北京大学
PEKING UNIVERSITY

Plasma-Based Muon Capture and GeV-Scale Acceleration

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Peking University
Mourou-Tajima Institute

2026.10.23-26

Outline

- **Introduction and motivation**
- **Surface muon acceleration**
- **GeV-scale muon acceleration**
- **Outlook**

Laser Electron Accelerator

1979年， Tajima and Dawson首先提出LPA.

John M Dawson（1930-2001）



Toshiki Tajima





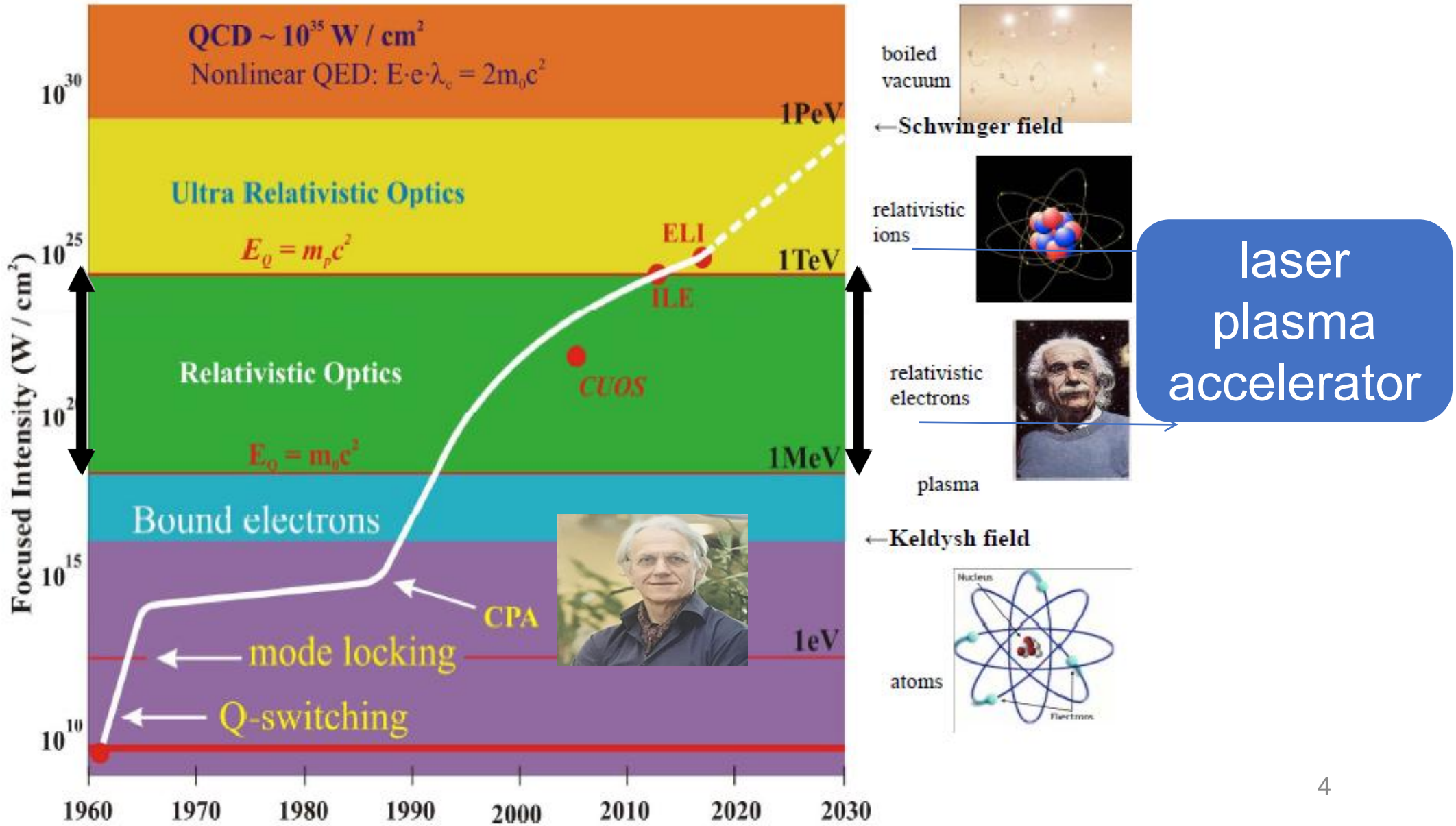
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

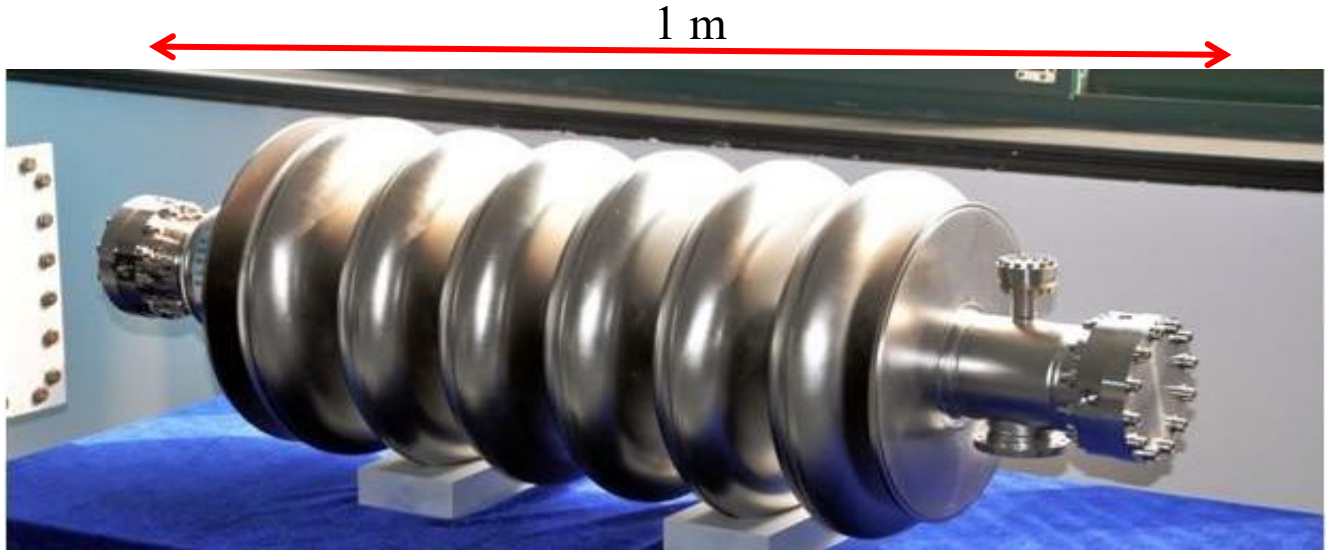
CPA laser Intensity is increasing



1000 times smaller, and fast!

RF accelerator

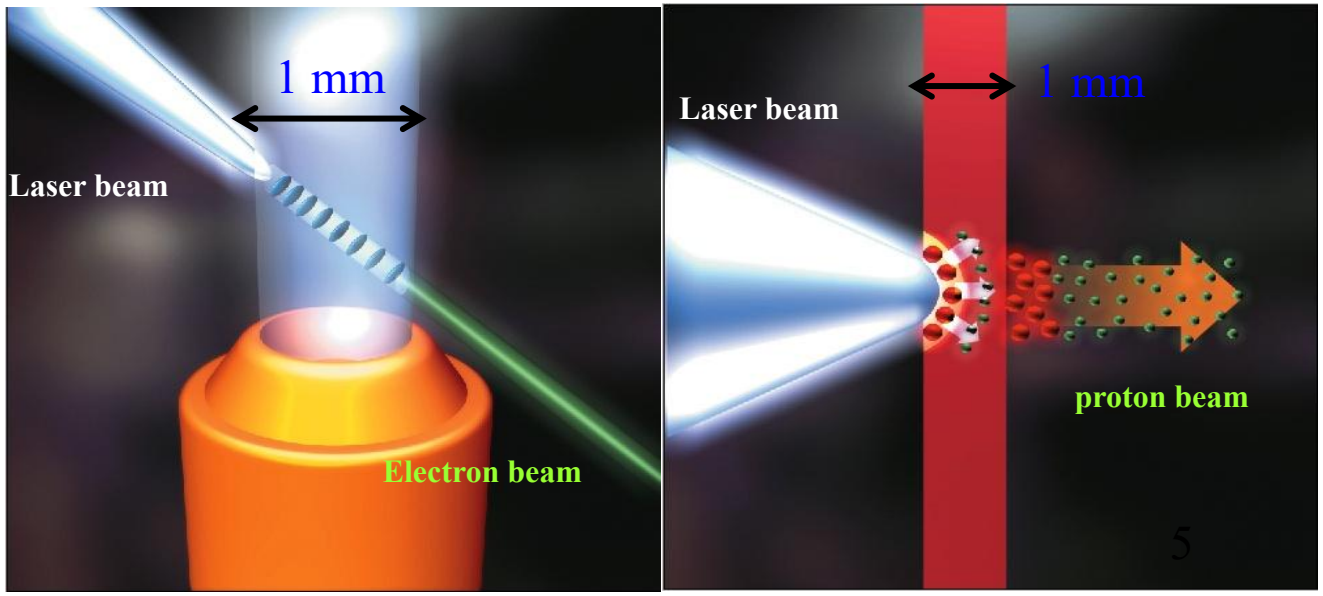
E = <100MV/m



laser plasma accelerator

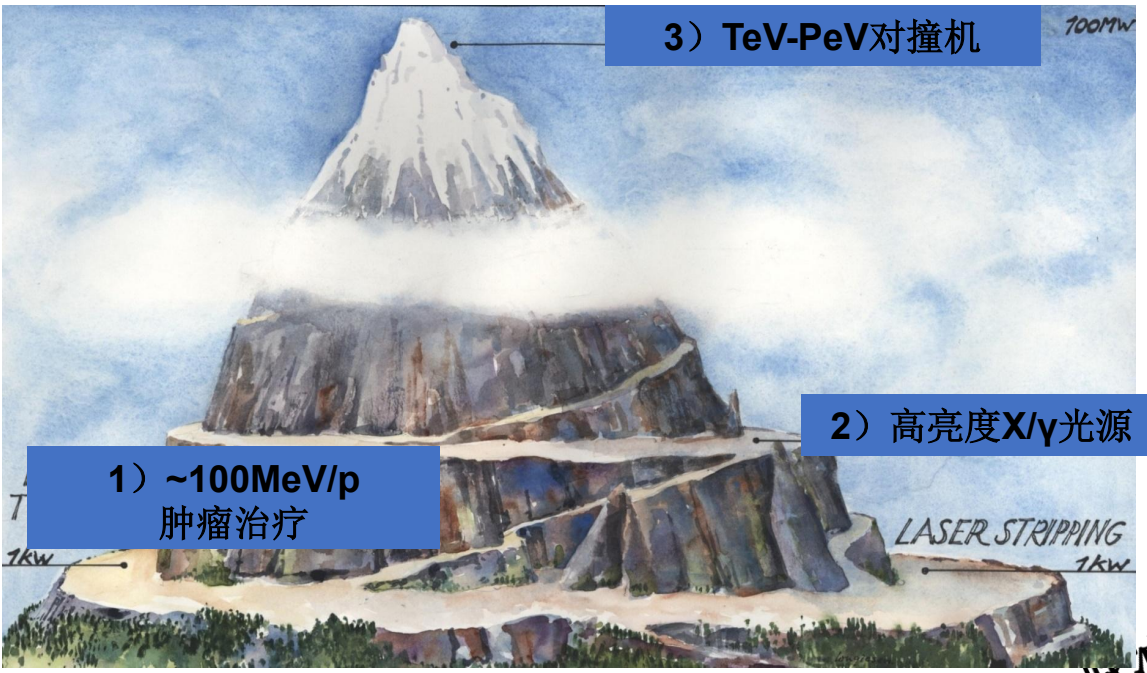
E > 100GV/m

1000 times smaller!



Laser Plasma Acceleration and Applications

1) ion accelerators; 2) high-brightness X/γ light sources; 3) colliders

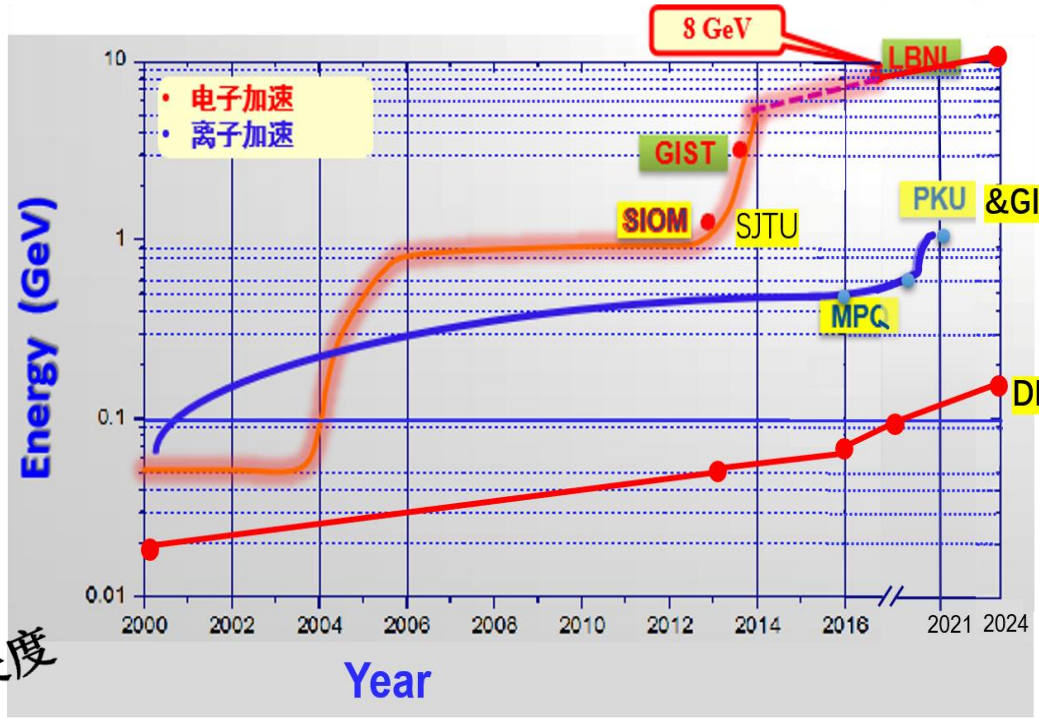


↑ 平均功率

→ 脉冲长度

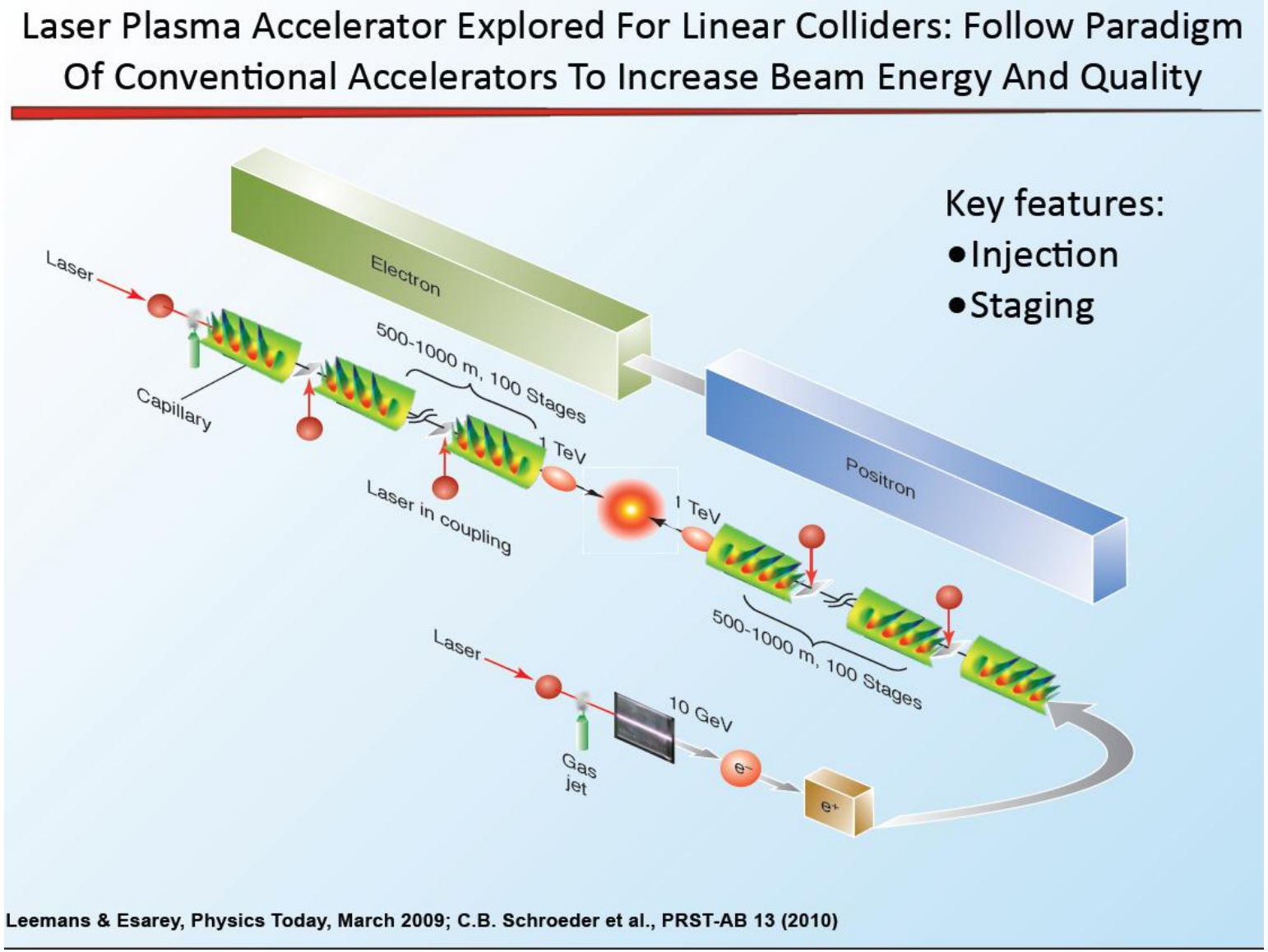
→ rep rate

ICFA+ICUIL



Matter and Radiation at Extremes, 2024, 9(1).
Nature Physics 20, 1211-1216 (2024)
Wang, Phys. Rev. X 11, 021049 (2021);

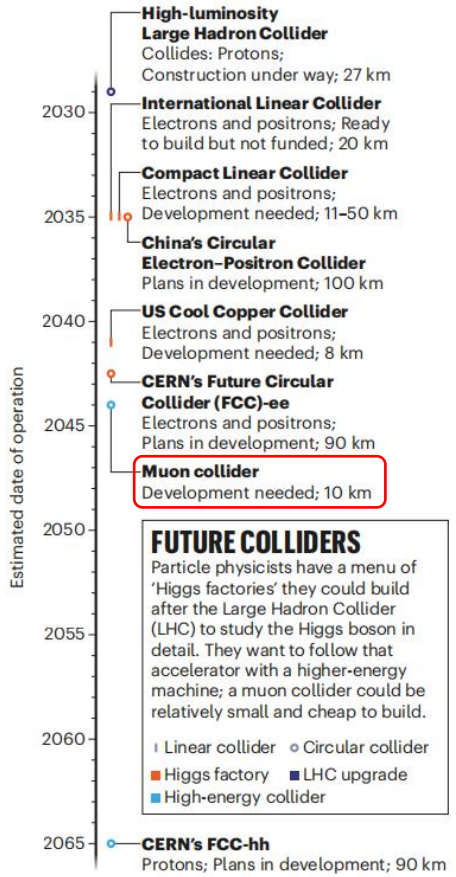
TeV electron collider by laser accelerator?



Build the world' first muon collider ?

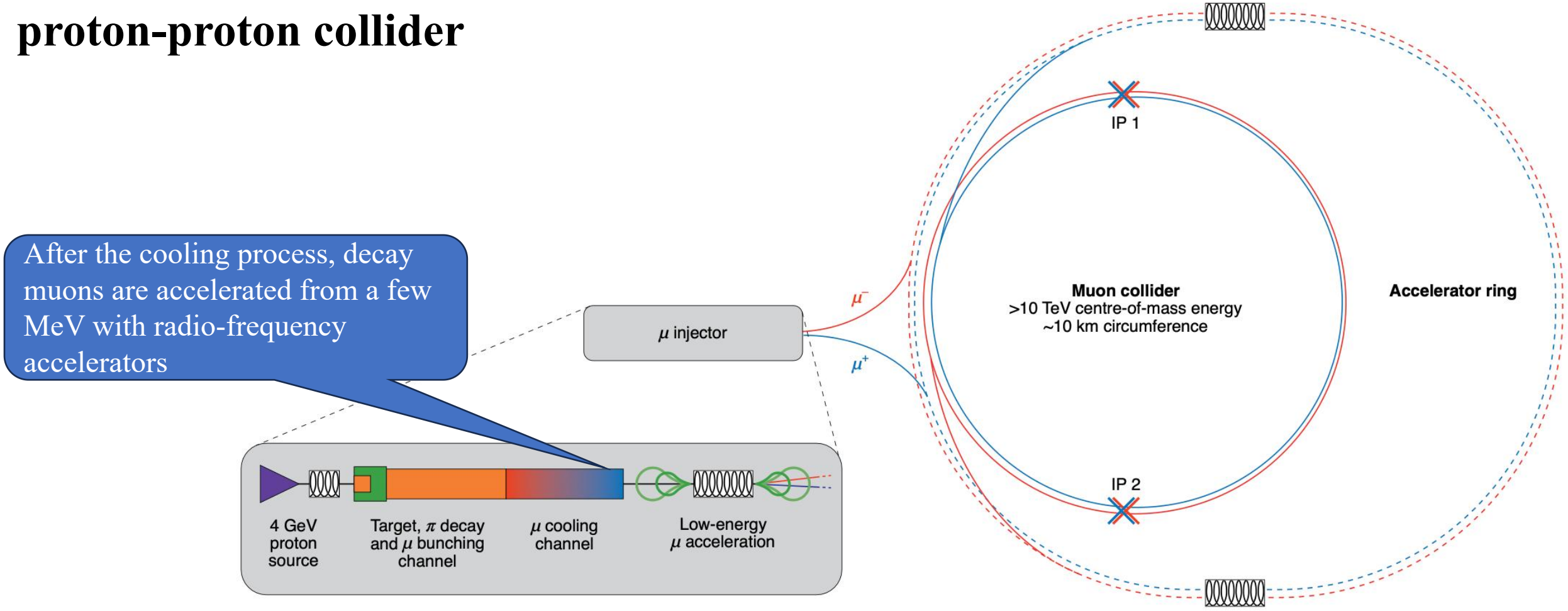


There are several possible particle accelerators that could follow the Large Hadron Collider.



Energy-efficient choice

10 TeV muon collider would provide similar discovery potential to a 100 TeV proton-proton collider



Muon colliders to expand frontiers of particle physics Nature Physics, VOL 17 , 2021, 289–292 (comment)

TeV muon collider by plasma-based acceeration

Challenges of muon collider:

1. Short lifetime: 2.2μs, at rest

2. Large initial phase space of the decay muon: low quality at beginning

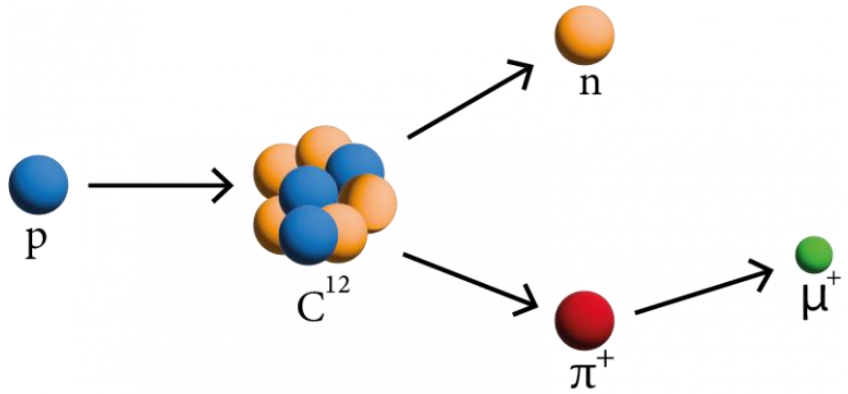
3. A significant velocity variation during the acceleration: multiple acceleration structure

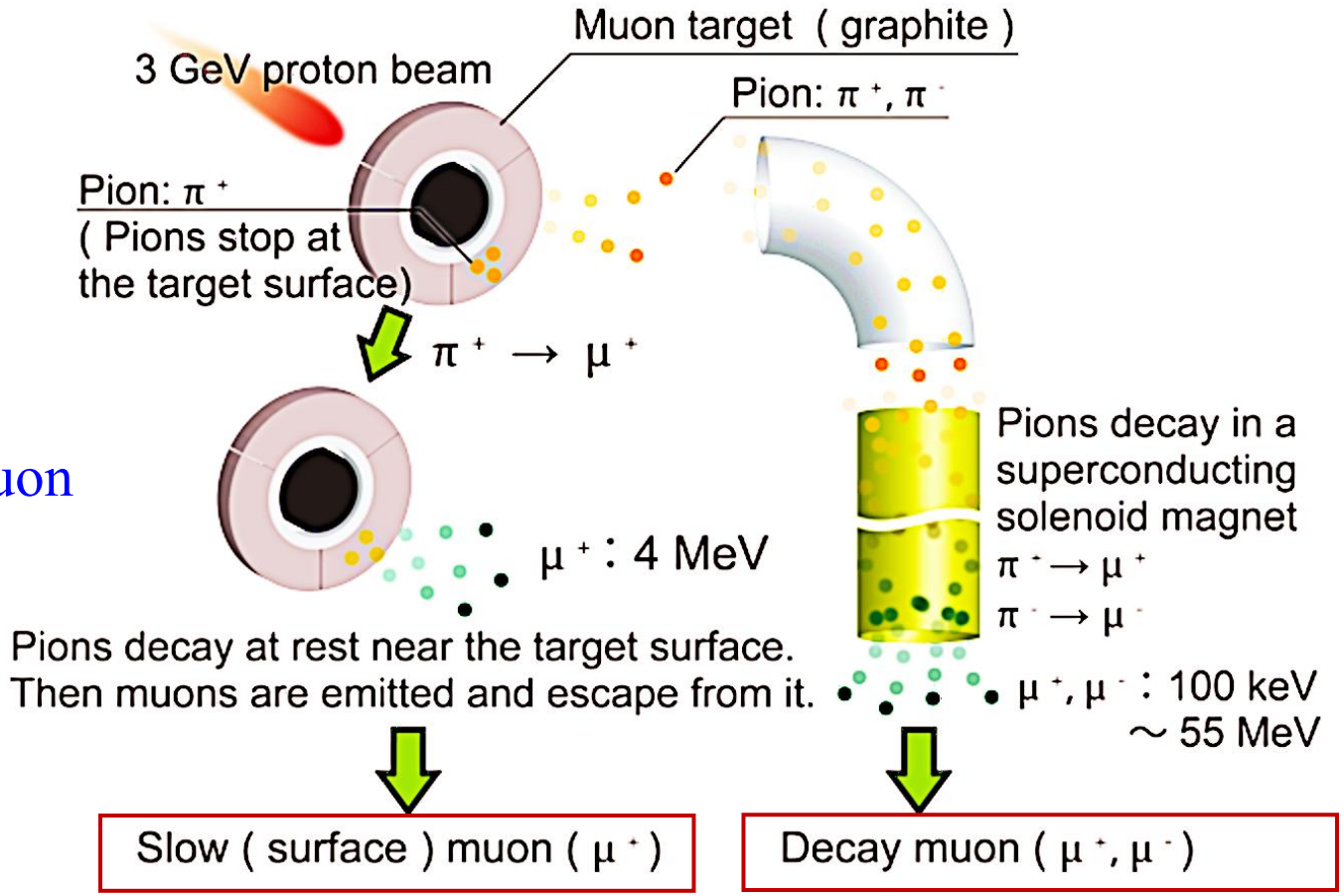
… …

Generation of muon beam

Muon ($\mu^{\pm}$)

- A short lifetime at rest, 2.2 μs
- Mass: ~207 m_e
- Two types: surface muon & decay muon

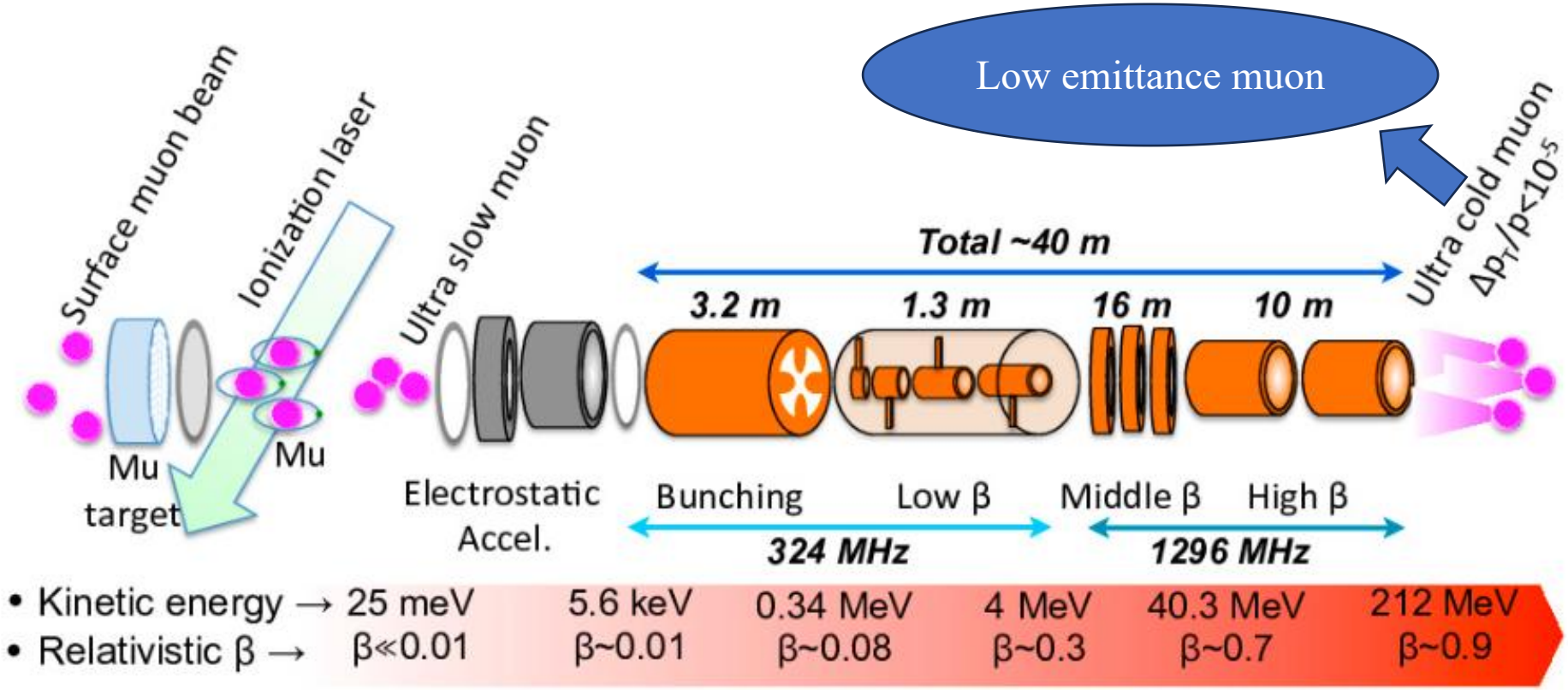




Surface muon (μ^+) to 200MeV

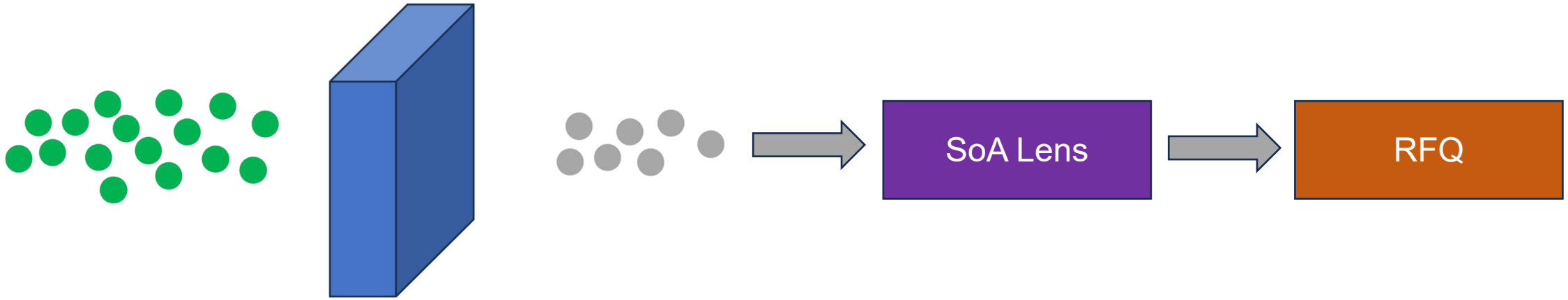
Muon anomalous magnetic moment measurement

Japan Proton Accelerator Research Complex (J-PARC) muon science facility (MUSE)



IOP Conf. Series: Journal of Physics: Conf. Series 874 (2017) 012055

First RF-based muon acceleration



Surface muon beam
μ^+ 2.9 MeV

Al degrader

cooling
Mu^- ($\mu^+ e^- e^-$) ~eV

Electrostatic acceleration
Mu^- 5.6 KeV

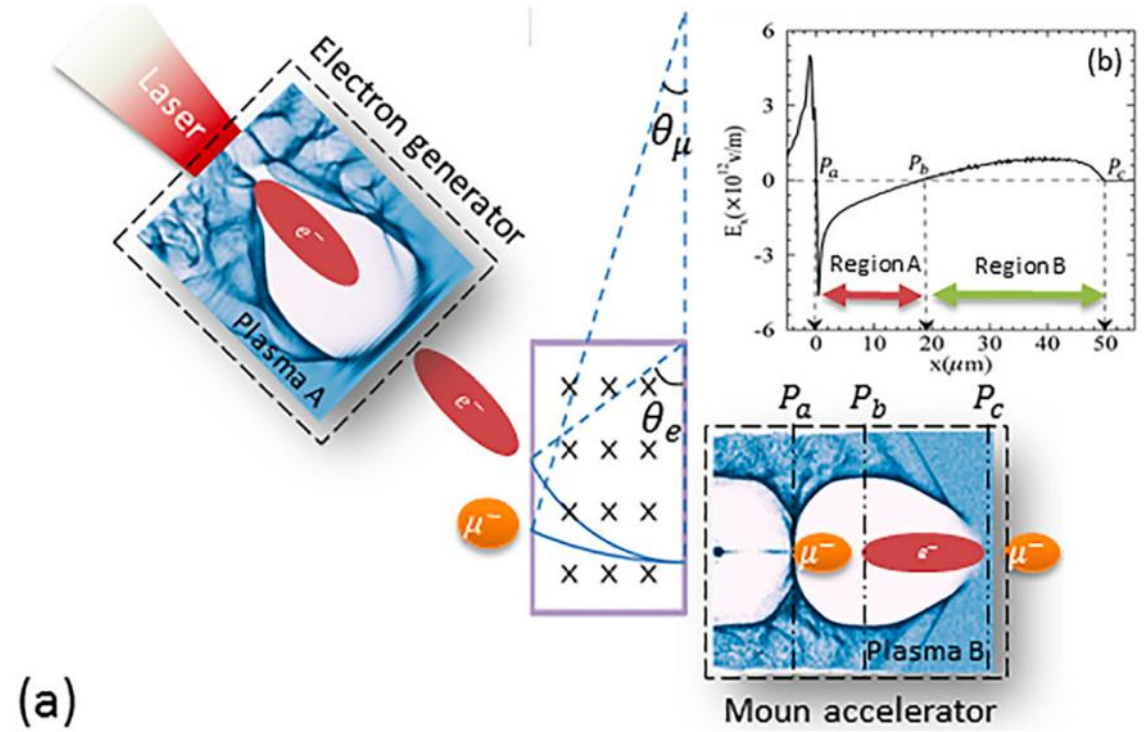
RFQ acceleration
Mu^- 89 KeV

- Limited by very low conversion efficiency of μ^+ to Mu^- : 8×10^{-7} (10^{-5})
- Could be greatly improved by using laser-dissociation ultraslow muon source (also difficult)
- Further acceleration from 89 KeV to 210 MeV: RFQ + drift tube linac (low beta) + disk-and-washer coupled cavity linac(middle beta) + disk loaded traveling wave structures (high beta)

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Acceleration of 200 MeV muon



Phys. Plasmas 28, 093101 (2021)
Phys. Plasmas 29, 103110 (2022)
Phys. Plasmas 31, 023109 (2024)

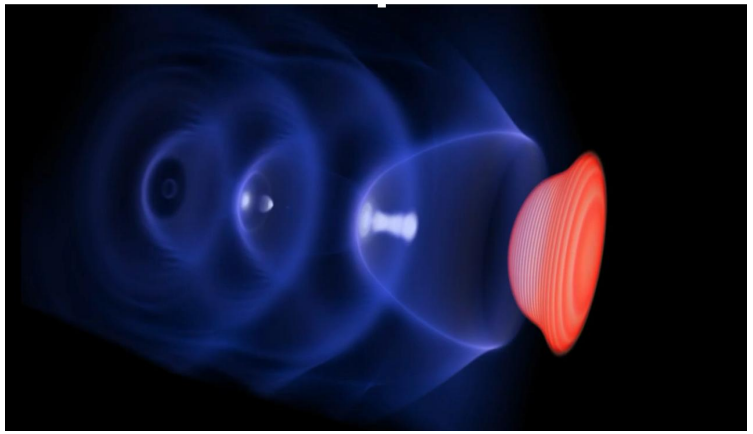
- Initial muon speed close to the light speed (~200 MeV or higher)
- Ultrashort duration: 10s fs

How do we capture slow muon?

- Train should be decelerated at first, passengers are loaded into the train carriages (bucket)

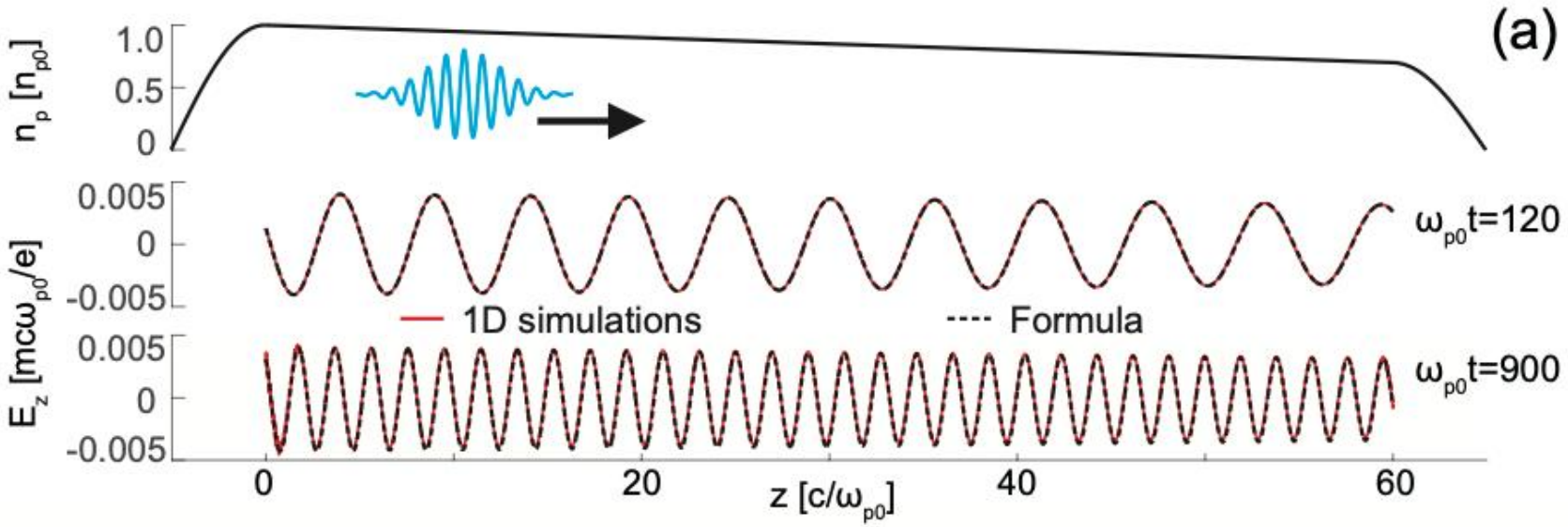


- The phase velocity of the wake is too high to accelerate low-energy muons (a small fraction of the light speed)



- Slow the wake in the plasma?

Slowdown of the wake by self-evolution



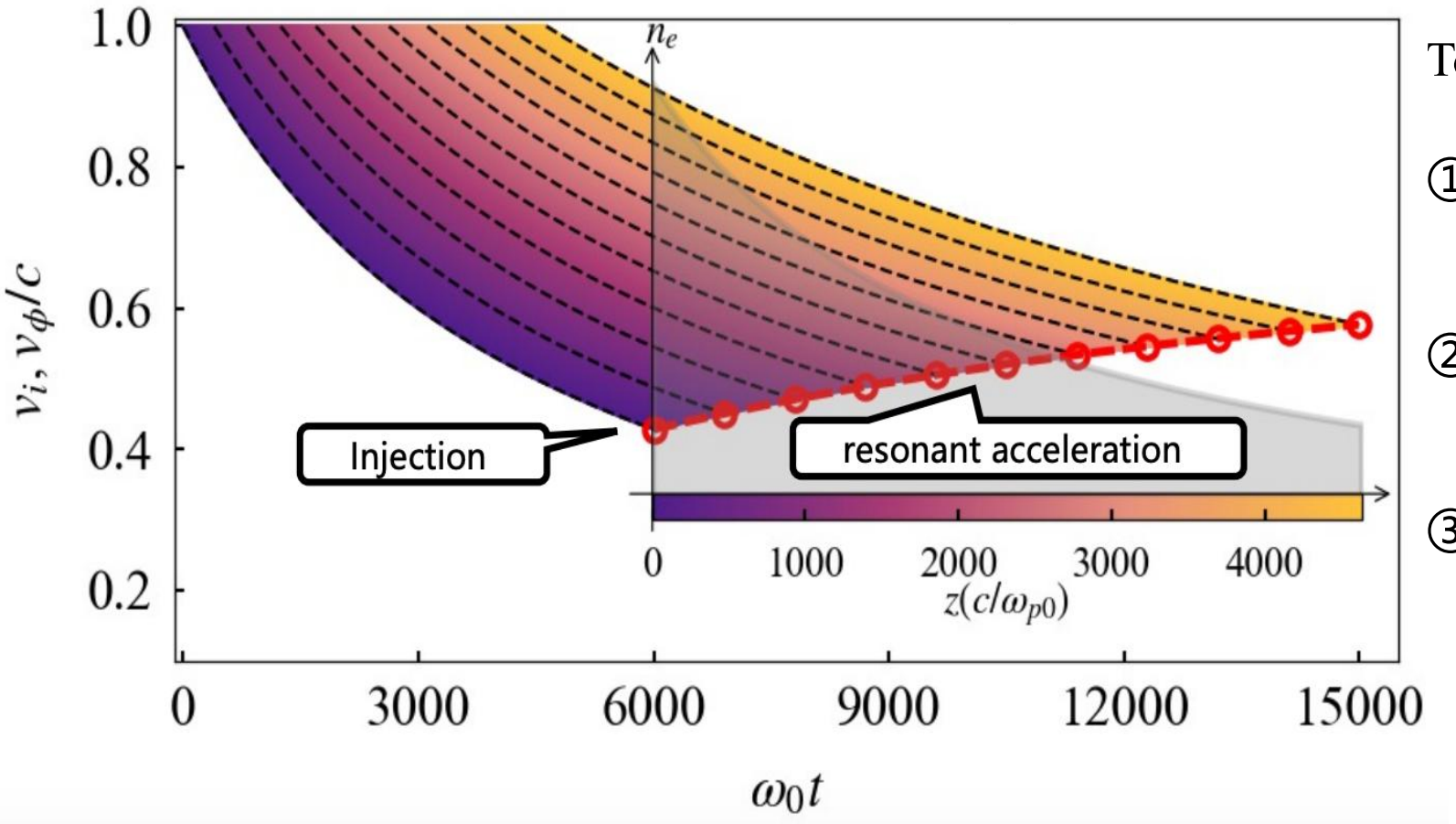
Self-evolution

$$v_\phi = \omega_p(z) \Big/ \left[\frac{\omega_p(z)}{v_d} - \frac{\mathrm{d}\omega_p(z)}{\mathrm{d}z} \left(t - \frac{z}{v_d} \right) \right]$$

Downramp:

Phase velocity (wavenumber) decreases (increases) with time evolution

Plasma Traveling Wave Acceleration(PTWA)



To get accelerated:

① Slowed down first to match the speed of the injected particle (delay time τ_d)

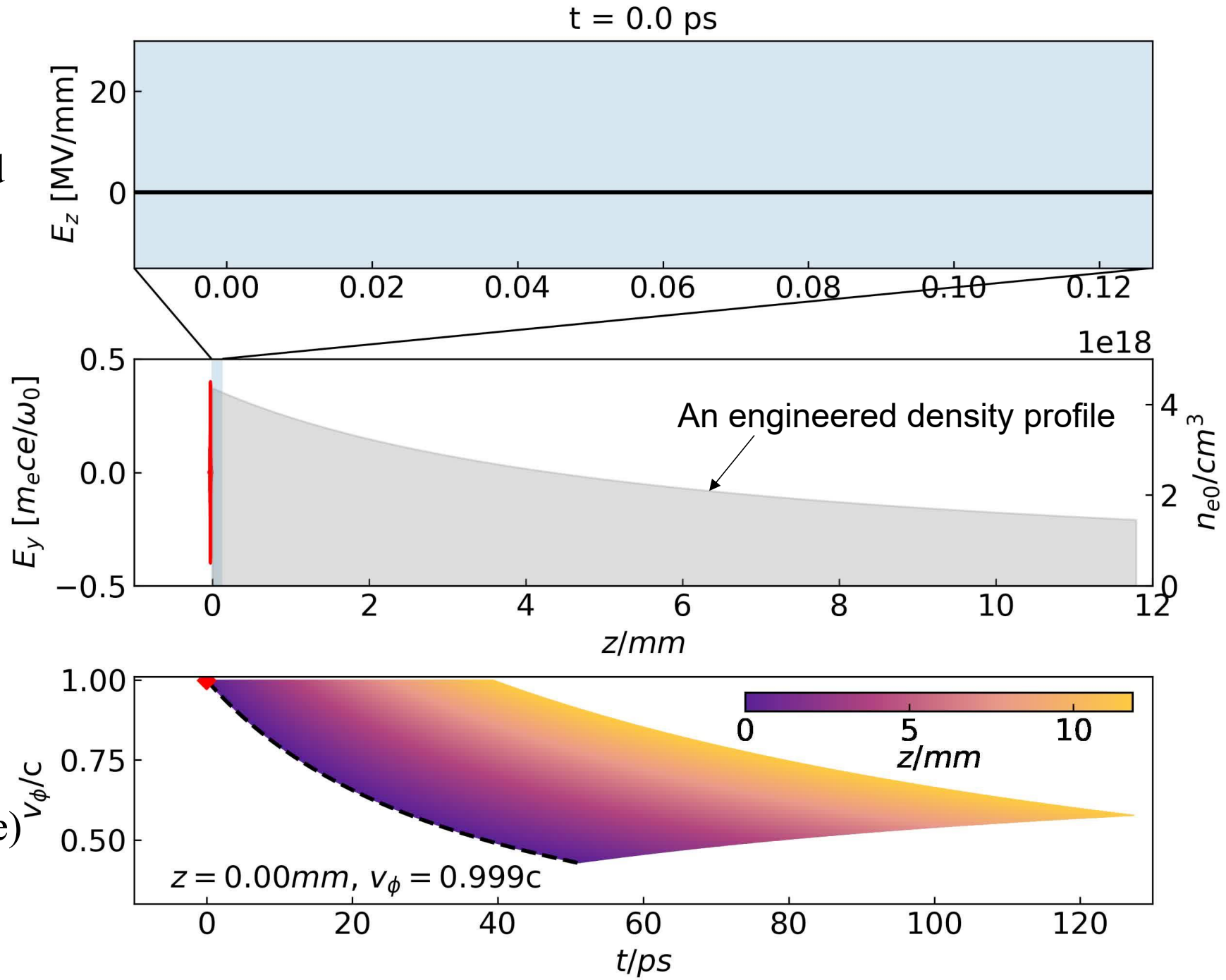
② Particles are injected into a bucket on time (initial particle speed β_{z0})

③ The phase velocity of this bucket increases gradually as the particle speed grows (acceleration phase ϕ_0)

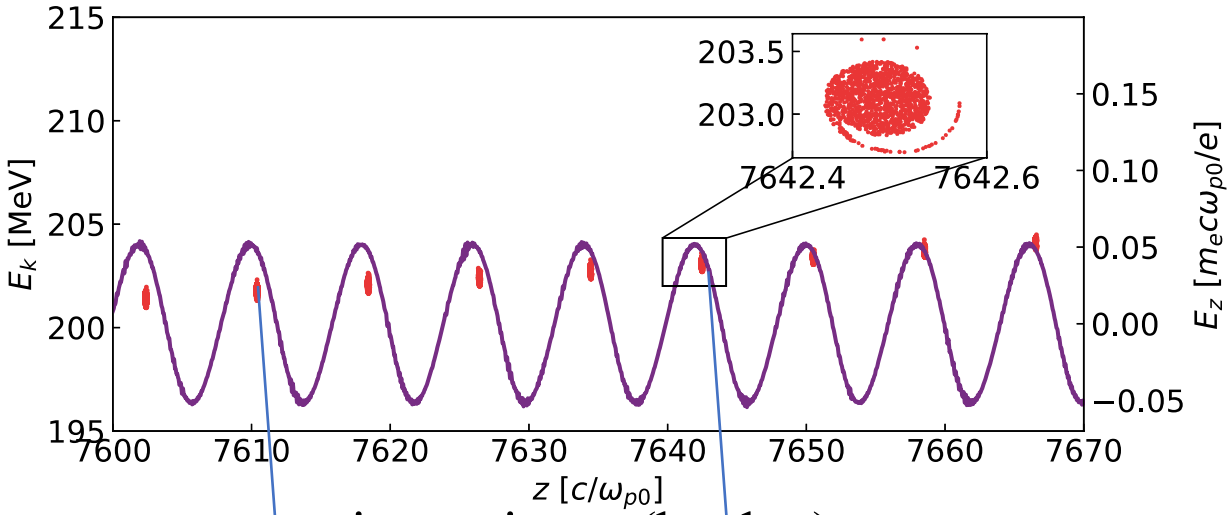
Accelerating field

laser electric field (red line)

Phase velocity evolution (black dashed line)



Muons in buckets from 4 MeV to 200 MeV



train carriages (bucket)



Laser

Intensity: $a_0 = 0.4$

Duration: $\tau = 34$ fs

Beam energy 4 MeV

energy spread σ = 1 MeV

Beam duration 850 fs (could be longer)

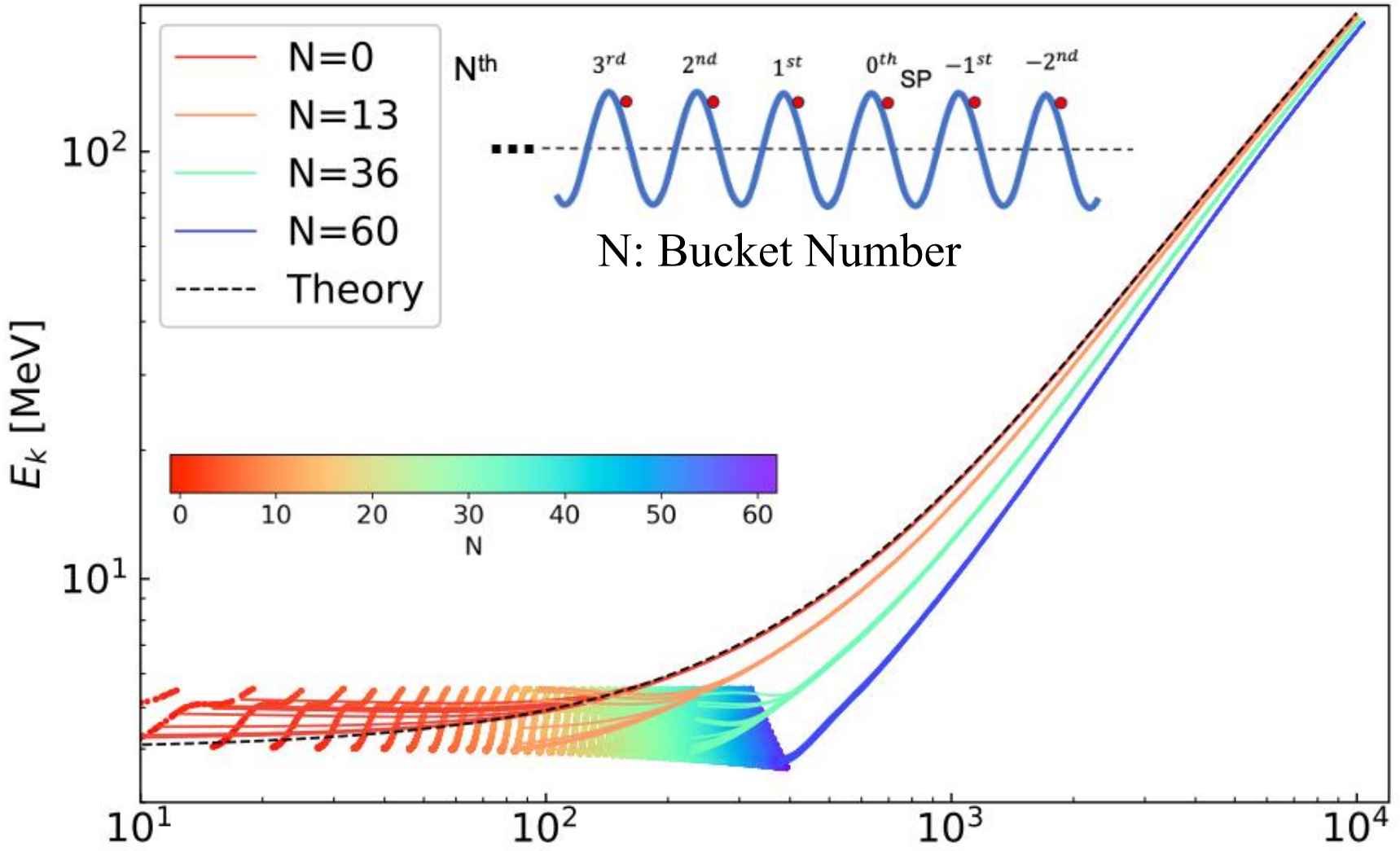
injection time $t = 51$ ps

Acceleration gradient: ~11GV/m

Micron beam duration: 100s as ~ a few fs

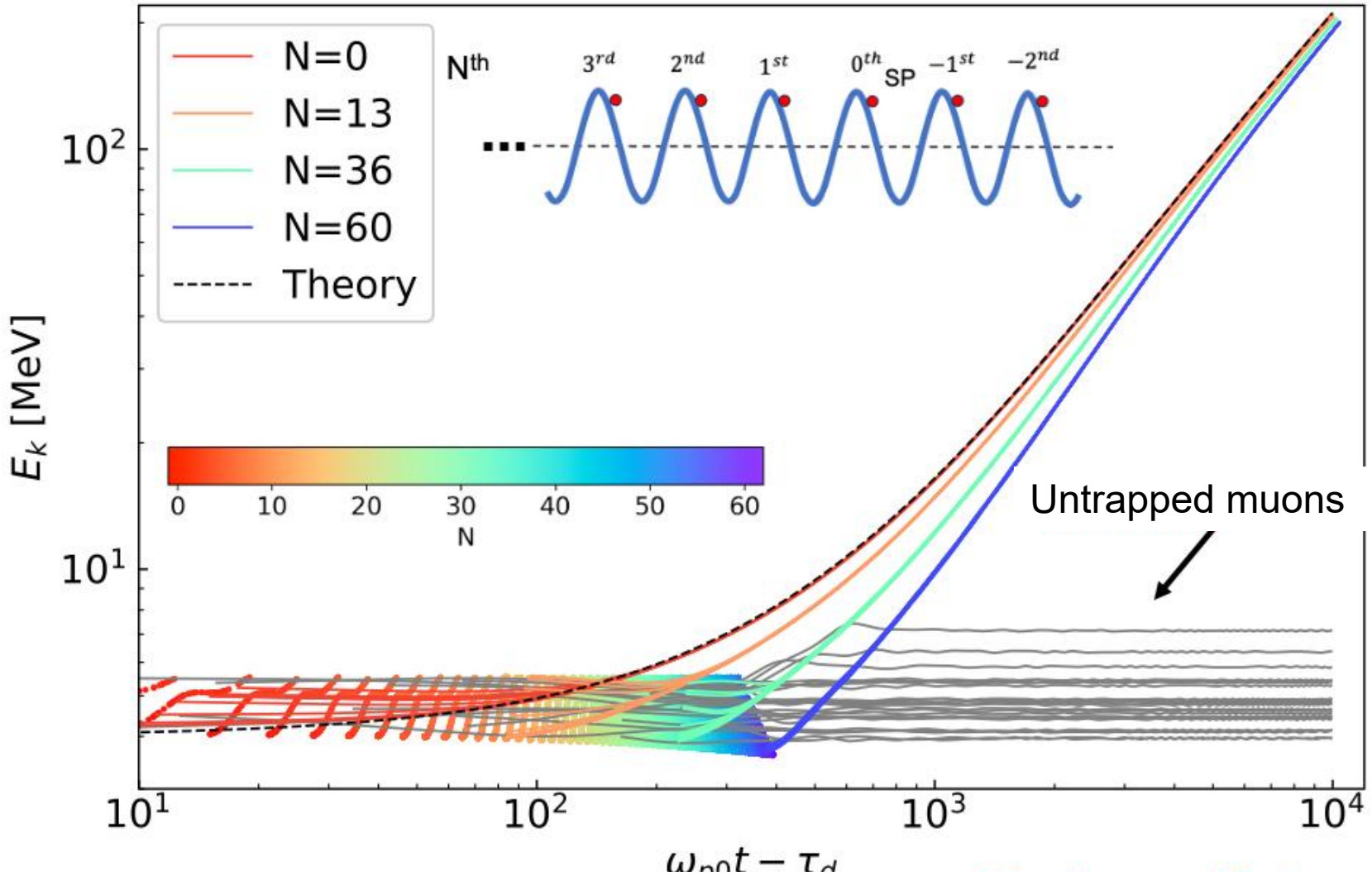
Micron beam energy spread: ~0.1%

Acceleration in different buckets or carriages



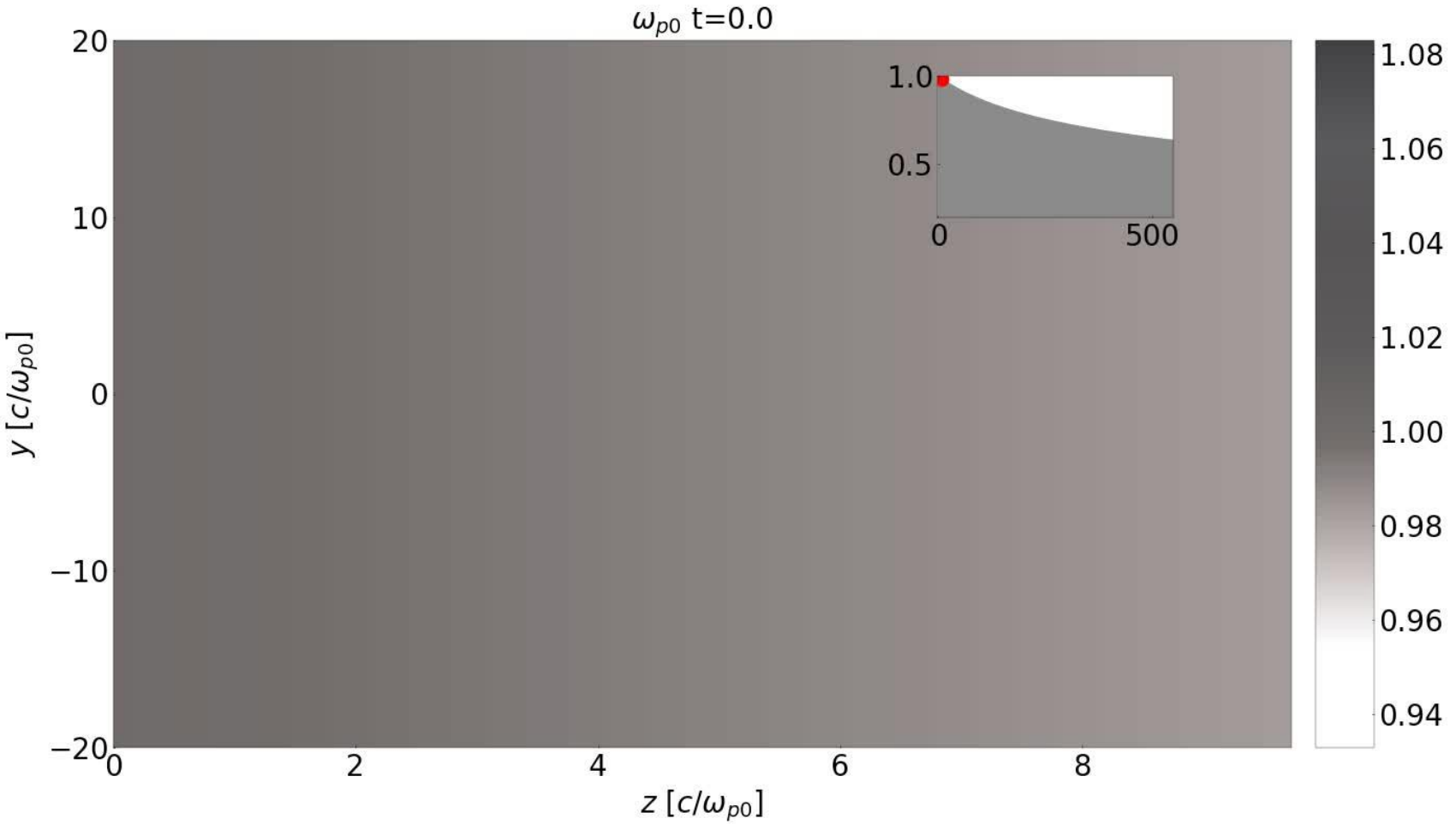


Capture efficiency 0.1%-1% with cooling



Could be improved by choosing a higher acceleration phase

2D PIC simulation



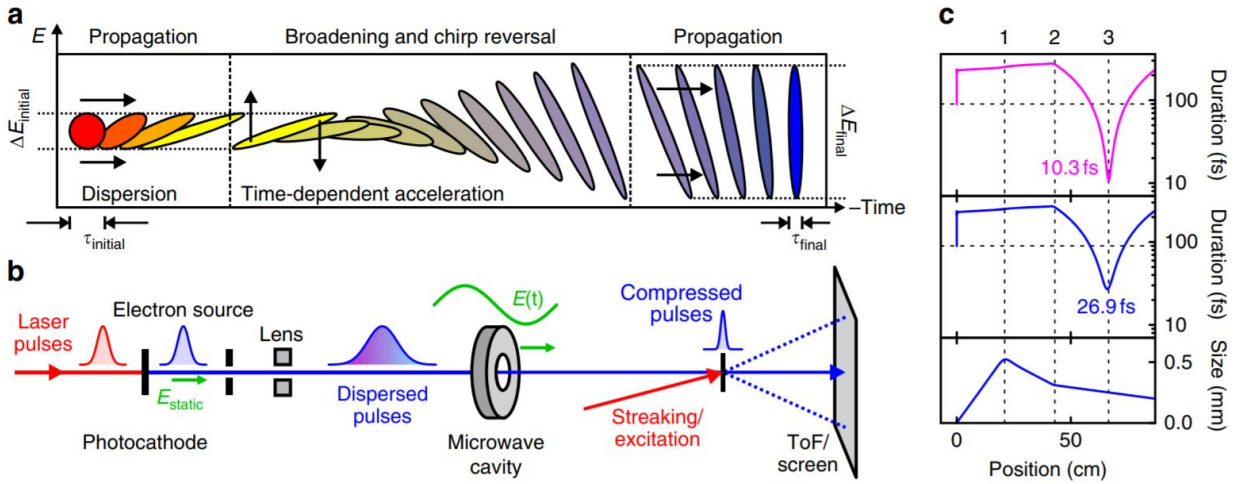
From 4 MeV(~0.2c) to 20 MeV(~0.5c)

Outline

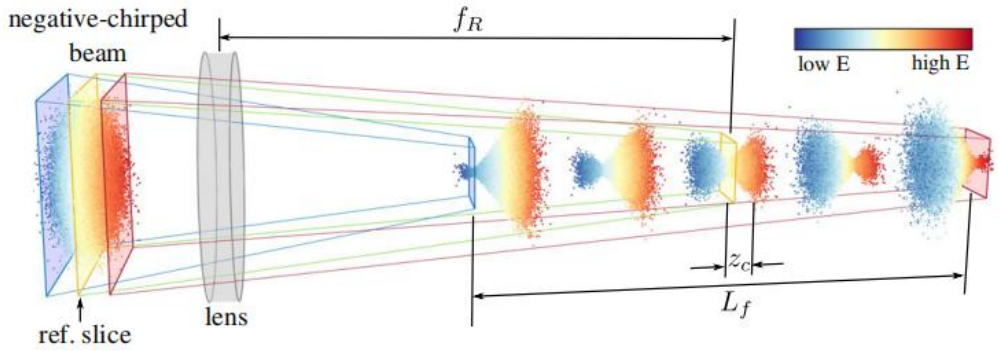
- Introduction and motivation
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Flying-Focus electron beam

A flying-focus electron beam controls wake phase velocity to match muon velocity

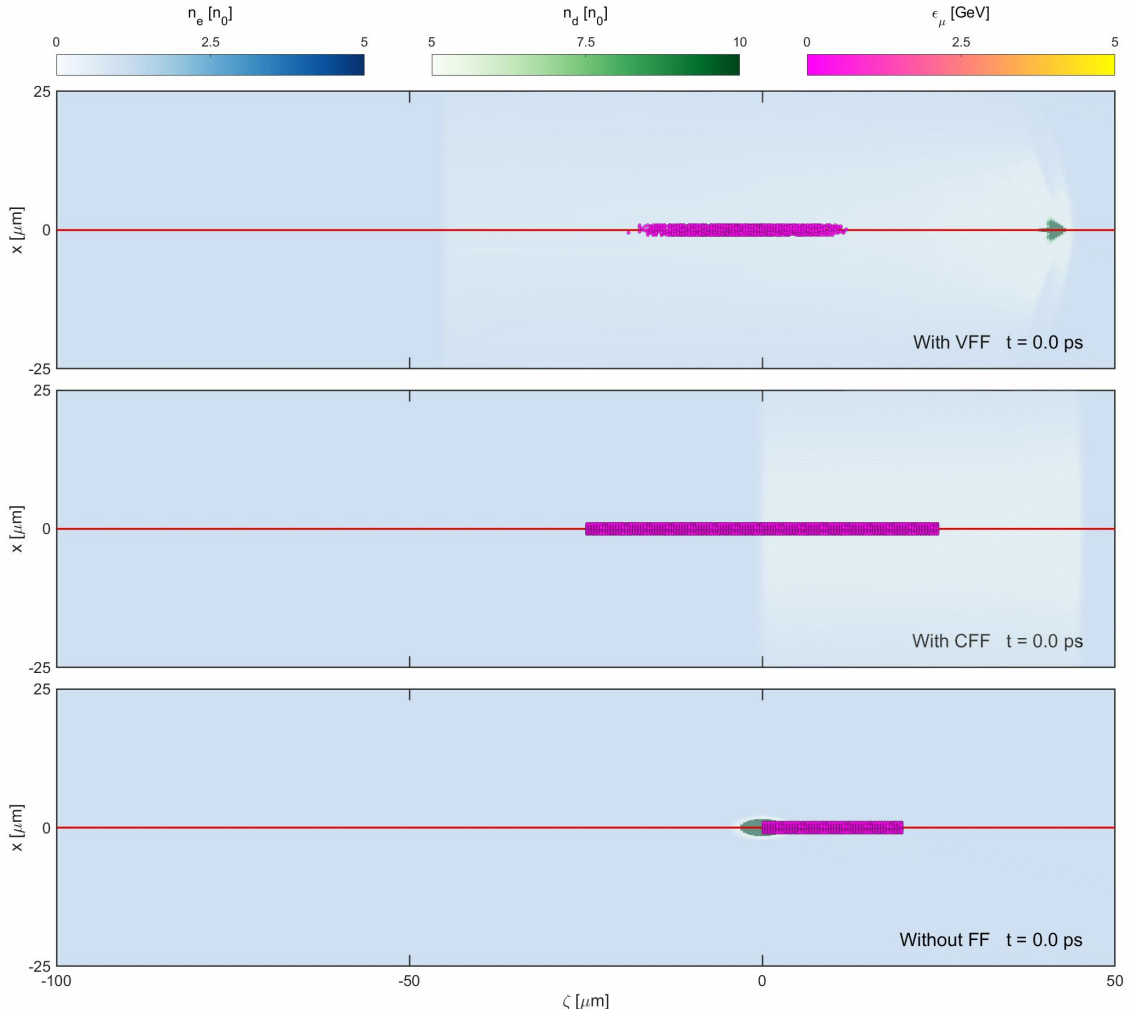


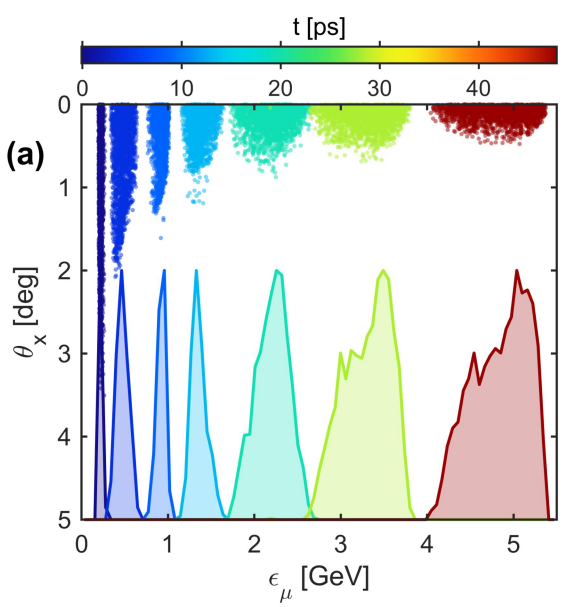
Nat Commun 6, 8723 (2015)

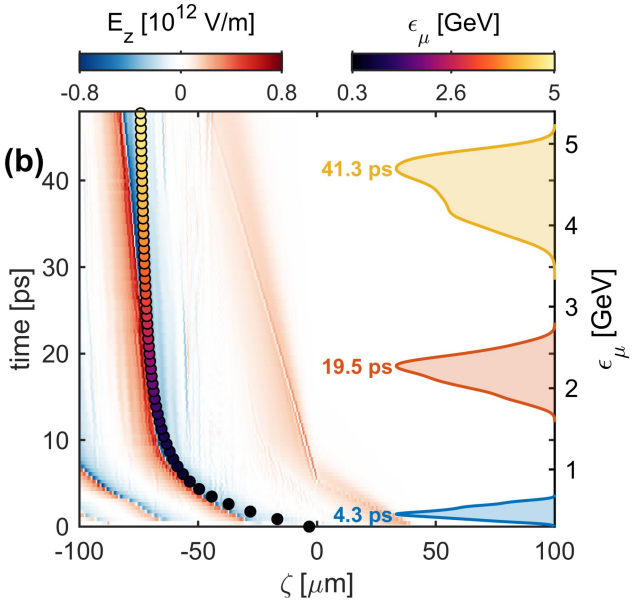


PRL 128, 174803 (2022)

3D PIC simulation results







Heavy-ion-driven plasma acceleration

HIAF: High Intensity Heavy-ion Accelerator Facility



HIAF束流性能工艺测试	
$^{18}O^{6+}$	2.5×10^{11}
$^{209}Bi^{31+}$	3.166×10^{10}
均打破国际流强记录	

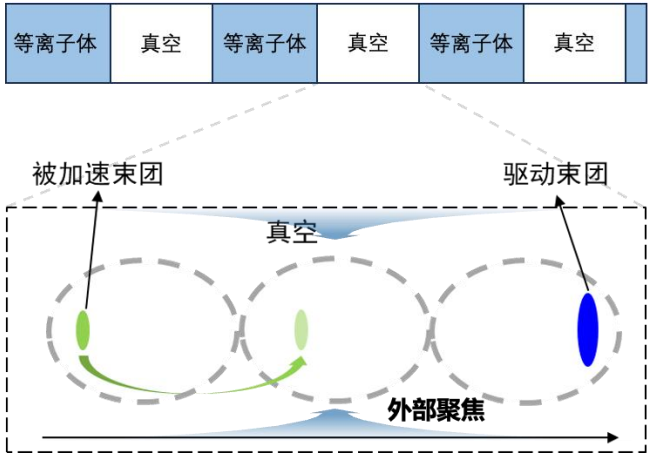
Why heavy-ion drivers?

High kinetic energy **High magnetic rigidity** **High charge density**

Phys. Plasmas 33, 033102 (2026)

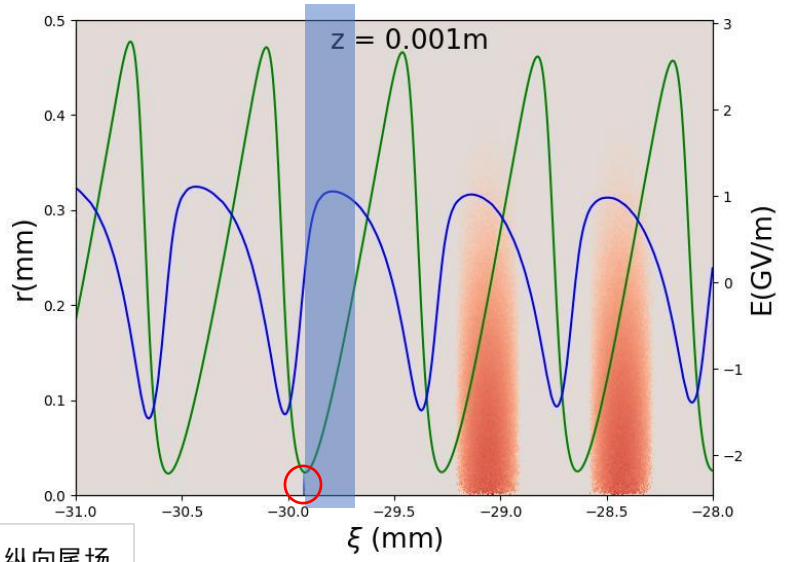
Plasma Phys. Control. Fusion 68 045010 (2026)

Drift-like Phase-shift Scheme

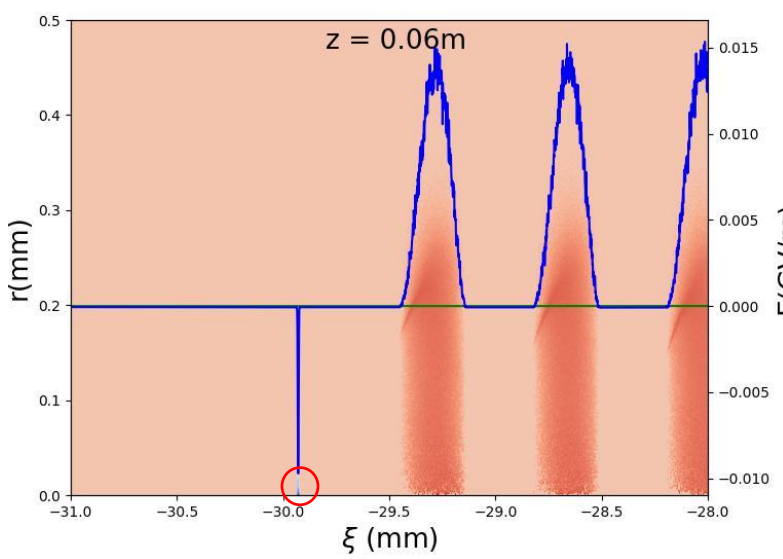


arXiv:2609.18517

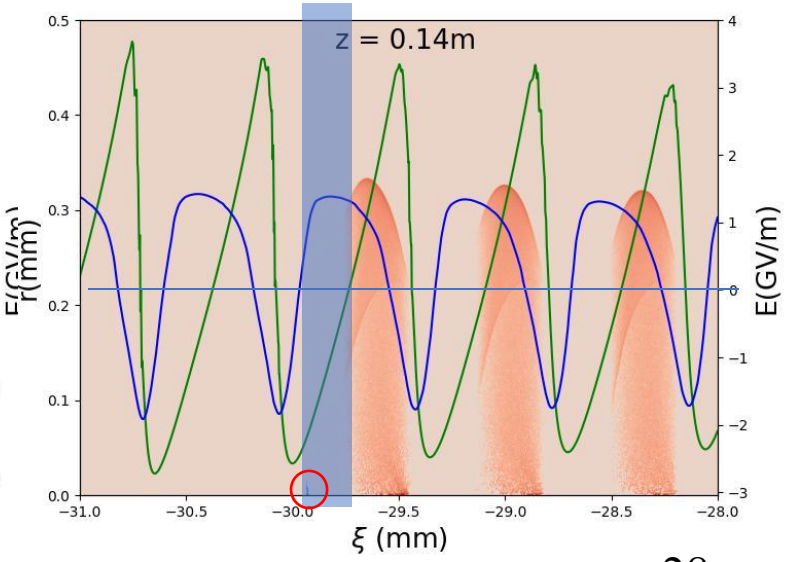
- Controlled phase slippage in vacuum gaps
- External focusing for transverse confinement
- Wakefield re-excitation in successive plasma sections



Initial phase

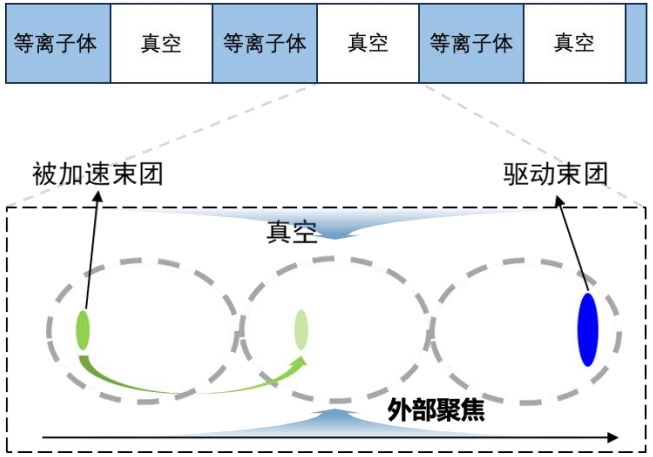


After 6 cm



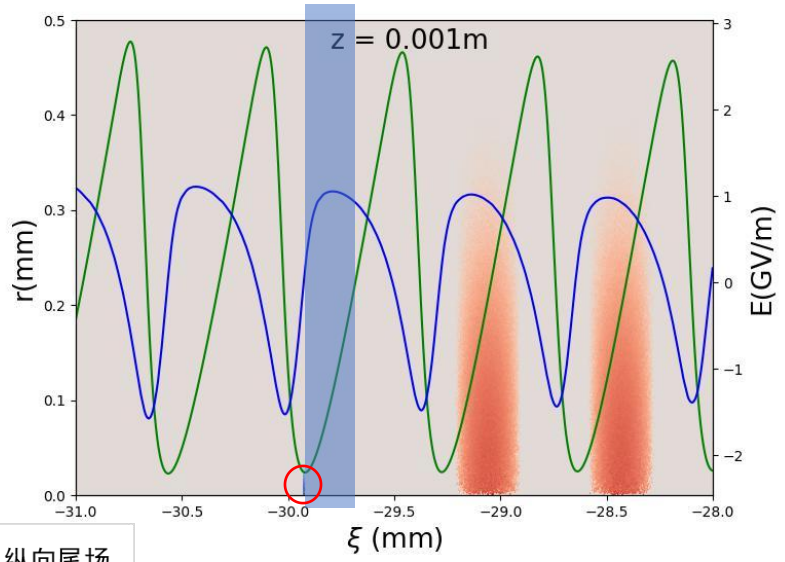
After 14 cm

Drift-like Phase-shift Scheme

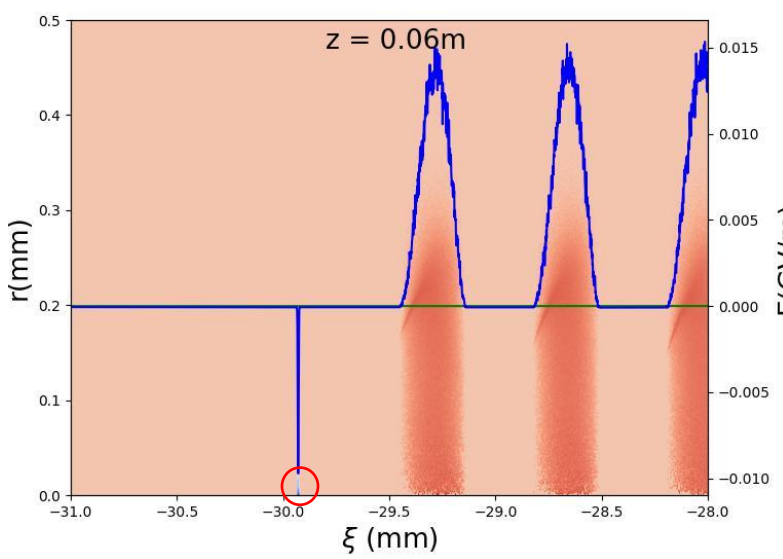


arXiv:2609.18517

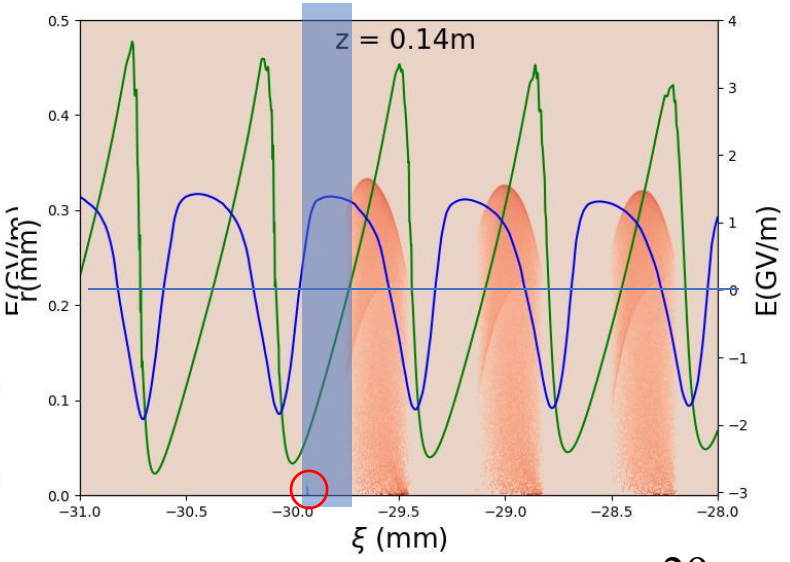
- Controlled phase slippage in vacuum gaps
- External focusing for transverse confinement
- Wakefield re-excitation in successive plasma sections



Initial phase



After 6 cm



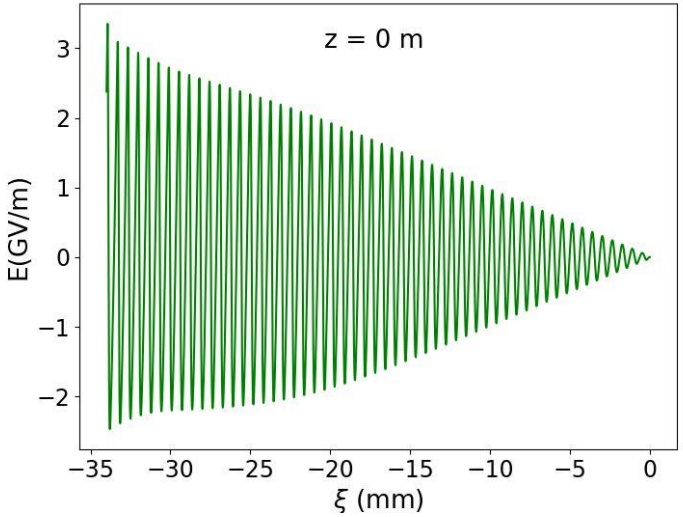
After 14 cm

Drift-like Phase-shift Scheme

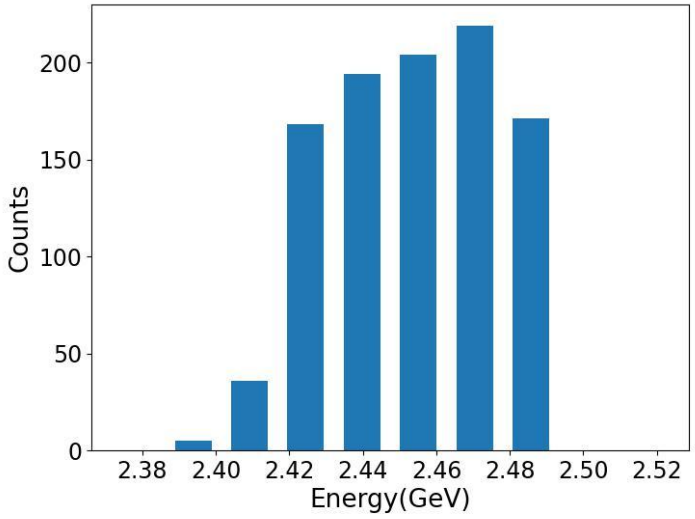
Driver: 209Bi83+, 9.58 GeV/u, 1×10^11

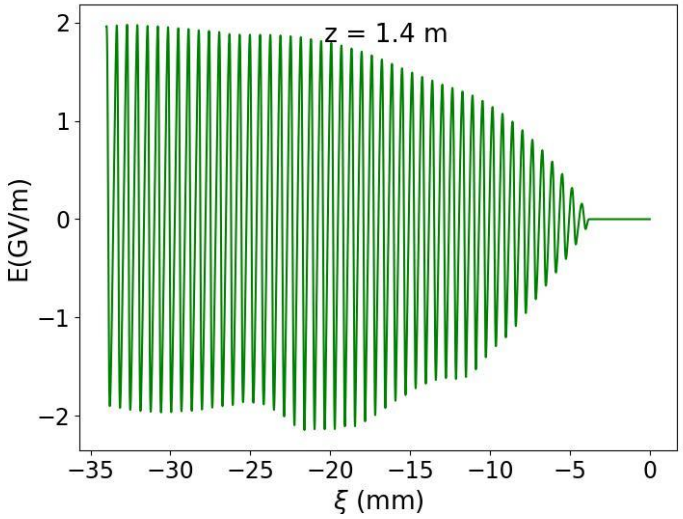
Stage I — Density Up-Ramp
0.85 → 1.97 GeV (0.6 m)
Stage II —Drift-like phase-shift
1.97 → 2.50 GeV (1.4 m)

Effective gradient: ~0.83 GV/m
Final energy spread: ~0.6%



Wakefield Evolution





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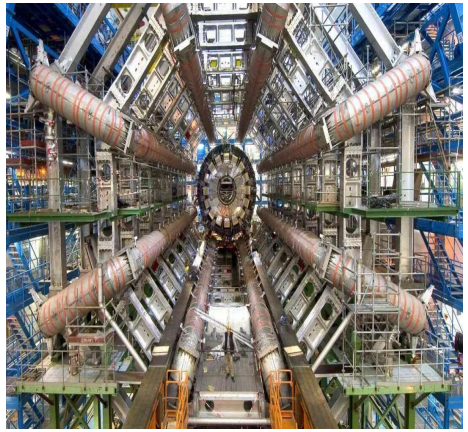
Huairou Science City— National Innovation Center

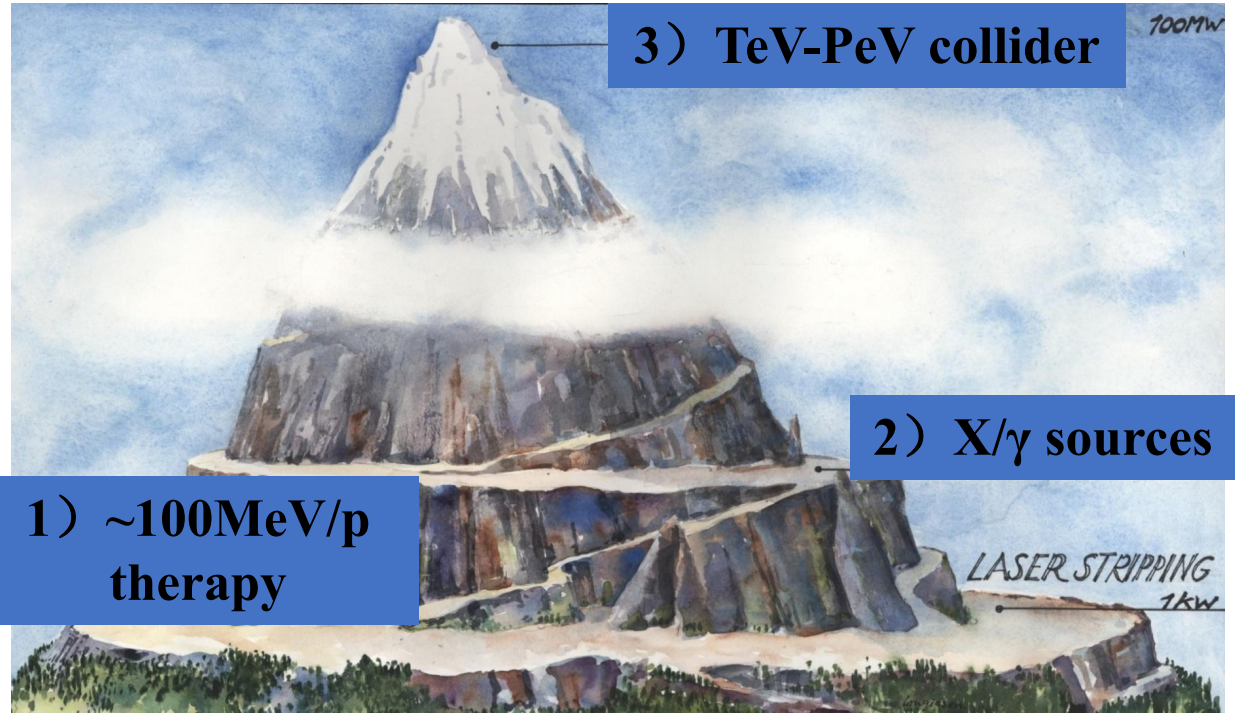




Applications in the future

laser accelerator: 1）ion acceleration; 2) X/γ source;3)TeV collider

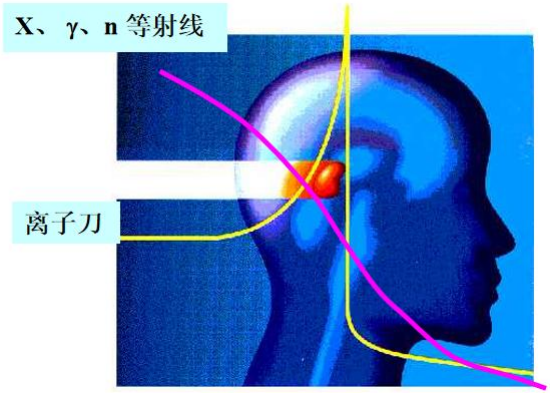




→Avg power

→Rep rate

↗Duration



ICFA+ICUIL joint workshop

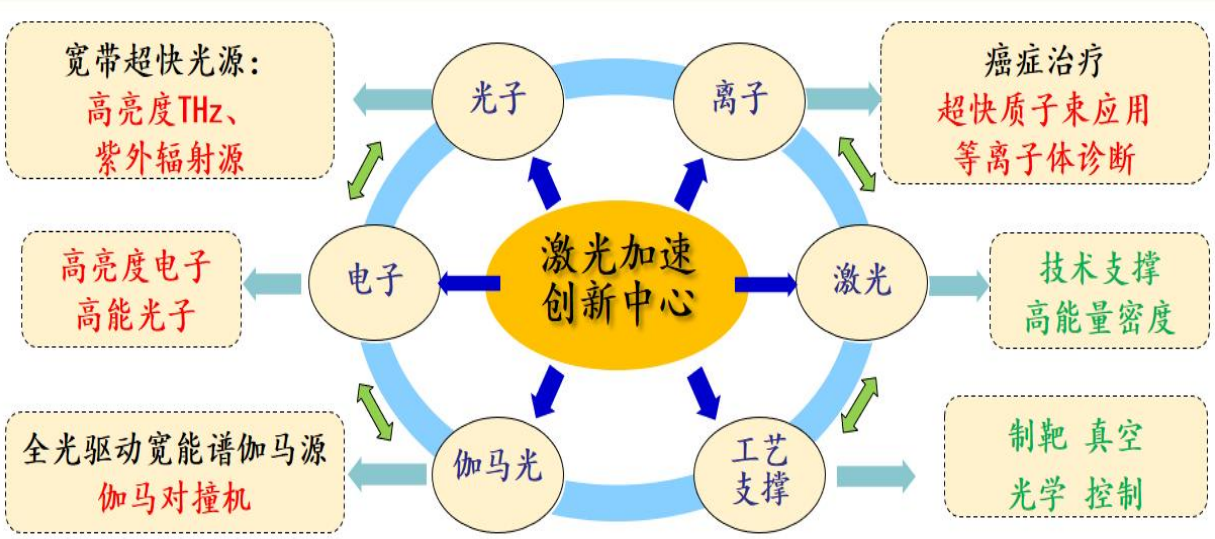
Beijing Laser Acceleration Innovation Center

The advanced laser accelerator research and application research platform:

1) Mechanism for laser immuno-radiotherapy

2) Laser driven ultrafast particle beam (muon, isotope...)







2022年12月入驻，2023年验收

First laser proton hospital in the world

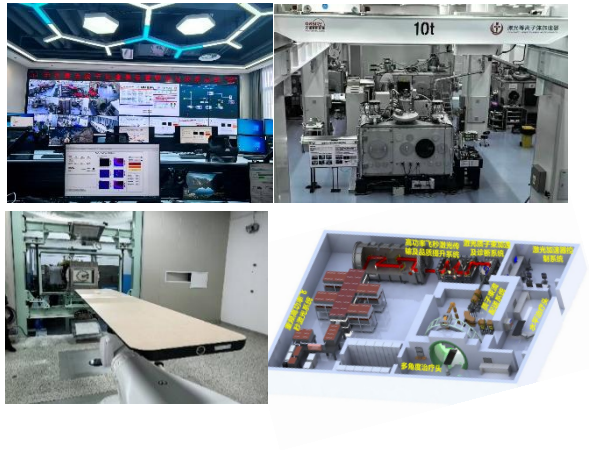
Both proton energy/density and stability issues were simultaneously solved, paving the way for the human tumor treatment study using the Hua Tuo 1 laser proton knife in 2026.







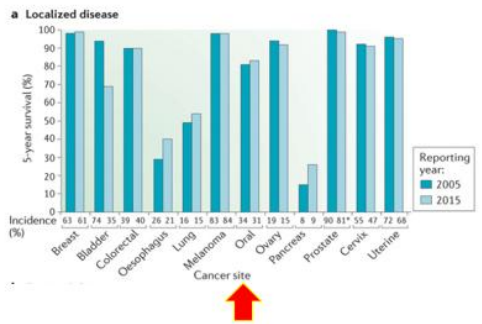
laser proton hospital



The first laser proton hospital in the world!

Prospects for Laser Accelerator Immunotherapy

localized tumor therapy

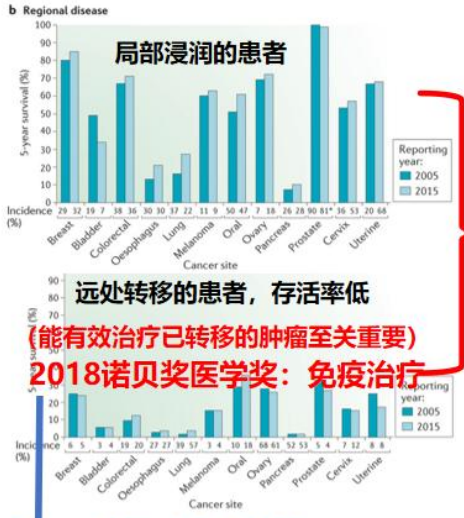


~10%

未浸润转移的局部肿瘤患者<10%，存活率高

（早期诊断至关重要）

2005~2015年美国
肿瘤患者5年生存率



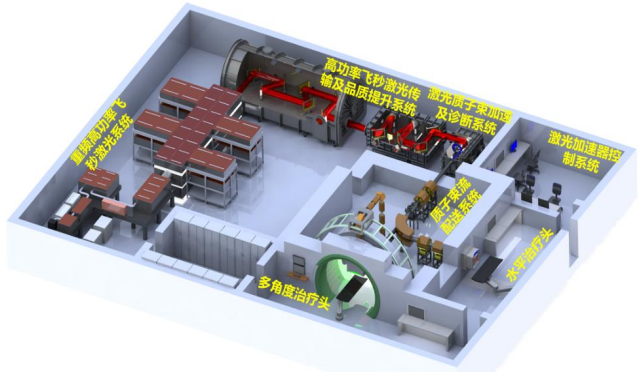
>90%

Nature Reviews Cancer 16(4): 201-8, 2016



激光加速器+免疫 ===免疫放疗 （2018）？

diffuse tumor



immuno-radiotherapy

Mourou&Tajima Institute

A Laser Acceleration Research Center

100 faculty members

10-15 faculty openings on ultrafast light-matter interaction



Prof. Gerard Mourou took chair professor position in M-Center, Jan. 2024





Conclusion

- **Low-energy muon capture:** Plasma traveling wave acceleration enable phase-stable capture and acceleration of low-energy surface muons in density-tailored plasmas.

- **Flying-focus acceleration:** Electron-beam flying focus provides tunable wakefield phase velocities and phase-matched muon acceleration to GeV energies.

- **Heavy-ion-driven acceleration:** Drift-like phase-shift scheme mitigate dephasing and extend the acceleration length, enabling muon acceleration to multi GeV energies.

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- 原子能院：王乃彦、郭冰
- **585**所：许敏
- 湖南大学：余金清

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~~~~~~thanks for your attention
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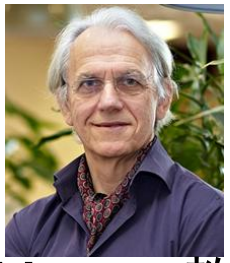
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Thanks for your attention!