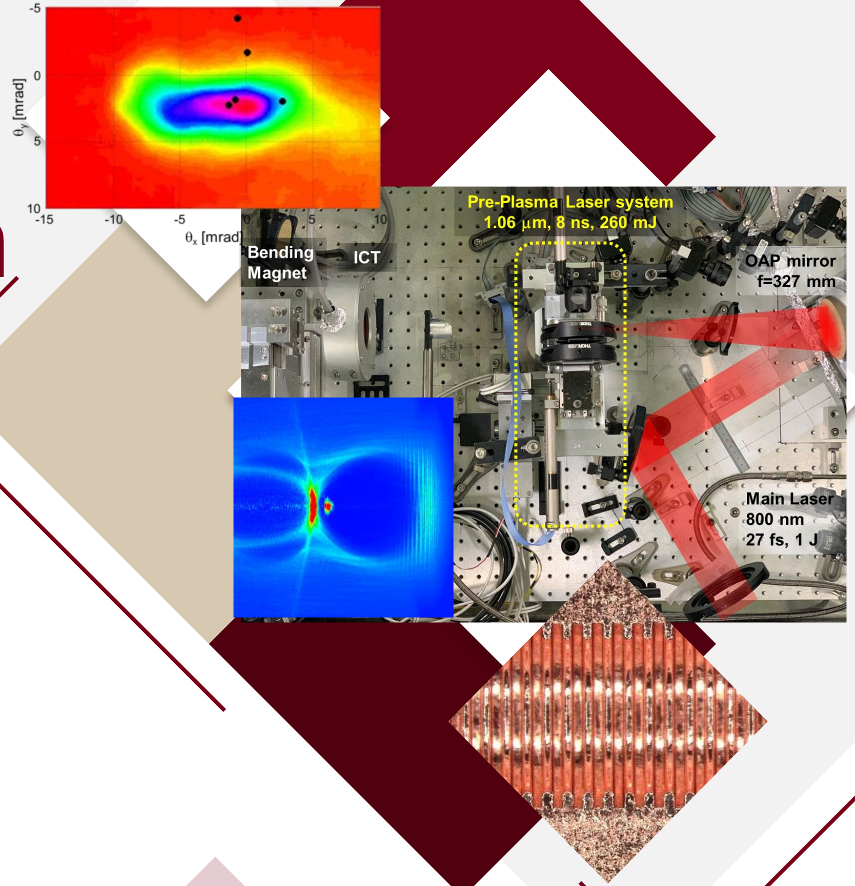
Korea University – IHEP Workshop

October 14~15, Korea University Seoul, Korea

Plasma Acceleration Research at KU



2024. 10. 15

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Korea University Sejong Campus

In Collaboration with

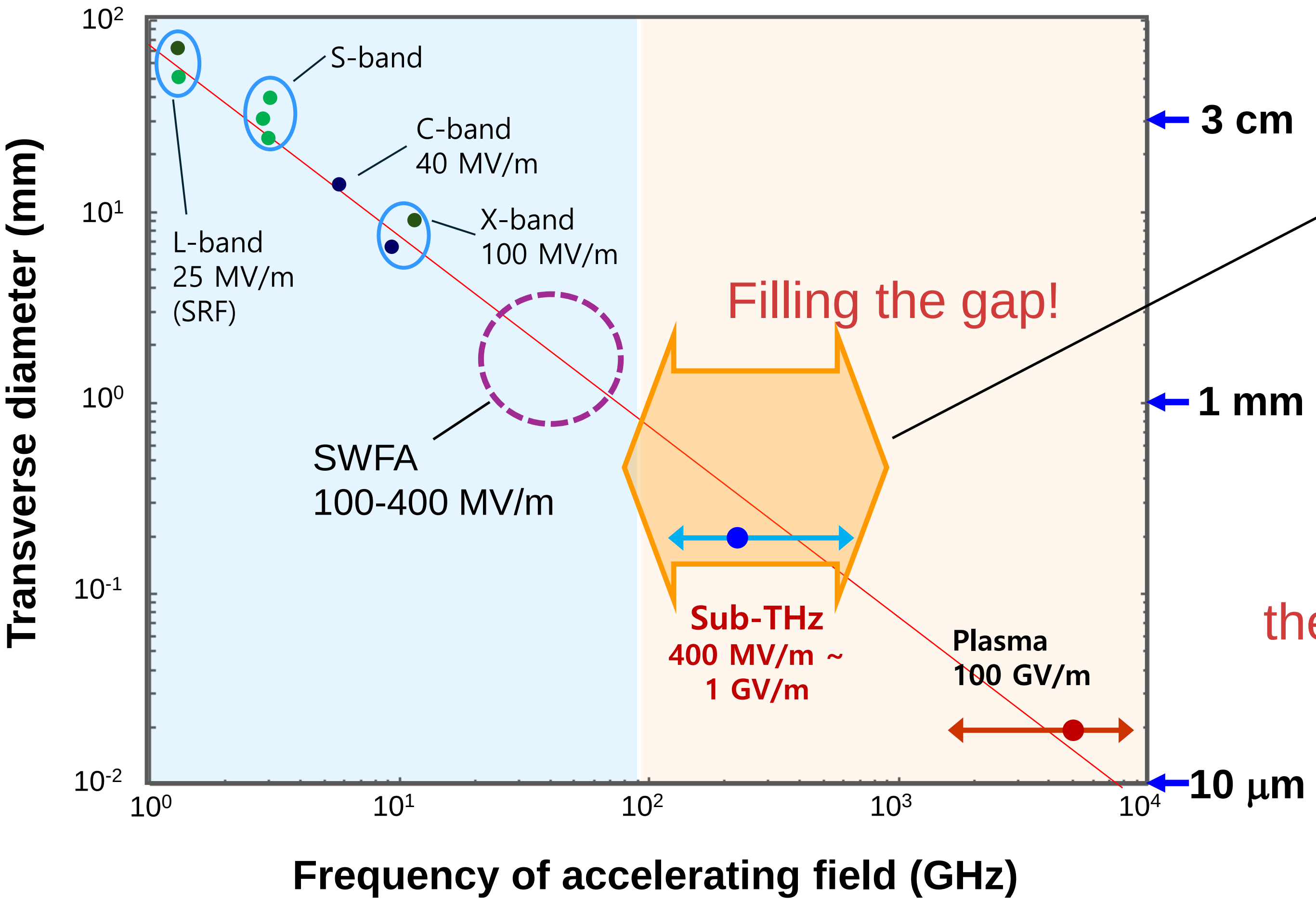
KAERI, KERI, SBU, NIU, ANL/AWA, PAL

In Collaboration with

- KAERI : K. Lee, H.-N. Kim
- KERI : J. Kim, K.-N. Kim, Y. Hwangbo
- UNIST : I.H. Nam
- Stoney Brook Univ. : V. Litvinenko
- Norther Illinois Univ. : G. Ha
- Argon National Lab./AWA : J. Power, G. Chen, E. Wisniewski, S. Doran, W. Liu
- Pohang Accelerator Lab. : J. H. Kim, H. Kong, H. J. Kwak, J. Kim, S.-H. Kim

Center for Compact Hybrid Accelerator Technology

Accelerator Size · Accelerating Gradient · RF Frequency



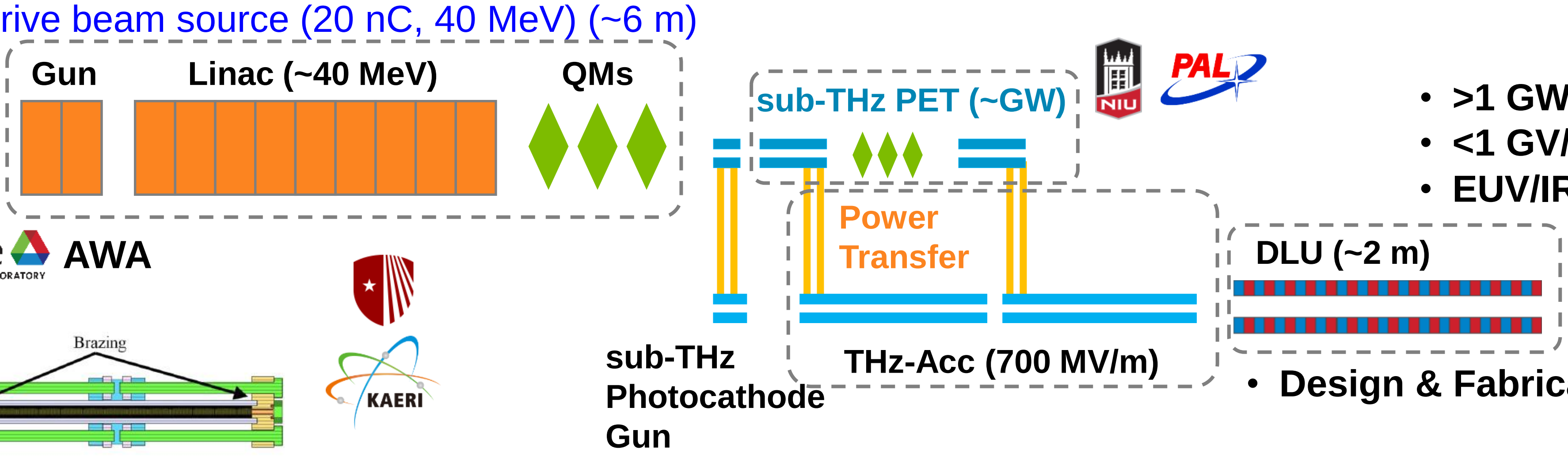
Could be…

- Higher gradient than GHz-SWFA
- Higher stability than plasma
- Compatible with nC charges

One of major challenges is
the fabrication of micro-structures

Milestones

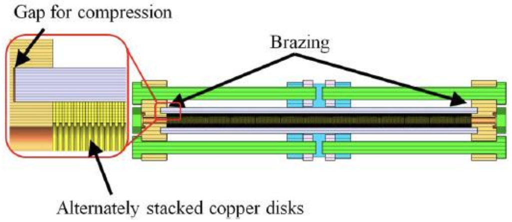
*PET : Power Extraction Tube

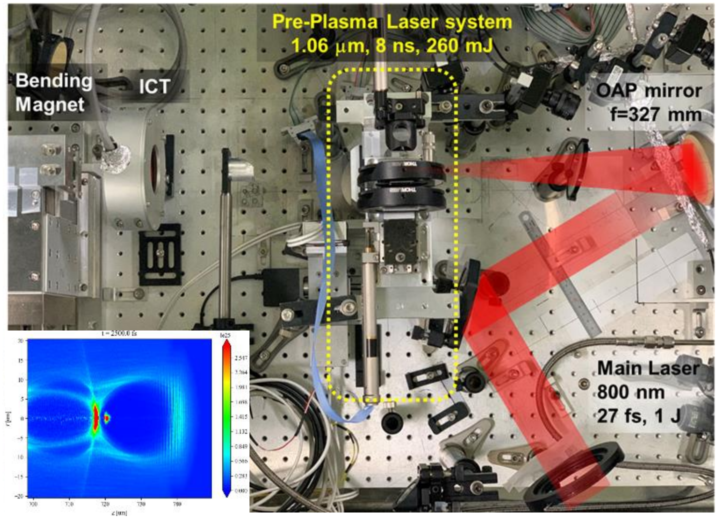


- >1 GW THz power
- <1 GV/m gradient
- EUV/IR generation @AWA tunnel

- Design & Fabricate a few sections, Testing

Argonne NATIONAL LABORATORY **AWA**





Short term demo: High Power generation from single PET

- High charge (~1 nC/bunch) bunch train (16 or more)
- Structure design and fabrication
- Experimental THz characterization method
- Experimental prep. (beamline design and RF measurement)
- **400 GHz structure for demo** of high-power and high-gradient, Fabrication

Long term demo:

- Drive beam BBU suppression
- THz power transfer
- Different structure types
- Structure design for EUV demo and fabrication

Laser Plasma Electron Injector

- **Plasma Targets**

  High vacuum $\rightarrow$ Solid target, Low Density Plasma

  High repetition rate $\rightarrow$ high vacuum, but depending on fs laser system

  Ionization effect $\rightarrow$ Ionization injection, Ionization diffraction

- **Beam quality:**

  Low Energy spread :

  Emittance :

  Bunch charge :

  Repetition rate :

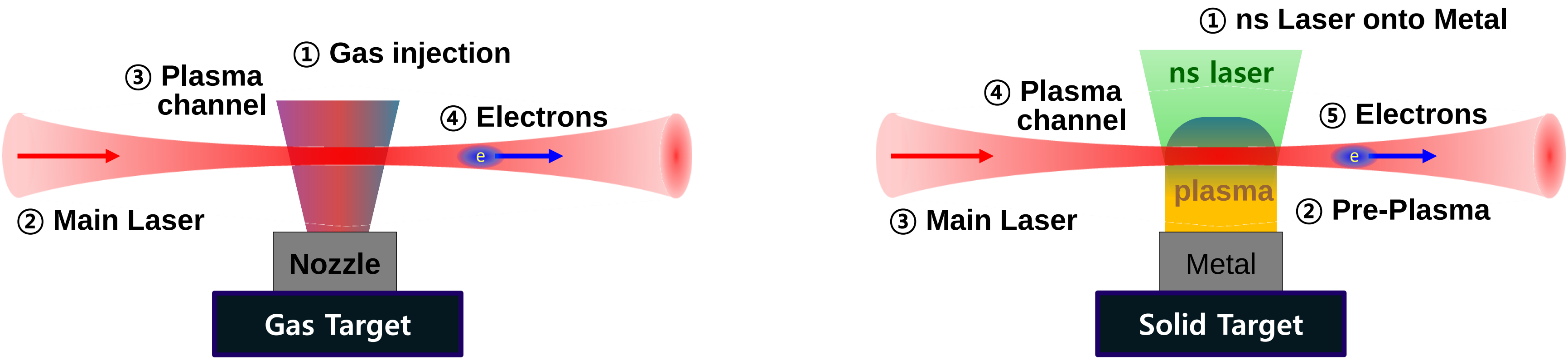
  Beam stability : Energy/charge jitter, Pointing Jitter, etc.

Plasma Targets

- **Gas target vs. Solid target**

  Gas → easy to use and control the density, **but**, stability, vacuum problem

  Metal → high vacuum, high rep. rate, stability, but, laser ablation, target, debris ...



- **Vacuum condition estimation :** ∅ 1.2 m x 0.6 m chamber

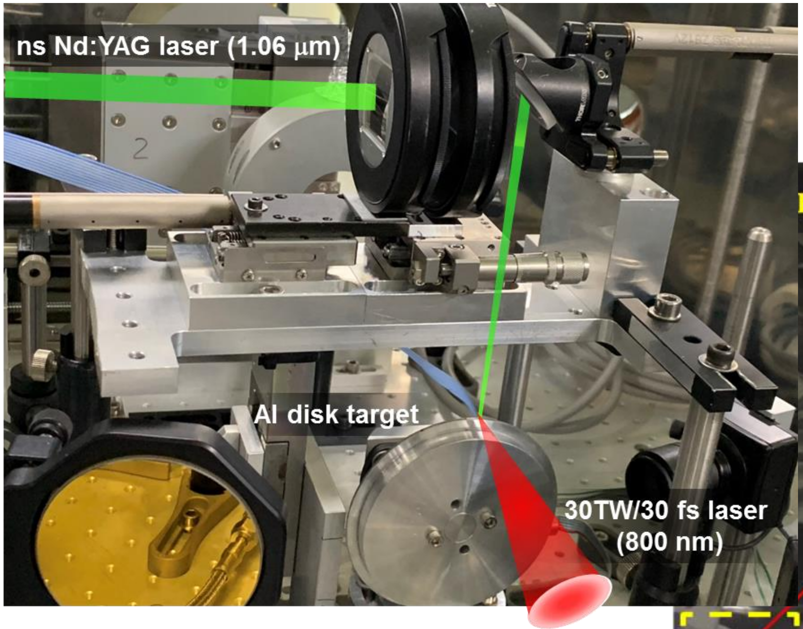
  He Gas jet : ∅1.0 mm supersonic nozzle - 2.5 ms opening time at 40 bar ⇒ 9×10^{20} particles ⇒ 4×10^{-2} Torr

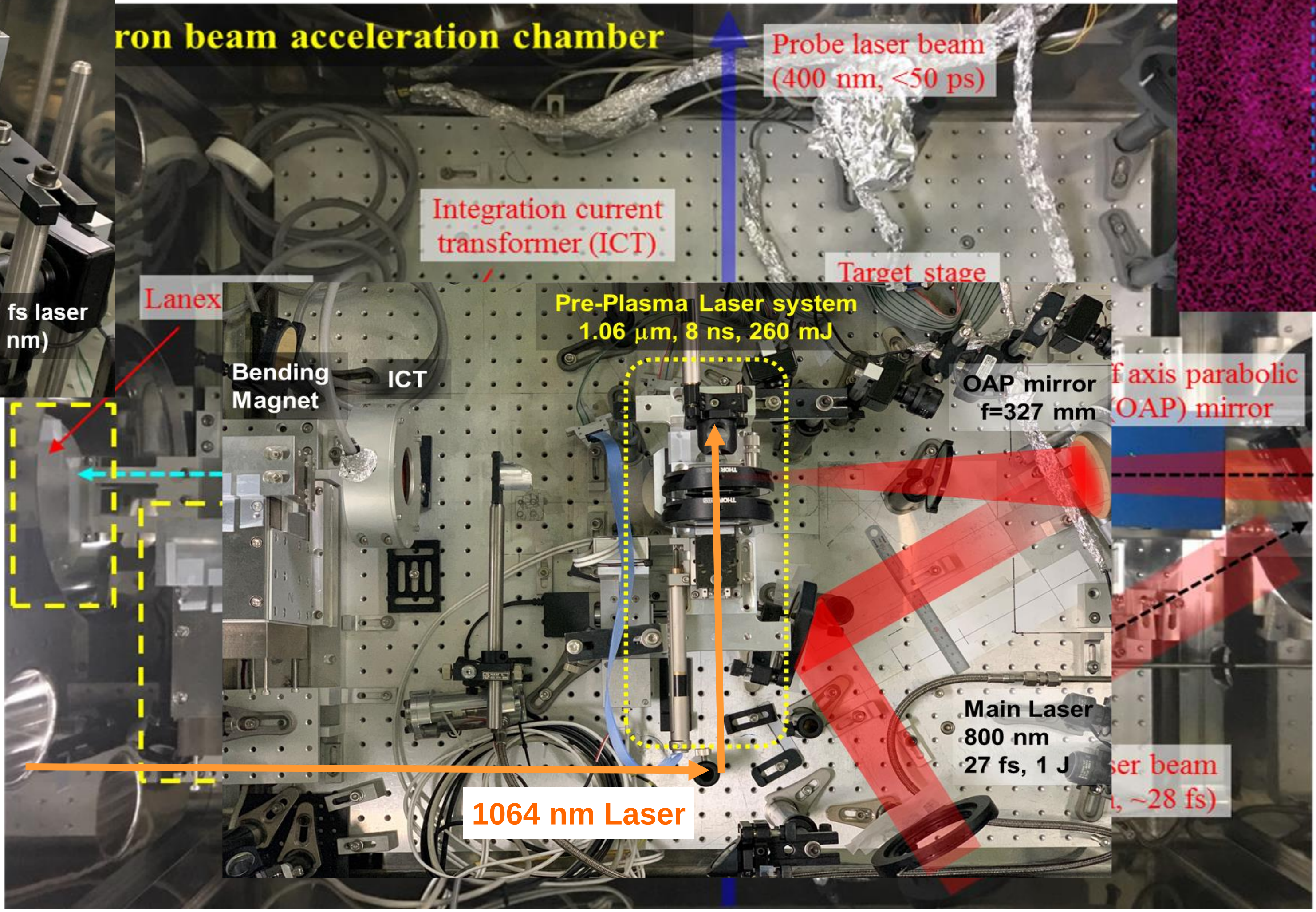
  Al plasma plume : ns Laser ablation : 2~5 mm (L), 100 μm(W), 10 μm (D) ⇒ 5×10^{15} ptls ⇒ 2×10^{-7} Torr

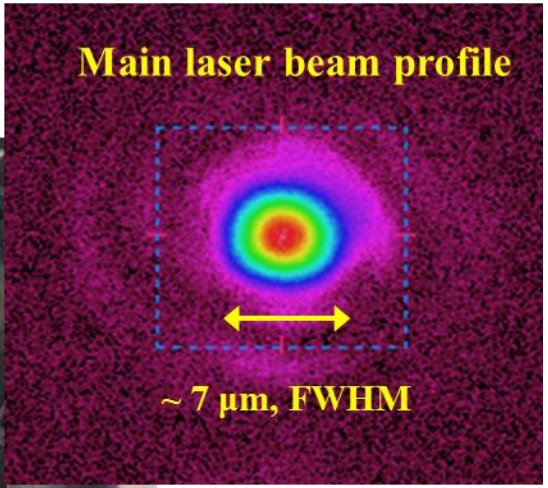
- **Plasma Density** : ns Laser - Pulse Energy, Intensity, Focal position, Delay time
- **Plasma length** : Beam size of ns Laser, Distance between Bi-prism and Target surface

Target Chamber with Al target

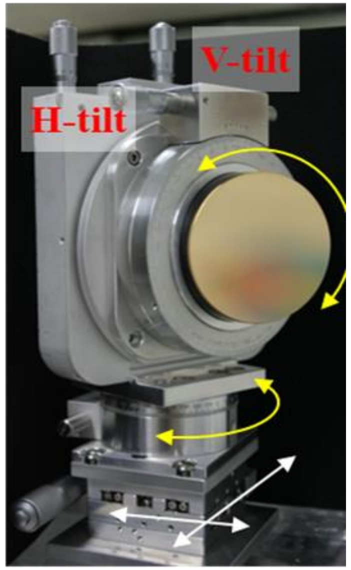
Cylindrical lens & Bi-prism







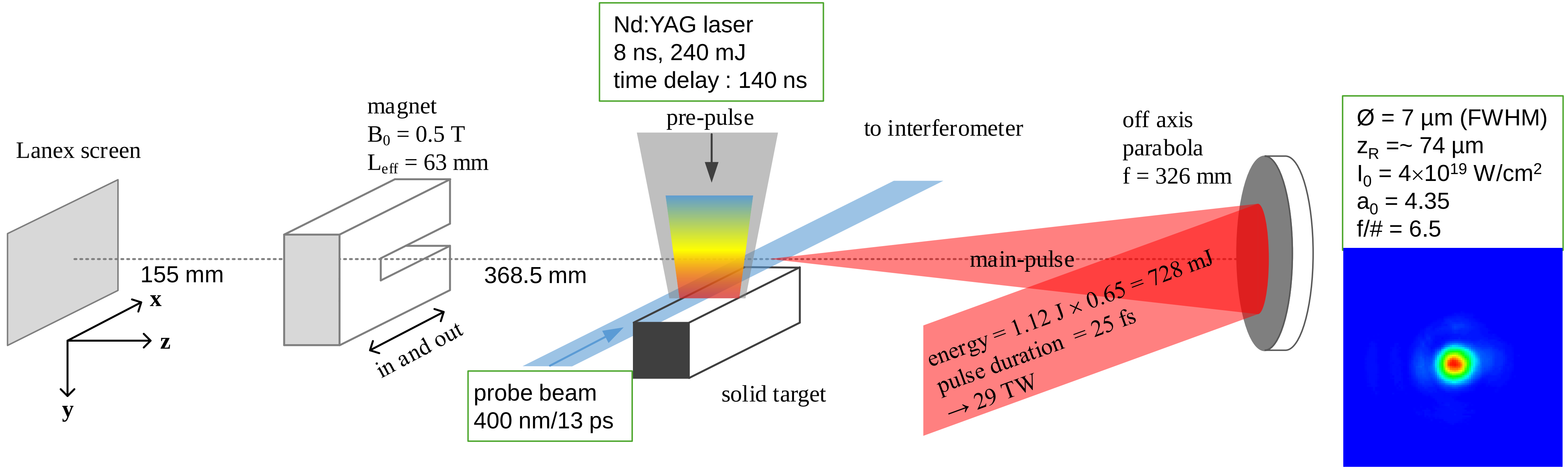
1064nm, 8 nsec,
10 mm dia.,
240 ~380 mJ



OAP Mirror mount

Schematic of LWFA with Al target

(ref. J. Kim et al., Proceedings of LAPD2017)



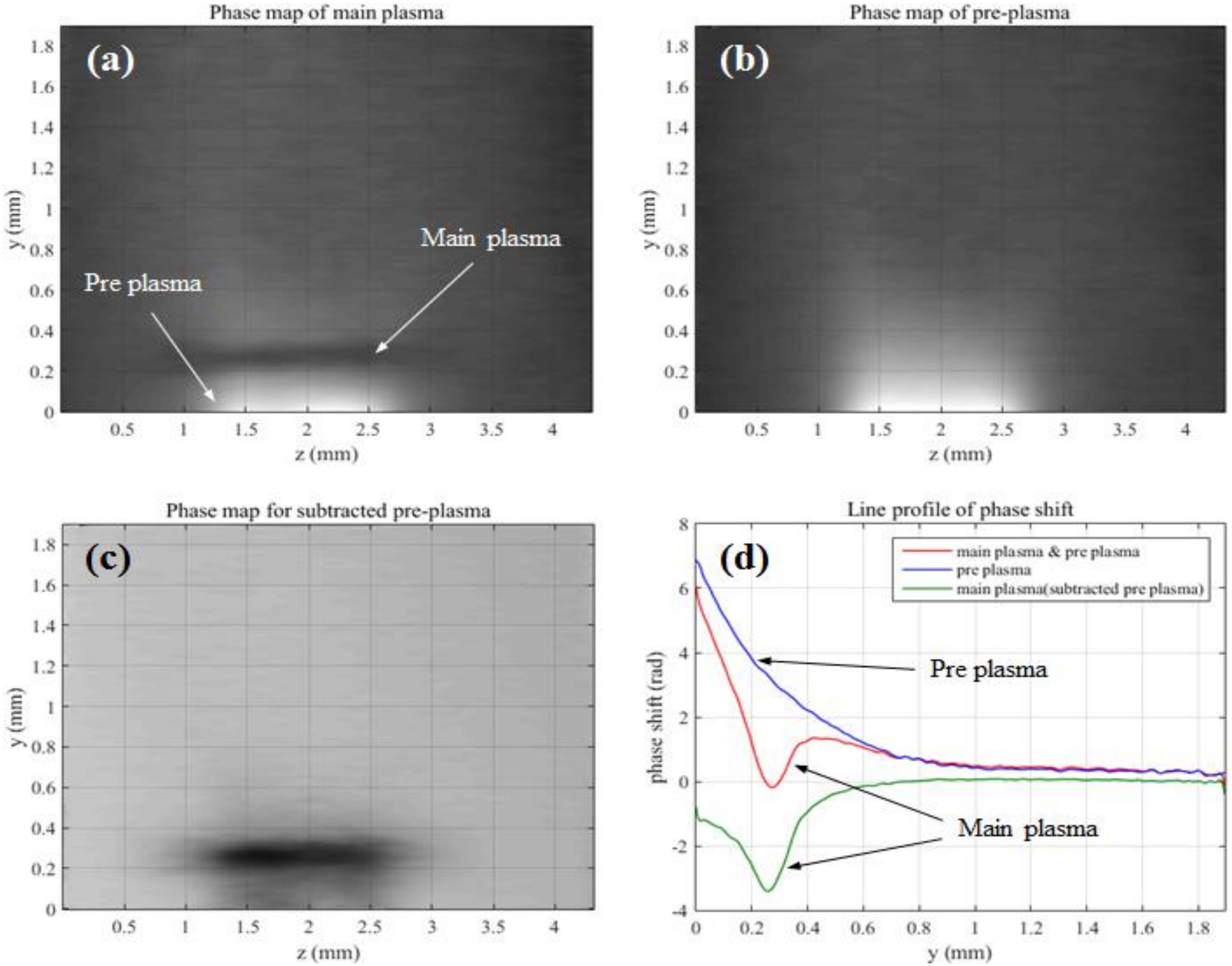
- **Plasma wavelength :** $\lambda_p = 3.3 \times 10^{10} n^{-1/2} = 8.5\ \mu m$
- **Laser pulse length :** $c\tau = 3 \times 10^{8} \times 27 \times 10^{-15} = 8.1\ \mu m$
- **Normalized vector potential :** $a_0 = 1.65$

$\Rightarrow$ **Operate in Bubble regime**

$\Rightarrow$ **Self injection + Ionization injection**

Pre-Plasma density

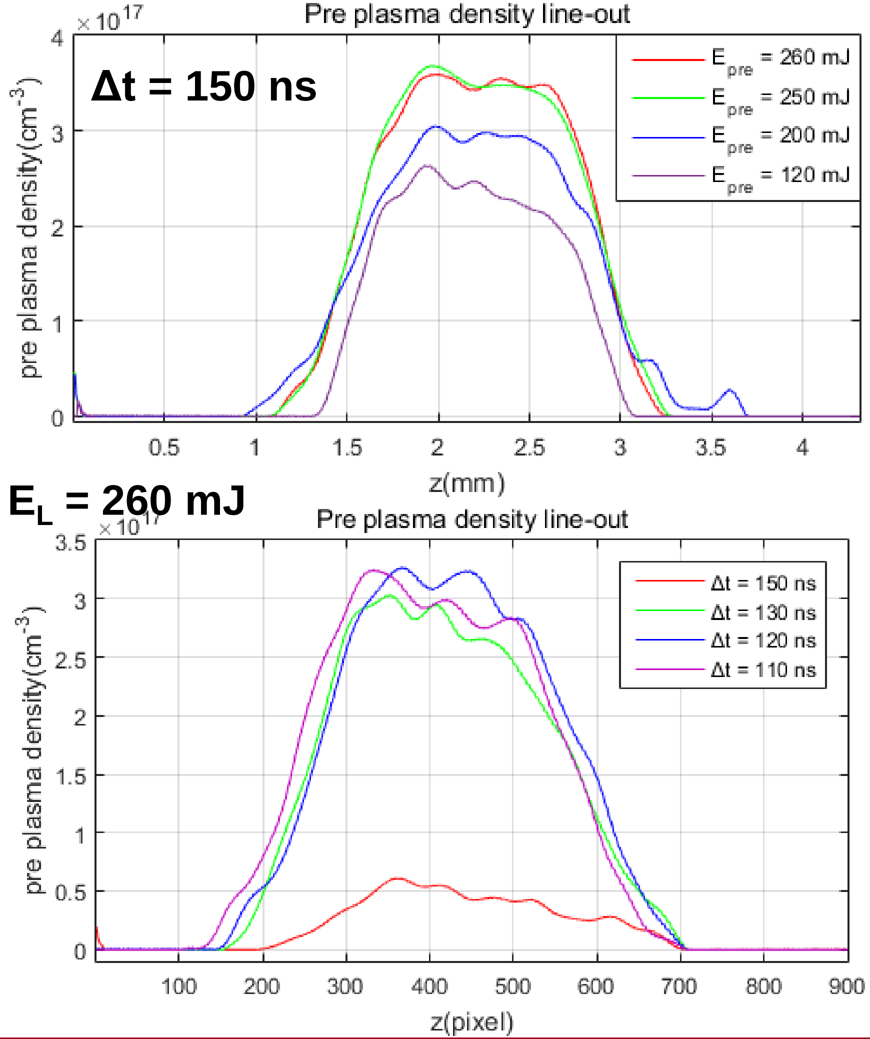
Phase of pre-plasma and main plasma of Aluminum target



Laser Width/length ~ 400 ㎛/1.5 mm

Laser Delay time: Δt = 110 ~ 150 ns

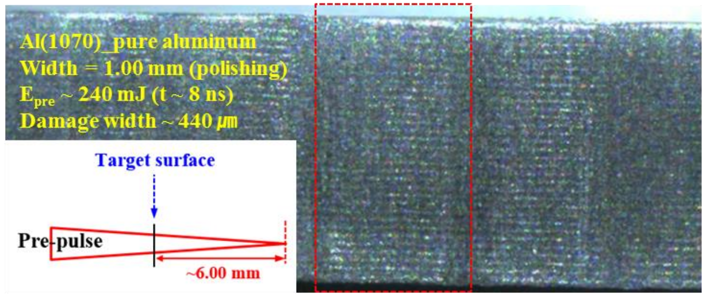
Laser pulse energy : 120 ~ 260 mJ

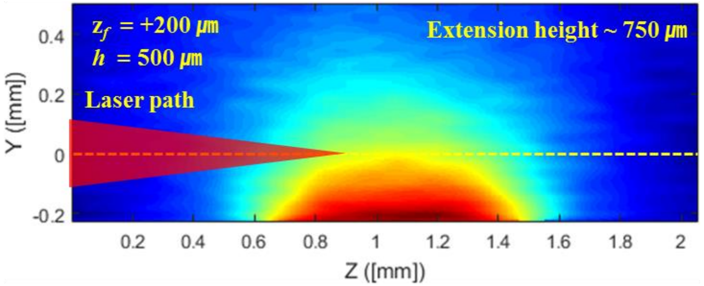


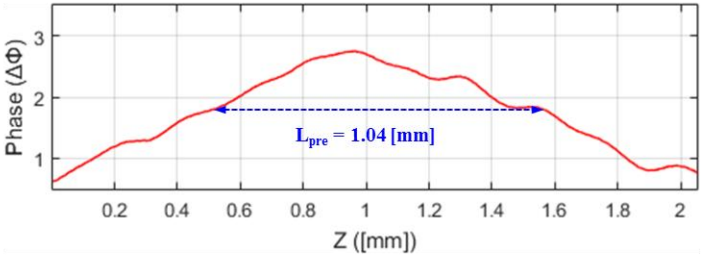
Dependence on the focusing position for laser ablation

(Courtesy of W. J. Ryu)

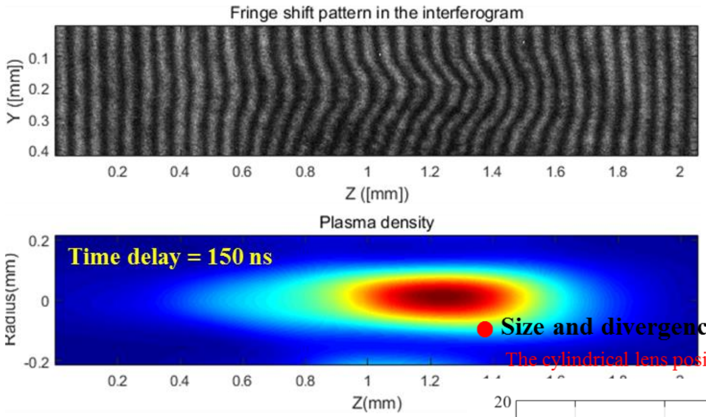
● **Target surface and Pre-plasma phase profile**

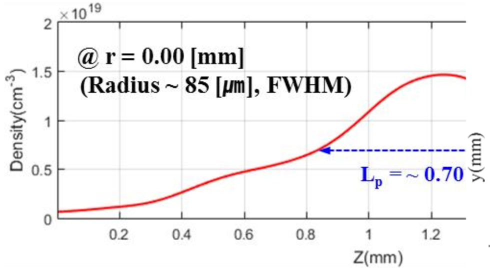






● **Main plasma density distribution profile**





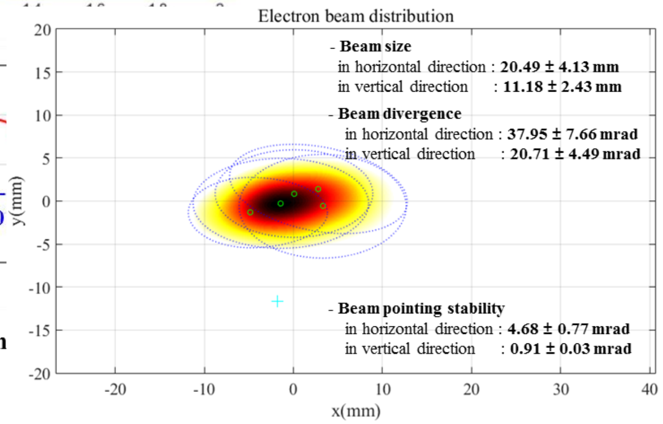
Plasma density (n_e) : ~1.47 × 10^{19} [cm

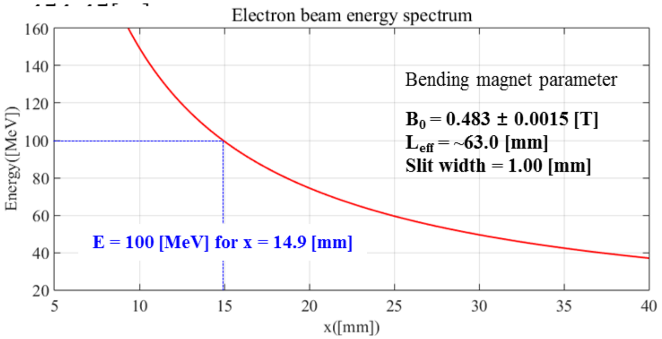
Plasma wavelength (λ_p) : ~8.71 [μm]

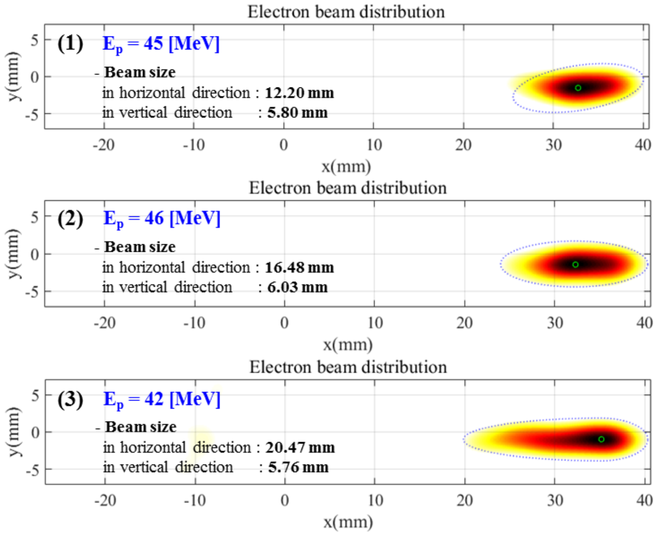
Dephasing length : $L_d = \frac{\sqrt{2}}{\pi} a_0 \frac{\lambda_p^{\,3}}{2\lambda_L^{\,2}}$

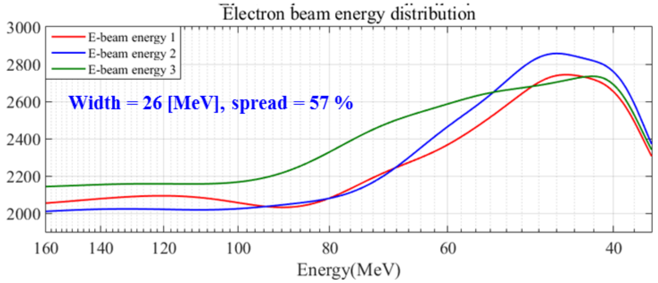
● **Size and divergence for the Electron beam profile**

The cylindrical lens position (CL) : +6.00 [mm]





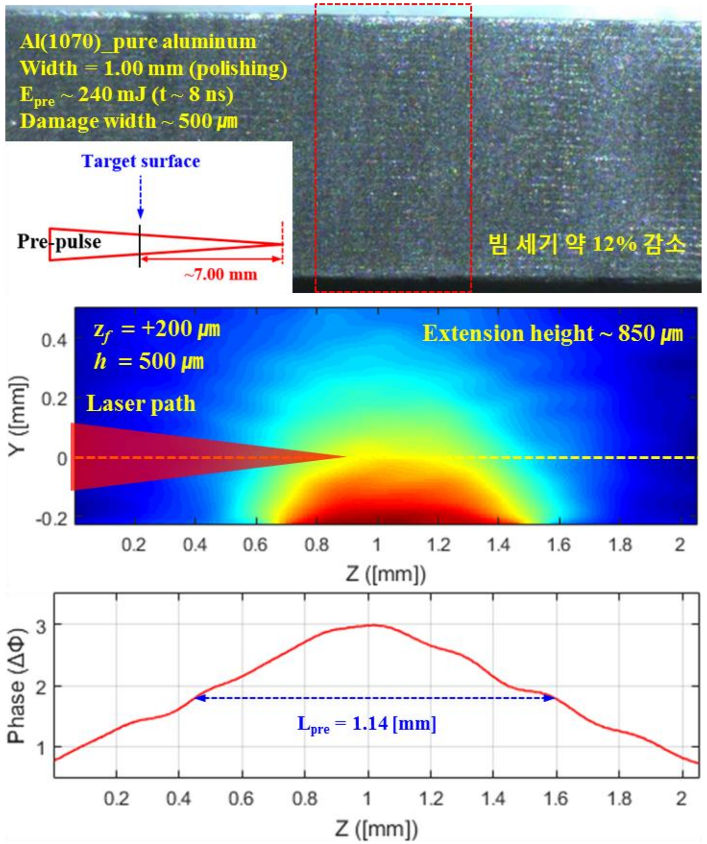




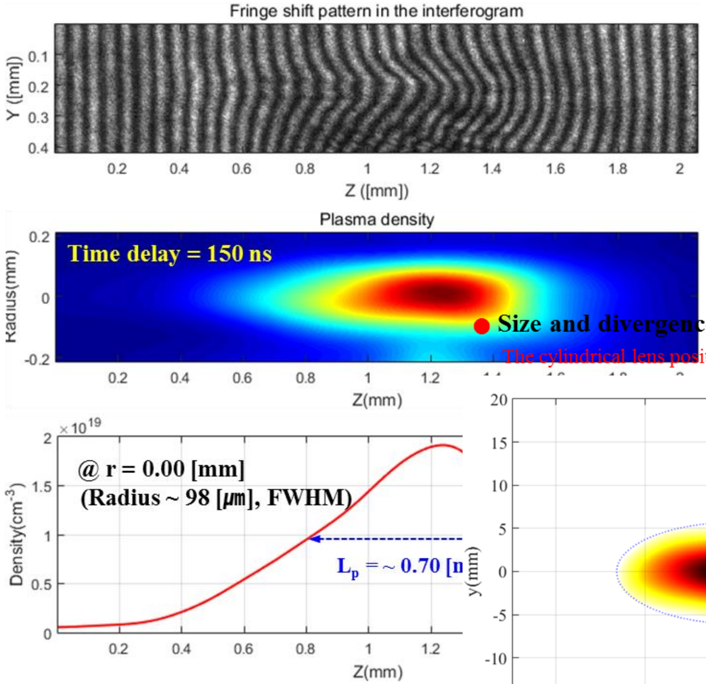
Dependence on the focusing position for laser ablation

(Courtesy of W. J. Ryu)

- Target surface and Pre-plasma phase profile



- Main plasma density distribution profile



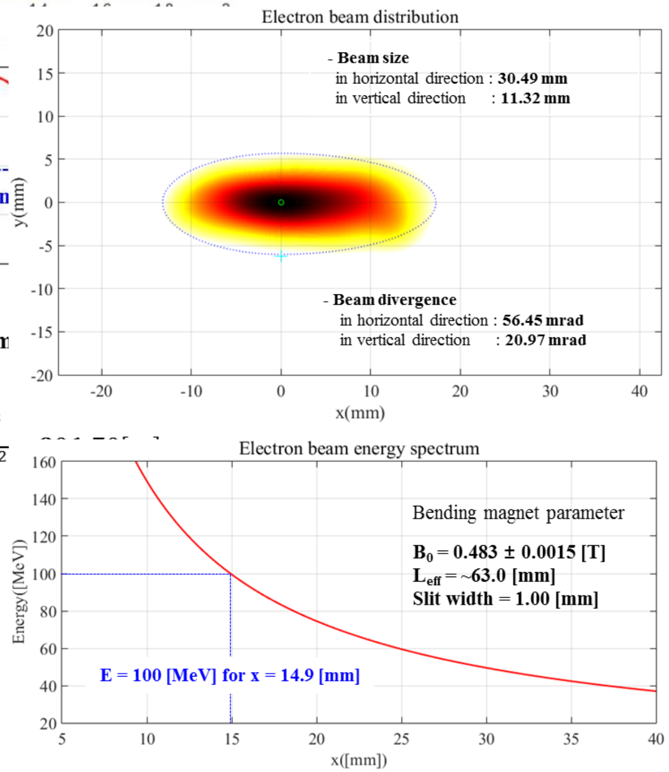
Plasma density (n_e) : ~1.91 × 10^{19} [cm

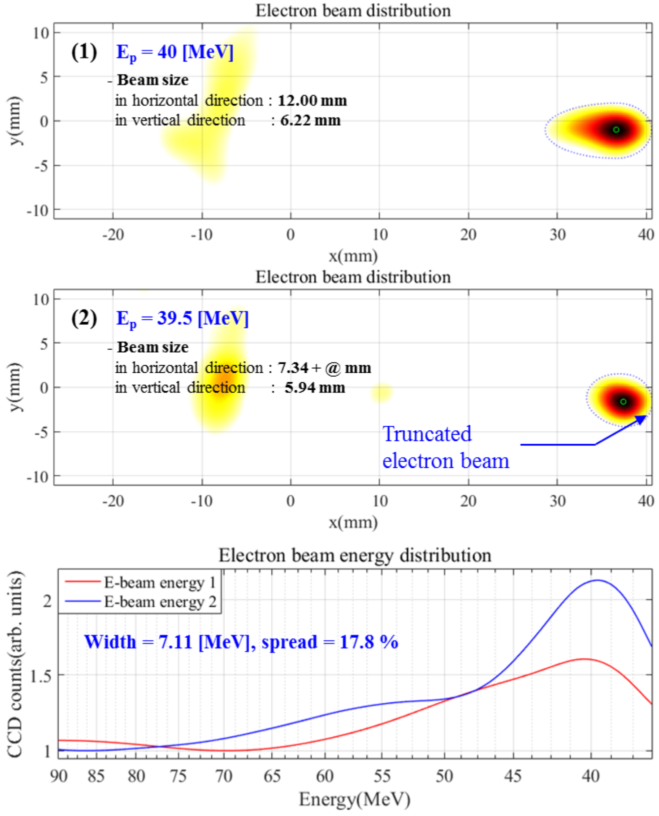
Plasma wavelength (λ_p) : ~7.64 [μm]

Dephasing length : $L_d = \frac{\sqrt{2}}{\pi} a_0 \frac{\lambda_p{}^3}{2\lambda_L{}^2}$

- Size and divergence for the Electron beam profile

The cylindrical lens position (CL) : +7.00 [mm]





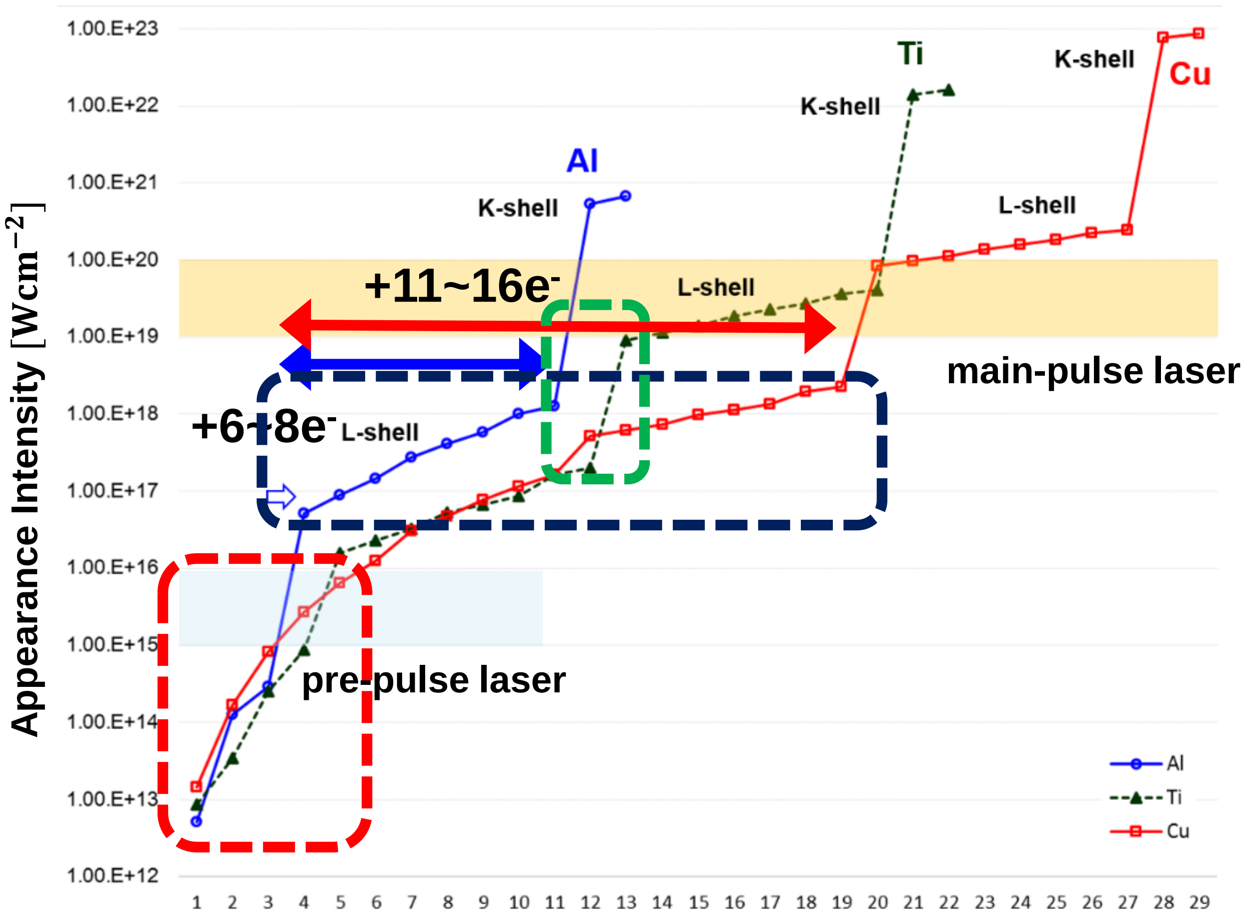
Issues on LWFA using Metal targets

- **Laser Propagation in the Plasma – Plasma wave/Wakefield**
  - Laser Diffraction – propagation of envelope
  - Self-focusing, Self-compression – due to interaction between main laser & Plasma
- Optical Field Ionization of metal ions by main laser
  - **Ionization Diffraction**
    due to Ionization process by main laser
    at 10^{16} W/cm^2 : He – He^{2+}; Al – Al^{3+}
    at 10^{19} W/cm^2 : He – He^{2+}, Al – Al^{11+}

  ⇒ Ionization by the main laser occurs in Al plasma, not in He
- **Electron injection and Trapping**
  - Self-injection via. Transverse wave-breaking
  - ionization injection

※ The threshold laser intensity for barrier suppression ionization (BSI) :

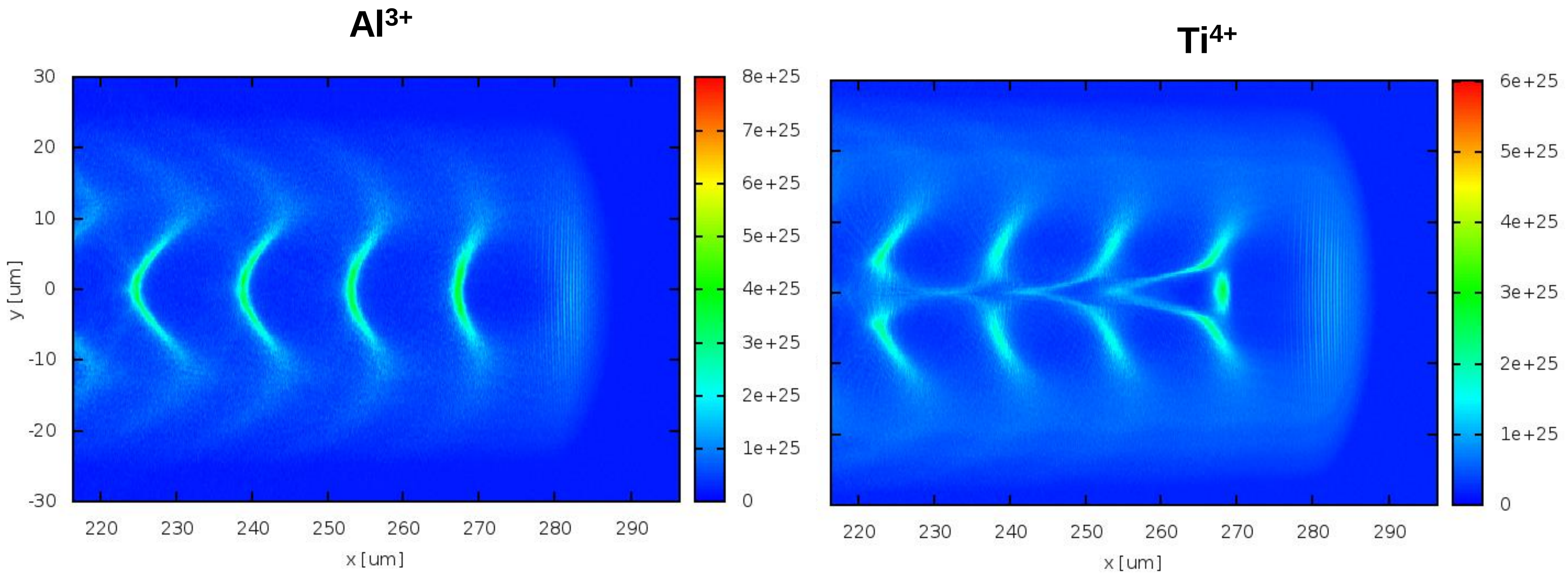
$$I_L = \frac{\pi^2 \epsilon_0^3 c}{2e^6} \frac{E_{ion}^4}{Z^2} \rightarrow I_L[\mathrm{Wcm^{-2}}] \approx 4.0 \times 10^9 \frac{(E_{ion}[\mathrm{eV}])^4}{Z^2}$$



Target materials: Al vs. Ti

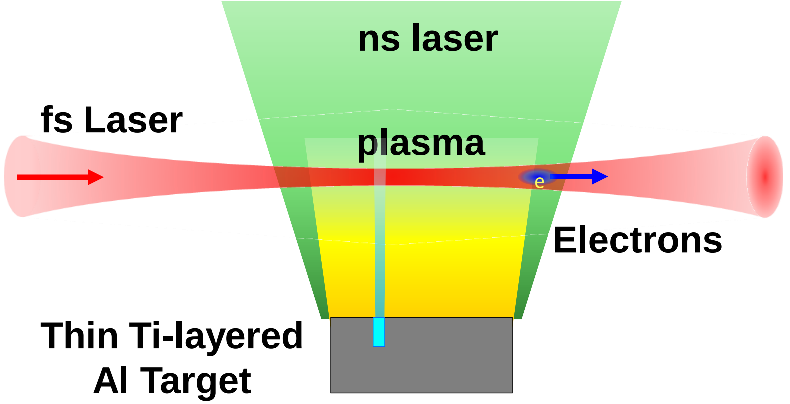
Simulation Parameters :

- $n_{e0} = 2.0 \times 10^{18}\ \mathrm{cm}^{-3}\ (n_{ef} = 7.33 \times 10^{18}\ \mathrm{cm}^{-3})$
- $I_0 = 8.0 \times 10^{19}\ \mathrm{Wcm}^{-2}\ (P_L = 62\ \mathrm{TW}),\ \ w_0 = 7\ \mu\mathrm{m}$



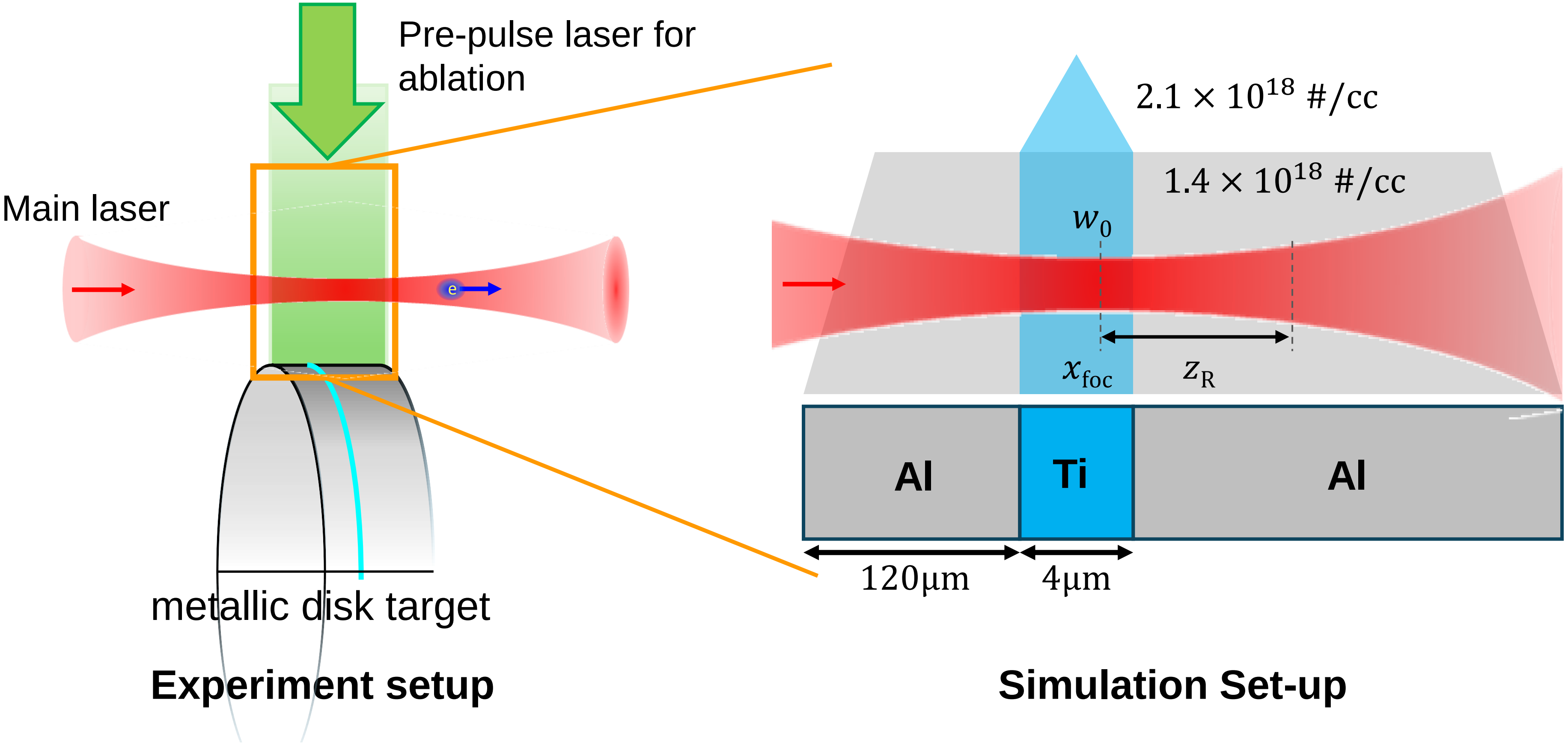
Ti target :

- Electron density near the optical axis is increased and separated, breaking the wake cavity.
  → It may use as controlled injection



LWFA with thin Ti-layered Al target

Possible Plasma Distribution by modifying metal target structure

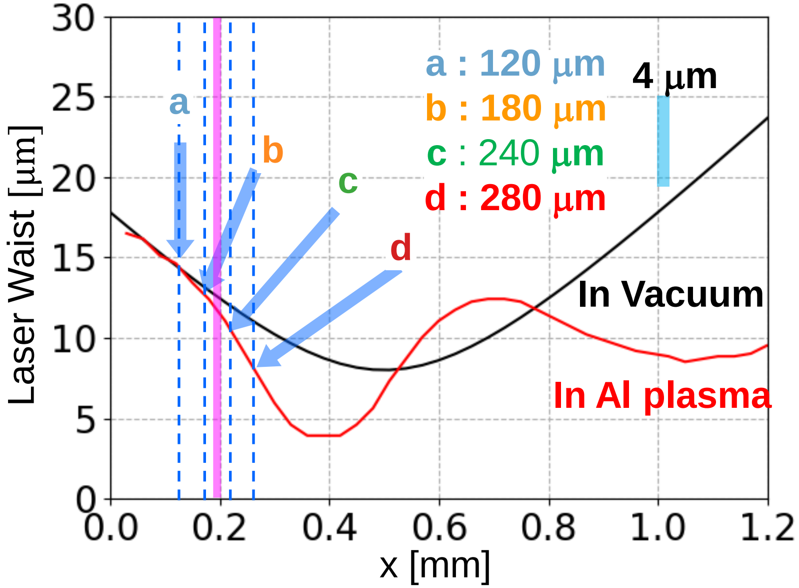


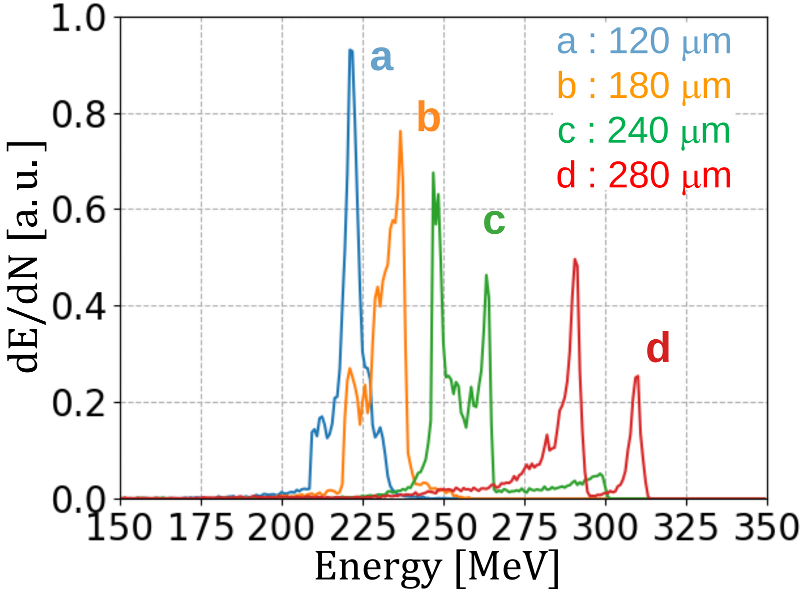
Experiment setup **Simulation Set-up**

How to realize? Need the simulation (FLASH : https://flash.rochester.edu/site/)

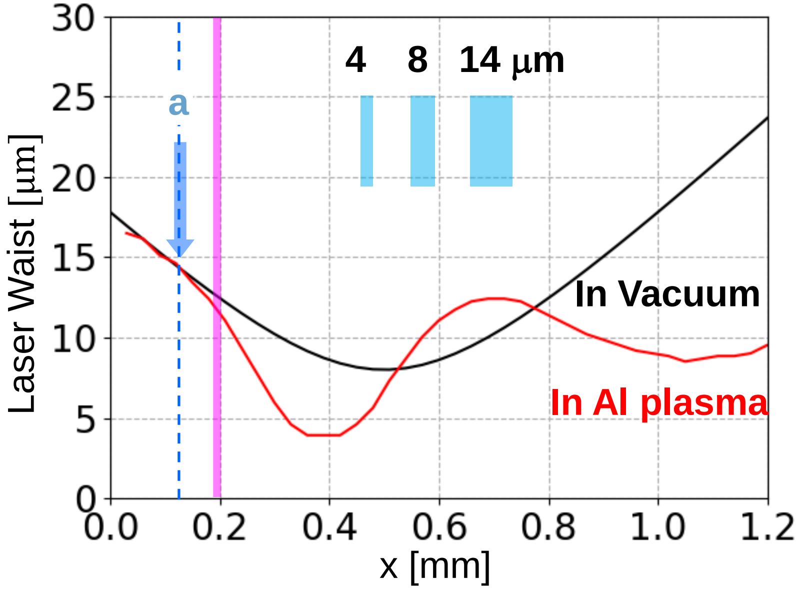
Controlled Injection with thin Ti-layered Al target

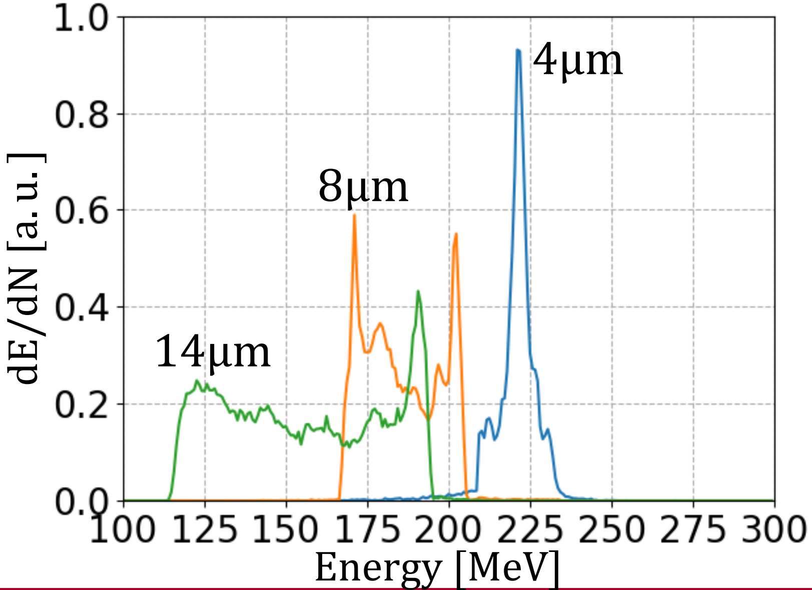
Ti layer Position
@Thickness 4 μm





Ti layer Thickness
@ Position (a)





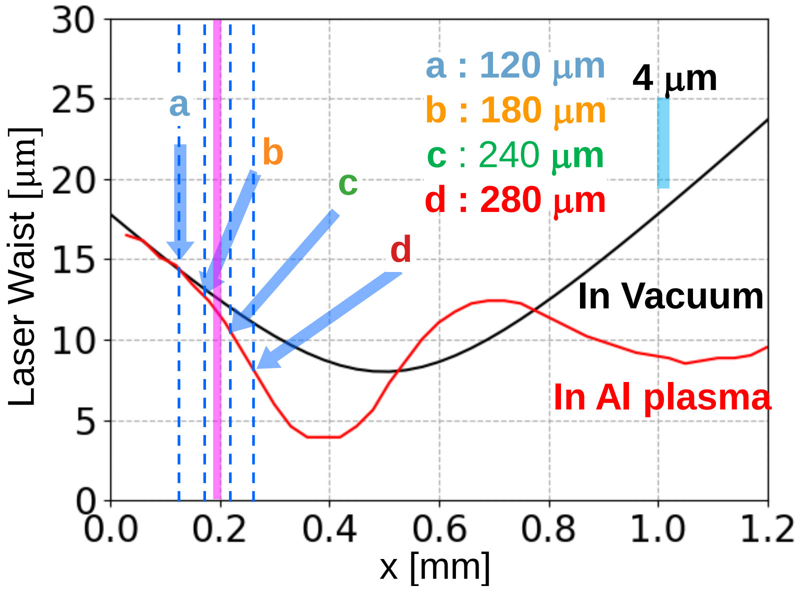
EPOCH 2D simulation

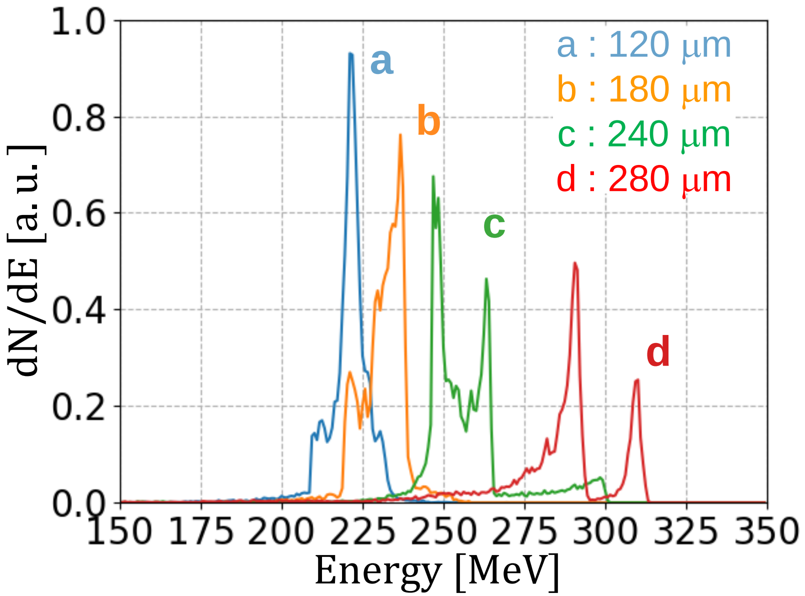
Simulation parameters	
P_L	70 TW
a_0	5.7
I_L	7.0×10^{19} W/cm
w_0	8.0 μm
n_{ef}/n_c	0.003
$n_{i,Al}$	1.4×10^{18} #/cc
λ_L	800 nm
τ_{FWHM}	25 fs
$f_{c,L}$	500 μm

* Starting point of injection of Electrons from L-shell of Al ion : ~200 μm

Controlled Injection with thin Ti-layered Al target

Ti layer Position @Thickness 4 μm





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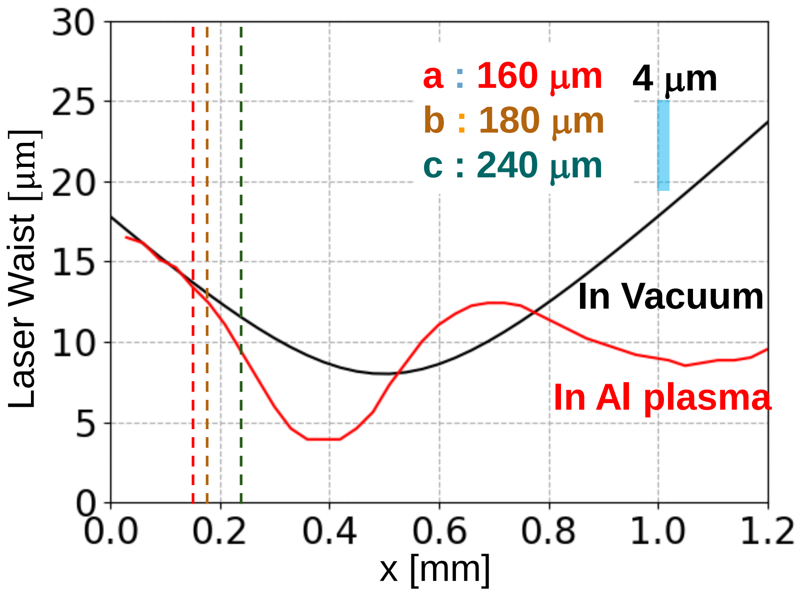
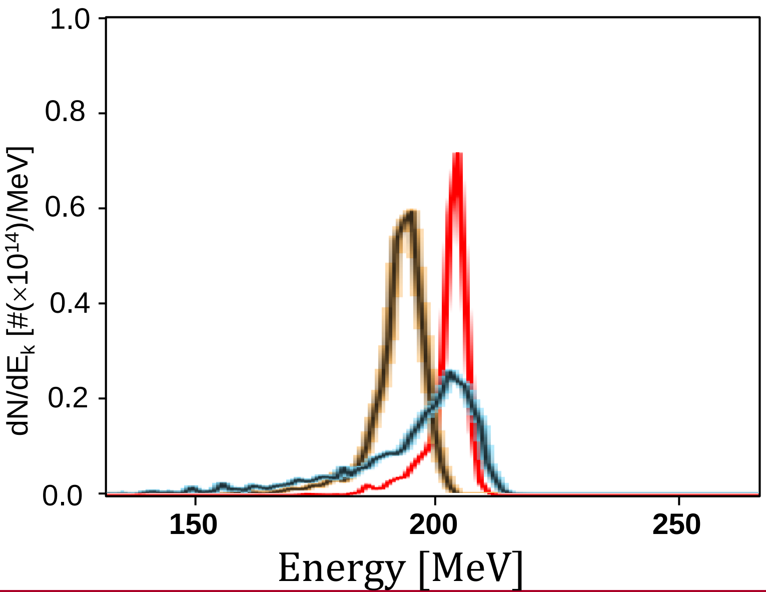
a_0	5.7
I_L	7.0×10^{19} W/cm
w_0	8.0 μm
n_{ef}/n_c	0.003
$n_{i,Al}$	1.4×10^{18} #/cc

Ti layer Position @Thickness 4 μm

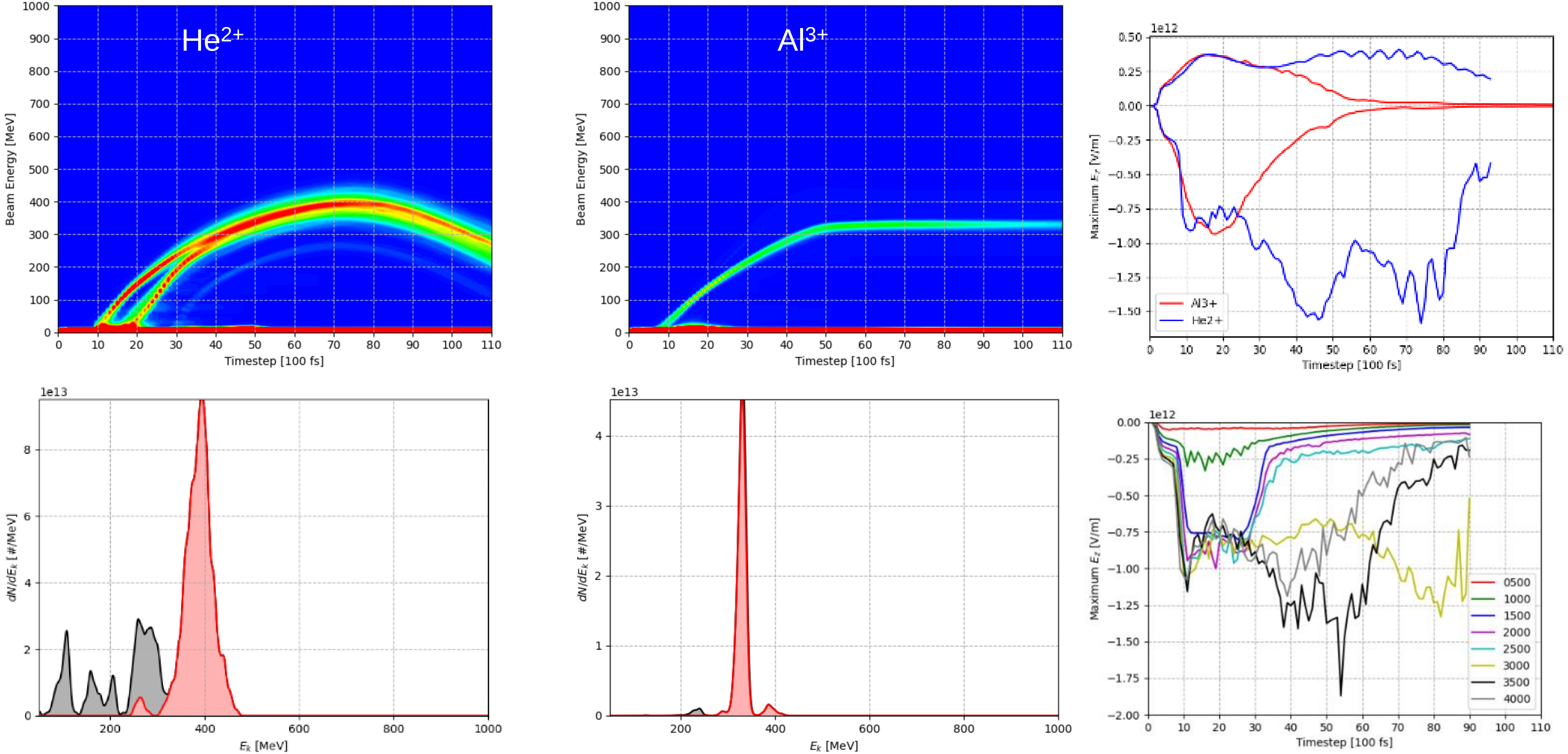




Smilei-AM simulation

Simulation parameters	
P_L	30 TW
a_0	4.27
I_L	5.0×10^{19} W/cm
w_0	7.0 μm
n_{ef}/n_c	0.001587
$n_{i,Al}$	2.8×10^{18} #/cc

Dephasing-free condition due to Ionization Diffraction

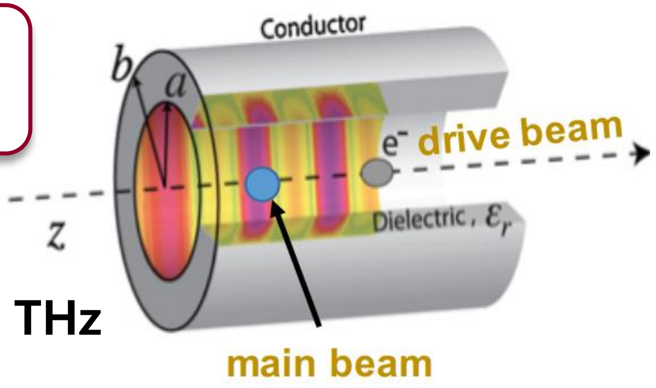


SWFA : Beam-driven sub-THz acceleration

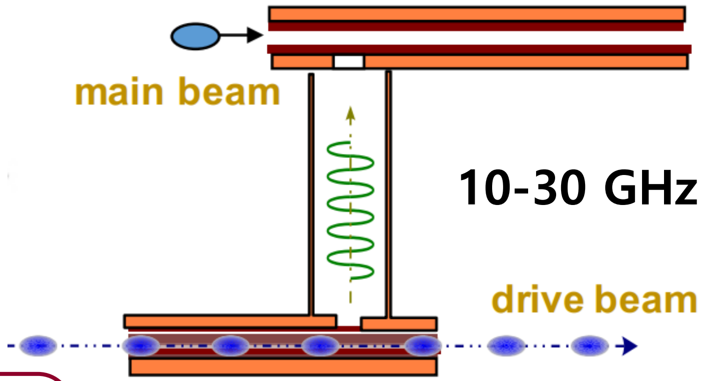
Easier to achieve
high-gradient than TBA

Difficulties from co-propagation
Drive beam manipulation needed

CWA



0.1-1 THz



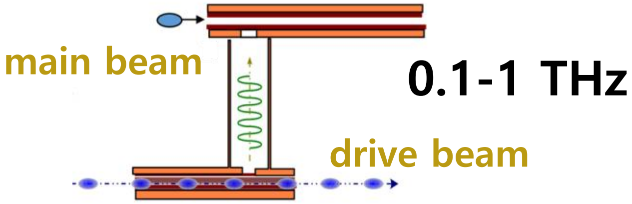
TBA

More mature than CWA

Limited gradient
Need two beamlines
Need high-charge bunch train

It could be a collection of advantages

- Higher gradient than GHz-TBA
- No co-propagation is needed
- No drive manipulation is needed
- Need to **tiny two** beamlines
- **A few to tens** of nC bunch train is needed

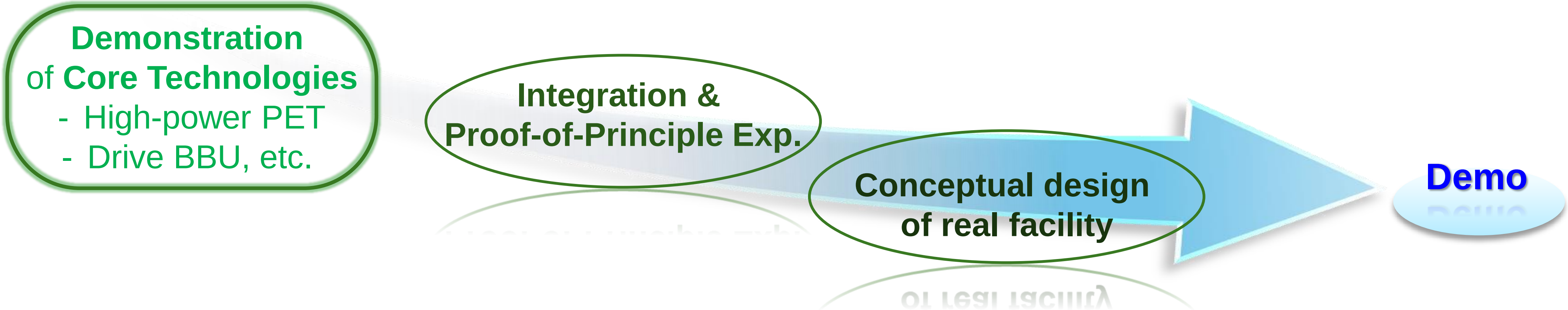


But, it still has several major concerns

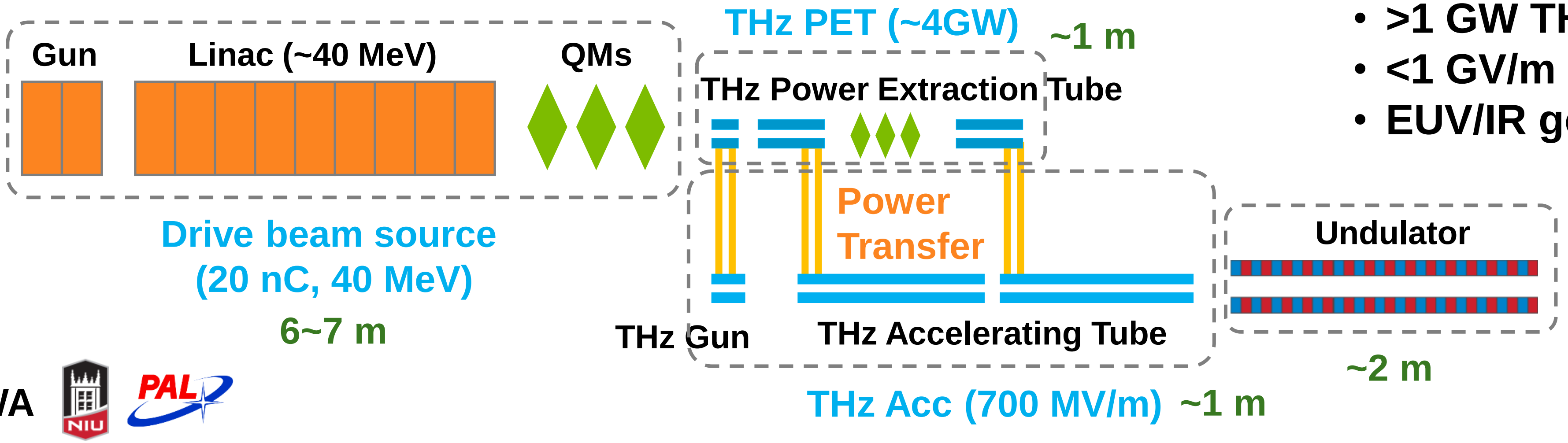
- **BBU** could be harder to handle
- Power extraction, transport, and injection could be **lossy**
- **Structure fabrication** is not straightforward

Plan & Concept of demo facility

- **The R&Ds on Core Technologies for THz-TBA :** Simulation, Design, Fabrication, Demonstration, etc.
- **Integration** of developed core technologies will be verified by **EUV generation** using THz-TBA.



Layout for Demo Facility - Total : 10 m



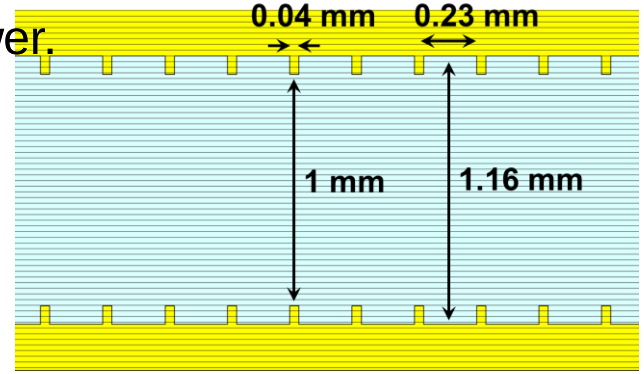
- >1 GW THz power
- <1 GV/m gradient
- EUV/IR generation

Argonne NATIONAL LABORATORY AWA NIU PAL

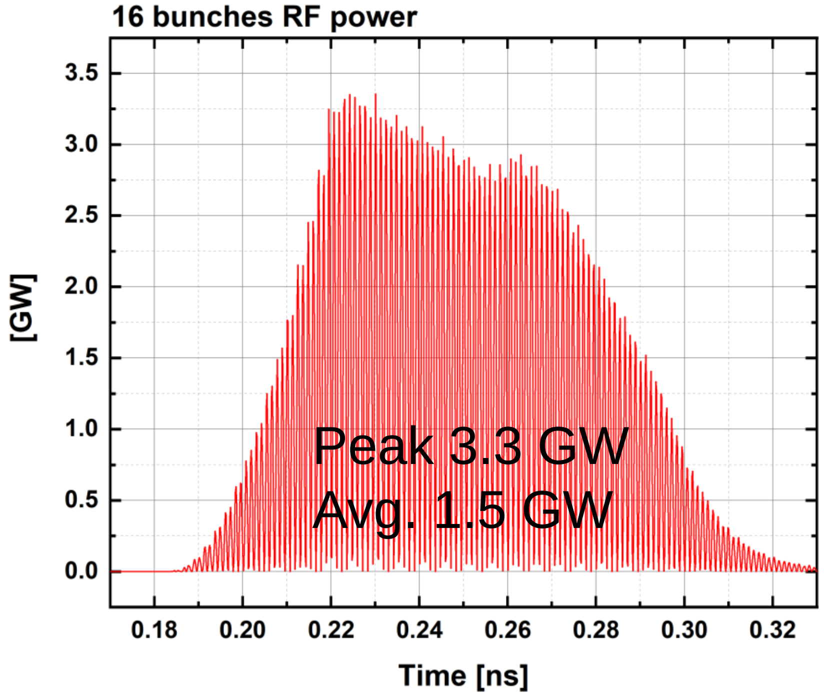
Structure design for 400 GHz PET

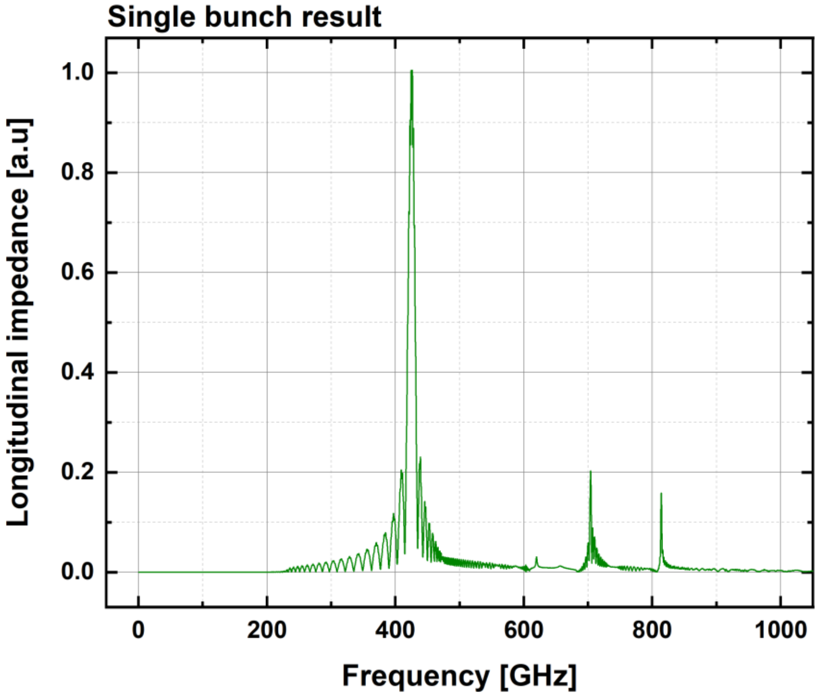
(Courtesy of H. Kong)

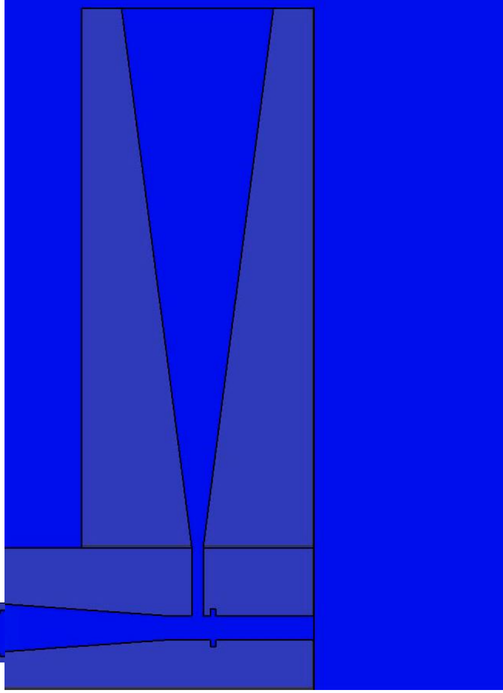
- Structure parameters were optimized to obtain GW power.
- Peak power of 3.3 GW is expected from a bunch train with 16 bunches and 1 nC/bunch.



The extraction options are under consideration





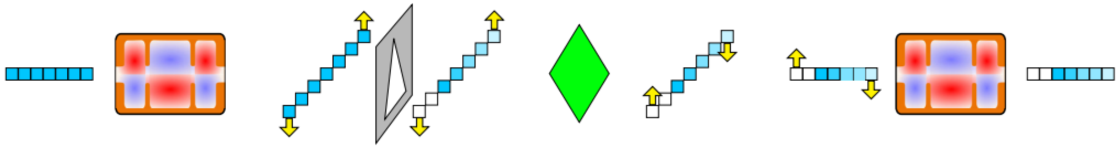


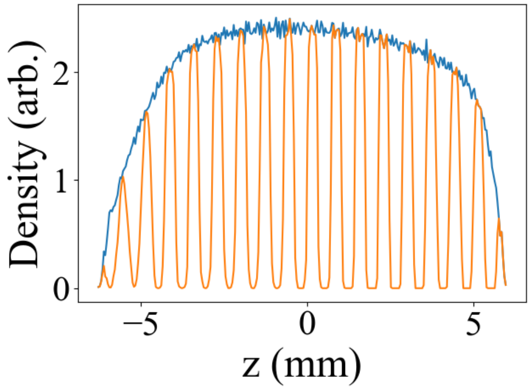
Preparation Drive beam shaping

(Courtesy of G. Ha)

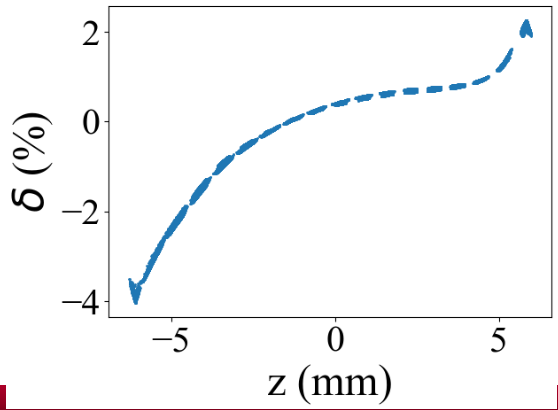
TDC-shaping

(Transverse Deflecting Cavity TDC)





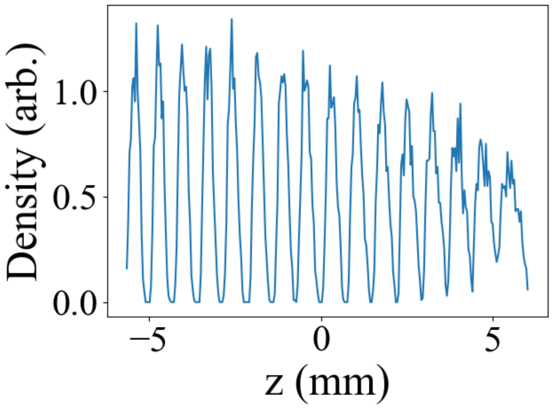
- High quality shaping
- Starting from 35 nC,
  15.4 nC remains (T: 44%)
- Low form factor
  (high form factor is available but more losses)



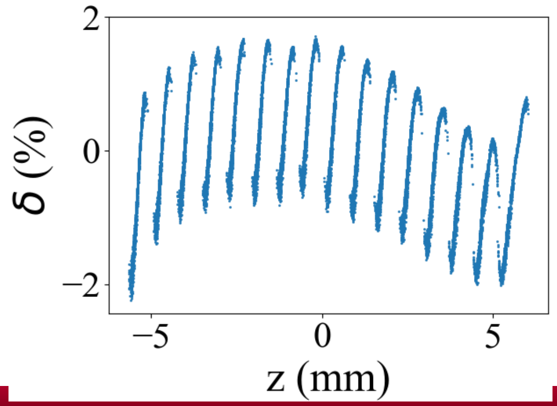
- Each micro-bunch has small energy spread
- Bunch-to-bunch has energy deviation
  (controllable up to some level)
- Needs 2-3 powerful TDCs

Laser-shaping

Laser shaping showed surprisingly good quality, so chose laser-shaping result as input



- (relatively) low quality shaping
- 19.2 nC, emittance is 2/3 of TDC-case
- Low form factor
  (high form factor is not available)

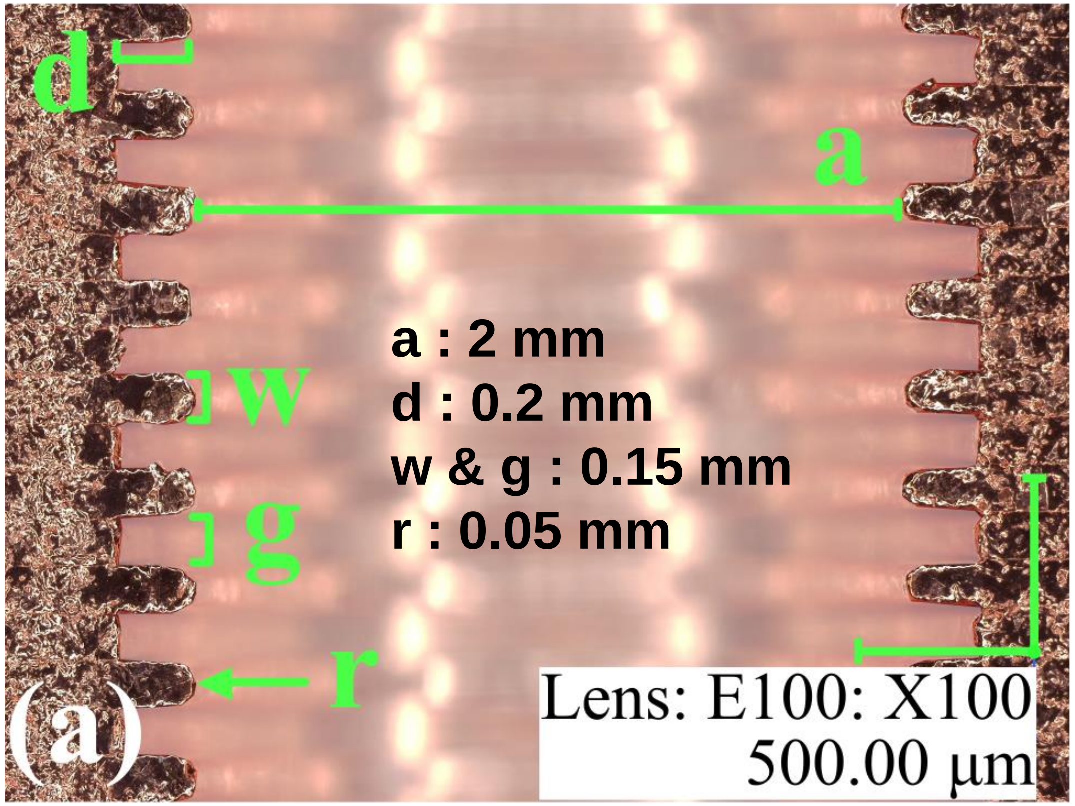


- Each micro-bunch has huge energy spread
- Bunch-to-bunch has small energy deviation
- Large laser split-delay stages

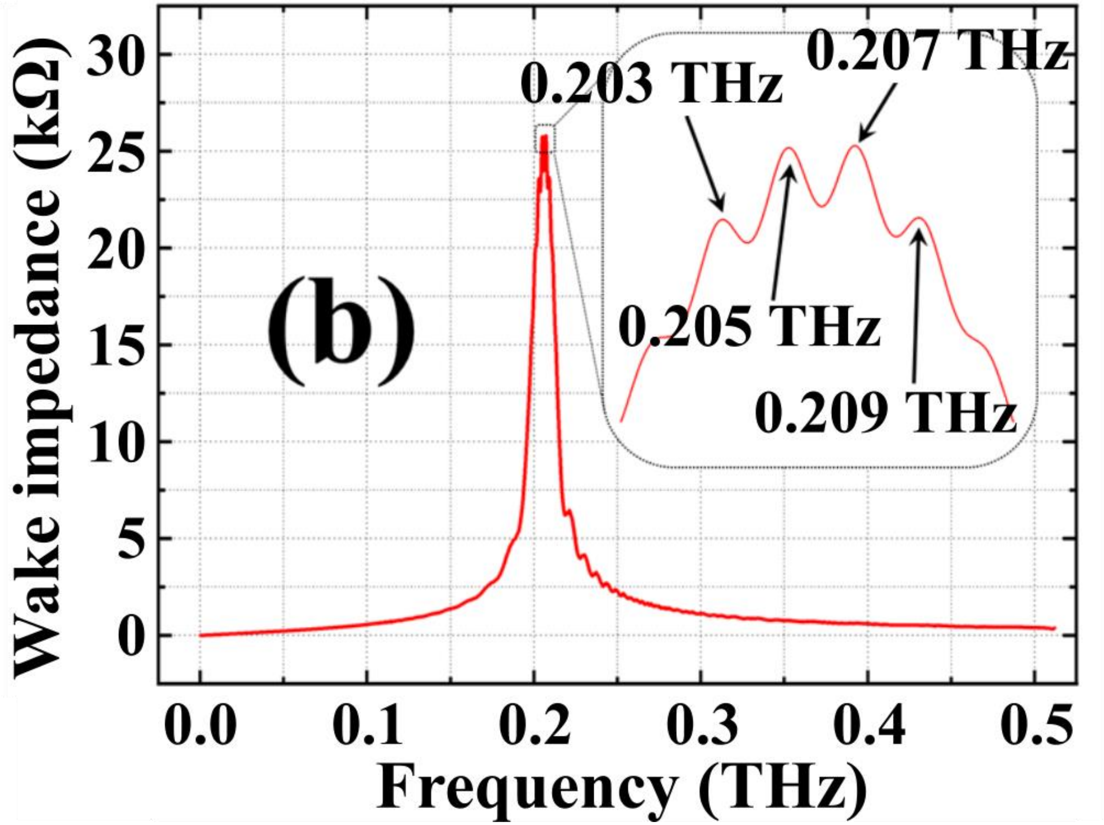
Pre-Experiments at 200 GHz : Structure and simulated spectrum

- Structure was successfully fabricated.
- Structure was designed to be compatible with ~0.2 THz.

Fabricated corrugated structure



Wake Impedance (CST simulation)

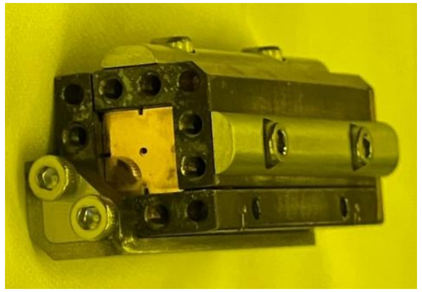


(ref. H. Kong et. al., Scientific Reports 13:3207 (2023))

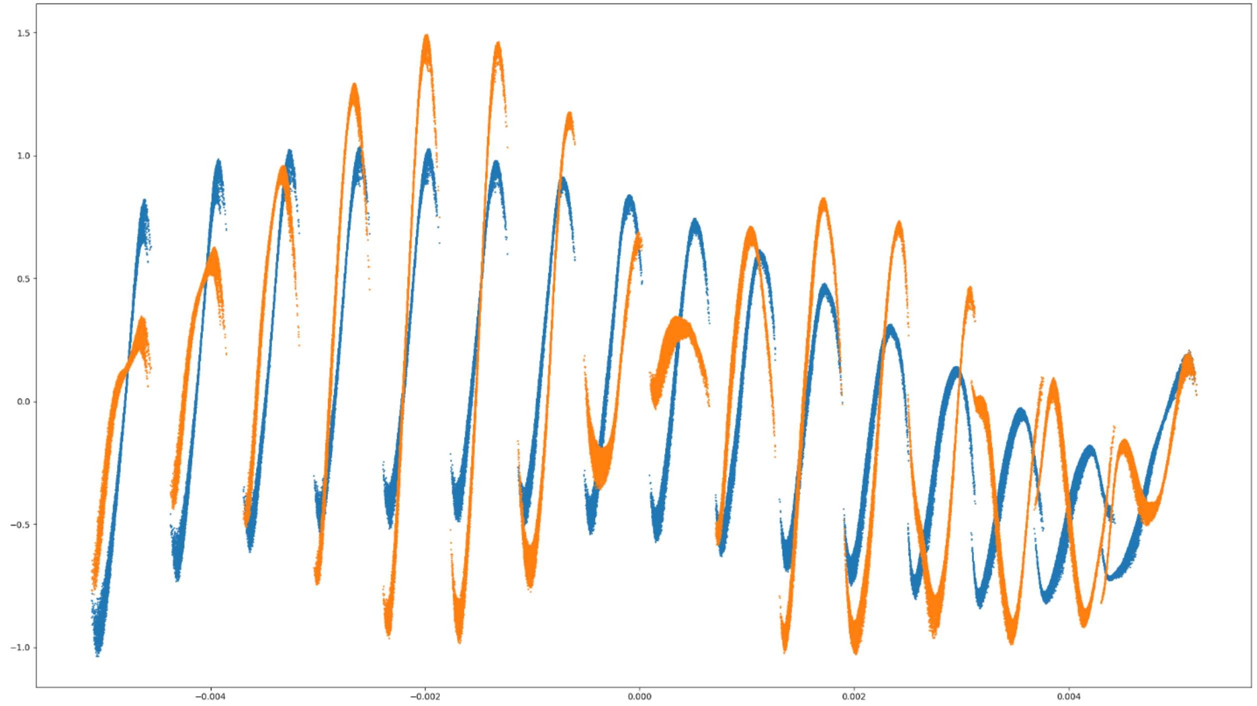
Preparation Drive beam for 400 GHz PET prototype

(Courtesy of M.K. Seo)

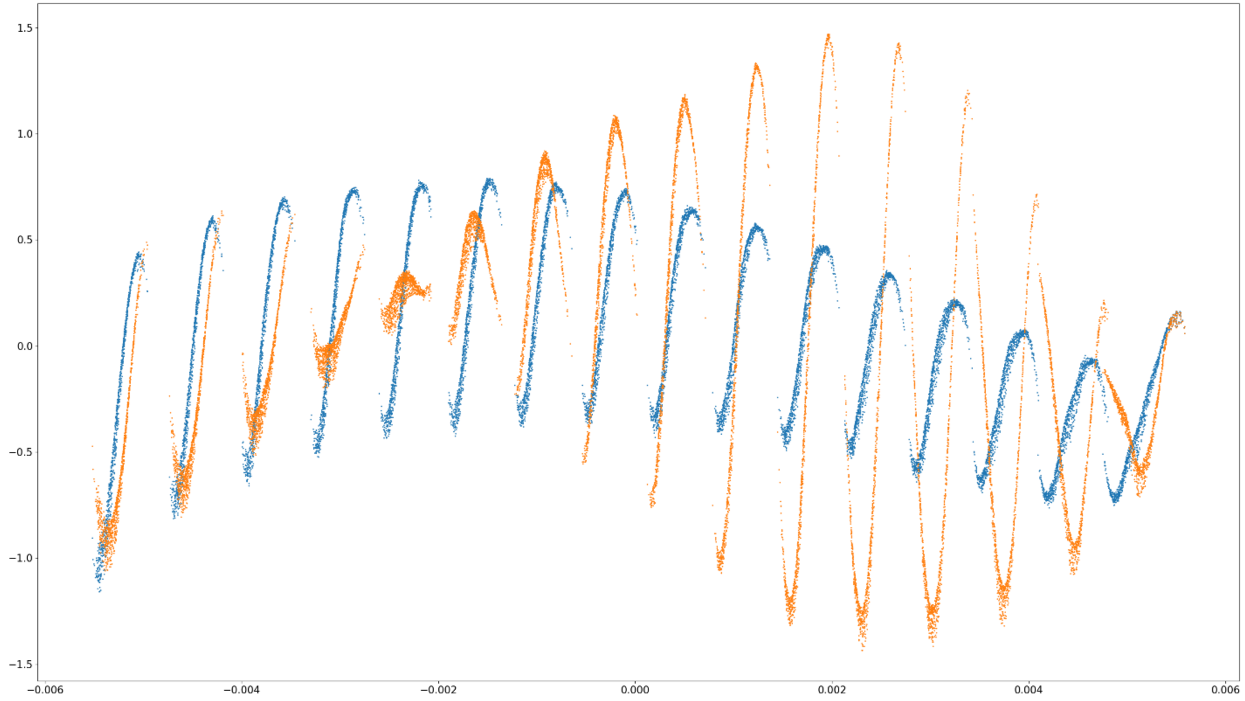
- Optimization of Drive beam for high power generation by adjusting the time separation between bunches



RF phase at Gun → 30°

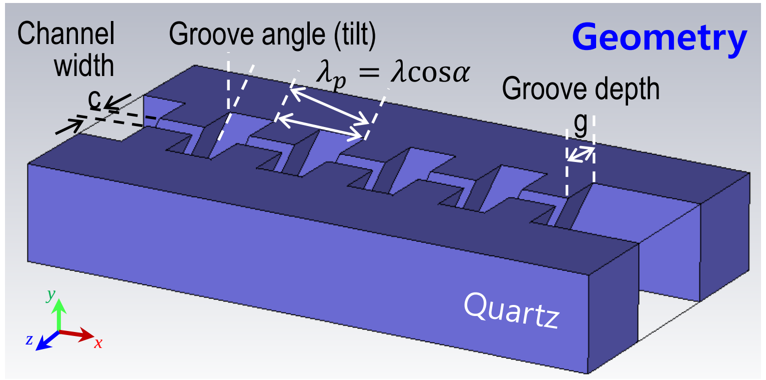


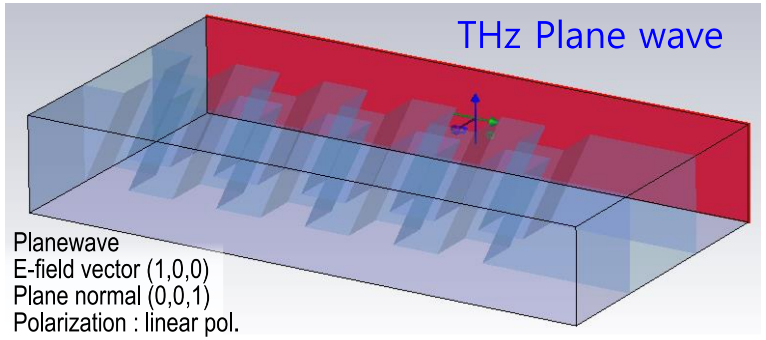
RF phase at Gun → 40°

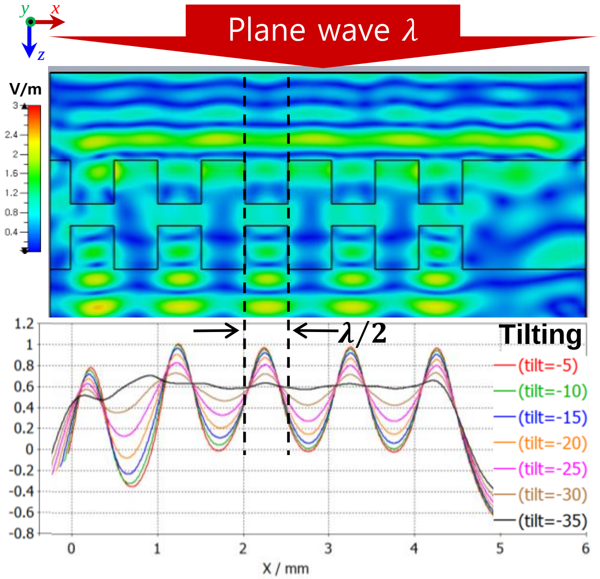


Design study of Dielectric Undulator

- **Design study of a DTU** (Dielectric THz Undulator) ⇒ 가속구조 설계기술과 전자기파 특성을 융합한 도전적인 연구

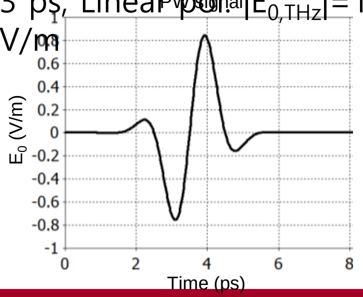


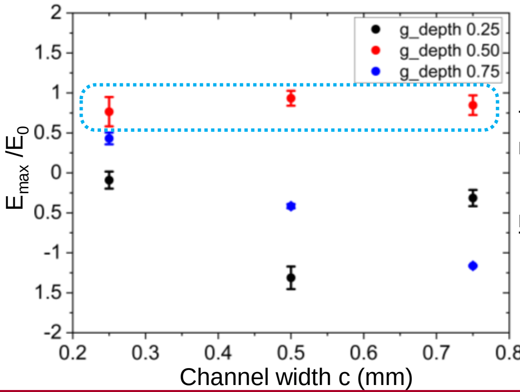


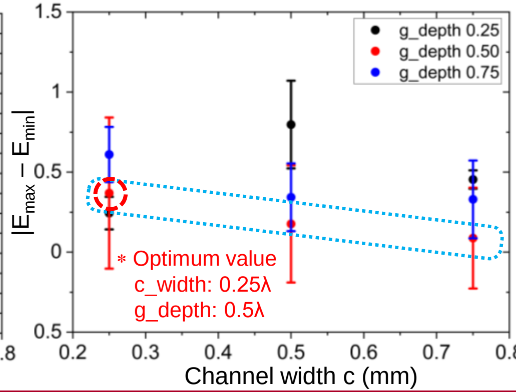


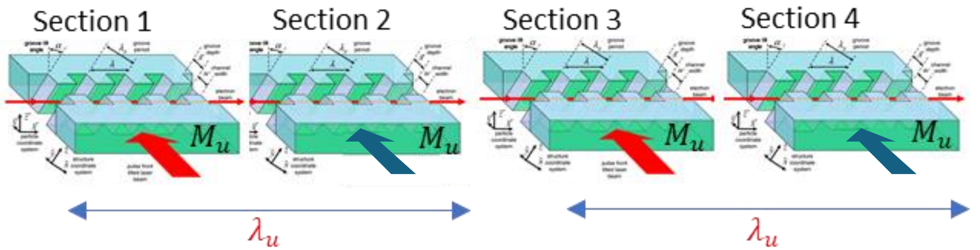
Parameter sweep
Tilting: 5 ~ 35°
Channel width: (0.25~0.75)λ
Groove depth: (0.25~0.75)λ

Input wave: 1 mm, 300 GHz,
3 ps, Linear pol. $|E_{0,THz}|=1$ V/m



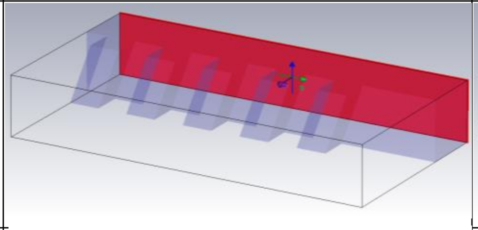
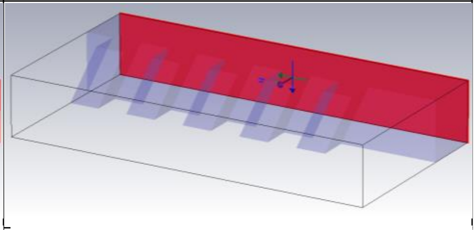
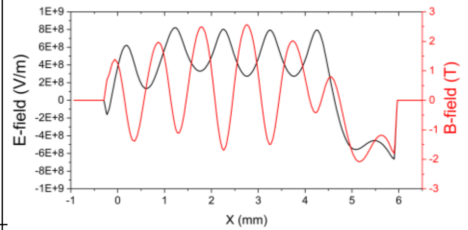
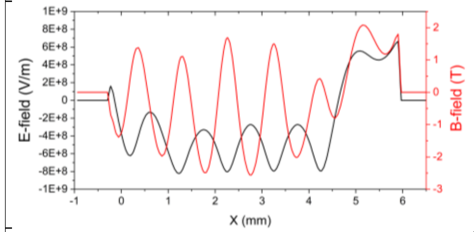
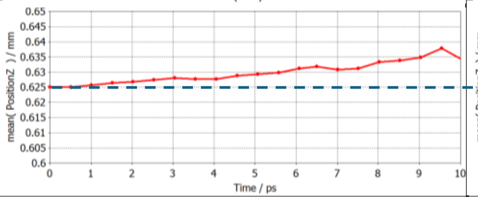
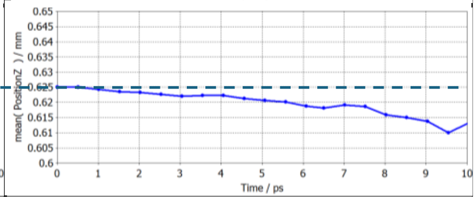






PIC simulation of 50 MeV electron beam in DTU

Spot size(rms): 1 μm; Bunch length: 10 μm; Bunch charge: 10 nC; ΔE=0

	Section 1 Plane normal (0,0,1) E-field vector (1,0,0)	Section 2 Plane normal (0,0,1) E-field vector (-1,0,0)
25 deg.		
E [V/m] B [T]		
Def. z_{mean} [mm]		

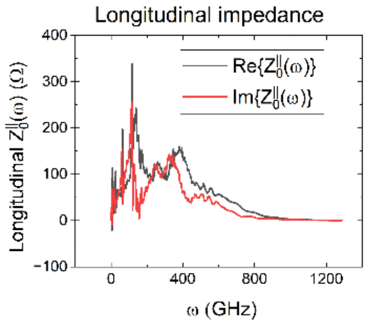
Multi-bunch instability for high gradient and high power

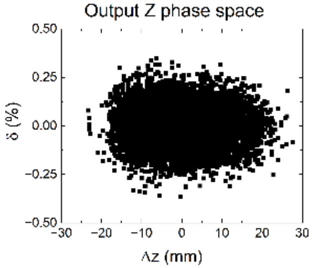
(Courtesy of B.-H. Oh)

- **Multi-bunch Instability by wakefield**

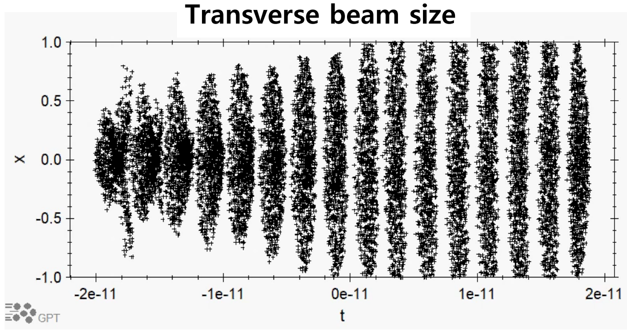
- **Beam distribution function** : $\psi = \psi_0 + \psi_1 e^{i\Omega s/c}$ (ψ_0: unperturbed; $\psi_1 e^{i\Omega s/c}$: perturbed by wake field due to impedance)
- **Single bunch instability**
  - Longitudinal impedance : $Z_0^{||}(\omega'),\ \omega' = p\omega_0 + l\omega_s$
  - Transverse impedance : $Z_0^{\perp}(\omega'),\ \omega' = p\omega_0 + \omega_\beta + l\omega_s$
- **Multi-bunch Instability** (M : # of bunches; μ: multi-bunch mode #)
  - m=1, l= 1,2,..: $\omega' = pM\omega_0 + \mu\omega_0 + \omega_\beta + l\omega_s;\quad \Omega^{(l)} - \omega_\beta - l\omega_s = \frac{MNr_0}{\gamma T_0^2 \omega_\beta^2 \sigma^2} \sum_{p=-\infty}^{\infty} i \frac{1}{(l)!} e^{-\frac{\omega'^2\sigma^2}{c^2}} \frac{Z_0^{\perp}(\omega')}{\omega'} \left(\frac{\omega'\sigma}{\sqrt{2}c}\right)^{2l}$

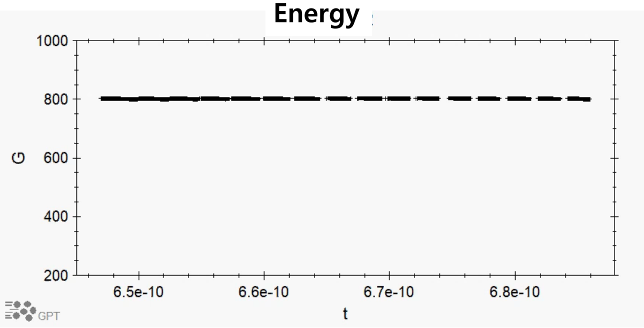
CST MS ⇒ Impedance calculation
Elegant ⇒ Beam tracking w. impedance





- Beam transport in PET structure





Summary

- The LWFA using laser-ablated metallic plasma has been developed for operating at high repetition rate and high vacuum.
- Metal having ionization level give different evolution of density map.
- The electrons depleted from L-shell of Ti ions ionized by the peak intensity of main laser may be localized near the optical axis, so can be useful for ionization injection.
- The ionization injection can be controlled by the location and the thickness of Ti layer.
- The low energy spread of electron beam can be obtained at a certain condition :

  - where the self-injection is barely occurred
  - that the ionization diffraction is rapidly increased, resulting the dephasing-free.
- KU-PAL-NIU-ANL collaborate to develop core methods and technologies to realize THz-TBA and their integration
- Fabrication of 0.4 THz structure is ongoing using LIGA method for a higher quality.
- Bunch train with 16 bunches having 1 nC each will be generated using laser pulse train.
- The peak power of 3.3 GW is expected from upcoming experiment