WG4 : Innovative Accelerator Techniques

Brief Summary of WG4

Number of talks : 20

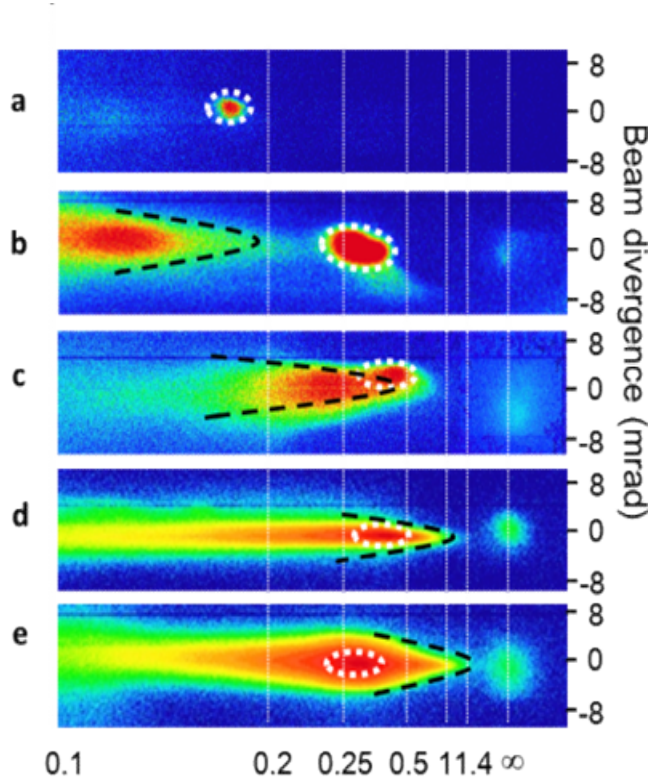
- **Russia : 4 (BINP 2, LPI, IAP)**
- **China : 6 (IHEP 2, SJTU 2, PKU, BNU)**
- **Japan : 3 (KEK, QST, Osaka U.)**
- **Korea : 3 (GIST, UNIST, PAL)**
- **Taiwan : 2 (NTHU, NCU)**
- **India : 2 (DU, ASU)**

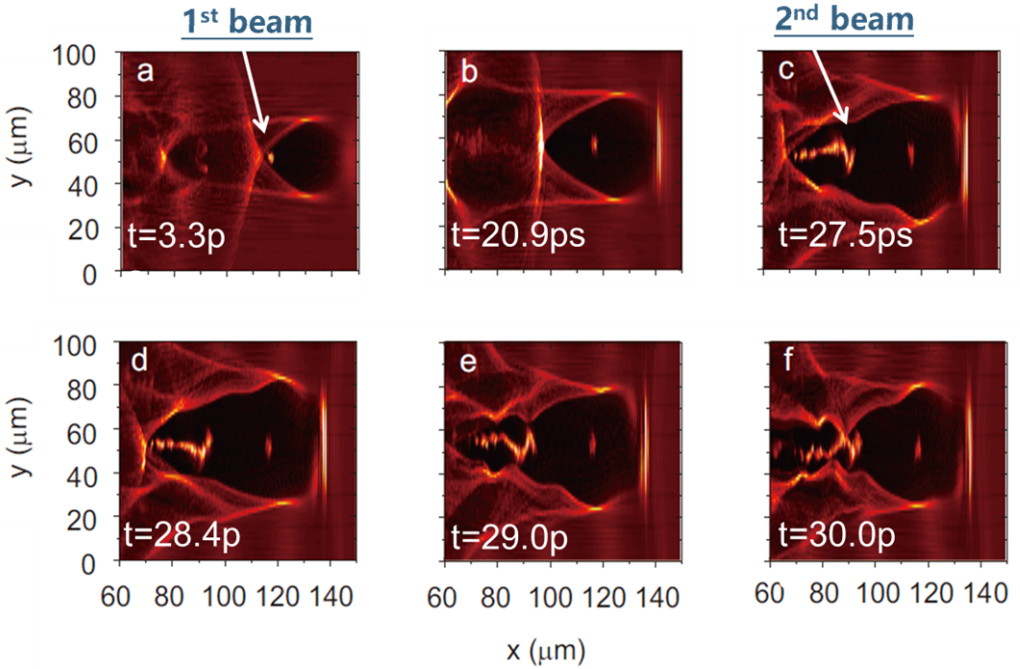
Main Research Activities

1. Electron acceleration
   - laser wakefield acceleration
   - dielectric laser acceleration
2. X-ray/γ-ray generation
   - betatron radiation
   - inverse Thomson scattering
   - e-beam+solid target
3. Ion acceleration
   - laser+thin foil

SJTU-Chen

e- & Betatron enhance: Oscillation Injection





Brilance=2×10^{23} phs/s/mm^2/mrad^2/0.1%BW

E_{max}= 1.4 GeV
E_{center}= 300 MeV
Q = 600pC > BL

Betatron E_{cri}= 15 keV
Photon = 4.5×10^8
Divergence = 6 mrad

$$\Delta E(\text{GeV}) = 1.7[P(\text{TW})/100]^{1/3}[10^{18}/n_e]^{2/3}[0.8/\lambda_0]^{4/3}$$
$$\sim 0.67 < 1.4 \text{ GeV (exp.)}$$

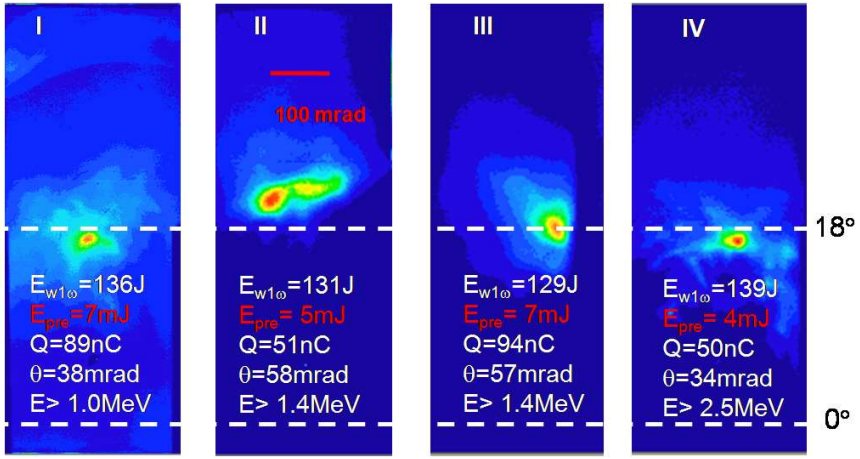
Electron charge is limited by beam loading effect in self injection. Oscillating injection results in much higher electron energy, charge and oscillation, and brighter betatron radiation.

PNAS 111, 5825(2014)

SJTU-Chen

Ultrahigh charge e-beam charge from solid

With suitable pre-pulse E_{pre} ~ 5 mJ



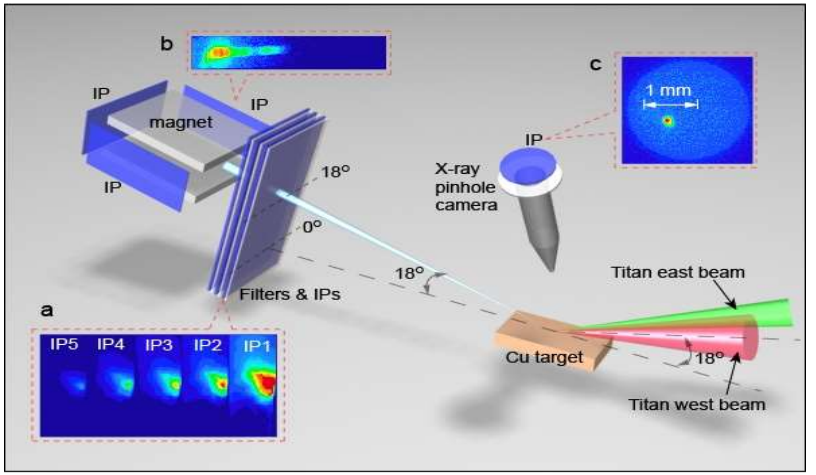
- Collimated: < 2°
- Directional: laser specular
- Charge: ~100 nC !

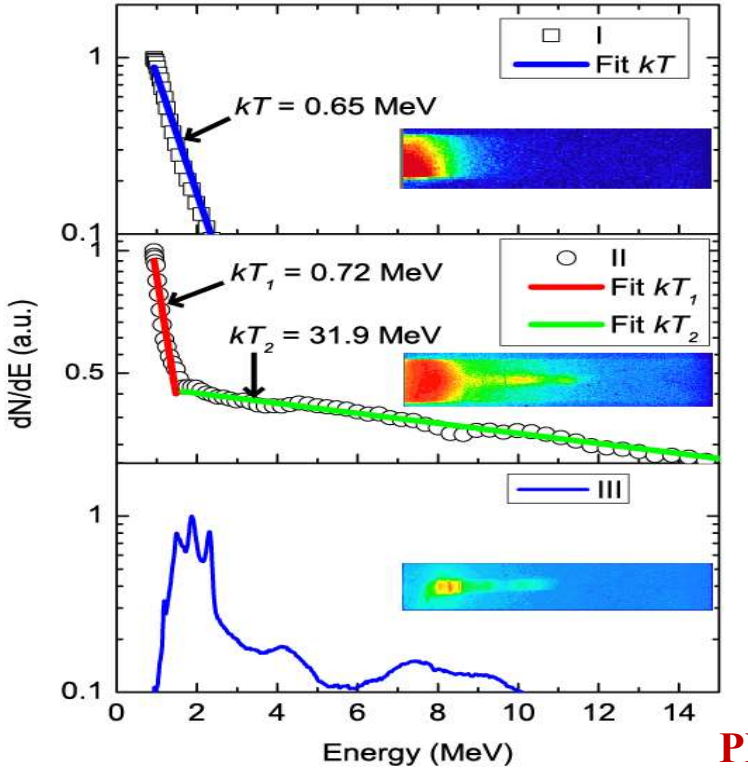
γ-ray bremsstrahlung source:

Yield： 2 x 10^{11}

Duration ~ ps, Size < mm

Suitable preplasma help ps laser to accelerate ultra-high charge e-beam, which lead to ultra-intense γ-ray sources.



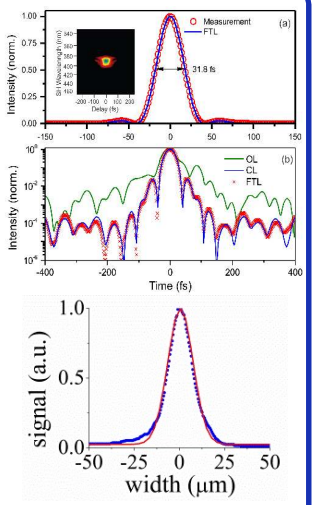


PNAS(2018)

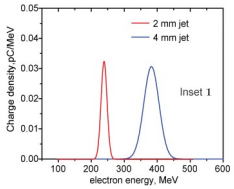
SJTU-Yan

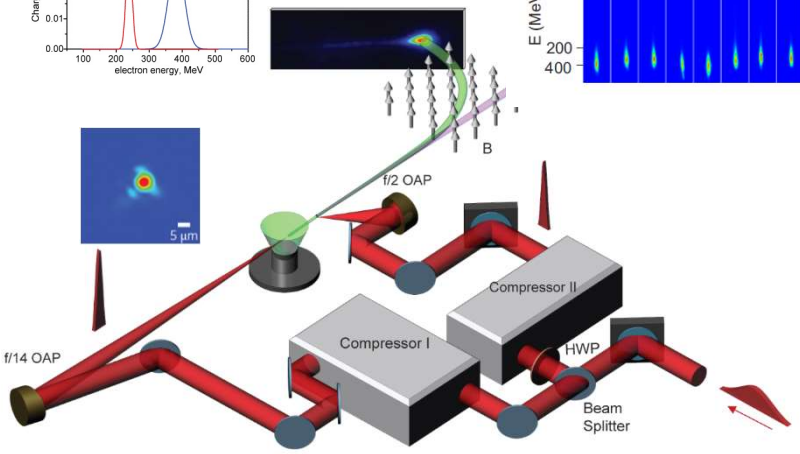
Summary: High-order Multiphoton Thomson Scattering

High-order Nonlinear regime

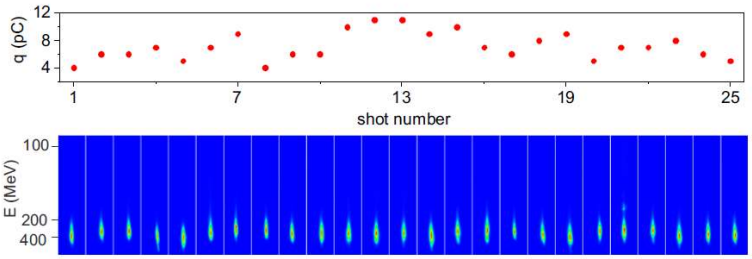


Adaptive Control of Spatial-Temporal





Electron stability

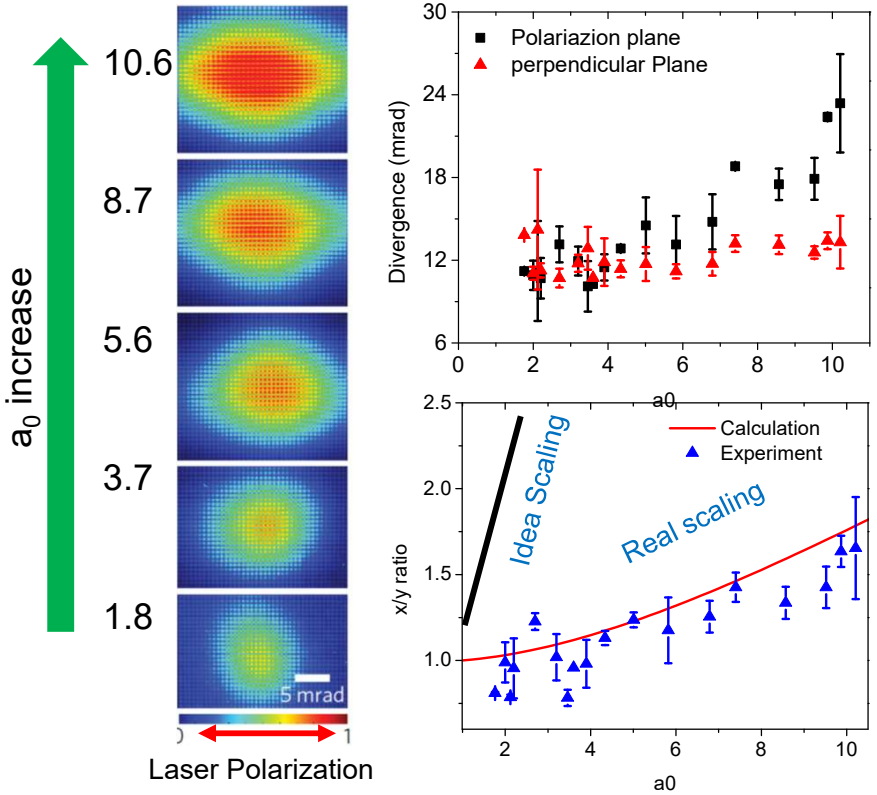


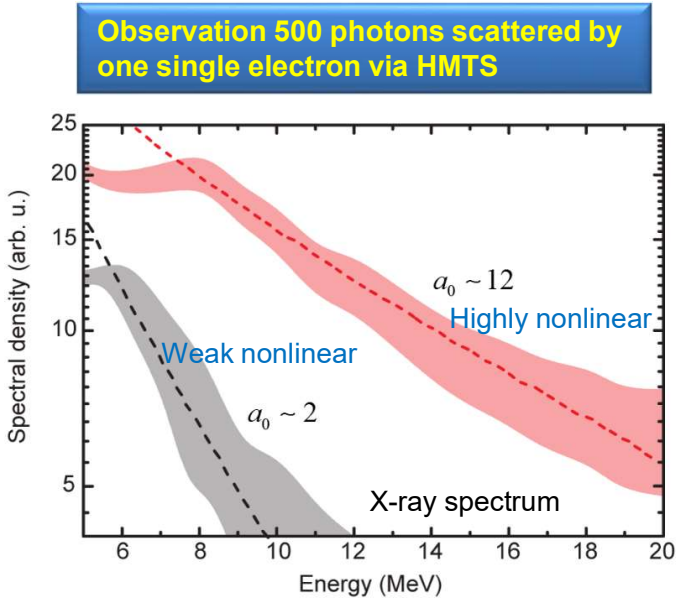
LWFA		
Gas	He	
Nozzle	2/4	mm
electron	200 /350	MeV

Scattering laser		
Energy	E_{Lmax}	3 J
Intensity	a_0	1.5~12

W. Yan et al, *Nature Photonics*, **11**, 514. (2017)
S. Banerjee, et al, PRAB, (2012)
G. Golovin, **W. Yan**, et al NIMA, 830 375-380 (2016)

Summary: High-order Multiphoton Thomson Scattering





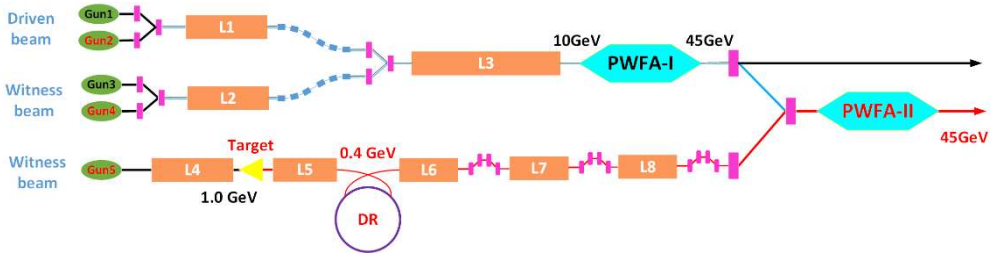
- Electron oscillation in the P plane getting larger with increase a_0.
- **Confirmed a0>10**

W. Yan et al, *Nature Photonics*, **11**, 514. (2017)

IHEP-Zeng

Studies of plasma based accelerators at IHEP

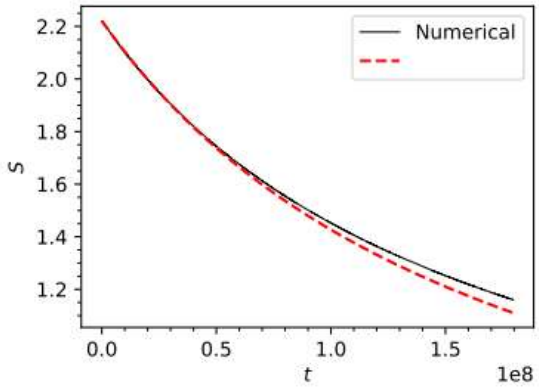
•CEPC Plasma Injector: 10 / 2.4 GeV e^- / e_+ boosted to 45.5 GeV using PWFA



Radiation Reaction of Betatron Oscillation in Wakefield

The area encircled by the electron trajectory in x-p_x phase space *S* reduces by a half in the length scale

$$L_S = \frac{8\sqrt{2}\pi}{k_p^2 r_e \sqrt{\gamma} S}$$

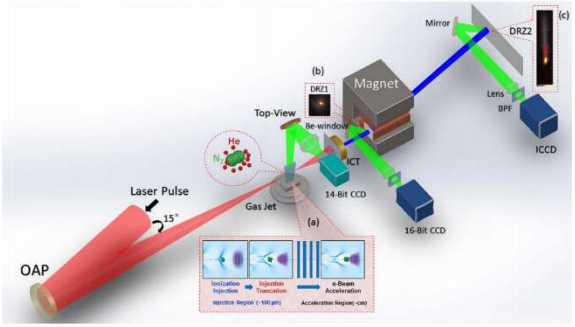


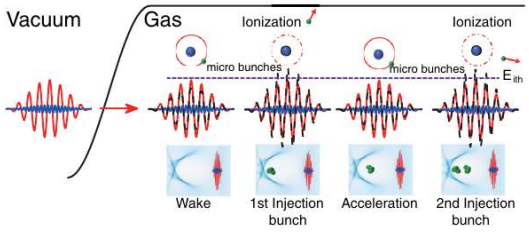
IHEP-Zeng

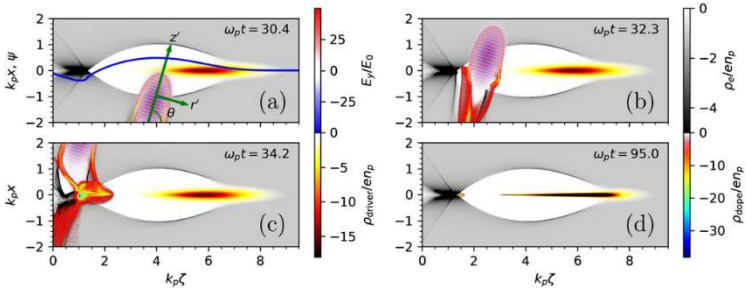
Studies of plasma based accelerators at IHEP

•LWFA Injector for SAPS: replacing the electron gun and low-energy Linac
- 100 TW laser system
- Stable >500 MeV e-beam generation
- Beam charge >100 pC
- Energy spread <5%
- Normalized emittance <10 mm mrad

Injection Scheme Studies for LWFA/PWFA
- Self-truncated Ionization Injection
- Dual-color Laser Ionization Injection
- Ponderomotively Assisted Ionization Injection



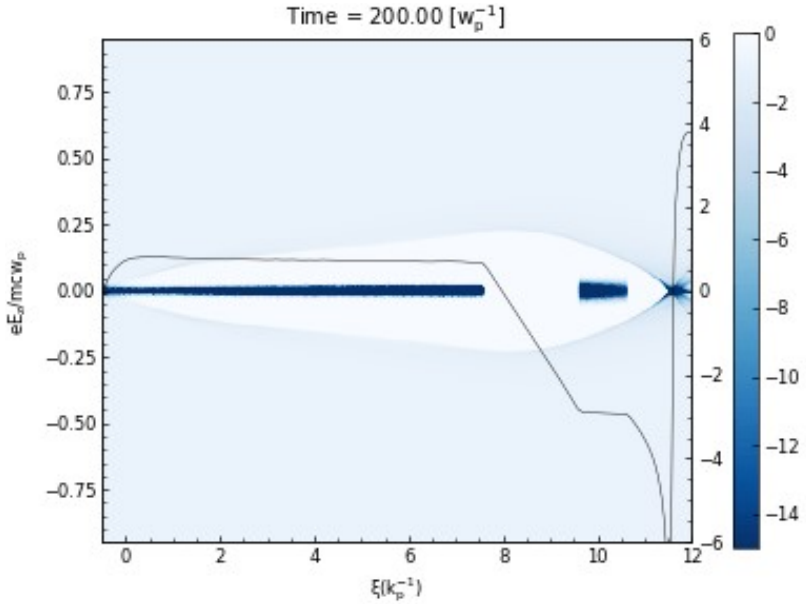




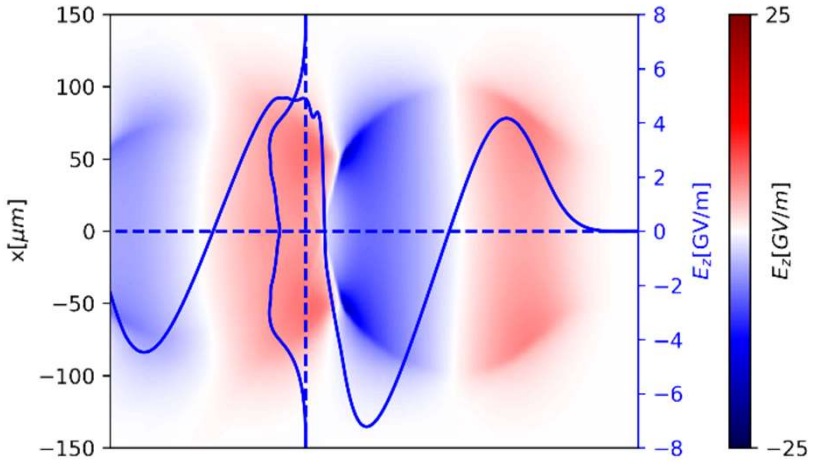
IHEP-Li

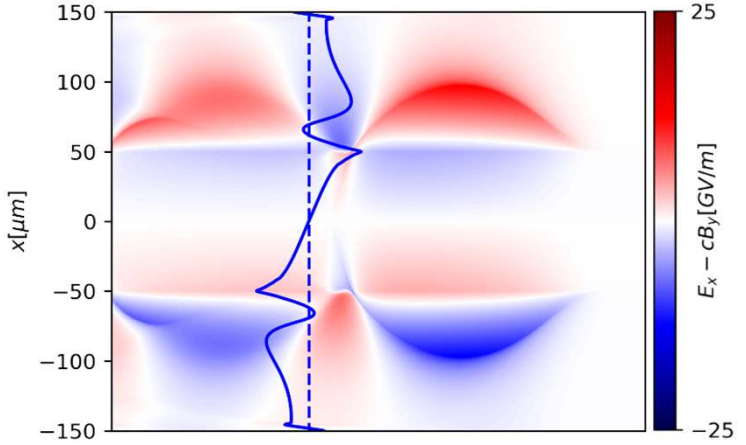
Stable HTR PWFA for e-

Accelerating distance (m)	10.65
Driver energy $E(GeV)$	10 → 1.30
Trailer energy $E(GeV)$	10 → 45.5
Normalized emittance $\epsilon_n(mm\ mrad)$	98.44
Charge(nc)	0.84 (0.78)
Energy spread $\delta_E(\%)$	0.56
TR	~ 4
Efficiency (%) (driver → trailer)	59.1



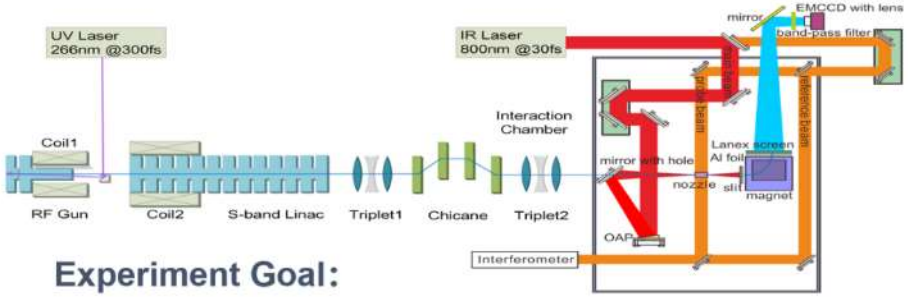
Asymmetric driver for e+ PWFA





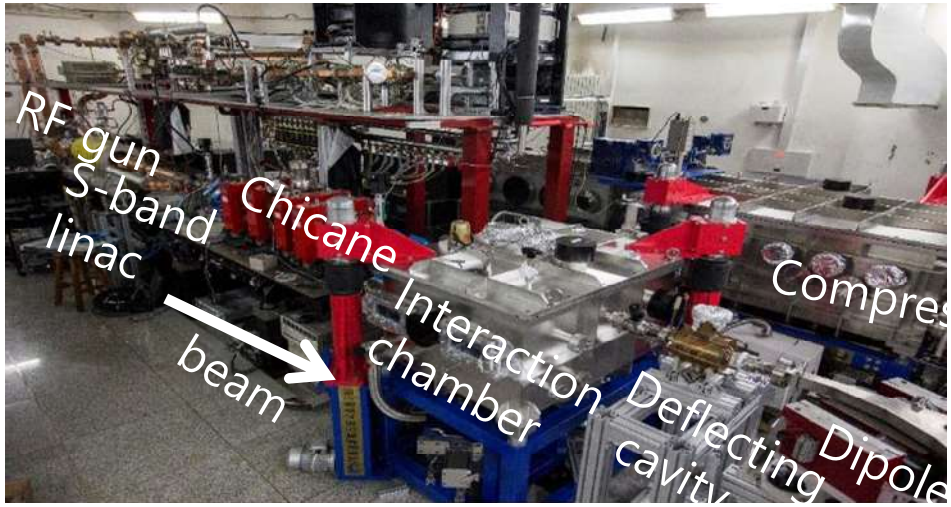
IHEP-Li

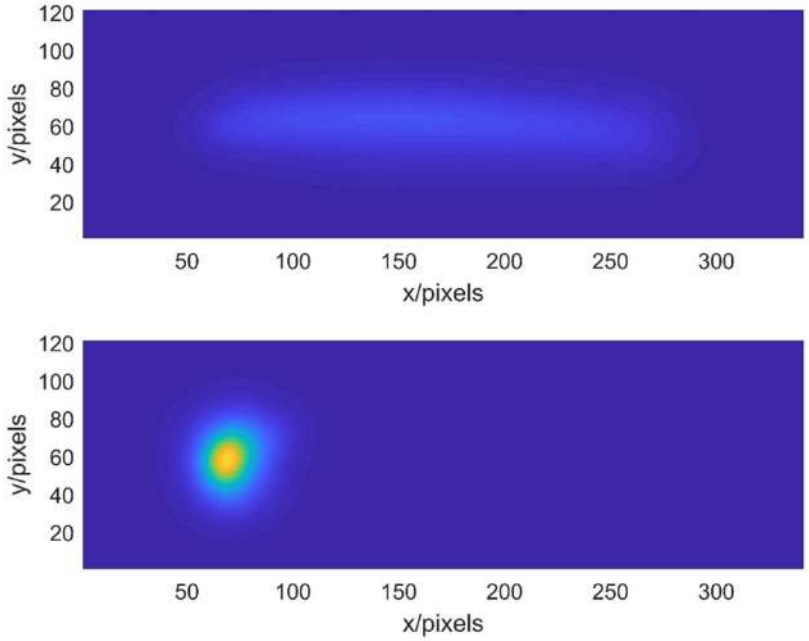
Plasma dechirper experiment @ THU lab

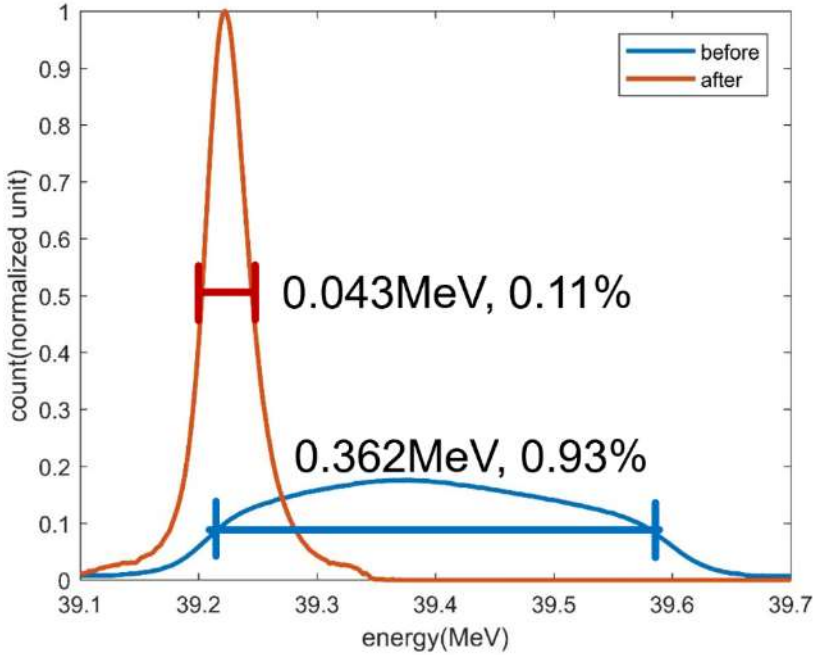


Experiment Goal:

1. Decrease the energy spread from 1% to 0.1%
2. Study Hollow channel impact on beam quality

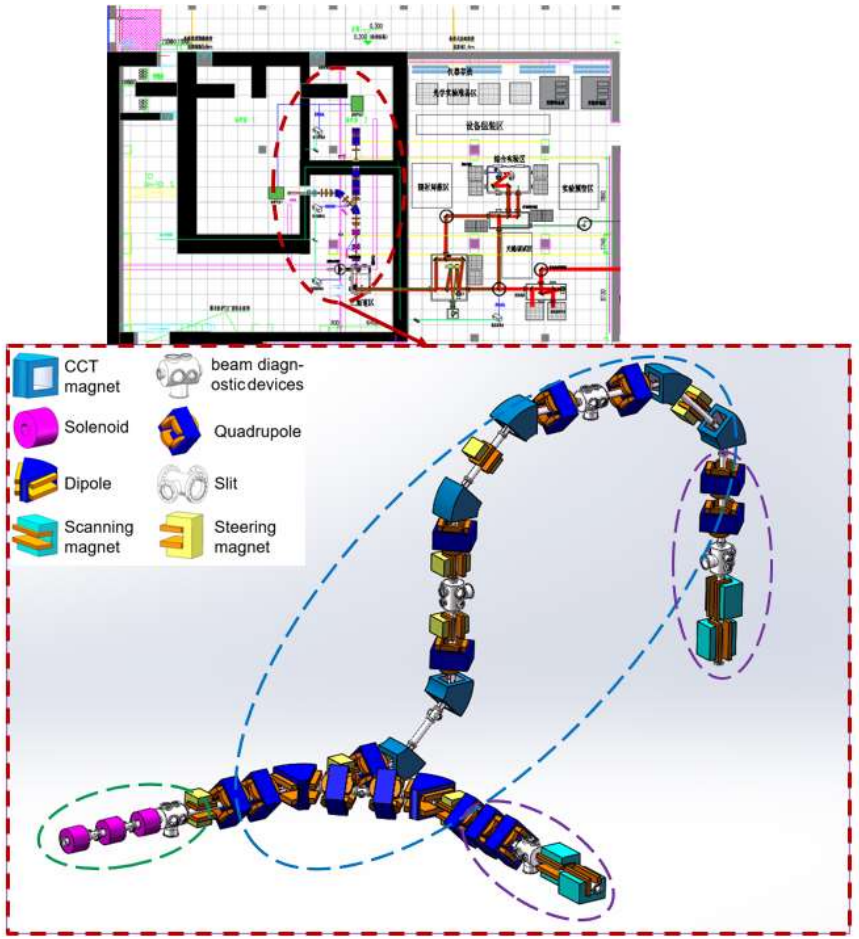






PKU-Zhu

- The report describes the background to the construction of CLAPA-II.
- The main development of CLAPA-II beam transport system is introduced.
- Laser accelerate beam initial macro library generation program is written.
- Achromatic beam transmission system has been design to transport large energy spread beam.



BNU-An

QPAD†: QuickPIC with Azimuthal Fourier Decomposition

Weiming An (anweiming@bnu.edu.cn), Fei Li, Viktor Decyk, Warren Mori

Quasi-Static Approximation

(x, y, z; t)

↓

(x, y, ξ=ct-z, s=z)

↓

$\partial_s \ll \partial_\xi$

↓

Plasma: (x, y; ξ)

Beam: (x, y, ξ, s)

\+

Azimuthal Decompostion

Fields (r, ! , ξ)

↓

Fields (r, ξ)$e^{im!}$

Field equations in QPAD

$$\boldsymbol{e}_r\frac{\partial\psi^m}{\partial r}+\boldsymbol{e}_\phi\frac{\mathrm{i}m}{r}\psi^m=(-E_r^m+B_\phi^m)\boldsymbol{e}_r-(E_\phi^m+B_r^m)\boldsymbol{e}_\phi,$$

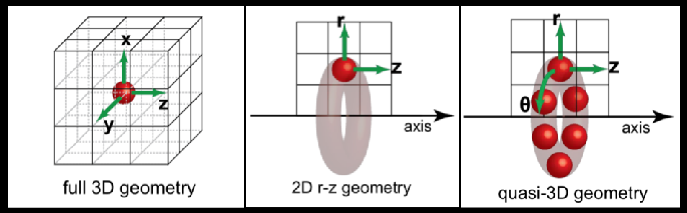
$$\triangle_m\psi^m=-(\rho^m-J_z^m),$$

$$\triangle_m B_r^m-\frac{B_r^m}{r^2}-\frac{2\mathrm{i}m}{r^2}B_\phi^m=-\frac{\partial J_\phi^m}{\partial\xi}-\frac{\mathrm{i}m}{r}J_z^m,$$

$$\triangle_m B_\phi^m-\frac{B_\phi^m}{r^2}+\frac{2\mathrm{i}m}{r^2}B_r^m=\frac{\partial J_r^m}{\partial\xi}+\frac{\partial J_z^m}{\partial r},$$

$$\triangle_m B_z^m=-\frac{1}{r}\frac{\partial}{\partial r}(rJ_\phi^m)+\frac{\mathrm{i}m}{r}J_r^m,$$

$$\triangle_m E_z^m=\frac{1}{r}\frac{\partial}{\partial r}(rJ_r^m)+\frac{\mathrm{i}m}{r}J_\phi^m$$



† Fei Li, Weiming An*, Viktor K. Decyk, Xinlu Xu, Mark J. Hogan, Warren B. Mori, et. al., Computer Physics Communications 261, 107784 (2021).

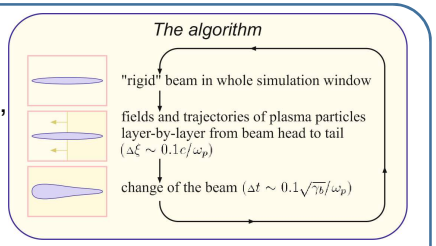
BINP-Lotov

Novosibirsk State University *THE REAL SCIENCE

K. Lotov, AFAD-2021, 17.03.2021

Innovative accelerator techniques in Novosibirsk (Konstantin Lotov): review of four groups

LCODE Team (Konstantin Lotov): development of a quasi-static code (freely available at https://lcode.info/), theory and simulations of PWFA & LWFA

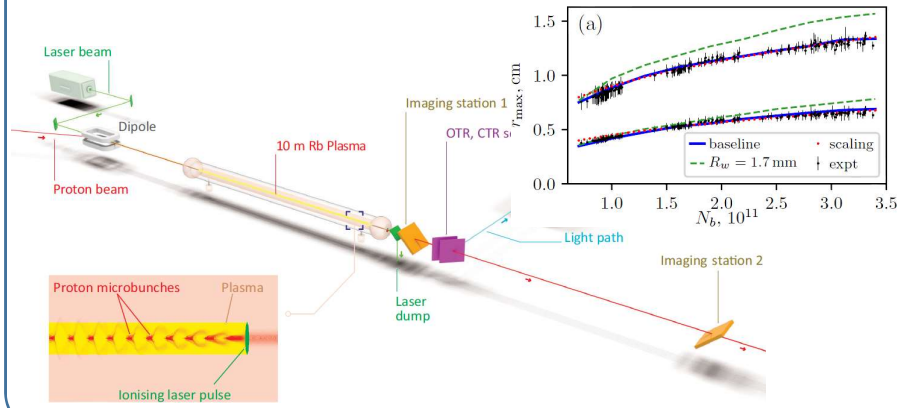


(beam energy/mc^2)$^{1/2}$ (window length / grid step) times faster

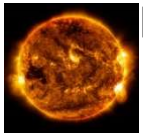
long time step for beam -1 dimension

[up to 10^9 for AWAKE baseline, compared to PIC]

Recent results: Quantitative agreement with AWAKE and FACET measurements at extreme simulation regimes (long beam, long propagation distance, or long-term wakefield evolution)



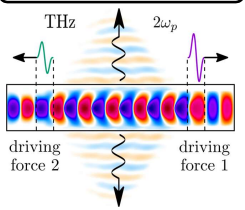
Radiation from beams and plasmas in various configurations (Igor Timofeev):

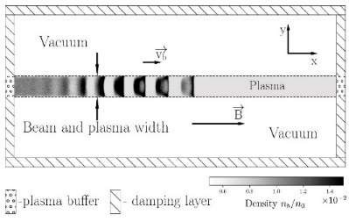


Astrophysical problems

Fusion facilities

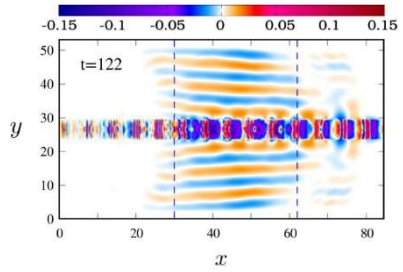
THz radiation sources

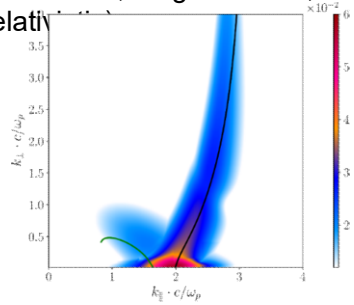




Key instruments:
PIC code with open boundary conditions,
algorithm for solving the dispersion equation (kinetic regime, arbitrary beam momentum distribution, magnetic field, relati

Several original methods of radiation generation proposed and studied:



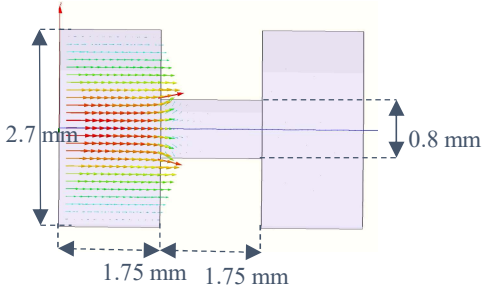


BINP-Lotov

Novosibirsk State University *THE REAL SCIENCE
K. Lotov, AFAD-2021, 17.03.2021

Innovative accelerator techniques in Novosibirsk (Konstantin Lotov): review of four groups

Novel W-band structures (A.Levichev, M.Arsentyeva): between conventional RF structures and plasmas in size and fields

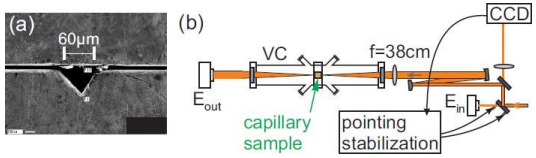


Operating frequency	85 GHz
Bunch charge	0.3 nC
Bunch distance	5.6 ns
RMS bunch duration	2.5 ps
Number of cavities in the structure	100
Lost energy	up to 5 MeV
Induced electric field	up to 25 MV/m

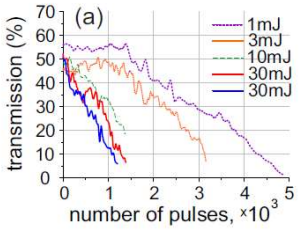
To be tested with a train of electron bunches from the SKIF linear accelerator

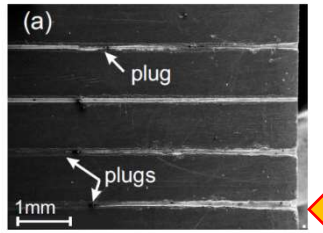
Laser-plasma experiments at Institute of Laser Physics (Vladimir Trunov): Two channel multiterawatt laser system based on OPCPA

Past: pulse propagation through narrow metal capillaries

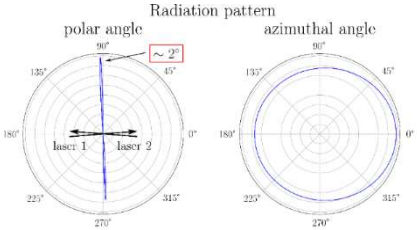


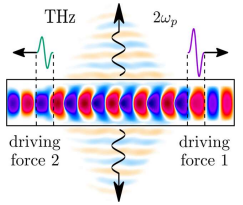
+ high transmission (70% through 2 cm)
- Capillary degradation
- Plug formation

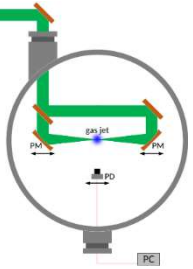




Future: LWFA, Compton γ-source, THz generation







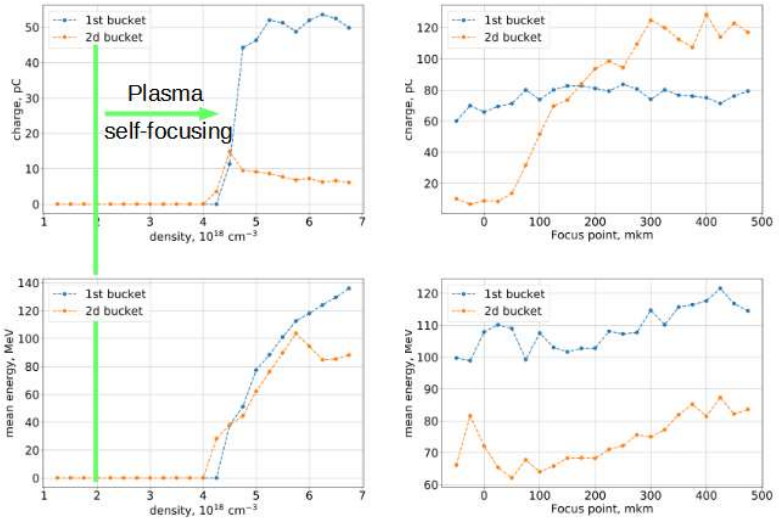
BINP-Tuev

Novosibirsk State University
THE REAL SCIENCE

Optimization of moderate-power laser pulse interaction with plasmas using quasistatic simulations

P. Tuev, K. Lotov

Trapped beams parameters



LCODE simulation

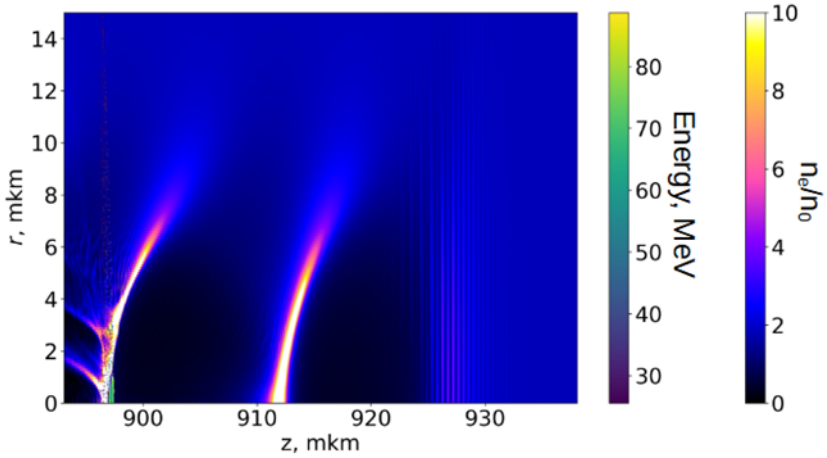
The code with QSA allow one to perform very fast parameter scans and qualitatively study self-trapping processes.

Conventional PIC simulations are needed to investigate in detail the optimal set of parameters.

Further development of QSA extensions will allow for global optimization of future experiments.

Generation of good quality quasimonoenergetic beam is possible using laser pulses of moderate power.

Focusing laser pulse inside the plasma allows to initiate self-trapping process for such laser systems.



	E, MeV	RMS, MeV	ε_n, mm mrad	Q, pC
FBPIC	77	16	8	20
LCODE	75	30	4	120

FBPIC simulation

Osaka U-Pathak

Overview of MIRAI project

Ion Acc. Group

Development of Ion Acc. & Target System

Laser — Accelerated Ions — Plasma

0.1 mm

Development of Beam Transport

K. Kondo, T. Shirai

QST NIRS, KPSI

Diagnostics Group

KPSI

QST KPSI

M. Kando

Electron Acc. Group

Development of Staging Acc.

1. *RF Photo-Cathode*
2. *λ³(Lamda Cube)* + Booster

T. Hosokai

Laser #1 — 20-100MeV e-beam

Laser #2 — GeV -class e-beam

S. Yamamoto

Micro Undulator — 1keV XFEL

Injectors — Beam Transport — Booster — Diagnostics

RF-Linac 20MeV, <10fC~1pC e-beam probe

Y. Otake

ISIR Osaka Univ., RIKEN, JASRI, KEK

Compact Laser Group

Ultra-compact , high-efficiency YAG laser for Ti:Sapphire pump

Development Large aperture DFC structure, New materials

IMS, RIKEN

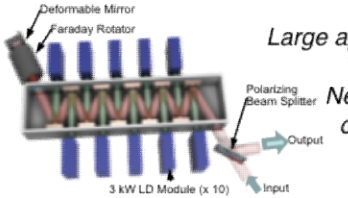
T. Taira

Ultra-compact high-Power Laser

Explore Applications

High-Power Laser Group

Development High-Power Pump lasers



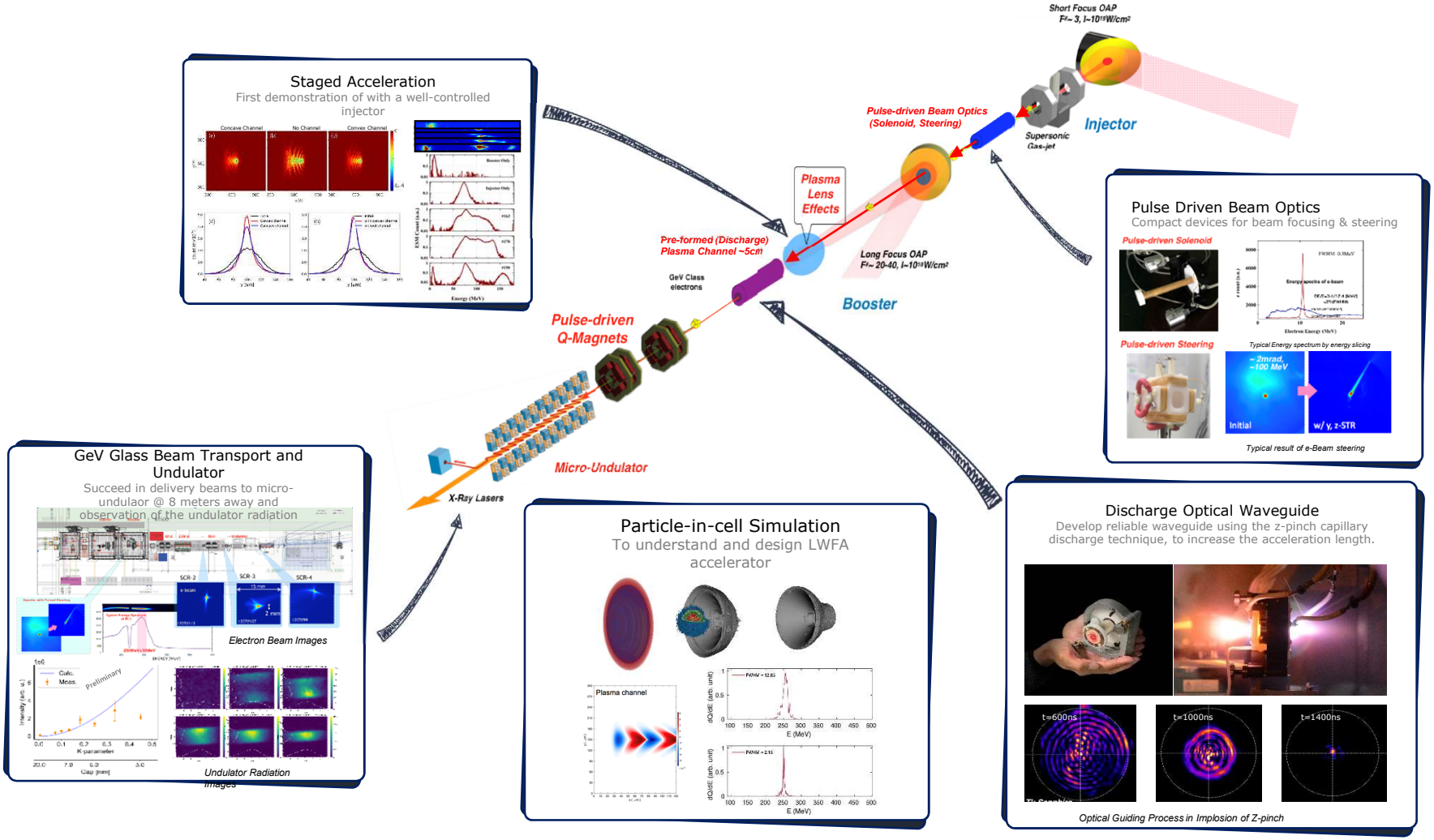
Large aperture Active Mirror Technologies, New materials for optical devices

ILE Osaka Univ.

J. Kawanaka

Osaka U-Pathak

Experimental concept



KEK-Koyama

Dielectric Laser Accelerator (DLA) Research at KEK and Univ. Tokyo

Kazuyoshi Koyama and Mitsuhiro Yoshida @KEK

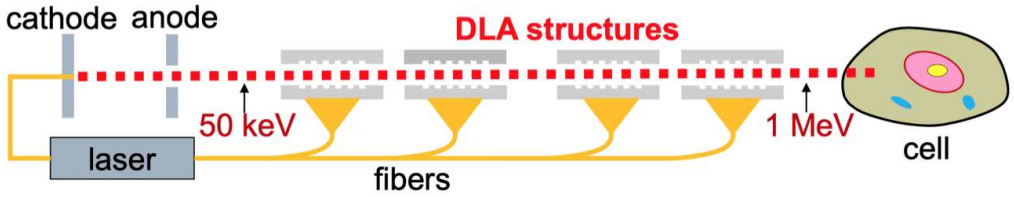
High gradient accelerators using the dielectric are studied.

The damage threshold : dielectric > metal

Sub-relativistic DLA for Radiobiology research

Electron beam parameters

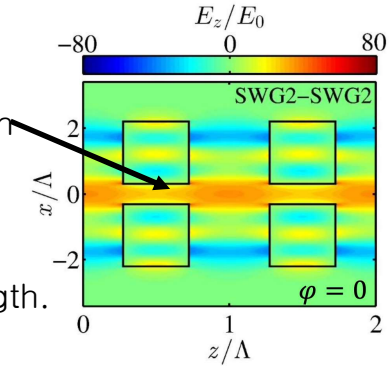
Electron energy (MeV)	1
Beam size (μm)	~ 0.5
Bunch length (attosec)	50
Electrons per bunch	160
Dose per bunch (Gy)	4.7
Dose for *N* bunches (Gy)	4.7x*N*



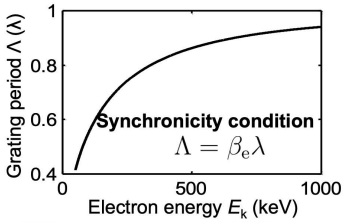
Tthe optical resonator consisting of a pair of sub-wavelength grating array is studied to decrease the required laser power.

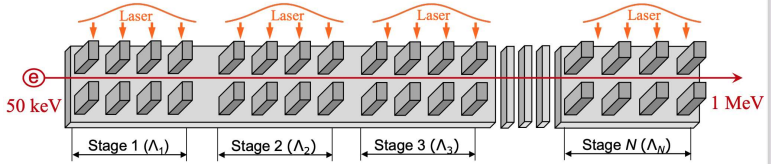
Field accumulation

Distribution of the longitudinal field strength.



Channel width *d* (nm)	~ 300
Enhancement factor A_c	< 10
Width per stage *W* (μm)	12
Laser beam waist w_0 (μm)	5
Laser pulse length t_p (ps)	0.1
Max field in silicon E_{max} (GV/m)	2





- To satisfy the synchronicity condition, every stage uses a different grating period.

The colonnade structure and the shingle side irradiation DLA.

KEK-Koyama

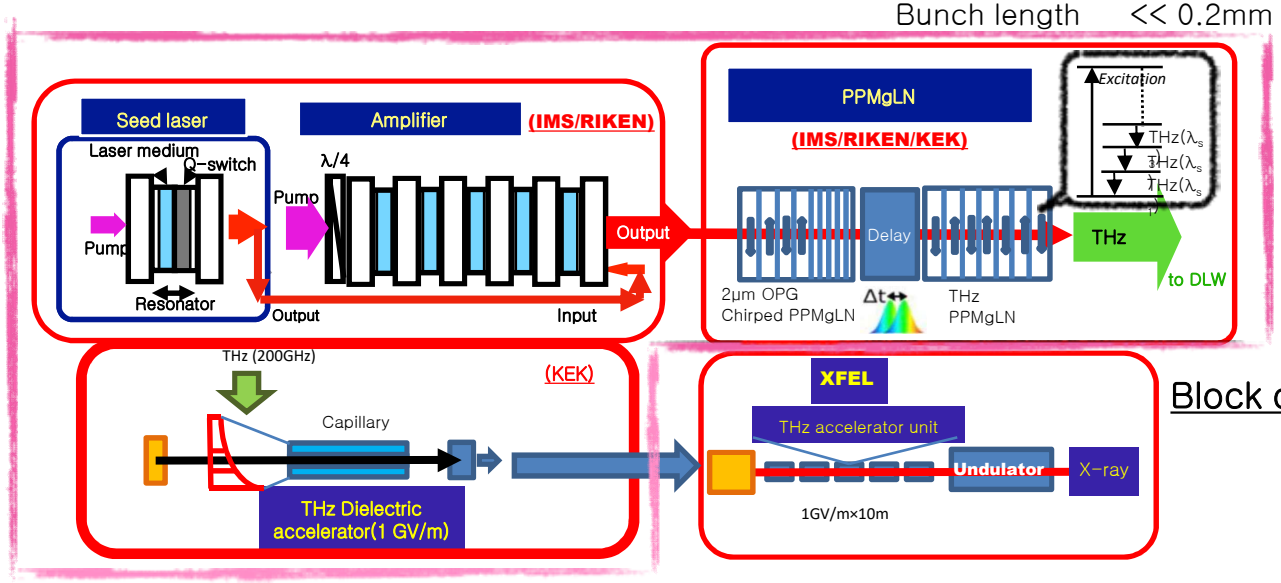
Dielectric Laser Accelerator (DLA) Research at KEK and Univ. Tokyo

Relativistic Dielectric Loaded Wall (DLW) accelerator for XFEL

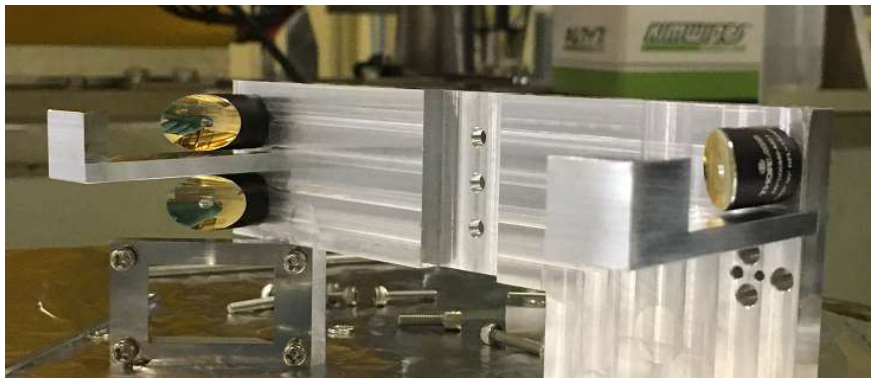
The intense THz wave is suitable to control bunch parameters.

Electron beam parameters

Electron energy > 10 GeV
Beam size < mm
Bunch length << 0.2mm (670 fs) for f=0.2 THz



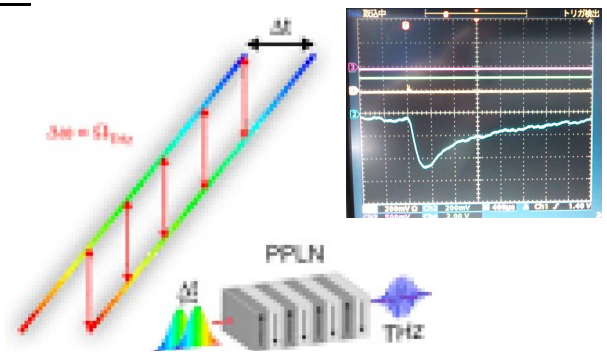
Block diagram of the DLW based XFEL



DLW test bench: parabolic mirrors and capillarys

THz-PPLN

THz-signal

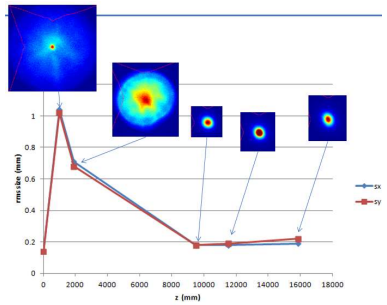


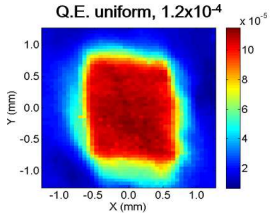
THz-wave generation

PAL-Nam

Advanced laser-plasma accelerator R&D plans at PAL-ITF

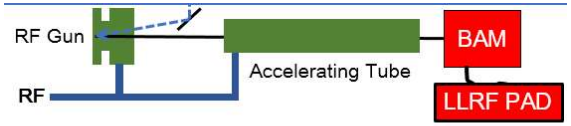
- PAT-ITF history

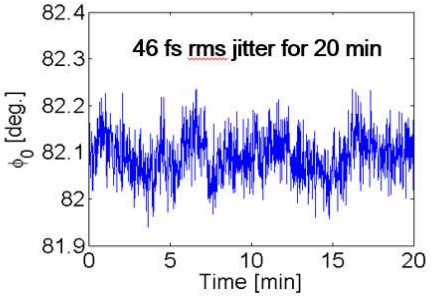




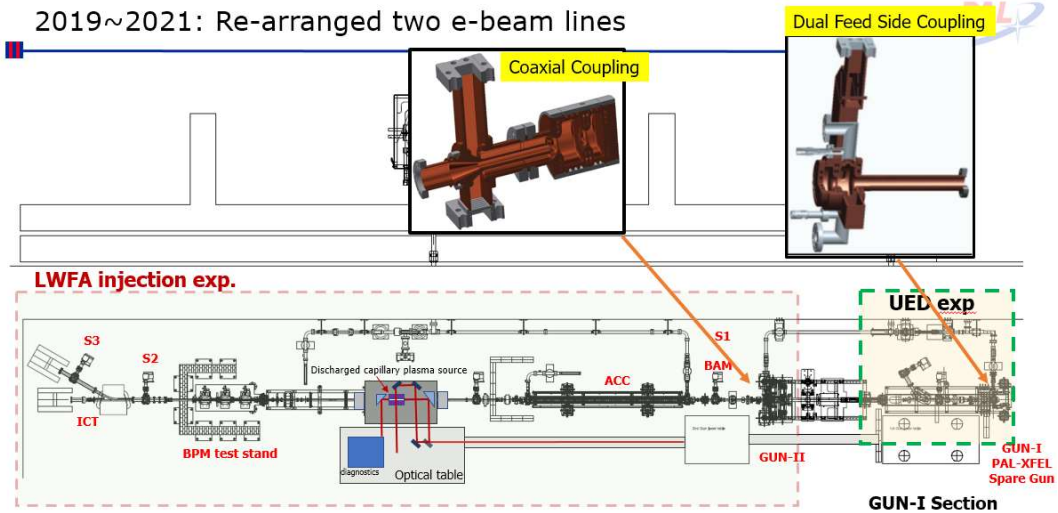
Oct. 2013, emittance goal (0.5 μmrad) achieved

- timing jitter: ~46 fs rms

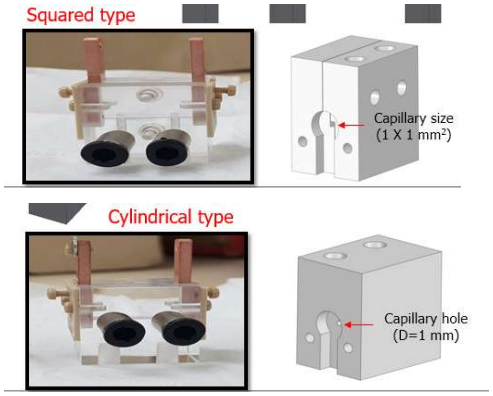




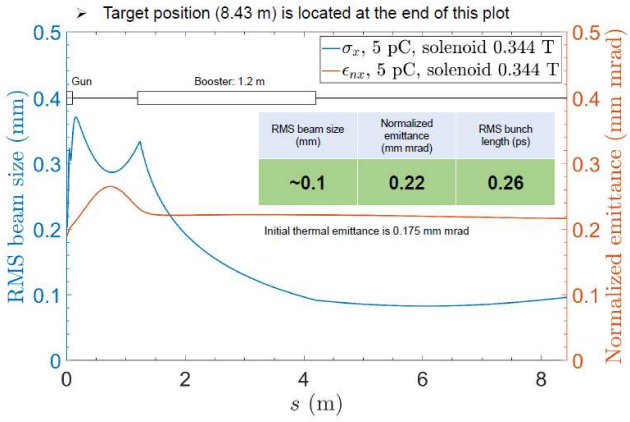
2019~2021: Re-arranged two e-beam lines



- Developed discharge capillary



- GUN-II: 5pC,100 fs e-beam



PAL-Nam

Advanced accelerator R&D Plans

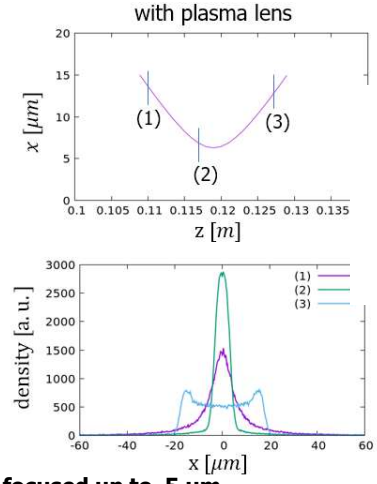
- Plasma lens

Capilary

$I_0 = 80\ [A]$
$R_0 = 500\ [\mu m]$
$L = 2\ [cm]$

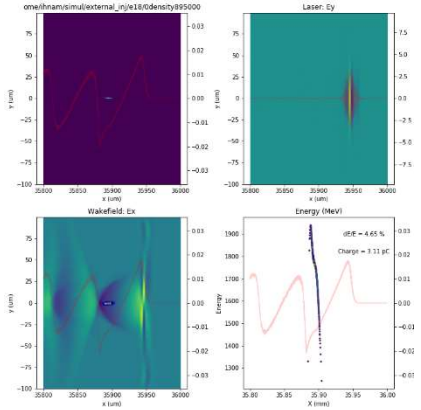
e-beam

$n_0 = 2.3 \times 10^{19}\ [m^{-3}]$
$L = 100\ [\mu m]$
$\varepsilon_N = 0.305\ [mrad\ mm]$
$\beta_x = 10\ [m]$
$\alpha_x = 7$
$charge = 1\ [pC]$



e-beam size can be focused up to 5 μm

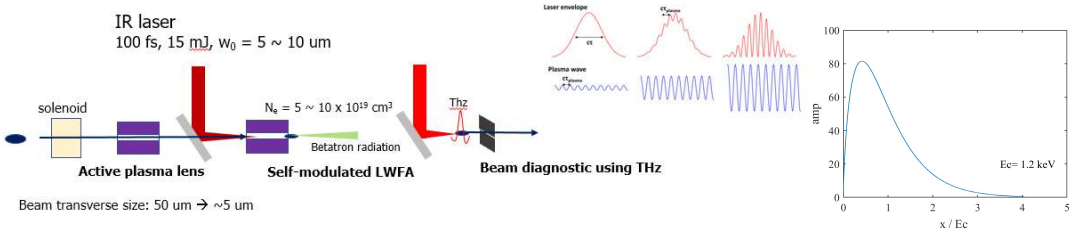
- LWFA with external injection simulation



Results:
- Beam energy = 2 GeV
- Emittance = 4 mm mrad
- Energy spread = 4%

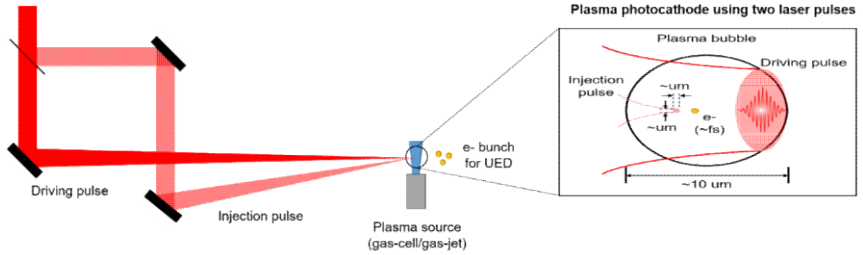
Target:
- Beam energy = 2 GeV
- Emittance = 1 mm mrad
- Energy spread = < 1%

- Betatron X-ray source



Betatron radiation X-ray source : ~ 0.1 – 4 keV

- Two laser pulse ionization injection scheme

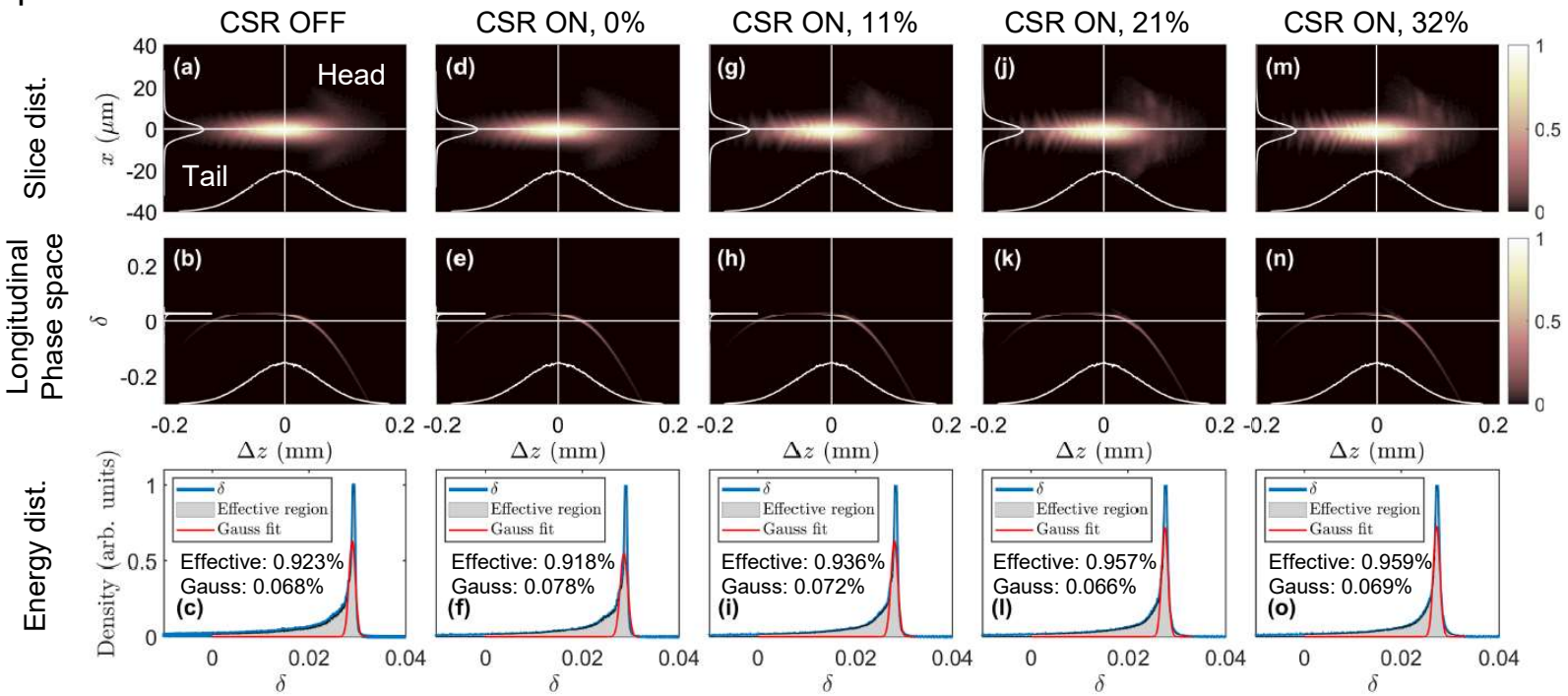


No intrinsic jitter between pump laser and e- beam for UED experiments

- We currently initiate various advanced accelerator R&D programs
- In the near future, we will upgrade the laser system up to tens of TW scale for LWFA, and install a bunch compressor for ultra short e-beam with a high current.

Electron beam loading

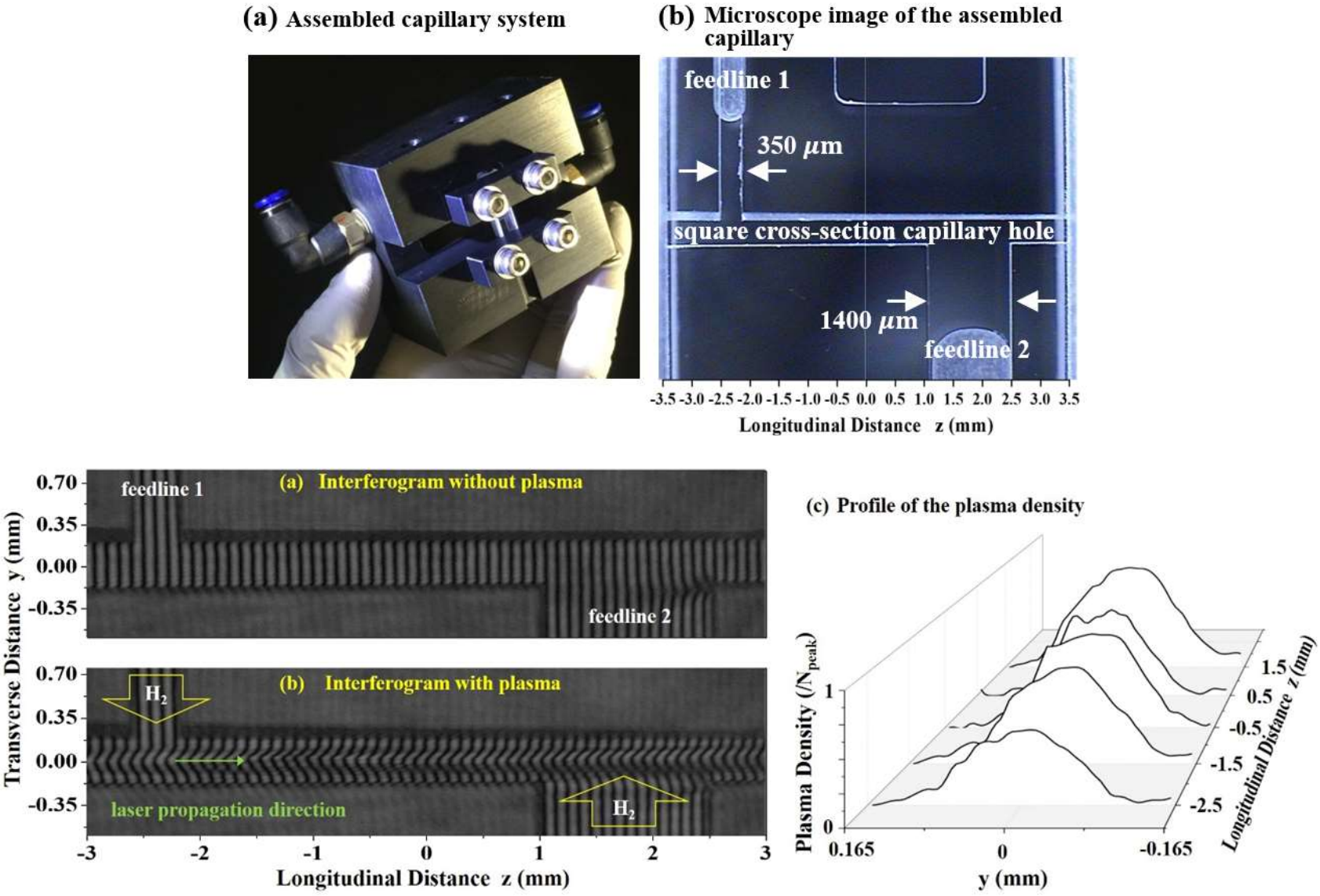
After 5 m plasma source:



- When the CSR effect is not fully suppressed, distortion of the slice distribution at the head becomes significant
- Also, CSR effect leads to the increase of the energy spread: but it does not contribute to the further growth during acceleration

➢ Ref.: S.-Y. Kim, S. Doebert, E. S. Yoon, M. Chung, *Phys. Rev. Accel. Beams* **24**, 021301, 2021

Development of a density-tapered capillary gas cell

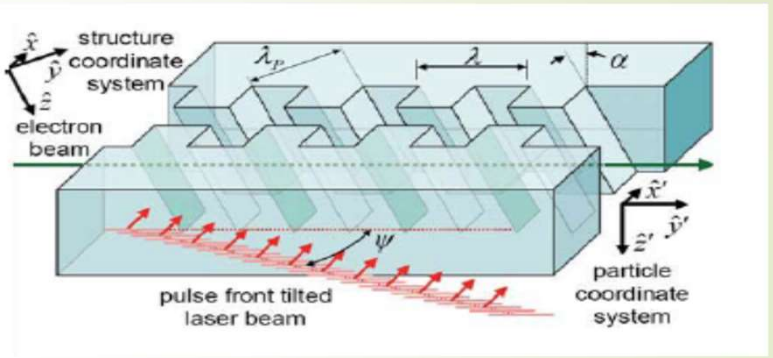


Envisaged DLA-driven Coherent Undulator Radiation

Dielectric laser accelerator (DLA)

~50 cm (GeV/m)

Dielectric undulator



T. Plettner, R. L. Byer, Phys. Rev. ST Accel. Beams **11**, 030704 (2008).

100 cm

electron bunch length ~ 1 nm
Bunch Charge = 0.1~ 1 fC
Gamma = ~500 MeV

Permitting x-ray superradiance

λ_u = 1 mm (N_u = 1000)

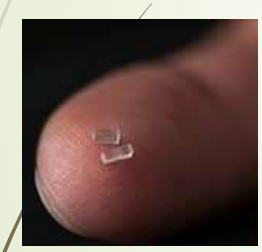
B_{peak} = 3 T (subject to laser damage)

a_u = ~0.22 (undulator parameter)

***good scheme to keep a_u for small λ_u**

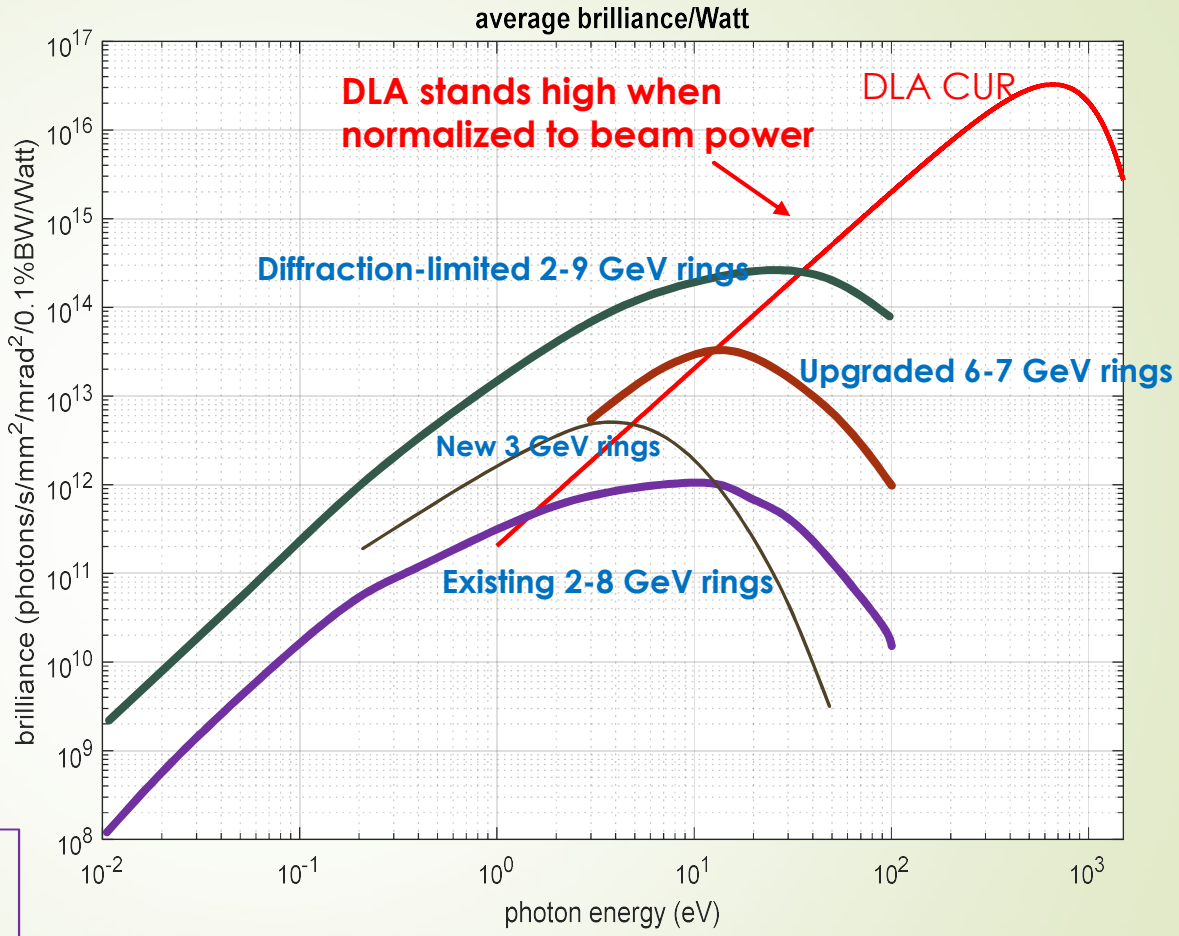
NTHU-Huang

~GW circulating power
(Taiwan photon source)



~25W power

Normalized to average beam power (DLA average beam power is much smaller)



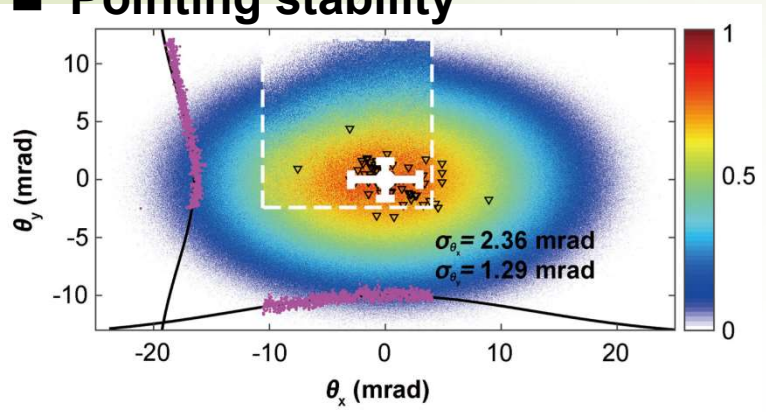
*Curves other than DLA CUR are adapted from Zirong Huang, SLAC-PUB-15449.

NCU-Pai

Stable laser-driven x-ray sources

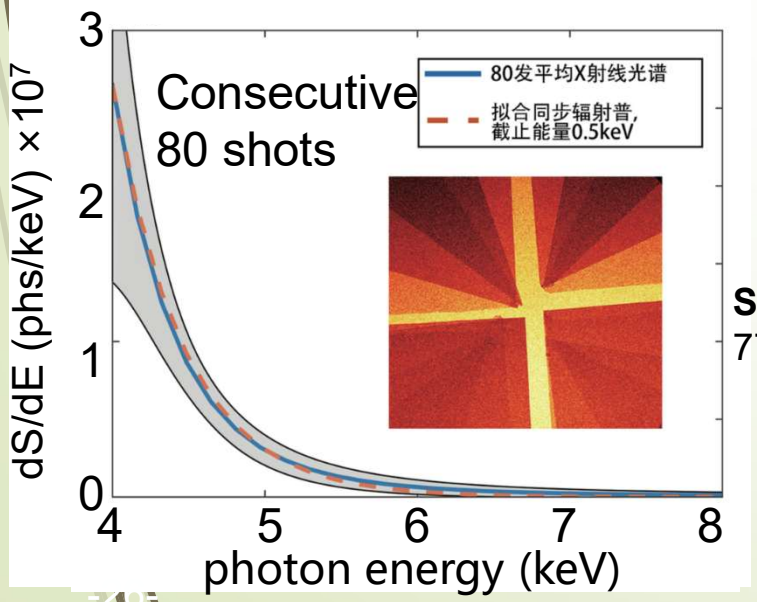
- **Using 20 TW laser in NCU, via ionization injection, betatron x-ray sources can be generated with very stable pointing, spectrum, photon numbers for shot-to-shot.**

■ Pointing stability

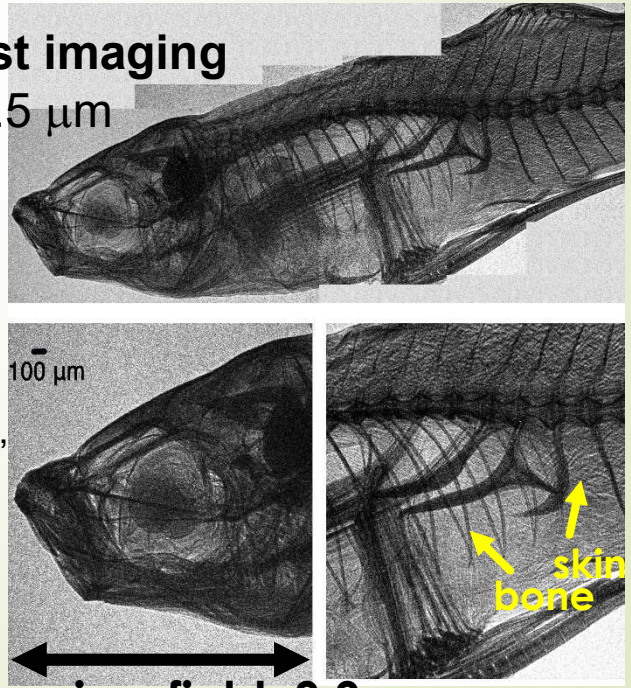


- Statistics of 80 shots
- Averaged divergence: 17.2 mrad^2 (FWHM)
- Pointing jitter: 2.35×1.29 mrad^2 (25.2× ×7.5%)
- Photon numbers: (2.2 ±0.3)×10^8 phs/shot

■ Stability of x-ray spectrum



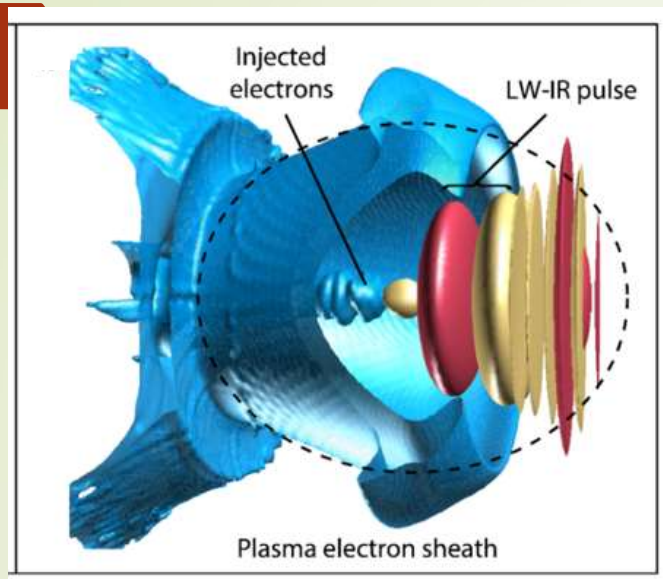
Phase-contrast imaging
Resolution: ~5.5 μm

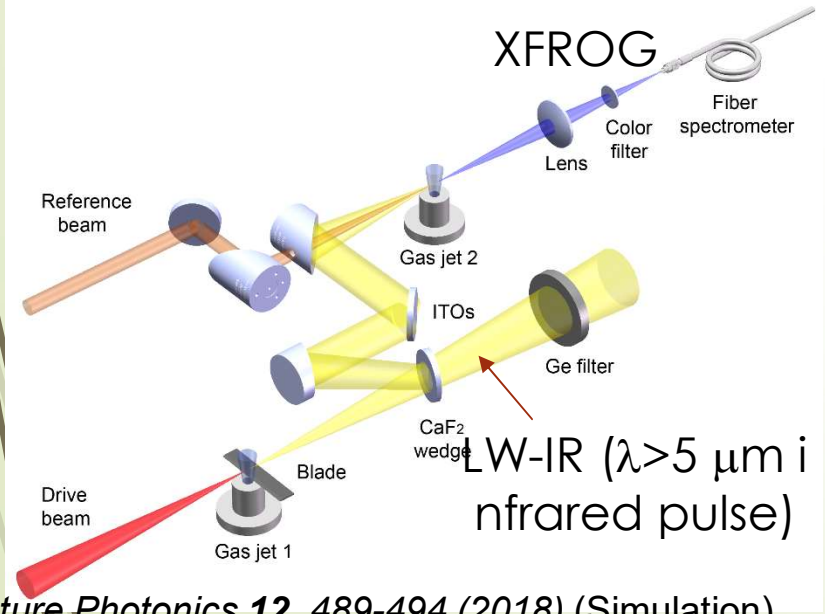


Scientific Reports, 9, 7796 (2019)

NCU-Pai

Tunable relativistic, single-cycle infrared pulses



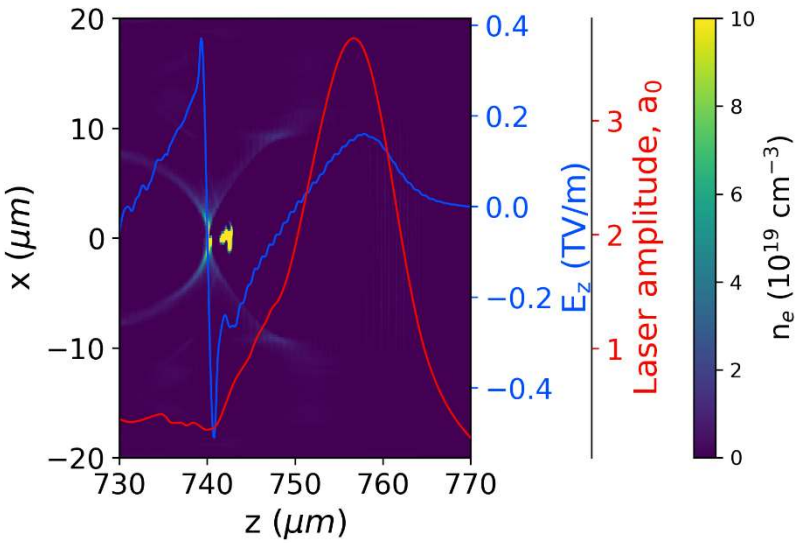


Nature Photonics ***12****, 489-494 (2018)* (Simulation).
Nature Communications **11,** 2787 (2020) (Experiment).

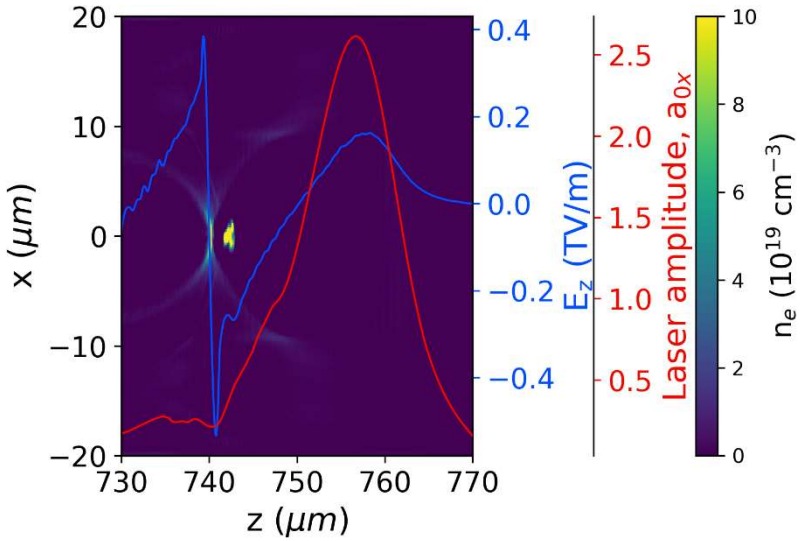
LW-IR (λ>5 μm infrared pulse)

Central wavelength	9.4 μm
Pulse duration (FWHM)	33 fs
LWIR energy (6-20μm)	(3.41±1.08) mJ
LWIR efficiency (6-20μm)	(0.84±0.27)%
Peak power	(103±33) GW
Peak a_0	1.53±0.25
Electric field	(0.52±0.08) TV/m
Overall energy (1.2-20μm)	> (15.0±4.8) mJ
Overall efficiency (1.2-20μm)	> (3.7±1.2)%

Simulation results



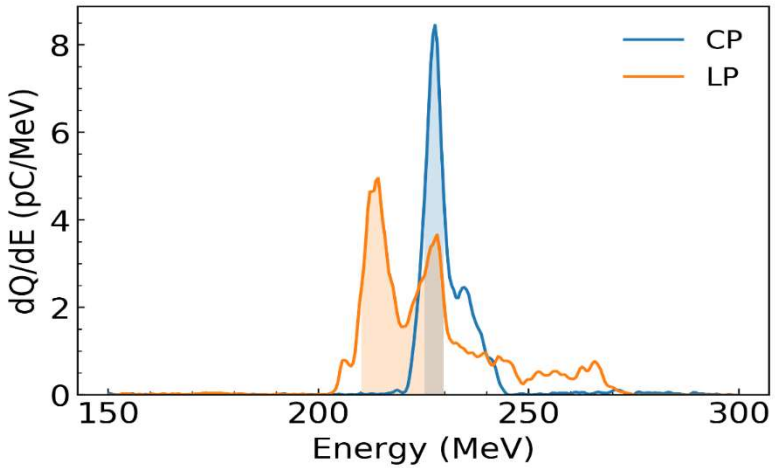
Linearly Polarized (LP)
Trapped charge = 95 pC



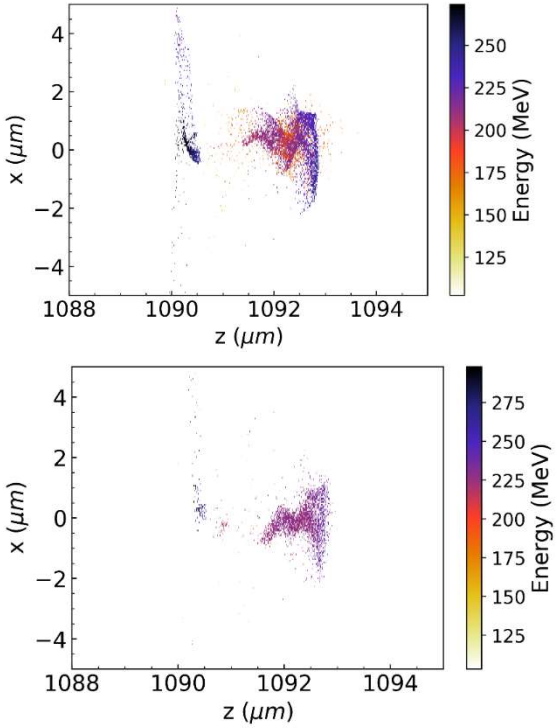
Circularly Polarized (CP)
Trapped charge = 68 pC

Circular polarization leads to significant differences in self-injection because it modifies the initial conditions for the electron trajectories and trapping is extremely sensitive to the details of the trajectory.

Better quality electron beam obtained from CP



	LP	CP
Relative energy spread (%)	9.3 %	2.6 %
Emittance ($\epsilon_x - \epsilon_y$) ($\pi\ mm\ mrad$)	$2 - 0.57$	$0.64 - 0.57$



ASU-Ghotra

Laguerre Gaussian laser beam driven electron acceleration

Harjit Singh Ghotra

Advanced Study Hub *(ASH), Punjab, India*

Summary

- Direct laser acceleration (DLA) of electron with intense high order modes of Laguerre Gaussian (LG) laser beam is investigated theoretically.
- The electron laser interaction is found to be sensitive with the radial (p) and azimuthal (m) mode indices for a polarized LG laser beam.
- Depending upon the order of mode indices (p,m), it is possible to derive the electron dynamics and energy gain with the variations of electric and magnetic fields characteristics of LG laser beam.
- Analysis with parameters
  - Low and High intensity
  - Presence and Absence of longitudinal fields
  - Mode index considerations
- The optimal values of beam parameters which leads to the most energetic electrons, is investigated and presented for the increasing power of LG mode indexed laser beam.

Thank you!