# Plasma dechirper for electron/positron beams in plasma based accelerator

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The 8th IPAC
May 16th 2017, Copenhagen, Denmark

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led by professor Wei Lu

# Outline

- Motivation for a plasma dechirper: the physical picture
- Theory and simulation verification
- Experimental demonstration of a plasma dechiper
  - Experimental platform
  - Plasma source based on laser ionization
  - Preliminary experimental results
  - Future works

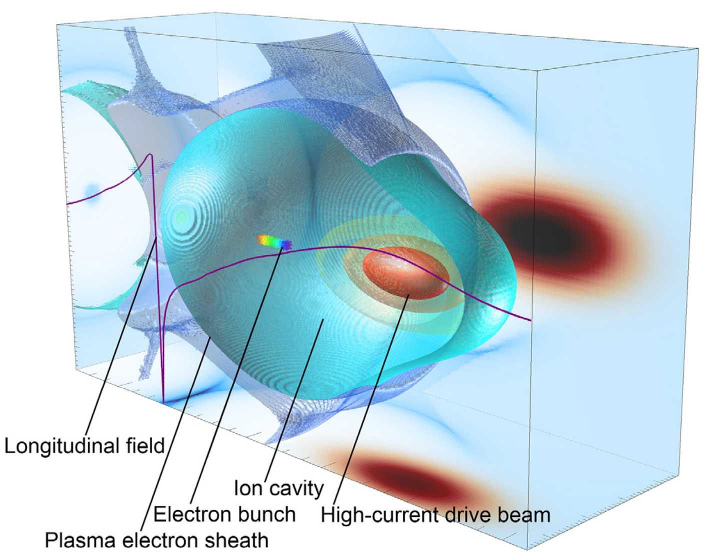
# Motivation for a plasma dechirper

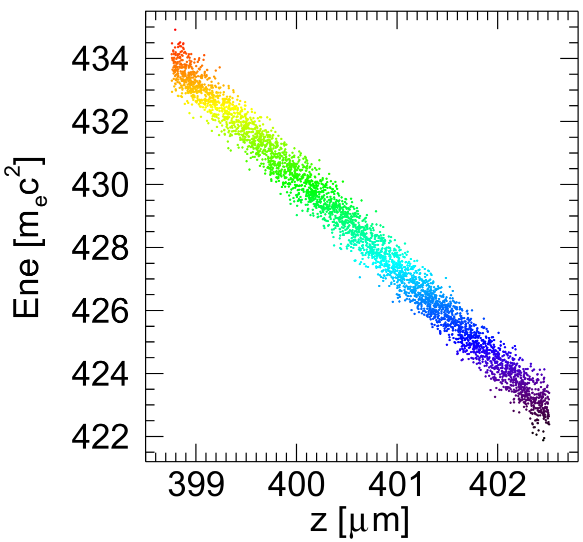
- Electron/positron beams with low energy spread at ~ 0.1% level are typically needed for challenging applications like FELs and colliders
- Achievable energy spreads in typical plasma based accelerators (PBA) are currently at ~ 1% level
- Simple methods for reducing the energy spreads from ~ 1% to ~ 0.1% level is highly needed
- **Can we do it, and How ?**

# Energy chirp dominates energy spread in PBA

- In PBA, slice energy spreads are mainly determined by injection methods, typically at MeV level or even lower
- Relatively large acceleration phase span in PBA leads to large energy chirp (approximately linear)

energy chirp reduction ➔ energy spread reduction

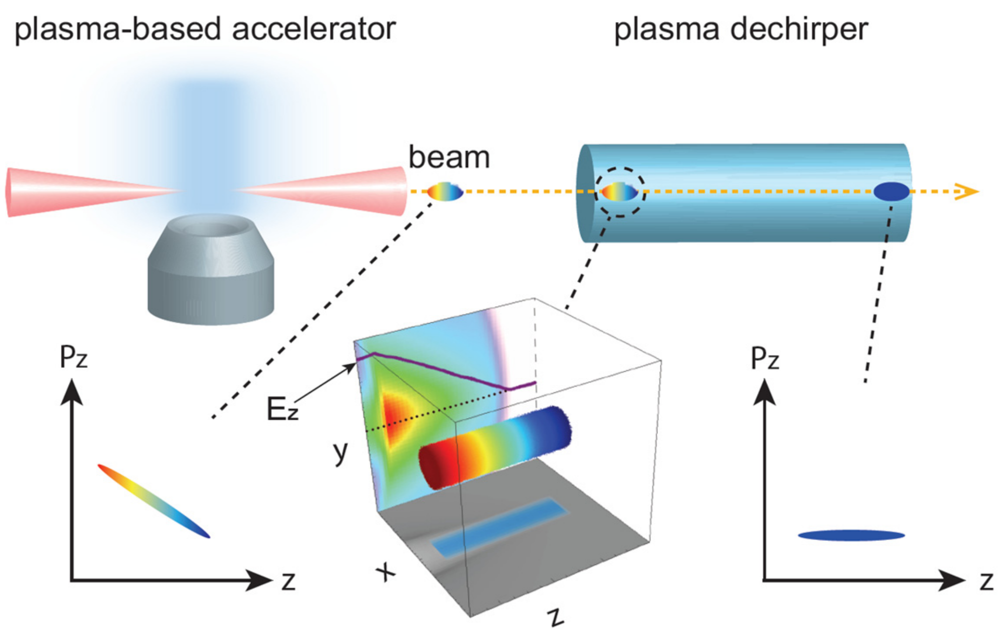



positive chirp

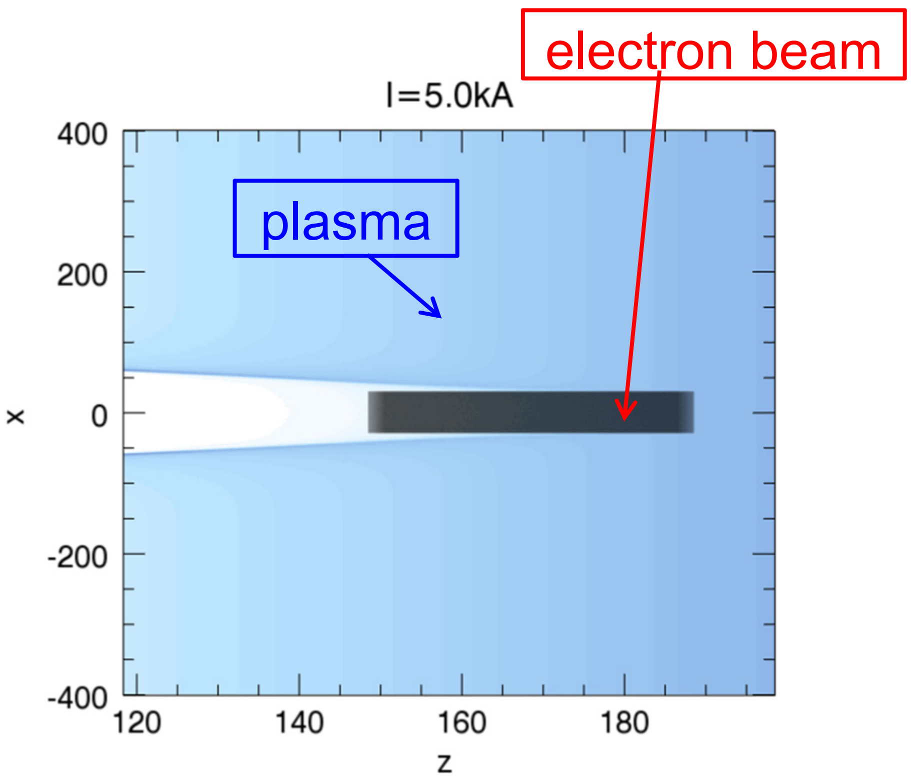
# Basic concept of a plasma dechirper

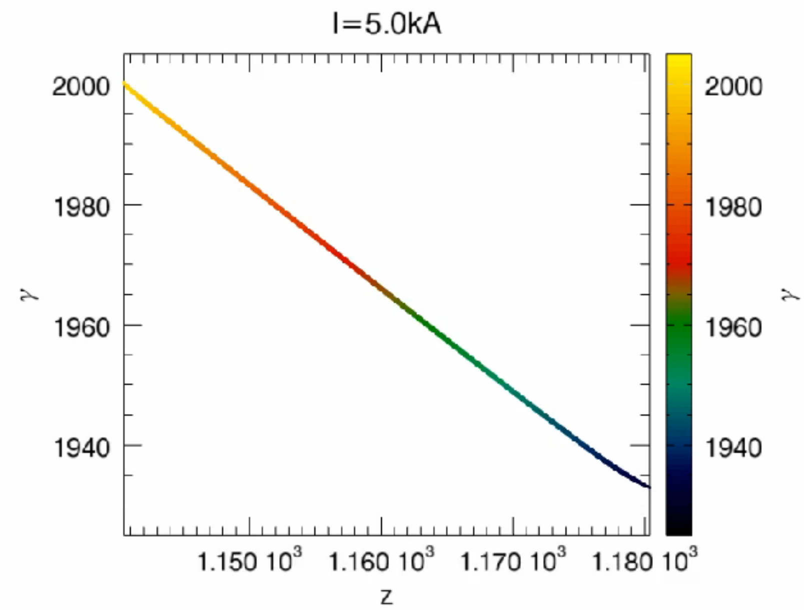
- **A two-steps strategy: divide and conquer**
  - **first step:** obtaining a stable positively-chirped beam with few percent energy spread
  - **second step:** post-processing the beam using a passive dechirper
    - ➢a tenuous uniform plasma
    - ➢a hollow plasma channel



# Physical picture with simulation illustration

**A sample 3D PIC simulation shows energy spread reduction from ~1% level to ~0.1% level or lower**




$$\text{energy spread: } 10MeV \rightarrow 0.97MeV$$

$$1\% \rightarrow 0.097\%$$

# Two important quantities for a plasma dechirper

- the minimum energy spread achievable

$$E_{rms\_min} = E_{rms\_init} G$$

- the plasma length for this minimum energy spread

$$d = \frac{\Delta E}{|qE_{z\_tail}|} X$$

G and X are two geometrical factors determined by beam profile

# Theoretical formulas for G and d

- G and d can be calculated based on the linear wakefield theory [1]

$$E_z(r,\xi) = Z'(\xi)R(r)$$

$$Z'(\xi) = -4\pi \int_{-\infty}^{\xi} d\xi' \rho_{\|}(\xi') \cos k_p(\xi - \xi')$$

$$R(r) = \frac{k_p^2}{2\pi} \int_0^{2\pi} d\theta \int_0^{\infty} r' dr' \rho_{\perp}(r') K_0(k_p |\vec{r} - \vec{r}\,'|)$$

- longitudinal flat-top, transverse flat-top profile $\rho_{\|}(\xi) = qn_b \Theta(\xi)\Theta(L-\xi),\ \rho_{\perp}(r) = \Theta(a-r)$

$$G_{ff} = \frac{2C}{\sqrt{48-24C+7C^2}} \qquad C = \frac{(k_p a)^2}{2} \times \frac{1-R(0)}{R(0)}$$

$$d_{ff} = \frac{2\sqrt{3} \times E_{rms\_init}}{mc\omega_p \frac{n_b}{n_p} k_p L \times R(0)} \times \frac{48 - 12C}{48 - 24C + 7C^2}$$

- longitudinal flat-top, transverse parabolic profile $\rho_{\|}(\xi) = qn_b \Theta(\xi)\Theta(L-\xi),\ \rho_{\perp}(r) = 1 - \frac{r^2}{b^2}$

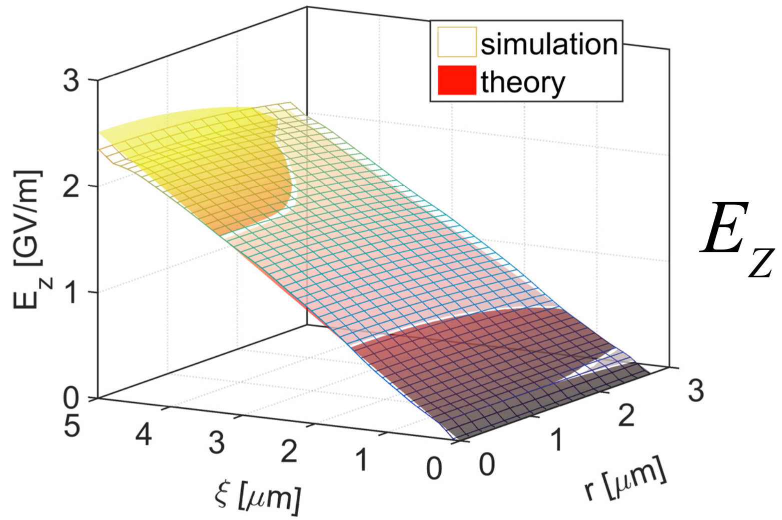
$$G_{fp} = \sqrt{\frac{640(k_p b)^4 D^2 - 1024(k_p b)^4 D + 412(k_p b)^4}{960(k_p b)^4 D^2 - 7680(k_p b)^2 D^2 + 46080 D^2 - 1584(k_p b)^4 D + 6720(k_p b)^2 D + 657(k_p b)^4}}$$

$$d_{fp} = \frac{2\sqrt{3} \times E_{rms\_init}}{mc\omega_p \frac{n_b}{n_p} k_p L \times R(0)} \times \frac{(640D^2 - 1056D + 438)(k_p b)^4 - 480(8D^2 - 7D)(k_p b)^2 + 15360D^2}{(320D^2 - 528D + 219)(k_p b)^4 - 320(8D^2 - 7D)(k_p b)^2 + 15360D^2} \qquad D = R(0)$$

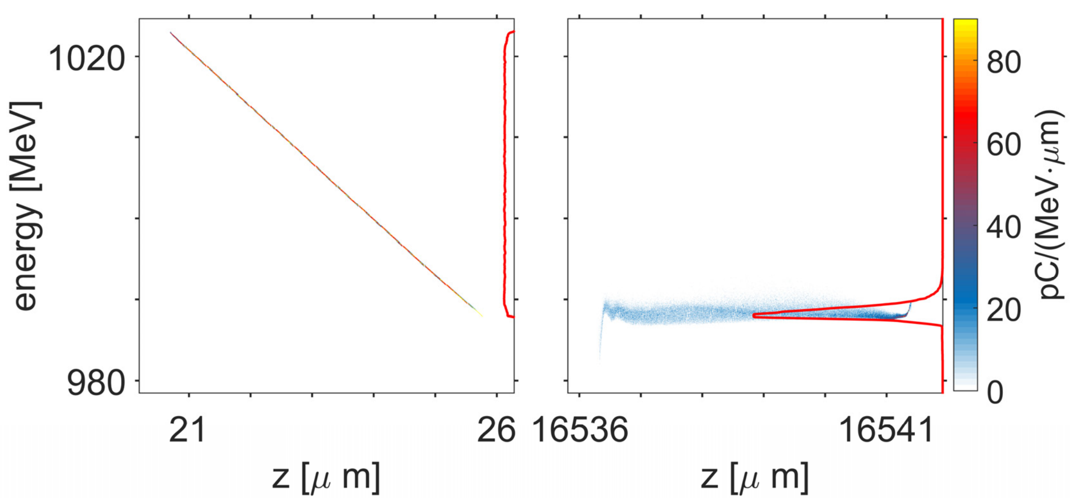
[1]. T. Katsouleas, et al, Beam Loading In Plasma Accelerators, *Particle Accelerators*, 1987, Vol. 22, pp. 81-99

# Verification by PIC simulations

## 3D PIC simulation of a flat-top electron beam




| | | |
|---|---|---|
| electron beam | energy | 1 GeV |
| | energy spread | 10 MeV (RMS) |
| | beam density | $2.4\times10^{18}cm^{-3}$ |
| | peak current | 2.5 kA |
| | pulse duration | L = 5.0 um |
| | transverse size | a = 2.85 um |
| plasma | density | $3.0\times10^{16}cm^{-3}$ |
| | length | 16.55 mm |



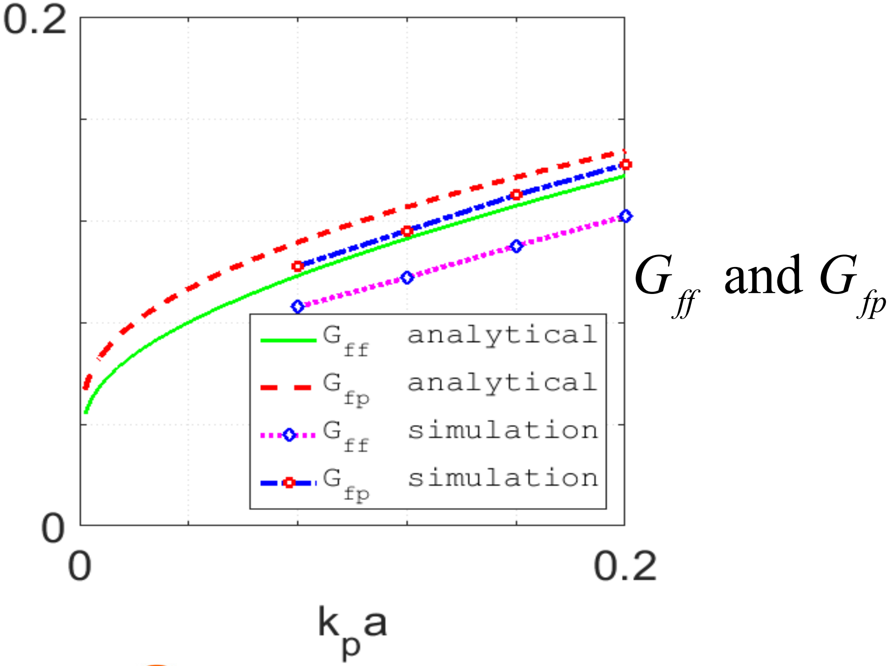

initial and final longitudinal phasespaces

energy spread:

$$10MeV \rightarrow 0.86MeV$$

$$1\% \rightarrow 0.086\%$$

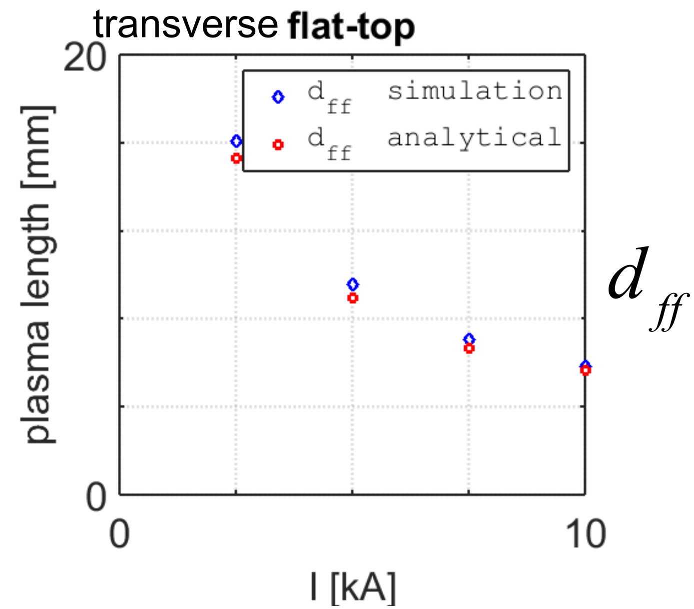
# G and d: theory vs simulation

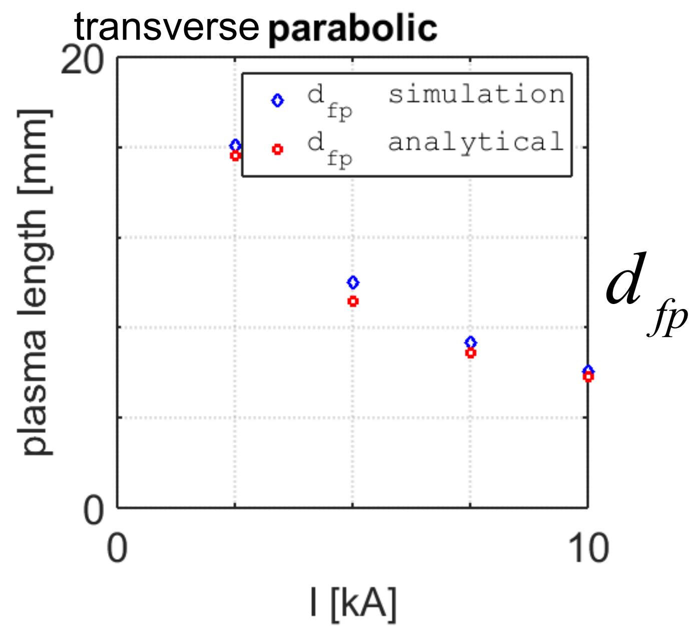



Agree very well !

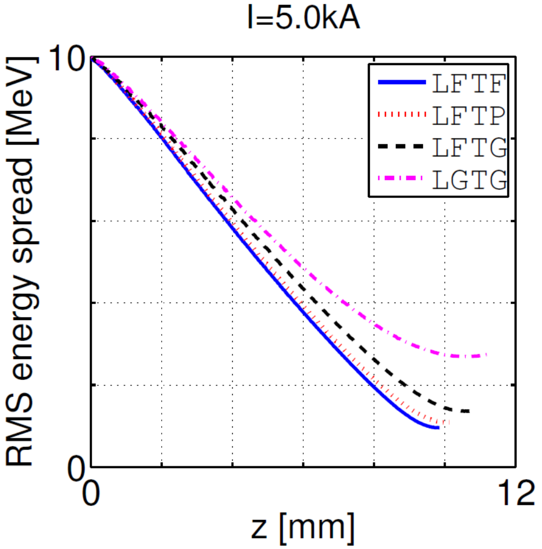
| beam current | beam density | transverse size |
|---|---|---|
| 2.5 kA | $2.4\times10^{18}cm^{-3}$ | a = 2.85 um |
| 5.0 kA | $2.4\times10^{18}cm^{-3}$ | a = 3.80 um |
| 7.5 kA | $2.1\times10^{18}cm^{-3}$ | a = 5.07 um |
| 10.0 kA | $1.8\times10^{18}cm^{-3}$ | a = 6.33 um |

$$b = \sqrt{2}a$$

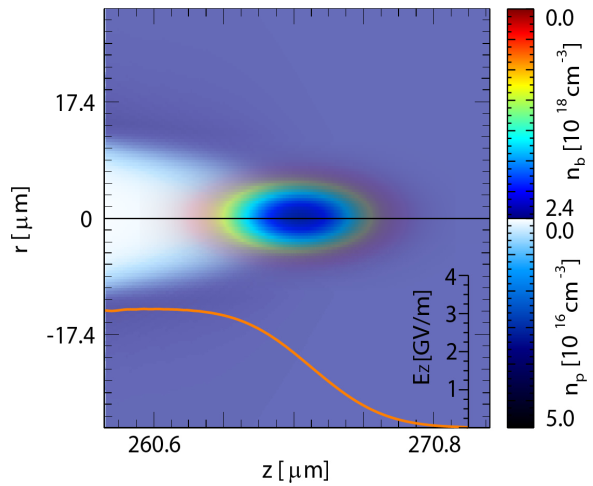


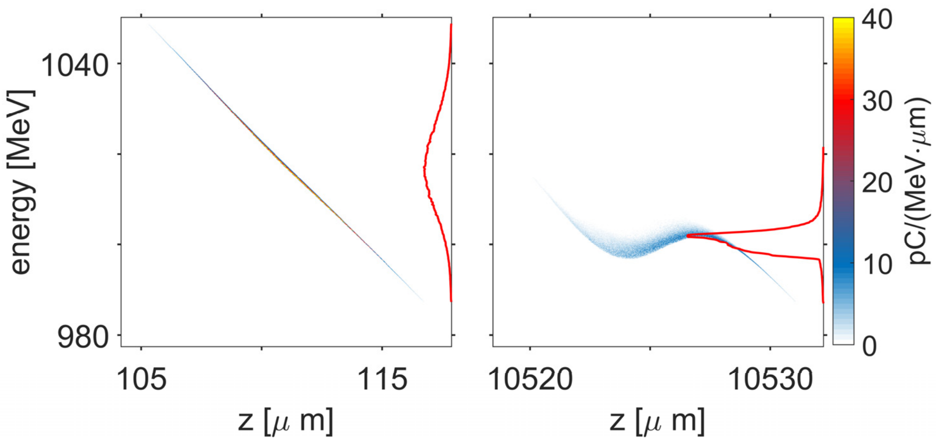
# Energy spread evolution for the beams with different density profiles




| | longitudinal profile | transverse profile |
|---|---|---|
| LFTF | flat-top | flat-top |
| LFTP | flat-top | parabolic |
| LFTG | flat-top | gaussian |
| LGTG | gaussian | gaussian |




bi-gaussian profile

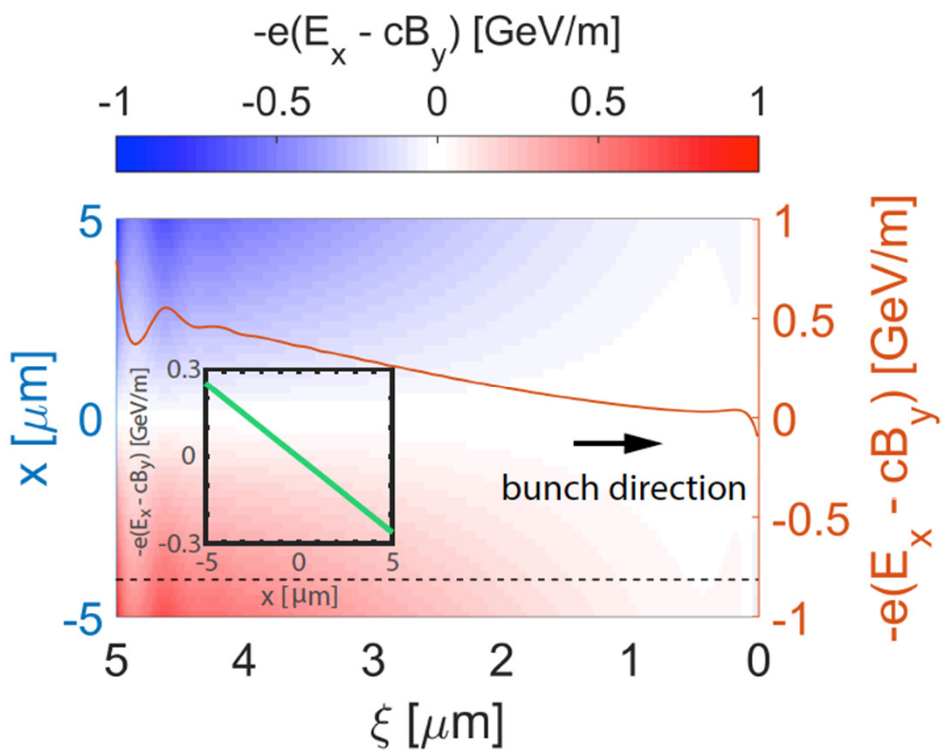



$$10\text{MeV} \rightarrow 2.6\text{MeV}$$

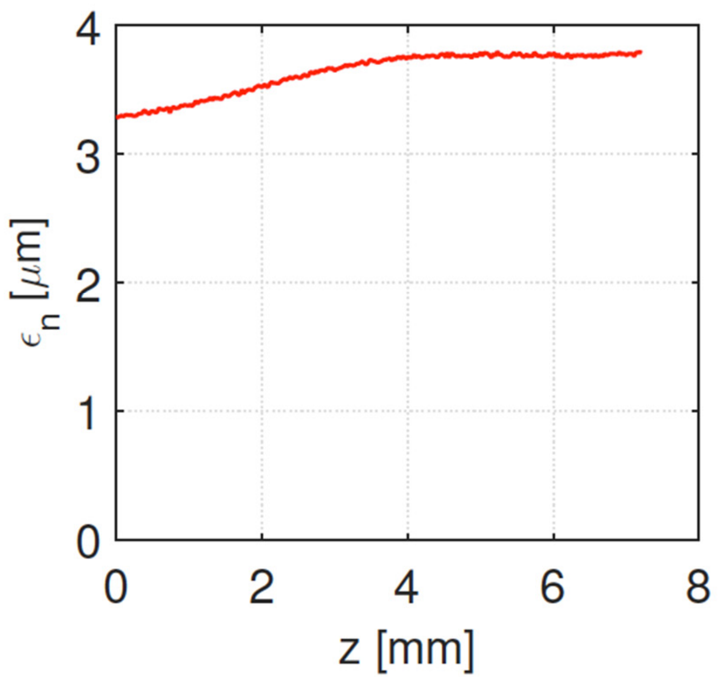
$$1\% \rightarrow \text{below } 0.3\%$$

# Emittance growth in a dechirper

**Projected emittance growth caused by longitudinally varied transverse focusing field ➔ phase space mismatch**




transverse focusing field




normalized emittance

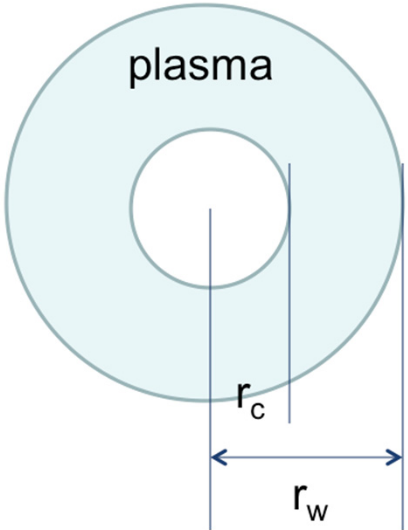
quasi-match ➔ 10~20% normalized emittance growth for ~ um emittance

# Solution for reducing emittance growth: A hollow channel plasma dechirper

- transversely uniform $E_z$ ➔ zero slice energy spread increase

- zero transverse focusing force within the channel ➔ negligible emittance growth

Methods for hollow plasma channel creation have been actively explored and demonstrated [1]

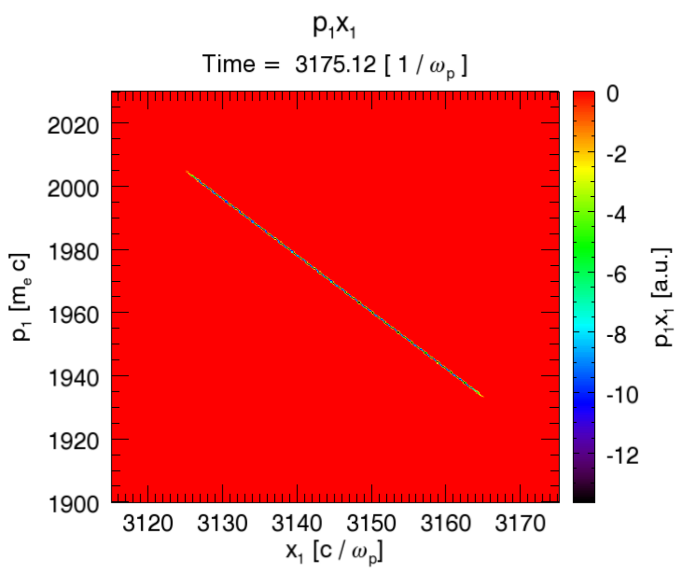



[1]. S. Gessner, et al, *Nature Communications*, 2016, Vol. 7, pp. 11785

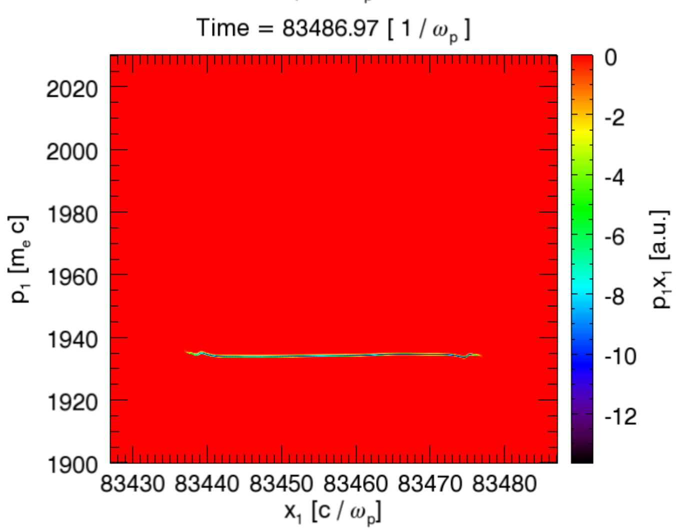
# Simulation verification

**The linear energy chirp can be totally removed without slice energy spread increase for a flat-top current profile**

initial longitudinal phasespace




final longitudinal phasespace

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|---|---|---|
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| | energy spread | 10 MeV (RMS) |
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| | peak current | 2.5 kA |
| | pulse duration | L = 5.0 um |
| | transverse size | a = 3.8 um |
| plasma | density | $3.0\times10^{16}$cm$^{-3}$ |
| | length | 10.6 mm |
| | inner radius | $r_c$ = 20 um |
| | outer radius | $r_w$ = 50 um |

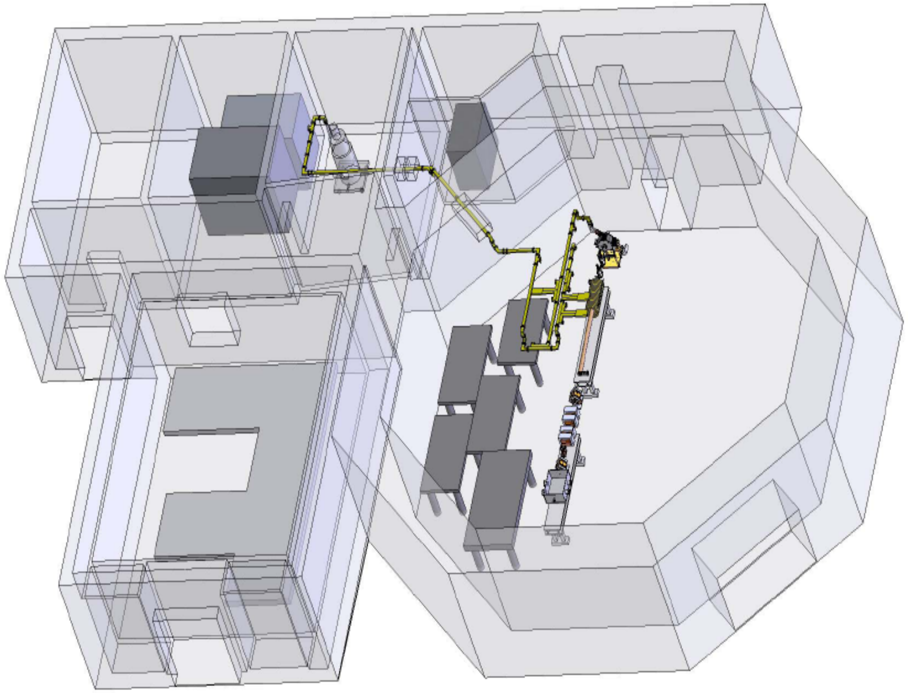
energy spread:

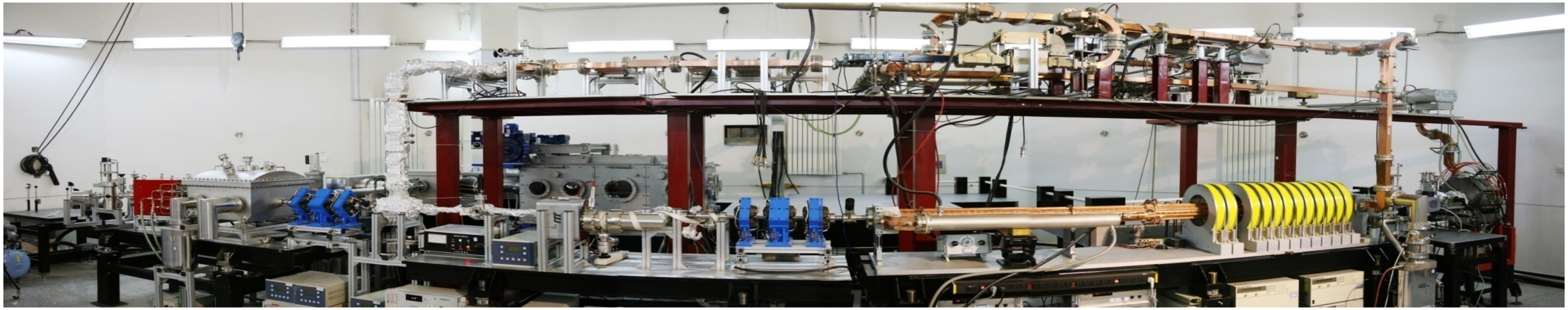
$$10MeV \rightarrow 0.075MeV$$

$1\% \rightarrow$ below $0.01\%$

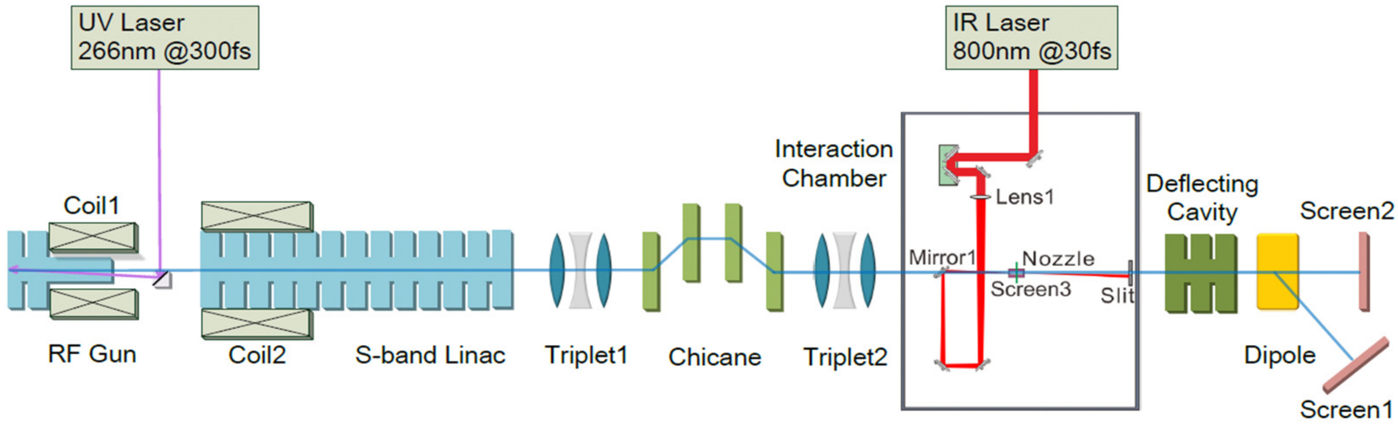
# Advanced Acceleration platform at THU

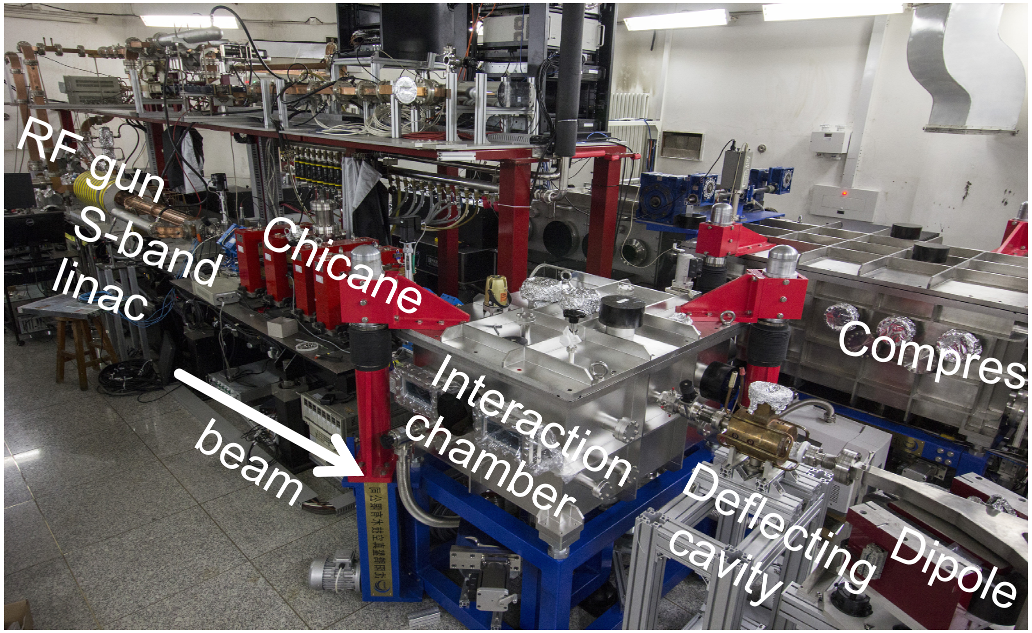
## 30 TW laser + 45 MeV Linac





# Experimental layout for plasma dechirper




**Beam diagnostics**

**energy spectrometer resolution: 2.3 keV @ 41.5 MeV**

# Plasma source based on laser ionization

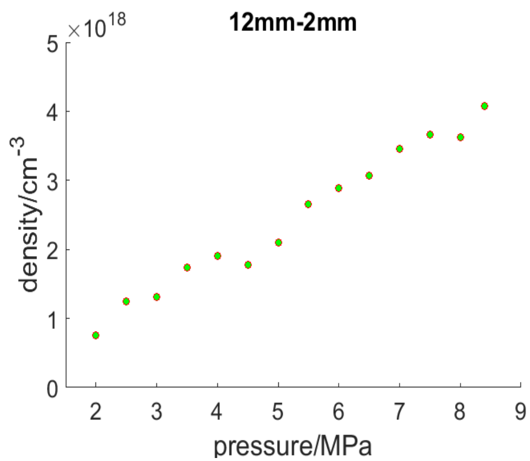
## laser ionization ($H_2$+He, ionizes the first electron of H)

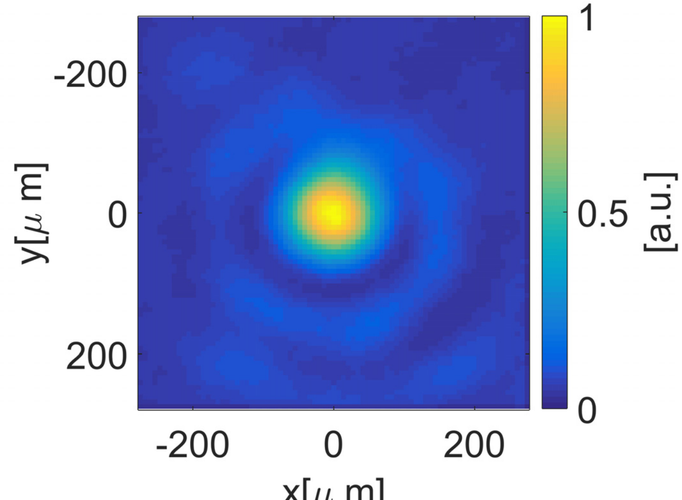
**mixture gas: He + H2 (1%, 0.1%, 0.01%)**

**ionization laser: 800nm, ~3.5mJ (on target), ~30fs, 110um (FWHM)**

| plasma parameters | |
|---|---|
| plasma density | ~$5\times10^{14}$ $cm^{-3}$ |
| plasma length | 12mm |
| plasma diameter | ~ 600 um |

**gas jet**



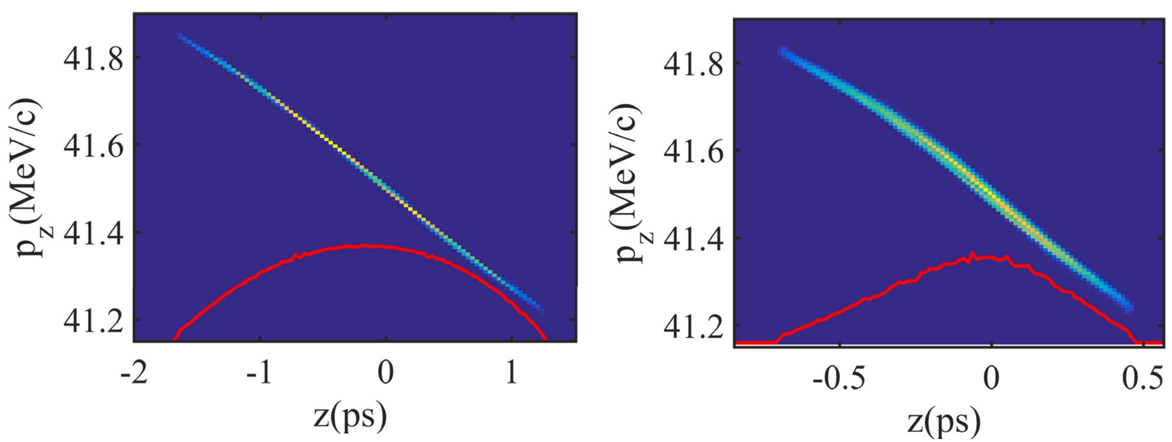




**ionization laser focal spot**

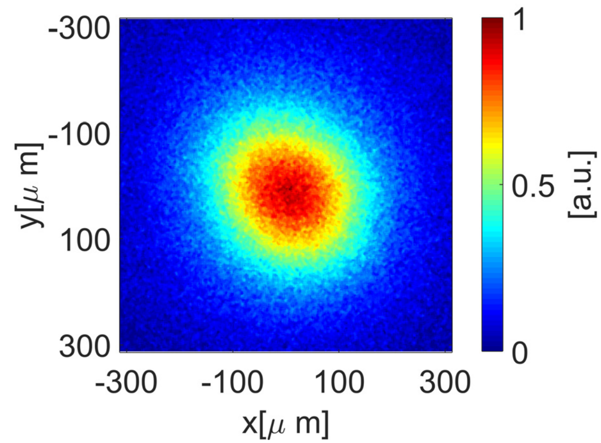
# Chirped beam generation

- **A positive linear energy chirp is imposed on the electron beam by off crest acceleration (25 deg) in the Linac**
- **The electron beam is weakly compressed by an Chicane from ~ 1 ps to ~ 300 fs (RMS)**

| electron beam parameters | |
|---|---|
| transverse size | σr=~100um |
| bunch length | σz=~300fs |
| charge | ~30pC |
| peak current | ~40A |
| mean energy | 41.5MeV |

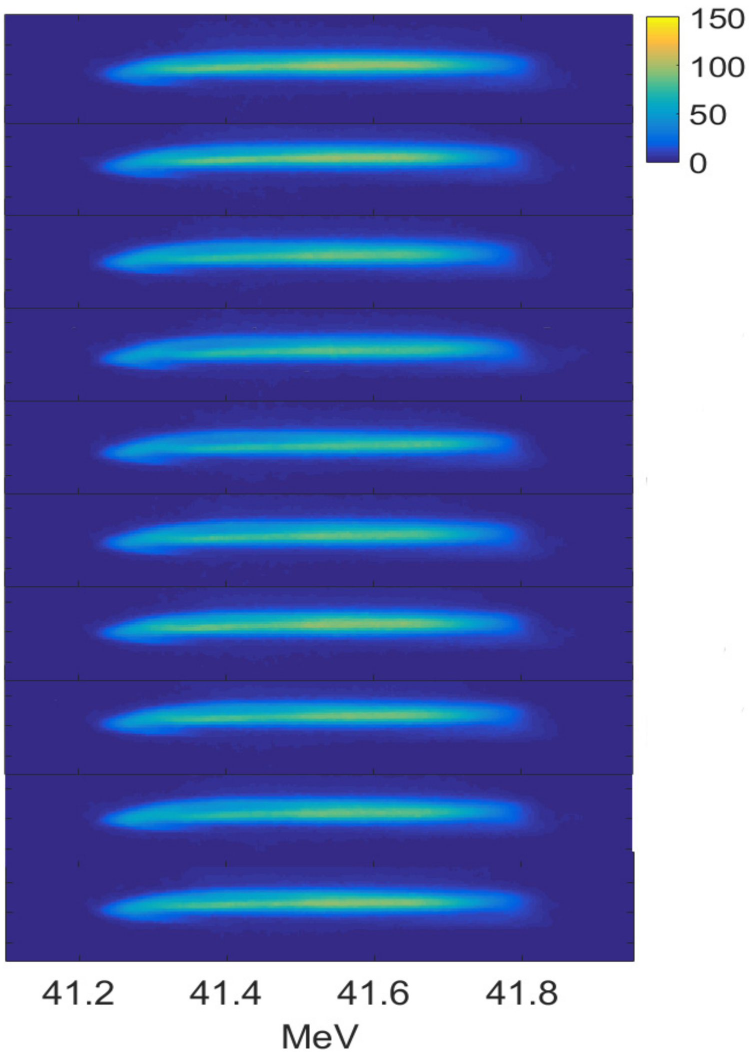


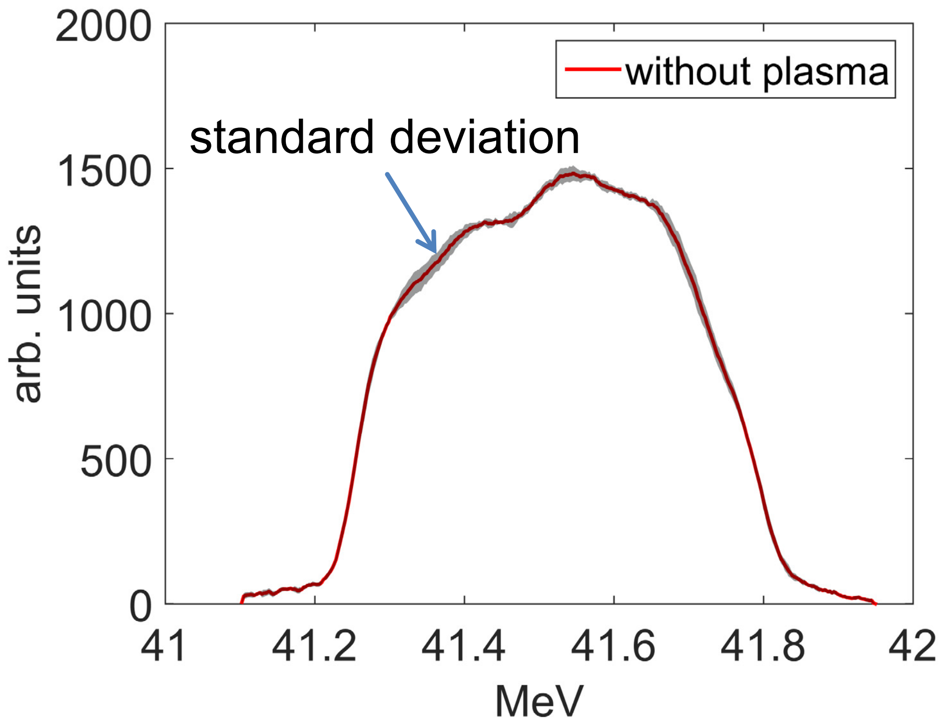

longitudinal phasespaces before and after Chicane (simulated by ASTRA)




beam waist profile

# Beam energy spectrum without plasma

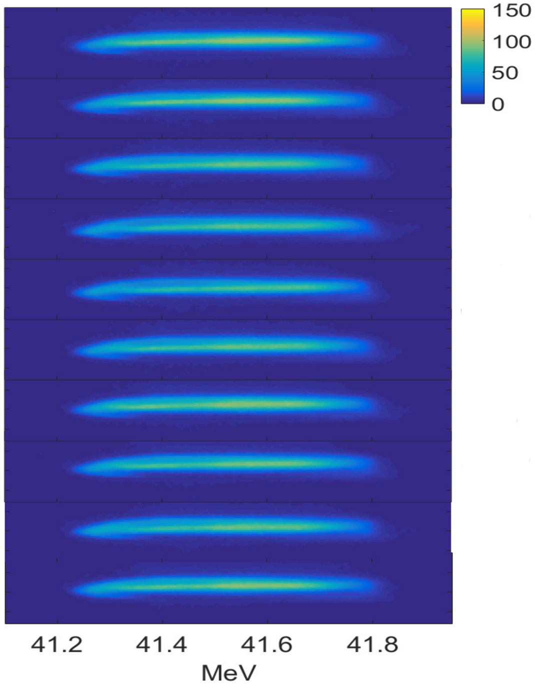


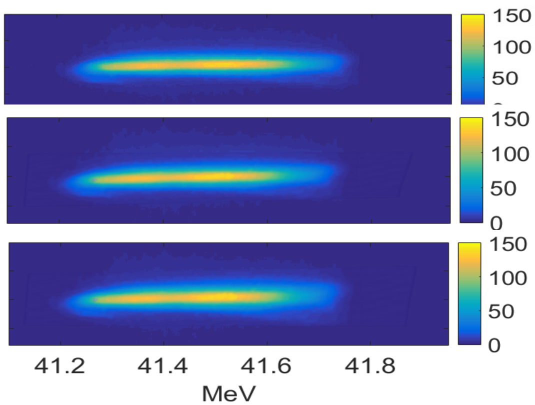

Beam energy profiles of 10 shots without plasma

# Beam energy spectrum with plasma

## experimental results

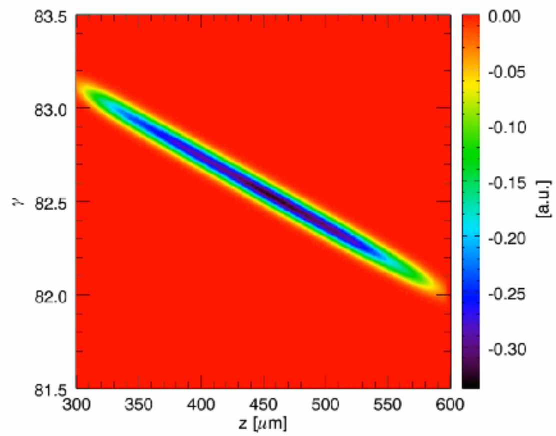


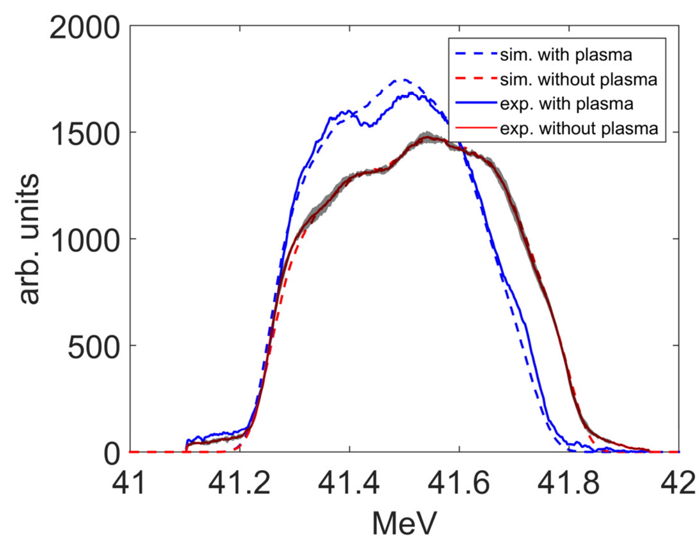

without plasma




with plasma

## 3D simulation results via OSIRIS




**0.5MeV → 0. 4MeV (FWHM)**

**1.20% → 0.96%**

# Current limitation of the preliminary experiment

**low current**

**large beam size**

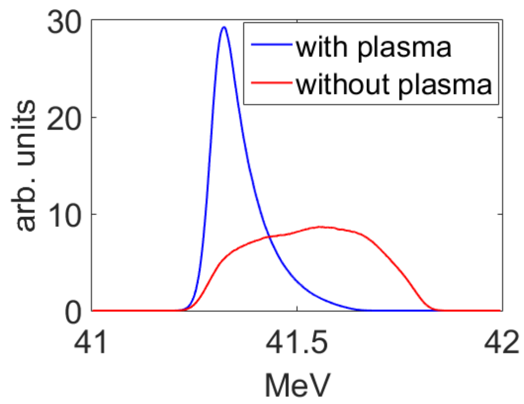
} **low beam density** → **low decelerating gradient**

# Future works

**two possible methods to optimize further experiments**

- with a longer plasma

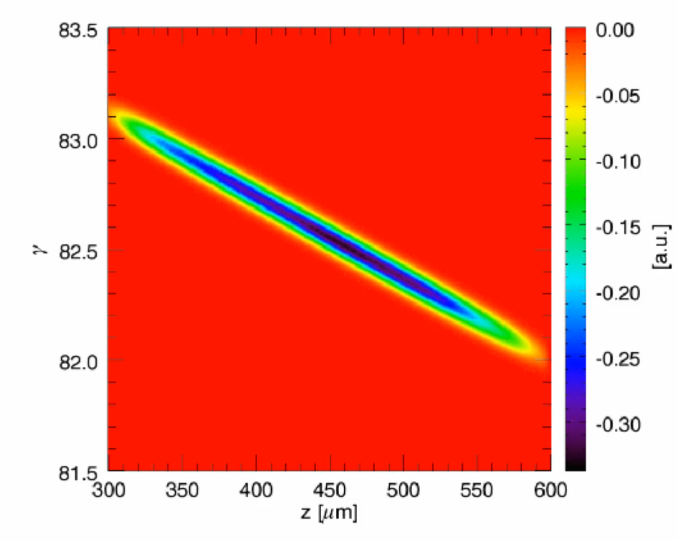
| | |
|---|---|
| Plasma density | ~5.0e14 cm-3 |
| Plasma length | 50mm |




beam energy spectrum with/without plasma

**0.5MeV ➔ 0. 4MeV (FWHM)**
**1.20% ➔ 0.24%**

3D simulation results via OSIRIS

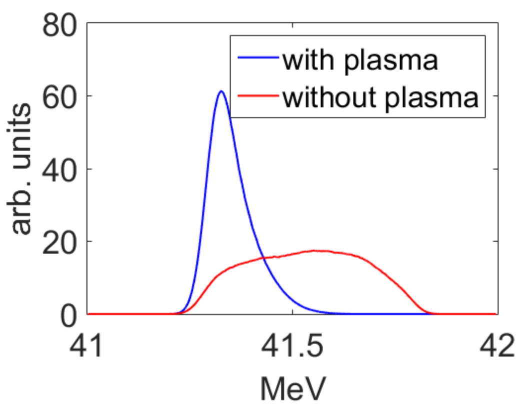


# Future works

**two possible methods to optimize further experiments**

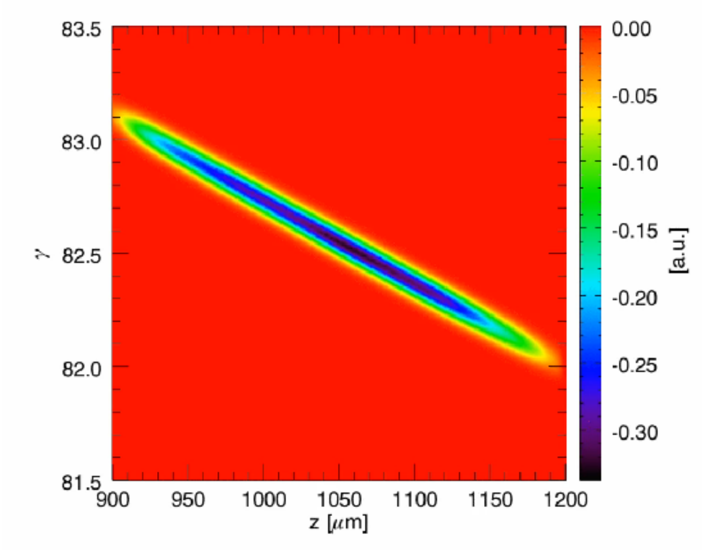
- with a higher beam current and smaller beam size ➔ increase beam density

| | |
|---|---|
| transverse size | σr=~40um |
| bunch length | σz=~300fs |
| charge | ~60pC |
| peak current | ~80A |
| mean energy | 41.5MeV |




beam energy spectrum with/without plasma

**3D simulation results via OSIRIS**




**0.5MeV ➔ 0. 4MeV (FWHM)**
**1.20% ➔ 0.24%**

# Summary

- We propose to use a plasma dechirper to reduce the linear energy chirp of electron/positron beam from PBA.
- A theoretical model is developed to obtain the minimum energy spread achievable and the plasma dechirper length for different bunch profiles, and verified using full 3D PIC simulations.
- Experimental result of energy-chirp reduction at THU is presented, which is a preliminary proof of this method.

# THANK YOU!