



北京大学
PEKING UNIVERSITY

Plasma-Based Muon Capture and GeV-Scale Acceleration

Xueqing Yan, Jiangdong Li, Xuezhi Wu, Liqi Han, Kejing Han, Xinlu Xu

Peking University
Mourou-Tajima Institute

2026.10.23-26



Outline



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



Laser Electron Accelerator

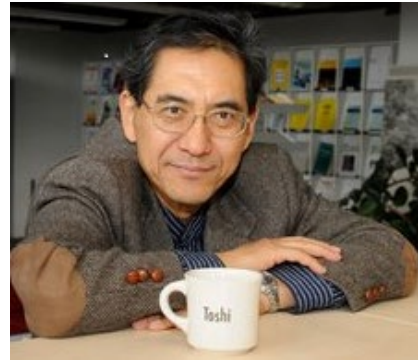


1979年, Tajima and Dawson首先提出LPA.

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

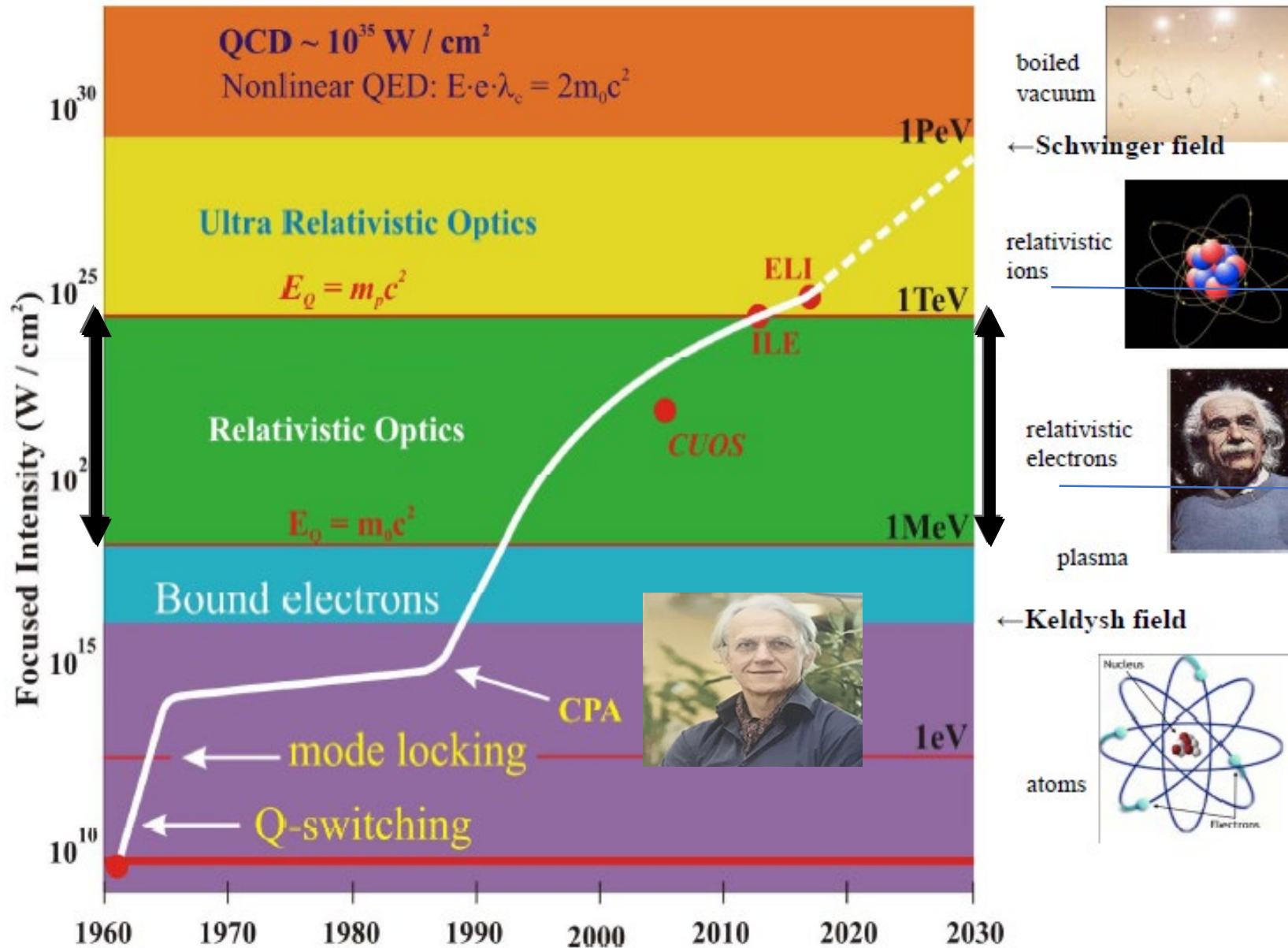
Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

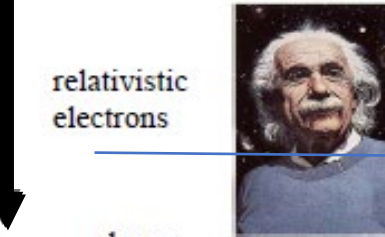
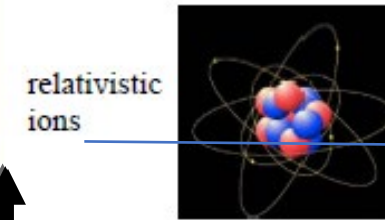
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18}cm^{-3} can yield 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

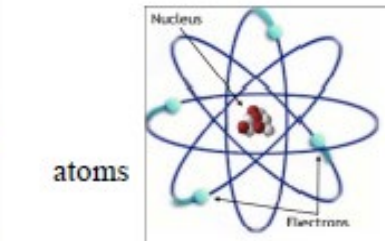


← Schwinger field



plasma

← Keldysh field



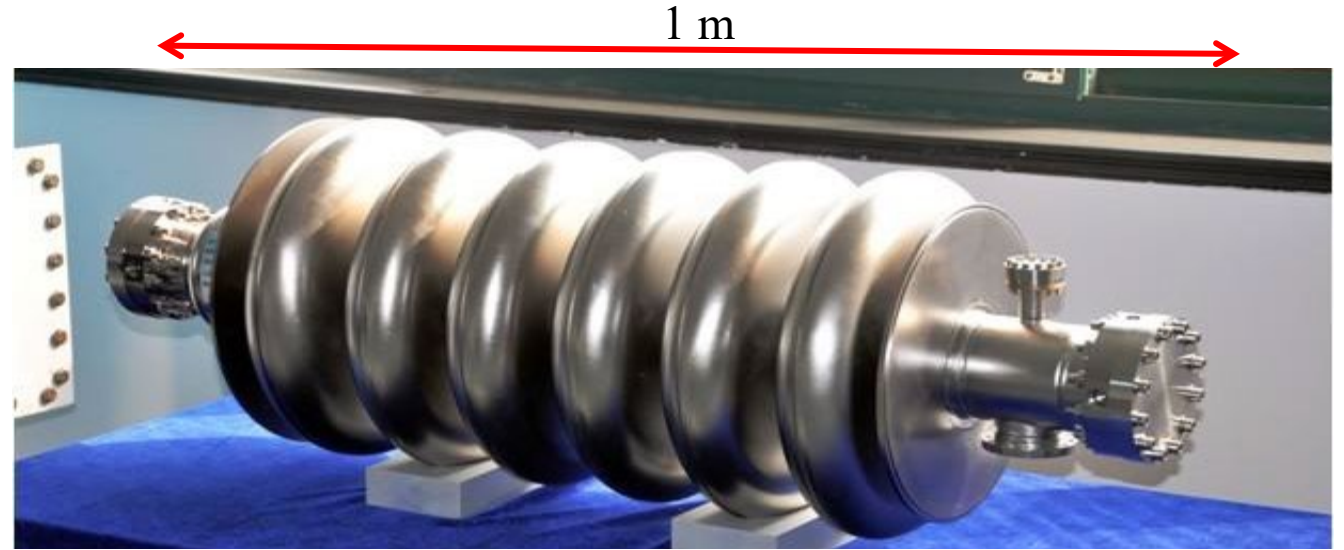
laser
plasma
accelerator



1000 times smaller, and fast!

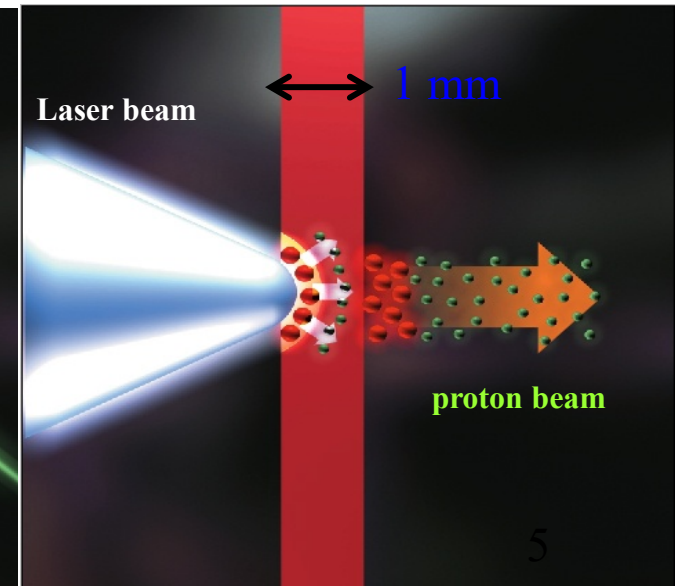
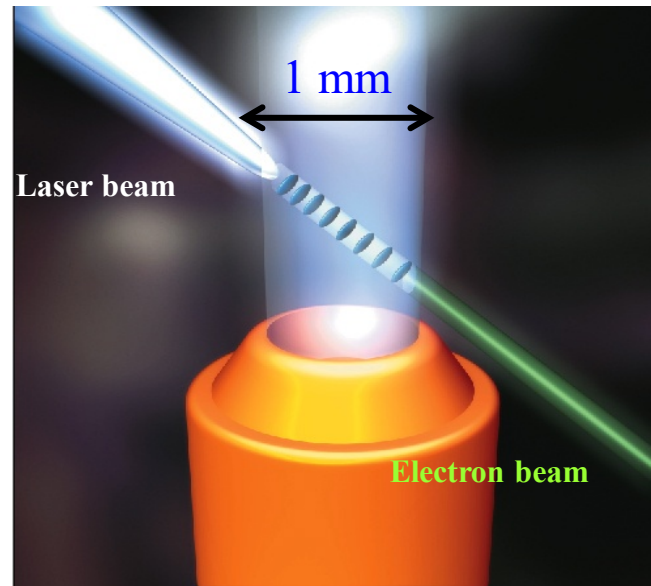


RF accelerator
 $E = < 100 \text{ MV/m}$



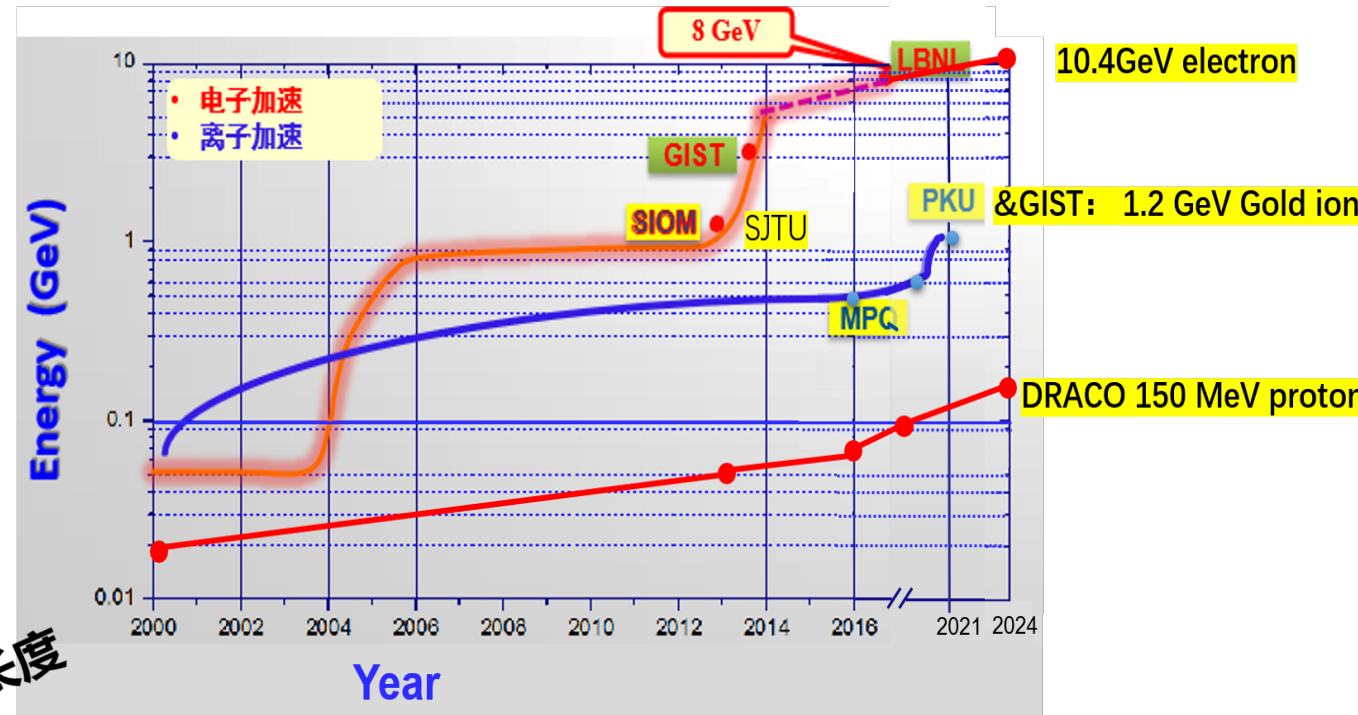
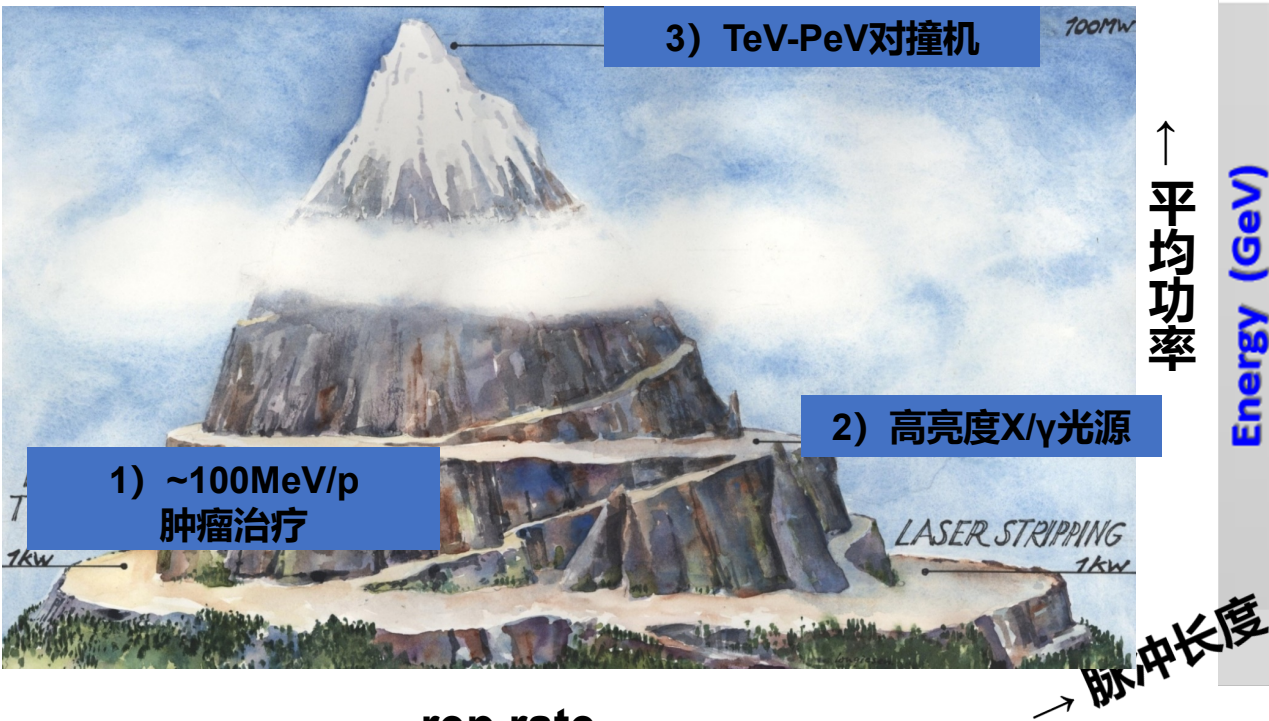
laser plasma accelerator
 $E > 100 \text{ GV/m}$

1000 times smaller!



Laser Plasma Acceleration and Applications

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



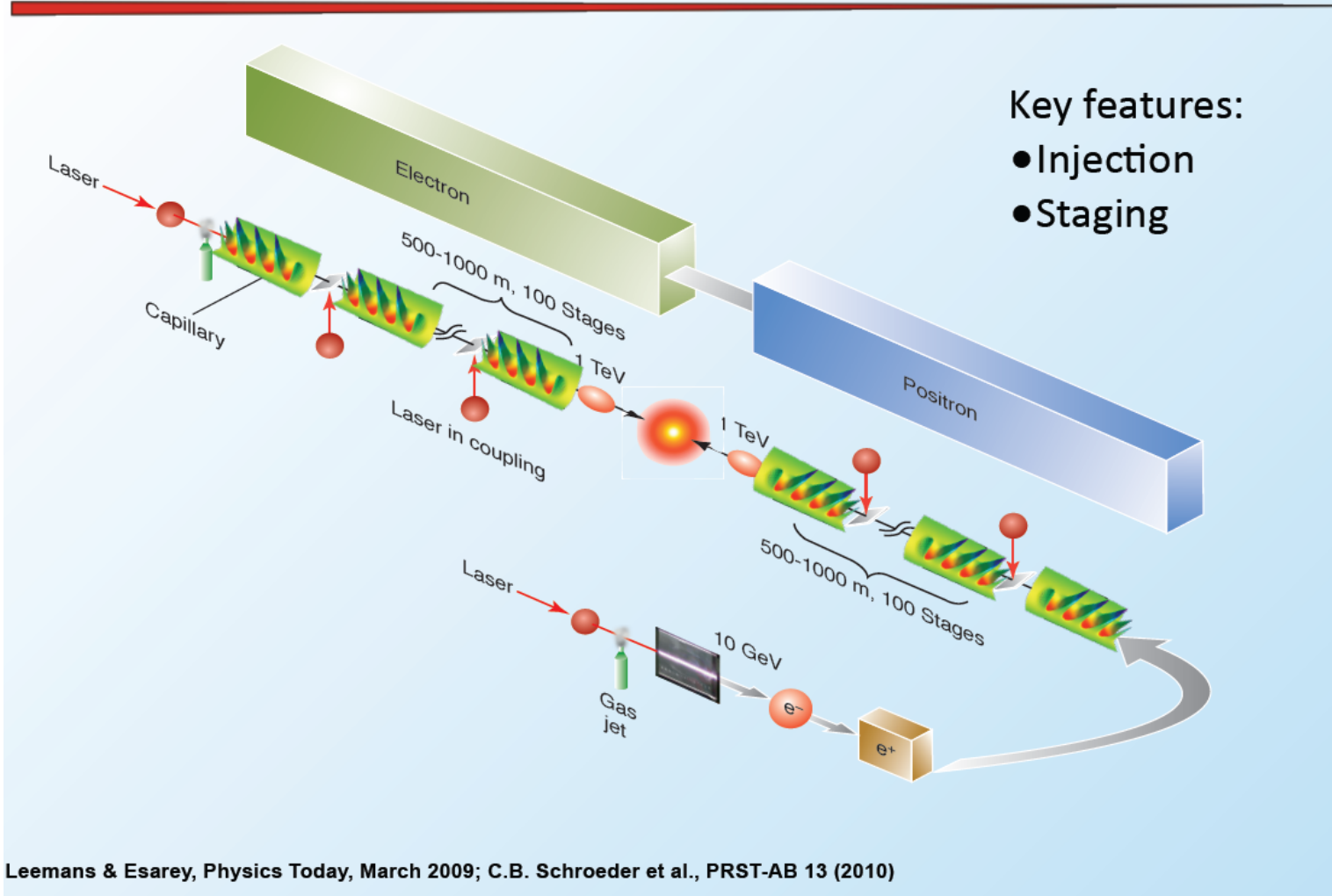
Matter and Radiation at Extremes, 2024, 9(1).
Nature Physics 20, 1211-1216 (2024)
Wang, Phys. Rev. X 11, 021049 (2021);



TeV electron collider by laser accelerator?



Laser Plasma Accelerator Explored For Linear Colliders: Follow Paradigm Of Conventional Accelerators To Increase Beam Energy And Quality

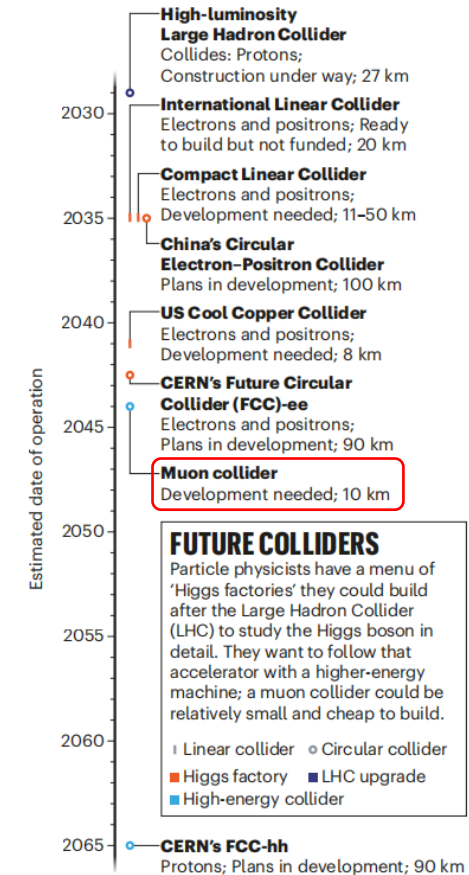




Build the world' first muon collider ?



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



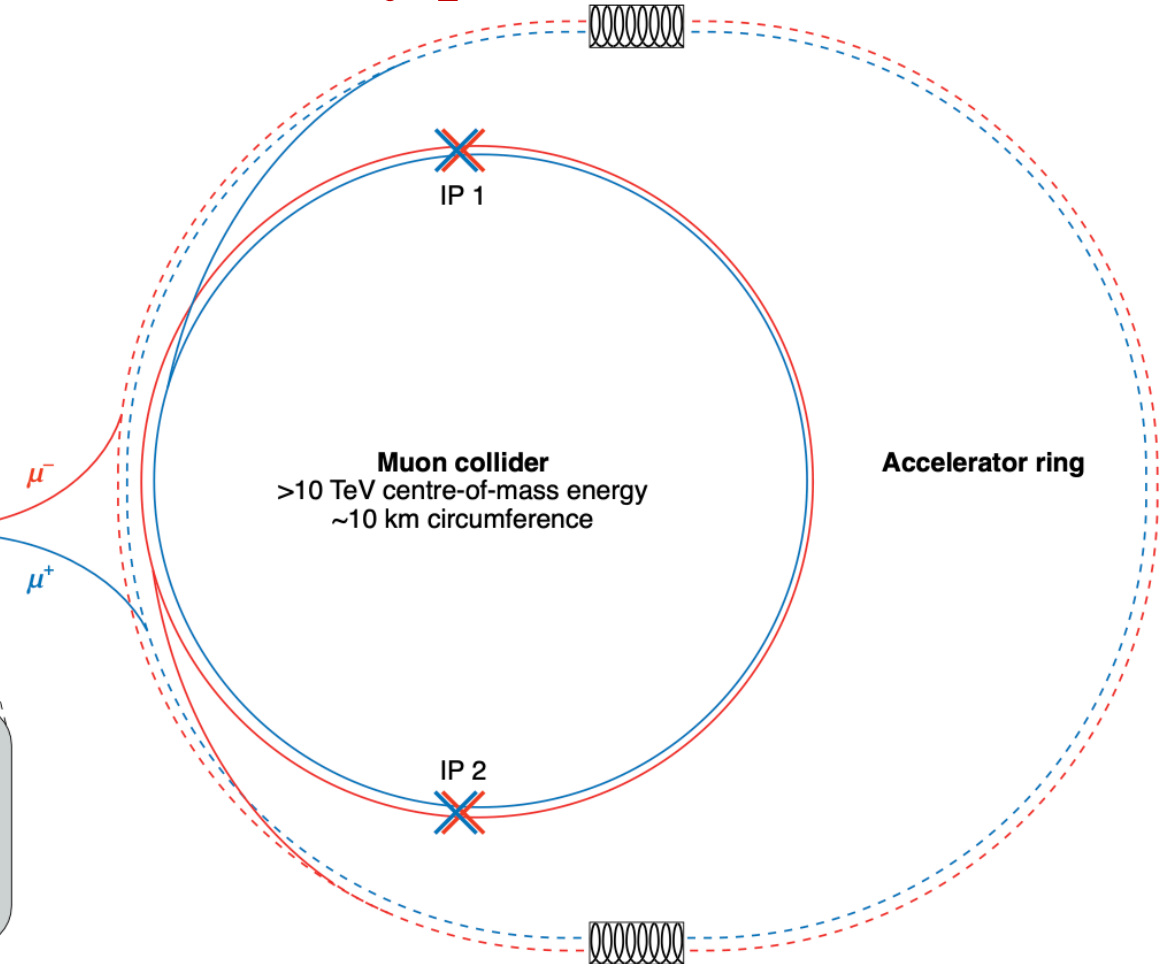
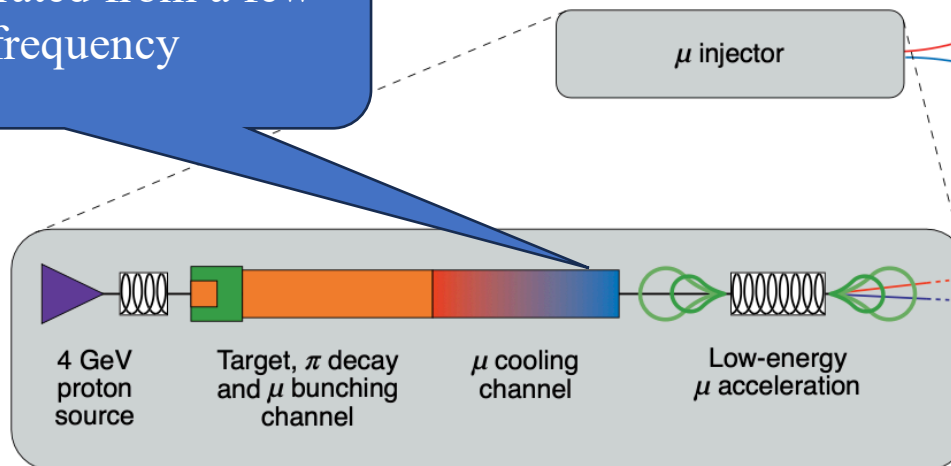


Energy-efficient choice



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

After the cooling process, decay muons are accelerated from a few MeV with radio-frequency accelerators





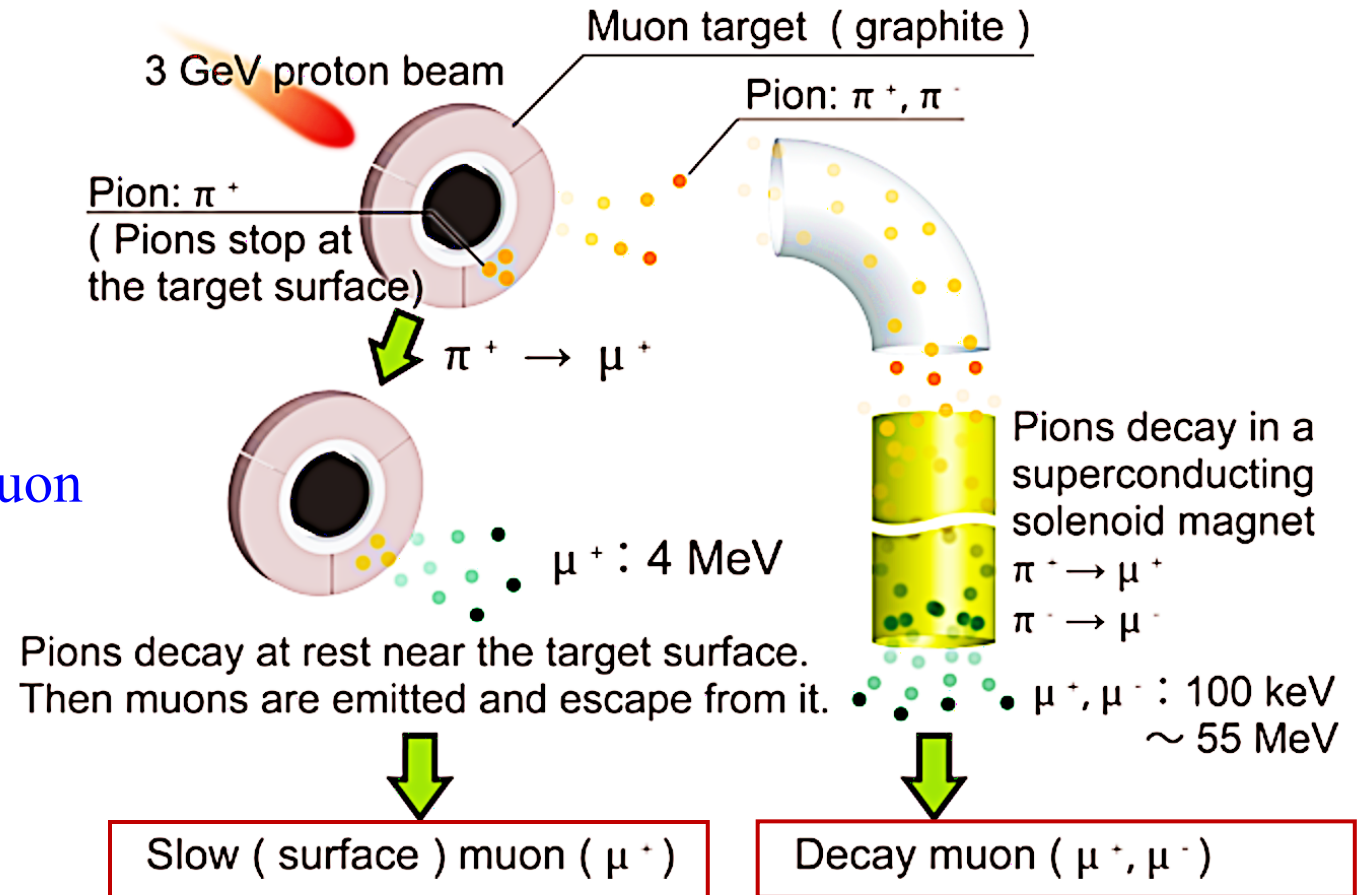
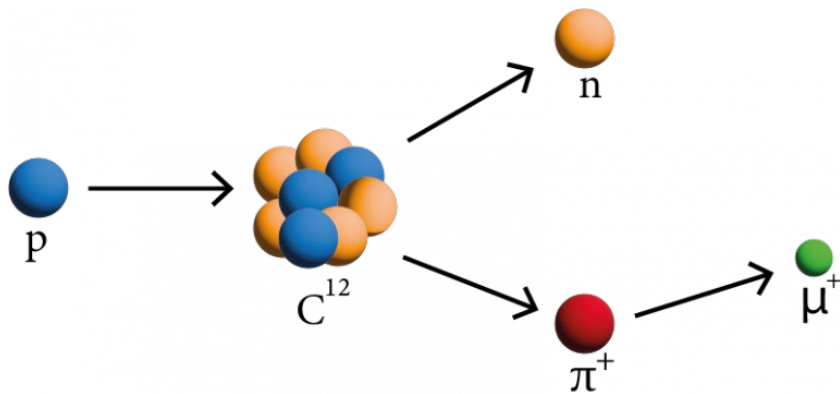
Challenges of muon collider:

1. Short lifetime: $2.2\mu\text{s}$, 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

... ..

Muon ($\mu^\pm$)

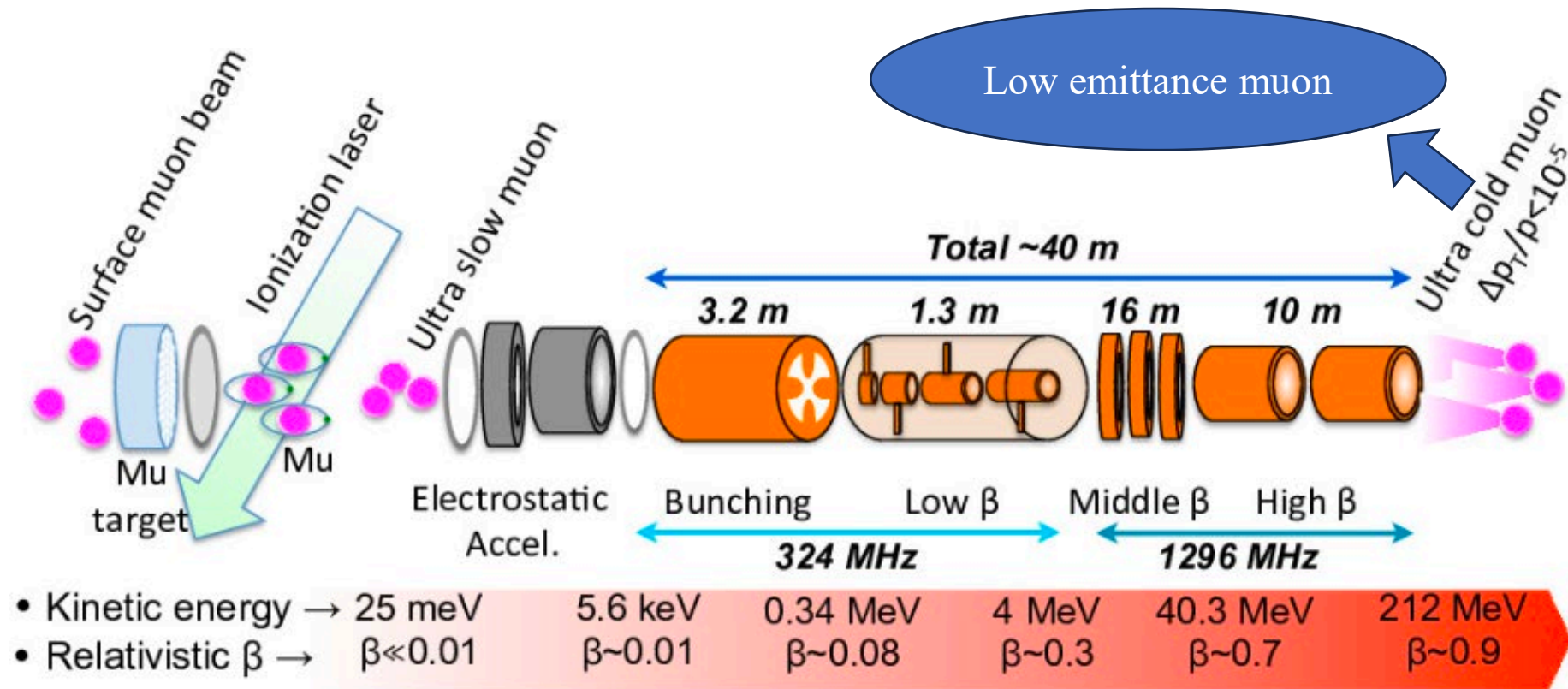
- A short lifetime at rest, $2.2 \mu s$
- Mass: $\sim 207 m_e$
- Two types: surface muon & decay muon



Surface muon (μ^+) to 200MeV

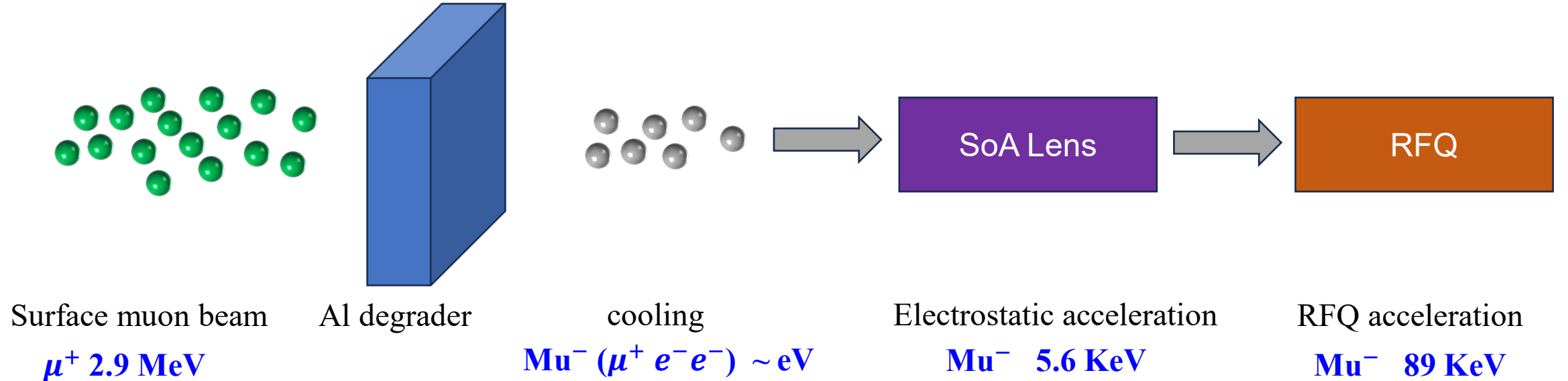
Muon anomalous magnetic moment measurement

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





First RF-based muon acceleration



- 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)

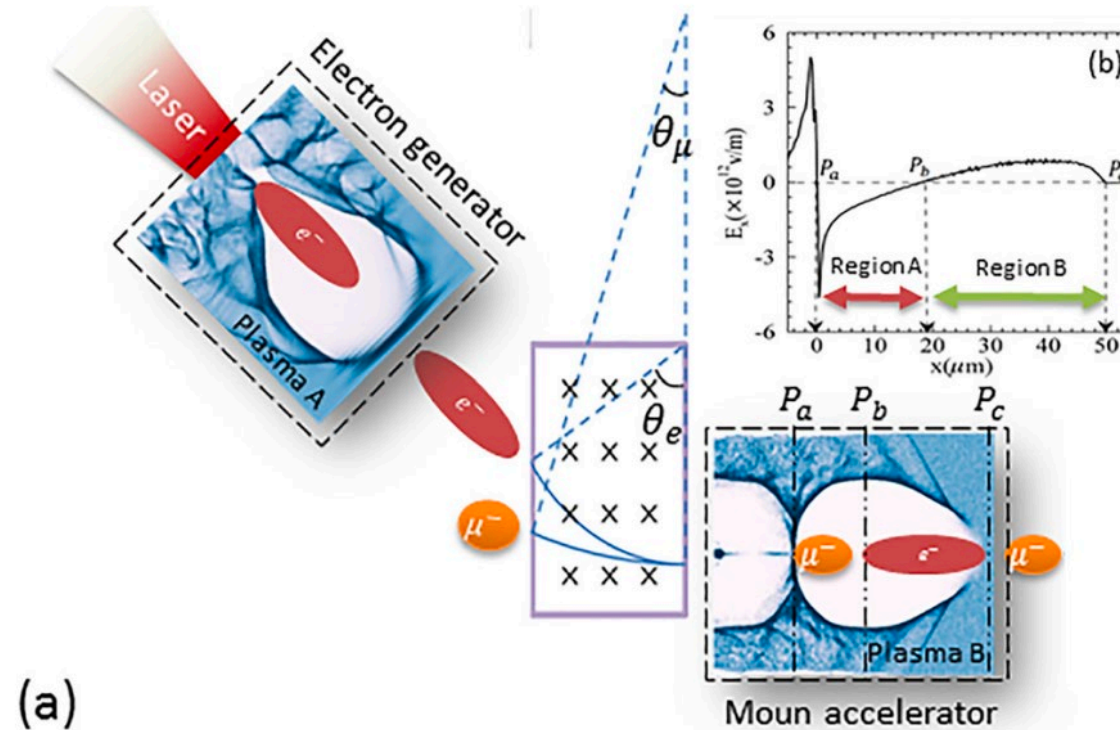


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Acceleration of 200 MeV muon



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

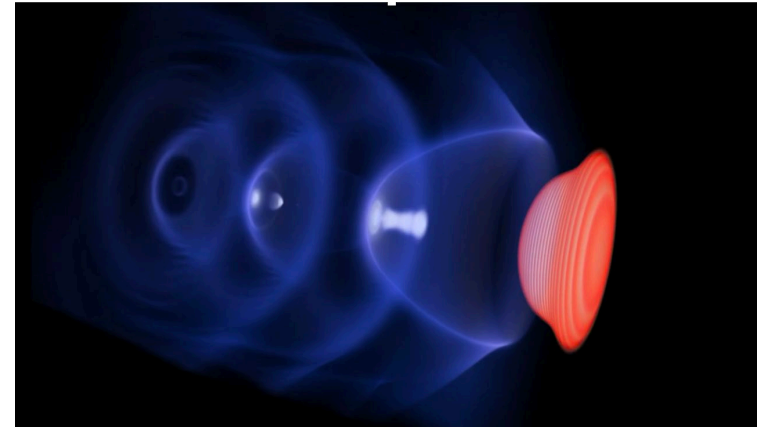
- Initial muon speed close to the light speed (~ 200 MeV or higher)
- Ultrashort duration: 10s fs



How do we capture slow muon?

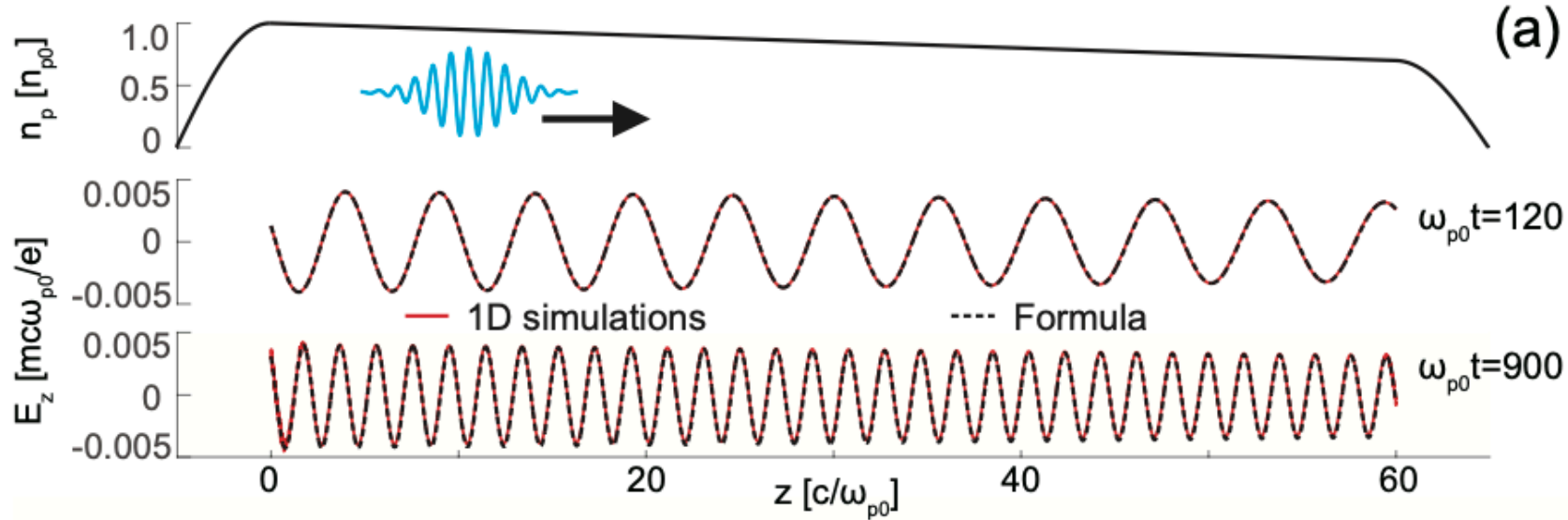


- Train should be decelerated at first, passengers are loaded into the train carriages (bucket)
- The phase velocity of the wake is too high to accelerate low-energy muons (a small fraction of the light speed)
- Slow the wake in the plasma?





Slowdown of the wake by self-evolution



Self-evolution

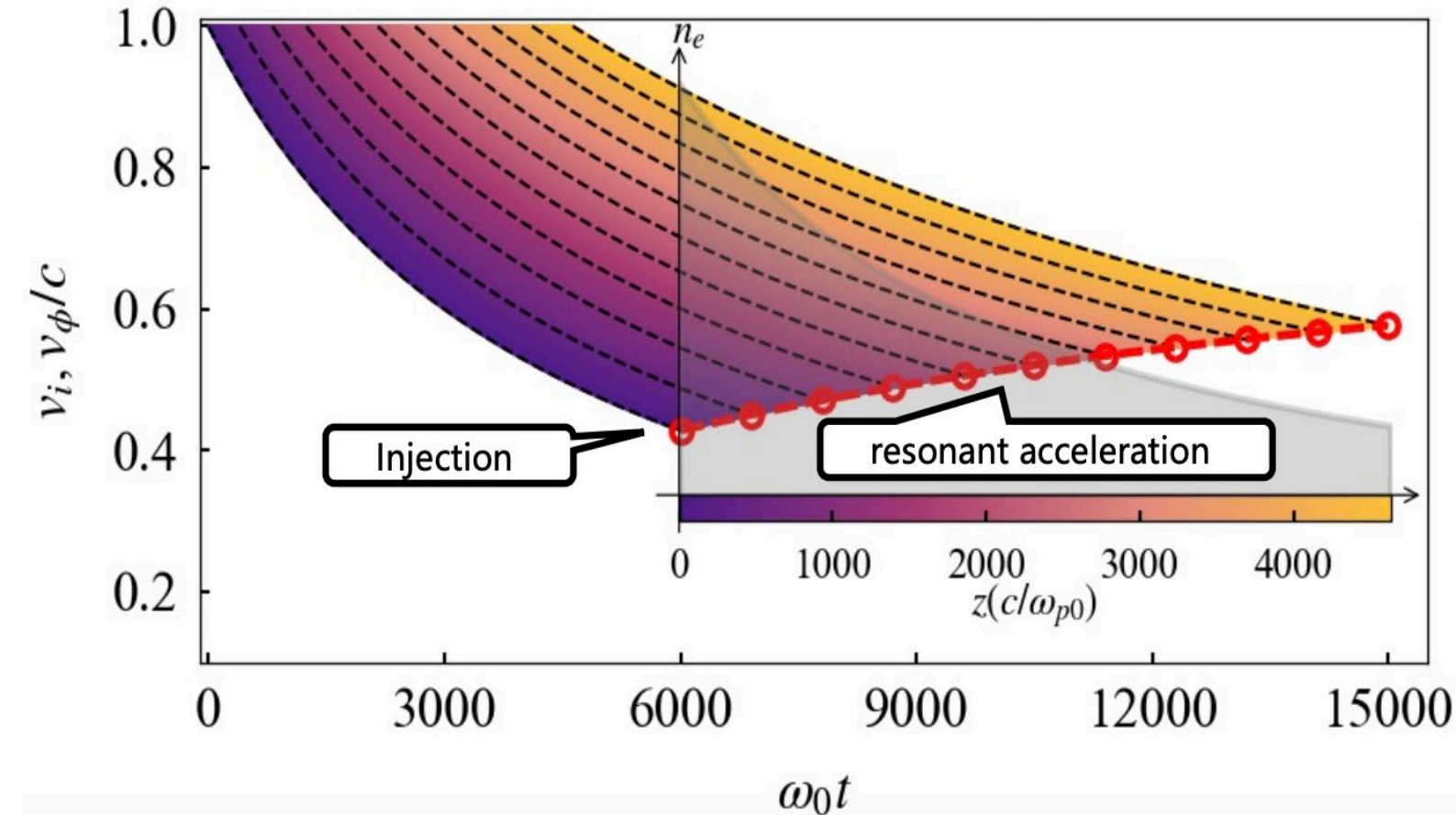
Downramp:

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

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



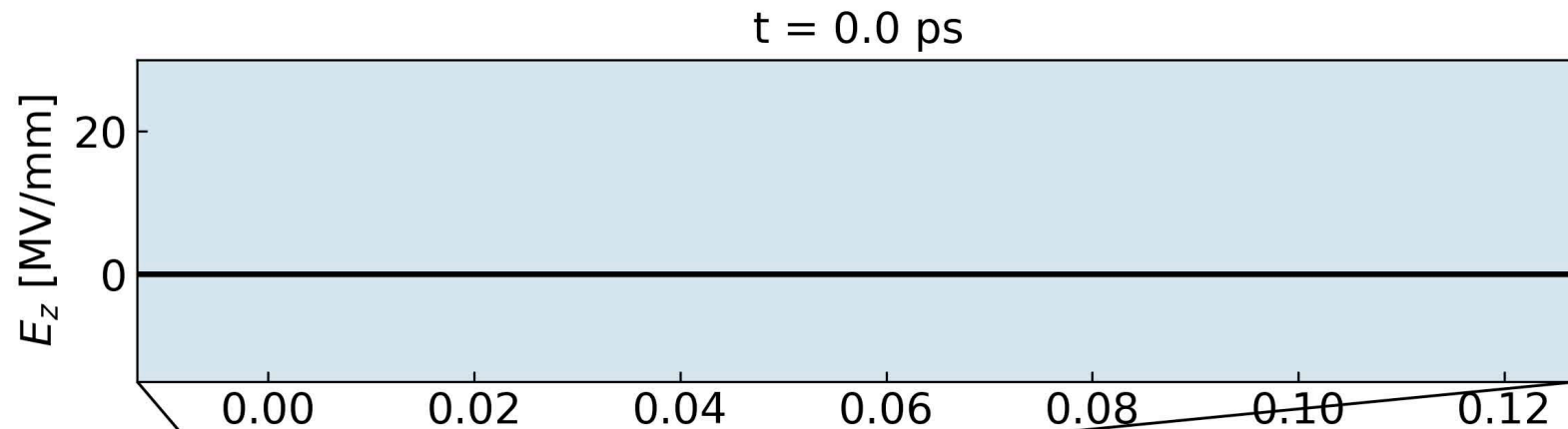
Plasma Traveling Wave Acceleration (PTWA)



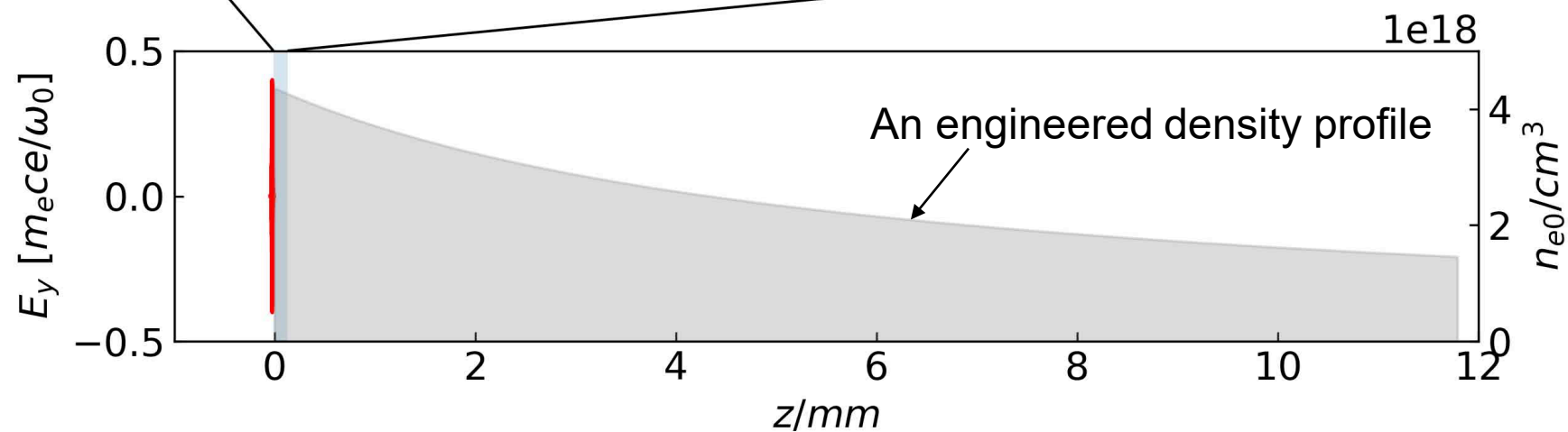
To get accelerated:

- 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)

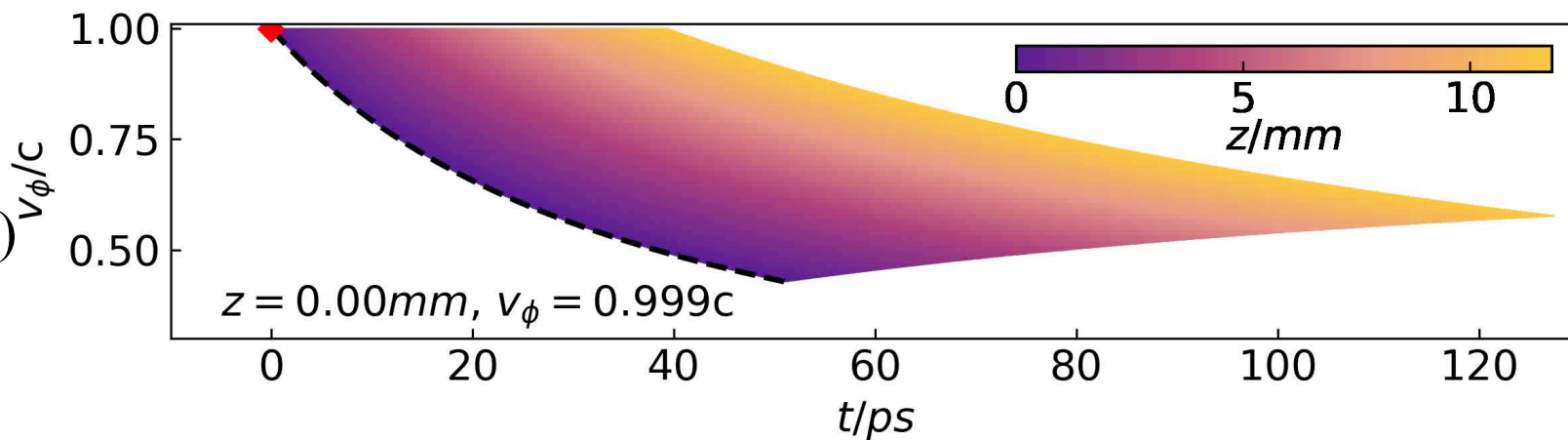
Accelerating field



laser electric field
(red line)

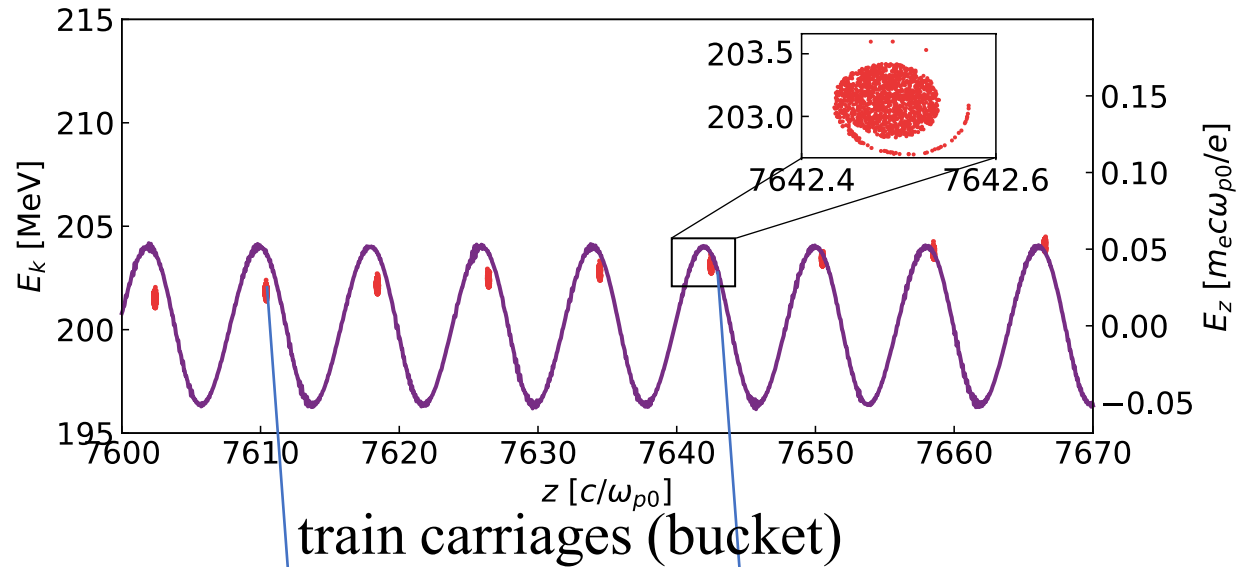


Phase velocity
evolution
(black dashed line)





Muons in buckets from 4 MeV to 200 MeV



Laser

Intensity: $a_0 = 0.4$

Duration: $\tau = 34$ fs

Beam energy 4 MeV

energy spread $\sigma = 1$ MeV

Beam duration 850 fs (could be longer)

injection time $t = 51$ ps

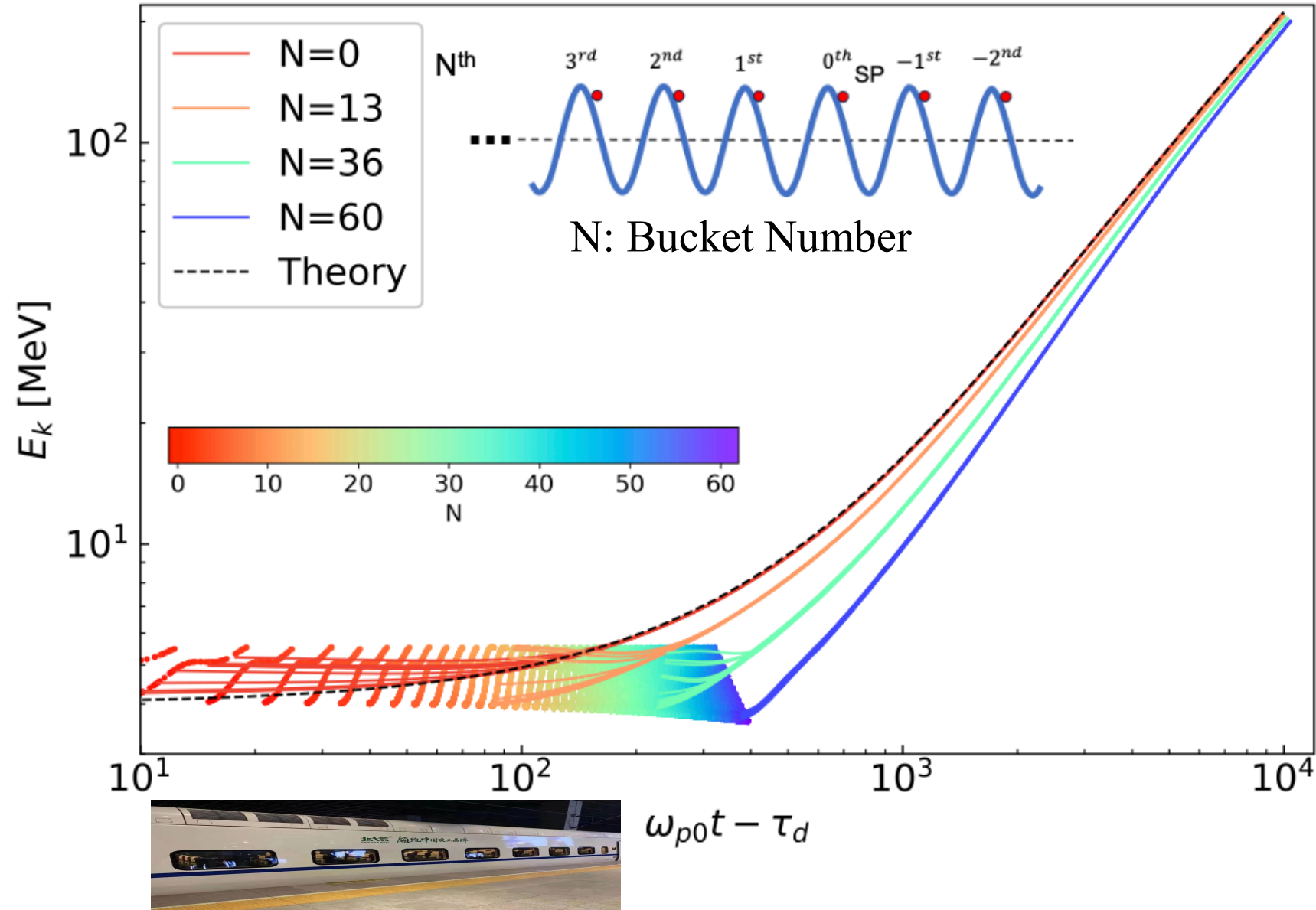
Acceleration gradient: ~ 11 GV/m

Micron beam duration: 100s as $\sim$ a few fs

Micron beam energy spread: $\sim 0.1\%$

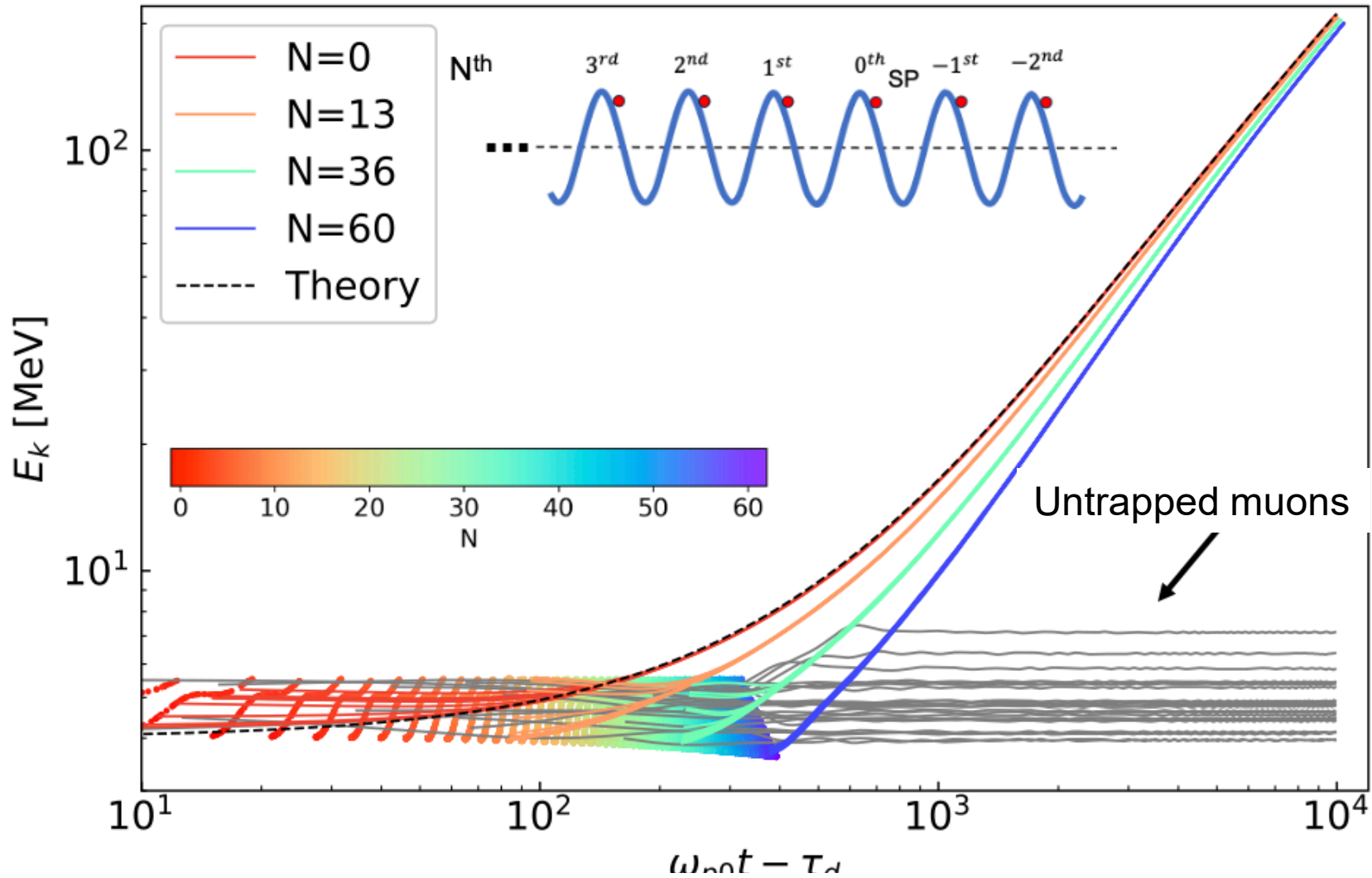


Acceleration in different buckets or carriages





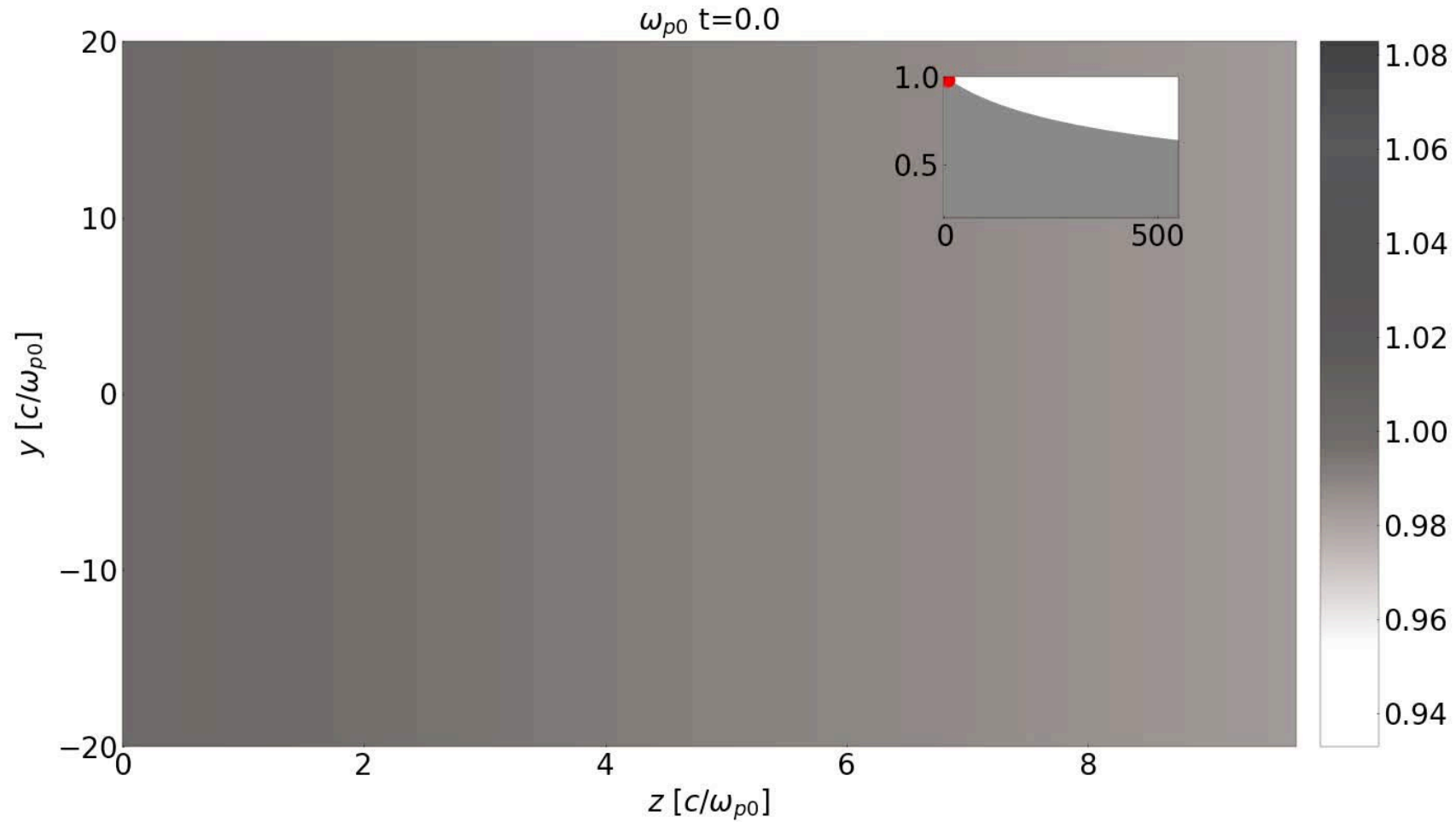
Capture efficiency 0.1%-1% with cooling



Could be improved by choosing a higher acceleration phase



2D PIC simulation



From 4 MeV($\sim 0.2c$) to 20 MeV($\sim 0.5c$)

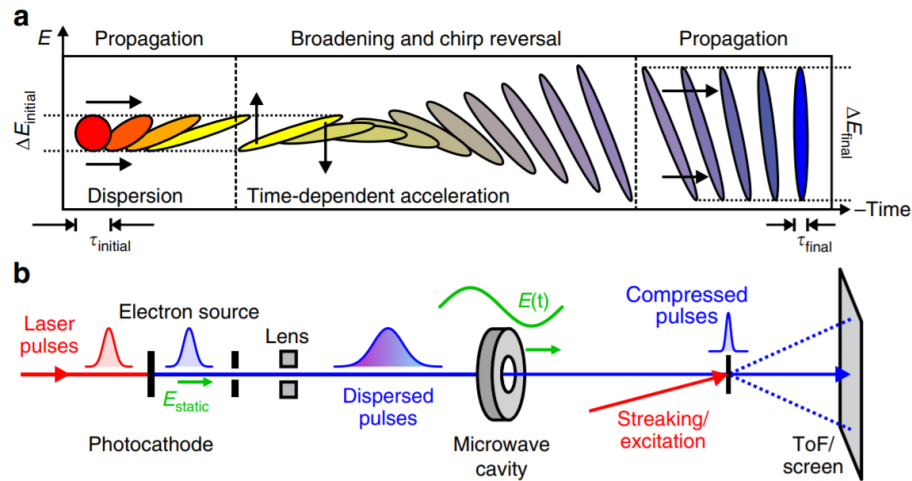


Outline

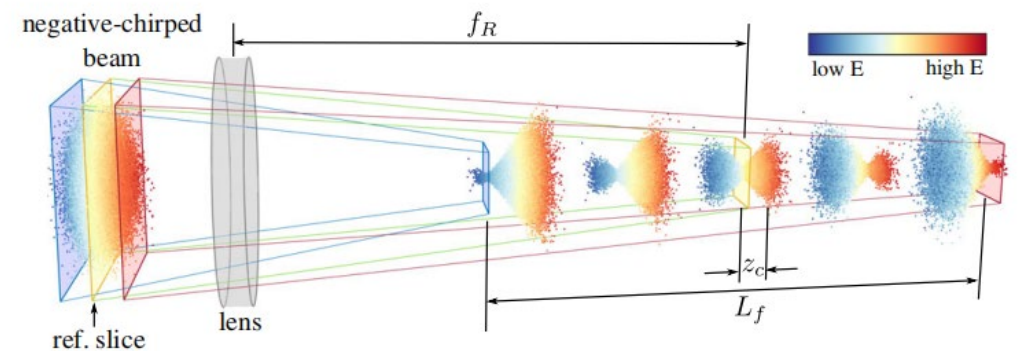
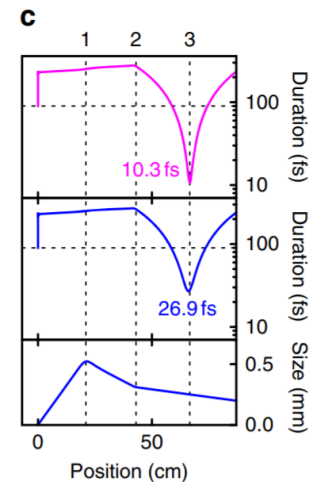


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A flying-focus electron beam controls wake phase velocity to match muon velocity



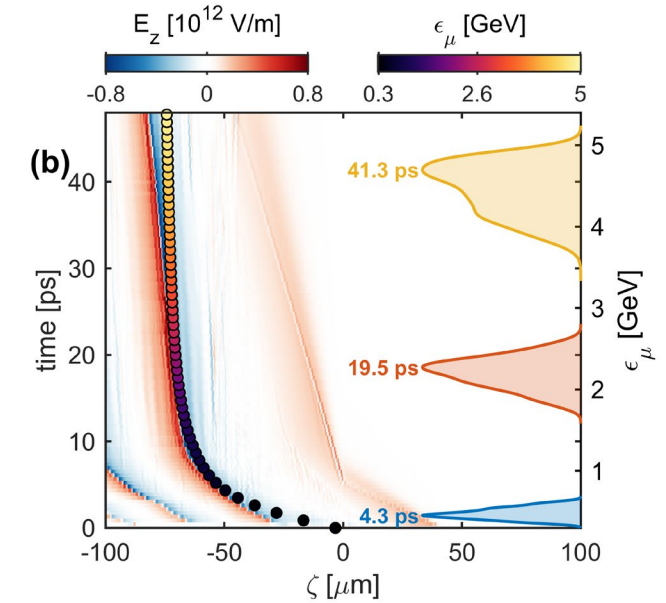
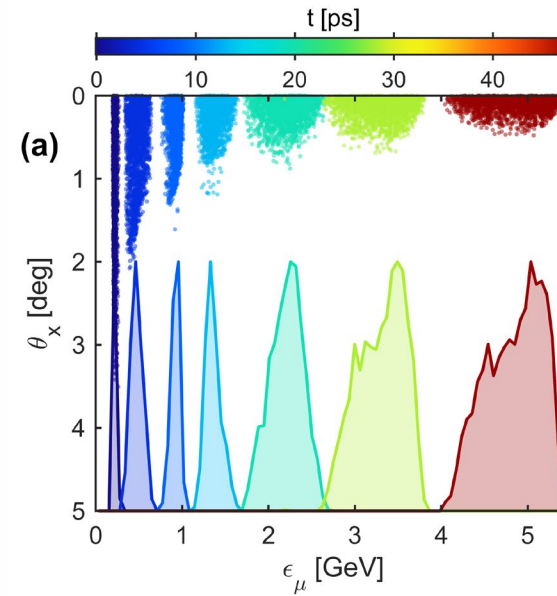
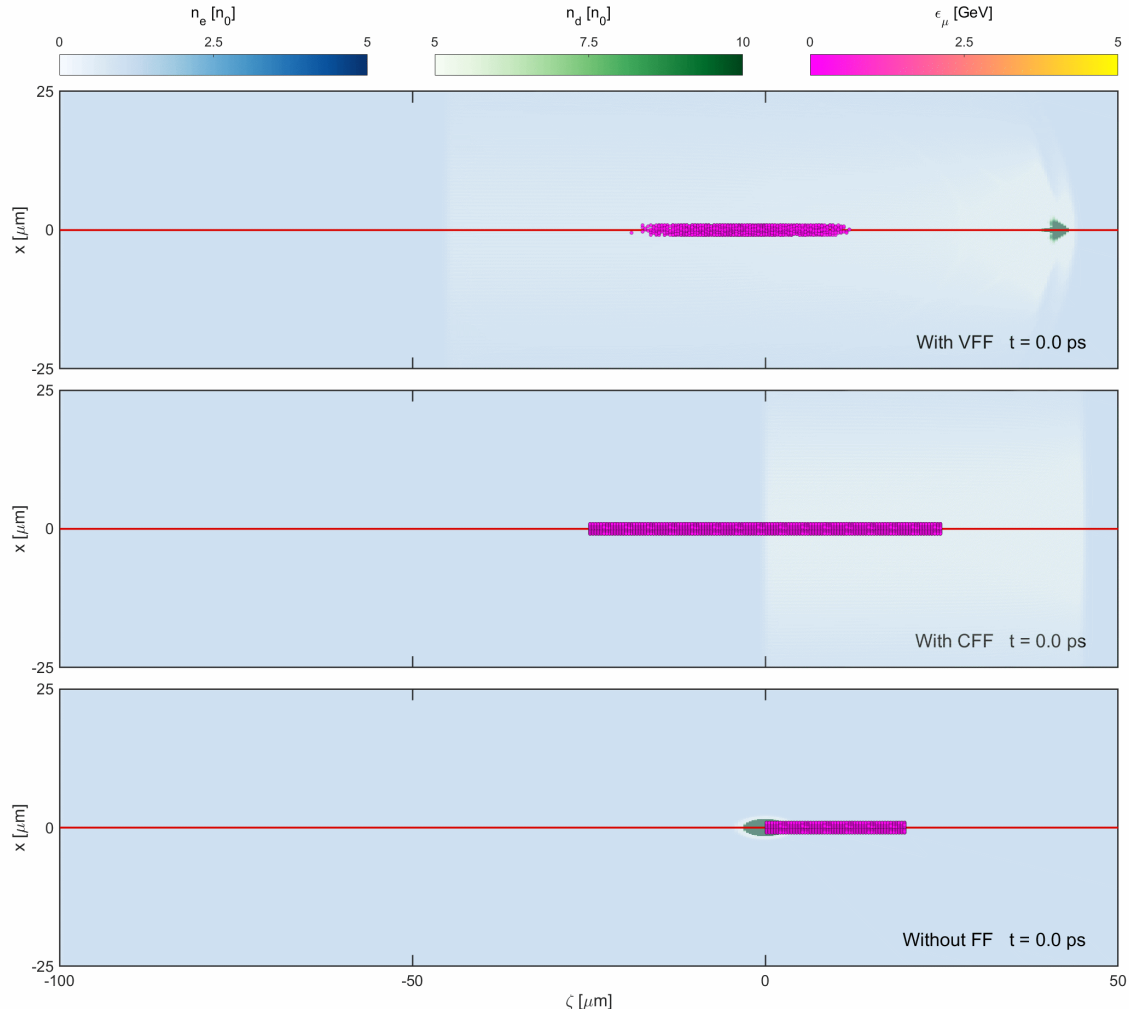
Nat Commun 6, 8723 (2015)



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	
$^{18}\text{O}^{6+}$	2.5×10^{11}
$^{209}\text{Bi}^{31+}$	3.166×10^{10}
均打破国际流强记录	

Why heavy-ion drivers?

High kinetic energy

High magnetic rigidity

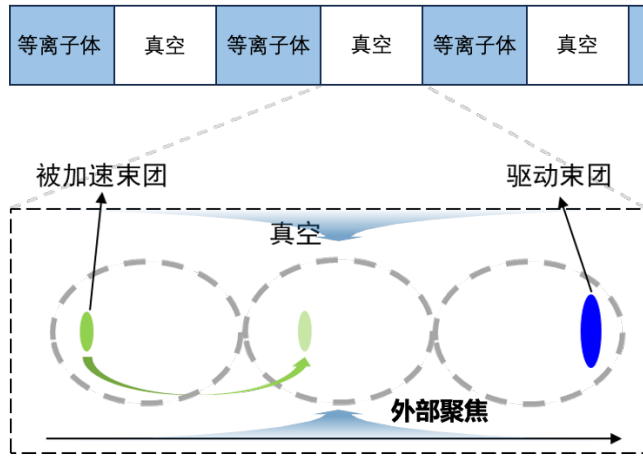
High charge density

Phys. Plasmas 33, 033102 (2026)

Plasma Phys. Control. Fusion 68 045010 (2026)

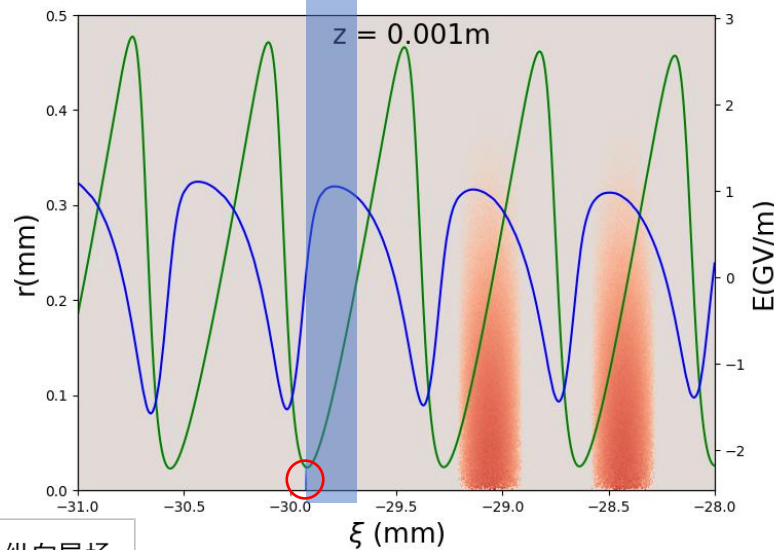


Drift-like Phase-shift Scheme

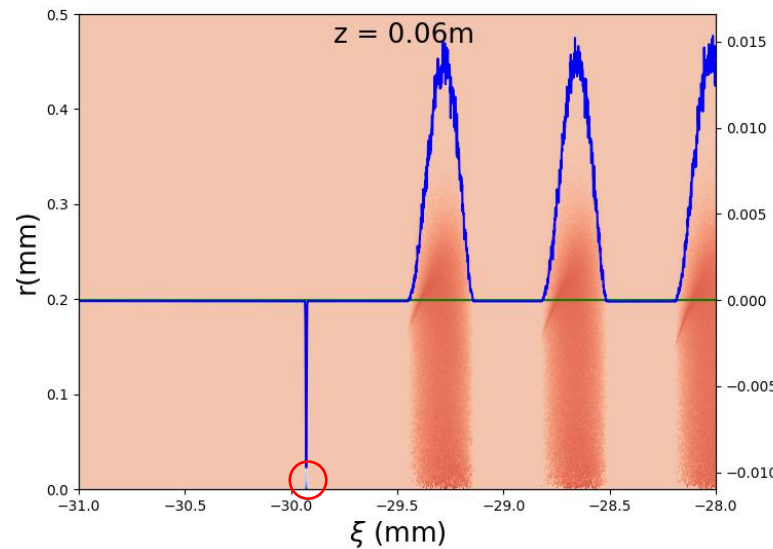


arXiv:2609.18517

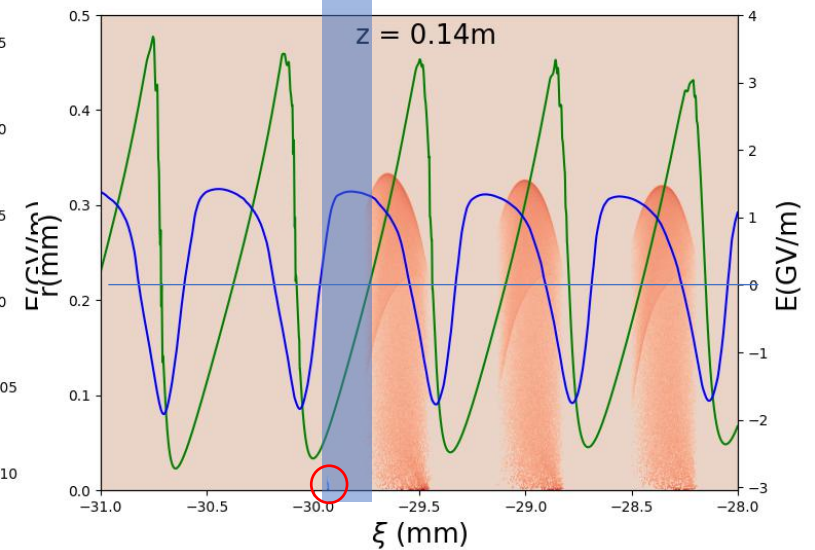
- Controlled **phase slippage** in vacuum gaps
- **External focusing** for transverse confinement
- **Wakefield re-excitation** in successive plasma sections



Initial phase



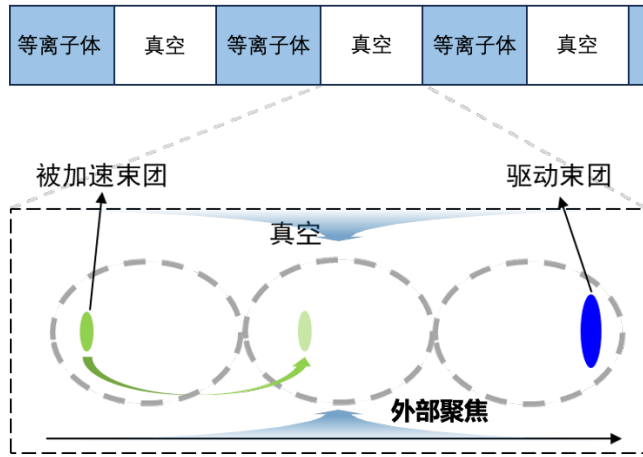
After 6 cm



After 14 cm

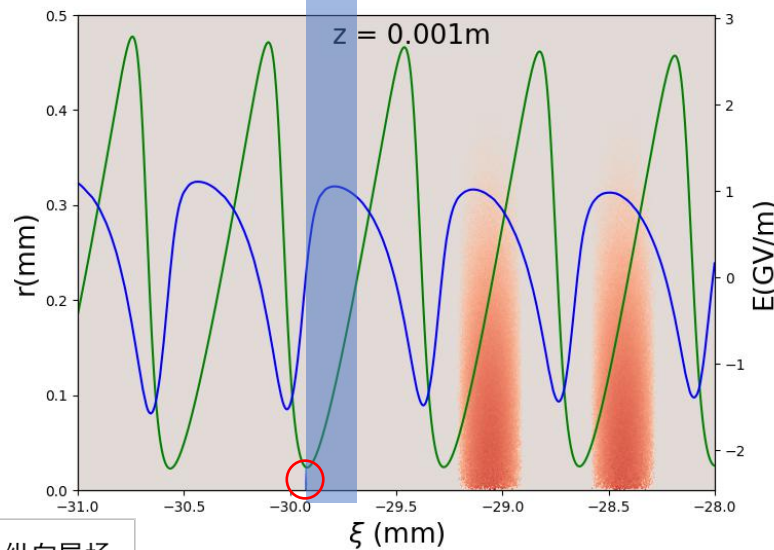


Drift-like Phase-shift Scheme

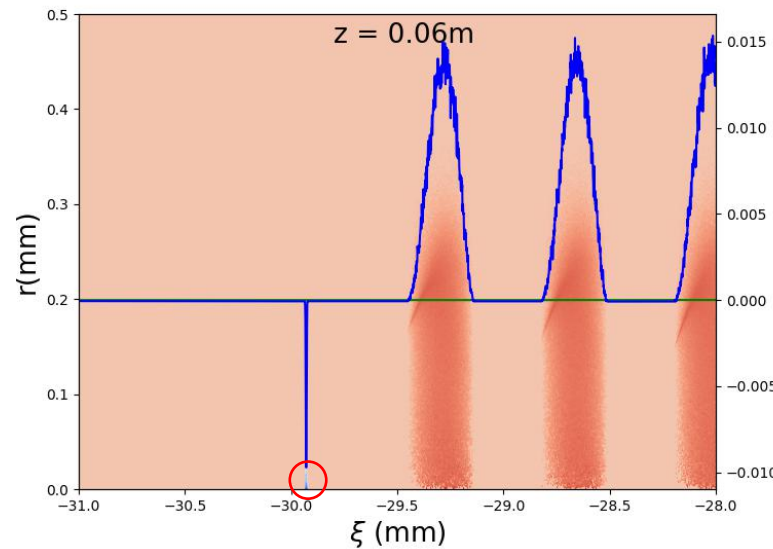


arXiv:2609.18517

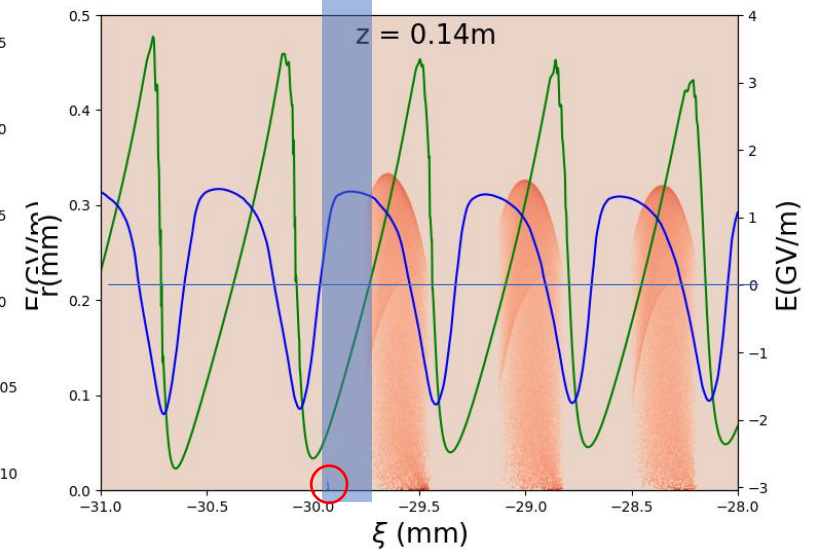
- Controlled **phase slippage** in vacuum gaps
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Initial phase



After 6 cm



After 14 cm



Drift-like Phase-shift Scheme



Driver: 209Bi^{83+} , 9.58 GeV/u, 1×10^{11}

Stage I — Density Up-Ramp

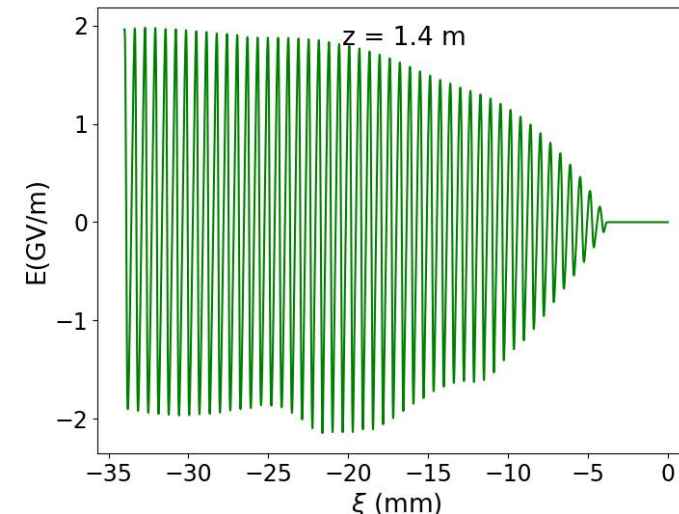
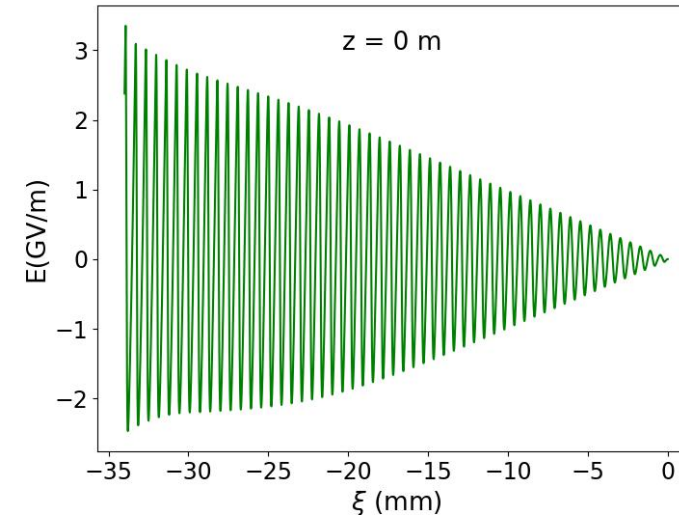
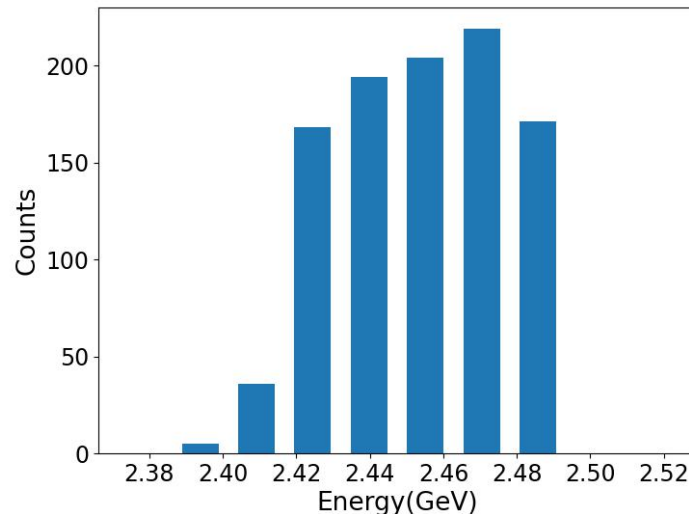
$0.85 \rightarrow 1.97$ GeV (0.6 m)

Stage II — Drift-like phase-shift

$1.97 \rightarrow 2.50$ GeV (1.4 m)

Effective gradient: ~ 0.83 GV/m

Final energy spread: $\sim 0.6\%$



Wakefield Evolution



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- ⊗ GeV-scale muon acceleration
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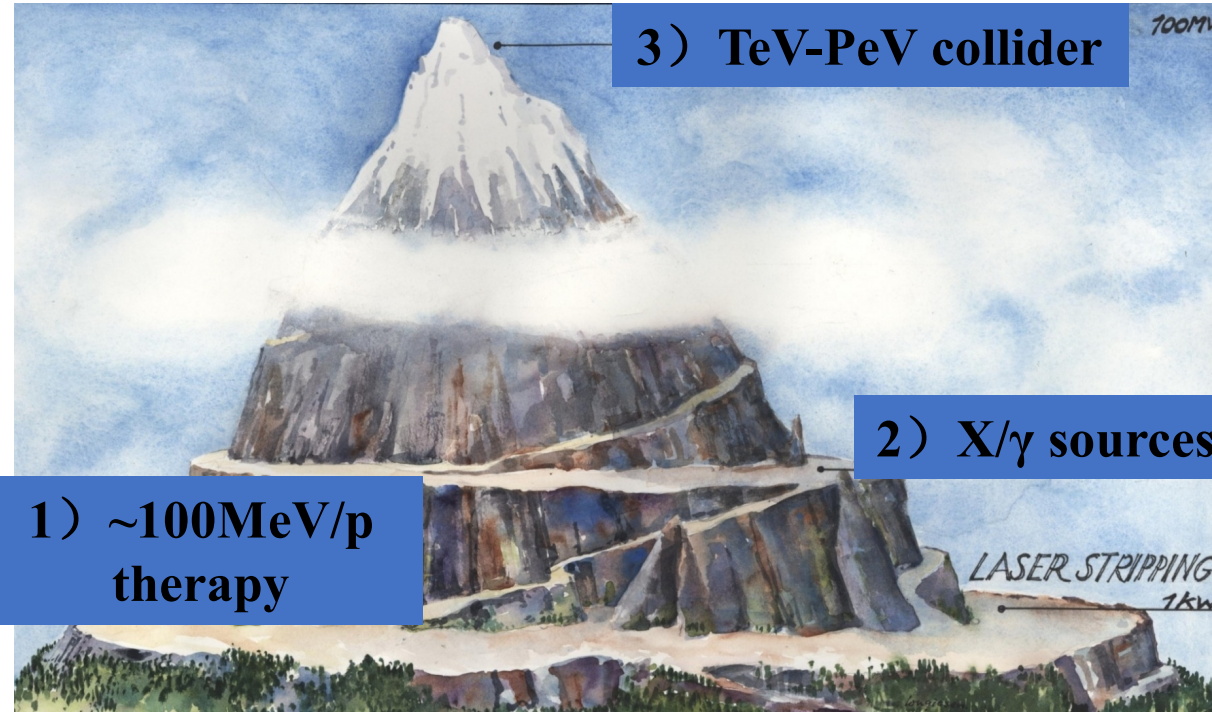
Huairou Science City—National Innovation Center





Applications in the future

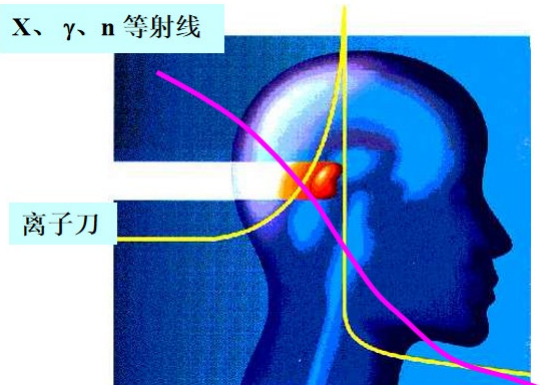
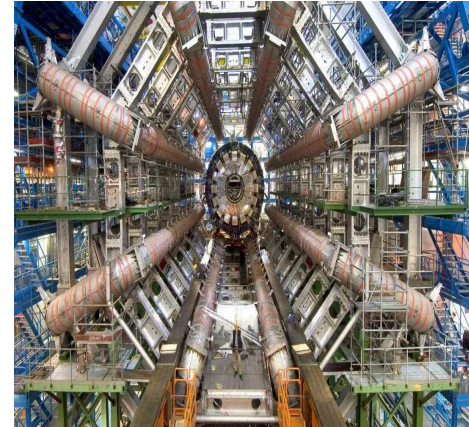
laser accelerator: 1) ion acceleration; 2) X/ γ source; 3) TeV collider



↑ Avg power

→ Rep rate

↗ Duration



ICFA+ICUIL joint workshop

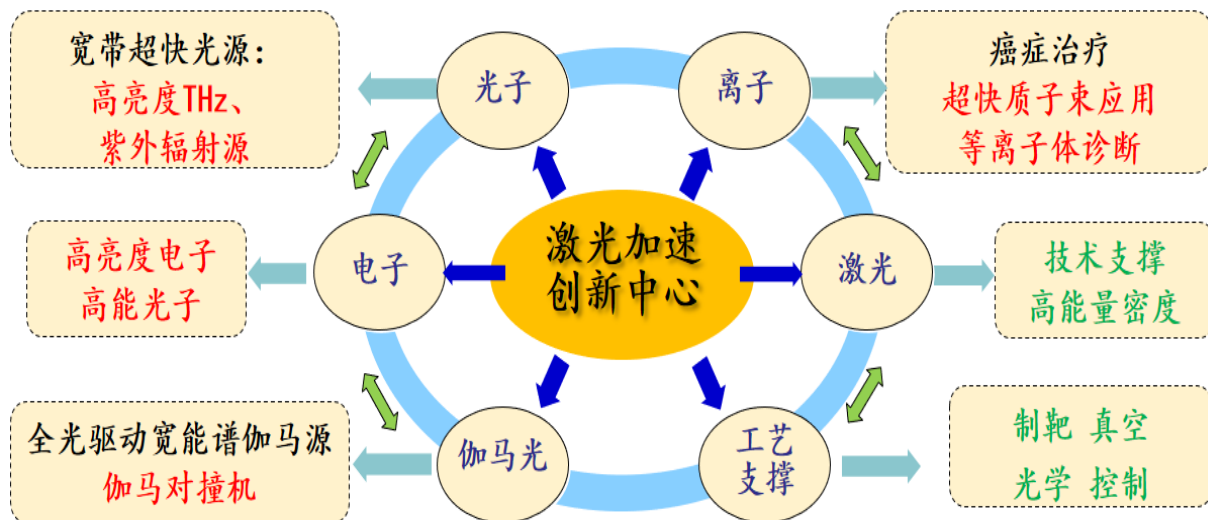
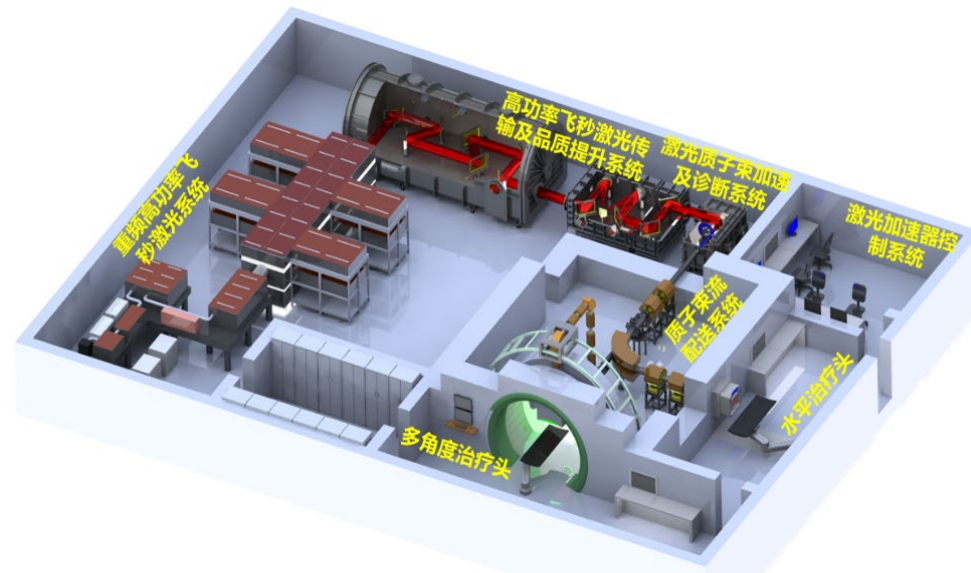


Beijing Laser Acceleration Innovation Center



The advanced laser accelerator research and application research platform:

- 1) Mechanism for laser immuno-radiotherapy
- 2) Laser driven ultrafast particle beam (muon, isotope...)



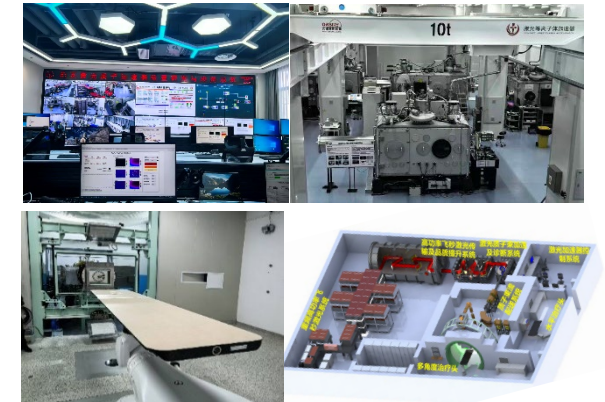
2022年12月入驻，2023年验收 35

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



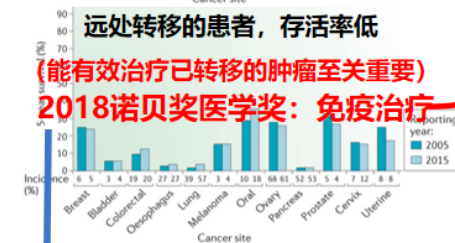
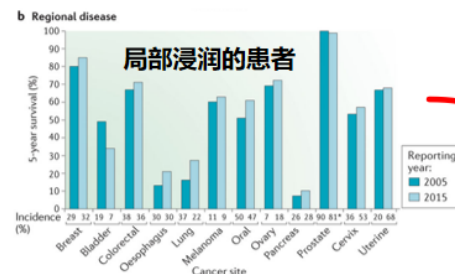
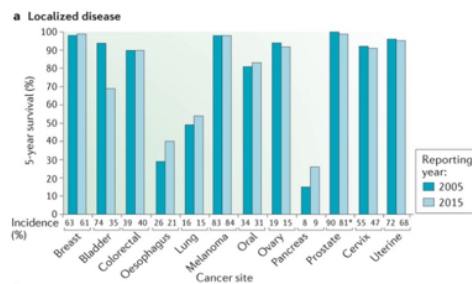
The first laser proton hospital in the world!



Prospects for Laser Accelerator Immunotherapy



localized tumor therapy



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)

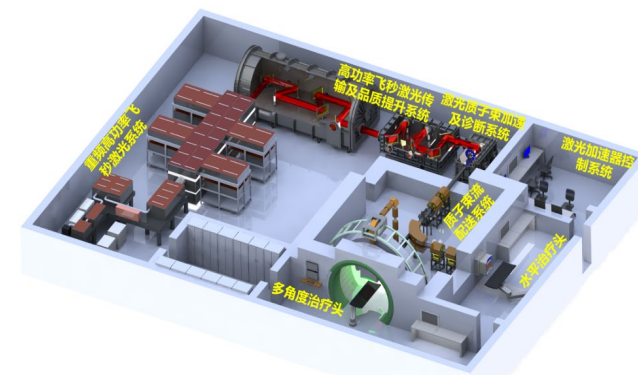
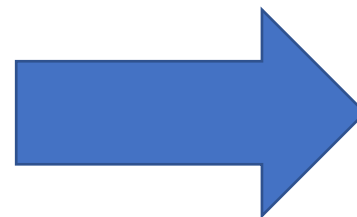
2005~2015年美国
肿瘤患者5年生存率

远处转移的患者，存活率低
(能有效治疗已转移的肿瘤至关重要)
2018诺贝尔奖医学奖：免疫治疗

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

激光加速器+免疫 === 免疫放疗 (2018) ?

diffuse tumor



immuno-radiotherapy



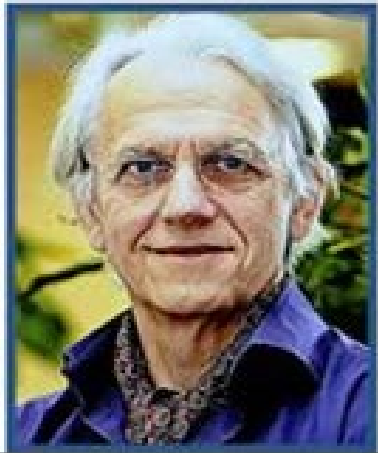


Mourou&Tajima Institute

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.

Acknowledgement



北京大学
PEKING UNIVERSITY

- **LOA/IZEST:** G.Mourou,T.Tajima
- **GIST:** C.H.Nam
- **LMU:** J.Schreiber
- 兰州近代物理所: 詹文龙、夏佳文、赵红卫、徐瑚珊、马立桢
- 上海高研院: 沈文庆、赵振堂
- 高能所: 陈和生、王生
- 上海交大: 张杰、盛政明、陈民
- 中科院理论物理所: 弓正
- 复旦大学: 马余刚、寿寅任
- **21**研究院: 欧阳晓平、王大辉
- 原子能院: 王乃彦、郭冰
- **585**所: 许敏
- 湖南大学: 余金清

Funding from NSFC/MOST/Beijing
~~~~~thanks for your attention

# CLAPA group@MT Institute



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林晨 研究员  
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陈佳洱 教授



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(高工)



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医学物理  
专职研究员、博士后等20人

**Thanks for your attention!**