KEK 第７回　勉強会
2021年1月27日(水) 10：00 〜12：00)@ ZOOM

KEK 第７回　勉強会

レーザープラズマ加速

（レーザー航跡場による電子加速）

- 大阪大学 産業科学研究所
  量子ビーム物理研究分野
  量子ビーム科学研究施設
  理学研究科物理専攻協力講座
- 理化学研究所放射光科学センター
  レーザー加速開発チーム

細貝 知直

hosokai@sanken.osaka-u.ac.jp

金展[1,2], *A.* ジドコフ[1,2], *N.* パサック[1,2], 松門 宏治[1,2], 水田 好雄[1,2], 酒井 泰雄[1,2],
清野 英晃[1], 末田 敬一[2], 神門 正城[3], 黄 開[3], 大東 出[3], 山本 樹[4], 武藤 俊哉[5]

[1] 大阪大学 産業科学研究所
[2] 理化学研究所放射光科学研究センター
[3] 量子科学技術研究開発機構関西研究所
[5] 高エネルギー加速器研究機構(KEK)
[6] 東北大学　電子光理学研究センター

手のひらサイズの高エネルギー 加速器を目指して

加速距離 30cmで 8GeVの電子加速に成功（2019）

PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

Editors' Suggestion **Featured in Physics**

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

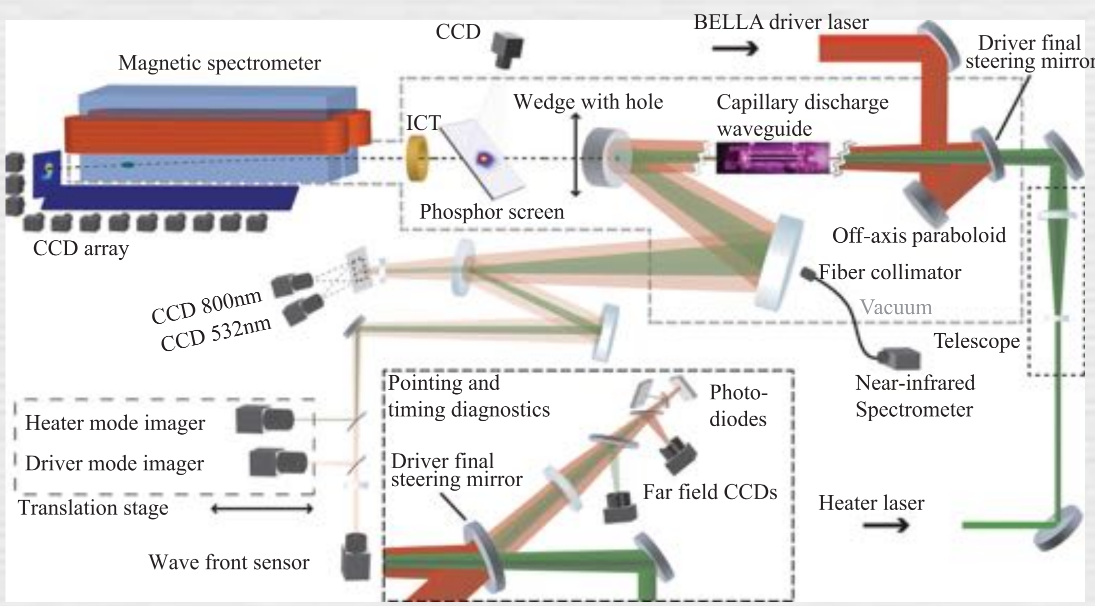
A. J. Gonsalves,[1,*] K. Nakamura,[1] J. Daniels,[1] C. Benedetti,[1] C. Pieronek,[1,2] T. C. H. de Raadt,[1] S. Steinke,[1] J. H. Bin,[1] S. S. Bulanov,[1] J. van Tilborg,[1] C. G. R. Geddes,[1] C. B. Schroeder,[1,2] Cs. Tóth,[1] E. Esarey,[1] K. Swanson,[1,2] L. Fan-Chiang,[1,2] G. Bagdasarov,[3,4] N. Bobrova,[3,5] V. Gasilov,[3,4] G. Korn,[6] P. Sasorov,[3,6] and W. P. Leemans[1,2,†]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*University of California, Berkeley, California 94720, USA*
[3]*Keldysh Institute of Applied Mathematics RAS, Moscow 125047, Russia*
[4]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409, Russia*
[5]*Faculty of Nuclear Science and Physical Engineering, CTU in Prague, Brehova 7, Prague 1, Czech Republic*
[6]*Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague, Czech Republic*

(Received 7 December 2018; revised manuscript received 30 January 2019; published 25 February 2019)

Guiding of relativistically intense laser pulses with peak power of 0.85 PW over 15 diffraction lengths was demonstrated by increasing the focusing strength of a capillary discharge waveguide using laser inverse bremsstrahlung heating. This allowed for the production of electron beams with quasimonoenergetic peaks up to 7.8 GeV, double the energy that was previously demonstrated. Charge was 5 pC at 7.8 GeV and up to 62 pC in 6 GeV peaks, and typical beam divergence was 0.2 mrad.

DOI: 10.1103/PhysRevLett.122.084801



S. Hooker
UK-Japan Workshop on High Energy Density Science, September 2007, Tokyo

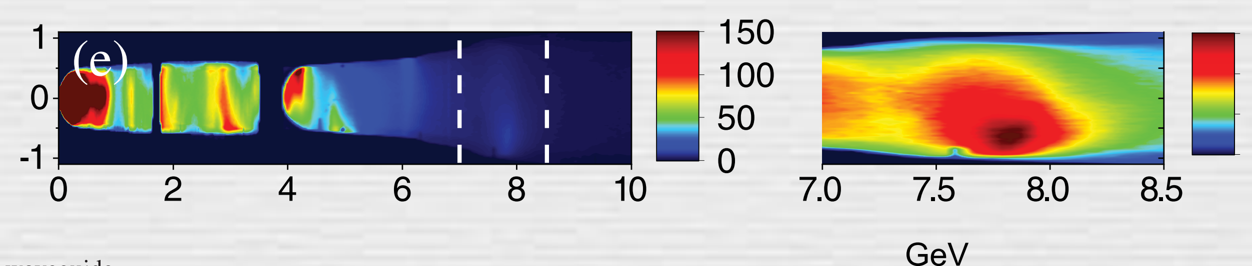


FIG. 2. Schematic layout of the BELLA LPA, including the heater laser system for enhancing the capillary discharge waveguide.

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加速距離 30cmで 8GeVの電子加速に成功（2019）

PHYSICAL REVIEW LETTERS 122, 084801 (2019)

Editors' Suggestion Featured i

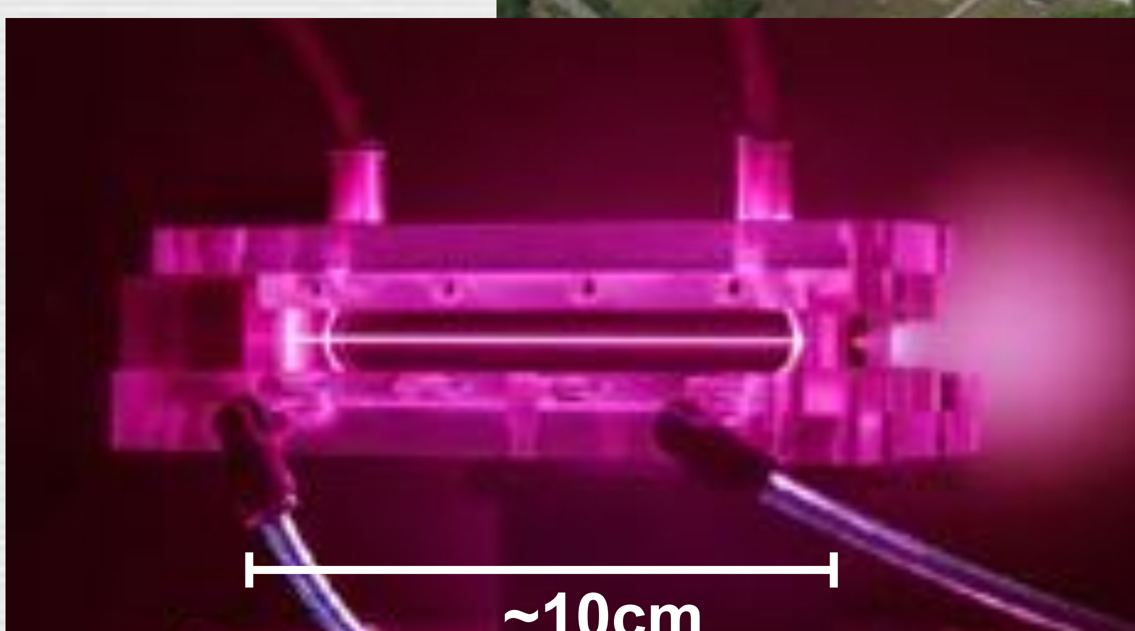
Petawatt Lase
in a I

A. J. Gonsalves,[1,*] K. Nakamura,[1]
S. S. Bulanov,[1] J. van Tilbo
L. Fan-Chiang,[1,2] G. Bagdasar
[1]*Lawrence*
[2]*U*
[3]*Keldysh*
[4]*National Research Nuclear*
[5]*Faculty of Nuclear Science*
[6]*Institute of Physics*

(Received 7 December

Guiding of relativistic
was demonstrated by in
inverse bremsstrahlung
nergetic peaks up to 7.8
7.8 GeV and up to 62 p

DOI: 10.1103/PhysRevLet



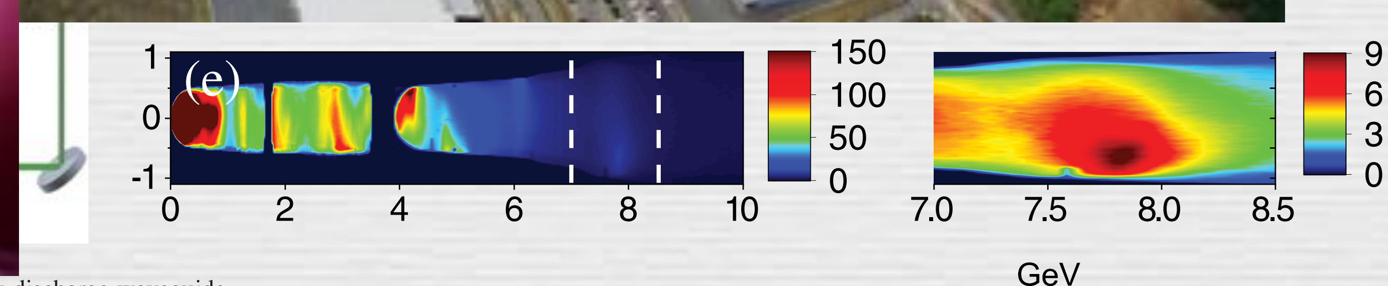
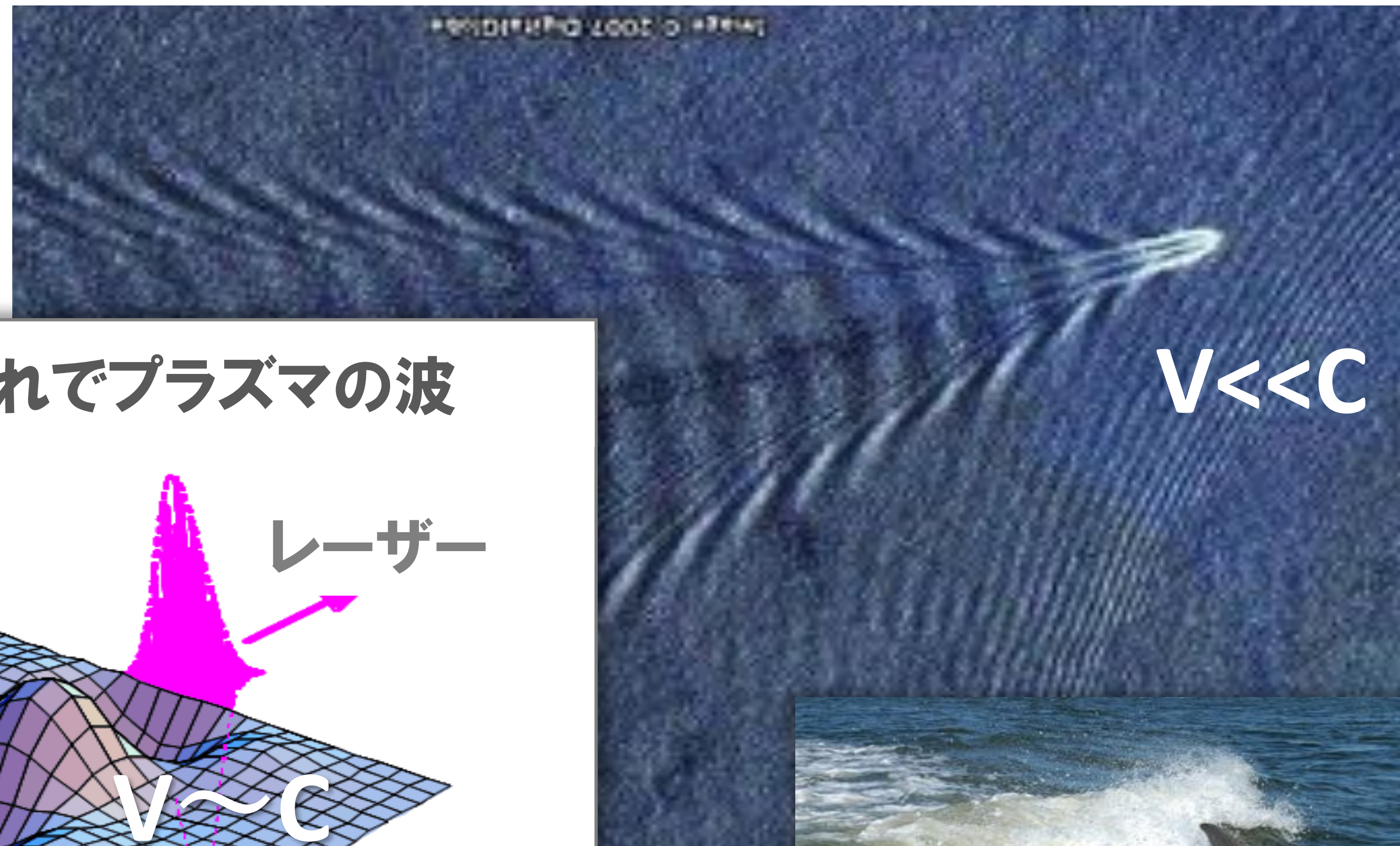


FIG. 2. Schematic layout of the BELLA LPA, including the heater laser system for enhancing the capillary discharge waveguide.

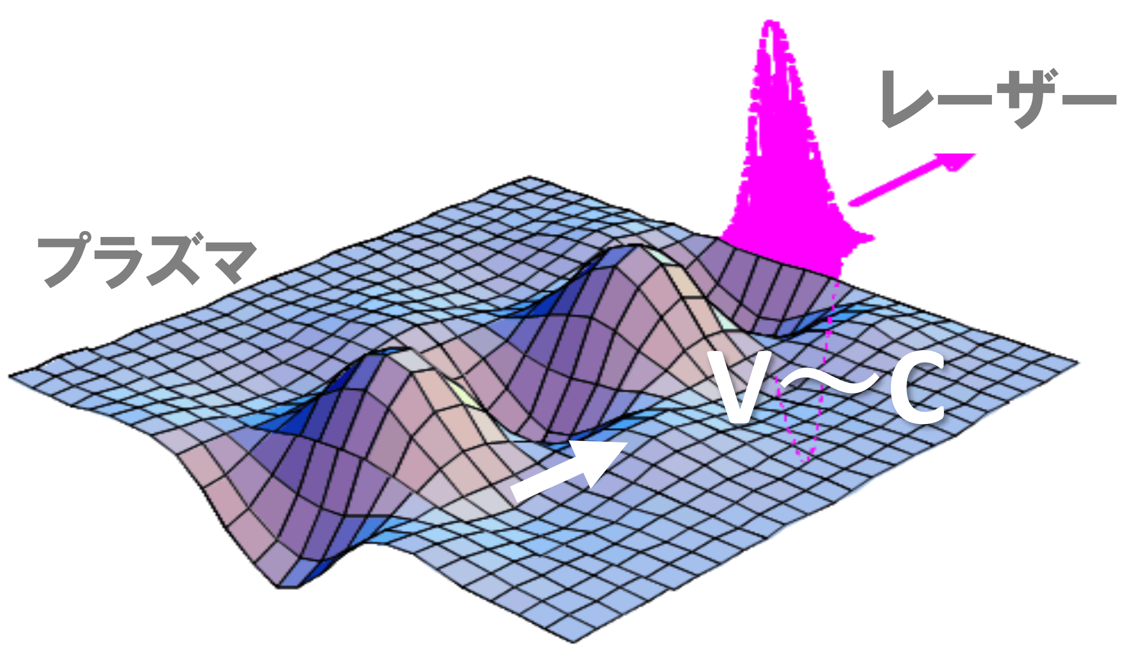
レーザー航跡場加速の原理

レーザーの力でプラズマに光速に近い速度の波をつくり粒子を加速

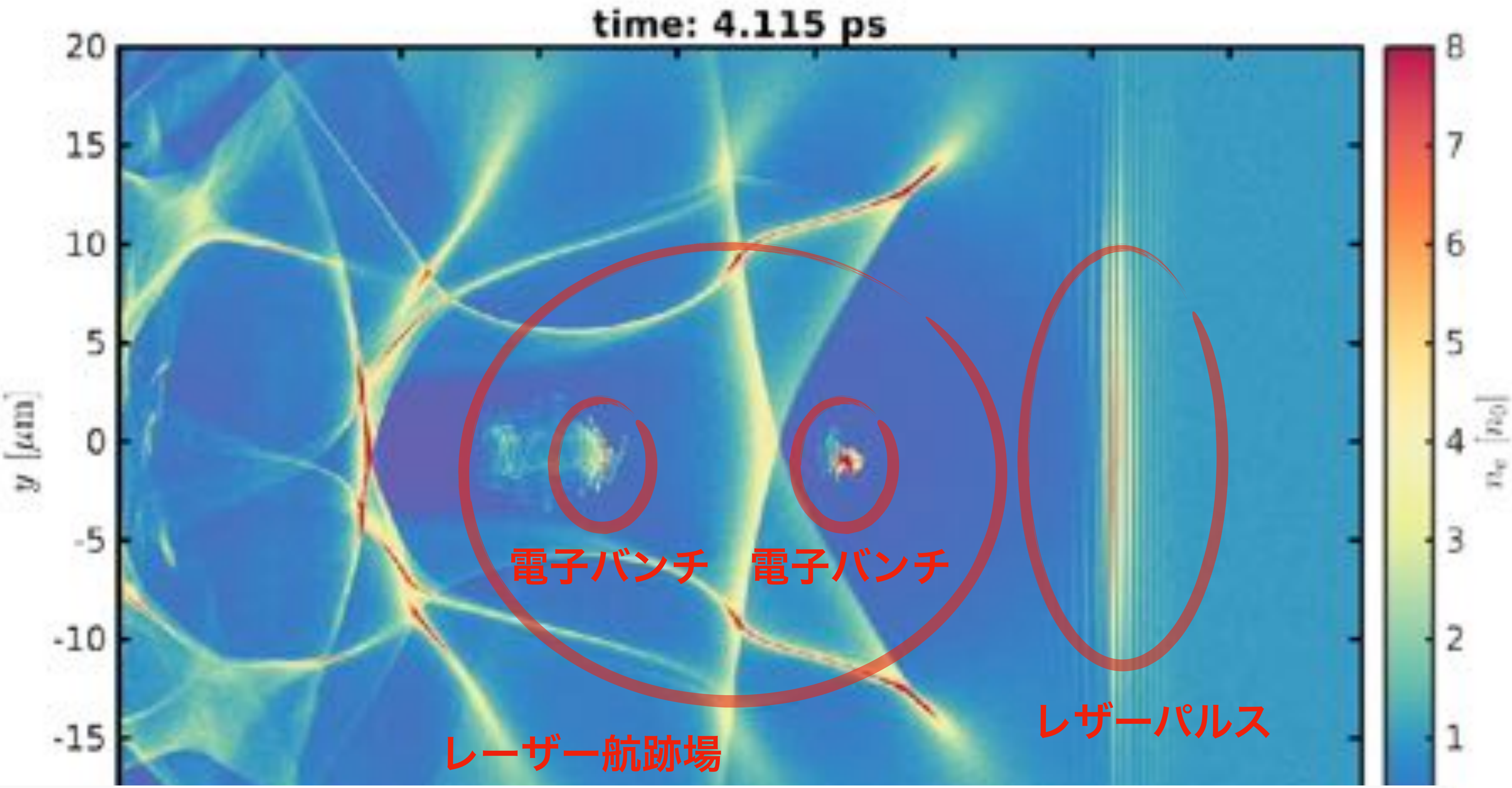
- ボートで立てられて海の波とイルカ



- レーザーで立てられでプラズマの波



レーザー航跡場電子加速のダイナミクス（シミュレーション）
Non-linear Wake-field

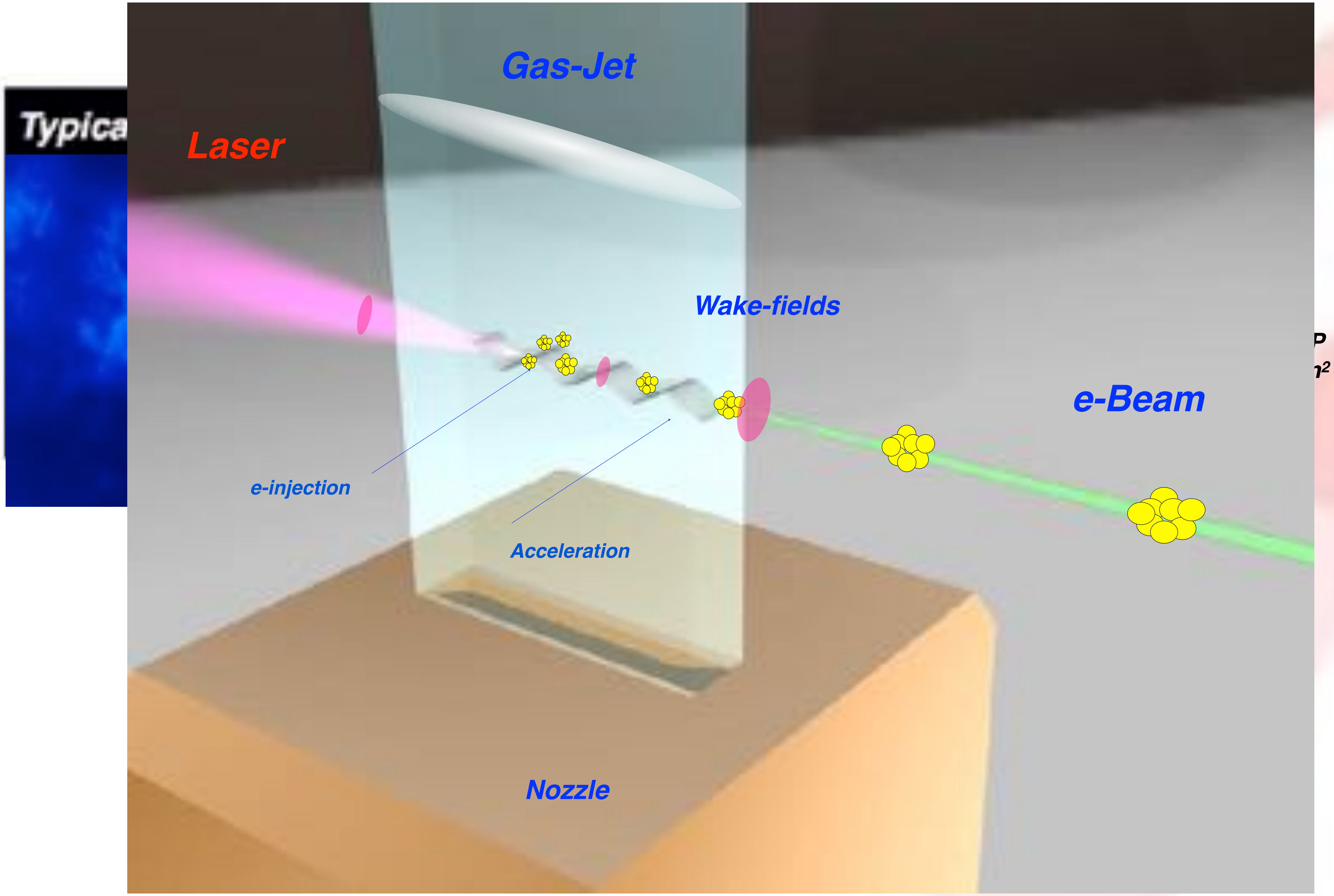


特徴

超高強度レーザーで作るプラズマで加速する

- 超高電界 > *100 GV /m*　（従来加速器の1000倍以上の加速電場）
- 極短パルス　<〜数フェムト秒

指向性の高い電子ビームの発生

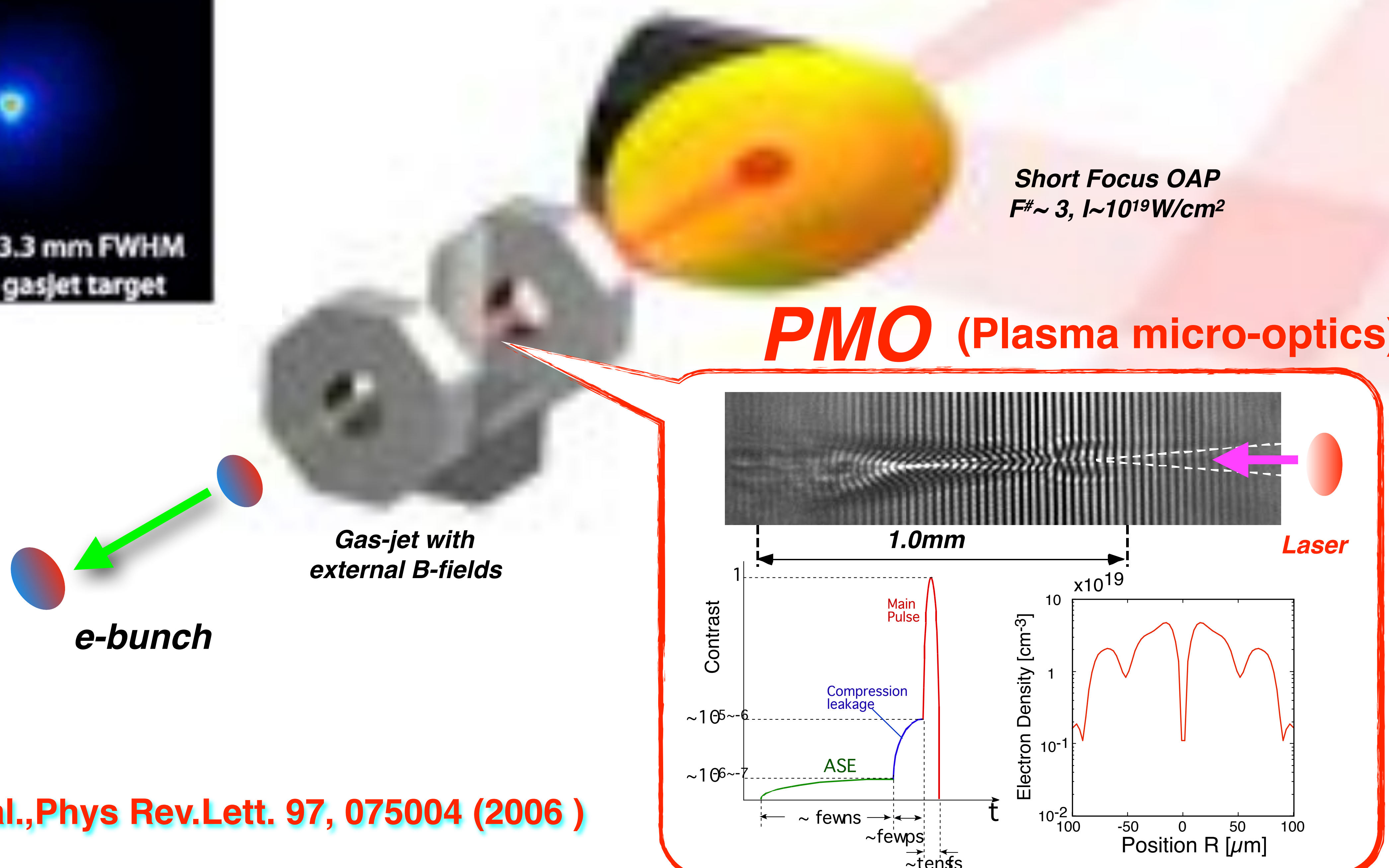


T.Hosokai,et al.,Phys Rev.Lett. 97, 075004 (2006)

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

指向性の高い電子ビームの発生

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

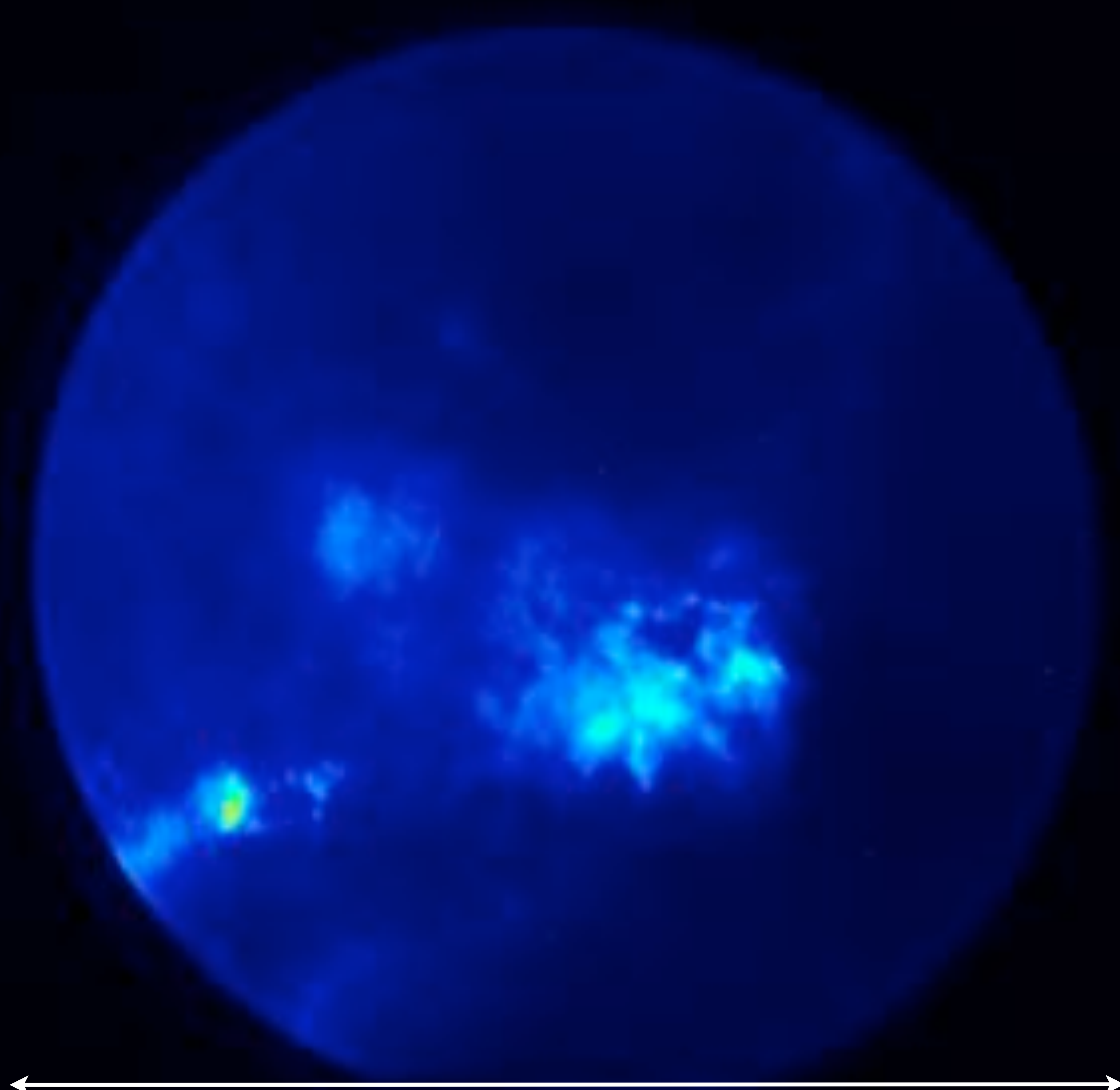


T.Hosokai,et al.,Phys Rev.Lett. 97, 075004 (2006)

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

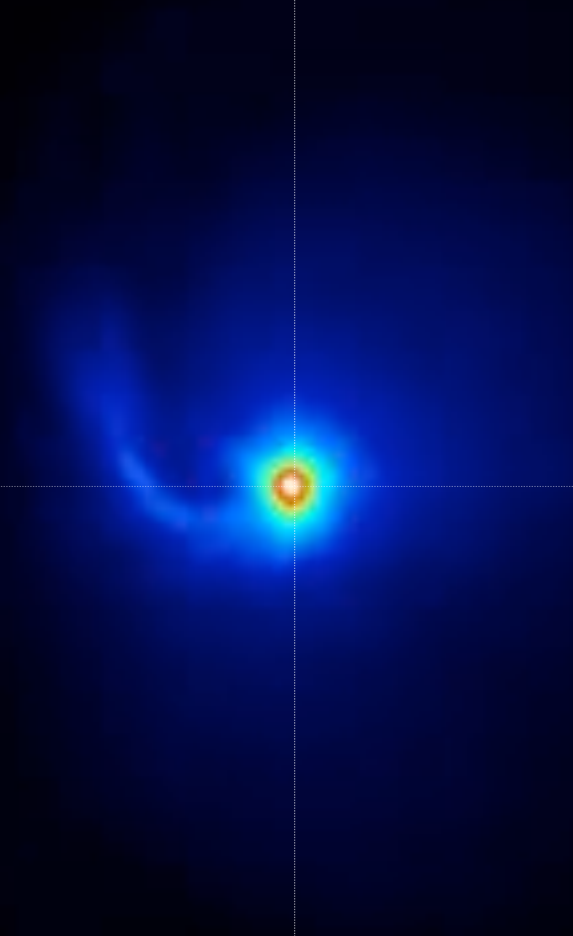
Laser pulse
Energy 600mJ
Pulse duration 25fs

Detector size: Φ13cm (746pixel)

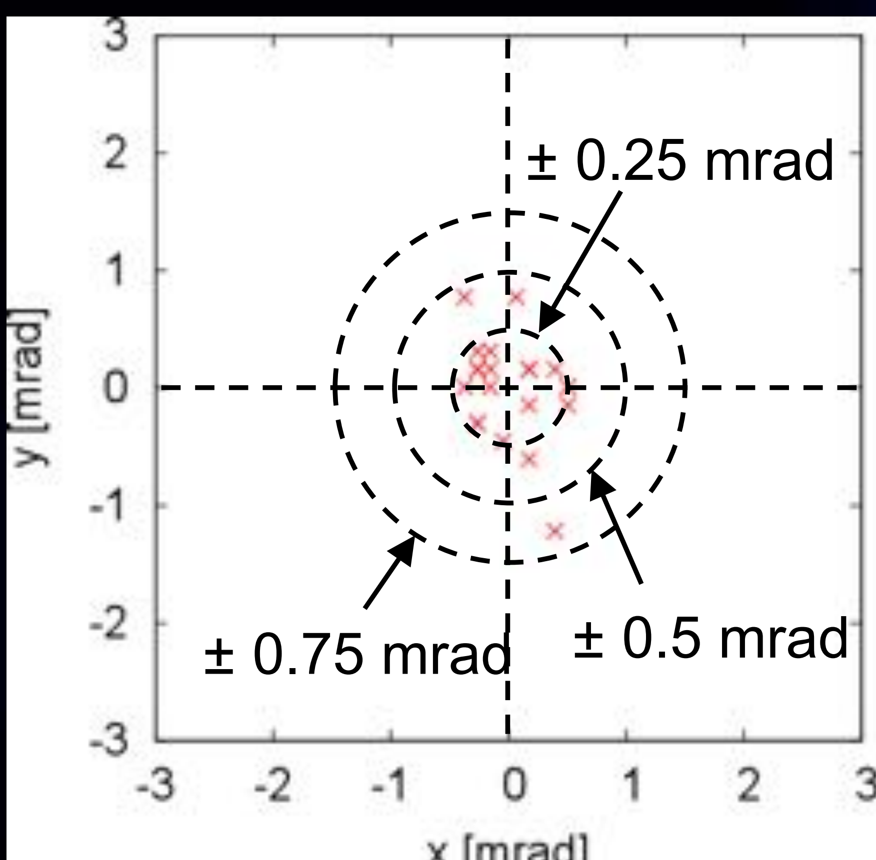
B~0.2T, Energy 600mJ

3

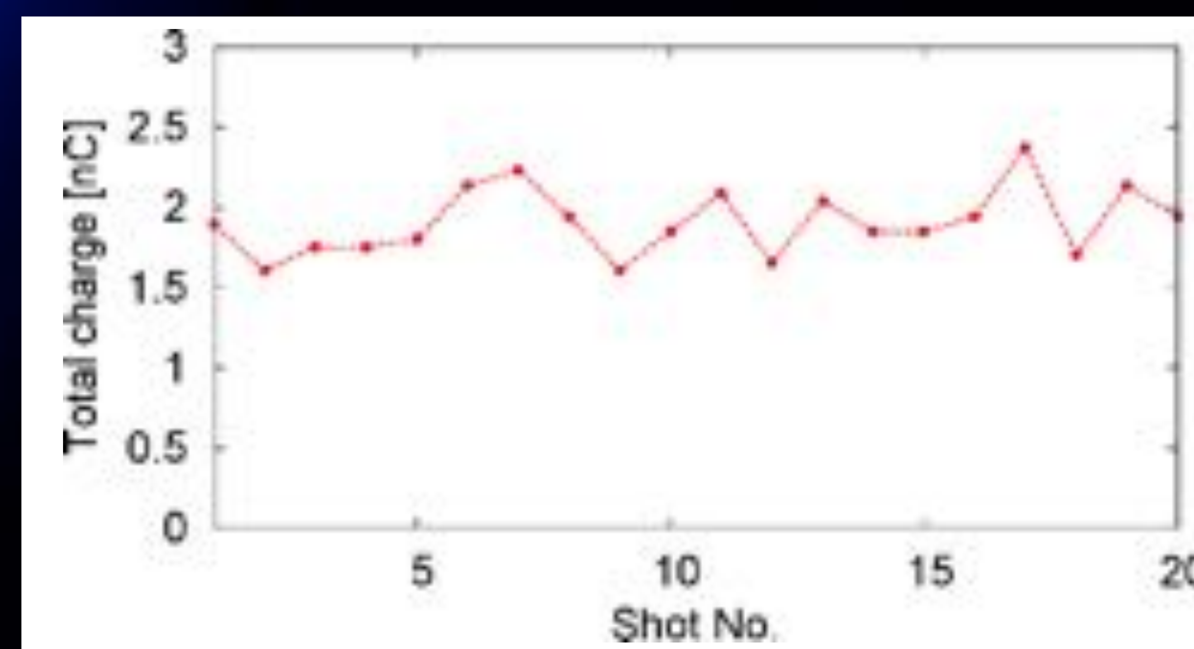
PMO provides excellent pointing stability !



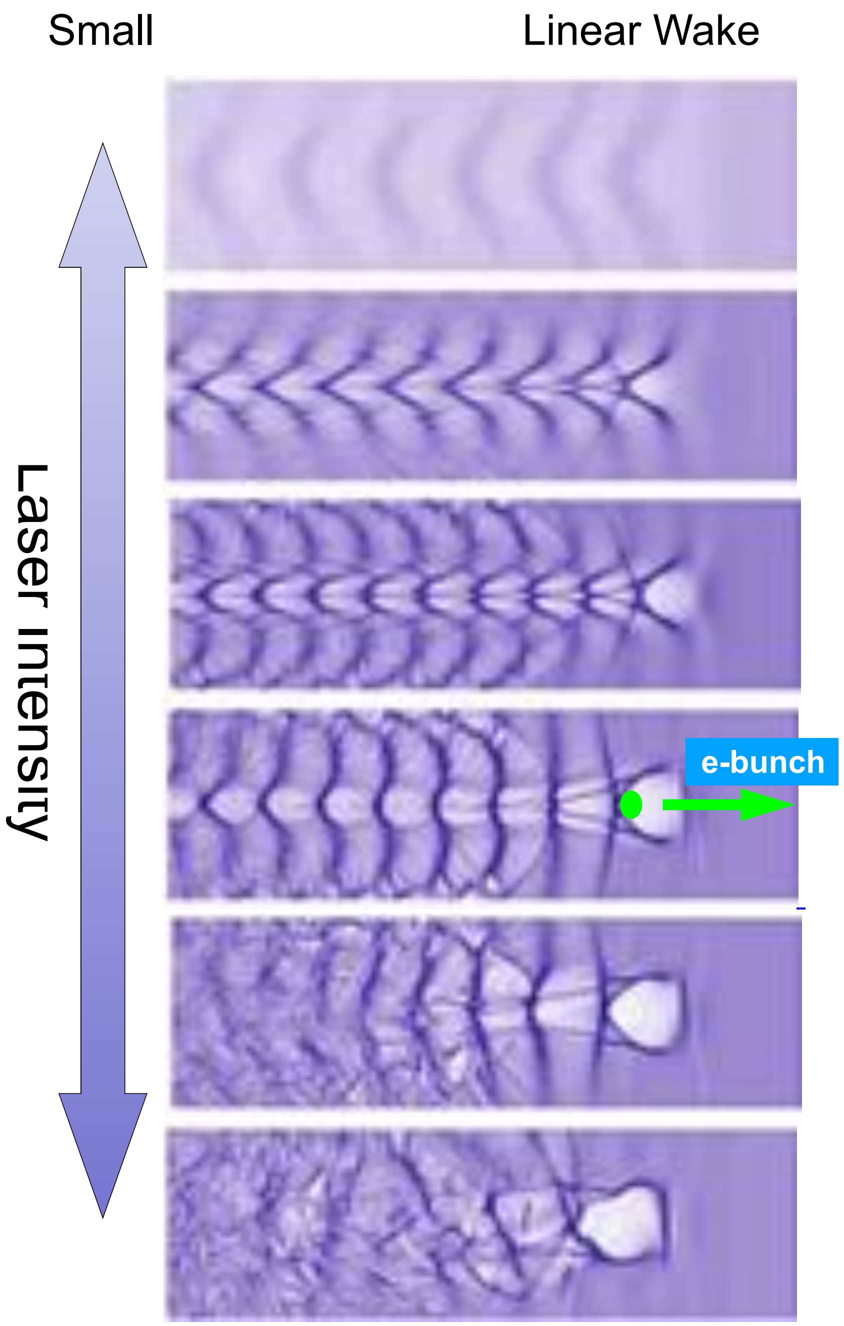
Pointing Stability
< ±300μrad

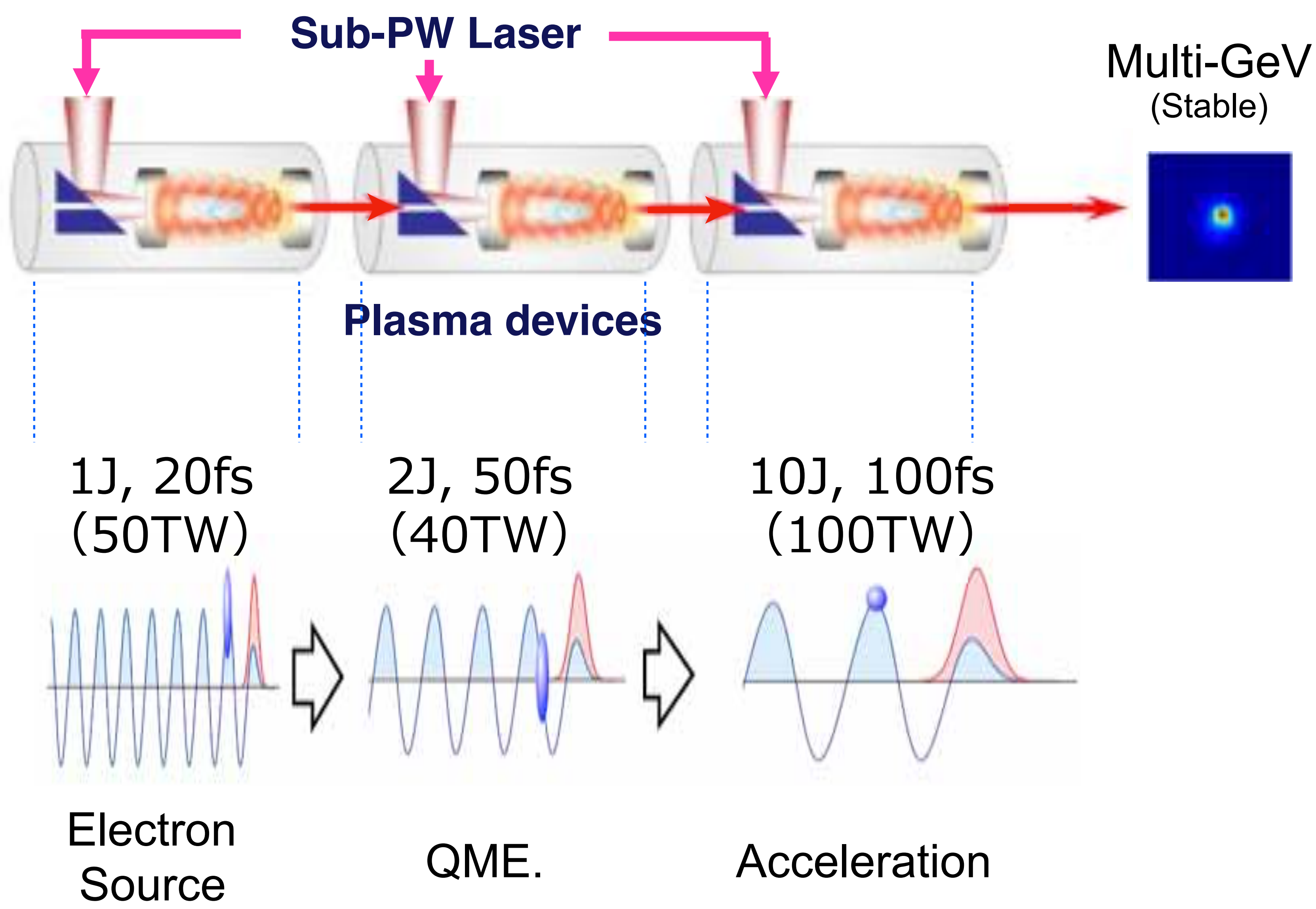


Total Carge
< 2nC ± 5%



レーザー航跡場の機能分離による性能向上
多段（ステージ）加速





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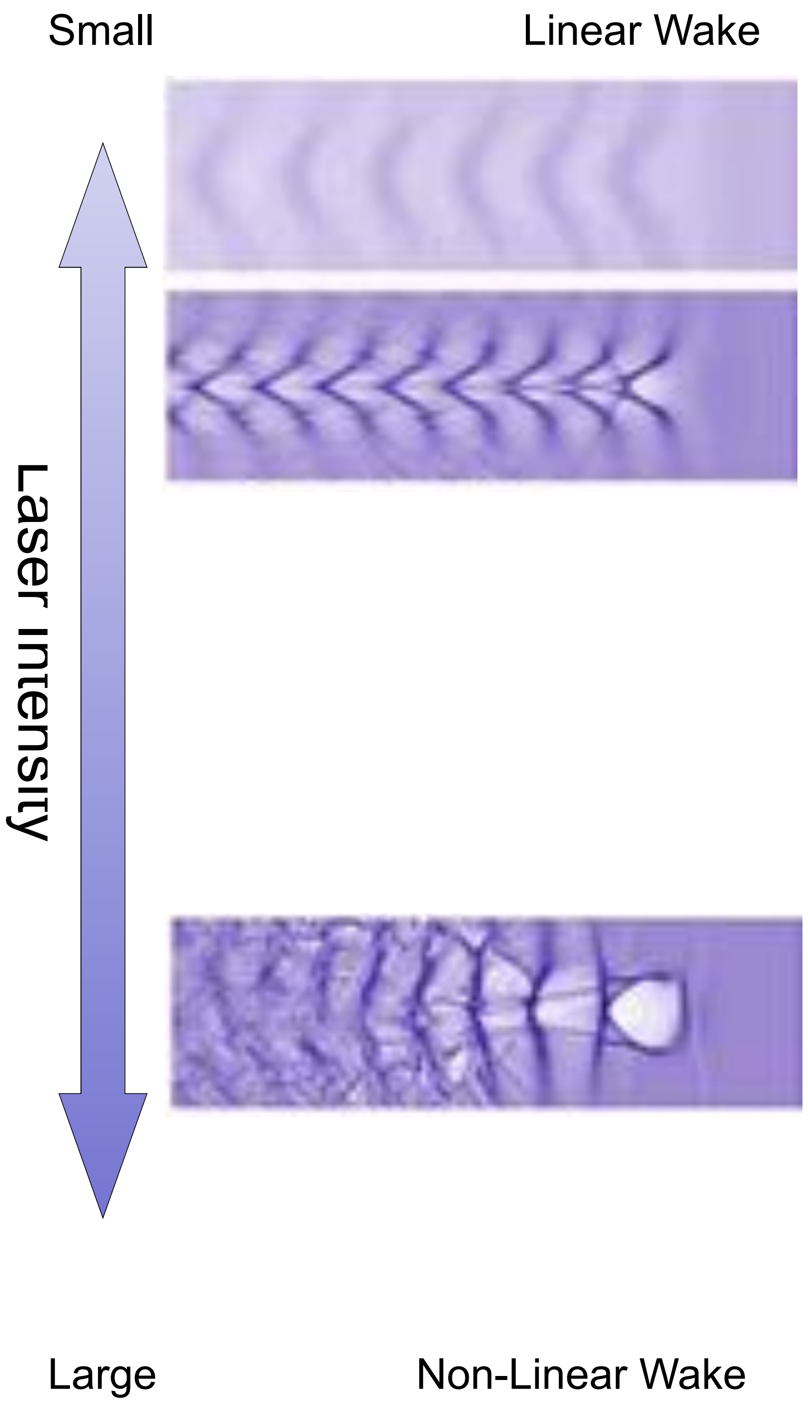
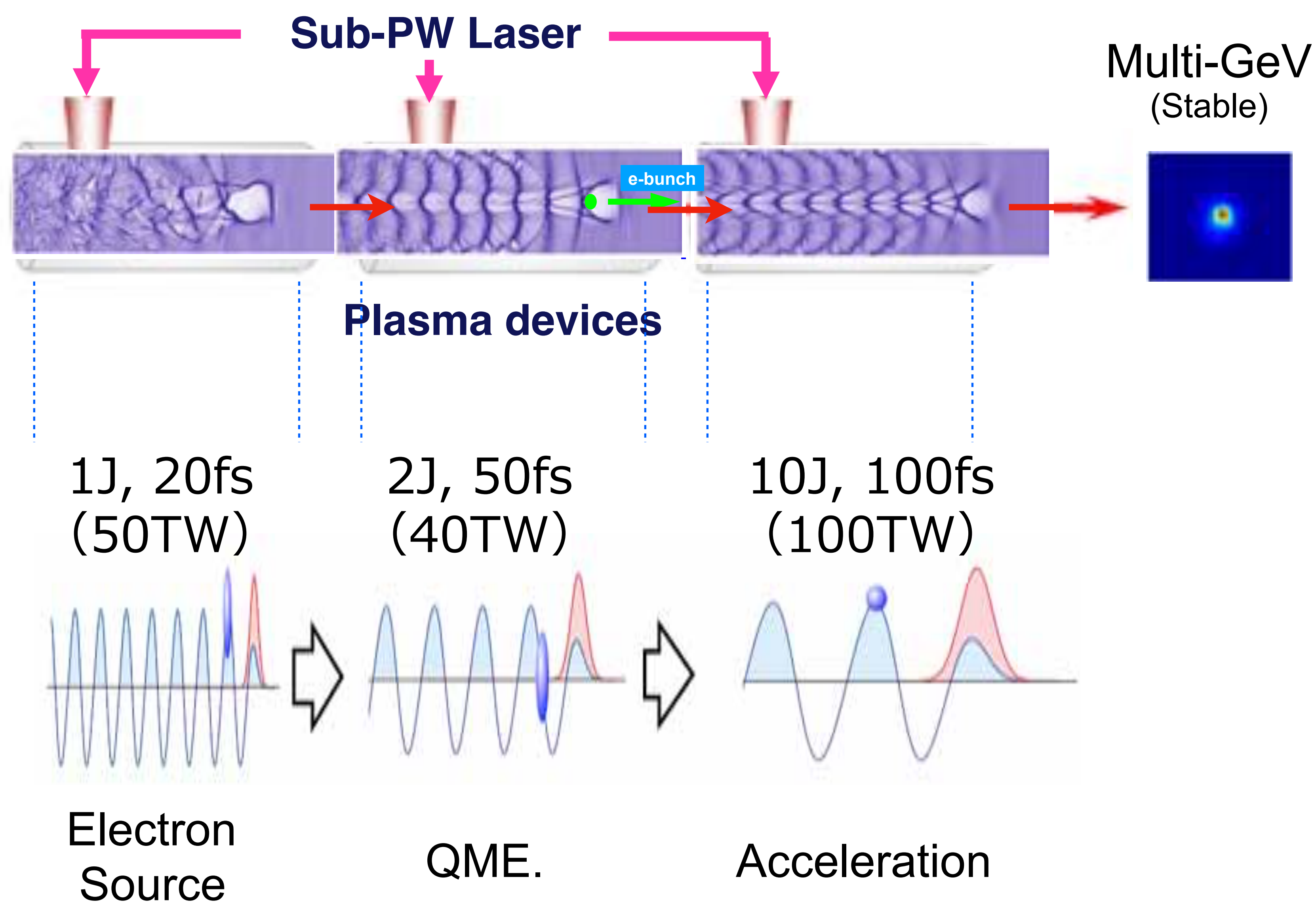
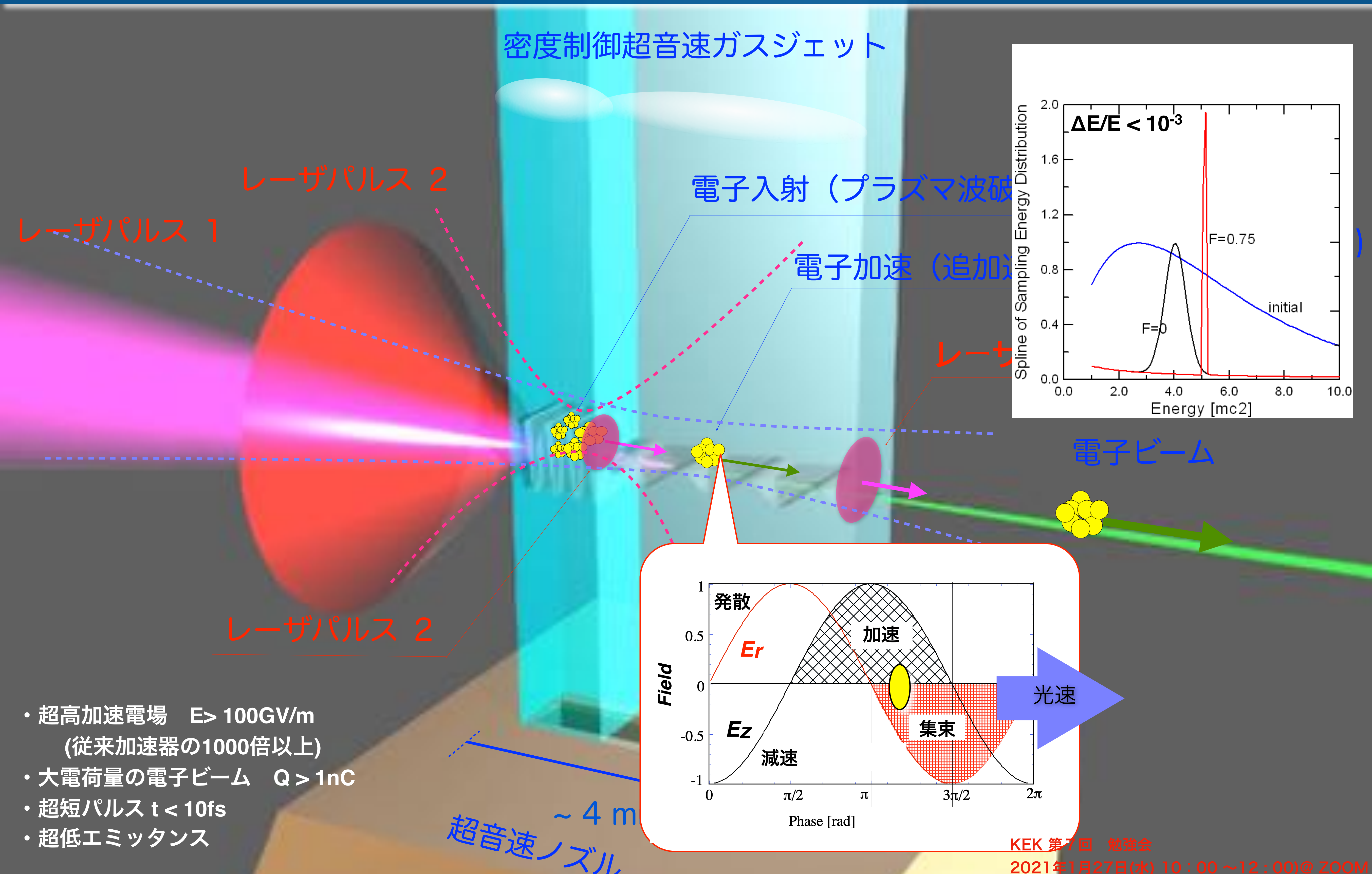




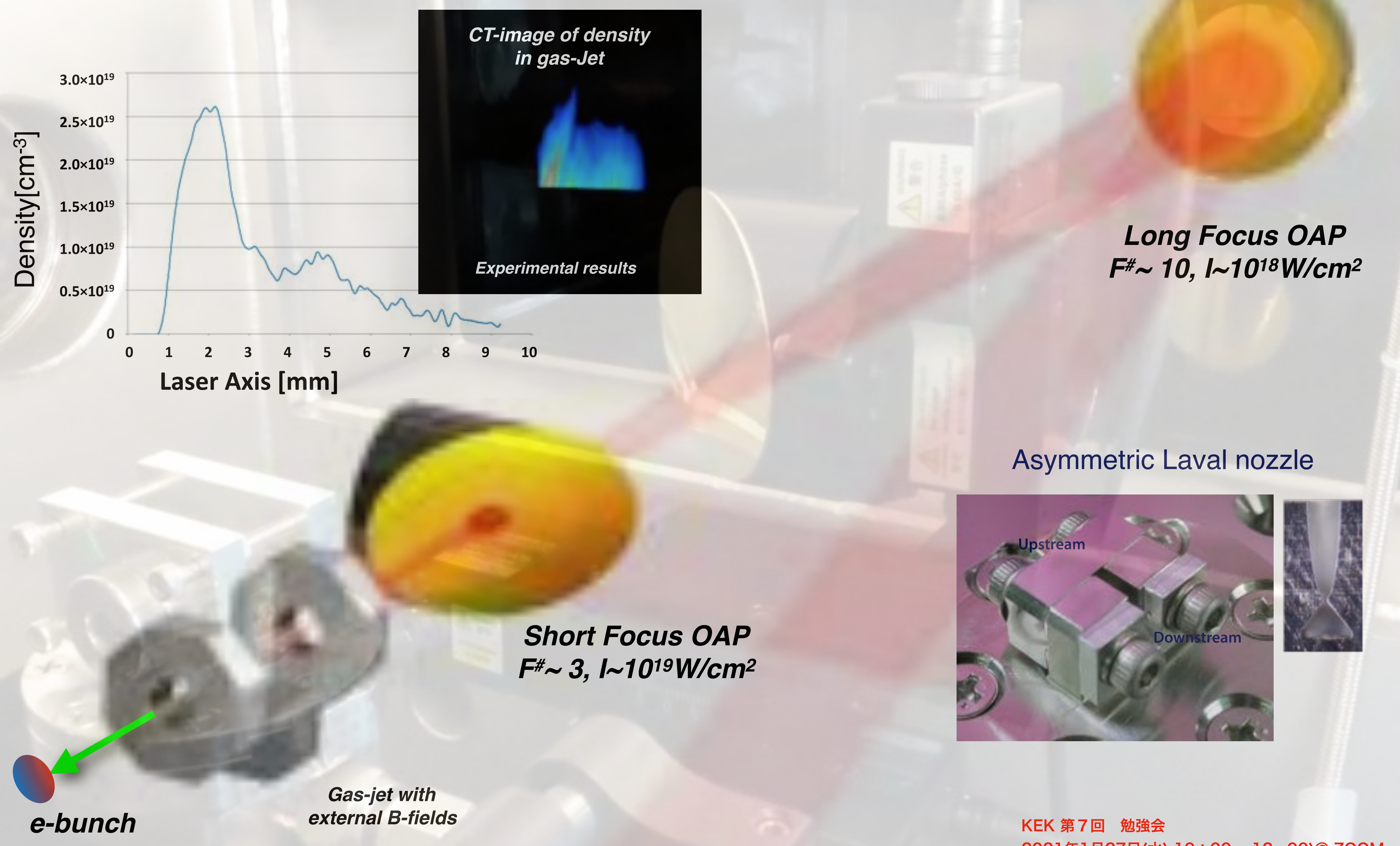
多段レーザー航跡場電子加速の原理実証



- 超高加速電場　E> 100GV/m
  (従来加速器の1000倍以上)
- 大電荷量の電子ビーム　Q > 1nC
- 超短パルス t < 10fs
- 超低エミッタンス

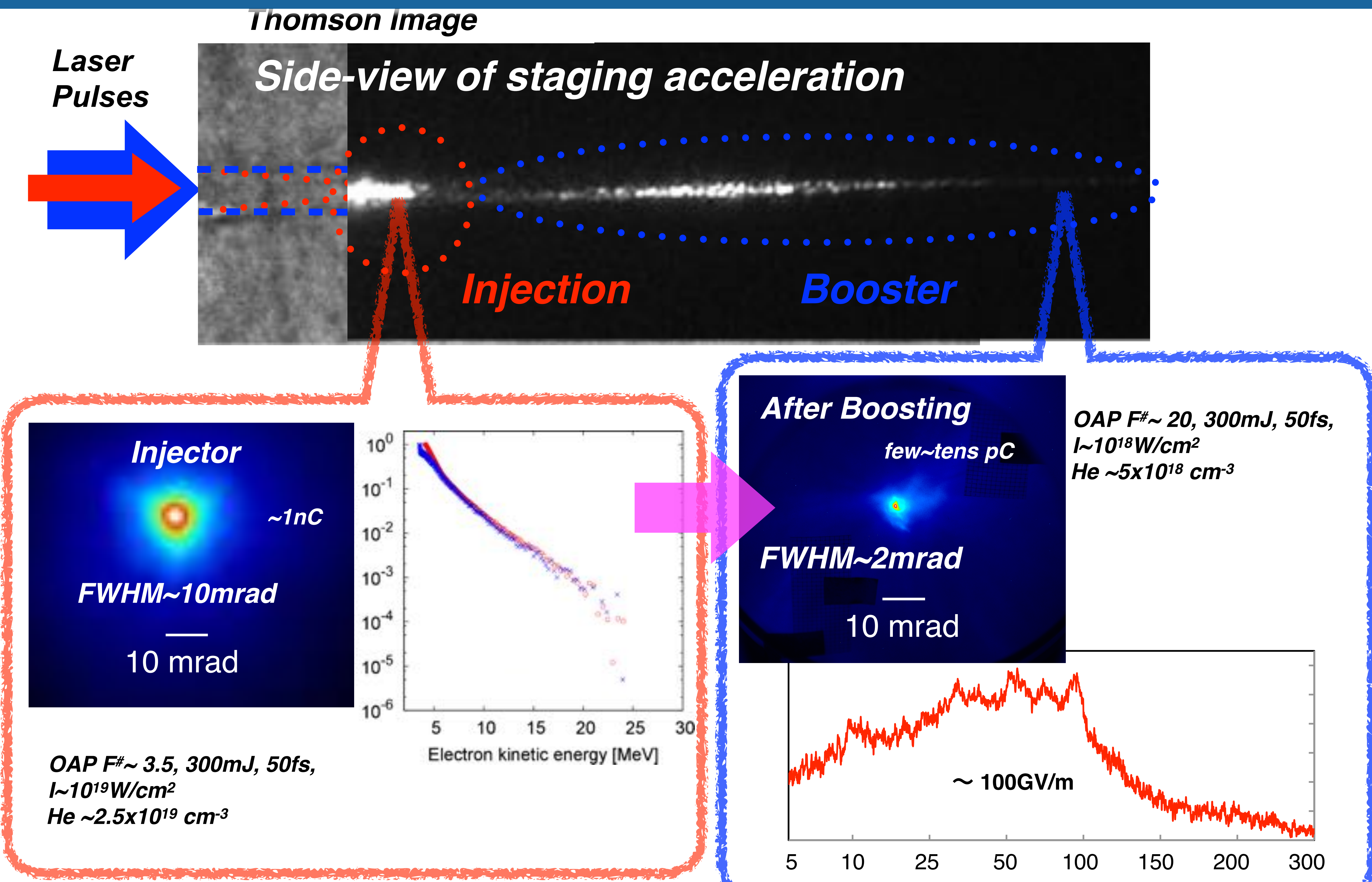
多段レーザー航跡場電子加速の原理実証実験

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



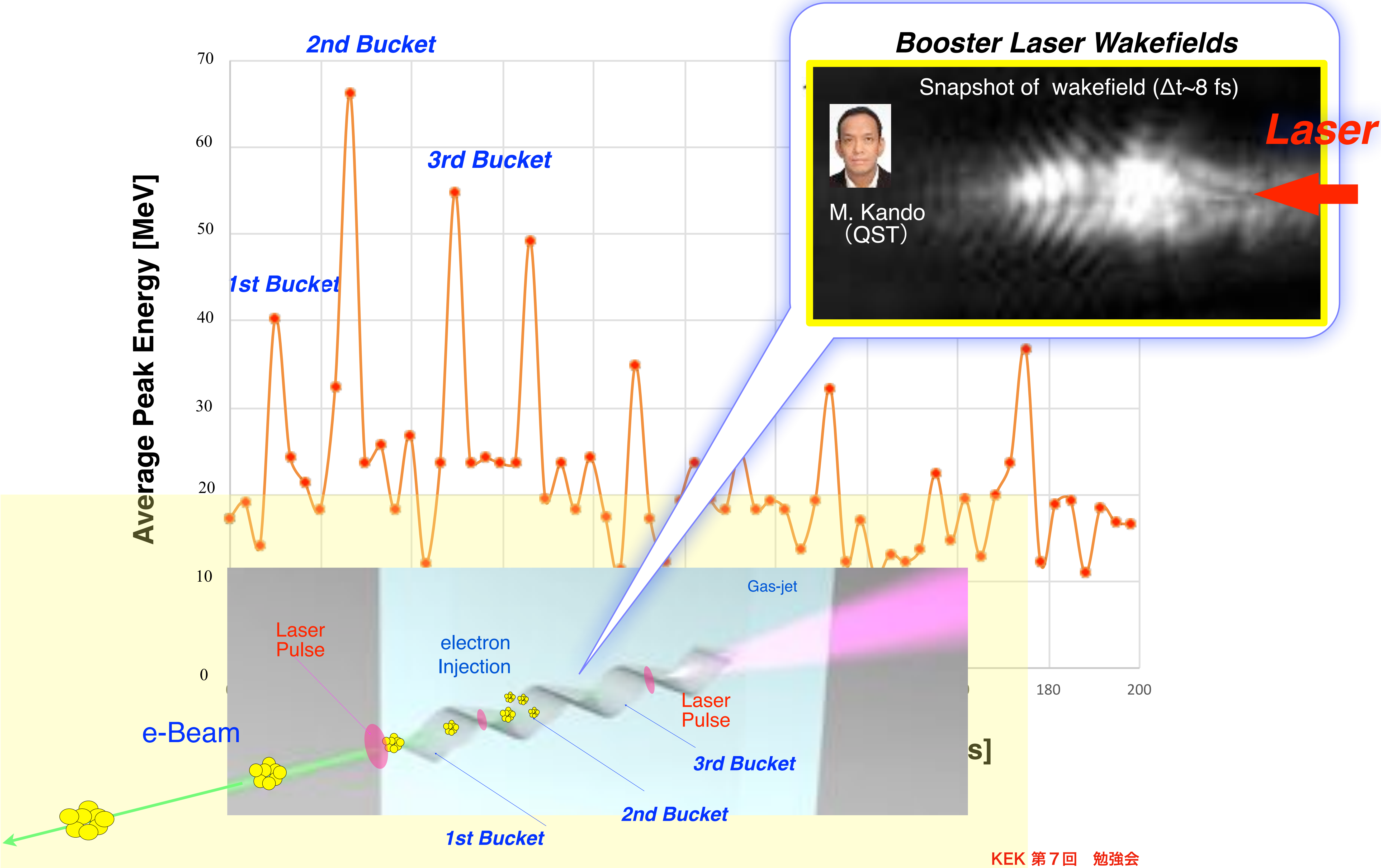
２段レーザー航跡場電子加速の原理実証

追加速航跡場へ入射した電子の加速と減速を確認



２段レーザー航跡場電子加速の原理実証

レーザー航跡場の周期構造を観測



LETTER

doi:10.1038/nature16525

Multistage coupling of independent laser–plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]

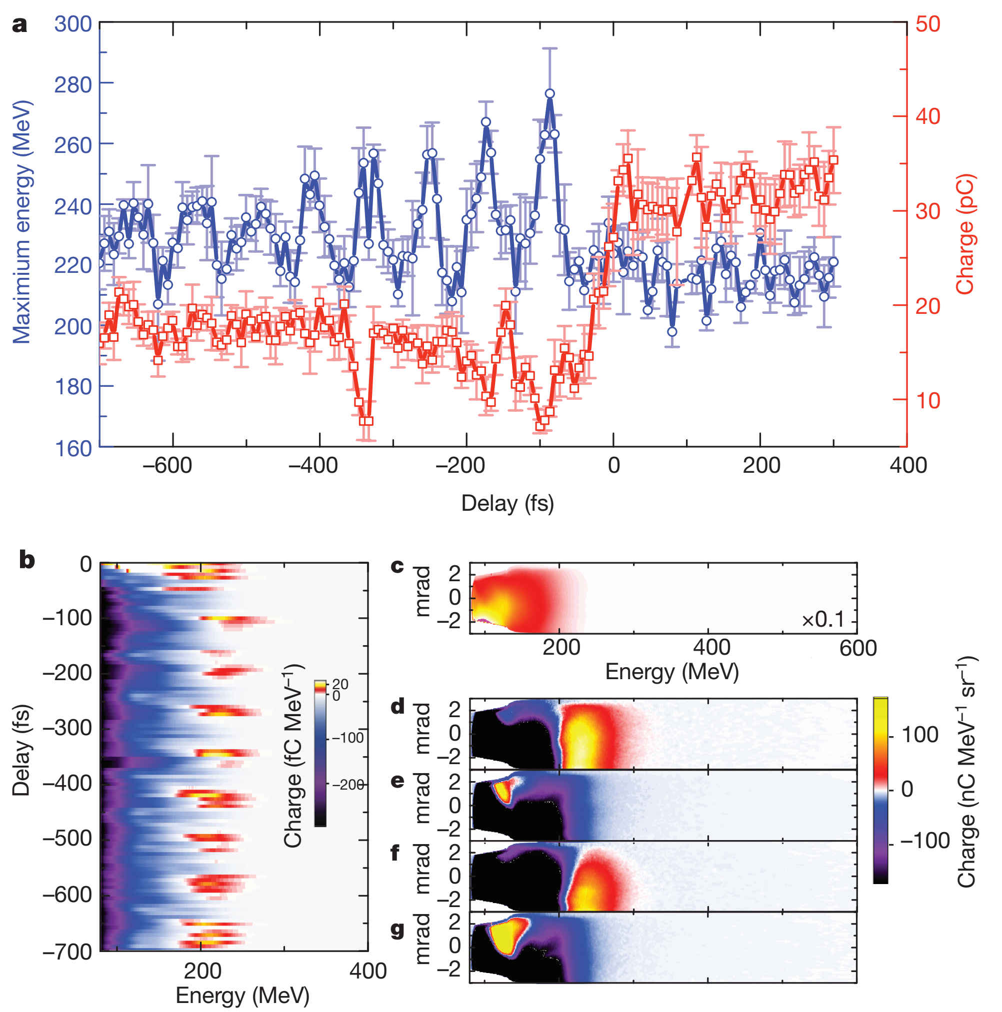
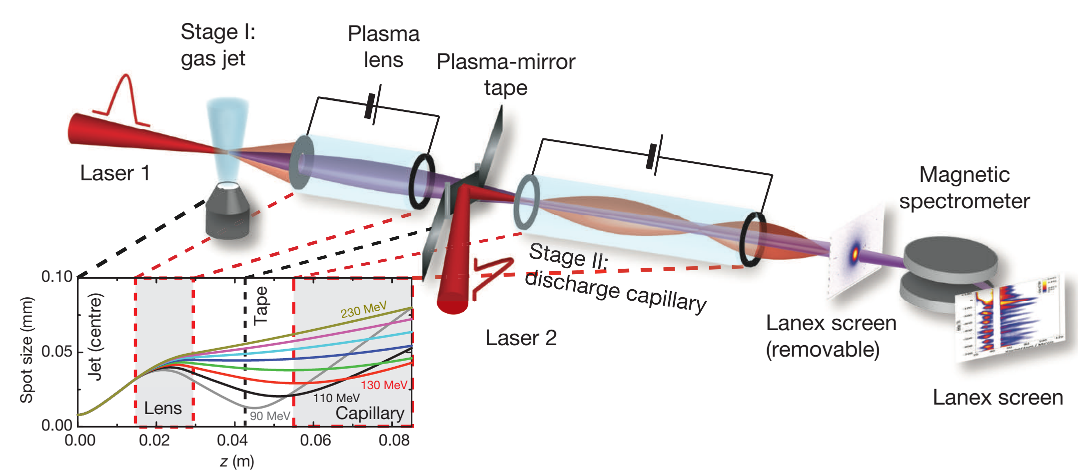


Figure 2 | Spectra of electron beams produced by staged acceleration. a, Maximum electron energy (blue) and total electron-beam charge (red) as a function of the delay between the two driving laser pulses. 'Positive delays' correspond to times before the arrival of laser 2. A single data point represents an average of five measurements; error bars represent the standard deviation. **b**, Waterfall plot of electron spectra (five-shot average), each with the reference from panel **c** subtracted, as a function of delay. **c**, 100-shot average unperturbed reference for delays of 100–300 fs before the arrival of the second laser pulse. **c**–**g**, Two-dimensional charge maps (five-shot average), with reference (**c**) subtracted for the first two maxima and minima of the energy oscillation shown in **a**—that is, for delays of −107 fs (**d**), −153 fs (**e**), −193 fs (**f**) and −240 fs (**g**). The *y*-axis in **c**–**g** shows the transverse angle in milliradians; '0' corresponds to the laser axis.



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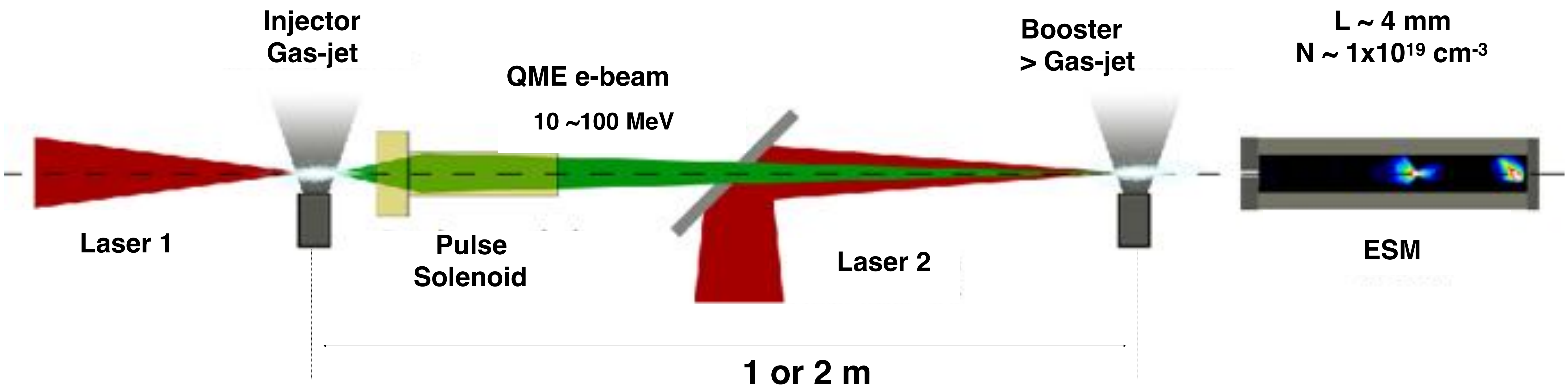
電子輸送を伴う多段レーザー航跡場加速

Injector beam（ E ~10MeV or 100MeV ）is delivered to wakefield at 1-2 m downstream.



e-Beam spot in vacuum
D~300μm (1/e^2)

Laser 2 spot in vacuum
D~30 μm (1/e^2)

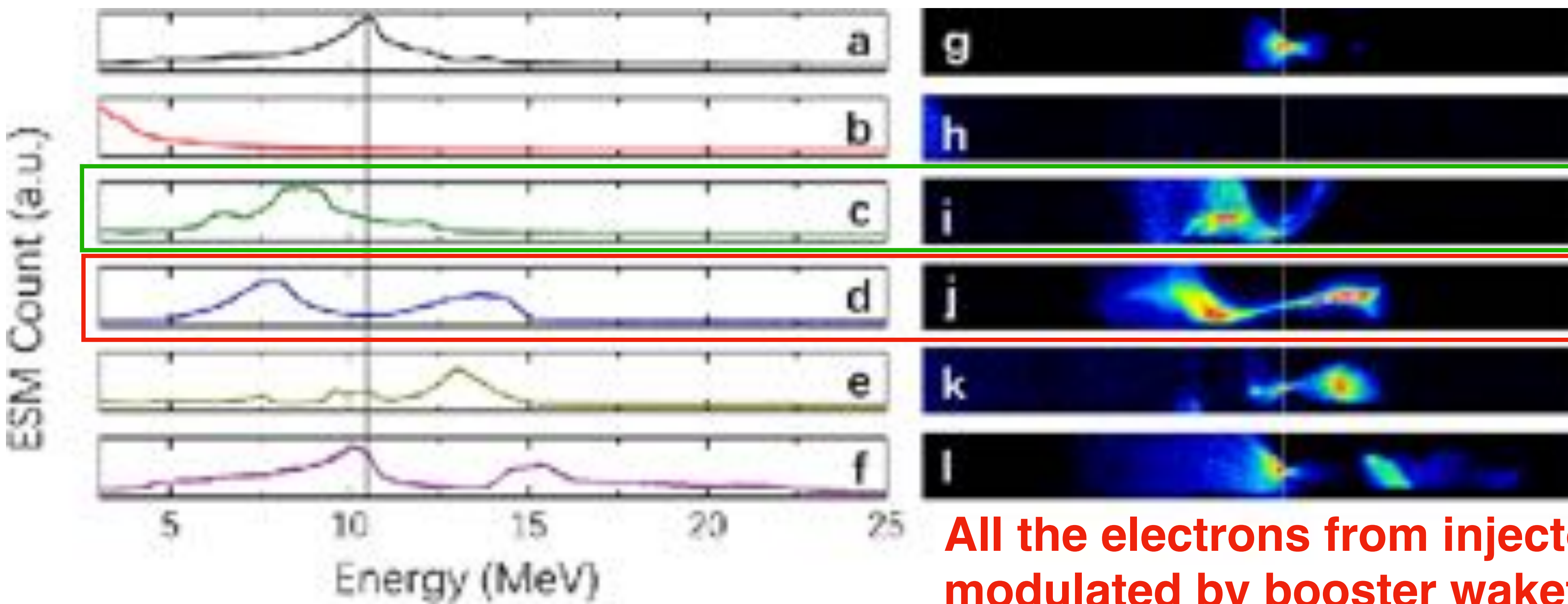
Laser 1(for Injector): f/3, f/10, 0.6-1.0 J, 30 fs
Laser 2(for booster): f/20, 0.3-2.0 J, 30-50 fs

Injection e-beam
~10 MeV or ~75MeV

電子輸送を伴うレーザー航跡場段階加速 *(~10MeV, 1m-transport)*

Injector beam become longer during the traveling to 2nd wakefield.

Energy spectra of e-beams modulated by booster wakefield (gas-jet 2)



Injector beam

1~2pC

After Boosting

1~2pC

All the electrons from injector are modulated by booster wakefields.

SCIENTIFIC REPORTS

natureresearch

OPEN

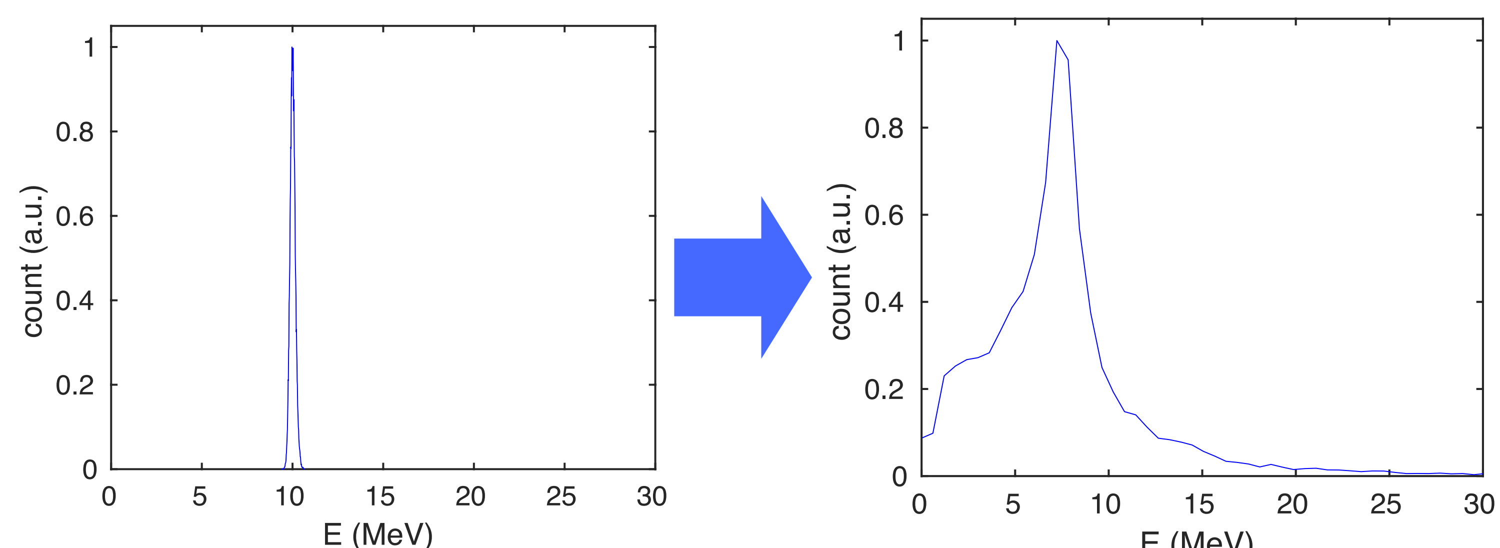
Coupling Effects in Multistage Laser Wake-field Acceleration of Electrons

Zhan Jin[1,2], Hirotaka Nakamura[3], Naveen Pathak[1,2], Yasuo Sakai[1,2], Alexei Zhidkov[1,2], Keiichi Sueda[2], Ryosuke Kodama[3] & Tomonao Hosokai[1,2*]

Staging laser wake-field acceleration is considered to be a necessary technique for developing full-optical jitter-free high energy electron accelerators. Splitting of the acceleration length into several technical parts and with independent laser drivers allows not only the generation of stable, reproducible acceleration fields but also overcoming the dephasing length while maintaining an overall high acceleration gradient and a compact footprint. Temporal and spatial coupling of pre-accelerated electron bunches for their injection in the acceleration phase of a successive laser pulse wake field is the key part of the staging laser-driven acceleration. Here, characterization of the coupling is performed with a dense, stable, narrow energy band of <3% and energy-selectable electron beams with a charge of ~1.6 pC and energy of ~10 MeV generated from a laser plasma cathode. Cumulative focusing of electron bunches in a low-density preplasma, exhibiting the Budker–Bennett effect, is shown to result in the efficient injection of electrons, even with a long distance between the injector and the booster in the laser pulse wake. The measured characteristics of electron beams modified by the booster wake field agree well with those obtained by multidimensional particle-in-cell simulations.

Typical energy spectra after boosting (2D-PIC)

Initial E~10MeV, 1m travel



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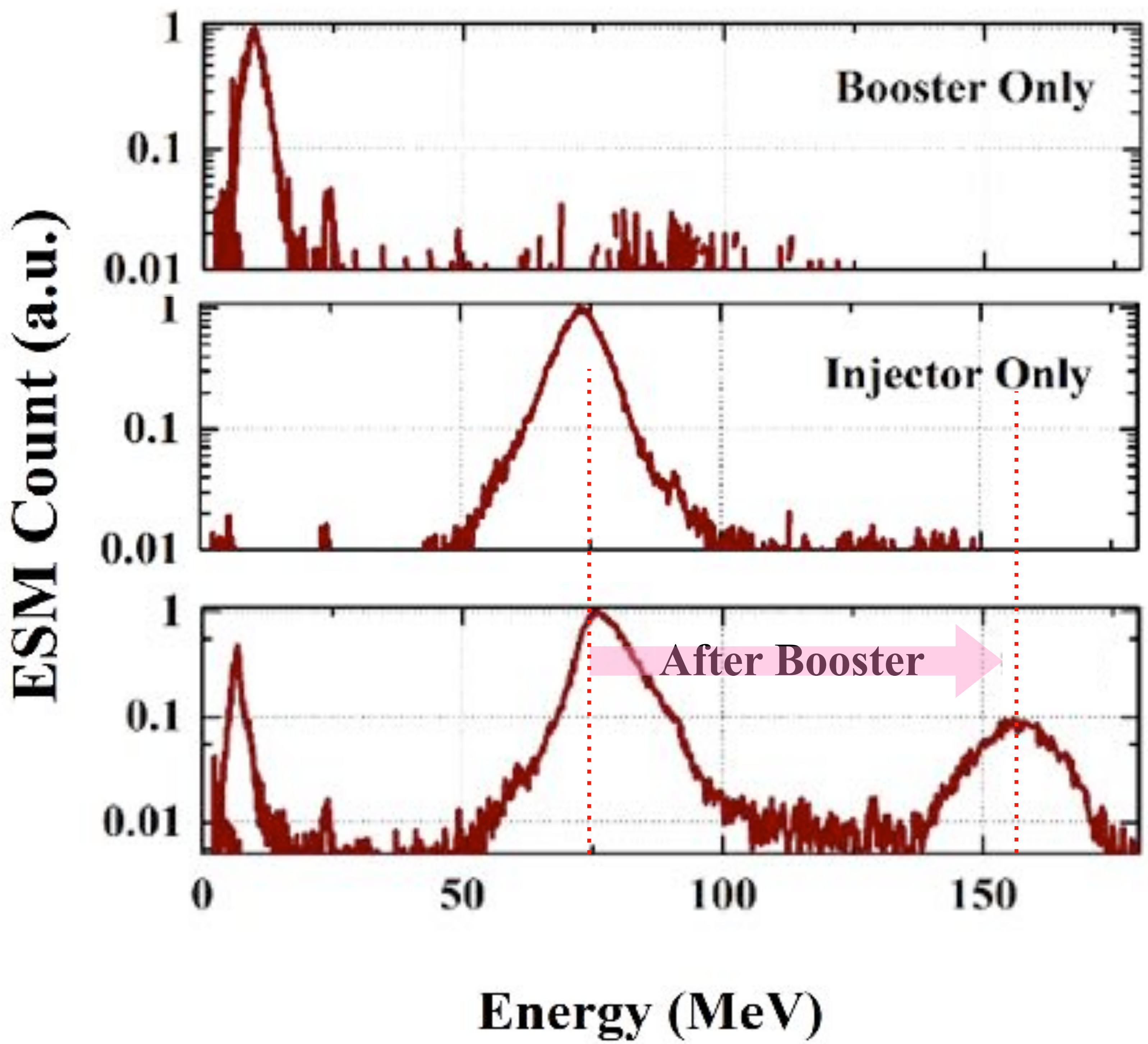
電子輸送を伴うレーザー航跡場段階加速 *(~75MeV, 2 m-transport)*

Injector beam become longer during the traveling to 2nd wakefield.



Distance between
Injector and Booster：2 m

Injector：

- Mixture gas (He~99% N2~1%),
- 4mm Step nozzle,
- Plasma density: 2 x 10^{18} /cm^3

Boosrter：

- He,
- 4mm Flat nozzle (Uniform)
- Plasma 1 x 10^{18} /cm^3

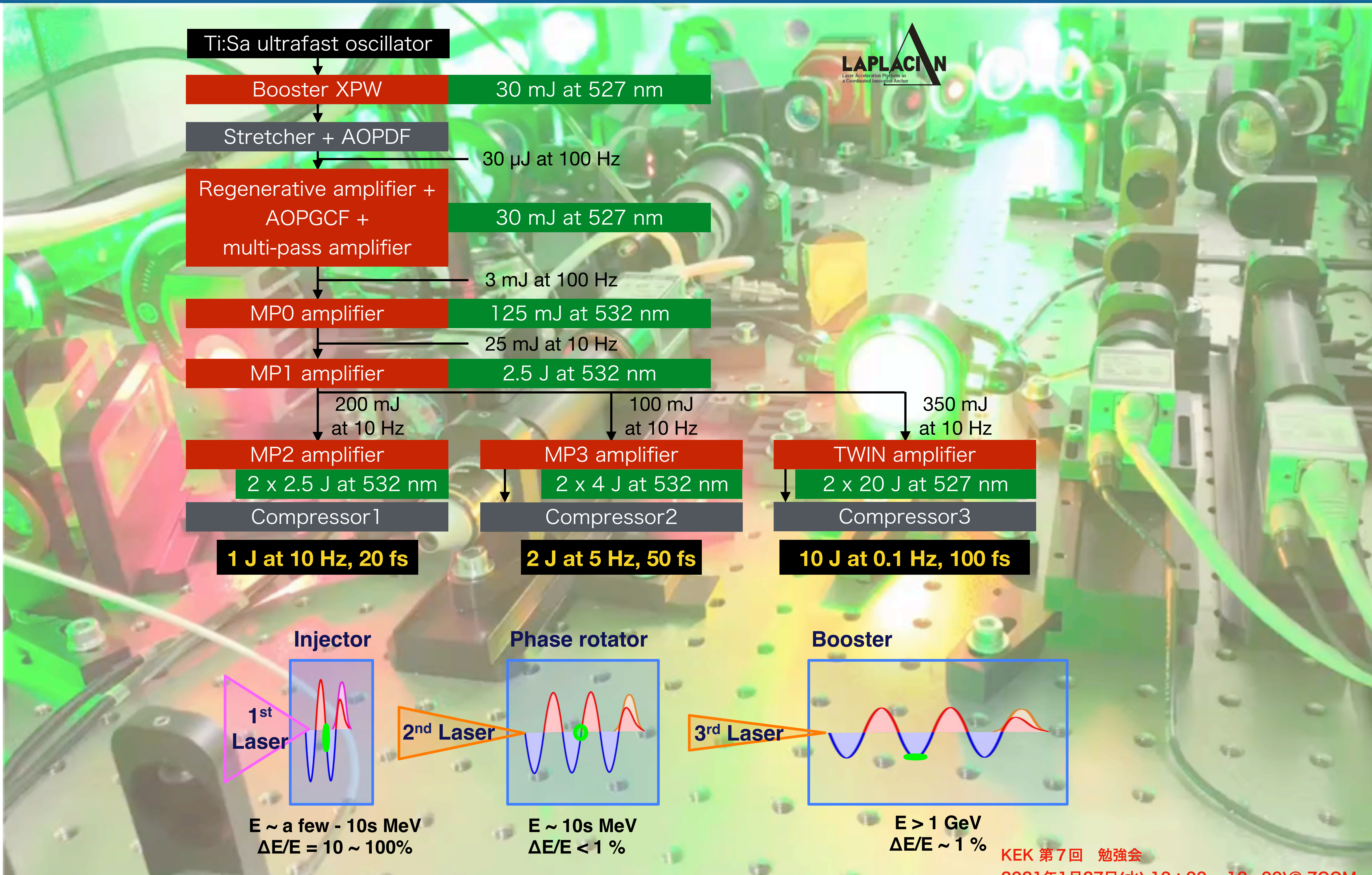
Energy Gain

～190 MeV/ cm

Charge ~ 2 pC/ shot

LWFA Platform @SPring-8

Synchronized 3 laser beams (1J-25fs, 2J-50fs, 10J-100fs)



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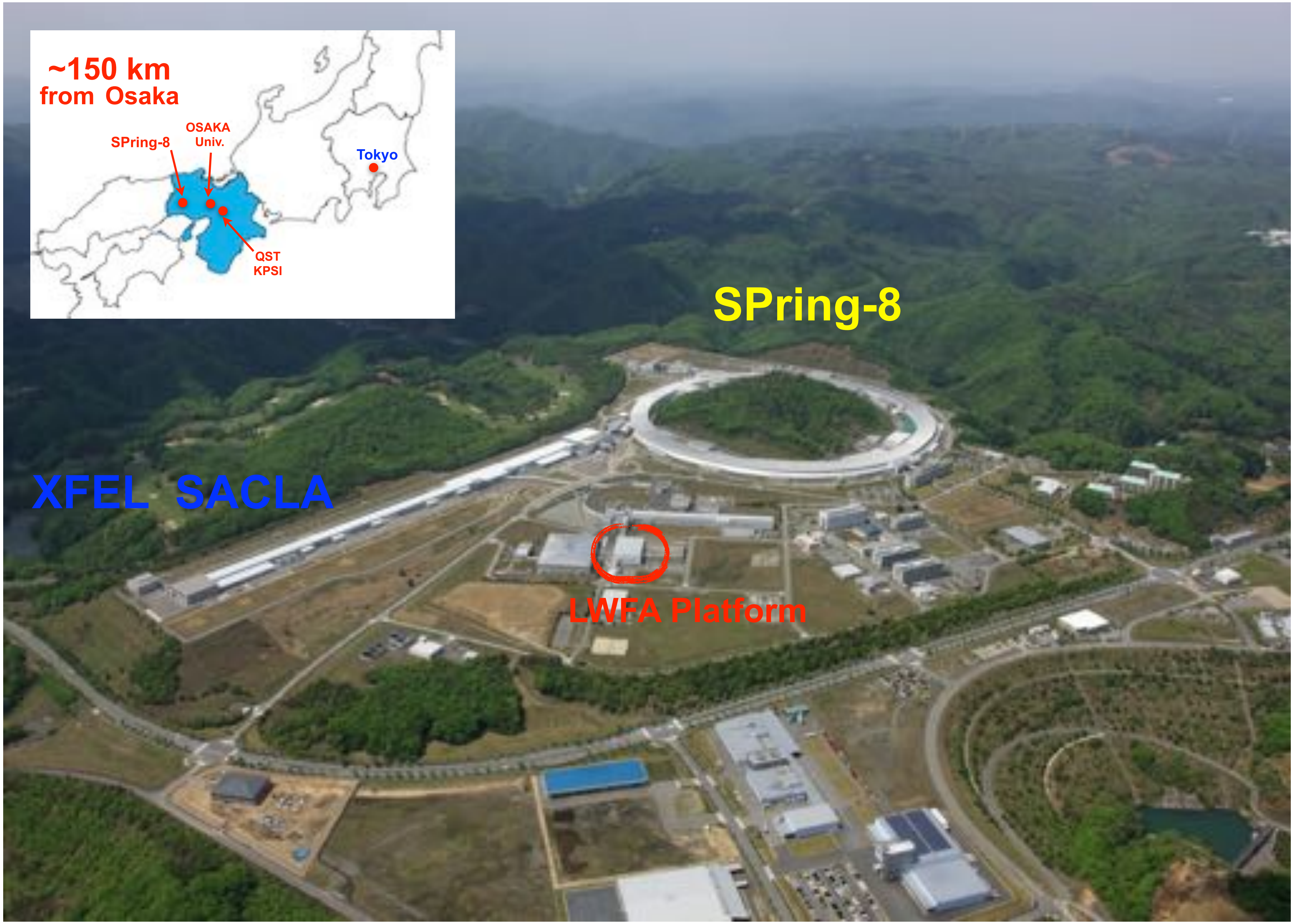
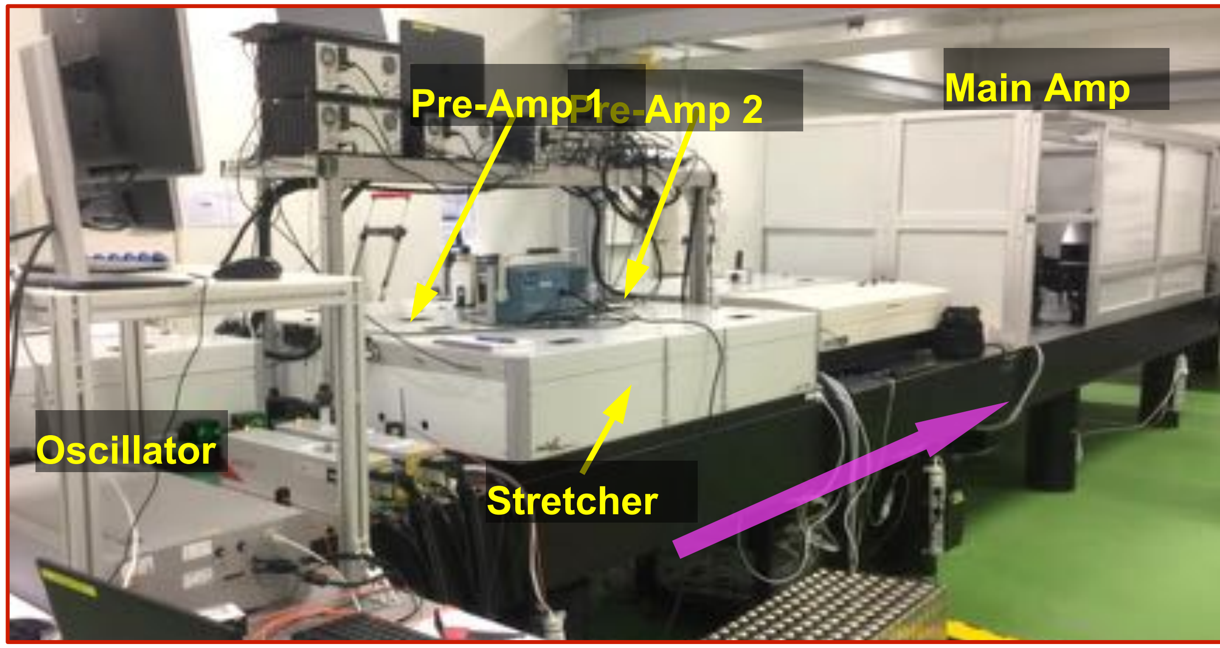
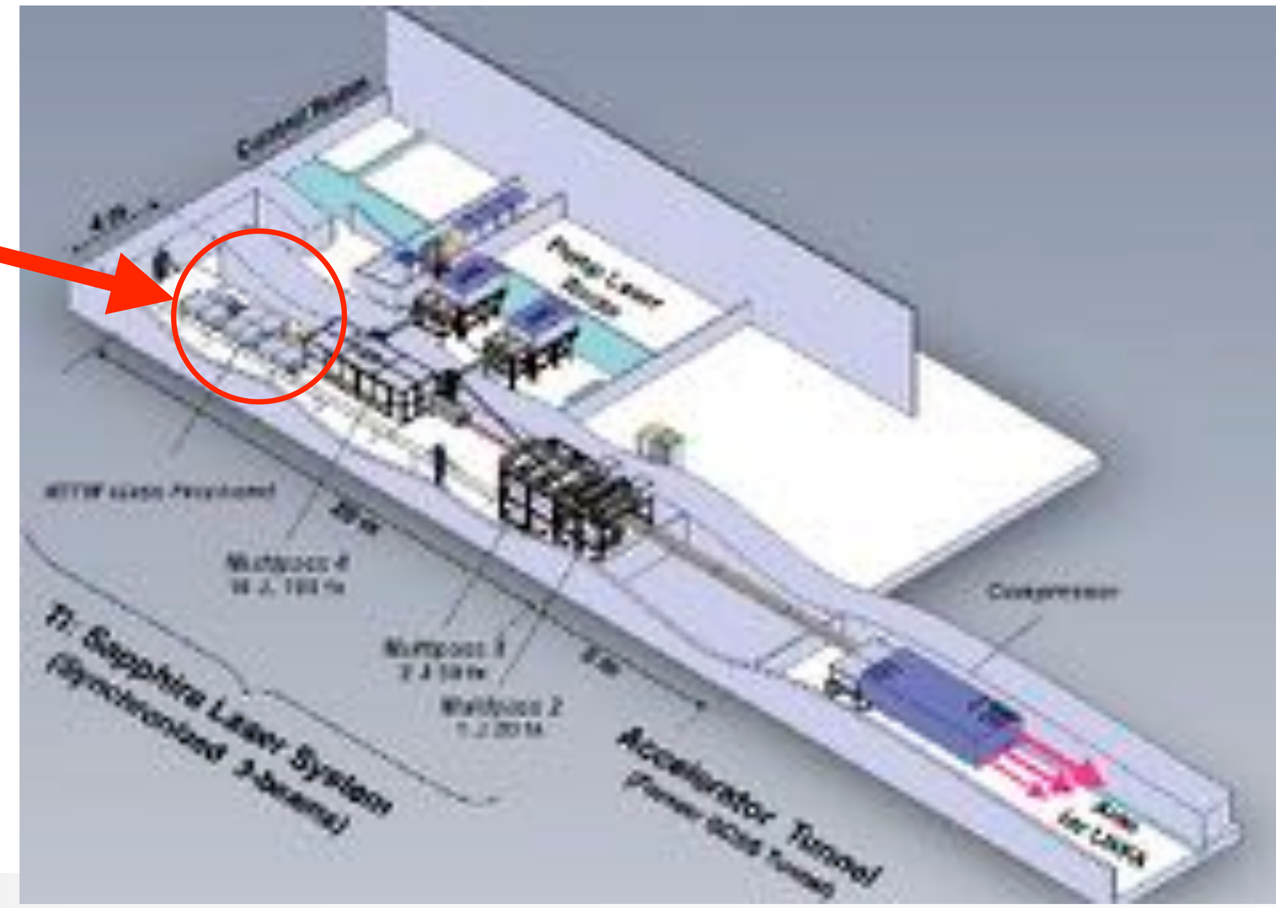
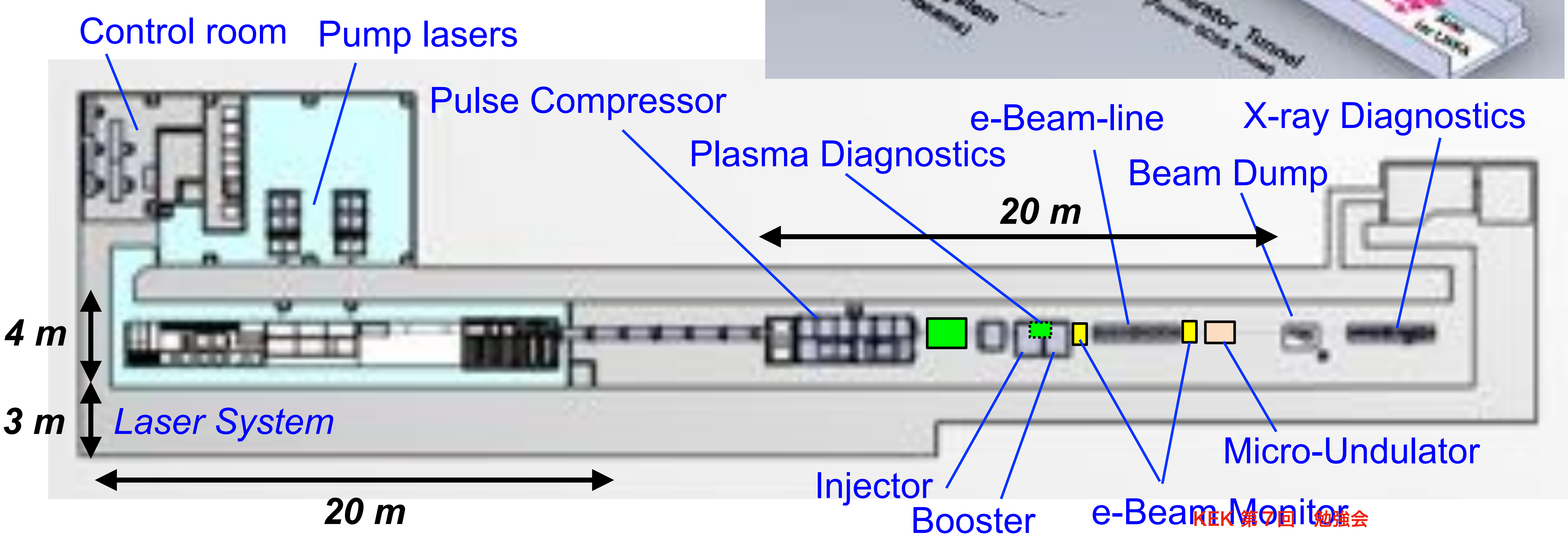
Overview of LWFA Platform @SPring-8



Overview of LWFA Platform @SPring-8

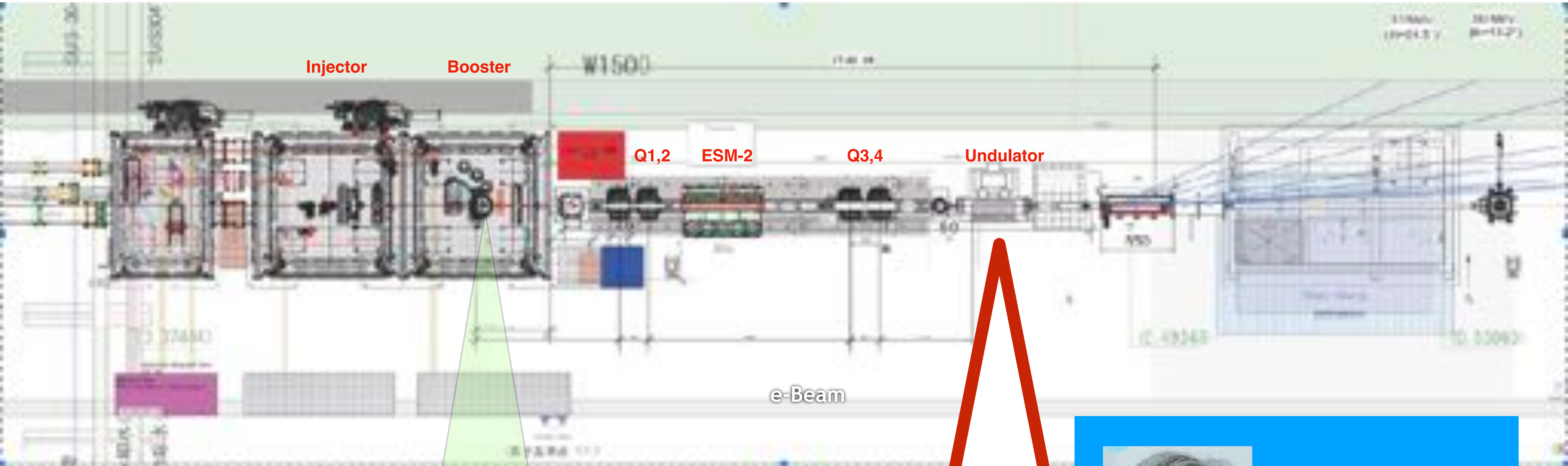


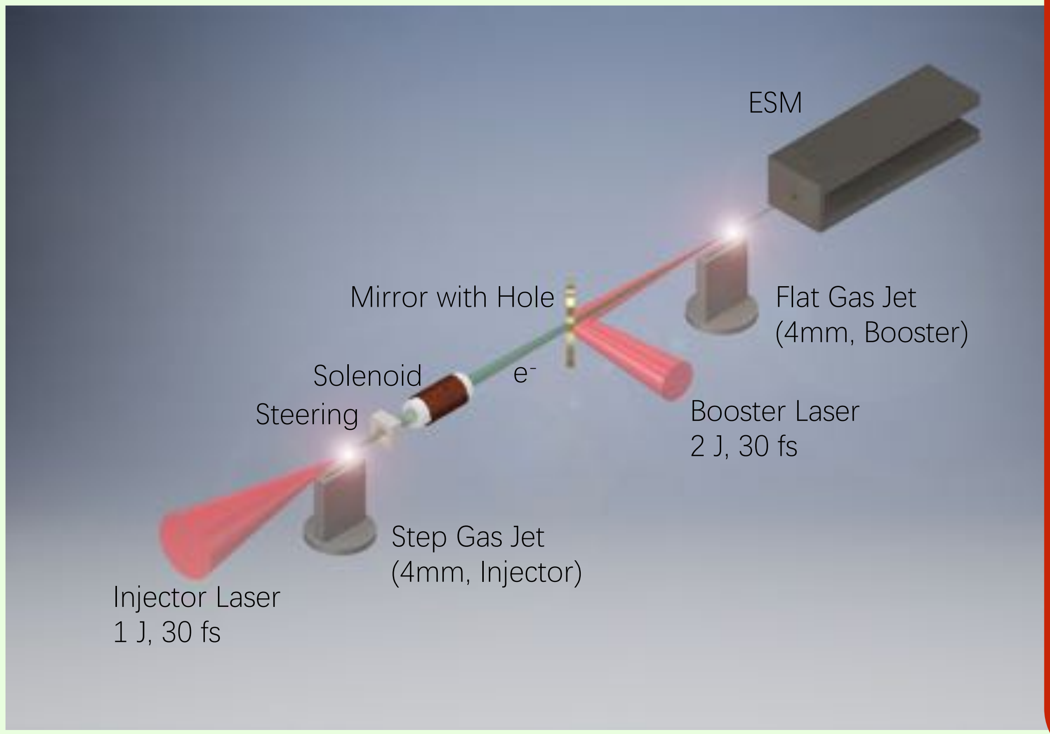


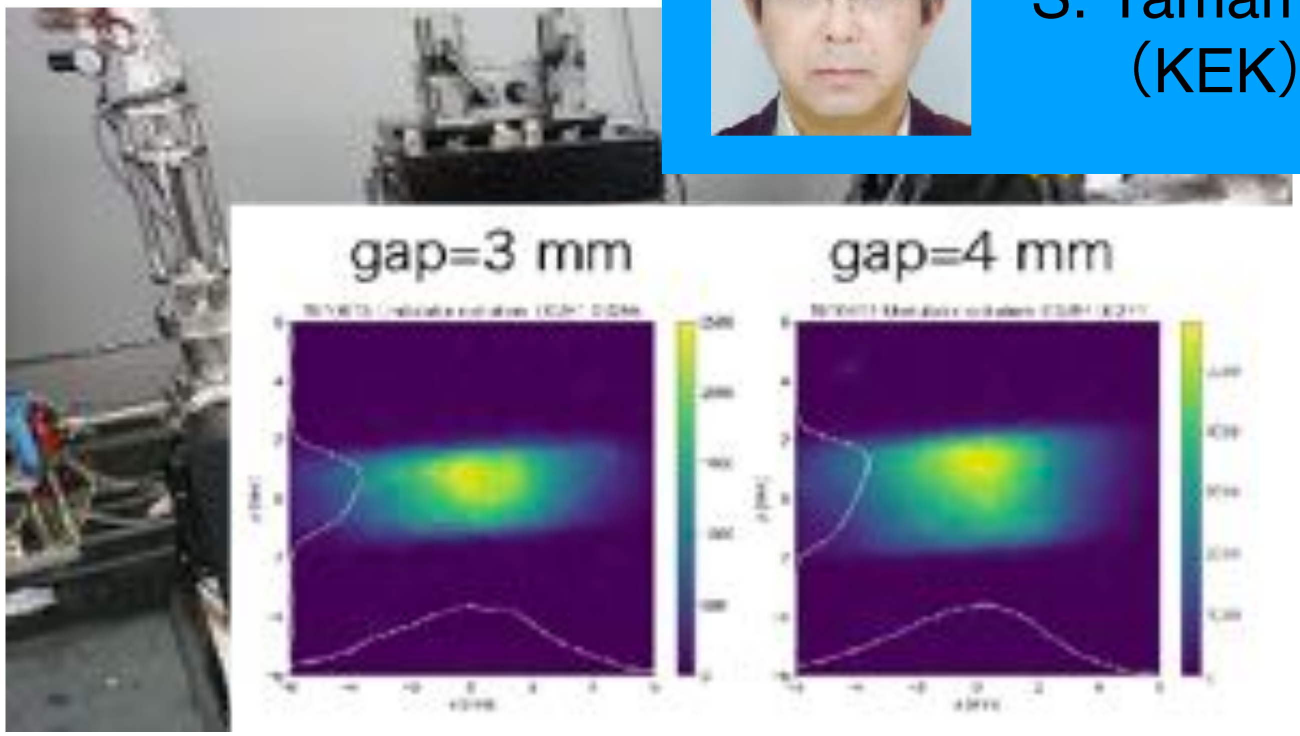


![JST MIRAI logo] JST-Mirai Program

アンジュレーター実験を開始（2019.9～）







S. Yamamoto
（KEK）

PHYSICAL REVIEW X **10,** 031039 (2020)

Decoding Sources of Energy Variability in a Laser-Plasma Accelerator

Andreas R. Maier,[1,2,*] Niels M. Delbos,[1] Timo Eichner,[1] Lars Hübner,[1,2] Sören Jalas,[1] Laurids Jeppe,[1]
Spencer W. Jolly,[1,3] Manuel Kirchen,[1] Vincent Leroux,[2,1,3] Philipp Messner,[4,1]
Matthias Schnepp,[1] Maximilian Trunk,[1]
Paul A. Walker,[2,1] Christian Werle,[1] and Paul Winkler[2,1]

[1]*Center for Free-Electron Laser Science and Department of Physics Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
[2]*Deutsches Elektronen Synchrotron (DESY), Notkestraße 85, 22607 Hamburg, Germany*
[3]*Institute of Physics of the ASCR, ELI-Beamlines Project, Na Slovance 2, 18221 Prague, Czech Republic*
[4]*International Max Planck Research School for Ultrafast Imaging & Structural Dynamics, Luruper Chaussee 149, 22761 Hamburg, Germany*

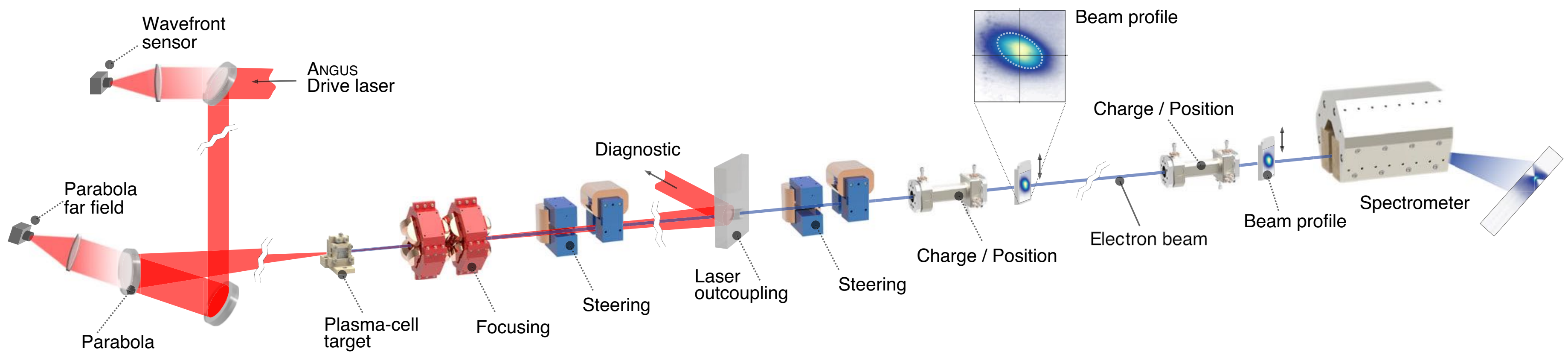


FIG. 1. The drive laser (red) is focused into a plasma-cell target, where it ionizes a nitrogen-doped hydrogen gas to form a plasma and then traps and accelerates electrons to an energy of 368 MeV. After the target, the laser is extracted from the beam axis for diagnostics. The electron beam (blue) is captured using a pair of electromagnetic quadrupoles and focused into a permanent magnet dipole spectrometer. The electron beam is adjusted to the accelerator design axis using steering dipoles. Retractable scintillating screens and cavity-type beam position monitors provide electron-beam profile, charge, and position information. For clarity, only a few of the installed laser diagnostics are shown. The whole setup is integrated into a controls system to enable live monitoring, tuning, and processing of the acquired data.

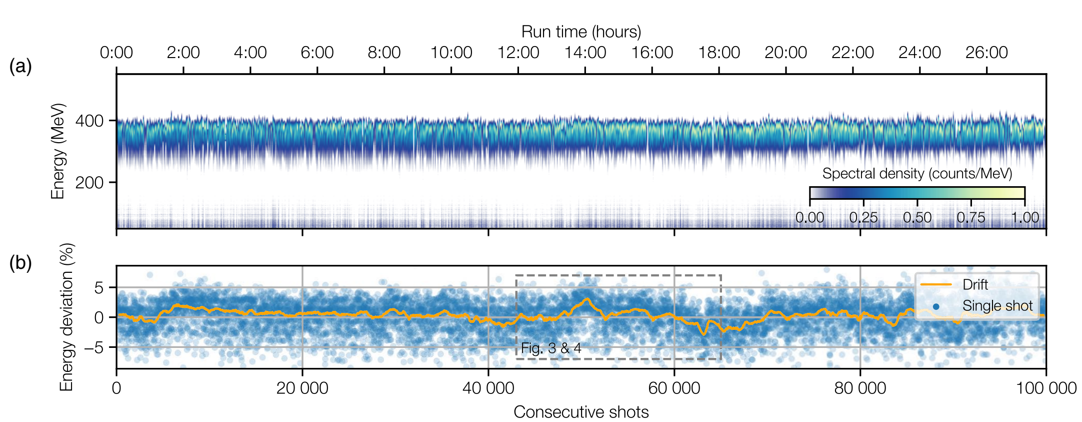


FIG. 2. Panel (a) shows the energy spectra of 100 000 consecutive laser-plasma generated electron beams. Here, each line represents one single shot. The camera images of the electron spectrometer screen are background corrected, projected onto the dispersive axis, and calibrated to a linear energy scale. The peak energy of each spectrum (dots) is shown in panel (b), together with the energy drift (solid line) calculated as the rolling average over a 6-min window, i.e., 360 shots. The percent-level energy drift can be attributed to a drift in drive laser parameters (compare Figs. 3 and 4).

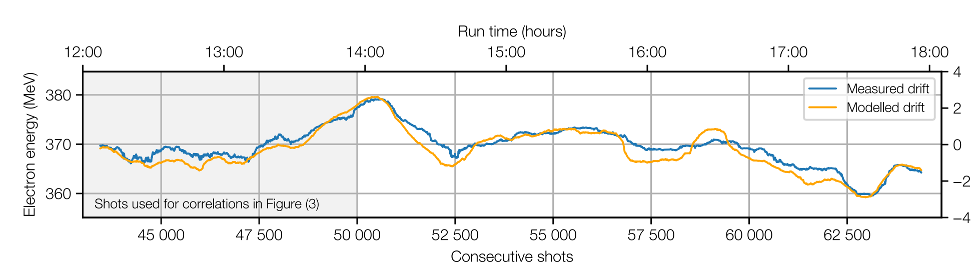


FIG. 4. To model the measured electron energy drift (blue), we used Eq. (1), the correlations presented in Fig. 3, and the drift of the measured laser energy, laser focus shift, and laser direction. As before, we calculated the drift as the 6-min rolling average (360 shots) of the single-event data. Only four noninvasively measured laser parameters are sufficient to predict (orange) the evolution of the electron energy with subpercent accuracy. The modeled electron energy is accurate for a 6-h (22 000 shots) time span, which significantly exceeds the 2-h time window (7000 shots) we used to correlate the laser and electron data.

KEK 第７回　勉強会
2021年1月27日(水) 10：00 ～12：00)@ ZOOM

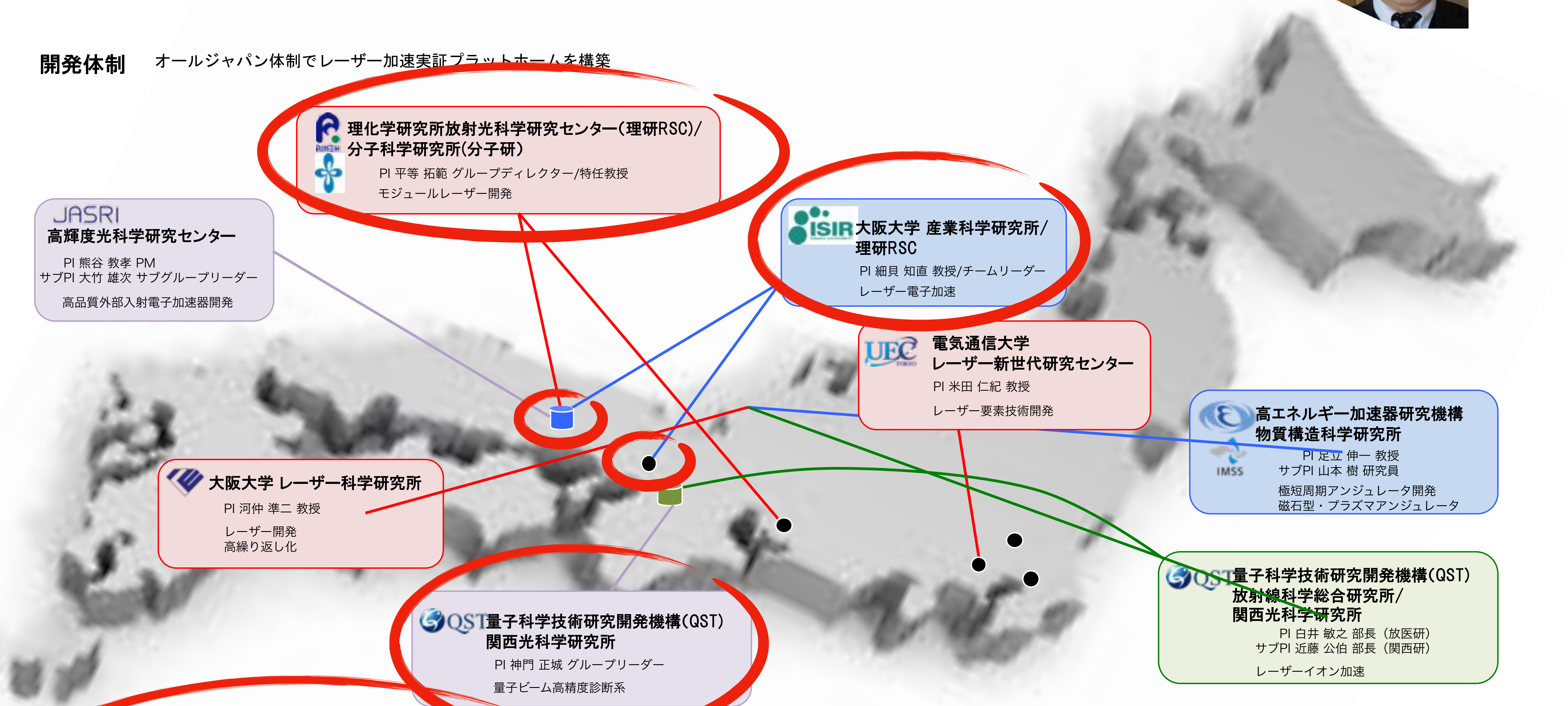
阪大産研量子ビーム物理研究分野 メンバー

JST-Mirai Program

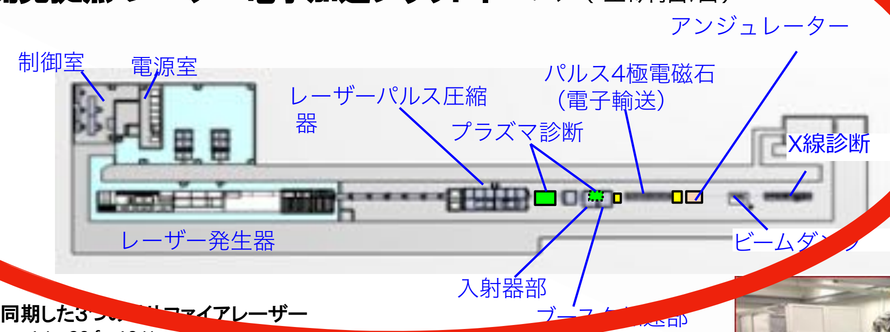
JST 未来社会創造事業　　　**開発体制**

- レーザー加速による量子ビーム加速器の開発と実証 - *(2017-2026)*

開発体制　オールジャパン体制でレーザー加速実証プラットホームを構築



開発拠点 レーザー電子加速プラットホーム（理研播磨）



同期した3つの[illegible]ファイアレーザー

- 1 J,　20 fs, 10 Hz
- 2 J,　50 fs,　5 Hz
- 10 J, 100 fs, 0.1 Hz

を用いて、ステージングレーザー加速、電子発生を行っている。

開発拠点 イオン加速実証プラットホーム（QST関西研）

プラットホームTIサファイアレーザー(開発中)

・1 J, 30-40 fs, 10 Hz

を用いて10 Hz動作のイオン加速を実証する。

J-KARENレーザー（Tiサファイアレーザー）

・20 J, 30 fs, 0.1 Hz

を用いてイオン加速の新しい効率的な加速法を研究する。

KEK 第7回　勉強会

2021年1月27日(水) 10：00 ～12：00)@ ZOOM

革新的研究開発推進プログラム ImPACT
(2013-2018)

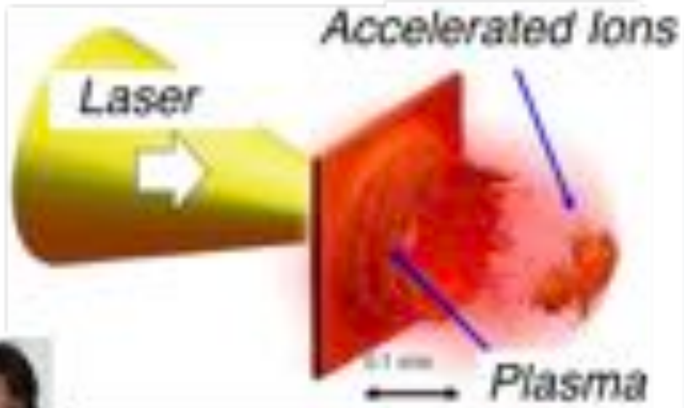
JST-Mirai Program

JST 未来社会創造事業 (2017-2026)

- レーザー加速による量子ビーム加速器の開発と実証 -

イオン加速器開発ユニット

イオン加速手法、ターゲットシステムの開発

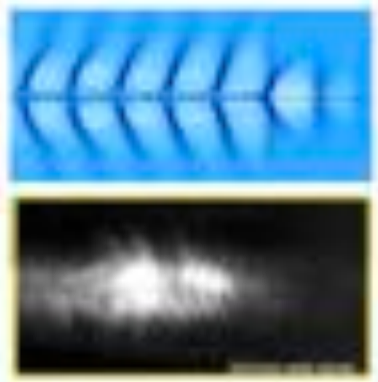



K. Kondo


T. Shirai

QST 放医研, 関西研

計測技術グループ




M. Kando

QST 関西研

電子加速開発ユニット

ステージングレーザー加速技術の開発

1. RF フォトカソード
2. レーザー駆動入射器

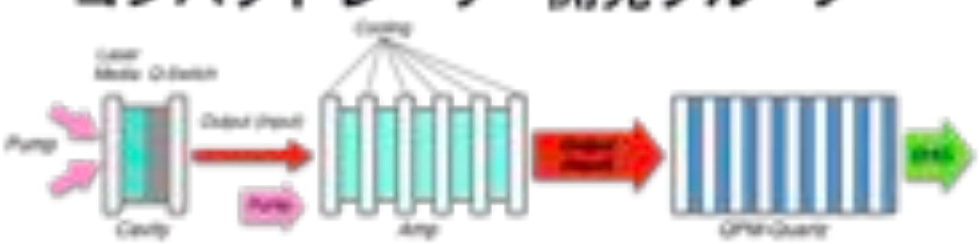
+ レーザー駆動ブースター


T. Hosokai


Y. Otake

阪大産研, 理研, JASRI, KEK

コンパクトレーザー開発グループ



チタンサファイア励起用YAGレーザーの小型化・高効率化開発

大口径DFC構造技術開発, 新材料開発

分子研, 理研

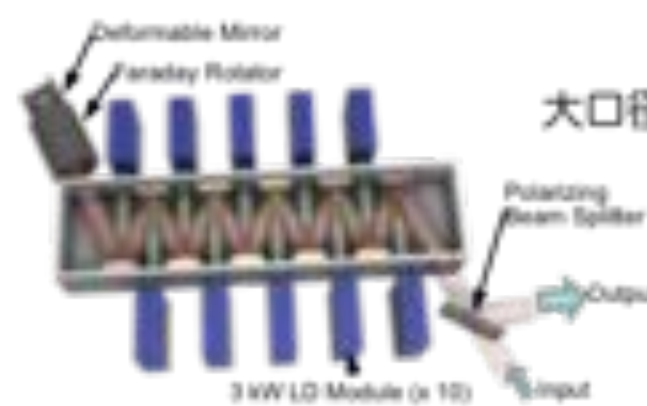

T. Tara

超小型・高出力レーザー

応用展開
製品化開発

ハイパワーレーザー開発グループ

極短パルスレーザー励起用レーザーのハイパワー化開発



大口径アクテブミラー技術開発,
新規光学材料,
素子開発

阪大レーザー研


J. Kawanaka

KEK 第７回　勉強会
2021年1月27日(水) 10：00 〜12：00)@ ZOOM

まとめ

- 高強度超短レーザーパルスとプラズマの相互作用で励起される加速電場は高周波加速器の加速電場の1000倍以上の強度が可能。

- レーザー航跡場加速研究は原理実証の基礎研究の段階からリピータブルな高品質ビーム源開発の段階へとシフトしつつある。

- レーザー加速駆動の電子ビームの実用化に向けて必要なもの
  - ・安定・リピータブルなドライバー（Ti:Sapphireレーザーの開発）
  - ・プラズマの制御技術の確立（加速機構・入射機構の解明と相補的に）
  - ・アプリケーションの探索
    - ・すでに数百MeV級の電子ビームなら卓上サイズレーザー（〜J級）利用可能
    - ・医療応用？
    - ・高エネルギー分野の検出器校正用としての光源？

- 理研SPring-8キャンパスにてオールジャパン体制の機関連携で研究開発を推進中（JST未来社会創造事業（大規模型））
- 圧倒的な研究者の不足（特に若手の研究者）
- 加速器分野の方々、ぜひ参加をお願いします！（近々、公募開始予定！！）