Research on Laser-driven Electron Accelerators in Japan

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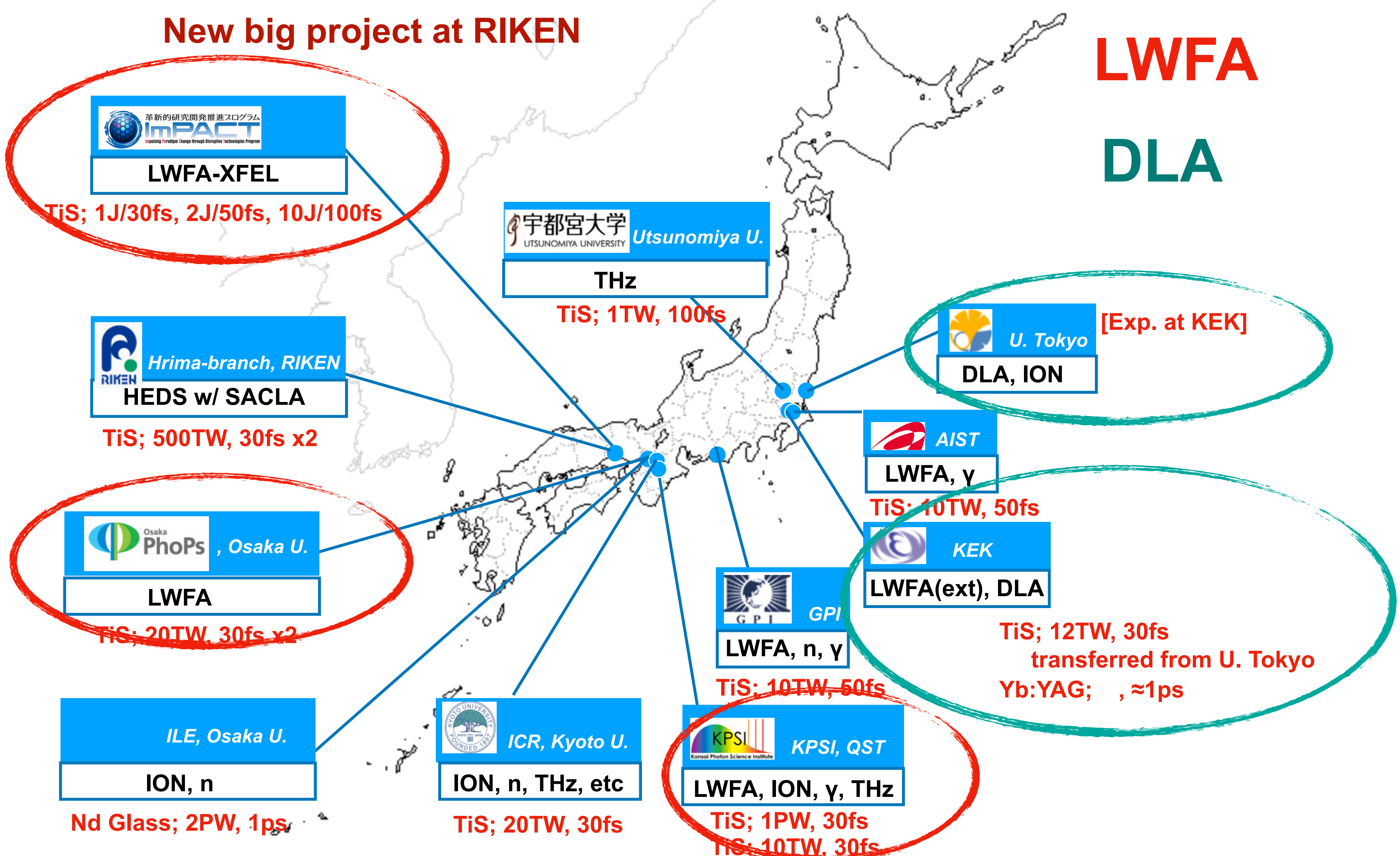
KEK



Project1: Overall Configuration @ LWFA Platform

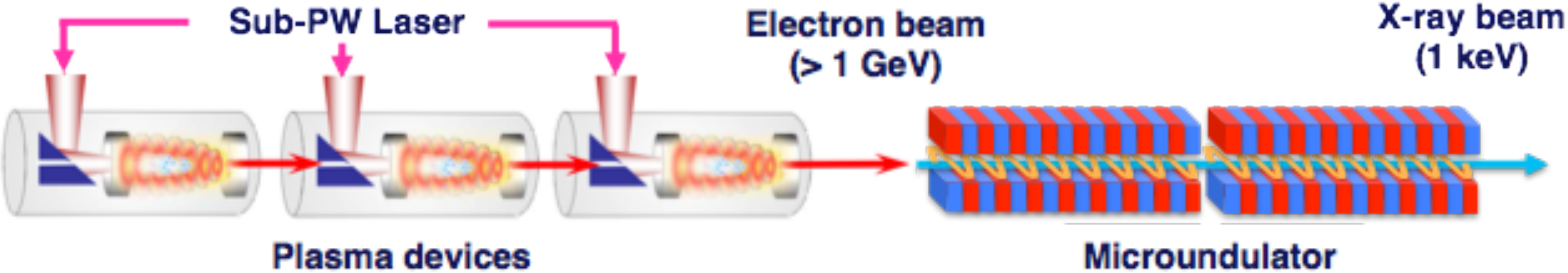
- Development of elemental technologies for future laser-driven XFEL -

***Repeatable** laser-driven GeV-class accelerator.*

Criteria：Acc.length < 10cm、Energy Gain >1GeV,　Energy Spread <1%, beam divergence <1 mm-mrad、Pulse duration ~10fs

PM: Yuji Sano
JST, TOSHIBA Corp.

Project 1B: Integrated platform for laser acceleration
Issue: Multi-stage acceleration and generation of 1 keV X-ray beam by a microundulator with a length of 10 m or less/platform development



Project 1A: Laser acceleration elemental technologies
Issue: Electron acceleration exceeding 1 GeV and modularize it as a plasma device

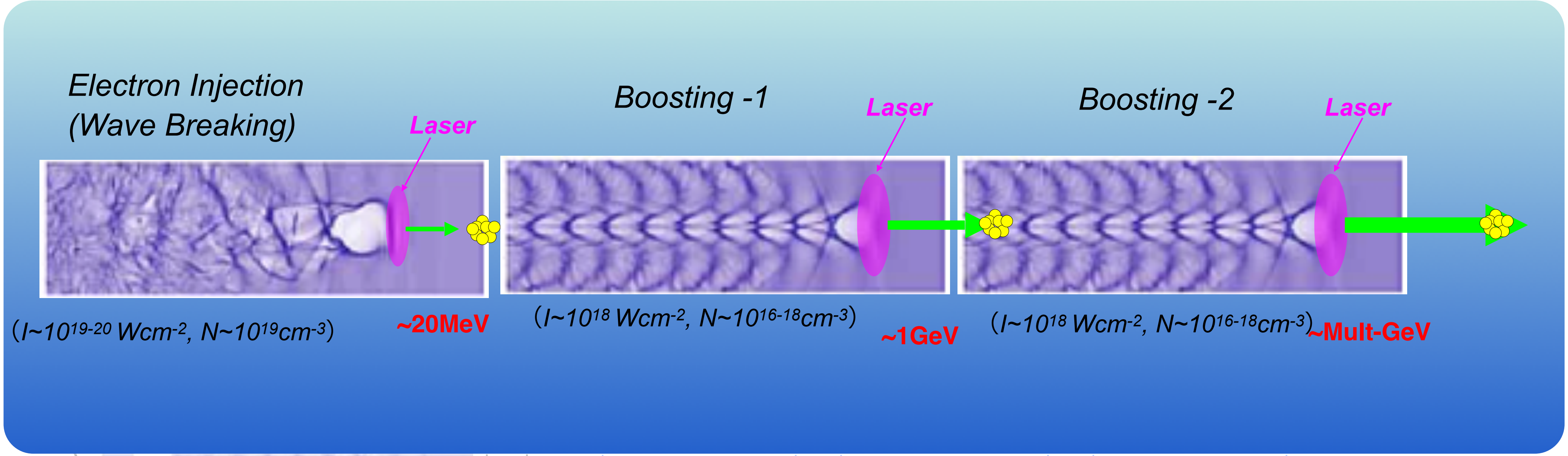
Project 1D: Beam measurement and control
Issue: Control of laser and electrons, and injection of electron to undulator

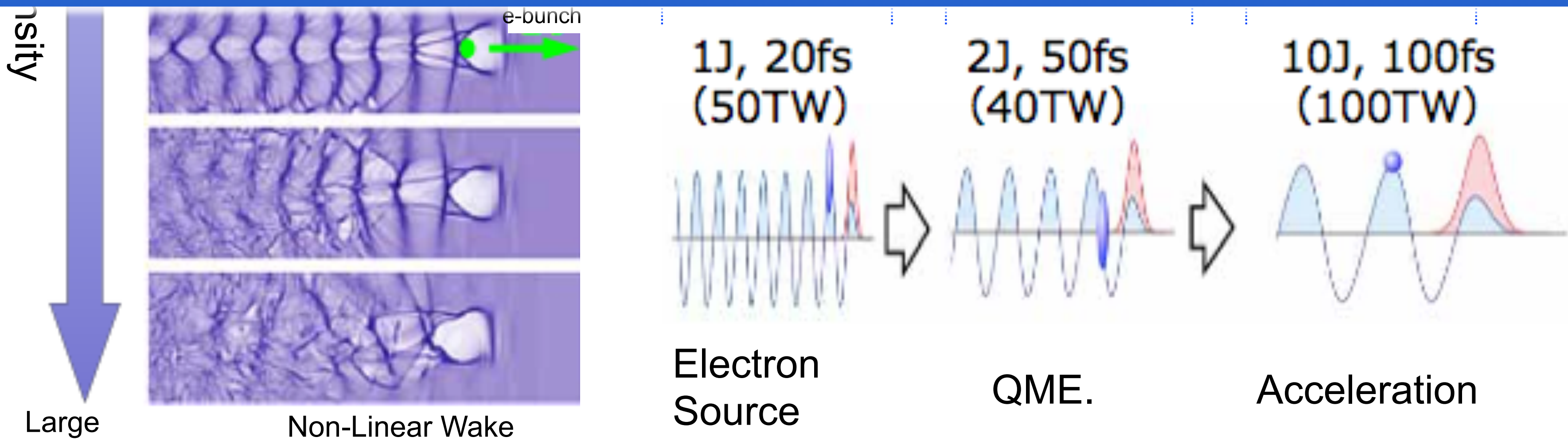
Project 3J: XFEL demonstration assessment
Issue: User demonstrations of laser acceleration XFEL.

Project 1C: Microundulator
Issue: Ultra-compact undulatory generating 1 keV X-ray beam

Project 3L: Evaluation of Microundulator

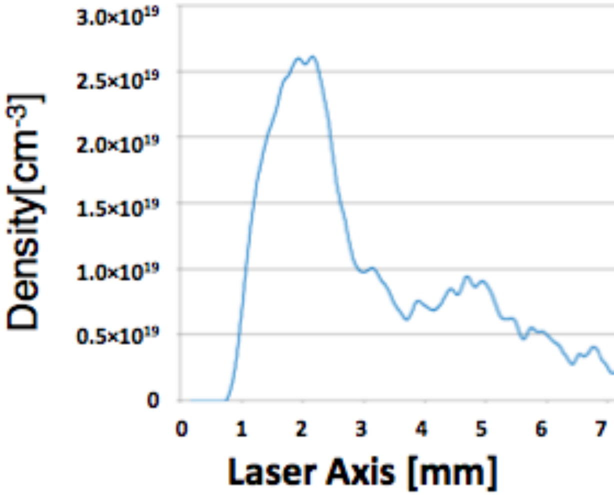
Aiming for Repeatable e-Beam with Staging Laser Wakefields

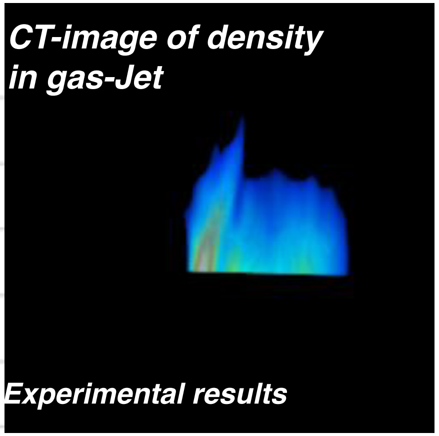


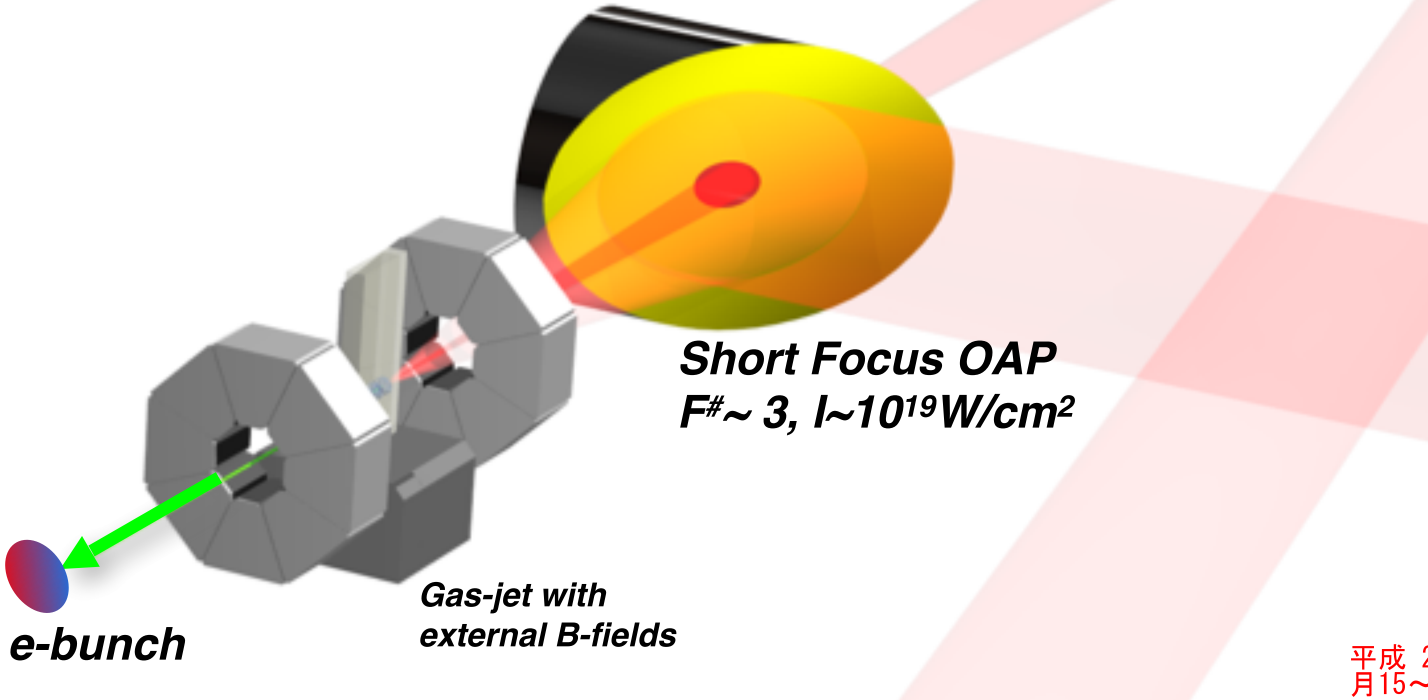


Proof-of-Principle;
Setup for Staging LWFA with Single Gas-jet Target

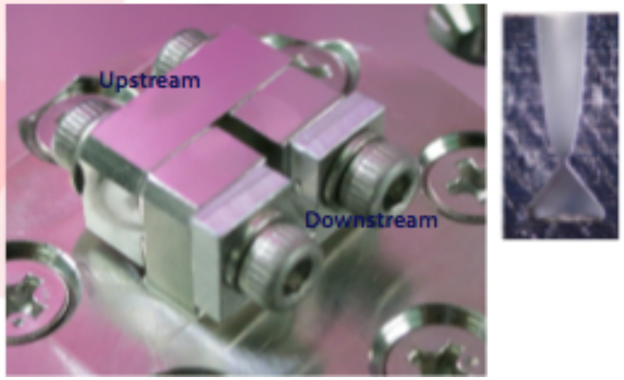
1. Stable supersonic gas-jet with step-density profile.







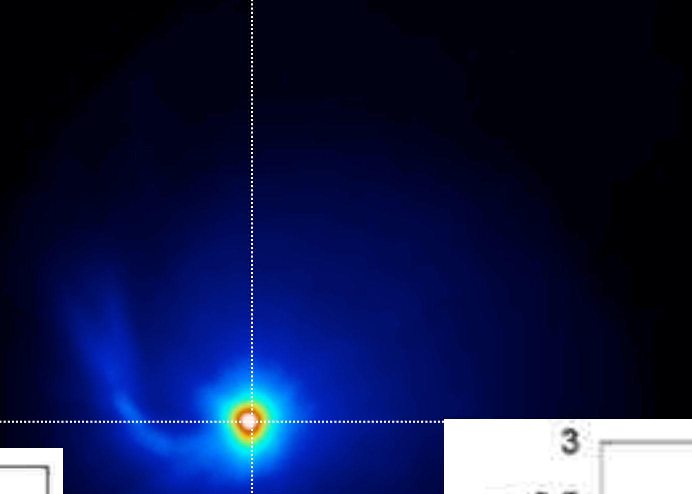
Asymmetric Laval nozzle



B~0.2T, Energy 600mJ

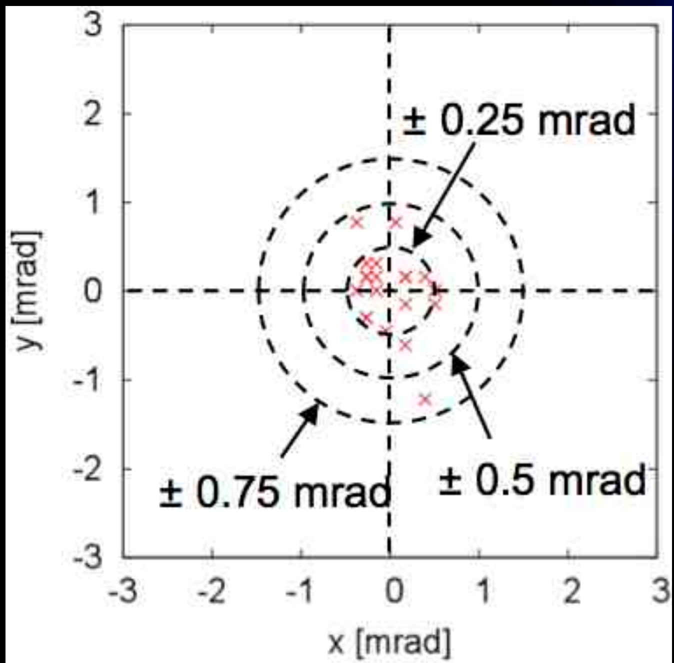
3

PMO provides excellent pointing stability !



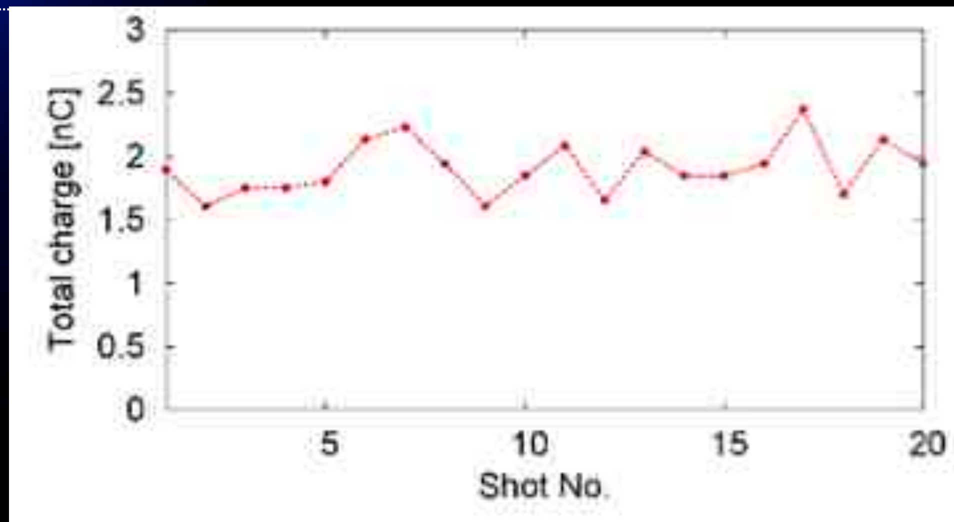
Pointing Stability

< ±200μrad



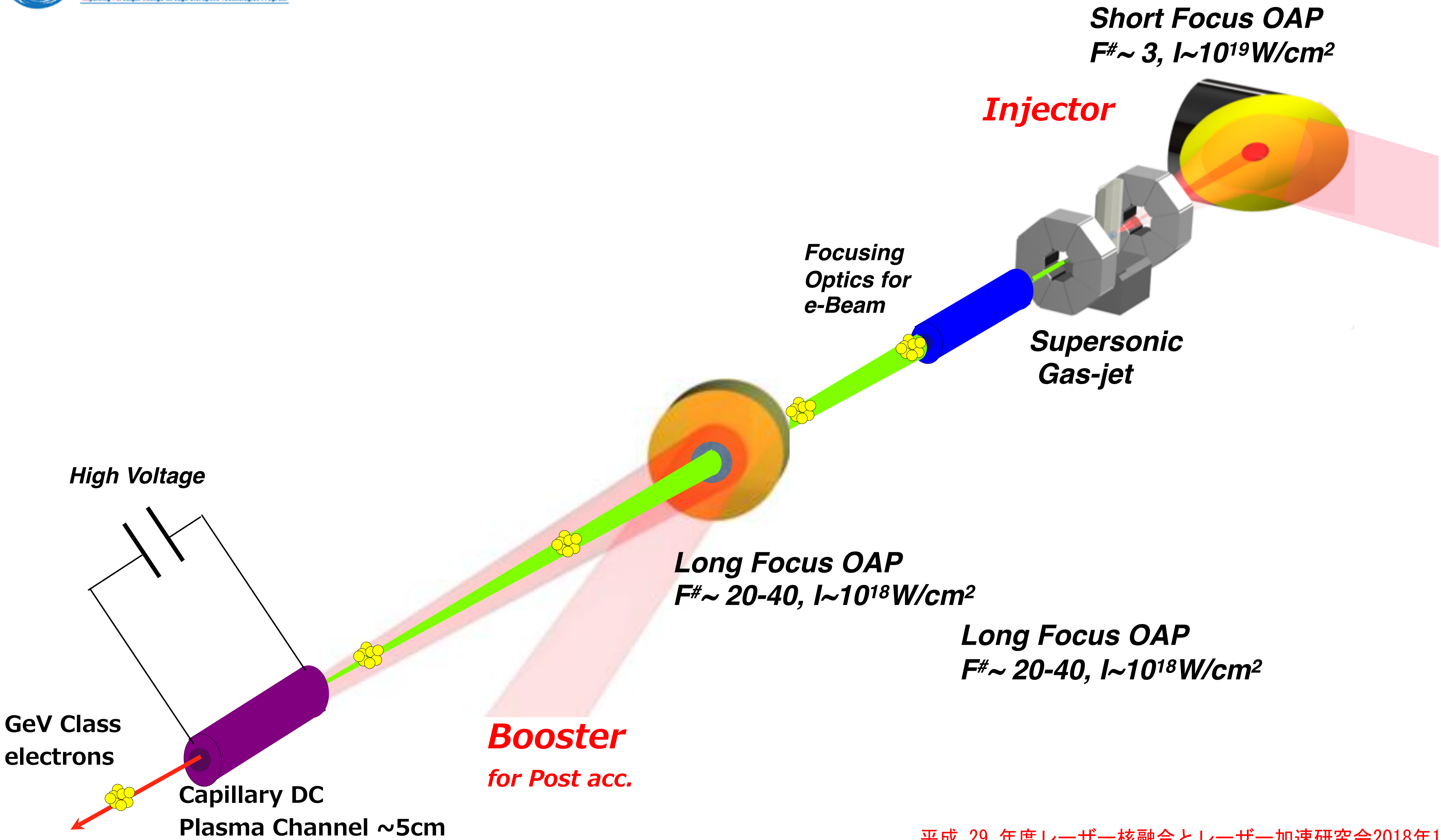
Total Carge

< 2nC ± 5%



The Picture of Staging LWFA at ImPACT Program

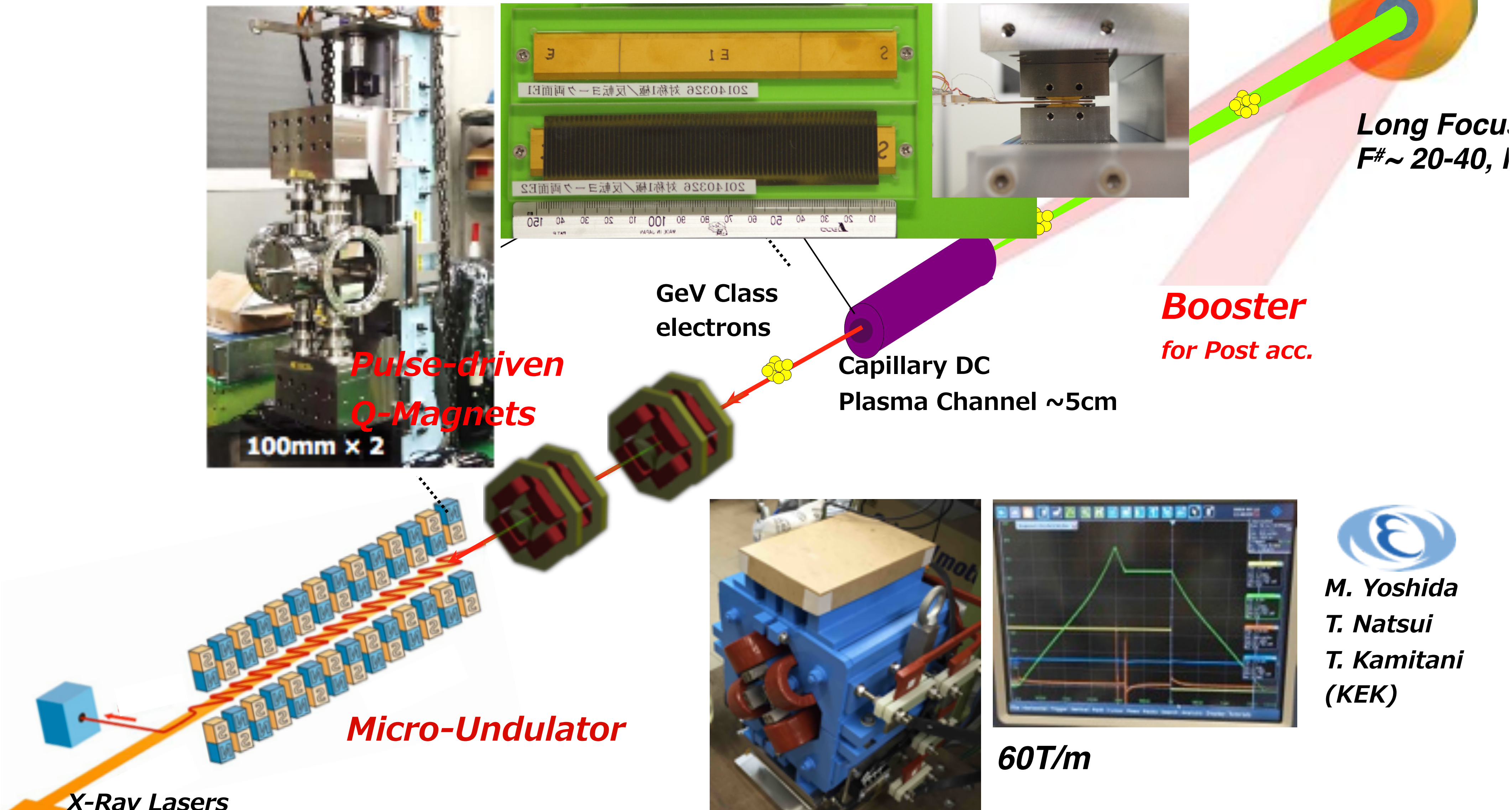
- Development of elemental technologies for future laser-driven XFEL -



Towards Laser-driven XFEL

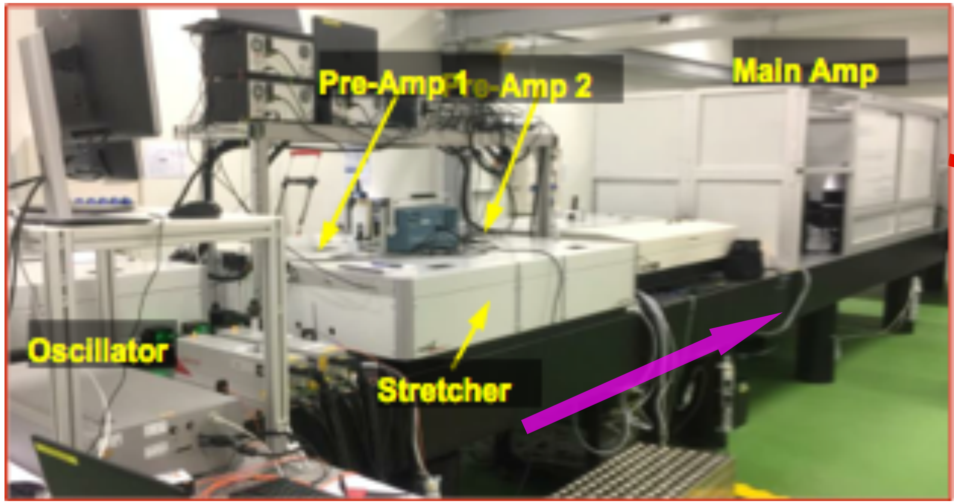
ImPACT-UPL; Pj1-1C:
Micro-Undulator

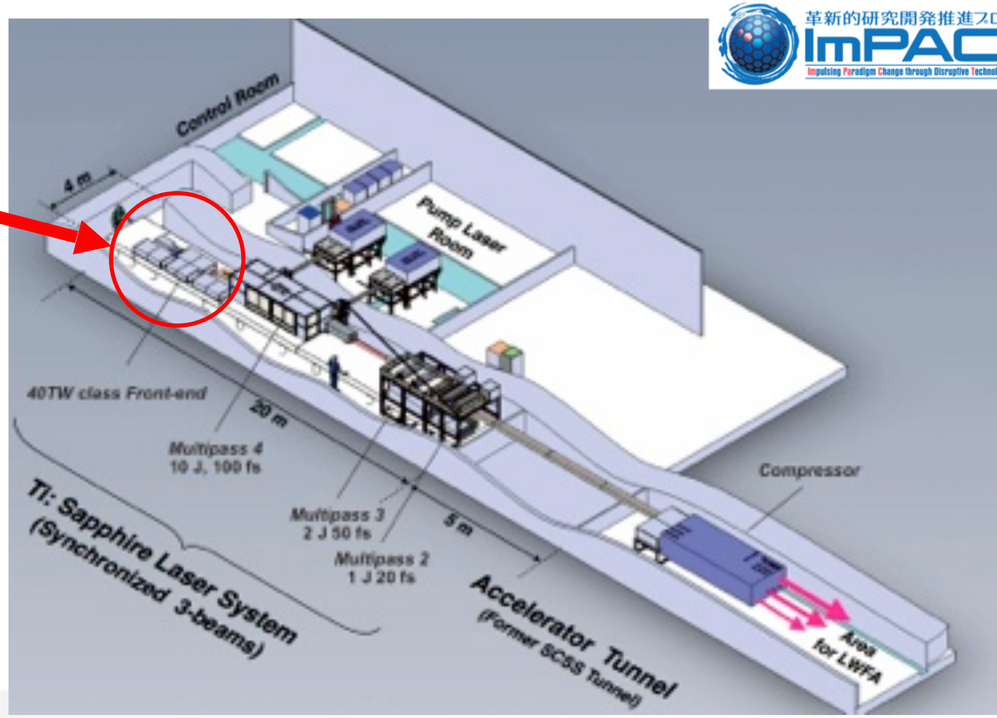
S. Yamamoto
(KEK)

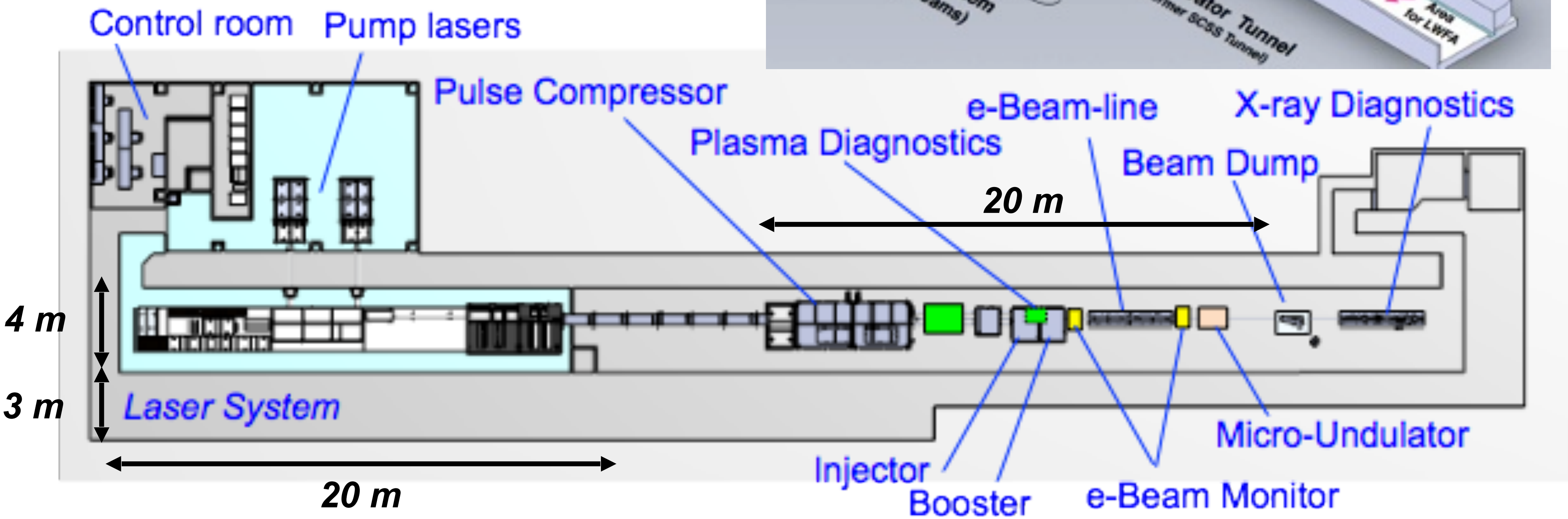


New Facility for LWFA @ SPring-8 Campus

LWFA Platform Laser & Acc Tunnel @ SPring-8 Campus







The First Shot at LWFA Platform (SP-8) was done on Jan. 14, 2018

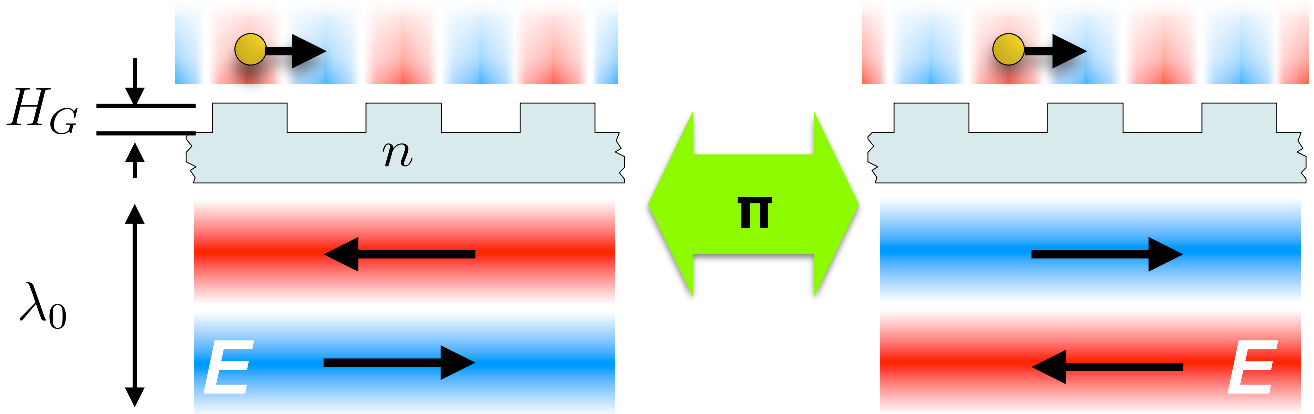
Summary

- ☑ Staging LWFA (Injector-booster scheme) has been demonstrated.
  We believe this technique can be scalable to repeatable GeV-class accelerators.
- ☑ Well-defined injector QME e-beam can be delivered repeatably to ~ 2 m downstream (position for boosting as 2nd stage).
- Chanel guide LWFA with preformed (discharge) plasmas has started.
- LWFA R&D program aiming for laser-driven XFEL(ImPACT-UPL) is on going, and LWFA platform is under construction at SP-8 Campus in Japan.

DLA ; Dielectric Laser Accelerator

Principle of the electron acceleration

In case $\frac{H_G}{\lambda_0} = \frac{1}{2(n-1)}$ **,**



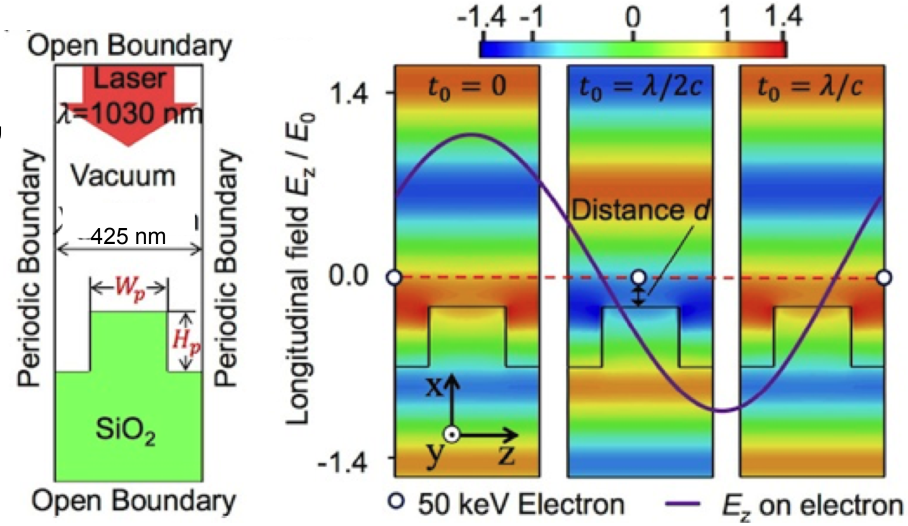
Optimum dimension

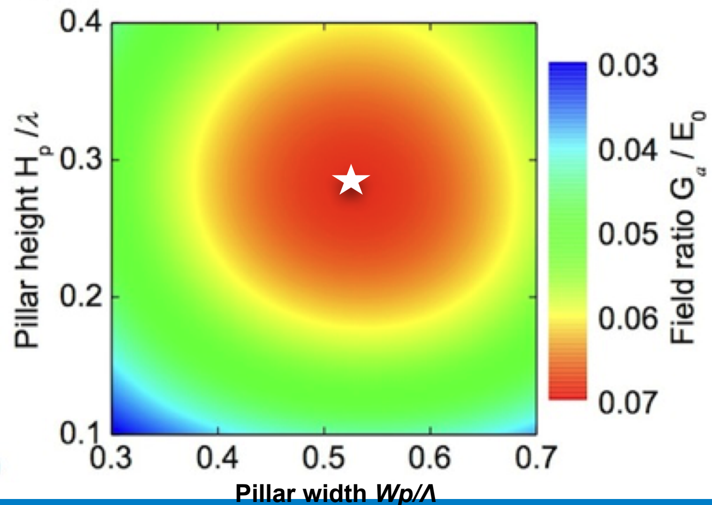
Λ = 425 nm,
Wp = 225 nm
Hp = 288 nm
L = 15 μm

$$\mathrm{div}\mathbf{D} = \mathrm{div}(\varepsilon\mathbf{E}) = 0$$

The evanescent field around the grating surface accelerates electrons.

In case $H_G < \lambda_0$ **,**





Electrons in a single grating DLA

$$E_z = \frac{icB_0}{\beta\gamma} e^{i(k_{mz}z + k_{my}y - \omega t + \phi)}$$

$$E_y = \frac{-cB_0}{\beta} e^{i(k_{mz}z + k_{my}y - \omega t + \phi)}$$

$$B_x = B_0 e^{i(k_{mz}z + k_{my} - \omega t + \phi)}$$

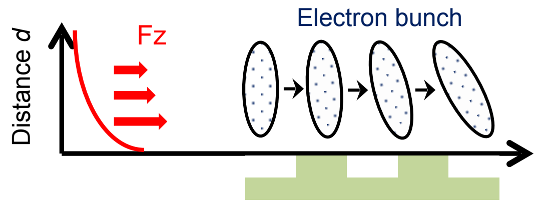
$$\beta = v/c = \lambda_G/\lambda_0, \quad \gamma = \left(1 - \beta^2\right)^{-1/2}$$

$$k_{my} = m2\pi/\beta\lambda\gamma$$

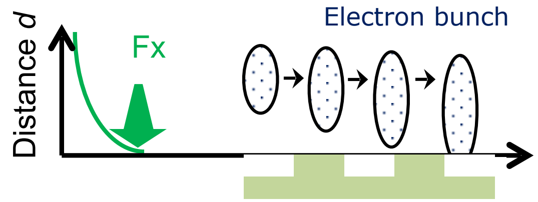
$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

$$F_z = -\frac{ec}{\beta\gamma} B_0 e^{-\frac{2\pi x}{\beta\gamma\lambda}} \sin(\phi)$$

$$F_x = \frac{ec}{\beta\gamma^2} B_0 e^{-\frac{2\pi x}{\beta\gamma\lambda}} \cos(\phi)$$

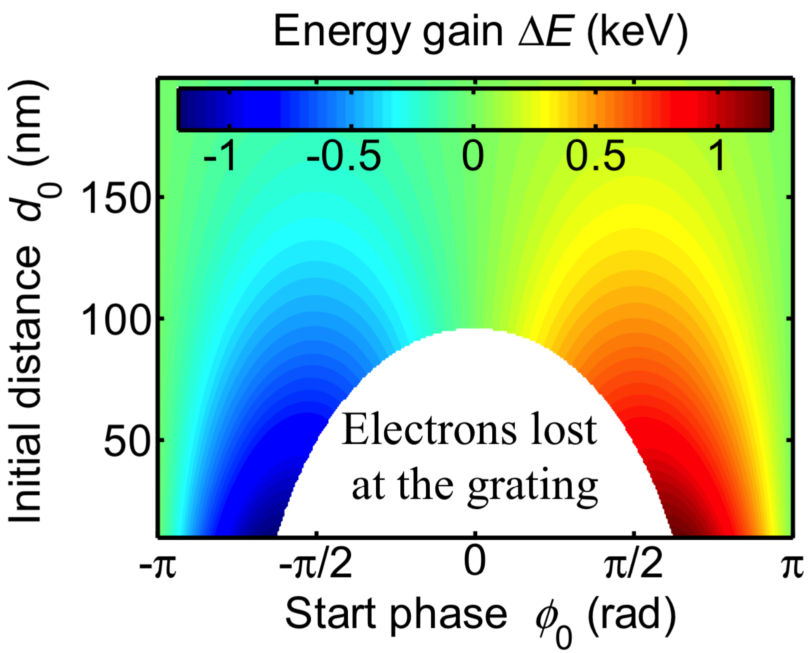


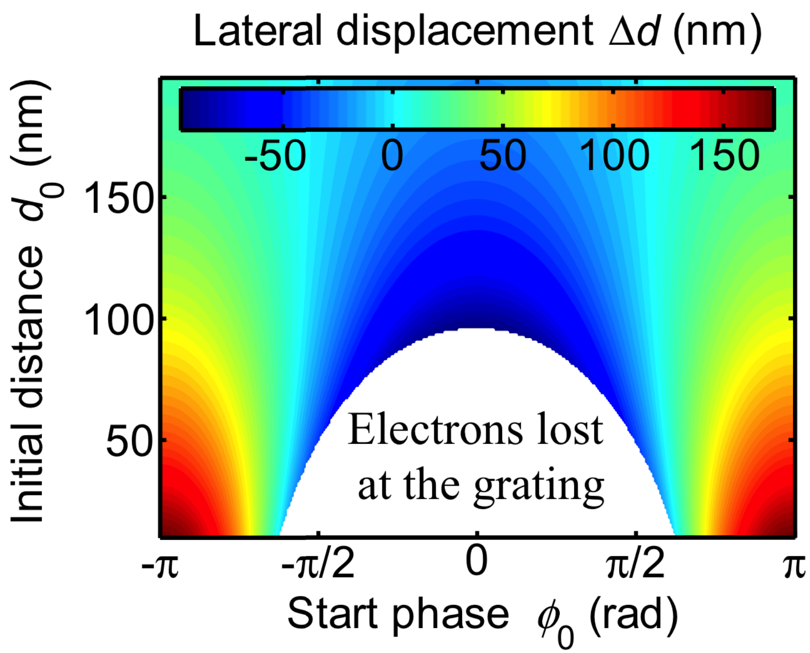
Large longitudinal field: Energy spread



Large transverse field: elongate

The strong deflection of electrons to the grating causes the loss of electrons.





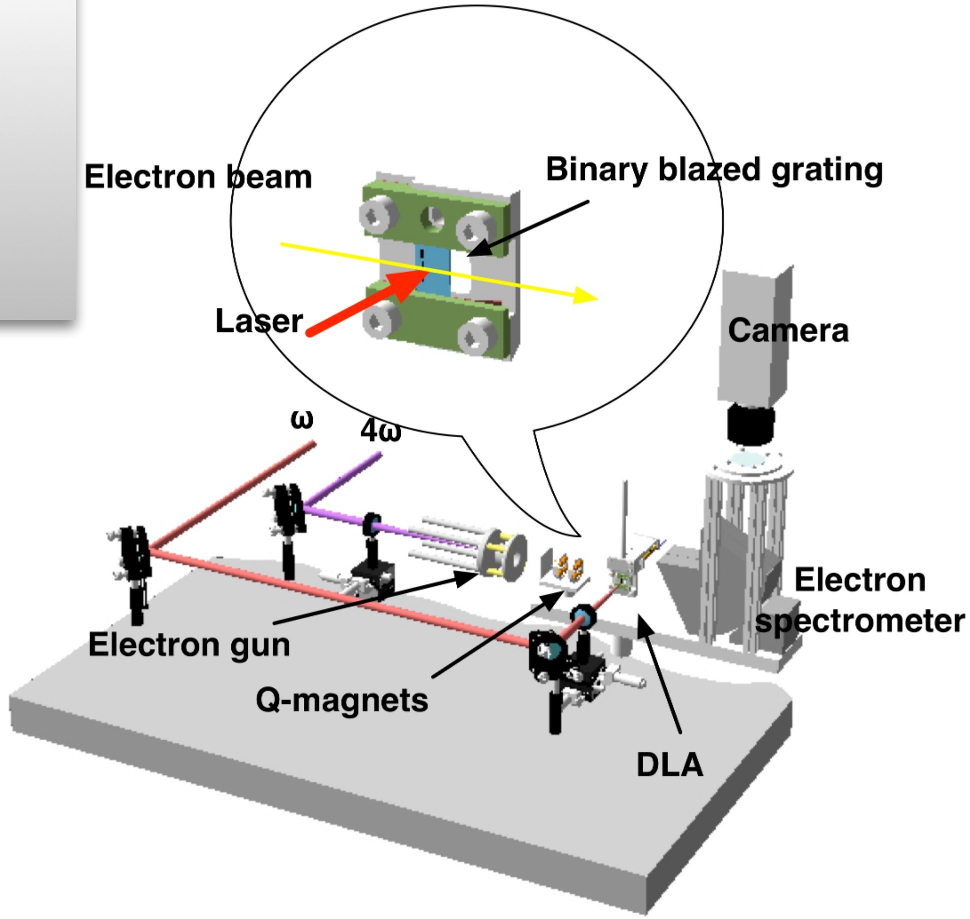
Grating and the setup of acceleration experiment

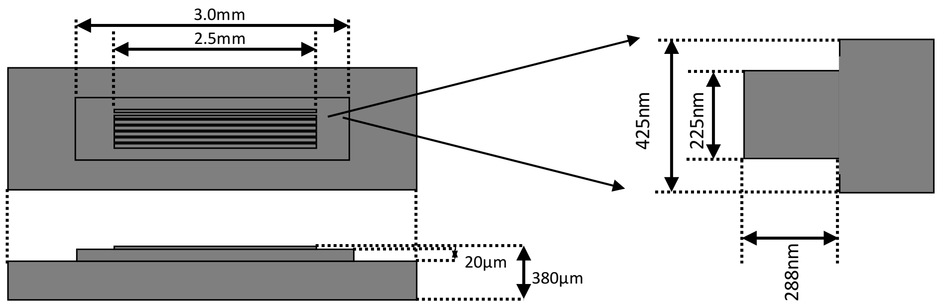
By the simulation

Λ = 425 nm,
Wp = 225 nm
Hp = 288 nm
L = 15 µm

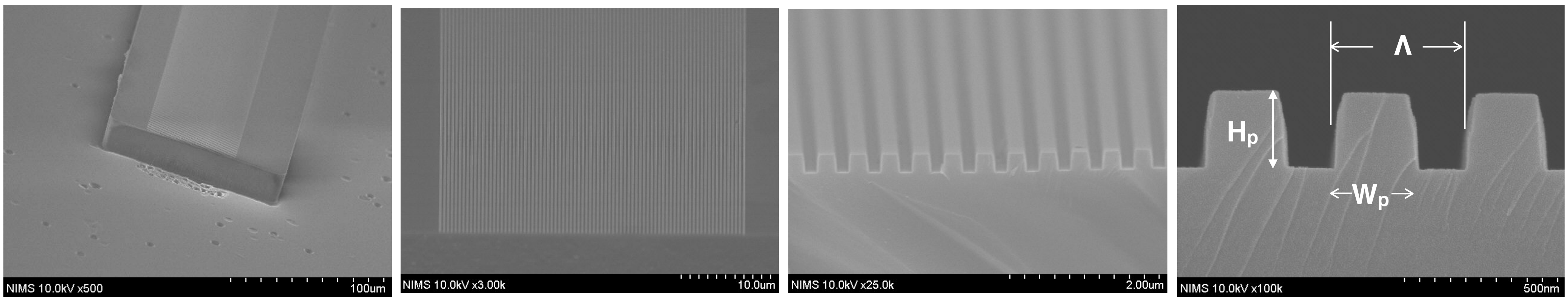
Fabricated grating

Λ = 425 nm,
Wp = 153 - 218 nm
Hp = 272 nm
L = 15 µm





Fabricated at the NIMS nonofab-platform.

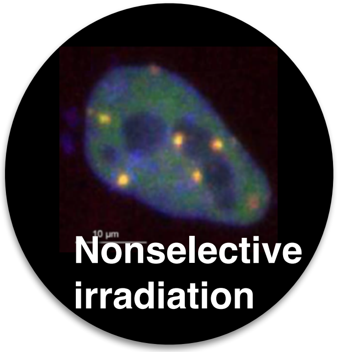


Application of DLA to the radiotionbiology research

A tabletop micro-beam machine makes it possible to irradiate a target site in a living cell.

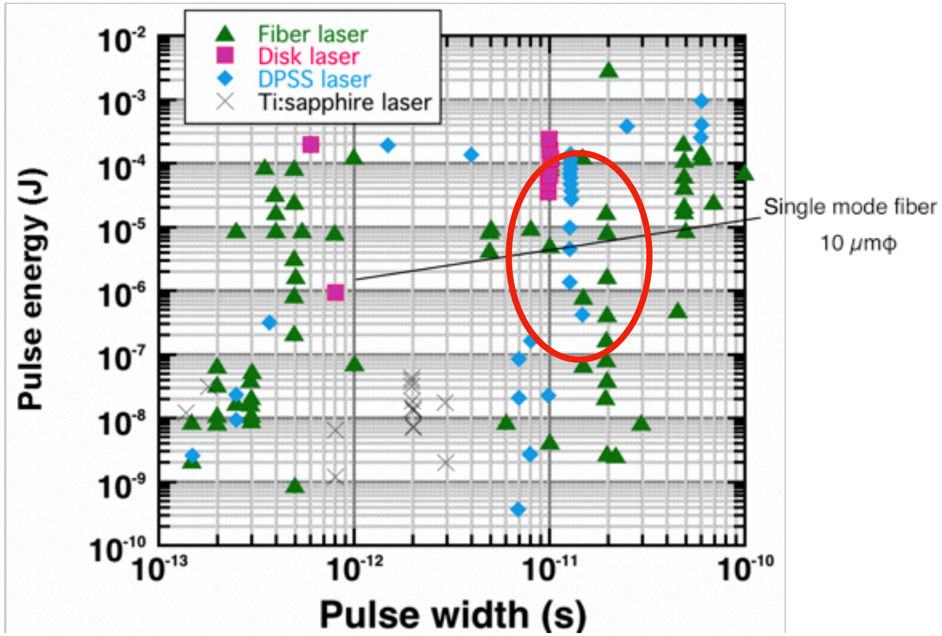
>100 electrons
≈1 MeV energy

K.Koyama, et al., J. Phys. B: At. Mol. Opt. Phys, 47, 234005 (2014) .
M. Uesaka, et al., Rev. Accel. Sci. and Tech., 9, 235 (2016) .

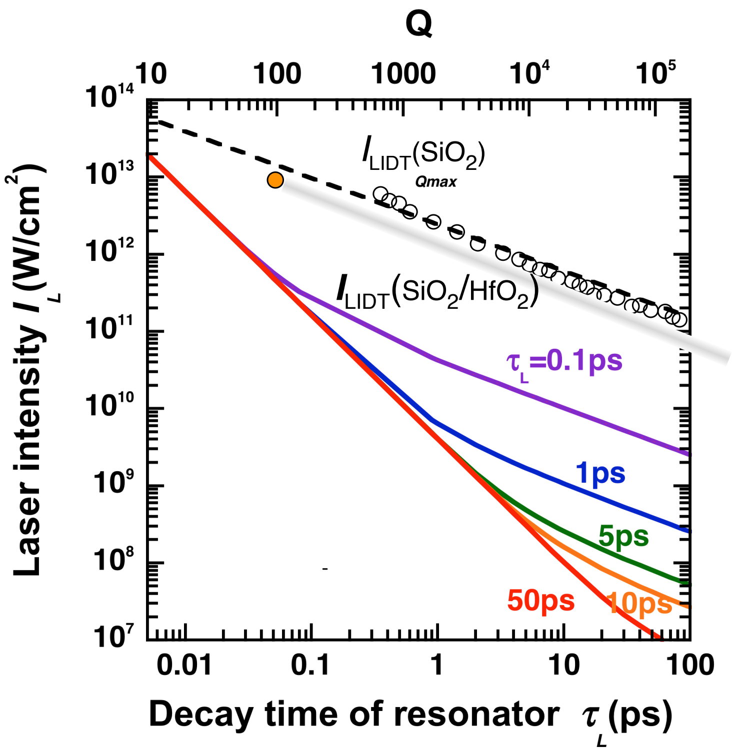


The DLA can produces the micro-beam with a sub-micron channel of the accelerator

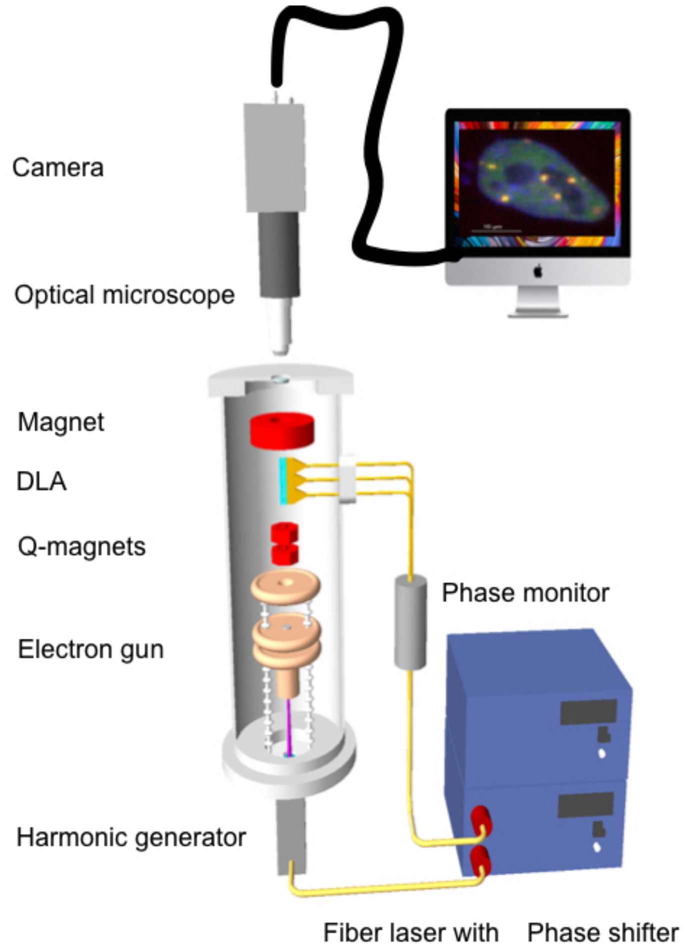
A whole system including a laser must be compact.



Resonator DLA energized by a compact laser



By adopting a high Q resonator to store the laser energy, the intense acceleration field might be produced by the moderately low intensity laser irradiation of long laser pulse (1 - 10 ps).



The reflectivity of the multi-layer of 8 HfO_2/SiO_2 pair is 99.6 %. The Q-factor is 390.

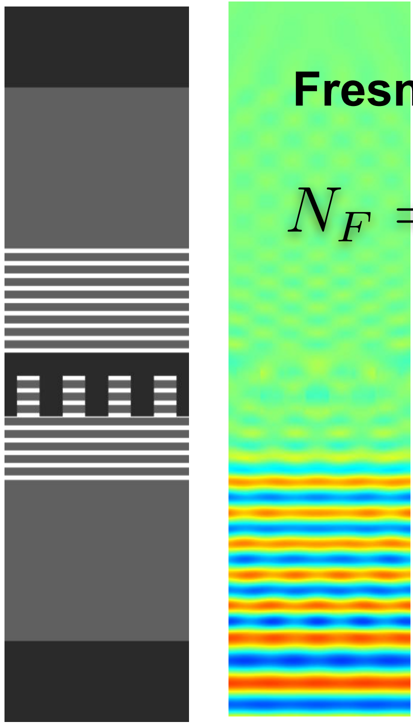
The multi-layer mirror of HfO_2/SiO_2 has high laser induced damage threshold (LIDT).

Multi-layer FP resonator DLA

Longitudinal electric fields of FP DLAs.

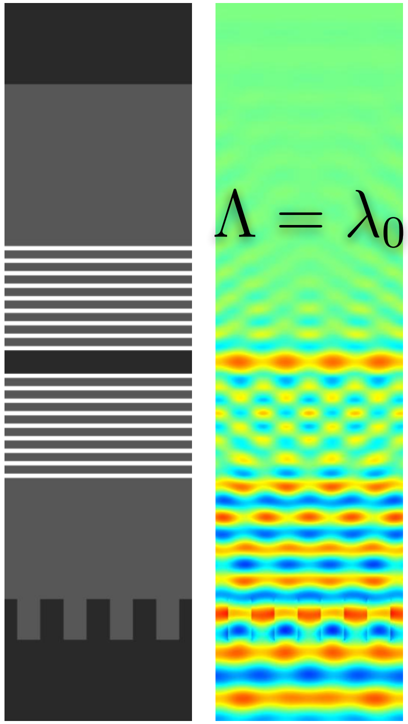
The grating is on an inner wall of the FP mirror.

The grating is on an outer wall of the FP mirror.



Fresnel number

$$N_F = \frac{a^2}{\lambda_0 \ell}$$



$$\Lambda = \lambda_0$$

The grating is on an outer wall of the FP mirror.

Small Fresnel number

$a \leq \lambda_0/4$

$\ell \sim \lambda_0/2$ $\quad N_F \lesssim 0.125$

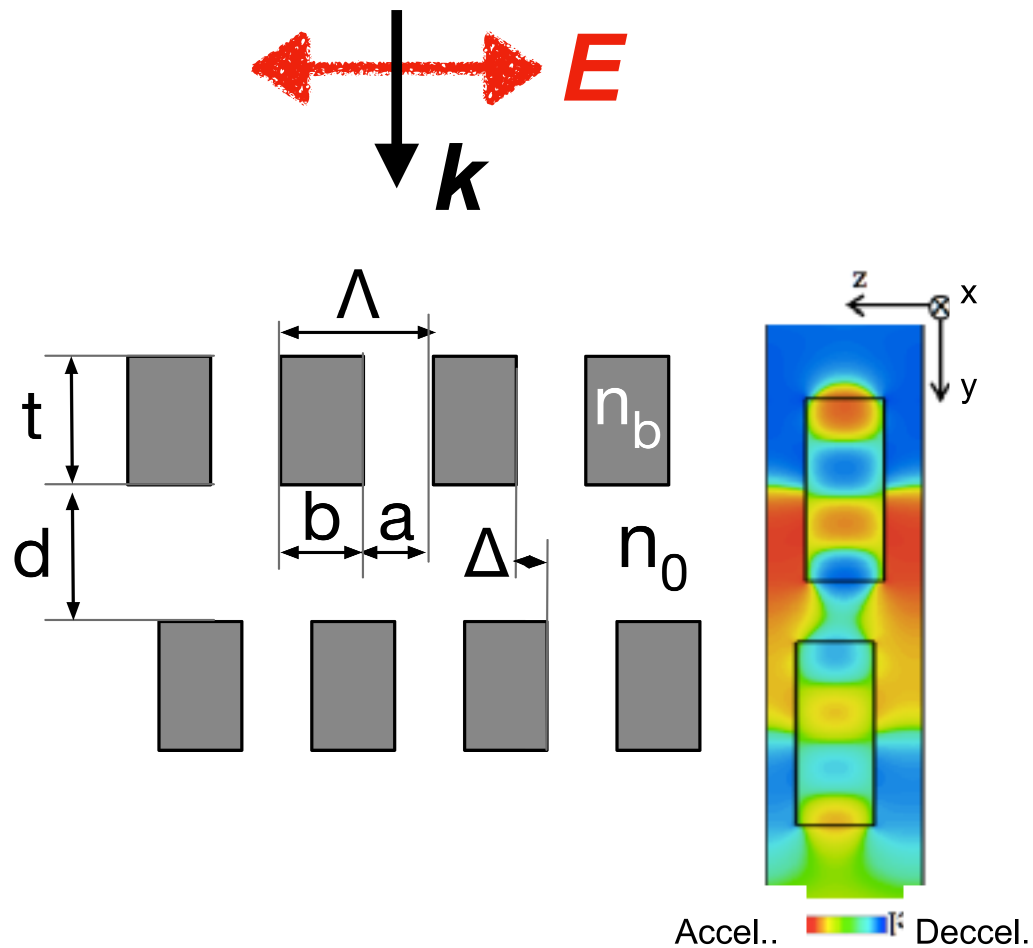
Low Q (Low Finesse)

Large Fresnel number

The image of the field is transferred to the resonator by the Talbot effect.

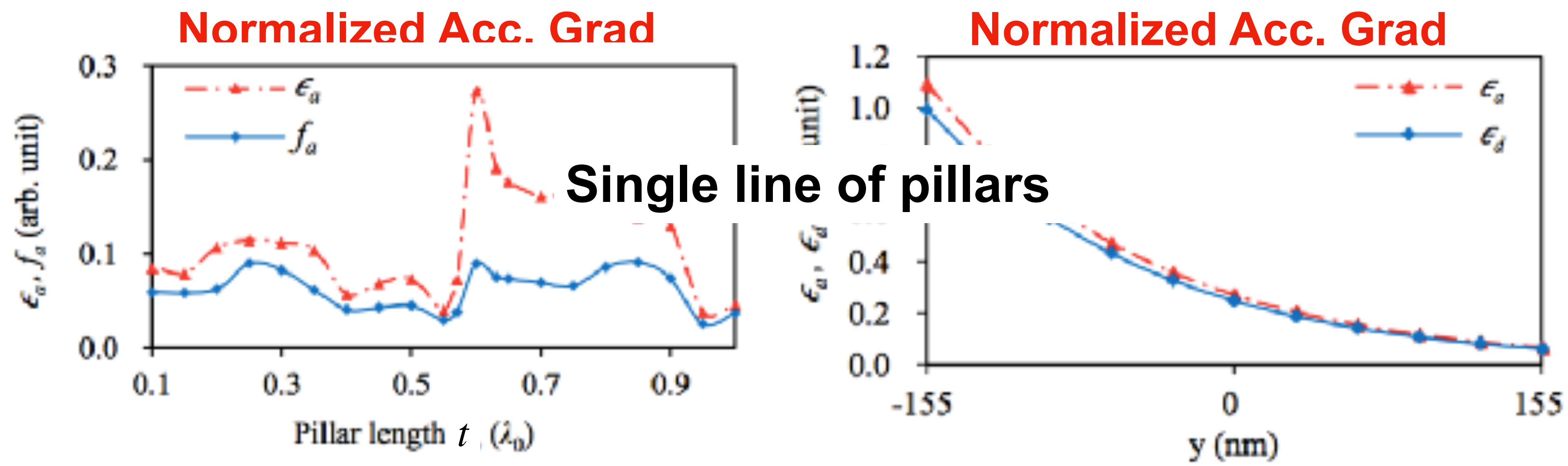
Talbot length $Z_T = \dfrac{\lambda}{1 - \sqrt{1 - \frac{\lambda^2}{\Lambda^2}}}$

Colonnade FP DLA

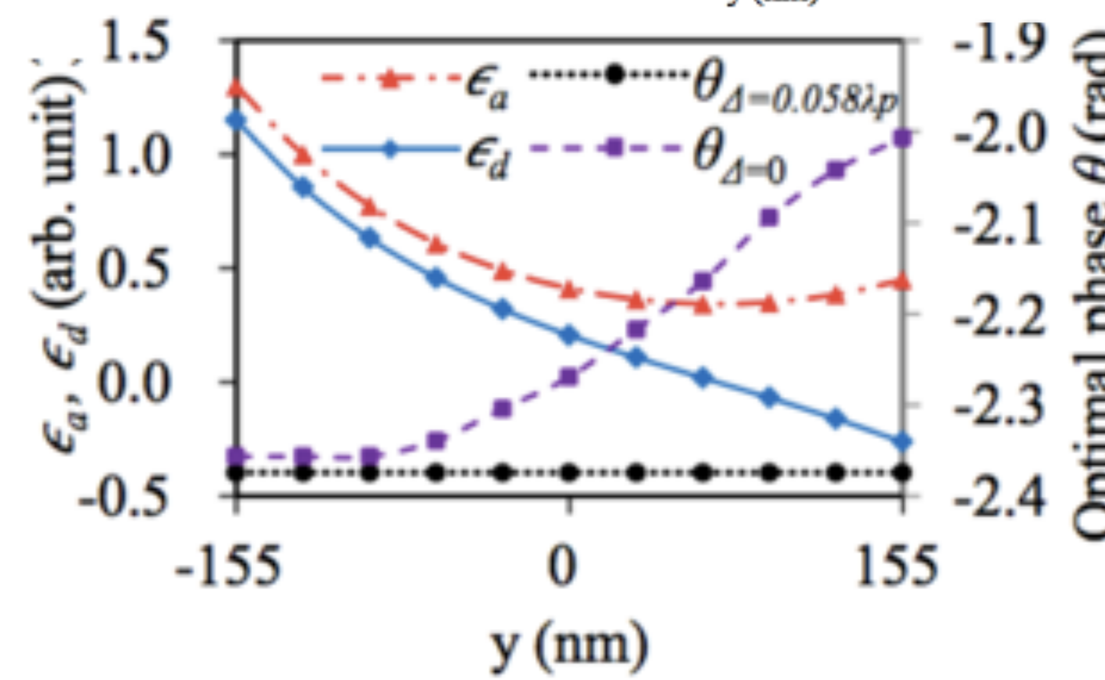


Dual lines of pillars

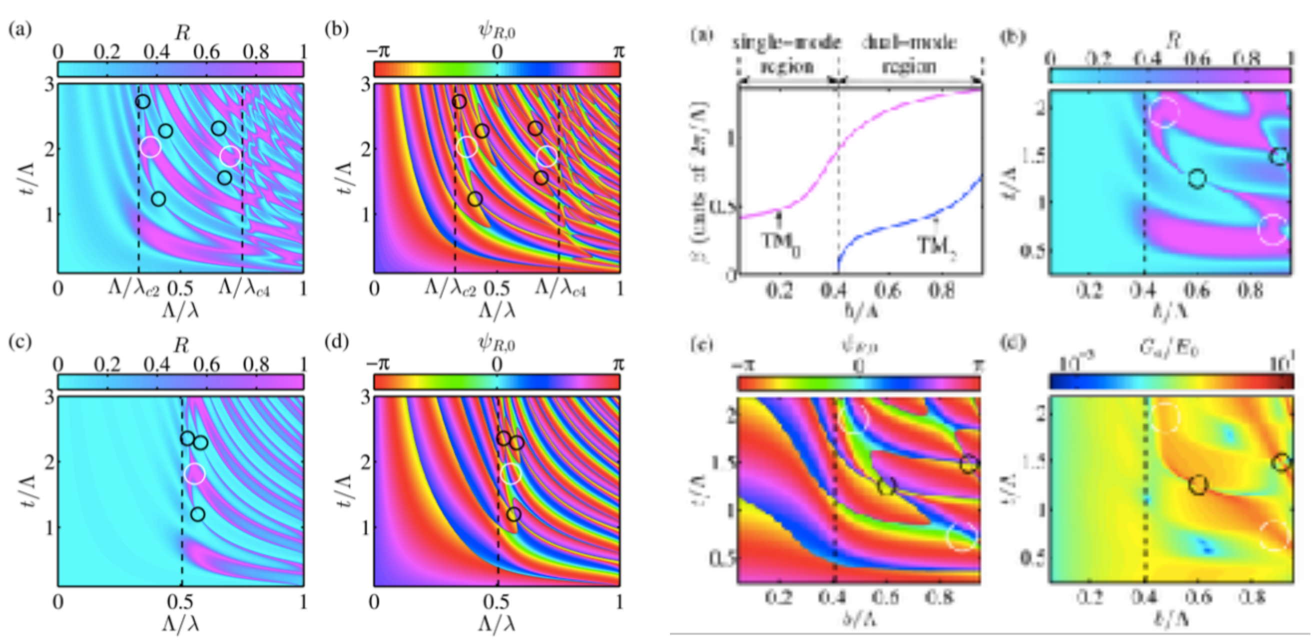
Z. Chen, et al., Rev. Laser Eng. **45**, 97-101 (2017).



Single line of pillars



Z. Chen, et al., Appl. Phys. Lett. **112**, 034102 (2018).



Laser

Wavelength 1550 nm

Peak fluence. 61 mJ/cm^2

Pulse length 100 fs

Acceleration

Maximum gradient; 0.73 GV/m for 50 keV electrons

Normalized acceleration gradient; 0.34

Acceleration factor ; 0.11 on axis.

Summary

LWFA is conducted under the ImPACT program, in order to demonstrate a LWFA based FEL.

(Osaka University, KPSI of QST, and KEK)

Pointing stability ≤ 200μrad, Charge ≤ 0.2 nC /pulse

Results of ImPACT program is utilized for the next research program, which is performed at Harima-branch of RIKEN.

Post acceleration in long plasma channels

Research on DLA is conducted, in order to deliver a micro-beam for the radiation biology research.

Sub-relativistic electron (< 1MeV)
Binary blazed gratings were fabricated.
The resonator-type DLA is studied.