Realization of a Stable Electron Beams by Laser Wakefield Acceleration (LWFA), and the ImPACT Program in Japan

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Council for Science, Technology and Innovation (CSTI)
Cabinet Office, Government of Japan
c/o Japan Science and Technology Agency (JST)

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Photon Pioneers Center, Osaka University

Annual MT Meeting@KIT Karlsruhe University
08-10 Mar. 2016

Outline

The 1st Topic. ***(Y. SANO's Part)***

- The ImPACT Program in Japan -

1. Introduction of ImPACT &ImPACT-UPL Program

The 2nd Topic. ***(T. HOSOKAI's Part)***

- Status of LWFA Research at PhoPs Osaka University -

1. LWFA research aiming at laser-driven XFEL;
Introduction of ImPACT-UPL; Project 1

2. Repeatable LWFA with Plasma Micro-Optics

3. 2 Beam driven staging LWFA

4. The latest results

5. Summary

The 1st Topic.

The ImPACT Program in Japan:
A Five-year National Program to Realize Ultra-compact Power Lasers and Applications

March 10, 2016

prepared by ***Yuji SANO***
Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT)
Council for Science, Technology and Innovation (CSTI)
Cabinet Office, Government of Japan
c/o Japan Science and Technology Agency (JST)

Foundation of ImPACT Program

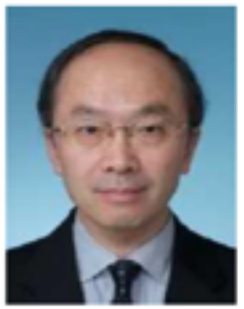
- In 2014, the cabinet office of the Japanese government launched the **ImPACT** program for promoting innovative and high-impact R&Ds.
- The goal of **ImPACT** is trigger off revolutions of society and industry in Japan through the resulting disruptive innovation.
- A five-year foundation until JFY2018 was set up to facilitate the flexible use of 55 billion yen ($480M) allocated in the supplementary budget of JFY2013.
- Twelve PMs were designated in June 2014, and each PM started the program after setting up R&D. Four more PMs were designated in September 2015.

ImPACT - UPL (Ubiquitous Power Laser)

Ubiquitous Power Laser

for

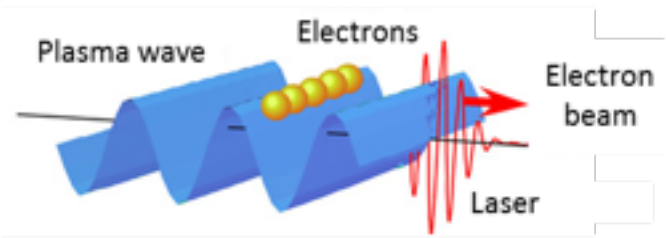
achieving a safe, secure and longevity society



SANO (Toshiba)

Comfortable living environment

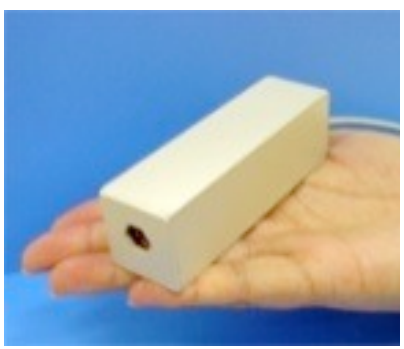
- **Project 1**: LWFA (Laser wakefield acceleration) of electrons and XFEL demonstration



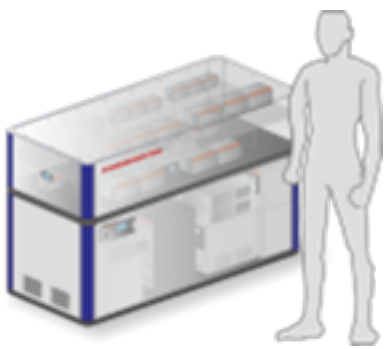
Laser wakefield acceleration of electrons

Ultra-compact XFEL

- **Project 2**: Development of ultra-compact optical pulse lasers for industry



Handheld laser

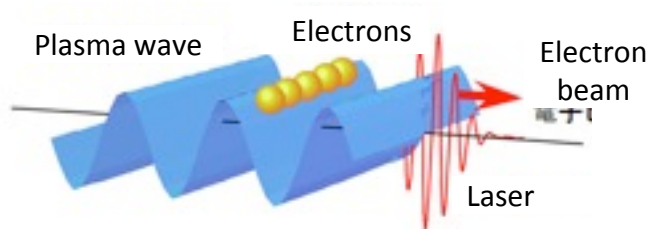


Tabletop laser

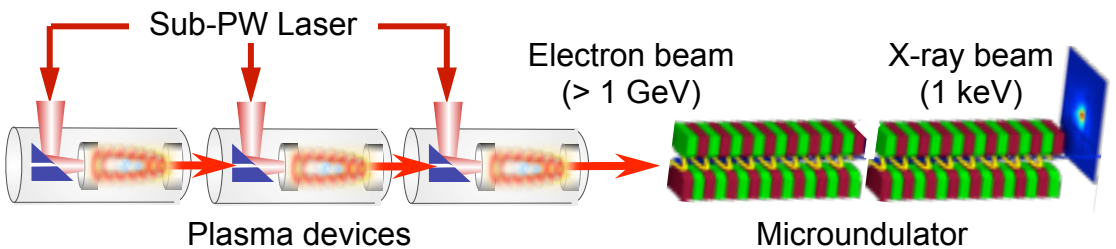
R&D Structure of ImPACT - UPL

Project 1 Laser acceleration & XFEL demonstration

Laser acceleration elemental technologies
Electron acceleration exceeding 1 GeV and modularize it as a plasma device



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



Plasma device & power source
Plasma channel for laser guiding and power source with large pulse current

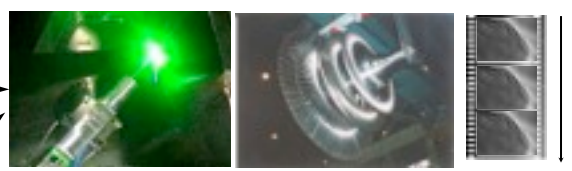
Wakefield & beam diagnosis
Control of laser and electrons, and injection of electrons to undulator

Microundulator
Ultra-compact undulator generating 1 keV X-ray beam

Project 2 Ultra-compact power laser

Microchip laser (handheld)
Pulse energy of > 20 mJ, 100 Hz with a weight of < 1 kg

High-power & high-rep rate laser (tabletop)
Pulse energy of 1 J, > 300 Hz by a tabletop-sized unit



Expansion to industrial applications (peening, forming, flaw detection etc.) and basic science applications (material behavior under extreme environments, etc.)

Project 3 Study of user needs and systemization assessment

Study of user needs and systemization assessment
Trend studies on “X-ray beam by laser-accelerated electrons” and “ultra-compact power lasers”

Principal Investigators of ImPACT - UPL

Project 1
Laser acceler.
& XFEL demo.

Laser acceleration technology
Prof. Hosokai, Osaka Univ.

Microundulator
Prof. Yamamoto, KEK

Innovative microundulator
Open bidding (under prep.)

Wakefield & beam diagnosis
Dr. Kando, JAEA

Plasma device & power source
Prof. Sasaki, Nagaoka Uni Tech

Platform for laser acceleration and XFEL demonstration
Prof. Kodama, Osaka Univ.

XFEL demonstration and assessment

Program Advisors

Program Manager
Dr. Sano

Project 2
Ultra-compact
power laser

Microchip laser
Prof. Taira, Institute Mol Sci

High-power & high-rep rate laser
Dr. Kawashima, Hamamatsu

Study of user needs and systemization assessment
Open bidding (under prep.)

Systemization and las applications

Project 3
Systemization & Assessment

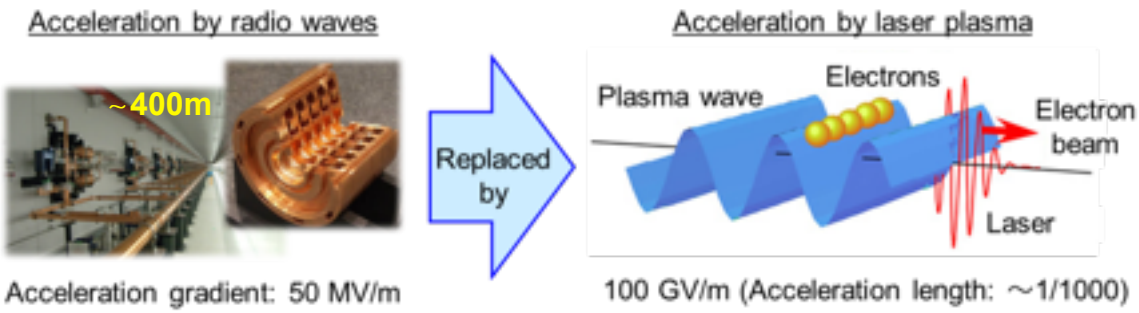
Project 1 Miniaturization of XFELs

- Reduce R&D cycle drastically (from years to months/weeks) by using XFELs anytime required

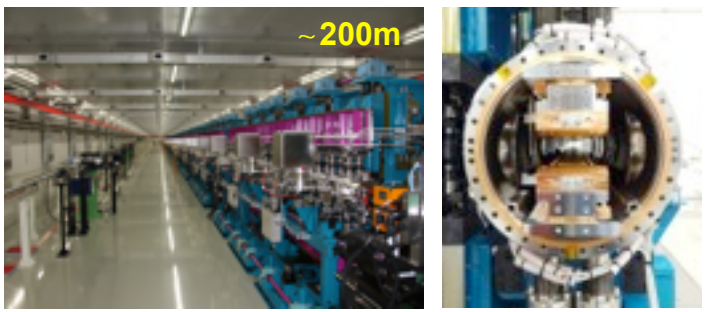
XFEL (SACLA) at Riken-Harima

Concept of mobile XFEL

- Reduce electron acceleration length by LWF from 400m to 10m or less

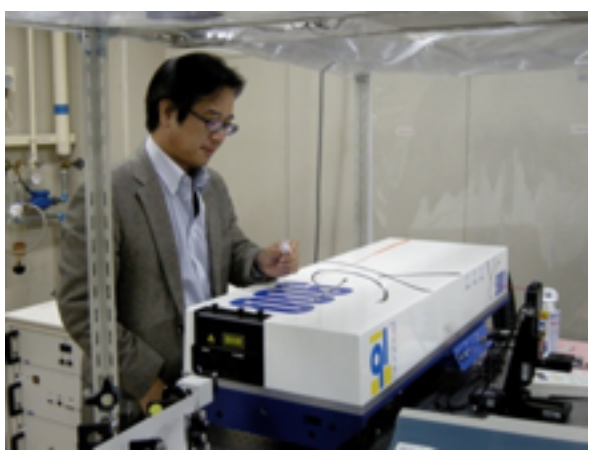


- Reduce undulator length by elaborated magnet technologies to 10m or less



Project 2 Miniaturization of Solid-state Lasers

- Specifications & Characteristics (an Example)
  - ✓ 20mJ/pulse (final goal: 100mJ) , 100Hz, <1ns, <1kg (handheld)
  - ✓ The ultra-miniaturization of lasers will be possible through the use of microchip laser, ceramic laser media, high-power LD technologies, etc.
  - ✓ The tabletop size can be reduced to a palmtop size after development.
  - ✓ System can be driven by a battery.



Replaced by

- Applications

Driver for Ti:sapphire lasers, Materials processing, Medical applications, Maintenance of infrastructures, Instrumentations, etc.

Timeline of ImPACT - UPL Development

	JFY2014	JFY2015	JFY2016	JFY2017	JFY2018	JFY2019
	▽ Start of program			▼ Int. Symp.	▽ End of program	

Pj-1
Laser accel. XFEL

▲ 300MeV electron accel.
▲ Plasma diagnosis
▲ Undulator
Elemental tech. develop.
Site preparation
▲ Site selection
▲ Completion of platform
Multi-staging accel.
▲ >1GeV electron accel.
▲ 1keV X-ray beam
Allications of Elemental tech.

Pj-2
Solid-state pulse laser

Elemental tech. develop.
Grade up
▲ 20mJ×100Hz (1kg)
▲ 1J×300Hz
▲ 100mJ (1kg)
▲ 3J technology
Specification survey
Commercialization
Systemization
Trial demonstration
Miniaturization

Elemental technology develop.
Applications / Evaluation
Systemization

革新的研究開発推進プログラム
ImPACT
Impulsing Paradigm Change through Disruptive Technologies Program

http://www.jst.go.jp/impact/index.html
http://www8.cao.go.jp/cstp/sentan/about-kakushin.html

Yuji SANO
Annual MT Meeting@KIT Karlsruhe University
10 Mar. 2016

The 2nd Topic.

Status of Laser Wake-Field Acceleration Research at PhoPs Osaka University;

Towards Practical Accelerators

Tomonao HOSOKAI *(ImPACT-UPL, LWFA Team PI)*

Stratagy Management and Support Office, Graduated School of Engineering, Osaka University

Photon Pioneers Center, Osaka University

Annual MT Meeting@KIT Karlsruhe University
08-10 Mar. 2016

ImPACT LWFA Research Team @ PhoPs, Osaka Univ.

Laser Acc. Group

T. HOSOKAI[1, 2], S. MASUDA[2], N. NAKANII[2], A. ZHIDKOV[2], H. NAKAMURA[1], N. PATHAK[2], T. OTSUKA[2], K. SUEDA[2], Z. JIN[2], J. OGINO[2], N. TAKEGUCHI[1](M1), K. OSAKO[1] (M1), Y. TAGUCHI[1] (M1), M. YANO[1] (M1),

Material Sci. Group

T. SANO[1], K. ARAKAWA[3],

Director (PhoPs) R. Kodama[1,2],

[1] Graduate School of Eng., Osaka University
[2] Photon Pioneers Center, Osaka University
[3] Interdisciplinary Faculty of Science & Eng., Shimane University

Osaka University

Osaka PhoPs Photon Pioneers Center, Osaka University

Collaborators

JAEA

M. KANDO's Group

KEK

S. YAMAMOTO

T. SASAKI

Annual MT Meeting@KIT Karlsruhe University
08-10 Mar. 2016

1. LWFA research aiming at Laser-driven XFEL "ImPACT-UPL Program; Project 1"

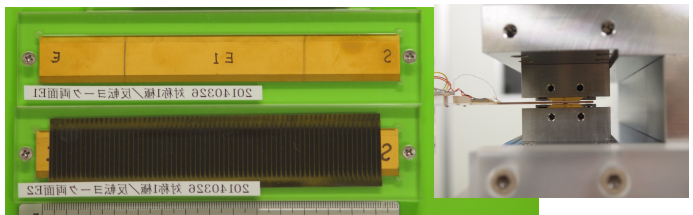
- Dream to mobile XFEL -

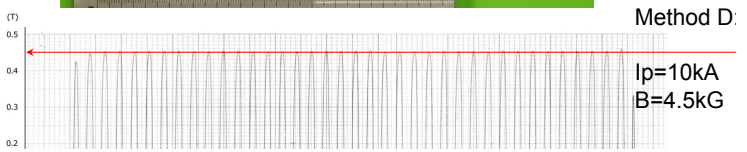
$$\lambda_x = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

X-ray wavelength

革新的研究開発推進プログラム ImPACT
Impulsing Paradigm Change through Disruptive Technologies Program

Micro-Undulator
Plasma Undulator





Prof. S. Yamamoto
(KEK)

Laser driven GeV class electron accelerator

✶Mobile XFEL?

Impulsing Paradigm Change through disruptive Technologies Program (ImPACT)

革新的研究開発推進プログラム
ImPACT
Impulsing Paradigm Change through Disruptive Technologies Program

Ubiquitous Power Laser for Achieving a safe, Secure and Longevity Society

PM: Yuji SANO

Project 1
Laser acceleration & XFEL demonstration

Laser a… ele…nology
Osaka …
(Associate Profe… i)
Osaka University

KEK
…nd
bi…

Beam monitoring
…pen bid…
JAEA
Plasma device p…

Open bi…

Osaka University
(Profess…

…ser

LAPLACIAN
Laser Acceleration Platform as a Coordinated Innovative Anchor

Program Advisors

Program Manager (PM)

XFEL demonstration and assessment

Project 3

Study of user needs and systemization assessment

Open bidding

Systemization and ultra-compact laser applications

Project 2
Ultra-compact power laser

Microchip laser
Institute for Molecular Science (Associate Professor Taira)

Waveform control laser
Open bidding

ImPACT Sano 検索

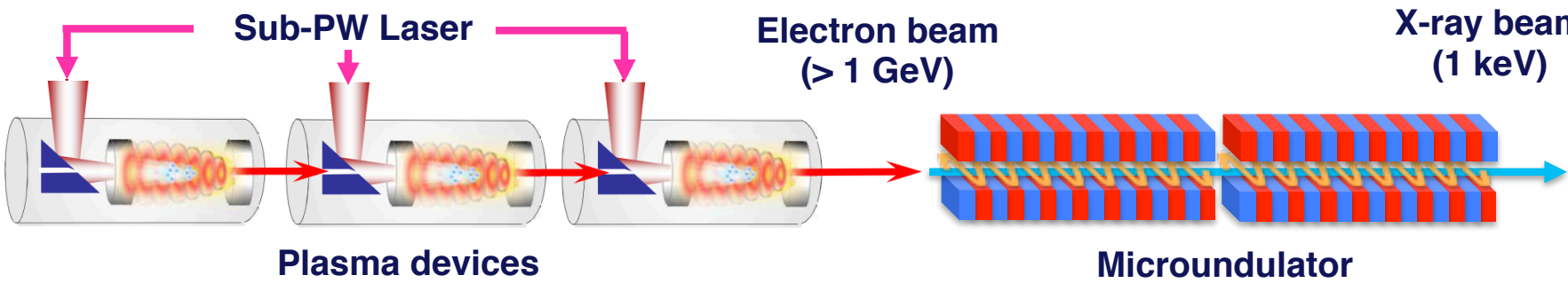
http://www.jst.go.jp/impact/program03.html

SPring-8/SACLA Road Map up to 2041

RING Type X-Ray

2041

Overall Configuration (Generation of X-ray beams through laser acceleration)



Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT Program)
Cabinet Office, Government of Japan

"Ubiquitous Power Laser for Achieving a Safe, Secure and Longevity Society"

~20M€ / 5 Years (2014.10~)

Project Manager: Yuji SANO

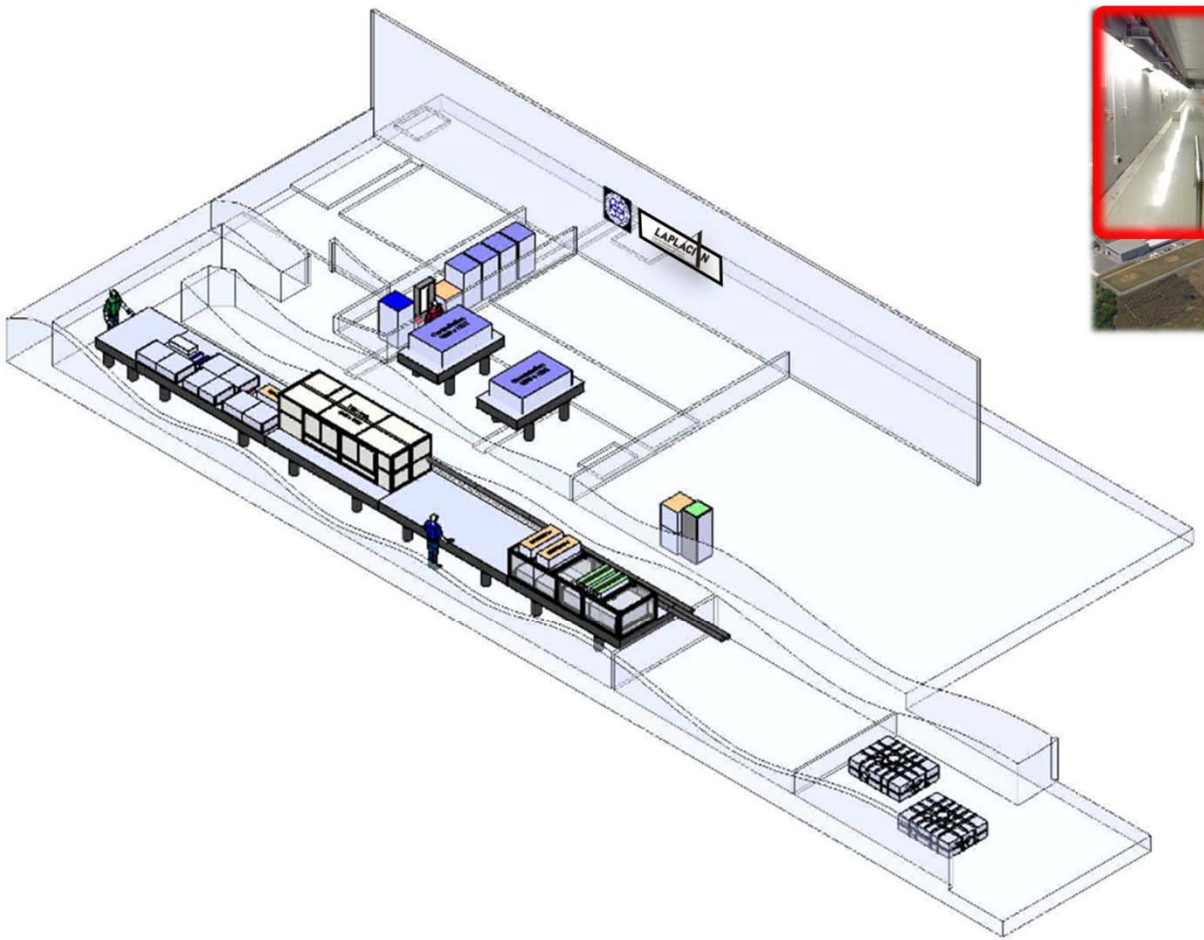
RIKEN

Presentation Material of Prof. T. ISHIKAWA, Director general of SACLA(XFEL Facility, Japan)

Annual MT Meeting@KIT Karlsruhe University 08-10 Mar. 2016

Laser Platform@HARIMA (SACLA)

Ti:Sa ultrafast oscillator



LAPLACIAN
Laser Acceleration Platform as a Coordinated Innovative Anchor

Laser **A**cceleration
PLAtform as a
Coordinated
Innovative **AN**chor

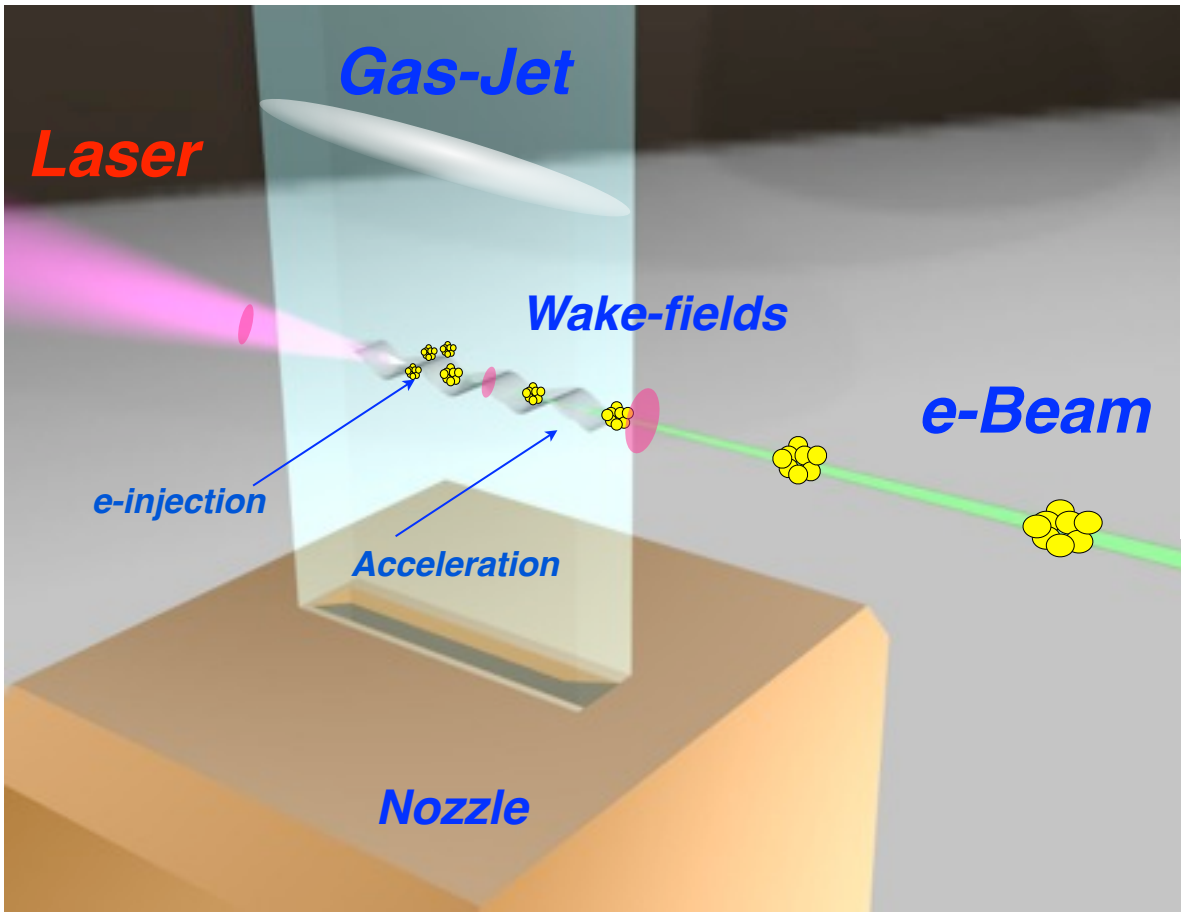
E ~ a few - 10s MeV
ΔE/E = 10 ~ 100%

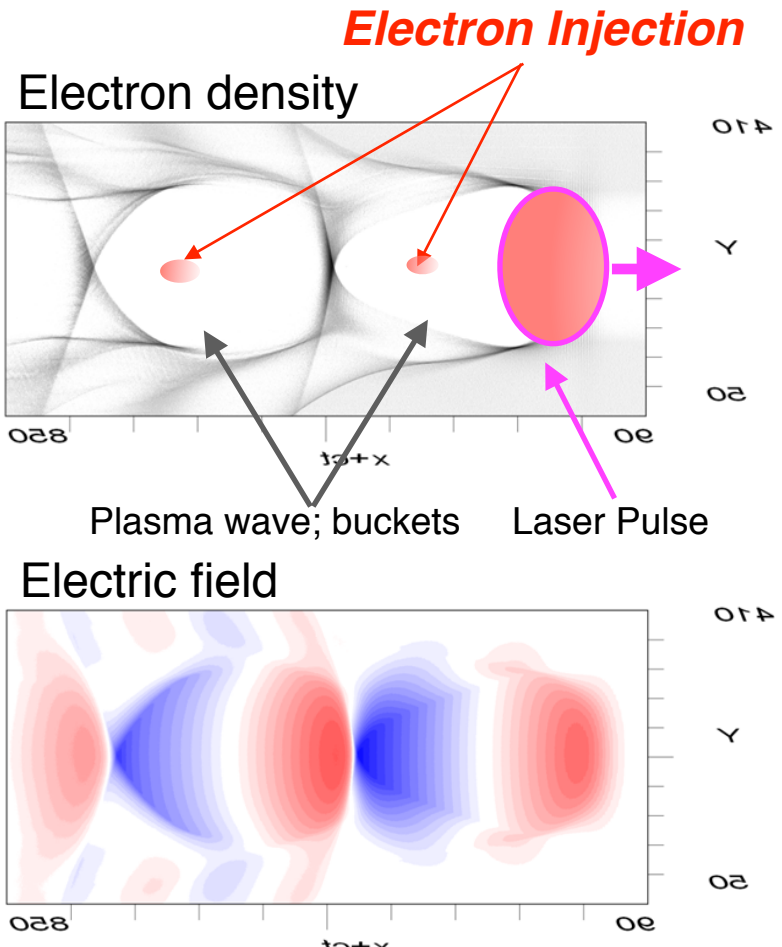
E ~ 10s MeV
ΔE/E < 1 %

E > 1 GeV
ΔE/E ~ 1 %

2. Repeatable LWFA with Plasma Micro-Optics

Laser Wake-field Acceleration (LWFA)





A.Zhidkov, et al

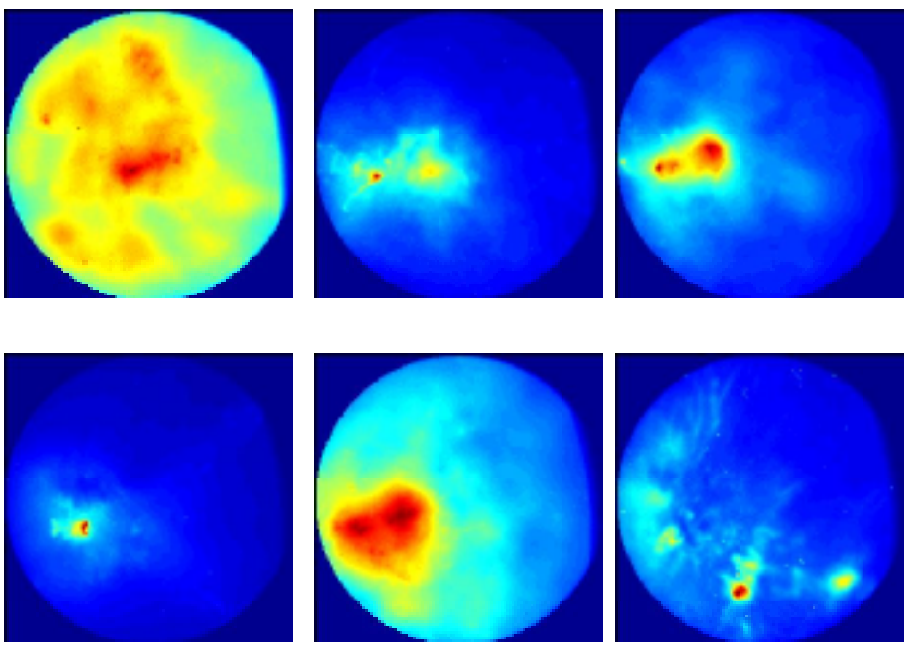
Potential of LWFA

- Ultra-high gradient >100 GV/m
- high- Charge > ~nC/pulse
- Ultra-short pulse< ~few fs
- small divergence < 0.1 mrad

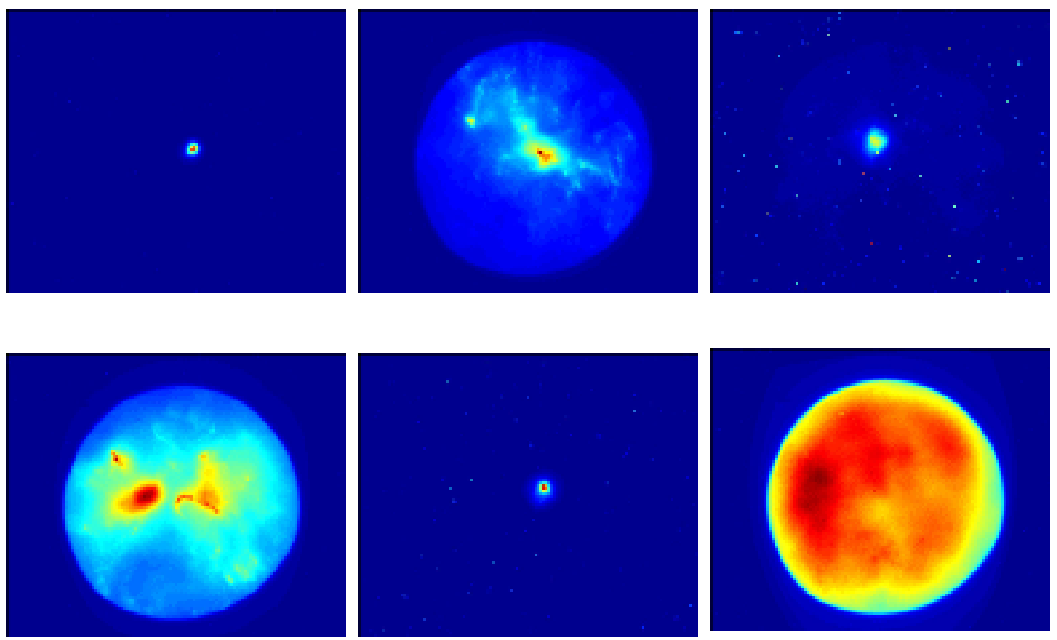
Electron beams driven by LWFA are repeatable ?

Repeatability is the crucial point for practical accelerator

Typical electron beam spots by LWFA



F# ~5, 10TW
Gas ~20Bar
RL~ 100μm
@ Tokyo Unniv.



F# ~20, 30TW
Gas ~10Bar
RL~1.0 mm
@LOA

Experimental Results,@ LOA, & U.Tokyo, 2001~2003
V.Malka, J.Faure, T.Hosokai et.al

Laser-driven Accelerators for Practical Use

Potential of LWFA

- Ultra-high gradient >100 GV/m
- high- Charge > ～nC/pulse
- Ultra-short pulse< ～few fs
- Low-emittance <<0.1 πmmmrad

Many Reports on LWFA e-Beams

with

High-Energy

Mono-energy

Ultra-short Bunch

High-Charge

Low-Emittance

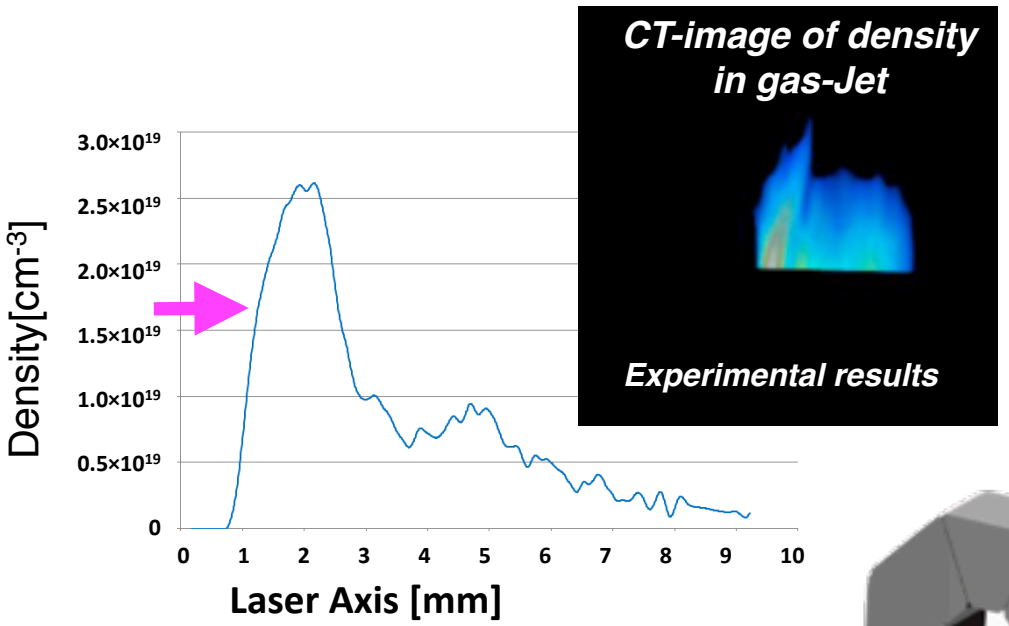
Repeatability?

Controllability?

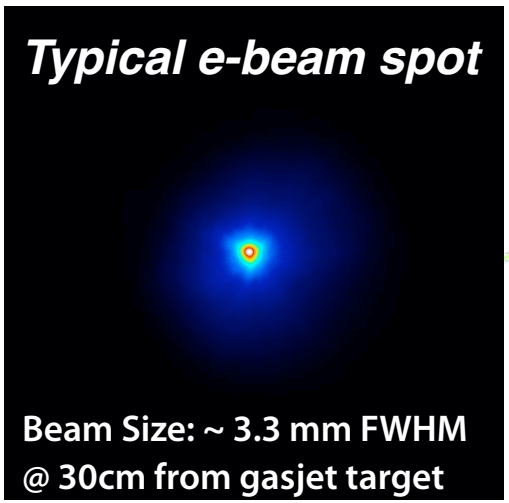
Robustness?

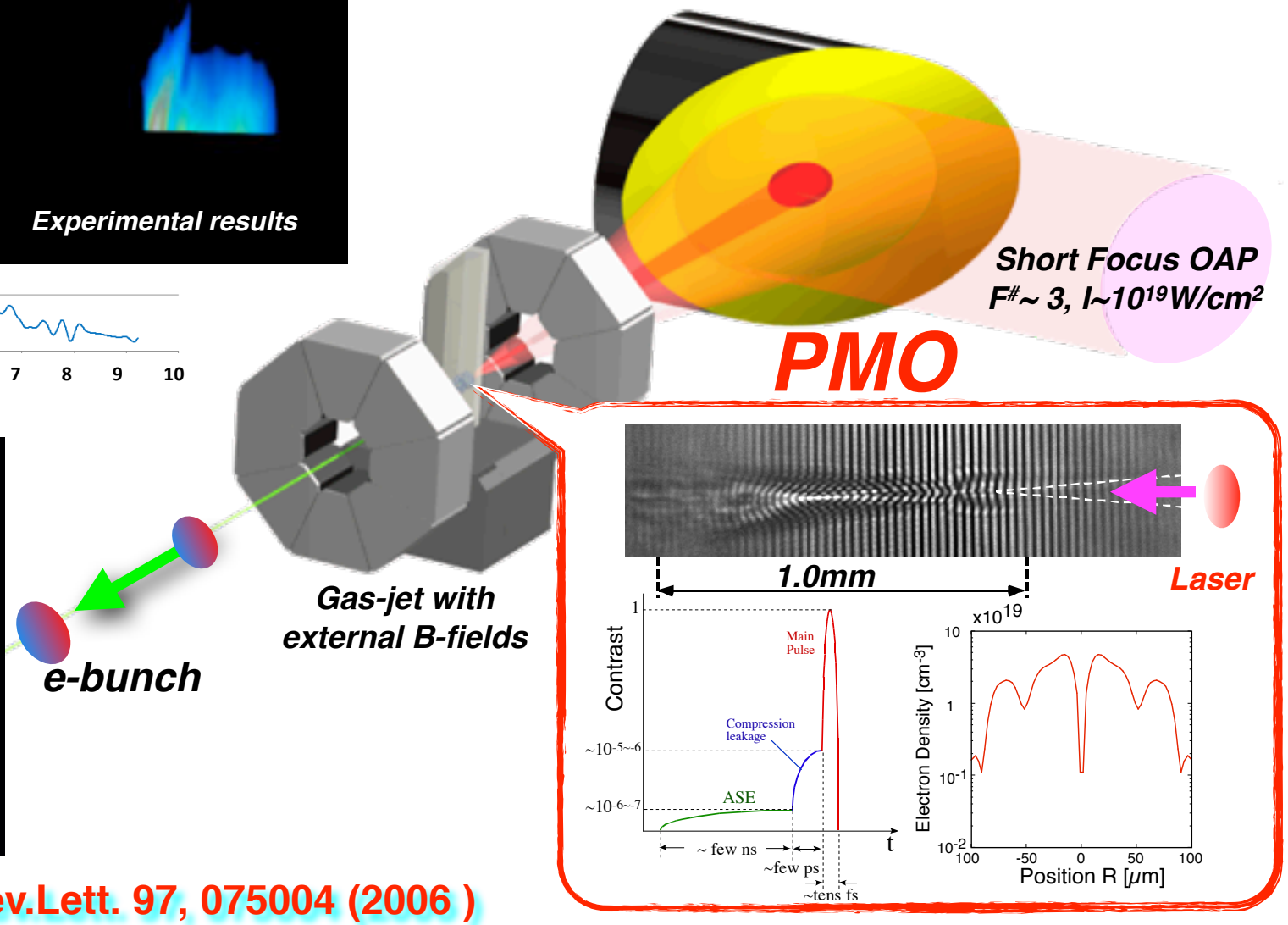
Aiming at Repeatable LWFA

1. Stable supersonic gas-jet with step-density profile.
2. Plasma micro-optics (PMO)



Y.Mizuta,*etal*, Phys.Rev.ST, 15, 121301 (2012)





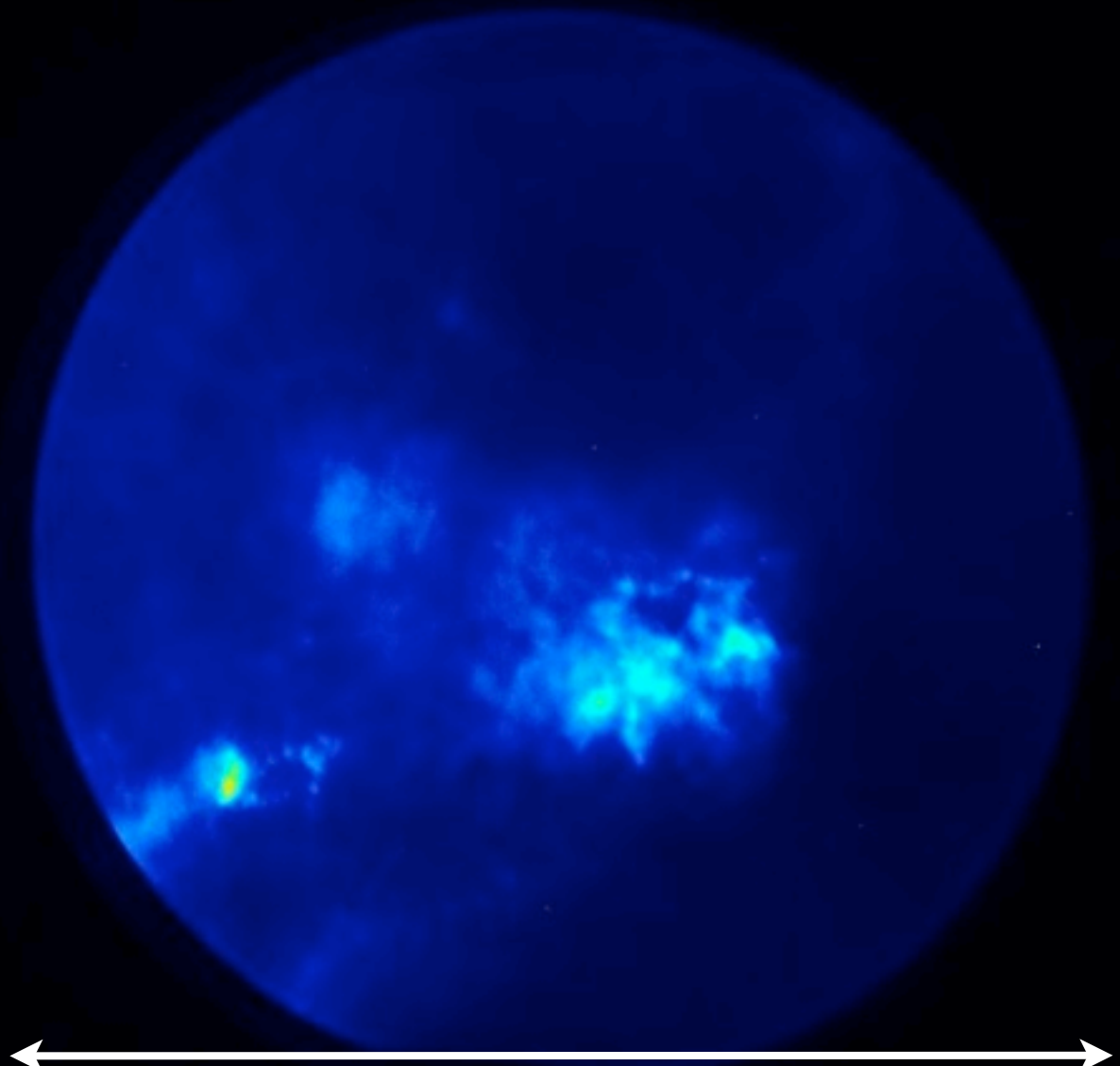
T.Hosokai,et al.,Phys Rev.Lett. 97, 075004 (2006)

T.Hosokai, et al., Appl. Phys. Lett. 96,121501 (2010)

nomagnet-He3MPa-600mJ-CFR200-638-ch4-285500-gasjet-best1.tif

Without PMO, Energy 600mJ

Typical e-Beam Profile



Gasjet target
He 3MPa
Nozzle type
1.2mm(laser axis) x 4mm

Laser pulse
Energy 600mJ
Pulse duration 25fs

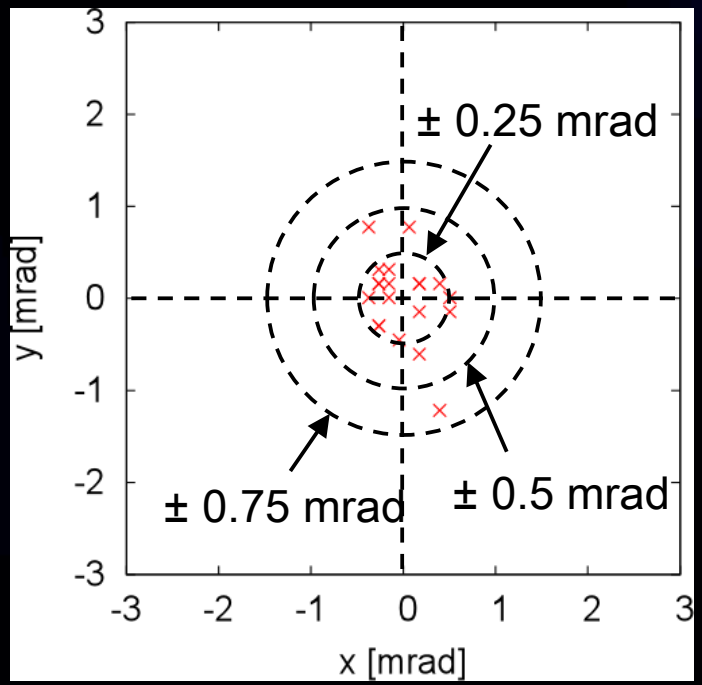
Detector size: Φ13cm (746pixel)

B~0.2T, Energy 600mJ

3 *PMO provides excellent pointing stability !*

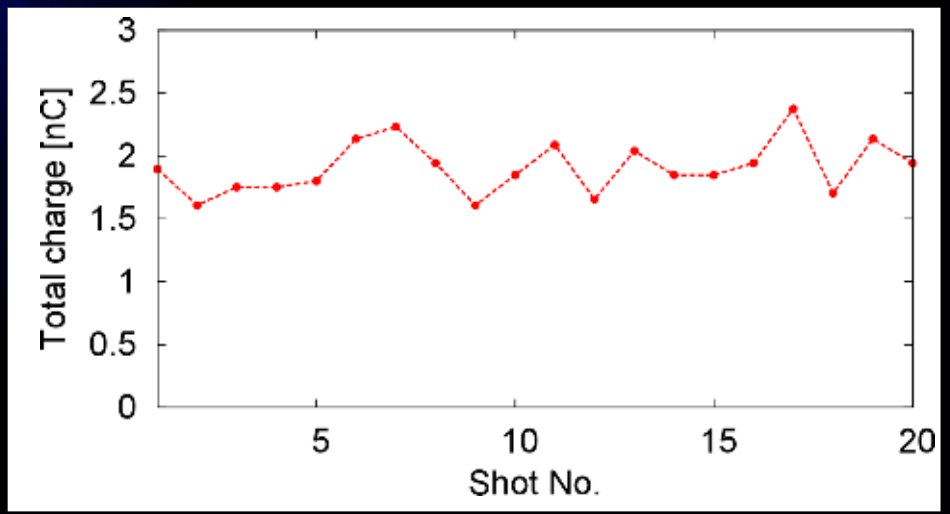
Pointing Stability

< ±200μrad



Total Carge

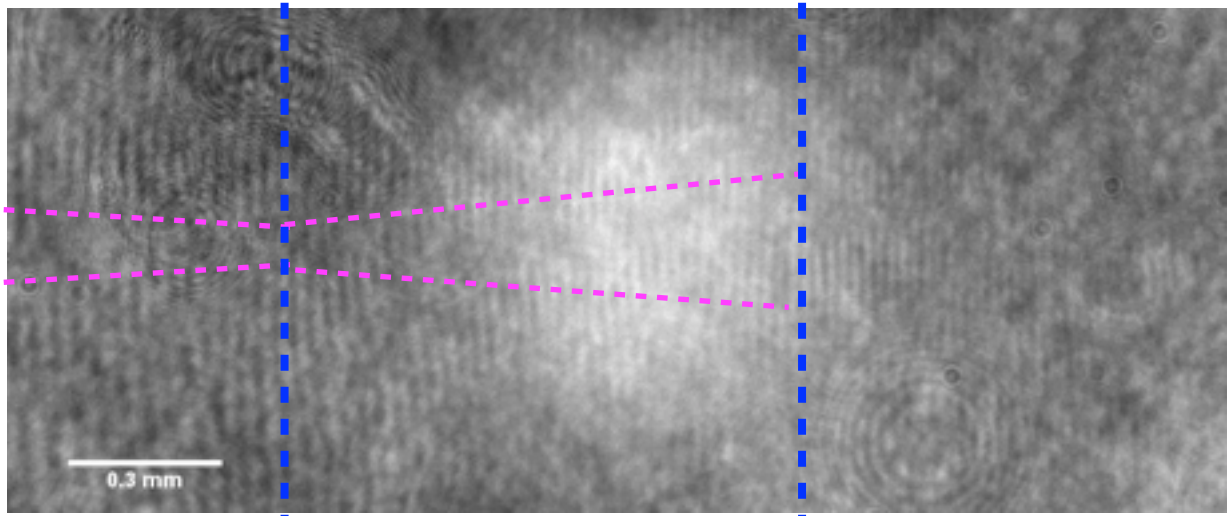
< 2nC ± 5%



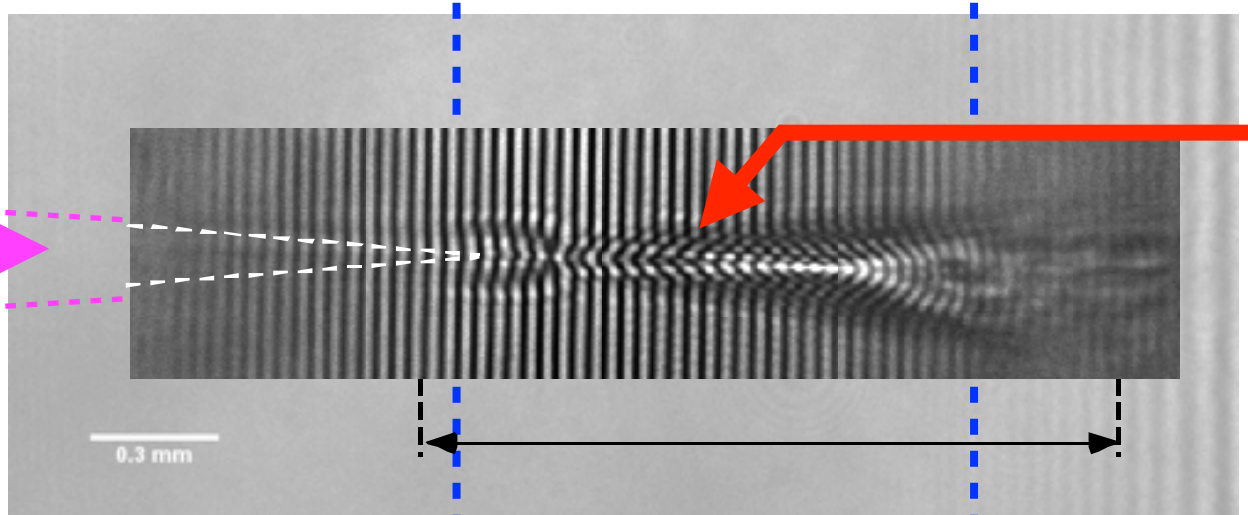
Advanced Plasma Micro- Optics
Key techniques for stable/Repeatable beam generation

$P < P_{critical}$

F#~6



Pulse width ~ 300 fs
Typical contrast ~10^{-3}@4ps,
~10^{-6}@ns
Peak power ~ <10^{16} Wcm^{-2}
P_{total}~ 10GW (< $P_{critical}$)
Ar gas-jet: N~2x10^{19} cm^{-2}



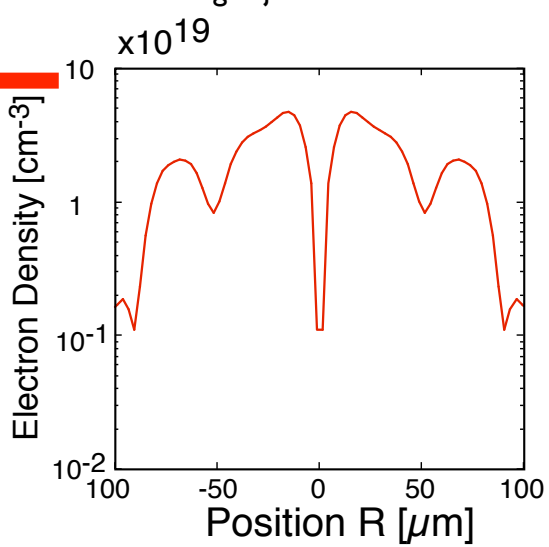
F#~6

ps Laser pulse

Gas boundary

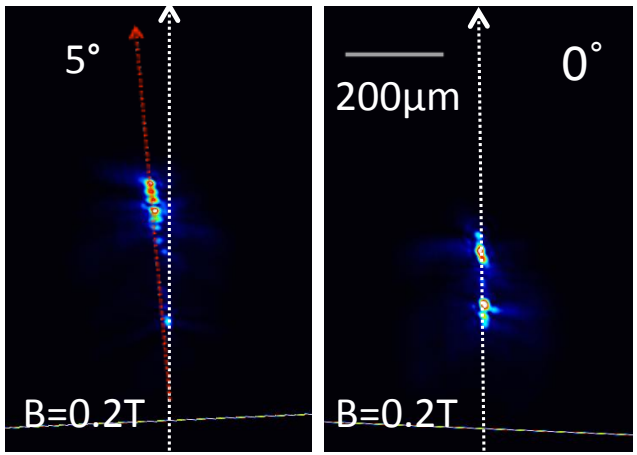
Gas boundary

Pulse width ~ 300 fs
Typical contrast ~10^{-3}@4ps,
~10^{-5}@ns
Peak power ~ <10^{16} Wcm^{-2}
P_{total}~ 10GW (< $P_{critical}$)
Ar gas-jet: N~2x10^{19} cm^{-2}



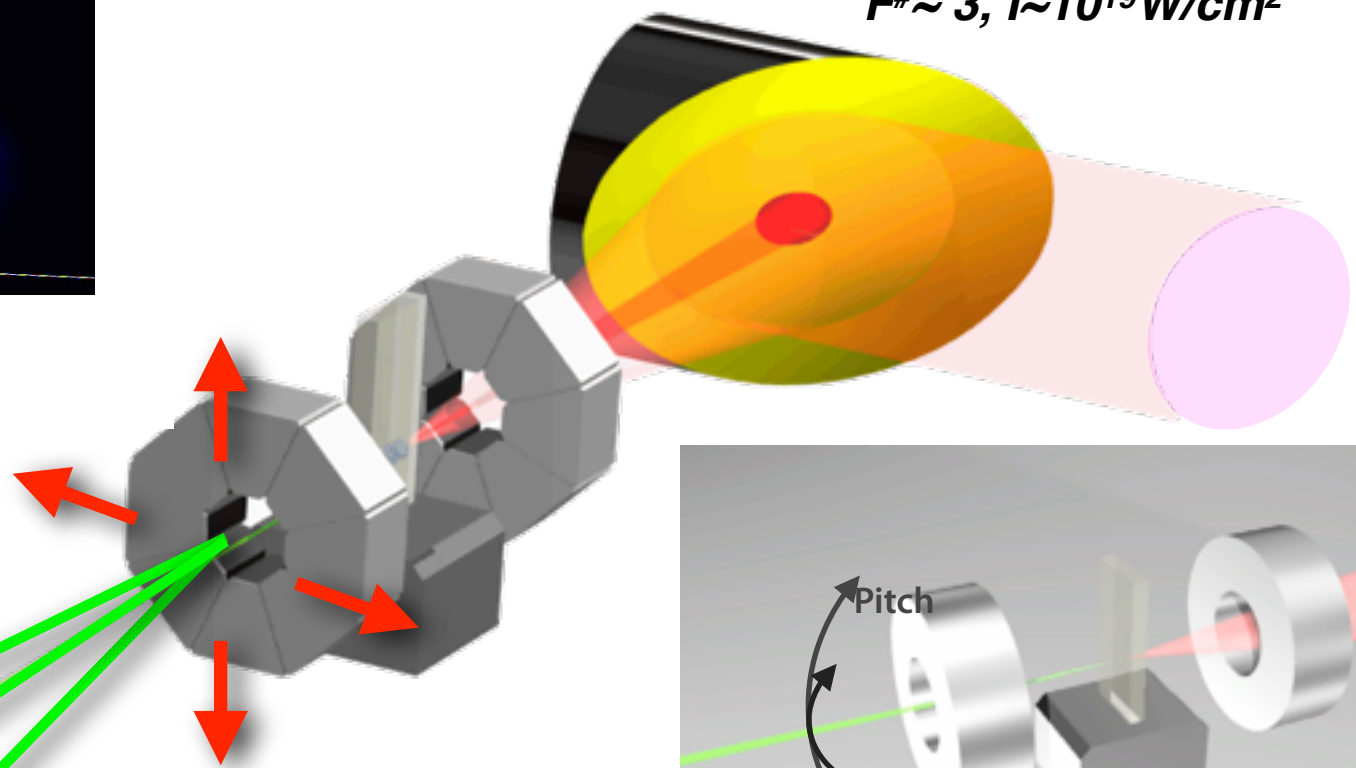
Y.Mizuta,*etal*, Phys.Rev.ST, 15, 121301 (2012)

Steering of e-beams using PMO
Key technique for staging LWFA



Thomson Scattering Images of Laser lights

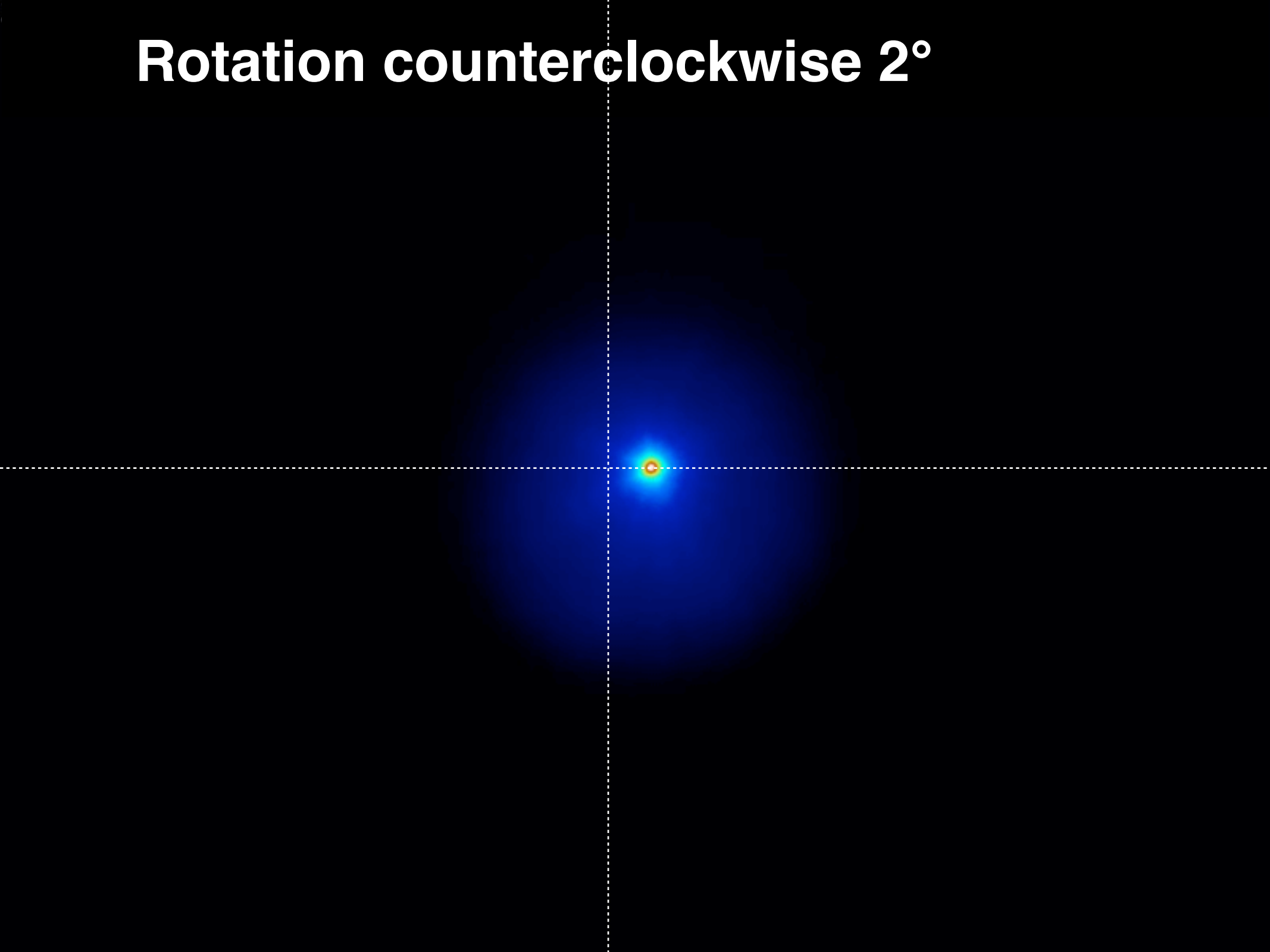
Short Focus OAP
F#~ 3, I~10¹⁹W/cm²



Supersonic Gas-jet + PMO

electron beams

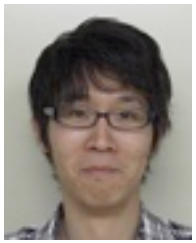
Y.Mizuta,*et al*, Phys.Rev.ST, 15, 121301 (2012)
N.Nakanii,*et al*, Phys.Rev.ST, 18, 021303(2015)


Rotation counterclockwise 2°

Rotation counterclockwise 3°

PMO allows us to steer e-beams as we wish !

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 021303 (2015)



Transient magnetized plasma as an optical element for high power laser pulses

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Underdense plasma produced in gas jets by low intensity laser prepulses in the presence of a static magnetic field, $B \sim 0.3$ T, is shown experimentally to become an optical element allowing steering of tightly focused high power femtosecond laser pulses within several degrees along with essential enhancement of pulse's focusability. Strong laser prepulses form a density ramp perpendicularly to magnetic field direction and, owing to the light refraction, main laser pulses propagate along the magnetic field even if it is tilted from the laser axis. Electrons generated in the laser pulse wake are well collimated and follow in the direction of the magnetic field; their characteristics are measured to be not sensitive to the tilt of magnetic field up to angles ±5°.

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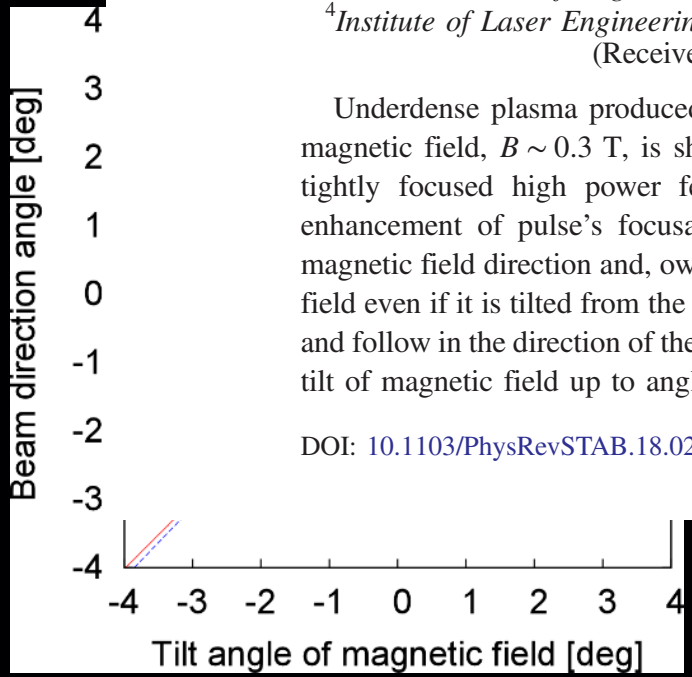
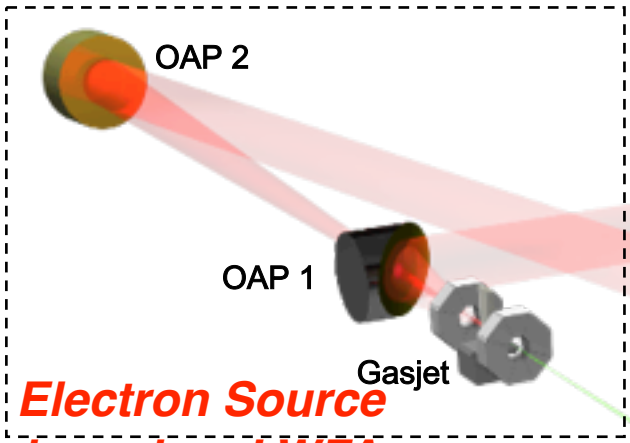


Single-shot ultrafast diffraction imaging for material sciences using LWFA electron beams

CREST 戦略的創造研究推進事業
Core Research for Evolutional Science and Technology

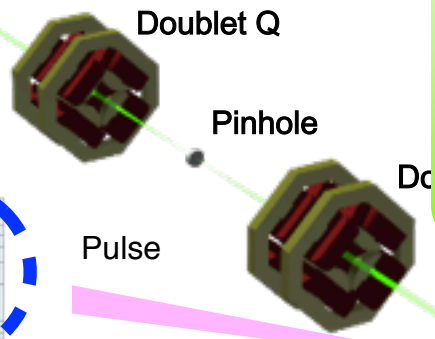


Electron source

Staging LWFA

Phase Rotation with Injection control

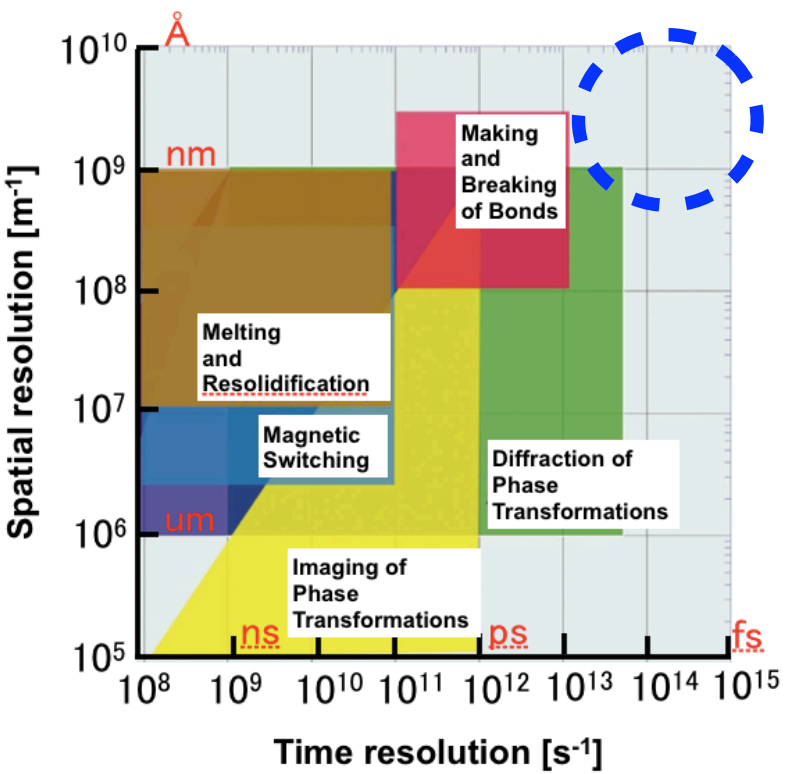
Electron Source based on LWFA

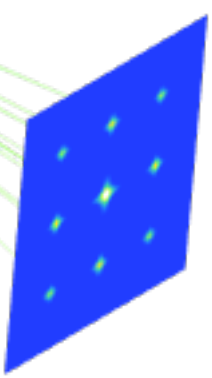


Requirements

< *Bunch duration* >	<10 -100 fs
< *Energy* >	<10 MeV
< *Divergence* >	~10^{-3} rad
< *Charge* >	<100pC/pulse
< *Energy spread* >	<10^{-3}

Electron transport





Imaging

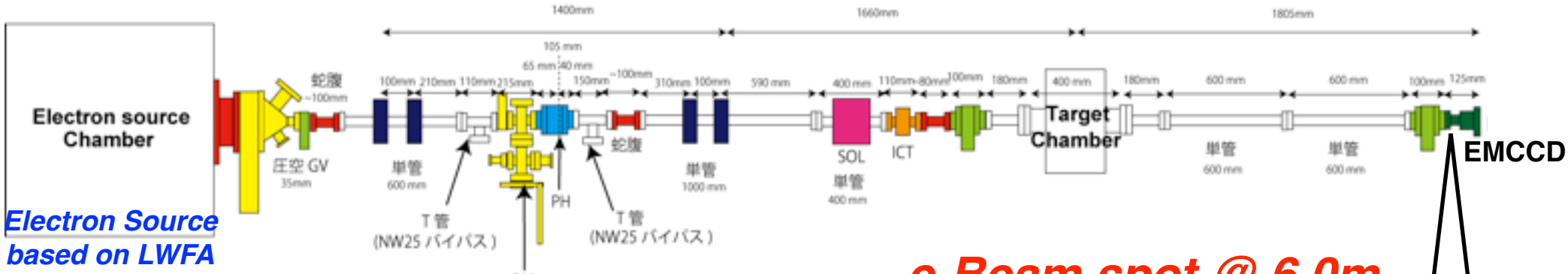
LWFA Beam-line for Ultra-fast Imaging (ver.1.0-beta)

40TW-25fs Laser System
Under upgrading to
40TW x 2 Beams

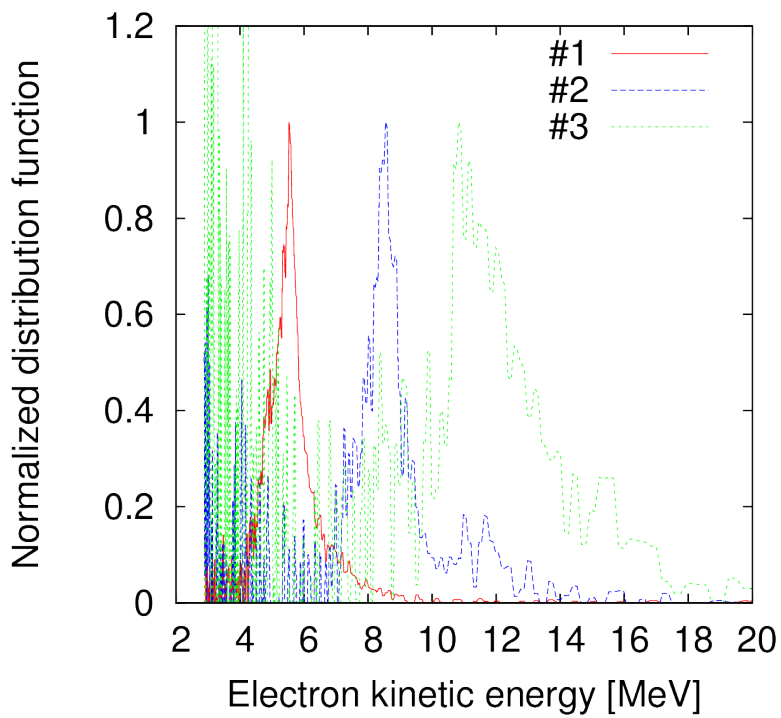
Control room

Status of Our e-Beams
Electron Beam Transport by Q-Magnets @ 6.0m

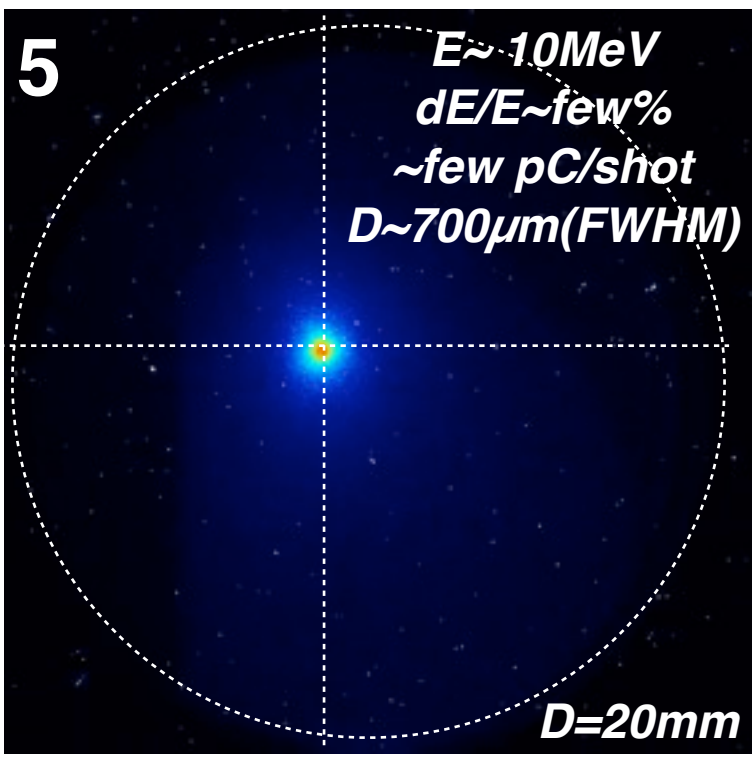
Annual MT Meeting@KIT Karlsruhe University
08-10 Mar. 2016



	Current of Q-magnet [A]			
	Q1	Q2	Q3	Q4
#1	1.455	-1.52	-1.4	0.9
#2	2.18	-2.28	-1.95	1.385
#3	2.91	-3.04	-2.5	1.87

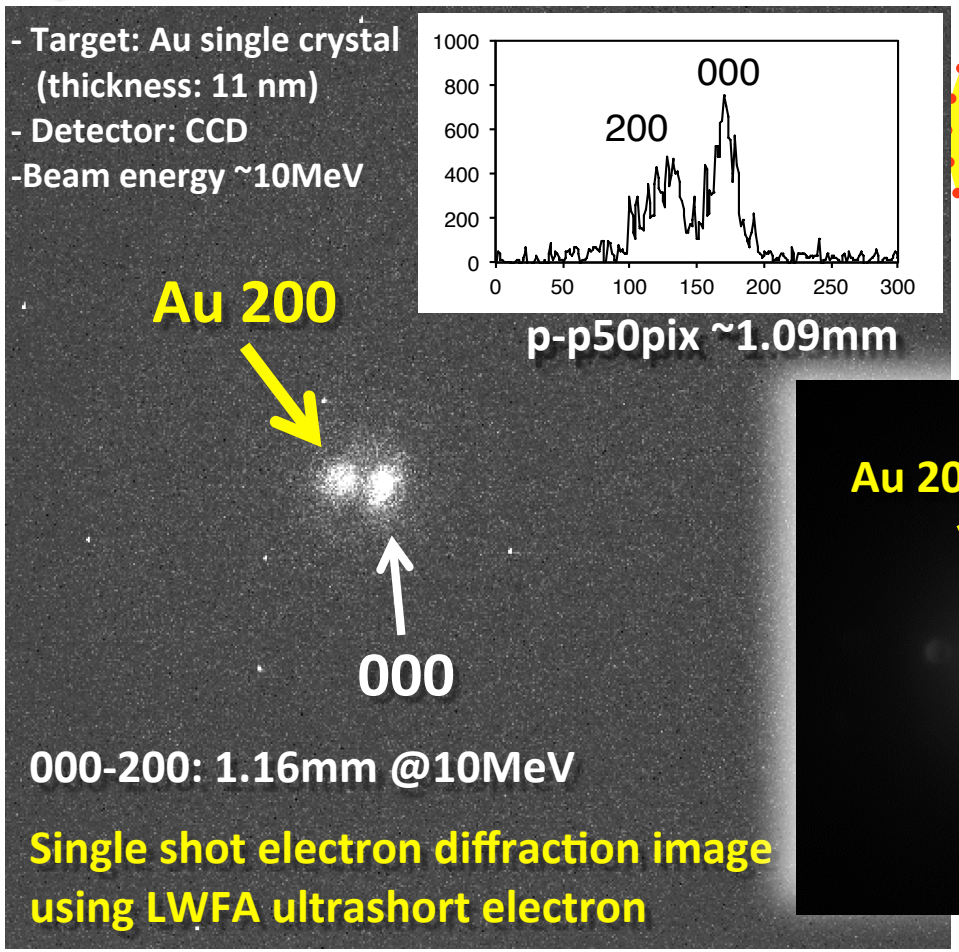


e-Beam spot @ 6.0m



LWFA can provide single-shot ultra-fast electron diffraction images

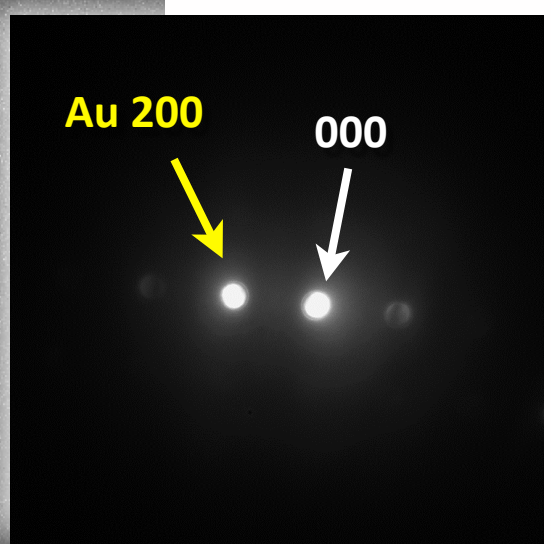
Single shot electron diffraction image using LWFA ultra-short electron



Au Single crystal (11nm)

E ~ 10MeV
dE/E ~few x 10^{-2}
Q ~ 1pC/shot
t < 100s fs

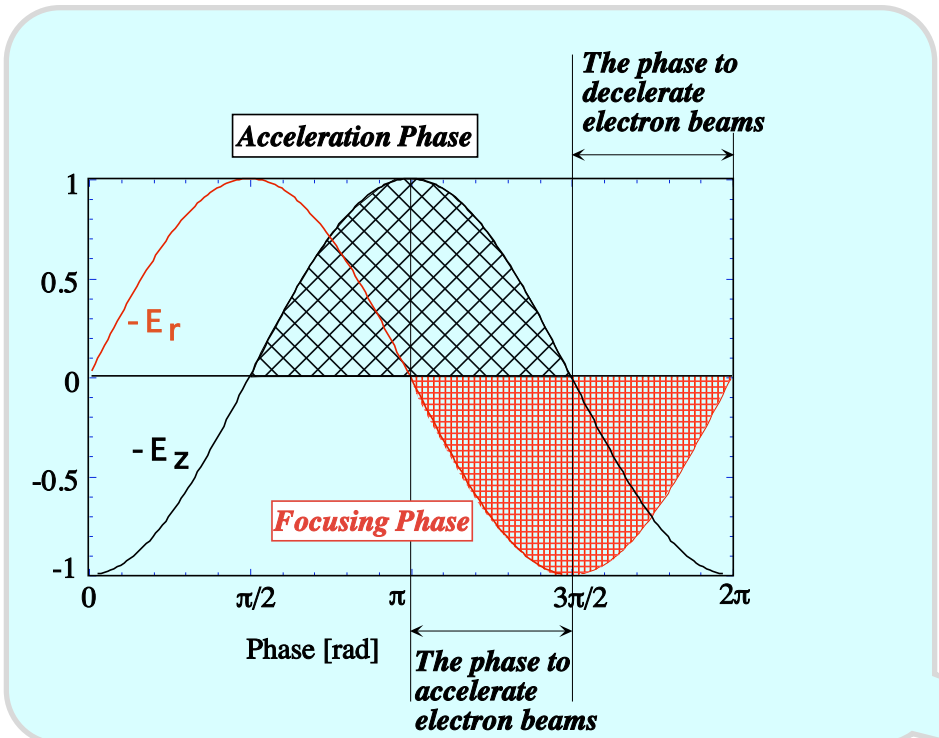
Injector for Multi-stage Acc.

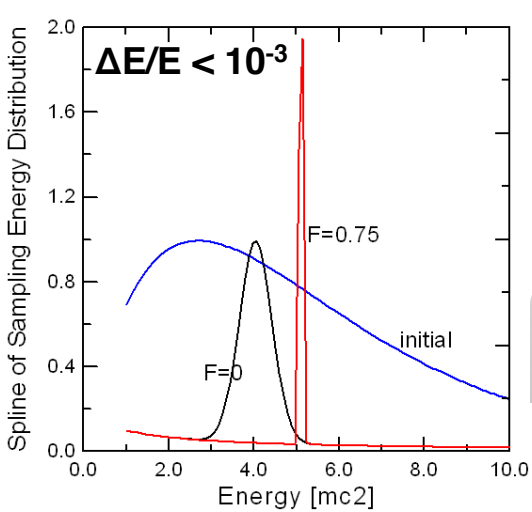


Electron diffraction image
using conventional 200 keV TEM

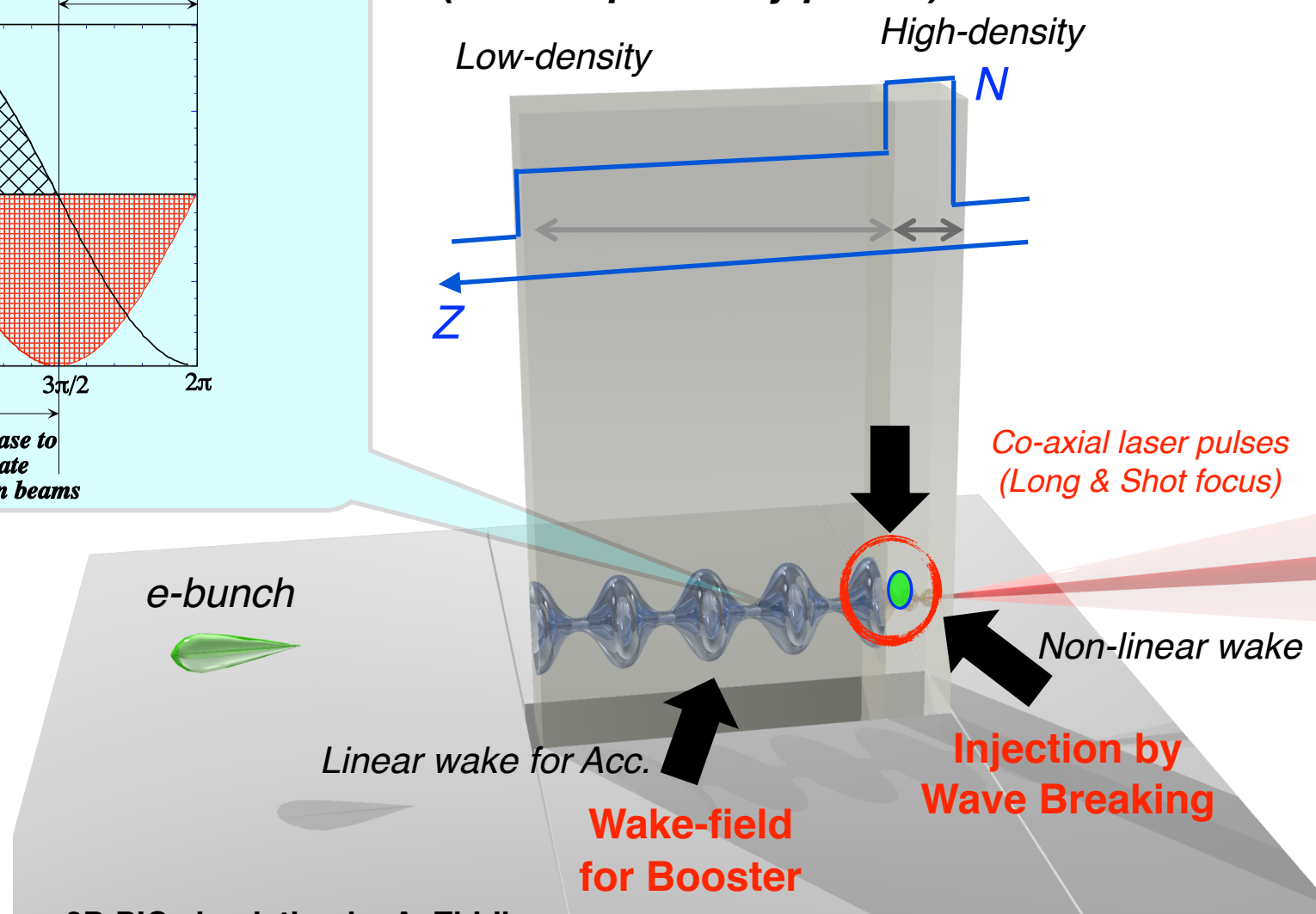
3. 2-Beam Driven Staging LWFA
- Injector-booster scheme -

Injector-Booster Scheme for LWFA



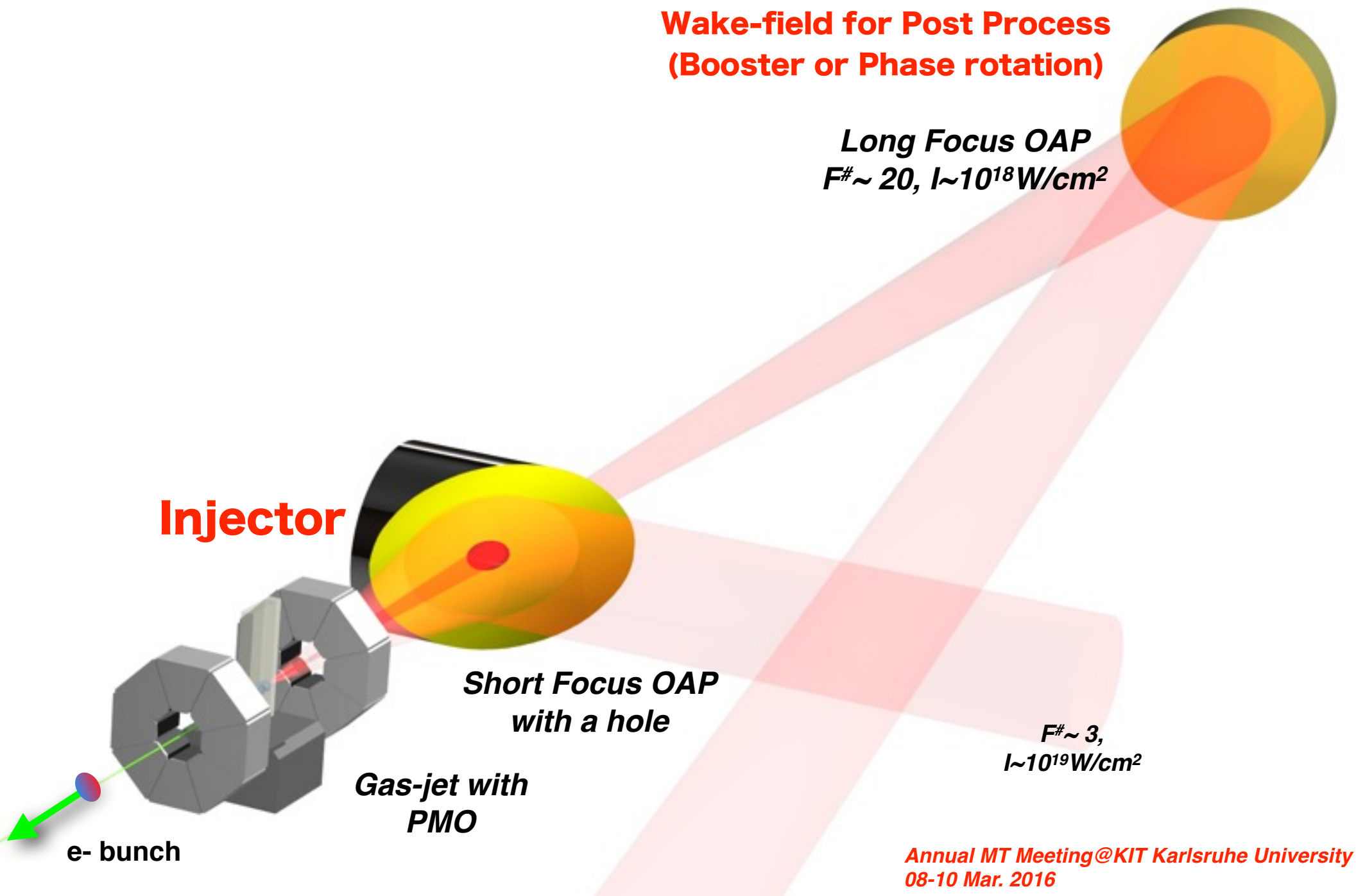


Supersonic gas-jet (with step-density profile)

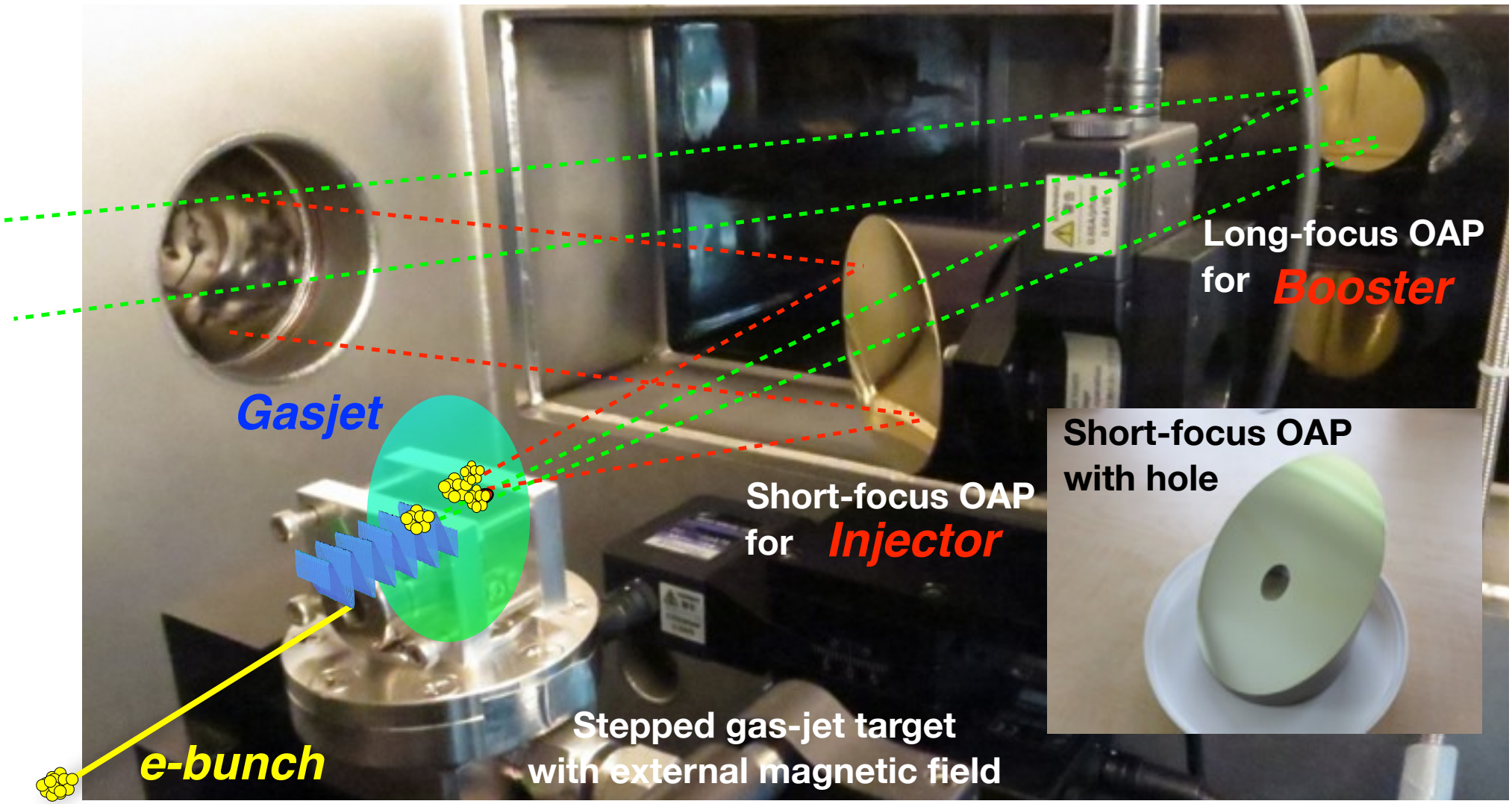


3D PIC simulation by A. Zhidkov

Setup for 2-beam driven staging LWFA



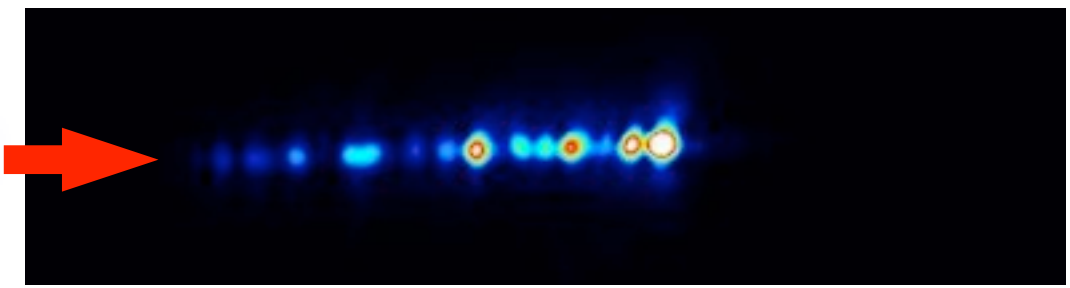
Injector-booster scheme of LWFA (2-beam-driven staging LWFA)



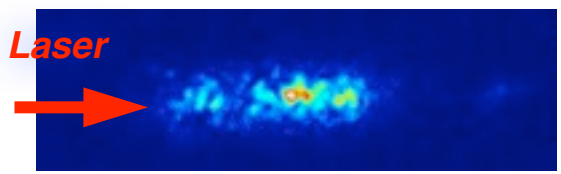
Stable laser wake-field in the booster
- wakefields with no electron injection can be produced-

Thomson Scattering lights (Laser propagation)

Stable Wake-fields (with PMO)

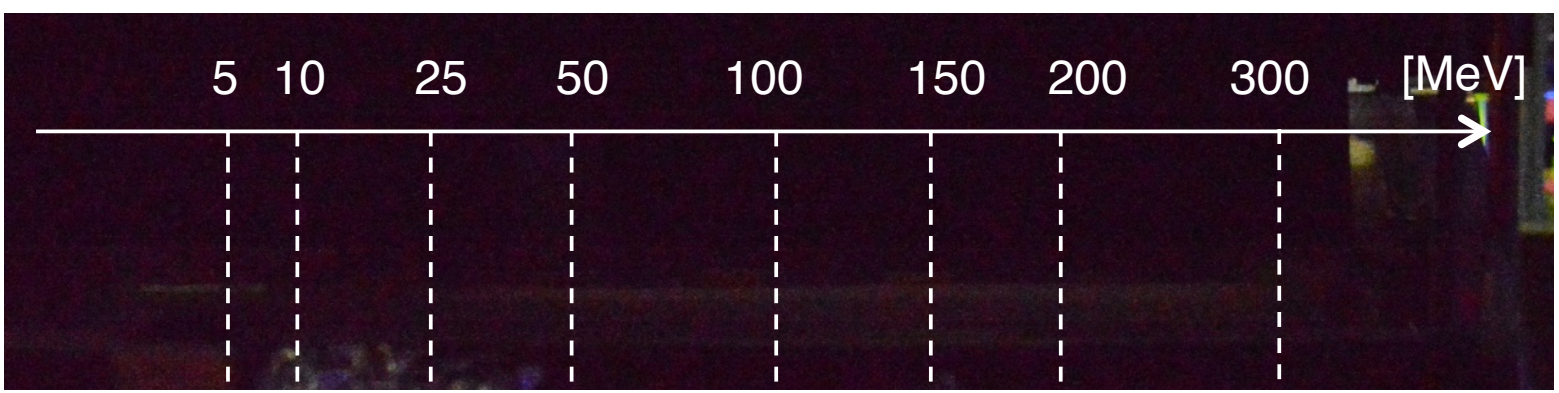


cf w/o PMO



Long Focus OAP F# ~ 20,
300mJ, 30fs, I<10¹⁸W/cm²
He: ~5x10¹⁸ cm⁻³

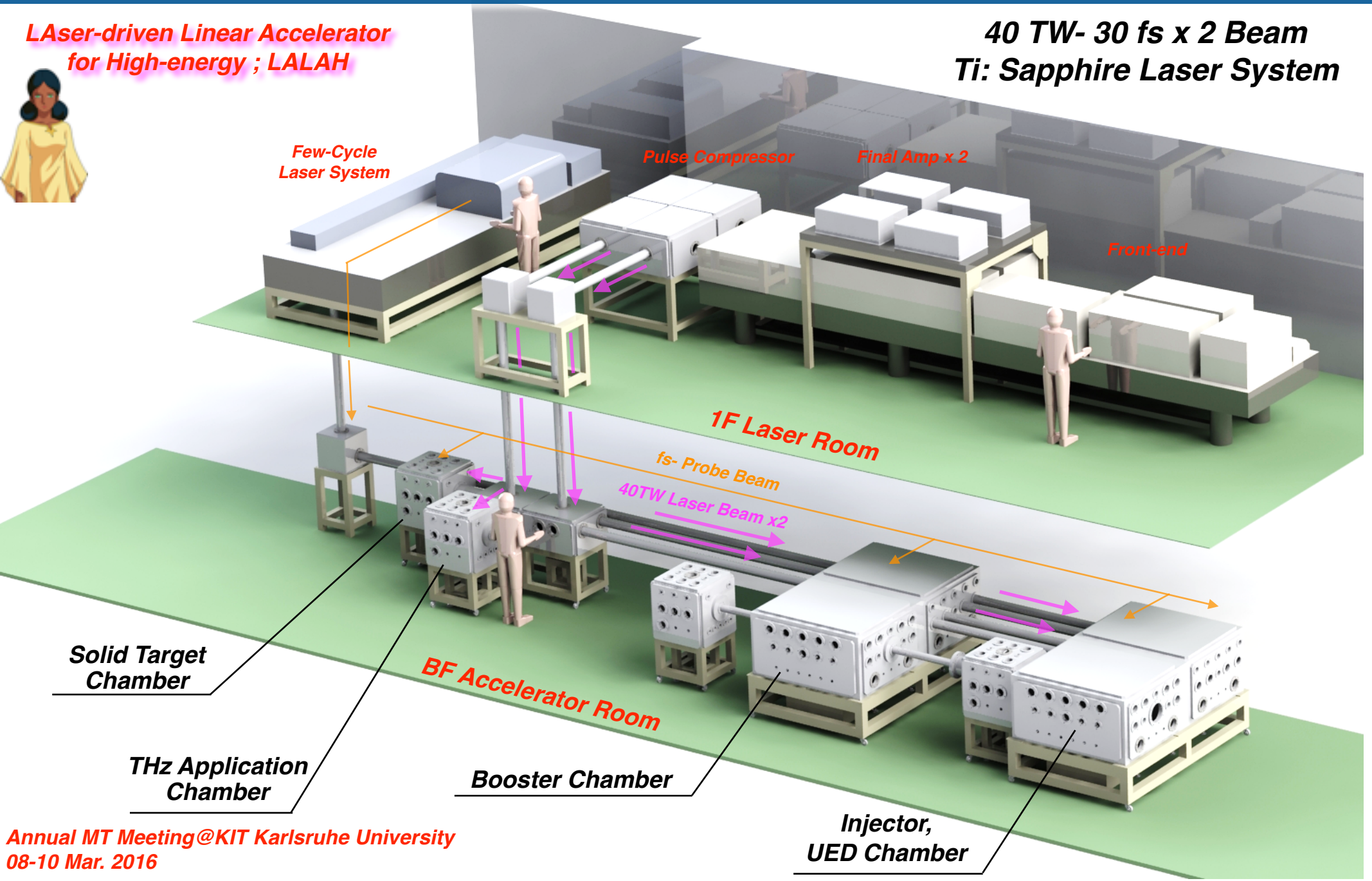
Energy Spectrum



4. The Latest Results

(No details)

New LWFA Beam Lines @ PhoPs (Osaka University Campus)



Summary

- LWFA program aiming at laser-driven tabletop XFEL(ImPACT) is on going, and LWFA platform is under constraction at XFEL facility SACLA in Japan.
- Staging LWFA (Injector-booster scheme) has been demonstrated aiming at practical high- energy LWFA accelerators. We believe this technique can be scalable to GeV class accelerators.
- Prototype of LWF accelerator with energy up to 100MeV has been developed as an injector. Mono-enegetic e-beams spectrum up to 100MeV are well-controlled (ie, repeatable, tunable) with present setup.
- Preliminary single-shot ultra-fast diffraction imaging with 10MeV electron beam have been done.

HEDS2016

International Conference on High Energy Density Sciences 2016

May 17 (Thu.) – 20 (Fri.), 2016 @ Pacifico Yokohama, Yokohama JAPAN

Laser-driven Particle Beams, High-Field Science, Radiation Sources, and High Power Laser Application etc.

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G. Korn (ELI-Beamlines, Czech Rep.)
Karl Krushelnick (U. Michigan)
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Liming Chen (IOP, China)
M.Kando (JAEA, Japan)
Y.Sano (JST, Japan)
and others

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