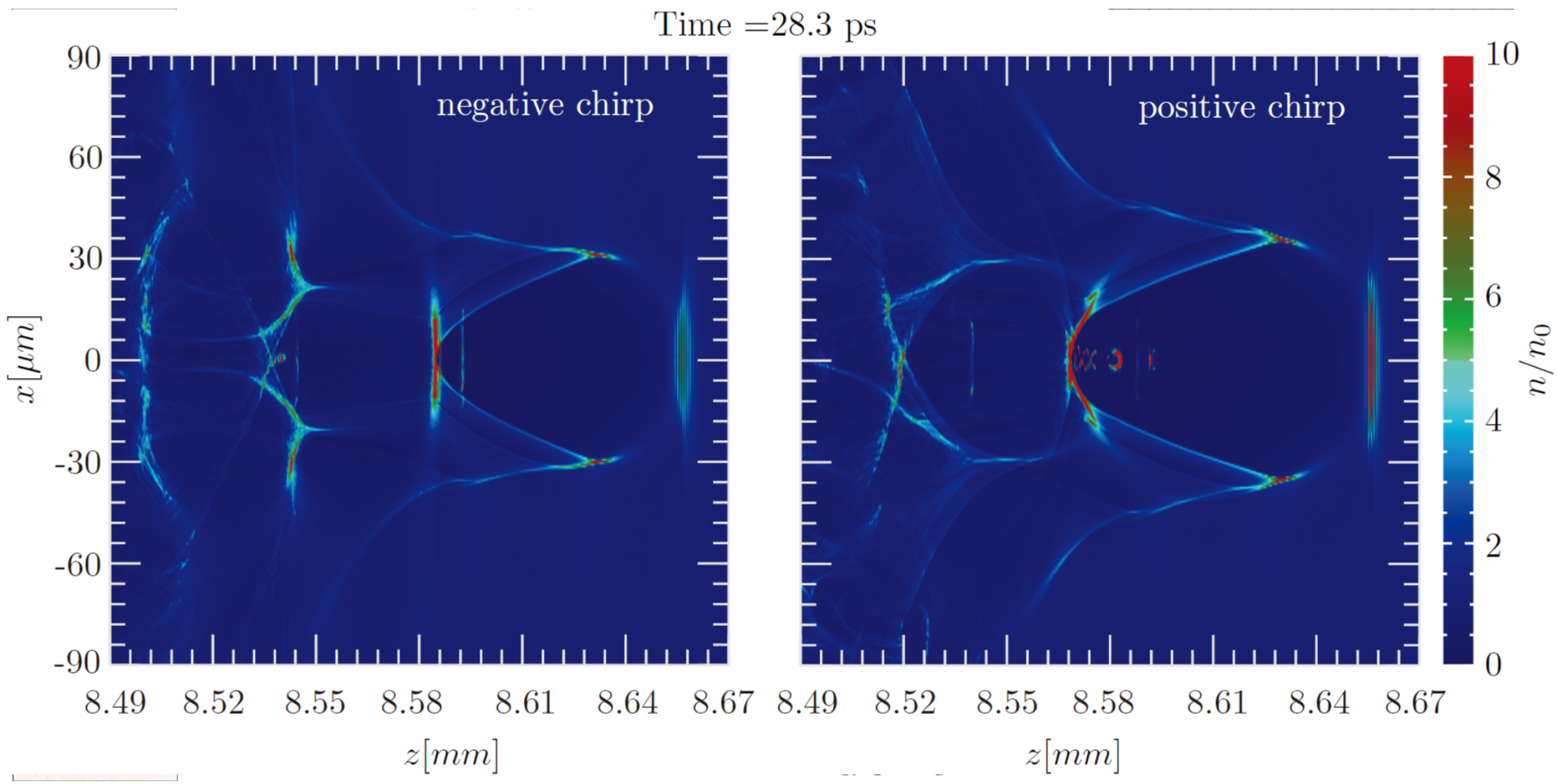
2D PIC simulation (OSIRIS)

25 J, focal spot ~ 30 micron, Ne ~ 1.0x10^{18} /cc, t = 60fs

Red: Positive chirp
Blue: Negative chirp



Positive chirped laser pulses provide earlier injection and higher acceleration field than negative chirp.



Control of spectral phase: GDD+TOD

Temporal profile

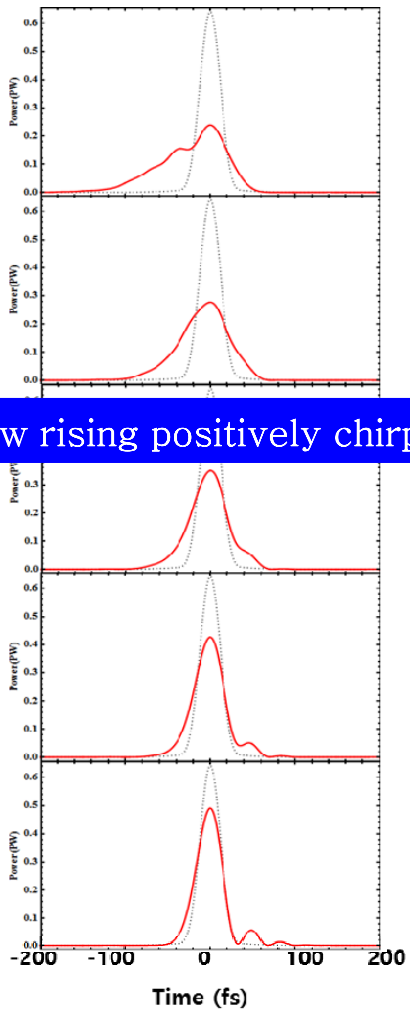
TOD = - 10000 fs^{-3}
τ = 75 fs

TOD = - 4000 fs^{-3}
τ = 61 fs

TOD = 0 fs^{-3}
τ = 46 fs

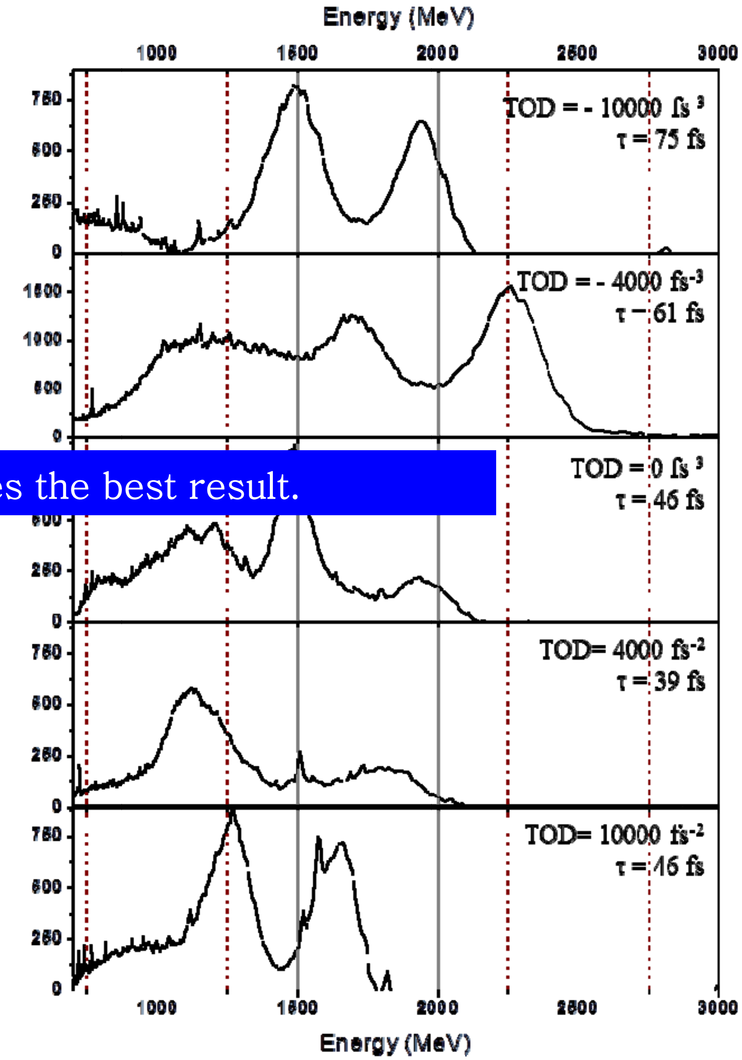
TOD= 4000 fs^{-2}
τ = 39 fs

TOD= 10000 fs^{-2}
τ = 46 fs



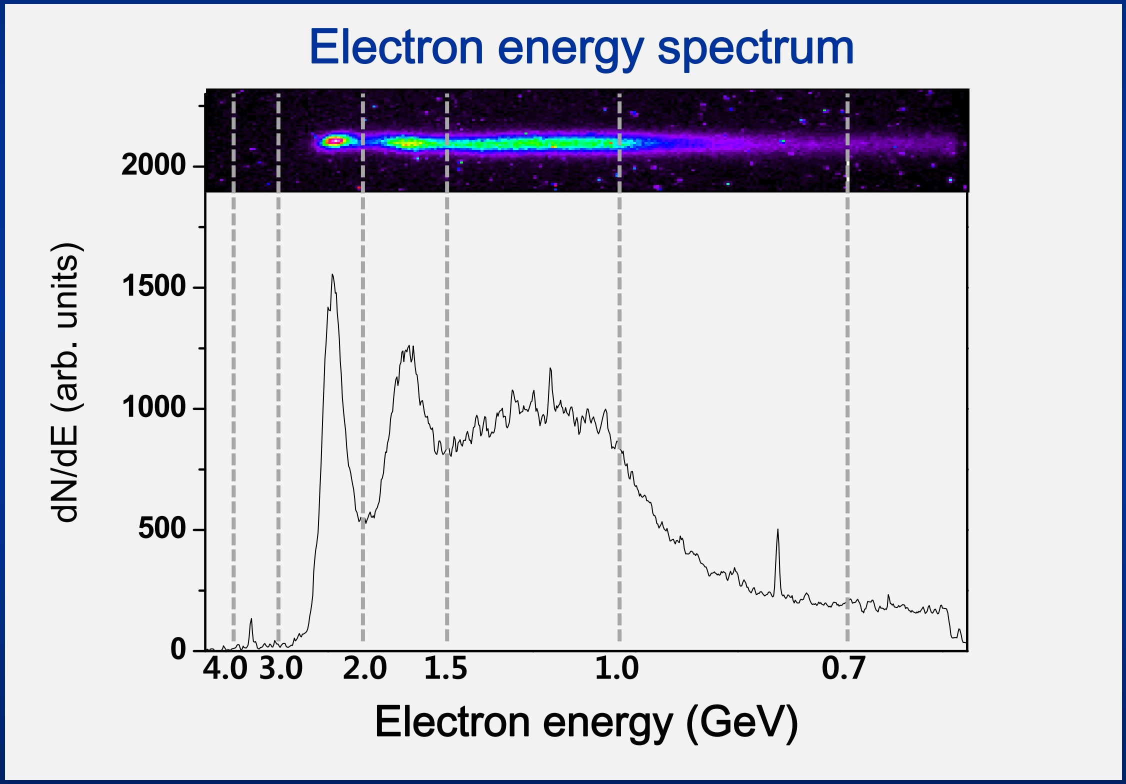
Slow rising positively chirped pulse gives the best result.

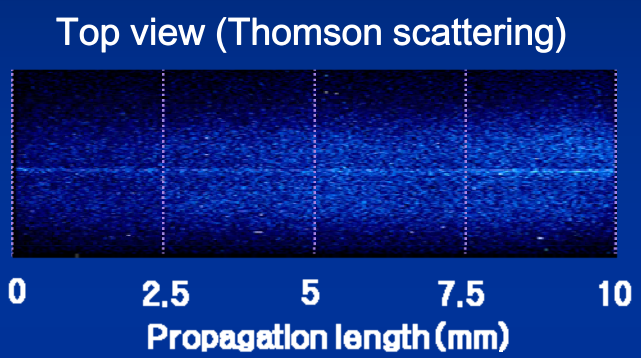
Electron spectrum



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)





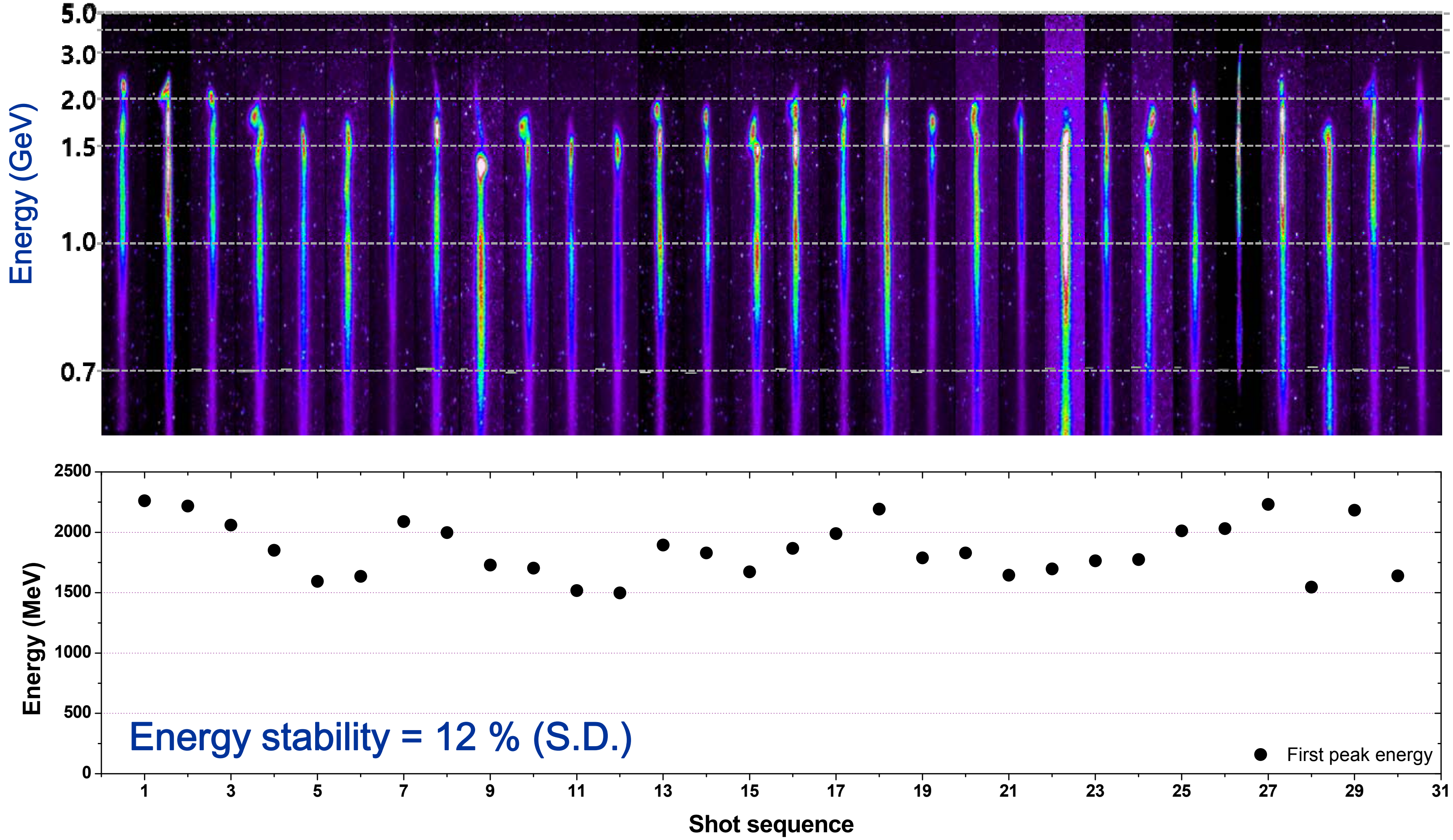
Smooth propagation over the whole medium length of 10 mm

Electron energy ≈ 2.3 GeV,

Charge over 600 MeV ≈ 70 pC

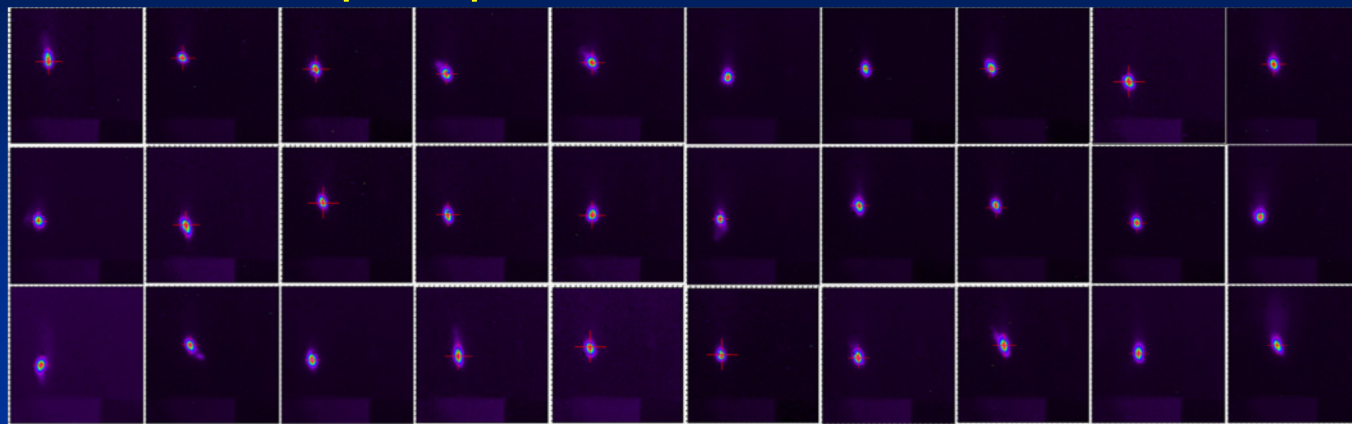
ΔE/E ≈ 10 %
(Resolution ≈ 7 %)

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

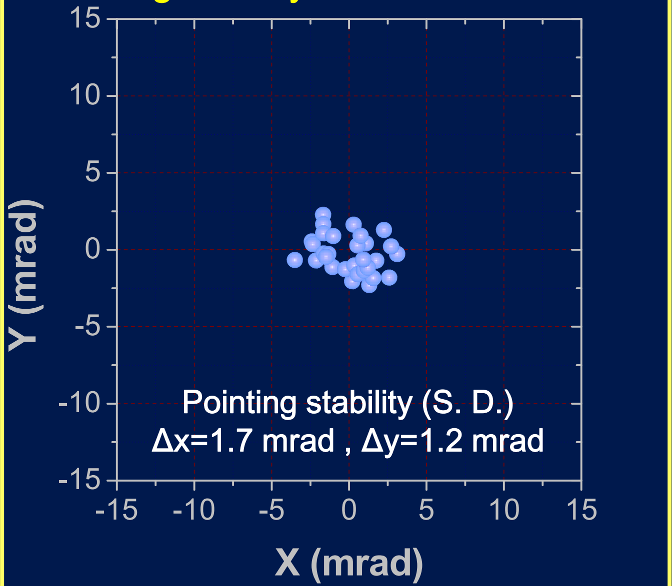


Stability of electron beam at the optimized conditions

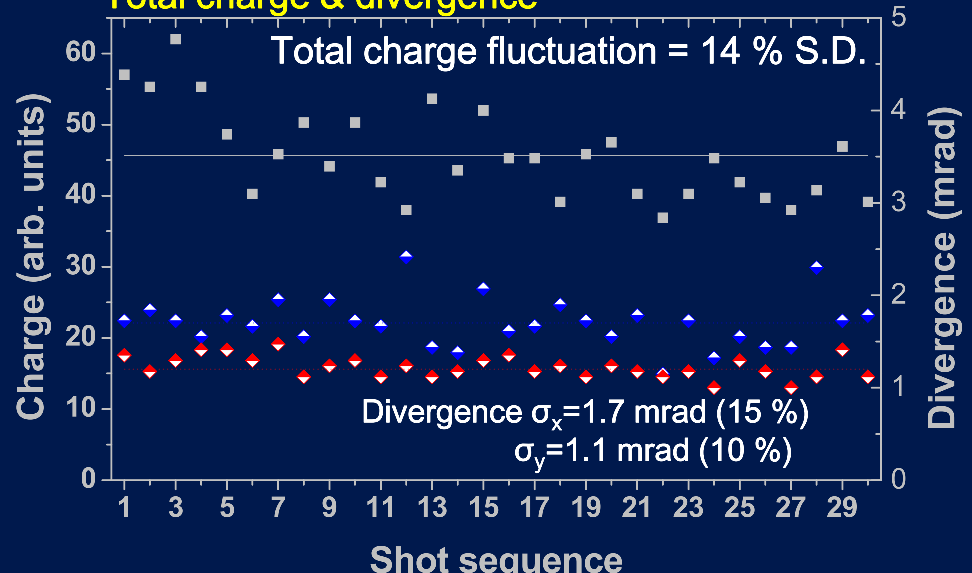
Spatial profile of the electron beam



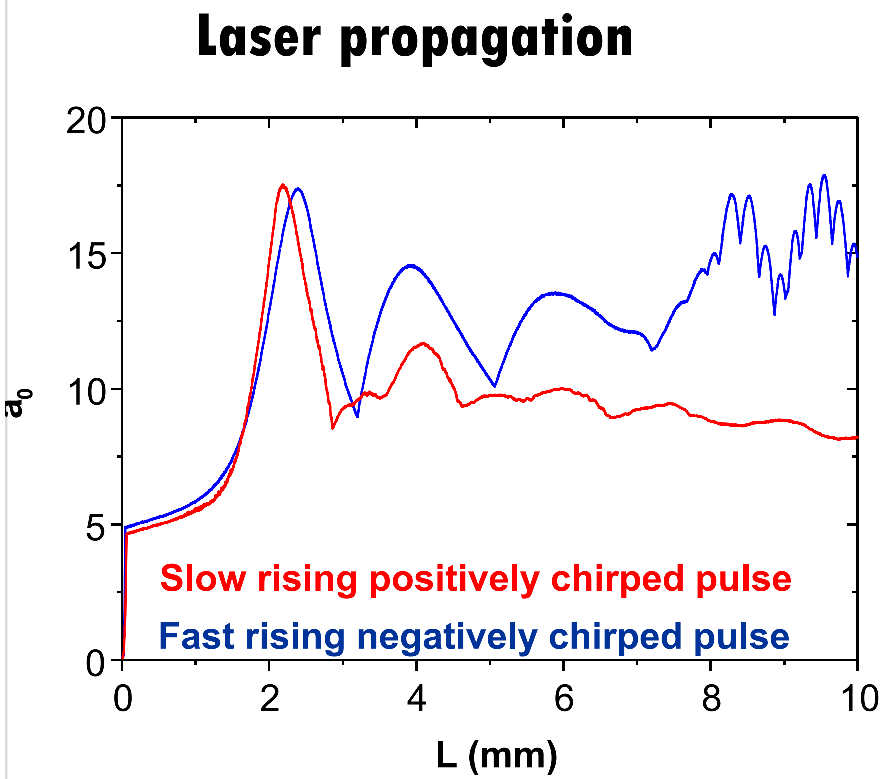
Pointing stability of the electron beam

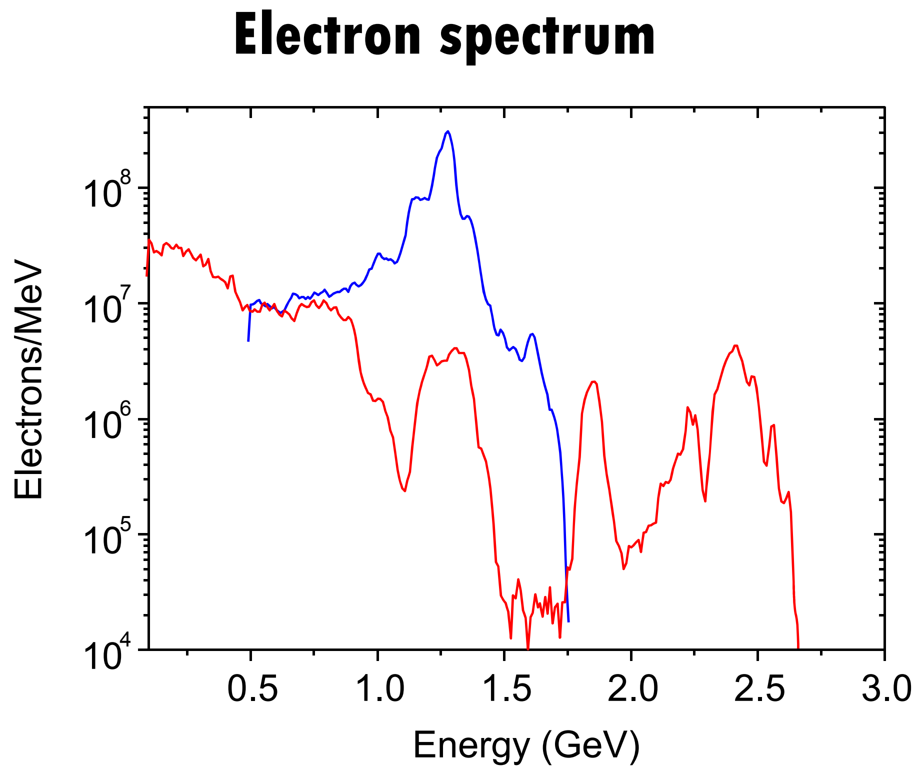


Total charge & divergence



3D PIC simulation (CALDER-Circ.) with GDD and TOD (60 fs)



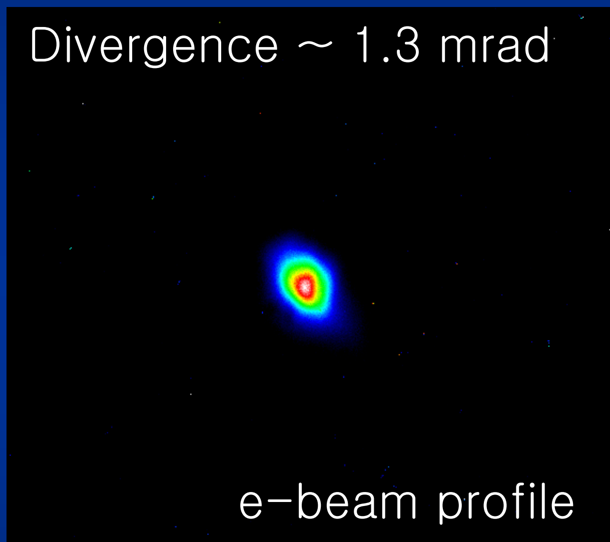


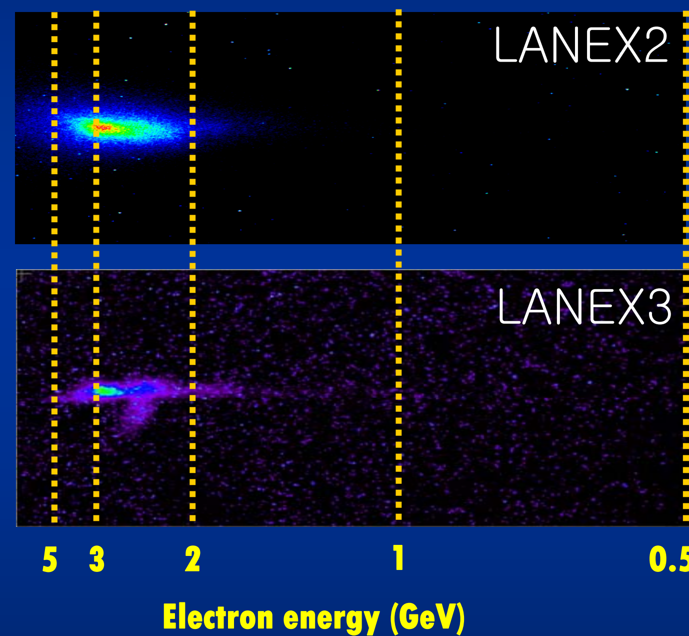
Slow rising positive chirped pulse with + GDD & -TOD → Stable propagation of laser pulse over long distance → Enhancement of electron energy and stability

Mono-energetic 3 GeV electron beam from 20-mm cell

PW beam line2, 30 J on target
Slowly rising positively chirped 50 fs pulse

~1x10^{18} electrons/cc





ΔE/E ≃ 20 %
(Resolution ≃ 15 %)

Contents

1. Introduction to PW lasers at CoReLS, IBS
2. LWFA driven by PW laser pulses
3. Coherent control of LWFA process
4. Toward 10 GeV electron beam using 4 PW laser
5. Summary

Strategy for 10 GeV electron beam

- Injection control
  - High density supersonic first jet + gas cell
  - Sharp density gradient injection
  - Enhancement & localization of injection by nano-particles

- Laser propagation control
  - Relativistic self-guiding.
  - Formation of guiding structure by pre-pulse of pump laser itself.
  - Laser guiding by external ns laser focused by axicon lens.

- Acceleration control
  - Coherent control of LWFA by manipulating spectral & spatial phase of laser pulse (Spectral spatial phase control)
  - Phase-lock acceleration or quasi phase matching scheme by modulating the density profile of medium.
  - Two-color laser scheme to enhance acceleration length.

LWFA over 10 GeV with 4 PW laser

With $L_{dp} < L_{pd}$ & $L_{acc} = L_{dp}$,

$$\Delta E[\text{GeV}] \approx 1.7 \left(\frac{P[TW]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_e[cm^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda[\mu m]}\right)^{4/3}$$

W. Lu, Phys. Rev. ST Accel. Beams ('07)

Requirements for generating electron beams over 10 GeV

4 PW laser: Energy per pulse ≈ 90 J
Pulse duration ≈ 22 fs

- Laser energy ≈ 90 J
- Pulse duration ≈ 70 fs
- Beam spot diameter ≈ 85 μm
- Normalized vector potential ≈ 2
- Medium density ≈ 2×10^{17} cm^{-3}
- Medium length (L_{dp}) ≈ 20 cm

⇨ 12-GeV electron beam

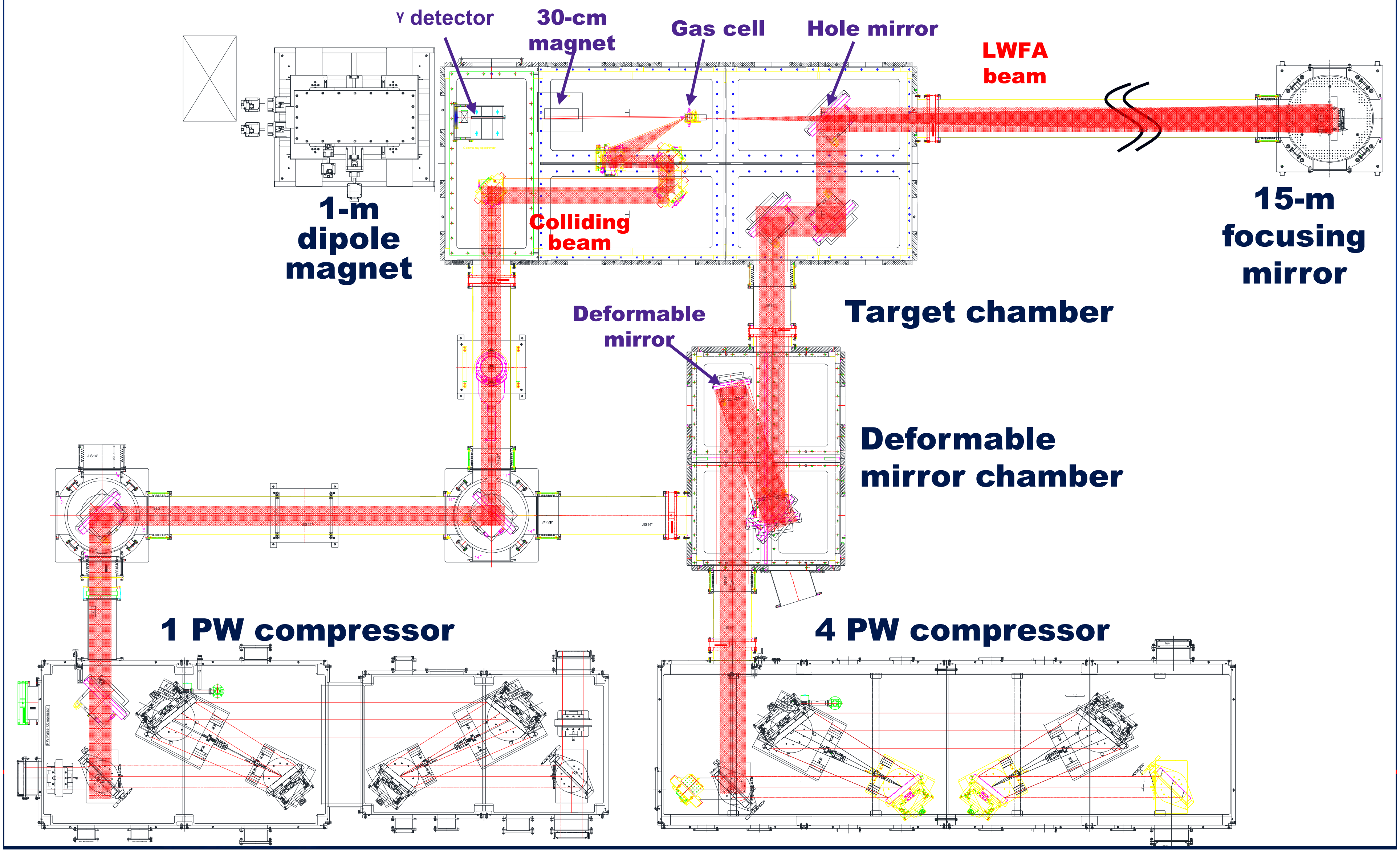
Technical Challenges

Self-injection in a low density medium
⇨ Dual gas medium, nano-particles

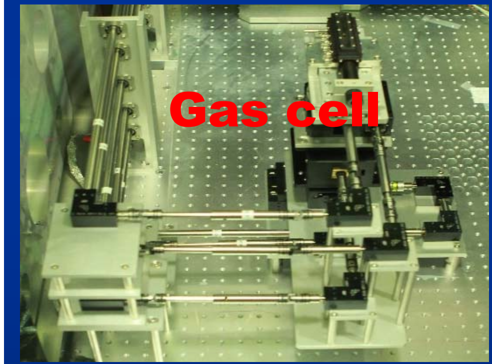
Acceleration beyond 10-cm length
⇨ Wave guide, Two-color scheme

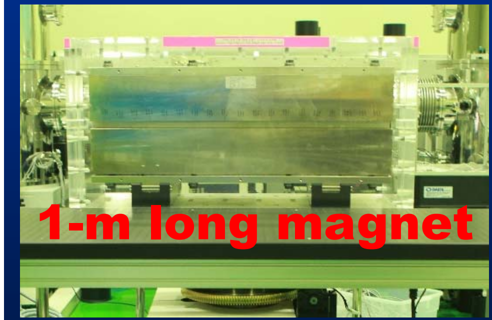
Preparation for LWFA experiment using 4 PW laser pulses

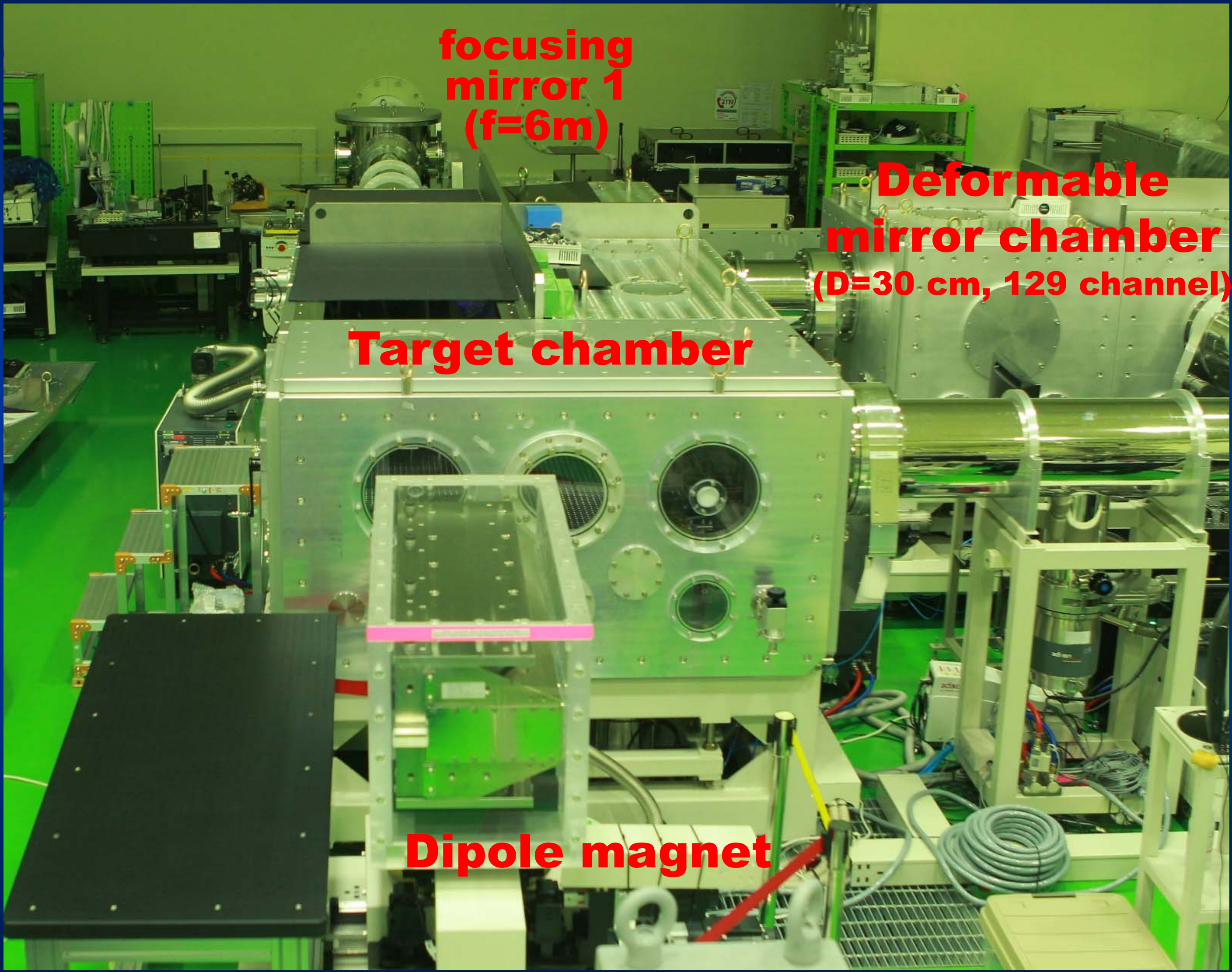
- **Optical layout for 4 PW LWFA**



Preparation for LWFA experiment using 4 PW laser pulses

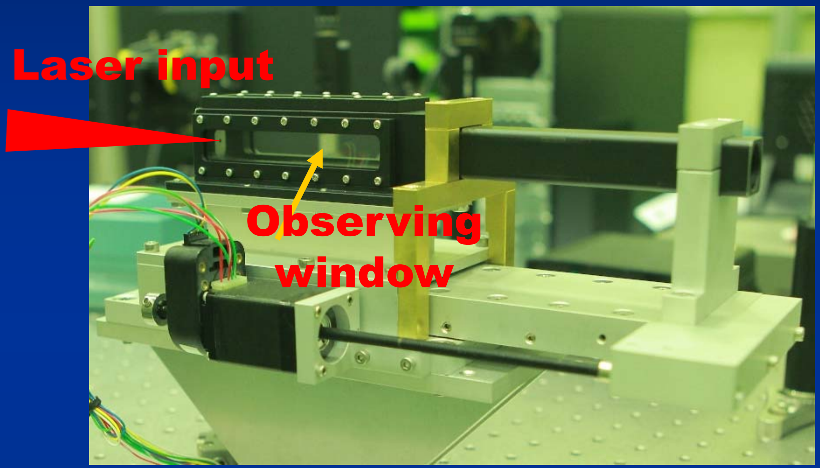






Preparation for LWFA experiment using 4 PW laser pulses

► **A long uniform gas cell**

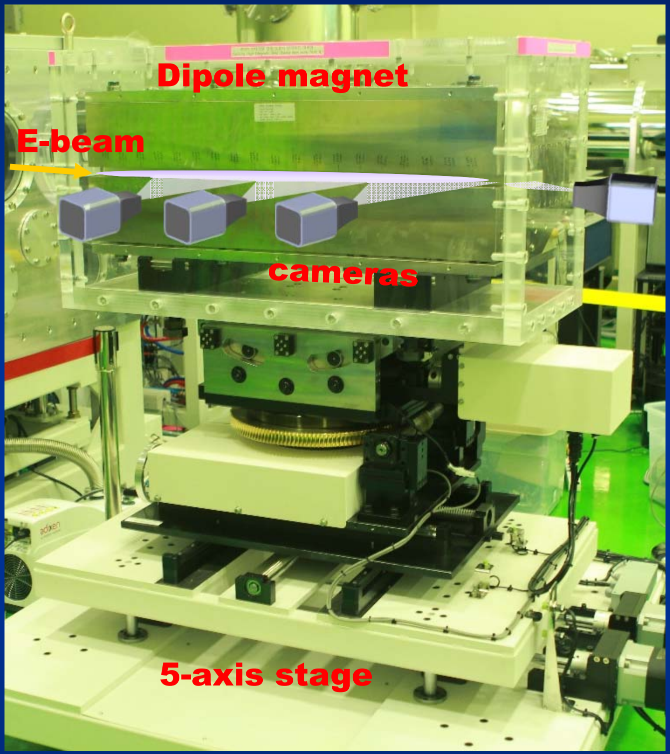


Prototype of 10-cm variable length gas cell

⇩

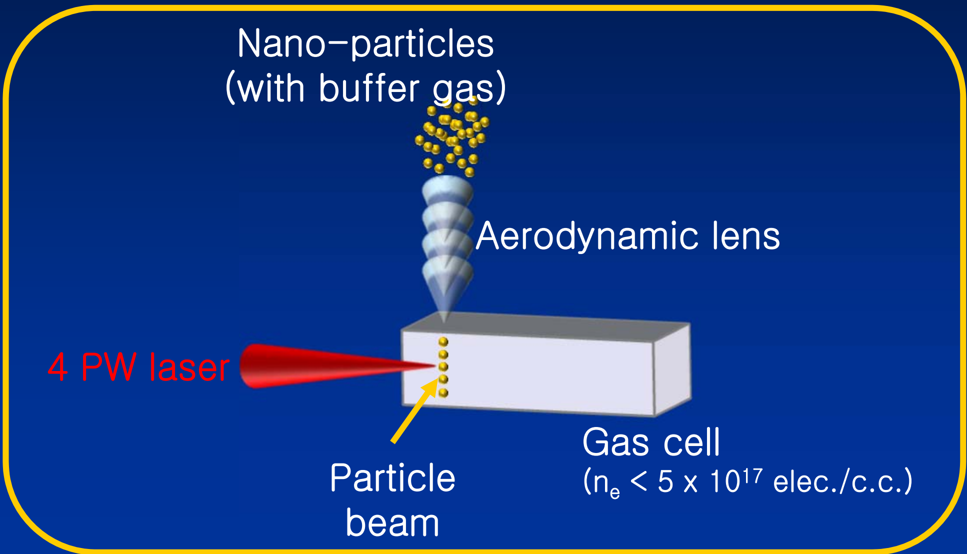
Combination of short gas jet & long gas cell is in development for dual-stage acceleration

► **1-m long dipole magnet**

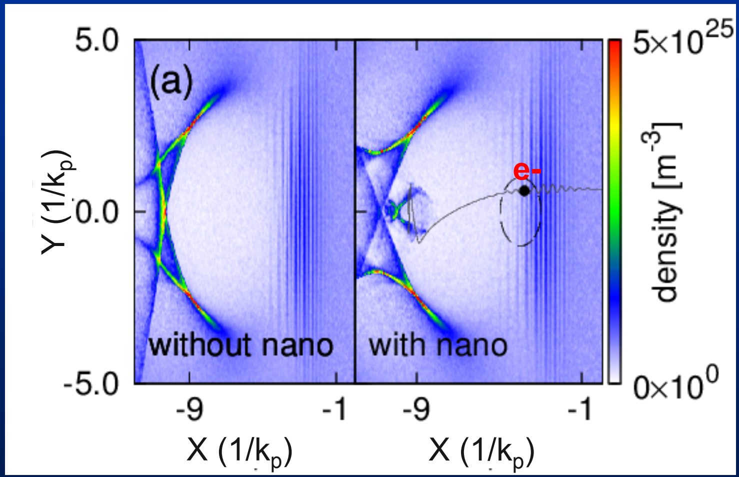


Variable gap dipole magnet (1.5~3 cm, 1.3 ~ 1.8 T)
Resolution < 10 % @ 10 GeV

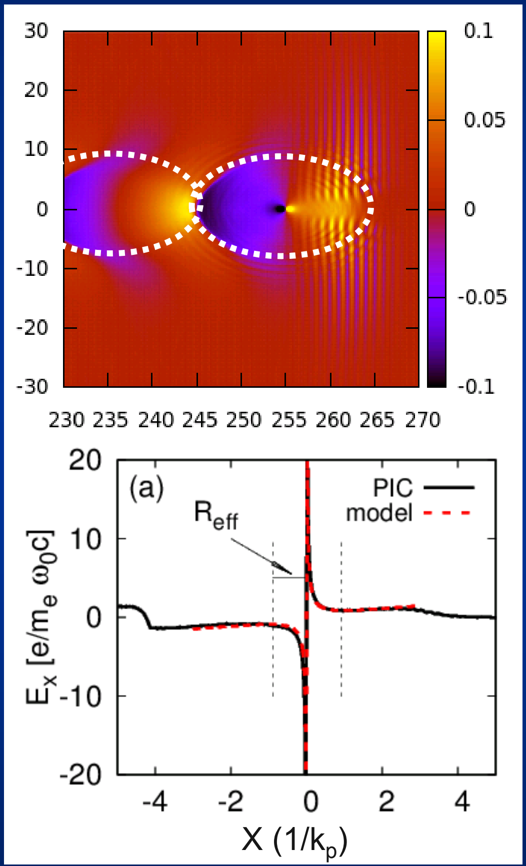
Controlled injection by nano-particles



Enhancement of injection by a nanoparticle



Nano-particles form additional field inside plasma bubble



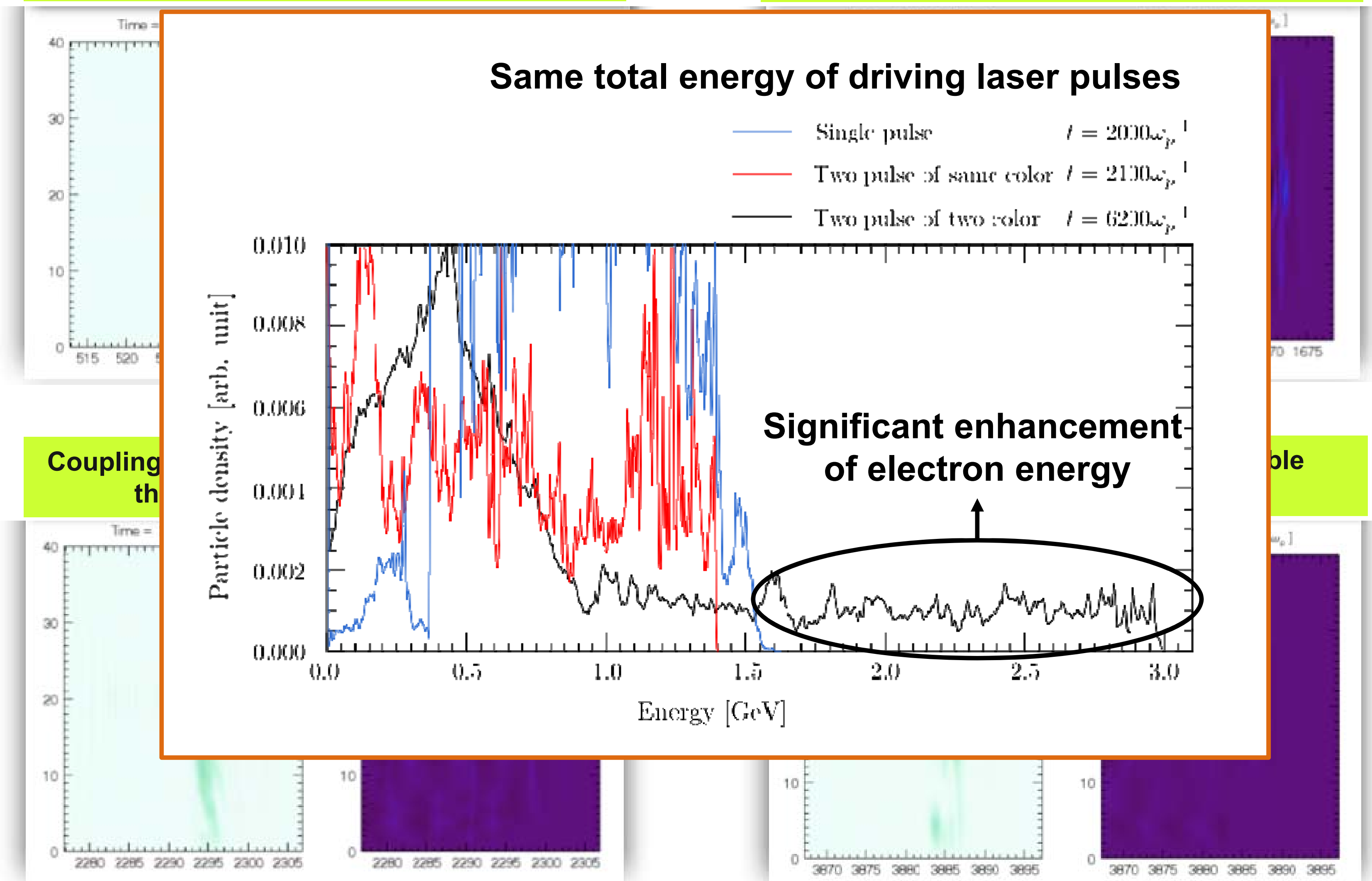
Theoretical study and experimental preparation is in progress

Purely optical two-stage LWFA by two-color field

Proof of Principle simulation with OSIRIS (2D)

Fundamental pulse drives the bubble and inject electrons

SH pulse is guided in the bubble driven by fundamental pulse



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Summary

1. Two PW laser beamlines, 1 PW and 1.5 PW at 30 fs, at CoReLS of IBS are operational for research on strong field science.
2. Laser particle acceleration has been explored. From the laser wakefield electron acceleration multi-GeV electrons were obtained.
3. Coherent control of LWFA process by manipulating the spectral phase components of PW laser pulses is very essential approach to obtain stable multi-GeV electron beam.
4. The 4 PW laser upgrade for increasing further the achievable laser intensity is being progressed.

IBS Center for Relativistic Laser Science

htkim@gist.ac.kr

- LLPG in center for relativistic laser science, IBS (Director. C. H Nam)

K. Nakajima, H. T. Kim, J. H. Shin, V. B. Pathak, M. H. Cho, C. Hojbota,
B. I. Cho, L. J. Bae, K. W. Shin, J. H. Jeon, S. H. Cho, B. J. Yu