Phase Space Matching of Staging Plasma and Traditional Accelerator Using Longitudinally Tailored Plasma Structure

Xinlu Xu*, Wei Lu, Warren Mori, Chan Joshi, Mark Hogan

Tsinghua University, Beijing, China
University of California Los Angeles, Los Angeles, CA, USA
SLAC National Accelerator Laboratory, Menlo Park, CA, USA

6th International Particle Accelerator Conference
May 4th, Richmond, VA

*xuxinlu04@gmail.com

L^2PA

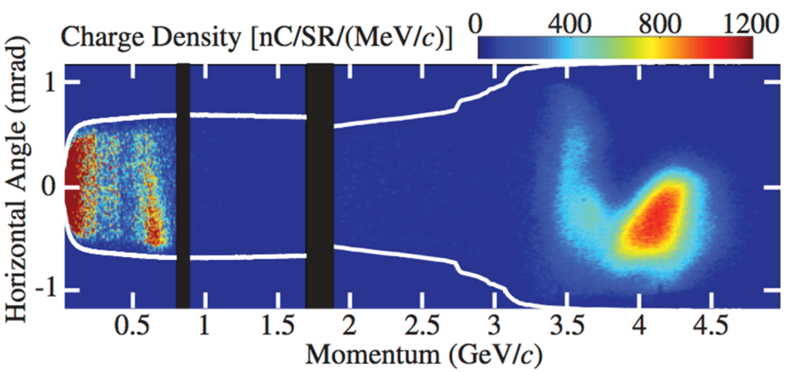
Laboratory of Laser Plasma Physics and Advanced Accelerator Technology at Tsinghua University

Major Collaborations

- **UCLA**
  Chan Joshi and Warren Mori
- **SLAC**
  Mark Hogan and FACET team
- **ANL**
  Wei Gai
- **BNL**
  Igor Pogoresky and Ilan Ben-Zvi
- **NCU**
  Jyhpyng Wang

Motivation – Plasma-based acceleration

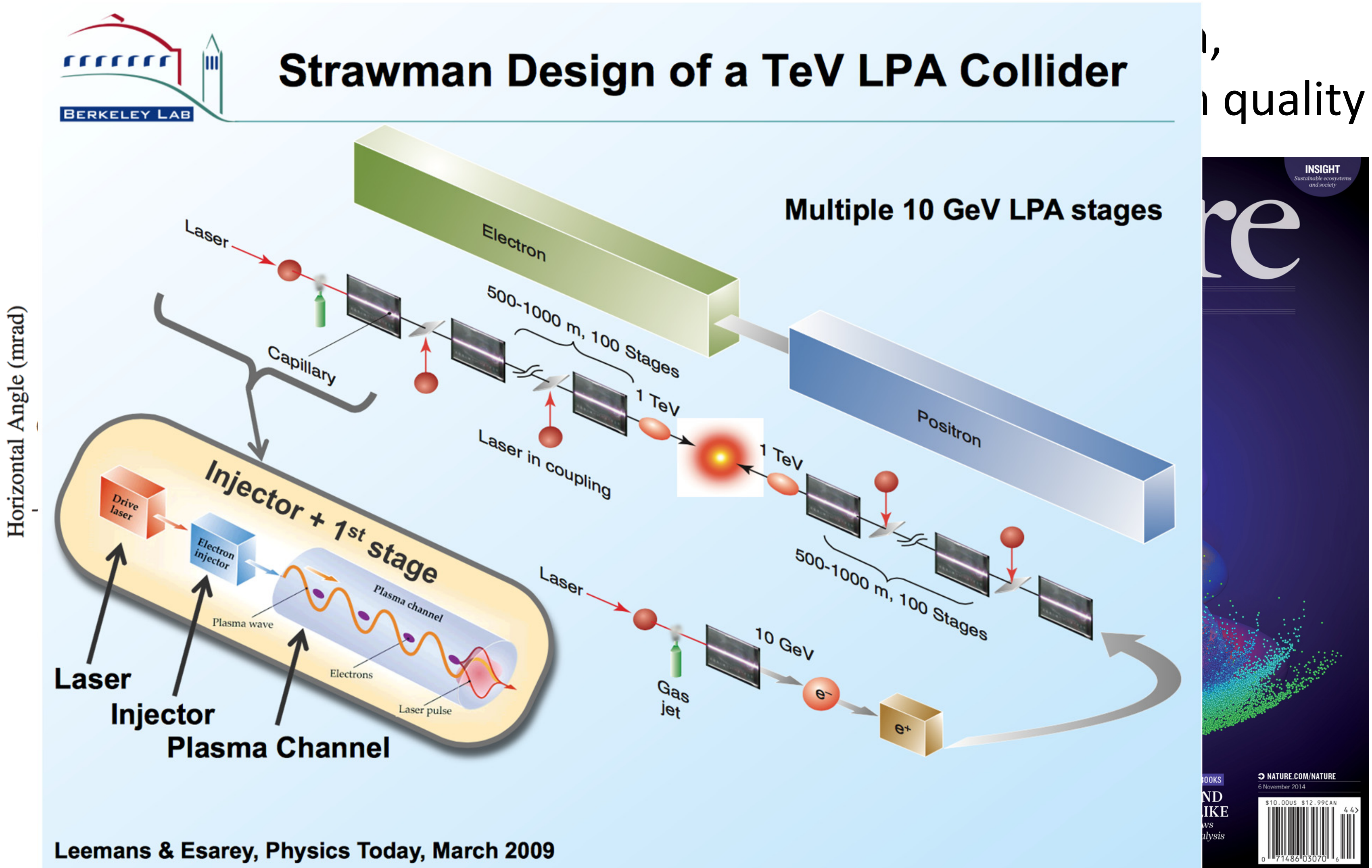
2014, LBNL, 16J laser, 4GeV



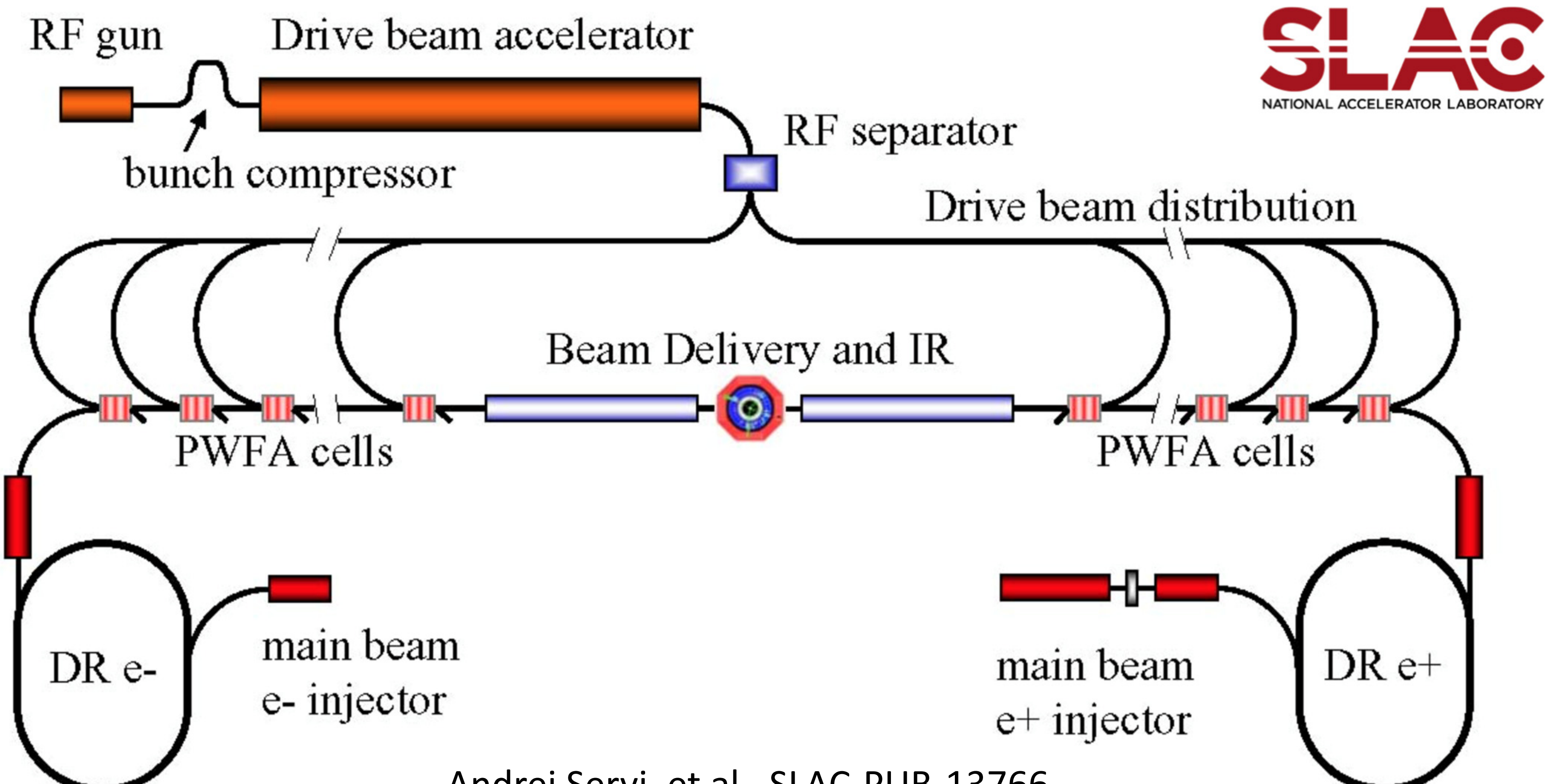
2014, SLAC, beam,
high efficient high quality

Motivation – Plasma-based acceleration

,
quality



Motivation – Plasma-based acceleration

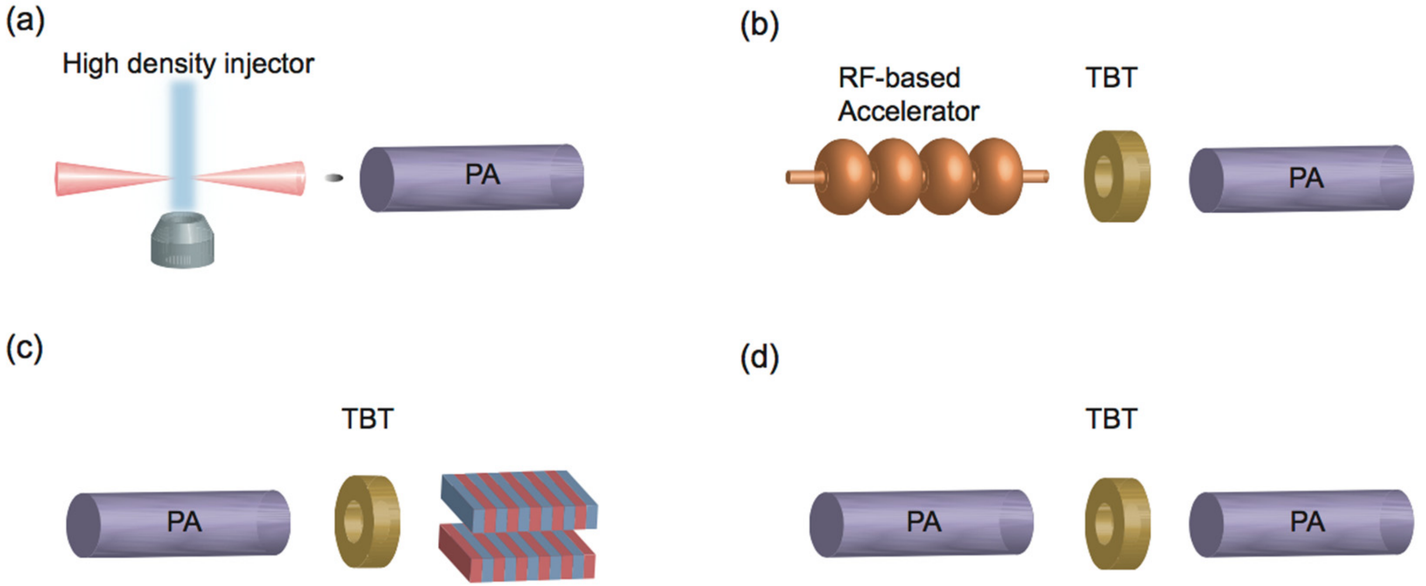


Andrei Seryi, et al., SLAC-PUB-13766

Leemans & Esarey, Physics Today, March 2009

Motivation - Staging

- Staging is critical for the future development of plasma based accelerators (PAs).

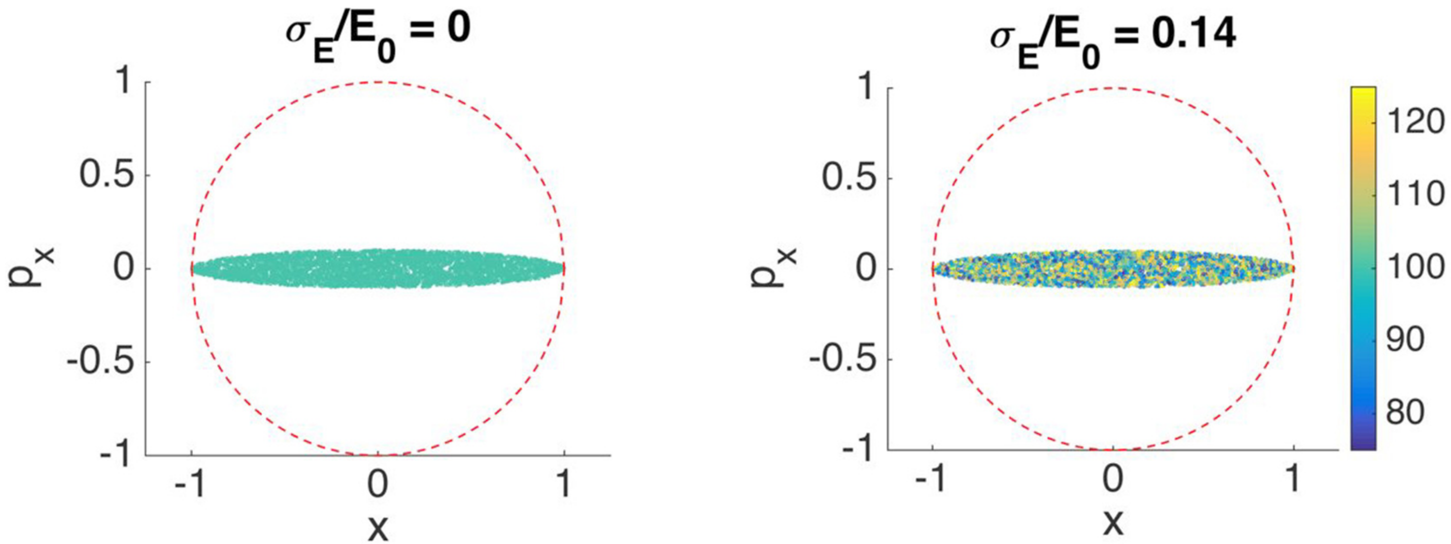


- Quadrupoles: the magnetic gradient G ~ 1000 T/m[1]
- Nonlinear plasma wake: the equivalent $G\ [T/m] \sim 3 \times 10^6\ n_p\ [10^{17}\ cm^{-3}]$

[1]T. Eichner et al., Phys. Rev. ST Accel. Beams 10, 082401 (2007); J. Harrison et al., Phys. Rev. ST Accel. Beams 15, 070703 (2012).

Motivation – Mismatch between stages

- When the beam propagates between different stages, serious transverse phase space mismatch may happen.

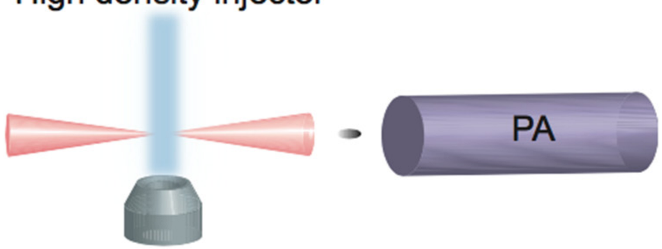


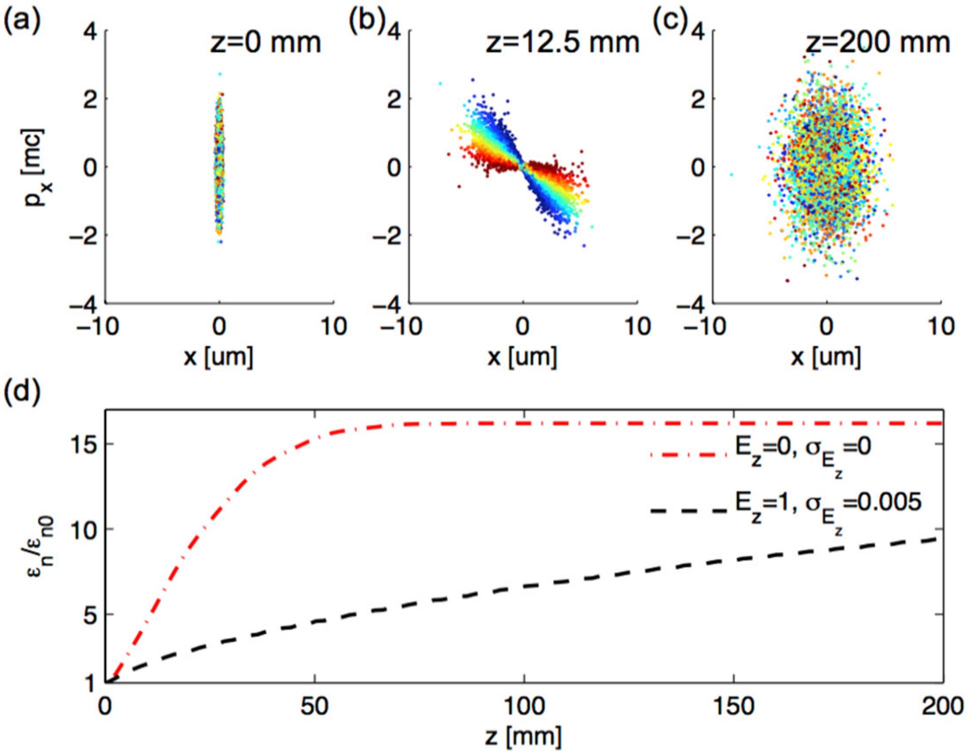
$$\frac{\epsilon_{n,sat}}{\epsilon_{n,i}} = \frac{\epsilon_{sat}}{\epsilon_i} \approx \frac{2}{\gamma_i \beta_F + \beta_i \beta_F^{-1} - \sqrt{(\gamma_i \beta_F + \beta_i \beta_F^{-1})^2 - 4}}$$

*P. Antici et al., Journal of Applied Physics 112, 044902 (2012); T. Mehrling et al., Phys. Rev. ST accel. Beams 15, 111303 (2012); M. Migliorati et al., Phys. Rev. ST Accel. Beams 16, 01111302 (2013).

Motivation – Mismatch between stages

- Take two-stage laser-plasma accelerator[1] as an example





$Y_0 = 200$, $\sigma_E/E_0 = 0.01$

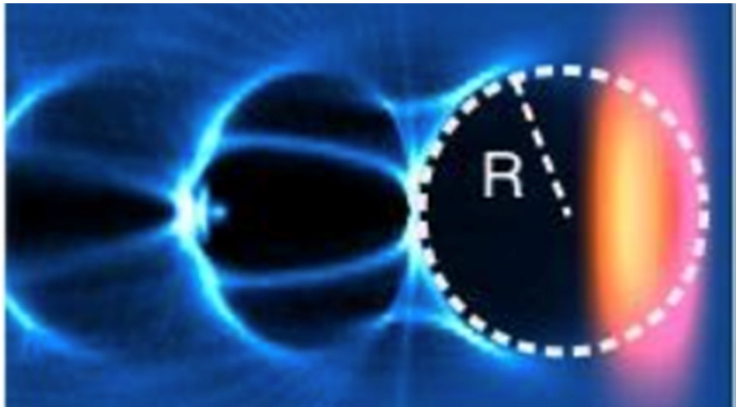
High density injector 10^{19} cm^{-3}

Free space drfit : 0.5 mm

Low density accelerator: 10^{17} cm^{-3}

[1]J. S. Liu et al., Phys. Rev. Lett. 107, 035001 (2011); B. B. Pollock et al., Phys. Rev. Lett. 107, 045001 (2011); A. J. Gonsalves et al., Nature Physics, 7, 862 (2011).

The concept of using plasma as a matching stage



$$E_z = -\frac{1}{2}\frac{e}{\epsilon_0}n_p\xi$$

$$E_r - B_\theta = \frac{1}{2}\frac{e}{\epsilon_0}n_p r$$

- We can use plasma with a tailored density profile as a transverse phase space matching components.

*W. Lu et al., Phys. Rev. Lett. 96, 165002 (2006); W. Lu et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007).

How to solve the profile parameters of the matching plasma?

- Start from the transverse motion equation:

$$\frac{\mathrm{d}^2 x}{\mathrm{d}z^2} + K(z)x = 0, \quad K(z) = \frac{ge^2}{2\gamma_0 mc^2\epsilon_0} n_p(z)$$

- Linear Profile: $n_p(z) = n_{p0}\left(1 - \frac{z}{l}\right)$
- Exponential Profile: $n_p(z) = n_{p0}\exp\left(-\frac{z}{l}\right)$
- Reciprocal I: $n_p(z) = n_{p0}\frac{l}{z+l}$
- Reciprocal II: $n_p(z) = n_{p0}\frac{l^2}{(z+l)^2}$ ⇒

$$\begin{cases} x = C_1\xi^{1/2}\cos(s\ln\xi) + C_2\xi^{1/2}\sin(s\ln\xi) \\ x' = C_1\xi^{-1/2}[\cos(s\ln\xi)/2 - s\sin(s\ln\xi)] \\ \quad + C_2\xi^{-1/2}[\sin(s\ln\xi)/2 + s\cos(s\ln\xi)] \end{cases}$$

where $\xi = z + l, s = \left|-g(k_{p0}l)^2/2\langle\gamma_b\rangle + 1/4\right|^{1/2}$

- Reciprocal IV: $n_p(z) = n_{p0}\frac{l^4}{(z+l)^4}$

where $0 \leq z \leq L$

How to solve the profile parameters of the matching plasma?

- The evolution of the beam C-S parameters:

$$\beta_f = M_{11}^2\beta_i - 2M_{11}M_{12}\alpha_i + M_{12}^2\gamma_i$$

$$\alpha_f = -M_{11}M_{21}\beta_i + (M_{11}M_{22} + M_{12}M_{21})\alpha_i - M_{12}M_{22}\gamma_i$$

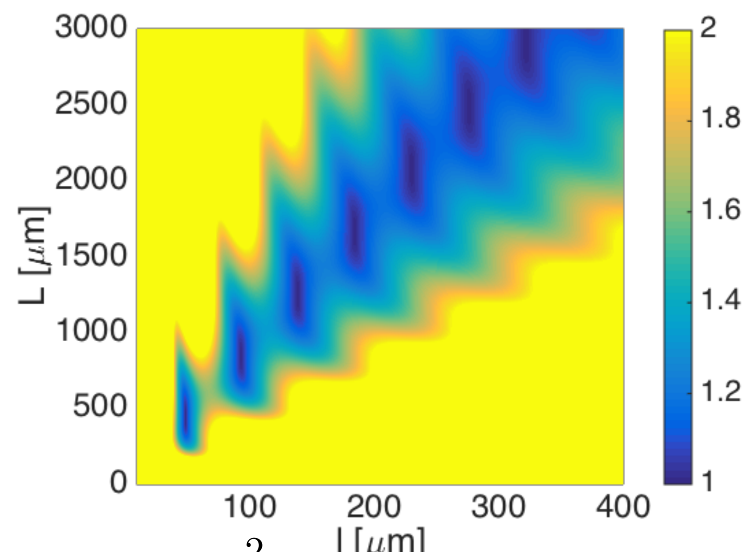
$$(\alpha_i, \beta_i, \alpha_{goal}, \beta_{goal}) \rightarrow (l, L)$$

➢ An example:

$$\alpha_i = 0, \beta_i = 20k_{p0}^{-1}$$

$$\alpha_{goal} = 0, \beta_{goal} = 200k_{p0}^{-1}$$

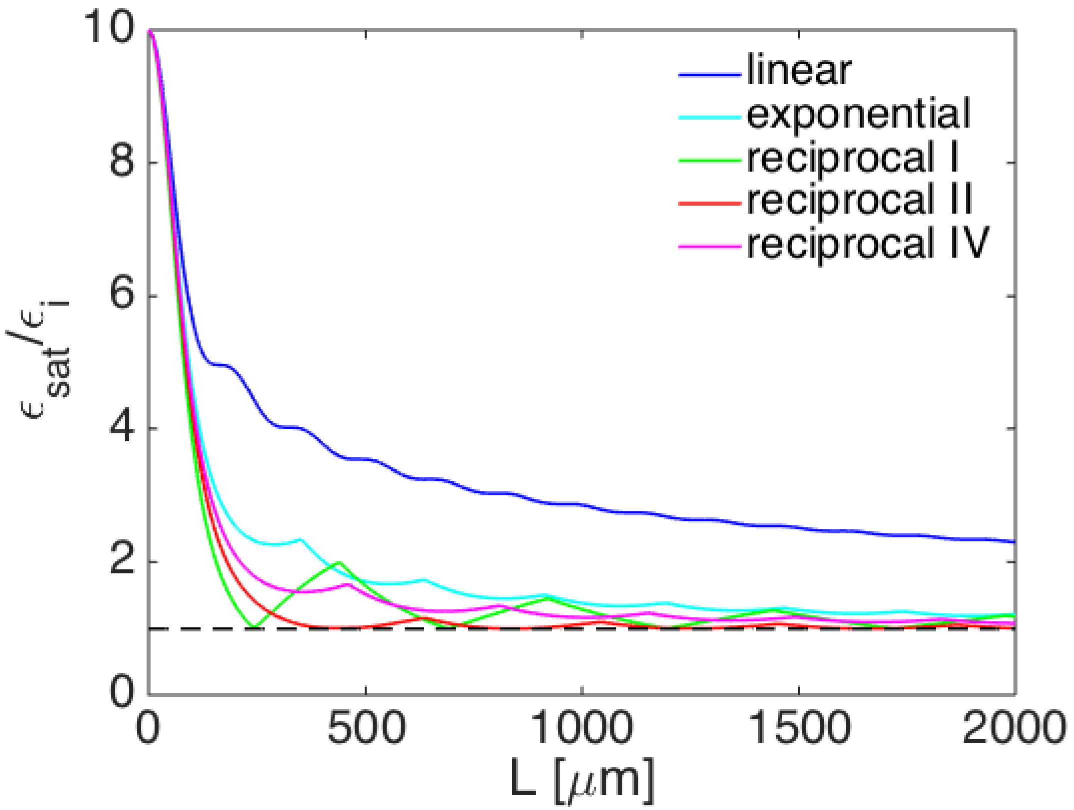
$$(k_{p0}^{-1} \approx 1.7\mu m)$$



$$\frac{\epsilon_{n,sat}}{\epsilon_{n,i}} \approx \frac{2}{\gamma(l,L)\beta_{goal} + \beta(l,L)\beta_{goal}^{-1} - \sqrt{(\gamma(l,L)\beta_{goal} + \beta(l,L)\beta_{goal}^{-1})^2 - 4}}$$

*S. –Y. Lee, Accelerator Physics (World Scientific Singapore, 1999.

The performance of the matching stage with different profiles

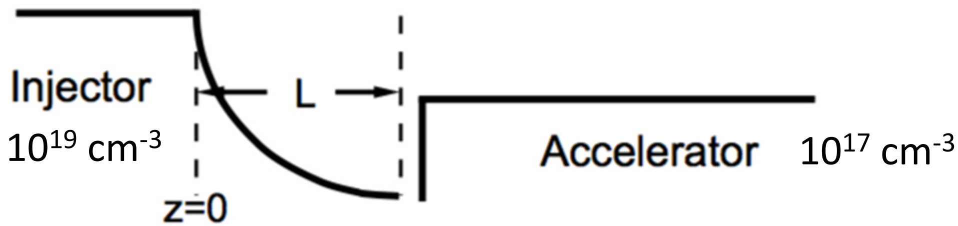


$$\frac{\epsilon_{n,sat}}{\epsilon_{n,i}} \approx \frac{2}{\gamma(l,L)\beta_{goal} + \beta(l,L)\beta_{goal}^{-1} - \sqrt{(\gamma(l,L)\beta_{goal} + \beta(l,L)\beta_{goal}^{-1})^2 - 4}}$$

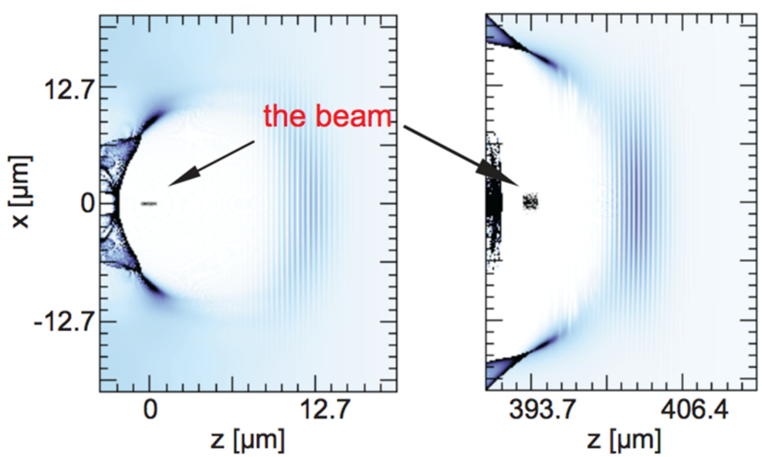
3D PIC simulations: Two-Stage LWFAs

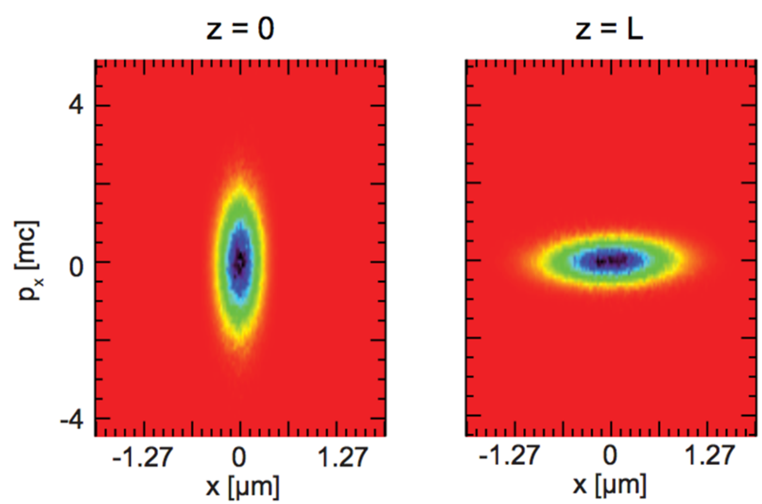
- Parameters: $\gamma_0 = 200, \beta_i = 33.7\mu m, \alpha_i = 0$

  $\beta_{goal} = 337\mu m, \alpha_{goal} = 0 \quad \Rightarrow l = 49\ \mu\text{m}, L = 394\ \mu\text{m}$



- OSIRIS results:



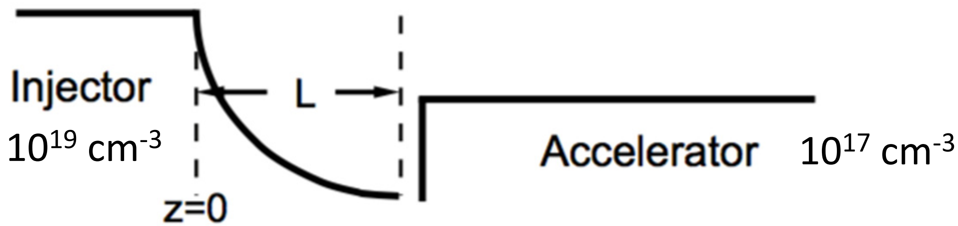


$\gamma_0 : 200 \rightarrow 192, \sigma_E/E_0 : 0.1 \rightarrow 0.105$

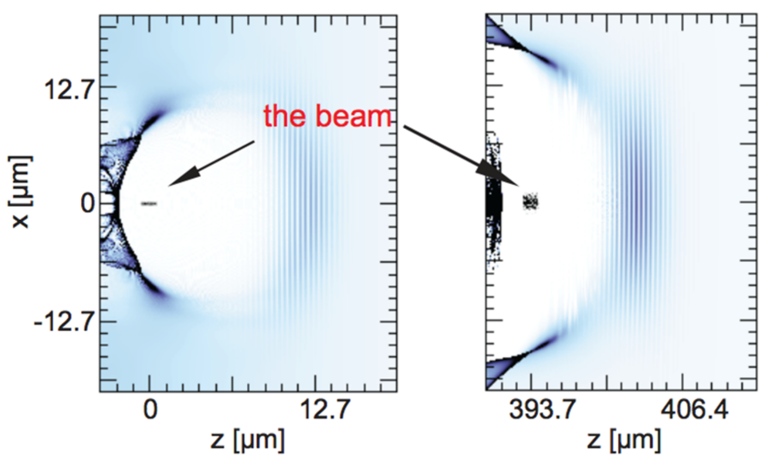
3D PIC simulations: Two-Stage LWFAs

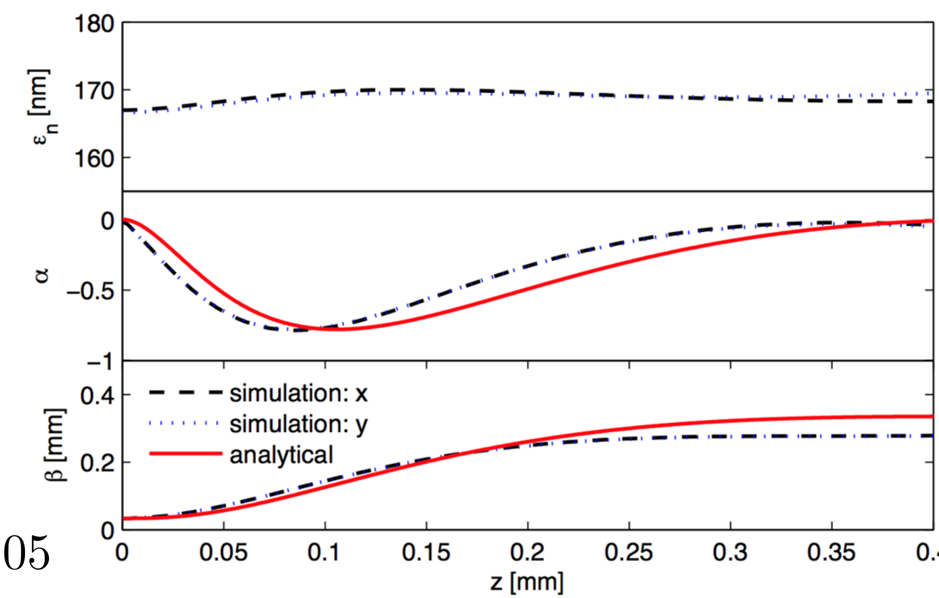
- Parameters: $\gamma_0 = 200, \beta_i = 33.7\mu m, \alpha_i = 0$

  $\beta_{goal} = 337\mu m, \alpha_{goal} = 0$ $\Rightarrow l = 49\ \mu\text{m}, L = 394\ \mu\text{m}$



- OSIRIS results:



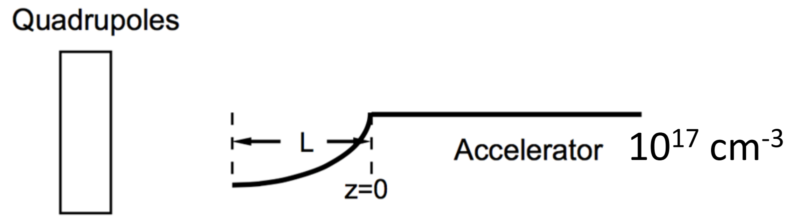


$\gamma_0 : 200 \rightarrow 192, \sigma_E/E_0 : 0.1 \rightarrow 0.105$

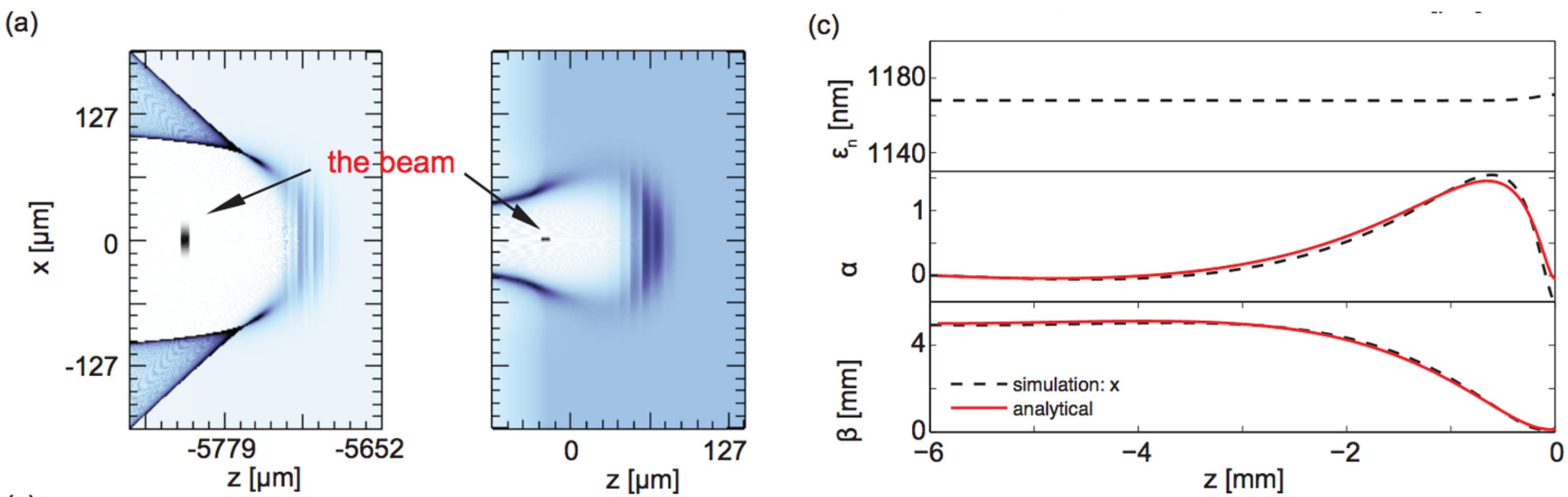
2D PIC simulations: External Injection

- Parameters: $\gamma_0 = 50, \beta_{goal} = 5mm, \alpha_{goal} = 0$

  $\beta_{goal} = 0.12mm, \alpha_{goal} = 0$ $\Rightarrow l = 0.116 \text{ mm}, L = 5.8 \text{ mm}$



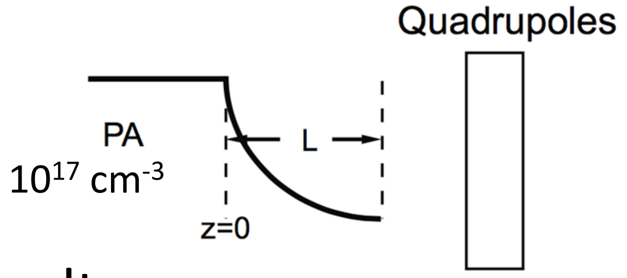
- OSIRIS results:



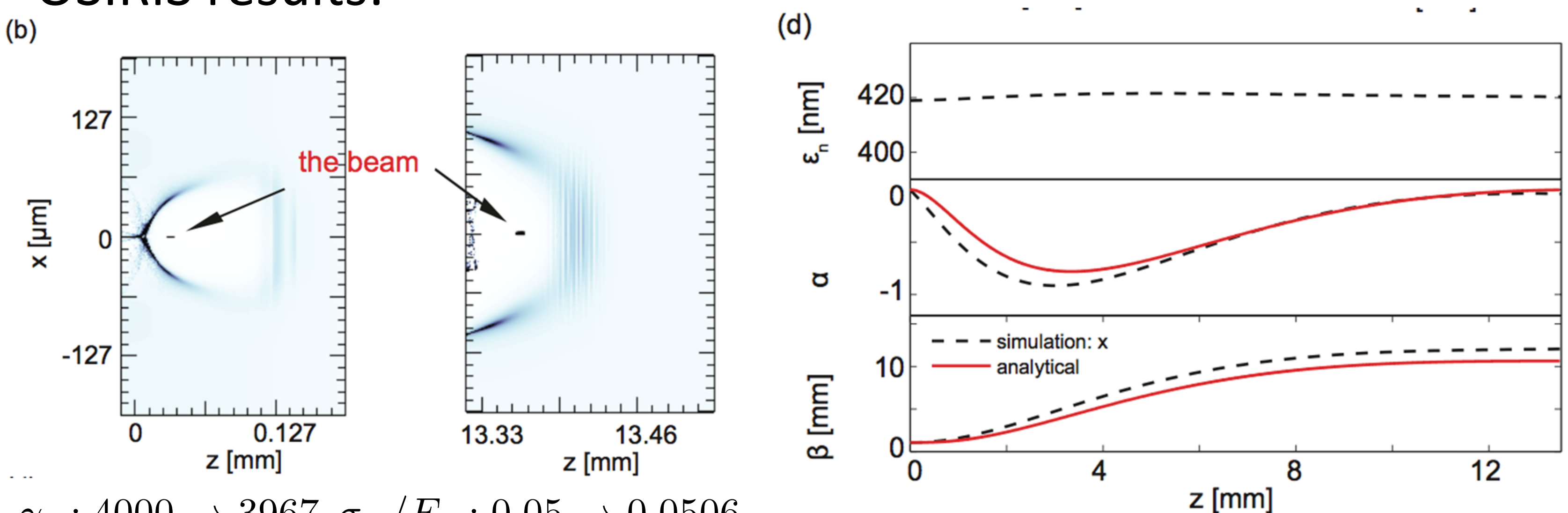
$\gamma_0 : 50 \rightarrow 44.8, \sigma_E/E_0 : 0.02 \rightarrow 0.0225$

2D PIC simulations

- Parameters: $\gamma_0 = 4000, \beta_i = 1.06mm, \alpha_i = 0$
  $\beta_{goal} = 10.6mm, \alpha_{goal} = 0 \quad \Rightarrow l = 1.55 \text{ mm}, L = 13.3 \text{ mm}$



- OSIRIS results:



$\gamma_0 : 4000 \rightarrow 3967, \sigma_E/E_0 : 0.05 \rightarrow 0.0506$

Conclusions

- Catastrophic emittance growth may happen when the beam propagates between plasma and traditional accelerators.
- A longitudinal tailored plasma structure is proposed as phase space matching components.
- Theoretical analysis and full 3-d PIC simulations are presented.

Thank you for your attention!