Beam-Driven Wakefield Accelerator Research at UNIST, Korea

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Ulsan National Institute of Science and Technology (UNIST)

AFAD Workshop 2021

*Acknowledgements: ITF group (PAL), AWAKE collaboration (CERN), BLAST program (LBNL), AWA group (ANL), PITZ group (DESY)
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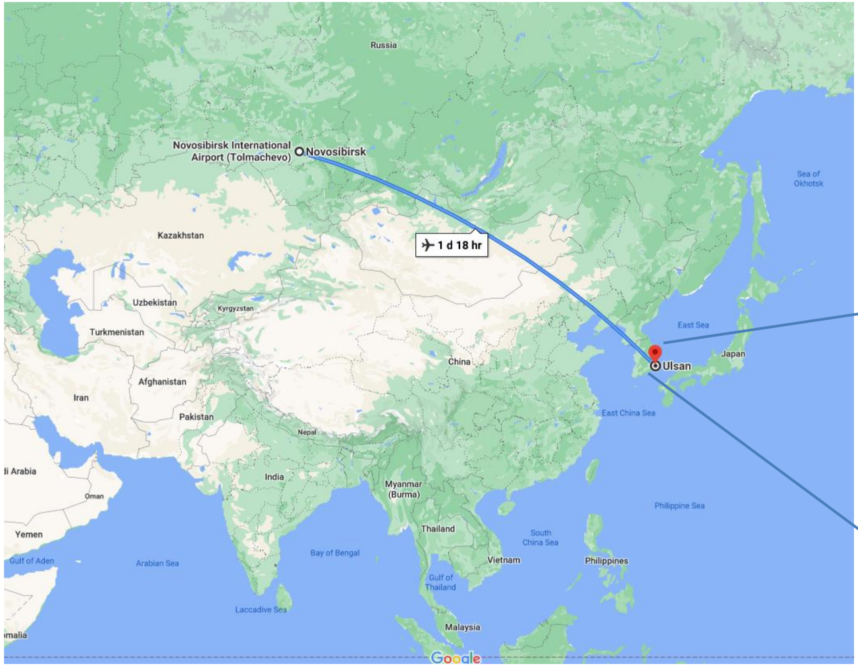
Ulsan and UNIST

Ulsan is South Korea's eighth-largest city overall, with a population of over 1.1 million inhabitants.



Ulsan is the industrial powerhouse of South Korea.
It has the world's largest automobile assembly plant operated by the Hyundai Motor Company; the world's largest shipyard, operated by Hyundai Heavy Industries; and the world's third largest oil refinery, owned by SK Energy.
In 2017, Ulsan had a GDP per capita of $65,093, the highest of any region in South Korea.

UNIST
(Ulsan National Institute of Science and Technology)
= One of the four public universities in South Korea which are dedicated to research in science and technology, founded in 2009

Background

~2010

New Journal of Physics
The open-access journal for physics

EDITORIAL

Focus on laser- and beam-driven plasma accelerators

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New Journal of Physics **12** (2010) 045003 (5pp)
Received 19 March 2010
Published 30 April 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/4/045003

There are far fewer PWFA than LWFA experiments being performed worldwide. This is because there are far fewer facilities that can provide the high-current, highly relativistic charged particle beams that are needed for such experiments [21]. The two main facilities are at the SLAC National Accelerator Laboratory and the Brookhaven National Laboratory, both in the United States. PWFA development is driven by its application in high-energy physics.

- → Recently, European countries started considerable investment for beam-driven wakefield accelerator researches (e.g., AWAKE).

- → In Korea, still laser-driven researches are dominant; only recently a full-scale research program on beam-driven wakefield took off, motivated by experience in producing high-current & high-quality electron beams for XFEL.

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Simulation Efforts

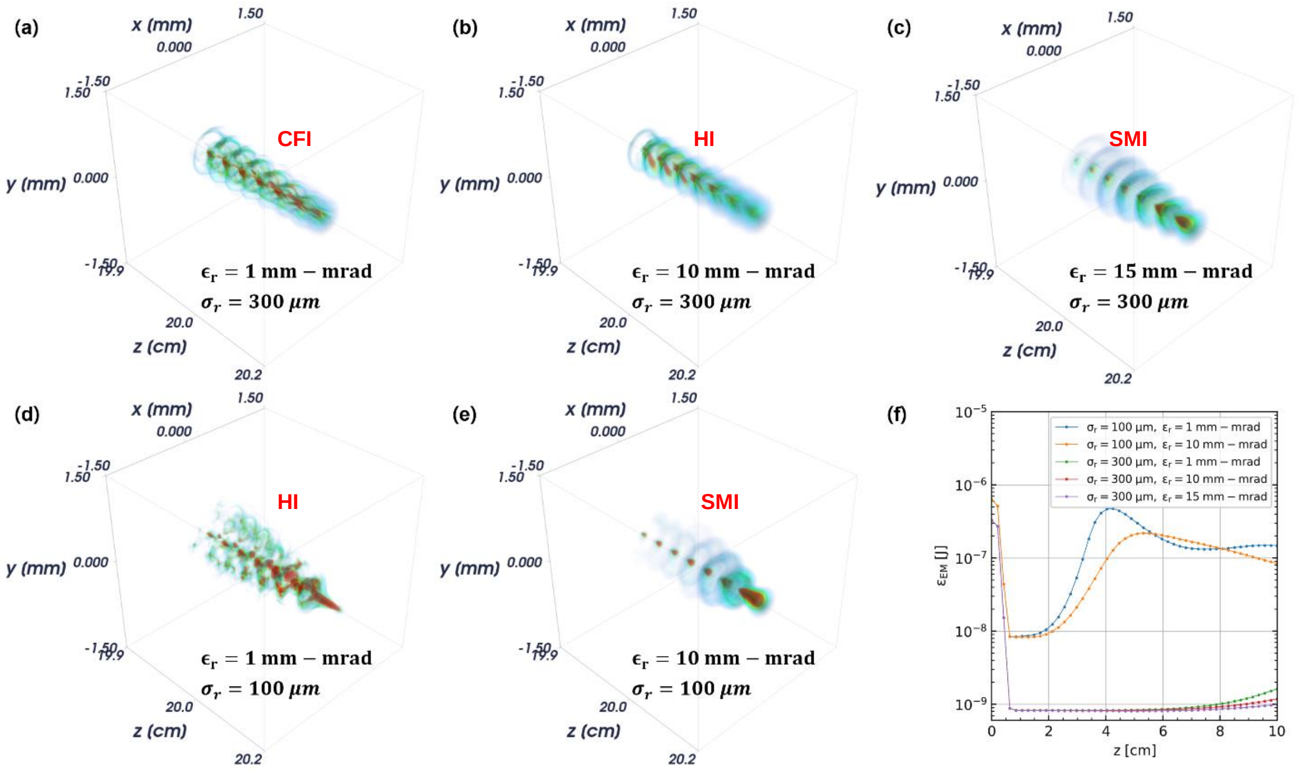
Plasma instabilities in beam-driven plasma wakefield; Trojan horse injection; and seeded self-modulation for AWAKE RUN 2 experiments

(Kook-Jin Moon's contribution)

Beam-plasma instabilities in long beam ($k_p\sigma_z \gg 1$) and over-dense ($n_b \ll n_0$) plasma regime

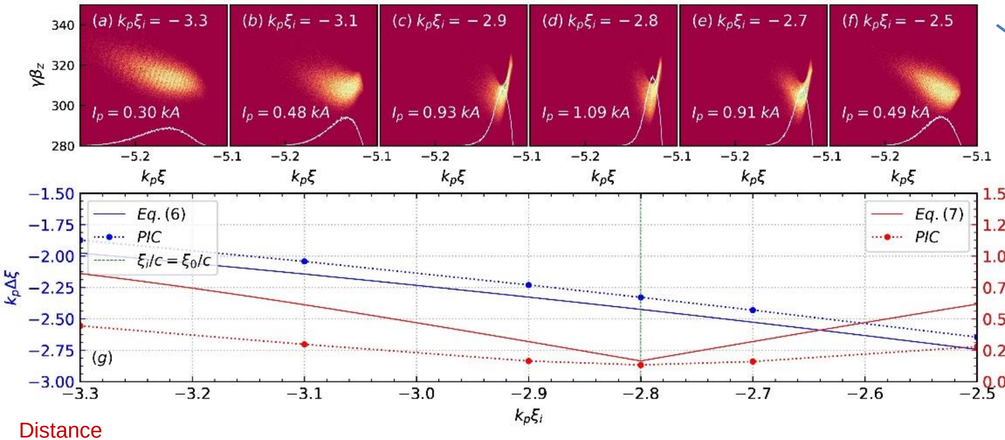
Current filamentation instability:
Typically $k_p\sigma_r \gg 1$

Hose instability &
Self-modulation instability:
Typically $k_p\sigma_r < 1$

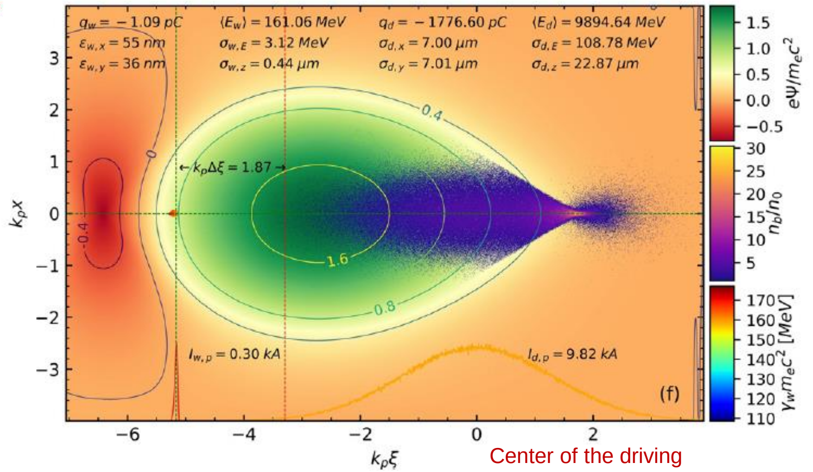


Beam-plasma instability can be selectively induced by adjusting beam radial size and transverse emittance.

[K. Moon et al., Phys. Plasmas 26, 073103 (2019)]



Longitudinal phase spaces of witness bunch:
The energy spread of witness bunch is affected by position of ionization laser pulse



Center of the driving beam

Distance from the ionization to trapping positions of the witness electrons

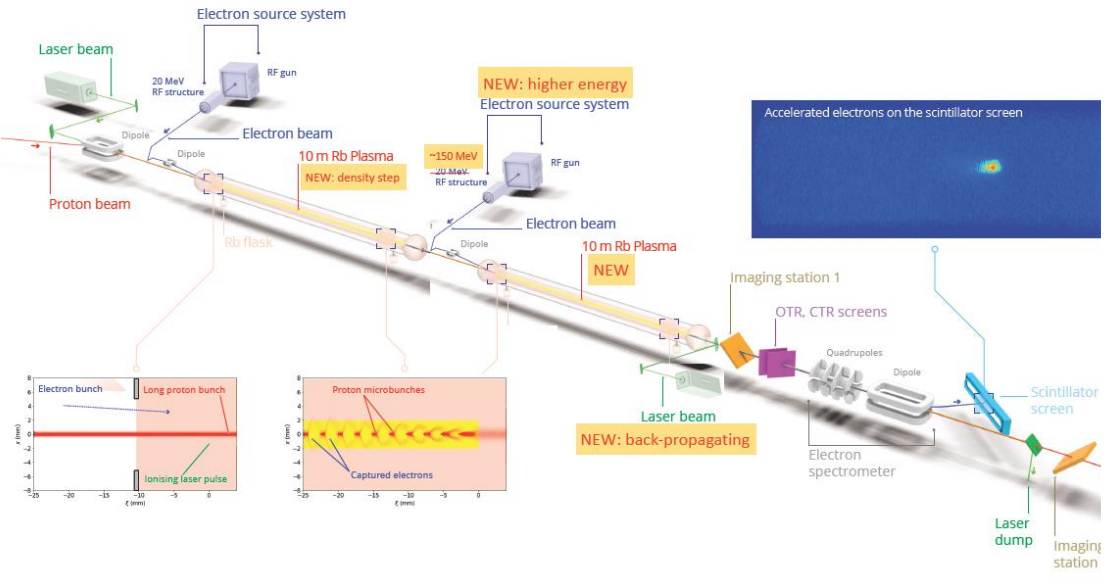
$$k_p\Delta\xi \approx -k_p(\xi_i - \xi_0) - \sqrt{k_p^2(\xi_i-\xi_0)^2 + 2E_0/\partial_{k_p\xi}E_{z,i}}, \quad (6)$$

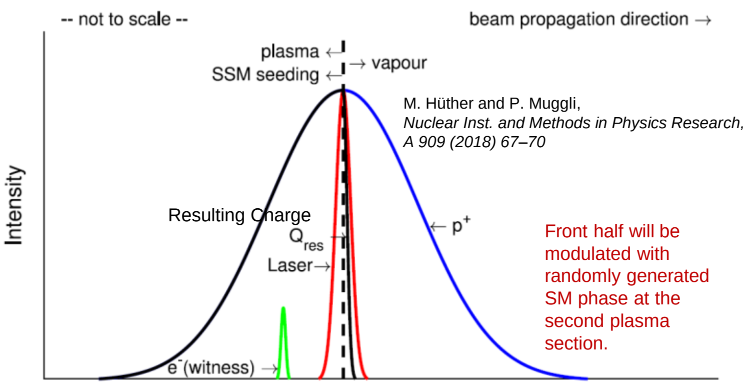
$$\sigma_z \approx \left(|\langle\xi_i\rangle - \xi_0| + \frac{\sigma_\psi L_i}{2}\right)\left(1 + \frac{\langle\xi_i\rangle - \xi_0}{|\Delta\xi|}\right)\frac{\sigma_\psi L_i}{|\Delta\xi|}, \quad (7)$$

Witness bunch longitudinal phase space is strongly affected by space charge field especially during short propagation distance.

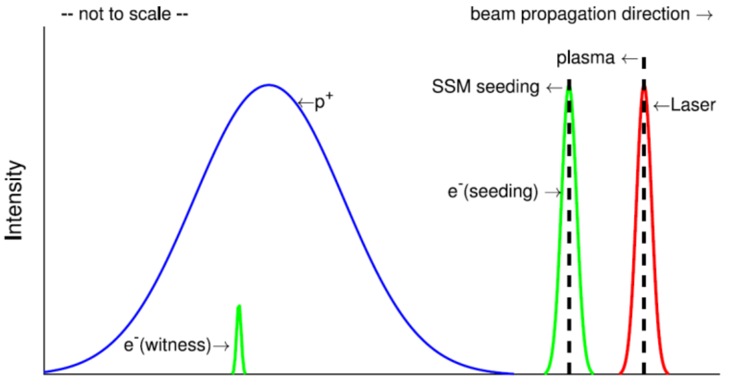
AWAKE RUN2 experiment and e-beam seeding

Edda Gschwendtner, 62nd Annual meeting of the APS Division of Plasma Physics, Nov 2020





Ionization front seeding



Electron beam seeding

Run 2 a): Demonstrate electron seeding of self-modulation in first plasma cell

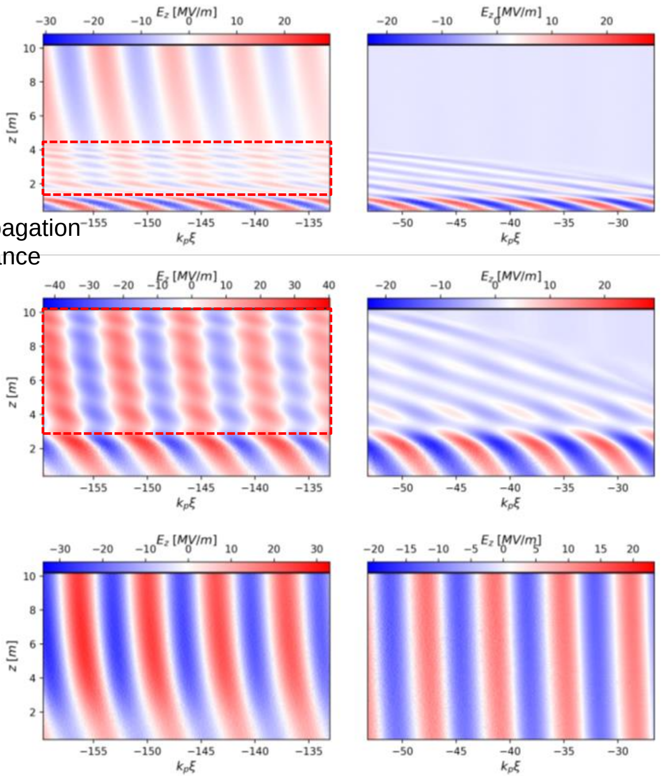
Run 2 b): Demonstrate the stabilization of the microbunches with a density step

Run 2 c): Demonstrate electron acceleration and emittance preservation

Run 2 d): Demonstrate scalable plasma sources

Seeded Self-Modulation phase determination by seed electron bunch

Seed & SSM wakefields superposed (a) **Seed wakefield** (b)

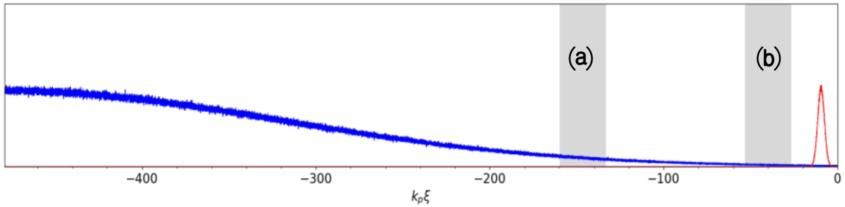


Propagation distance

10 MeV

20 MeV

160 MeV



Seed beam energy 10, 20 MeV ($\langle v_{z,s}\rangle \ll \langle v_{z,p}\rangle \sim c$)

- Dephasing seed wakefield during SSM development.
- Seed and SSM driven wakefields alternately interfere constructively and destructively. Phase oscillations observed (red dotted boxes): Any effects?

Seed beam energy 160 MeV ($\langle v_{z,s}\rangle \sim \langle v_{z,p}\rangle \sim c$)

- Non-evolving seed wakefield during SSM development.
- Seed and SSM driven wakefields interfere constructively.

We are looking for electron bunch parameters that lead to the “best” self-modulation as an ongoing study.

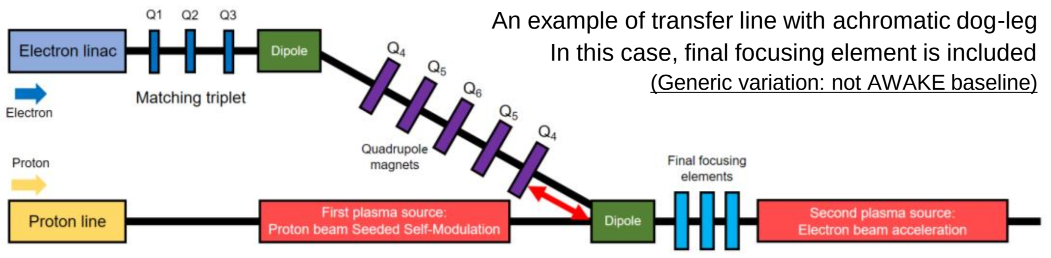
→ Preliminary experiment on electron beam injection into plasma (next month)
→ Proton run in November

Design and optimization

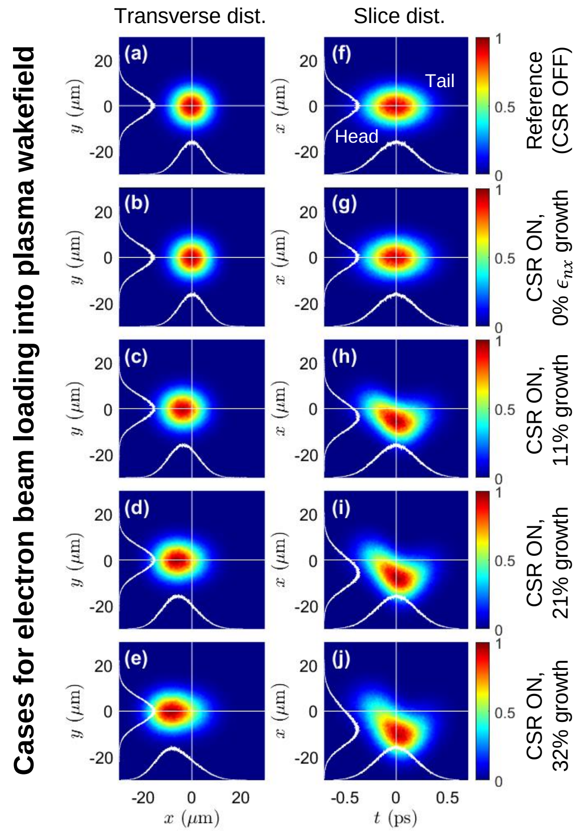
Studies on optimization of electron transfer line
and beam loading into beam-driven plasma wakefield

(Seong-Yeol Kim’s contribution)

Electron beam loading



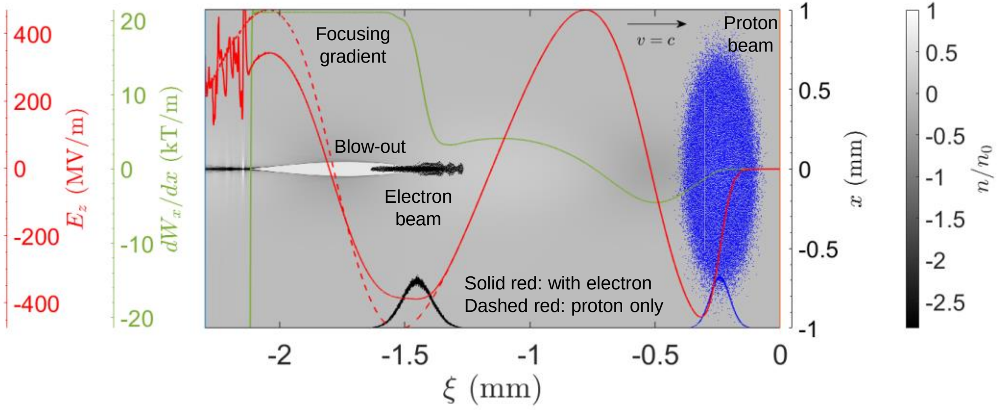
An example of transfer line with achromatic dog-leg
In this case, final focusing element is included
(Generic variation: not AWAKE baseline)



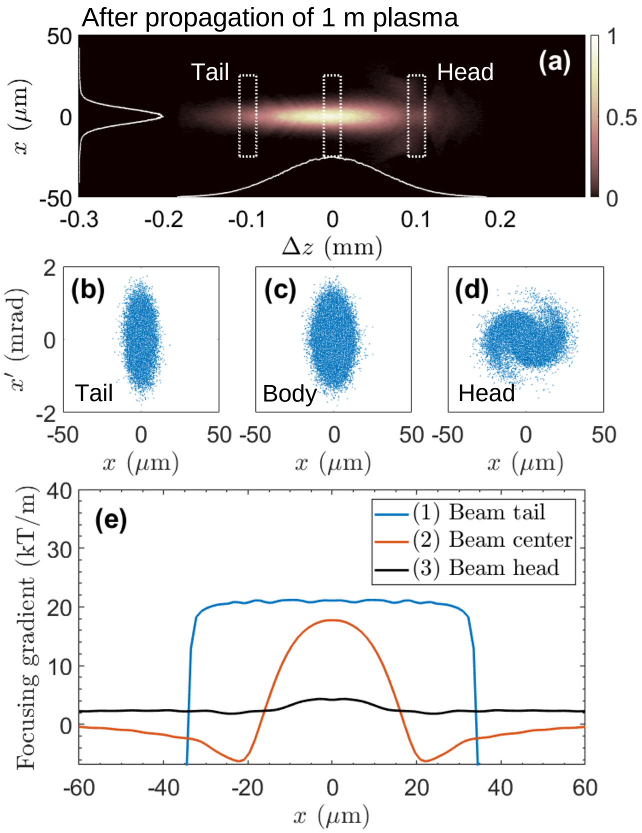
- Beam-driven plasma wakefield acceleration (PWFA) with external electron injection scheme
  - Need to control / optimize transfer line to match the electron beam parameters for injection requirement
  - Two ultimate goals of PWFA: increase in acceleration (capturing) efficiency and preservation of emittance
- Research motivation:
  - Coherent synchrotron radiation (CSR) on the electron beam: source of emittance growth and non-linear distortion of beam phase space
  - Investigation of beam loading with CSR effect: is it significant on additional emittance growth during acceleration?

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

Electron beam loading



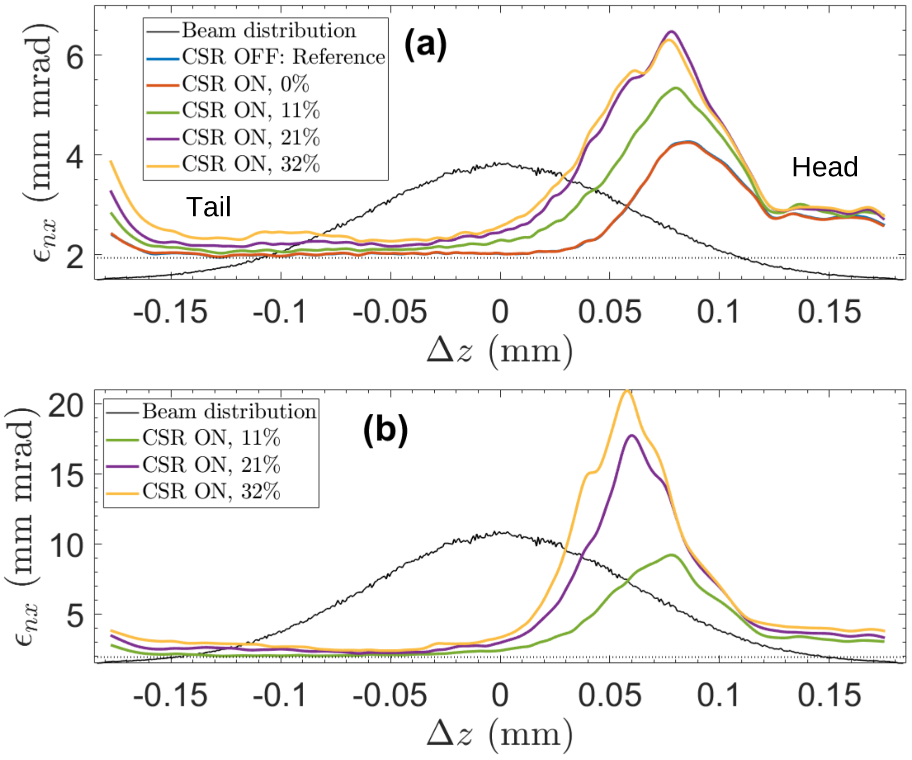
- PWFA and beam loading simulations with simplified model*
  - Electron beam density: 31 times higher than background plasma density, generating blow-out regime
  - At electron beam head, blow-out starts to develop; focusing gradient is not constant along slice
  - Inside blow-out regime, focusing gradient is constant and very strong
  - This feature is called head-erosion (emittance growth is mostly at the beam head; next slide)



➢ *: V. K. Berglyd Olsen, E. Adli, P. Muggli, *Phys. Rev. Accel. Beams* **21**, 011301, 2018

Electron beam loading

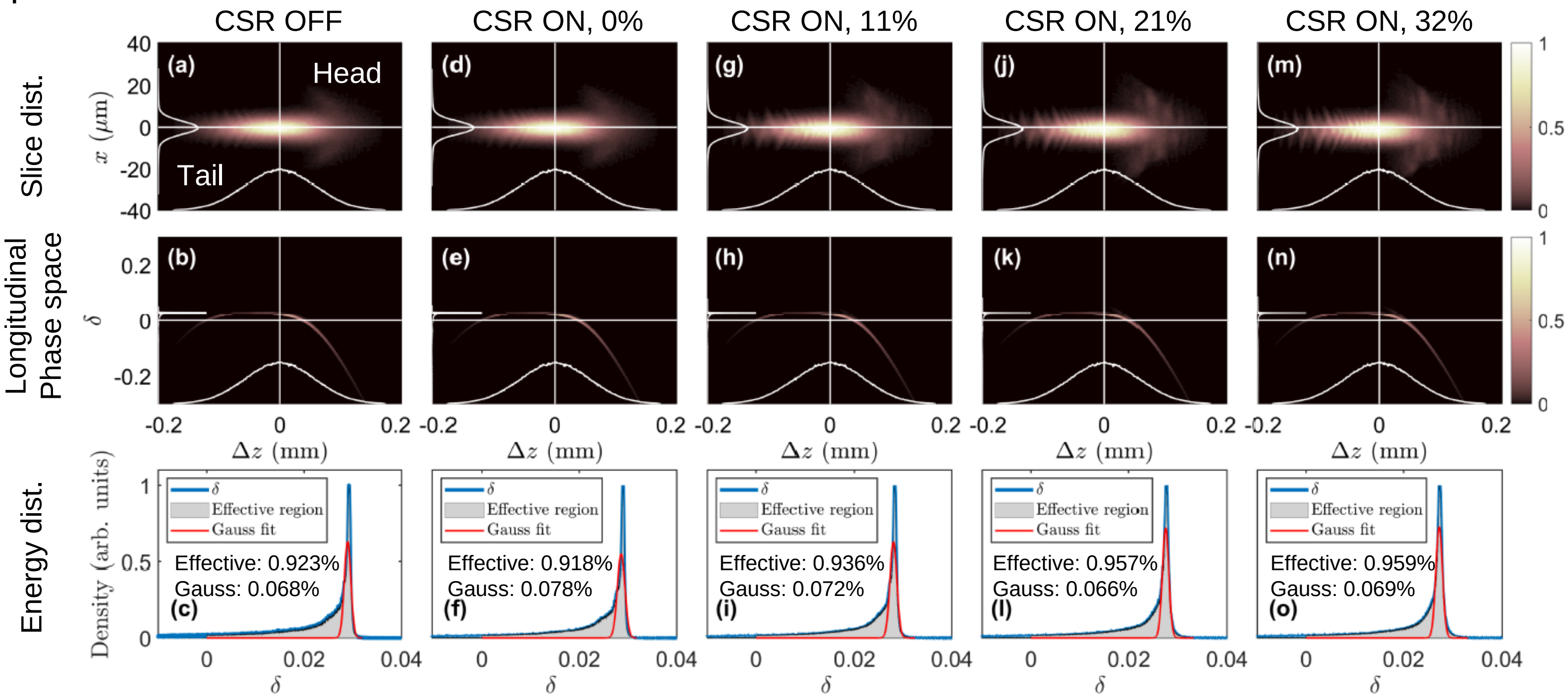
- Slice emittance of the electron beam after 5 m plasma source
  - Initial emittance before injection: ~2 mm mrad
  - Black solid and dashed lines: longitudinal electron distribution and initial emittance
  - (a): case where the beam centroid and angle before injection are not adjusted
  - (b): case where the beam centroid and angle are adjusted
  - Blue and orange curves at (a): case without CSR effect and fully suppressed case, respectively
  - If the CSR effect along the transfer line is not suppressed: additional increase of the emittance at the electron head is significant



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

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

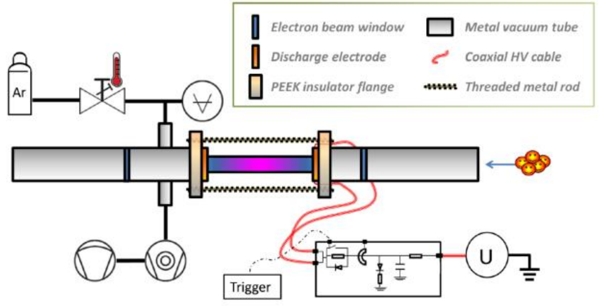
Plasma source development

Status of Argon discharge plasma source for
beam-driven plasma wakefield acceleration experiment

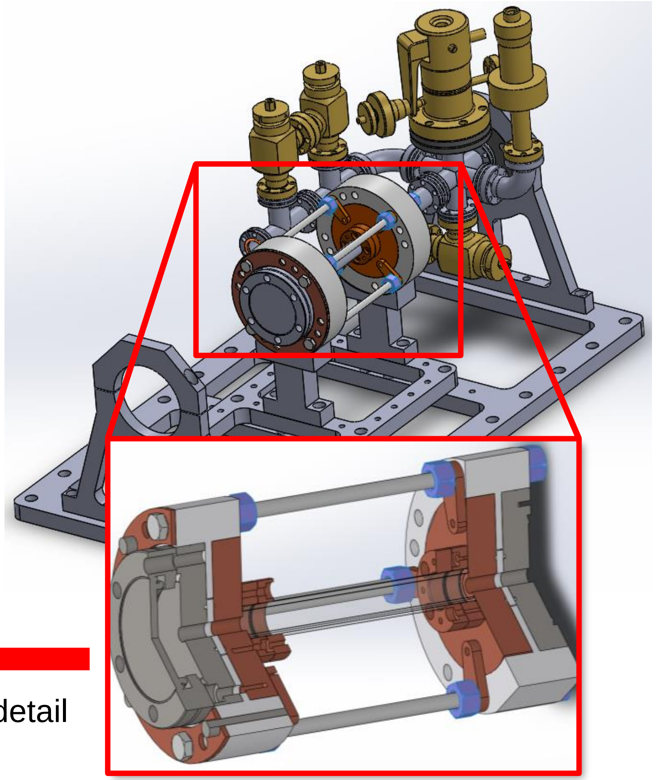
(Jun-Yeong Jeong’s contribution)

Plasma source: target

- Plasma source for plasma wakefield experiments
  - Electron beam self-modulation / other instabilities
  - Electron acceleration through plasma wakefield
- Design target
  - Plasma density: order of 10^{15} /cm^3
  - Dimension:
    - Diameter 10 mm
    - Length 100 mm / 200 mm
  - Attachable for any electron beamline

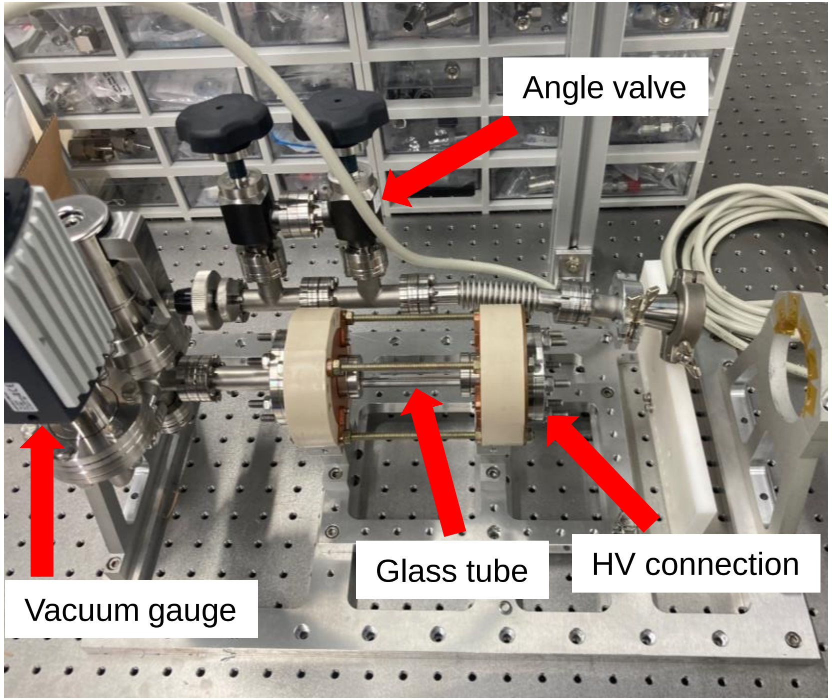


➢ Reference: G. Loisch, Ph.D. Thesis (2019)

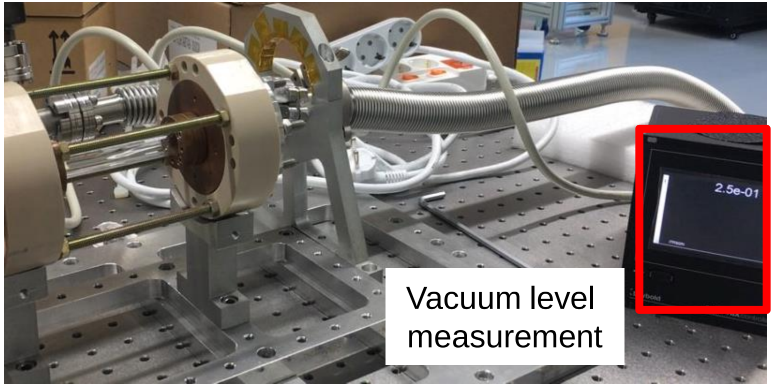


Schematic view for detail

Plasma source: progress

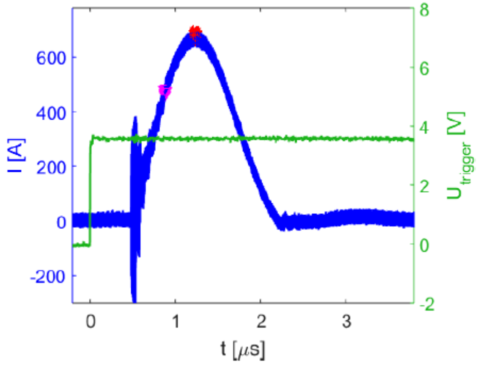


- Left figure: plasma source system
- Pressure control of the plasma source
  - Vacuum test done (minimum ~ 10^{-3} mbar)
  - Gas injection & pressure control
    - Gas pressure: maintained at 10^{-1} mbar

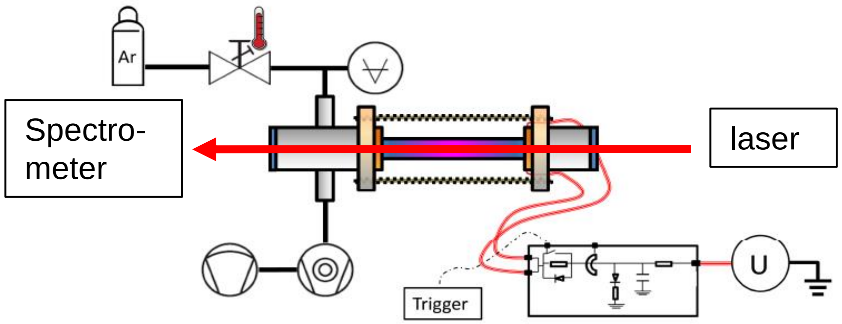


Plasma source: plan

- Discharge circuit development
  - Based on DC high voltage
    - Voltage: Maximum 2 kV
  - Apply pulsed current periodically in same voltage
    - Frequency: 10 Hz (same as beam repetition rate)
    - Discharge current: over 500 A
    - It makes arc discharge, which allows higher plasma density



- Plasma density measurement
  - Use laser to measure spectral line
  - Based on Stark effect
  - Planned to carry out the measurement at Pohang Accelerator Laboratory



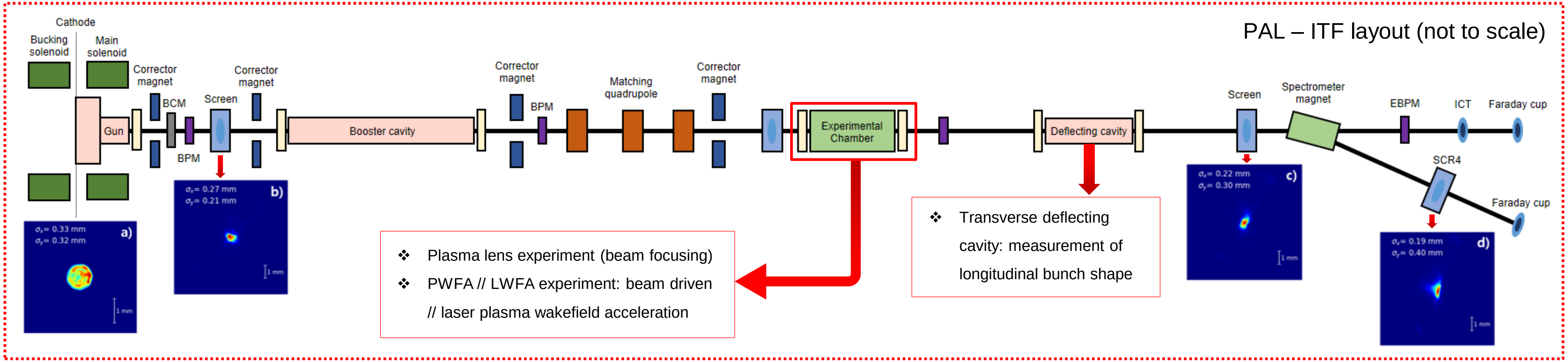
➢ Reference: G. Loisch, Ph.D. Thesis (2019)

Injector Test Facility

Optimization and commissioning of electron injector:
Injector Test Facility at Pohang Accelerator Laboratory

(Seong-Yeol Kim's contribution + More by Dr. Nam's talk)

Commissioning status of PAL – ITF



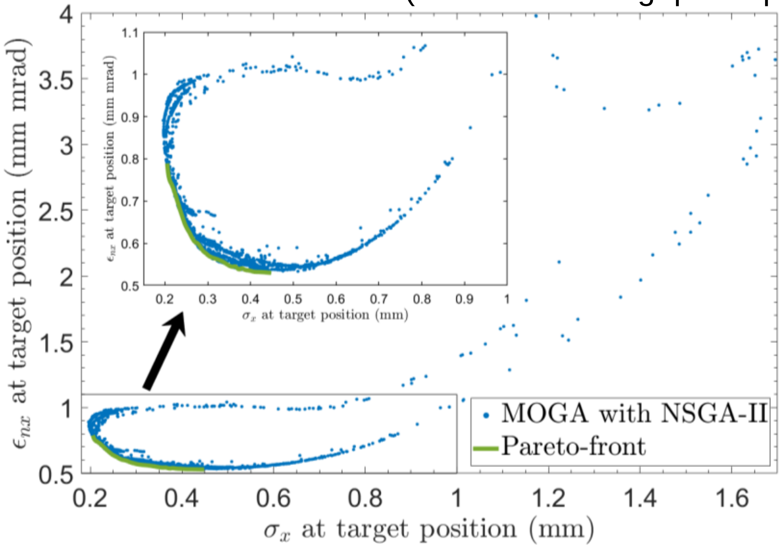
- Commissioning of the electron injector of PAL – ITF
  - Electron beam focusing experiment using active plasma lens
  - Electron beam-driven plasma wakefield experiment
  - Source of external injection for laser-wakefield acceleration
  - Experiment using 8-port BPM for coupling measurement
- For those planned experiments: parametric scanning and optimization based on multi-objective genetic algorithm

Beam energy (gun // booster)	6 // 70 MeV
Beam charge	200 pC
Initial UV pulse length	3 ps FWHM
Normalized emittance	< 1 mm mrad
RMS beam size	0.1 mm (for lens experiment)
RMS energy spread	~ 0.1%

J. Hong, C.-K. Min, J.-H. Han, Performance of S-band photocathode RF gun with coaxial coupler, In Proc. FEL 2019

Injector optimization based on genetic algorithm

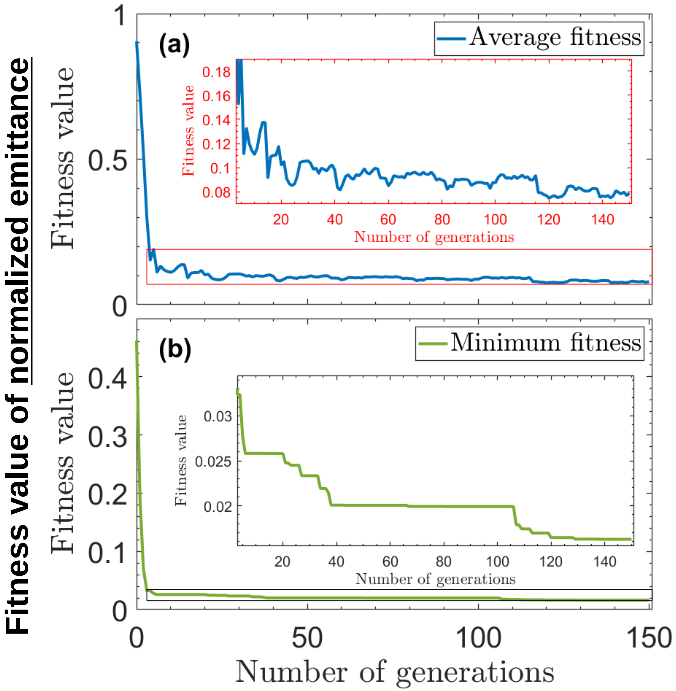
Search parameter space (beam size, emittance) and Pareto-front (without matching quadrupoles)



- **Multi-Objective Genetic Algorithm** based injector optimization
  - # of individuals in population: 36, # of generations: 150
  - ASTRA tracking simulation used with Python
  - 4 input variables: B-field and position of main/bucking solenoids
  - 2 targets: beam size of 0.22 mm, emittance of 0.47 mm mrad
  - Further optimization on-going with large # of generations

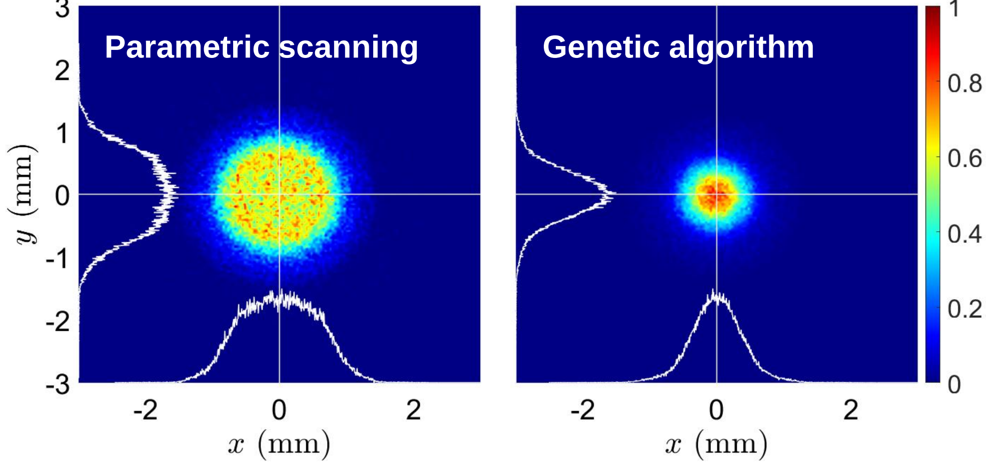
Fitness functions for emittance and beam size

$$f_\epsilon = 1 - e^{-\left(\frac{x-\epsilon_{target}}{\epsilon_{target}}\right)^2}, \quad f_\sigma = 1 - e^{-\left(\frac{y-\sigma_{target}}{\sigma_{target}}\right)^2}$$

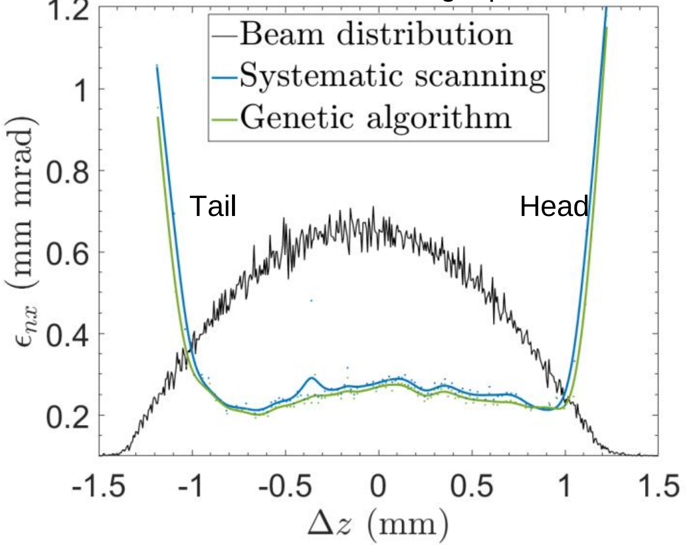


Injector optimization based on genetic algorithm

Transverse distribution at target position
(without matching quadrupole magnets)



Slice emittance at target position



At target	Parametric	Genetic
RMS beam size (mm)	**0.56**	**0.40**
Normalized emittance (mm mrad)	**0.47**	**0.42**

- Fine-tuning of the variables can be done with MOGA
- Future works: Genetic algorithm based optimization for additional objectives (bunch length and energy spread)
- Neural–Network machine learning based optimization

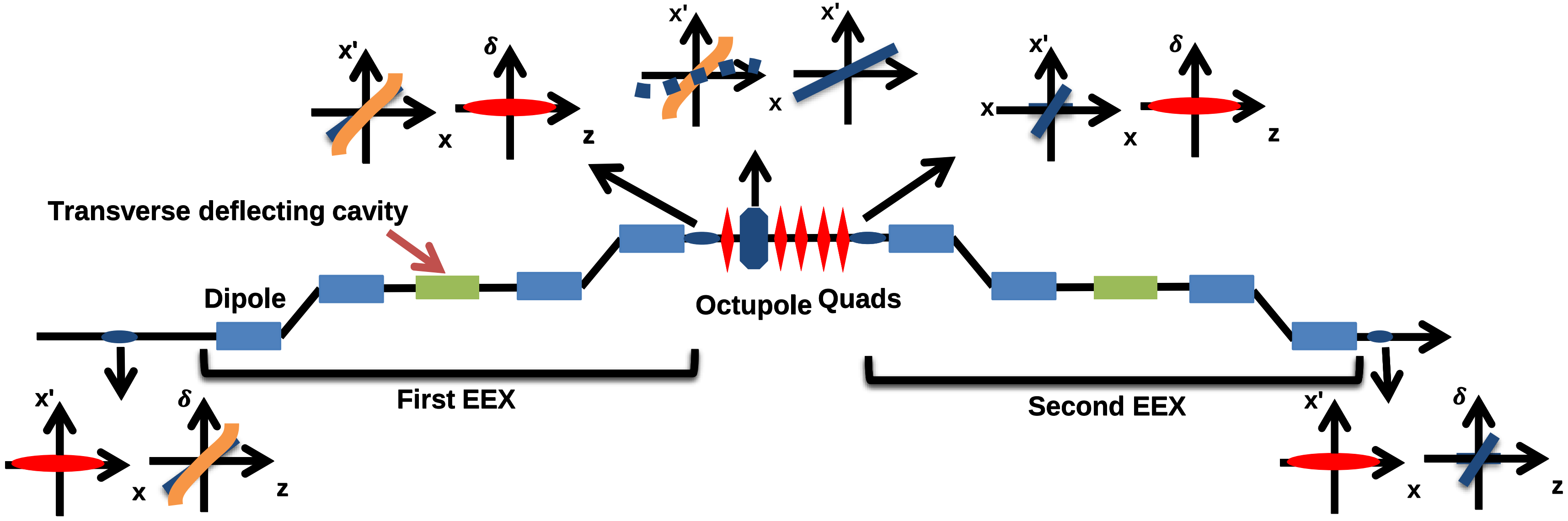
Beam manipulation

Longitudinal phase space manipulation using Double Emittance Exchange (DEEX)

(Ji-Min Seok's contribution)

Longitudinal phase space manipulation using DEEX

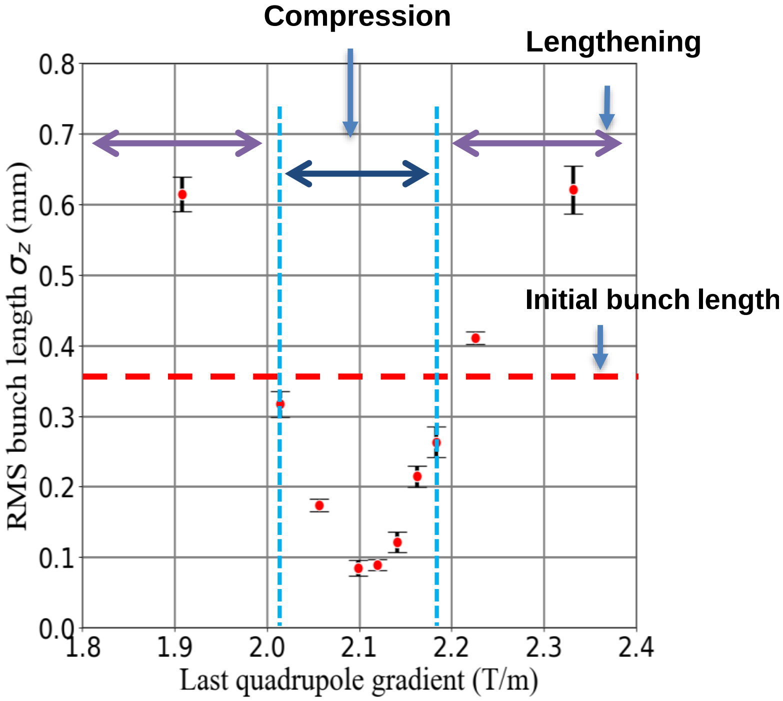
- Nonlinear longitudinal phase space manipulation



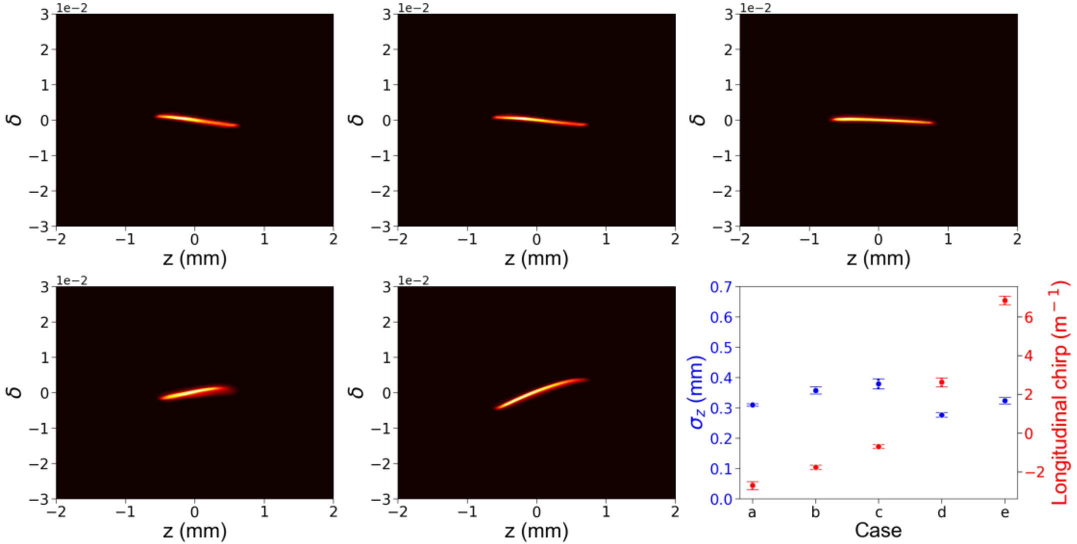
These functions can be carried out simultaneously.

Experiment results (preliminary)

Tunable bunch compression

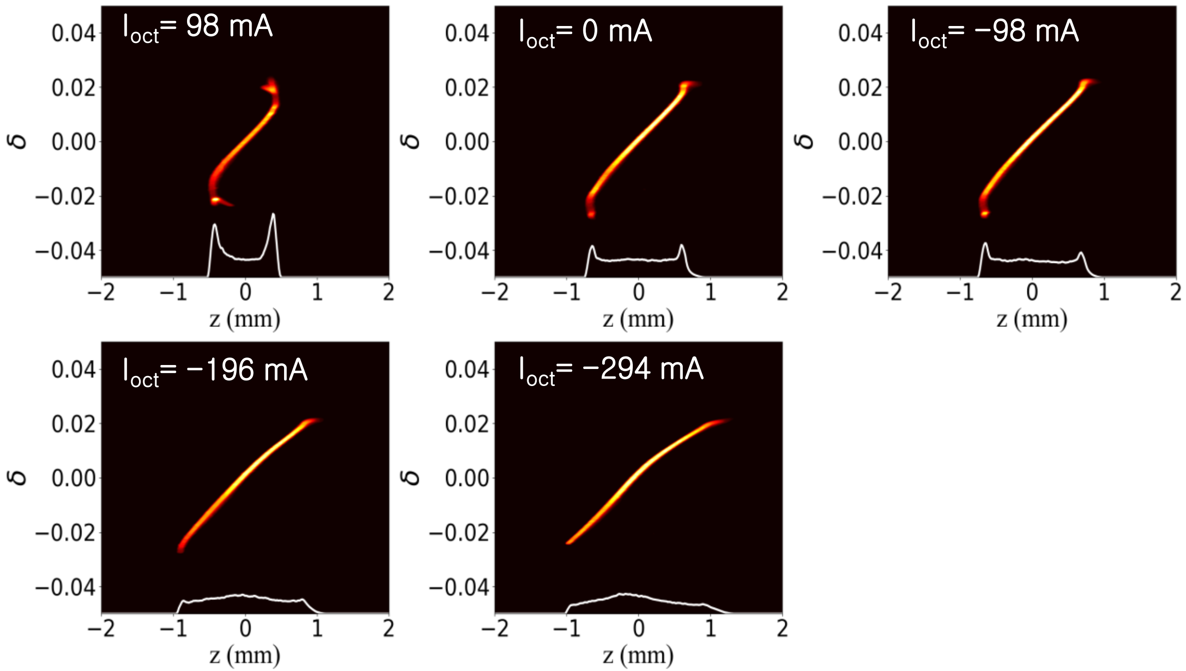


Longitudinal chirp control



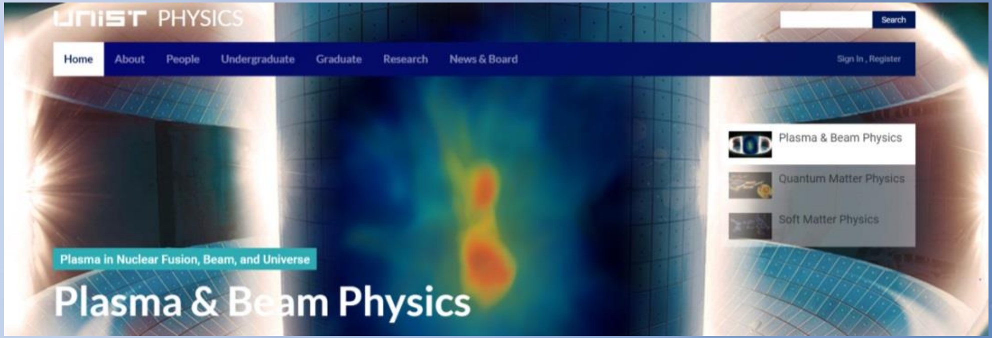
Experiment results (preliminary)

Nonlinear longitudinal phase space manipulation



Conclusion

- Research on beam-driven plasma wakefield has begun in Korea
  - Beam-plasm instabilities, witness beam injection, seeded self-modulation, beam manipulation, etc.
  - Participation in AWAKE experiments at CERN and DEEX/AWA at ANL
  - Design of Argon discharge plasma source: application to PWFA experiments
- Various studies and experiments at PAL–ITF are planned (More by Dr. Nam’s talk)
  - Active plasma lens experiment with electron beam
  - PWFA – LWFA acceleration experiment with external injection scheme
  - Optimization of electron beam with genetic algorithms and machine learning
  - Beam manipulation for PWFA application (e.g., control of energy spread & bunch shape)



Thank you
for your attention !