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Laser Accelerators at Peking University

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Outline

- Institute of Heavy ion Physics@ Peking University
- Introduction to Laser Plasma Accelerator
- The Compact laser plasma accelerator (CLAPA-I and CLAPA-II)
- Summary

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Institute of Heavy ion Physics

4.5 MV Electrostatic — Defense & Nuclear Data

2×6 MV Tandem — Aerospace Chips & Nuclear Materials

Large-scale 2 K Cryogenic Circulating Liquid Helium System

2×1.7 MV Tandem — Materials Research

Large-scale AMS Facility

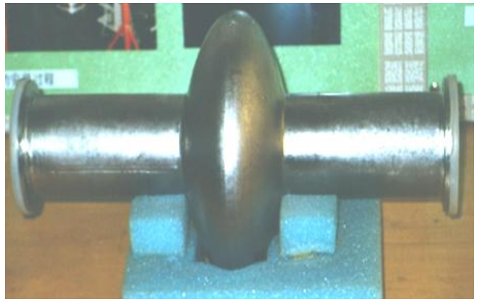
Magnetic Resonance Imager

Institute of Heavy ion Physics

❑ Has set multiple "China's firsts"

The first accelerator – based neutron source

The first domestically produced superconducting accelerator

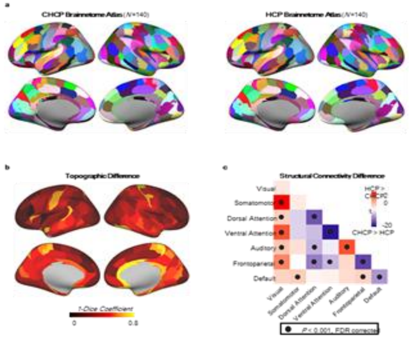


The world's first 1% energy spread laser ion accelerator

1991 | 1992 | 1994 | 2008 | 2017 | 2022

The first accelerator mass spectrometer

The first 1.3 GHz 9 cell superconducting cavity



The first Chinese Human Connectome Project. (CHCP)

Laser Plasma Laboratory

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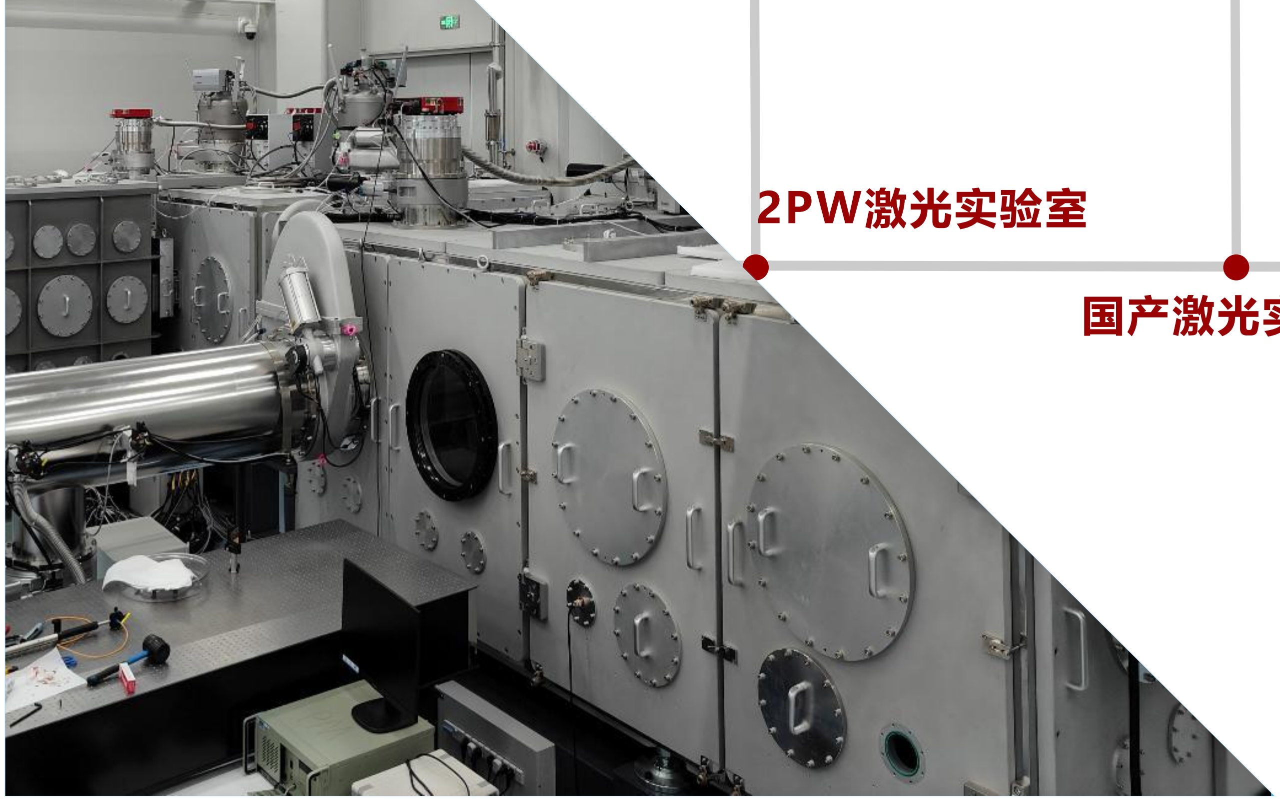
■ **The world’s highest-average-power petawatt laser and its dedicated experimental platform.**



2PW激光实验室

国产激光实验室

中央控制室

质子加速靶场

肿瘤辐照实验室

束流传输实验室

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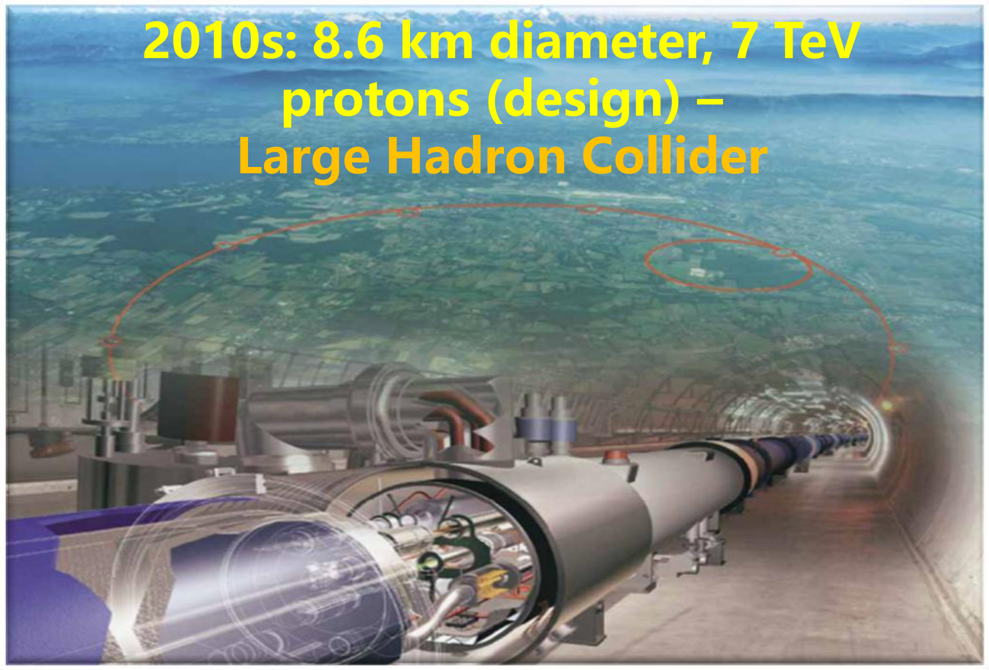
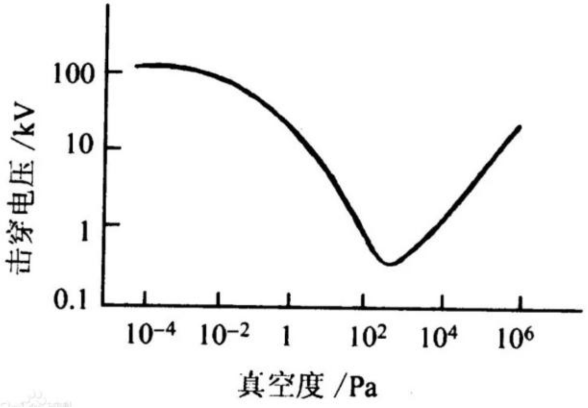
Challenge of Charged-Particle Accelerators

1930s: 10 cm diameter, 80 keV ions – the earliest cyclotrons



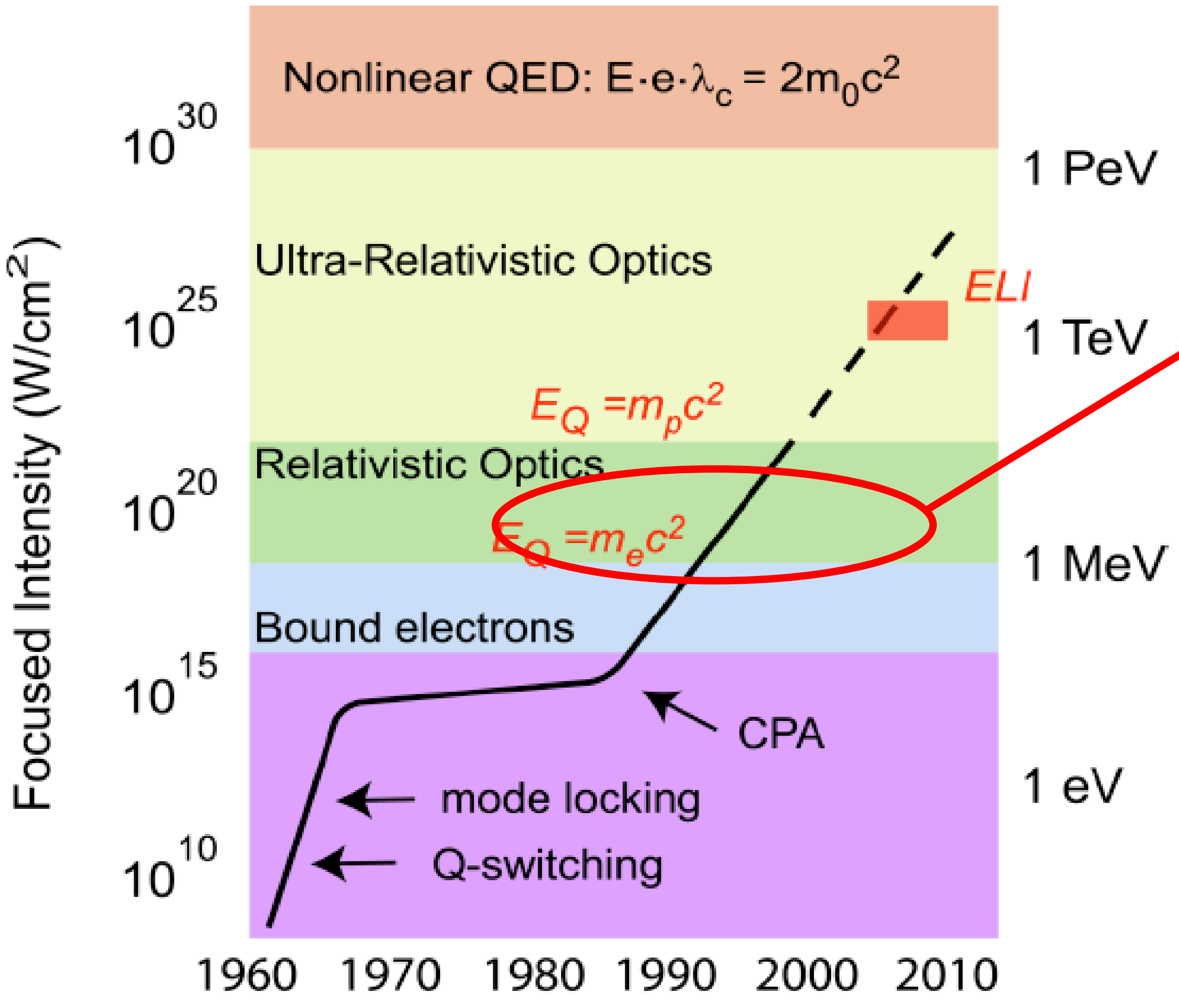
Vacuum breakdown limits the electric gradient to the order of tens of MV/m.
To reach higher energies, accelerator size and cost must keep increasing.



① Raising the accelerating gradient;

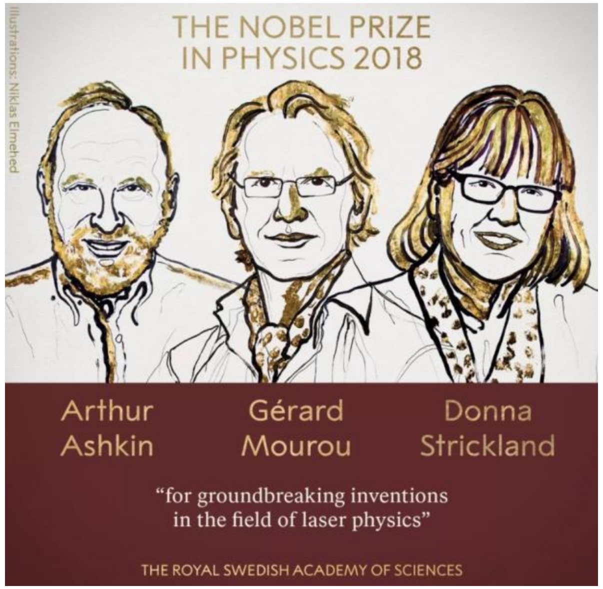
② Finding one medium that can withstand high gradients.

Laser can provide ultrahigh E field



Focused Intensity vs. Year (T. Tajima and G. Mourou, PRSTAB2002)

- $I_0 = 10^{18-22}$ W/cm²
- $E_0 = \left(\frac{2I}{\varepsilon_0 c}\right)^{1/2}$ **>1-100 TV/m**
- **Millions times beyond conventional RF accelerators!**



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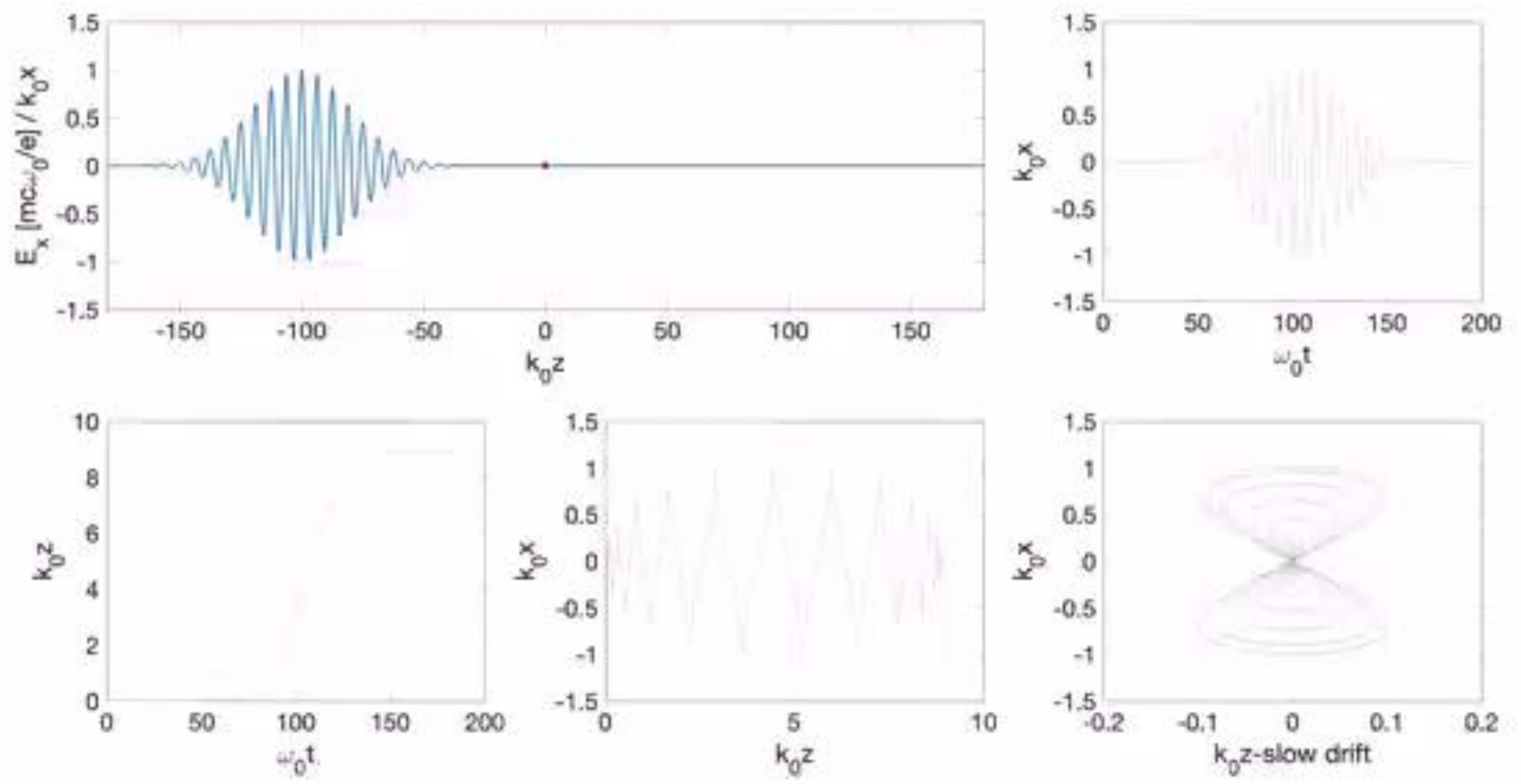
Can E_{laser} be used directly for acceleration?



How to use laser for acceleration?

The Lawson–Woodward theorem is a fundamental result concerning the acceleration of free particles in electromagnetic fields. It states that under certain conditions a free particle in vacuum cannot be accelerated by an electromagnetic wave:

1. The electron moves linearly at high energy.
2. The particle is far from any sources (dielectrics, conductors, plasmas).
3. No electrostatic or magnetostatic fields are present in the region.
4. Idea vacuum with no boundary conditions.
5. Nonlinear effects are neglected.

High gradient laser accelerator

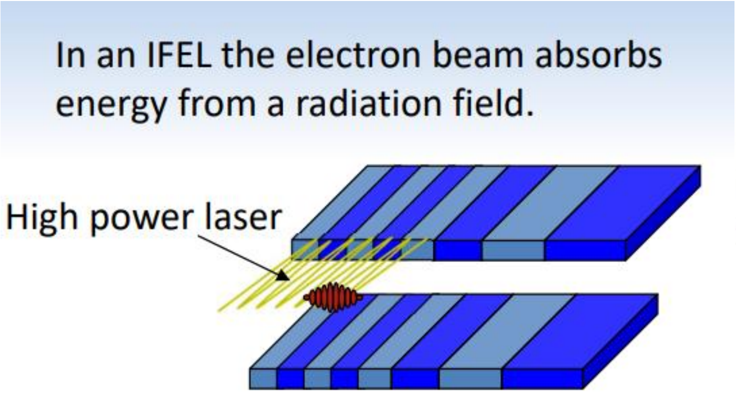
Laser accelerators deliberately break these ideal conditions to circumvent the Lawson–Woodward prohibition.

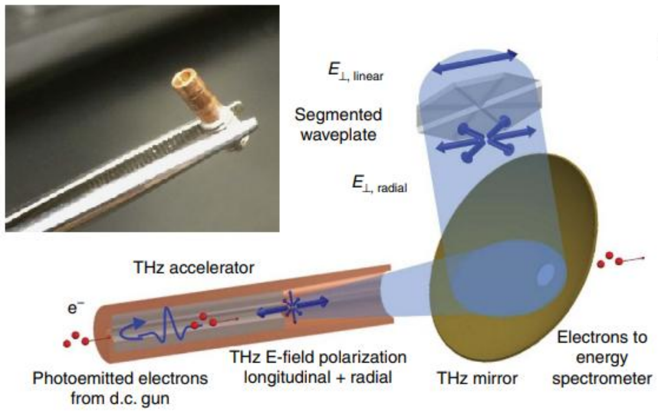
① Laser Vacuum Accelerator: inverse FEL/quasi-pondermotive acceleration….(break 1/3/5)

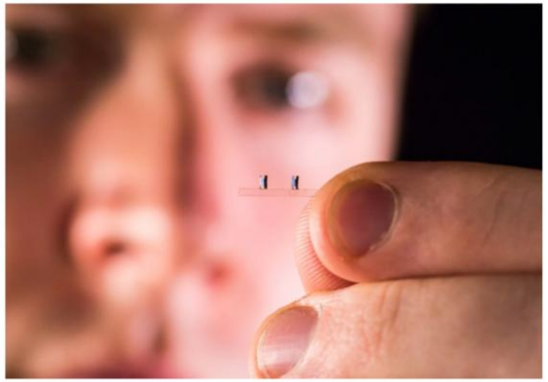
② Laser-induced THz accelerator： THz regime ($\boldsymbol{E} \propto \boldsymbol{f}^{1/2}\boldsymbol{\tau}^{-1/4}$) (break 2/4)

③ Dielectric laser accelerator： integration with nanophotonic materials(break 2 /4)

④ Laser Plasma Accelerator： using plasma as the medium, combining high gradients with extended interaction lengths (break all!)

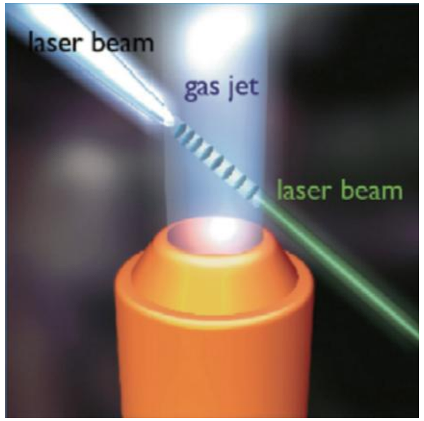






'Accelerator on a Chip'

–SLAC/Stanford



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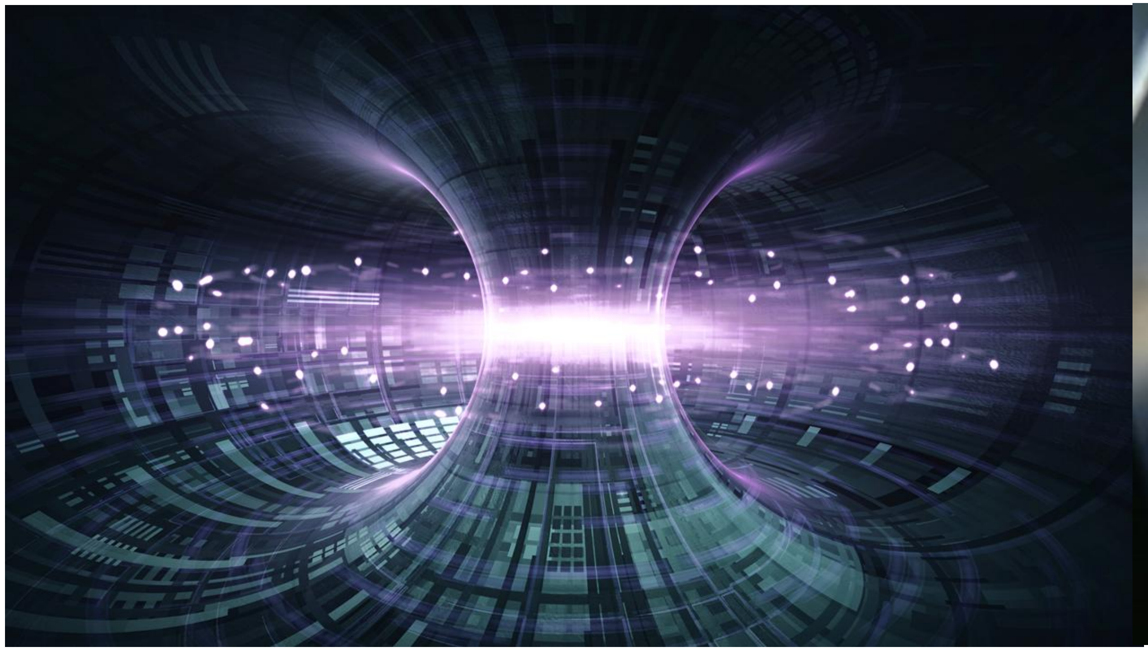
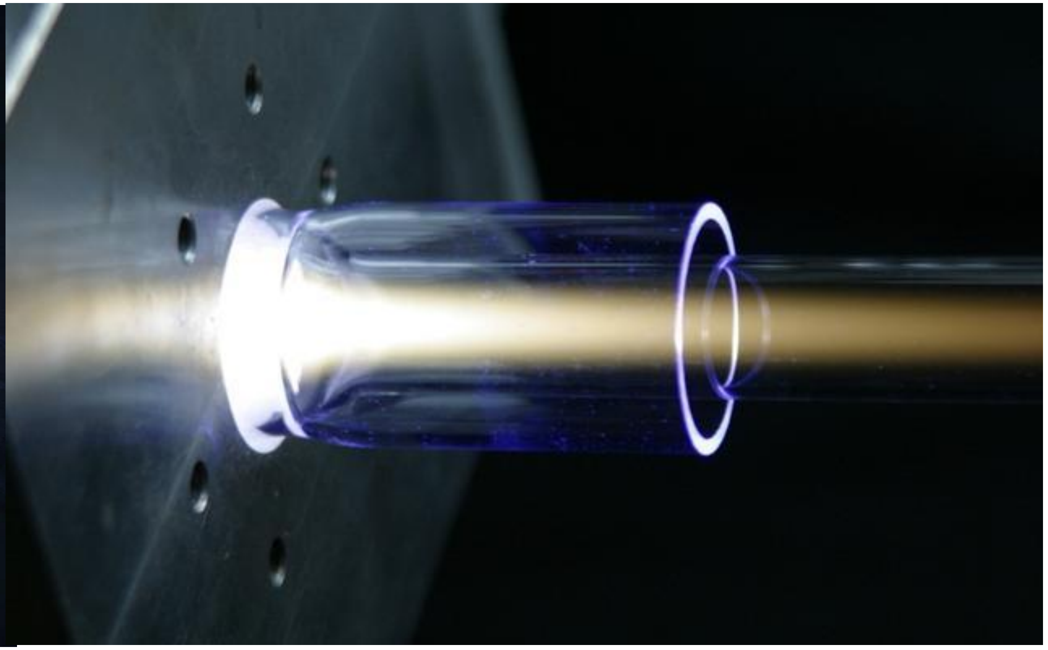
Plasma and Its Advances

- Plasma is the fourth state of matter, accounting for 99 % of the visible universe.
- It is not subject to electrical breakdown thresholds.
- Plasma can sustain extreme temperatures, currents, and electromagnetic fields.
- Composed of charged particles, it can be controlled over long distances by electromagnetic fields.





LPA was first proposed in 1979

$$E_0(V/m) \approx 96\sqrt{n_0(cm^2)}$$

$n_0 = 10^{18}\ \mathrm{cm}^{-3} \Rightarrow E_0 \approx 96\ \mathrm{GV/m}$

$L_d = 1\ \mathrm{cm} \Rightarrow E_{electron} \approx 1\ \mathrm{GeV}$

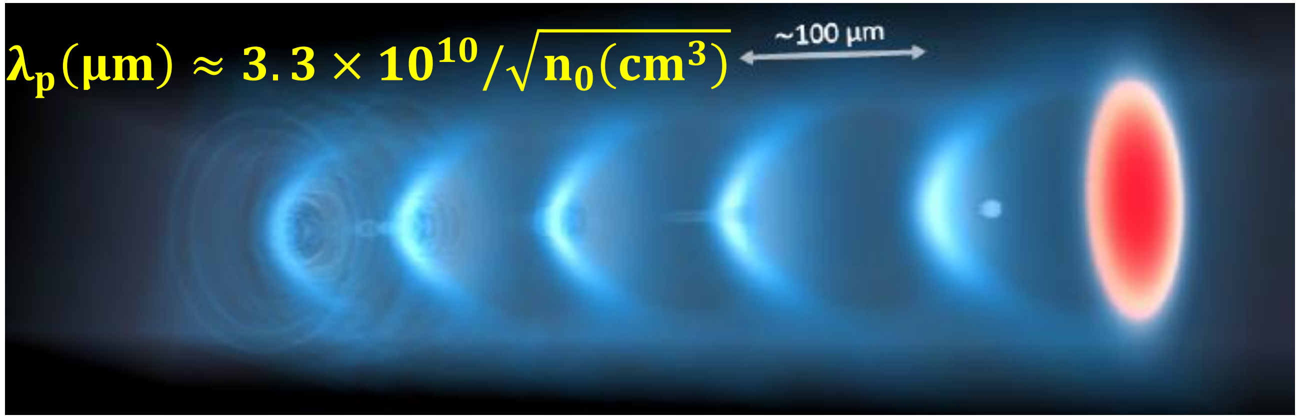
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

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.

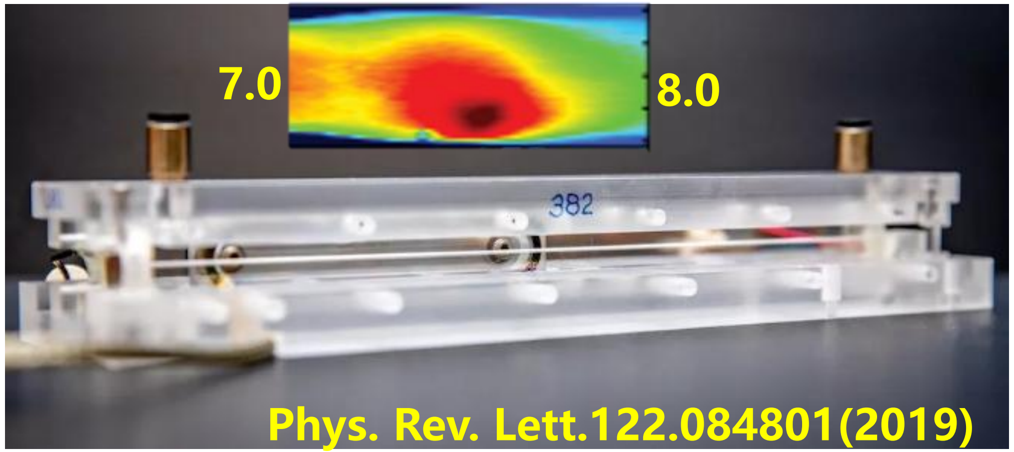
Laser wakefield acceleration



$$F_p = -m_e c^2 \nabla (a^2/2)$$

The term "ponderomotive" derives from the Latin word *pondero*, meaning "to weigh" or "to measure," and the Greek root *motive*, signifying "motion" or "driving." Together, *ponderomotive* denotes **a force that drives and imparts motion to objects**.

In 2019, LBNL accelerated electrons to 7.8 GeV using a 20-cm-long discharge capillary channel.

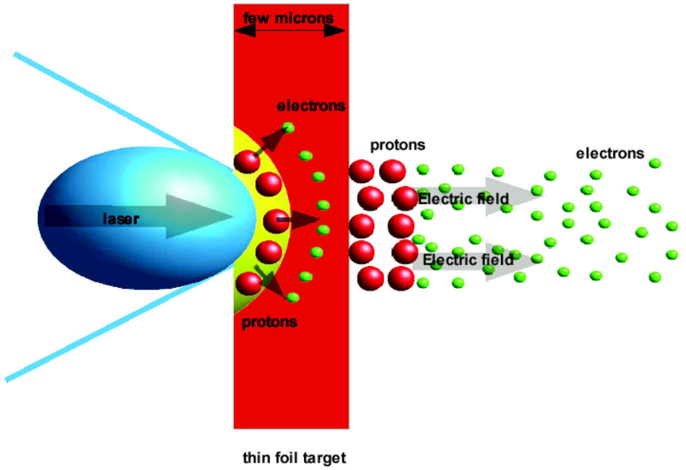


The picture of laser ion acceleration

- Because ions are much heavier, they cannot be directly driven by the laser;
- Ion acceleration relies on the electrostatic field arising from electron–ion charge separation within the plasma.

Target Normal Sheath Acceleration (TNSA)

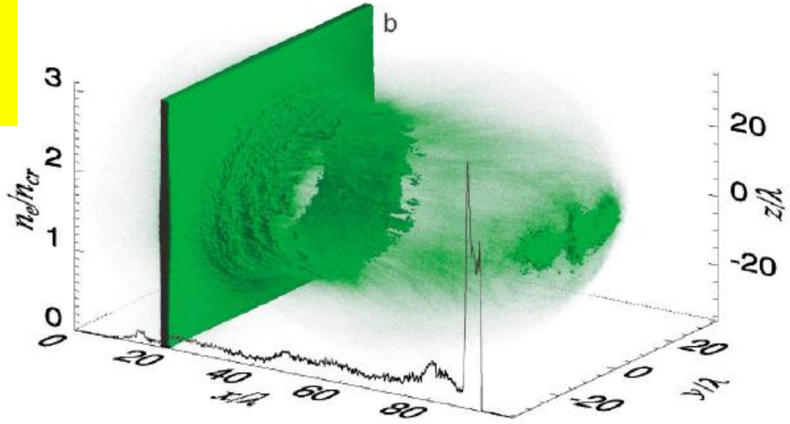
$$a < \frac{n_e L}{n_c \lambda}$$



- $E_{acc} \sim I^{0.5-1} \sim \mathrm{TV/m}$
- d_{acc} ~ Microns distance

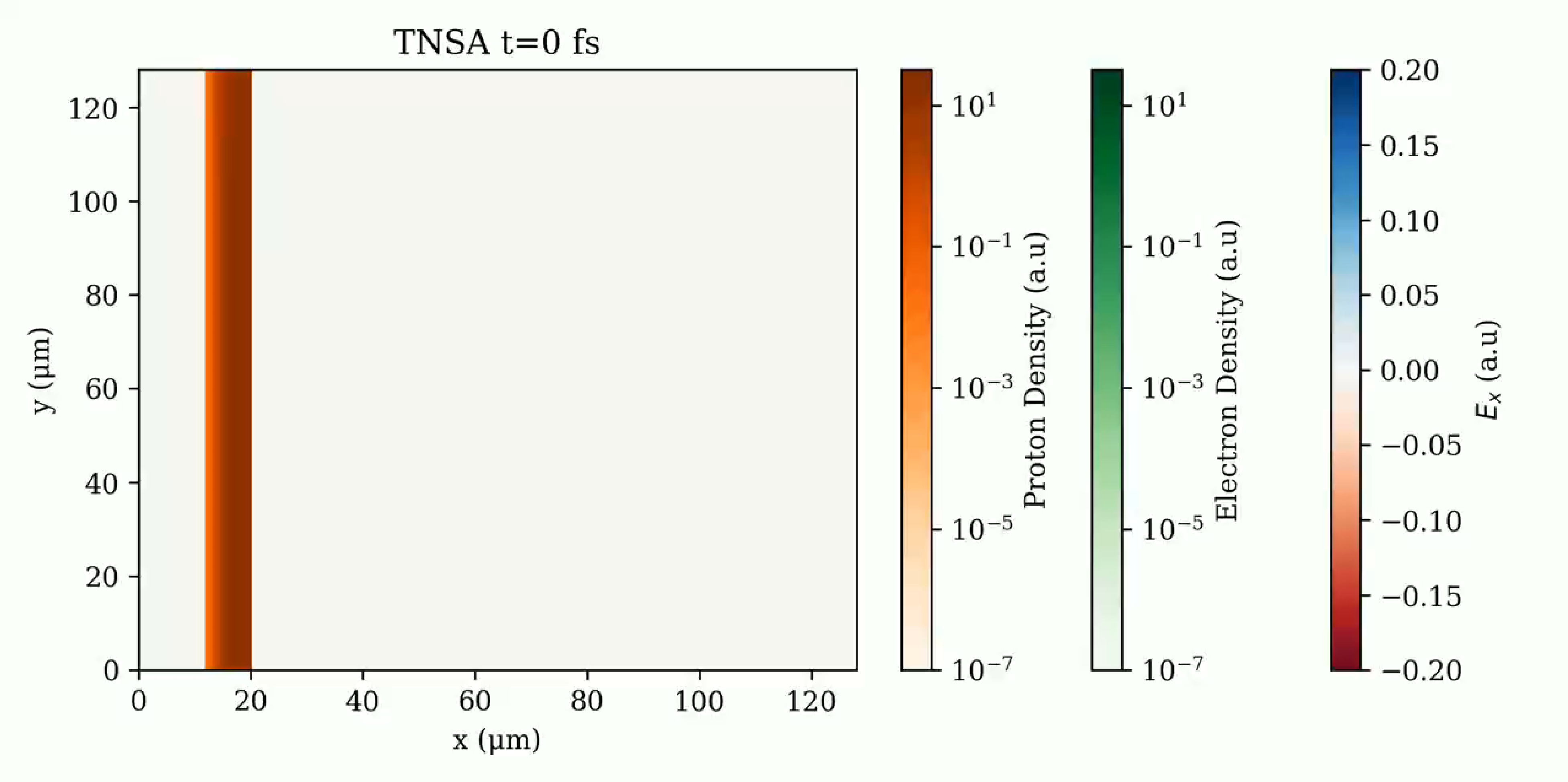
Radiation Pressure Acceleration(RPA)

$$a \sim \frac{n_e L}{n_c \lambda}$$

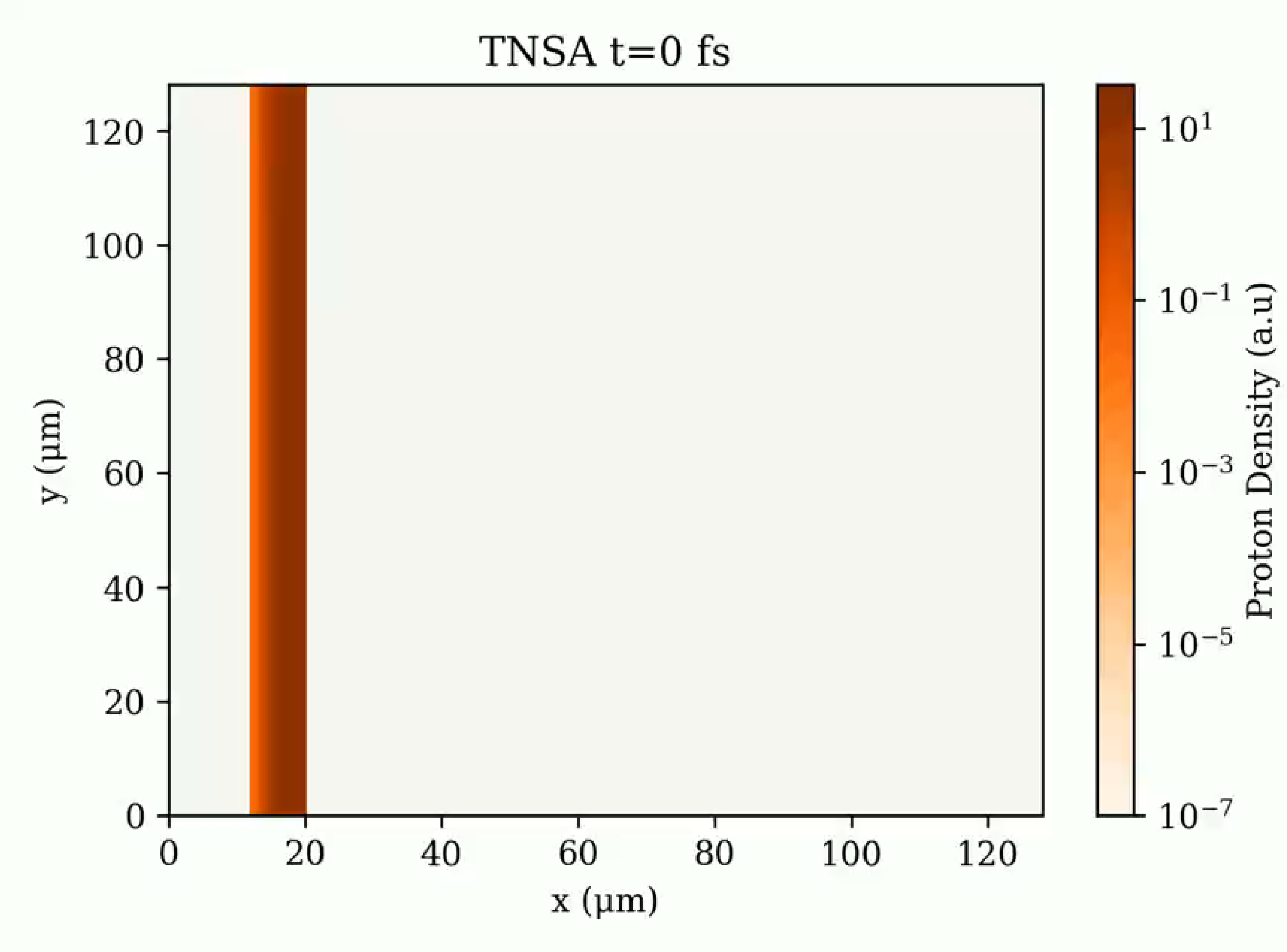


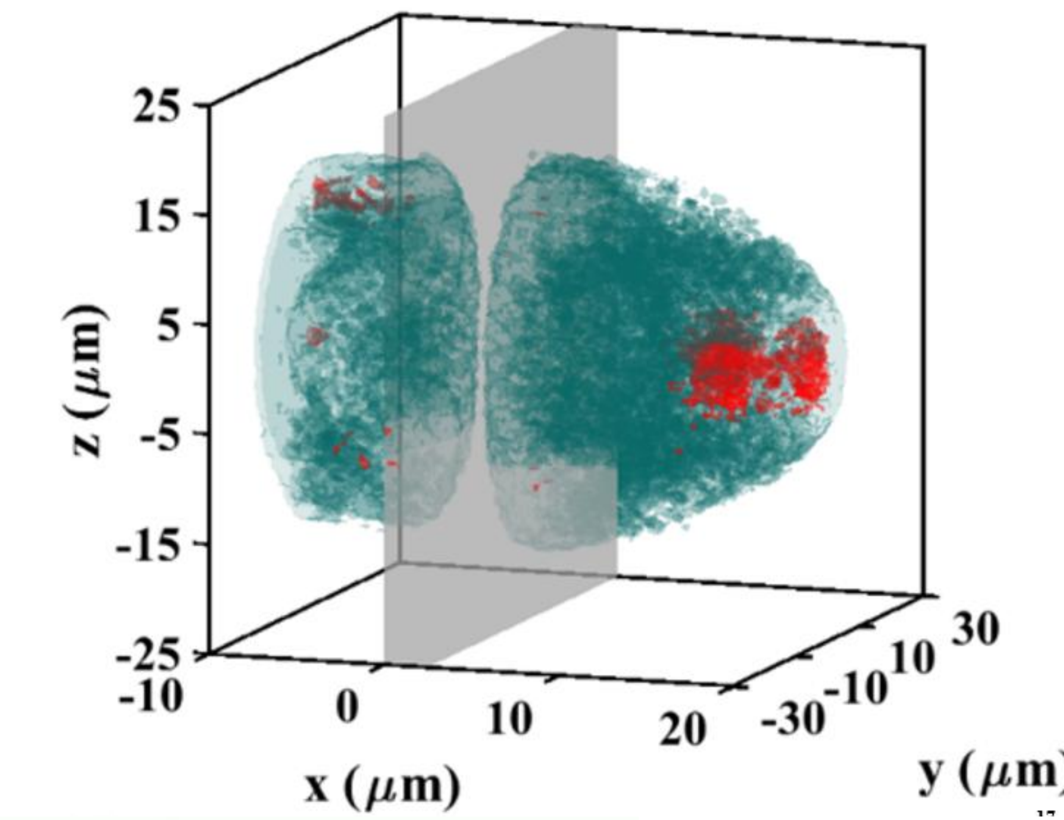
PRL 92, 175003 (2004)

Simulation of laser acceleration Physics process



Simulation of laser acceleration Physics process





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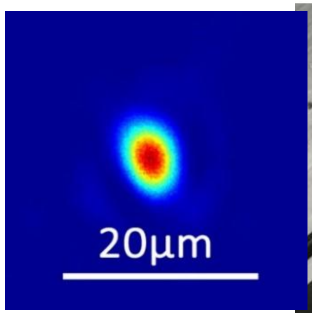
The setup of laser ion accelerator

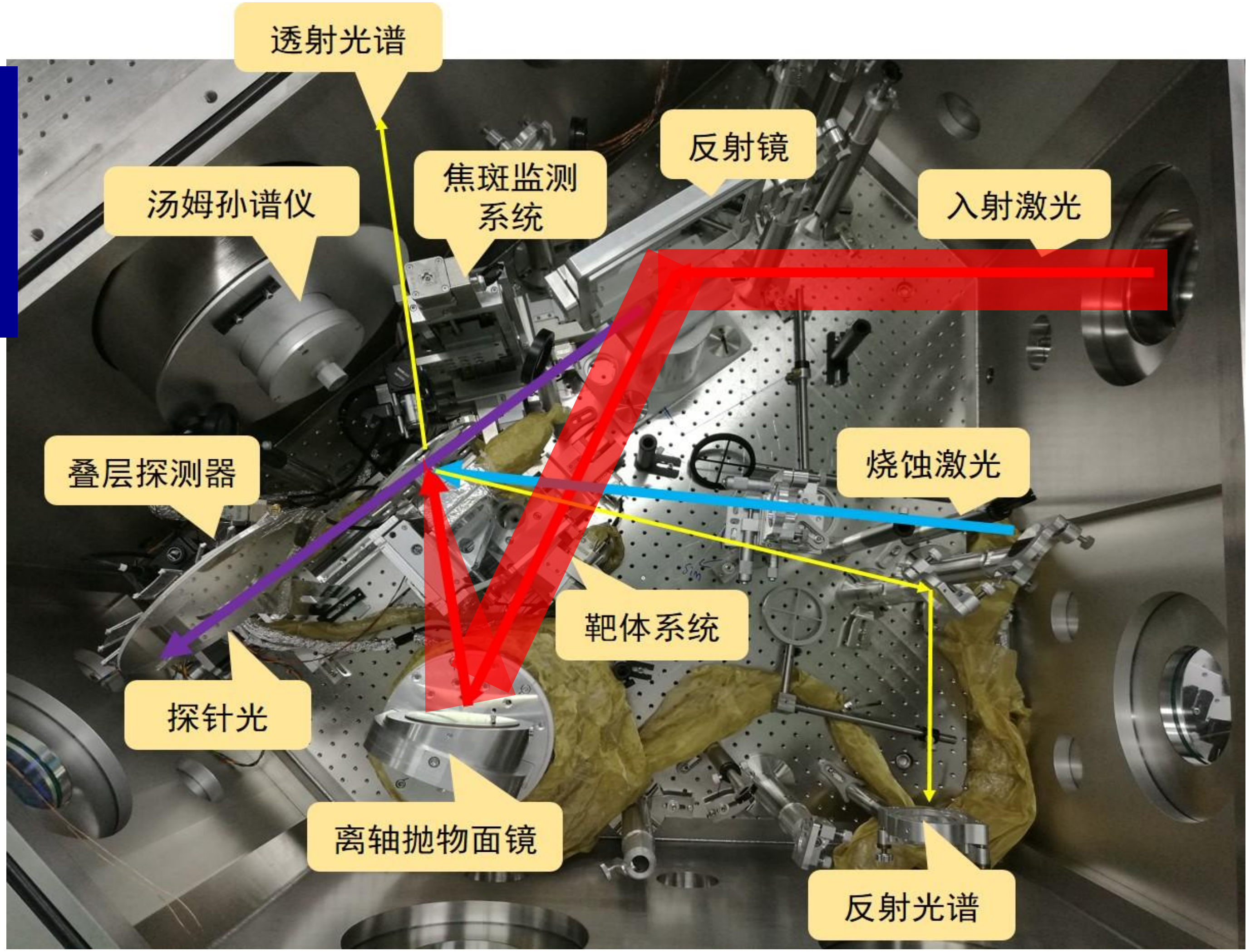
Laser parameters:

- Energy：1.8J
- Duration：30fs
- Intensity：8.3×10^{19} W/cm^2
- Spot size：4.5μm×5.3μm（FWHM）



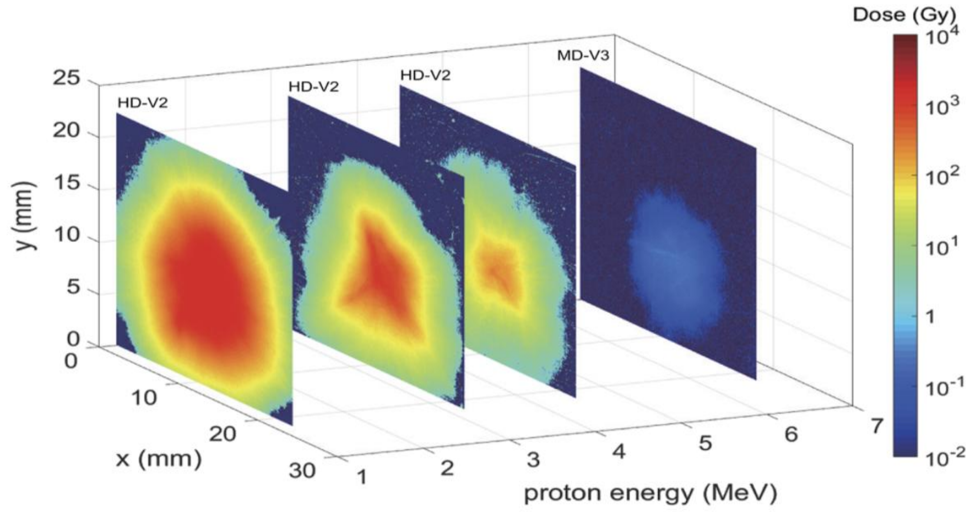
Target parameters:

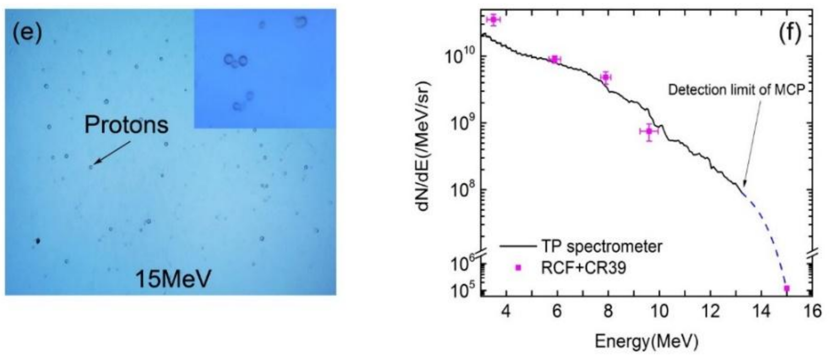
- Mirco-thickness solid foil



Characteristics of Laser Accelerated Protons

Typical energy spectrum and angle distribution of TNSA laser accelerated proton beam

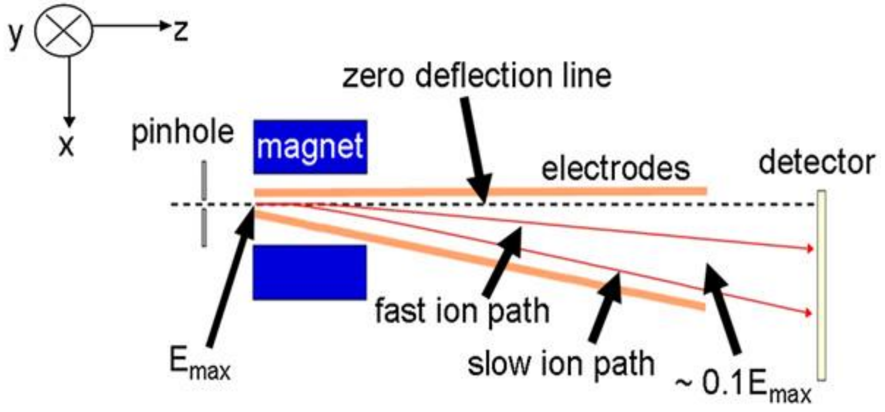


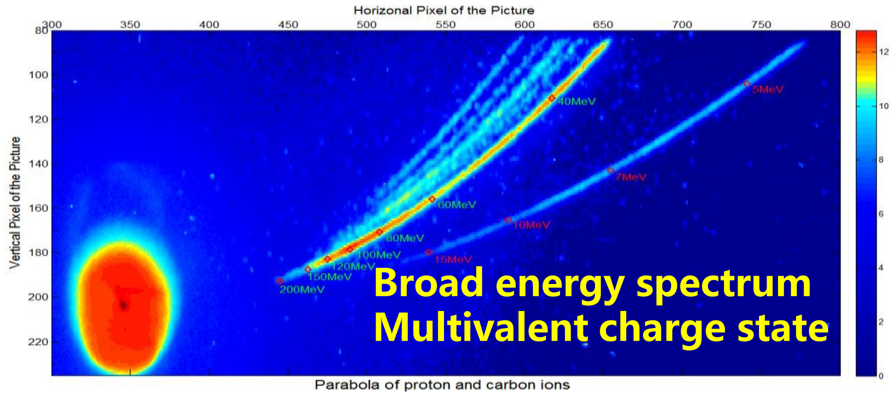


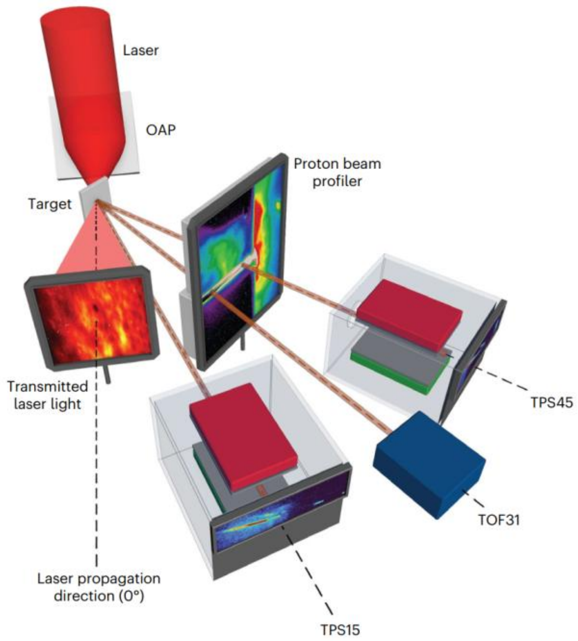
- Point source ~μm
- Particle number ~10^9-10^{13}
- Short pulse ~ps-ns
- Low emittance ~mm·mrad
- **Large divergence angle ~10°**
- **Broad energy spread~100%**

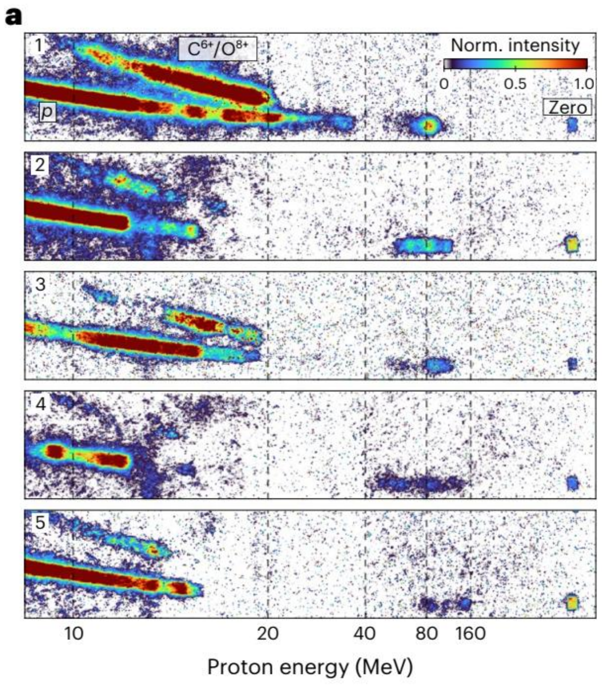
Laser ions also have wide energy-spectra

Using the DRACO-PW laser, a 30 fs laser pulse with 6.5×10^{21} W/cm^2 intensity was focused on a 250 ± 25 nm thickness plastic target, which created the laser-accelerated protons at a record energy of **150 MeV**.





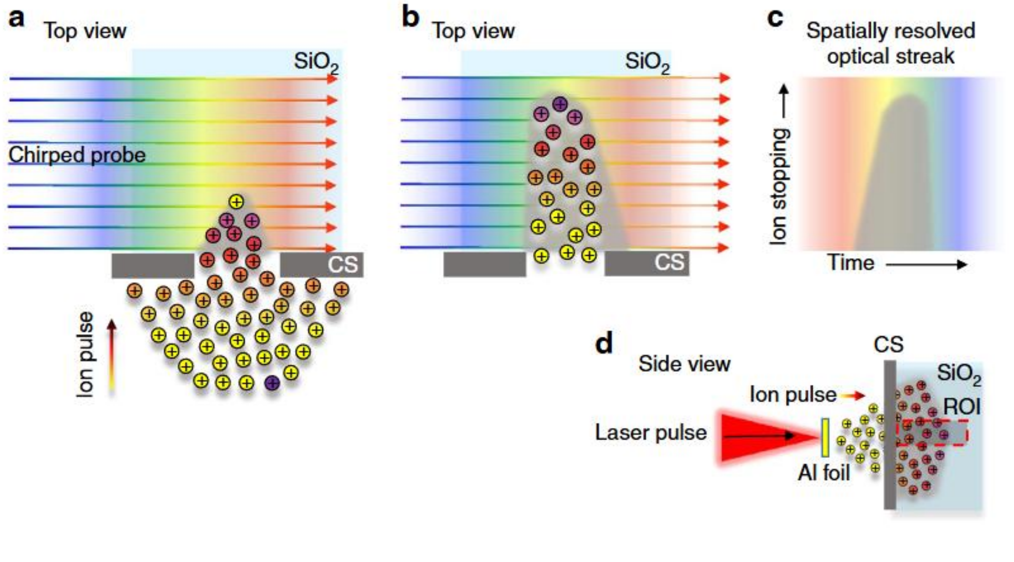




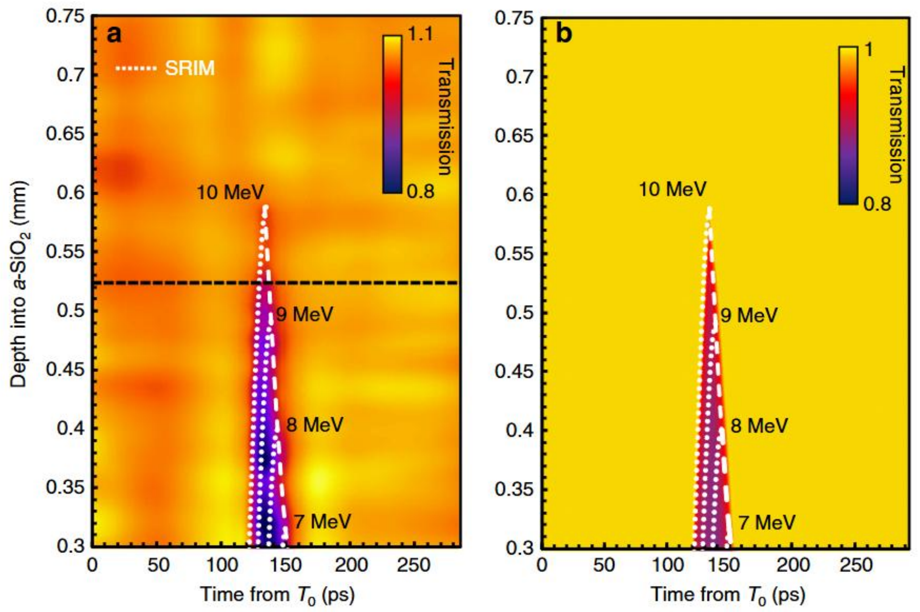
Nature Physics 20, 1211-1216 (2024)

Laser-accelerated protons with ps duration

- A synchronized chirped laser pulse tracked the transient opacity induced in SiO_2 by these protons, yielding a minimum pulse width of **3.5 ± 0.7 ps** and extending ultrafast science into the regime of ion interactions.
- At 10^{10}–10^{12} ppp, the peak current exceeds the **kilo-ampere level**.



Transient opacity induced by ions in SiO_2



Nat Commun 7, 10642 (2016).

Proton Radiotherapy Based on Laser Accelerator

- In 2022, there were **19.96 M** new cancer cases and **9.74 M** cancer-related deaths worldwide. In China, the numbers were about **4.82 M** and **2.57 M.**
- Proton therapy is an advanced radiation treatment technology that requires precise adjustment of the proton beam to ensure the therapeutic beam accurately targets the tumor site.

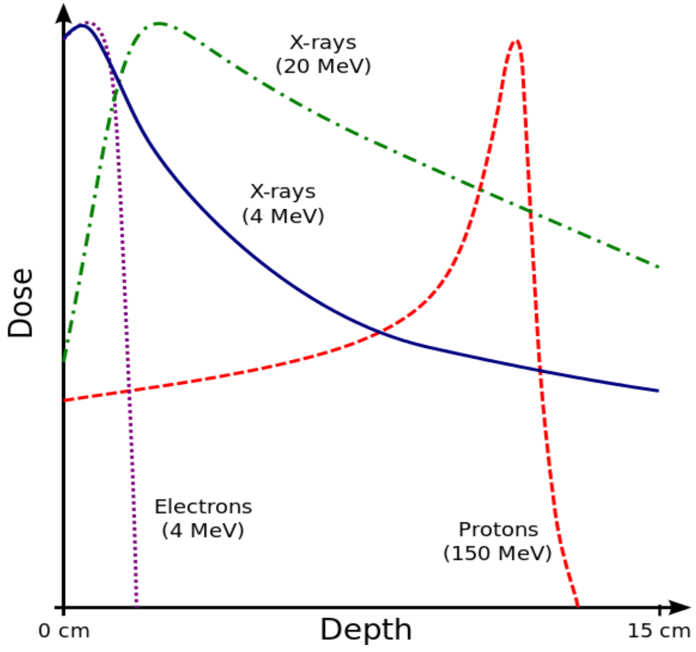
Advantages:

1.Ultra-high dose rate $\mathbf{10^9\ Gy/s}$;

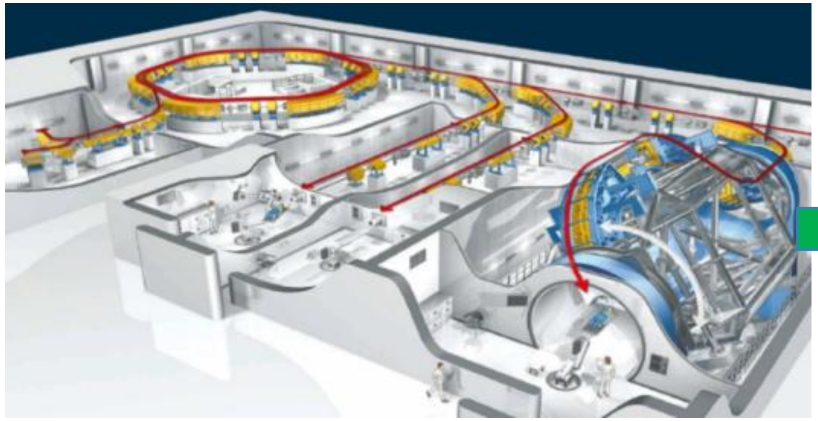
2.Lower equipment complexity;

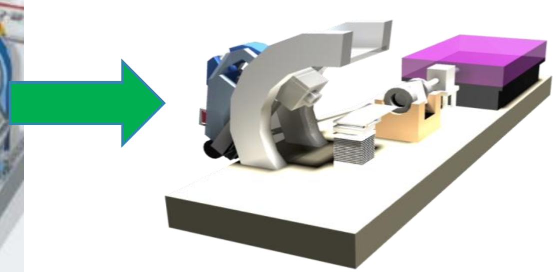
3.Compact size;

4.Combines radiotherapy with immunotherapy.



常规加速器治疗设备





激光装置

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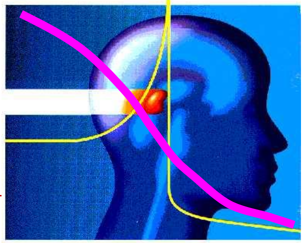
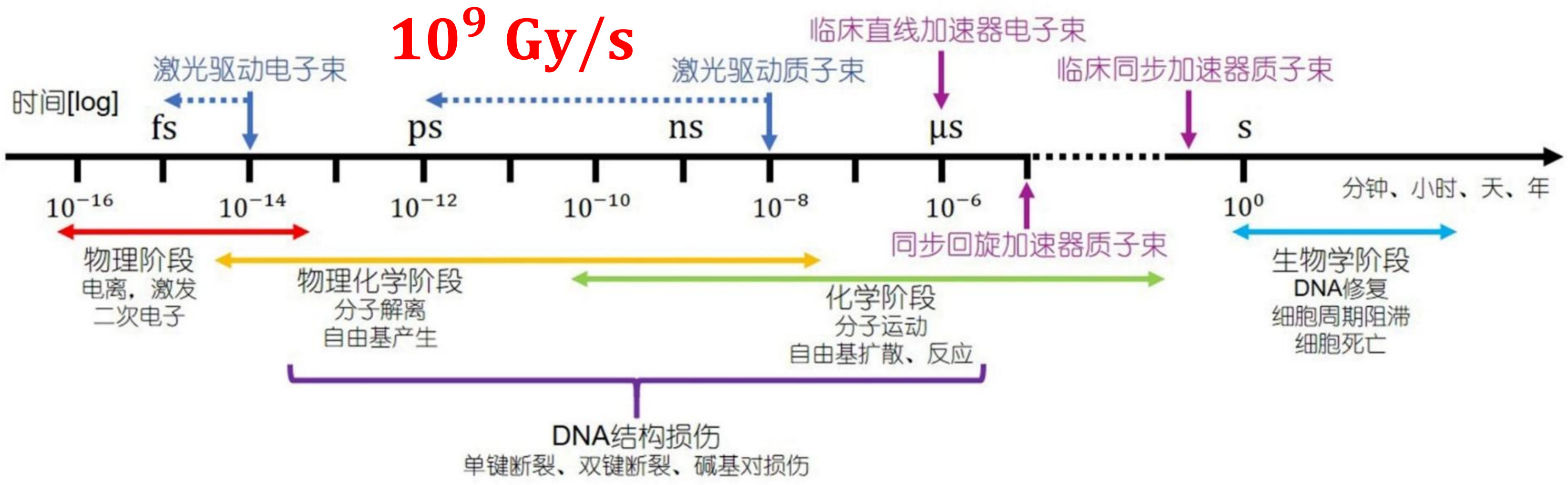
High-dose-rate FLASH irradiation beam

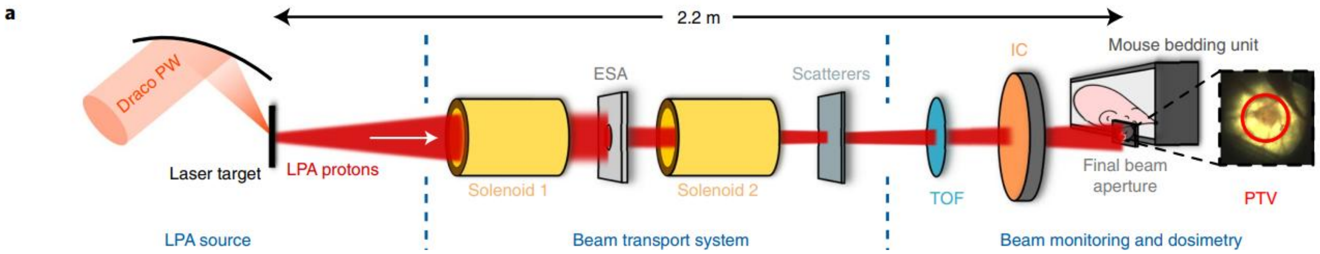


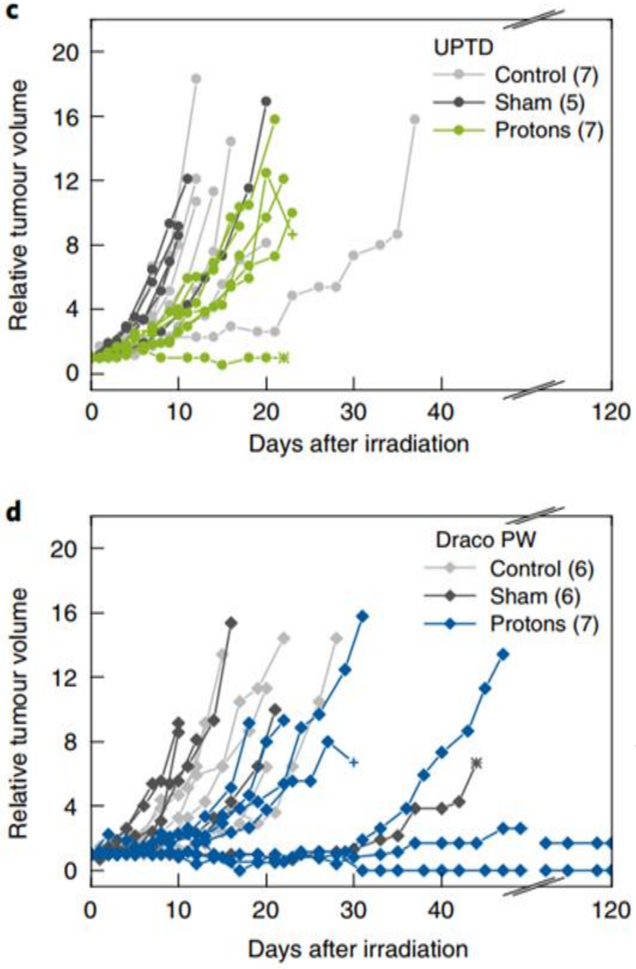


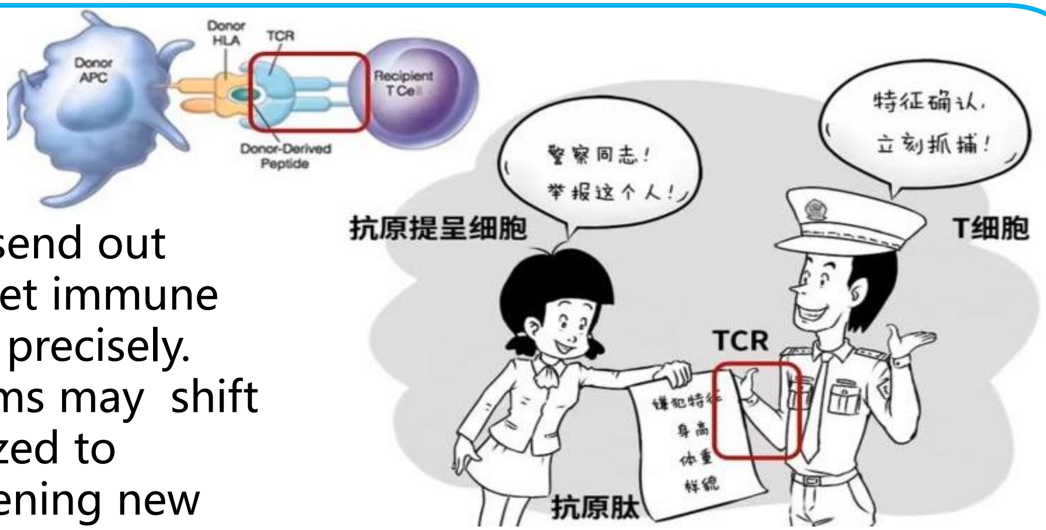
Stage	Time	Core mechanism	Extremely high dose rate beam
Physical Stage	$<10^{-15}$ s	ionization, excitation, secondary particle production	**to be clarified**
Physical-chemical Stage	$10^{-15\text{-}12}$ s	Molecular dissociation, electron hydration, free radicals production	**to be clarified** (Production saturation of free radicals and hydrated electrons?)
Heterogeneous chemical Stage	$10^{-12\text{-}6}$ s	free radicals diffusion, reaction and attack on DNA/biomolecular	oxygen depletion, radicals recombination, ROS scavage, Fenton reaction
Homogeneous Chemical Stage	$10^{-6\text{-}0}$ s		
Biochemical Stage	$10^{0\text{-}3}$ s	DNA repair, enzymatic reaction	less damage to normal cells, strong damage to cancer cells
Biological Stage	$>10^{3}$ s	cellular response (cell cycle arrest, death), tissue response	immune response to cancer cells

Ultrahigh dose rate（FLASH）radiation

Experiments have verified that laser accelerated protons **appear to confer a greater suppressive effect** on tumor cells (tissue) than conventional approaches.





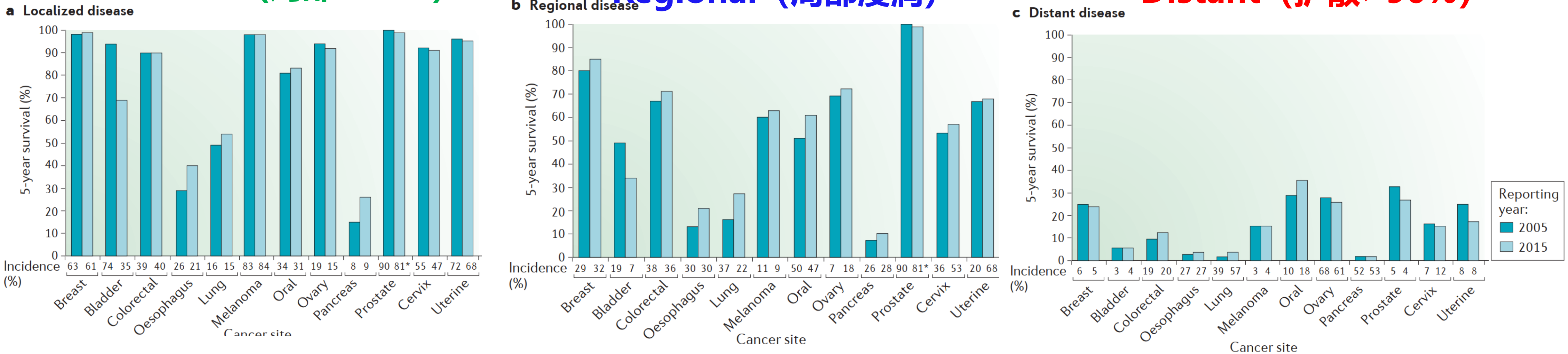


- Laser-irradiated tumors send out "danger" signals that let immune cells spot and kill cancer precisely.
- Laser-driven proton beams may shift radiotherapy from localized to disseminated cancer, opening new treatment paths.

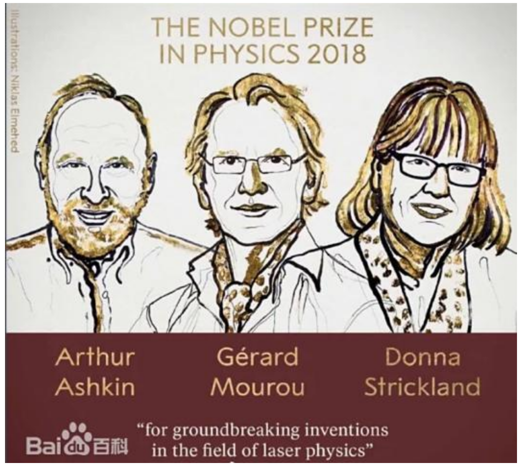
Nature Physics | VOL 18 | 2022 | 316–322

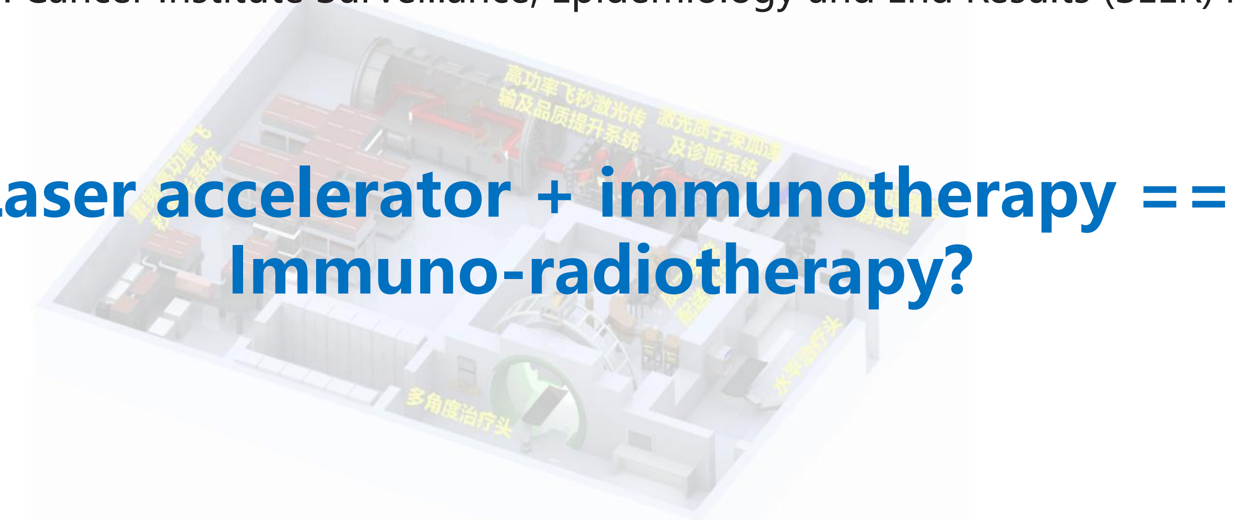
Immuno-radiotherapy?

Localized(局部<10%) **Regional（局部浸润)** **Distant（扩散>90%)**

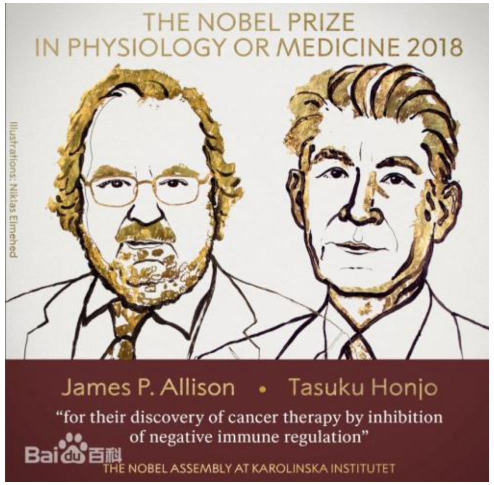


5-year survival for cancer patients of localized (organ confined), regional (invasion to lymph nodes) or distant (metastases detected by imaging) using the US National Cancer Institute Surveillance, Epidemiology and End Results (SEER) registries.



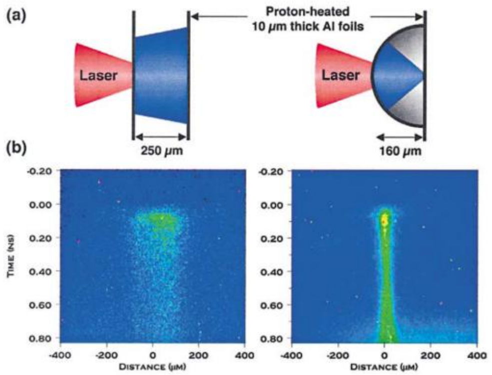


Laser accelerator + immunotherapy ==
Immuno-radiotherapy?



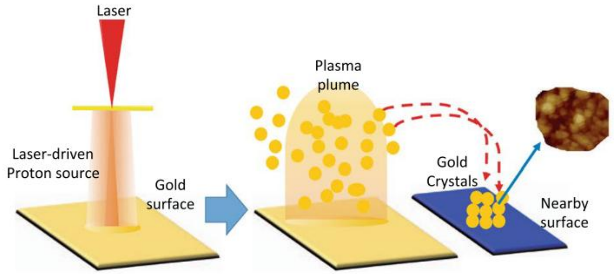
Irradiation applications with ultra-intense beam

Short
(picosecond level)
Warm dense matter generation



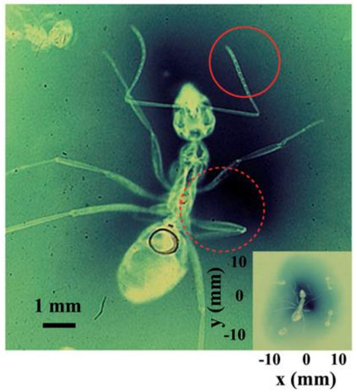
PRL 91(12):125004(2003).

Intense
(instantons current~ kA)
Material irradiation under extreme conditions



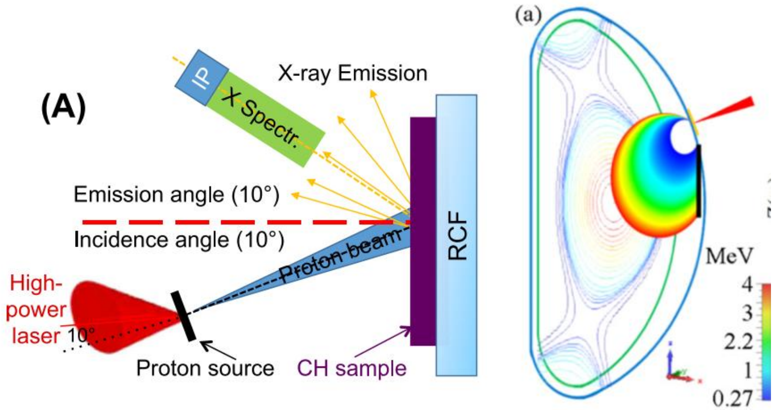
SR 7(1):1-9(2017).

Small
(source size ~ μm)
Proton radiography



AIP Advances 11,085316(2021).

Wide
(energy spread ~ 100%)
Ion analysis



SR 7:40415 (2017).
NF 62, 106028 (2022).

Compared to traditional accelerators, laser-accelerated proton beams exhibit unique beam characteristics, offering novel opportunities for research and potential applications across a wide range of scientific fields.

Plasma Based Beam Device

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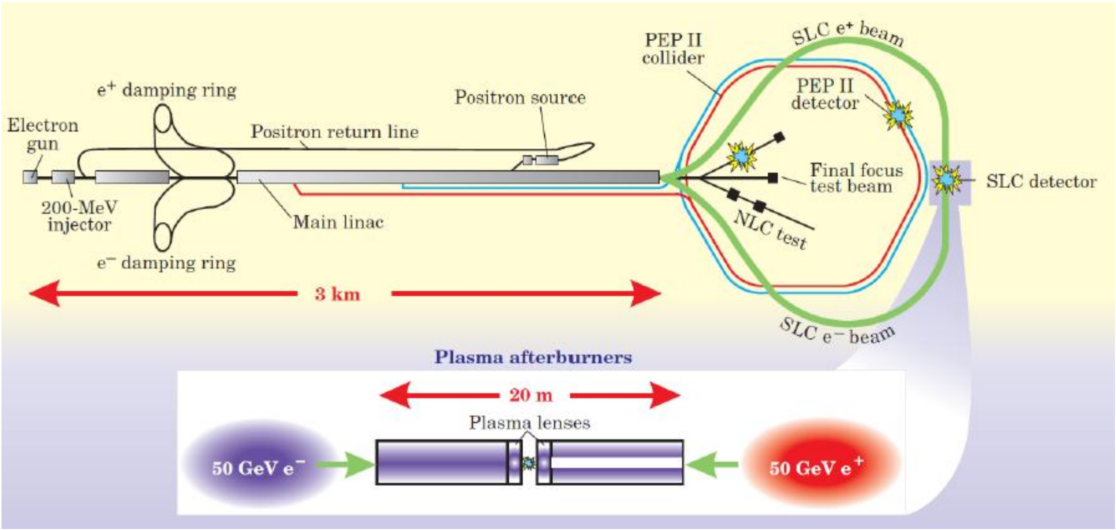
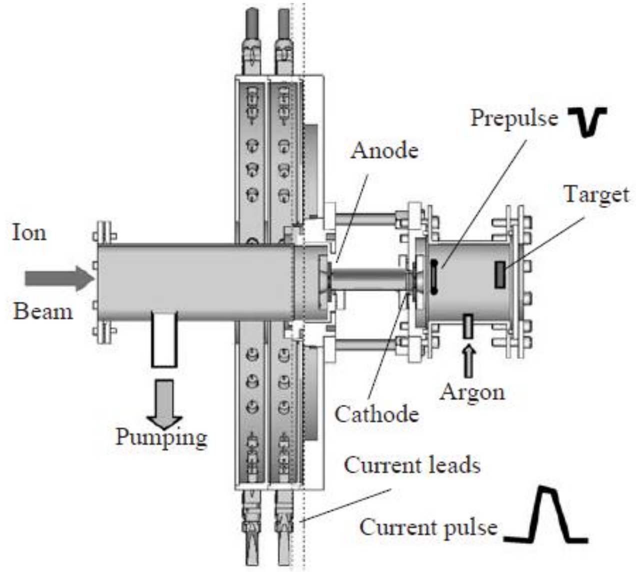
- Plasma can serve as an ideal medium for neutralizing space charges. It can be employed as a novel component for controlling the transmission of particles.
- When interacting with strong lasers and particle beams, plasma exhibits various nonlinear effects.



Plasma used as the extraction for high-energy colliders



Plasma as the injection for heavy ion driven fusion

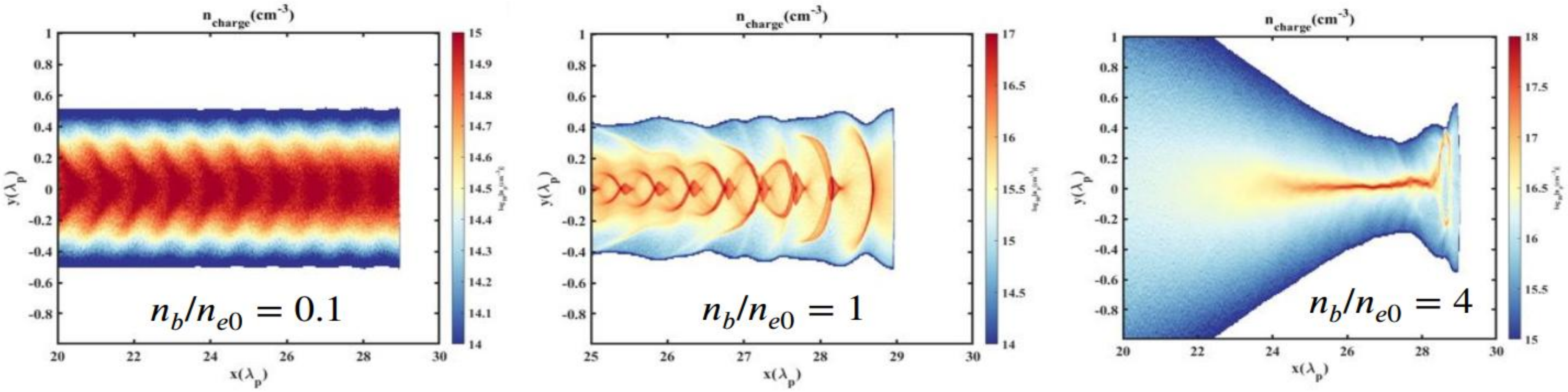
Phys Rev Lett. 66(13): 1705-8 (1991). Physics Today. **56**, 47 (2003). Phys. Part. Nucl. Lett. **5**, 582 (2008).

Pictures of passive plasma lens

Passive plasma lens (PPL) :

- Beam self-generated magnetic field
- Magnetic field gradient **~MT/m**
- Bottleneck: focusing characteristics strongly depend on beam parameters

Small perturbation | **Periodic wakefield** | **Self-generated magnetic field**



Pictures of for active plasma lens

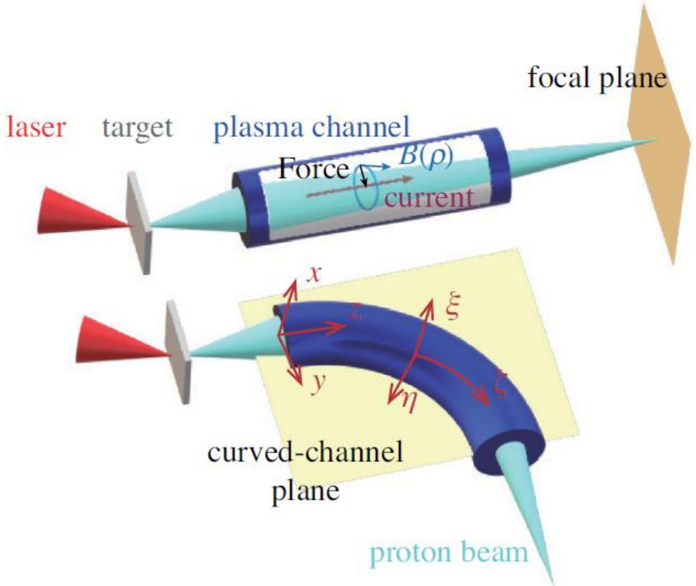
Active plasma lens (APL):

- External current
- Magnetic field gradient **~kT/m**
- Good stability and adjustability
- Bottleneck: complex structure, multiple external devices, high power consumption, Z-pinch effect

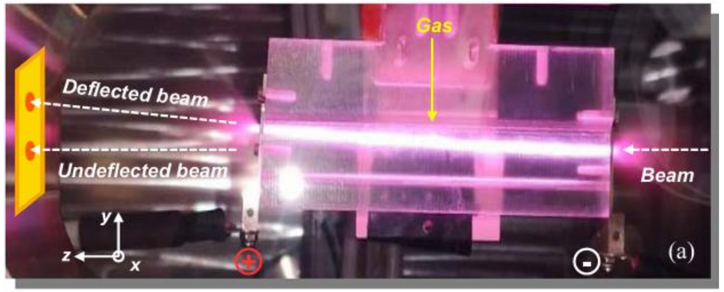
Hill equation

$$\frac{d^2\rho}{dz^2} + K\rho = 0$$

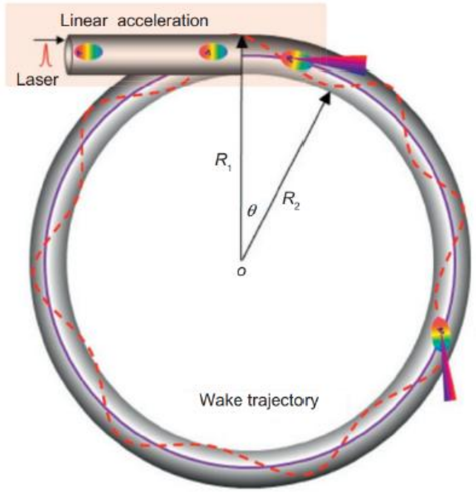
$$\begin{cases} \frac{d^2\xi}{d\zeta^2} + K\xi = 0 \\ \frac{d^2H}{d\zeta^2} + KH = 0 \end{cases}$$



PRAB 24, 031301 (2021). PRAB 27, 052802 (2024).



Light: Sci. Appl. 5, e16015 (2016)



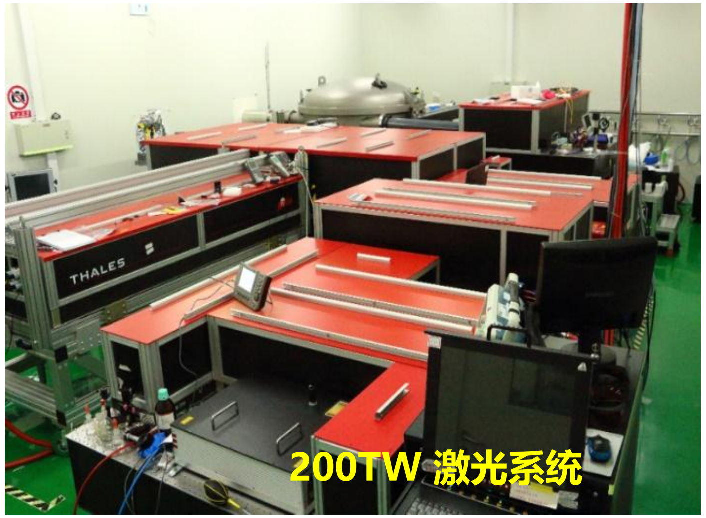
PRL 132, 215001 (2024)

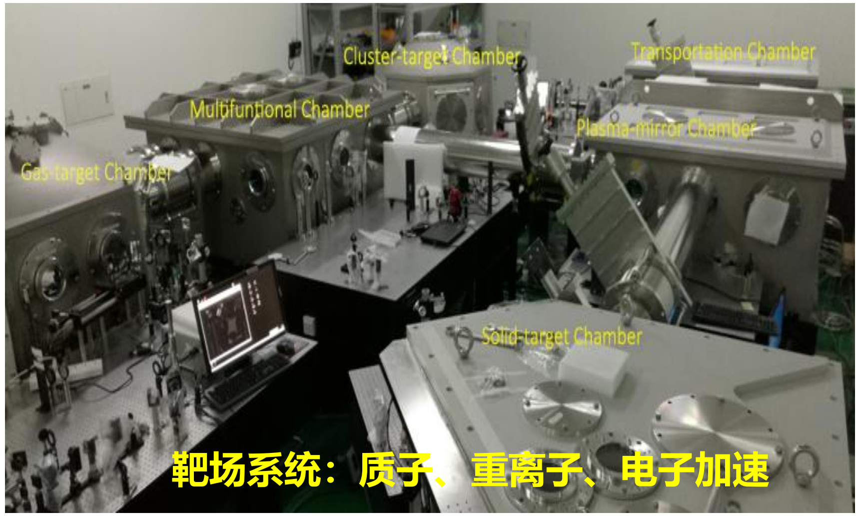
Outline

- Institute of Heavy ion Physics@ Peking University
- Introduction to Laser Plasma Accelerator
- The Compact laser plasma accelerator (CLAPA-I and CLAPA-II)
- Summary

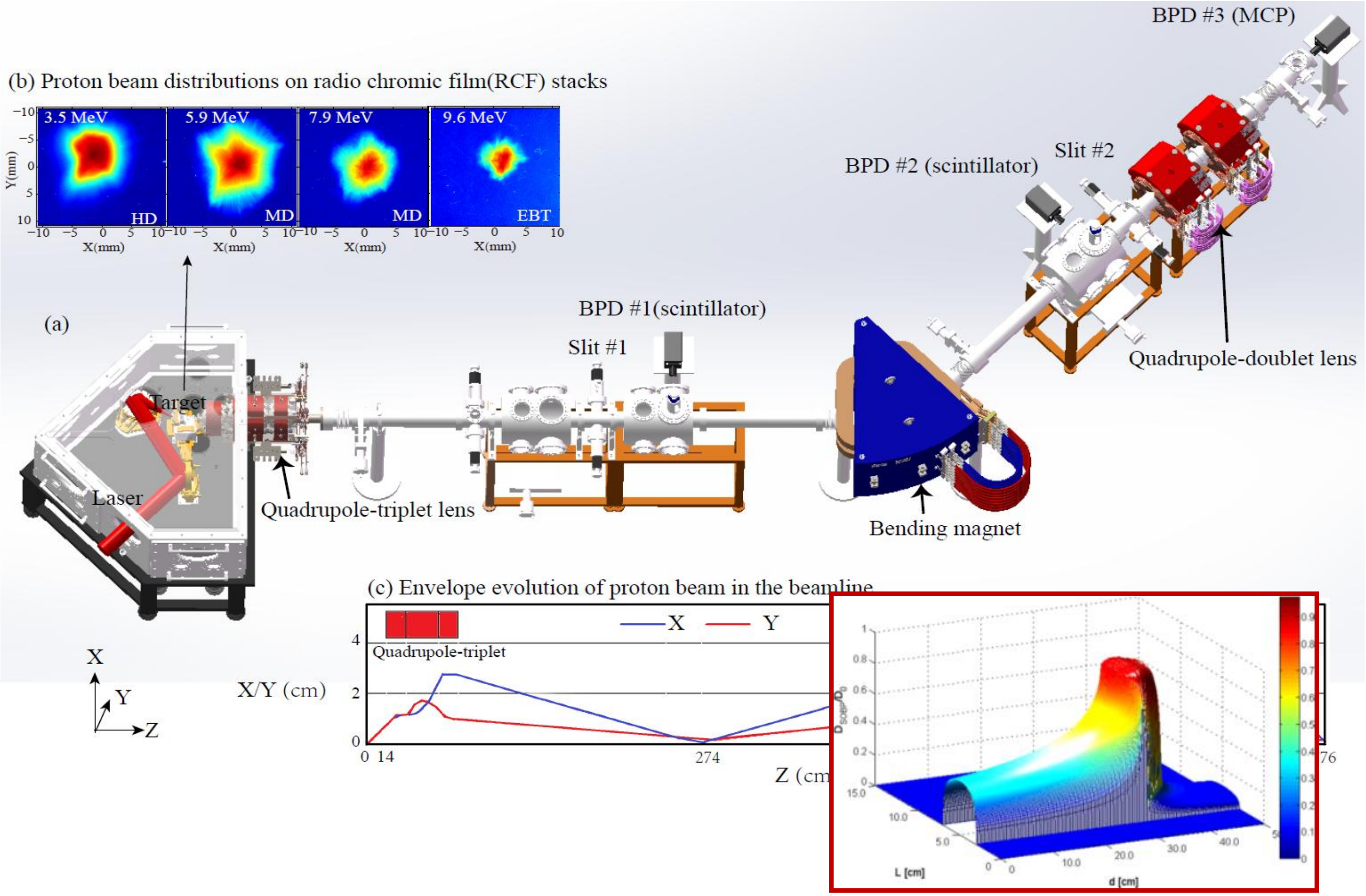
CLAPA-I

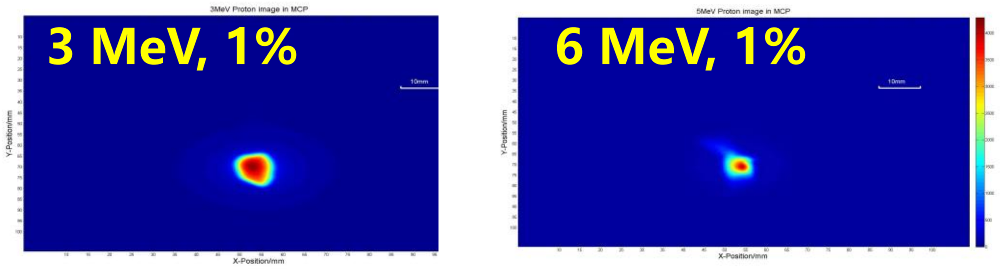
- 2013-2018，Peking University built the first 1% energy spread laser proton accelerator, which can generate proton beam with 1-15 MeV energy ps-ns duration and ultrahigh dose rate.
- **C**ompact **LA**ser **P**lasma **A**ccelerator，**CLAPA-I**.

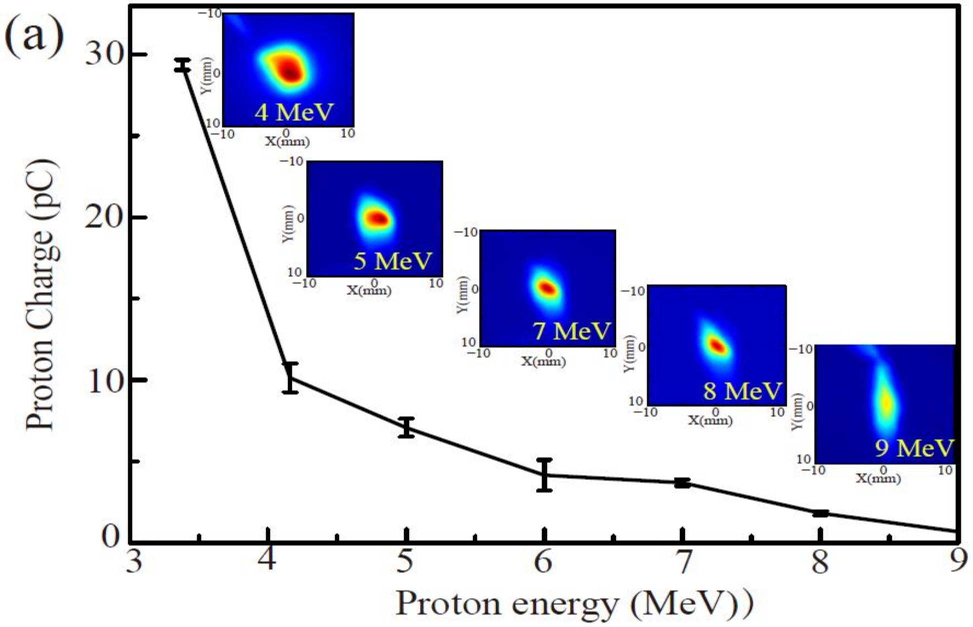




1% energy spread proton beams



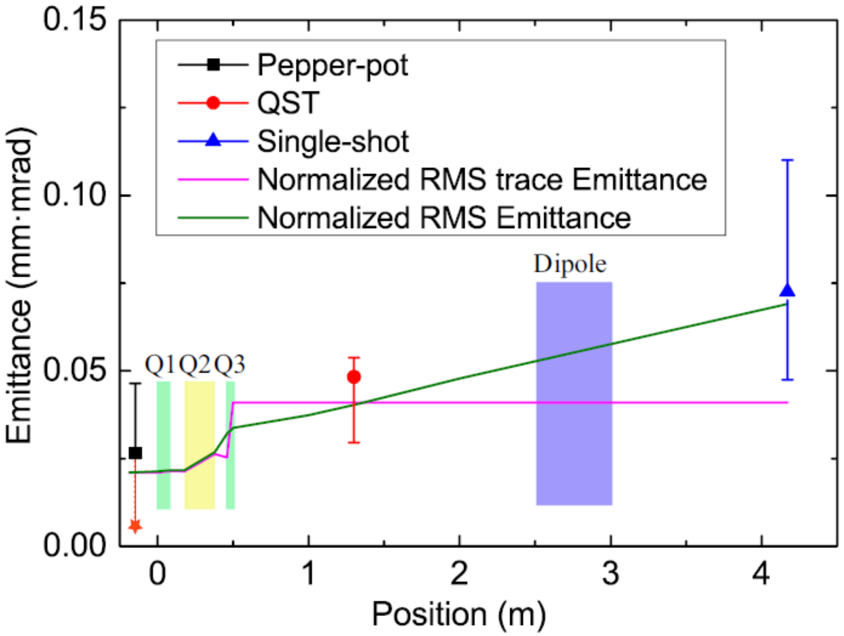


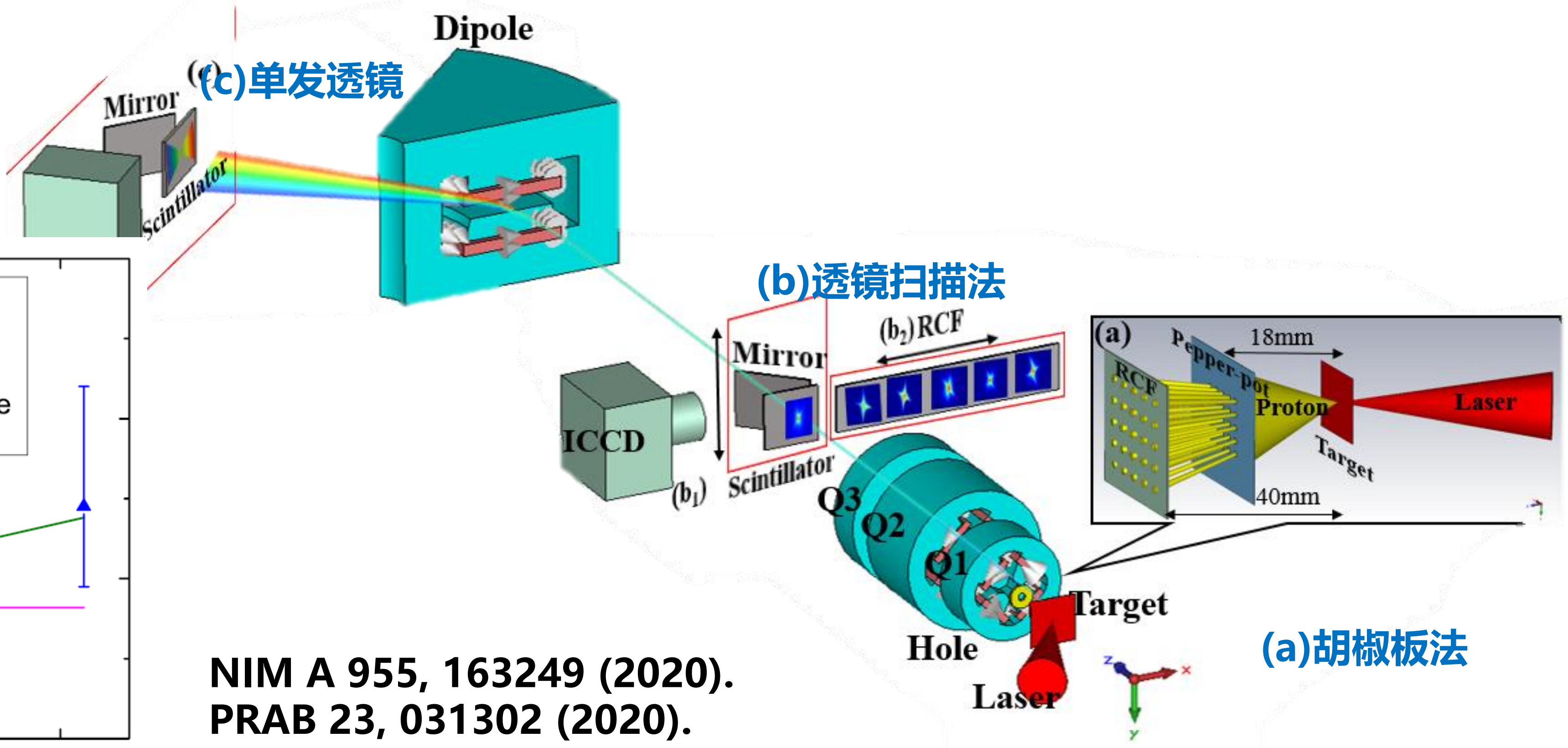


PRAB 22, 061302 (2019). PRAB 23,031302 (2020).

The emittance of laser driven protons

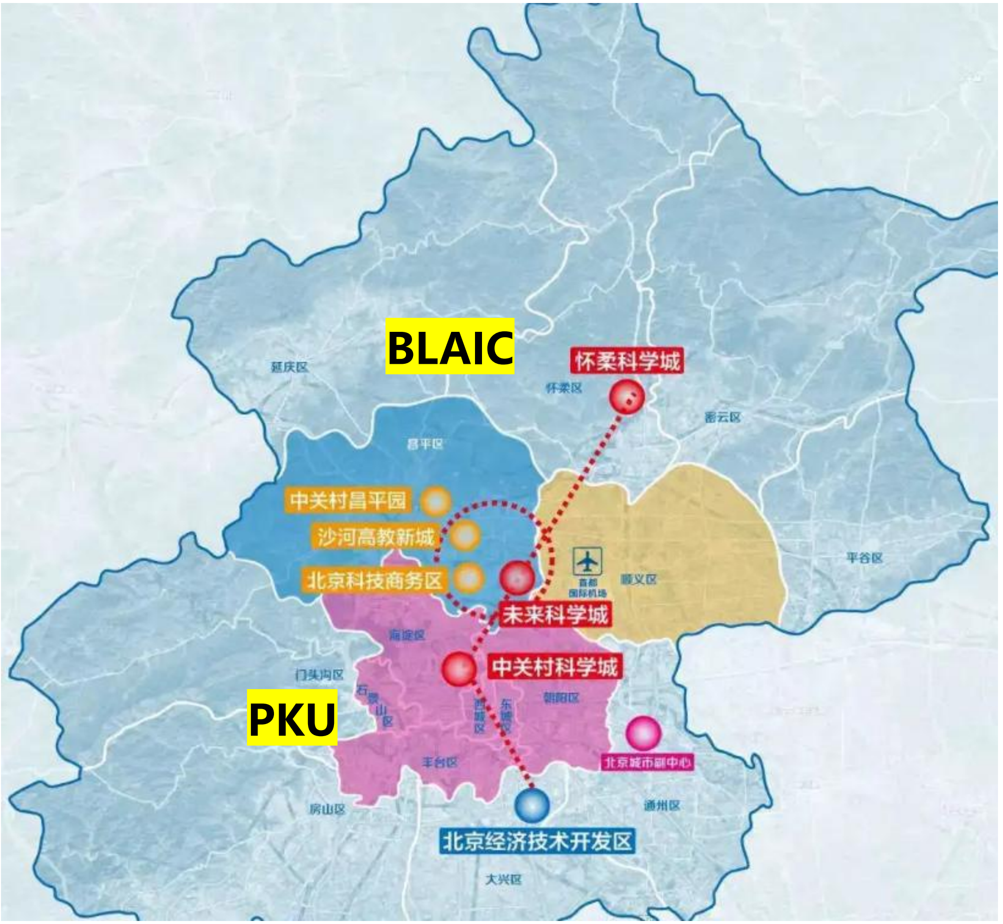
- The emittance of CLAPA proton beam was measured to be **0.01-0.1 mm mrad,** using three different methods at different positions along the transport beamline: **pepper-pot method**, **quadrupole triplet scan**, and **single-shot emittance measurement**.



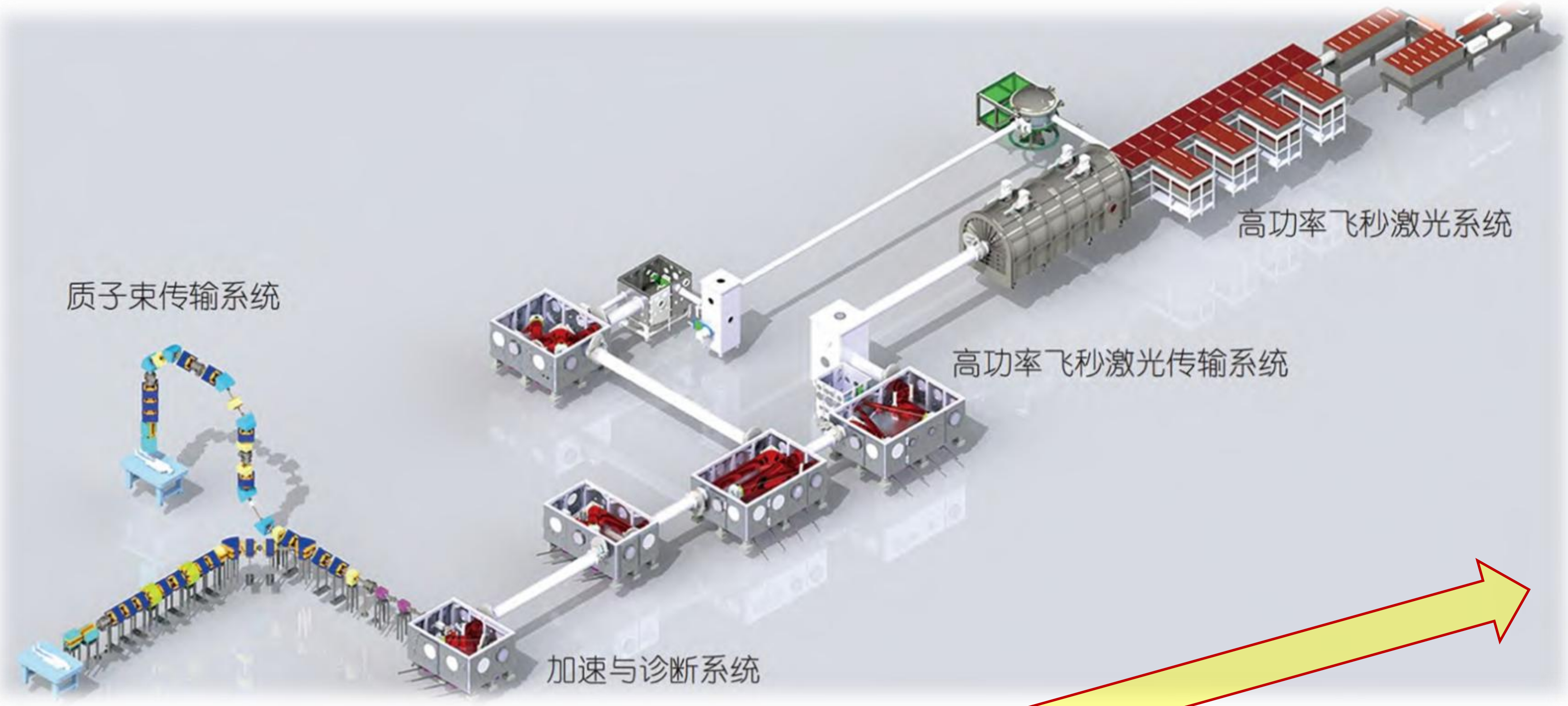


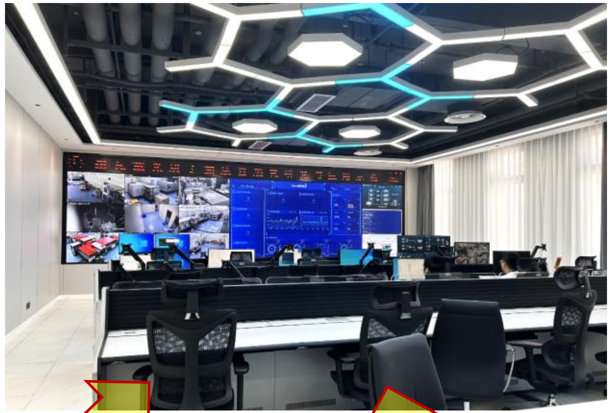
NIM A 955, 163249 (2020).
PRAB 23, 031302 (2020).

Beijing Laser Acceleration Innovation Center

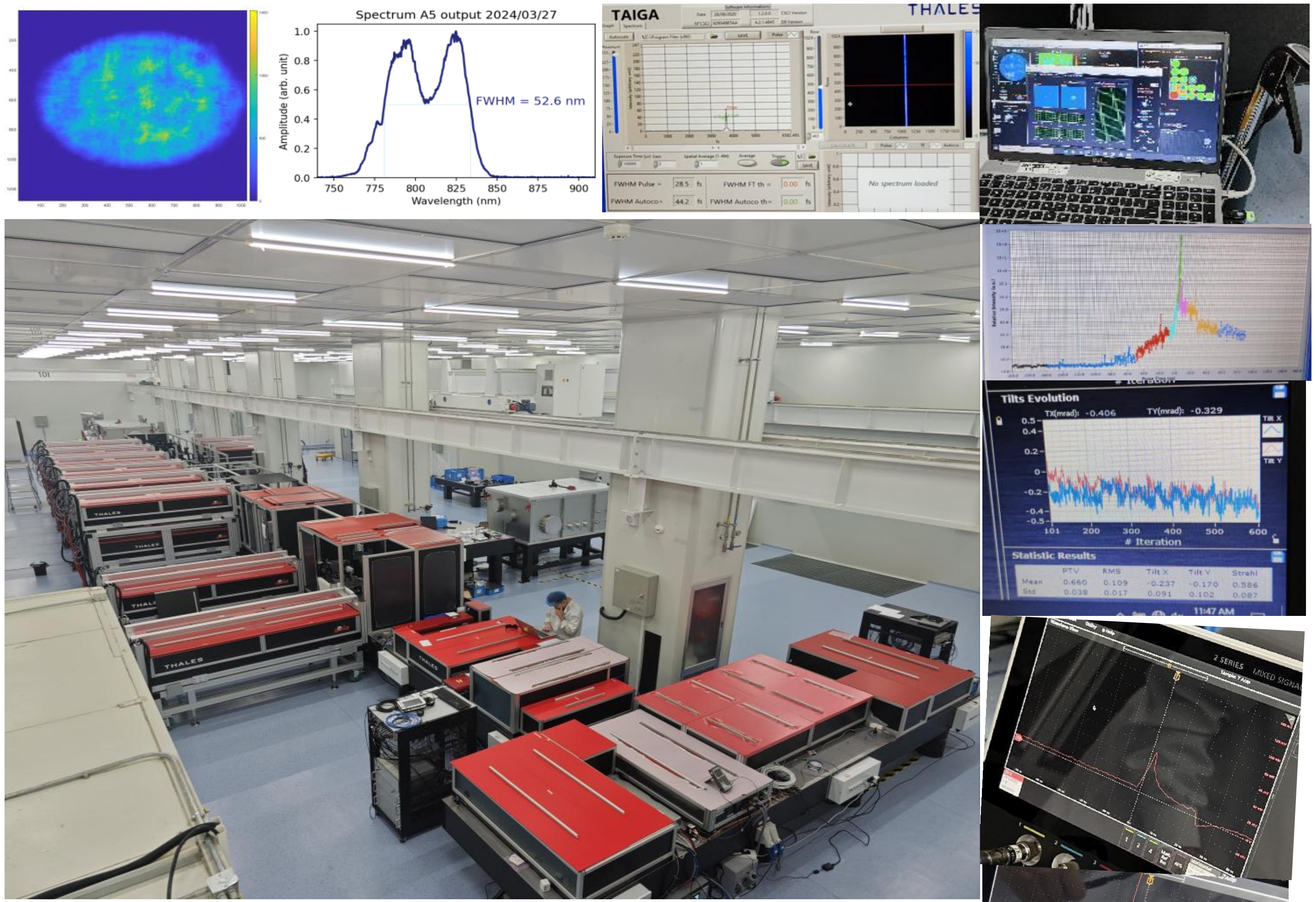


CLAPA-II





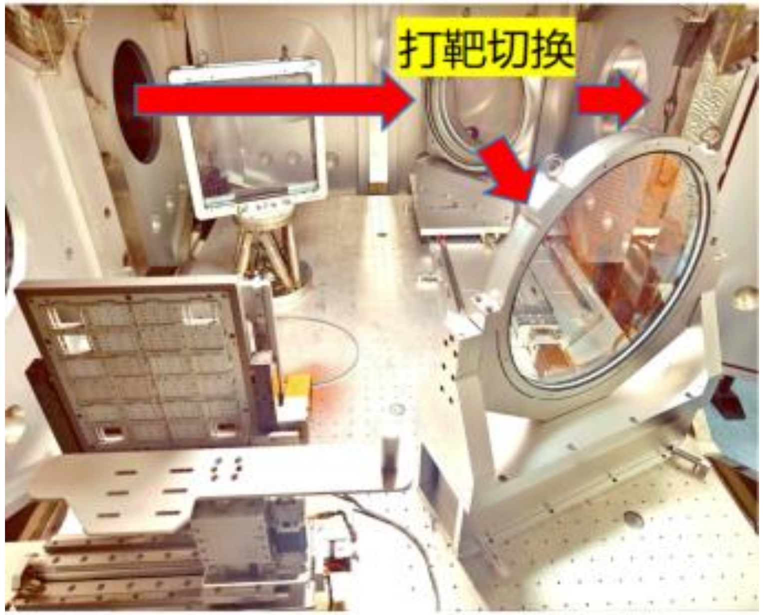
The world highest-average-power PW laser



Value	Min	Max	Average	Deviation	Peak To Va	Samples
90.373199	83.261199	90.931991	90.183673	0.3716412	7.6707916	600
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	600

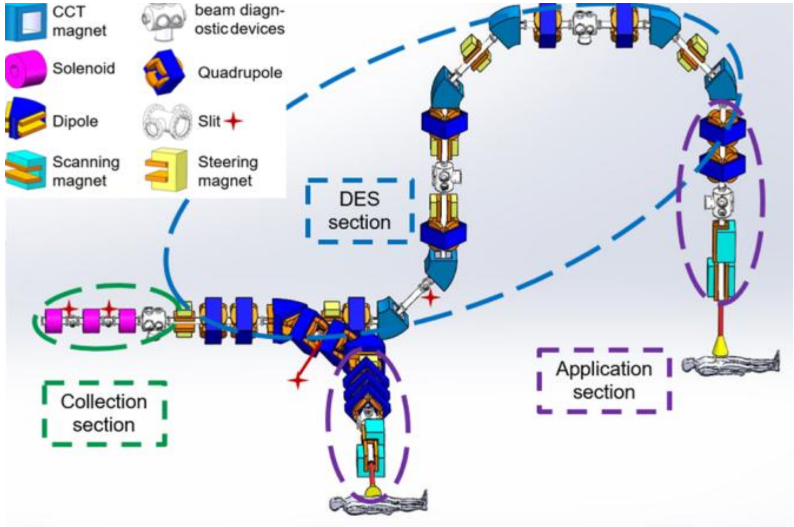
2PW laser system

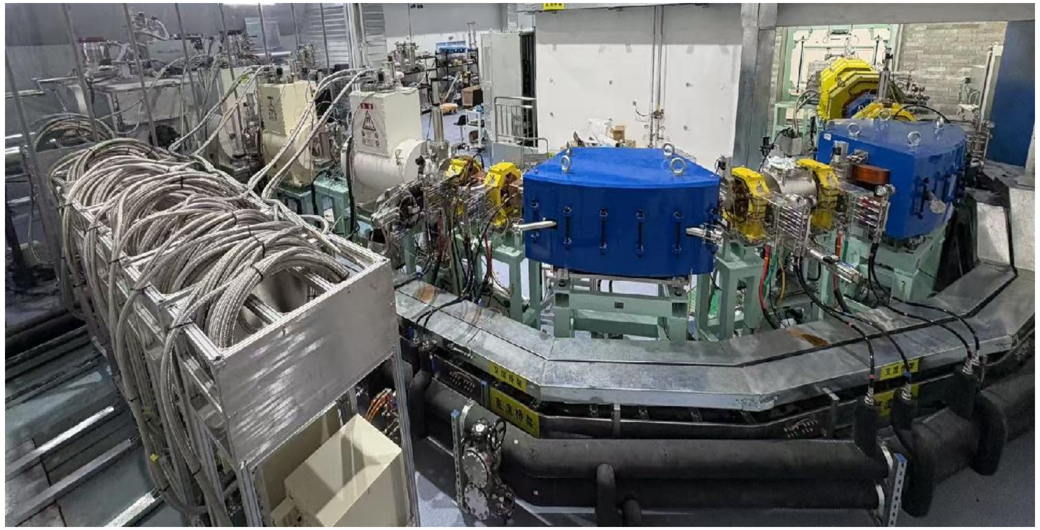
- **Peak power**: 2.44 PW (最高峰值功率)
- **Pulse energy**: 72 J (单脉冲能量)
- **Pulse duration**: 39 fs (脉宽)
- **ns contrast ratio**: >10^{10} (纳秒对比度)

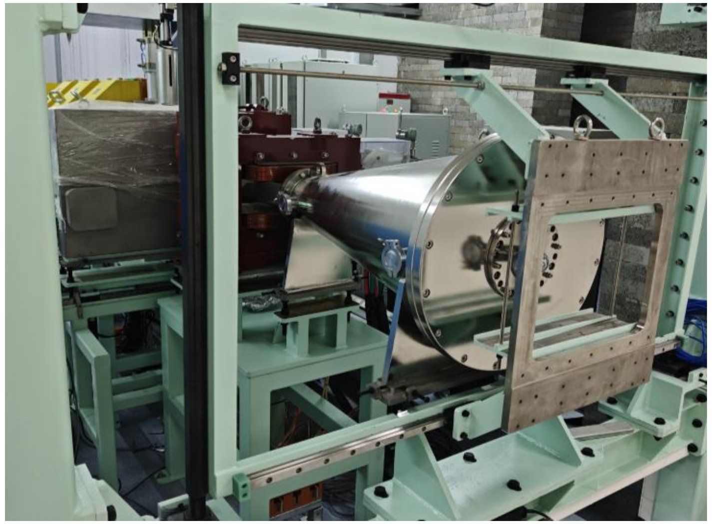


Acceleration section

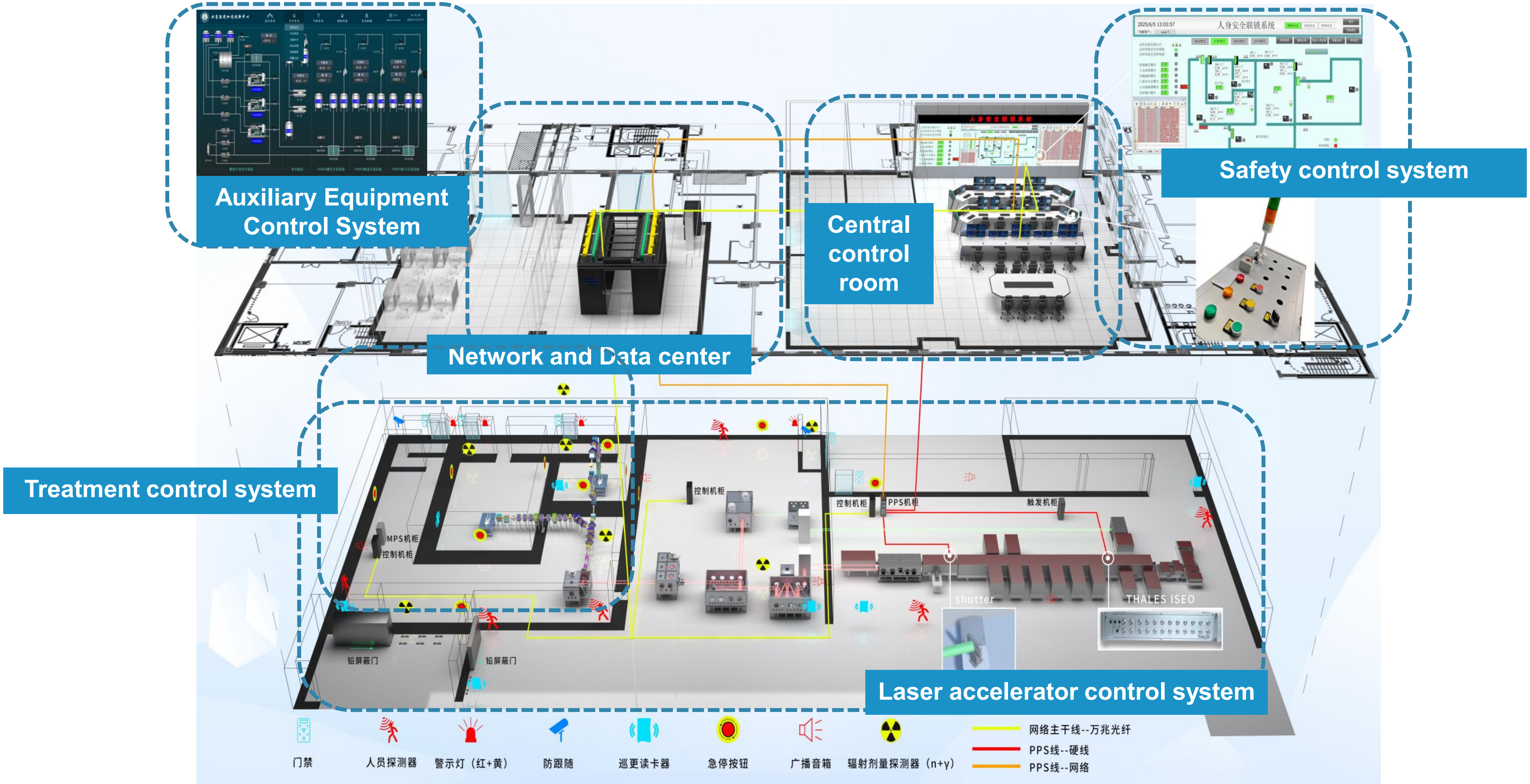
Beam delivery and treatment room







Data and control system



Outline

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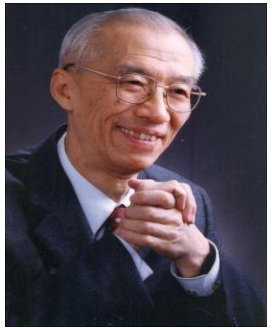
Summary

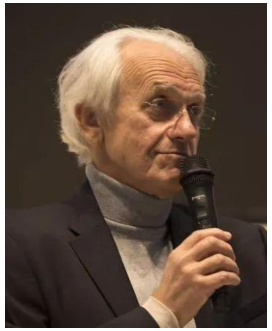
- Laser proton accelerators feature TV/m high gradients and can generate beams with extremely high peak current and dose rate, showing unique applications in tumor radiotherapy, material irradiation under extreme conditions, etc.
- Peking University is constructing a PW laser proton accelerator and the first laser accelerator-based tumor radiotherapy device.

颜学庆

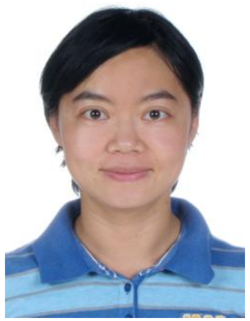
陈佳洱



Gerard Mourou



赵研英



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THANKS!

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