AFAD Asian Forum for Accelerators and Detectors 2023

Simulations studies on the development of an advanced electron/ion accelerator using a laser-plasma interaction in Korea University Sejong Campus

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"대한민국을 이끌어 온 자랑스럽고 위대한 역사, 눈부신 고대의 새로운 백년도 지켜가겠습니다."

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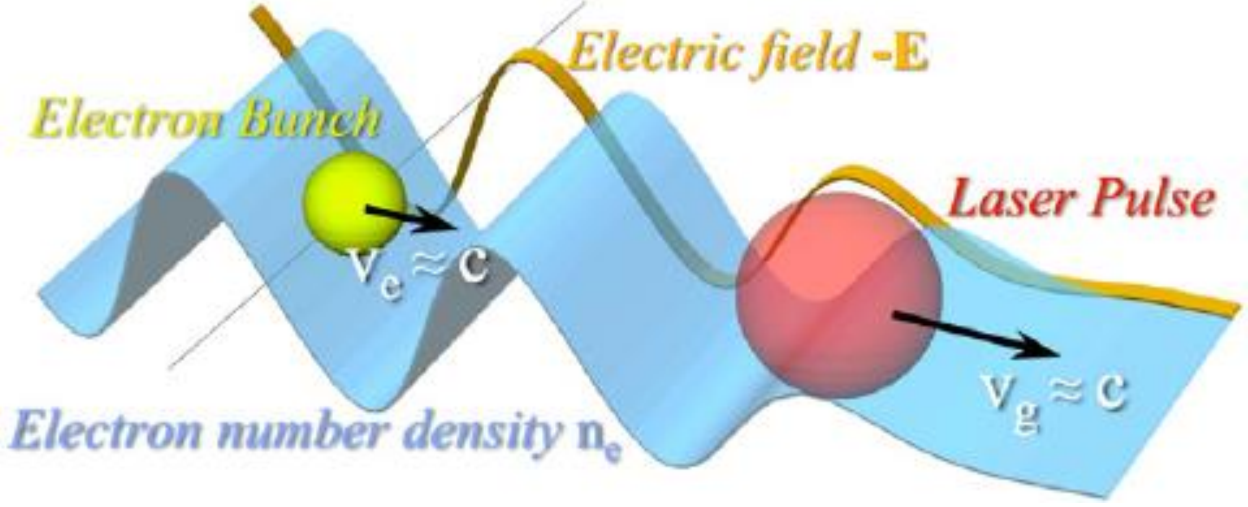
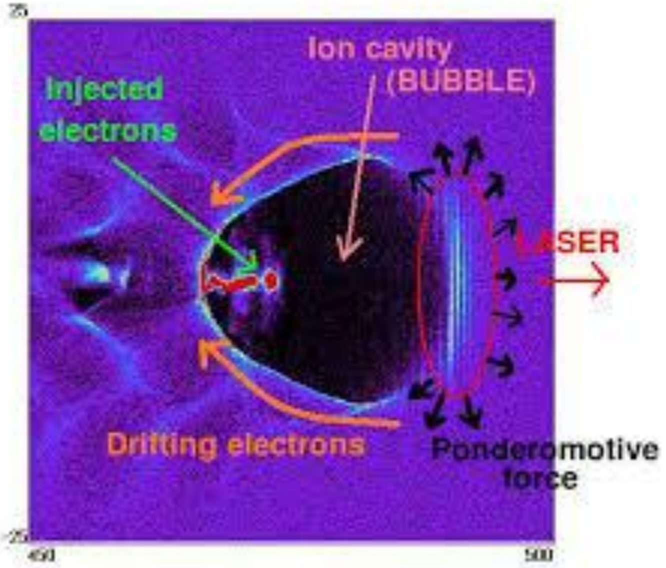
Laser Wakefield Acceleration (LWFA)

- **Laser wakefield acceleration (LWFA) :** Electron acceleration mechanism via the laser-plasma interaction
  - ✓ TV/m order of E-field than conventional RF (radio-frequency) accelerator
  - ✓ Wide applications (e.g., tumor therapy, compact light sources, an injector of a high-energy accelerator)

- **Required e-beam spec for FEL or collider:** <0.5% of beam spread & >100 pC of charge density



[Felicie Albert et al., PPC.56(8):084015 (2014)]



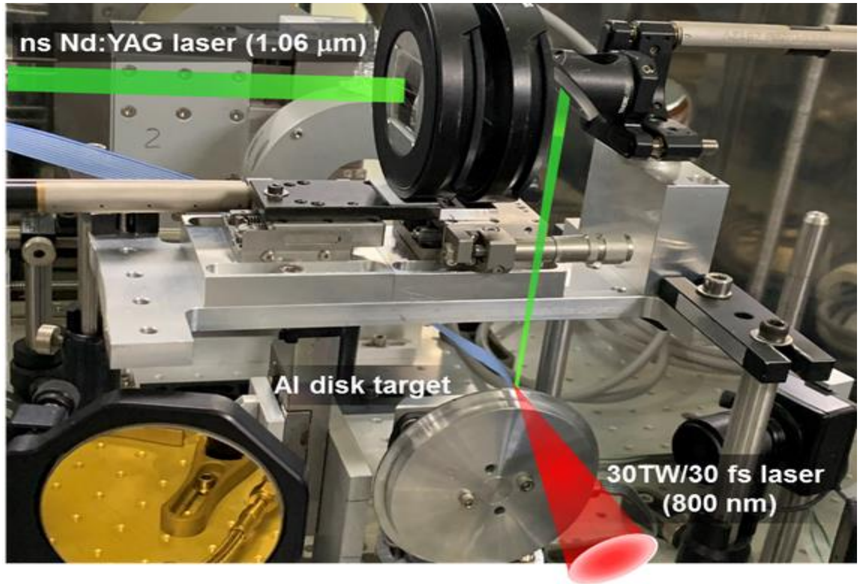
[Leonida A. Gizzi, Miniworkshop su Acceleratori, 17 Feb 2015 INFN]

LWFA using Laser-ablated Metal Target

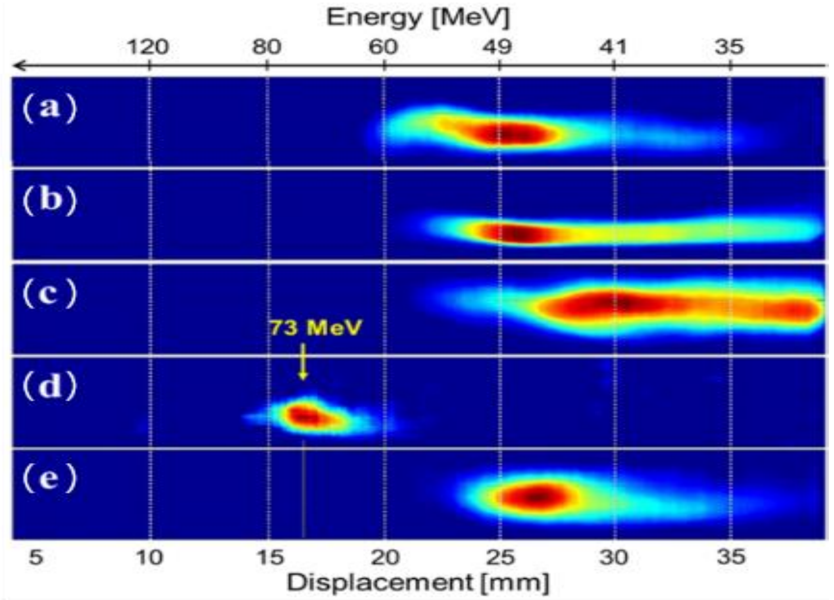
- **T. Matsuoka et al (2009) :** LWFA using laser-ablated **Teflon** $(CF_2)_n$ target
- **B. S. Rao et al. (2013) :** LWFA using laser-ablated **Nylon** $(C_{12}H_{22}N_2O_2)_n$ target

- Efficient to maintain a high-vacuum condition and to increase the repetition ratio.)

- Carbon-based plasma can damage easily optical equipment!!
  → Using laser-ablated metal (e.g., Al) target was suggested.



[LWFA equipment in KAERI]

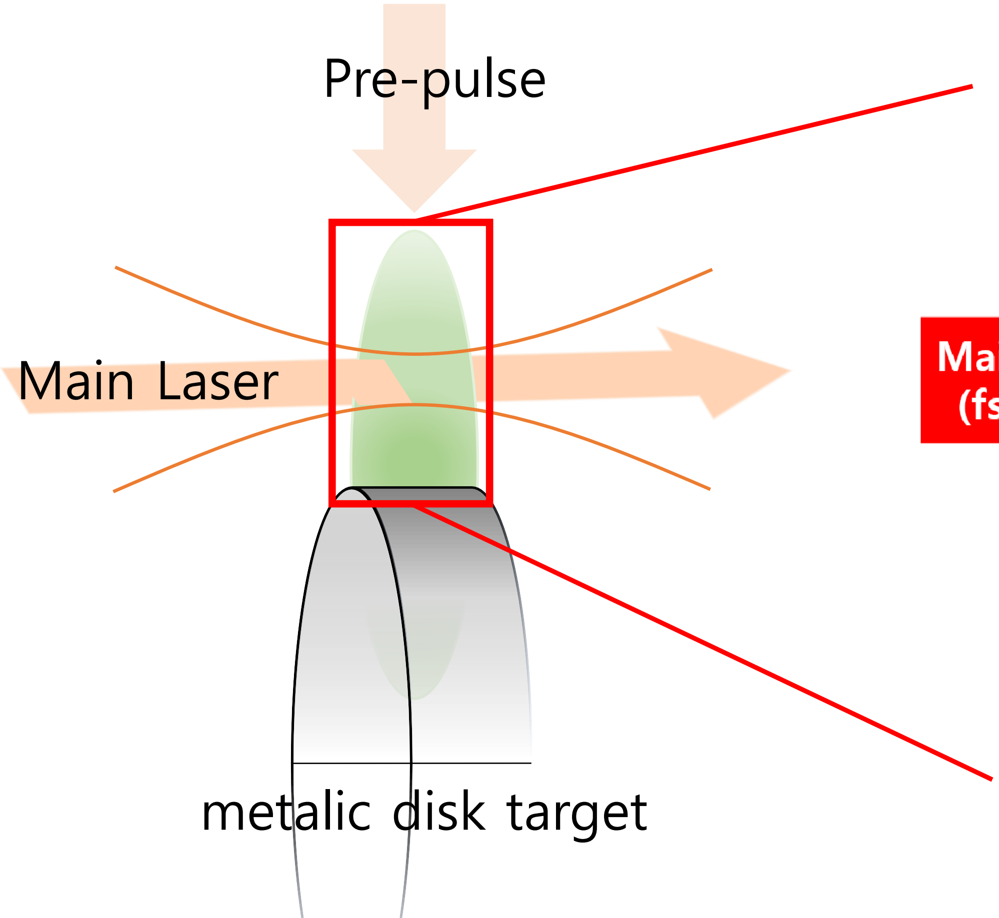


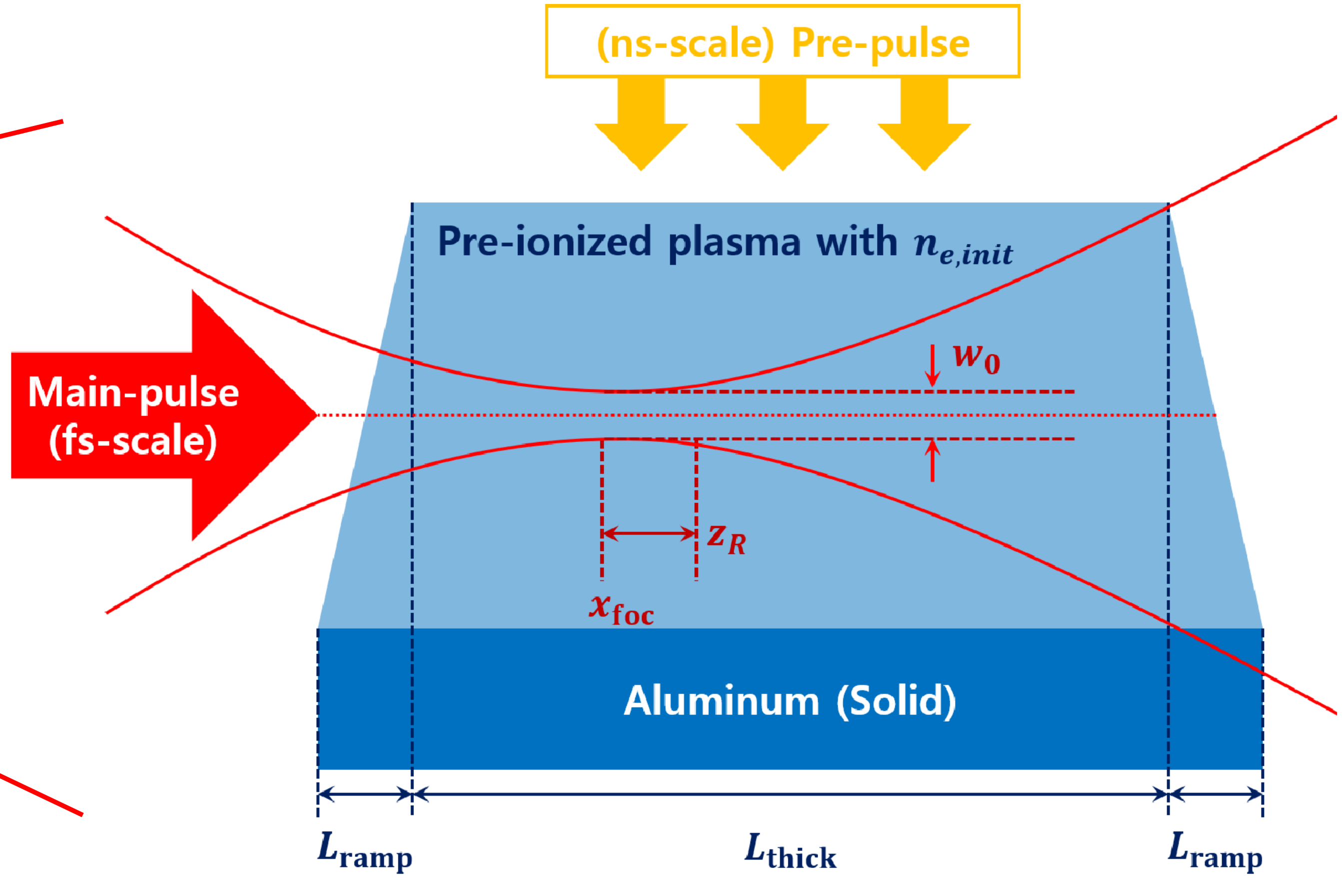
[S. Y. Shin and S. H. Park, Proc. SPIE 11778, 1177807 (2021)]

Simulation Scheme

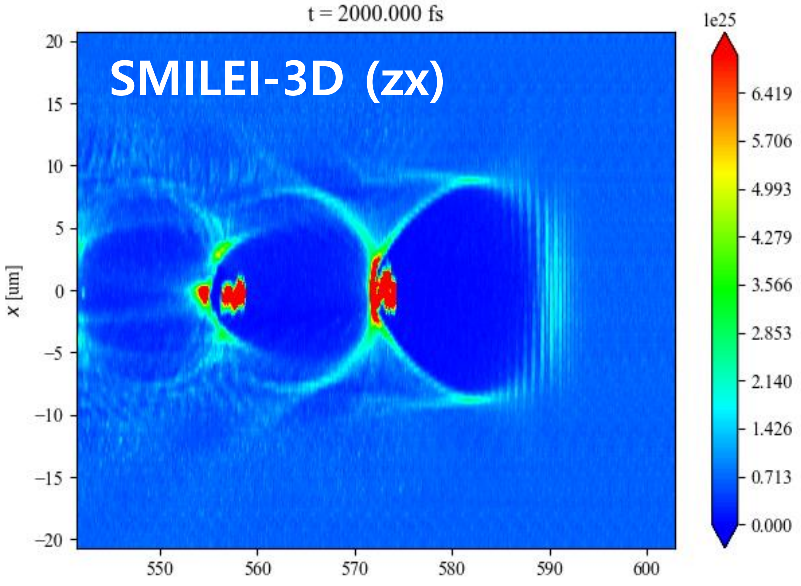
- $\lambda_L = 800$ nm
- $P_L = 20(30) \sim 50(100)$ TW
- $w_0 = 7(10)$ μm
- $I_L = 2 \sim 7 \times 10^{19}$ Wcm^{-2}
- $n_e = 2 \sim 9 \times 10^{18}$ cm^{-3}
- $\tau_L = 25$ fs & $x_{foc} = 500$ μm < 1 mm

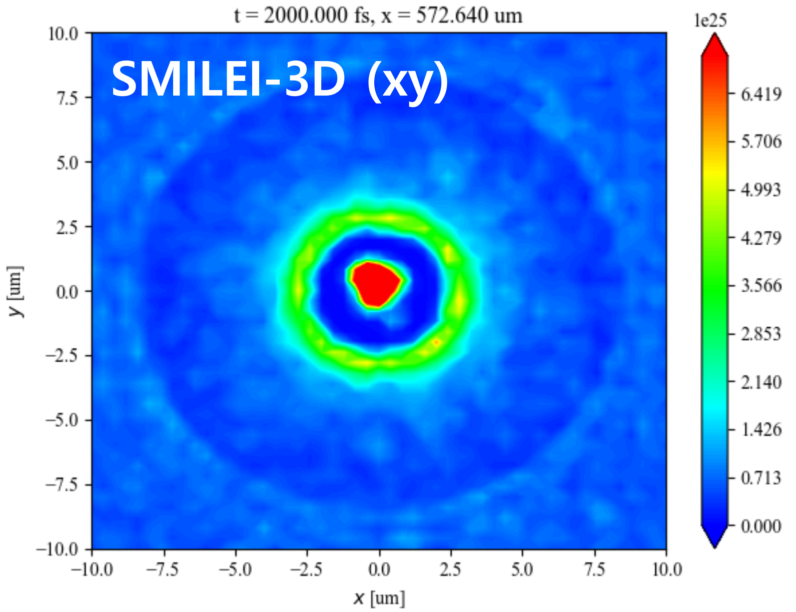
- **EPOCH** : https://github.com/Warwick-Plasma/epoch
- **SMILEI** : https://smileipic.github.io/Smilei/

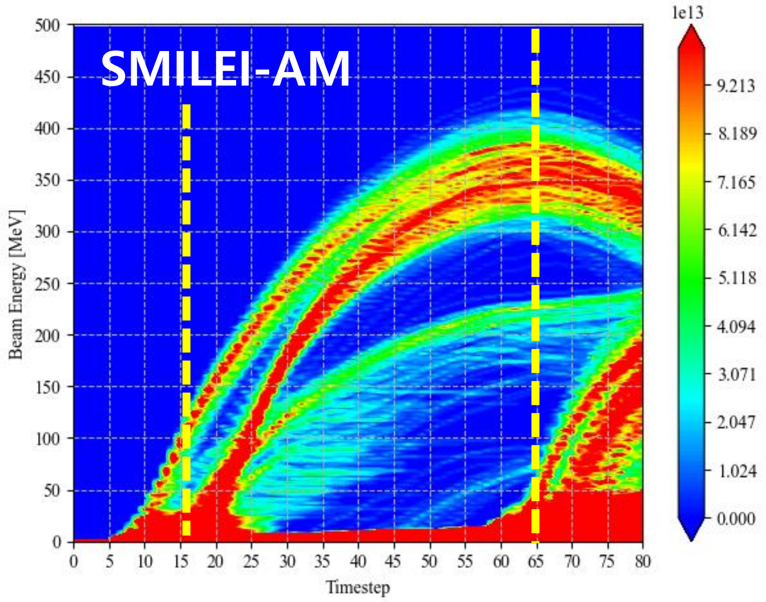


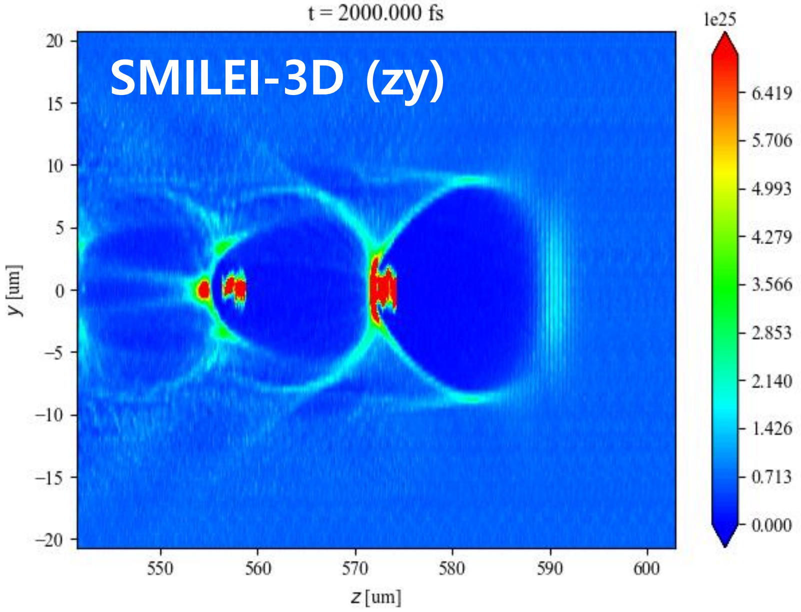


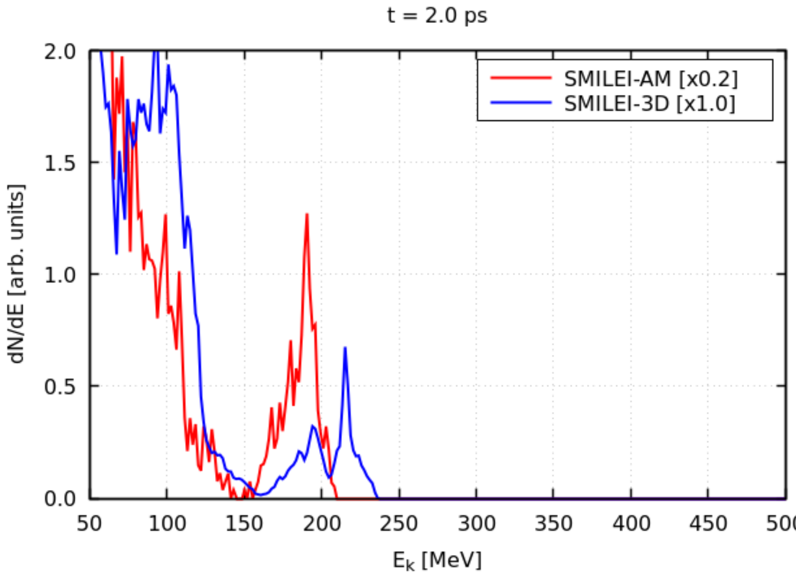
Representative Figures For He, w_0 = 10.0 μm





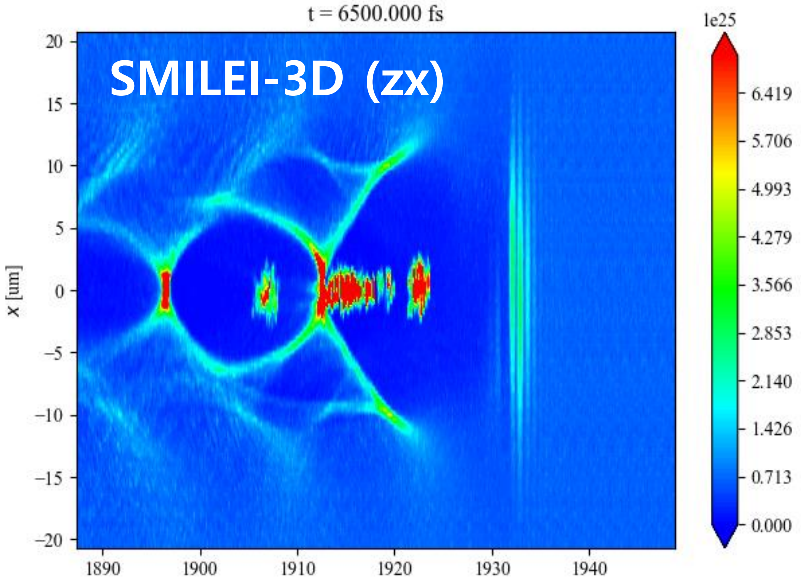


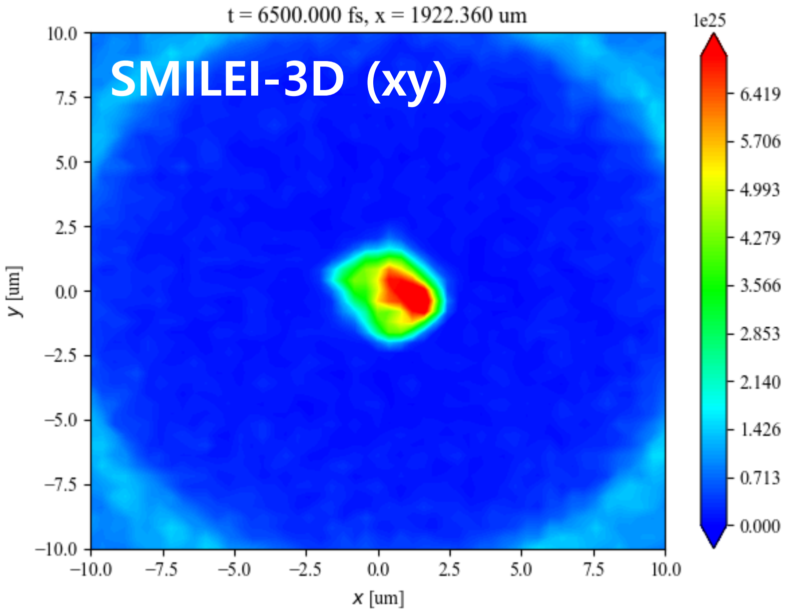


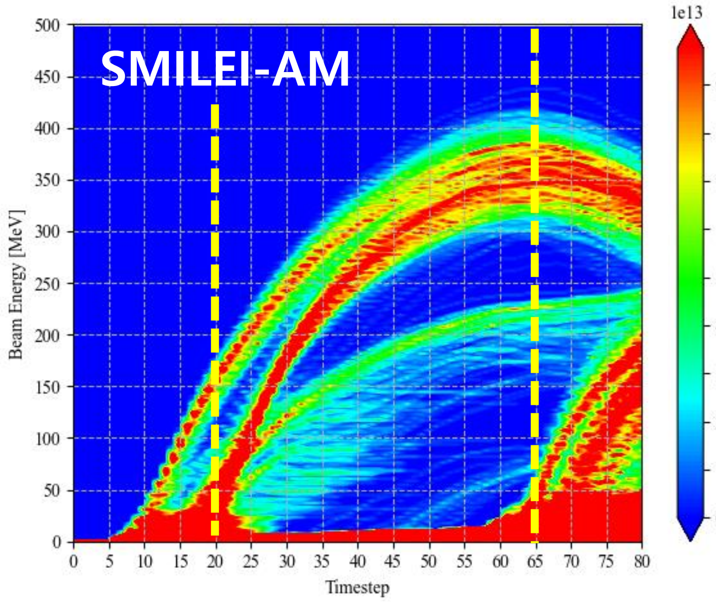


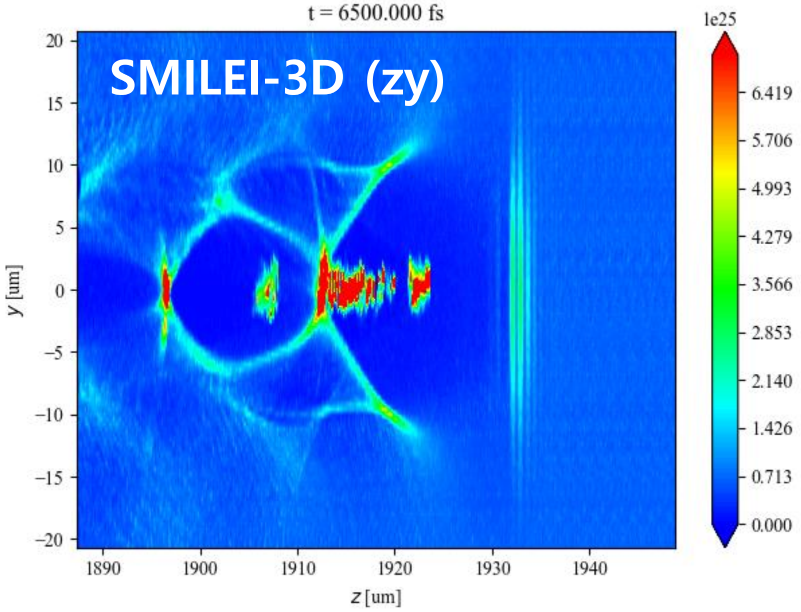
- $P_L = 30$ TW
- $w_0 = 10$ μm
- $a_0 = 3.0$
- $I_L = 1.9 \times 10^{19}$ Wcm^{-2}
- $n_e = 5.9 \times 10^{18}$ cm^{-3}
- $n_e/n_c = 0.003376$

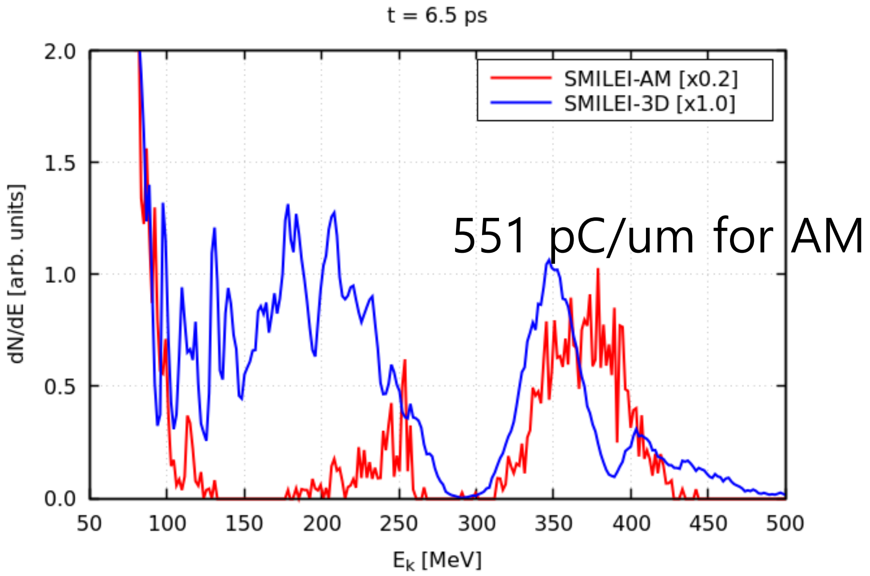
Representative Figures For He, w_0 = 10.0 µm











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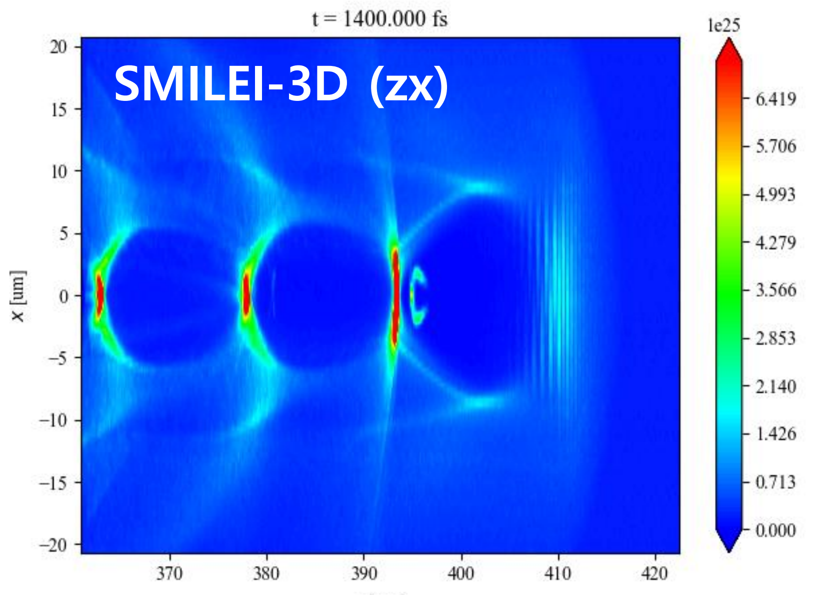
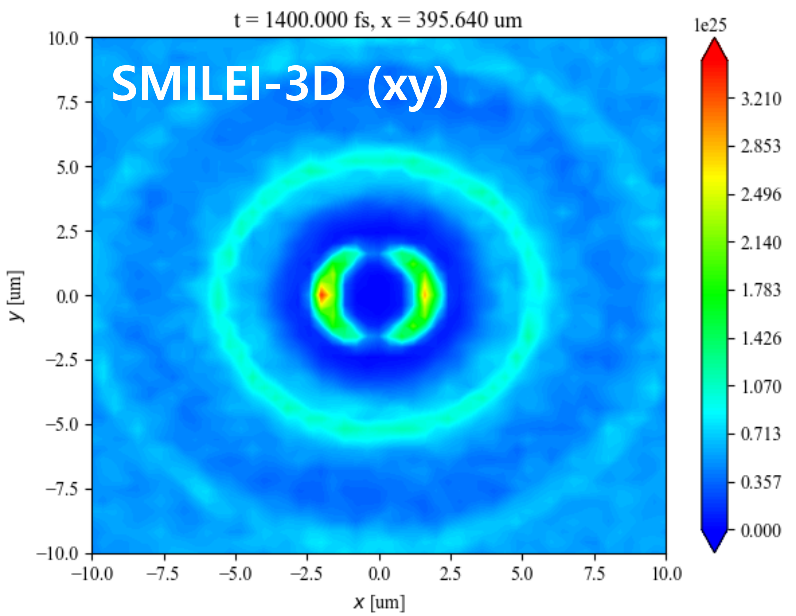
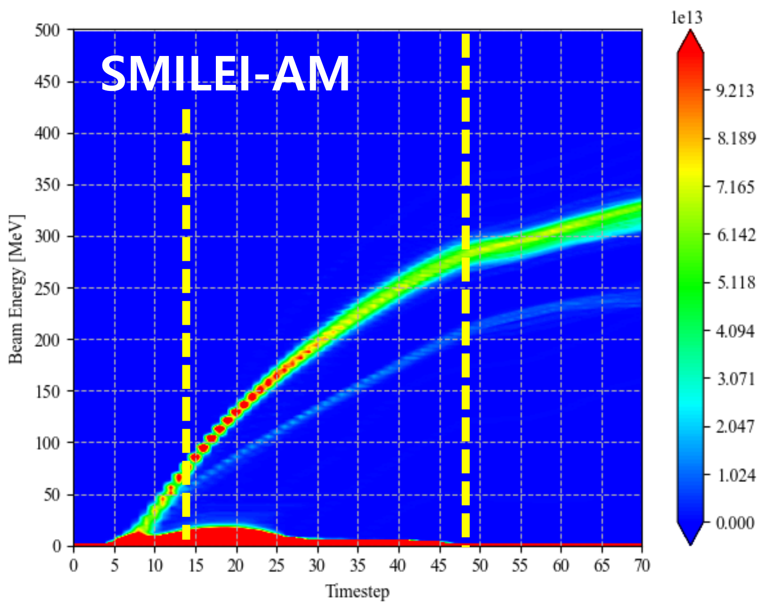
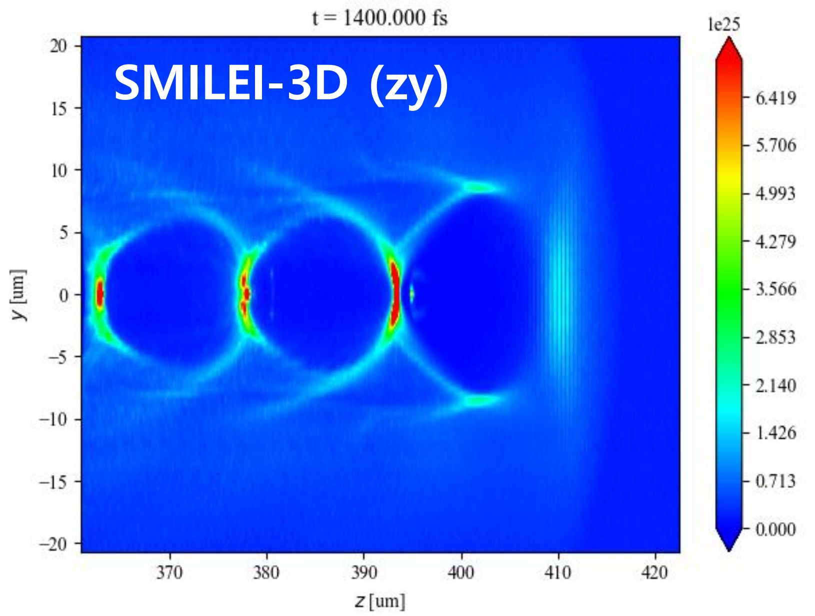
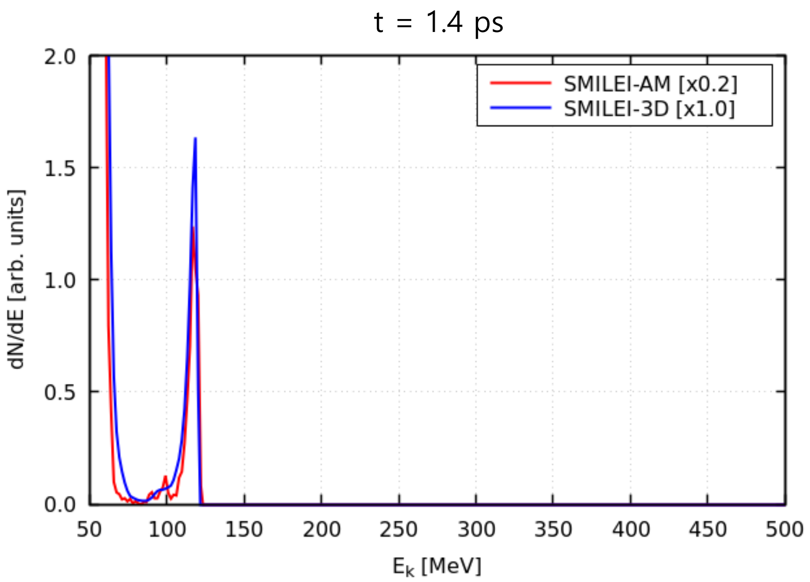
Representative Figures For Al, w_0 = 10.0 μm











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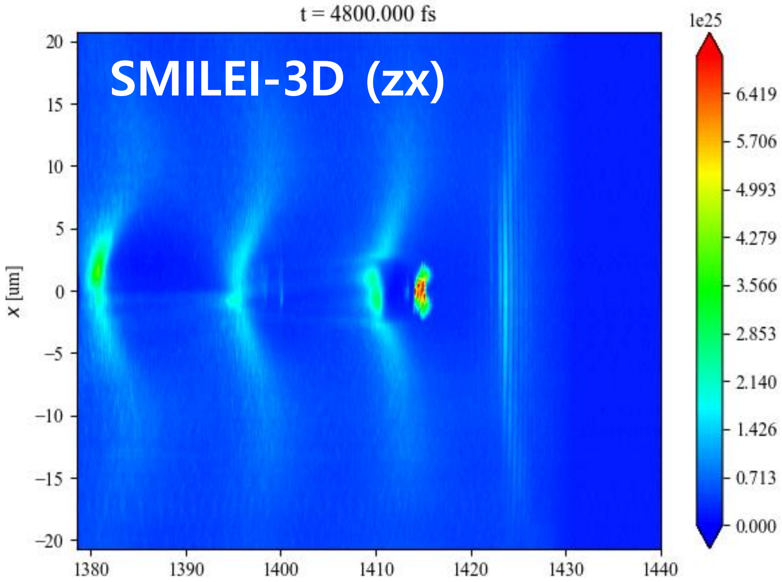
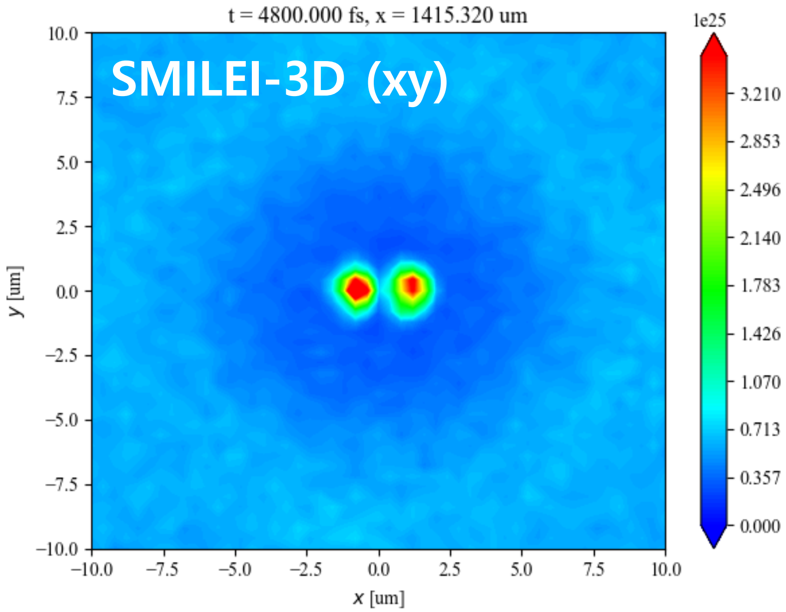
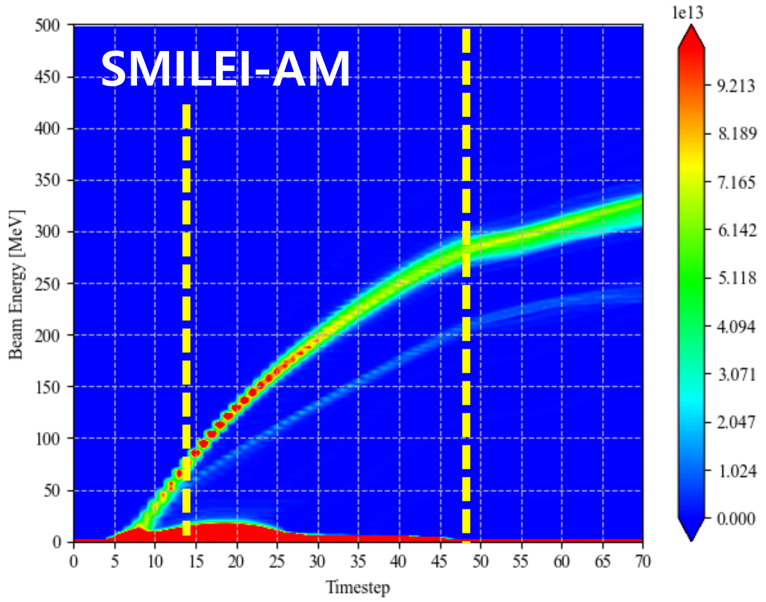
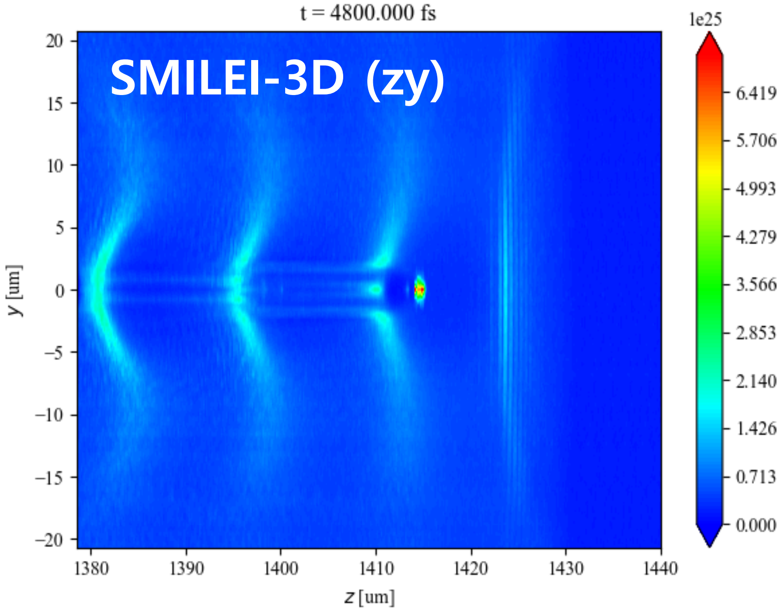
- $n_e = 5.9 \times 10^{18}$ cm^{-3}
- $n_{ef}/n_c = 0.003376$
  $(i.e., n_{ef} = n_{ei} \times 11/3)$

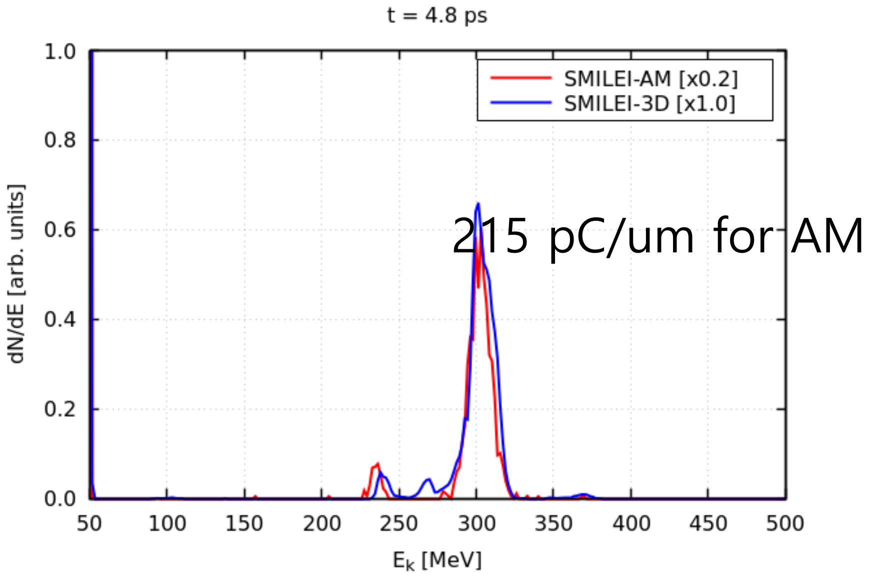
Representative Figures For Al, w_0 = 10.0 μm











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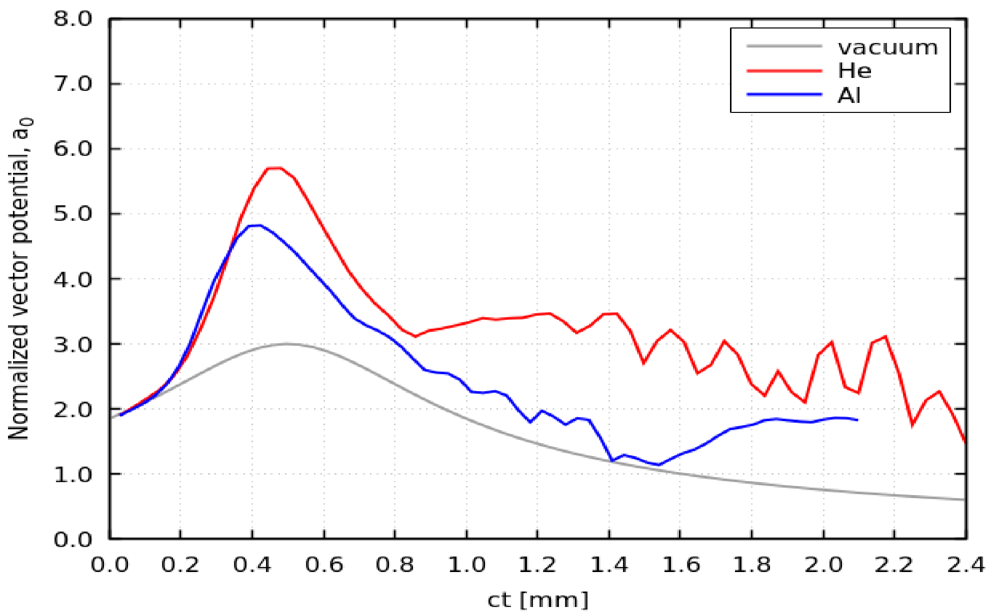
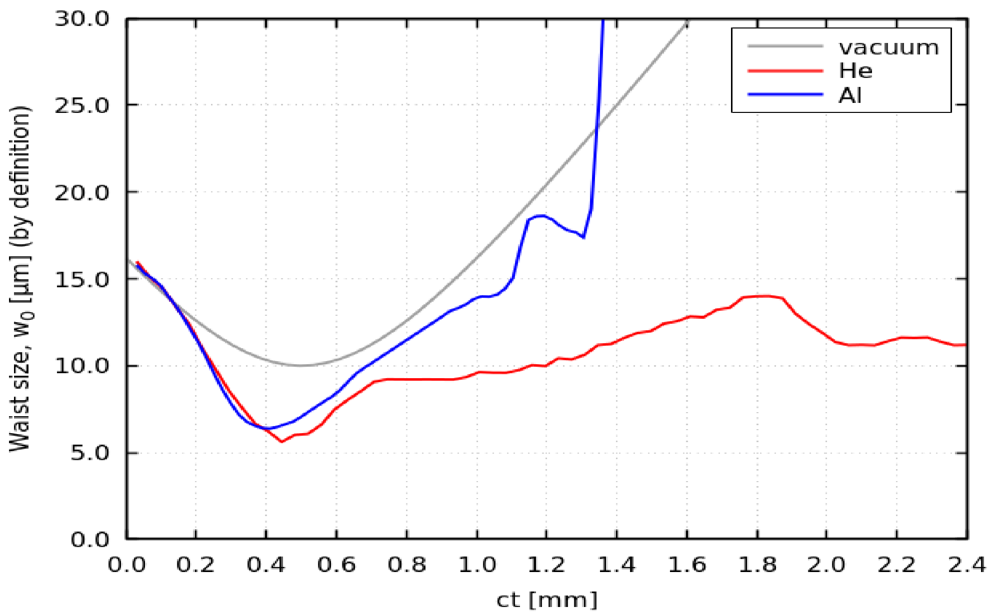
- $n_{ef}/n_c = 0.003376$ $(i.e., n_{ef} = n_{ei} \times 11/3)$

Ionization effects on LWFA

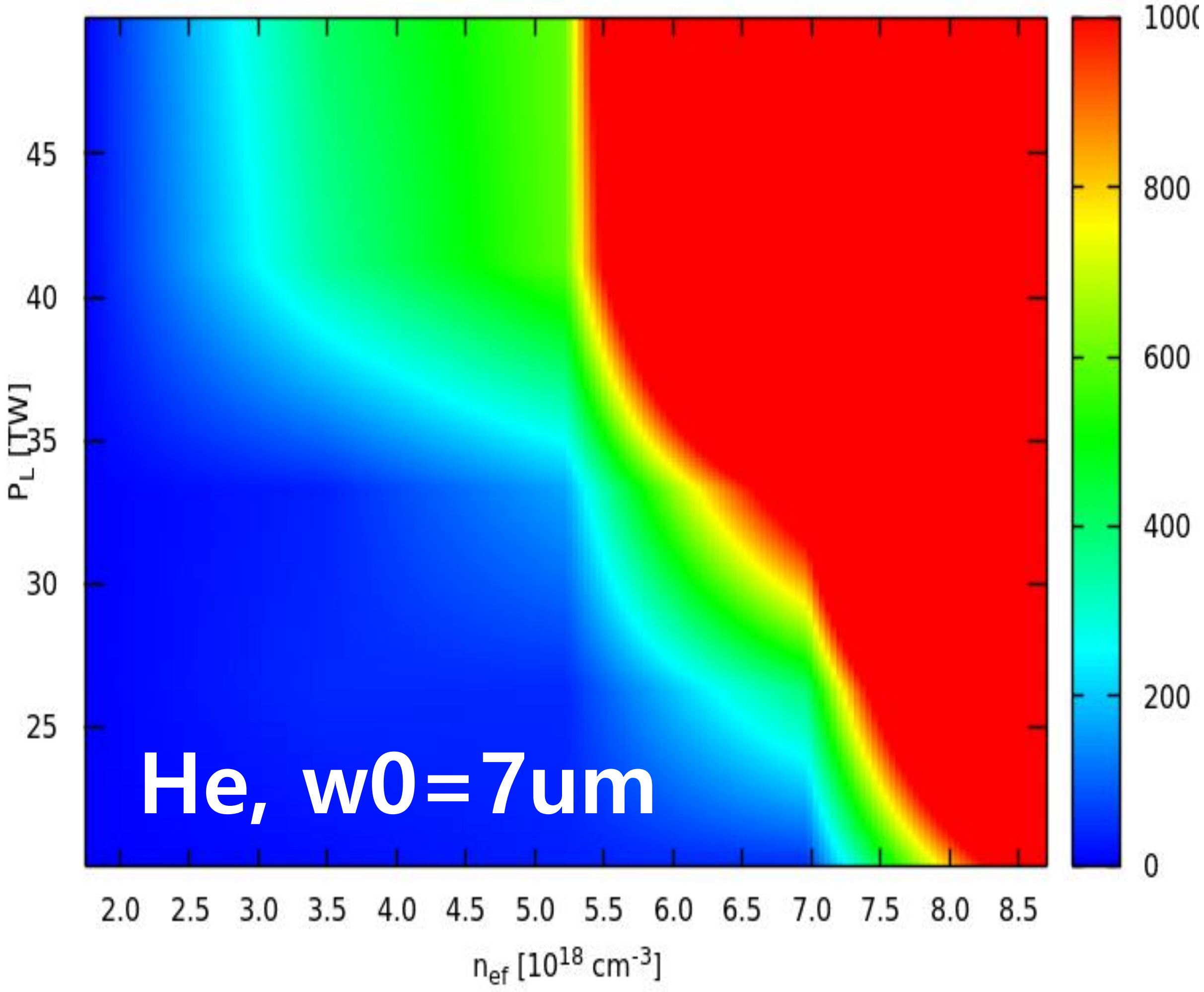
- **He plasma :** can be assumed that it is fully-ionized.
- **Al plasma :** ionization process in-situ is important roles;
  - ✓ Laser power or intensity is decreased.
  - ✓ Laser is more diverge from the ionization diffraction. (*i.e.*, it is hard to self-focusing!!)

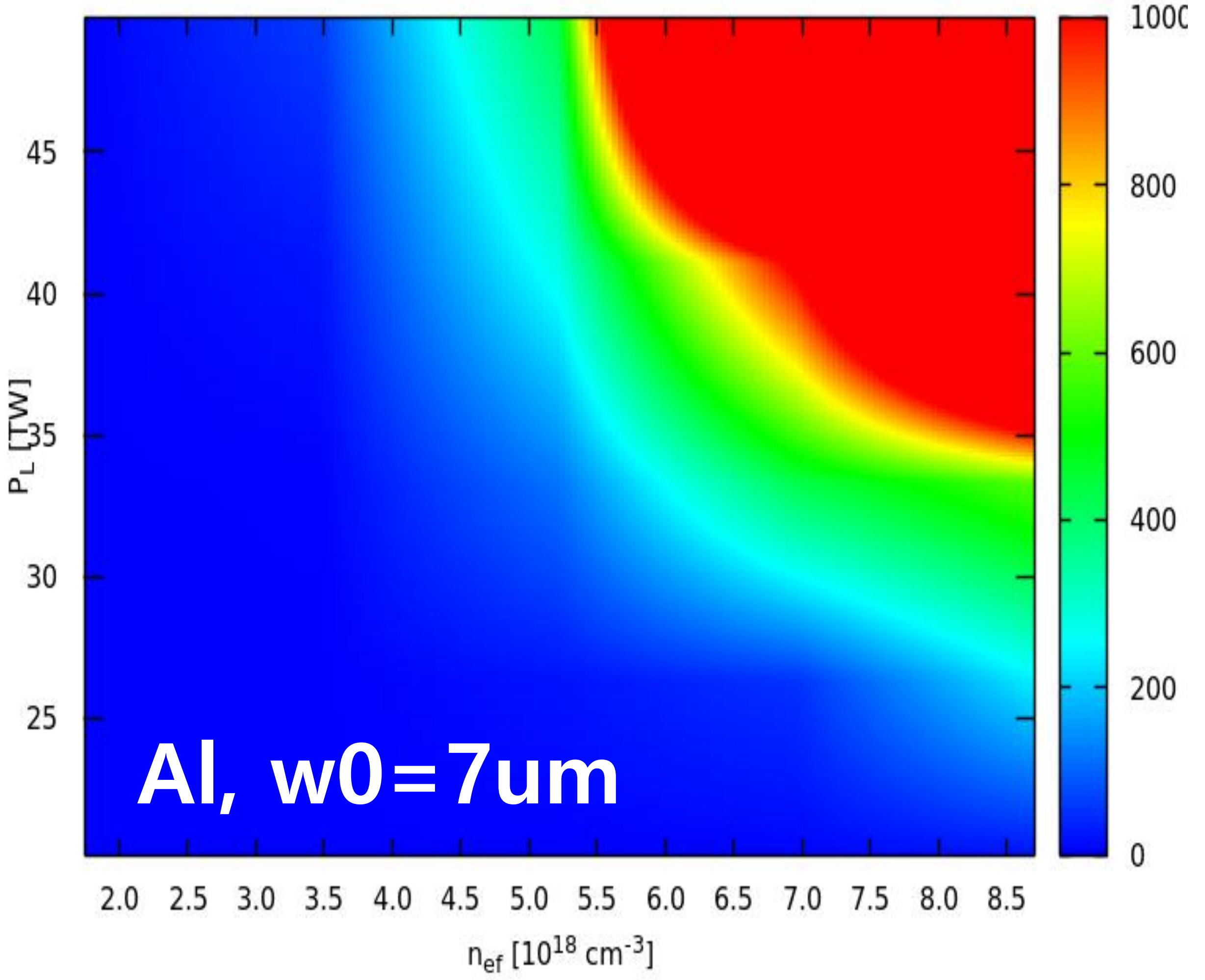
    → Recommended to use the short waist size.



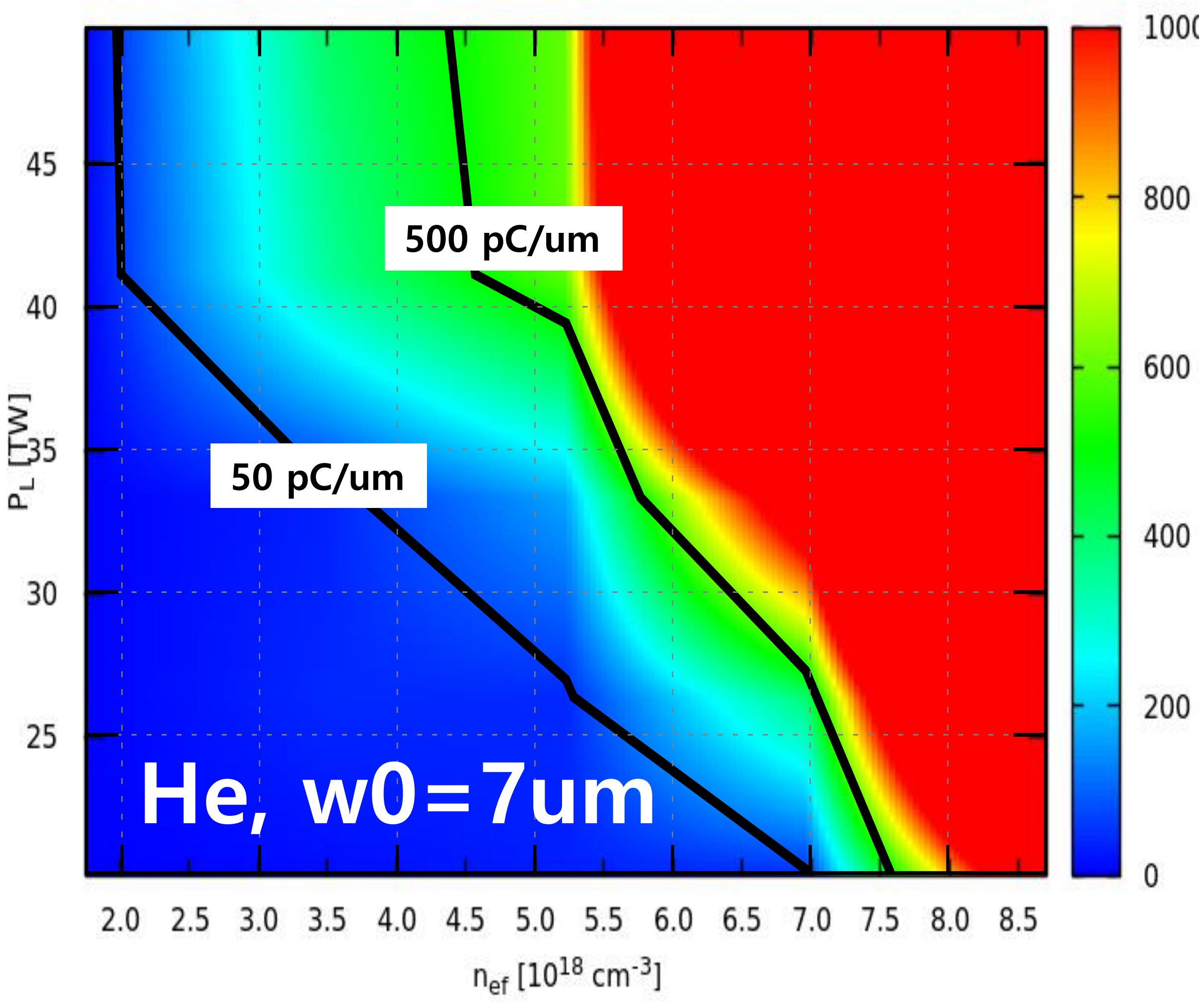


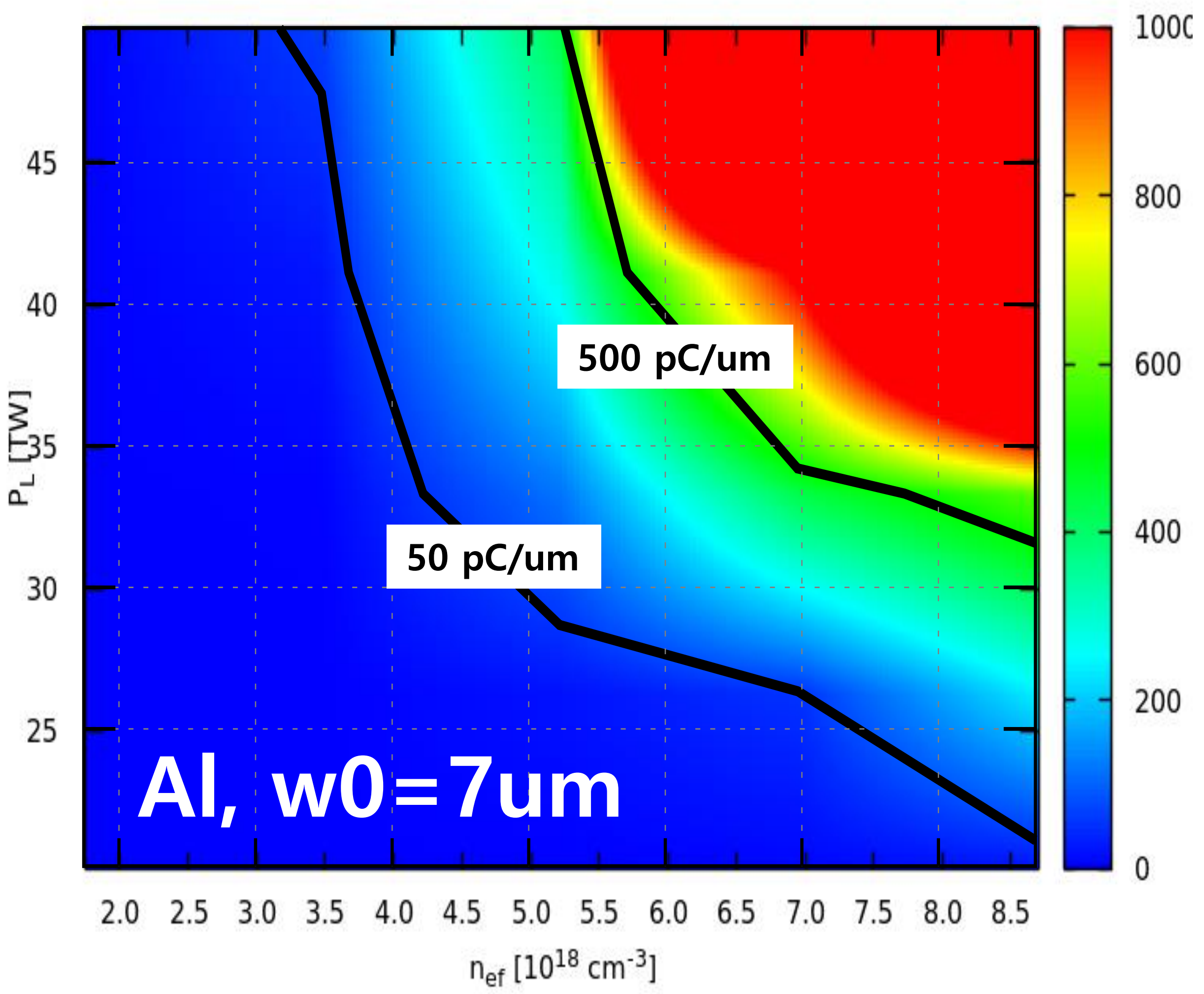
Parametric Studies; Charge Density





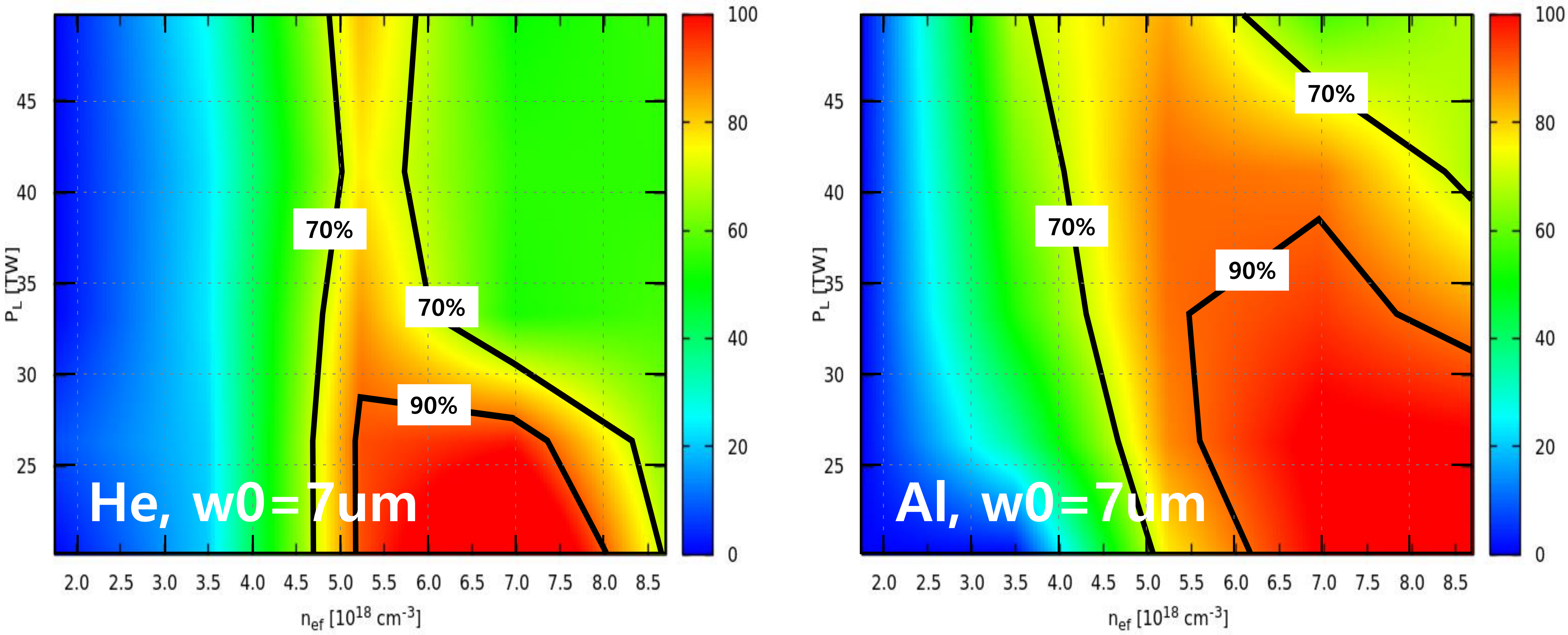
Parametric Studies; Charge Density





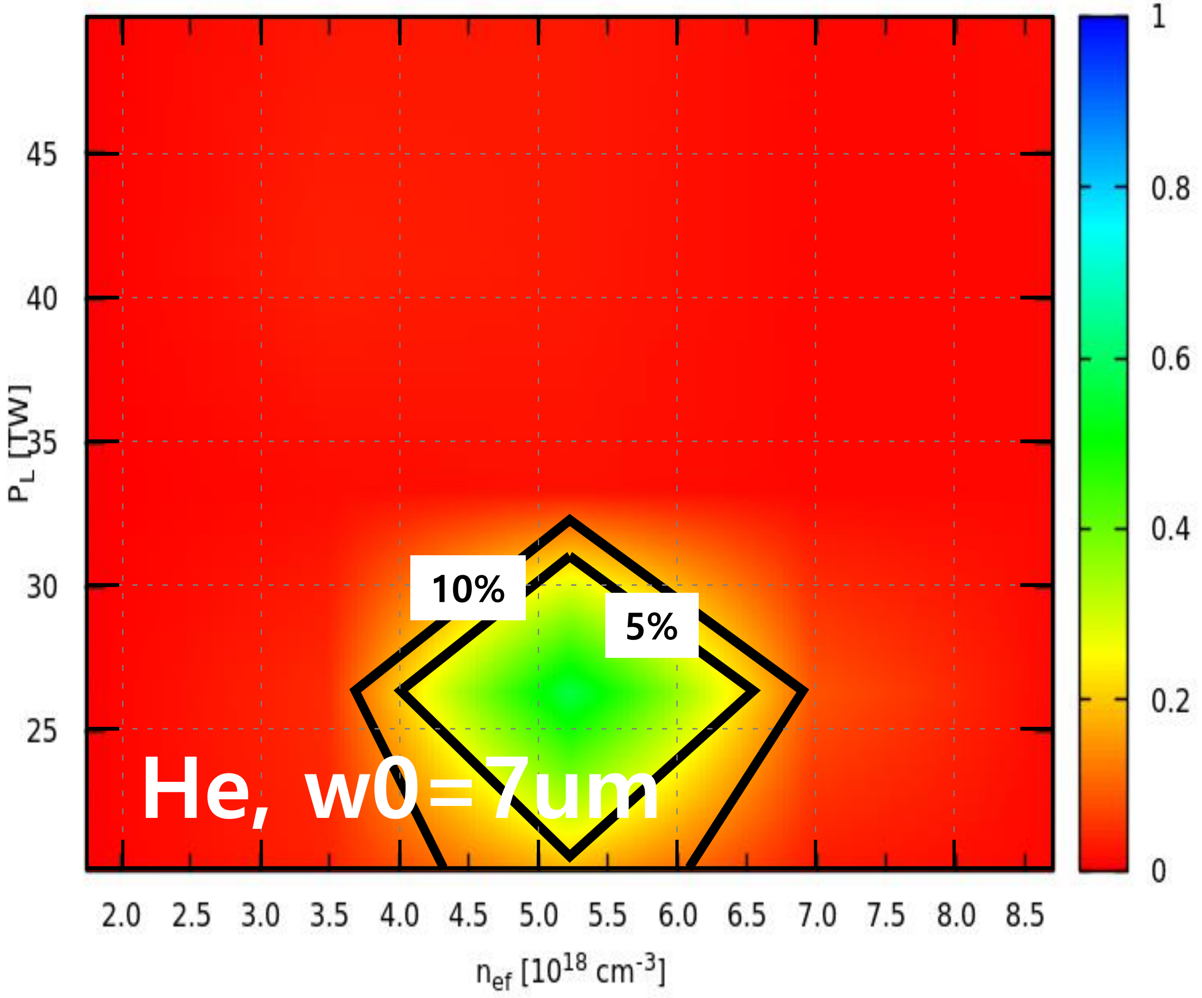
Parametric Studies; Beam Energy (vs. Lu's eqn.[1])

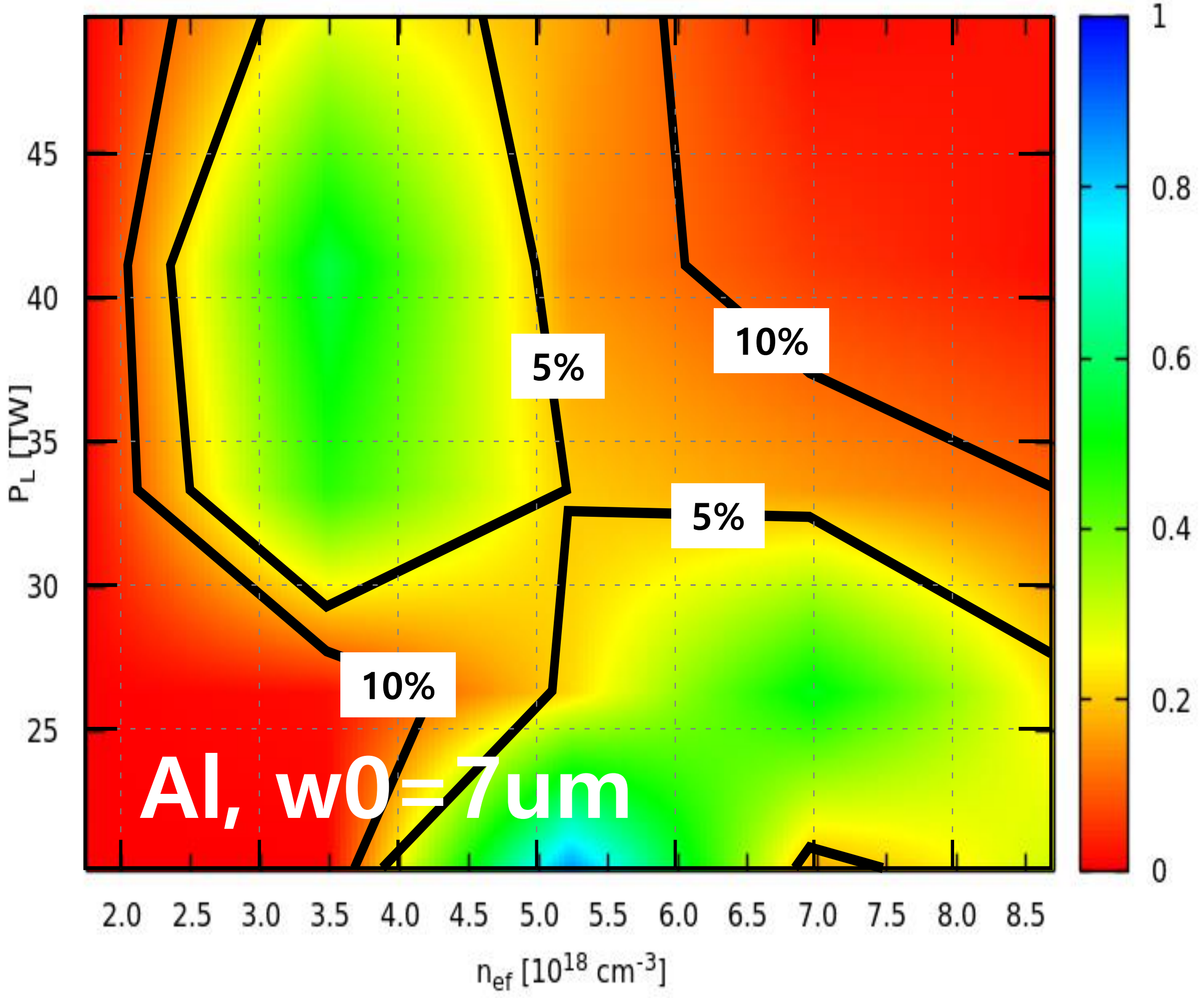
[1] W. Lu et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007)



Parametric Studies; Beam Spread

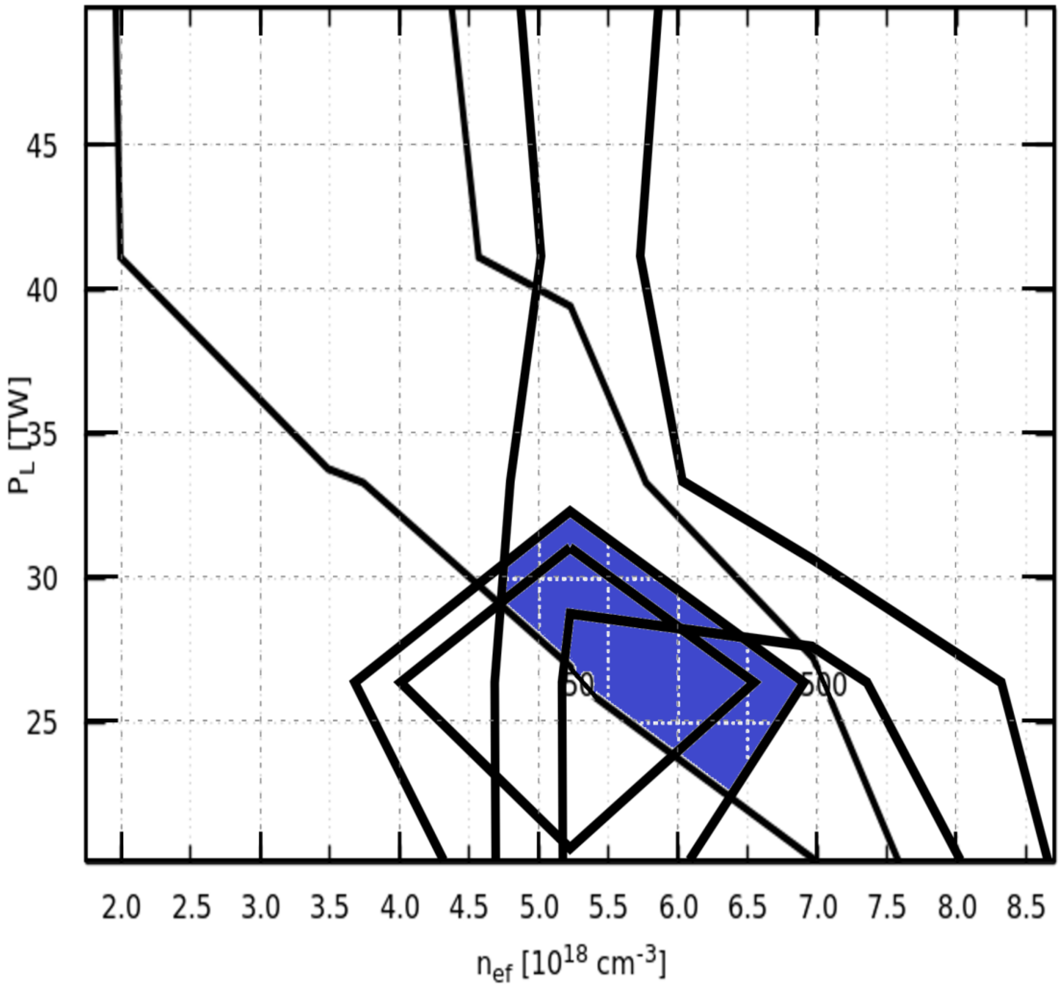
$$\text{Beam Spread} \equiv \frac{\text{FWHM width}}{\text{Peak (or Average) Energy}} \times 100$$

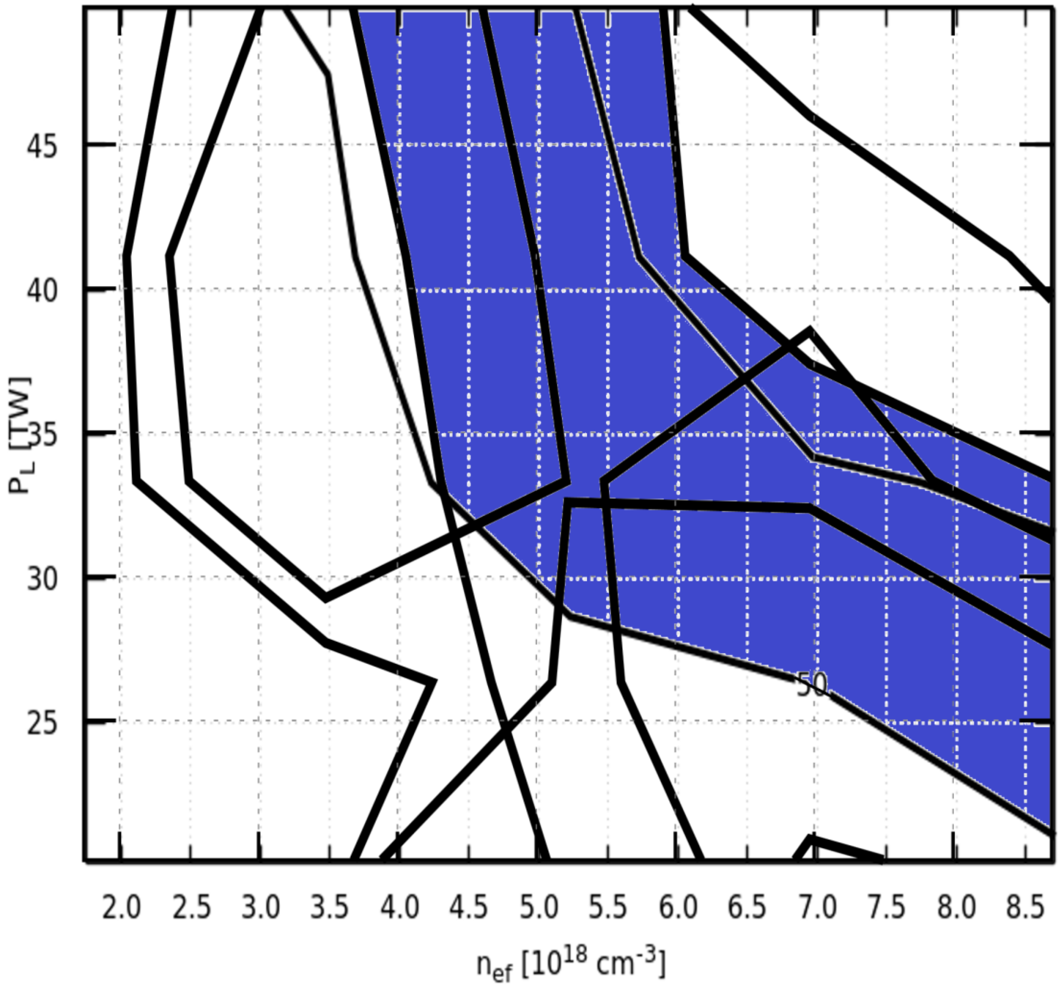




Parametric Studies; Optimum Region

>50 pC/μm, >70% of E/E_{Lu}, and <10% of Beam spread





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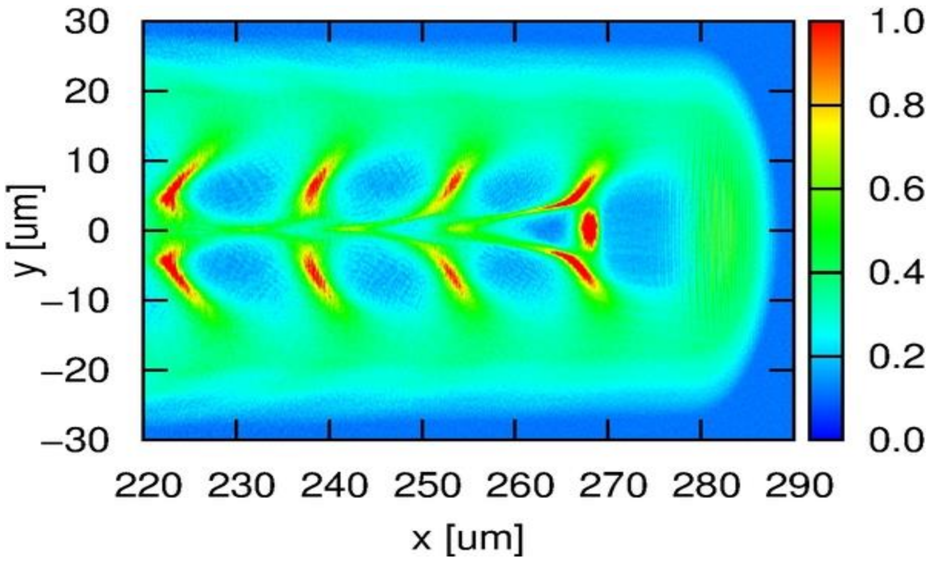
Motivation

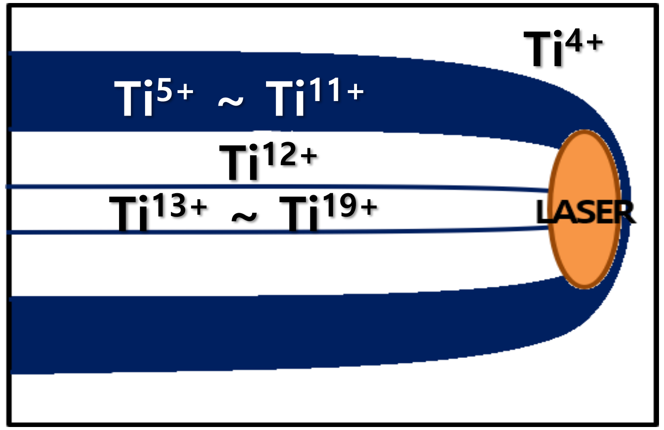
- **Other materials for target :**
  - ✓ **H, He :** Typical materials for gas jet targets in LWFA.
  - ✓ **N, O, F :** Use as dopants in gas jet target. (ionization injection)
  - ✓ **Na, Mg :** Easy to explode.
  - ✓ **Al, Ti, Cu** : **Investigate three different cases of ionization**.

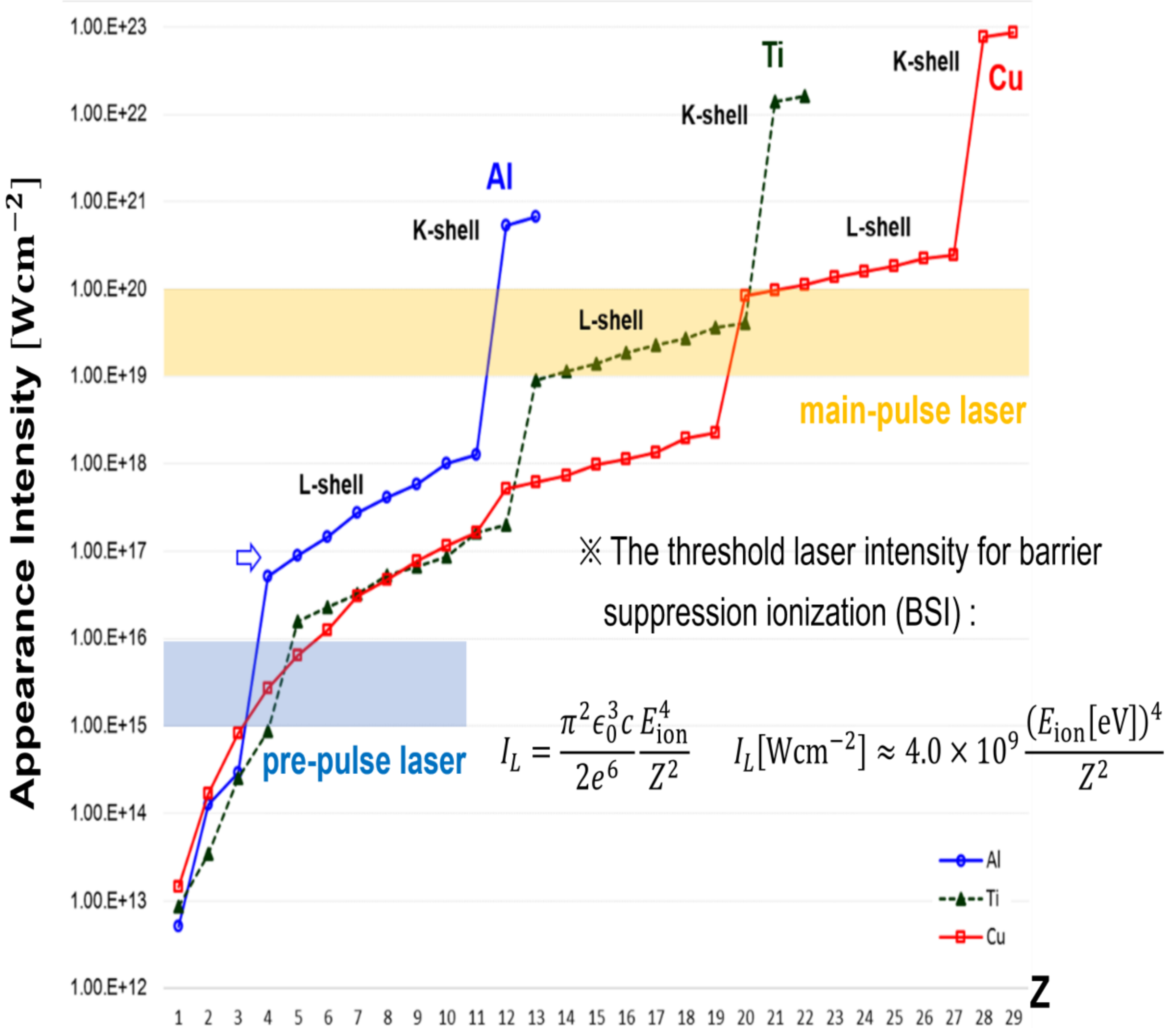
Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Motivation

- **Ti target :** <u>can be generated electron beam!!</u>

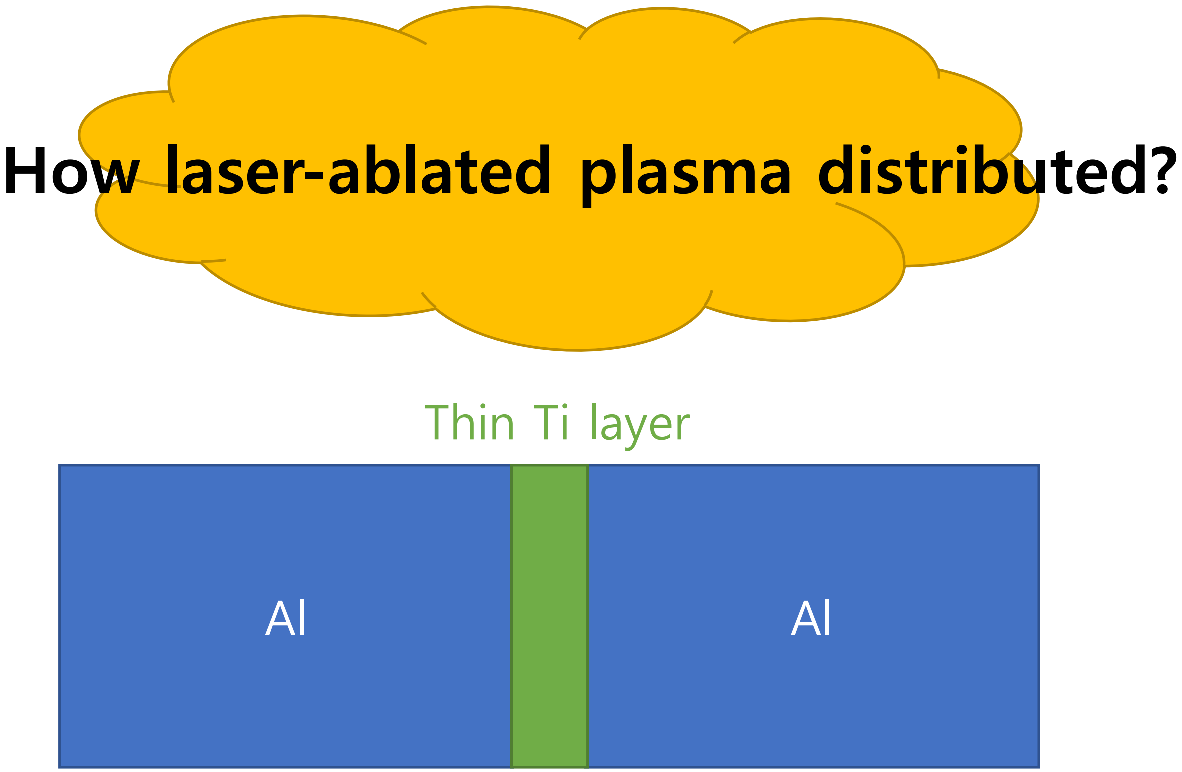


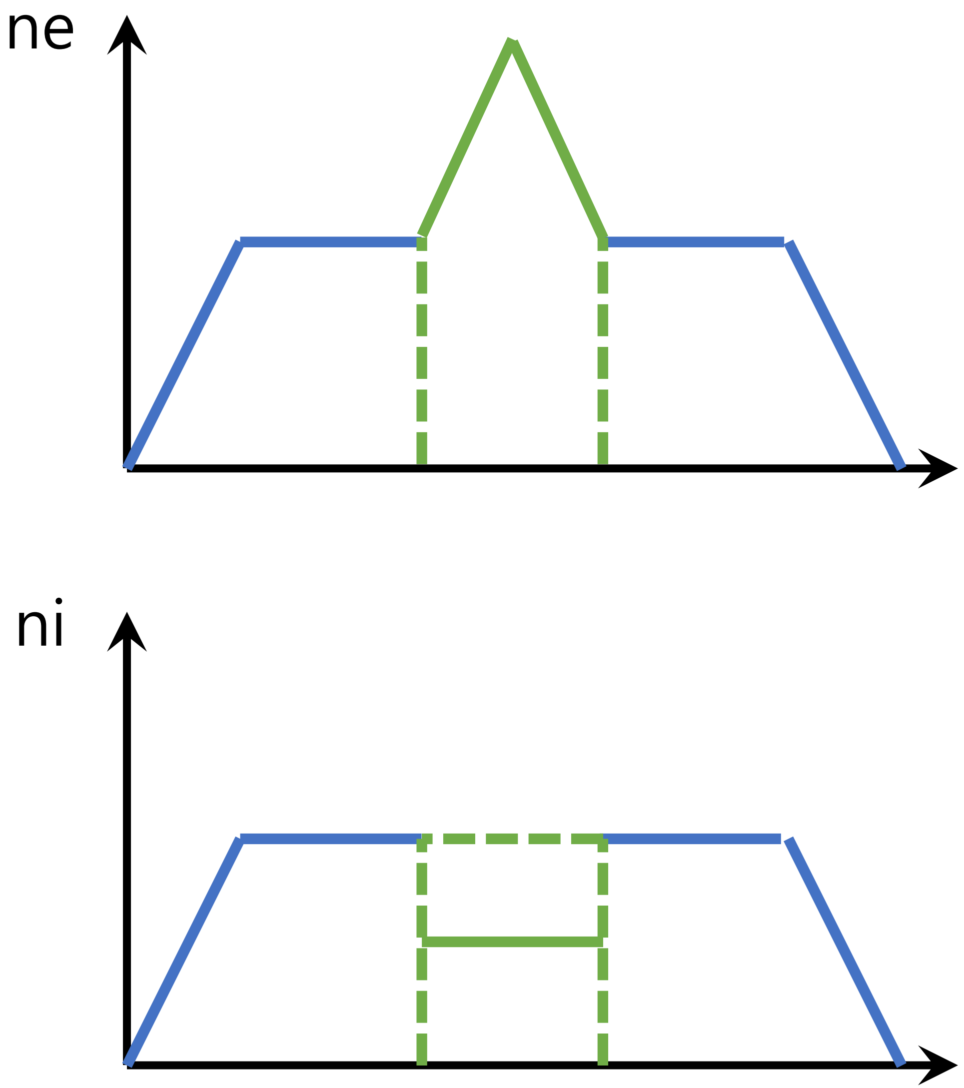




Motivation

- **Suggestion :** "Al – thin Ti layer – Al" (ATA) target

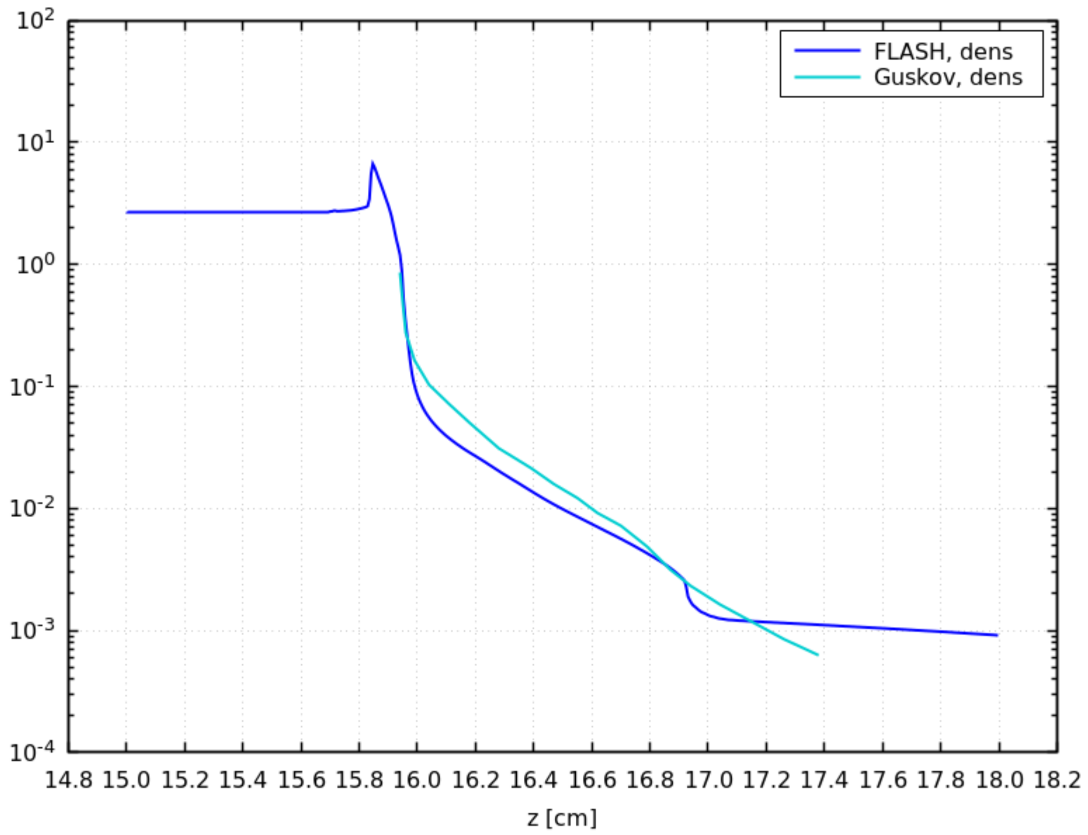


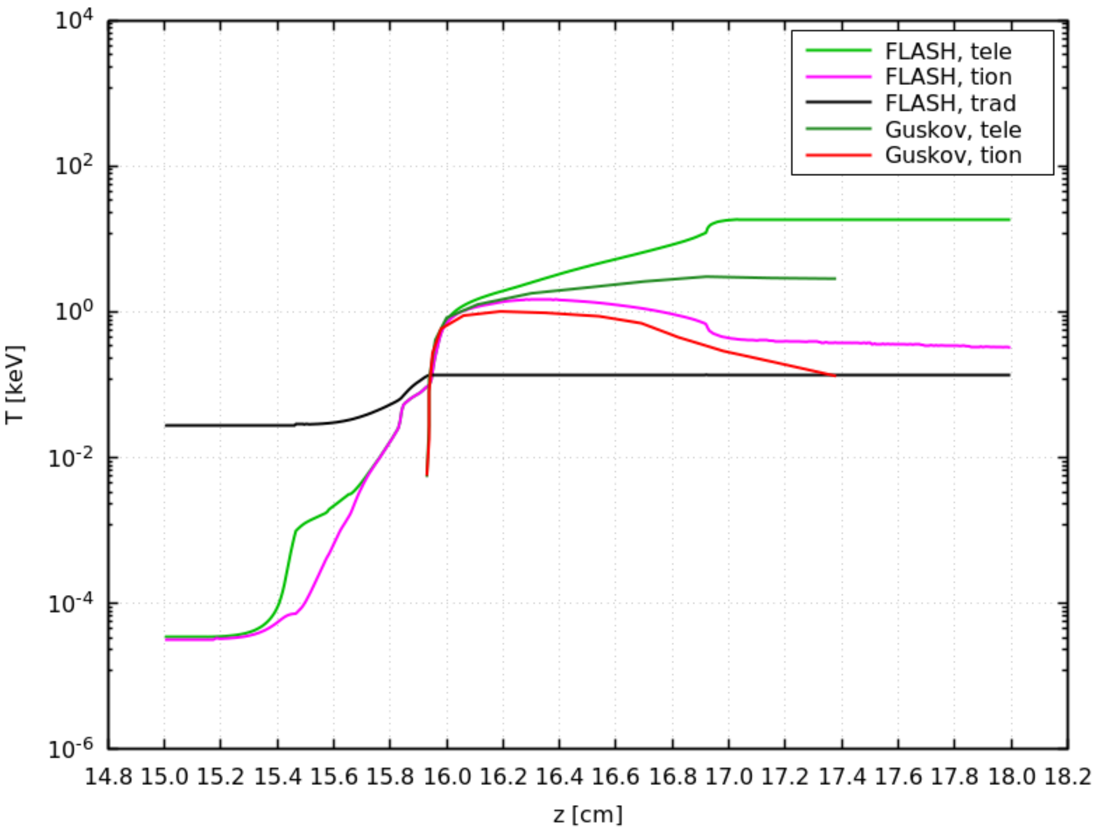


Benchmark Study with S. Yu. Gus'kov (2016)[2]

[2] S. Yu. Gus'kov et al., J. Phys.: Conf. Ser. 688, 012023 (2016)

- **FLASH :** https://flash.rochester.edu/site/



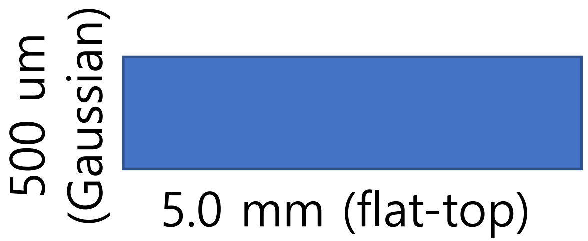


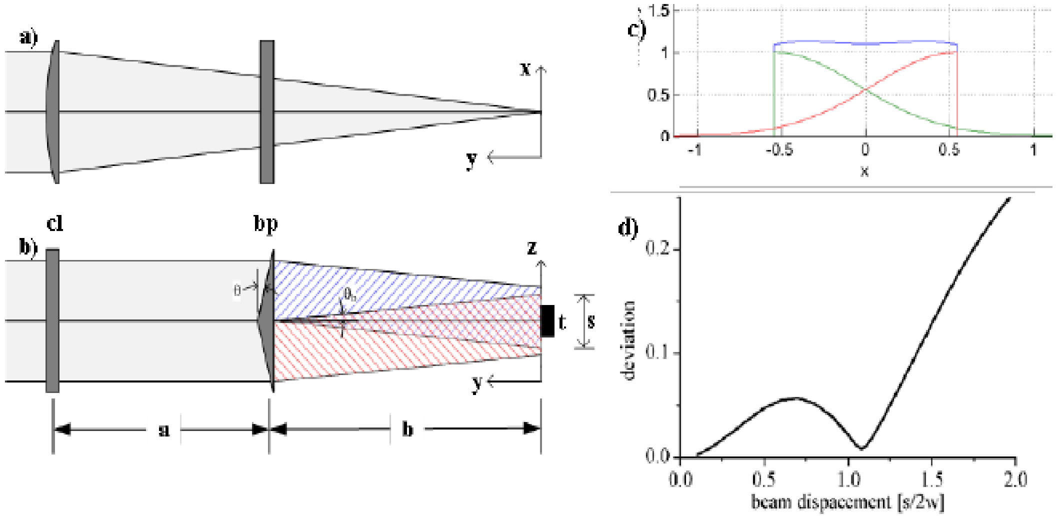
Benchmark Study with J. Kim (2016)[3]

[3] J. Kim et al., JINST 11, C03012 (2016)

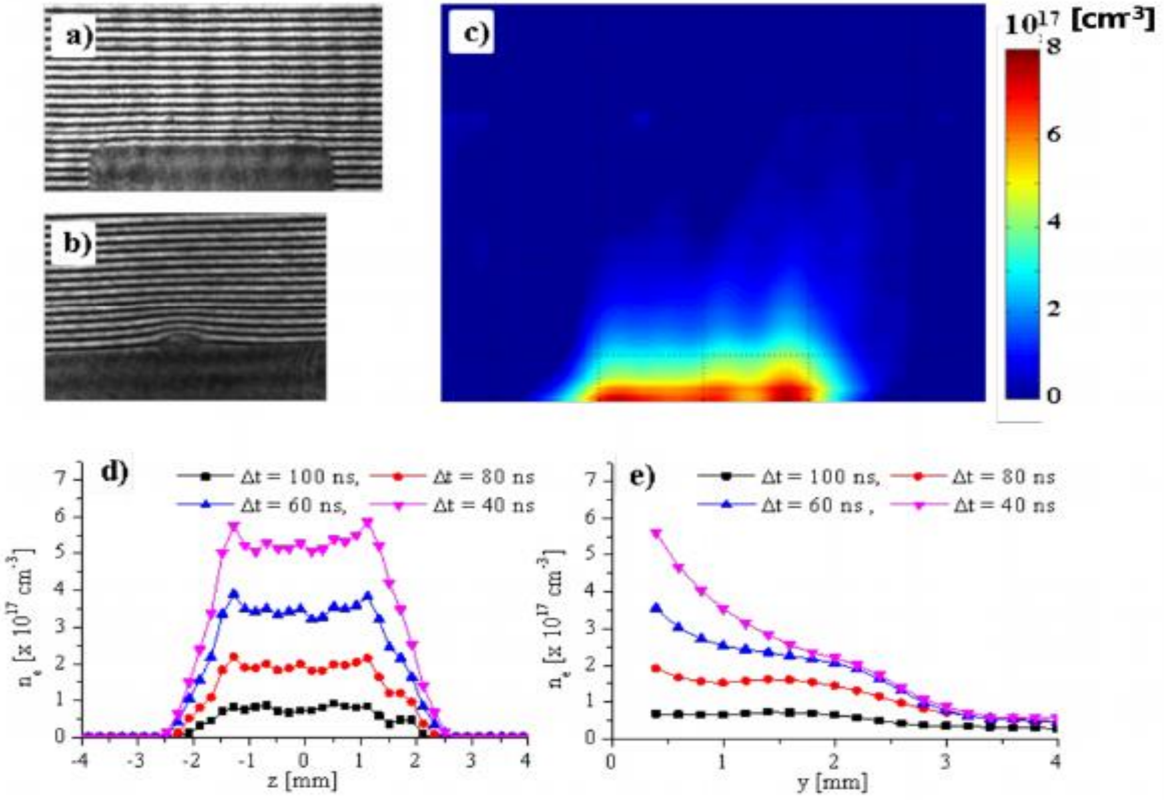
- J. Kim's experiments is very closely related our studies. (= prototype)

"Line laser source by using biprism"





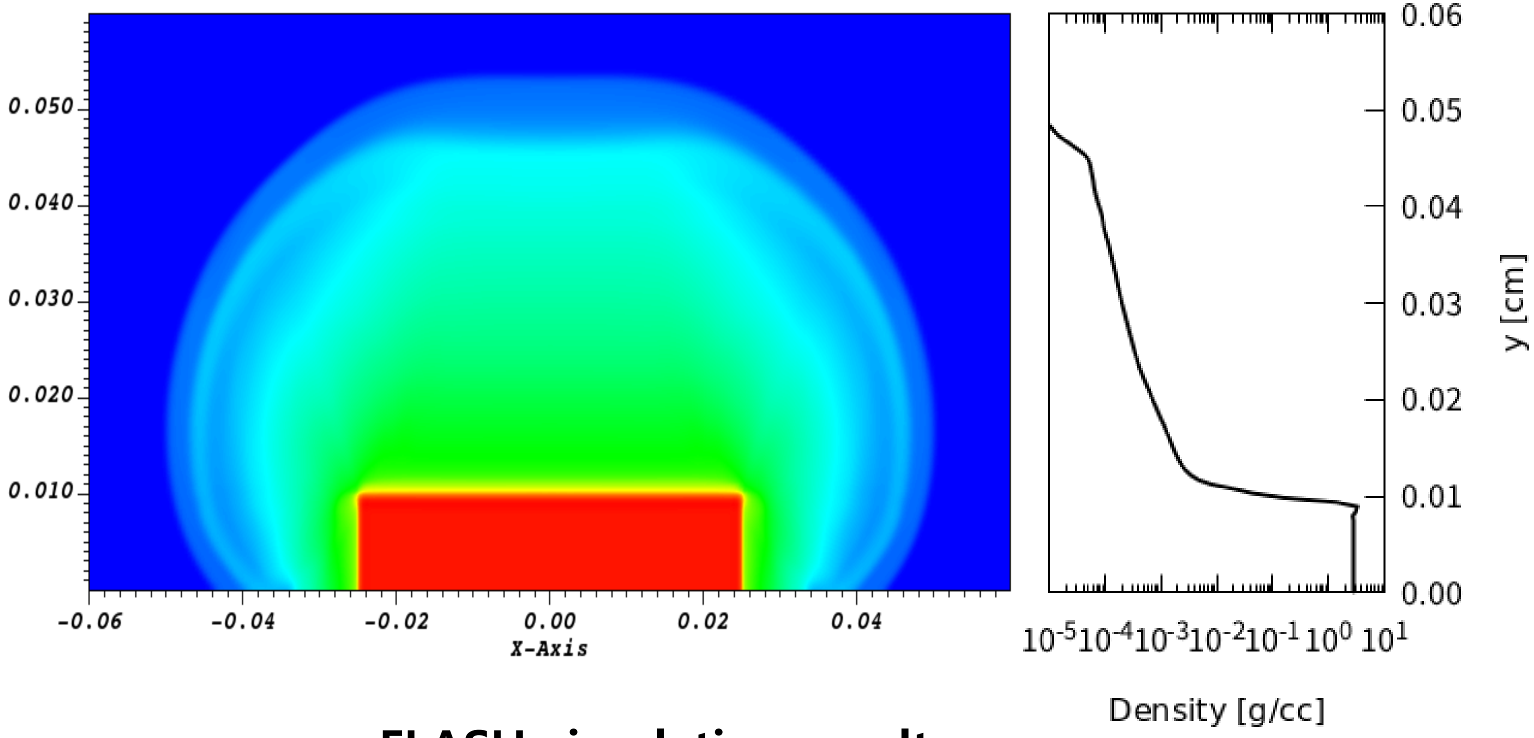
Experimental data



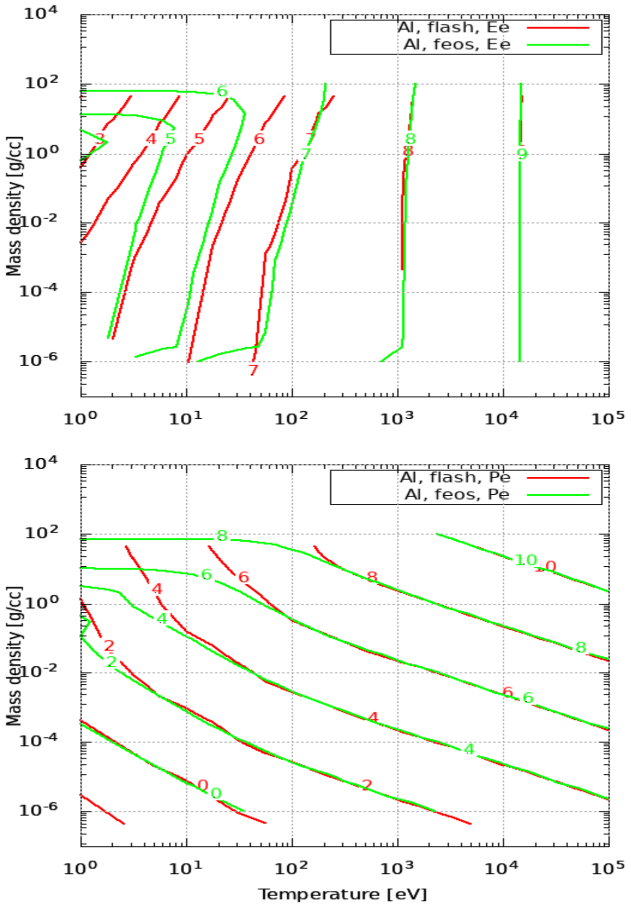
Benchmark Study with J. Kim (2016)[3]

[3] J. Kim et al., JINST 11, C03012 (2016)

- We are studying with FLASH (hydrodynamic code) simulations, but we cannot get well-fit results



FLASH simulation result



EOS data of Al material

Contents

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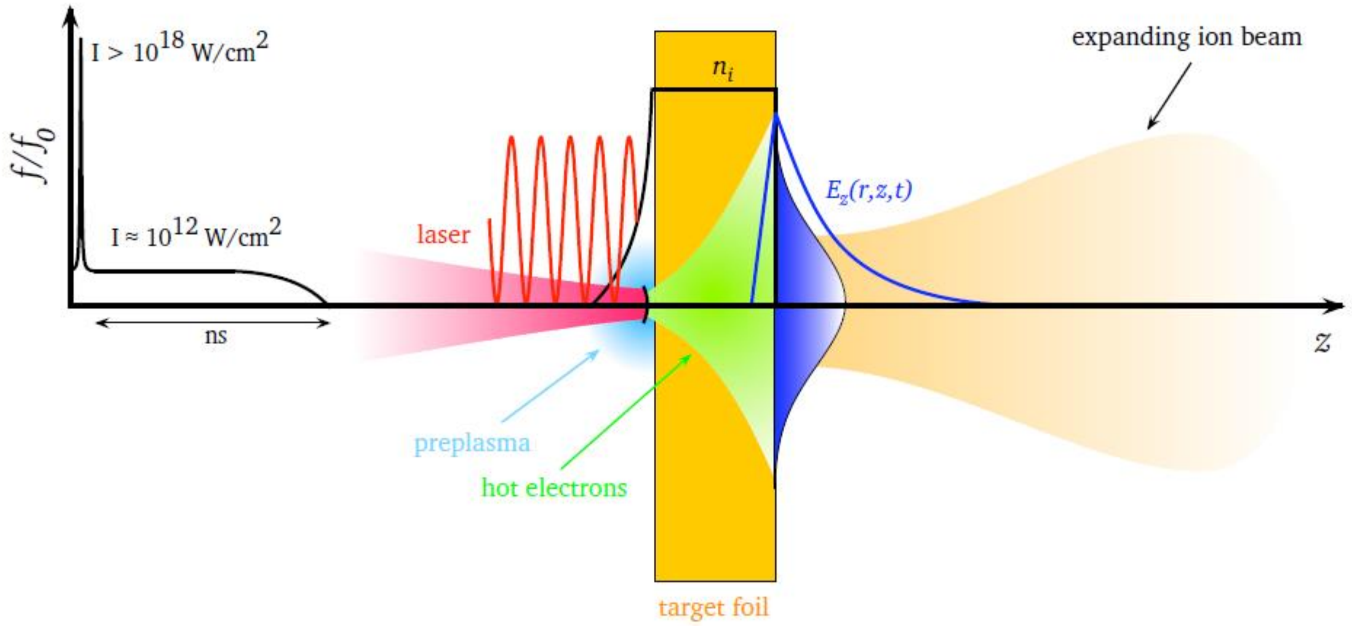
Target Normal Sheath Acceleration (TNSA)

- **Target normal sheath acceleration :** Ion (proton) acceleration mechanism via the laser-plasma interaction
- Protons stem from water vapour and hydrocarbon contamination, which are always present on the target surface, owing to the limited achievable vacuum conditions.



[M. Roth et al., Vol. 1 (2016): Proceedings of the 2014 CAS-CERN Accelerator School: Plasma Wake Acceleration]

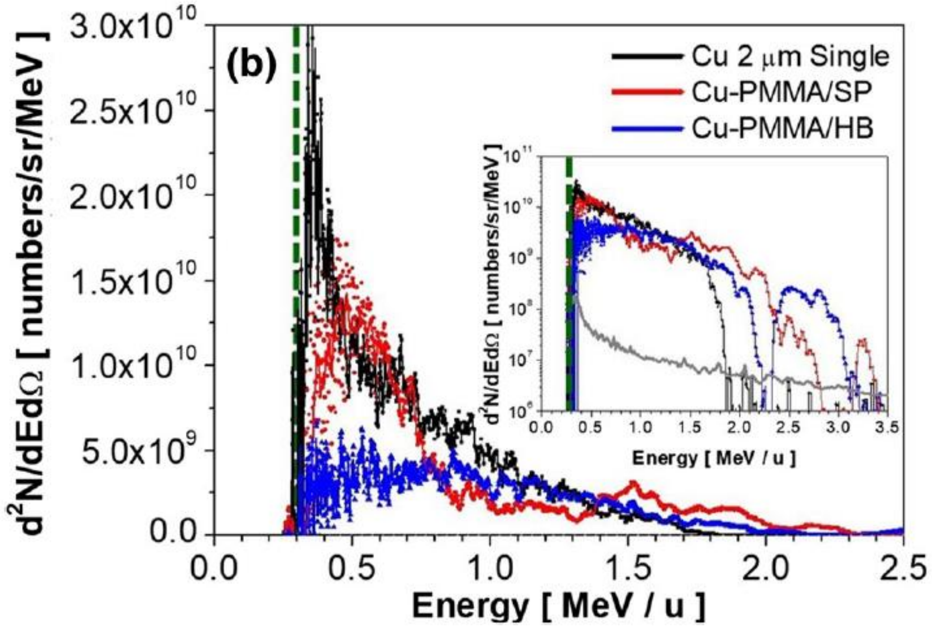
Contamination layer example :
12-Å-thick layer consisting of 27% gold,
60.5% hydro-carbons (CH2),
and 12.2% water vapor (H2O)

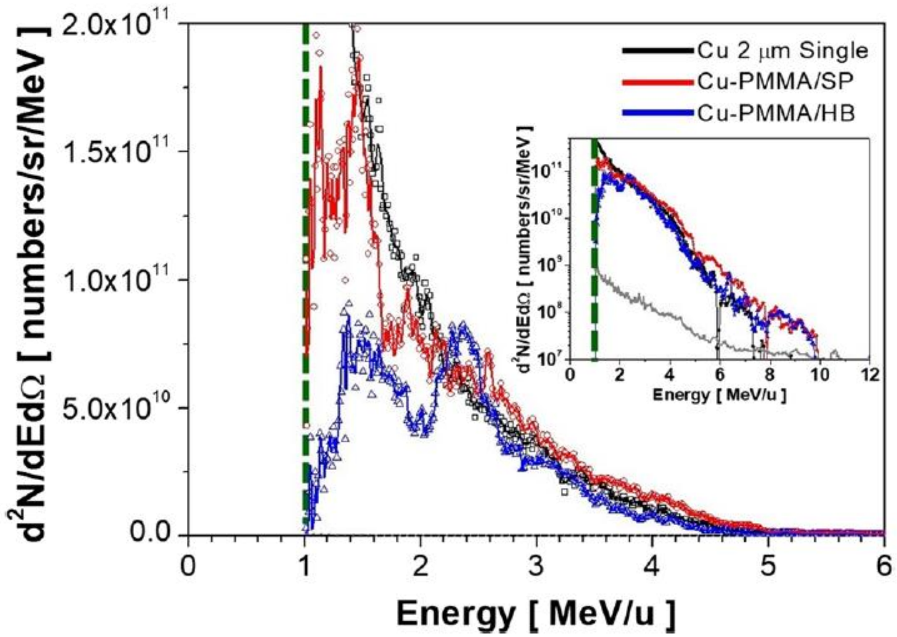
[M. Allen et al., PRL 93, 265004 (2004)]

TNSA with Cu+PMMA target in KAERI

- In KAERI (Korea Atomic Energy Research Institute), various TNSA experiments are performing.
- **Representative experiment setup :** 2 μm Cu foil + 100 nm ~ 950 nm PMMA (Polymethyl methacrylate) layer.

- PIC code simulations in Korea University Sejong Campus are supported.

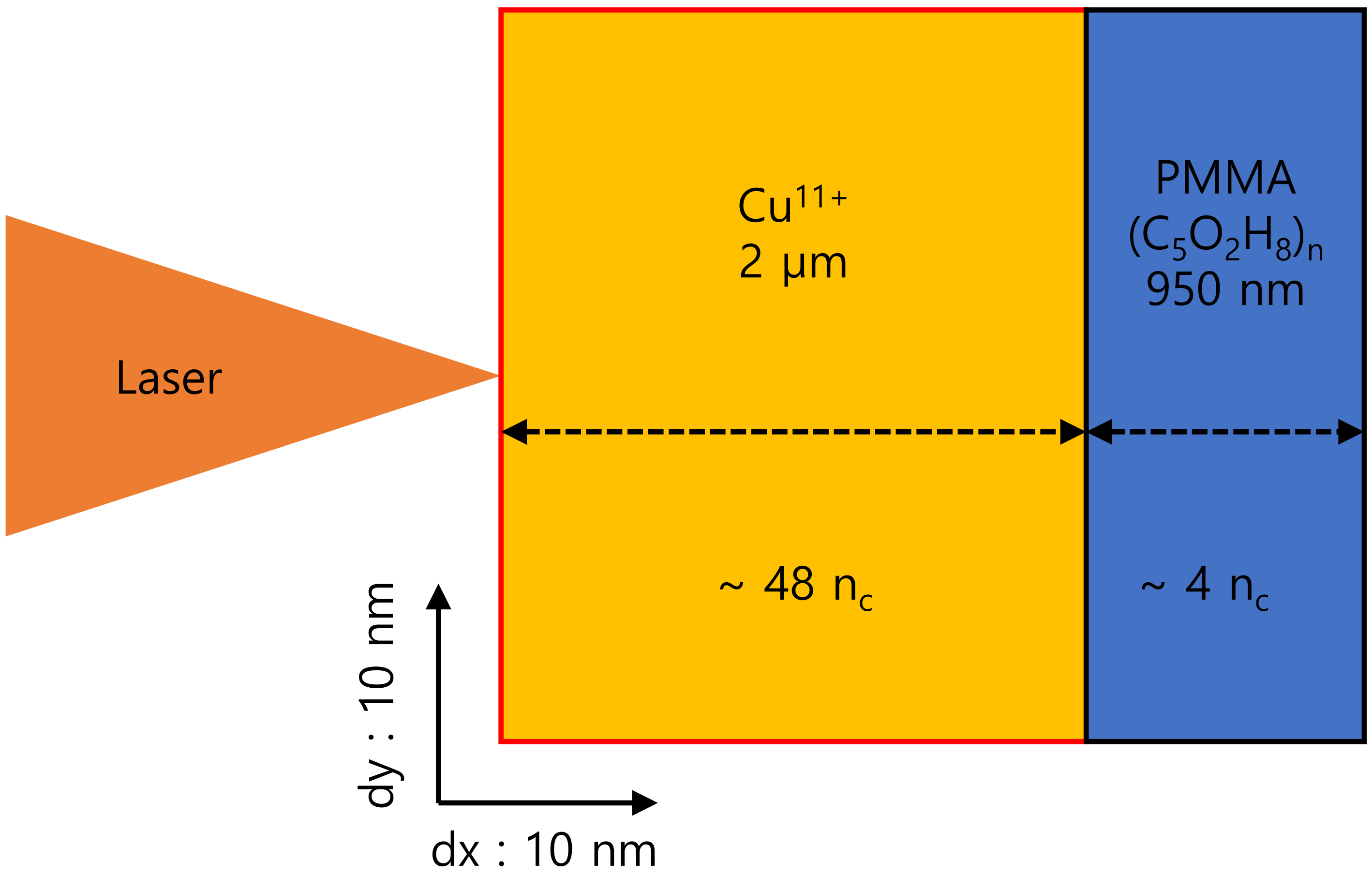




[H. –N. Kim et al., JKPS 81, 391-396 (2022)]

Simulation Scheme

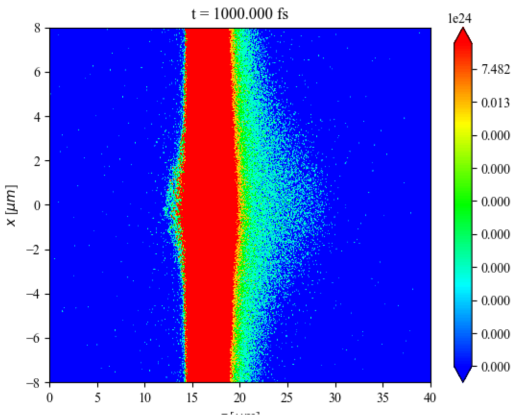
- **SMILEI :** https://smileipic.github.io/Smilei/



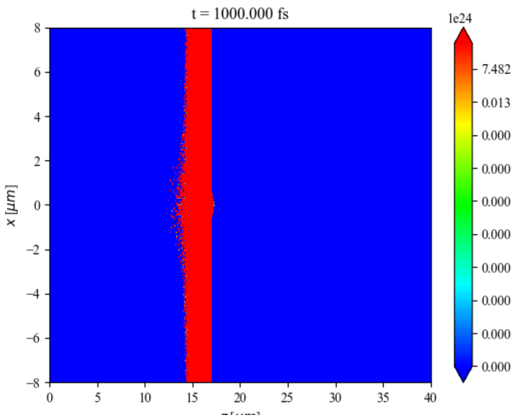
- $\lambda_L = 800$ nm
- $a_0 = 11.8/\sqrt{1.4}$
- $I_L = 3 \times 10^{20}$ Wcm^{-2}
- $\tau_L = 25$ fs

- **Ionization process ??**
- **Collisional process ??**
- **And so on...**

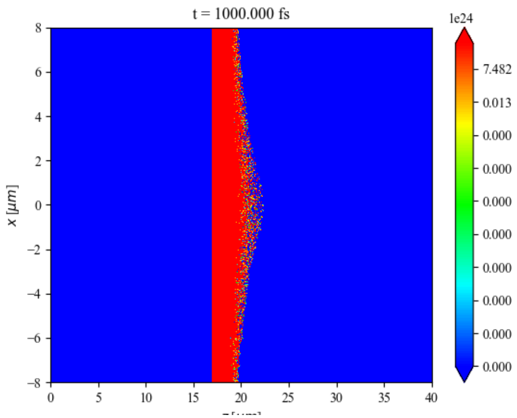
Benchmark Study with H.-N. Kim (2022)



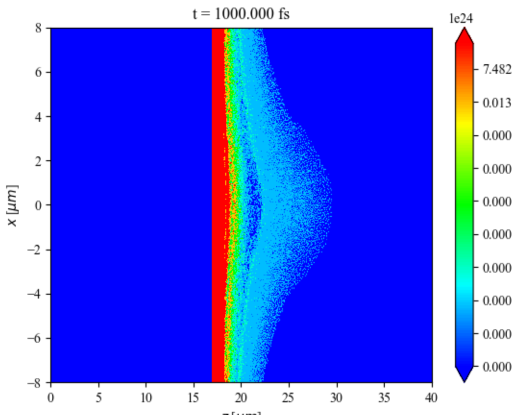
Electron



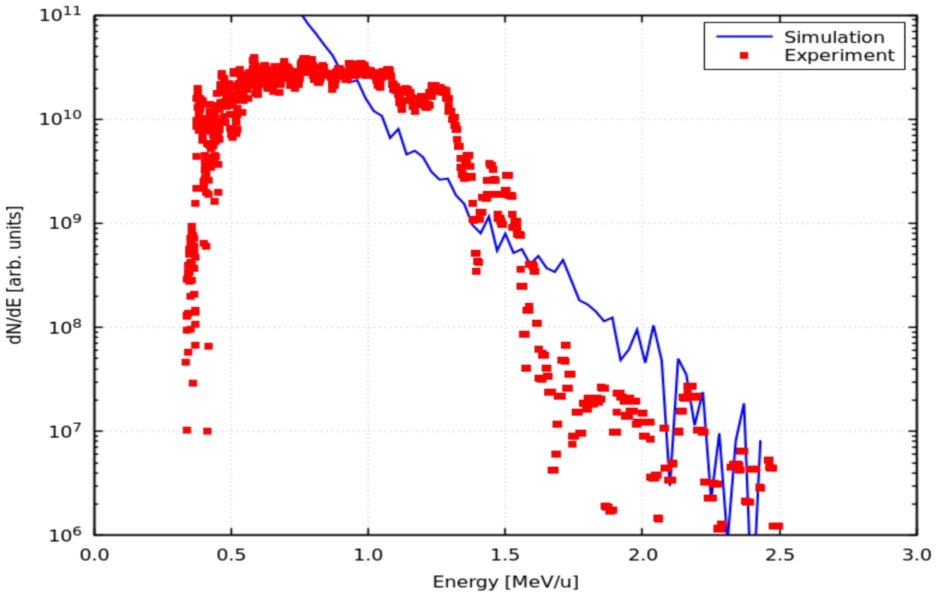
Copper

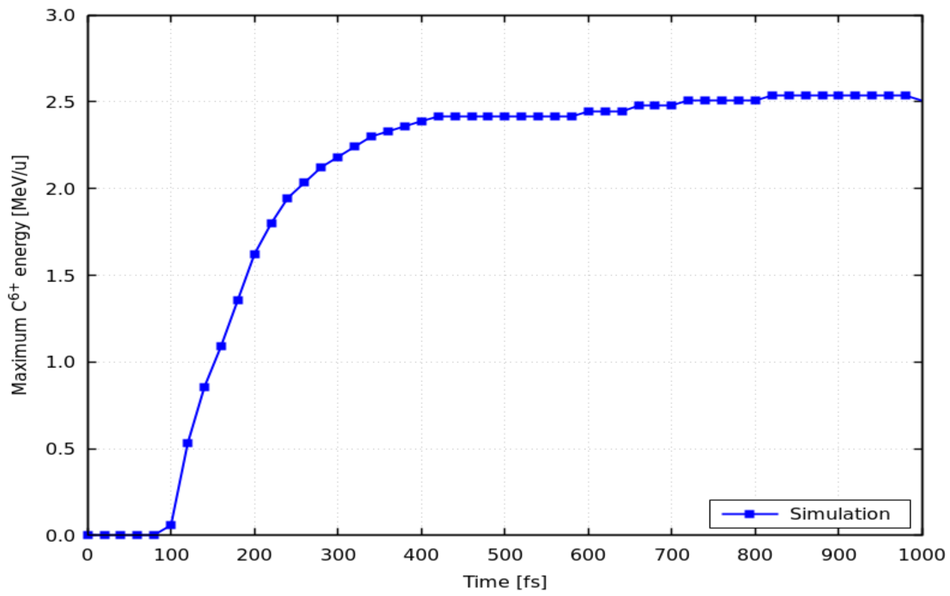


Carbon



Proton





Summary

- We are studying with various simulations:
  - **LWFA using laser-ablated metal target**
    - ✓ Comparison He vs. Al target
    - ✓ Find optimum condition
    - ✓ Suggestion a new structured target (e.g., Al-Ti-Al (ATA) target)
  - **Laser ablation process on the metal target**
    - ✓ Prediction of pre-plasma state
  - **Ion acceleration using TNSA with structured target**
    - ✓ Comparison with experimental data
    - ✓ Suggestion a new structured target

APPENDIX

" 대한민국을 이끌어 온 자랑스럽고 위대한 역사, 눈부신 고대의 새로운 백년도 지켜가겠습니다."

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Precedent Research for LWFA

- **S. Goldienko & A. Pukhov (2005) :** handy formulae of e-beam energy in LWFA for extremely high-power laser condition ($a_0 \gg 1$).

- **W. Lu et al. (2007) :** re-described formulae for $2 \lesssim a_0 \lesssim 4$,

$$\Delta E\ [\mathrm{GeV}] \simeq 1.7 \left(\frac{P\ [\mathrm{TW}]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_e\ [\mathrm{cm}^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda_0\ [\mu\mathrm{m}]}\right)^{4/3}$$

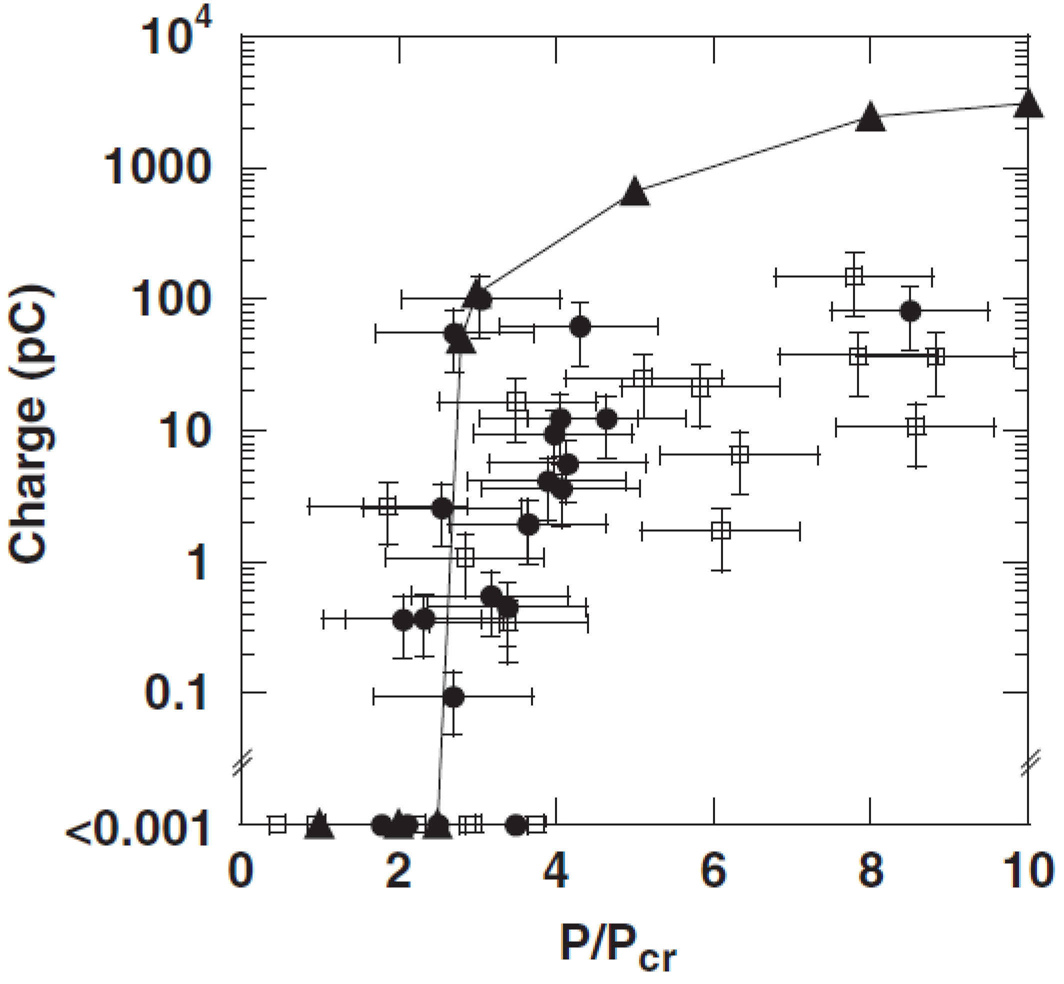
- **D. H. Froula et al. (2009) :** noted the beam injection threshold driven by their experiment data.

$$\frac{P}{P_c} > 3$$

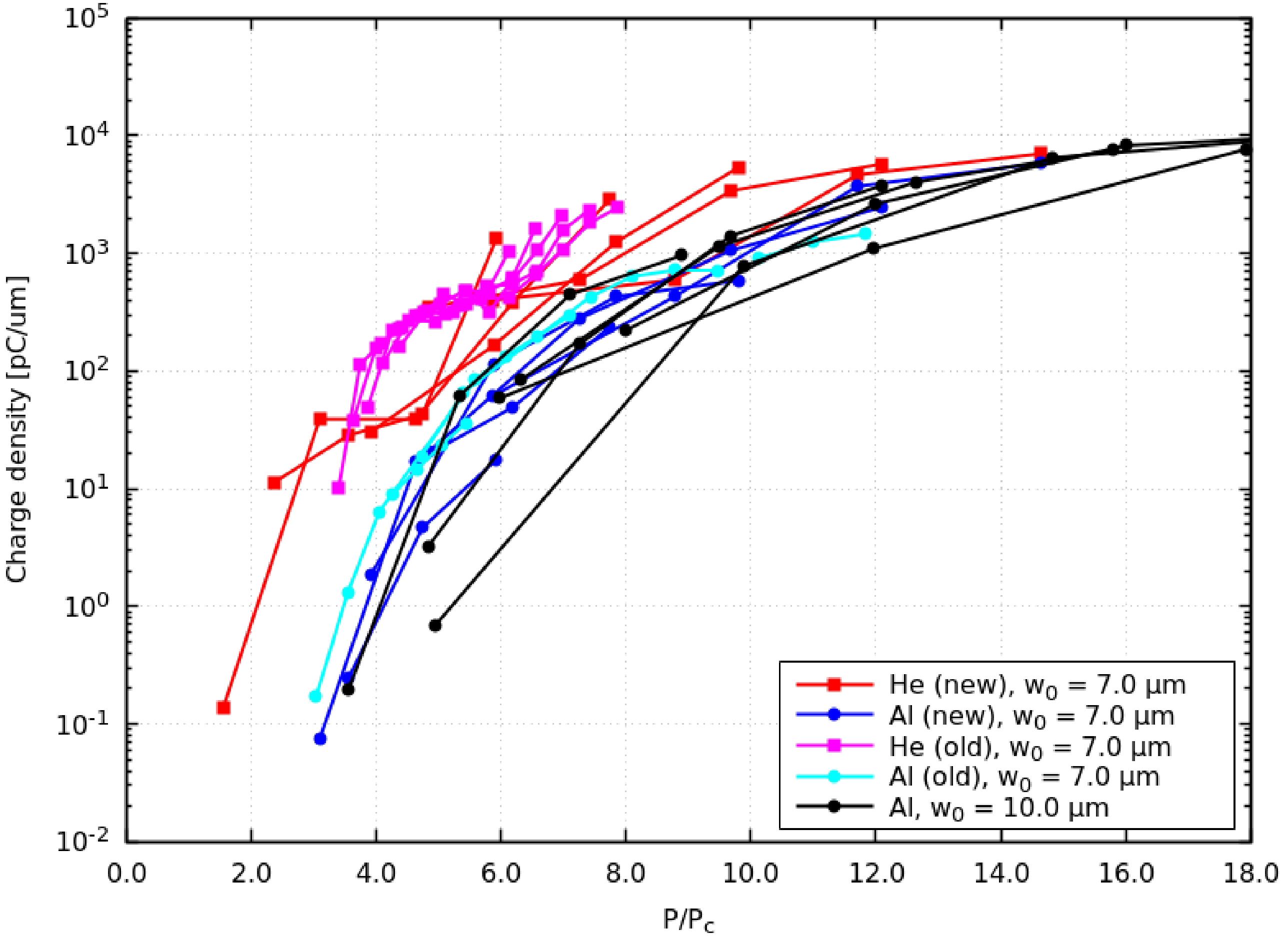
- **S. P. D. Mangles et al. (2012) :** suggested new formula of injection threshold for high-density regime.

$$\frac{\alpha P}{P_c} > \frac{1}{16}\left[\ln\left(\frac{2}{3}\frac{n_c}{n_e}\right) - 1\right]^3$$

Parametric Studies; Charge Density

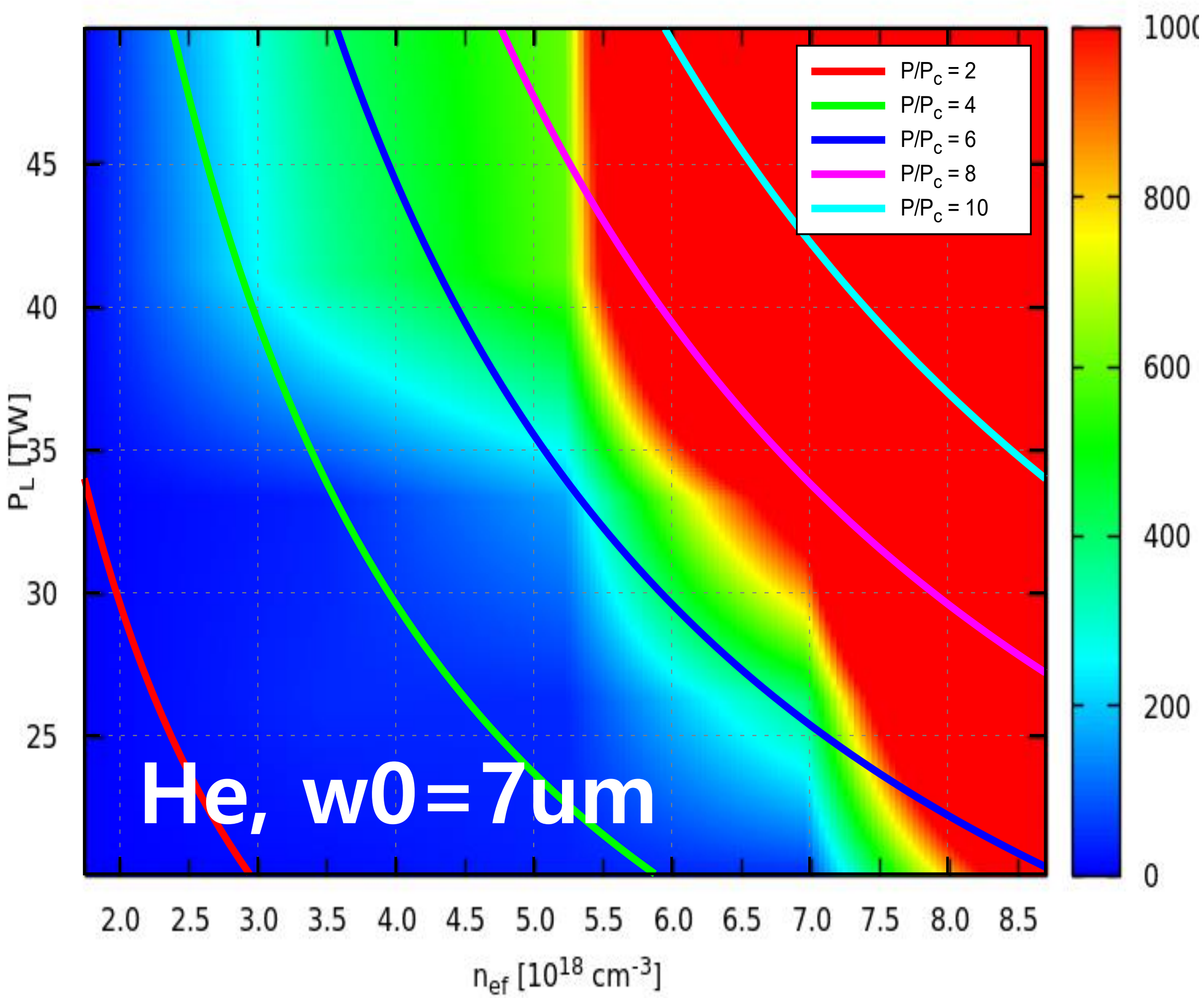


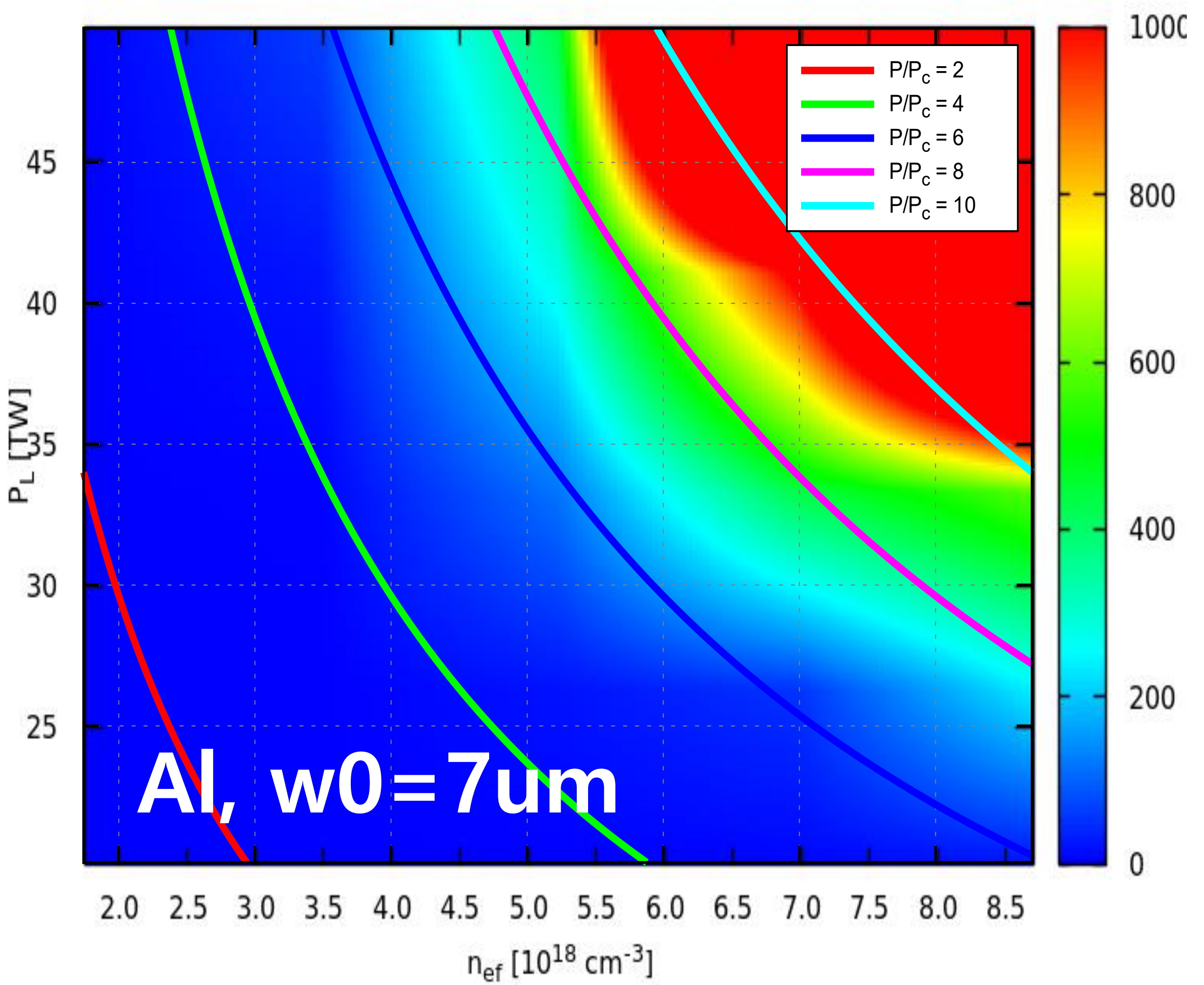
[D. H. Froula et al., PRL 103, 215006 (2009)]



[Our results]

Parametric Studies; Charge Density





Parametric Studies; Charge Density