Asian Forum for Accelerators and Detectors 2023

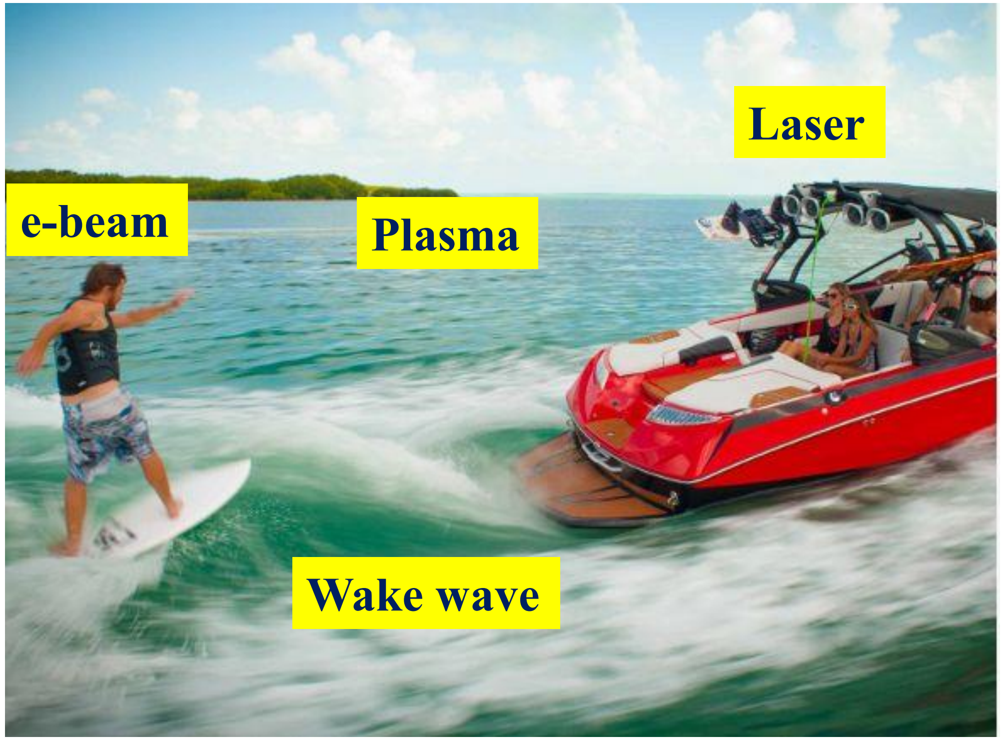
Laser wakefield accelerator with external injection for soft X-ray free electron laser at PAL-eLABs

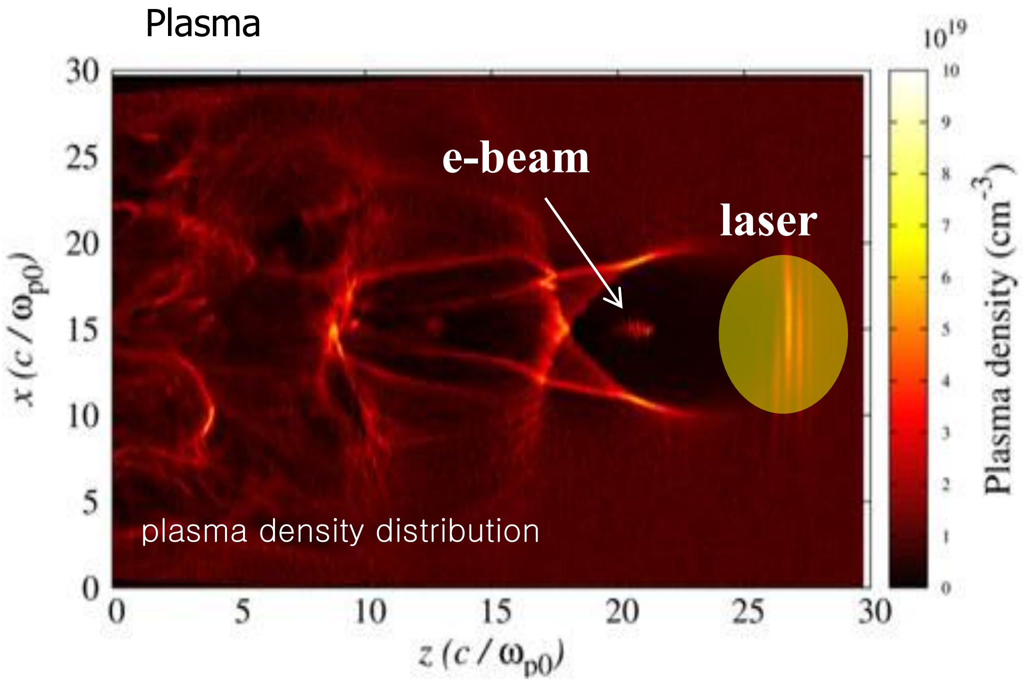
Inhyuk Nam

On behalf of e-LABs & PAL-XFEL team

포항가속기연구소
POHANG ACCELERATOR LABORATORY

Advanced compact accelerator: Laser-plasma accelerator





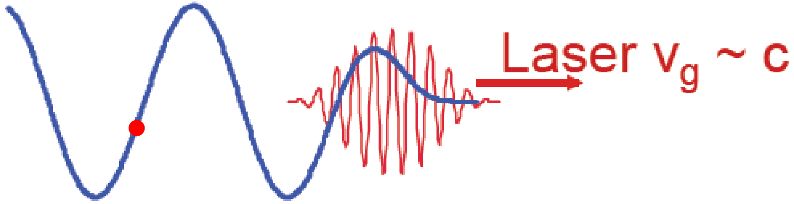
- Electric field in laser-plasma acceleration

$$E_z[V/m] = (m_e c \omega_p)/e \approx 100\sqrt{n_p[cm^{-3}]}$$

ex) If $n_p = 10^{18}$ [cm^{-3}]

$$E_z \approx 100\ GV/m$$

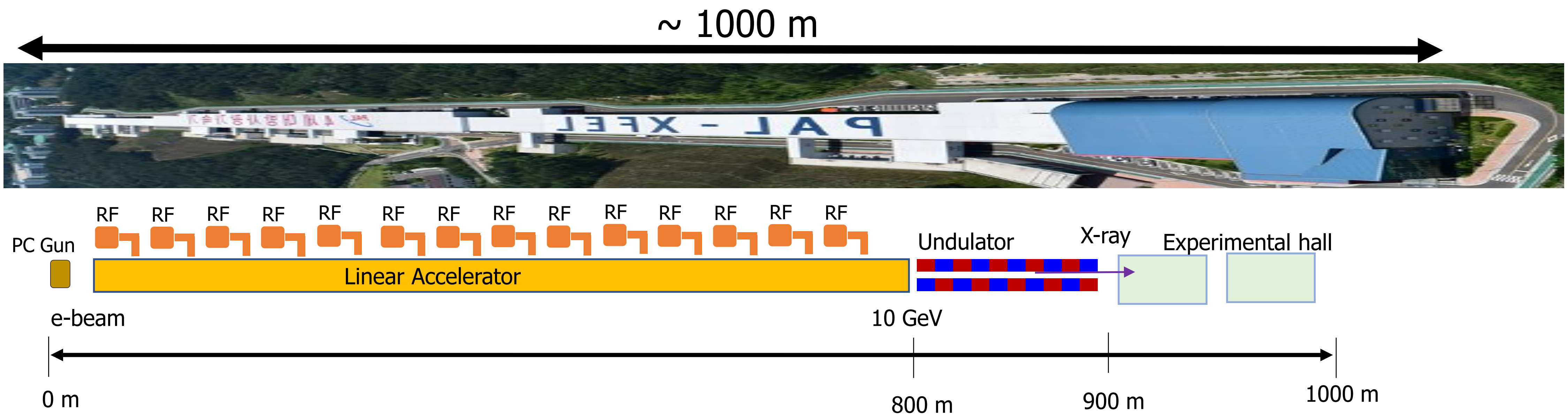
Limits due to Breakdown of metal in LINAC



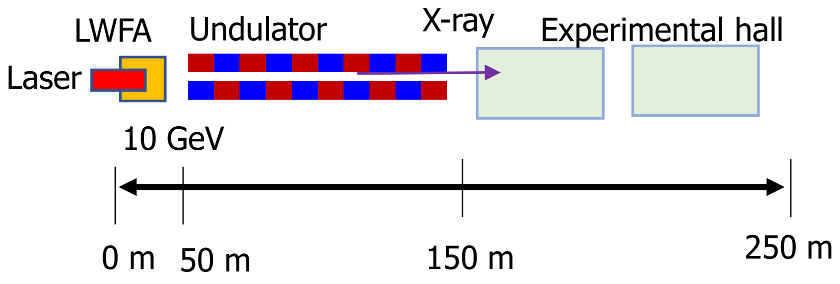
3 order higher than conventional RF accelerator

No breakdown limit because plasma is already broken down

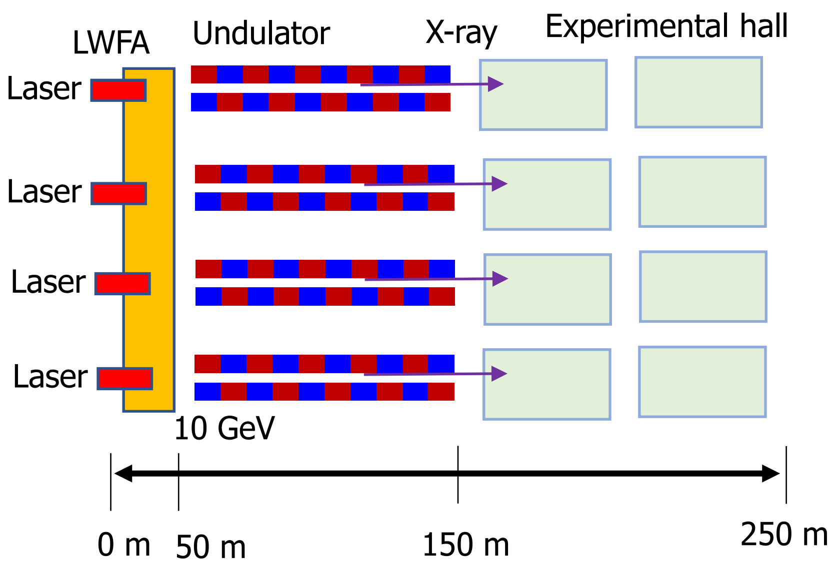
Future compact x-ray free electron laser (XFEL) based on LWFA



XFEL based on LWFA



Multiple XFEL based on LWFA



Recent milestone in last 3 years

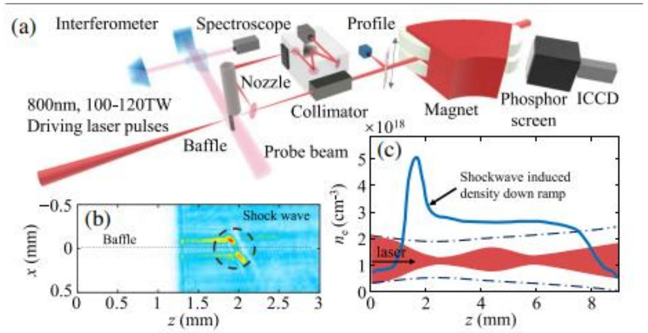
- First soft X-ray at 27nm FEL lasing with LWFA (Nature, 2021)
  - SIOM (China)

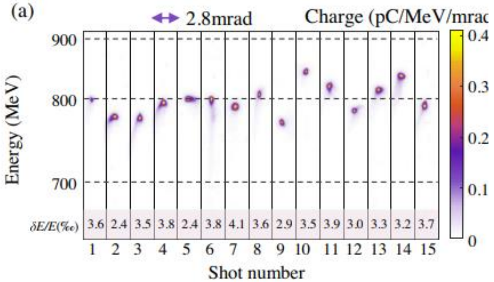
- First SASE/seeded FEL lasing with PWFA (Nature, 2022)
  - SPARC_LAB (Italy)

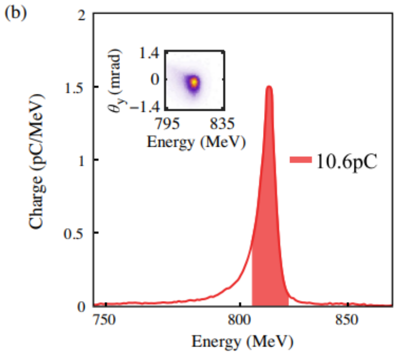
- LWFA with external injection from RF photocathode GUN (Nature Physics, 2021)
  - Tsinghua univ., UCLA (China, US)

- SASE/seeded FEL lasing with LWFA (Nature Photonics, 2022)
  - Laboratoire d’Optique Appliquée (LOA), HZDR (France, Germany)

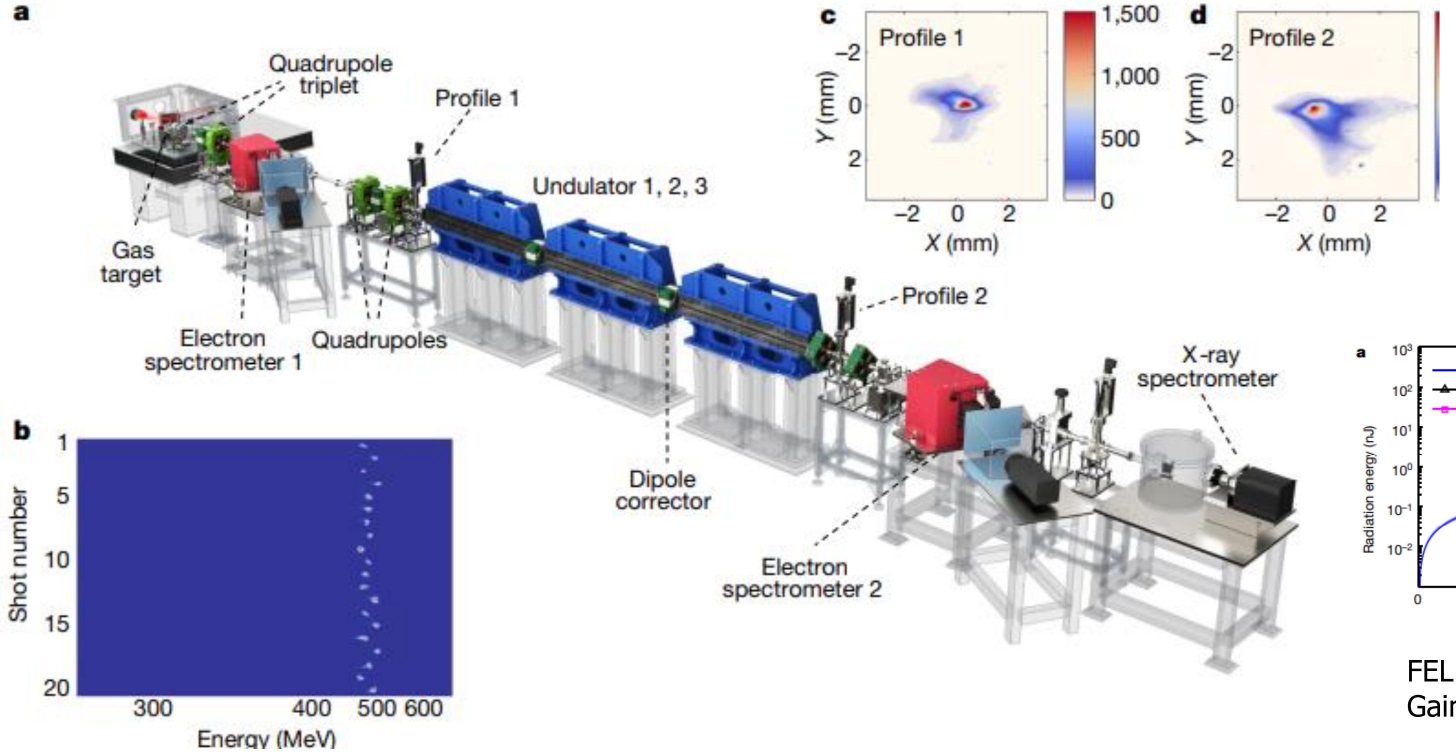
SIOM, China Nature 2021

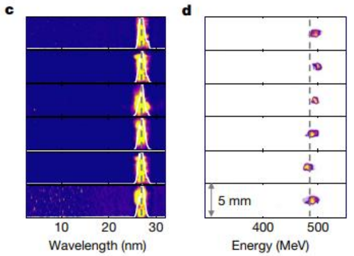


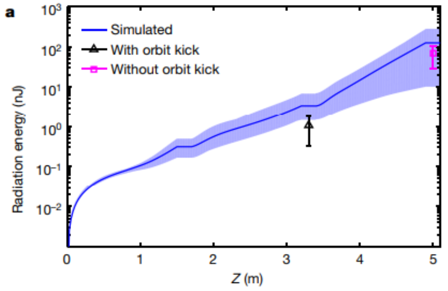




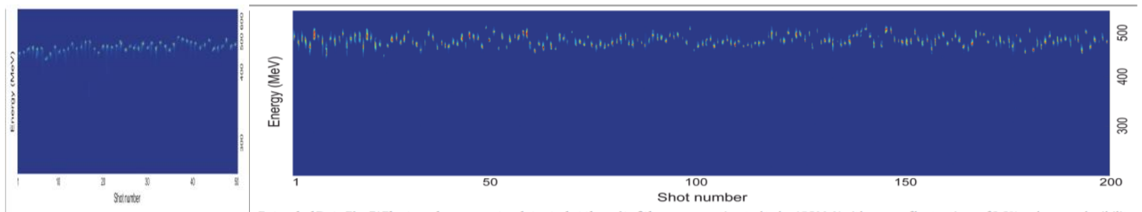
PRL 126,214801 2021







FEL energy = 0.8nJ -> 30 nJ
Gain curve: simuation



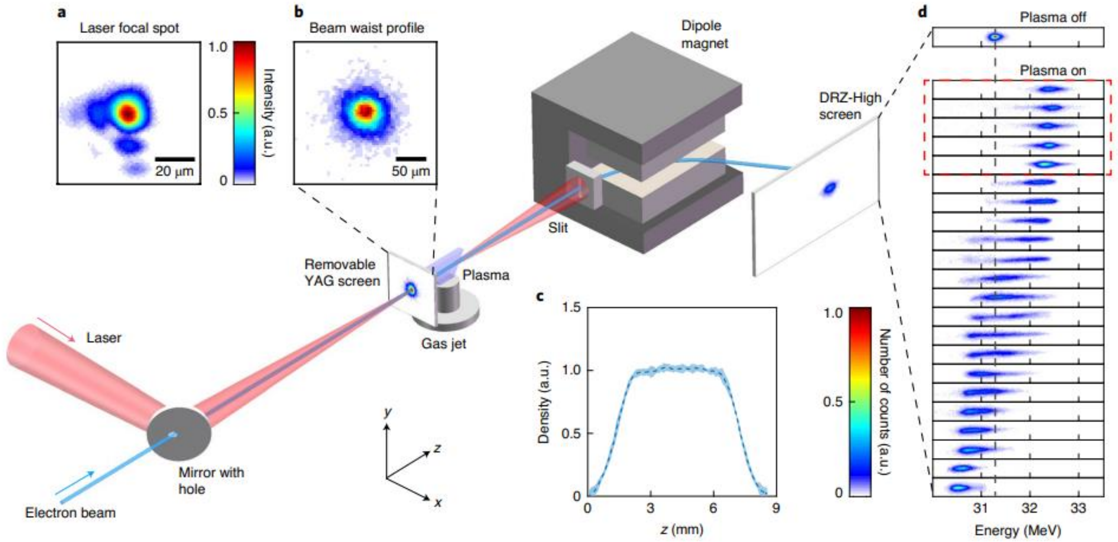
Extended Data Fig. 7 | Electron-beam spectra detected at the exit of the undulators. Energy spectra of electron beams for 200 consecutive shots detected with spectrometer 2. The average energy of the electron beam was estimated to be 485 MeV with energy fluctuations of 3.3% and a reproducibility of approximately 100%.

Laser
200 TW/1hz , 23.7 fs, a0 = 1.3
Jitter = 0.55 %, 1.5 urad

E-beam
490 MeV, es = 0.5%, 30 pC
Div = 0.2 mrad
Energy fluctuation = 3%

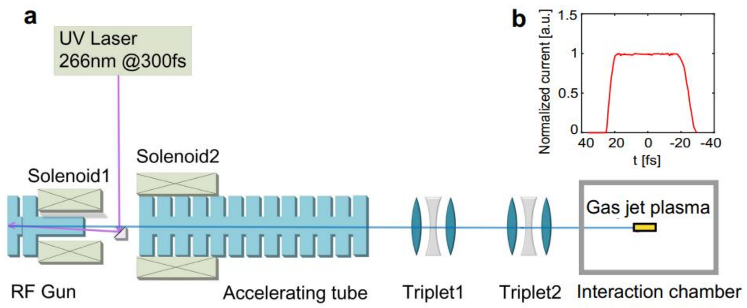
Wentao Wang, et. al., Nature 595, 516-520 (2021)

Tsinghua, UCLA, Nat. Phys. 2021



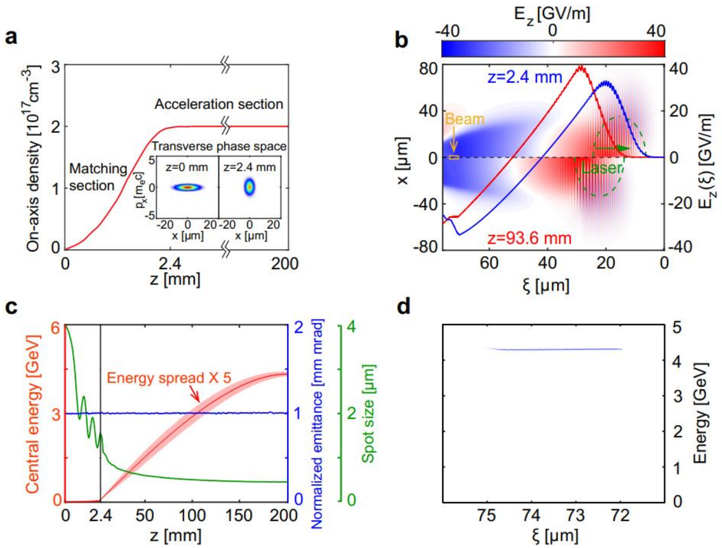
TTX beamline Tsinghua (2011)

singhua Thomson scattering X-ray source (TTX), MeV UED



Extended Data Fig. 5 | Ultrashort electron beam generation and transport. a, The schematic layout of the high-brightness S-band LINAC beamline at Tsinghua University. **b**, The simulated beam current profile (charge 20 fC) using the code ASTRA according to the experimental settings, where the beam head locates at the right.

PIC simulation



E-beam
E = 31.3 MeV, 13 fs, 20fC
Ne = 6 x 10^{17} cc (43 um)

Laser
- 600 mJ, 40 fs
- F = 12.7
- Focal spot = 12 um
- Zf = -3.5 mm

Gas jet
- 6 mm
- Up ramp = 2.4 mm

~ 100 % capture efficiency

Yipeng Wu, et. al., Nat. Phy. 17, 801-806 (2021)

EuPRAXIA consortium

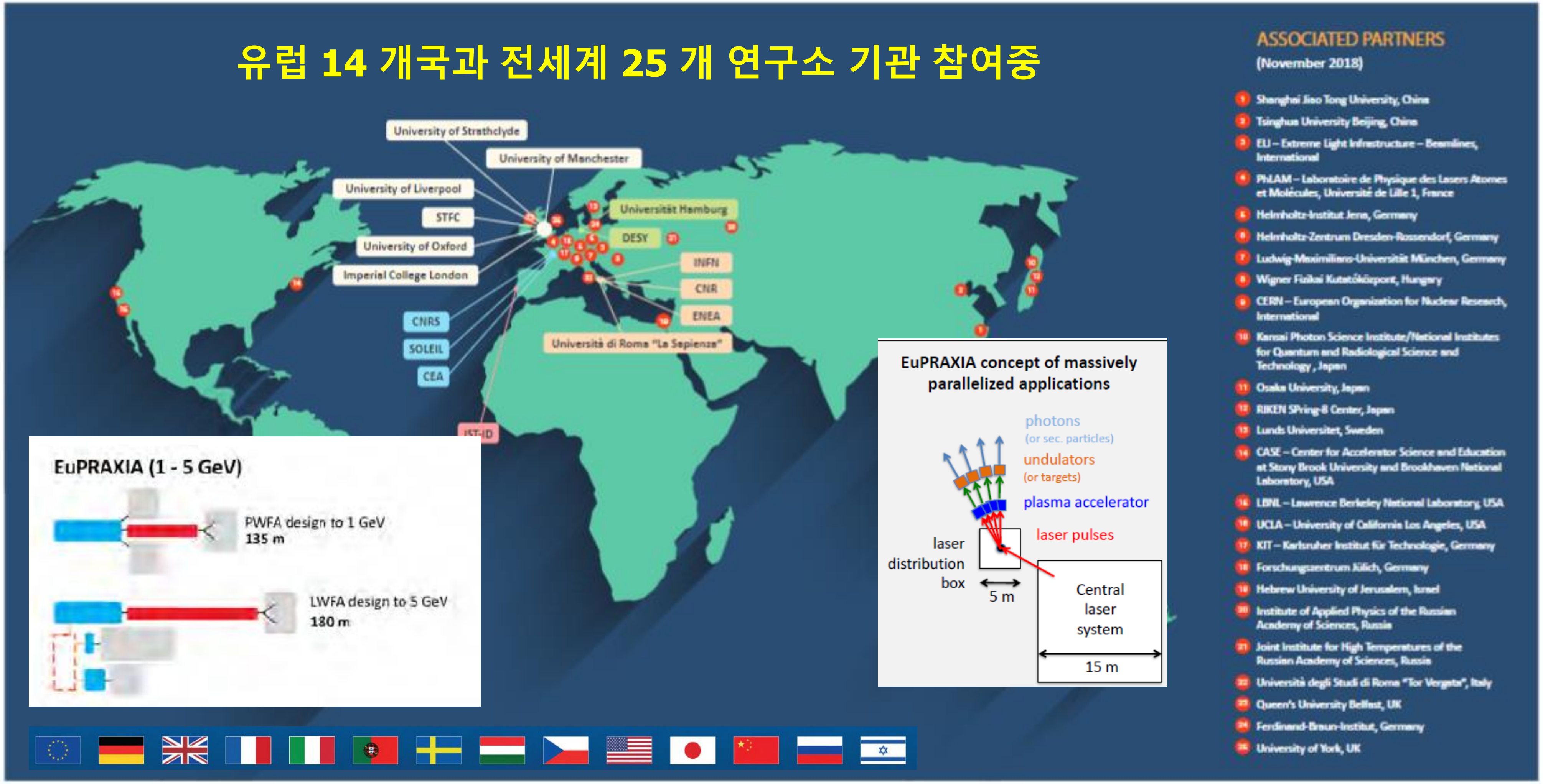


Figure 1.1: Partners and associated partners of the EuPRAXIA Consortium.

RF photocathode GUN for LWFA research

	E [GeV]	ΔE/E [%]	Q [pC]	σ_τ [fs]	ε_n [mm mrad]	f [Hz]
Operational						
FLASH Forward [93]	0.4–1.25		50–800	50–6,000	1–3	4×10^4–3×10^6
SPARC_LAB [94]	0.03–0.15	0.1–0.2	20–1,000	1×10^4–2×10^4	1–5	10
CLEAR (CERN) [95]	0.06–0.22	<0.2	10–500	1.67×10^3–8×10^3	3–20	1–25
Planned / under development / commissioning						
FACET II [90, 91]	10	0.4–1.8	500–3,000	3.3–333		1–30
SINBAD-ARES [92]	0.1		0.5–200	0.8–10	<0.5	50
ELI-Beamlines (HELL) [89]	0.1–5	0.1–10	10–1×10^5	1–10		10
EuPRAXIA	0.1–5.9	0.1–4	20–100	0.8–12	0.1–1.5	20–100
e-LABs	**0.005-0.07**	**0.1-10**	**0.1-500**	**50-5000**	**0.3**	**10**

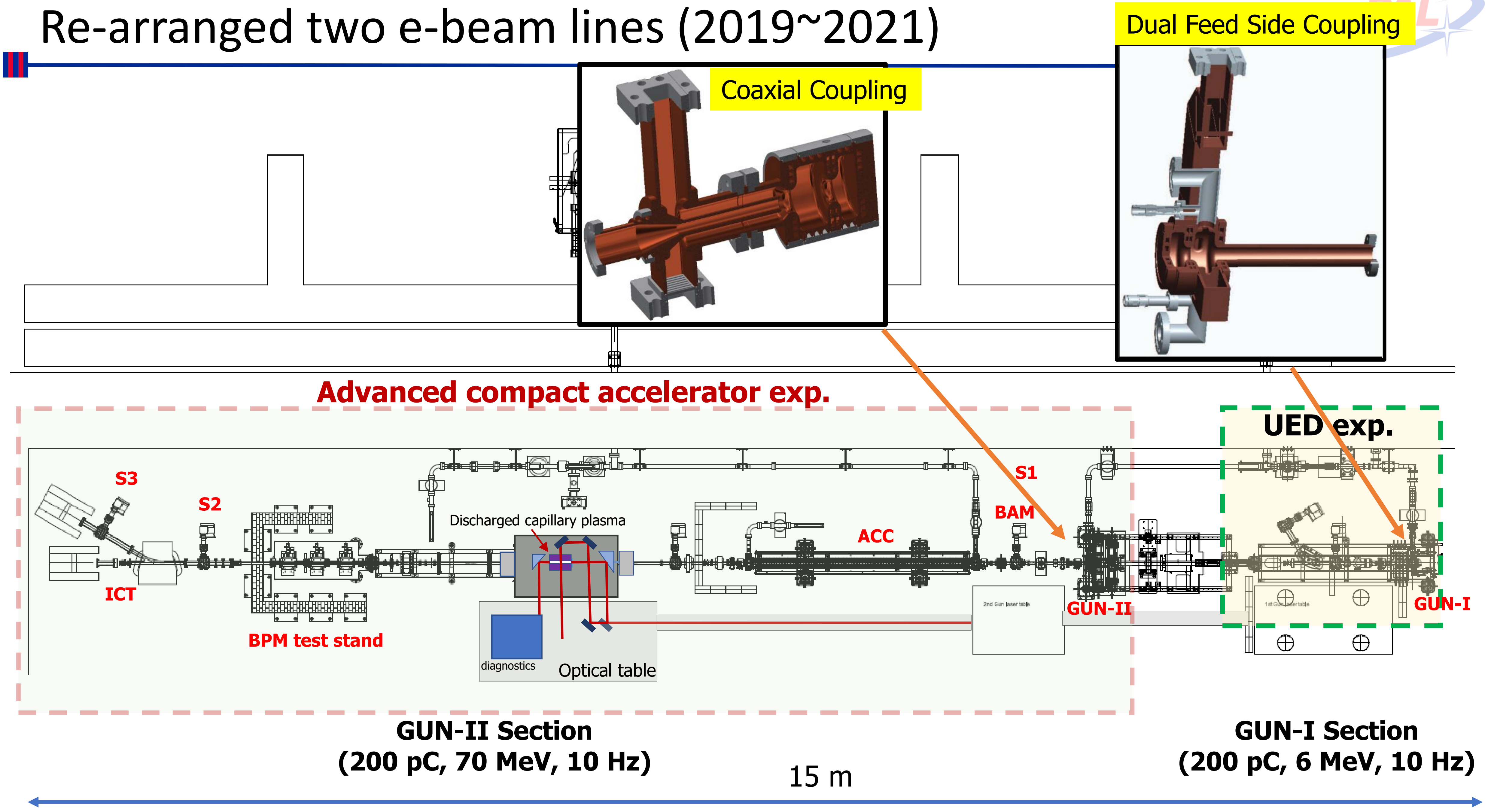
Table 2.1: Summary of the electron beam properties of several accelerator test facilities currently in operation or under development. To provide a reasonable comparison with the performance proposed for EuPRAXIA, only infrastructures with beam energies of at least 100 MeV and allowing external users for experiments are considered.

Outline

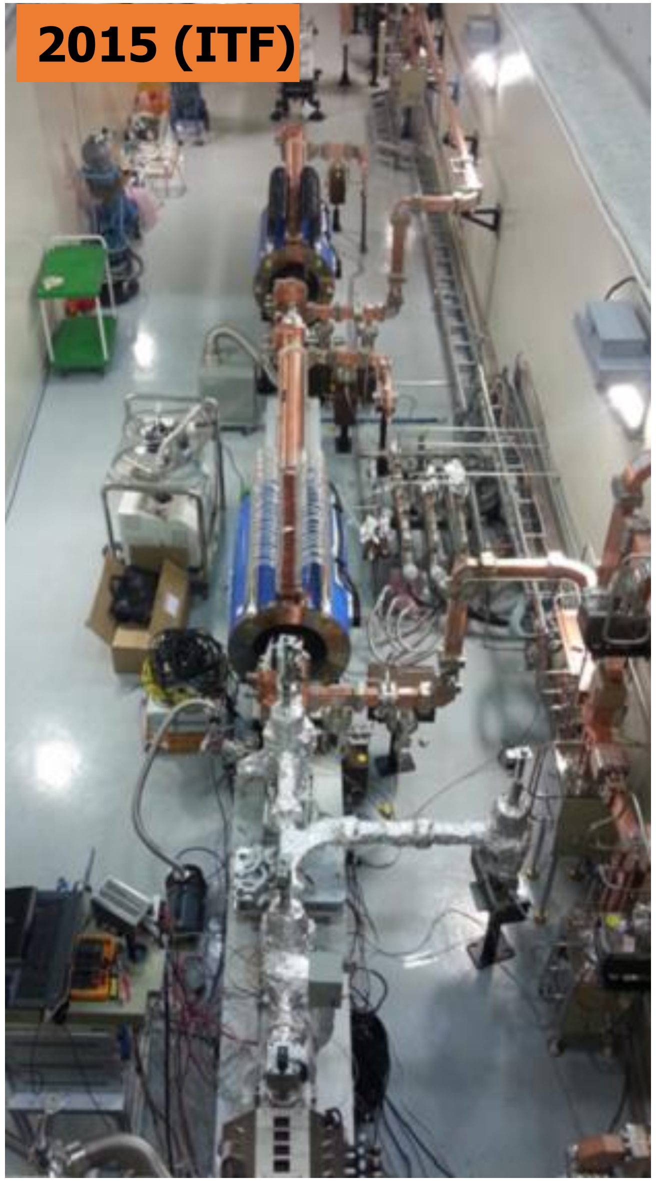
- Introduction of LWFA for X-ray free electron laser
- Introduction of PAL-eLABs
- Simulation results for LWFA with external injection from photocathode gun
- Development of capillary gas-cell for LWFA and plasma lens
- Summary

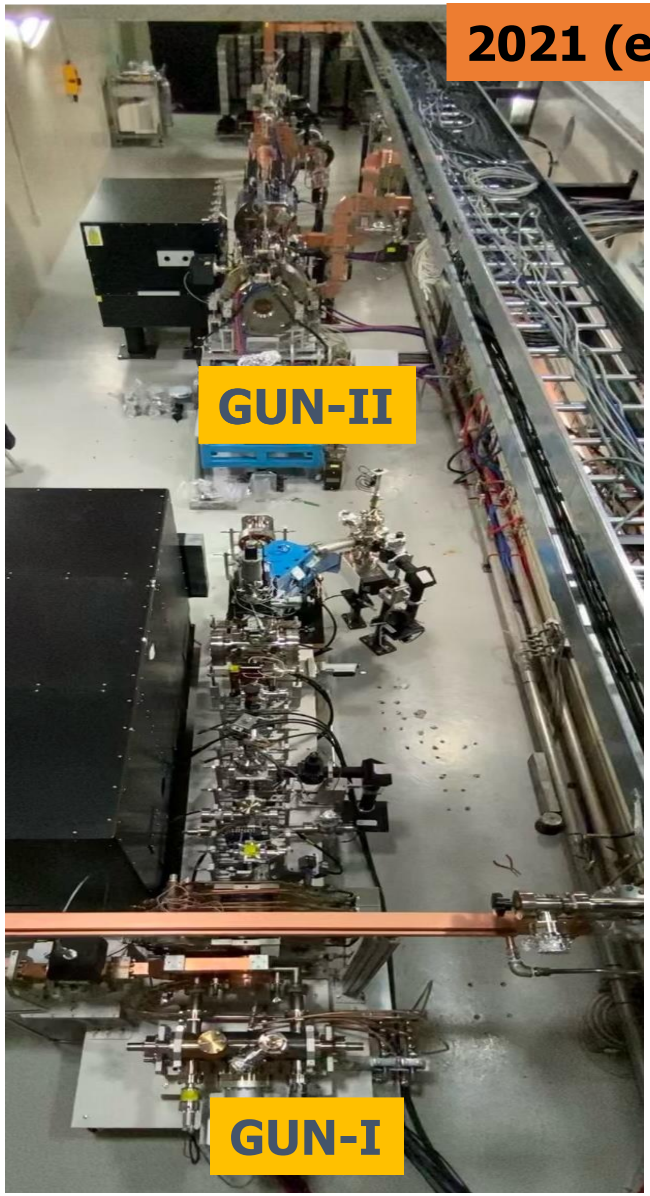
ITF (**I**njector **T**est **F**acility) → ***e*-LABs** (**e**lectron **L**inear **A**ccelerator for **B**asic **s**cience)

Re-arranged two e-beam lines (2019~2021)



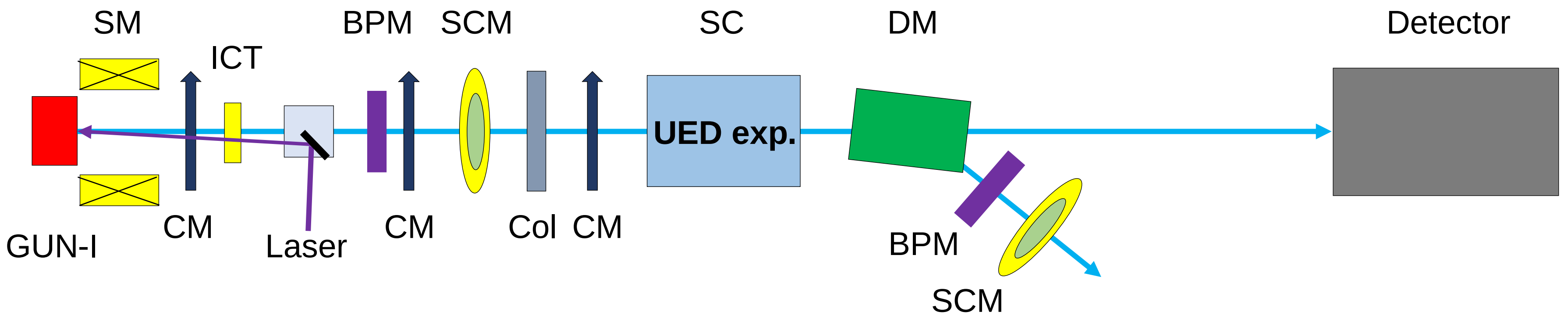
e-LABs re-arrangement (2021)



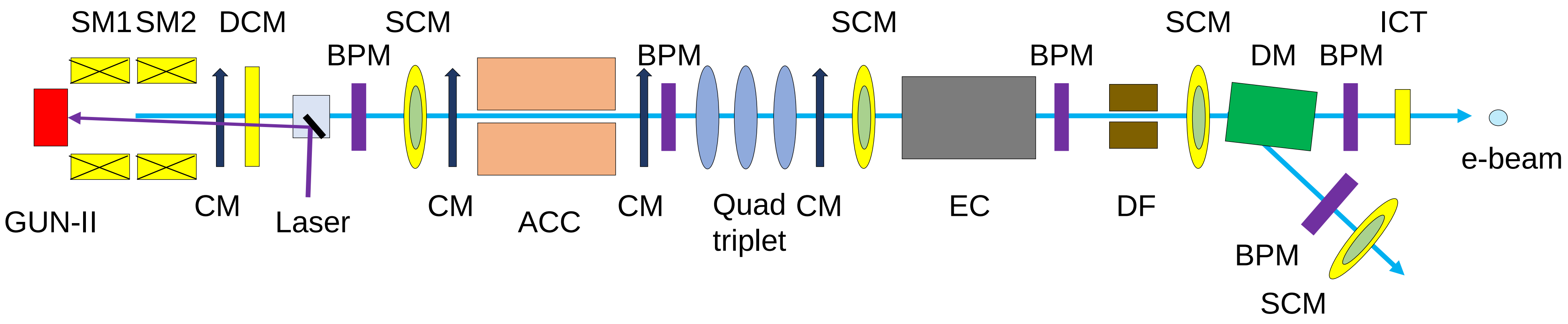


GUN-I, GUN-II schematic diagram

GUN-I



GUN-II



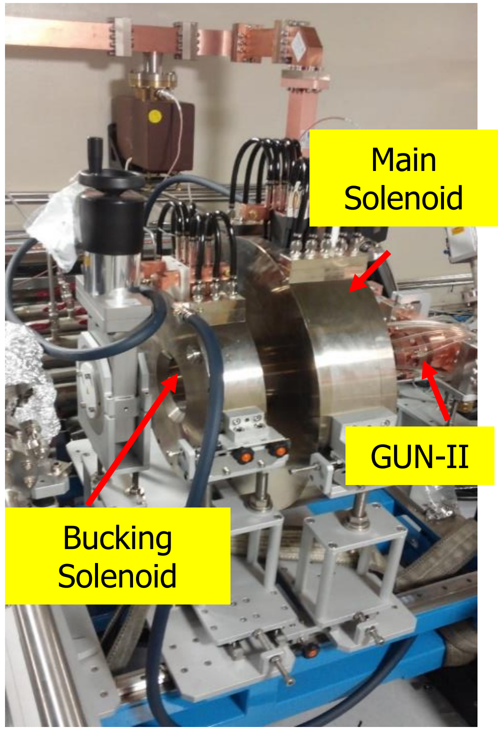
SM: Solenoid, CM: Corrector magnet, DCM: Dark current monitor, BPM: Beam position monitor, SCM: Screen monitor, Col: Collimator, SC: Sample chamber, DM: Dipole magnet, ACC: Accelerator, EC: Experimental chamber, DF: Deflector, ICT: Integrating current transformer

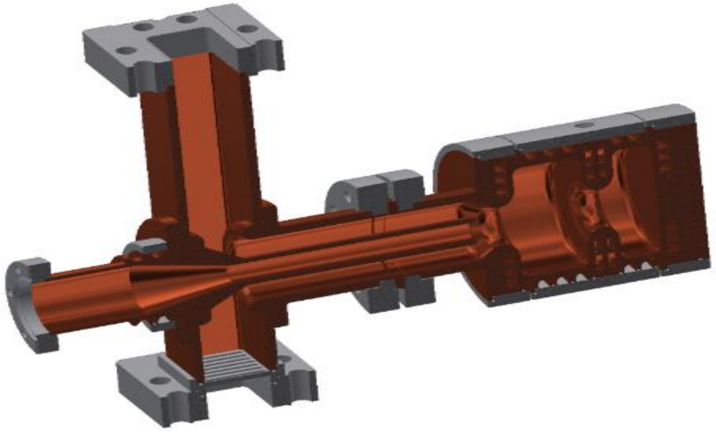
Beam commissioning for GUN-II is currently on going.

GUN-II configuration and e-beam profile

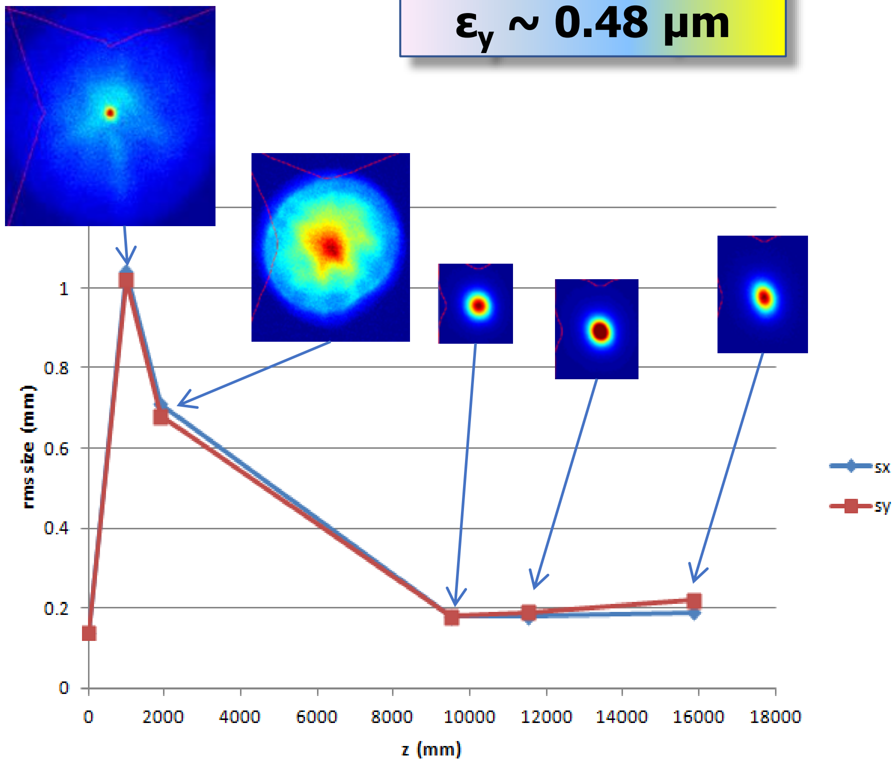
❖ **GUN-II Type**

- Alternative RF gun for PAL-XFEL
- Coaxial coupler type
- $f = 2856$ MHz
- $Q_0 = 14400$
- $f_{rep} = 10$ Hz
- $\tau_{pulse} = 2.5$ μs

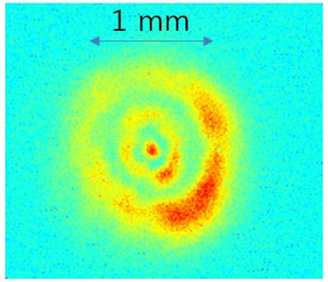




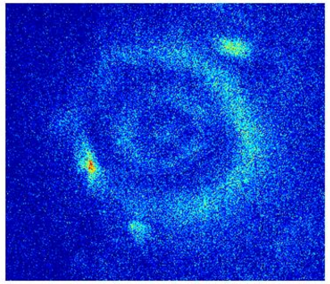
$\varepsilon_x \sim 0.41$ μm
$\varepsilon_y \sim 0.48$ μm



Evolution of e-beam transverse profile

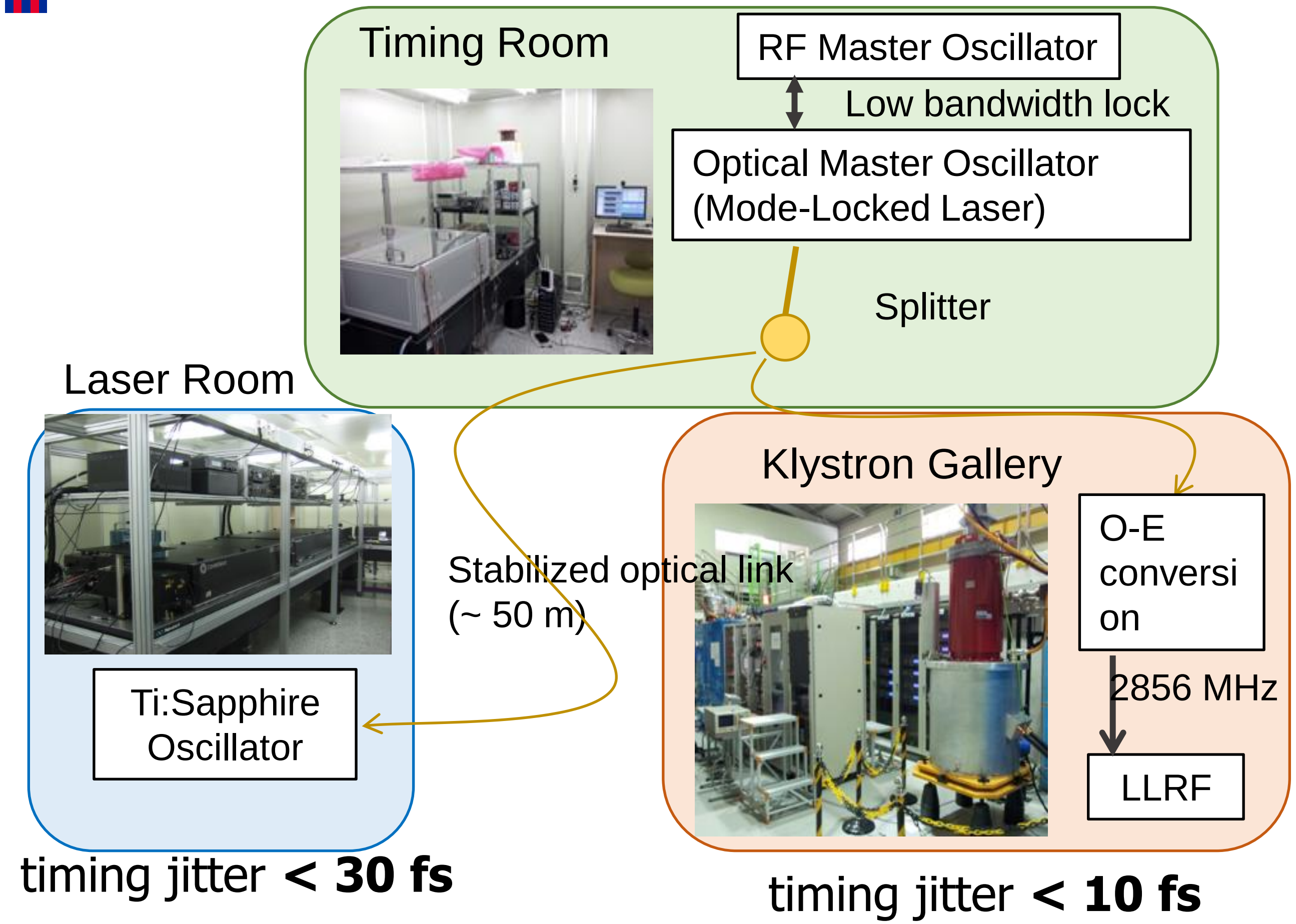


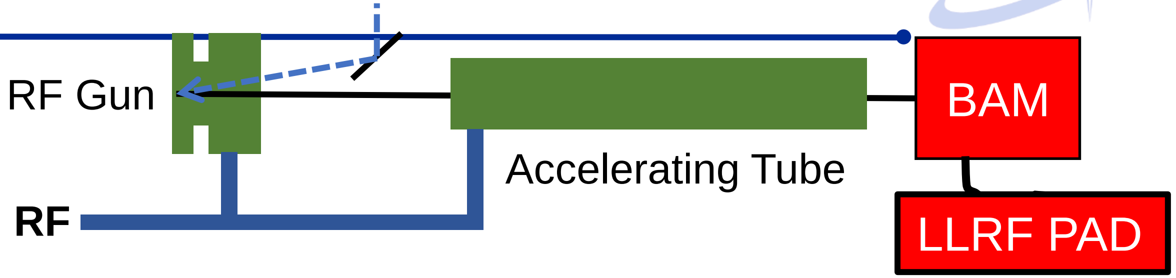
Virtual cathode (laser profile)

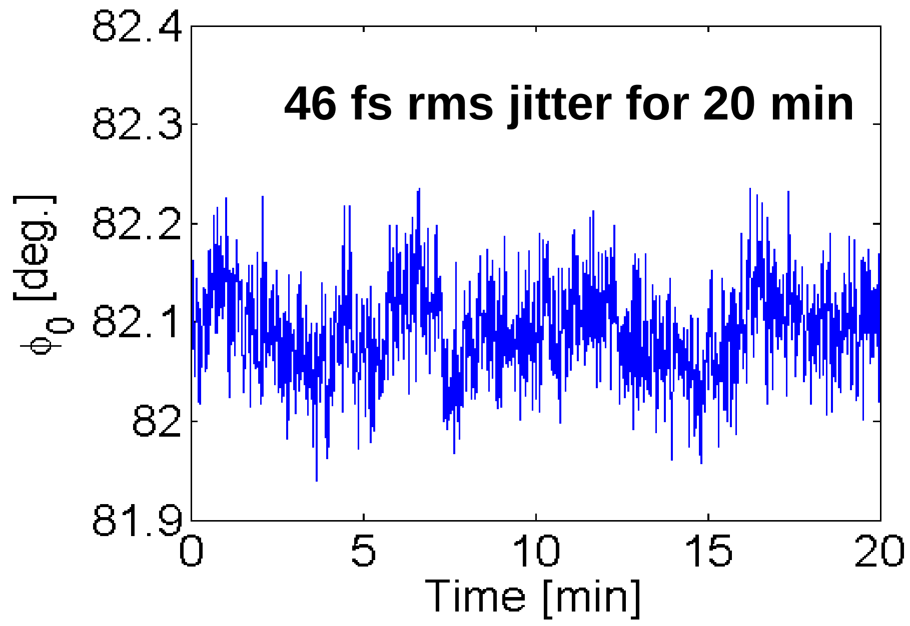


E- beam image at 1st screen

Optical timing synchronization test







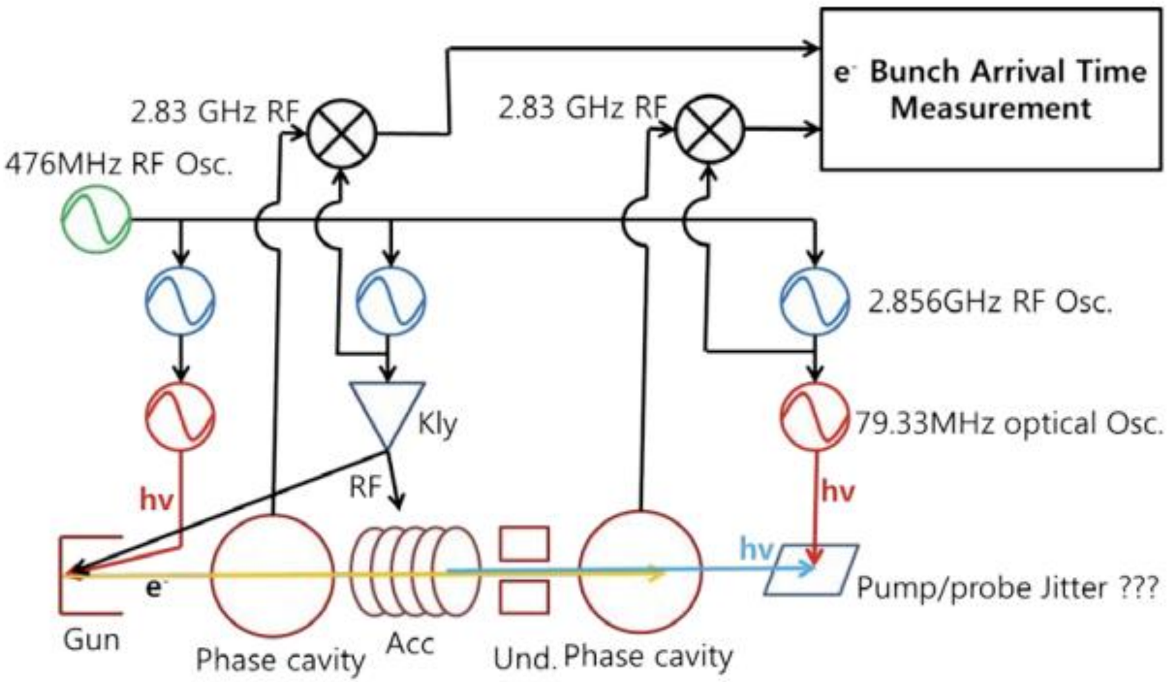
Kwangyun Jung, et al., *Opt. Lett.* **39**, 1577(2014)

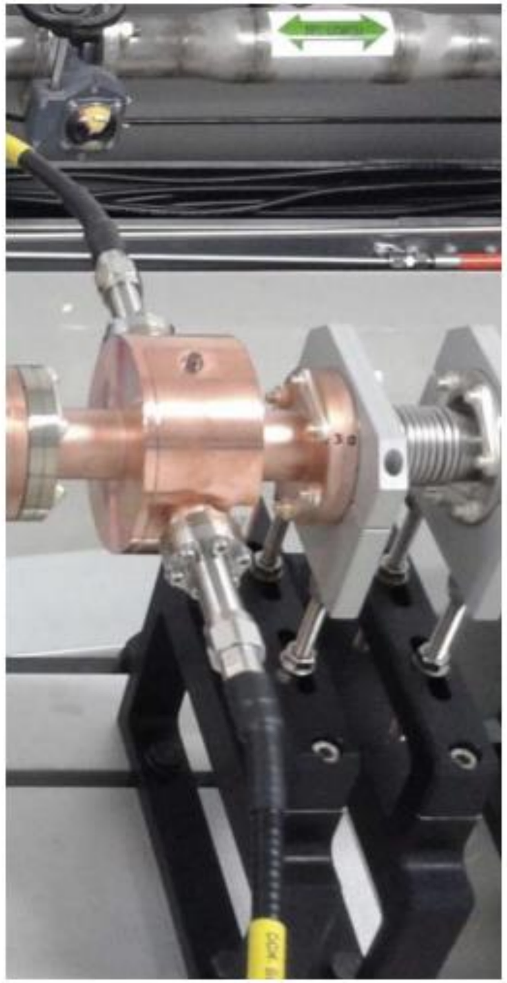
Kwangyun Jung, et al., *J. Lightwave Technol.* **32**, 3742(2014).

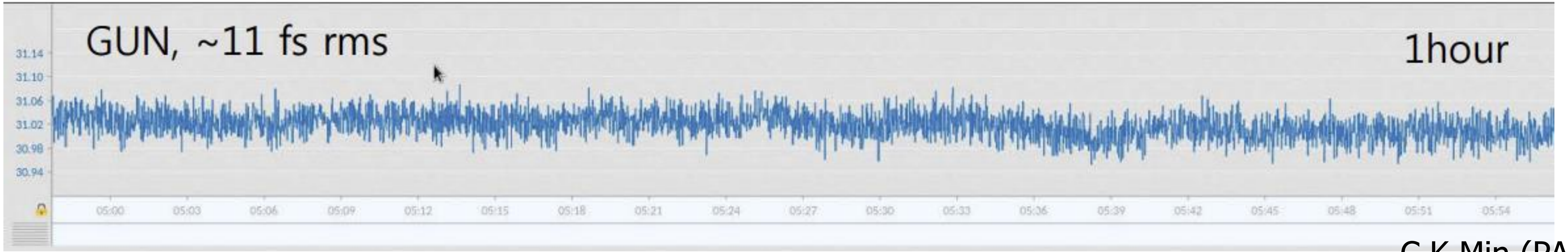
C.K Min (PAL)

PAL-XFEL

Monopole S-band cavity (phase cavity)







C.K Min (PAL)

e-LABs: e-beam based research beamlines

e-beam parameters

	GUN-I	GUN-II
GUN type	Four ports side coupled	Coaxial coupled
Charge	<1 pC	<250 pC
Emittance	~0.5 μm	
Energy	<6 MeV	<70 MeV
Energy spread	$<2x10^{-3}$	$\sim 2x10^{-4}$
Rep. rate	10 Hz	
RF Phase stability	$5x10^{-2}$ deg	
RF Amp. stability	$5x10^{-4}$	

Researches at e-LABs

GUN-I

- Ultrafast electron diffraction (UED)
- User beamline in the future

GUN-II

- E-beam based R&D beamline
- Advanced compact accelerators
- New conceptual accelerator technology
- Other e-beam based researches

Laser & electron parameter for laser-plasma accelerator

Optical laser parameter

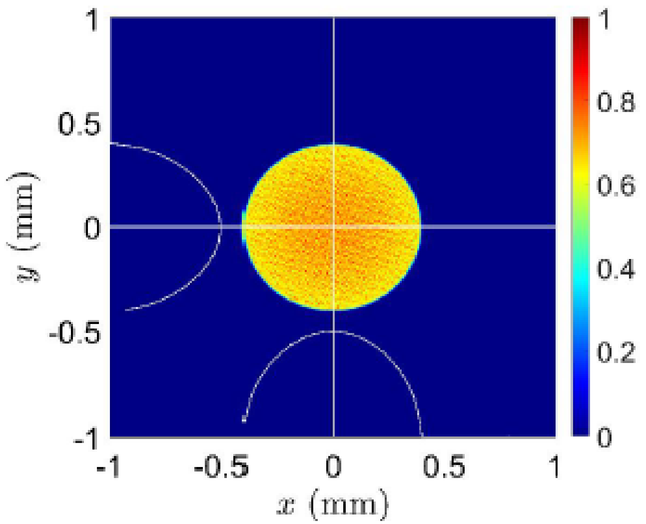
	Currently	Upgrade plan
Energy	14 mJ @760 nm ~1 mJ @253 nm	> 1 J @760nm (~ 10 TW)
Pulse width	2 - 3 ps	~65 fs
Rep. rate (Max)	120 Hz	<1 Hz
Energy stability	0.2% @760 nm <1% @253 nm	<1% @760 nm
Beam size (at Gun)	0.1 - 3 mm (full beam)	0.6 - 0.8 mm
Sync. jitter	~100 fs	~10 fs

e-beam parameter (GUN-II)

	Requirement
Charge	50 pC
Emittance	~0.5 μm
Beta	0.005 (Beam size ~ 5 μm)
Peak current	~2 kA
Pulse length	30 fs

Beam size, emittance using 50 pC beam

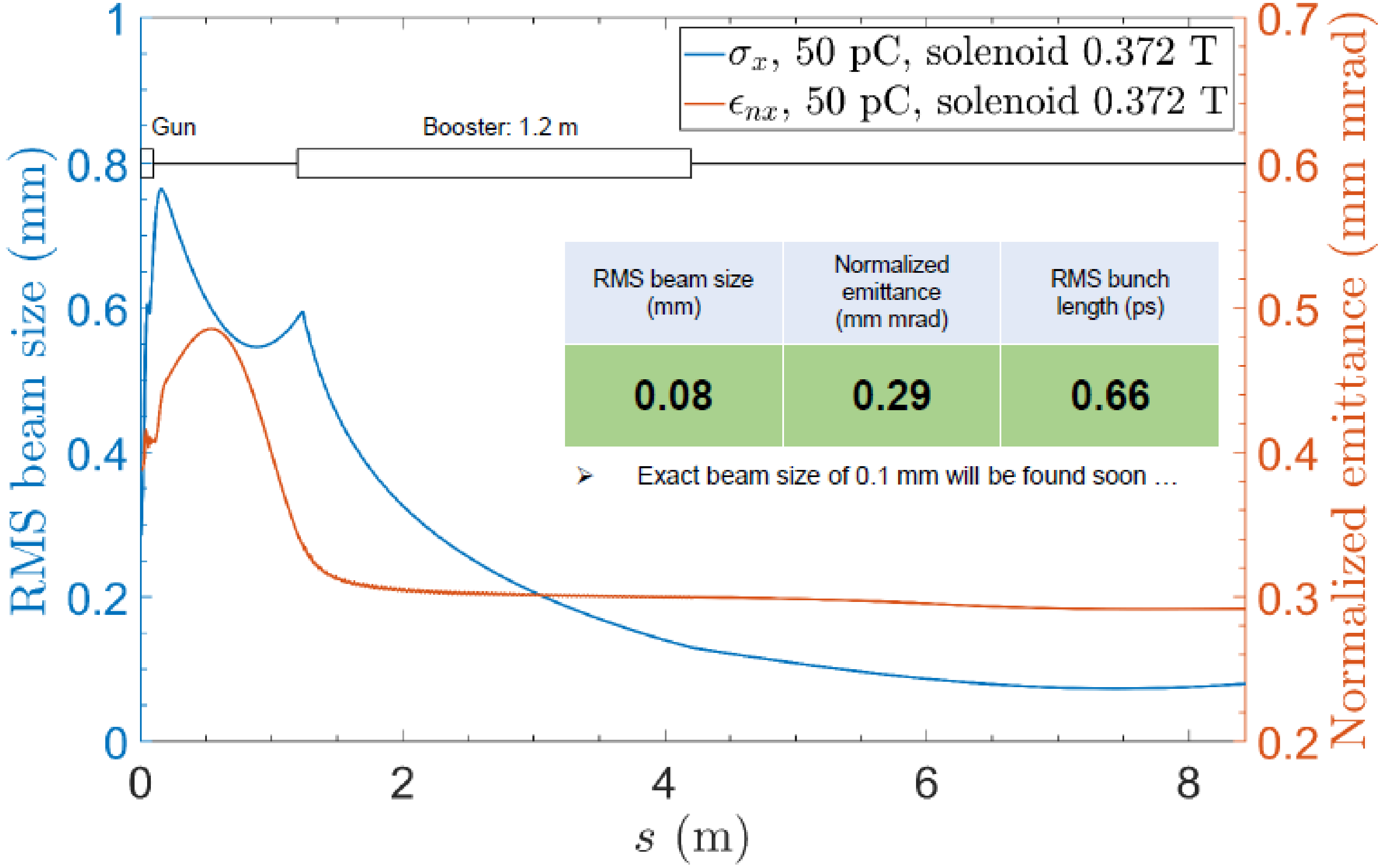
Initial distribution



Un-truncated Initial RMS beam size	0.8 mm
Truncate parameter C_sig	0.50
Truncated RMS beam size	0.2 mm
RMS bunch length	0.1 ps

Only charge is different

➢ Target position (8.43 m) is located at the end of this plot



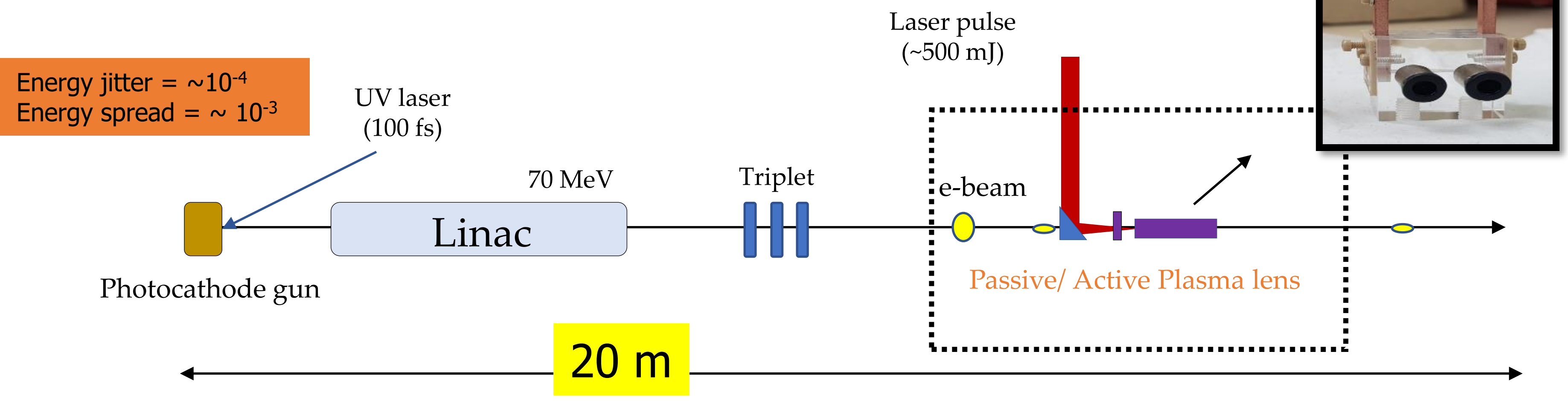
RMS beam size (mm)	Normalized emittance (mm mrad)	RMS bunch length (ps)
0.08	**0.29**	**0.66**

➢ Exact beam size of 0.1 mm will be found soon …

Advanced accelerators with external injection at PAL e-LABs

- Layout for advanced accelerator R&D (under installation)

Developed Capillary gas-cell

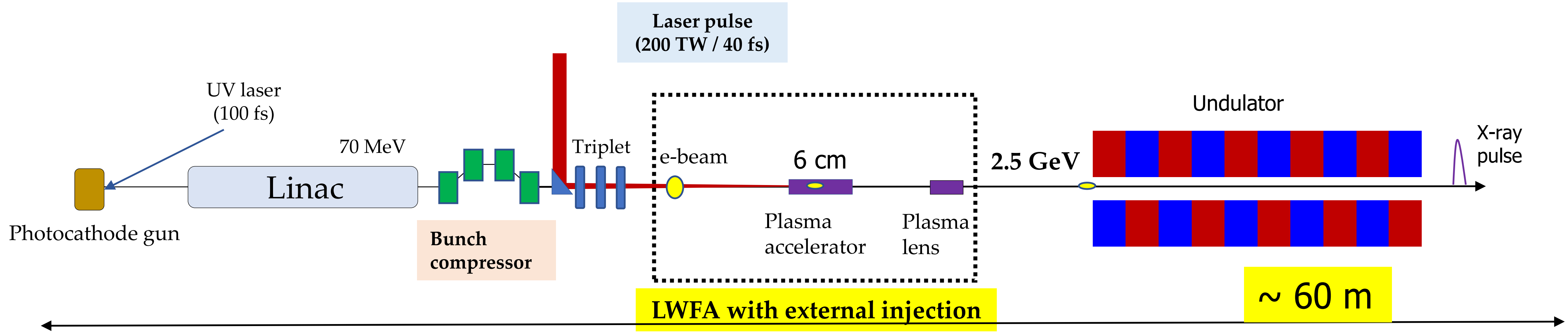


On-going works

- Passive /Active plasma lens test
- Develop long capillary plasma source
- Mode matching condition (emittance preservation)

- Layout for advanced accelerator R&D (Future plan)

- **Compact Soft X-ray free electron laser**



PIC simulation (JoPIC)

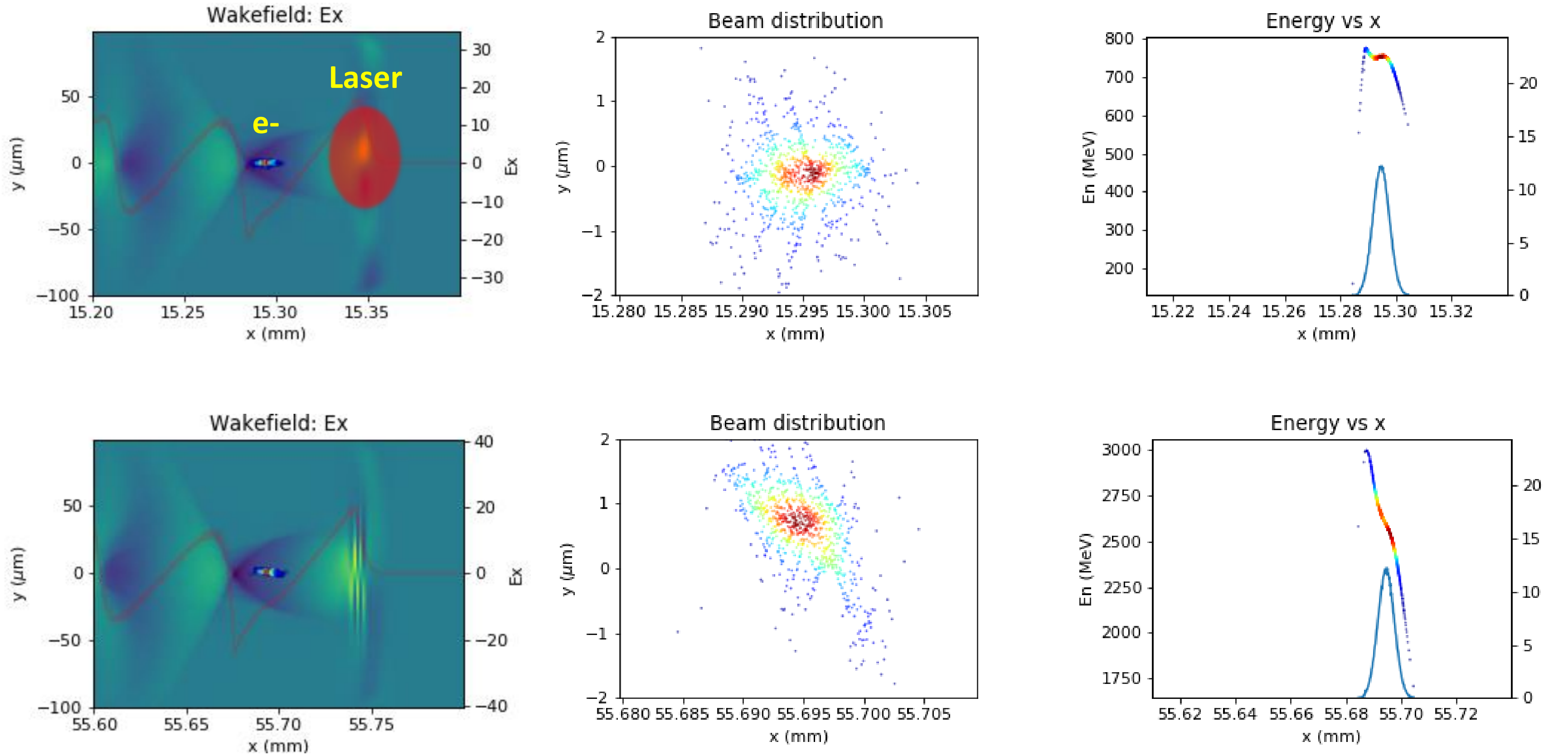
e-beam (from RF photocathode)
- Charge: 50 pC
- Pulse duration: 30 fs (FWHM)
- Energy: 70 MeV
- Peak current: 2 kA
- Emittance: 0.4 mm mrad
- Beta: 0.004
- Beam size: 5 μm

Laser
- a_0: 2
- λ_0: 800 nm
- Pulse duration: 65 fs
- Pulse width: 35 um (FWHM)

Plasma
- N_e: 3 x 10^{17} cm^{-3}
- Ramp: 30 mm
  (matching Gaussian ramp)
- Guiding structure

PIC parameters
- 2-Dimension
- Box size: 200 x 200 μm^2
- $dx = \lambda_0/20$
- $dy = \lambda_0/10$

LWFA with external injection



Target:
- Beam energy = 2.5 GeV
- Emittance = 1 mm mrad
- Energy spread = < 1%

Results:
- Beam energy = 2.5 GeV
- Emittance = 5 mm mrad
- Energy spread = 5 %

Optimization is still ongoing

FEL simulation (SIMPLEX)

e-beam

- Electron energy: 2.5 GeV
- Bunch length: 3 µm
- Bunch charge: 50 pC
- Normalized emittance: 1 mm mrad
- Peak current: 2 kA
- Energy spread: 1 %
- Slice energy spread: 3 x 10^{-4}

Undulator (same as PAL-XFEL)

- Undulator strength: K=3.5
- Periodic length: 3.5 cm
- Undulator length: 5 m
- Number of segment: 8

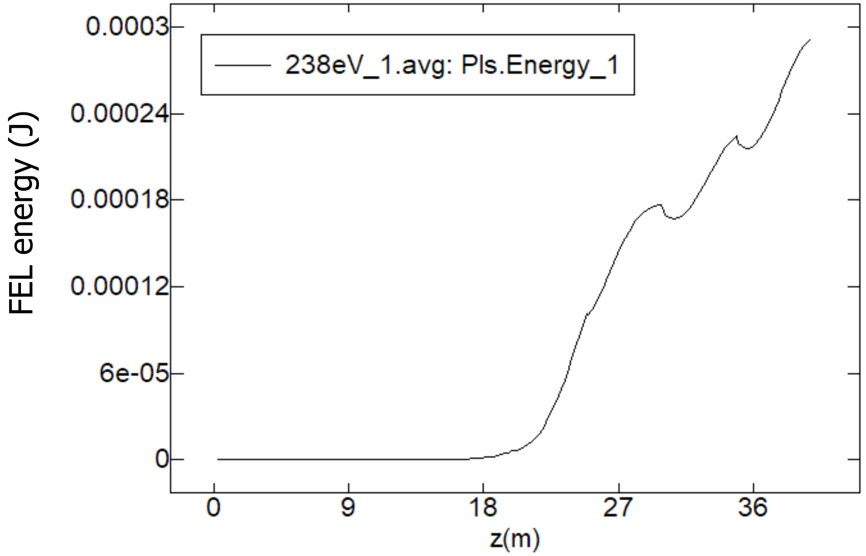
FEL parameters (E_c=230 eV)

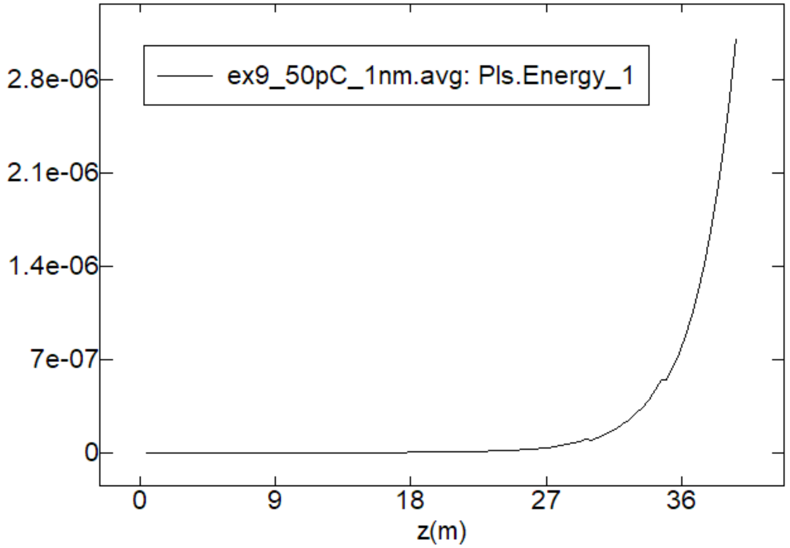
- Pierce parameter: 1 x 10^{-3}
- Gain length: 1.27 m
- Saturation length: 26 m

E_c = 230 eV (K = 3.5)

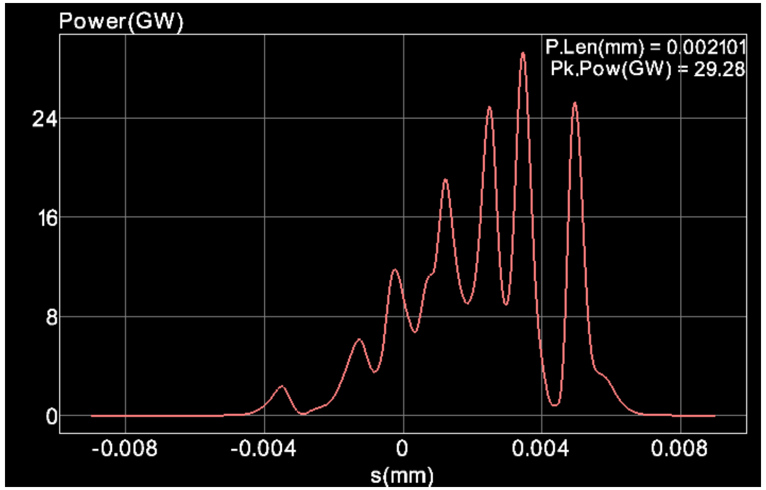
E_c = 1057 eV (K = 1.1)

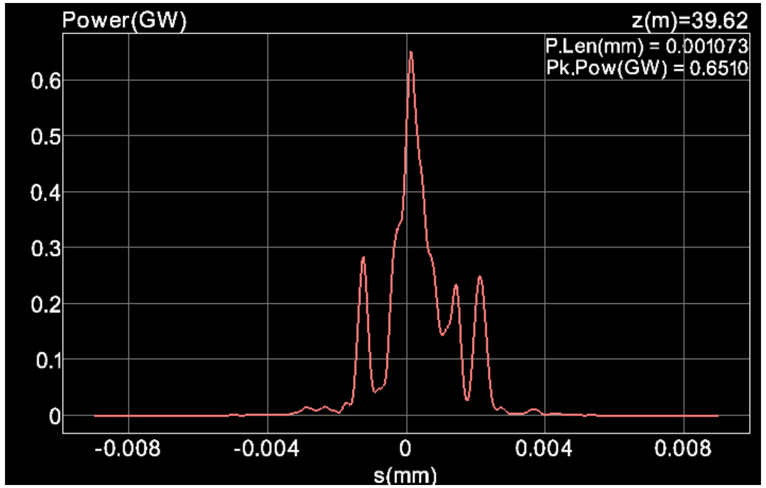
Gain curve





Power

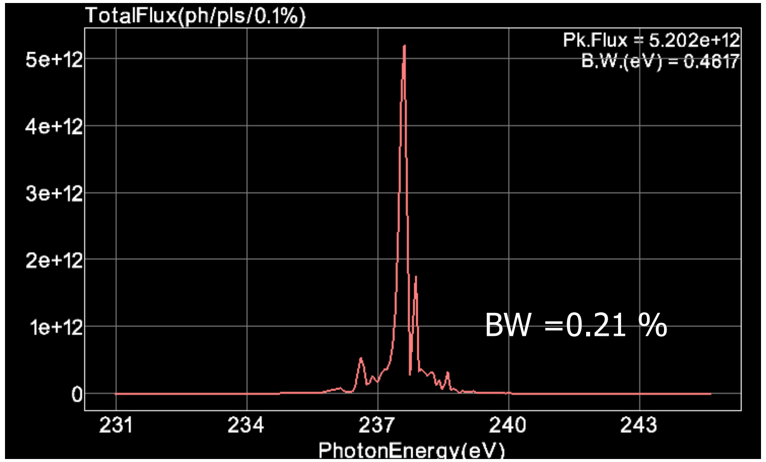




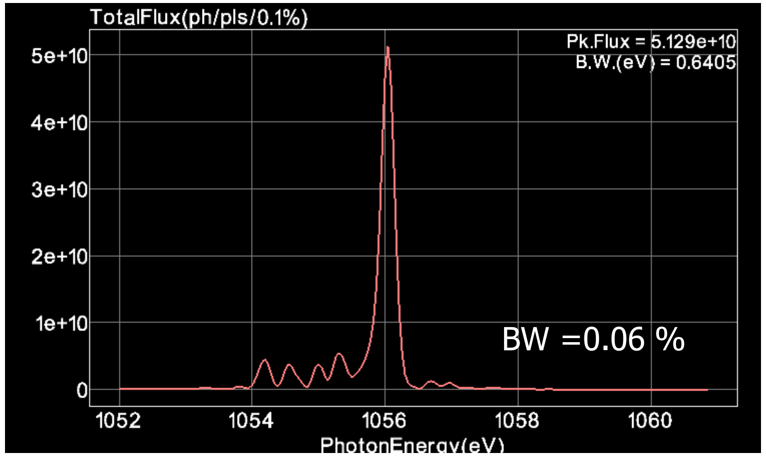
FEL simulation results

Spectrum

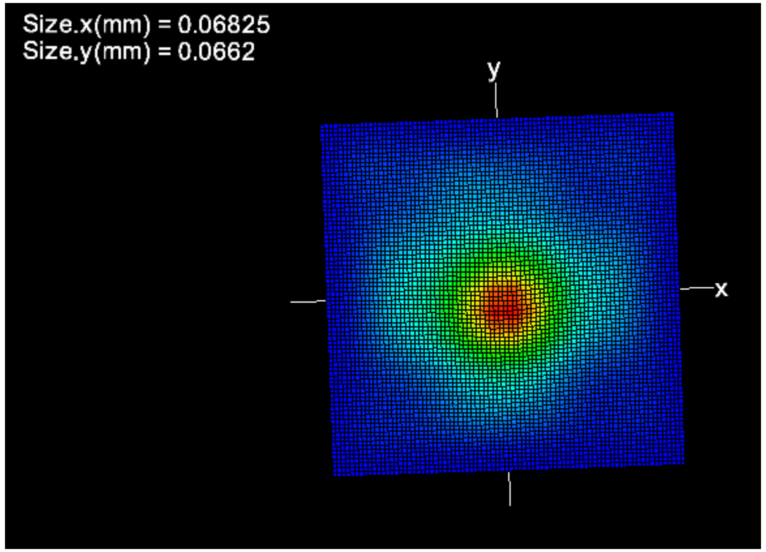
E_c = 230 eV (K = 3.5)

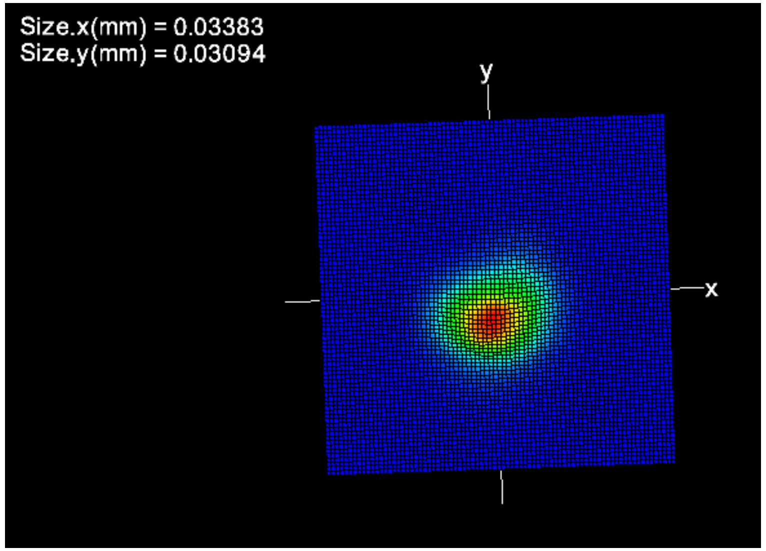


E_c = 1057 eV (K = 1.1)



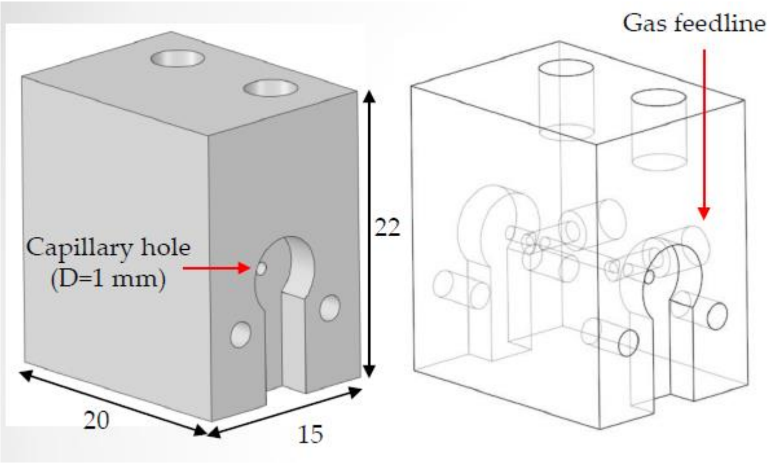
Beam profile

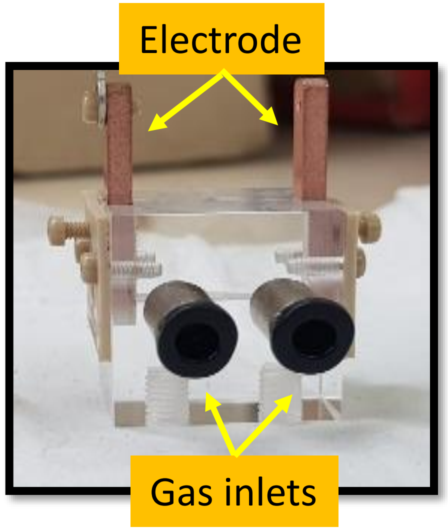




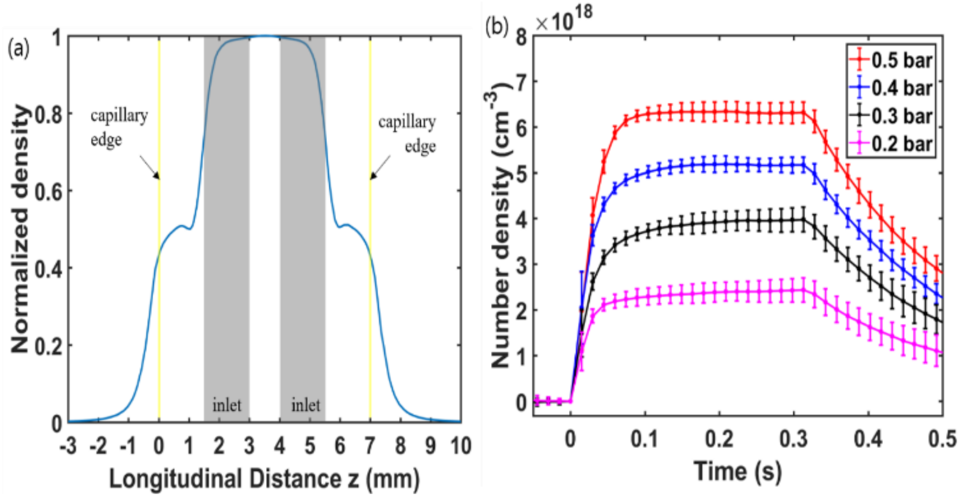
Capillary plasma source development

Cylindrical capillary gas-cell (Sapphire)

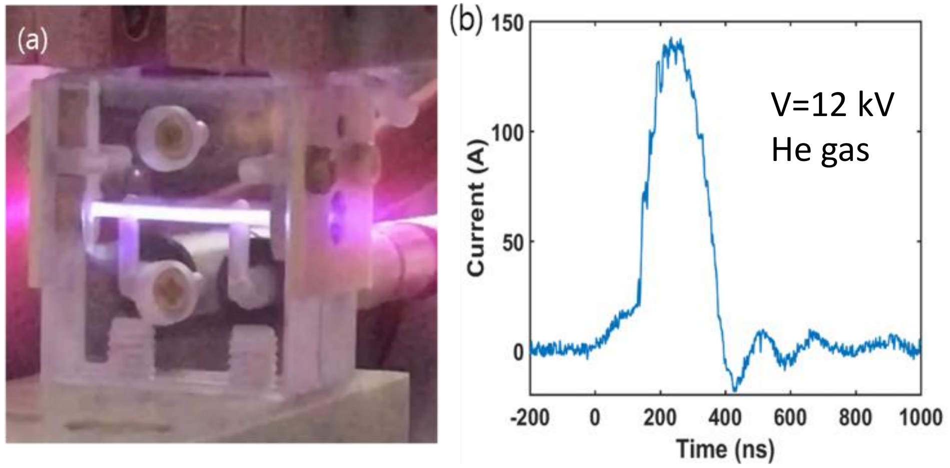




Gas density profile in a capillary



Capillary discharge plasma



Advantages of new capillary gas-cell

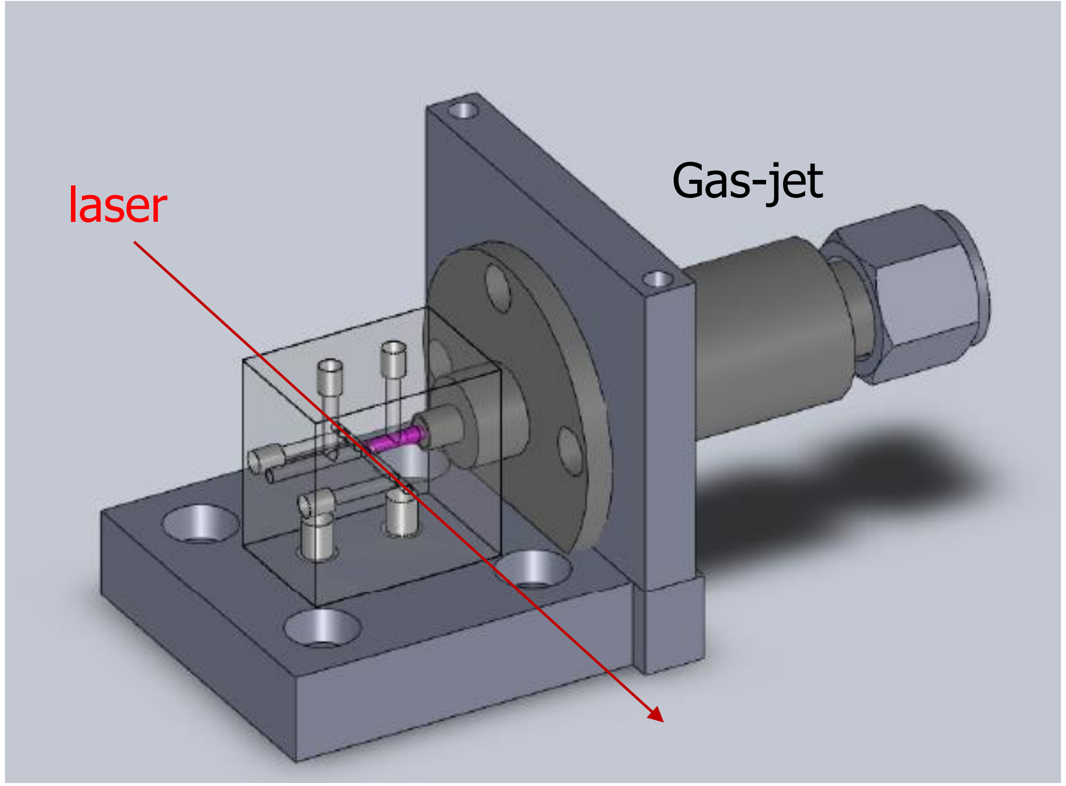
- ✓ **No housing**
- ✓ **Direct gas injection**
- ✓ **Easy to combine (squared capillary)**
- ✓ **Multi-coupling for long-distance capillary**

LEE, Sihyeon, et al. One-Body Capillary Plasma Source for Plasma Accelerator Research at e-LABs. *Applied Sciences*, 2023, 13.4: 2564.

Capillary gas-cell with flat nozzle gas jet

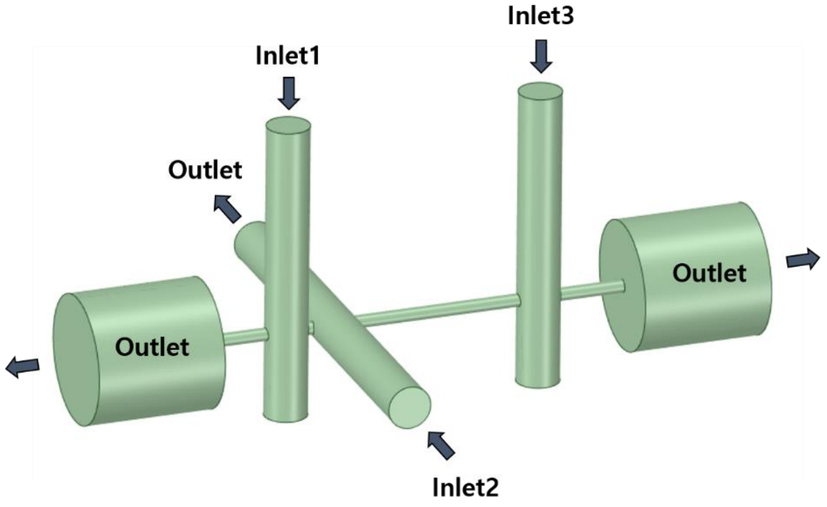
15 mm + gas jet

3 types of tip

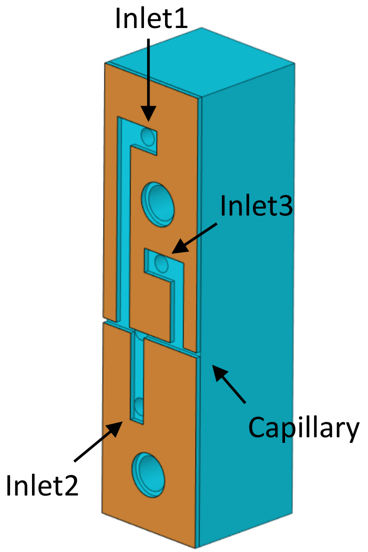


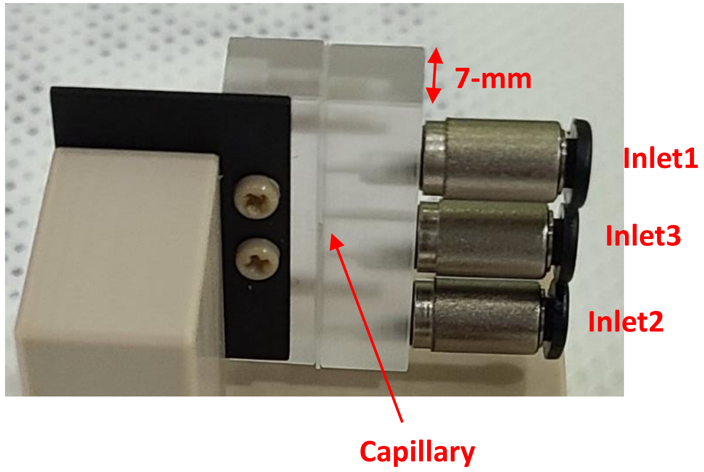
New capillary gas-cell w/ down ramp profile

Design of capillary gas-cell w/ down ramp

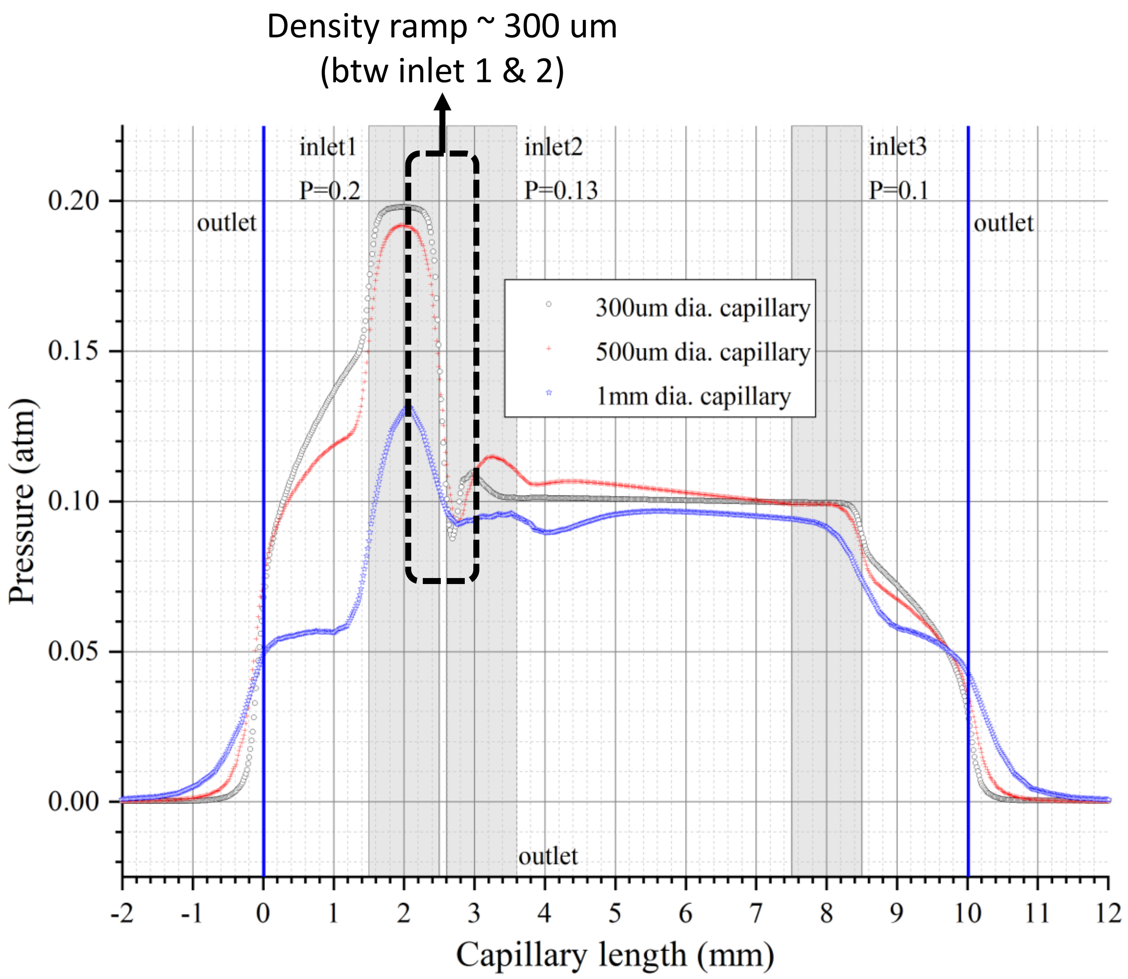


7-mm long capillary gas-cell





Pressure distribution along a capillary (CFD)



Summary

- Milestone results for FEL lasing based on e-beam from LWFA/PWFA in last 3 years
- Renewed injector test facility to electron beam based R&D facility (ITF → e-LABs)
- Installed two electron beamlines (commissioning for GUN-I & -II is on-going)
  - GUN-I: UED beamline (<3 MeV, <100 fs)
  - GUN-II: Advanced compact accelerators, THz based researches, other e-beam based R&D (<70 MeV, <2 ps)
- Plan to install TW laser system and bunch compressor for plasma accelerator applications
- Simulation of compact Soft XFEL using plasma accelerator with external injection (PIC, SIMPLEX)
- Developed capillary discharge plasma source for active plasma lens & plasma accelerator applications