Onassis Science Lecture Jul. 5, 2023

Strong Field QED Experiment Performed With a Multi-PW Laser

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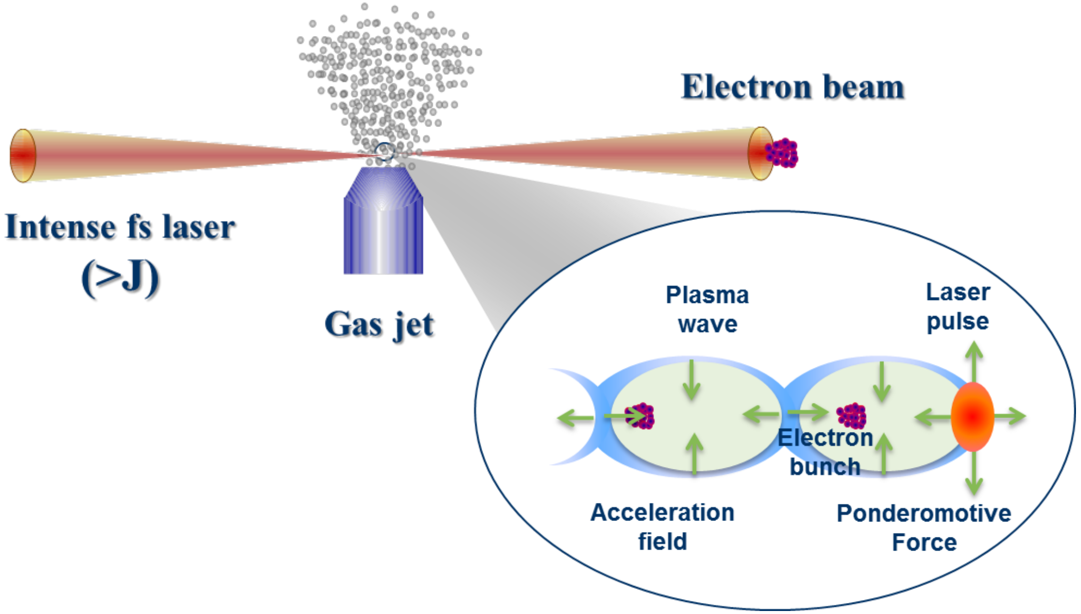
Overview: Strong field QED research

A. Laser-driven electron acceleration

B. Nonlinear Compton scattering

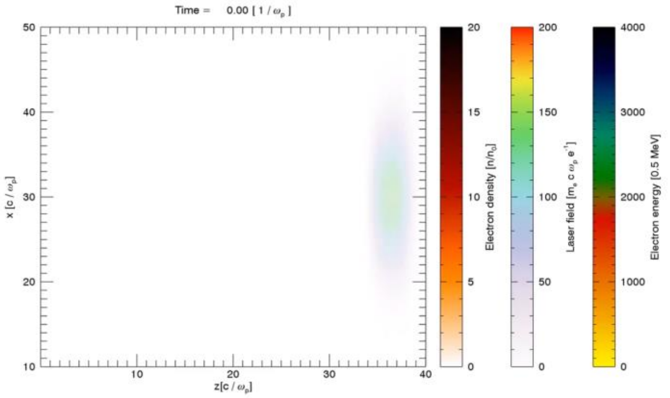
Laser Wakefield Electron Acceleration



Wake waves by ship

Surfing to the wave

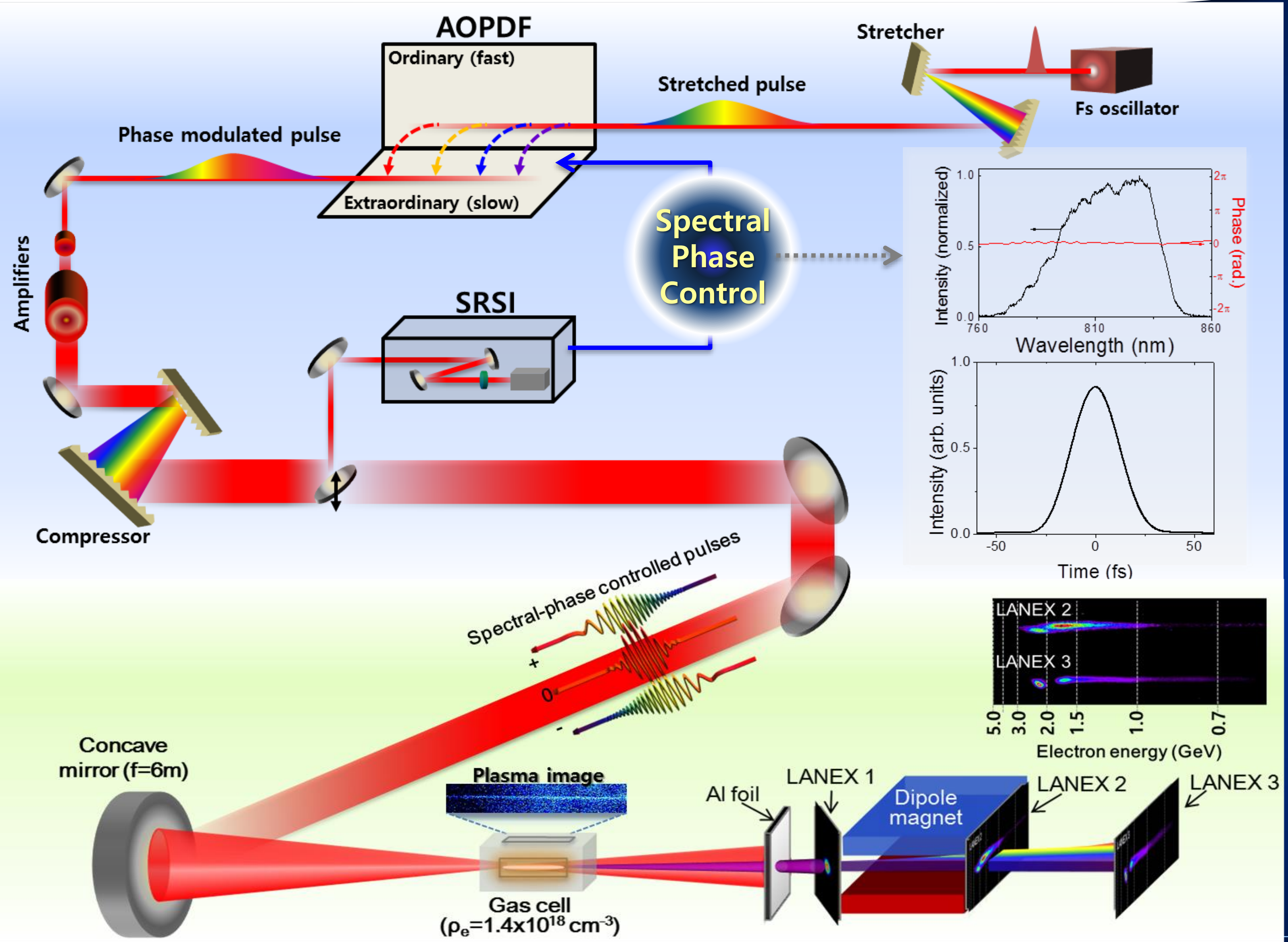
LWFA (2D PIC)



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

Huge acceleration field
> 100 GeV/m

LWFA with structured PW laser pulses



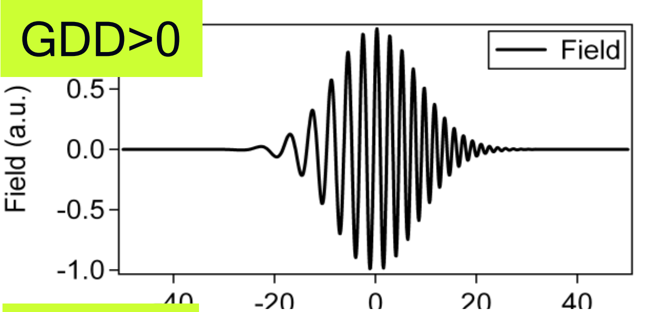
Coherent Control of Laser-Matter Interactions

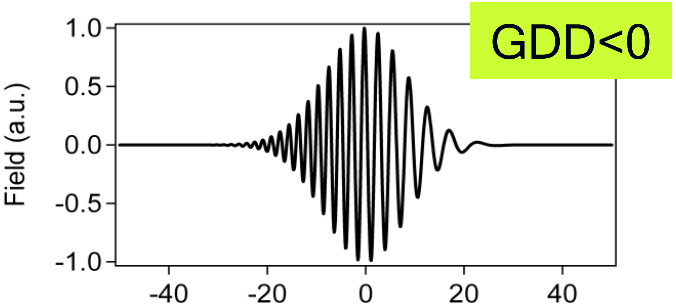
spectral phase:

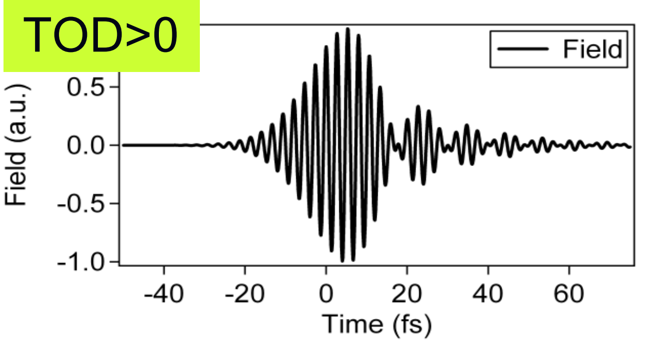
$$\boxed{\varphi(\omega) = \varphi_0 + \varphi_1 \frac{\omega-\omega_0}{1!} + \varphi_2 \frac{(\omega-\omega_0)^2}{2!} + \varphi_3 \frac{(\omega-\omega_0)^3}{3!} + \ldots}$$

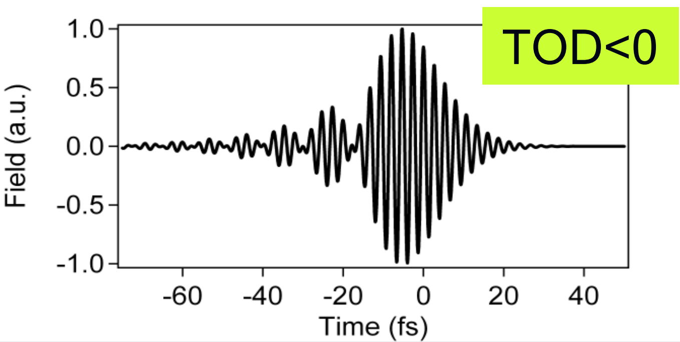
where $\varphi_2 = \left.\frac{d^2\varphi}{d\omega^2}\right|_{\omega=\omega_0}$ = group-delay dispersion (GDD) = linear chirp ,

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



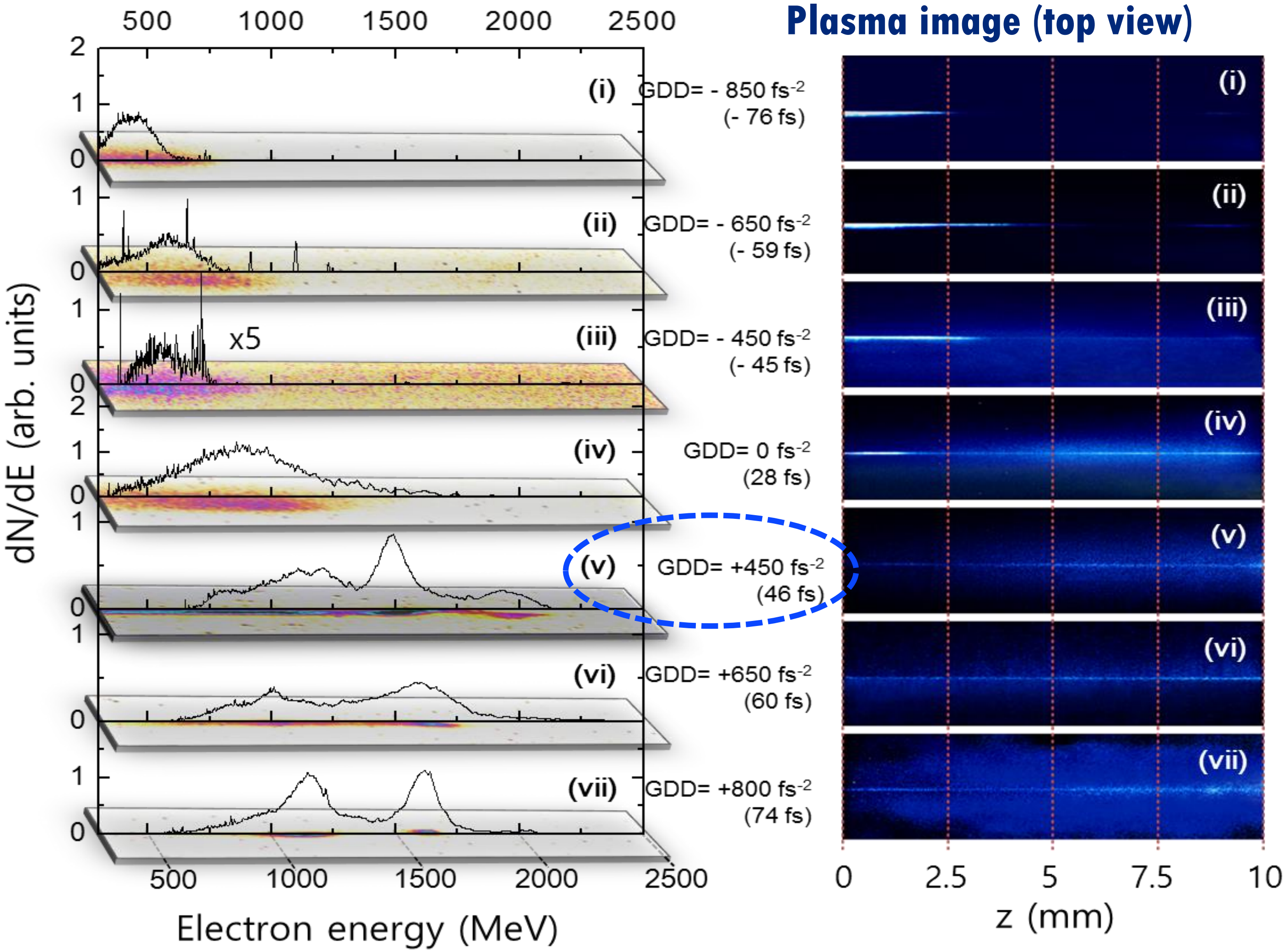






Control of spectral phase: GDD

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



Plasma image (top view)

Control of spectral phase: GDD+TOD

Temporal profile

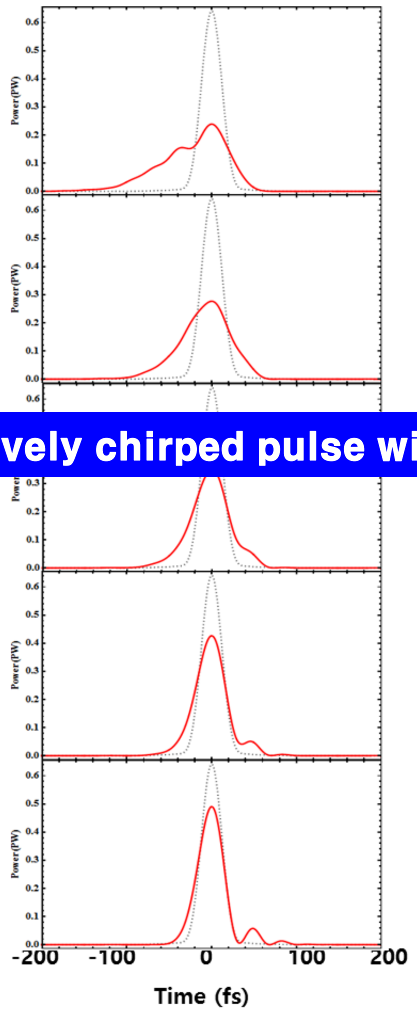
TOD = - 10000 fs^{-3}
τ = 75 fs

TOD = - 4000 fs^{-3}
τ = 61 fs

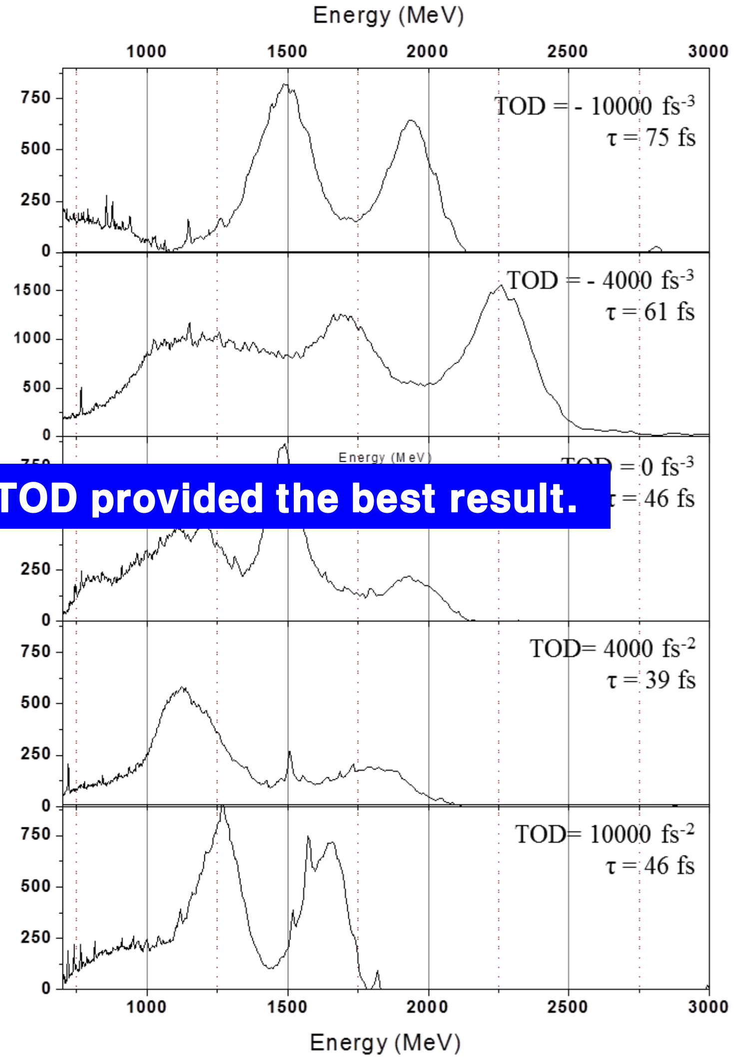
TOD =
τ = 46 fs

TOD= 4000 fs^{-2}
τ = 39 fs

TOD= 10000 fs^{-2}
τ = 46 fs



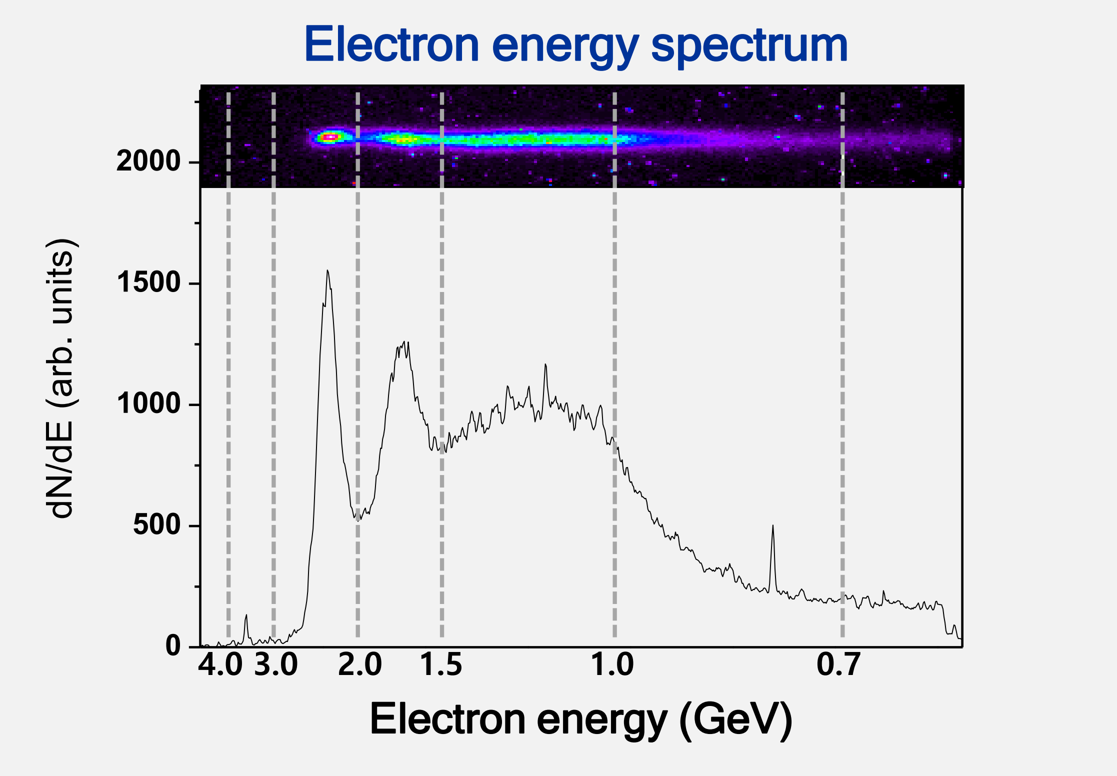
Electron spectrum



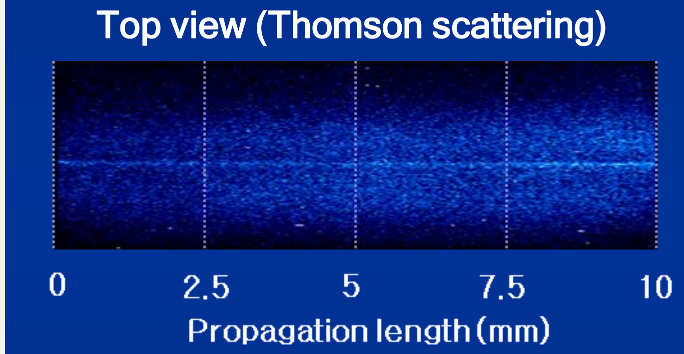
Positively chirped pulse with negative TOD provided the best result.

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 ($a_0=3$)



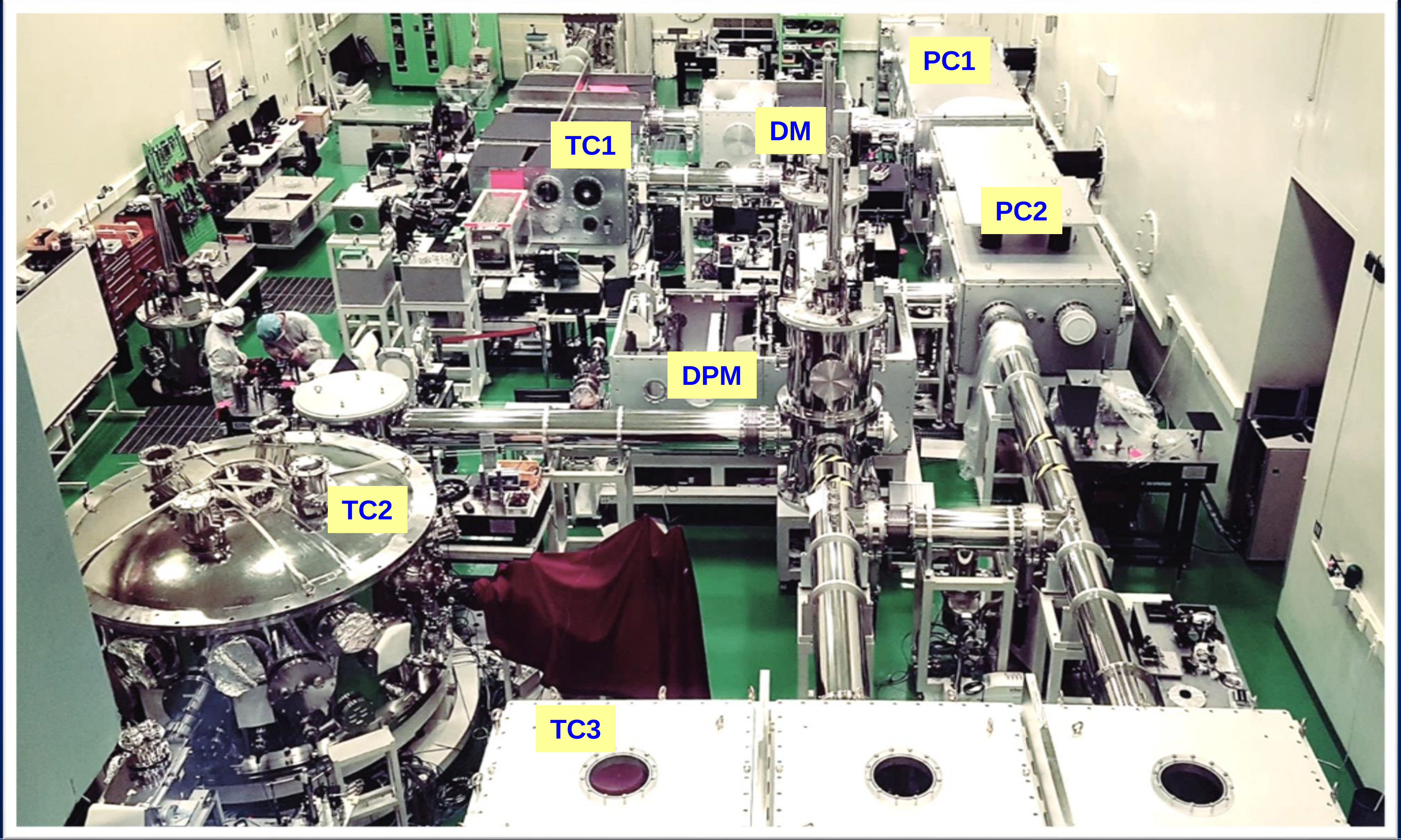
$E_e > 2$ GeV after GDD and TOD control



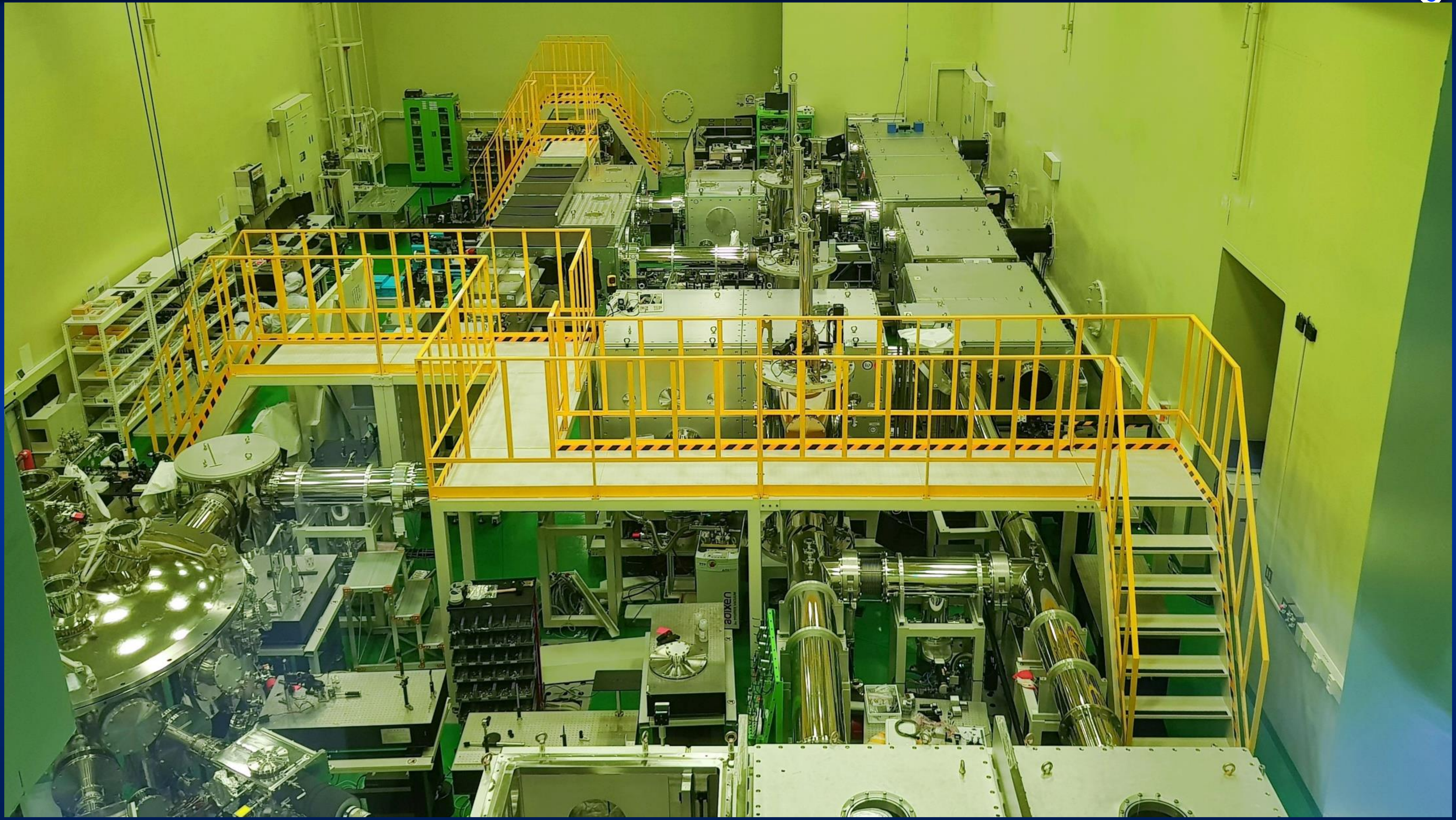
Smooth propagation over the whole medium length of 10 mm

HT Kim et al., Sci Rep (2017)

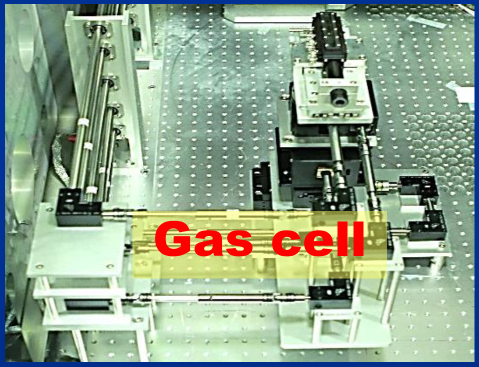
PW Laser Experimental Area

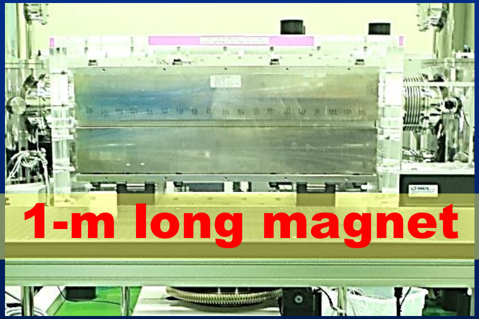


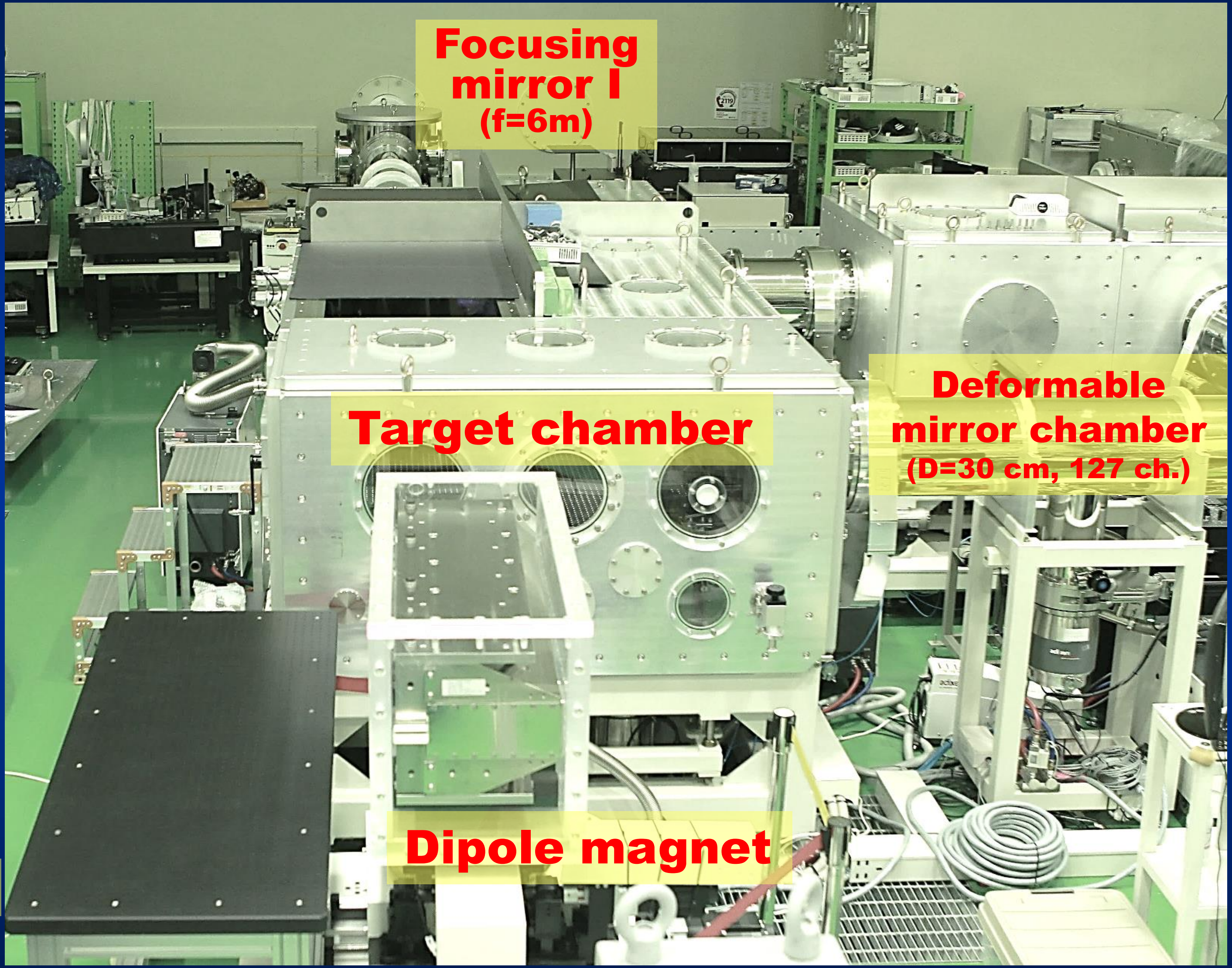
PW Laser Experimental Area (2018)



Target chamber for LWFA with 4 PW laser



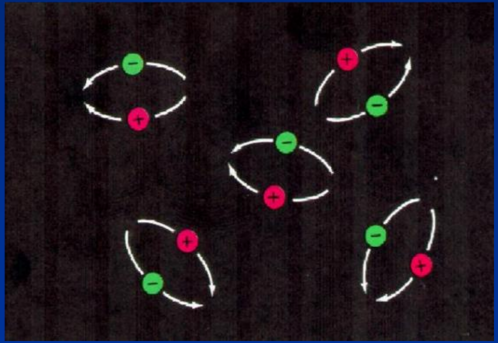




Pair production from vacuum

Vacuum fluctuations (quantum vacuum)

Creation and annihilation of electron-positron pairs occurs continually in quantum vacuum.



$$\delta E = mc^2$$

$$\rightarrow \delta t = \hbar/mc^2$$

$$\rightarrow \delta x = c\delta t = \hbar/mc = \bar{\lambda}_C$$

Schwinger field (E_S) for nonlinear optics in vacuum

Field-driven pair production over $\bar{\lambda}_C$ in vacuum

$eE_S\bar{\lambda}_C = m_e c^2$ where $\bar{\lambda}_C = \dfrac{\hbar}{m_e c} = 3.9 \times 10^{-11}$ cm

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

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

Strong Field Quantum Electrodynamics (QED)

quantum electrodynamics (QED): relativistic quantum field theory of electrodynamics
(quantum mechanics + special relativity)

QED: anomalous magnetic moment of electron
Lamb shift of the energy levels of hydrogen ($^2S_{1/2}$ and $^2P_{1/2}$)

χ_e: quantum nonlinearity parameter for strong-field QED

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

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

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

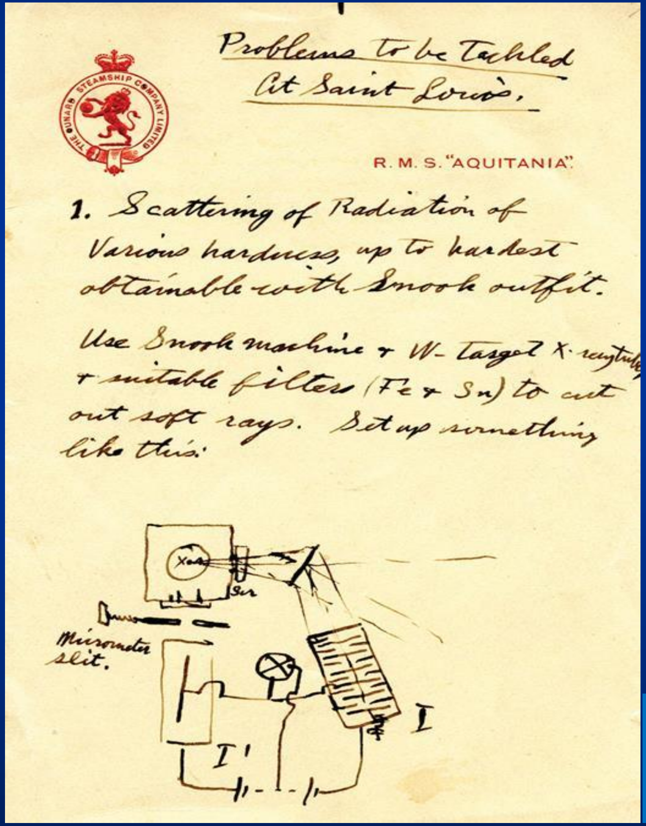
Pair production when $\chi_e \gtrsim 1$,

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

For a 2.5-GeV electron, $I \sim 10^{-8} I_S = 2\times 10^{21}\ \mathrm{W/cm^2}$ for $\chi_e = 1$

Compton scattering

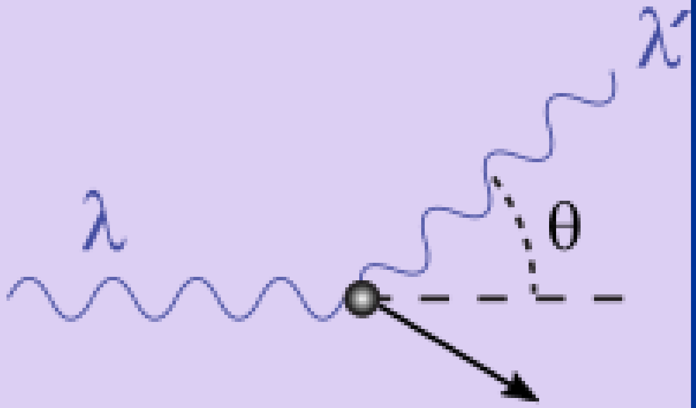
Compton scattering:
the scattering of an x-ray or gamma-ray photon with an electron,
resulting in a decrease in energy (increase in wavelength) of the photon


Problems to be Tackled
At Saint Louis.

R. M. S. "AQUITANIA".

1. Scattering of Radiation of Various hardness, up to hardest obtainable with Snook outfit.

Use Snook machine + W-target X-ray tub + suitable filters (Fe + Sn) to cut out soft rays. Set up something like this:



A. H. Compton, Phys. Rev. **21**, 483 (1923).
(x-ray source: Mo K_a at 17 keV)

$$\lambda' - \lambda = \frac{h}{mc}(1 - \cos\theta),$$

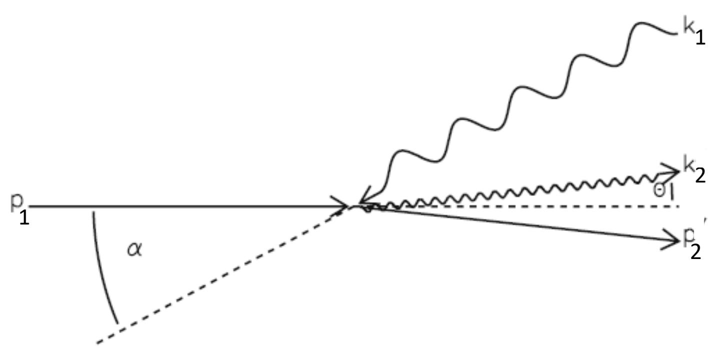
$$\text{or } E_{\gamma'} = \frac{E\gamma}{1 + \frac{E\gamma}{mc^2}(1 - \cos\theta)},$$

$$\text{with } E_\gamma = \frac{hc}{\lambda}$$

Problems to be tacked at Washington Univ in St. Louis
(memorandum written in his return journey to US from Cambridge in 1920)

Compton scattering bet. an ultra-relativistic electron & a photon

Inverse Compton scattering (Compton back-scattering):
a high-energy charged particle transfers part of its energy to a photon, resulting in an increase in energy (decrease in wavelength) of the photon.



$$\text{Energy} - \text{momentum conservation,} \qquad p_1^\mu + k_1^\mu = p_2^\mu + k_2^\mu \qquad (1)$$

$$p^\mu = (E/c\,, \vec{p}) = (\gamma mc, \gamma m\vec{v}\,);\ k^\mu = (\hbar\omega/c,\, \hbar\vec{k})$$

$$(p_1^\mu + k_1^\mu)(p_{1\mu} + k_{1\mu}) = (p_2^\mu + k_2^\mu)(p_{2\mu} + k_{2\mu}) \rightarrow \ p_1^\mu\, k_{1\mu} = p_2^\mu k_{2\mu}$$

$$p^\mu p_\mu = \gamma^2 m^2 c^2 - \gamma^2 m^2 v^2 = m^2 c^2; \quad k^\mu k_\mu = 0$$

$$k_{2\mu} \times (1), \qquad k_{2\mu}(p_1^\mu + k_1^\mu) = k_{2\mu}(p_2^\mu + k_2^\mu) = k_{2\mu} p_2^\mu = p_1^\mu k_{1\mu}$$

$$A_\mu B^\mu = A_0 B_0 - \vec{A}\cdot\vec{B}, \qquad E_i = \hbar\omega_0 = \hbar c k_1;\ E_f = \hbar\omega_2 = \hbar c k_2$$

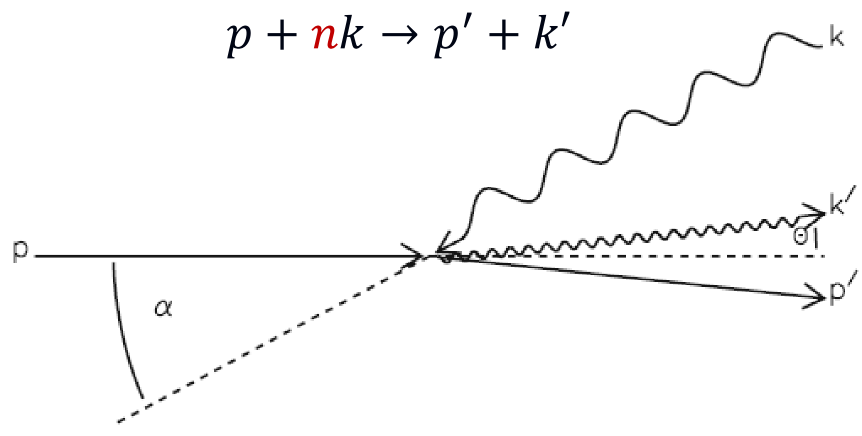
$$\gamma m E_f(1 - \beta\cos\theta) + \frac{1}{c^2} E_i E_f\{1 + \cos(\alpha - \theta)\} = \gamma m E_i(1 + \beta\cos\alpha)$$

Energy of scattered photon

$$\rightarrow\ E_f = \frac{\gamma mc^2(1 + \beta\cos\alpha)}{\gamma mc^2(1 - \beta\cos\theta) + E_i\{1 + \cos(\alpha - \theta)\}} E_i = \frac{1 + \beta\cos\alpha}{1 - \beta\cos\theta + \dfrac{E_i}{\gamma mc^2}\{1 + \cos(\alpha - \theta)\}} E_i$$

For for $\beta \approx 1, \theta \approx 0,\quad E_f = \dfrac{1 + \cos\alpha}{1 - \beta + \dfrac{E_i}{\gamma mc^2}(1 + \cos\alpha)} E_i \qquad \rightarrow E_f = 2\gamma^2(1 + \cos\alpha) E_i$

Nonlinear Compton scattering in a strong EM field


$p + nk \rightarrow p' + k'$

Energy-momentum conservation under a background EM field

$$p^{\mu} + \frac{a_0^2 m^2 c^2}{4 k_{\nu} p^{\nu}} k^{\mu} + n k^{\mu} = p'^{\mu} + \frac{a_0^2 m^2 c^2}{4 k_{\nu} p'^{\nu}} k^{\mu} + k'^{\mu}$$

EM-field-dressed momentum

classical nonlinearity parameter: $a_0 = \frac{eE_0}{m\omega c} = \frac{eA_0}{mc^2}$

Energy of the scattered photon

$$\varepsilon_{\gamma'} = \hbar\omega' = \hbar c k' = \frac{n\gamma^2(1+\beta\cos\alpha)}{\gamma^2(1-\beta\cos\theta) + \left[\frac{n\gamma\varepsilon_L}{mc^2} + \frac{a_0^2/4}{1+\beta\cos\alpha}\right][1+\cos(\theta-\alpha)]}\varepsilon_L$$

$(\varepsilon_L = \hbar\omega_0)$

For $\beta \approx 1, \theta \approx 0$,

$$\varepsilon_{\gamma'} = \frac{2n\gamma^2(1+\cos\alpha)}{1 + \frac{a_0{}^2}{2} + \frac{2n\gamma\varepsilon_L}{m_e c^2}(1+\cos\alpha)}\varepsilon_L$$

Bamber et al., PRD **60**, 092004 (1999); Melissinos, Strong Field Laser Physics, 497 (2008)

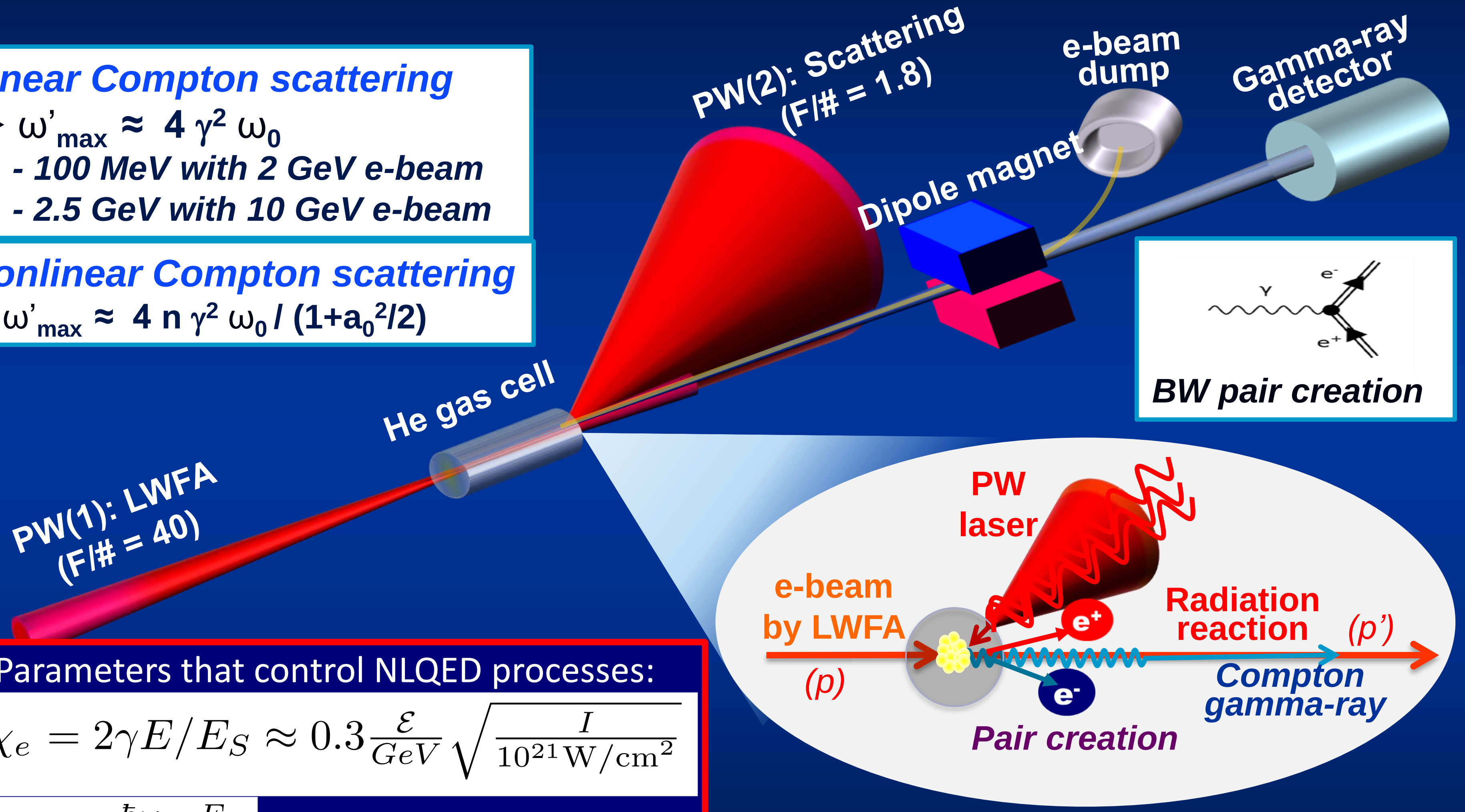
Strong field QED: All-optical Compton scattering

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

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



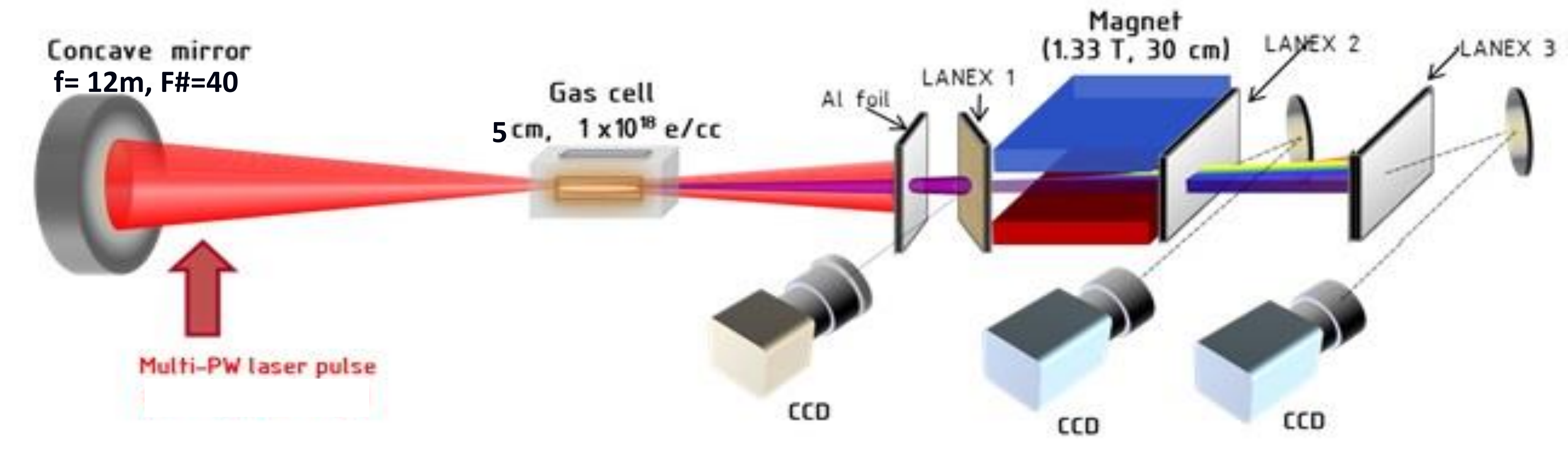
Parameters that control NLQED processes:

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

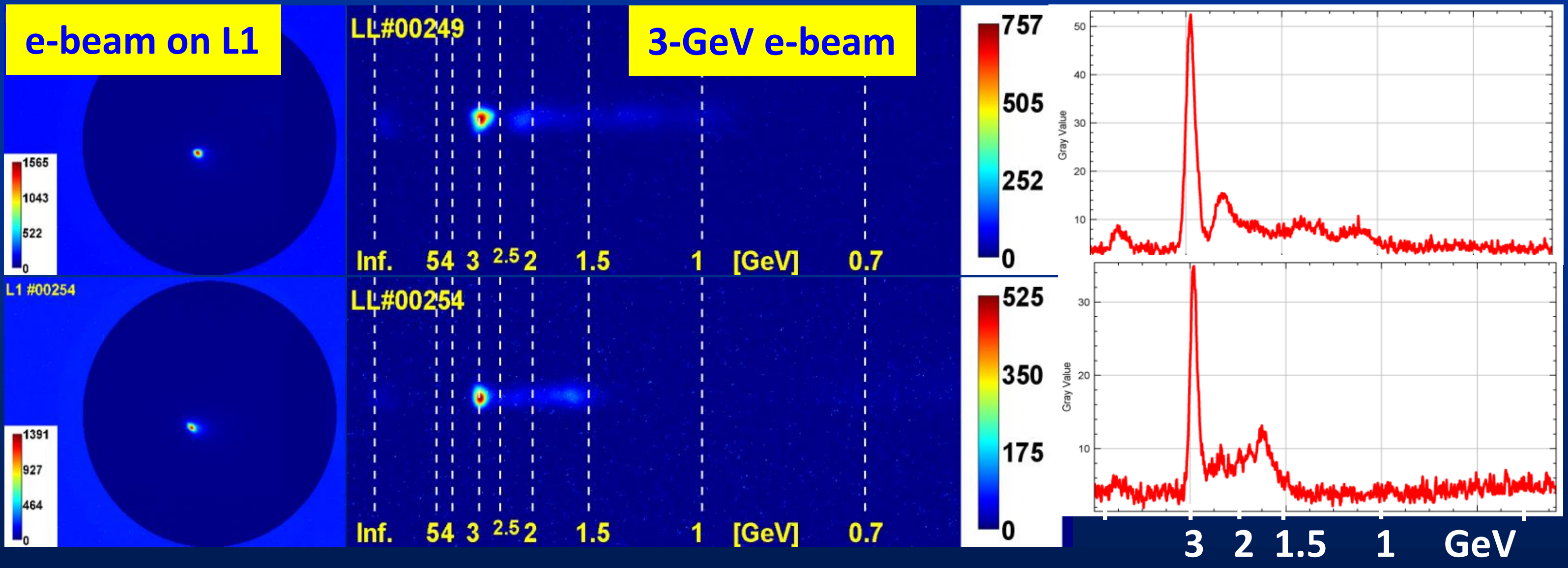
$$\chi_\gamma \approx \frac{\hbar\omega}{m_e c^2}\frac{E}{E_s}$$

Generation of Multi-GeV Electron Beams

Laser: 25 fs, I ≈ 2 x 10^{19} W/cm^2 (a_0 ≈ 3); target: He + 3% Ne

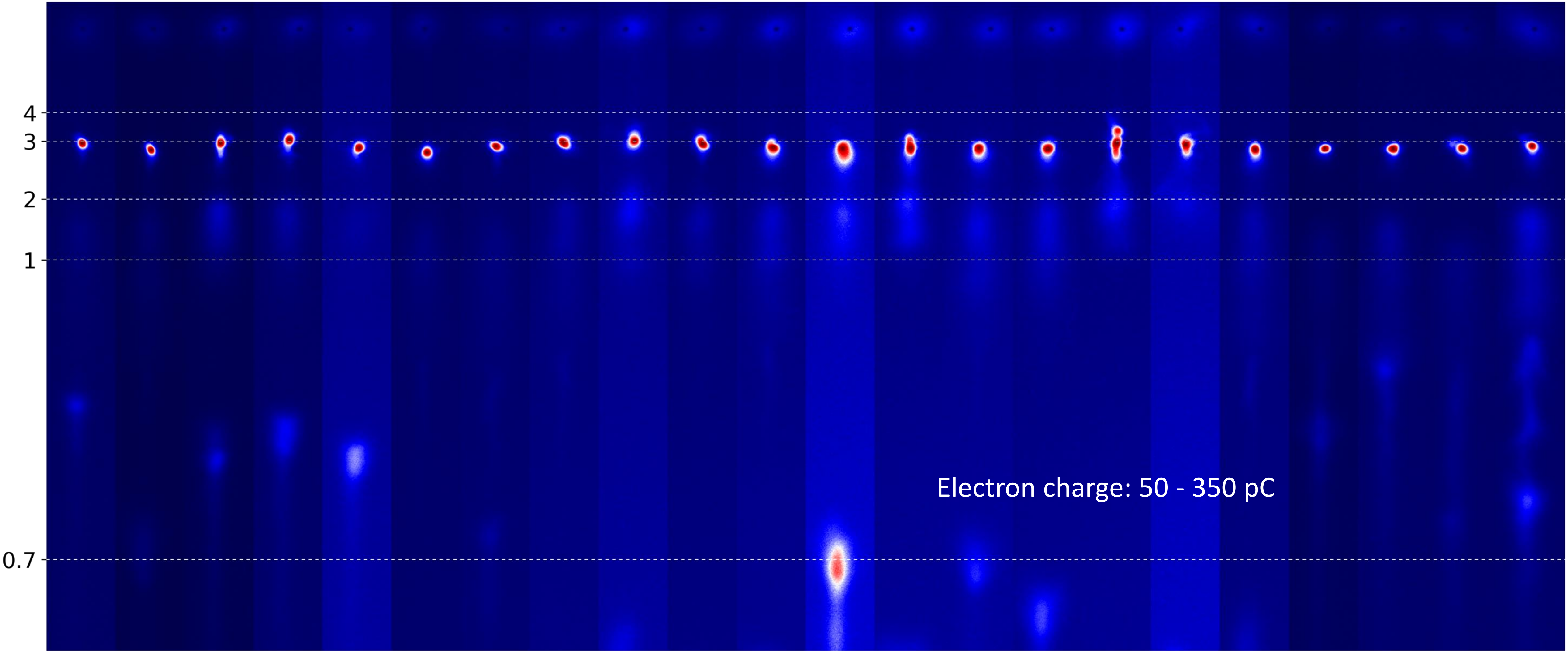


- linear pol. @800 nm, 25 fs
- Gas cell with He +3%Ne
- Focusing with f=12m (f/# = 43)

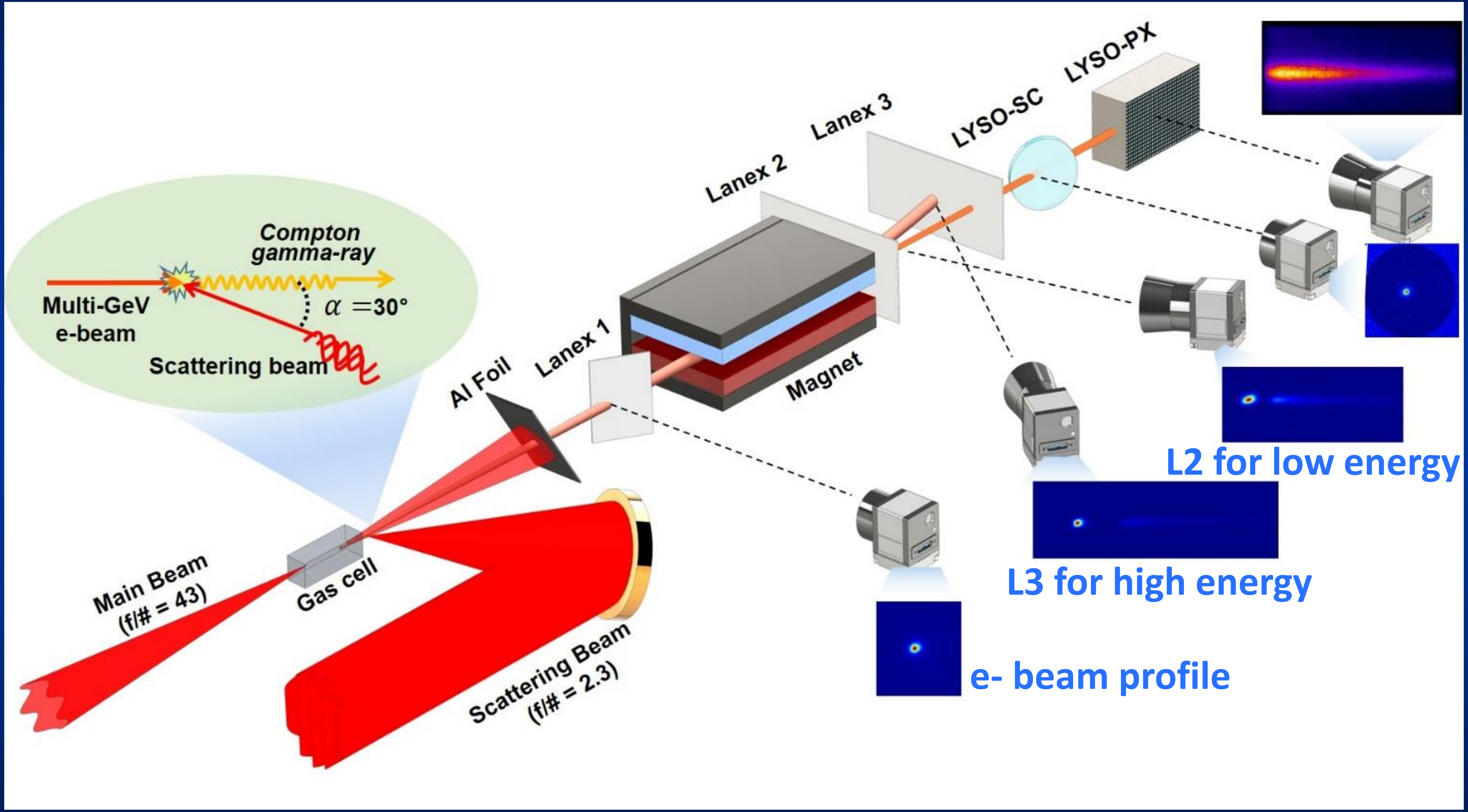


Low divergence ~ 1mrad
Low Energy Spread <2%
100-200 shots per day
Charge: up to 350 pC
Energy: up to 3.5 GeV

Reproducible monochromatic electron beam



All Optical Nonlinear Compton Scattering Experiment



L2 for low energy

L3 for high energy

e- beam profile

Pixelated LYSO for γ-ray energy spectrum

Single crystal LYSO for γ-ray beam profile

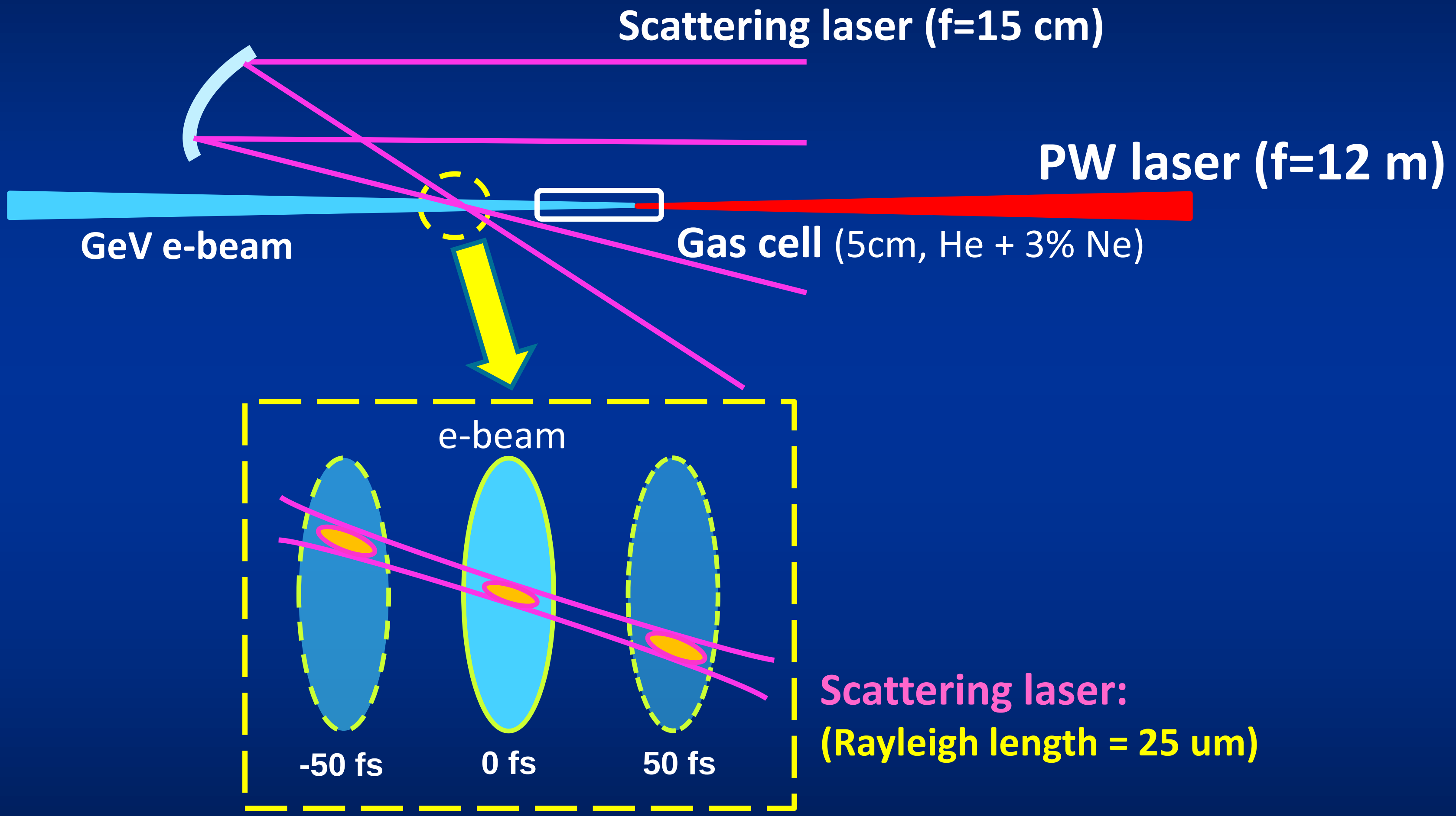
Main Beam

- 25 fs
- I= 3x10^{19} W/cm^2
- Spot size: 45 µm

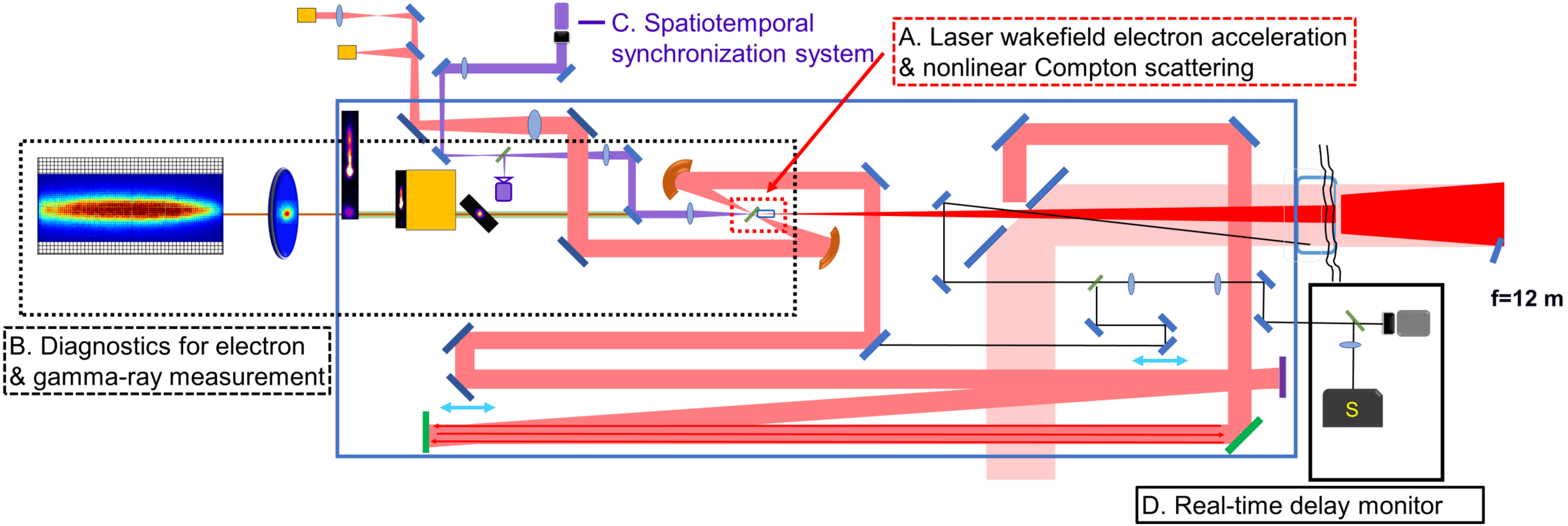
Scattering Beam

- 25 fs
- I= 4x10^{20} W/cm^2
- Spot size: 2.5 µm
- a$_0$ = 14

Geometry for nonlinear Compton scattering



Experimental Setup for Nonlinear Compton Scattering



C. Spatiotemporal synchronization system

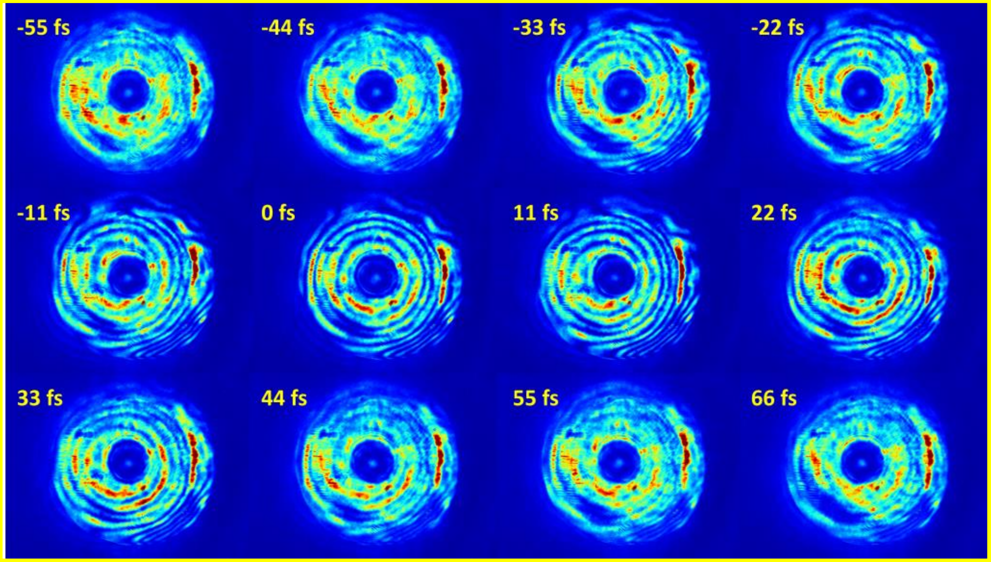
A. Laser wakefield electron acceleration & nonlinear Compton scattering

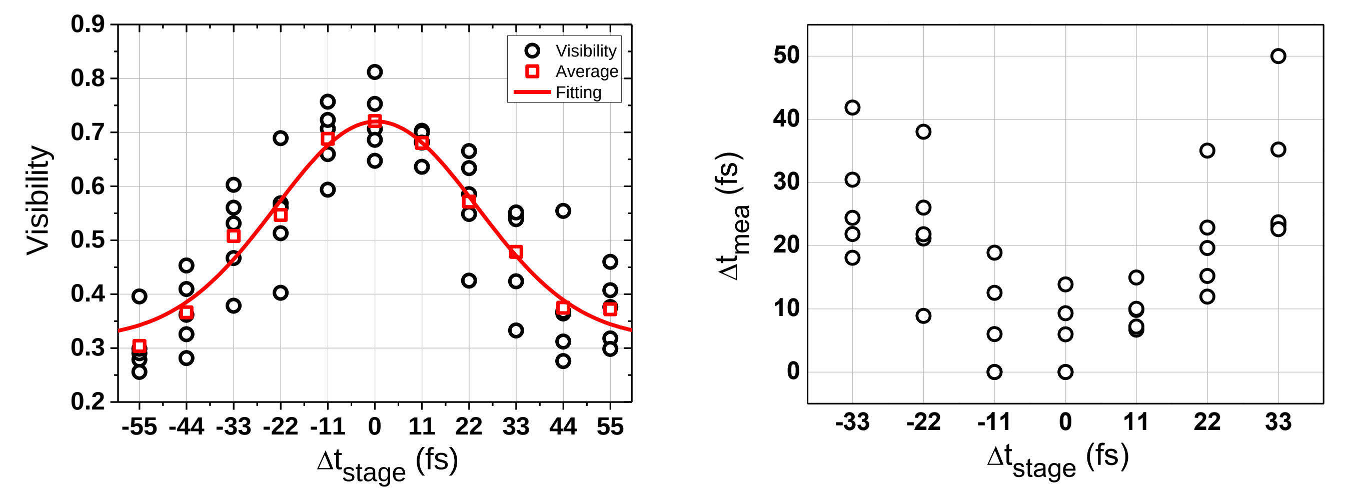
B. Diagnostics for electron & gamma-ray measurement

D. Real-time delay monitor

Temporal synchronization for Compton scattering

Spatial interferogram in the setup 1





- The visibility of interference varied with the time delay.
- The zero time delay was set where the visibility is the highest.

❖ visibility, $\eta' = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}$

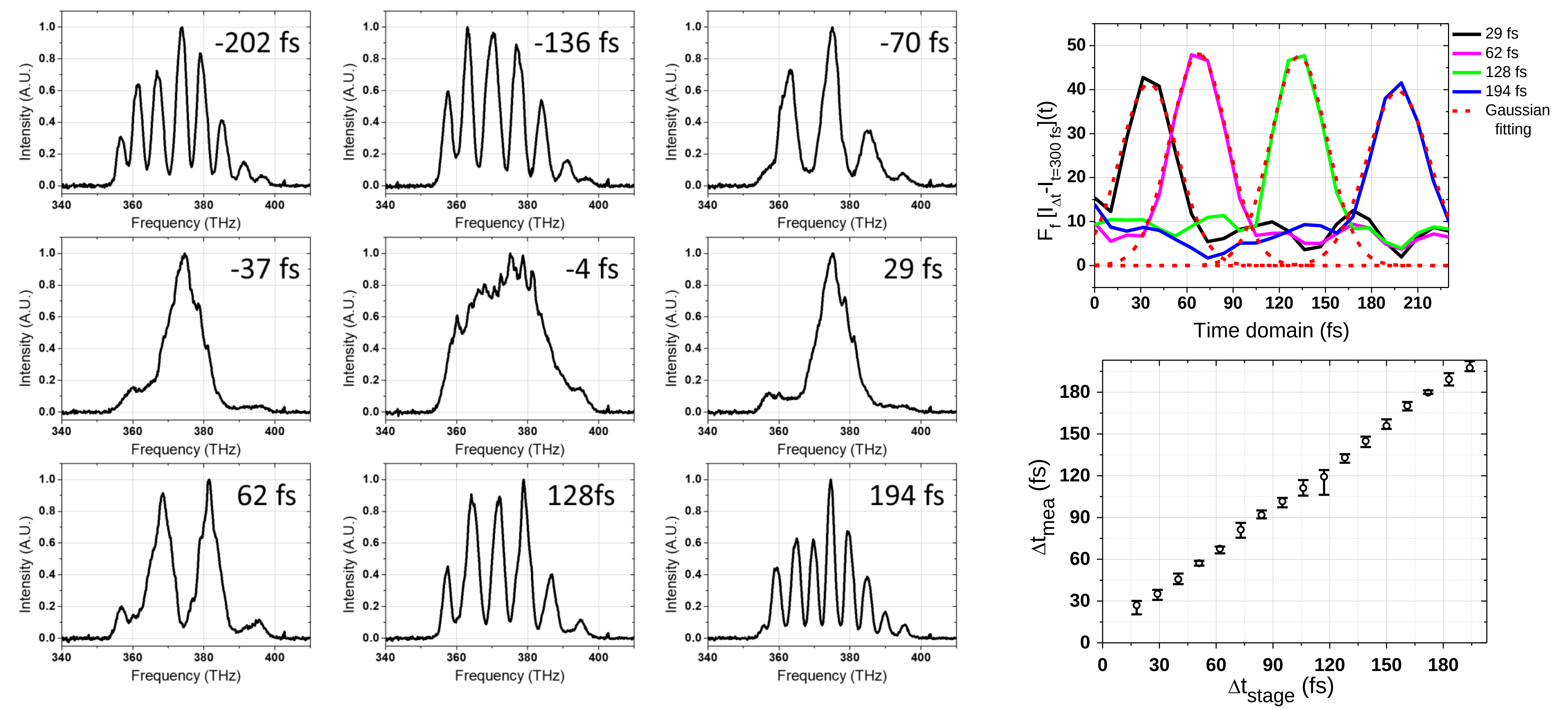
$$\eta' = 0.40 \times \exp\left(-\frac{\Delta t^2}{2\times 23.5^2}\right) + 0.32$$

$$\Rightarrow \quad |\Delta t_{mea}| = \sqrt{2 \times 23.5^2 \times \ln\frac{0.40}{(\eta' - 0.32)}} \ (fs)$$

accuracy of time delay ($\frac{\sum_{i=1}^{n}(\Delta t_{mea}-\Delta t_{stage})_i^{2}}{n}$): 11 fs

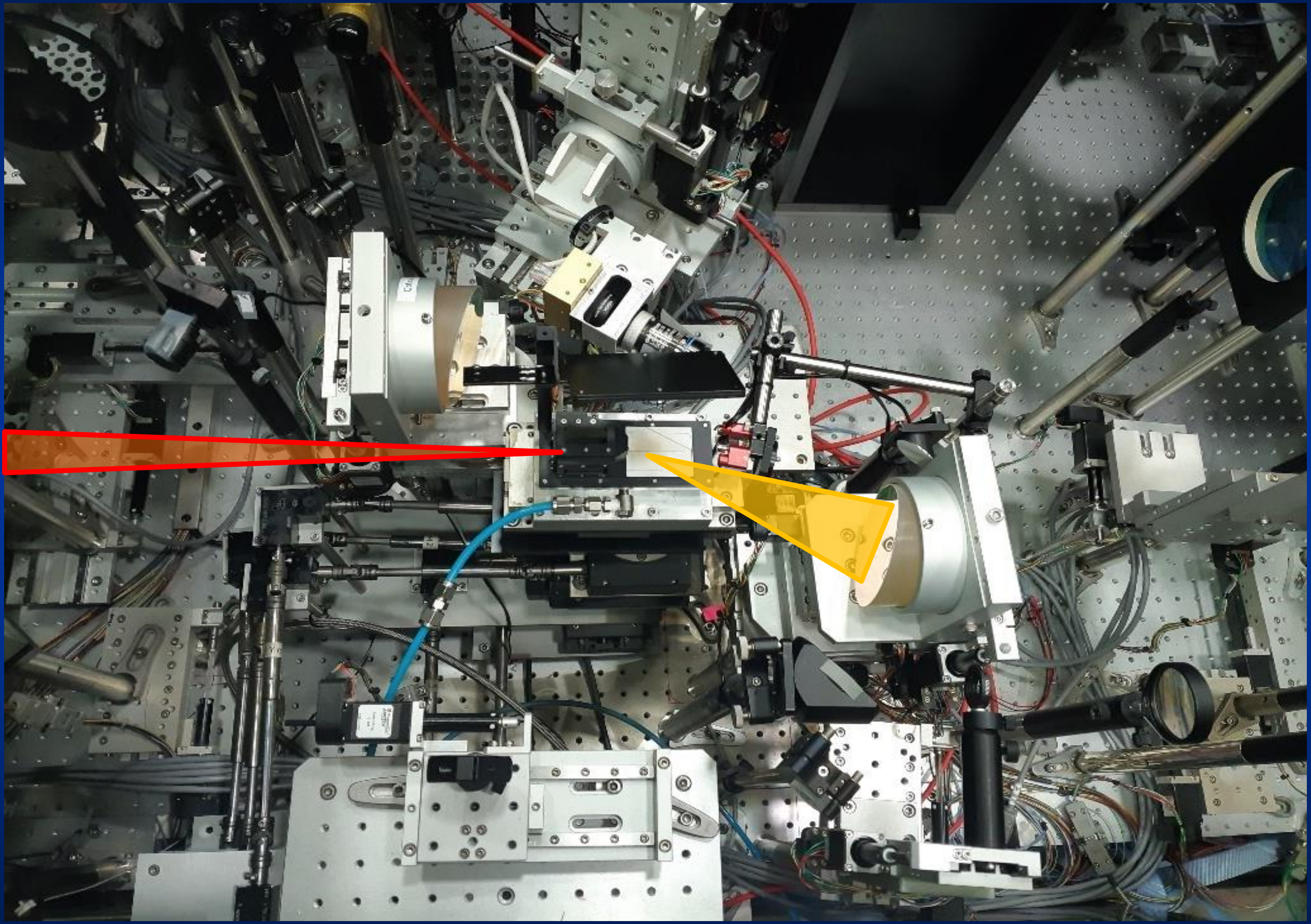
Temporal synchronization for Compton scattering (2)

Real-time delay monitoring with a spectral interferometer in the setup 2

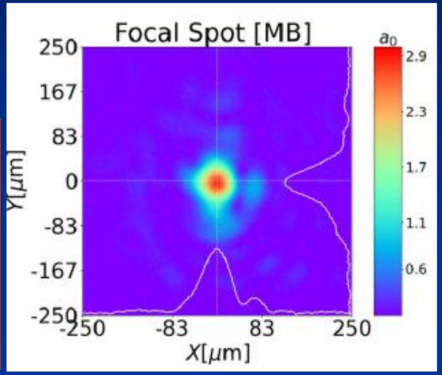


For the time delay > 20 fs the temporal jitter measured was 7 fs

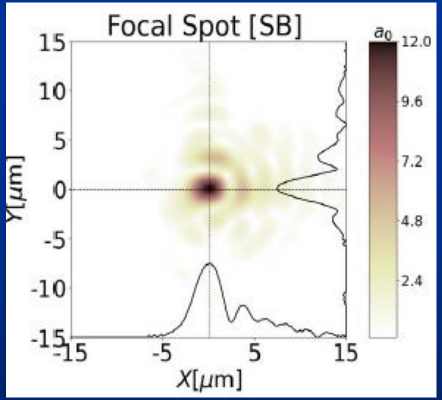
Experimental Chamber of Compton Scattering



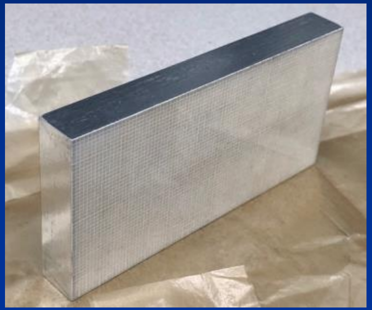
Main beam
τ= 25 fs
I= 3×10^{19} W/cm^2
W_0 = 45 μm

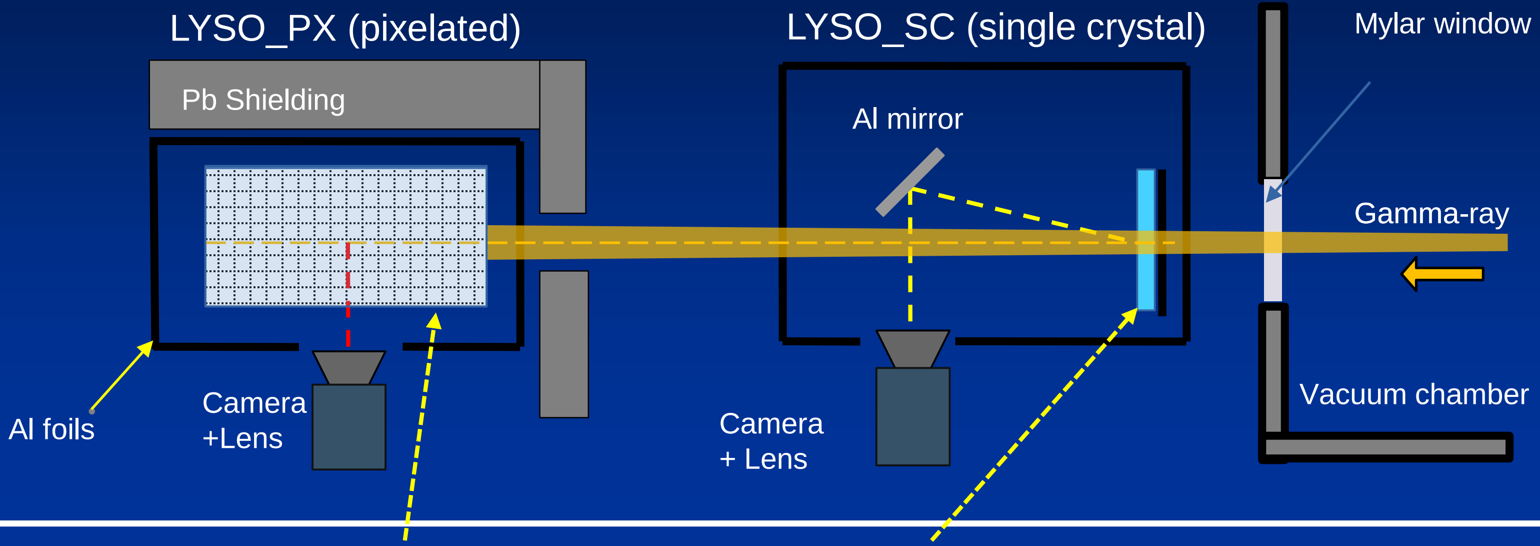


Scattering beam
τ= 25 fs
I= 4×10^{20} W/cm^2
W_0 = 2.5 μm

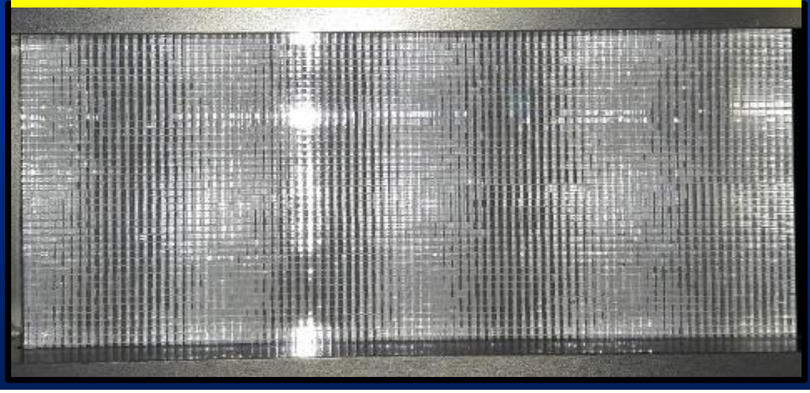


Diagnostics of Gamma-ray beam





Pixelated LYSO(Ce): 45x90 pixels
Pixel size: 1mm x 1mm x12.5mm

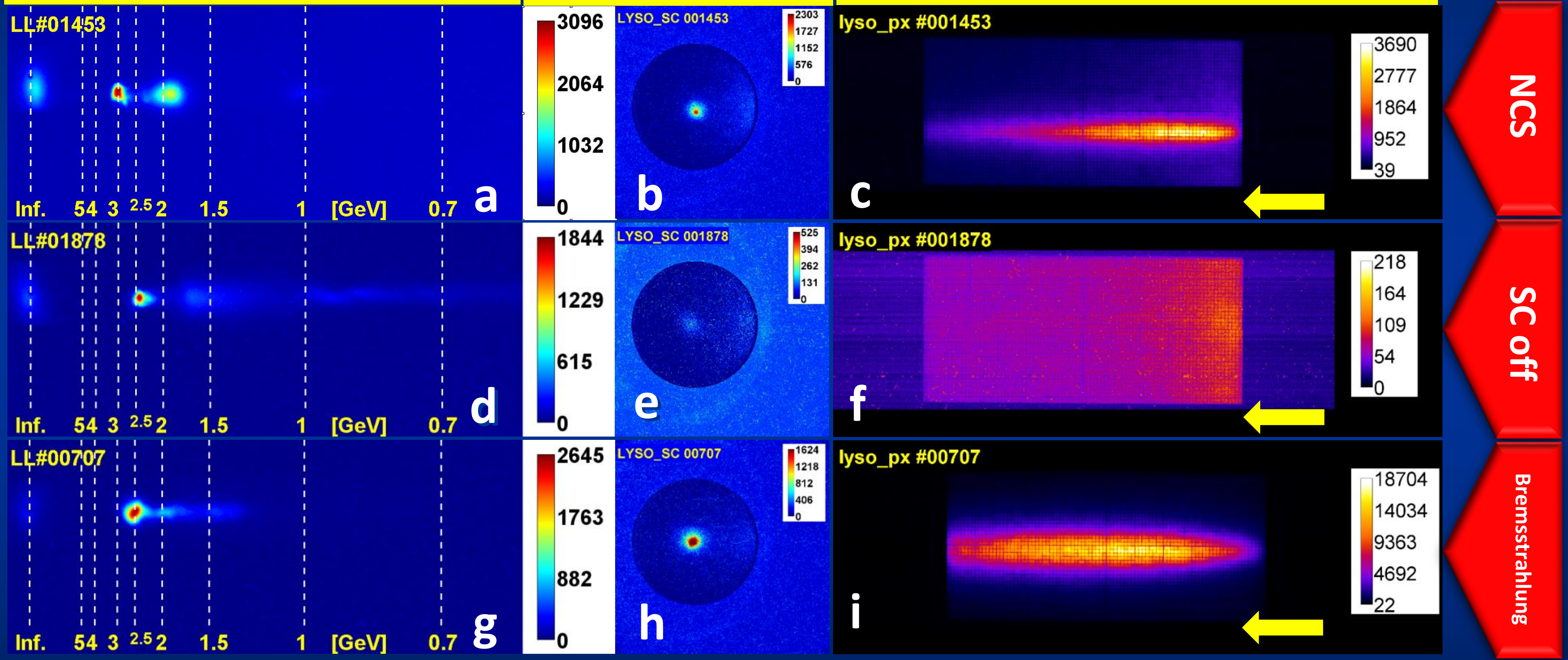


LYSO(Ce)_SC:90mm x 5mm

Material: LYSO	**$Lu_{1-x}Y_xSi_2O_5$ (x=0.1)**
Density [g/cm3]	**7.15**
Emission wavelength [nm]	**320-420**
Light yield [photons/MeV]	**2.9×10^4**
Decay time [ns]	**40**
Z_{eff}	**66**
Radiation length X_0 [cm]	**1.1**
Moliere radius [cm]	**2.1**

Demonstration of nonlinear Compton scattering

Electron spectrum (Lanex3)	γ-ray image (LYSO-SC)	Measurement of γ-ray spectrum (LYSO-PX)



Clear measurement of Compton scattering signal!

Reconstruction methods

Two methods were applied to reconstruct the gamma-ray spectra.

Simultaneous Iterative Reconstruction Technique (SIRT)

NO Functional form assumed for the spectrum, Originally for pair spectrometer, adapted for LYSO

$$g_j^{(k+1)} = g_j^{(k)} + \alpha \frac{\sum_i S_{ij} \times \left(\frac{r_i - \sum_m S_{im}\, g_m^{(k)}}{\sum_m S_{im}} \right)}{\sum_m S_{mj}}$$

$g_j^{(k+1)}$ - next iteration for the spectrum

S_{ij} - lineout response (px i, energy #j); Computed in GEANT4

r_i - summed lineout response for px. i, from experiment

Trial function-based minimization of the response error (TFM)

Parametrized by critical energy(E_c)

Functional form: $\frac{dN}{dE} = A \times E^{-2/3} \times e^{-\frac{E}{E_c}}$

Minimizes the expression :

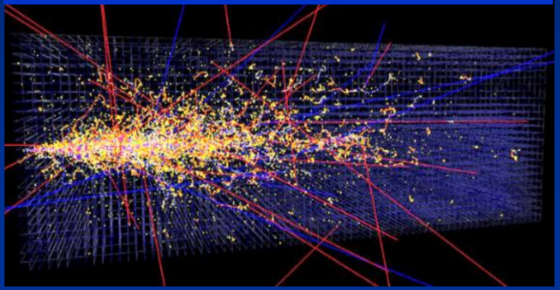
$$\min_{A,E_c} \left[r_i - \sum_j \left(S_{ij} \frac{dN(E_j)}{dE} dE_j \right) \right]$$

S_{ij}: lineout response (px #i, energy #j); computed in GEANT4

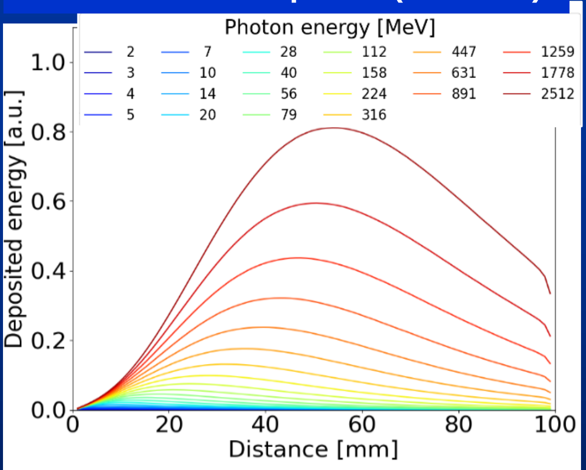
r_i: lineout response for px i, from exp.

E_j: energy #j

GEANT4 Simulation of LYSO

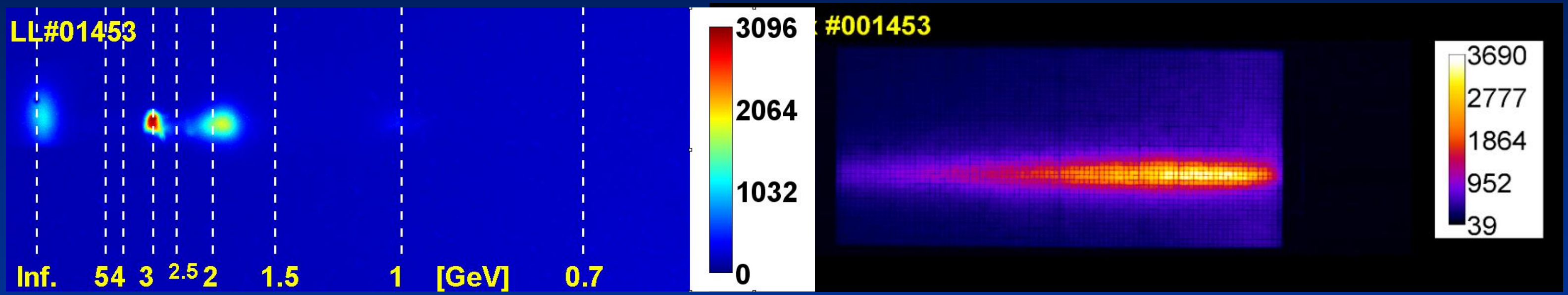


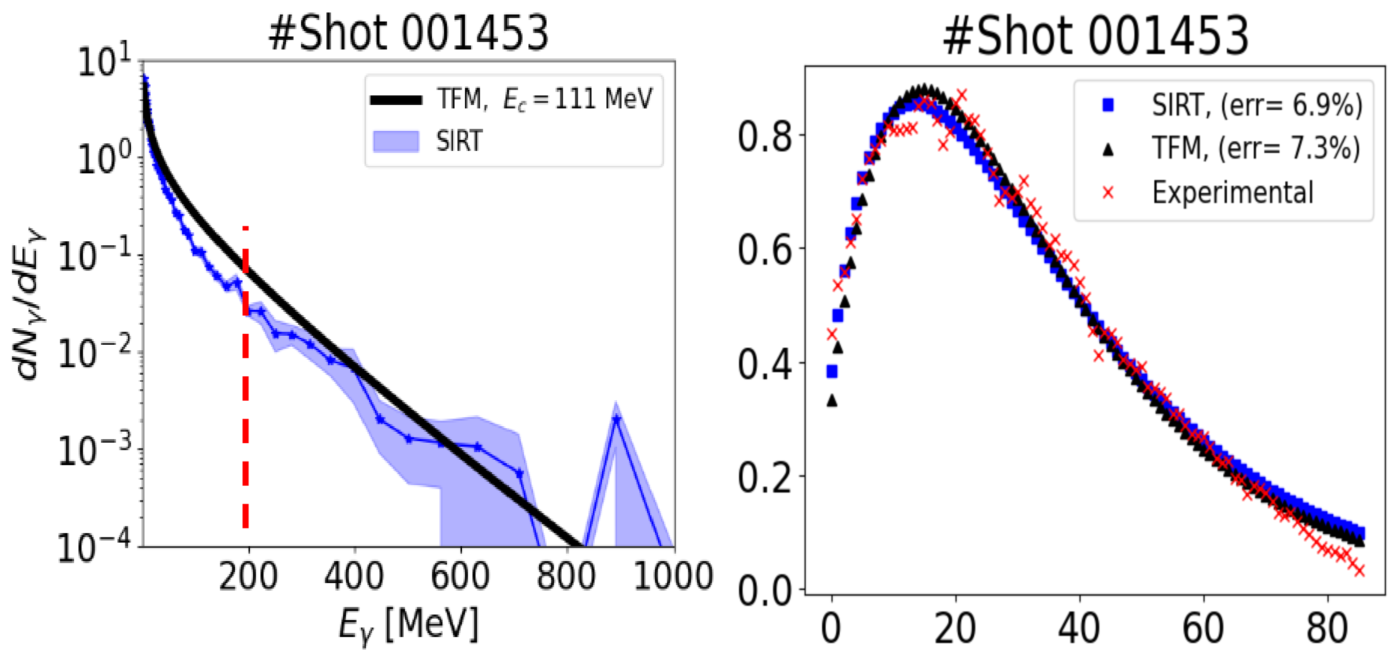
LYSO Lineout response (GEANT4)



D. Haden et al., Nucl. Inst. and Met. A 951, 163032 (2020)
K. Behm et al., Review of Scientific Instruments 89, 113303 (2018)

Reconstruction of gamma-ray spectrum (2)





Linear Compton scattering:

$$\varepsilon_{\text{cutoff}} = 2\,(1+\cos\theta)\,\gamma^2\,\varepsilon_L$$

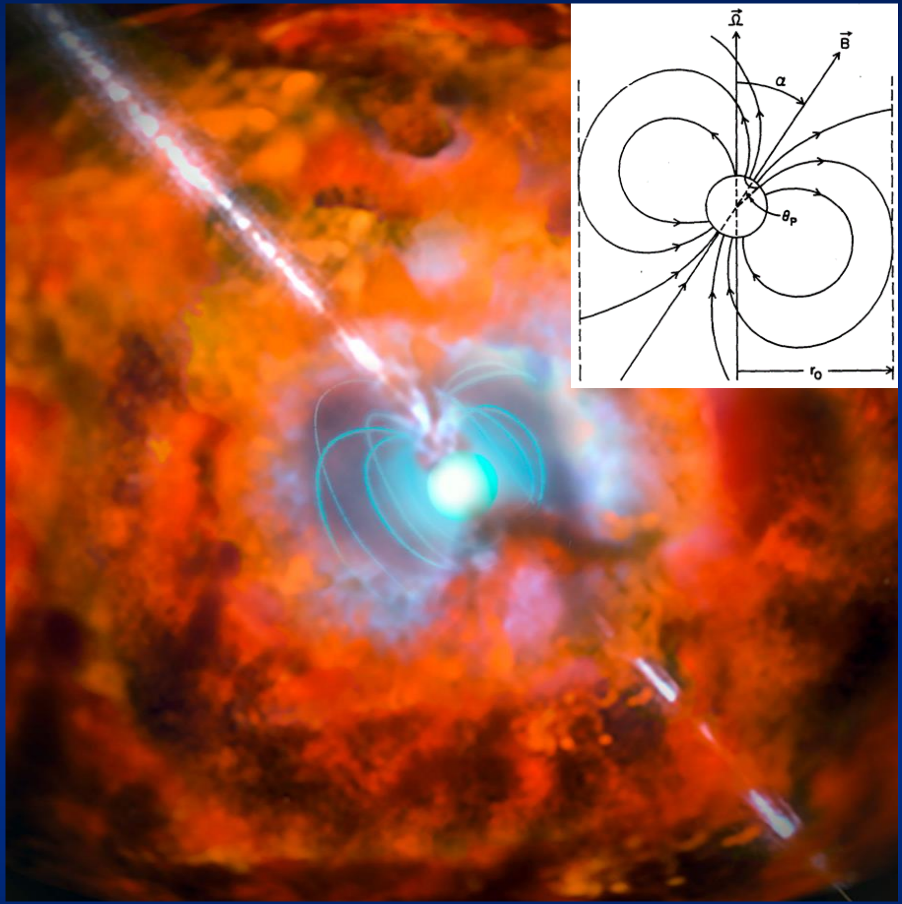
for E_e=3 GeV, $\varepsilon_{\text{cutoff}}$ = 200 MeV.

Nonlinear Compton scattering:

$$\varepsilon_\gamma = \frac{n}{1+\frac{a_0{}^2}{2}+\frac{2n\gamma\varepsilon_L}{m_e c^2}(1+\cos\theta)}\,\varepsilon_{\text{cutoff}}$$

$$\text{Or } n = \frac{\left(1+\frac{a_0{}^2}{2}\right)}{\left(1-\frac{\varepsilon\gamma}{\gamma m c^2}\right)}\,\frac{\varepsilon_\gamma}{\varepsilon_{\text{cutoff}}},$$

Magnetar: Astrophysical QED lab



Gamma-ray burst and supernova powered by a magnetar: GRB 111209A/SN 2011 kl (eso 1527)

Magnetar

Extremely magnetized neutron star

$B \sim 50 B_c$ ($B_c = 4.4 \times 10^{13}$ G)

QED processes in the vicinity

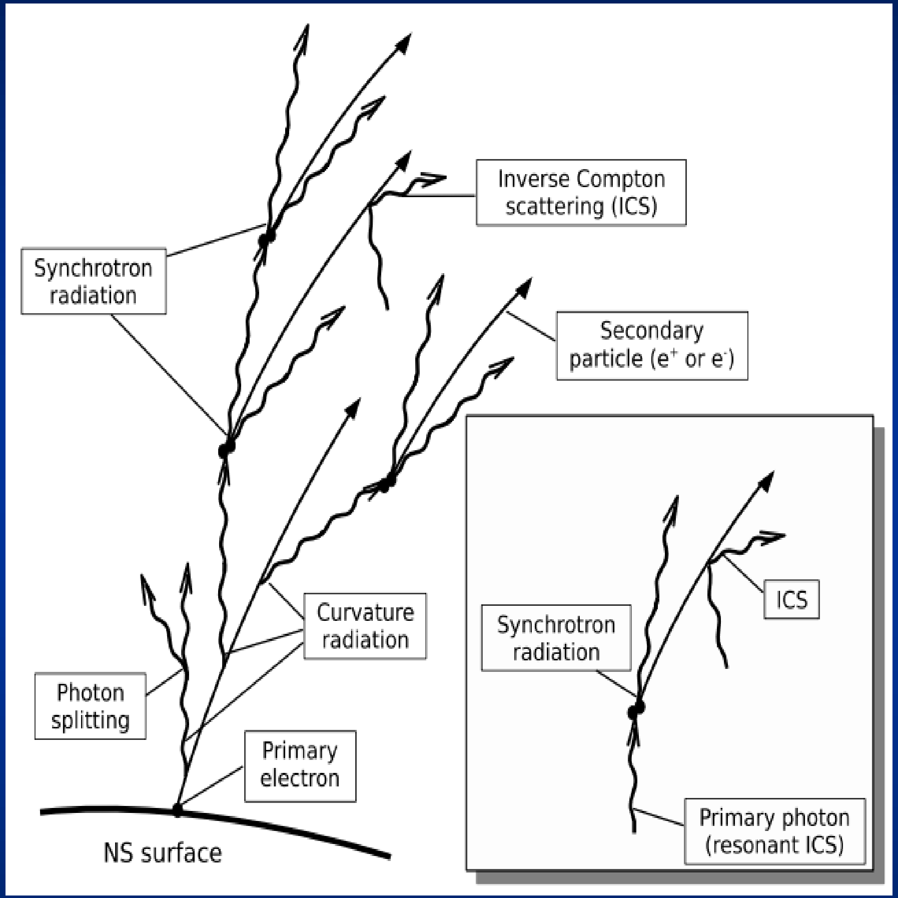
- magnetic photon splitting ($\gamma + B \rightarrow \gamma\gamma$)
- magnetic pair creation ($\gamma + B \rightarrow e^+e^-$)
- inverse Compton scattering (resonant/non-resonant)

→ pair cascade

→ **e^+e^- plasma**

- **vacuum birefringence**

→ Astrophysical lab of strong-field QED



Medin and Lai, MNRAS 406, 1379 (2010)

Summary

1. Ultrahigh power CPA lasers have opened up new challenging research areas in strong field physics.
2. By applying the laser wakefield electron acceleration scheme, mono-energetic multi-GeV electron beams have been produced.
3. As part of strong field QED research, nonlinear Compton scattering (NCS) between a laser-driven GeV electron beam and an ultrahigh intensity laser pulse has been explored. The scattering of a multi-GeV electron with several hundred laser photons produced 100’s MeV gamma-rays.
4. Strong field QED phenomena, such as radiation reaction and Breit-Wheeler pair production, will be also explored.

CoReLS website: https://corels.ibs.re.kr/html/corels_en/

CoReLS Members

Trekking to a cedar forest (summer 2019)