Staging acceleration to improve an energy spread in laser wakefield acceleration

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Japan Atomic Energy Agency

Collaborators

R. Kodama's Group (Osaka Univ.)
T. Hosokai's Group (Osaka Univ.)
S. Yamamoto's Group (KEK)
T. Sasaki's group (Nagaoka Univ. Tech.)

Program Manager

Y. Sano (JST)

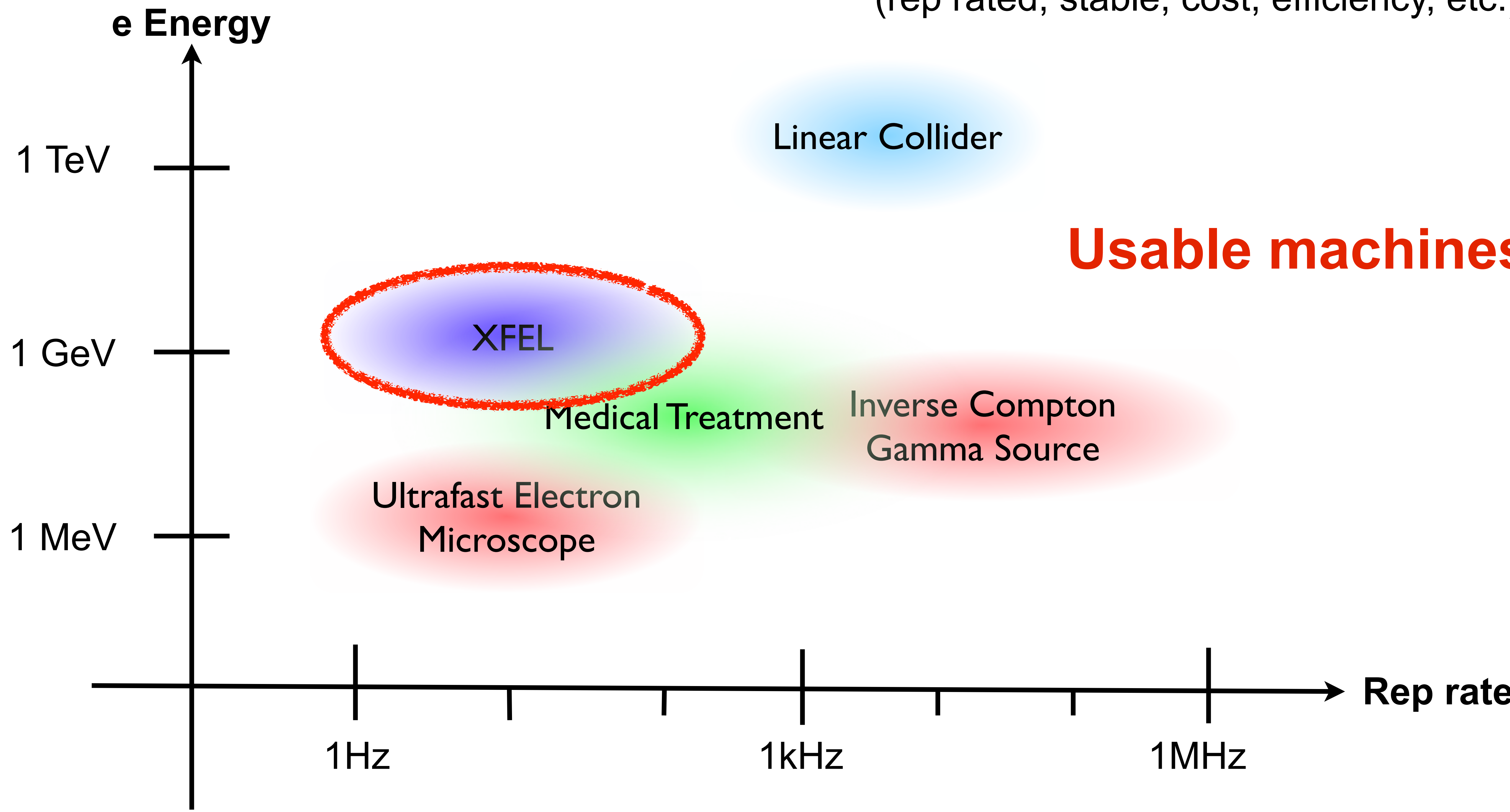
2nd European Advanced Accelerator Concepts Workshop,17 Sep. 2015

Contents

Laser electron acceleration: what's next?

- many successful experiments on laser electron acceleration

Laser technology is a key for applications!
(rep rated, stable, cost, efficiency, etc.)



Usable machines!

ImPACT project (FY2014-2018)

ImPACT=Impulsing Paradigm Change through disruptive Technologies Program

"Ubiquitous Power Laser for Achieving a Safe, Secure and Longevity Society" (PM: Dr. Sano)

■ Overview

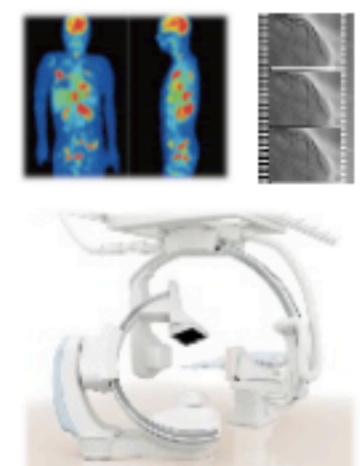
Ubiquitous quantum beam technologies and devices will be developed through power laser ultra-miniaturization and integration with plasma and accelerator technologies, which will have applications in equipment diagnosis, security, advanced medicine and other fields, and will help to achieve a safe, secure and longevity society.

■ Impact on Industry and Society in the Event of Achievement

- ✓ Enabling the use of XFEL* (a National Critical Technology), which currently exists in only two locations in the world, at each institution.
- ✓ Industrial innovation through analysis on the atomic level, ubiquitous equipment diagnosis and repair, biological imaging, quantum beam radiotherapy and so on, anytime, anywhere

XFEL（SACLA） Conception of tabletop XFEL

Diagnosis and life-extension of structures



Advanced medical solutions

Disruptive technology=laser acceleration!, Hi-risk, Hi-return

ImPACT: R&D Groups

Project 1
Laser acceleration & XFEL demonstration

- **Laser acceleration elemental technology** — Osaka Univ. (Prof. Hosokai)
- **Microundulator** — KEK (Prof. Yamamoto)
- **Beam monitoring and control** — JAEA (Dr. Kando)
- **Plasma device power source** — Nagaoka Univ. Tech. (Prof. Sasaki)

→ **Integrated platform for laser acceleration** — Osaka Univ. (Prof. Kodama)

↕ **XFEL demonstration and assessment**

Program Advisors

↕

Program Manager (PM: Dr. Sano)

Project 3

Study of user needs and systemization assessment — Open bidding

Project 2
Ultra-compact power laser

- **Microchip laser** — Institute for Molecular Science (Prof. Taira)
- **Waveform control laser** — Hamamatsu Photonics (GD Kawashima)

→ **Systemization and ultra-compact laser applications**

Required parameters for XFEL based on 1D

Z. Huang & K. J. Kim, PRST-AB 10, 034801 (2007)

SASE FEL

Pierce parameter

$$\rho = \left[\frac{1}{16} \frac{I_e}{I_A} \left(\frac{K[JJ]}{\sigma_x k_u} \right)^2 \frac{1}{\gamma^3} \right]^{1/3}$$

$$N_{u,sat} \sim 1/\rho$$

$$L_s \sim \lambda_u/\rho$$

typically ~10^{-3}-10^{-4}

X-ray

X-ray wavelength

$$\lambda_x = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

Output power of XFEL

$$P_{out} \sim \rho P_{beam}$$ e-beam power

e-beam

energy spread

$$\Delta\gamma/\gamma < \rho$$

unnormalized emittance

$$\varepsilon_{un} \leq \lambda_x/(4\pi)$$

$I_A = ec/r_e \approx 17$ [kA] Alfven current

I_e Electron beam peak current

σ_x Electron beam rms beam radius

$\gamma = E_0/mc^2$ ratio of electron beam energy to rest energy

$K = \frac{eB_0}{mck_u} = 0.934 B_0[\mathrm{T}] \lambda_u[\mathrm{cm}]$ dimensionless undulator parameter (cf. a_0)

undulator period

maximum magnetic flux density

$[JJ] = J_0\left(K^2/(4+2K^2)\right) - J_1\left(K^2/(4+2K^2)\right)$ $J_n(x)$: nth order Bessel function of 1st kind

XFEL parameter examples: zero-order

Project goal

$E_x = 1\ \mathrm{keV}$ $\qquad \lambda_x[\mathrm{nm}] = 1.24/E_x[\mathrm{keV}]$ $\qquad \lambda_x = 1.24\ [\mathrm{nm}]$

Case I. SACLA undulator

$\lambda_u = 1.8\ [\mathrm{cm}],\ \ K = 2.1$ -> $\gamma = 4.8 \times 10^3$ $, E_0 = 2.5\ [\mathrm{GeV}]$ possible!

Case II. Short-period undulator (KEK, under development)

$\lambda_u = 0.4\ \mathrm{cm}, \quad K = 0.15\ (B_0 = 0.4\ \ \mathrm{T})$

$\gamma = 1.3 \times 10^3, \quad E_0 = 0.65\ [\mathrm{GeV}]$ possible!

Energy spread should be smaller than the following values.

$$\rho = \begin{cases} 2.5 \times 10^{-3} & (\text{case I}) \\ 5.9 \times 10^{-4} & (\text{case II}) \end{cases}$$

challenge

The emittance should satisfy $\varepsilon_{un} \le \lambda_x/(4\pi) = 9.87 \times 10^{-5}\ \mathrm{mm\ mrad}$

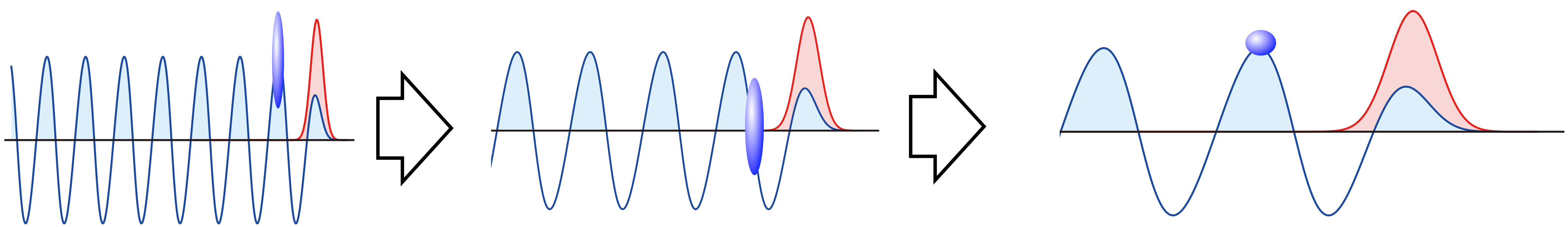
$$\varepsilon_n \approx \gamma \varepsilon_{un} < \begin{cases} 0.48\ \mathrm{mm\ mrad} & (\text{case I}) \\ 0.13\ \mathrm{mm\ mrad} & (\text{case II}) \end{cases}$$

possible!

our strategy
to get monochromatic electrons

Multi-staging laser electron acceleration

- We use separate-function accelerating stages.
- In the latter part, the longer pulse duration is employed.



Injector	Phase rotator	Booster
3-10 TW	3-10 TW	>100 TW
<30 fs	**~60 fs**	**~100 fs**
$a_0>1$	$a_0\leq1$	$a_0\leq1$

Nakanii's talk (yesterday)
Hosokai's talk (tomorrow)

- Preliminary implementation at Osaka Univ. (T. Hosokai's lab.)
- Booster acceleration test with **J-KAREN-P** laser.

Finally, all the system will be implemented at the **integrated platform "LAPLACIAN"** (**RIKEN, Harima**).

Theoretical consideration supports proper staging

S. V. Bulanov, in preparation

Unlimited acceleration

In inhomogeneous plasma target the wake wave phase velocity depends on the laser power and plasma density as

$$\gamma_w = \sqrt{a}\left(\frac{\omega}{\omega_{pe}}\right) = \left(\frac{\mathcal{P}}{\bar{\bar{\mathcal{P}}}}\right)^{1/6}\left(\frac{n_0}{n_{cr}}\right)^{1/3}$$

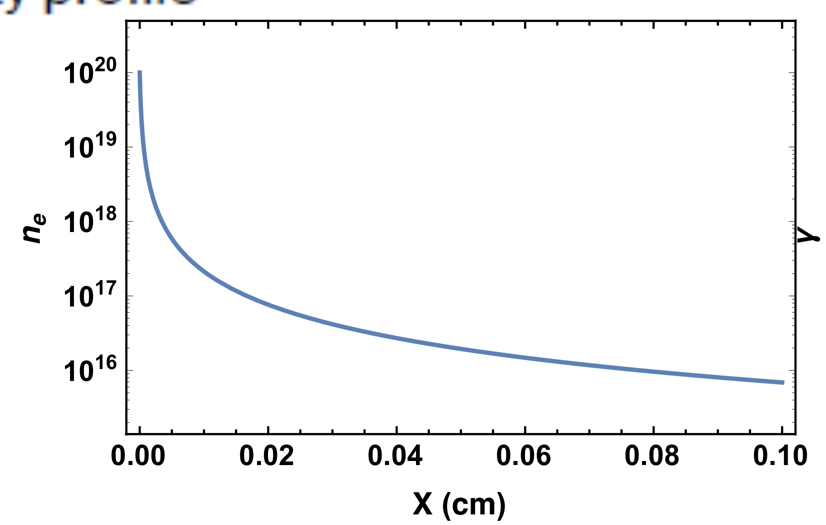
and for electron energy we have $$\frac{d\gamma}{dx} = \frac{eE}{m_e c^2} = \sqrt{a}\left(\frac{\omega_{pe}}{c}\right) = \frac{2\pi}{\lambda}\left(\frac{\mathcal{P}}{\bar{\bar{\mathcal{P}}}}\right)^{1/6}\left(\frac{n_0}{n_{cr}}\right)^{1/3}$$

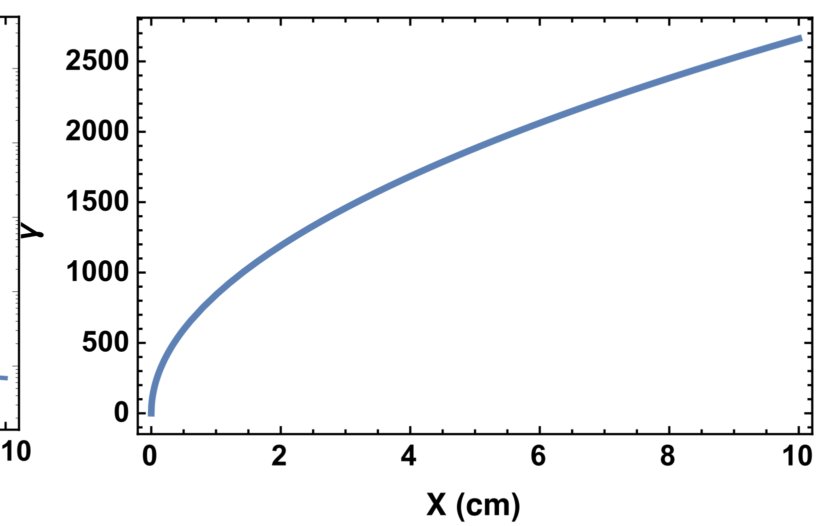
This yields the equation for the density profile

$$\frac{d}{dx}\left(\frac{\omega}{\omega_{pe}}\right)^{2/3} = \frac{2\pi}{\lambda}\left(\frac{\omega_{pe}}{\omega}\right)^{1/3}$$

Its solution

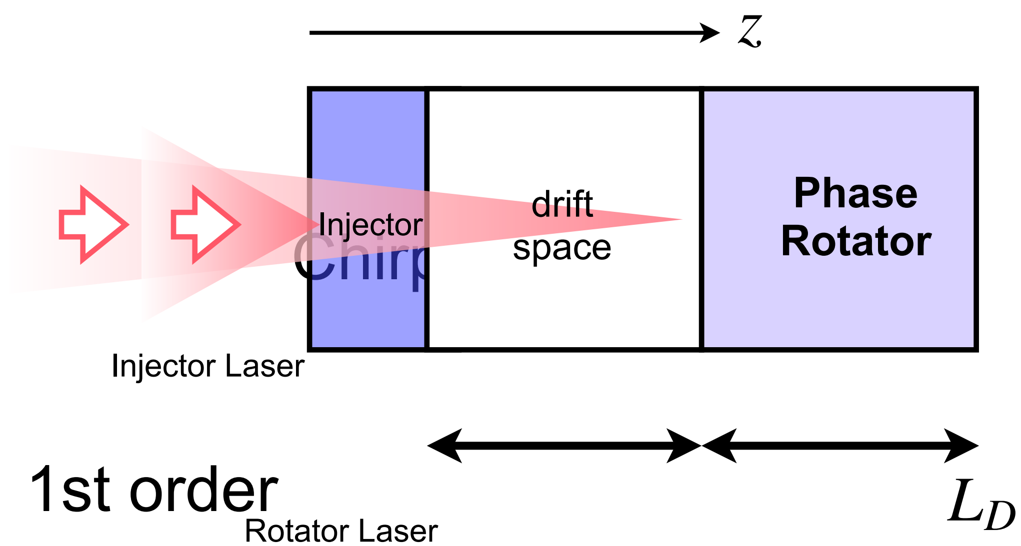
$$n(x) = n_{cr}\left(\frac{\pi x}{\lambda} + \left(\frac{\omega}{\omega_{pe}(0)}\right)^{4/3}\right)^{-3/2}$$





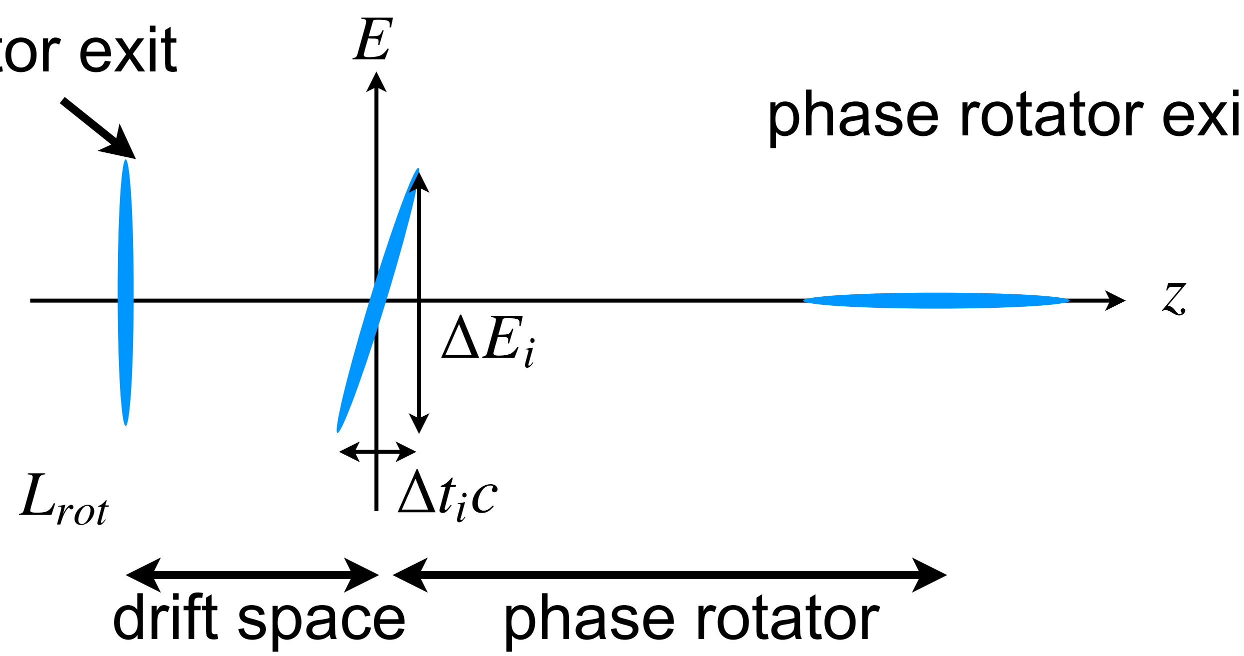
The electron energy asymptotically grows as $$\gamma(x) = \left(\frac{\mathcal{P}}{\bar{\bar{\mathcal{P}}}}\right)^{1/6}\left(\frac{\pi x}{\lambda}\right)^{1/2}$$

Design of phase-space rotator



1st order

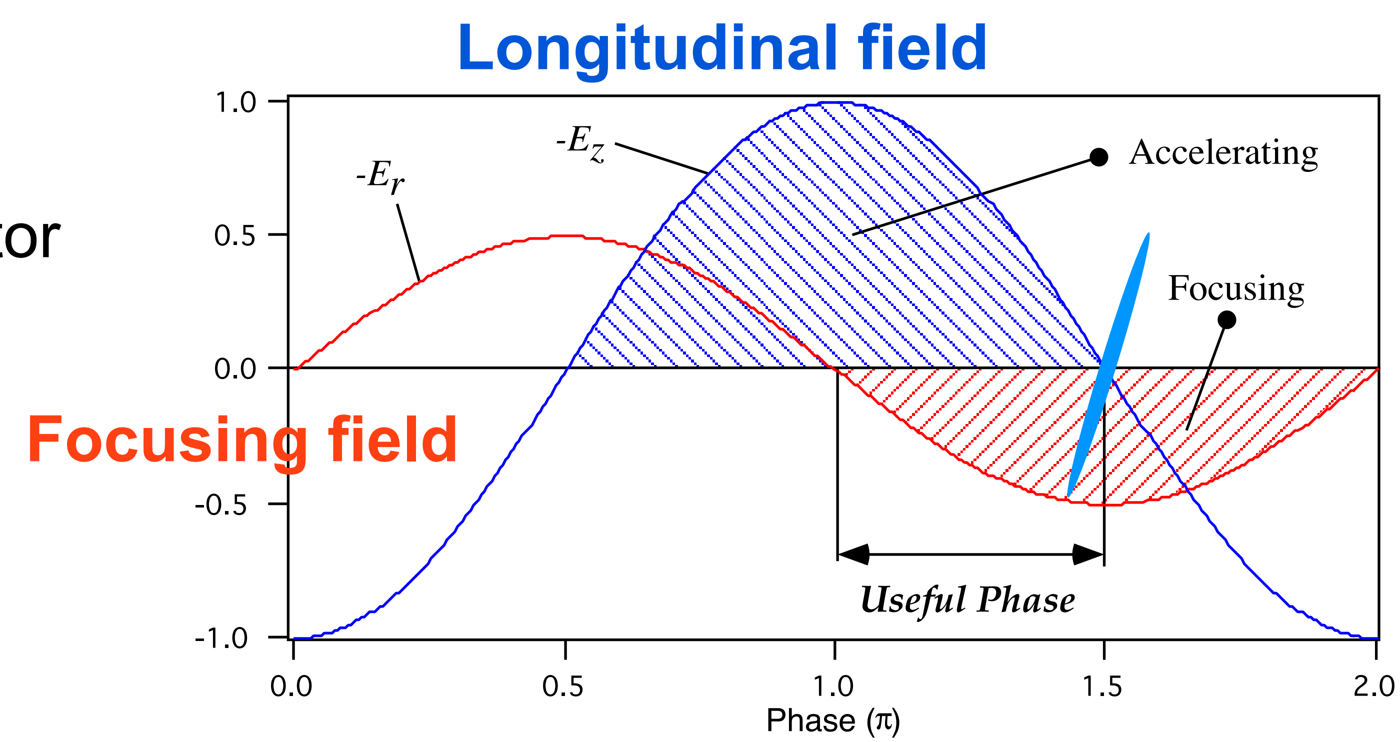
$$\frac{E_{acc}L_{rot}}{\lambda_p} = \frac{\Delta E_i/2}{\Delta t_i c}$$



Input electron beam: $\Delta E_i,\ \Delta t_i$

Parameters of Phase-space rotator

$$E_{acc},\ L_{rot},\lambda_{p,r}$$

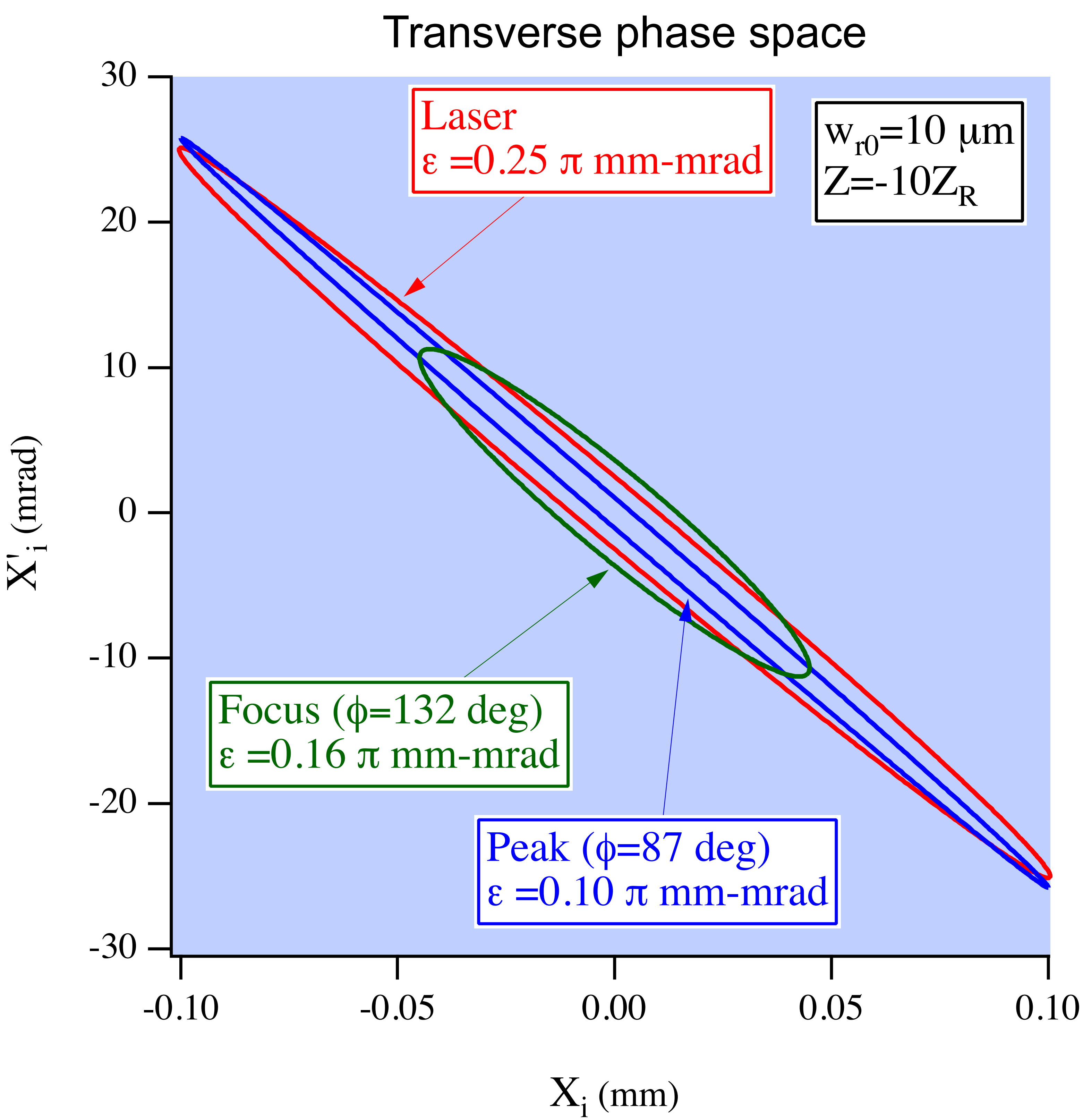


These 3 parameters are determined so as to cancel the chirp of electron beam.

Example parameters for phase rotator

				Case I	Case II
Injector	e-energy	E_i	MeV	30	10
	dispersion	$\Delta E_i/E_i$	MeV	3	1
Drift space	length	L_D	m	0.3	0.01
	chirp rate		MeV/μm	1.7×10^{-1}	1.9×10^{-1}
	e-pulse duraton	Δt_i	fs	30	8.8
		$\Delta t_i c$	μm	8.8	2.6
Phase rotator	phase		deg.	0	0
	laser amplitude	$a_{0,r}$	-	0.7	0.5
	laser pulse duration	τ_r	fs	100	50
	laser power	P_r	TW	106	14
	spot radius	$w_{0,r}$	μm	80	40
	pl. wavelength	$\lambda_{p,r}$	μm	80	40
	length	L_{rot}	μm	1560	810
	pl. density	$n_{e,r}$	cm^{-3}	1.7×10^{17}	6.9×10^{17}

Beam matching to the wake is important



Example: dE/E=10%

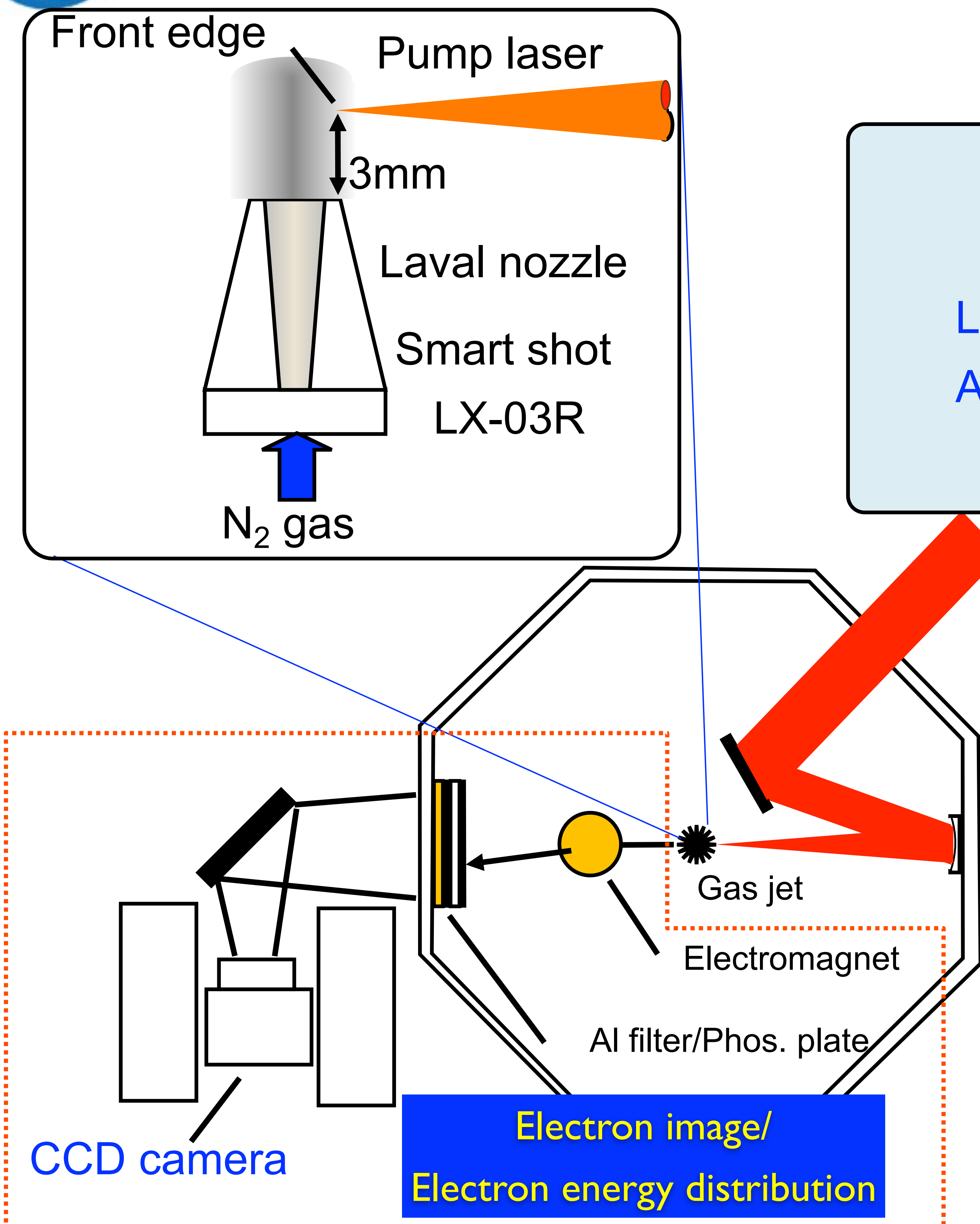
laser vacuum waist	10 μm
electron vacuum focus (peak)	4.6 μm
(focus)	14 μm

Message:

- transverse matching is important!
- matching depends on phase!

Injector results at JAEA

Injector: example



Pump laser (from JLITE-X)

f/22 OAP

(f=646mm)

Laser condition

λ=800nm

E=160±4.8mJ, τ=40fs (i.e. P= 4TW)

Laser intensity: 9x10^{17} W/cm^2 (a0=0.6)

ASE pedestal: 2x10^{-6}(-500ps<t<-1ps)

2x10^{-8}(<-500ps)

Target condition

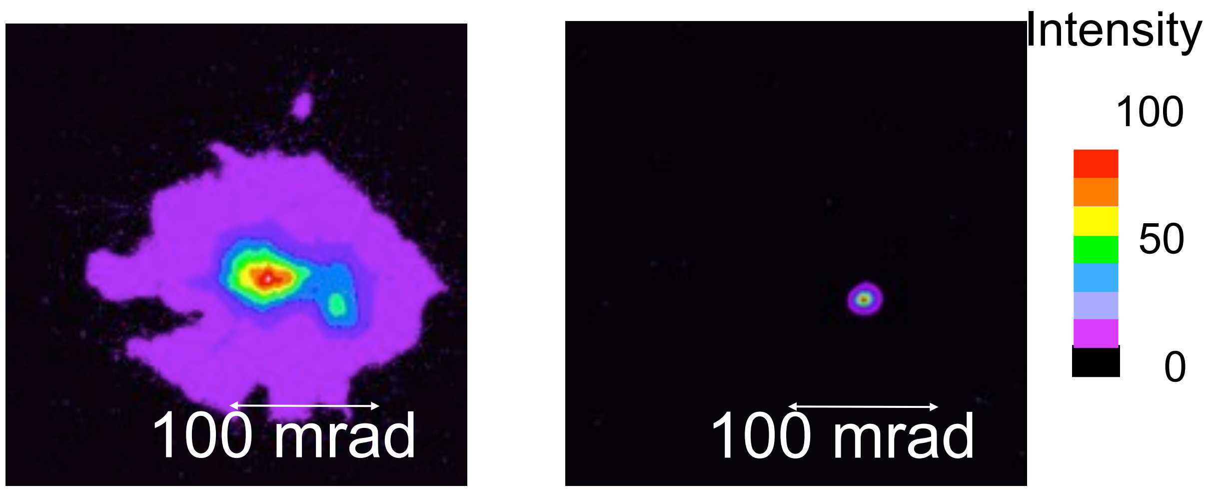
Density scale: ~3500 um

Neutral Gas density:

0.3x10^{18} cm^{-3}(N_2)

Experimental results of e-beam generation

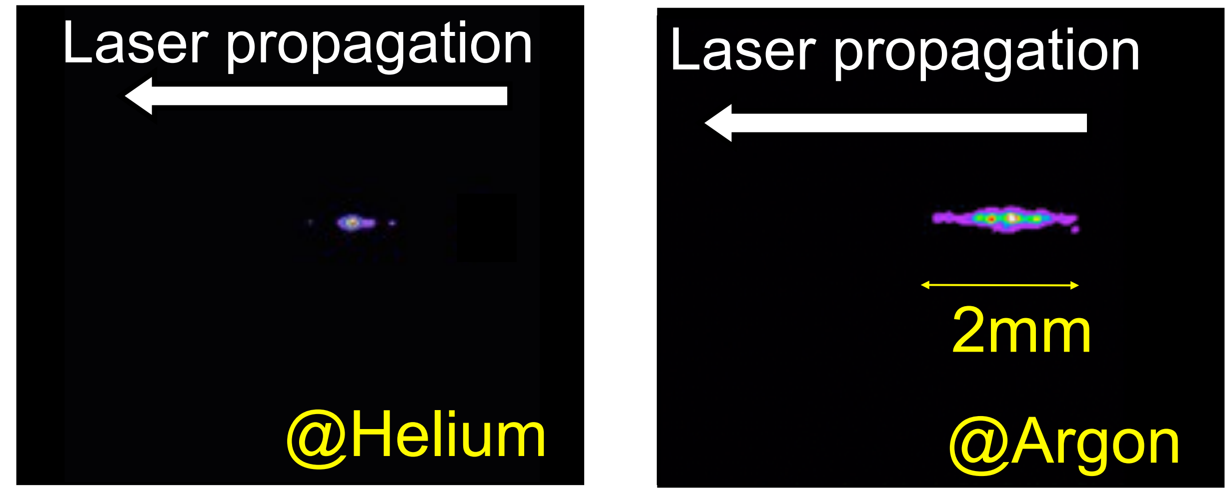
e-beam spatial profile



Helium Argon

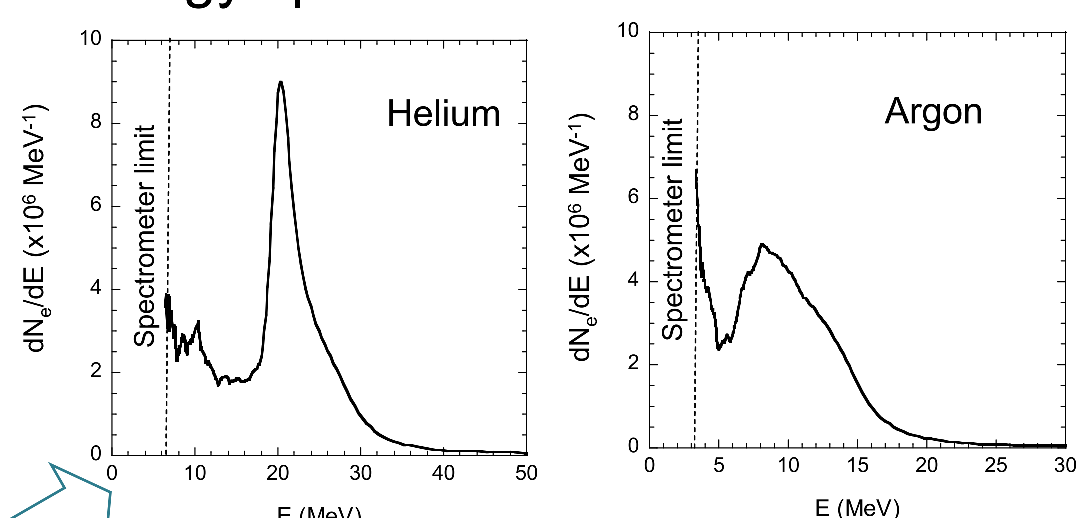
M Mori et al., PRST-AB

Thomson scattering image



Argon : better pointing but broader energy spread

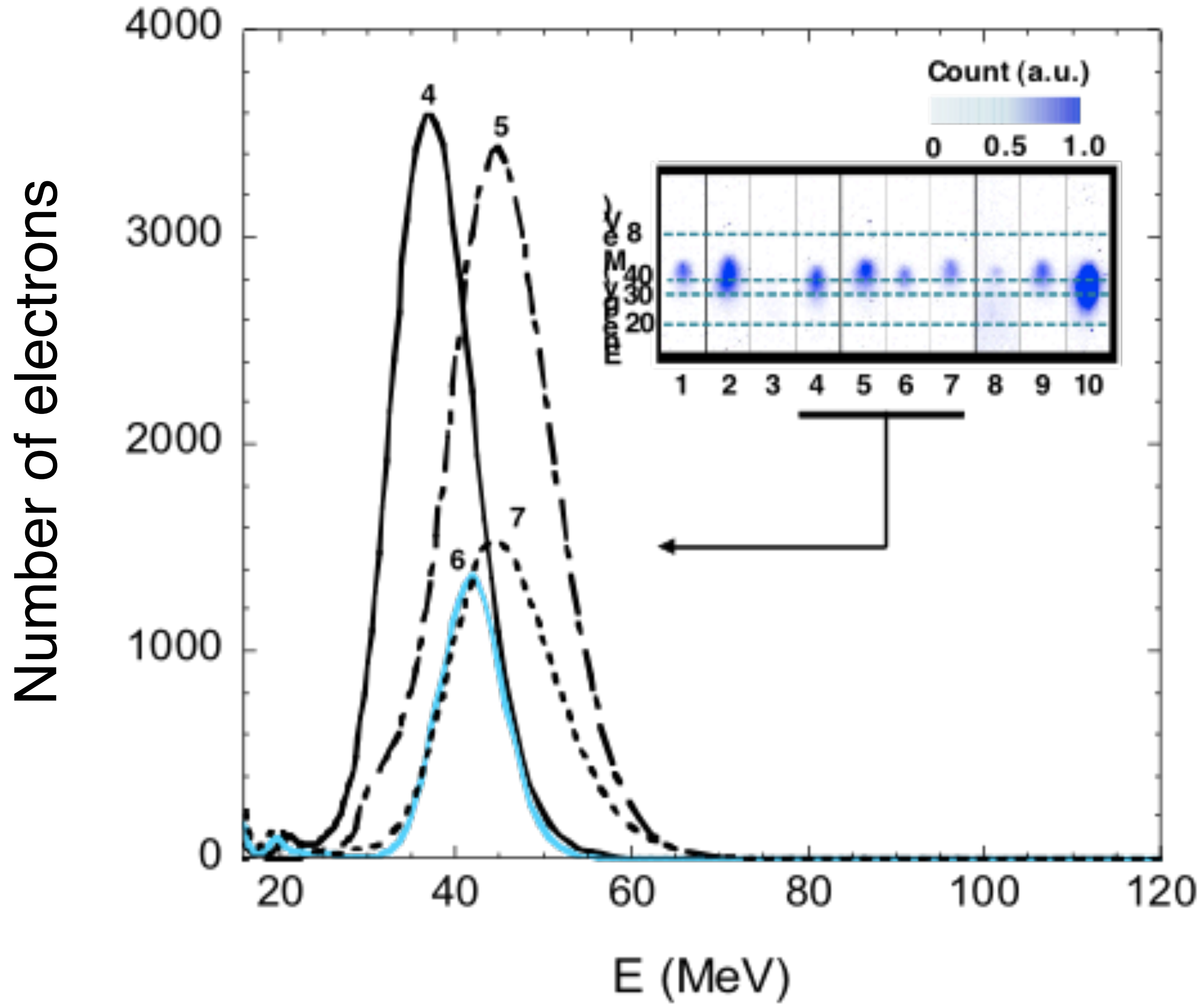
Target	Helium	Argon
Pointing stability (mrad) (rms)	9.8	2.4
Beam divergence (mrad) (avg±s.d.)	29.8±8.8	10.4±2.0
Peak Energy (MeV) (avg±s.d.)	24.8±3.6	8.5±0.8
Yield (pC/shot)	19.8±10.6	9.2±3.3
QME reproducibility (%)	38	84

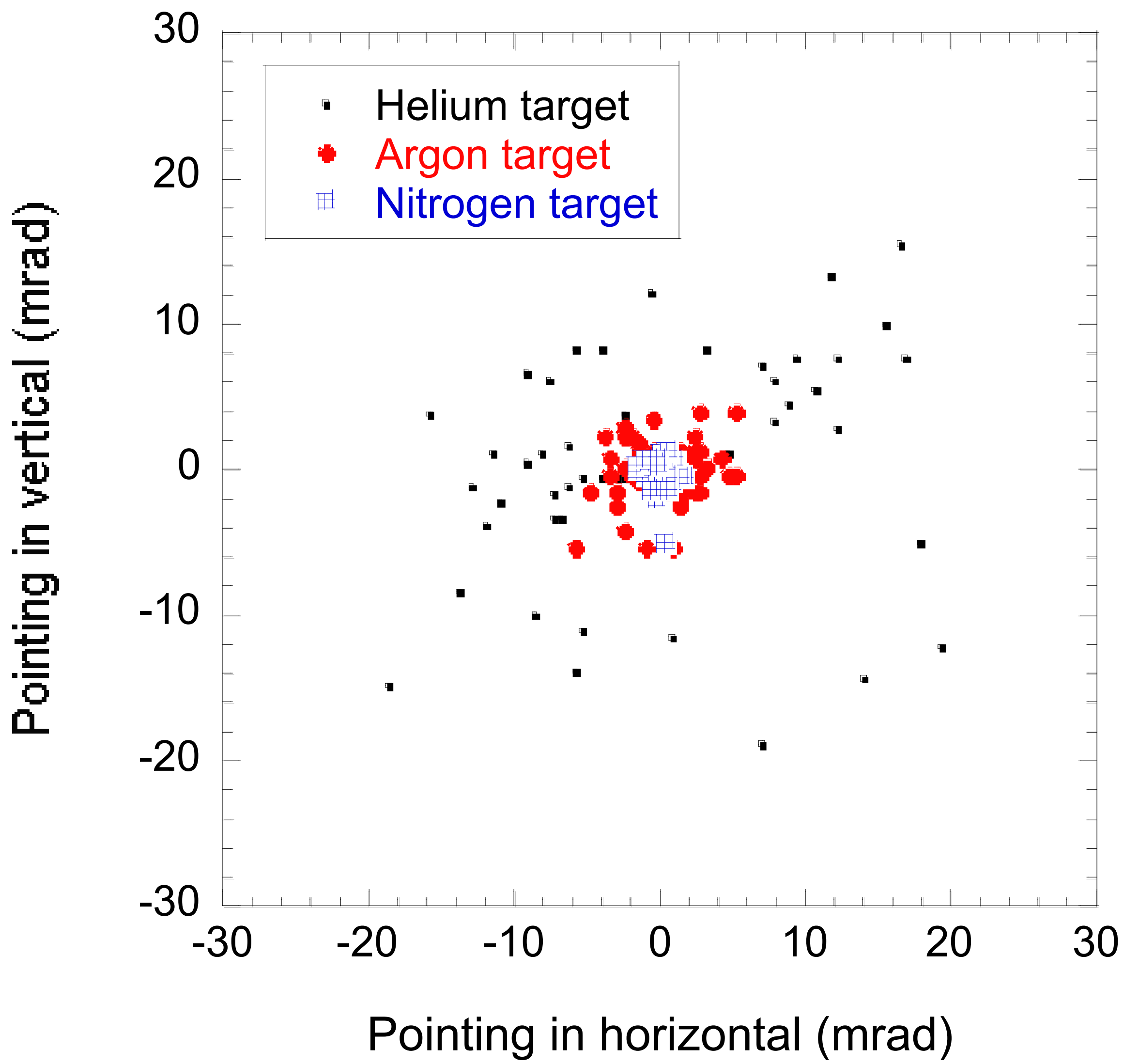


Energy spectra

N2 gas is suitable in our case

Mori et al, IPAC2010





Pointing stability (1.7mrad)

JAEA mission

Wakefield mesurement

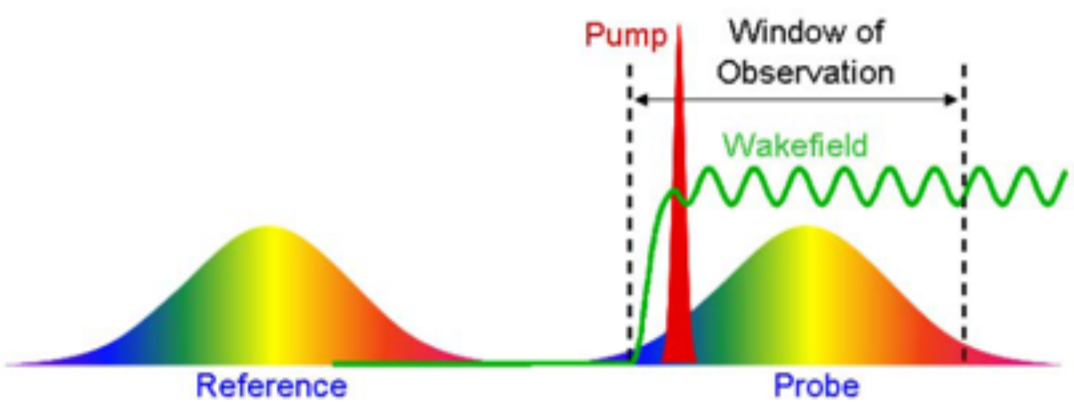
Plasma wave (wakefield) is one of the important parameters.

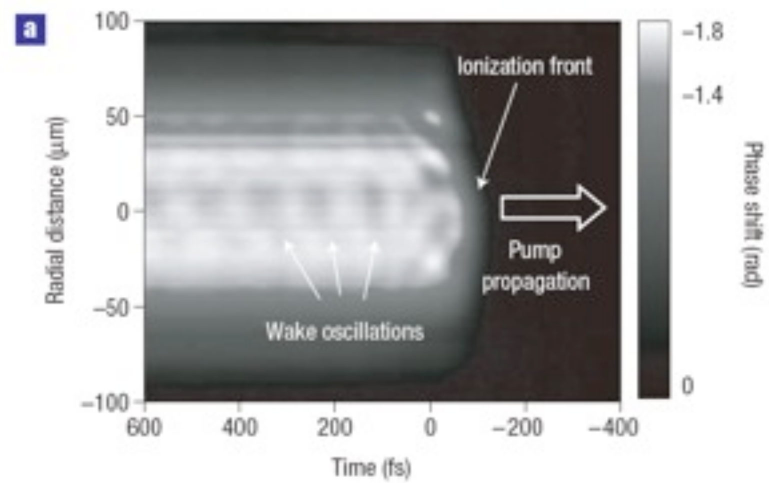
Electron energy, focusing

Also important in phase rotation

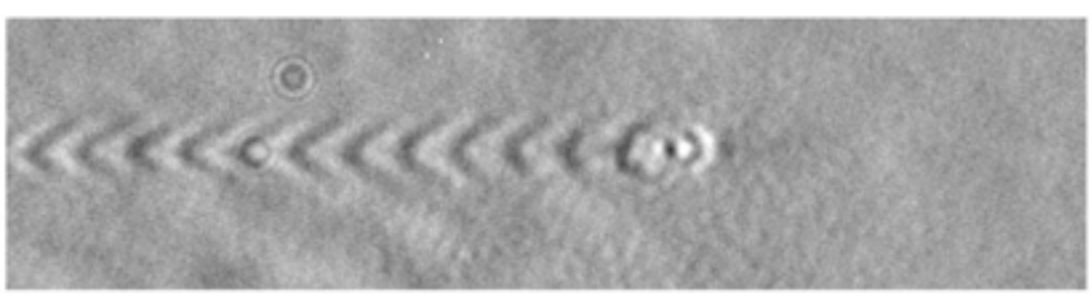
1. Single-shot based measurement: Frequency-Domain Holography

N. Matlis, M. Downer, Nature Phys. 2, 749 (2006)





2. Sub-10 fs probe -shadowgraphy

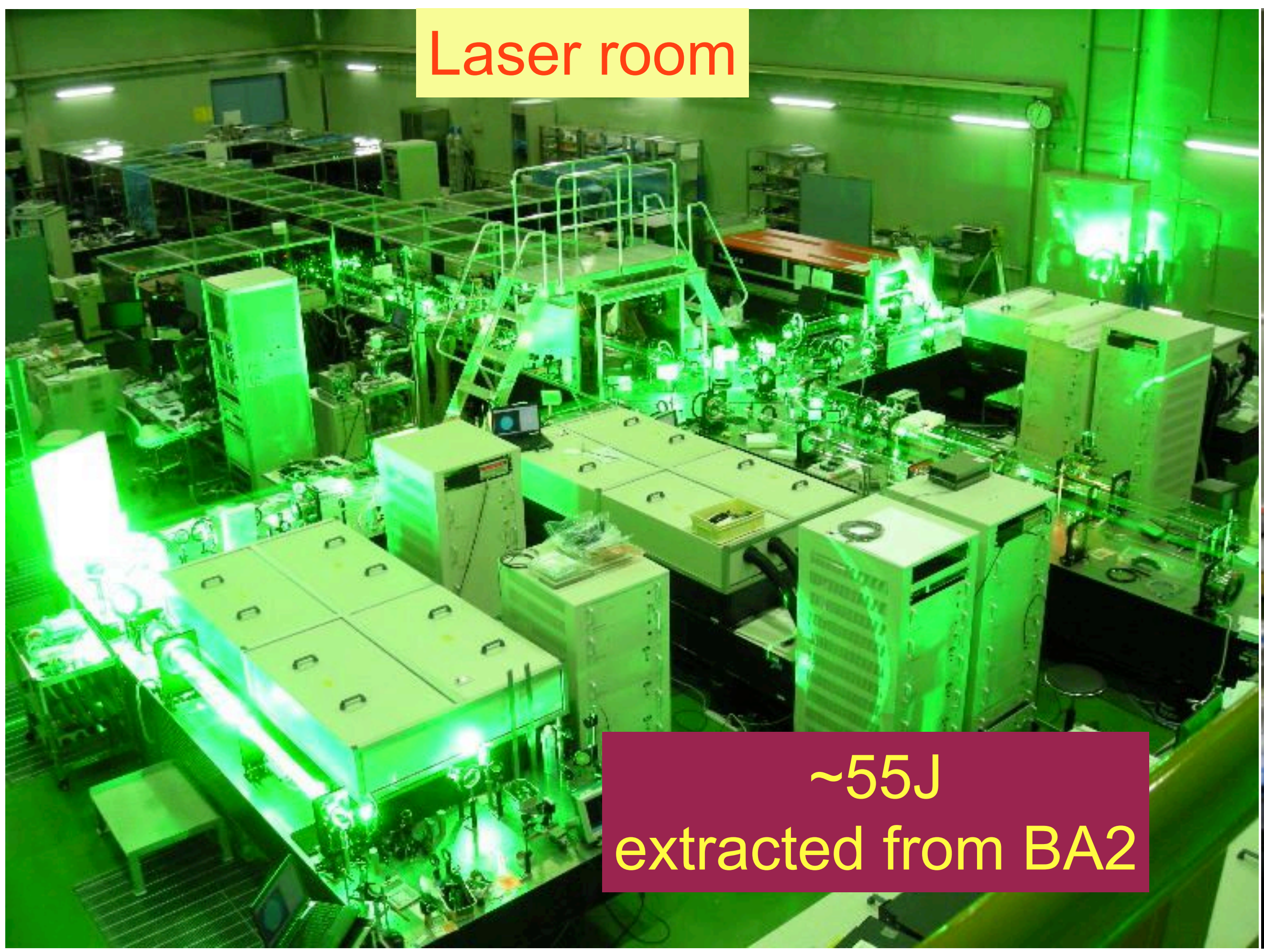


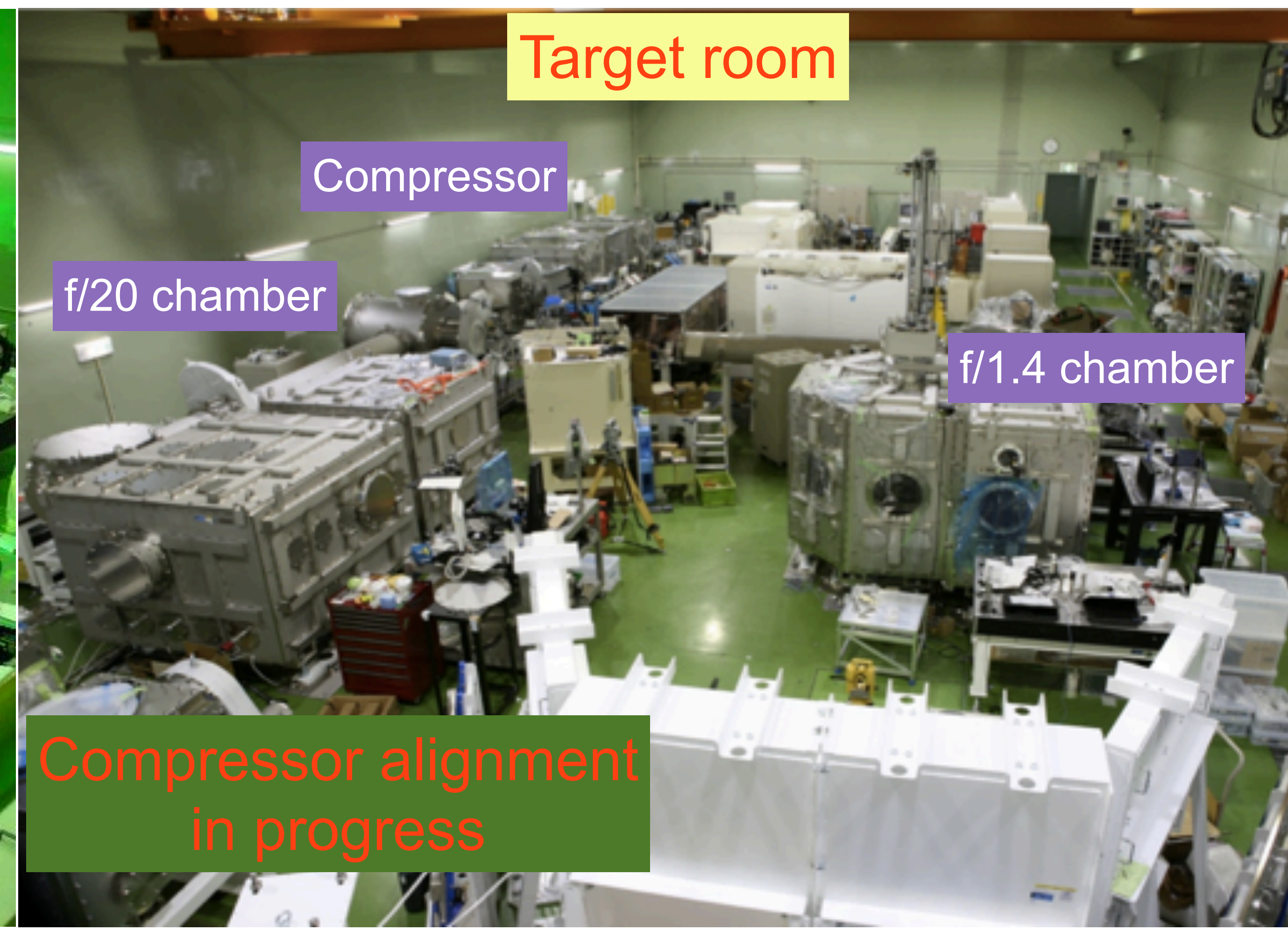
A. Buck et al.,Nature Phys, **7**, 543 (2011)
M. B. Schwab et al., APL, **103**, 191118 (2013)
A. Sävert et al., PRL **115**, 055002 (2015)

Booster acceleration test

At KPSI-JAEA, we are upgrading our J-KAREN laser to PW level on target. 30 fs, ~30 J (1 PW on target), 0.1Hz. “J-KAREN-P”

Challenges:
- Chirp pulse effect
- Stable acceleration
- long propagation (~10cm) in waveguide

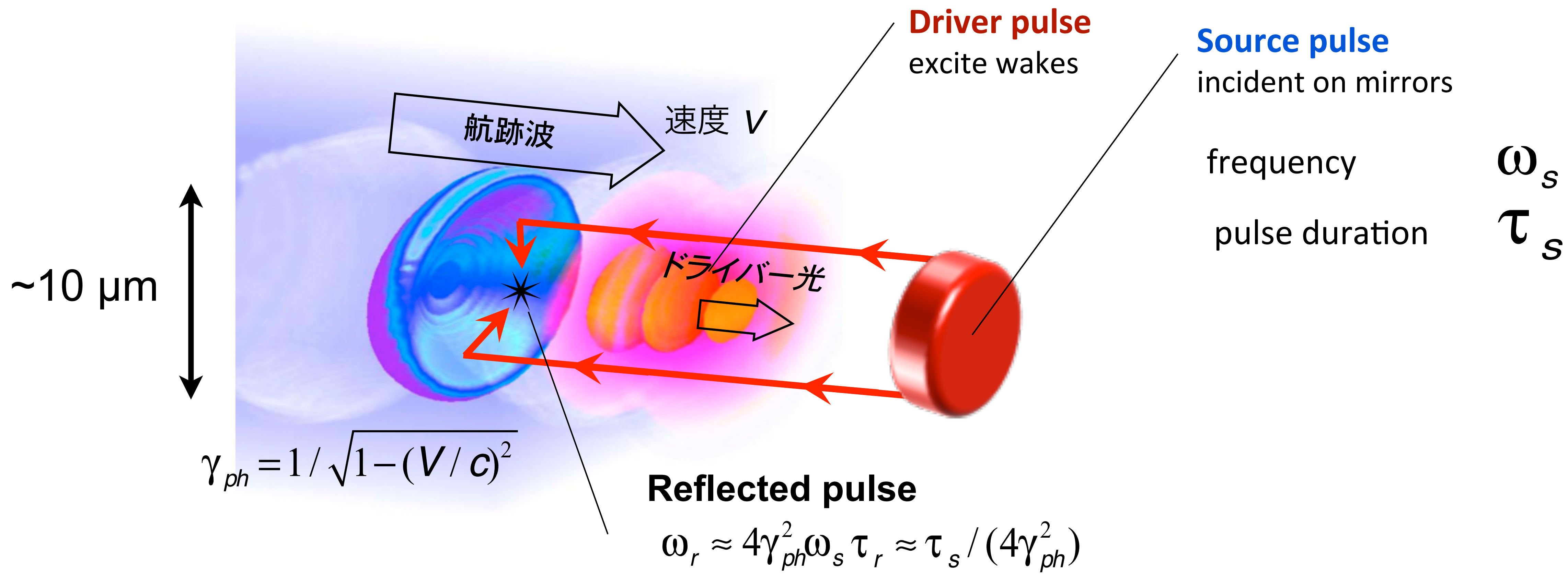




Pulse alignment method

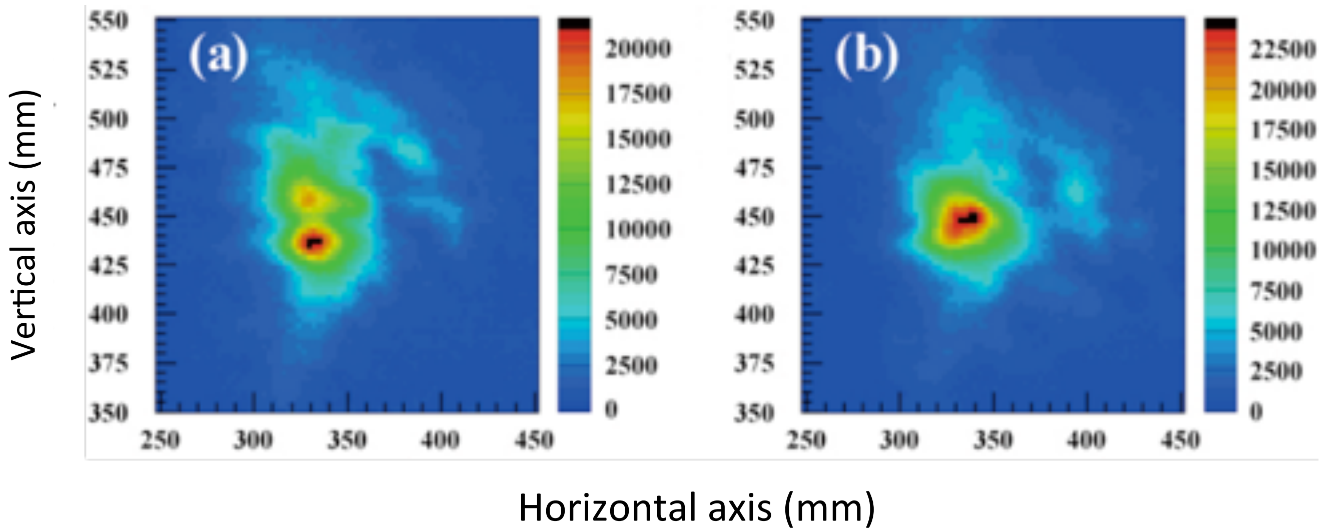
- In multi-staging acceleration, alignment method is necessary for two (or three) pulses properly.

- At JAEA, in the study of ***relativistic flying mirrors***, which uses **nonlinear wake** as a moving mirror, we have developed several techniques.



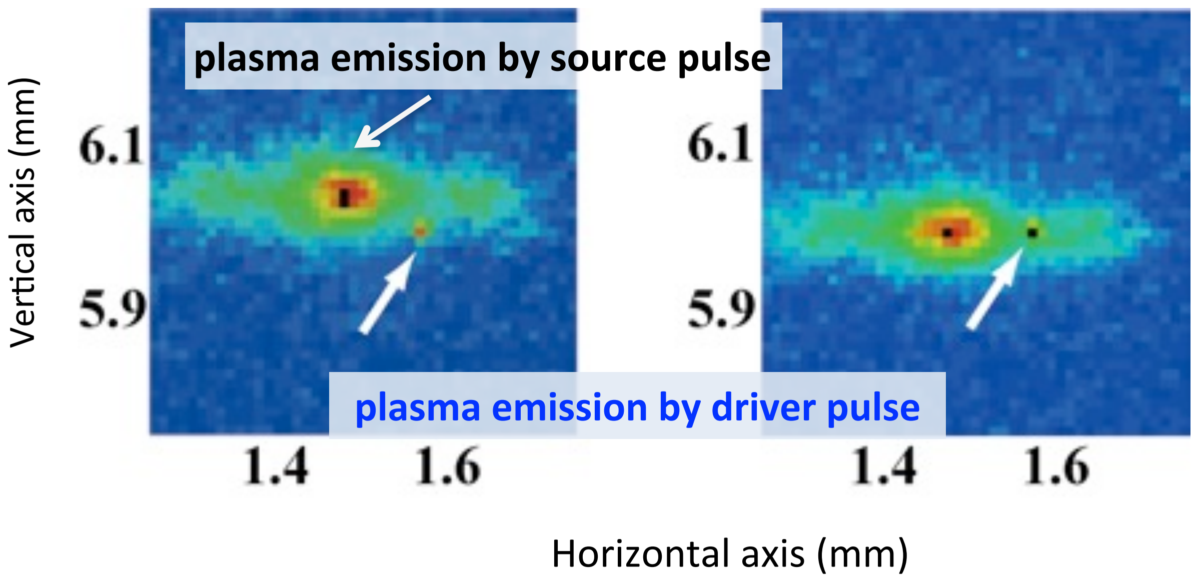
Several alignment method

ex1） Far-field (Two laser pulses), online



- Spatial resolution ~15μm

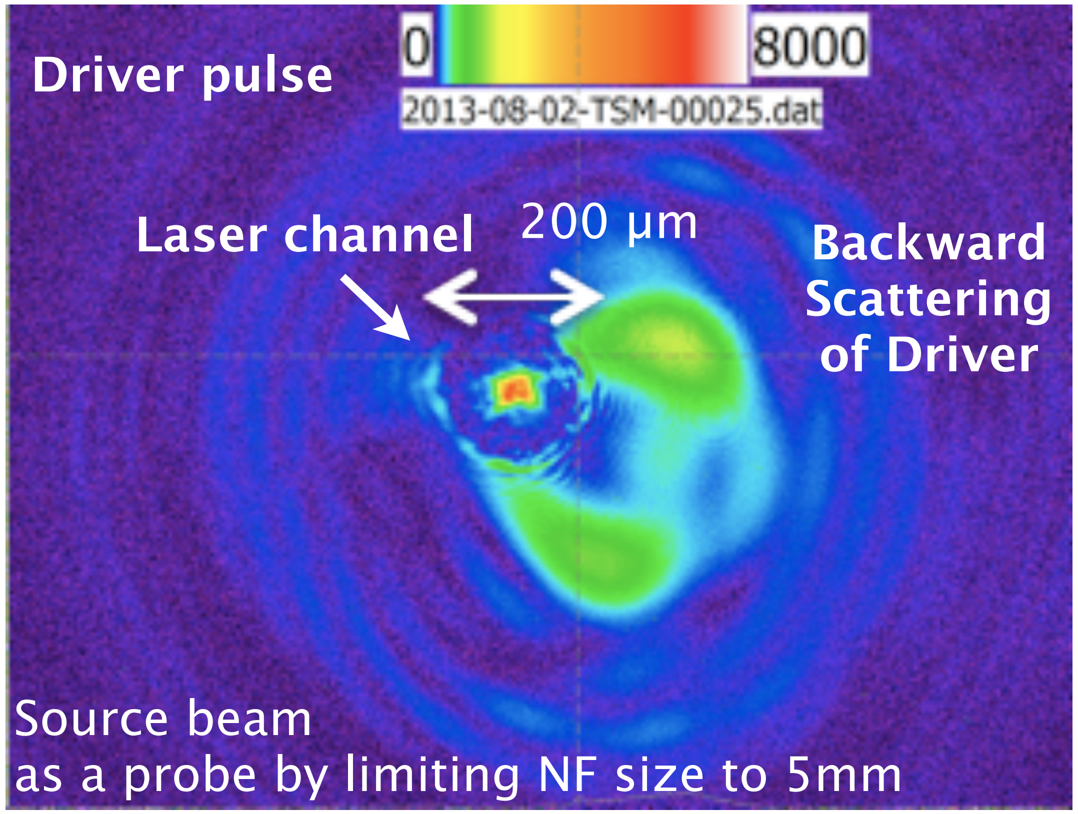
ex2） XUV imaging



- spatial resolution ~ 6μm

K. Kawase, M. Kando et al. APEX **3**, 016101 (2010)

ex3) Longitudinal shadowgram (main channel reflection)



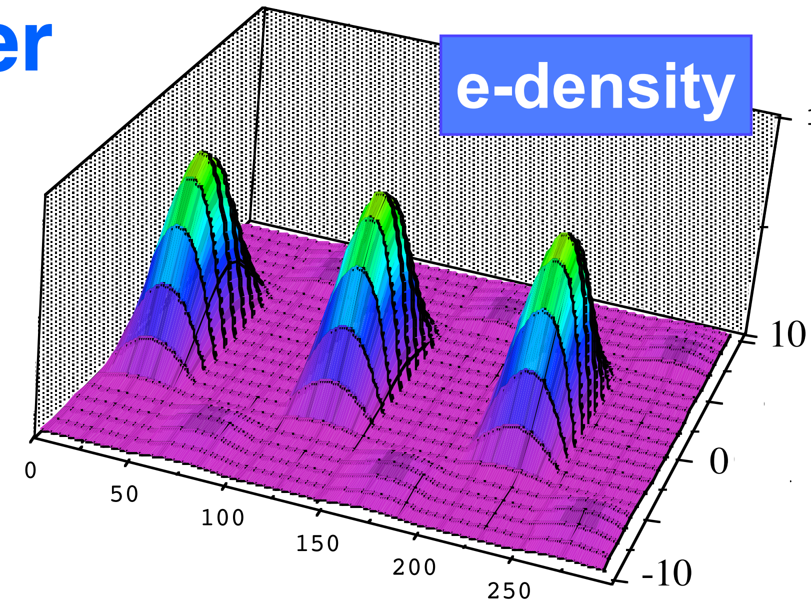
M. Kando et al., in preparation

- Spatial resolution ~ 2μm

We have developed suitable alignment methods when two laser pulses are used.

Importance of laser stabilization

- **Electric fields are determined by laser**
  - Intensity
  - Profiles (both radial and longitudinal)



Density

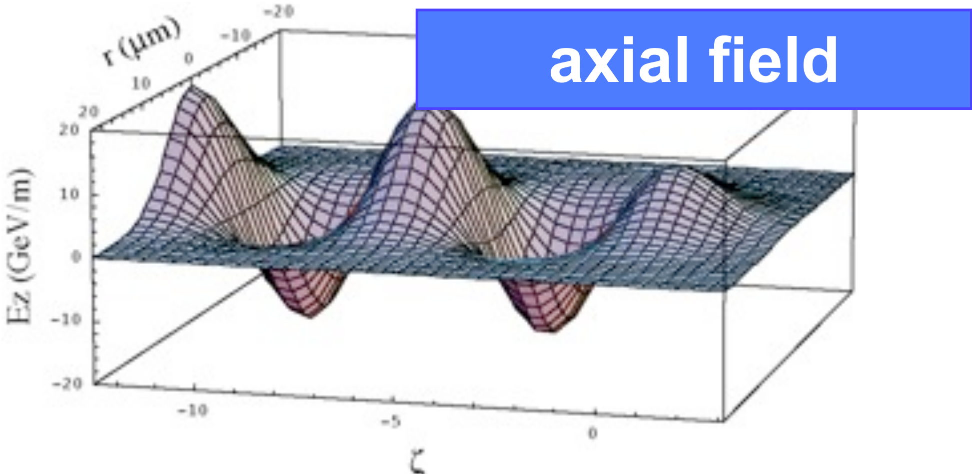
$$\frac{\delta n}{n} = \frac{k_p a_0^2}{2}\left[1 + \frac{4}{k_p^2 \sigma_r^2}\left(1 - \frac{r^2}{\sigma_r^2}\right)\right]\exp\left(-\frac{r^2}{\sigma_r^2}\right)\sin\left(k_p \varsigma\right)$$

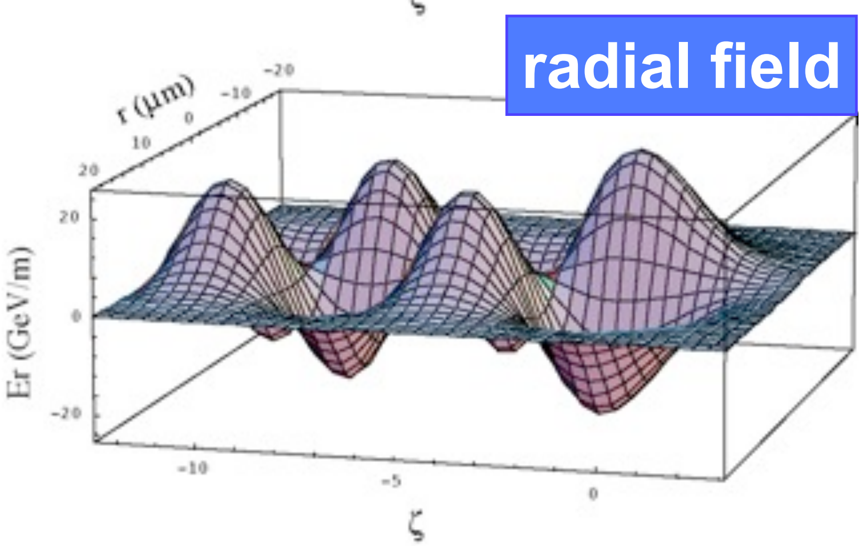
Axial electric field

$$eE_z(r,\varsigma) = \frac{\sqrt{\pi} mc^2 k_p^2 \sigma_z a_0^2}{2}\exp\left(-\frac{r^2}{\sigma_r^2} - \frac{k_p^2 \sigma_z^2}{4}\right)\cos\left(k_p \varsigma\right)$$

Radial electric field

$$eE_r(r,\varsigma) = \frac{\sqrt{\pi} mc^2 k_p \sigma_z a_0^2 r}{\sigma_r^2}\exp\left(-\frac{r^2}{\sigma_r^2} - \frac{k_p^2 \sigma_z^2}{4}\right)\sin\left(k_p \varsigma\right)$$





Normalized laser amplitude

$$a_0 = 8.5 \times 10^{-10} \lambda_0[\mu m]\sqrt{I[W/cm^2]}$$

In the linear regime(a_0<<1) the amplitudes are proportional to a_0^2 (=intensity)

Stability of laser (example: J-KAREN)

Power amp mode: 2012.9.27

Spot radius ($1/e^2$, μm)	x: 18.0±1.5 y: 20.7±2.6	8.4% 12.6%
Energy (J)	0.648±0.011	1.8%
Pulse duration (FWHM, fs)	38.5±6.4	16.6%
Pointing (rms, μrad)	x: 4.6 y: 5.9	12% 14%

Intensity

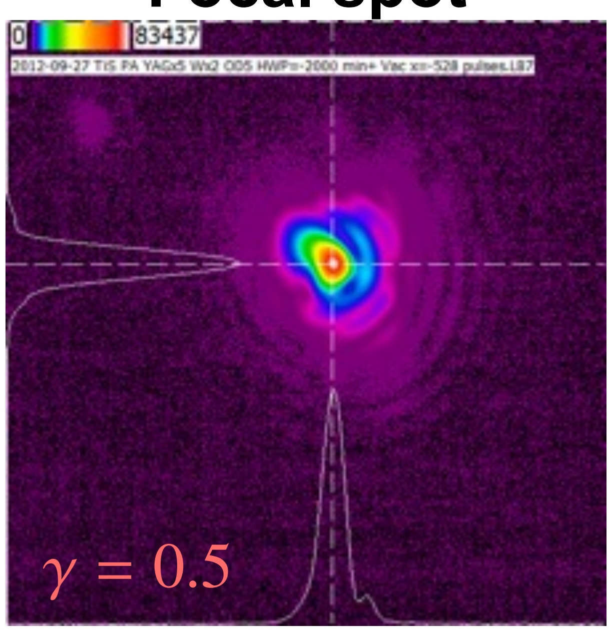
I=(4.3±0.7)×10^{18} W/cm^2 (17%)

a_0=1.44±0.12 (8.6%)

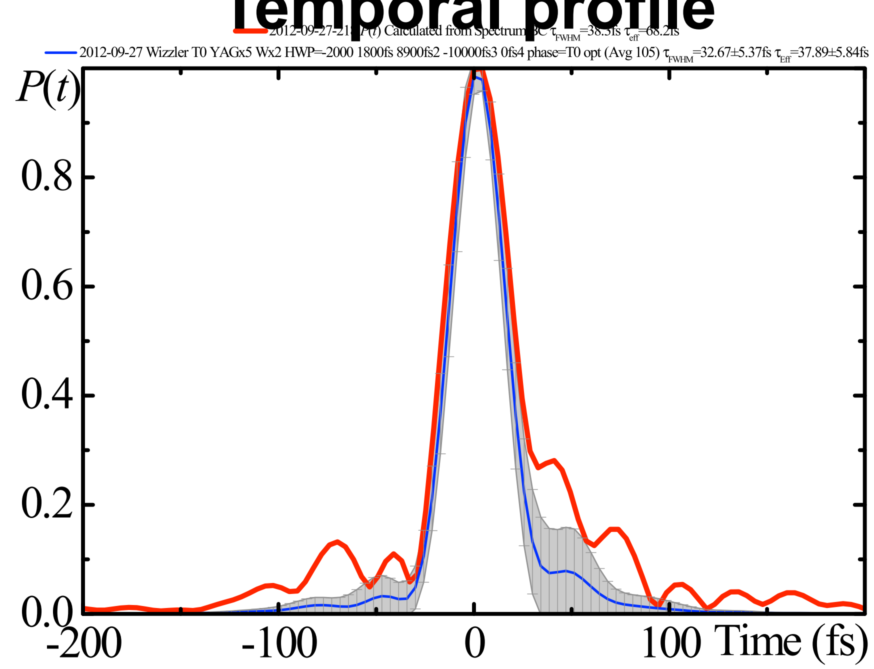
In the project,

- ☐ improve the intensity stability
- ☐ improve pointing stability

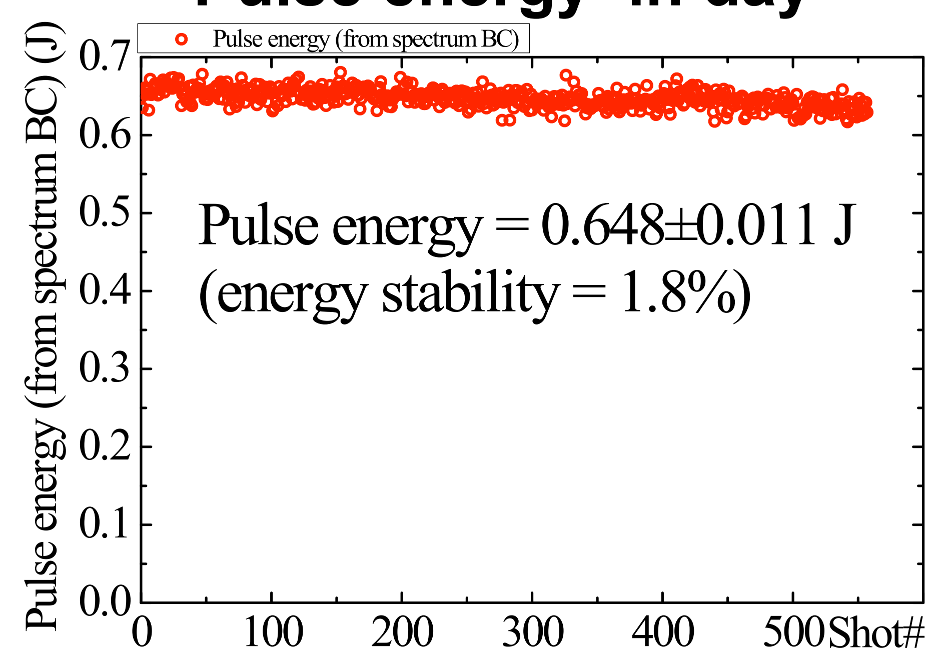
Focal spot



Temporal profile



Pulse energy in day



Causes of instability

- air fluctuation
- vibration from the ground
- temperature drift
- nonlinear effects in laser amp.
- angular chirp
- strehl ratio
- etc.

In this project,

- We will improve laser stability.
    - Test bench, implementation to J-KAREN-P
- The know-how will be used in the Platform laser.

Summary

- The ImPACT program for “laser acceleration based XFEL” has been started.
- Minimum goal : 1 GeV, 1% spread, Q=1pC, t=1fs (kA), 1 μm
- We presented our strategy to get high quality beams with rough estimate. Detailed calculation with PIC is in progress.
- At JAEA, we will measure wakefield, alignment method, booster acceleration, laser control and stabilization.

Call for post-docs! (2 persons, deadline: 30 Oct. 2015)
http://www.jaea.go.jp/english/news/recruitment/re15090901.html