Generation of TeV muon by laser plasma accelerator

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Outline

- Introduction and motivation
- acceleration of slow muon
- TeV muon acceleration
- Outlook

Nobel Prizes in Physics

In the 20th century nearly half of the Nobel Prizes in Physics are related to high-energy particle acceleration and its applications!

- ●Muon？
- ●as 2023
- ●CPA（2018）
- ●Higgs
- ●muon（L Lederman 等)
- ●J/ψ（丁肇中等)
- ●nuclear structure（R Hofstadter)
- ●anti Proton（E Segrè 和O Chamberlain)
- ●C-W accelerator（J Cockcroft ）
- ●radioactivity（F Lorence)
- ●neutron（Fermi)
- ●neutron（Chadwick)
- ●nucleus（Rutherford)
- ●proton（Rutherford)
- ●electron（Thomson)

1900 1920 1940 1960 1980 2000 2020 2030 2040

Lser 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

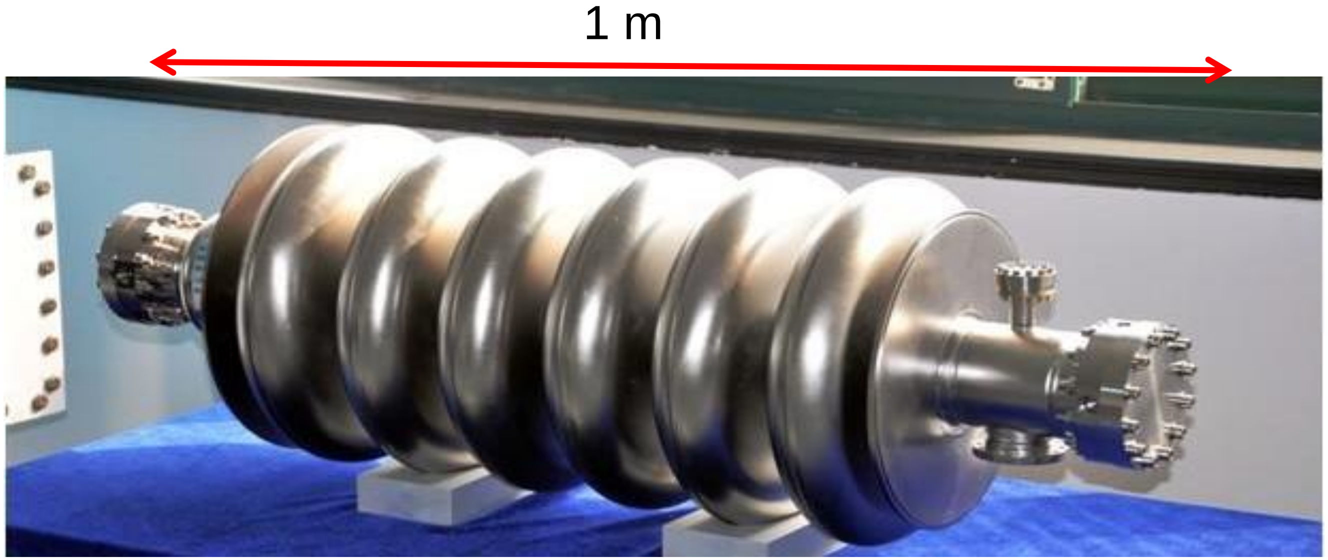
Laser Electron Accelerator

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.

1000 times smaller, and fast!

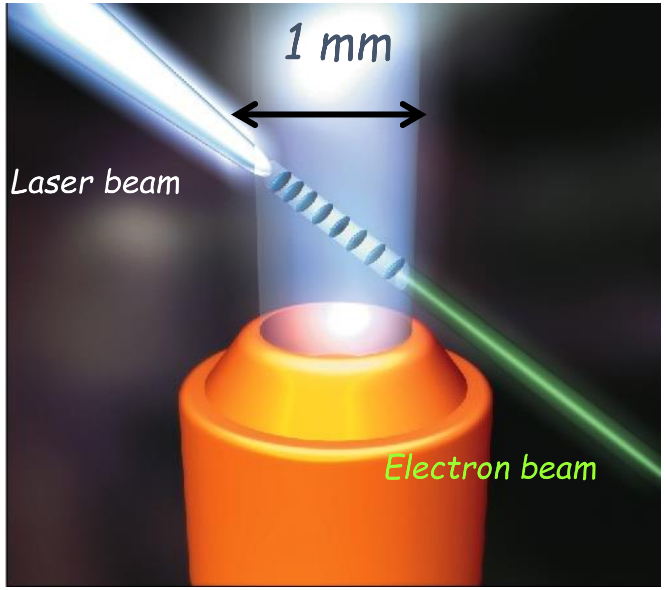
RF accelerator
E = <100MV/m

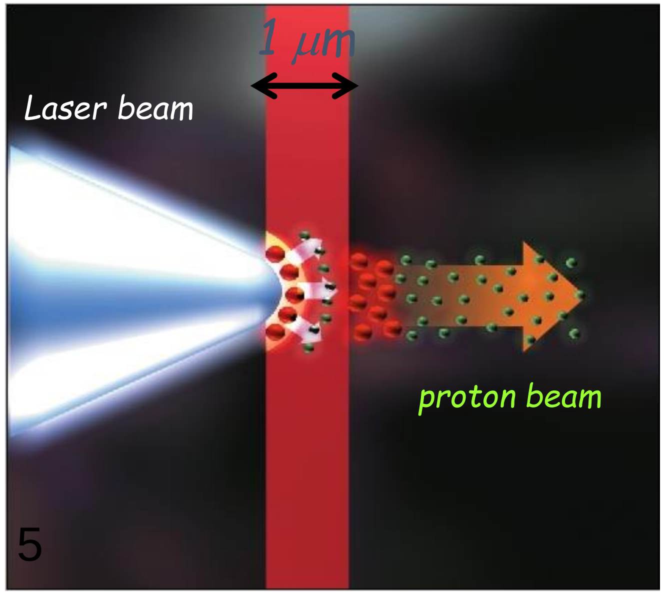


laser plasma accelerator

E > 100GV/m

1000 times smaller!

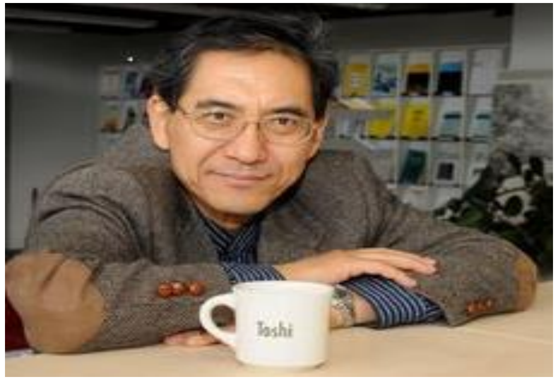




Nobel prize report

CPA

Inventor of Laser Wake Accelerator –Tajima is disappointed !!!



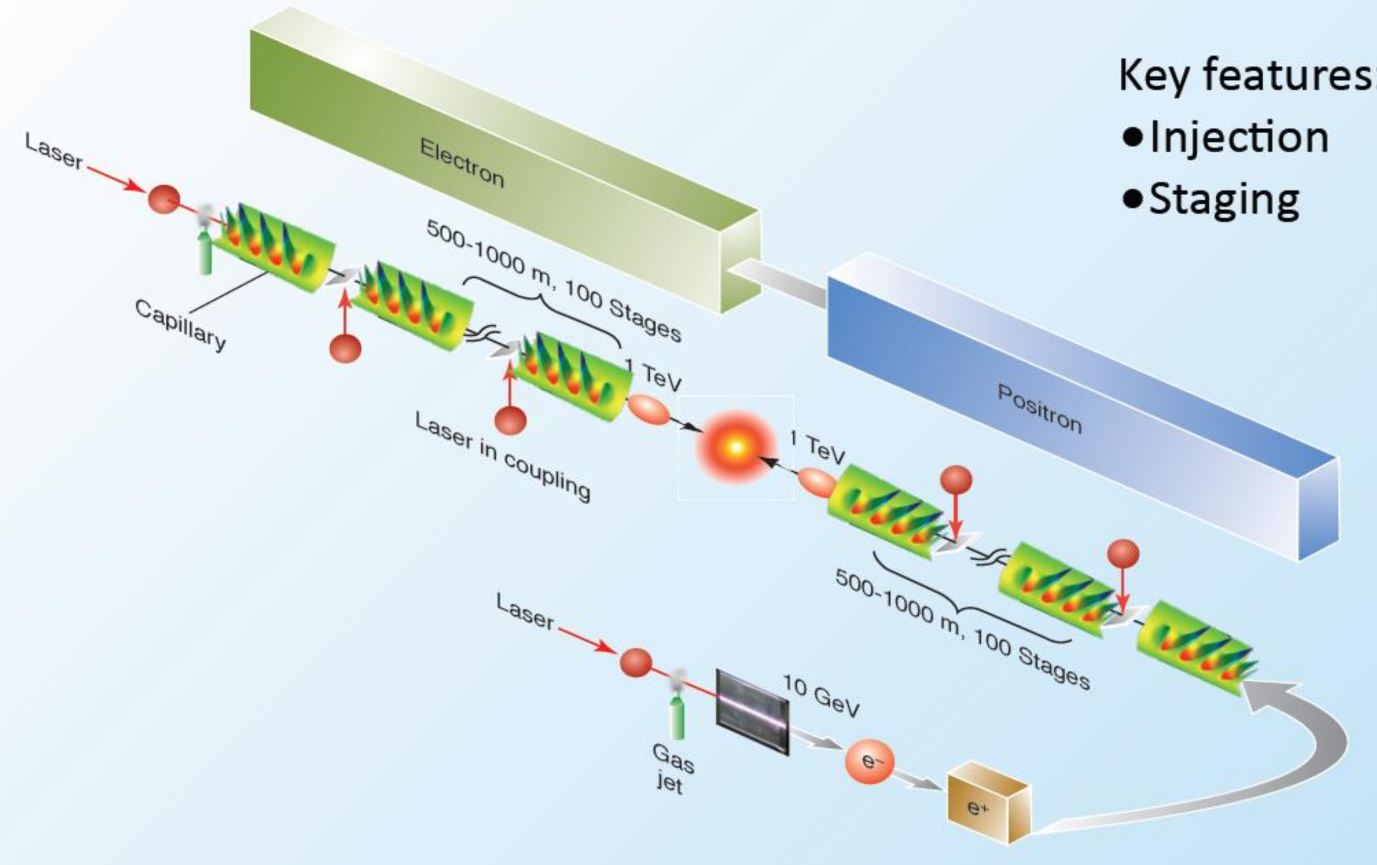
离子能量?	Will be Ok
能散？	OK
稳定性?	OK
可靠性？	OK

Nobel prize report:

At Lawrence Berkeley National Laboratory in California, a petawatt-class laser at the Berkeley Lab Laser Accelerator (BELLA) facility is used to accelerate electrons to 4.2 GeV over a distance of 9 cm [78]. This is an acceleration gradient of at least two orders of magnitude higher than what can be obtained with RF technology. That there are many remaining challenges before laser accelerators can be used for medical applications is well understood [79].

TeV collider by laser accelerator? electron collider ?

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

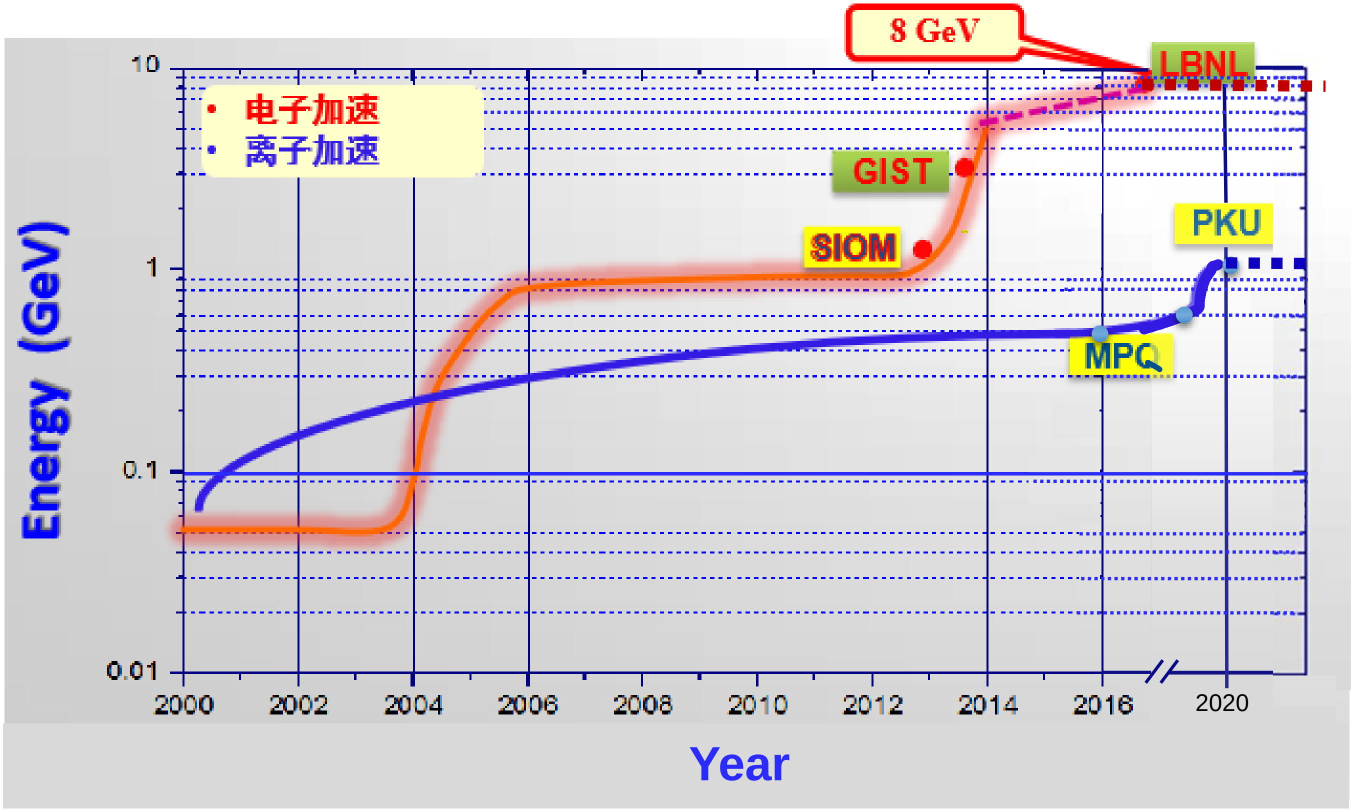


Key features:

- Injection
- Staging

Leemans & Esarey, Physics Today, March 2009; C.B. Schroeder et al., PRST-AB 13 (2010)

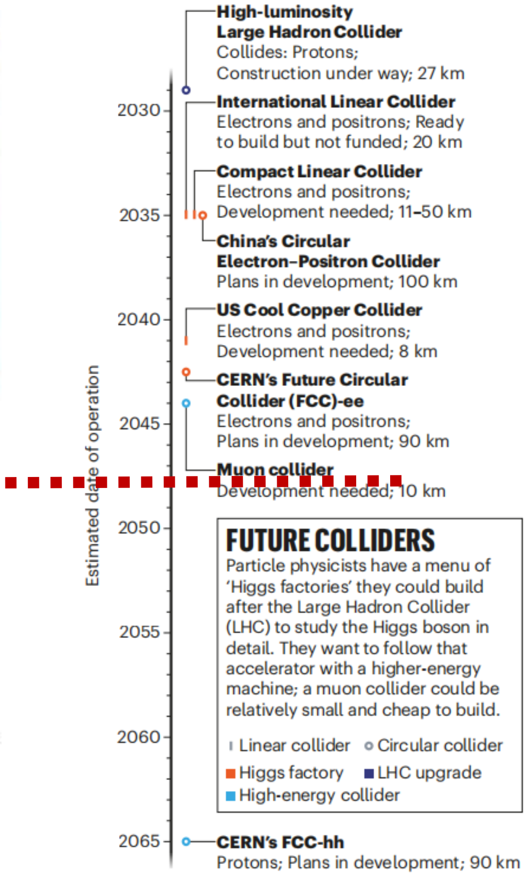
Progress of laser acceleration



Wang, ..., Yan, Ma*, Nam* Phys. Rev. X* **11, 021049 (2021);**
Ma*, ... , Yan*, et al., ***Phys. Rev. Lett.*** (2019);

BUILD THE WORLD'S FIRST MUON COLLIDER ?

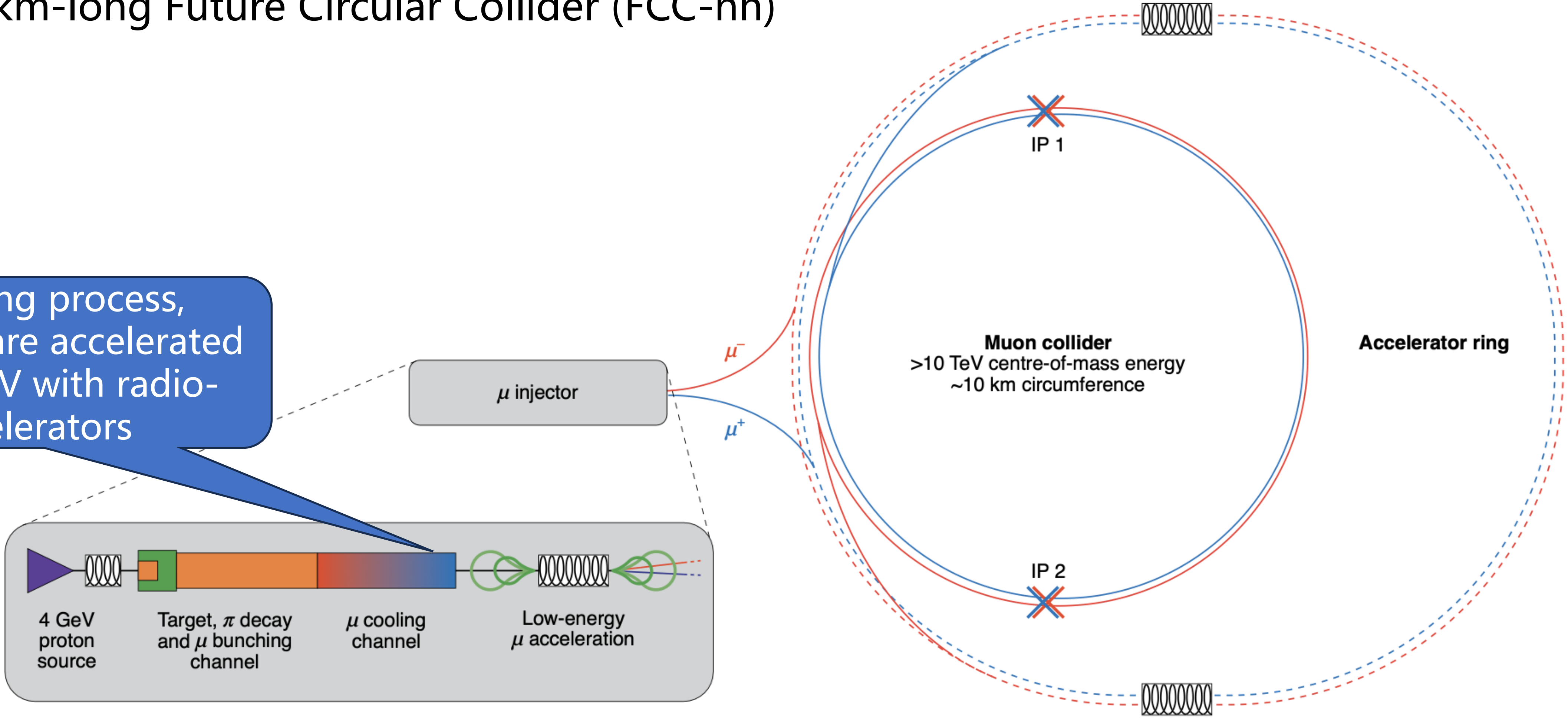
There are several possible particle accelerators that could follow the Large Hadron Collider.



the energy-efficient choice for exploring new physics

10 TeV muon collider would provide similar discovery potential to a 100 TeV proton-proton collider (100-km-long Future Circular Collider (FCC-hh)

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



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

TeV MUON collider by laser accelertion technology ?

Challenges of MUON accelerator:

1. Short lifetime (2.2μs, at rest)

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

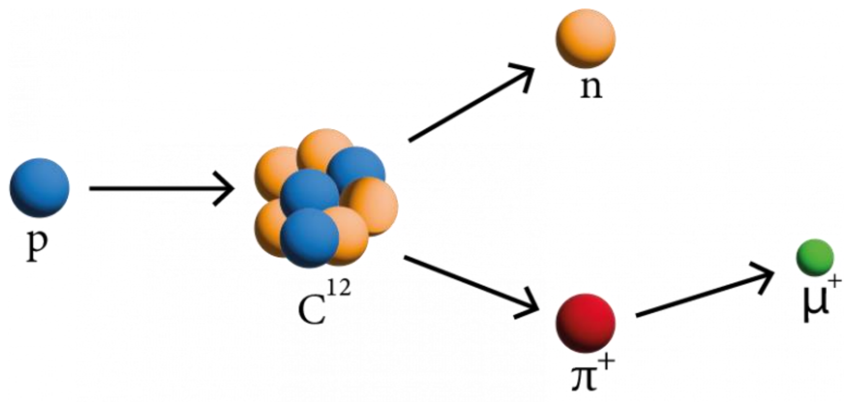
3. A significant velocity variation during the acceleration: multiple acceleration structure

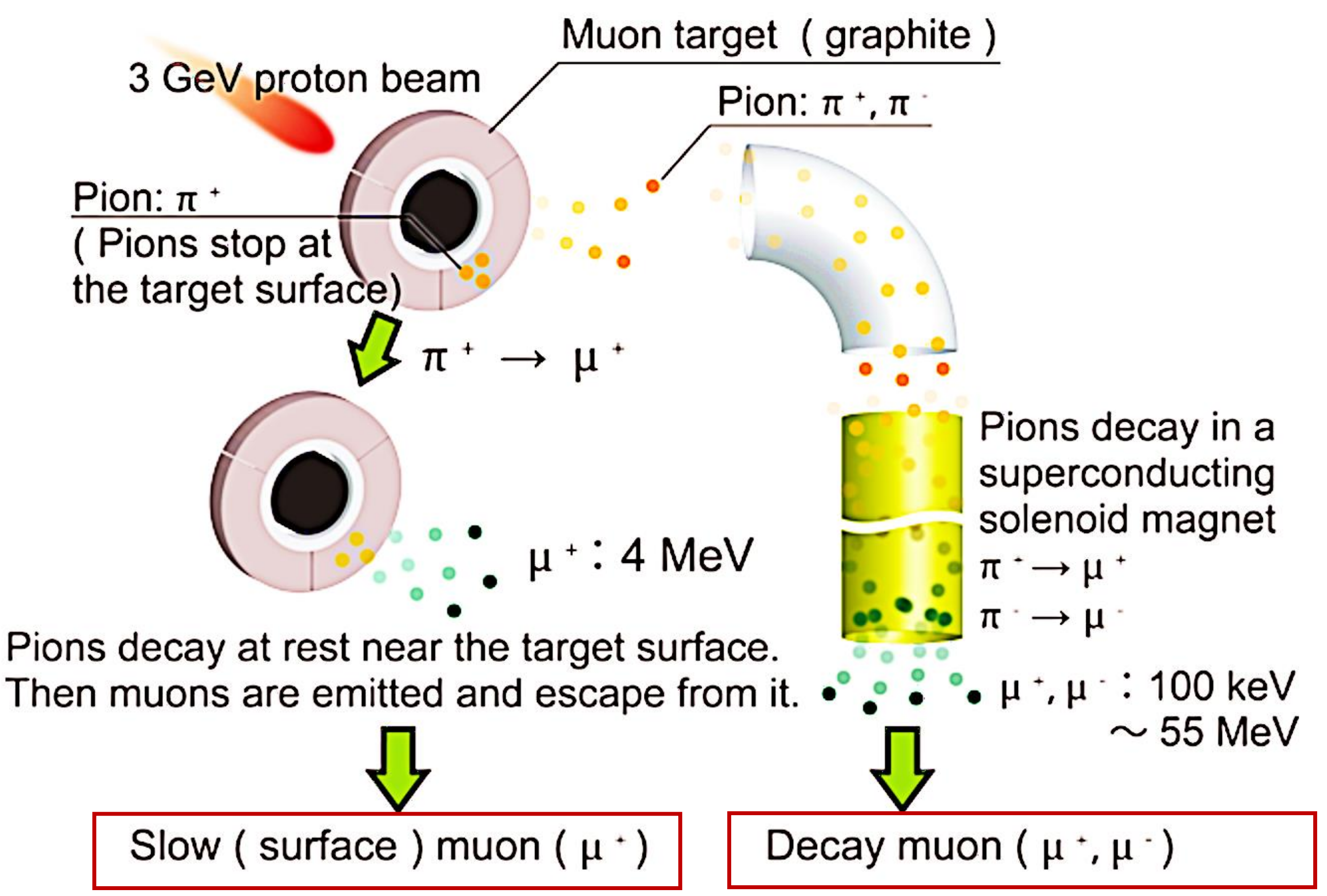
... ...

Generation of Muon beam

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

- An unstable fundamental particle with a short lifetime at rest, 2.2 μs
- Mass: ~207 m_e
- Two types: surface muon & decay muon

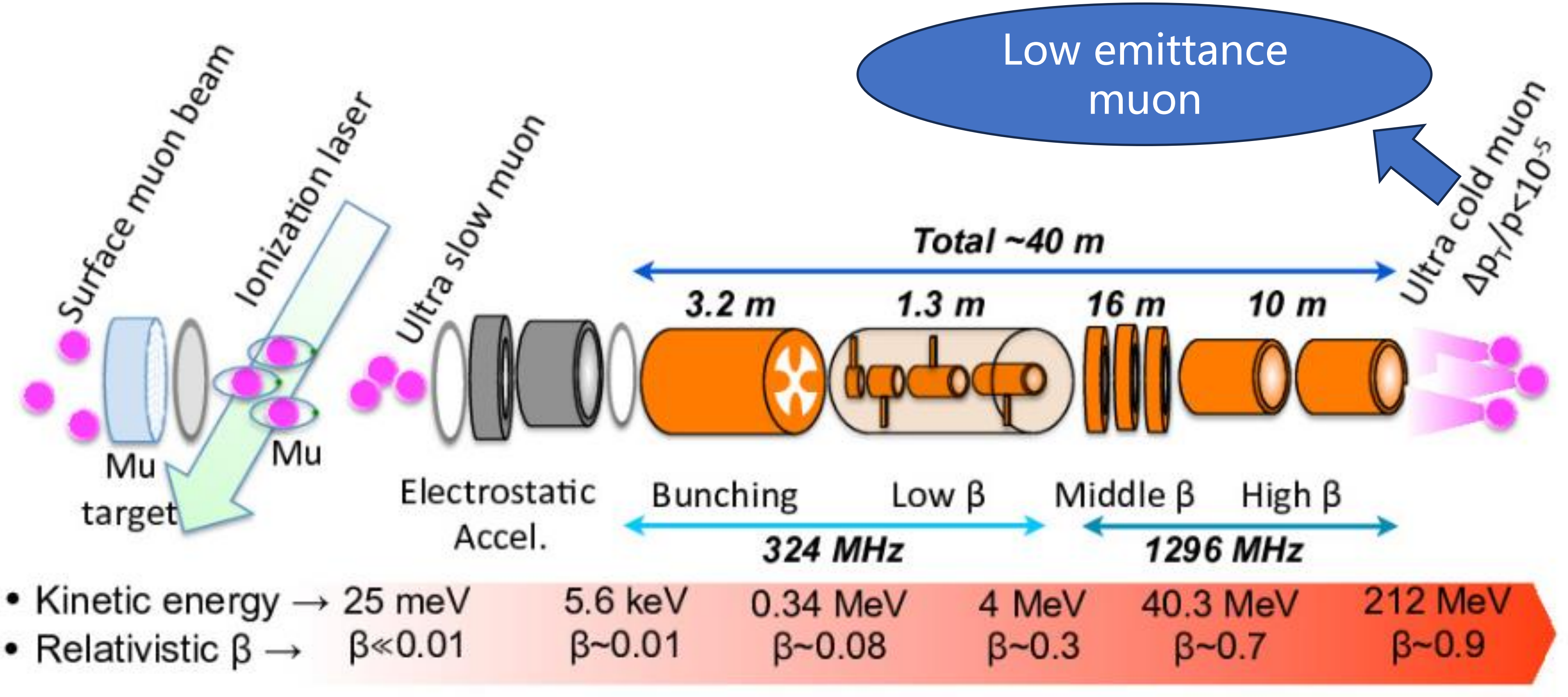




Surface Muon (μ^+) to 200MeV

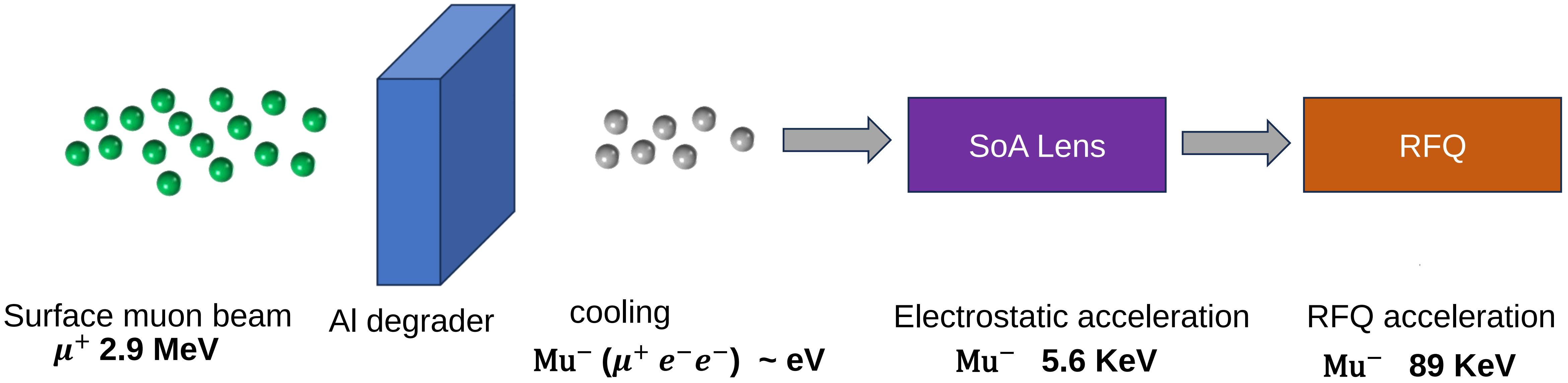
Muon anomalous magnetic moment measurement

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



- Limited by very low conversion efficiency of μ^+ to Mu^- : 8×10^{-7}
- 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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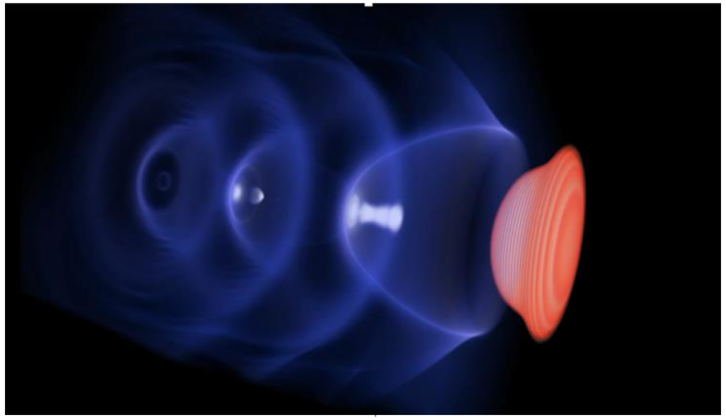
Plasma acceleration of slow muon

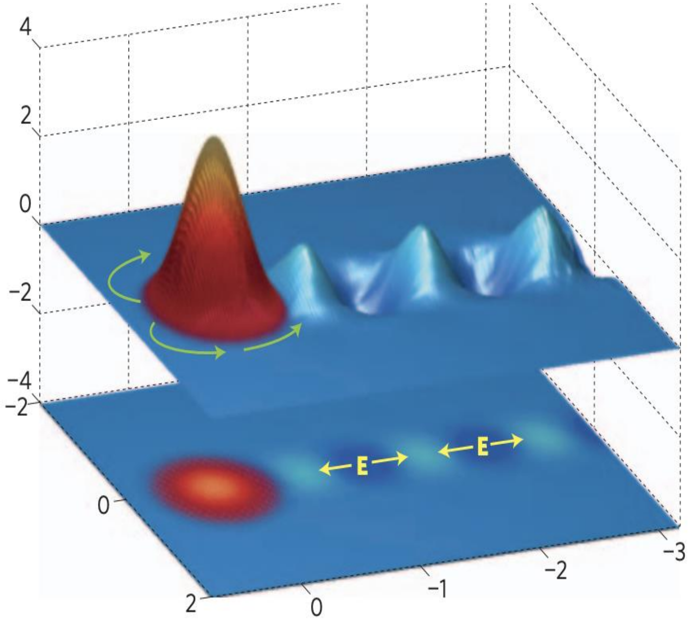
Nonlinear wake



Underdense plasma:

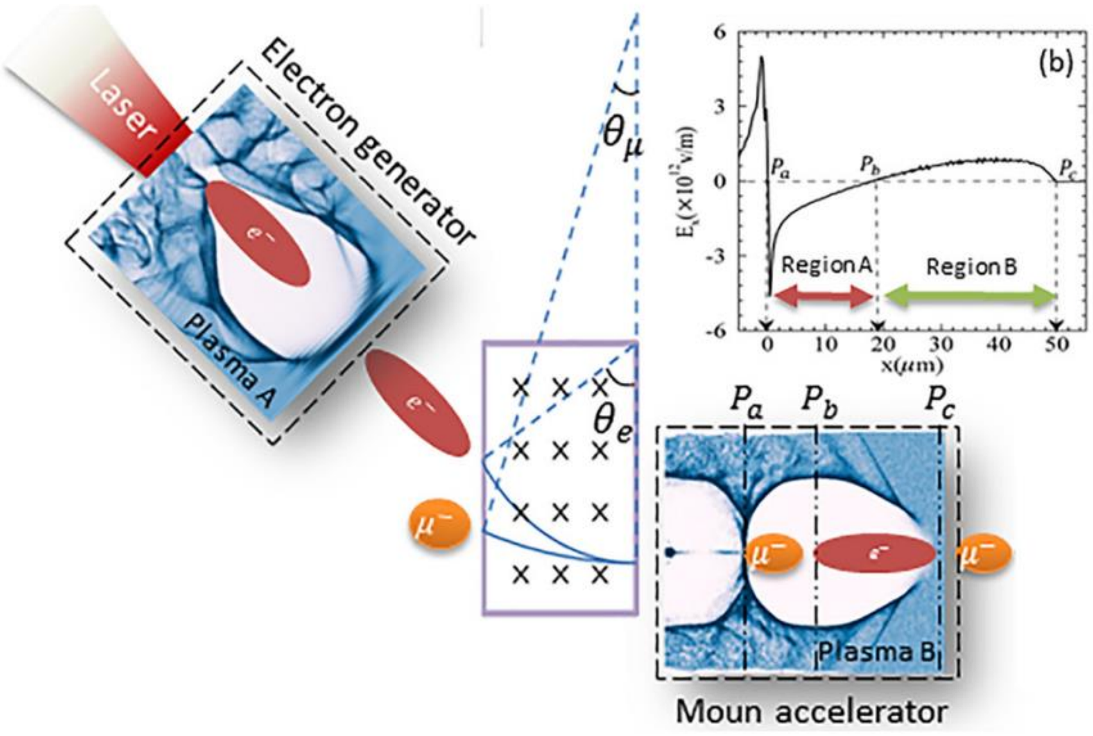
- The phase velocity of the wake is close to c, too high to accelerate low-energy muons (0.2c, c is the light speed)

- High acceleration gradient (100GV/m)



Linear wake

capture and acceleration of 200 MeV Muon



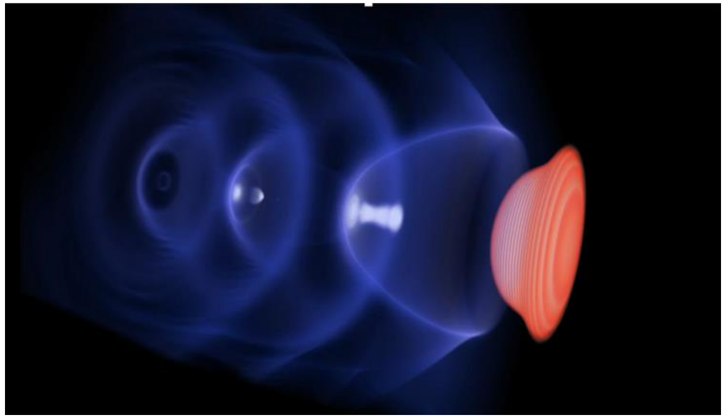
Phys. Plasmas 28, 093101 (2021)
Phys. Plasmas 29, 103110 (2022)
Phys. Plasmas 31, 023109 (2024)

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

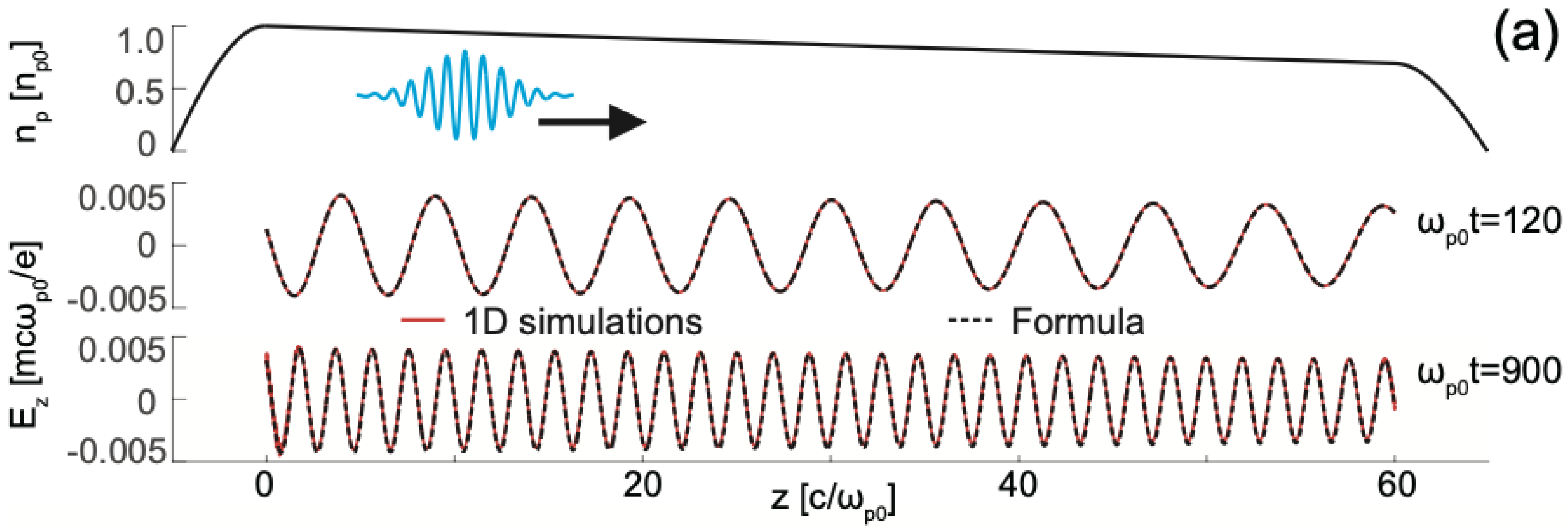
How do we capture slow muon?

- 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



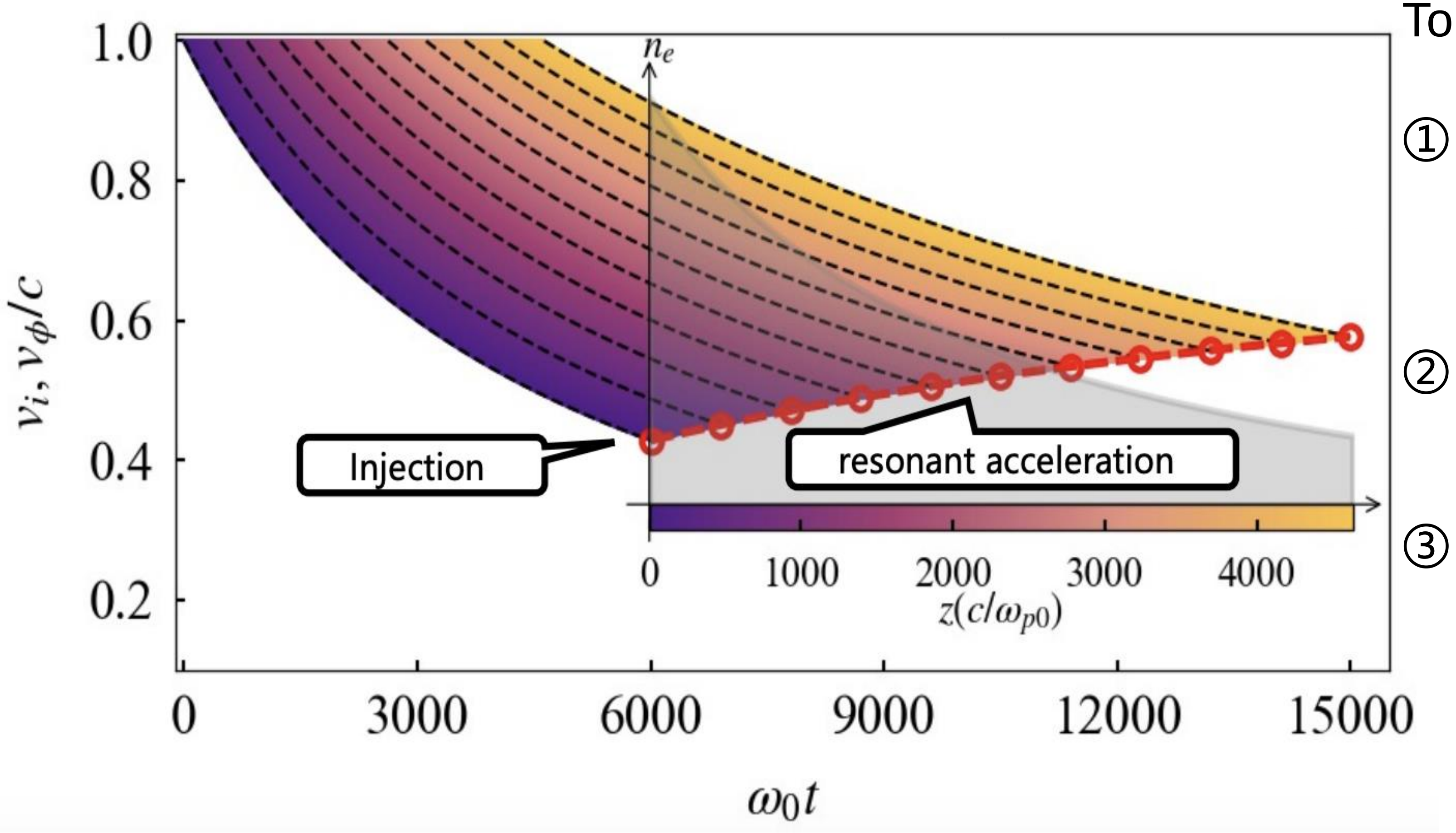
Self-evolution

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

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)

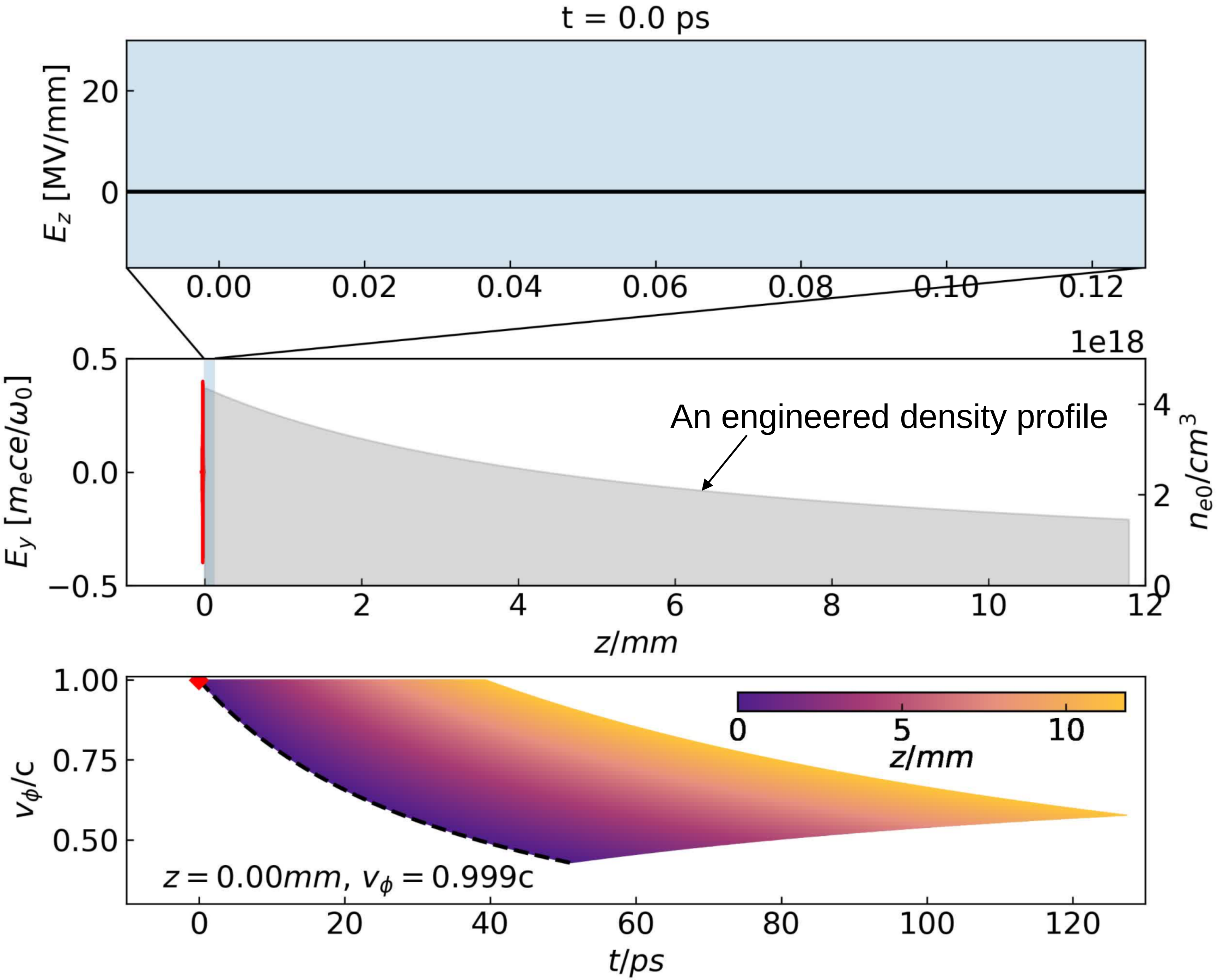
② Particles are injected into a bucket on time (initial particle speed β_{z0})

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

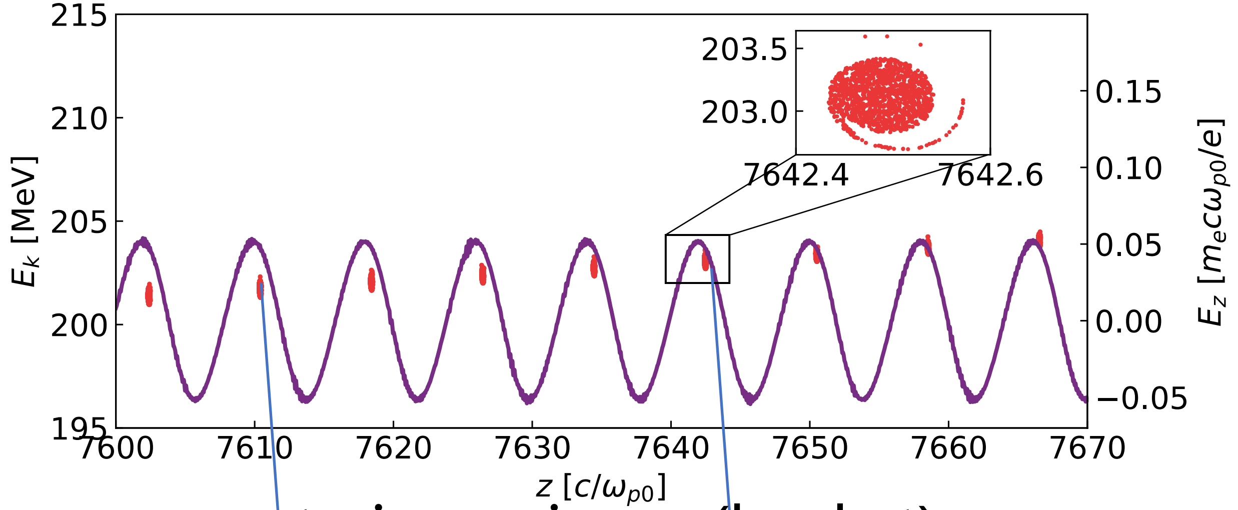
Accelerating field

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)

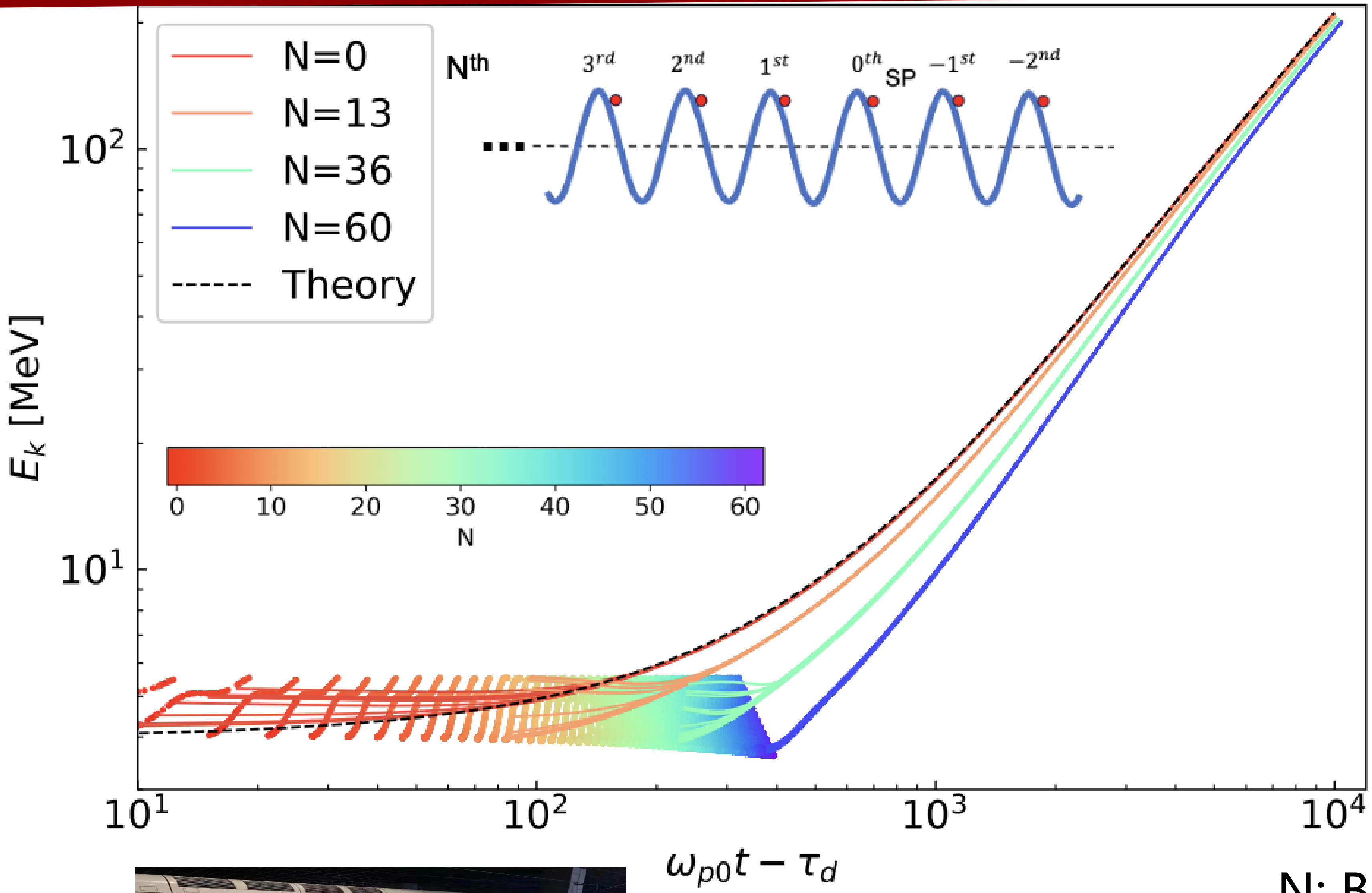
injection time $t = 51$ ps

Acceleration gradient: ~11GV/m

Micron beam duration: 100s as ~ a few fs

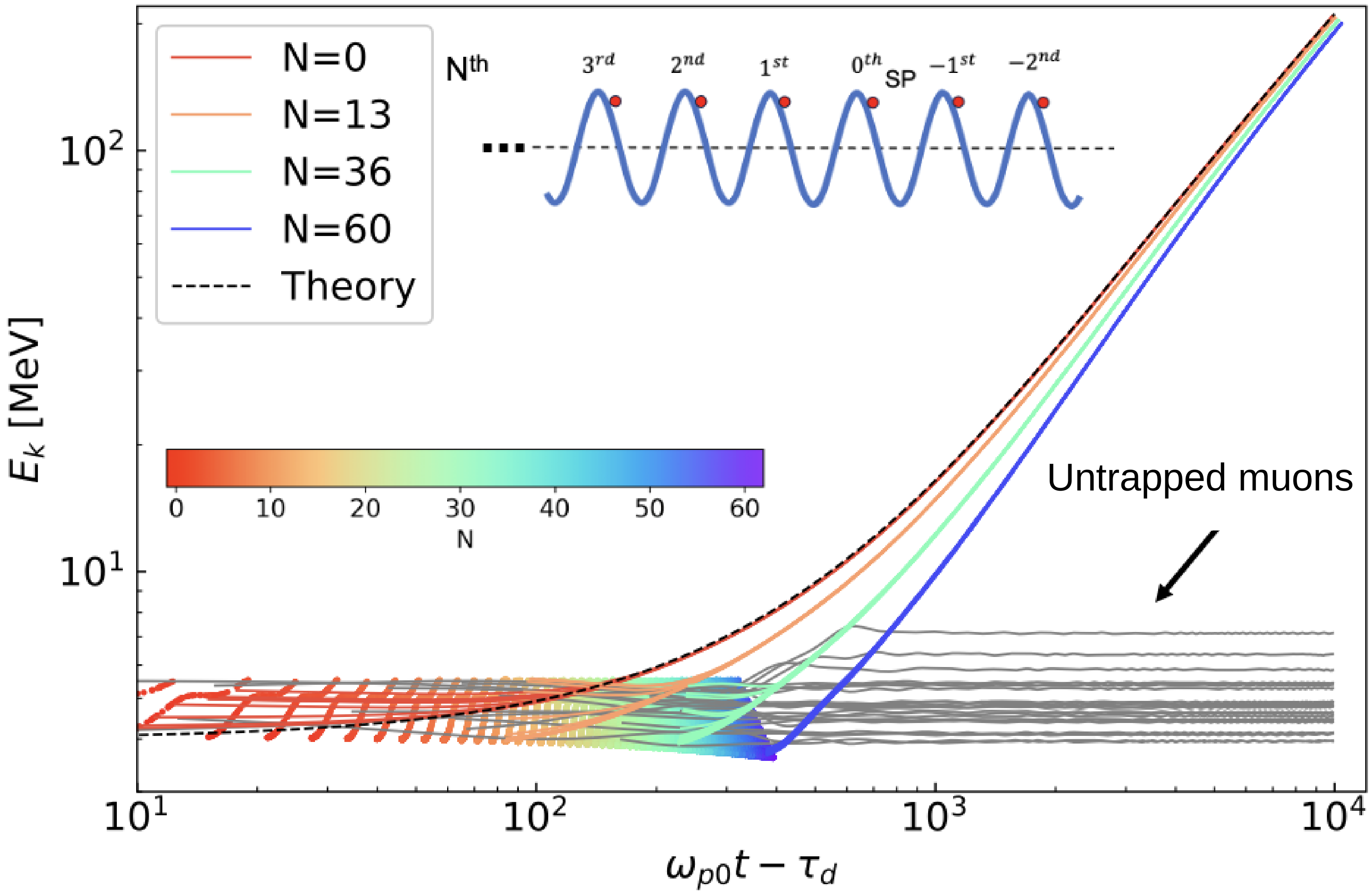
Micron beam energy spread: ~0.1%

Acceleration in different buckets or carriages



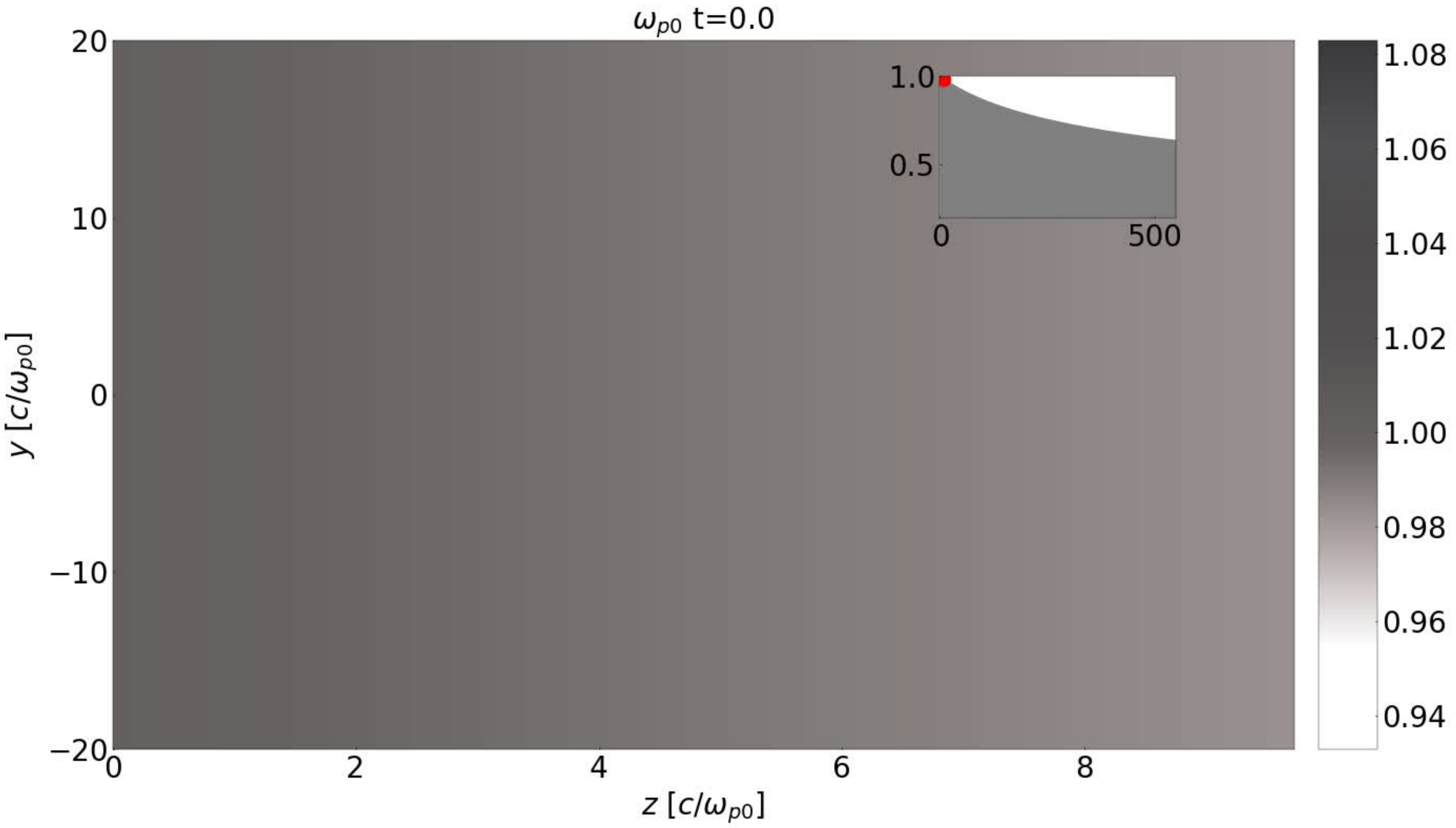
N: Bucket Number

Capture efficiency 0.1%-1% with cooling



Could be improved by choosing a higher acceleration phase

2D PIC Simulation



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

Acceleration of low-energy muon

	RF-based	Plasma-based (PTWA)
Acceleration gradient	**10 MV/m**	**10 GV/m**
Cooling	**Must**	**Optional**
From low beta to high beta	**Multi-stage**	**Single-stage**
Transverse emittance	**0.1 π.mm.mrad**	**0.1 π.mm.mrad**
Initial muon energy	**mono-energetic**	**large energy spread (1MeV-4MeV)**

Transverse emittance acceptance could be increased by using a wider beam driver

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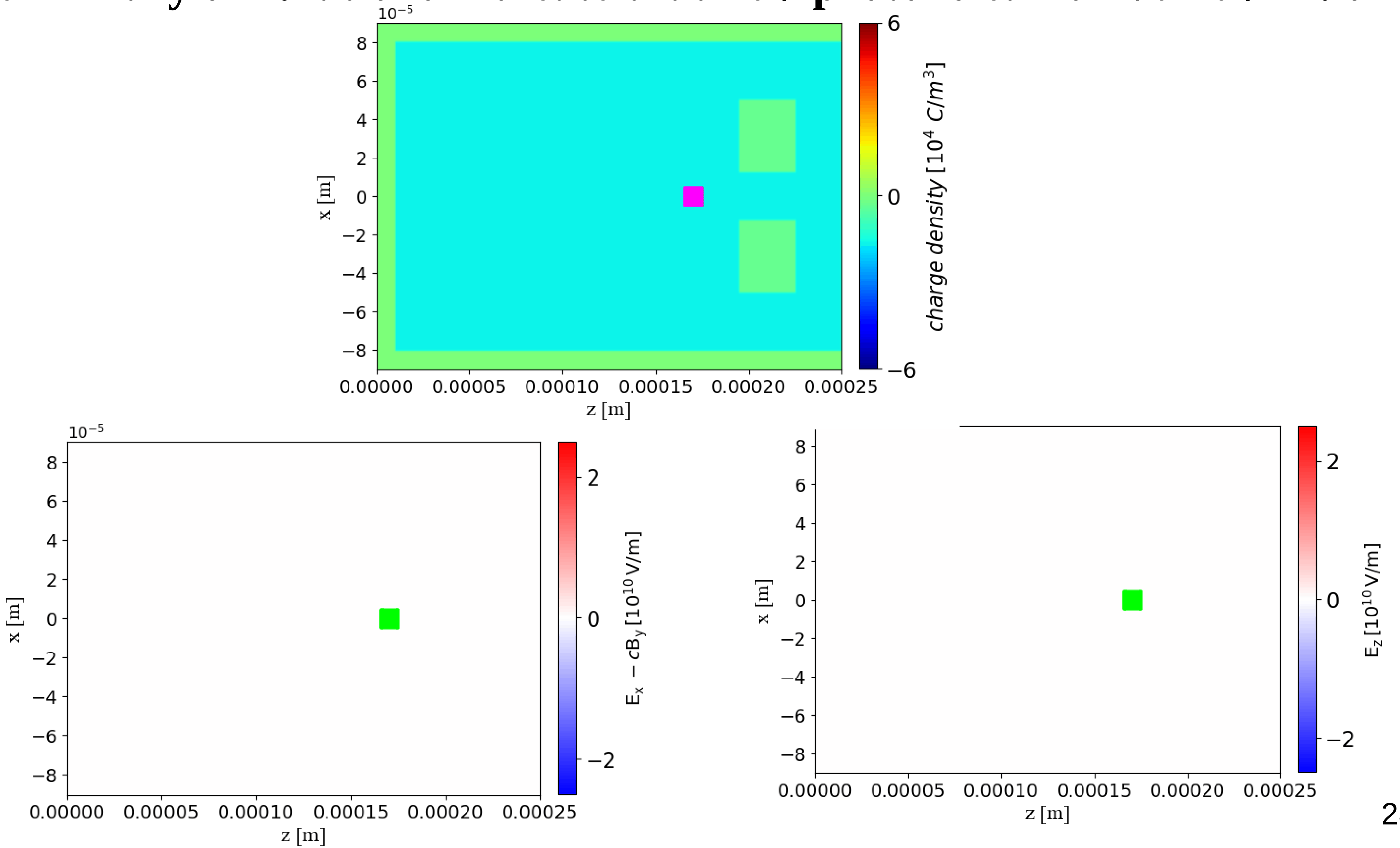
Preliminary simulations indicate that TeV protons can drive TeV muon



~TeV muon acceleration

proton energy	distance	injected energy	final energy
0.1TeV	1.2m	19.3GeV	26.71GeV
1TeV	4.01m	80.4GeV	154.5GeV
7TeV	11.24m	226.3GeV	746.1GeV

by Prof. Jinqing Yu, Hunan university

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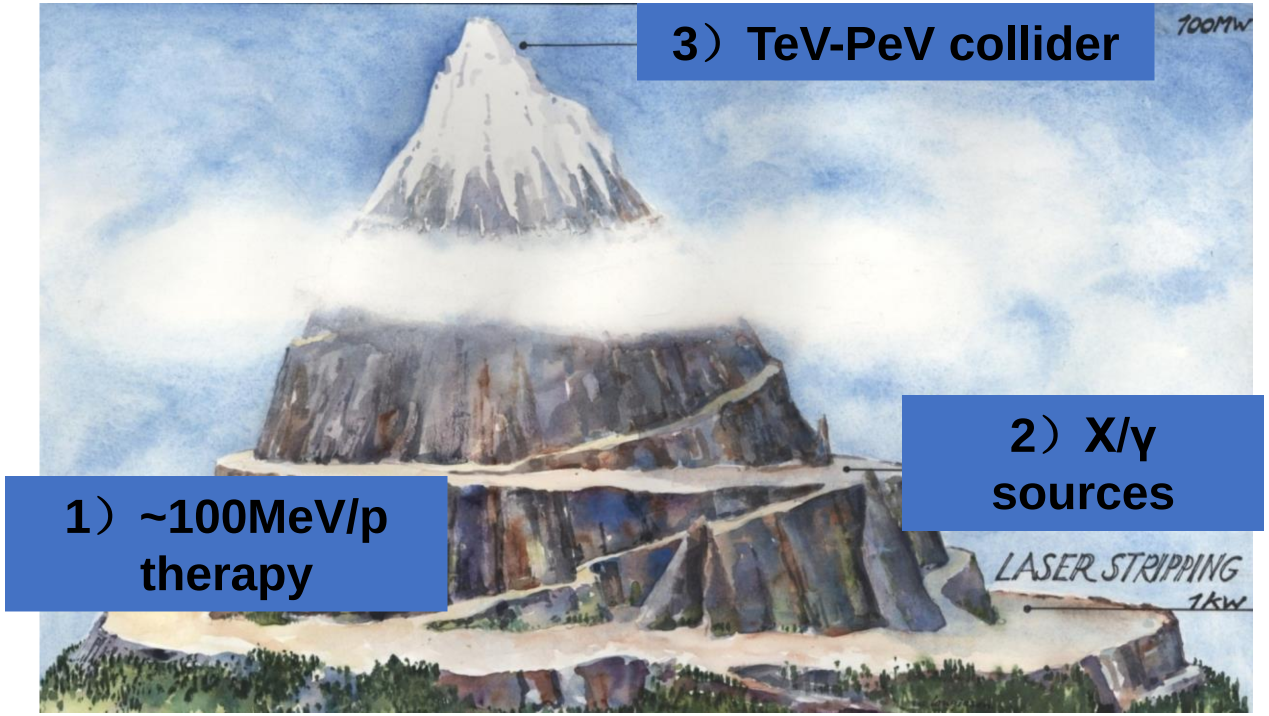
Huairou Science City— National Innovation Center

Applications in the future

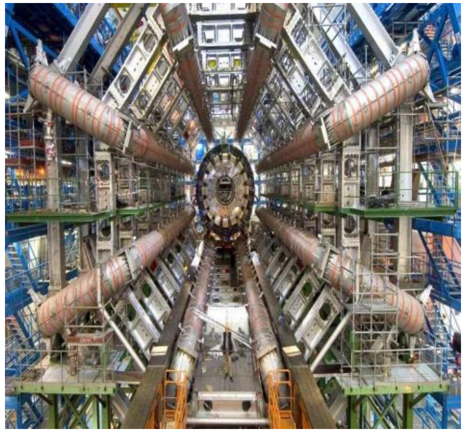
laser accelerator: 1） ion acceleration; 2) X/γ source;3)TeV collider

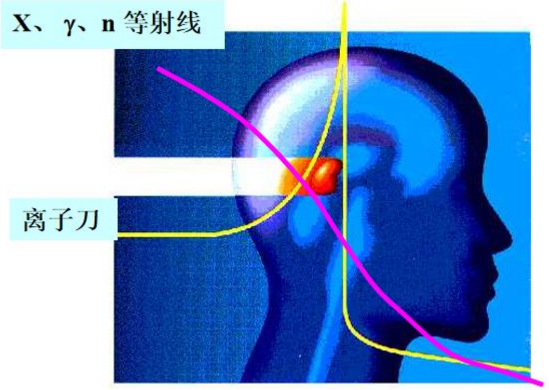


↑ avg power

→rep rate

↗脉冲长度





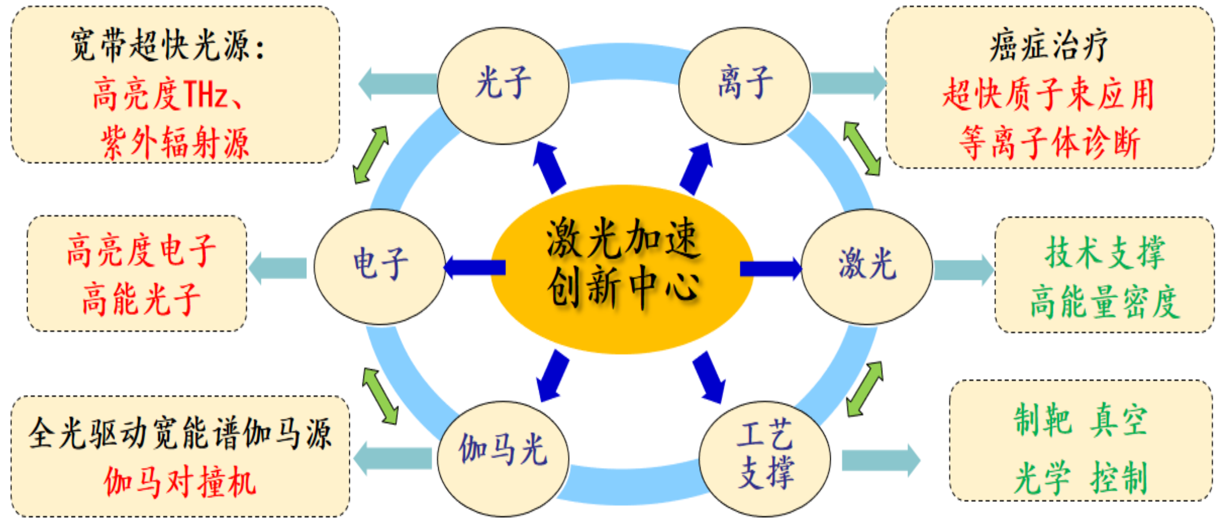
ICFA+ICUIL joint workshop

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...)



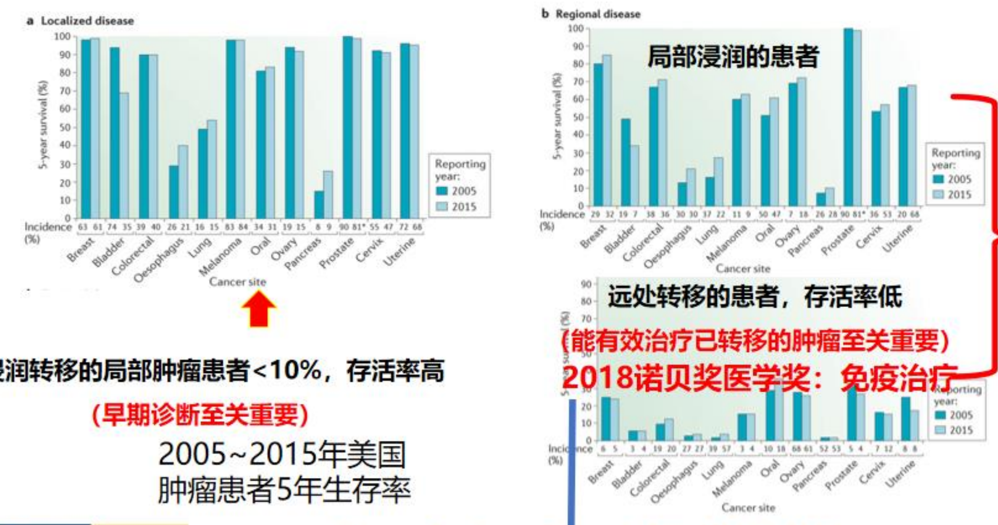
2022年12月入驻，2023年验收

Prospects for Laser Accelerator Immunotherapy

localized tumor therapy

diffuse tumor

~10%



>90%

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

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

激光加速器+免疫 ===免疫放疗 （2018）？

immuno-radiotherapy

M研究所设想

M研究所拟参照李政道研究所、丹麦玻尔研究院、美国普林斯顿高等研究院的建设，引入全球顶尖的科学家，首批引入的科学家包括2018年诺贝尔物理学奖获得者Gerard Mourou和D.Strickland。

外方主任：G.Mourou 或者D.Strickland

中方主任： 高原宁

Conclusion

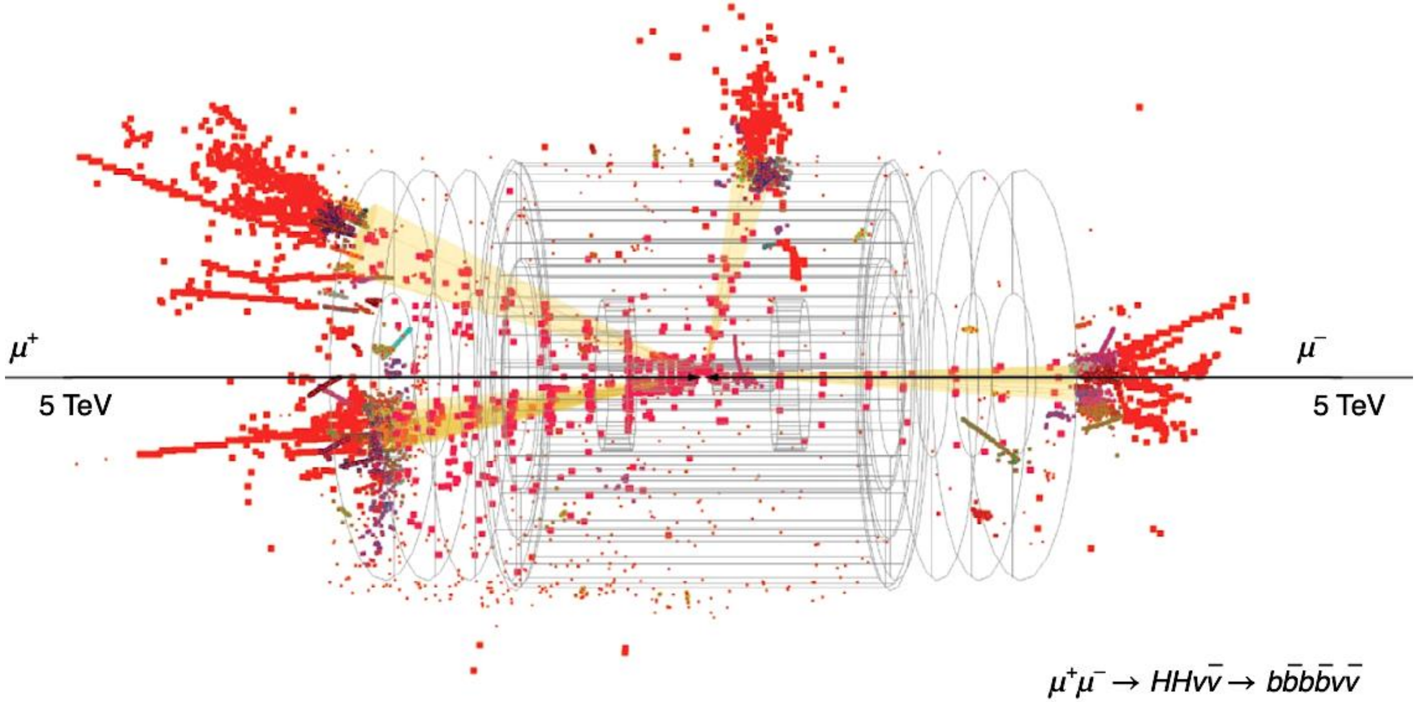
- Muons can be accelerated effectively and efficiently in evolving plasma traveling waves in density-tailored plasma.
- This mechanism exhibits high acceleration gradients and maintains low energy spread and high robustness.
- Attosecond muon/ion pulse trains may enable new paths toward attosecond science using muon/ion beams.
- This acceleration could serve as a crucial bridge for further accelerating muons within nonlinear wakefields to TeV.

Thanks for your attention!

Muon collider (μ^+, μ^-)

Muon collider

- Compared to electron-positron colliders, much less synchrotron radiation losses
- 10 TeV muon collider would provide similar discovery potential to a 100 TeV proton-proton collider (100-km-long Future Circular Collider (FCC-hh)



A muon collider is expected to be the most energy-efficient choice for exploring new physics

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

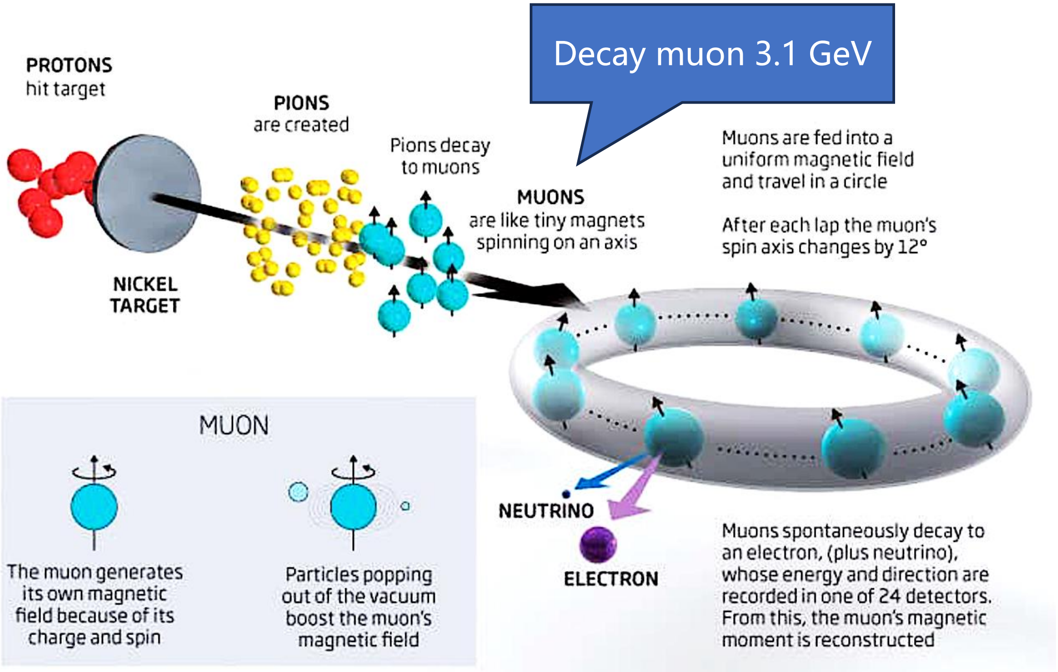
Muon magnetic moment anomaly

Muon magnetic moment (g − 2)μ/2 anomaly: explore physics beyond the Standard Model

Table 2
A summary of the development of the muon $g-2$ experiments.

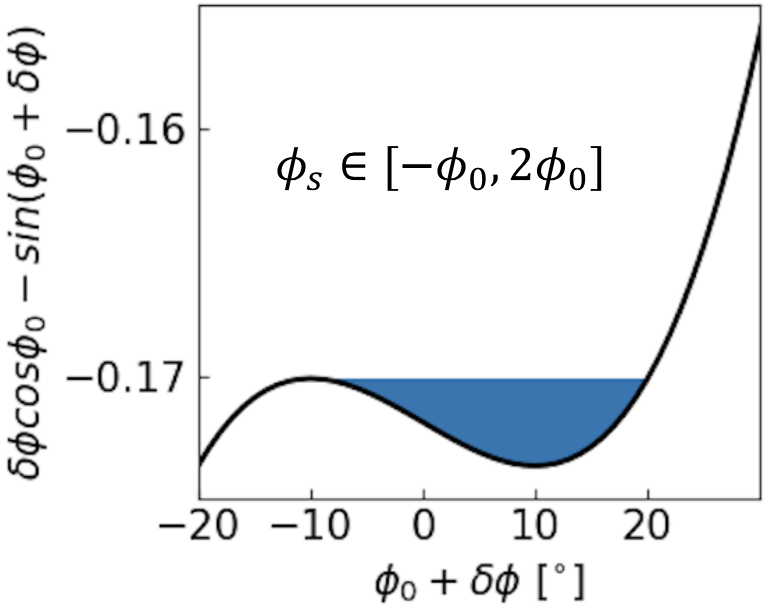
Experiment	Magnet	Approach	γ_μ	$\delta a_\mu / a_\mu$
CERN I (1965)	Long dipole magnet, $B = 1.6$ T	μ injection	1	0.4%
CERN II (1974)	$R = 2.5$ m storage ring, $B = 1.71$ T	p injection	12	270 ppm
CERN III (1978)	$R = 7.1$ m storage ring, $B = 1.47$ T	π injection	29.3	7.3 ppm
BNL (2006)	$R = 7.1$ m storage ring, $B = 1.45$ T	μ injection	29.3	0.54 ppm
FNAL Run-1 (2021)	$R = 7.1$ m storage ring, $B = 1.45$ T	μ injection	29.3	0.46 ppm

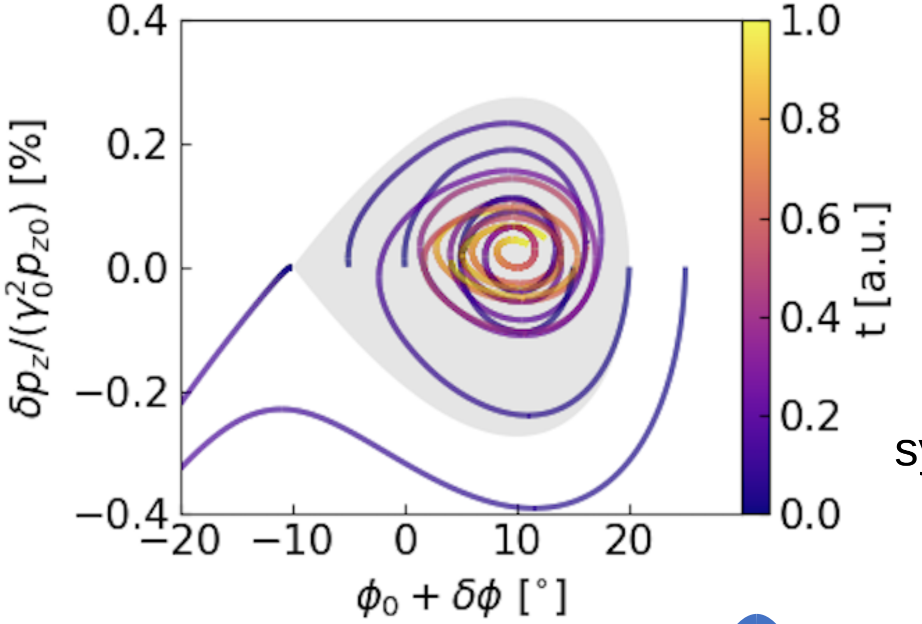
Nuclear Physics B 975 (2022) 115675



Low emittance muon ~210 MeV → More compact storage ring → Higher precision 0.1 ppm

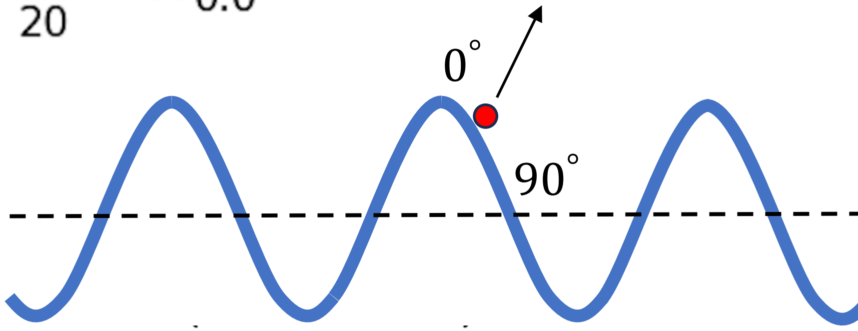
Phase stability analysis





$\beta_i = \beta_\phi$

synchronous particle (SP)



$$\frac{\mathrm{d}^2\delta\phi}{\mathrm{d}t^2} \approx -\frac{q\omega_p\hat{E}_z}{\gamma_0^2 p_{z0}}[\cos(\phi_0+\delta\phi)-\cos\phi_0]$$

$\phi_0 \in [0^\circ, 90^\circ]$

$$H\left(\delta\phi, \frac{\delta p_z}{\gamma_0^2 p_{z0}}\right) = \frac{\omega_p}{2}\left(\frac{\delta p_z}{\gamma_0^2 p_{z0}}\right)^2 + \frac{q\hat{E}_z}{\gamma_0^2 p_{z0}}[\delta\phi\cos\phi_0 - \sin(\phi_0+\delta\phi)]$$