上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Recent studies on plasma channel based laser wakefield staging scheme and radiation source at SJTU

Min Chen, Ji Luo, Ming Zeng, Qian Zhao, Feng Liu, Su-Ming Weng, Nasr Hafz, Zheng-Ming Sheng, and Jie Zhang

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Key Laboratory for Laser Plasmas， SJTU

2019.05.15-LPAW 2019-MedILS, Croatia

Collaborators

University of Strathclyde: D. A. Jaroszynski, P. McKenna

University of California: W.B. Mori

Lawrence Berkeley National Lab (BELLA-Center): C.B. Schroeder, E. Esarey, W.P. Leemans

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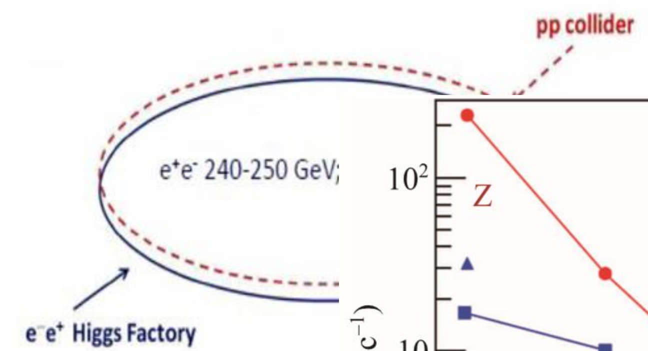
University of Nebraska-Lincoln: D. Umstadter, W.C. Yan, G. Golovin

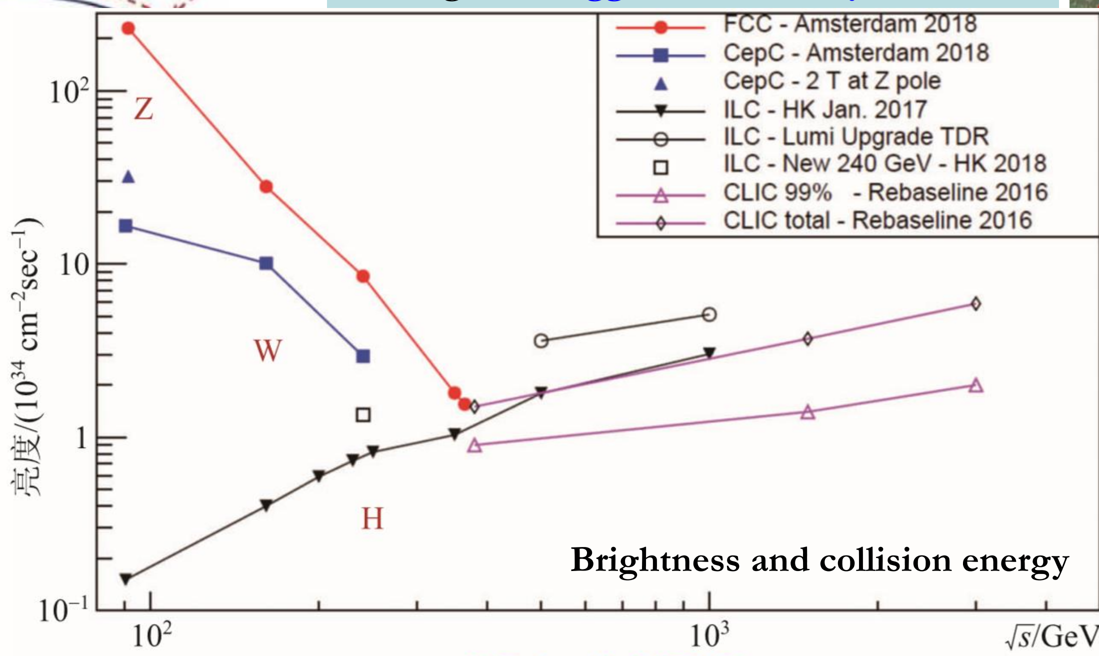
Collisions outside the field!

CHINA'S CEPC debate!

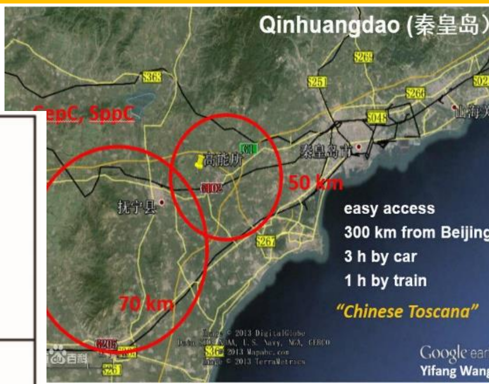
The circular electron positron collider (CEPC) built or not? (+SPPC) >20 billion $



CEPC is a future large collider facility serving as a Higgs boson factory, and



F. Bedeschi, INFN-Pisa

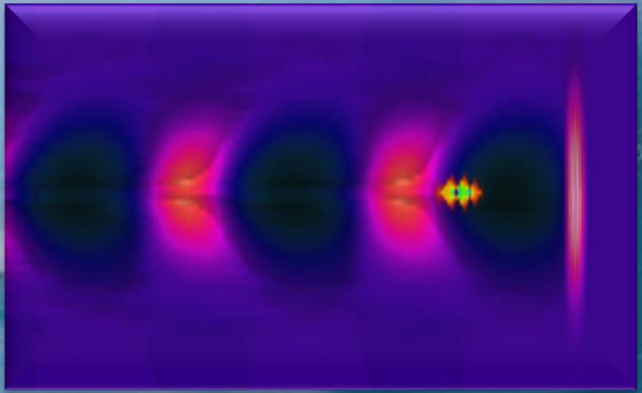


Prof. Yifang Wang (56)
Director of Institute of High Energy Physics, CAS
Breakthrough Prize in Fundamental Physics in 2016

For TeV electron accelerator, I think definitely we need new acceleration technologies!

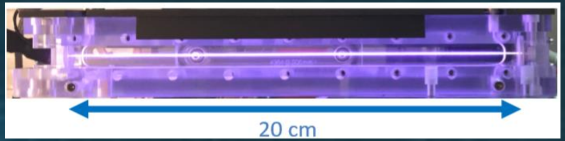
Prof. Chen-Ning Yang (97)
1957 Nobel Prize Laurate
in Physics for work on parity nonconservation of weak interaction with Prof. TD Lee.

Wakefield Acceleration — Electron Surfing

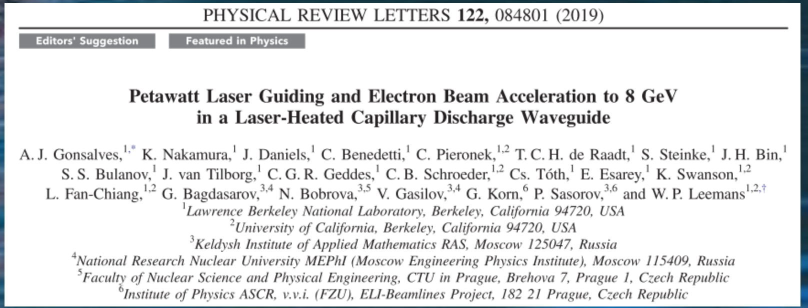


Wakefield has a giant acceleration gradient

SLAC 50GeV 3.2km→ 0.001km



LBNL: 8 GeV within 20cm


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*
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[3]*Keldysh Institute of Applied Mathematics RAS, Moscow 125047, Russia*
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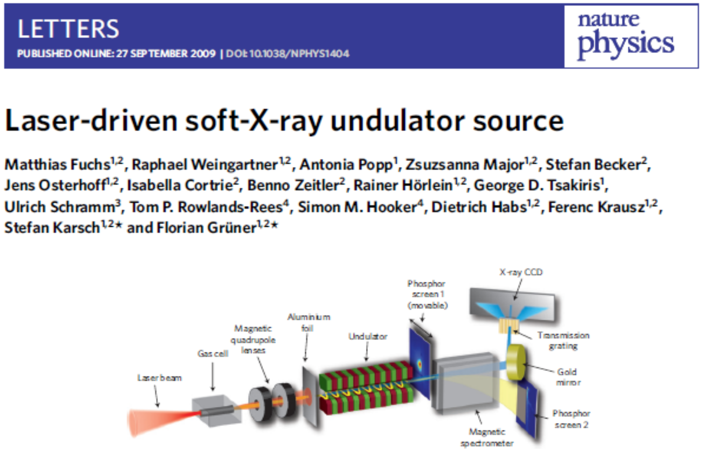
[5]*Faculty of Nuclear Science and Physical Engineering, CTU in Prague, Brehova 7, Prague 1, Czech Republic*
[6]*Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague, Czech Republic*

Main Applications of LWFA

1. Betatron Radiation Source


LETTERS

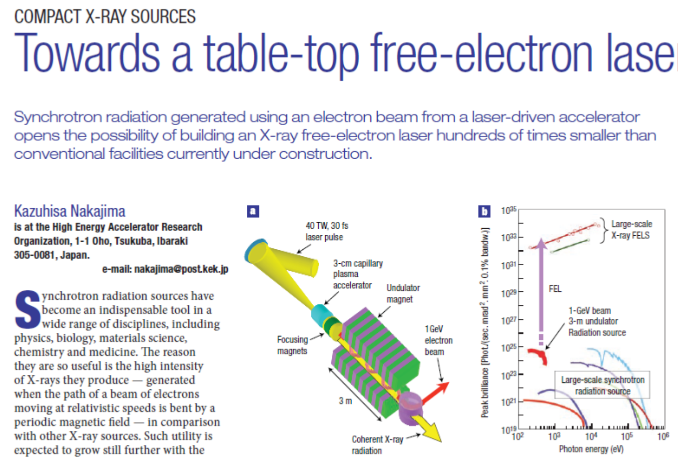
PUBLISHED ONLINE: 27 SEPTEMBER 2009 | DOI: 10.1038/NPHYS1404

nature physics

Laser-driven soft-X-ray undulator source

Matthias Fuchs[1,2], Raphael Weingartner[1,2], Antonia Popp[1], Zsuzsanna Major[1,2], Stefan Becker[2], Jens Osterhoff[1,2], Isabella Cortrie[2], Benno Zeitler[2], Rainer Hörlein[1,2], George D. Tsakiris[1], Ulrich Schramm[3], Tom P. Rowlands-Rees[4], Simon M. Hooker[4], Dietrich Habs[1,2], Ferenc Krausz[1,2], Stefan Karsch[1,2]* and Florian Grüner[1,2]*

3. LWFA based FEL


COMPACT X-RAY SOURCES

Towards a table-top free-electron laser

Synchrotron radiation generated using an electron beam from a laser-driven accelerator opens the possibility of building an X-ray free-electron laser hundreds of times smaller than conventional facilities currently under construction.

Kazuhisa Nakajima

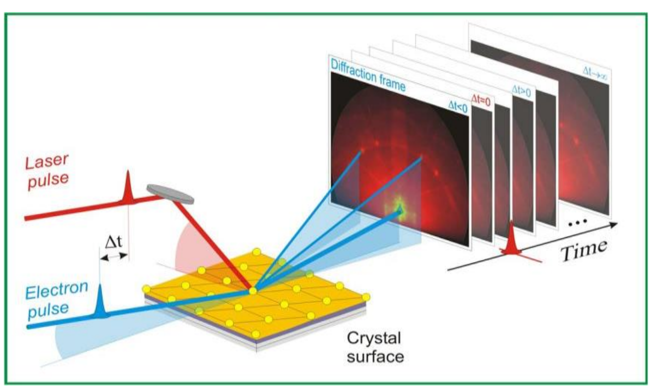
is at the High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0081, Japan.

e-mail: nakajima@post.kek.jp

Synchrotron radiation sources have become an indispensable tool in a wide range of disciplines, including physics, biology, materials science, chemistry and medicine. The reason they are so useful is the high intensity of X-rays they produce — generated when the path of a beam of electrons moving at relativistic speeds is bent by a periodic magnetic field — in comparison with other X-ray sources. Such utility is expected to grow still further with the

2. LWFA based UED

PRST-AB,19, 021302(2016); Nature Photonics, 10.1038/NPHOTON.2017.46



4. TeV electron positron collider

Physics Today, March, 44, 2009

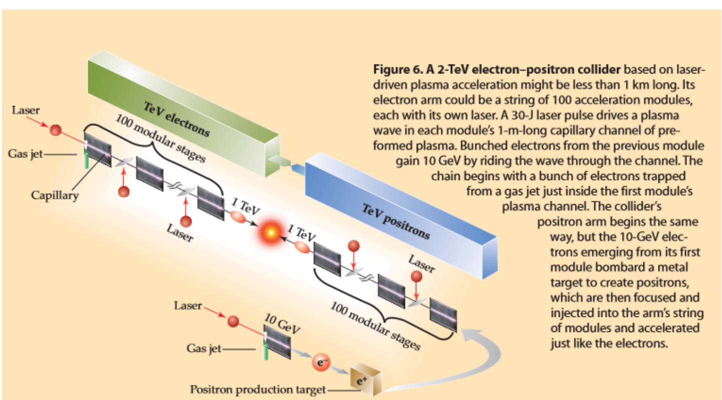


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

Main challenges of LWFA

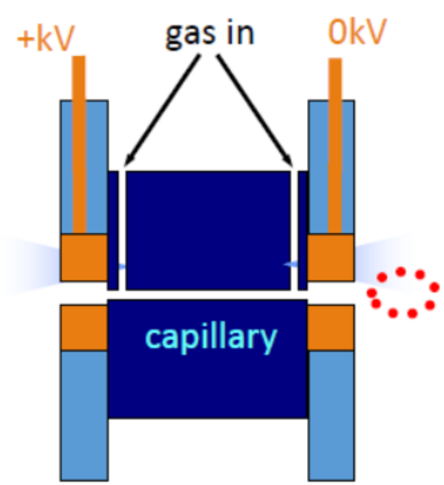
Challenge 1: High Energy — Electron Positron Collider

1. Laser Guiding– Diffraction
2. Velocity matching- Dephasing
3. Staging– Depletion

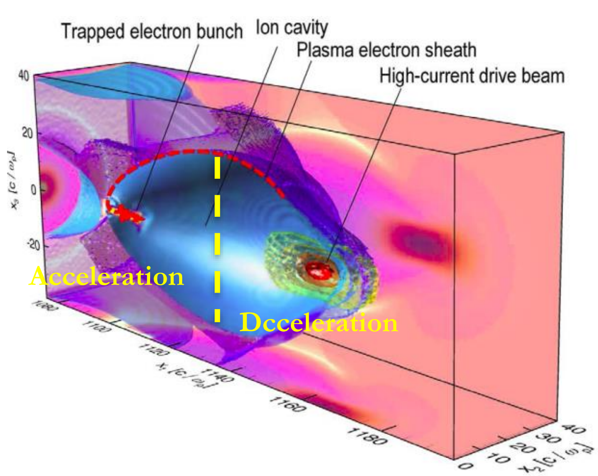
Challenge 2: High Quality—Radiation Source

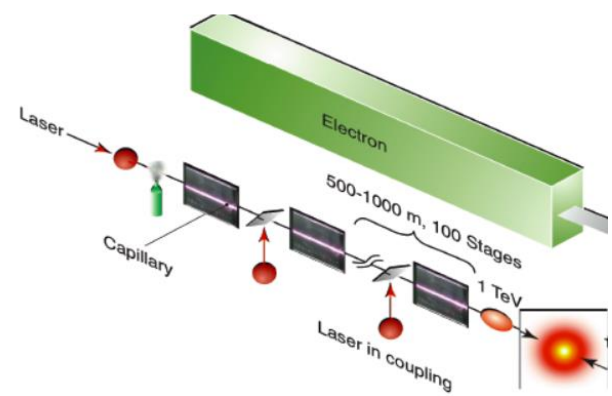
1. Electron injection
2. Transverse motion control
3. Longitudinal control

Next generation collider



Next generation radiation source





Laser Plasma Studies at SJTU

SJTU – Group (2007)

Leader: Prof. J. Zhang

Laser:

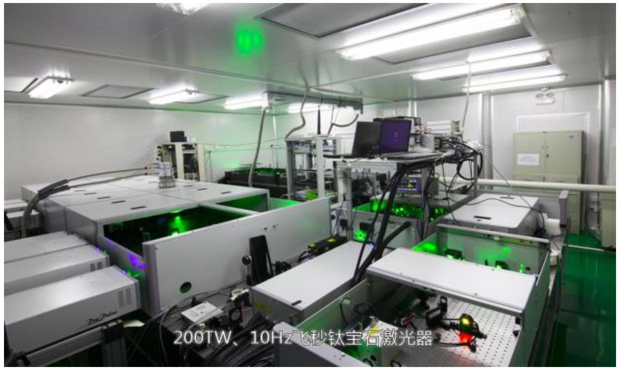
- 200TW laser system 10Hz，5J/25fs;
- kHz laser system;
- 400J laser system.
- 100TW 2.2μm laser 100fs

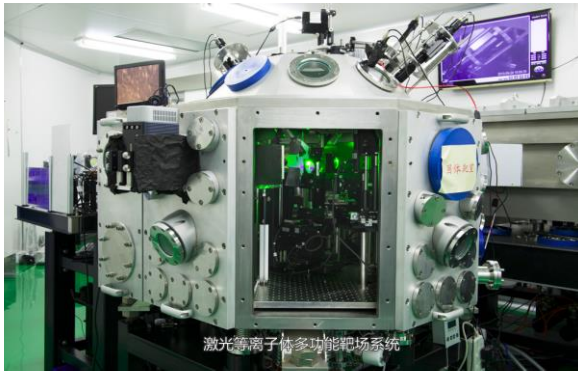
Topics:

High power laser technology,

Fusion Science, Laser Plasma

Both laser， experiment & theory group.

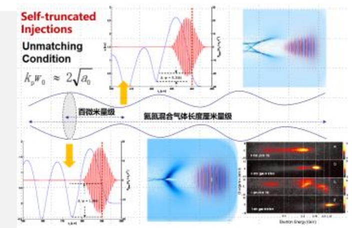


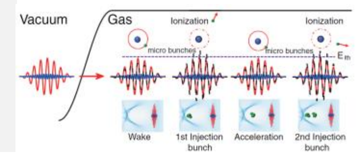


LWFA studies at SJTU (2014-2018)

SJTU Main topics:

1. **Electron injection in Wakefield**
   - a) **Self-truncated ionization injection and experimental demonstration.** Phys. Plasmas 21, 030701 (2014); Sci. Rep. 5, 14659 (2015)
   - b) **Two-color laser induced ionization electron for energy spread as low as 0.29%.** Phys. Rev. Lett.114, 084801 (2015)
   - c) **External magnetic field assisted ionization injection.** NJP. 20, 063031 (2018)
   - d) **Electron Trapping from Interactions between Laser-Driven Relativistic Plasma Waves.** Phys. Rev. Lett., 121, 104801 (2018) Collaborated with UNL
   - e) **…**



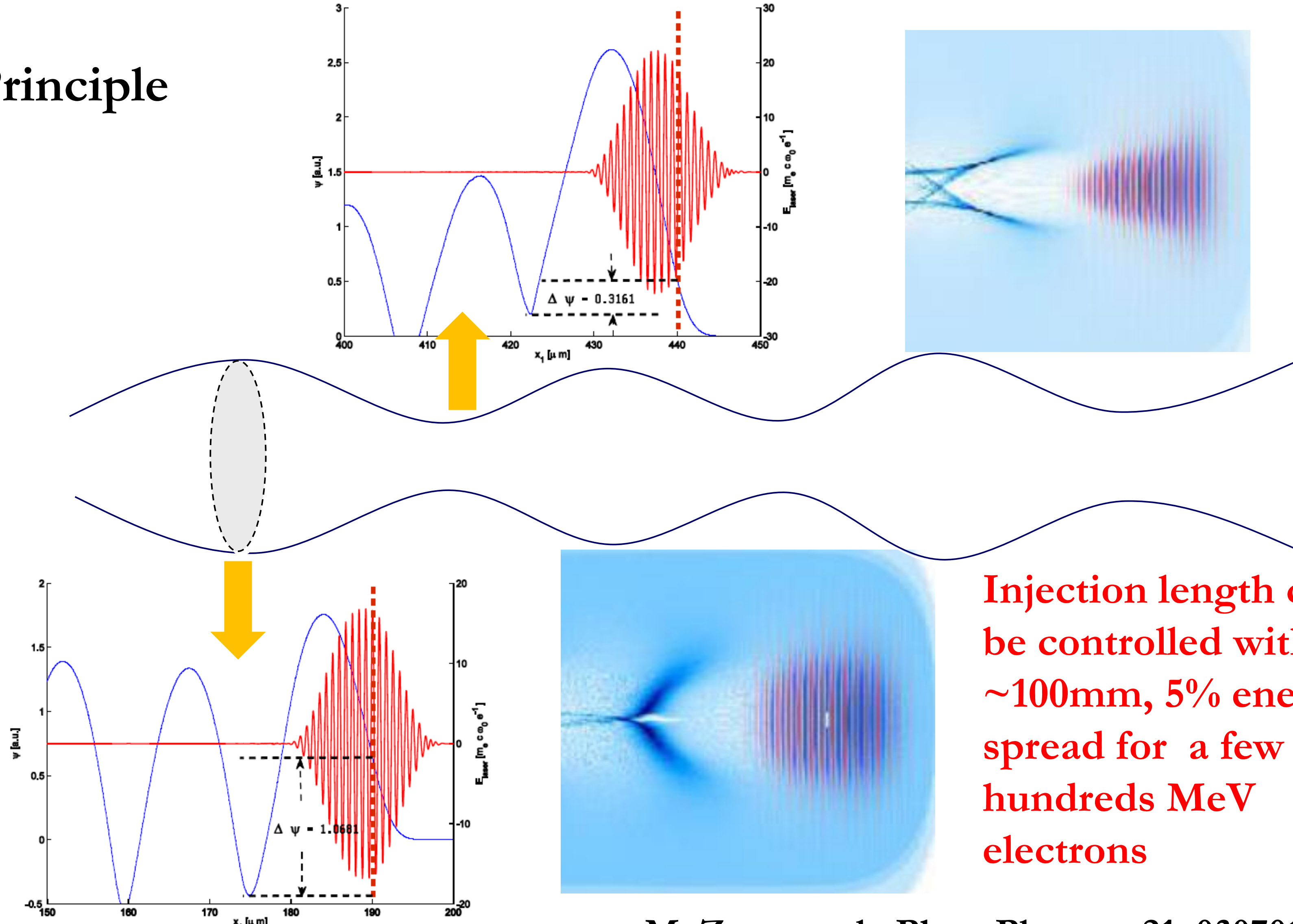


2. **New staging scheme for LWFA**

3. **Radiation in Wakefield (From THz to γ-ray)**

Laser self-evolution induced self-truncated ionization injection

Principle



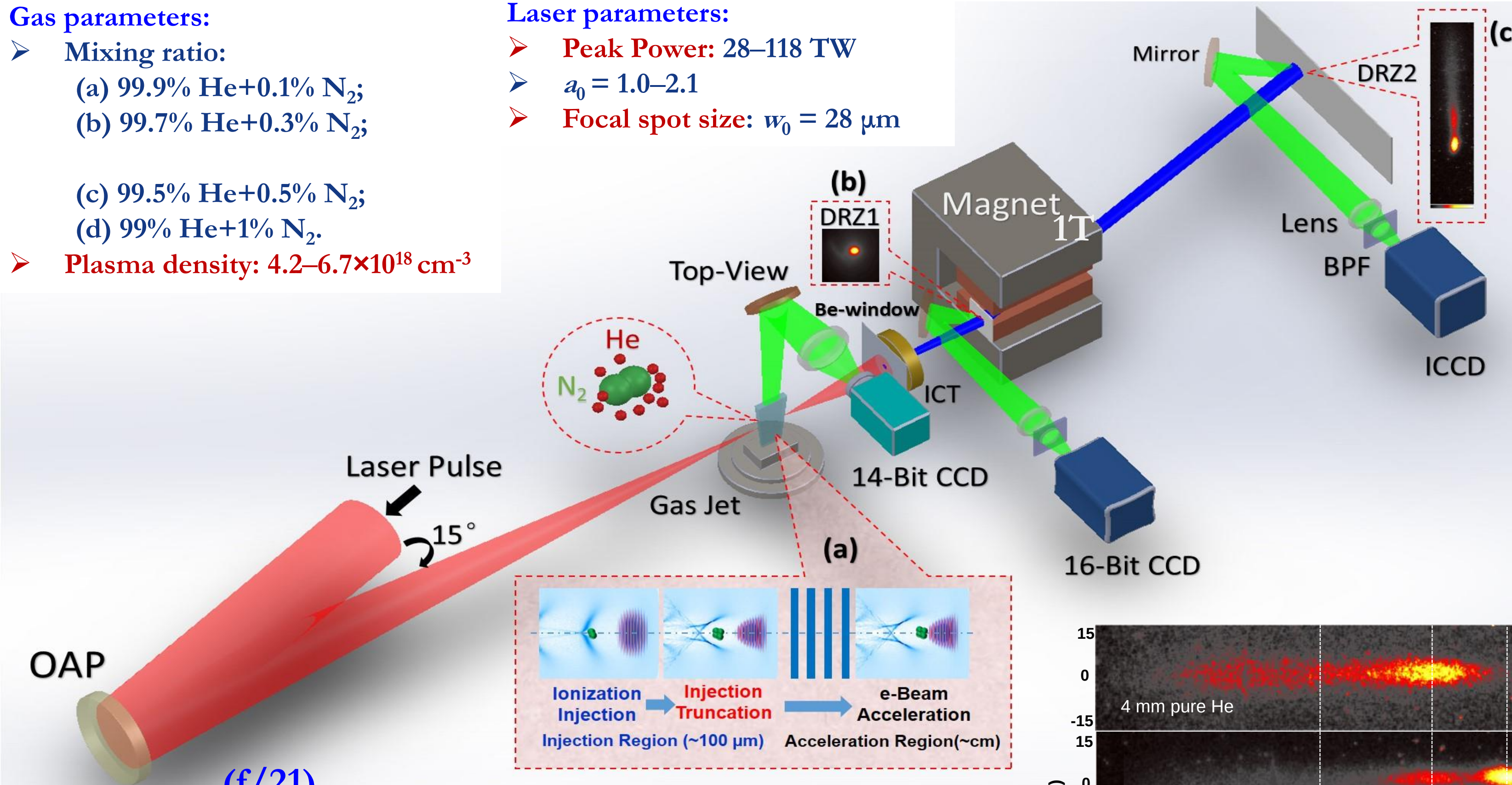
Injection length can be controlled within ~100mm, 5% energy spread for a few hundreds MeV electrons

M. Zeng et al., Phys. Plasmas 21, 030701 (2014).

1.2GeV electron acceleration at SJTU

Gas parameters:
- Mixing ratio:
  - (a) 99.9% He+0.1% N_2;
  - (b) 99.7% He+0.3% N_2;
  - (c) 99.5% He+0.5% N_2;
  - (d) 99% He+1% N_2.
- Plasma density: 4.2–6.7×10^{18} cm^{-3}

Laser parameters:
- Peak Power: 28–118 TW
- a_0 = 1.0–2.1
- Focal spot size: w_0 = 28 μm



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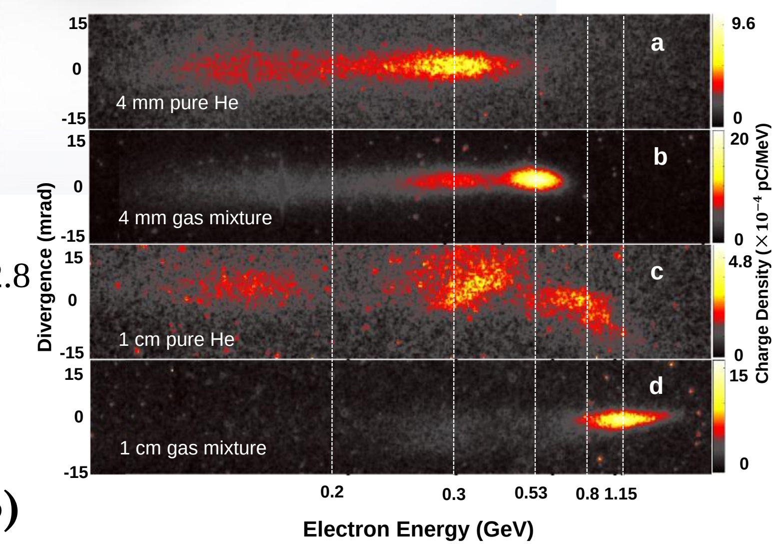
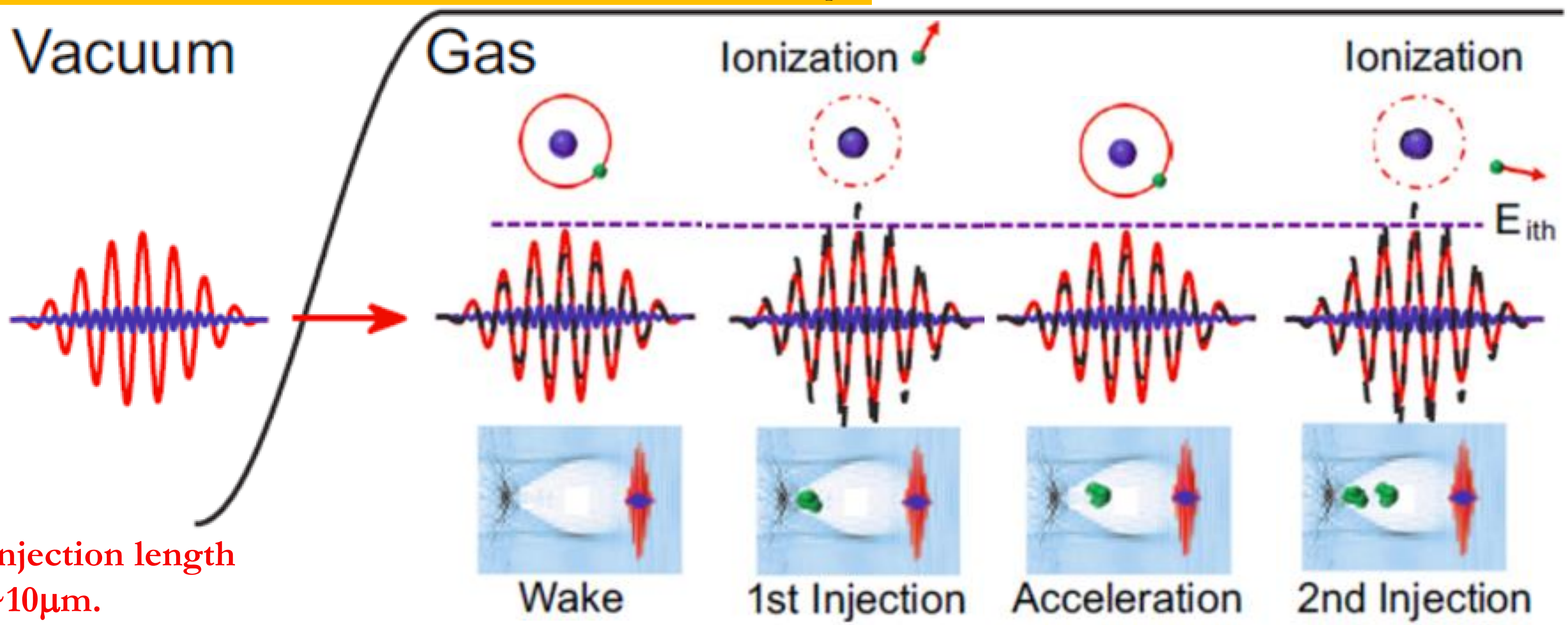


Unmatched laser-plasma condition: $k_p w_0 \sim 7-13 >> 2\sqrt{a_0} \sim 2.0-2.8$

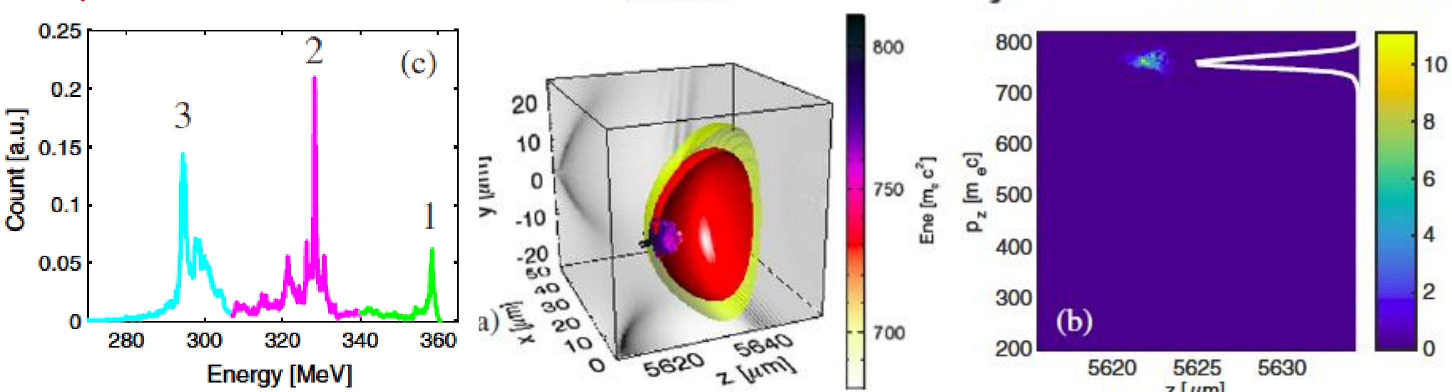
S. Li, N. Hafz, et al., Opt. Express 22, 29578 (2014).
M. Mirzaie, S. Li, N. Hafz et al., Sci. Rep. 5, 14659 (2015)

Two color laser ionization injection to generate multi-peak electrons

Laser pulses with difference frequency have different $v_{p.}$



Injection length ~10μm.



Simulation shows energy spread can be smaller than 0.5%.

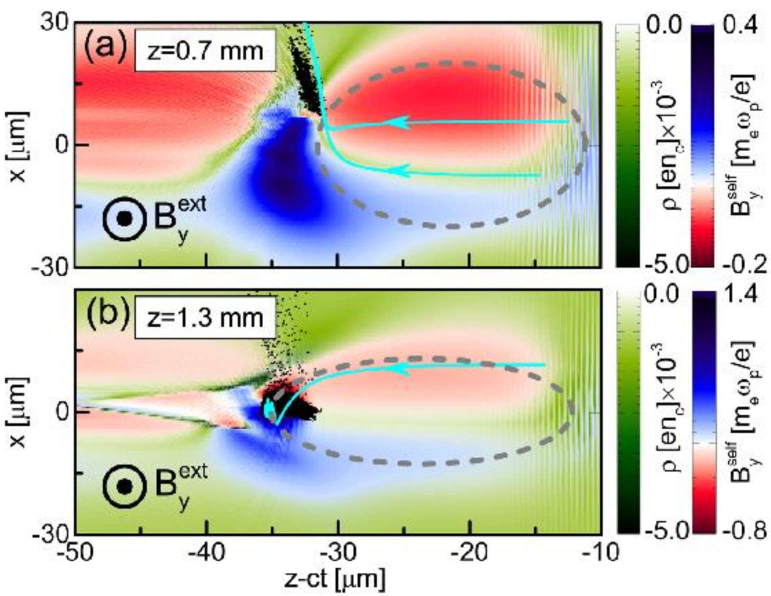
M. Zeng, *et al.*, PRL, 084801 (2015)

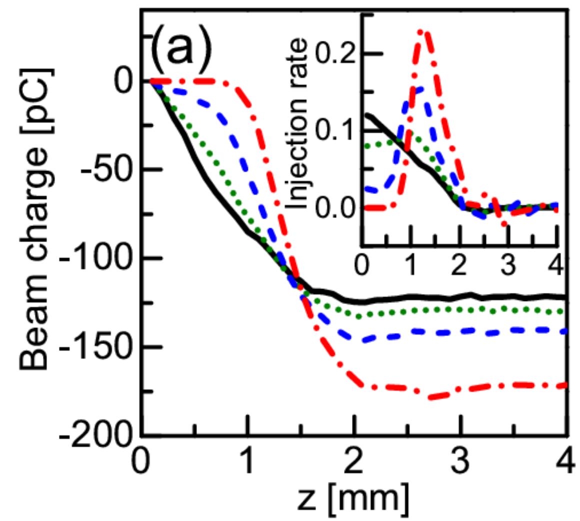
External transverse B field controlled injection

Injection condition with external B field：

J. Vieira et al., PRL 106, 225001 (2011)

$$\Delta\psi \leq \frac{\sqrt{1+u_\perp^2}}{\gamma_\phi} - 1 + \Delta\Psi^{ext} \quad \Delta\Psi^{ext} = b_0 v_\phi (x_i - x_f)/2$$





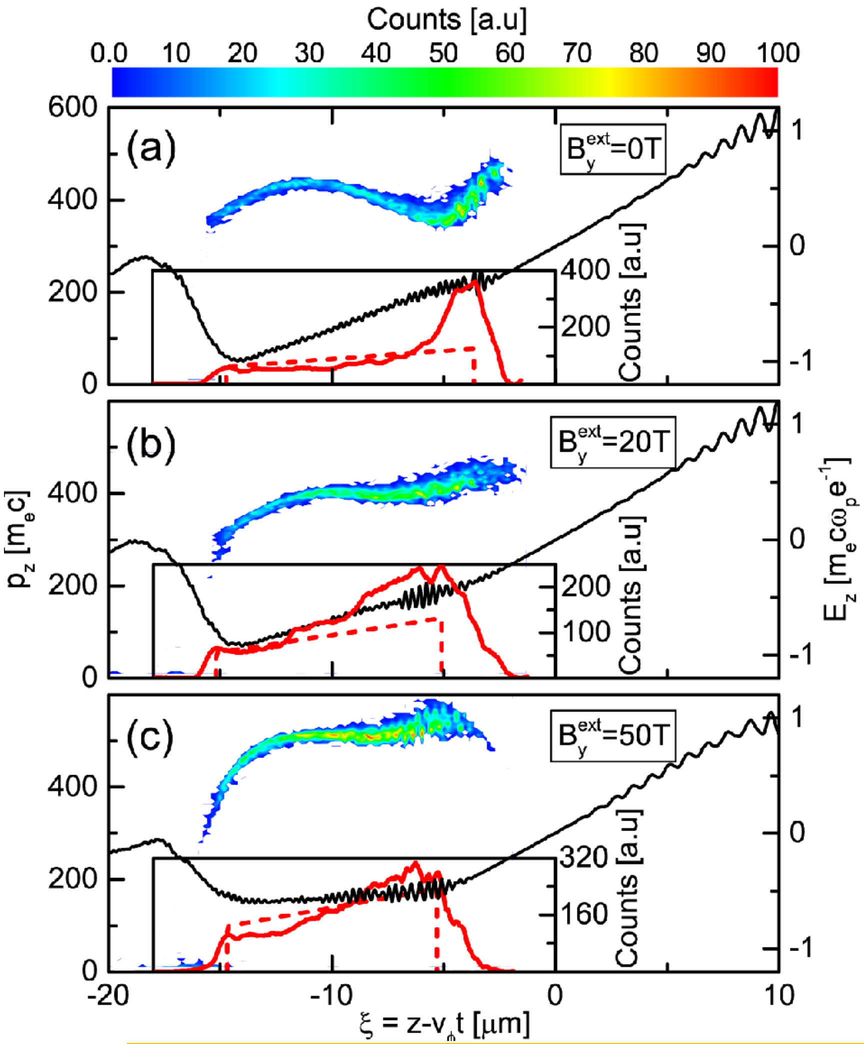
$$b_{crit} = 2R_m(U_0 + b_0 R_m - b_0 x_\phi)/(R_m^2 - x_\phi^2)$$

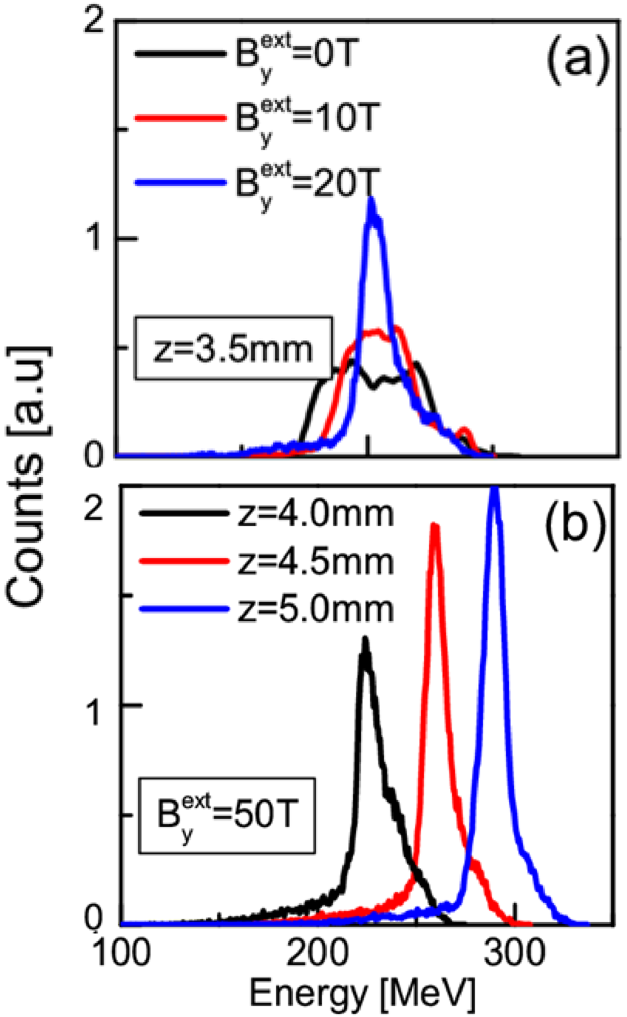
The self-generated magnetic field must be larger than b_{crit} for the transverse trapping.

- The relativistic self-focusing, B_{self} increases, so the injection will be triggered at a particular propagation distance.
- The injection can enhance B_{self} in return, which finally leads to an avalanche of electron injection.

Q. Zhao, *et al.*, New J. Phys. 20, 063031 (2018)

Controlled injection charge distribution reduce energy spread





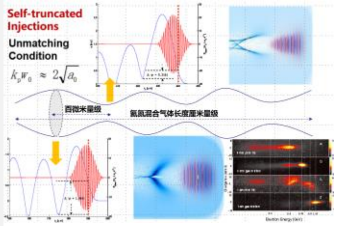
A linearly modified charge profile under an ETMF can result in an uniform wakefield, i.e., the beam loading is optimized.

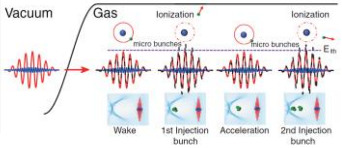
LWFA studies at SJTU (2014-2018)

SJTU Main topics:

1. Electron injection in Wakefield

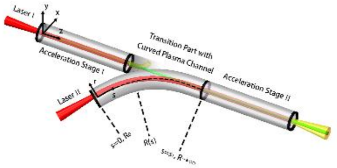
a) **Self-truncated ionization injection and experimental demonstration.** Phys. Plasmas 21, 030701 (2014); Sci. Rep. 5, 14659 (2015)
b) **Two-color laser induced ionization electron for energy spread as low as 0.29%.** Phys. Rev. Lett.114, 084801 (2015)
c) **External magnetic field assisted ionization injection.** NJP. 20, 063031 (2018)
d) **Electron Trapping from Interactions between Laser-Driven Relativistic Plasma Waves.** Phys. Rev. Lett., 121, 104801 (2018) Collaborated with UNL
e) …





2. New staging scheme for LWFA

a) **Multistage Coupling of Laser-Wakefield Accelerators with Curved Plasma Channels.** Phys. Rev. Lett., 120, 154801 (2018)



3. Radiation in Wakefield (From THz to γ-ray)

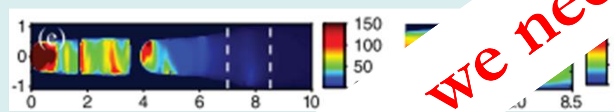
Different drivers for wakefield acceleration

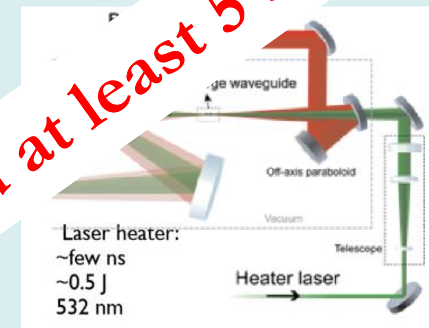
Laser beam driven： 10GeV→ 50GeV

T. Tajima, et al., PRL, 43, 267 (1979).

A. Gonsalves, et al., PRL, 122, 084801 (2019)

8GeV within 20cm.





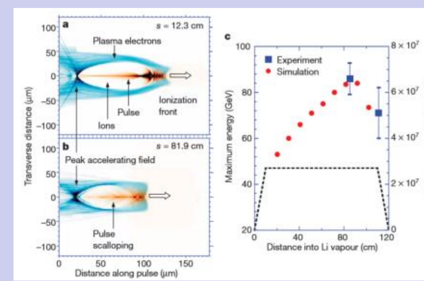
For acceleration of 50GeV beam by LWFA, we need at least 5 stages.

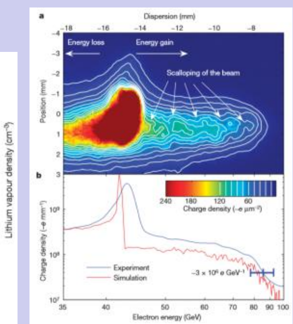
Electron beam driven： 50G… 100sGeV

P. Chen, et al., PRL, 54, 693 (1985).

Ian Blumenfeld, et al., Nature, 445, 7…).

An energy gain of more than 42GeV … in a plasma wakefield accelerator of 85cm le… by a 42GeV electron beam at SLAC.



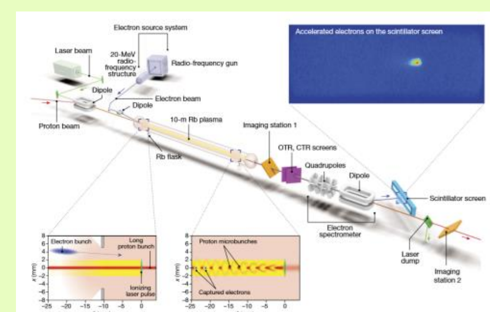


Proton be… …iven： 100sGeV→ TeV

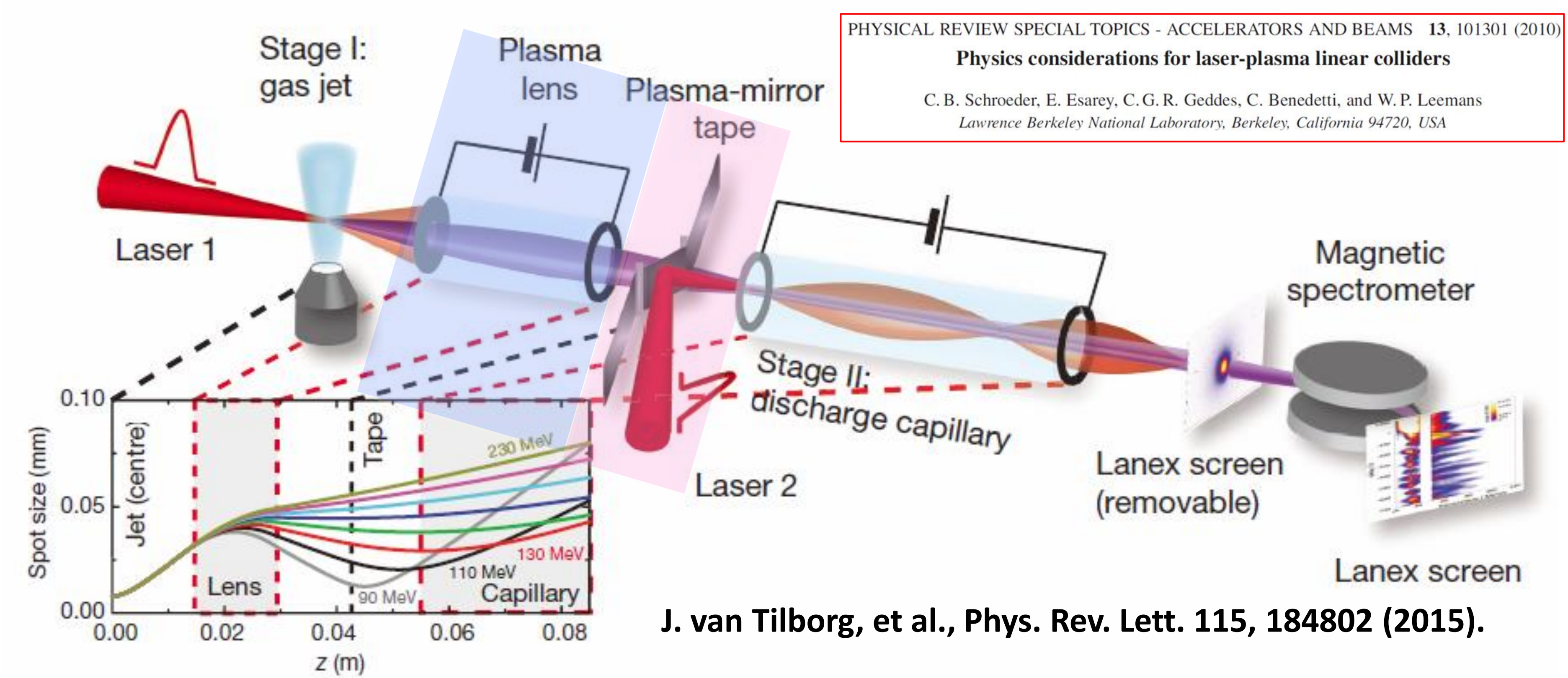
A. Caldwe… Nature Physics, 5 363 (2009).

E. Adli… …ature, 561, 363 (2018).

A… …n to 2.0 ± 0.1 GeV is achieved with a plasma … of 6.6 × 1014 cm−3 with a density difference of …2% ± 0.1% over 10 m.



Current staging scheme: plasma mirror & lens



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 101301 (2010)

Physics considerations for laser-plasma linear colliders

C. B. Schroeder, E. Esarey, C. G. R. Geddes, C. Benedetti, and W. P. Leemans

Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

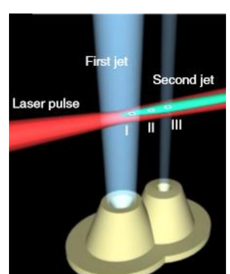
J. van Tilborg, et al., Phys. Rev. Lett. 115, 184802 (2015).

T. Sokollik, et al. AIP Conf. Proc. 1299, 233 (2010).

First stage： 120MeV

Multistage Coupling： 3.5%，

Energy gain: 100MeV



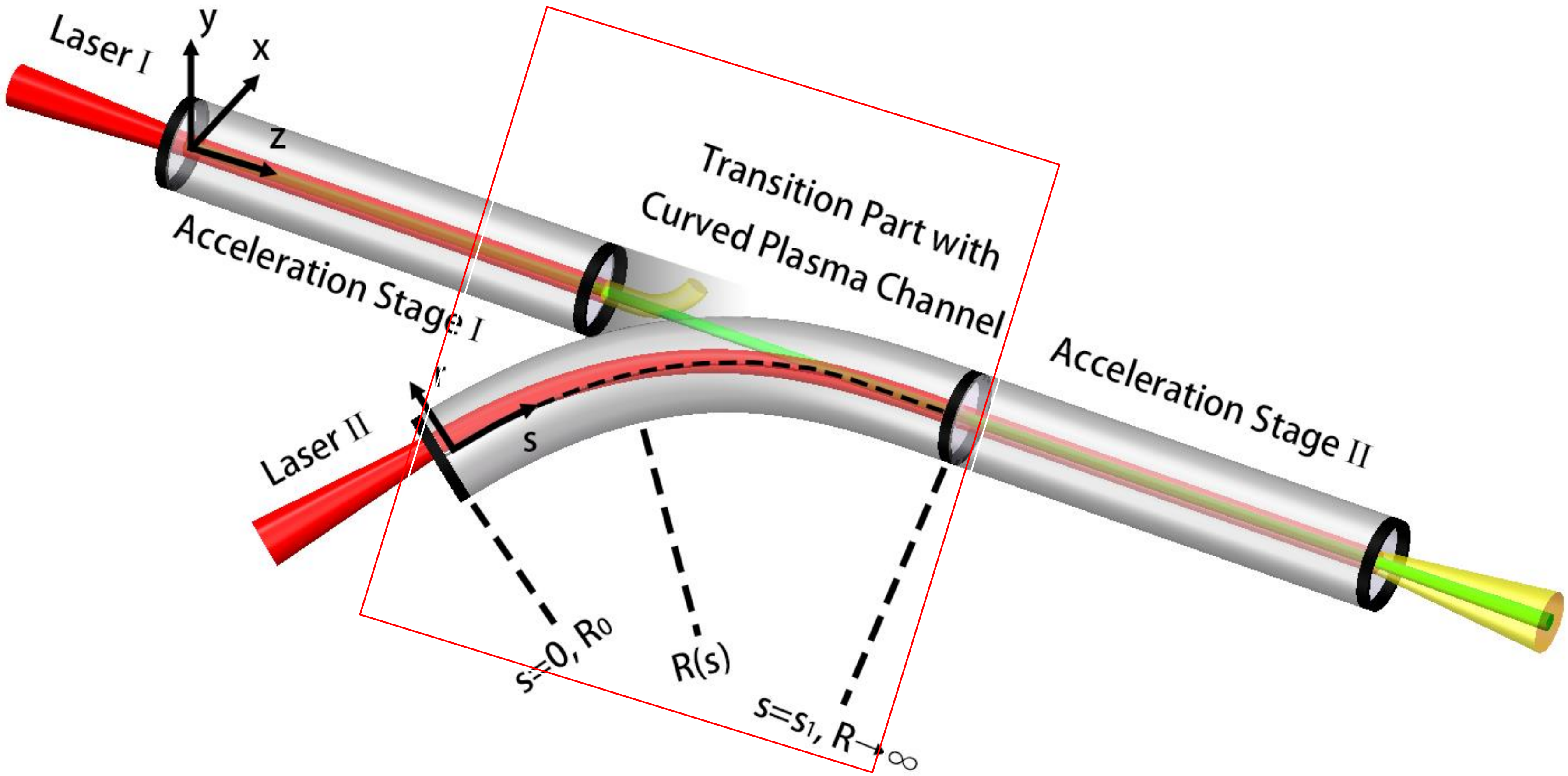
BERKELEY LAB

Other plasma lens schemes:

C. Thaury, et al., Nat. Commun. 6, 6860 (2015).

S. Steinke et al. Nature 530, 190 (2016).

Curved plasma channel based staging?



1. Accelerated electrons always propagate in the straight channel.
2. Fresh laser is stably guided from a curved plasma channel to the straight one without centroid oscillation.

J. Luo, M. Chen, W.Y. Wu, et al. PRL, 120, 154801 (2018)

Intense laser guiding in a curved plasma channel

Wave function of the vector potential: $(c^2\nabla^2 - \partial^2/\partial t^2)A_y = \omega_p^2 A_y$

Parabolic plasma channel: $n_p(r) = n_0 + \Delta n \cdot (r^2/w_0^2)$

Laser envelope evolution equation:

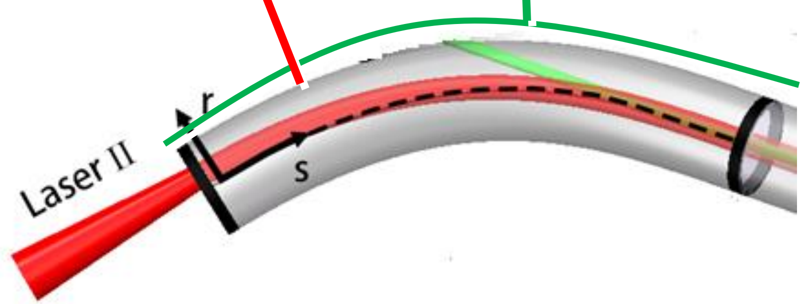
Channel transverse

Channel curvature effect

$$i\frac{\partial a}{c\partial t} = \left[-\frac{c}{2\omega_l}\frac{\partial^2}{\partial r^2} + \frac{\omega_l}{2c}\frac{n_0}{n_{cr}}\left(1 + \frac{\Delta n}{n_0}\frac{r^2}{w_0^2}\right) - \frac{\omega_l}{c}\frac{r}{R}\right]a$$

Initial value:

$$a(t=0,r) = a_0 \exp[-(r-r_0)^2/w_0^2]$$



Time-Dependent Schrödinger Equation (TDSE)

A. J. W. Reitsma et al. POP 14, 053104 (2007)

Intense laser guiding in a curved plasma channel

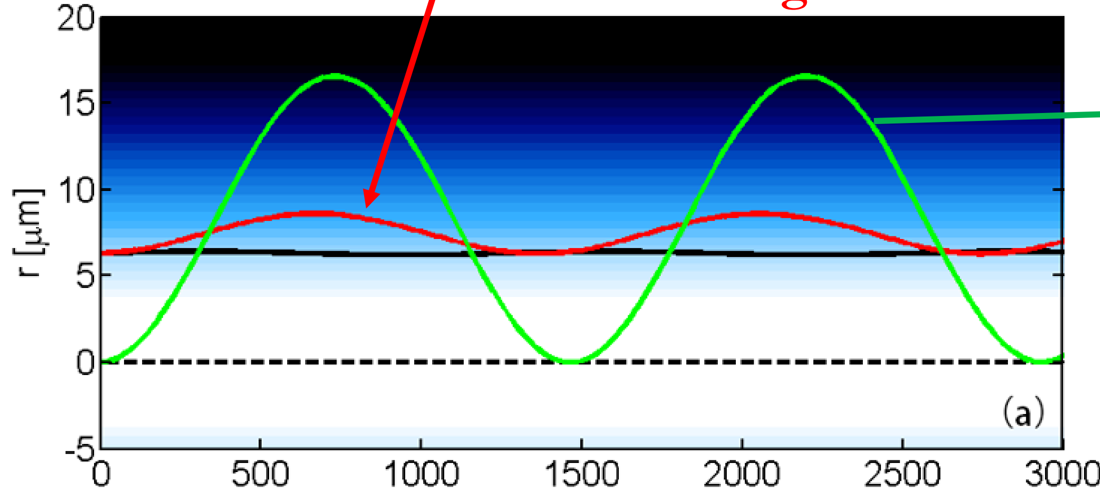
Laser intense effect: $\frac{n_0}{(1+|a|^2/2)^{1/2}}$

$$i\frac{\partial a}{c\partial t} = \left[-\frac{c}{2\omega_l}\frac{\partial^2}{\partial r^2} + \frac{\omega_l}{2c}\frac{n_0}{n_{cr}}\left(1+\frac{\Delta n}{n_0}\frac{r^2}{w_0^2}\right) - \frac{\omega_l}{c}\frac{r}{R}\right]a$$

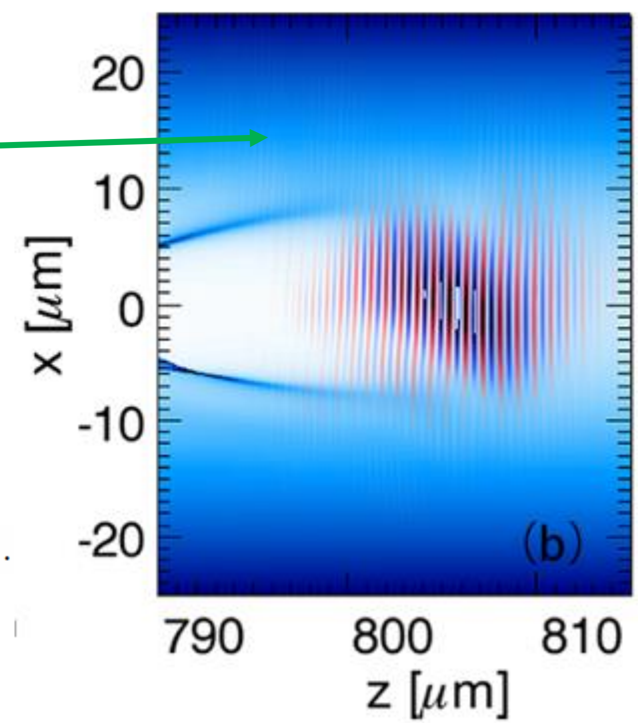
Nonlinear Time-Dependent Schrödinger Equation (TDSE)

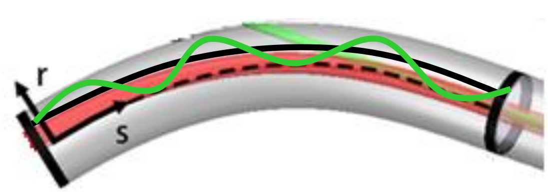
Equilibrium centroid motion: $\Rightarrow$ $r_{equ} = \frac{n_{cr}}{\Delta n}\frac{w_0^2}{R}$

Treat a curved channel as a straight channel



$\lambda_l = 0.8\ \mu m,\ w_0 = 8\ \mu m,\ R_0 = 10\ mm,\ n_0 = 10^{-3}\ n_{cr}.$





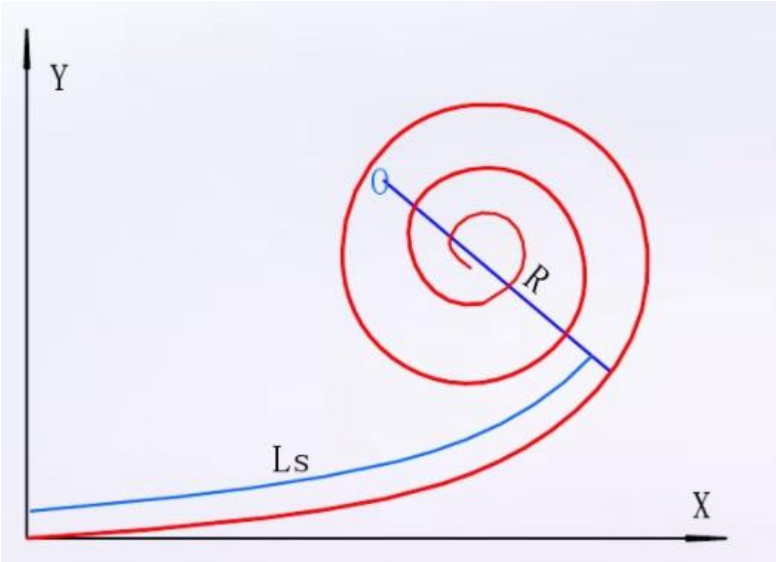
Stable off-center motion → oscillation in straight channel

Large transverse oscillation → laser profile distortion

Transition line curved plasma channel

$$i\frac{\partial a}{\partial t} = \left[-\frac{c^2}{2\omega_l}\frac{\partial^2}{\partial r^2} + \frac{\omega_l}{2}\frac{n_0}{n_{cr}}\left(1+\frac{\Delta n}{n_0}\frac{r^2}{w_0^2}\right) - \omega_l\frac{r}{R}\right]a$$

Curvature is varying.



Transition line curved plasma channel

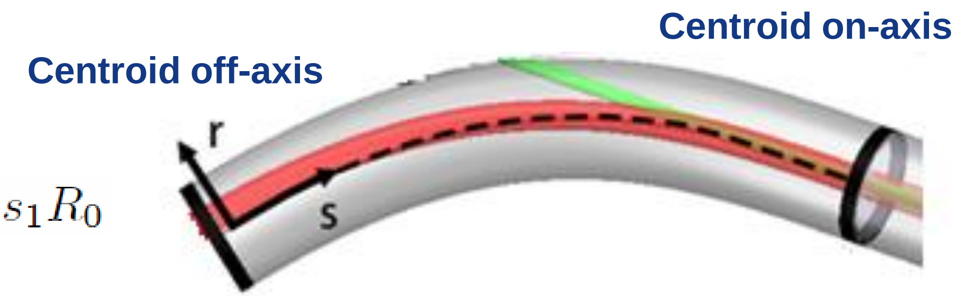
Transition Curve： $(s_1\text{-}s)\cdot R^{\alpha}$=Const

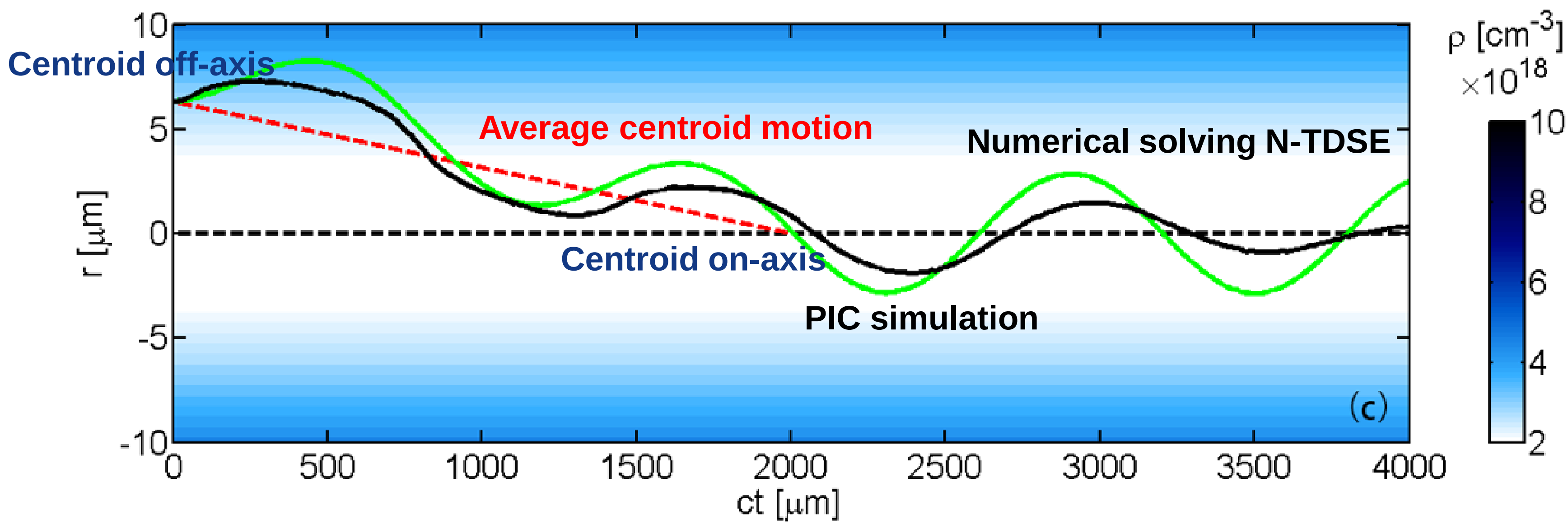
$$r_{equ}=\frac{n_{cr}}{\Delta n}\frac{w_0^2}{R}=\frac{n_{cr}}{\Delta n}\frac{w_0^2}{R_0}(\frac{s_1-s}{s_1})^{1/\alpha}$$

Fixed dr_{equ}/ds ⇨ **α=1,** $(s_1-s)\cdot R=s_1R_0$

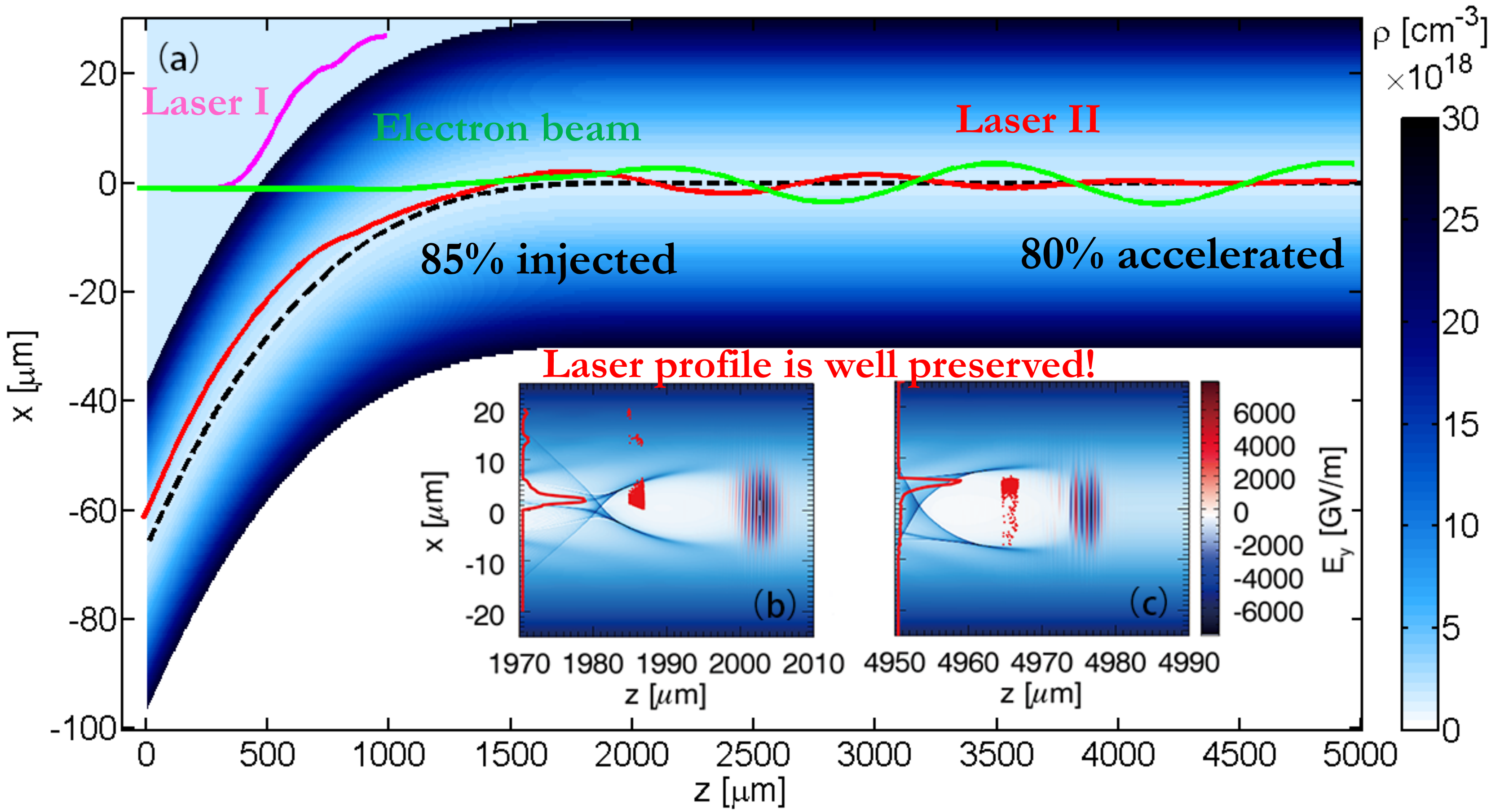
$$\theta=(s_1-s)^2/2s_1R_0.$$

$$\begin{cases} z=\int d(s_1-s)\cdot cos\theta\approx s\approx ct \\ x=\int d(s_1-s)\cdot sin\theta\approx(s_1-ct)^3/(6s_1R_0) \end{cases}$$



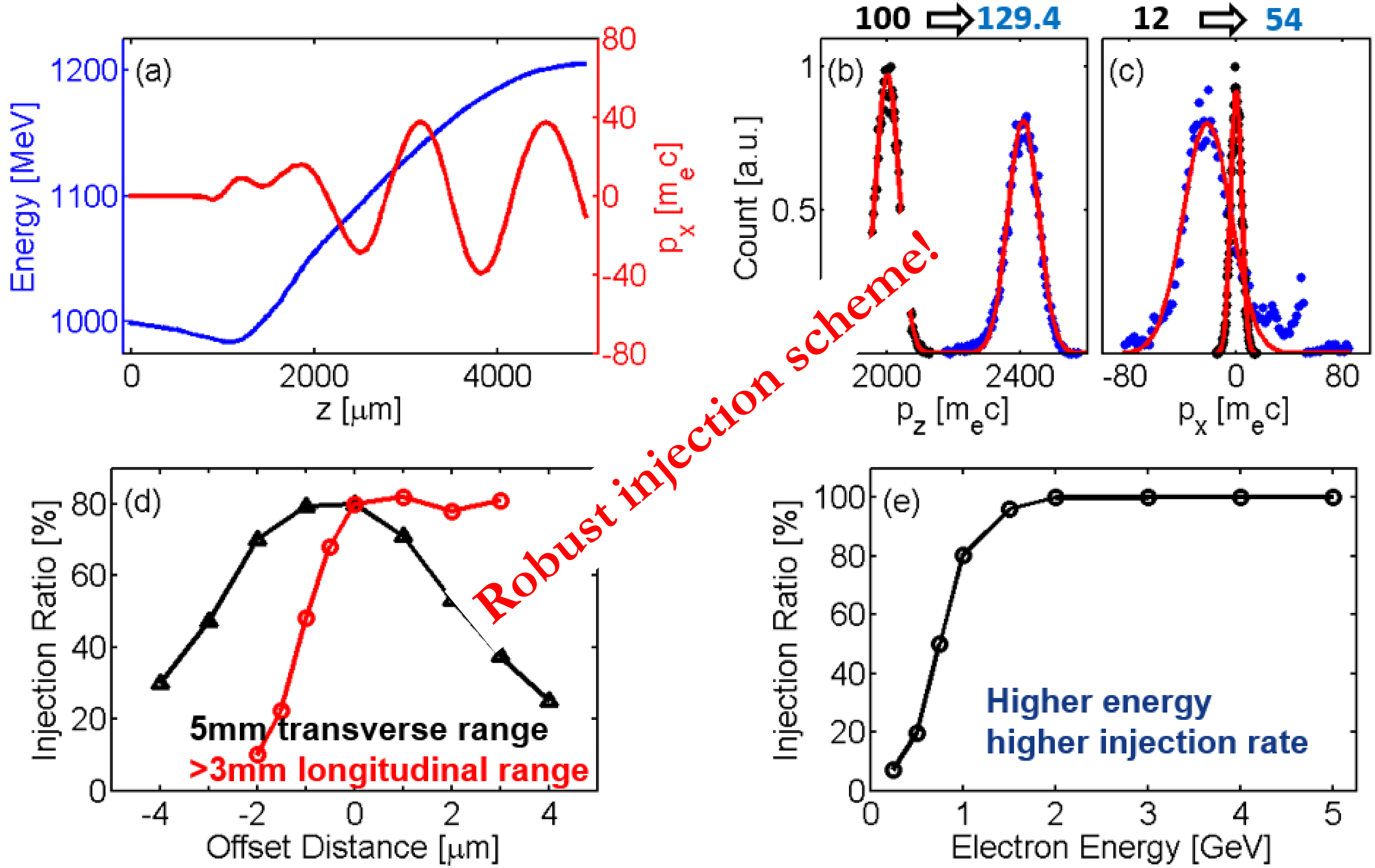


PIC simulation of staging scheme

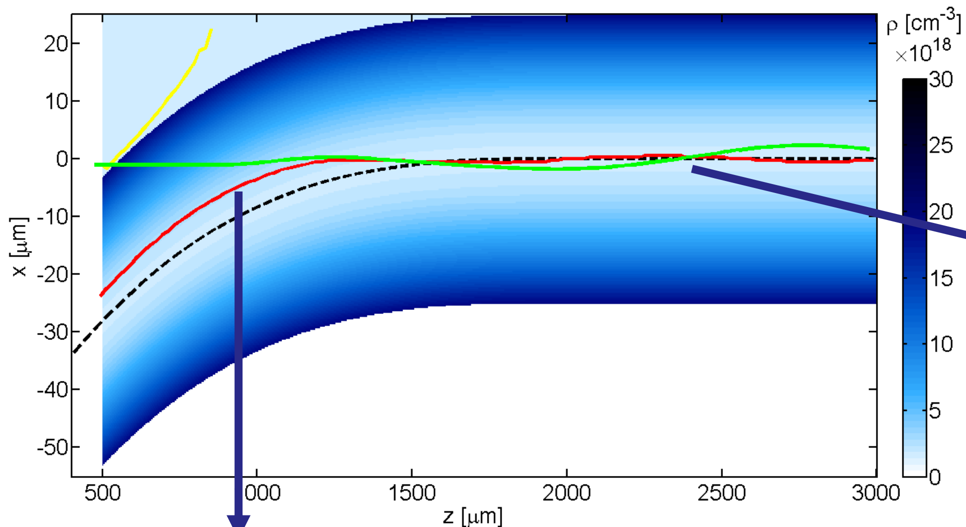


Laser I: a_0=0.7, Sin-squared longitudinally envelope, τ=15fs, w_0=8μm;
Laser II: a_0=2.0, Gaussian longitudinally envelope, τ=20fs, w_0=8μm.
e- beam: E_0=1GeV, $(\Delta E)_{FWHM}$=50MeV, $\langle p_x \rangle = p_y = 0$, $(\Delta p_x)_{FWHM}$=12$m_e c$,
r_b=0.5μm, l_b=2μm, Incidence angle=5.7°, off-axis = 6.33μm,
Channel: R_0=10mm, s_1=2000μm.

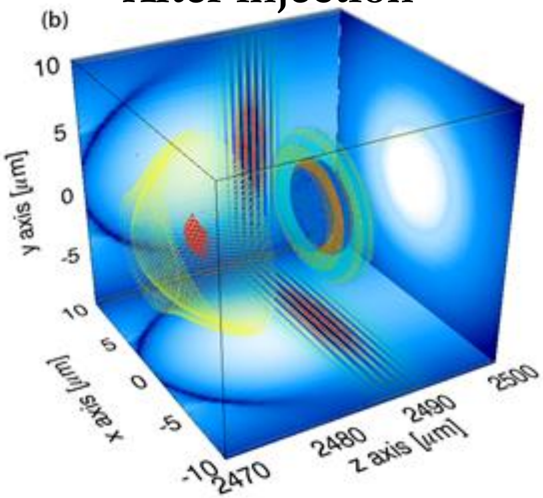
Beam Quality variation and injection tolerance

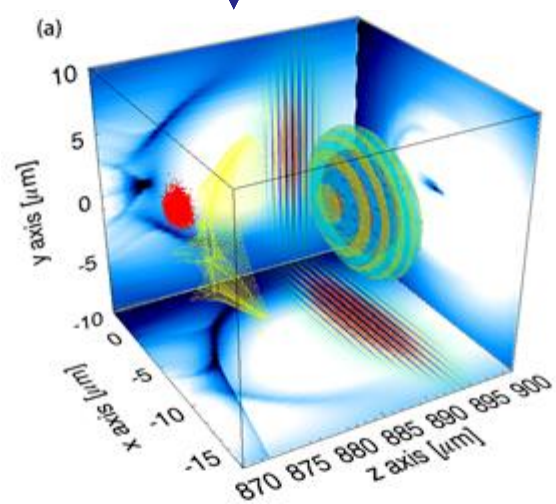


Three dimensional simulations

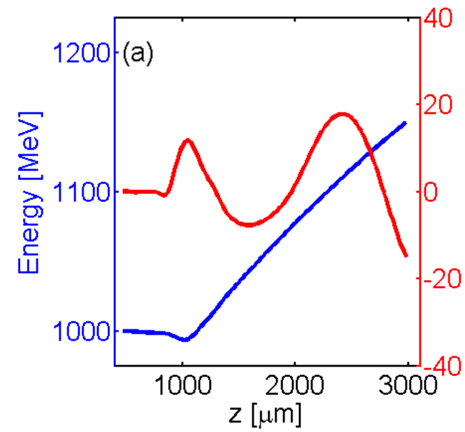


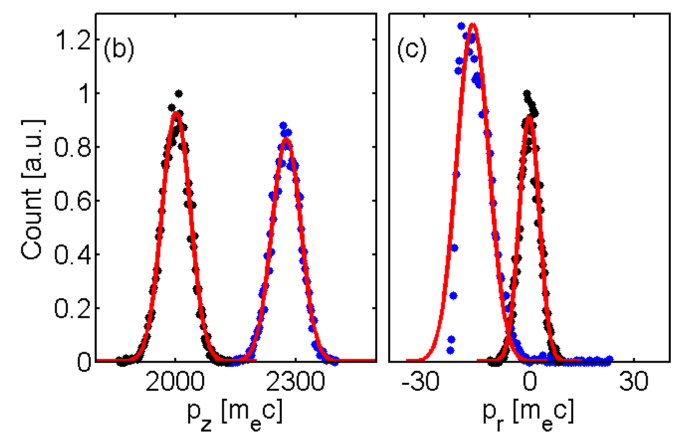
After injection





Before injection





In 3D, about 92.6% electrons are injected in the second stage.

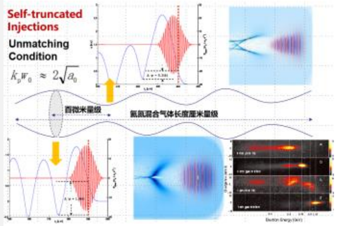
J. Luo, M. Chen, W.Y. Wu, et al. PRL, 120, 154801 (2018)

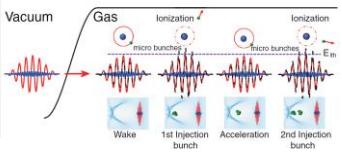
LWFA studies at SJTU (2014-2018)

SJTU Main topics:

1. Electron injection in Wakefield

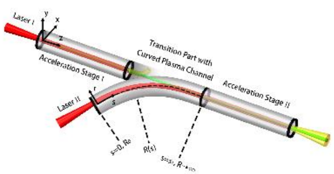
a) **Self-truncated ionization injection and experimental demonstration.** Phys. Plasmas 21, 030701 (2014); Sci. Rep. 5, 14659 (2015)
b) **Two-color laser induced ionization electron for energy spread as low as 0.29%.** Phys. Rev. Lett.114, 084801 (2015)
c) **External magnetic field assisted ionization injection.** NJP. 20, 063031 (2018)
d) **Electron Trapping from Interactions between Laser-Driven Relativistic Plasma Waves.** Phys. Rev. Lett., 121, 104801 (2018) Collaborated with UNL
e) …





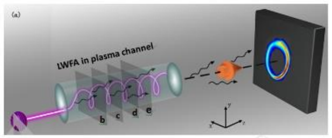
2. New staging scheme for LWFA

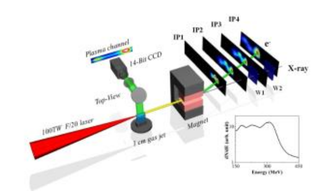
a) **Multistage Coupling of Laser-Wakefield Accelerators with Curved Plasma Channels.** Phys. Rev. Lett., 120, 154801 (2018)



3. Radiation in Wakefield (From THz to γ-ray)

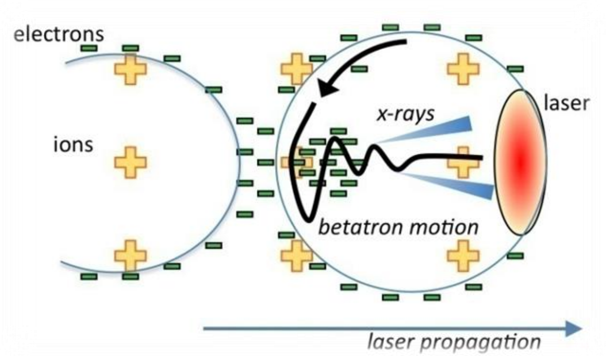
a) **Tunable synchrotron-like radiation from centimeter scale plasma channels.** Light: Science & Applications, 5, e16015 (2016).
b) **A compact tunable polarized X-ray source based on laser-plasma helical undulators.** Sci. Rep. 6, 29101 (2016)
c) **High-order multiphoton Thomson scattering.** Nature Photonics, 11, 514 (2017) with UNL
d) …

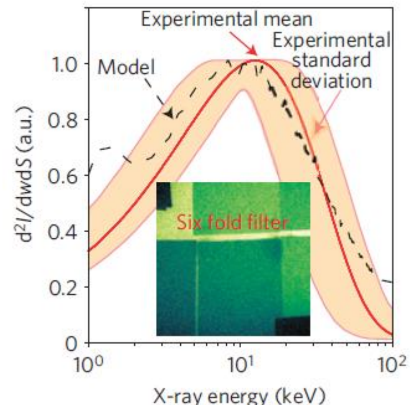




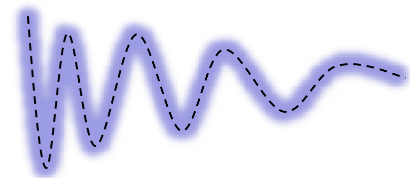
Usual radiation of LWFA electrons

1. Betatron radiation due to transverse field in wake





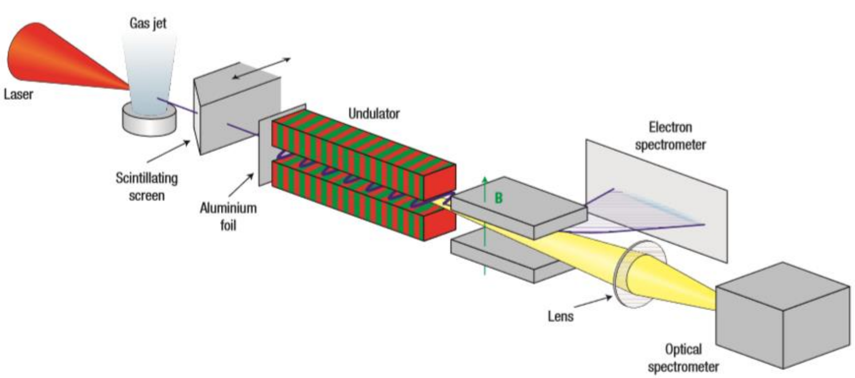
S. Kneip et al., Nature Phys. 6, 980 (2010)

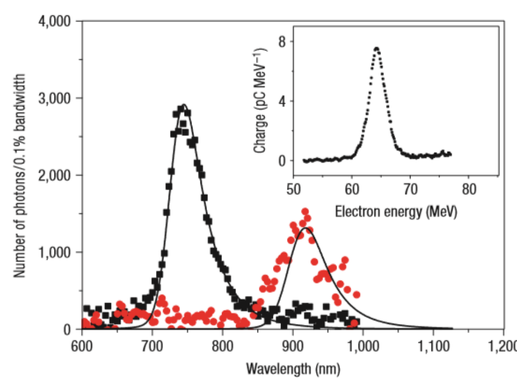


Lack of efficient tunability on oscillation period and amplitude

2. External magnetic undulator

Beam injected into Undulator: Synchrotron Radiation (XUV, X-ray)





Coupling is not so easy

H.-P. Schlenvoigt, et al., Nat. Phys. 4, 130 (2008).

Using plasma channel to guide and control laser & electron oscillations

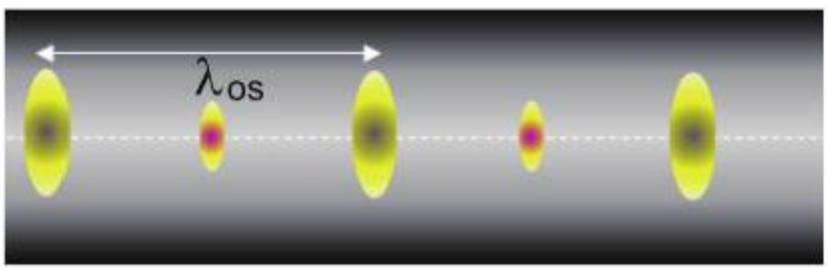
$$|a|^2 = (a_0 r_0/g_s)^2 \exp(-2r^2/r_s^2)$$

$$r_s = r_i \text{ and } r_s = (\Delta n/\Delta n_c)^{1/2} r_0^2/r_i$$

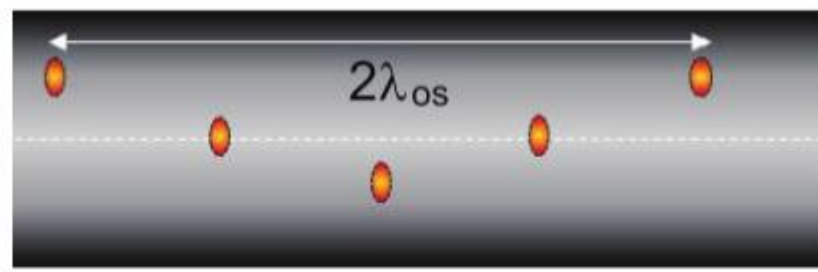
$$\frac{d^2R}{dz^2} = \frac{1}{Z_M^2 R^3}\left(1 - \frac{\Delta n}{\Delta n_c} R^4\right)$$

Laser spot size evolution

On-axis injected laser propagates in channel



Off-axis injected laser propagates in channel

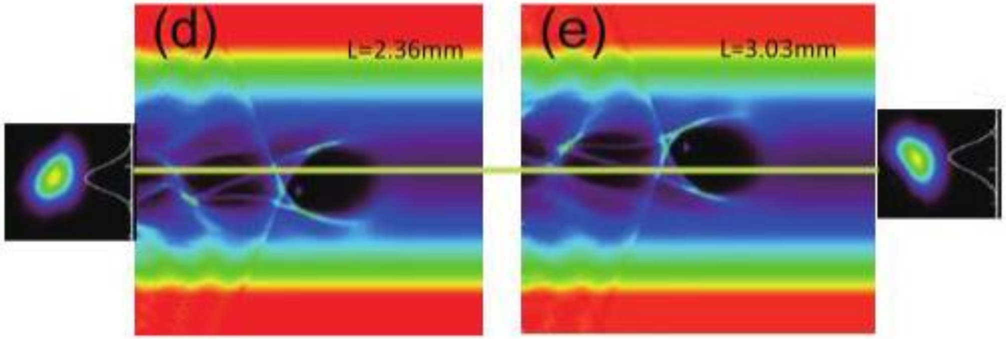


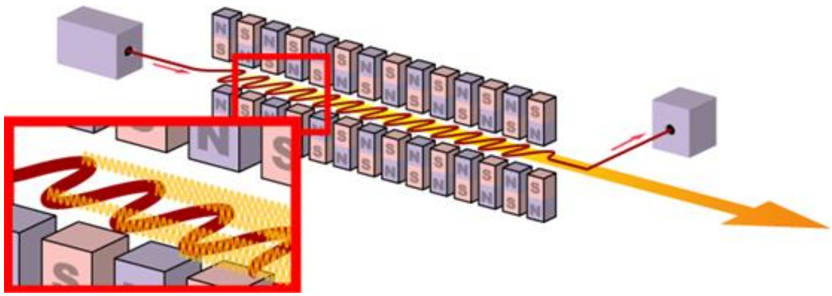
$$\lambda_{os} = \pi Z_M (\Delta n/\Delta n_c)^{1/2}$$

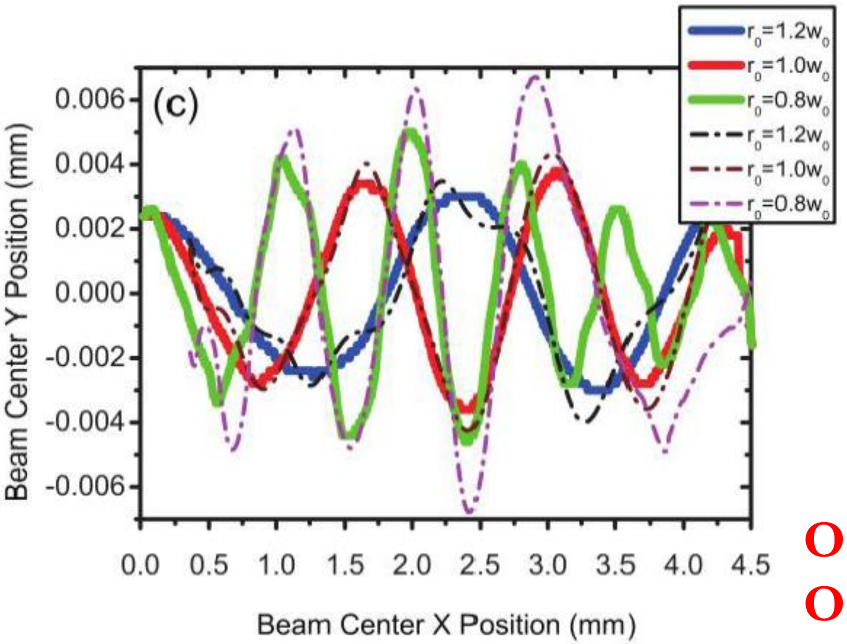
Laser, wake and electrons oscillate in channel

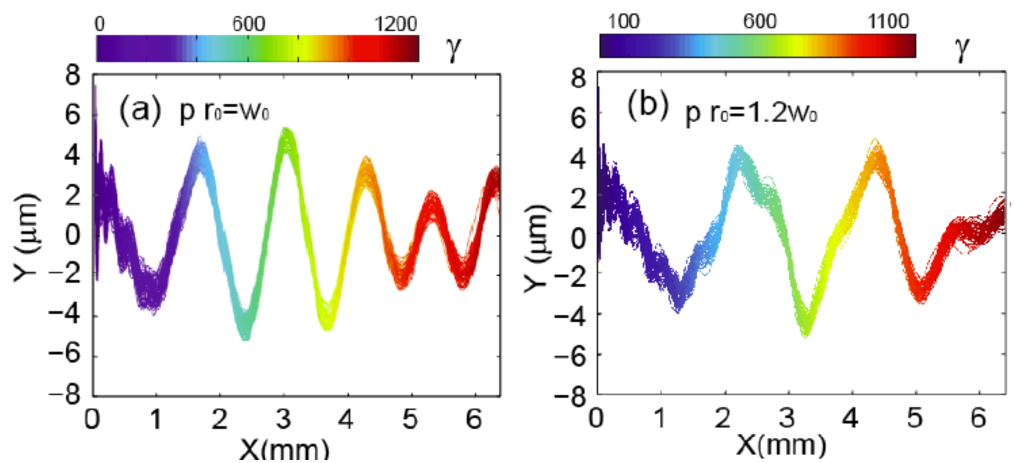
M. Chen *et al.*, Light: Science & Applications, 5, e16015 (2016)

Using plasma channel as an undulator







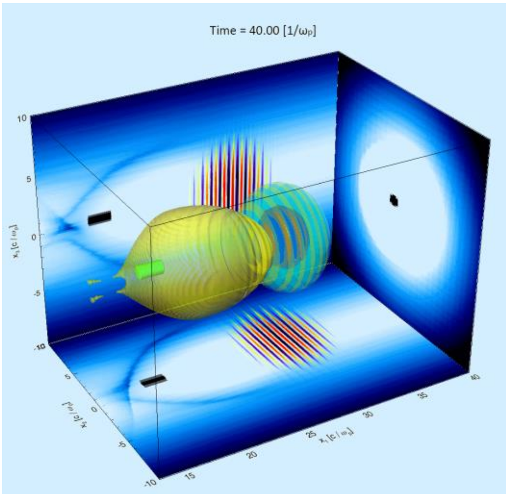


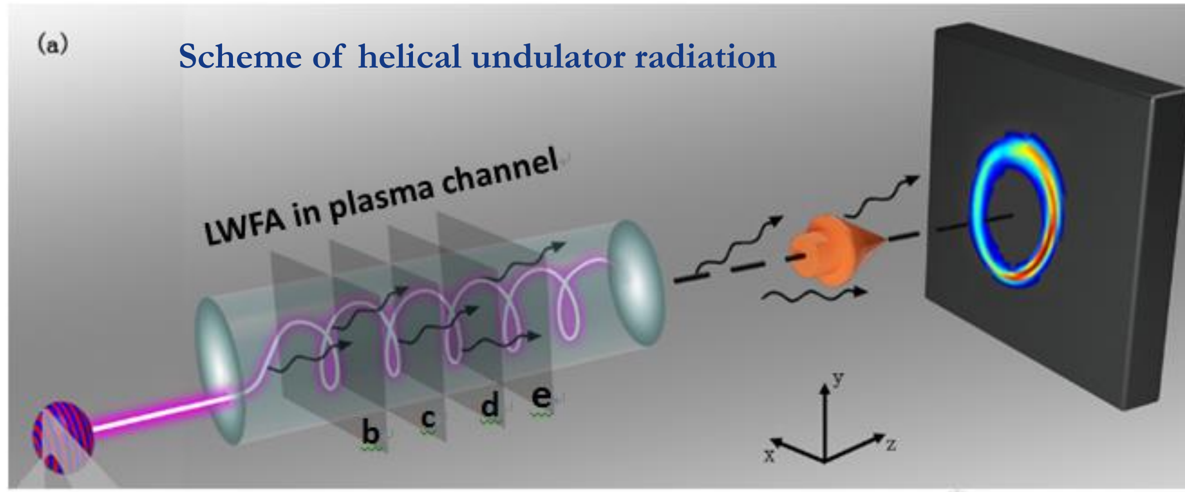
Oscillation period: plasma density

Oscillation amplitude: injection position

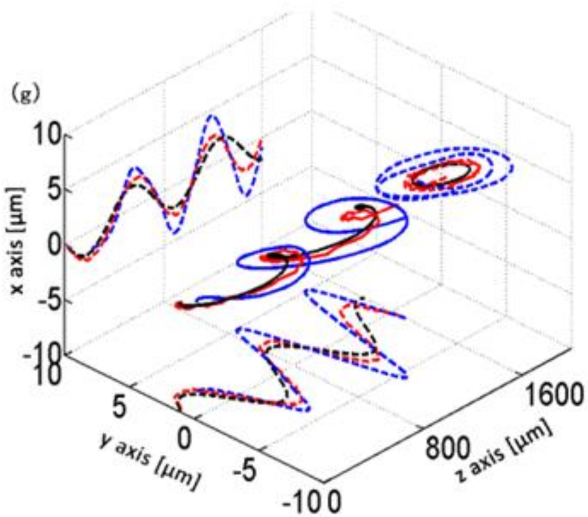
M. Chen *et al.*, Light: Science & Applications, 5, e16015 (2016)

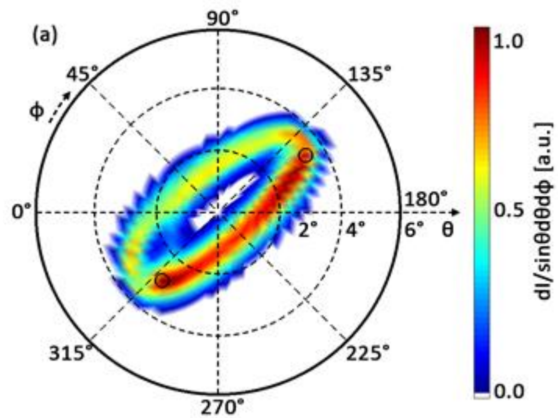
Radiation from helical plasma undulator

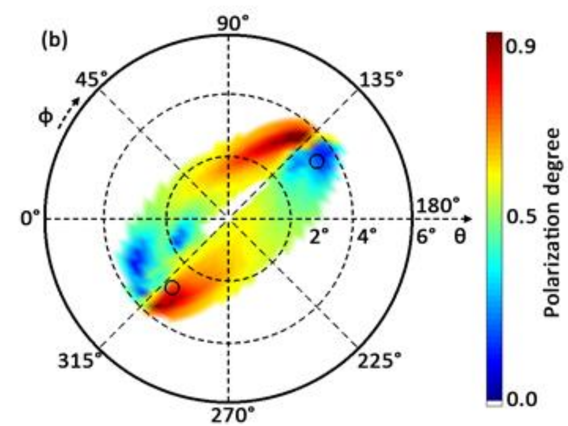




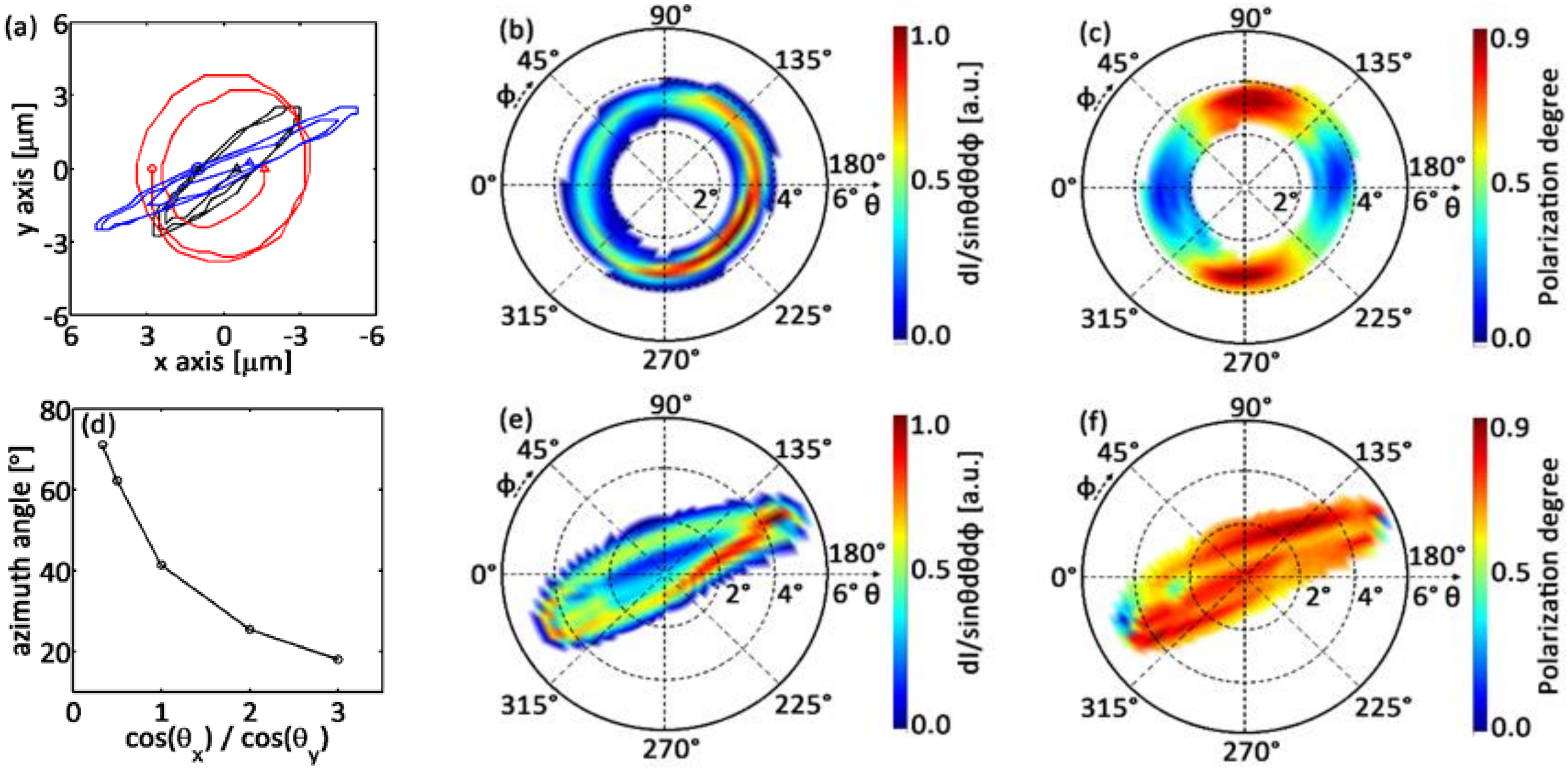
Laser and e$^-$ beam center trajectories







Tunability on intensity, distribution and polarization

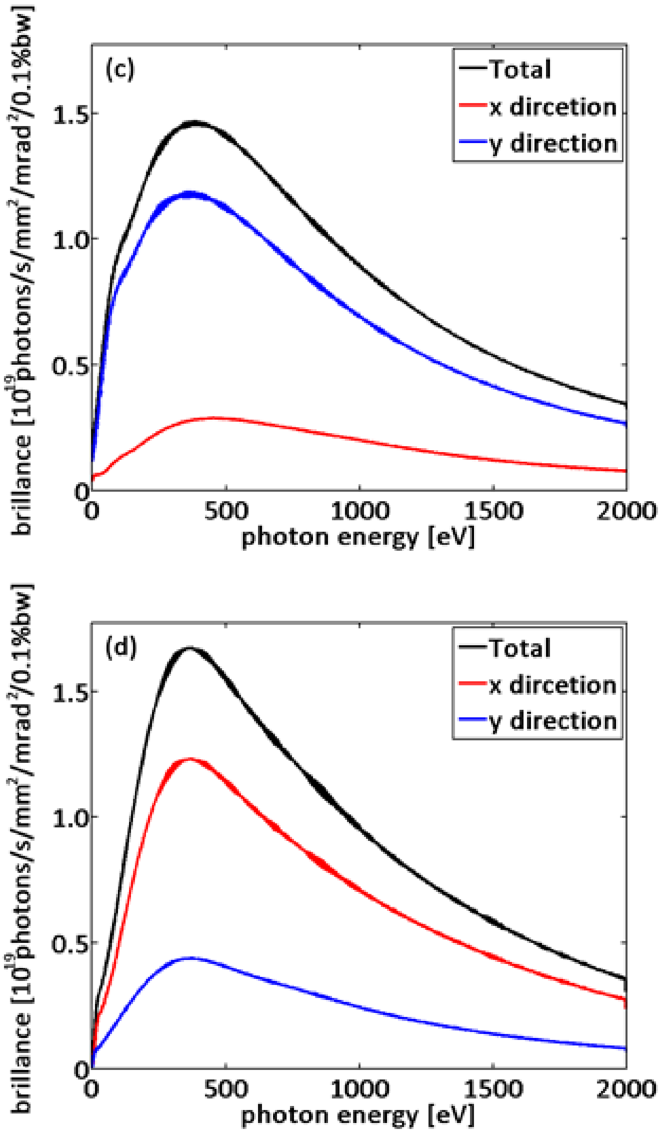


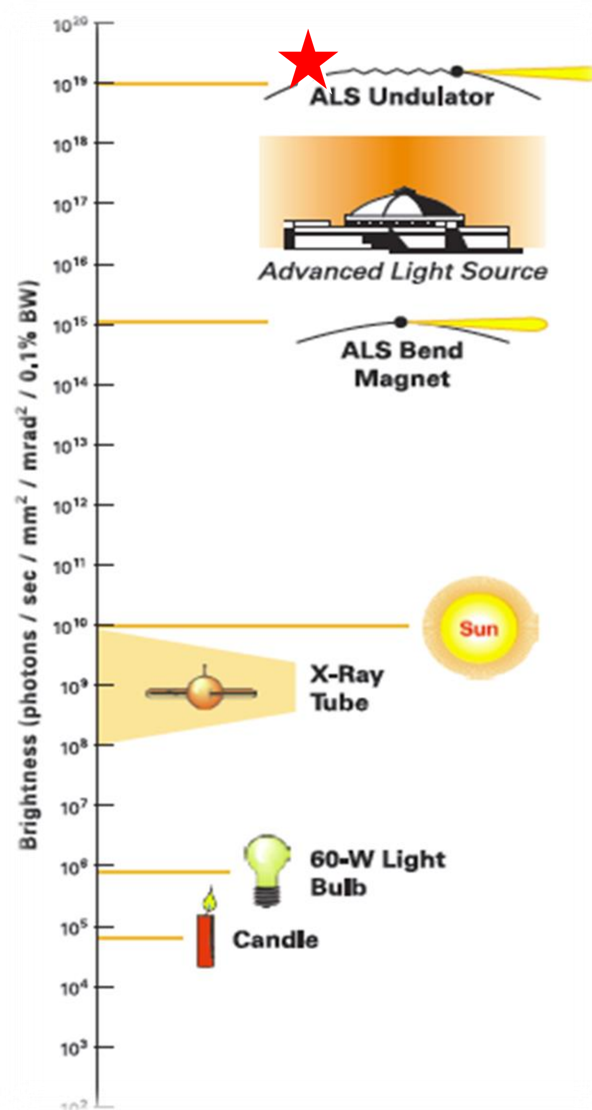
Radiation pattern control through tuning the laser injection angle

Spatial distribution of radiation intensity

Spatial distribution of radiation polarization

Radiation brightness





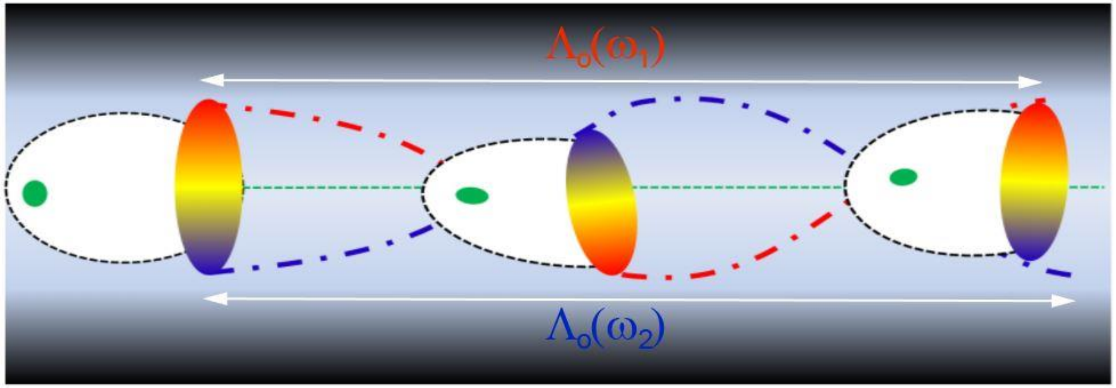
For 4.5pC charge
2×10^{19} photons/s/mm^2/mrad^2/0.1%BW

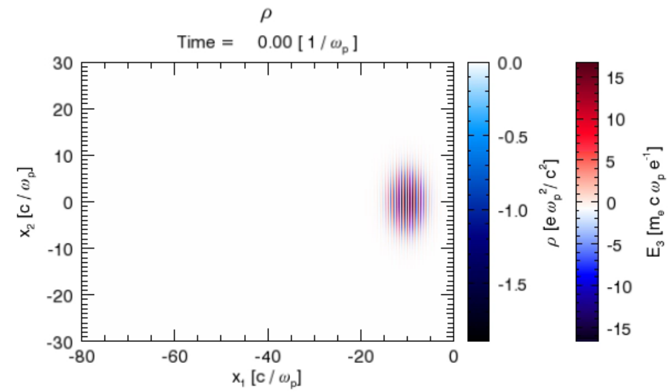
Photon energy tunable from 400eV to 1.5keV

Similar as 3rd synchrotron radiation sources

J. Luo *et al*, Sci. Rep. 6, 29101 (2016)

Transverse spatial chirp induced radiation





A parabolic plasma channel :

$$n(r) = n_0 + \Delta n\, r^2/r_0^2$$

The refractive index :

$$\eta_r = 1 - [1 + (\Delta n/n_0)\,(r^2/r_0^2)]\,\omega_{p0}^2/2\omega^2$$

Laser pulse normalized electric field intensity :

$$a = eE/m\omega_0 c$$

$$\approx a_0 \exp(-r^2/W_0^2)\exp(-\xi^2/L_0^2)\cos[(\omega_0+\omega')t]$$

$$\omega = \omega_0 + \omega' \;(\omega' = \alpha\omega_0\, y/W_0)$$

Laser phase velocity:

$a_0 = 2.0$

$\lambda_0 = 0.8\mu m$

$W_0 = 10\lambda_0$

$L_0 = 6T_0$

$\alpha = 0.0125$

$n(r) = n_0 + \Delta n\, r^2/r_0^2$

$n_0 = 0.001 n_c$

$\Delta n = \Delta n_c = (\pi r_e r_0^2)^{-1}$

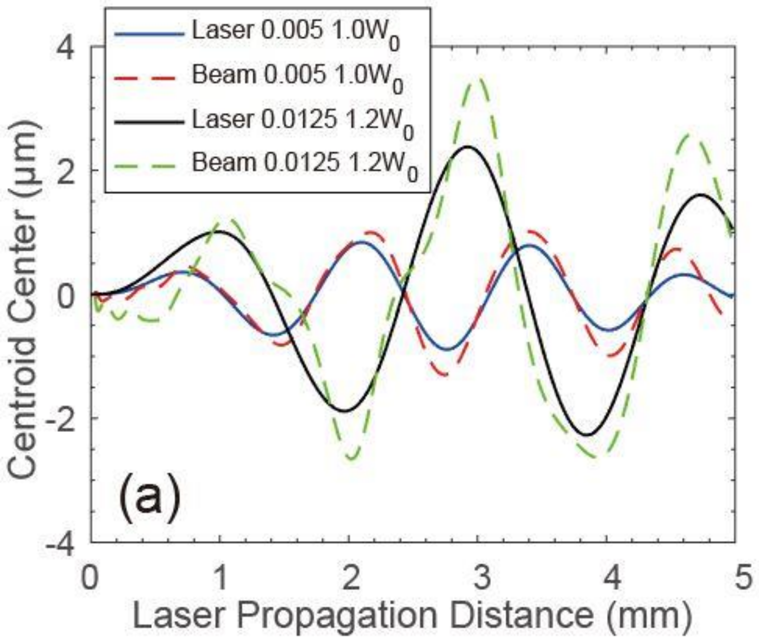
$r_0 = 1.0 W_0$

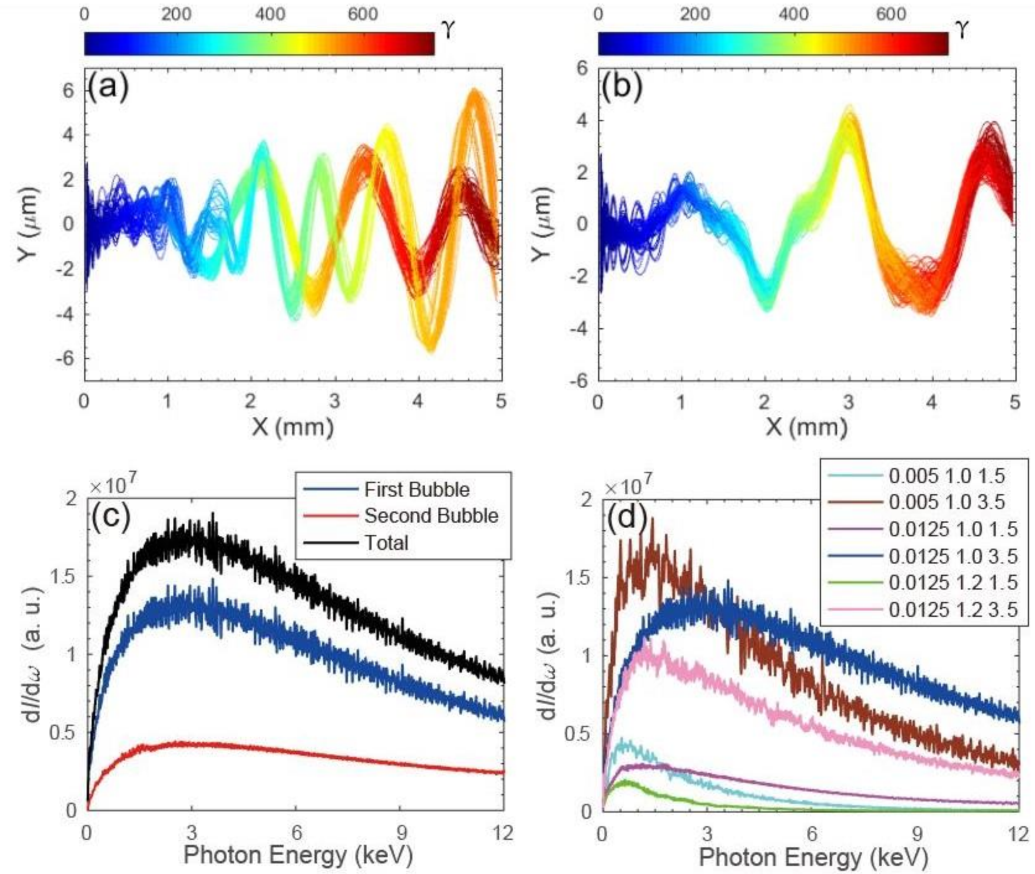
Ionization injection

Transverse spatial chirp can induce transverse centroid oscillation of laser inside a plasma channel, which makes controllable wake and beam oscillation. (Currently the effects of transverse chirp on focus and pulse duration have been neglected.)

Beam oscillation and radiation

α, r_0 effects on laser and electron beam oscillation



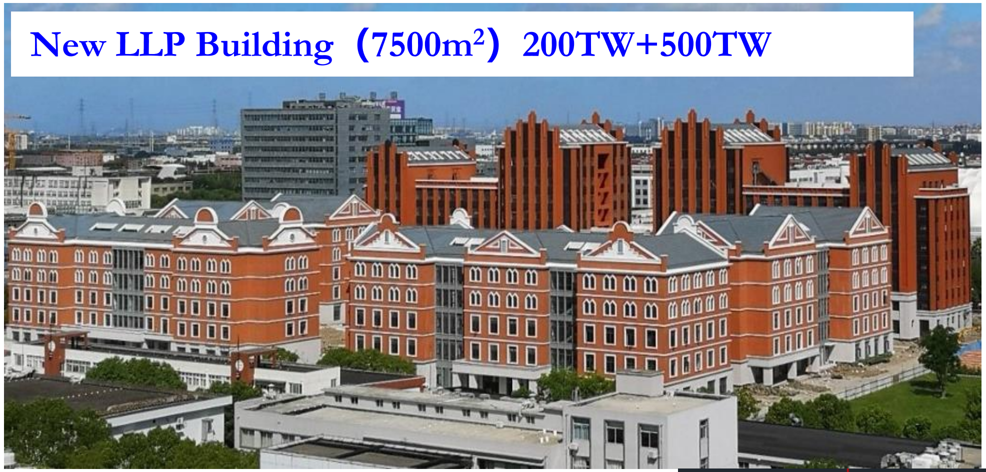


Initial simulation studies show that oscillation amplitude is proportional to the transverse chirp and oscillation period depends on the channel width.
Both radiation intensity and spectrum can be controlled through laser and channel parameters.

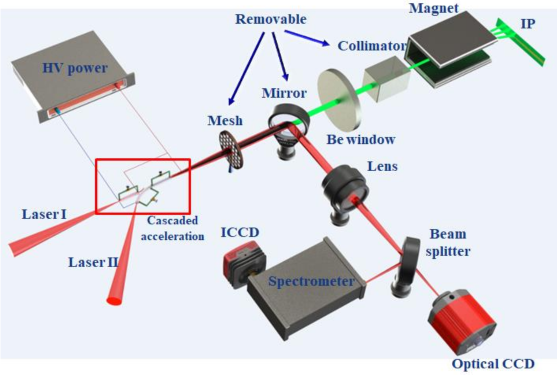
Future studies at LLP, SJTU (2019-2024)

SJTU Main plans: Upgrade the current 200TW to 200+500TW two-beam system.

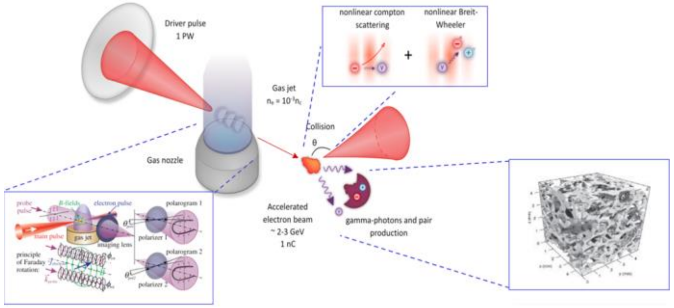
1. Demonstration of high quality two-color laser ionization injection (~0.1% Energy spread, low emittance)
2. Staged laser wakefield acceleration (curved plasma channel, 1GeV→ 1.5GeV)
3. LWFA based nonlinear Thomson scattering sources

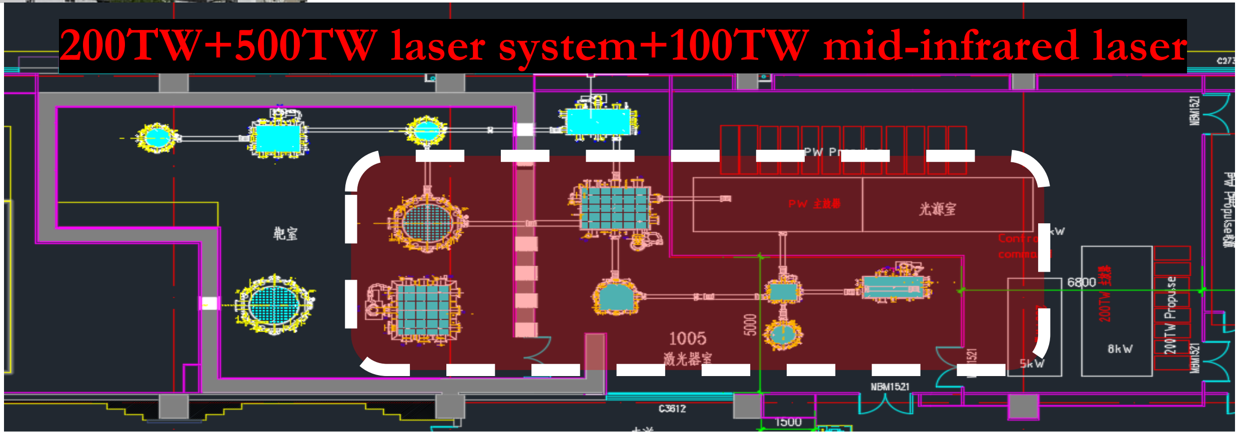


Curved plasma channel based controlled radiation and staging studies.



LWFA based electron, photon source & Applications





Summary

- Improved ionization injection schemes are studied to reduce the energy spread.
- Curved plasma channel based multistage laser wakefield acceleration is numerically demonstrated.
- Plasma channel based undulator radiation is proposed and demonstrated in simulations. Helical plasma undulator and polarization controllable radiation can be realized by this method.

Thanks for your attention!

minchen@sjtu.edu.cn

References:

[1] J. Luo, et al. Phys. Rev. Lett., 120, 154801 (2018) Staging

[2] Q. Zhao et al., NJP., 20, 063031 (2018) Injection

[3] M. Zeng et al., Phys. Rev. Lett. 114, 084801 (2015) Injection

[4] M. Mirzaie et al., Sci. Rep. 5, 14659 (2015) Injection

[5] M. Chen et al., Light： Science & Applications. 5, e16015. (2016) Radiation

[6] J. Luo, et al, Sci. Rep. 6, 29101 (2016) Radiation