PASJ 2024第21回日本加速器学会年会

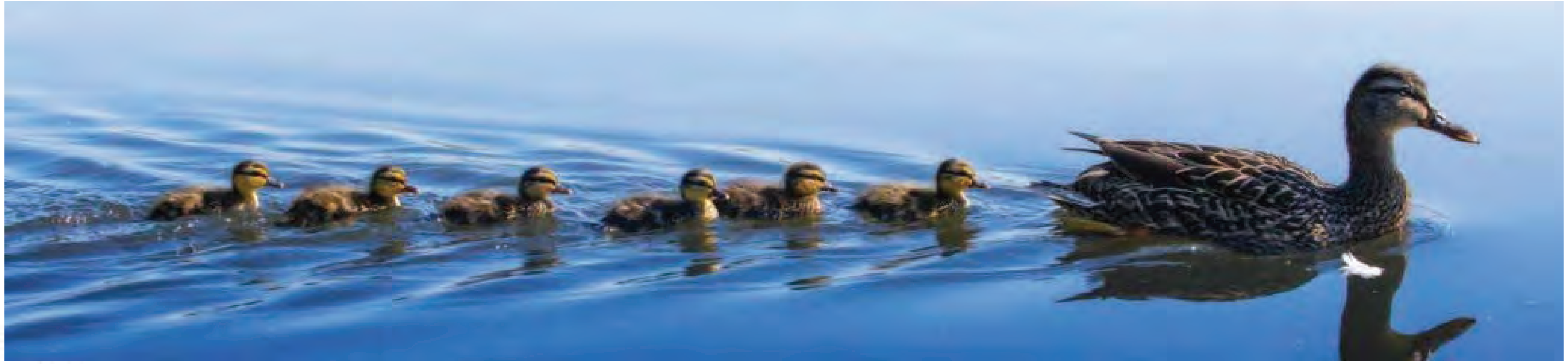
小型XUV-FELを目指したLWFAの開発

Development of LWFA Towards a Table-top XUV-FEL

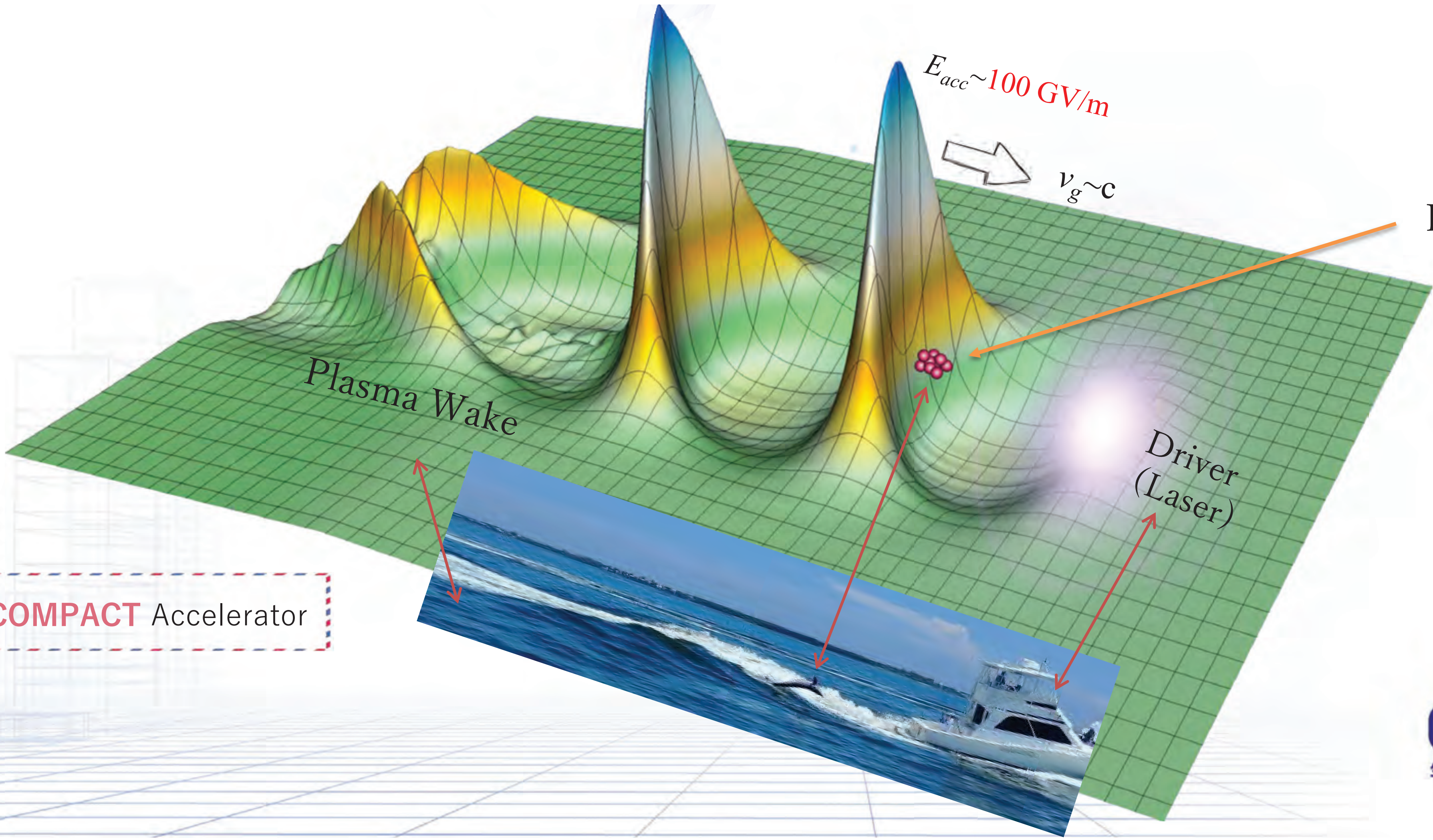
Z. Jin(金 展)[1,3], Y-J. Gu[1,3], Z-Z. Lei[1,3], S. Sato[1,3], A. Zhidkov[1,3], A. Rondepierre[1,3], K. Huang[2,3], N. Nakanii[2,3], I. Daito[2,3], M. Kando[2,3], and T. Hosokai[1,3]

[1]SANKEN, Osaka University, Japan
[2]Kansai Institute for Photon Science (KPSI), QST, Japan
[3]Laser Accelerator R&D, RIKEN SPring-8 Center, Japan

Riding a wave (acceleration)

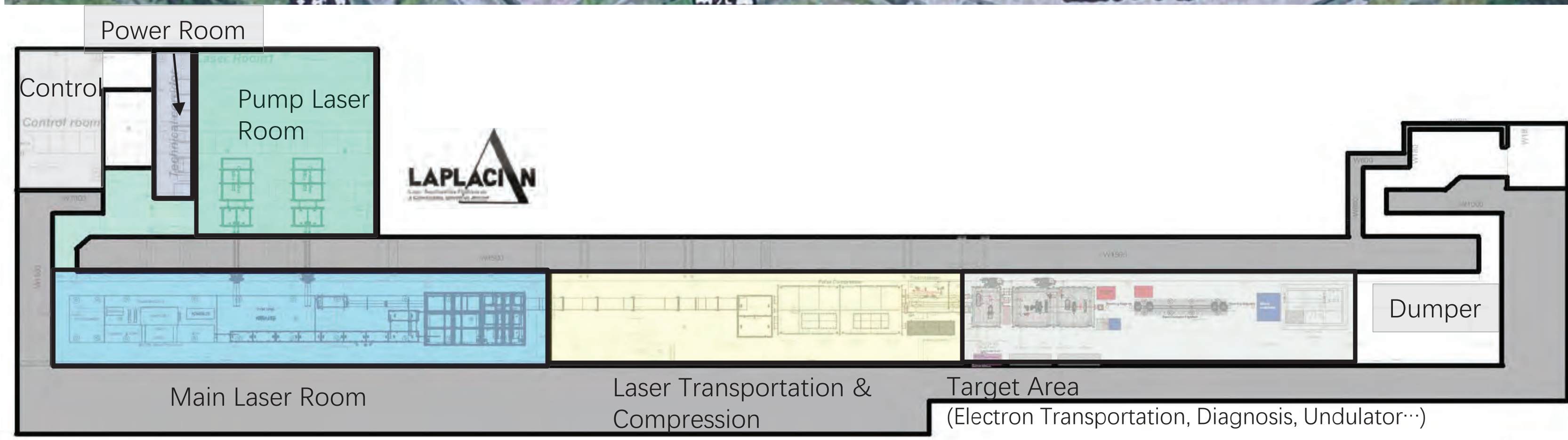


Laser Wakefield Acceleration (LWFA)



A **COMPACT** Accelerator

大阪大学
OSAKA UNIVERSITY



2014-2018 ImPACT 革新的研究開発推進プログラム

JST MIRAI 未来社会創造事業 2018-

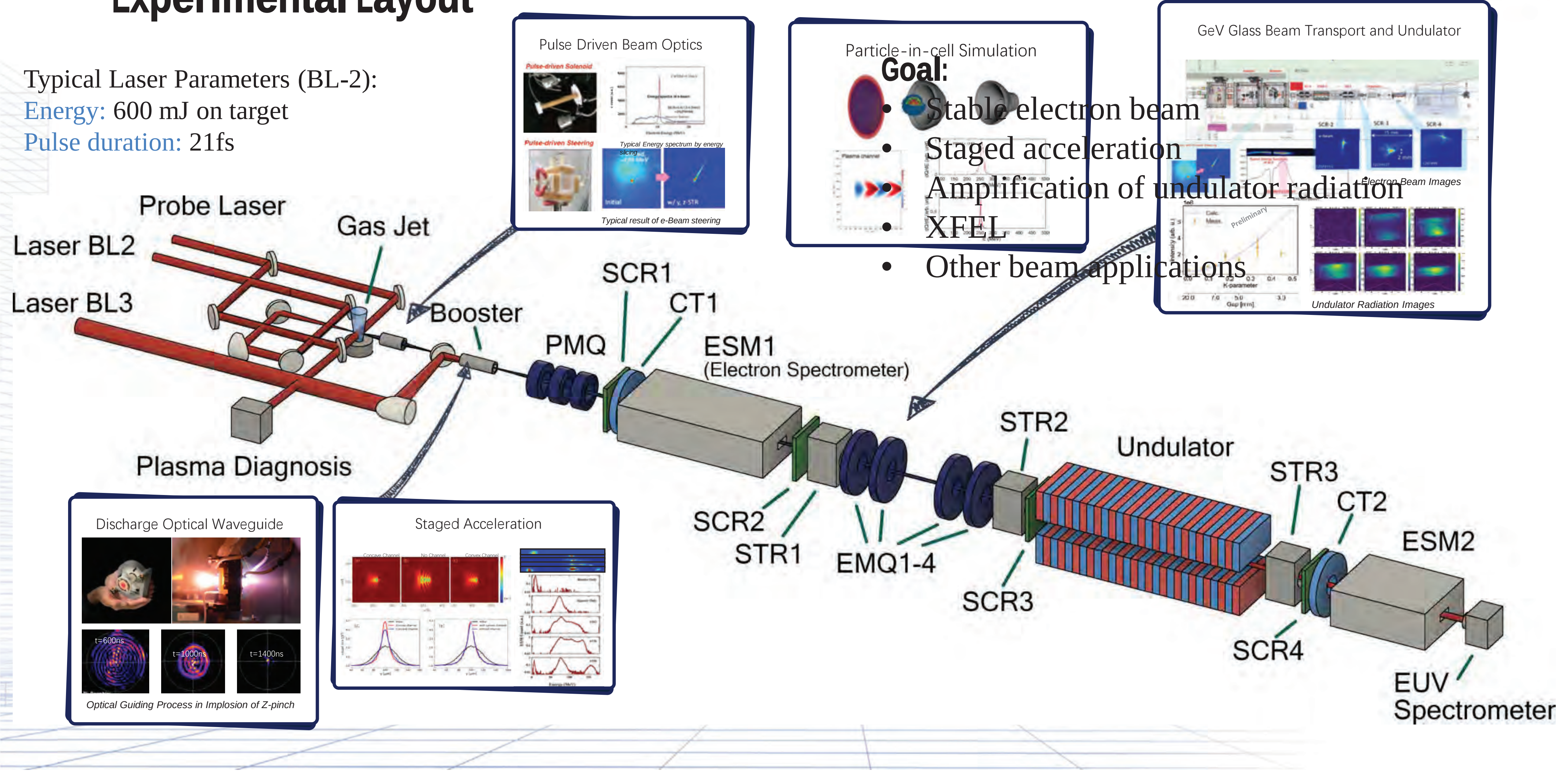
OU 2027 MASTER PLAN
生きがいを育む社会の創造

Experimental Layout

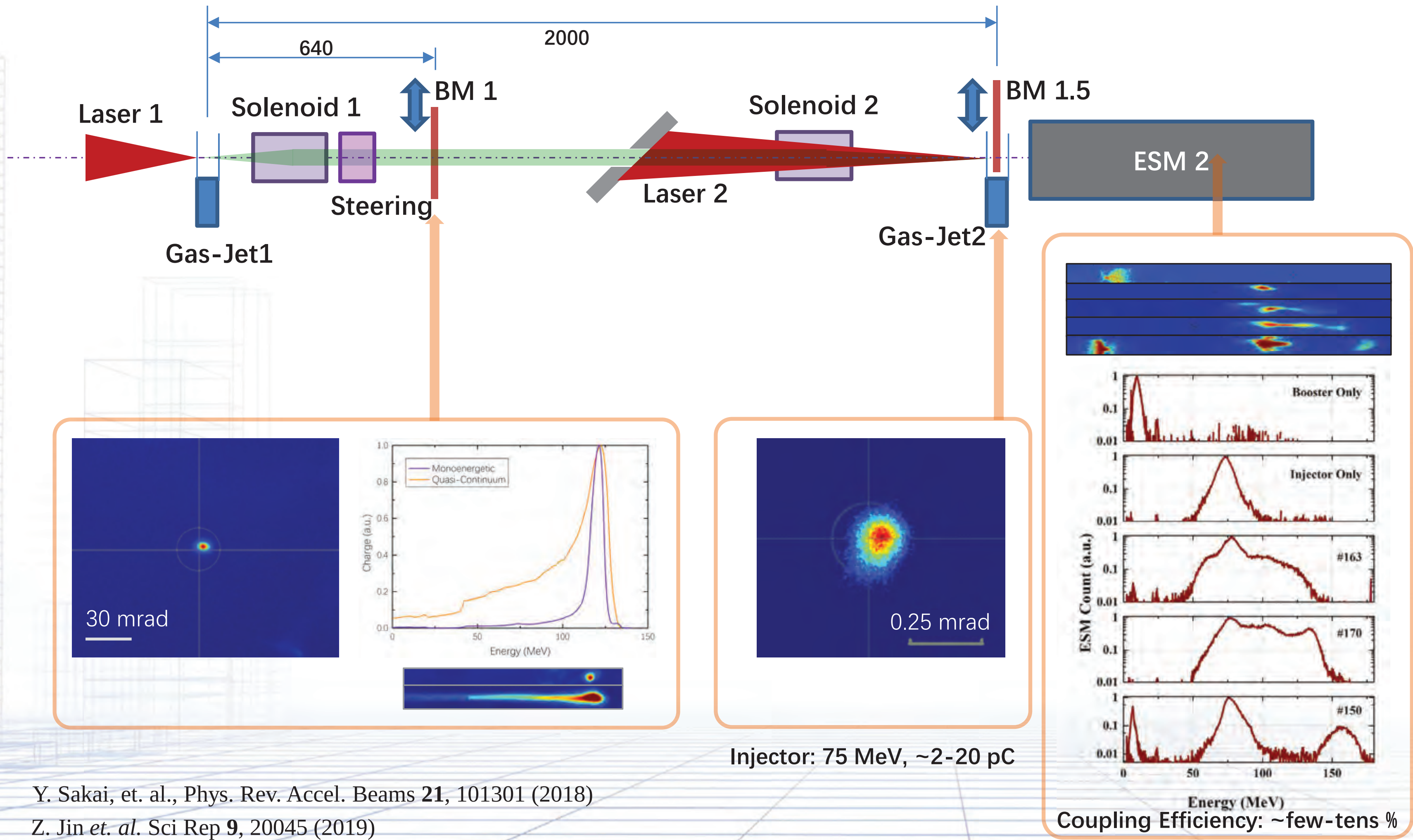
Typical Laser Parameters (BL-2):
Energy: 600 mJ on target
Pulse duration: 21fs

Goal:

- Stable electron beam
- Staged acceleration
- Amplification of undulator radiation
- XFEL
- Other beam applications



Demonstration of 2-staged acceleration



Injector: 75 MeV, ~2-20 pC

Coupling Efficiency: ~few-tens %

Problem:

Stability
and
Repeatability

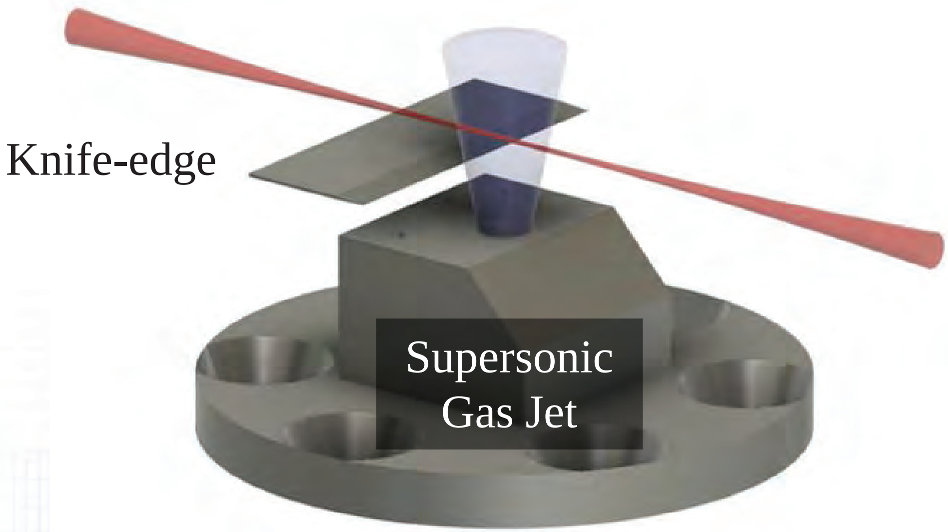
Y. Sakai, et. al., Phys. Rev. Accel. Beams **21**, 101301 (2018)
Z. Jin *et. al.* Sci Rep **9**, 20045 (2019)

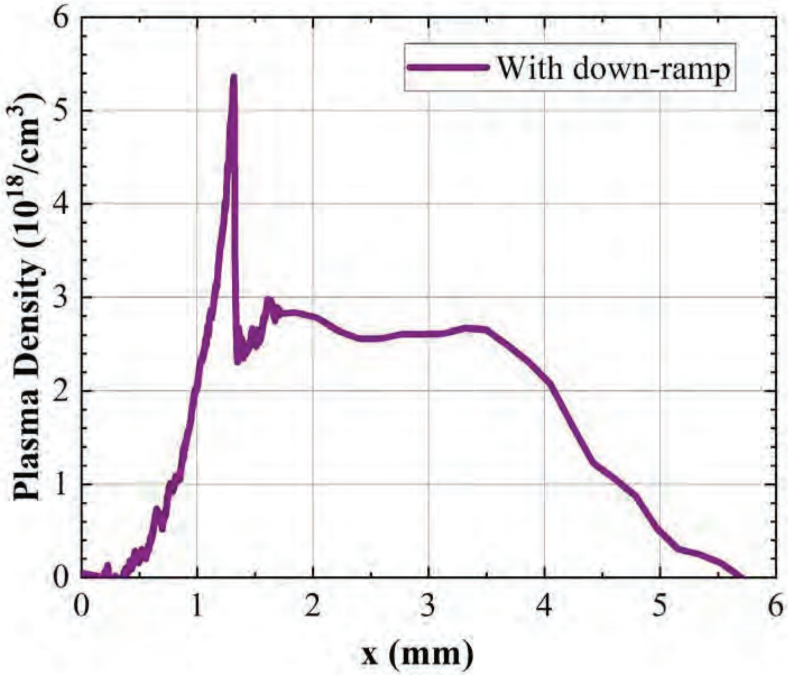
To improve the stability of electron beams

- Introduce Injection Control
  - Colliding laser pulses injection
  - Ionization injection
  - Shock injection (Density down ramp)
- Improve Laser Stability (typically wavefront stability).
- Improve gas Target Stability (with fluid simulation).

Shock Injection

(Density down-ramp)

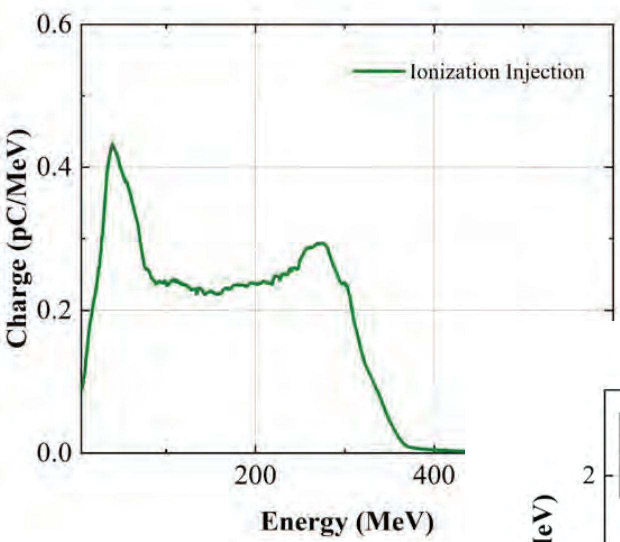


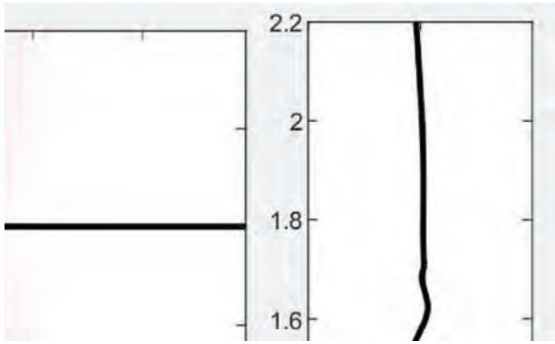


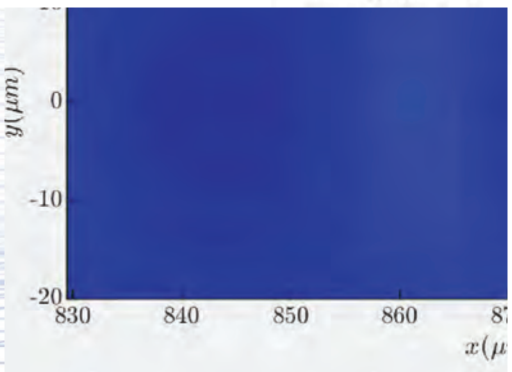
[1] H. Ekerfelt, et al., Sci Rep, 7, 12229, 2017
[2] J. Götzfried et al., Phys. Rev. X, 10, 041015, 2020
[3] H.-E. Tsai et al., Physics of Plasmas, 25, 043107, 2018

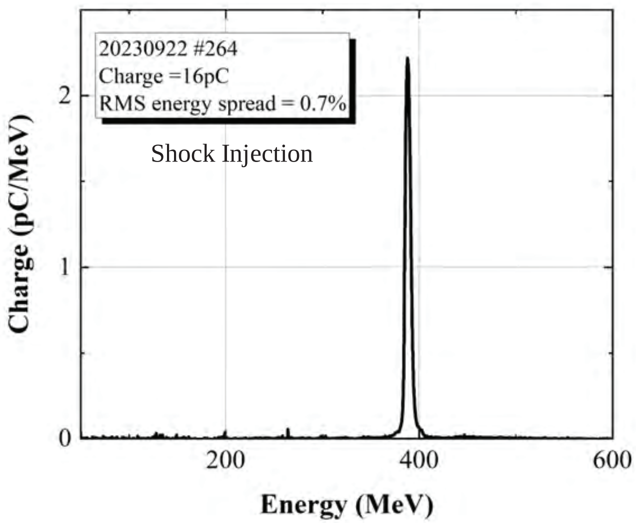
Density down-ramp injection

Method: create a down-ramp of plasma density by gas mix, or by a shock.









- Wakefield size gets larger when plasma density becomes lower.
- Electrons get trapped while experiencing such a transition.

✓ Injection is localized.
✓ Injection charge can be controlled with density gap.
✓ High quality electron beam.

× Strongly depends on the laser and density profile stability.

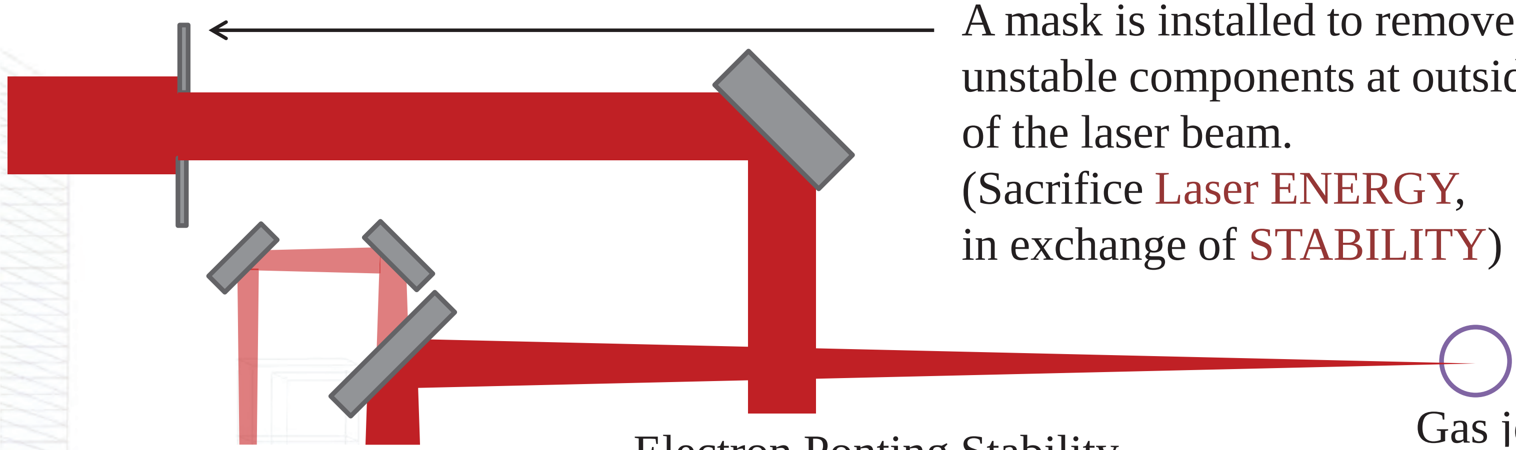
[1] H. Ekerfelt, et al., Sci Rep, 7, 12229, 2017
[2] J. Götzfried et al., Phys. Rev. X, 10, 041015, 2020
[3] H.-E. Tsai et al., Physics of Plasmas, 25, 043107, 2018

大阪大学
OSAKA UNIVERSITY

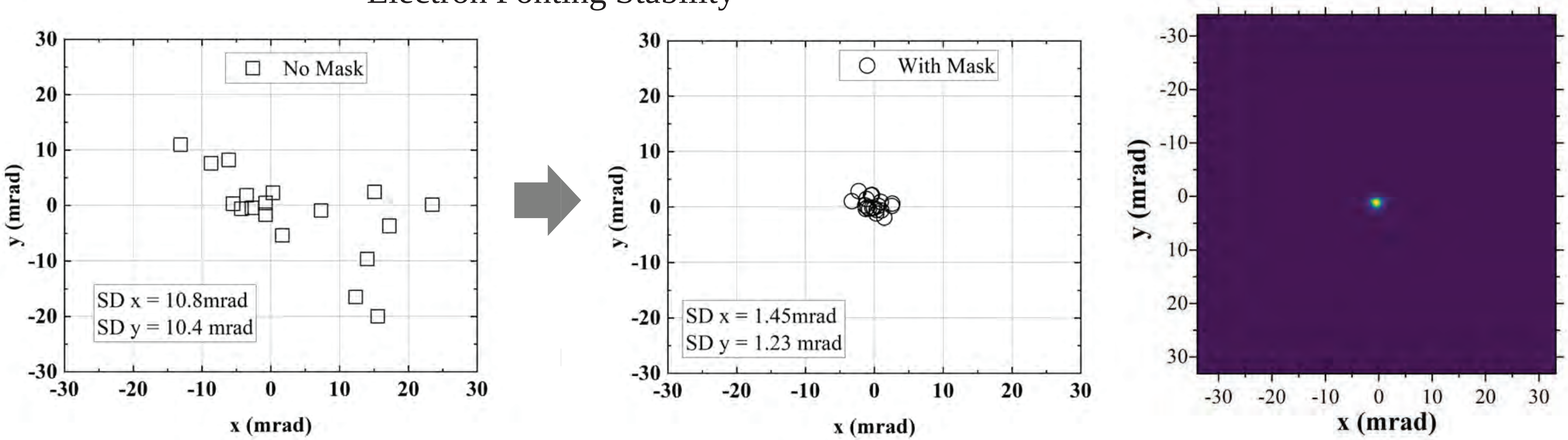
- Introduce injection control
- **Improve the laser stability (typically, wavefront stability)**
- Improve gas target stability

Improve Laser Wavefront

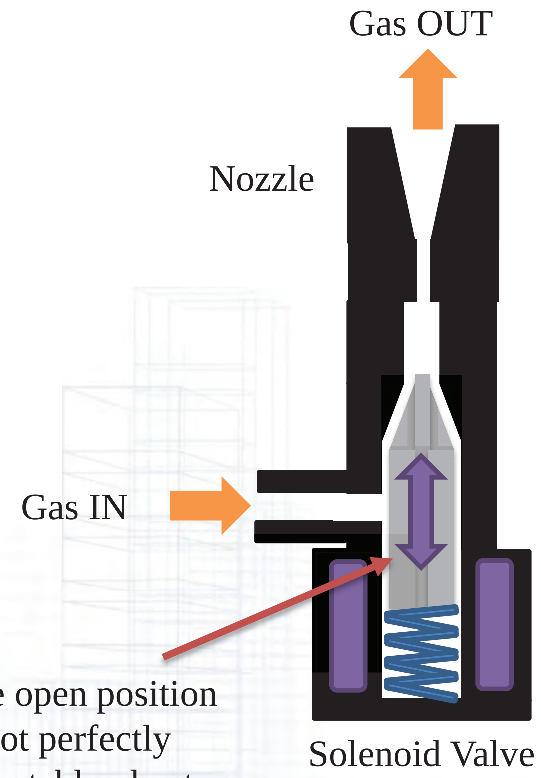
A mask is installed to remove the unstable components at outsider of the laser beam.
(Sacrifice Laser ENERGY, in exchange of STABILITY)



Electron Ponting Stability

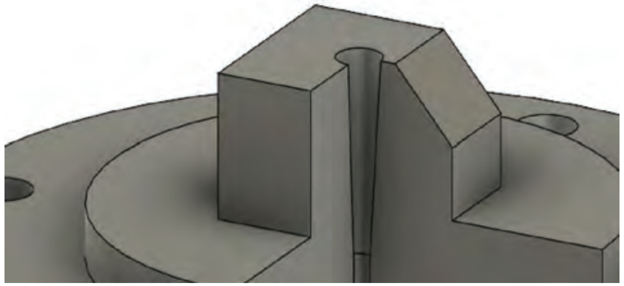


Supersonic Gas Jet

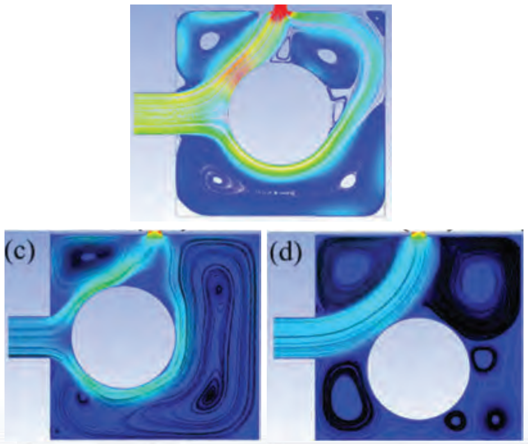


The open position is not perfectly repeatable, due to mechanic accuracy.

A simple conical nozzle



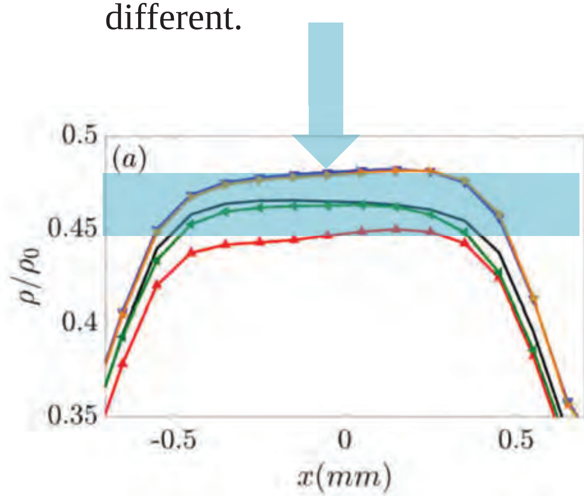
2D CFD simulation



The velocity distributions and streamlines for solenoid valve positions.

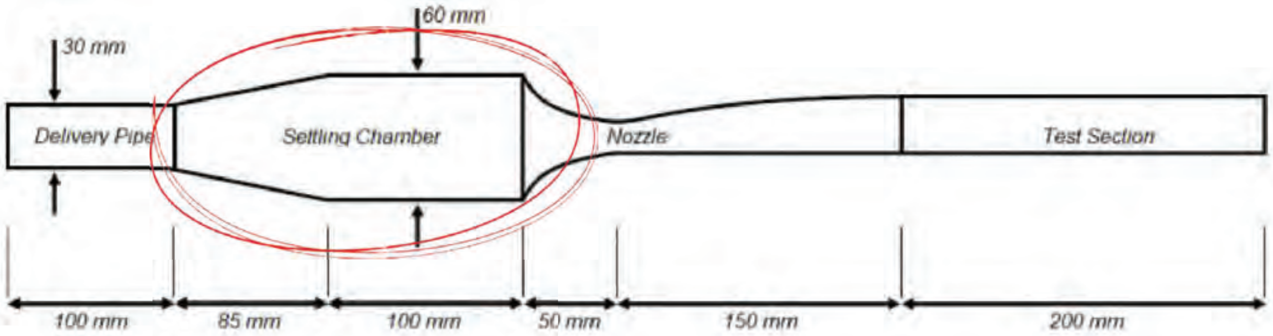
- Introduce injection control
- Improve the laser stability (typically, wavefront stability)
- **Improve gas target stability**

The mechanical instability of the solenoid valve introduce a 13.5% (p-v) of gas density different.



The gas density profile above the nozzle.

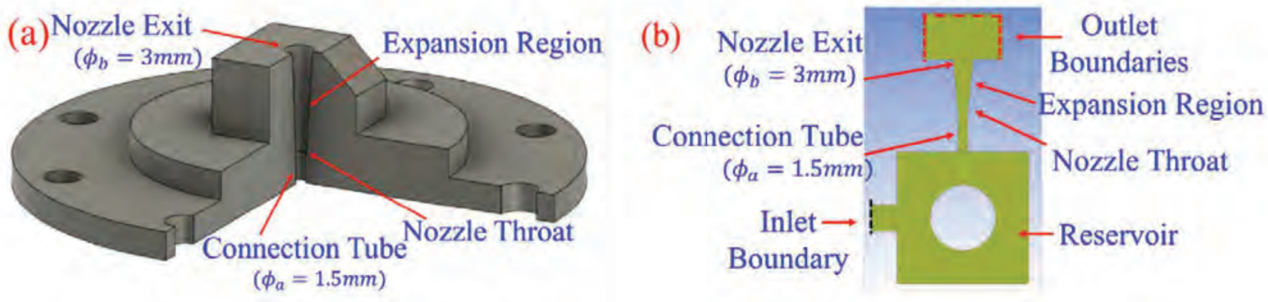
Stilling Chamber (Supersonic Wind Tunnel)



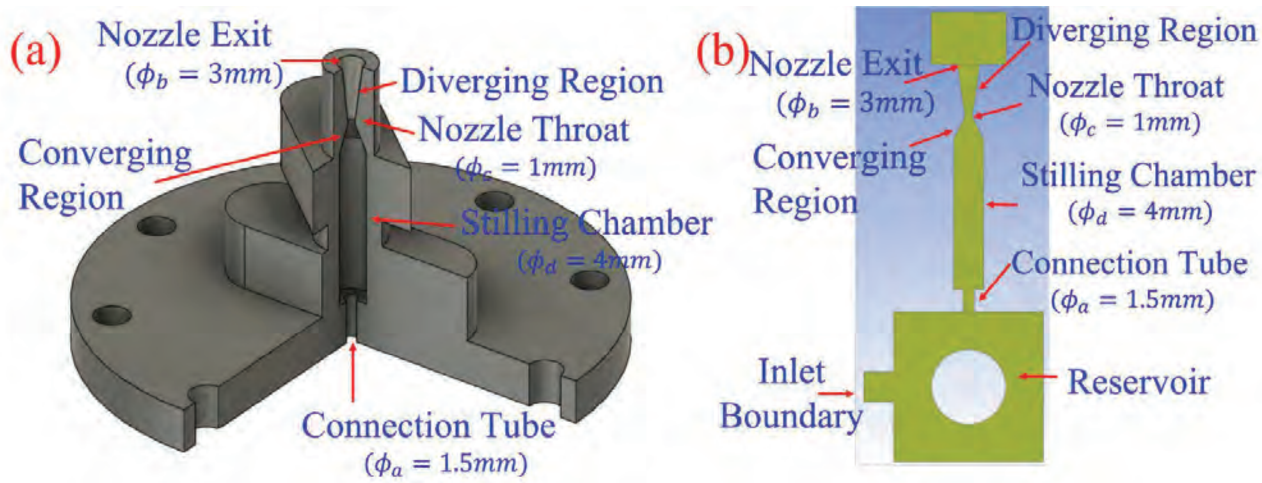
https://rocketgirl.blog/2018/06/17/supersonic-wind-tunnel-part-3-flow-analysis/

Stilling Chamber

Simple-Conical Nozzle

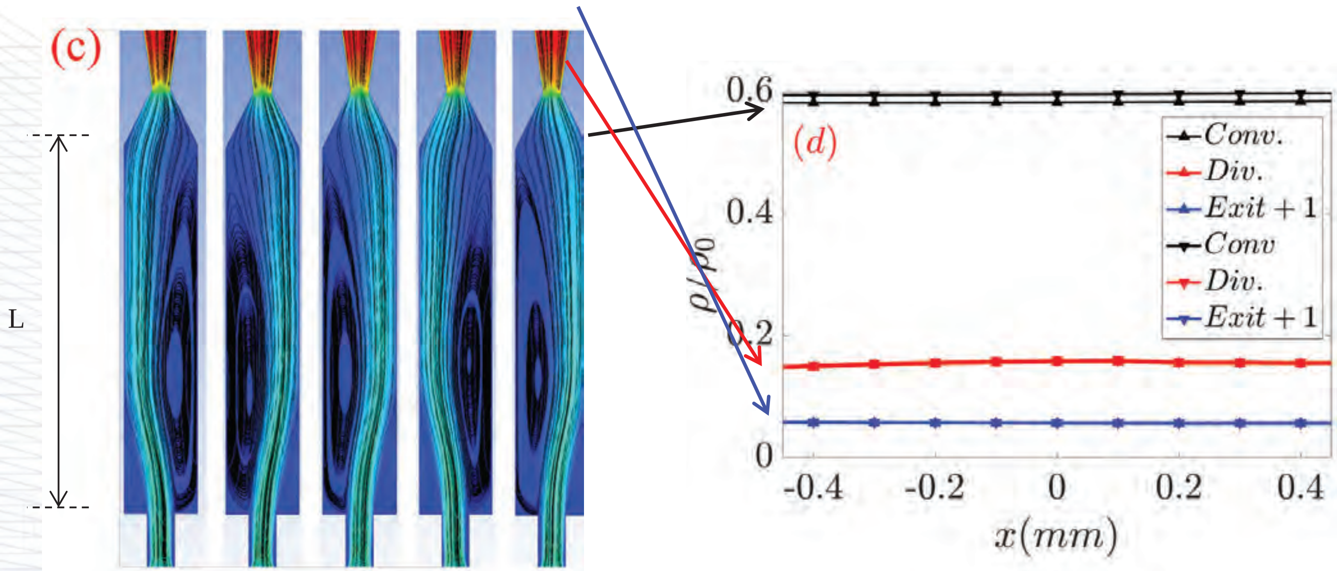


Converging-Diverging Nozzle with stilling chamber



Z. Lei, et al., *Rev. Sci. Instrum.* **95**, 015111 (2024)

Effect of Stilling Chamber



The instability is first suppressed by stilling chamber.

The instability is further suppressed by converge region.

The final density stability can be reduced from 13.5% to 2.5 % (P-V) with the help of stilling chamber and converge region.

Length of the stilling chamber (L) is set to be longer than the characteristic length of the turbulent structures.

The gas density profile at converging region (black), diverging region (red) and 1mm above the exit (blue) for different valve positions.

Z. Lei, et al., *High Power Laser Sci. Eng.* **11**, e91 (2023)

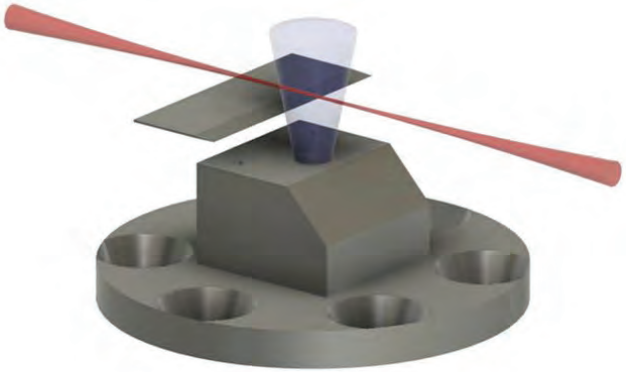
CFD Simulation vs Experimental Measurement

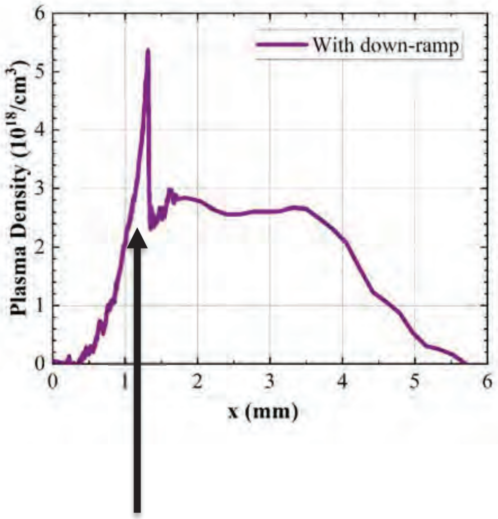
Gas density profile is measured by Mach-Zehnder interferometer.

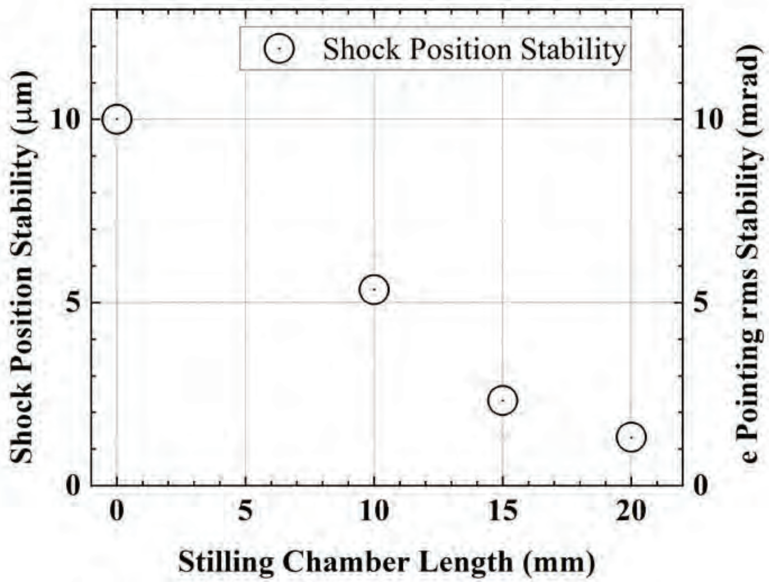
	Simple-Conical		Converging-Diverging with stilling chamber	
	Simulation	Measurement	Simulation	Measurement
Instability in std. (%)	4.7	4.5	1	1.3
Instability in p-v (%)	13.5	13	2.5	4

Experimental measurement is quite consistent with the fluid simulation, which shows that the instability can be suppressed by 3-5 times with the optimized C-D nozzle.

Shock Position Instability

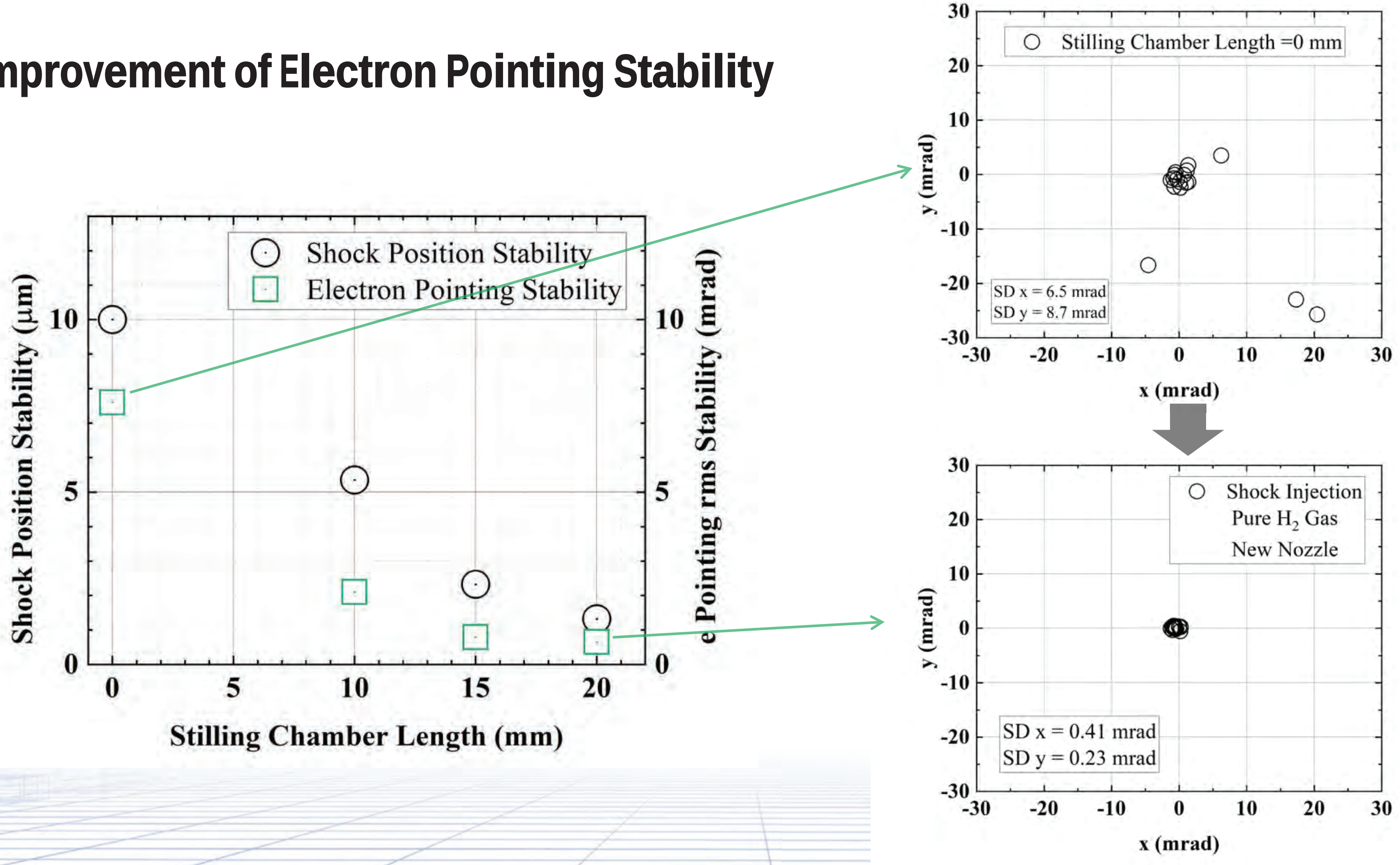






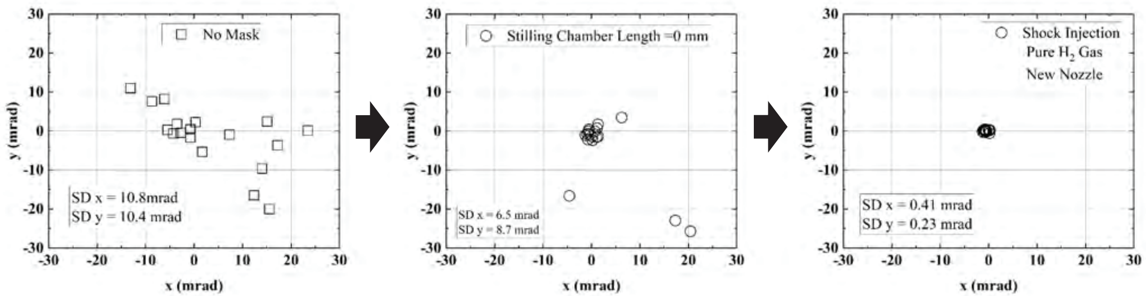
Stability of shock position is measured by both interferometry and Schlieren imaging.

Improvement of Electron Pointing Stability



Summary

- LWFA electron beam quality has been improved, by:
  - Introduce injection control
  - Improve laser stability
  - Improve gas target stability



- Undulator gain has been successfully observed.
(THOA08 レーザープラズマ電子加速を用いたXUV FELの発振実験 by M. Kando (KPSI, QST))
(FROA06 Laser 加速電子Beamを用いたXUV-FEL実証試験のための，極短周期Undulator磁石技術に基づく，小型・軽量Undulatorの開発 by S. Yamamoto (KEK-IMSS))

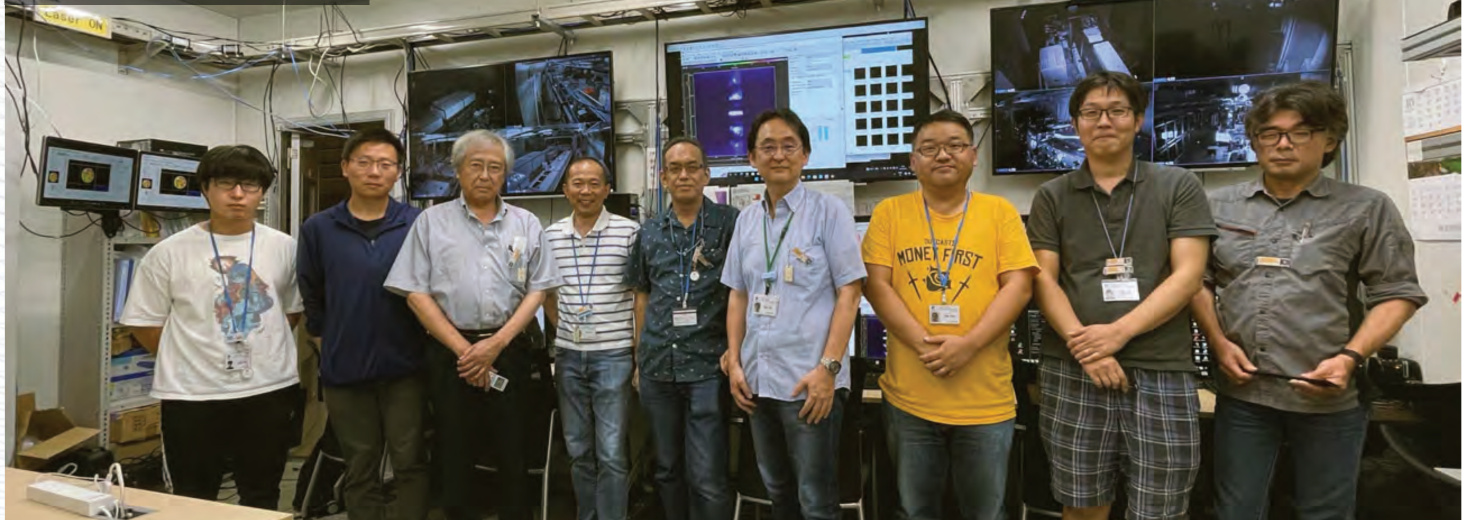
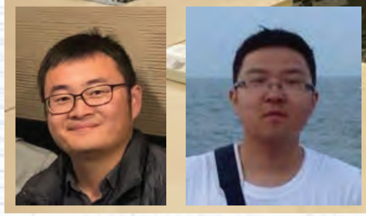
To do

- Further improvement of **laser stability**.

大阪大学
OSAKA UNIVERSITY

Thank you for your attention !

Experiment Team

Laser Peening Team


Simulation Team


OU MASTER PLAN 2027
生きがいを育む社会の創造