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Laser Ion Accelerator and Its Applications

Chen Lin, Wenjun Ma, Yanying Zhao, Kun Zhu, Gen Yang, Xueqing Yan

Peking University, Beijing, China

22/10/2021

Outline

- Research Background
- Applications of Laser Accelerated Ions
- Compact LAser Plasma Accelerator at PKU
- Summary

PART 01

Research Background

Laser Plasma Accelerator

John Dawson （1930-2001）

Toshiki Tajima

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

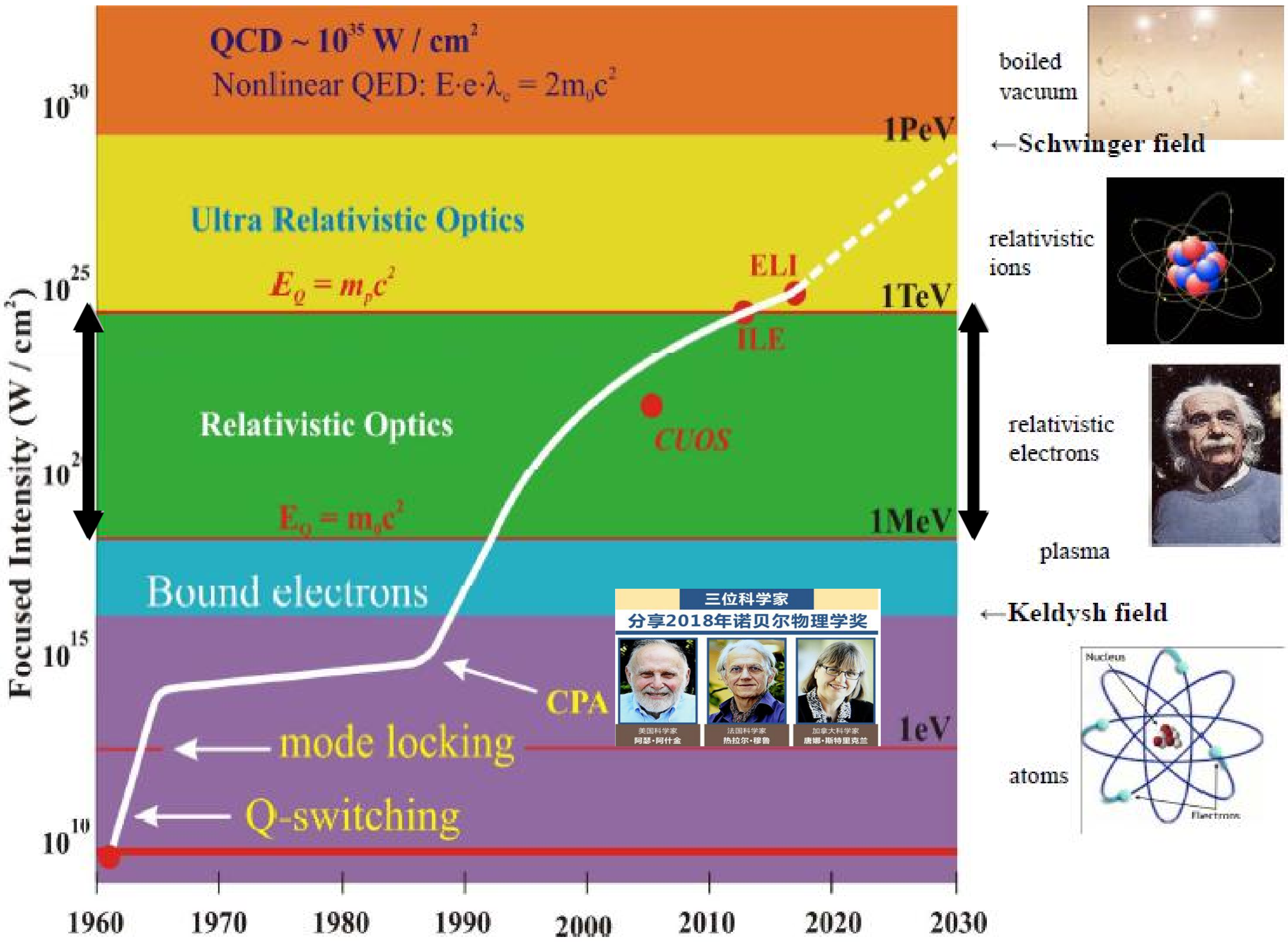
Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024

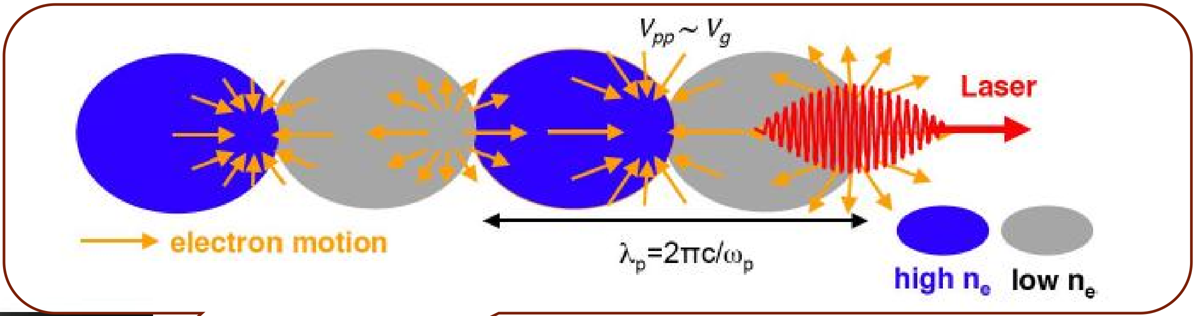
(Received 9 March 1979)

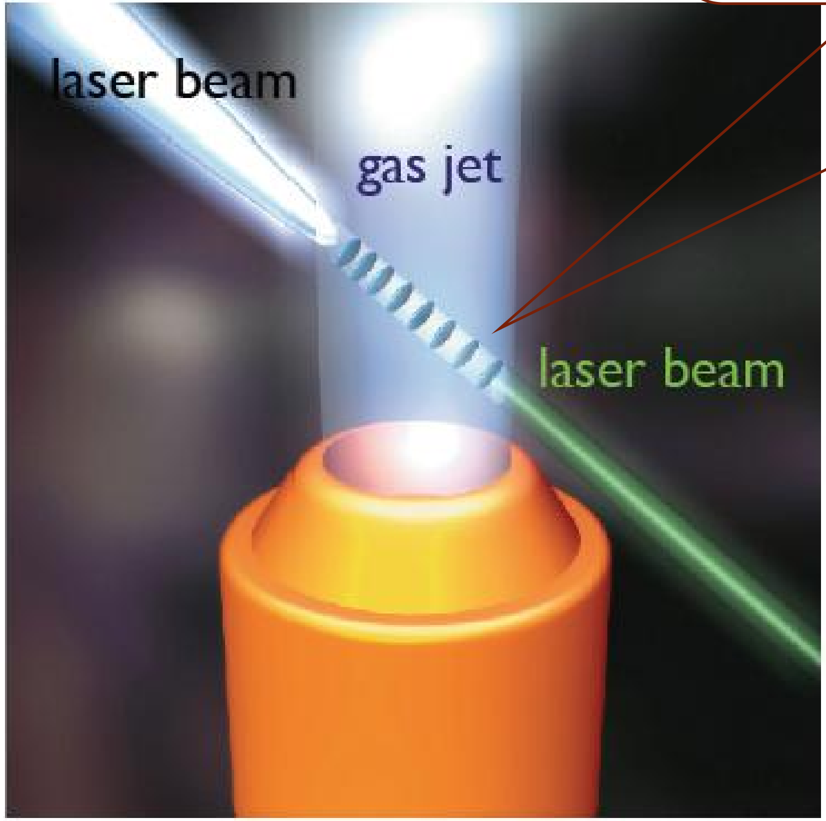
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield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

Focused Laser Intensity



Laser Electron Acceleration





Scheme of principle

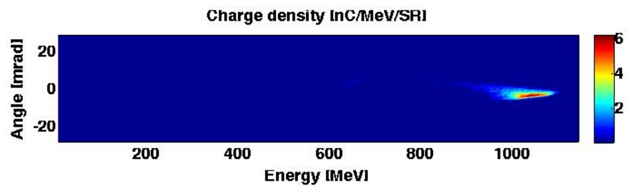
Gradient ~100 GV/m!

Progress of Laser Electron Acceleration

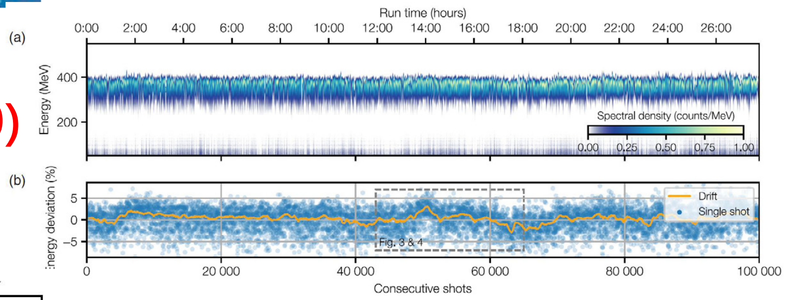
➢ Beam Quality

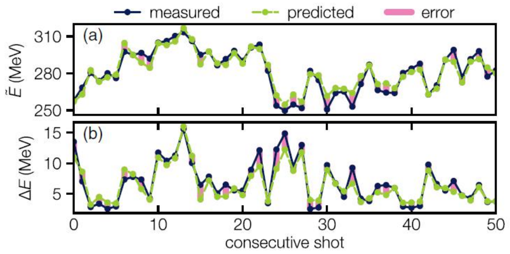
Nature(2004)

PRL (2006)



PRX (2020)

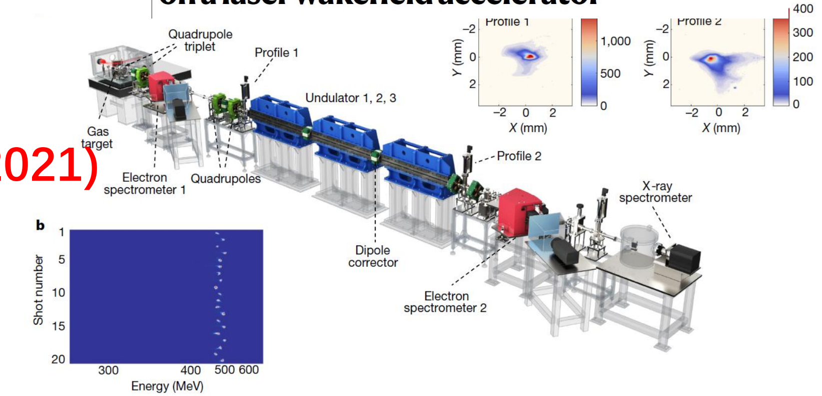




PRL (2021)

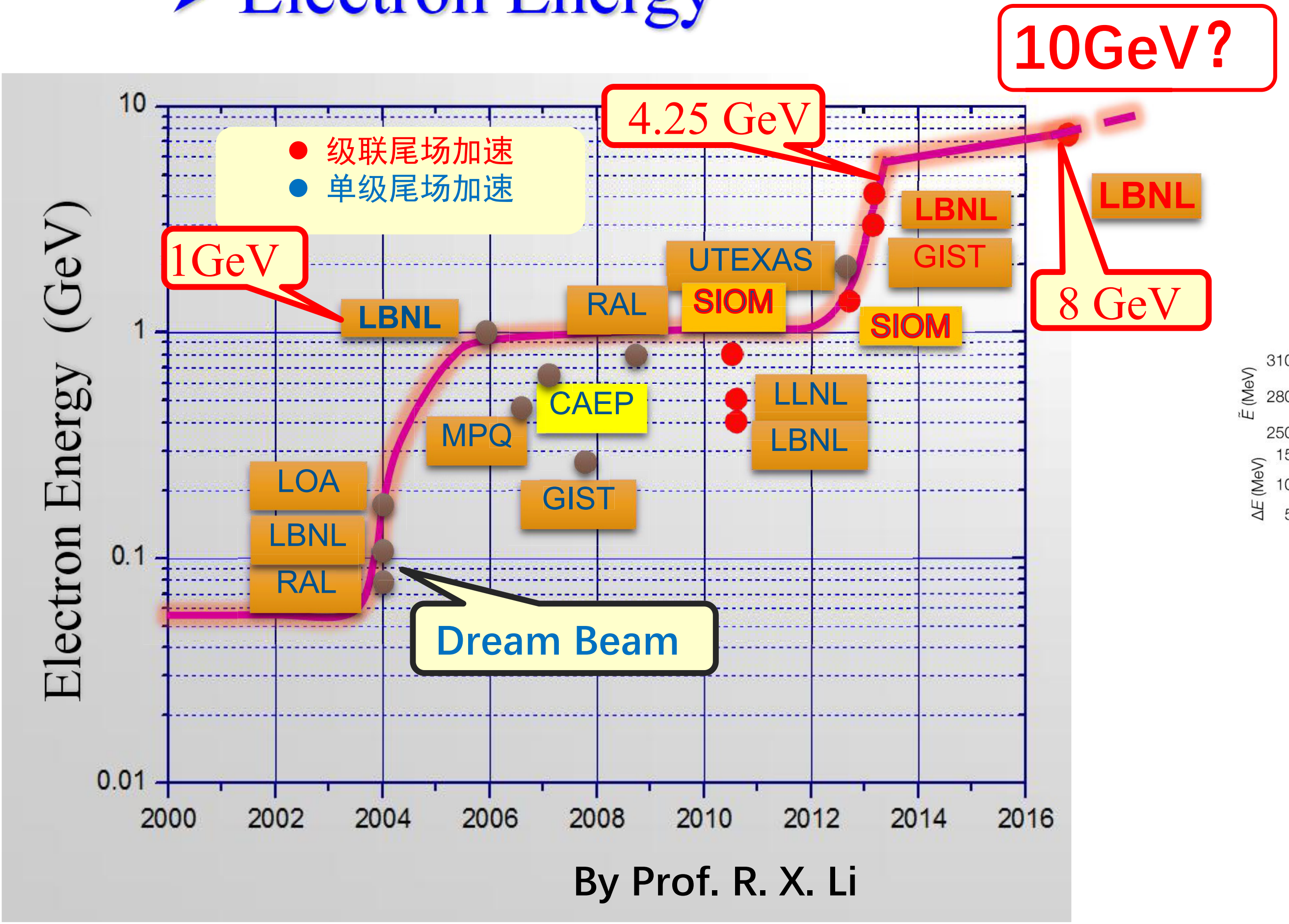
Article

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator



Nature (2021)

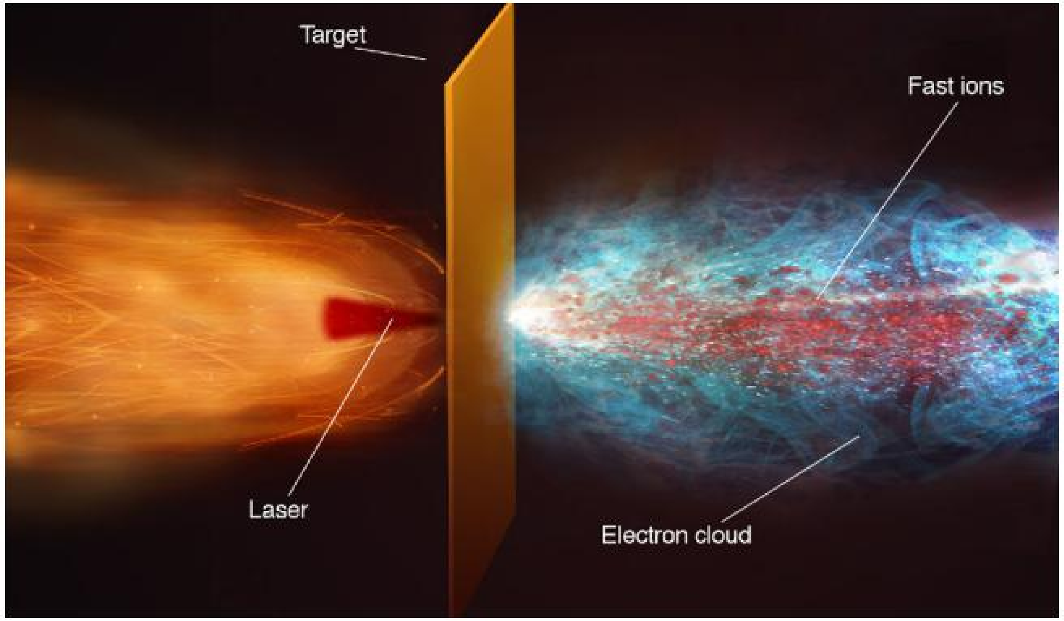
➢ Electron Energy



Laser Ion Acceleration

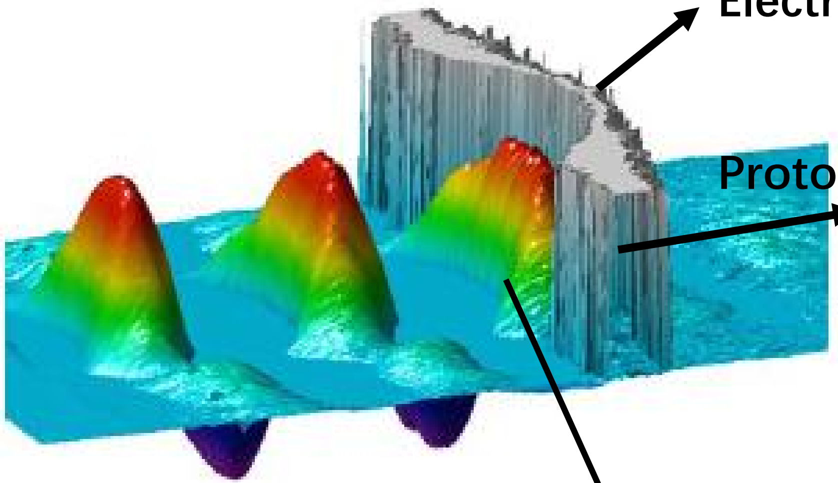
Target normal sheath acceleration (TNSA)

$E_{ion} \sim I_{laser}^{1/2}$



Radiation pressure acceleration (RPA)

$E_{ion} \sim I_{laser}$



REVIEWS OF MODERN PHYSICS, 85, 751 (2013)

Progress of Ion Acceleration

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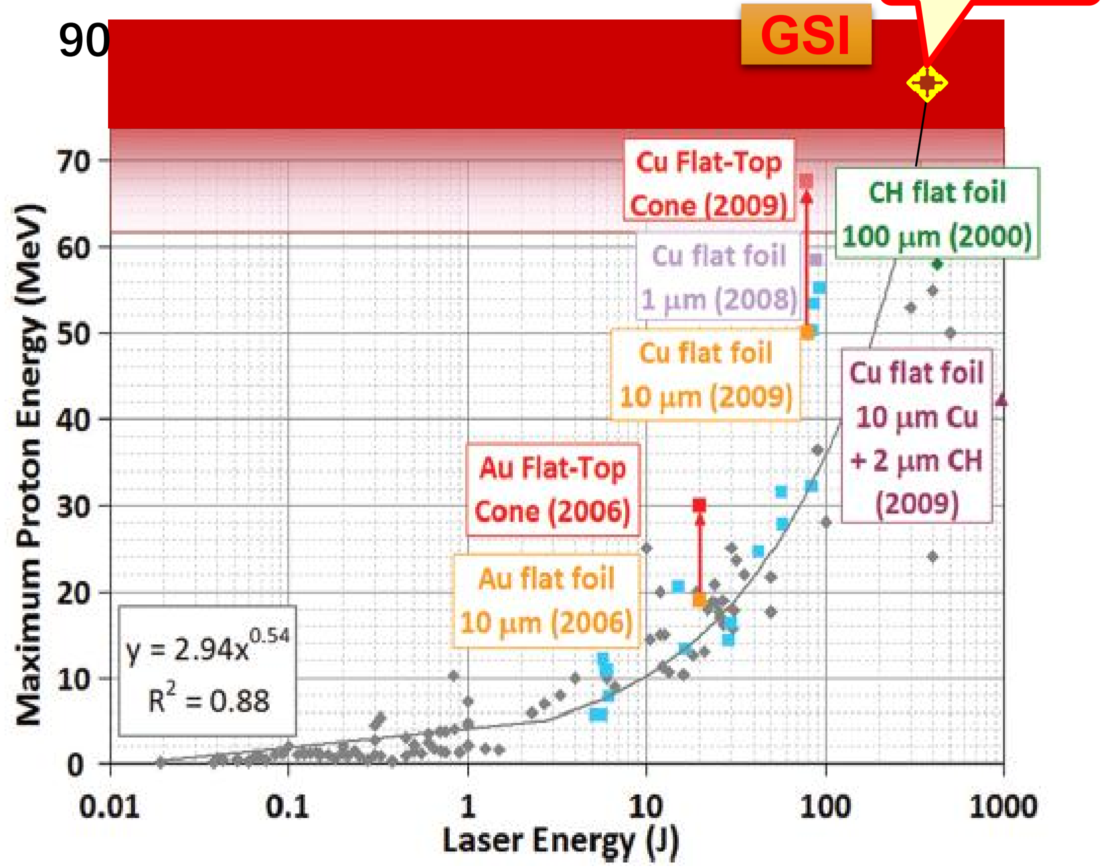
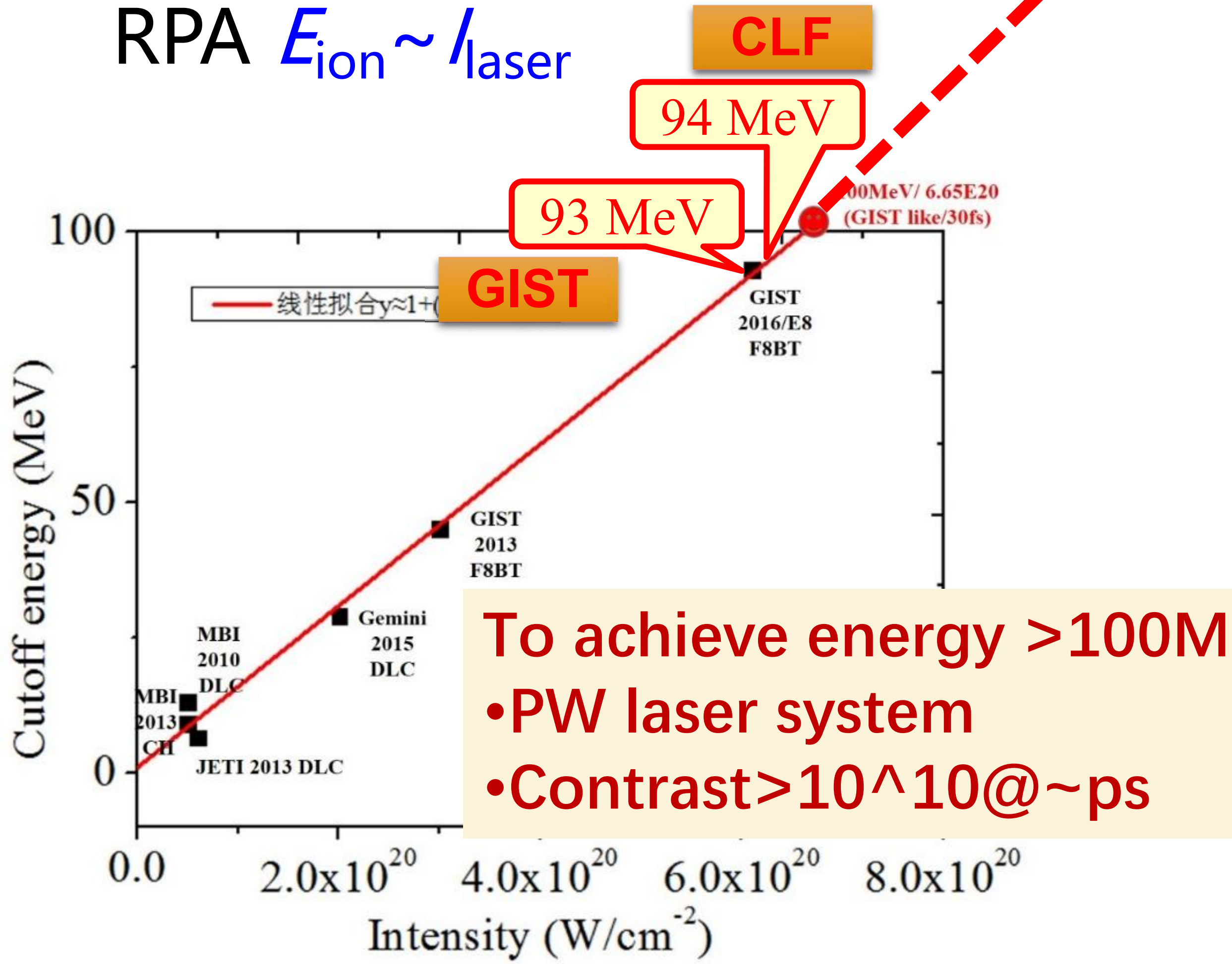
200MeV@2*10^21 W/cm2!

TNSA $E_{ion} \sim I_{laser}^{1/2}$



Phys. Rev. Lett. 116, 205002 (2016).

RPA $E_{ion} \sim I_{laser}$



To achieve energy >100MeV
- PW laser system
- Contrast>10^10@~ps

Statistics of World Laser >100TW

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REVIEWS OF MODERN PHYSICS, VOLUME 91, JULY–SEPTEMBER 2019

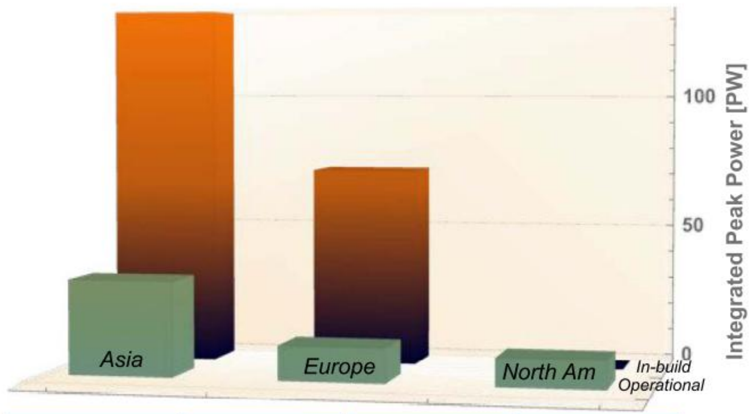
Nobel Lecture: Extreme light physics and application*

Gerard Mourou†
École Polytechnique, 91128 Palaiseau Cedex, France

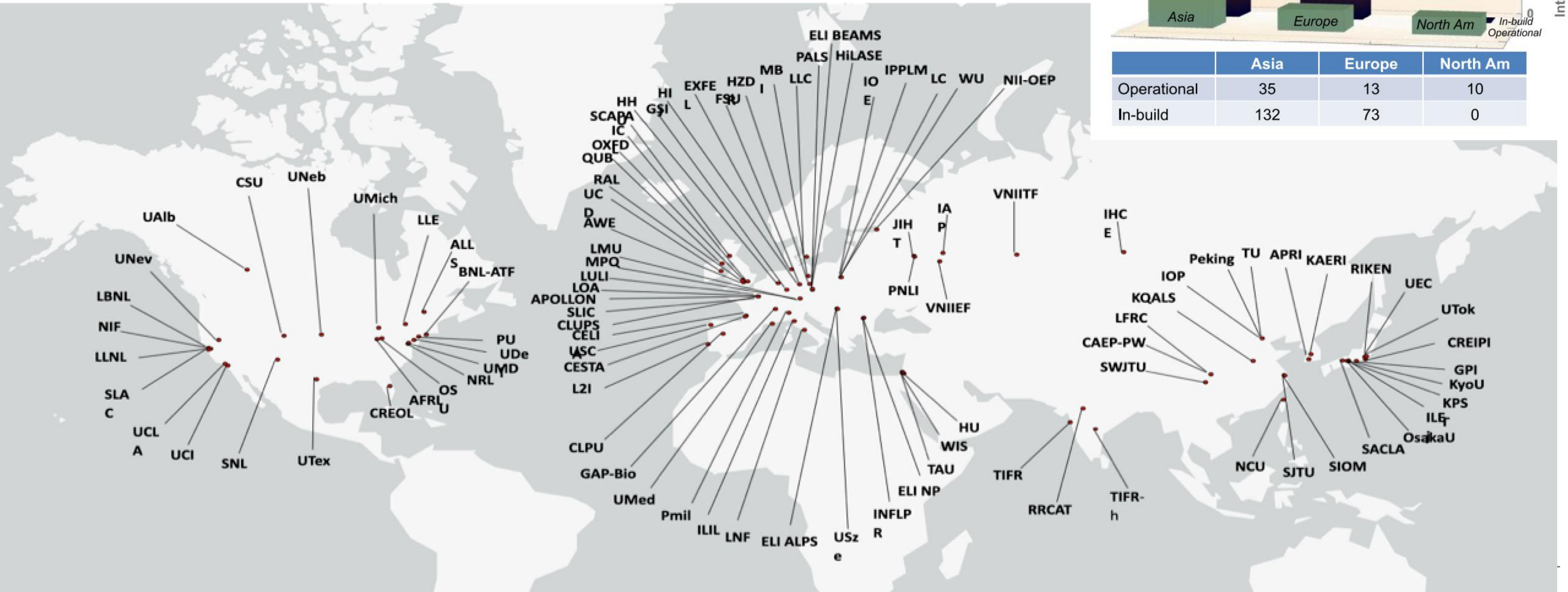
High Power Laser Science and Engineering, (2019), Vol. 7, e54, 54 pages.

Petawatt and exawatt class lasers worldwide

Colin N. Danson[1,2,3], Constantin Haefner[4,5,6], Jake Bromage[7], Thomas Butcher[8], Jean-Christophe F. Chanteloup[9], Enam A. Chowdhury[10], Almantas Galvanauskas[11], Leonida A. Gizzi[12], Joachim Hein[13], David I. Hillier[1,3], Nicholas W. Hopps[1,3], Yoshiaki Kato[14], Efim A. Khazanov[15], Ryosuke Kodama[16], Georg Korn[17], Ruxin Li[18], Yutong Li[19], Jens Limpert[20,21,22], Jingui Ma[23], Chang Hee Nam[24], David Neely[8,25], Dimitrios Papadopoulos[9], Rory R. Penman[1], Liejia Qian[23], Jorge J. Rocca[26], Andrey A. Shaykin[15], Craig W. Siders[4], Christopher Spindloe[8], Sándor Szatmári[27], Raoul M. G. M. Trines[8], Jianqiang Zhu[28], Ping Zhu[28], and Jonathan D. Zuegel[7]



	Asia	Europe	North Am
Operational	35	13	10
In-build	132	73	0



Statistics of World Laser>1PW

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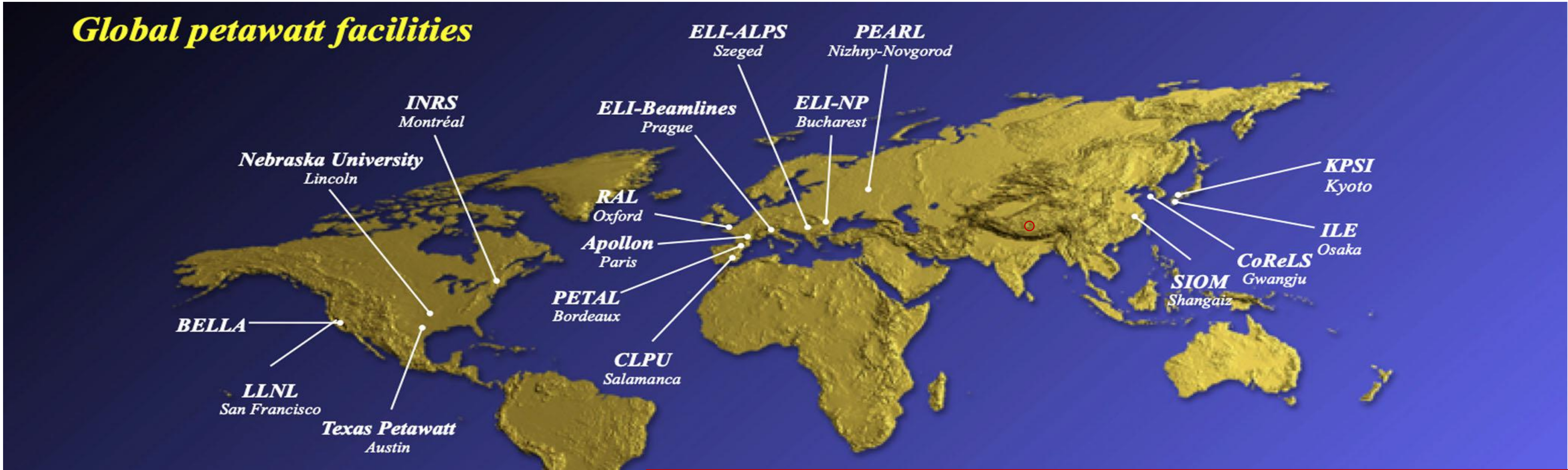


>20 in operation or under construction worldwide.

>5 under construction in China.

(China has seen the greatest growth internationally in the development of ultra-high-power lasers and in their applications.)

Challenges of Laser Acceleration

Advantages

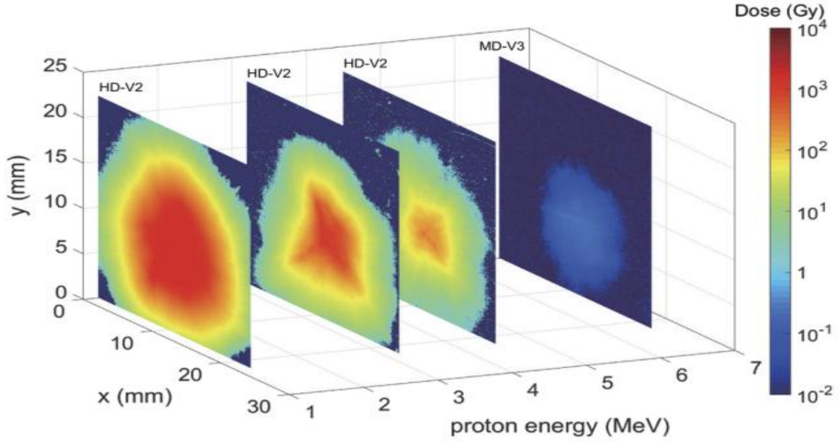
- Acceleration gradient **GV/m-TV/m!!!**
- Acceleration distance ~ **few mm -few microns**

Challenges:

Energy?
Charge?
Energy spread?
Stability?
Reliability?...

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].

Characteristics of Laser Driven Ion Beam



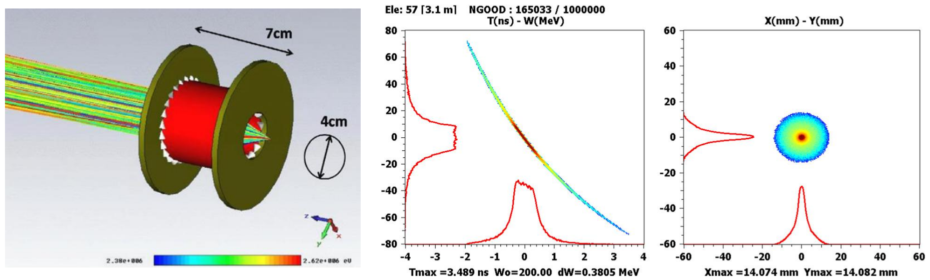
- Large energy spread ~ 100%
- Large diverge angle ~ 10°
- Small emittance ~ 0.1 π mm.mrad
- Small initial size, spot source ~ 5μm
- Short pulse duration ~ ps to ns
- High peak current ~ 10^9-10^{11}ppp, KA

new features for beam optics

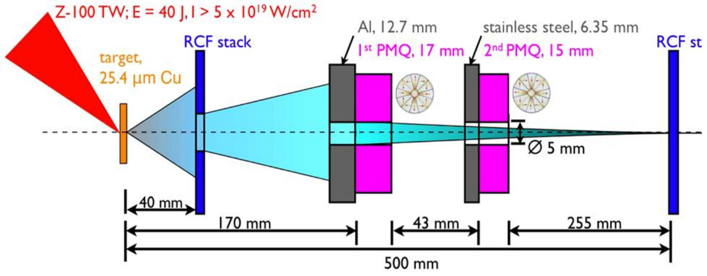
The laser driven ion beams can not be used directly for many applications. Special designed beam line needs to be employed.

Beam Line of Laser Driven Protons

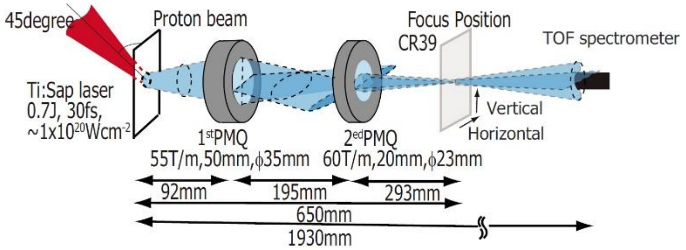
Pulsed solenoid



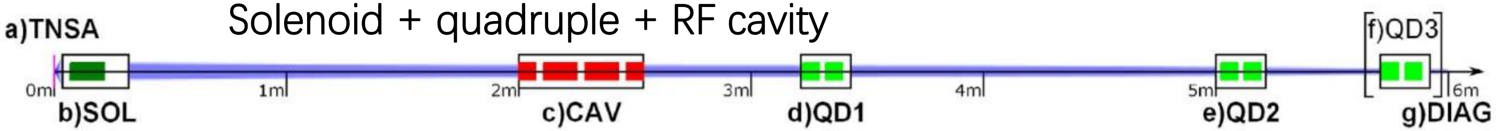
Electronic Quadruple



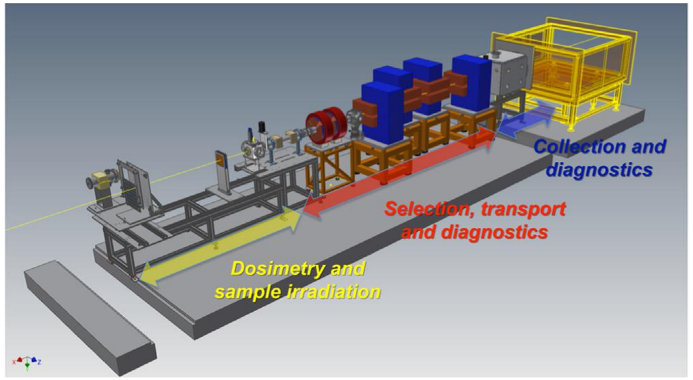
Permanent Quadruple



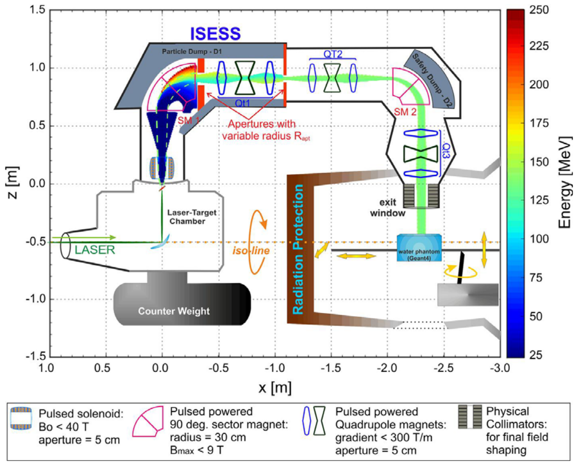
Solenoid + quadruple + RF cavity



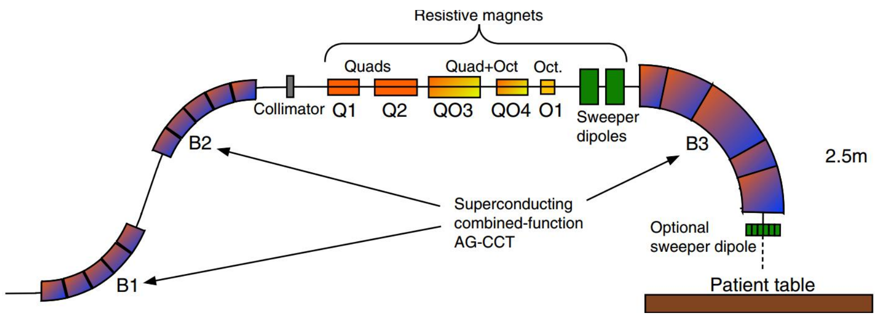
ELI beam line design



Dresden gantry design



Berkeley beam line design



P. Antici *et al.*, *Physics of Plasmas* **18**, 073103 (2011).
I. Hofmann *et al.*, *Phys. Rev. ST Accel. Beams* **16**, 041302 (2013).
T. Toncian *et al.*, *Science* **312**, 410 (2006).
D. Jahn *et al.*, *NIM-A* **909**, 173 (2018).
F. Romano *et al.*, *NIM-A* **829**, 153 (2016).
S. Busold *et al.*, *Scientific Reports* **5**, 12459 (2015).
F. Romano *et al.*, *NIM-A* **829**, 153 (2016).
U. Masood et al., Applied Physics B **117**, pages41–52 (2014).
U. Masood *et al.*, *Physics in Medicine & Biology* **62**, 5531 (2017).
J. G. ZHU *et al.*, *Phys. Rev. ST Accel. Beams* **22**, 061302 (2019).

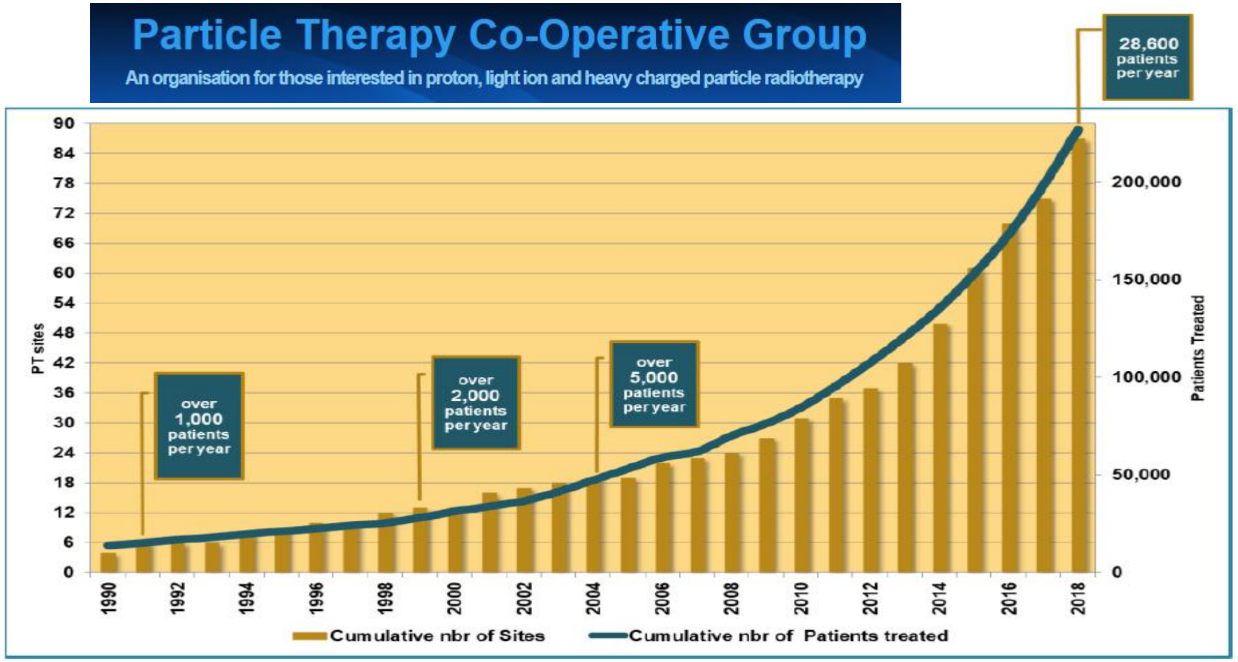
PART 02

Applications of Laser Accelerated Proton Beam

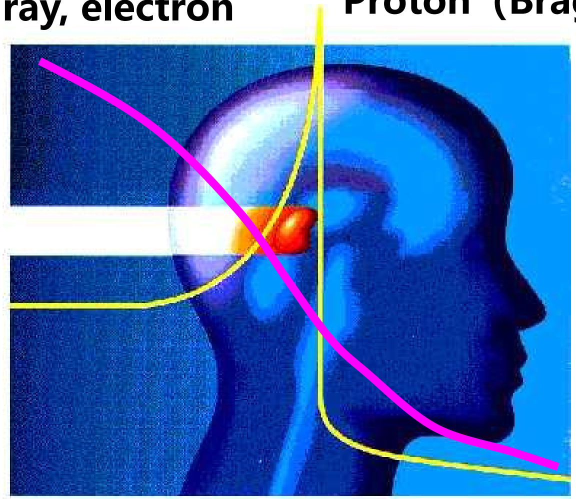
- Flash irradiation (FLASH-IR)
- Transient heat flux irradiation

Advantages of Proton Radiotherapy

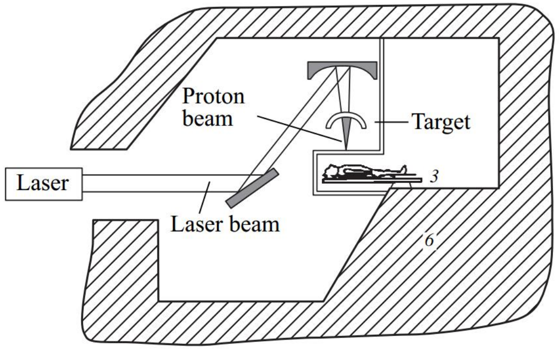
- Proton beam radiotherapy can effectively protect the surrounding healthy tissue due to the Bragg peak effect.
- According to Particle Treatment Co-operative Group(PTCOG) statistics about patients treated with particles, by the end of 2020, more than **290,000** cancer cases were treated with proton or other ions radiotherapy worldwide and more than **6,700** cases are in China.
- The averaged cancer local control rate is 95% and the averaged five-year survival rate is 80% with proton radiotherapy, performing significantly better than most cancer treatments.



X-ray, electron **Proton (Bragg peak)**



Laser accelerated protons was first proposed for radiotherapy in 2002!



Plasma Physics Reports **28** (5), 453 (2002).

Ultra-high Dose Flash Irradiation (FLASH-IR)

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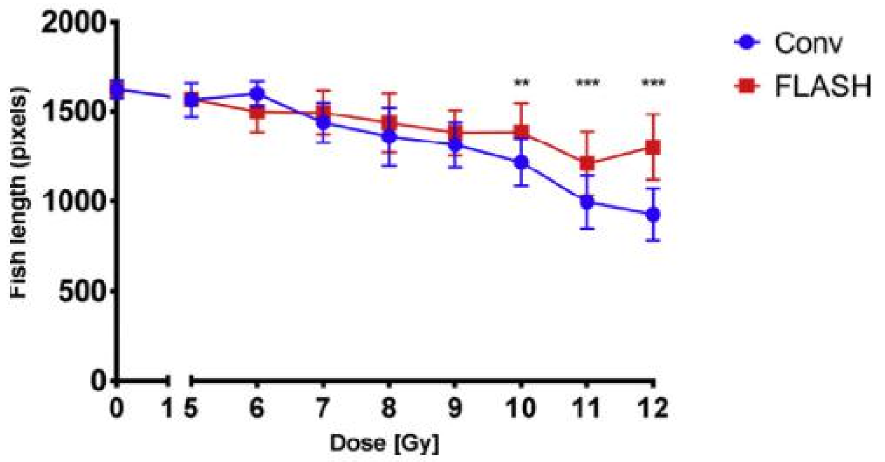
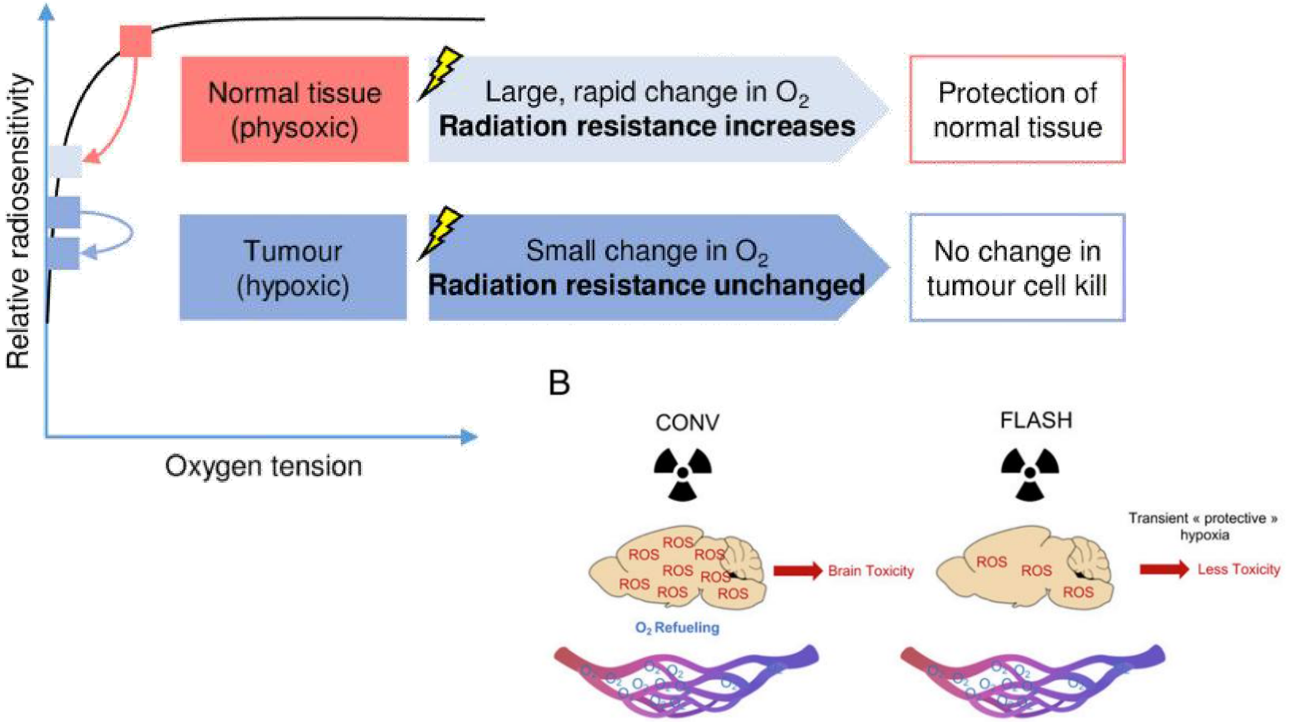
- Conventional radiotherapy： 0.1-2 Gy/s
- Ultra-high dose rate FLASH Radiotherapy： >40 Gy/s
  - originated in the 1960s
  - has attracted wide attention since 2014
  - degree of tumor tissue control is similar
  - degree of normal tissue damage decreased

Dose escalation Conv vs FLASH RT (4hpf)



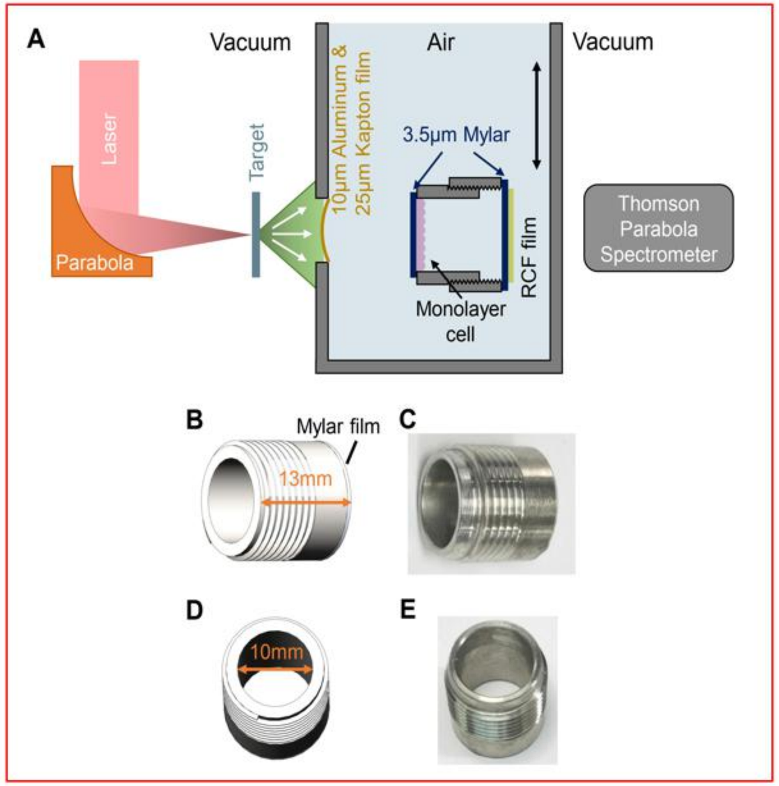


Clinical Oncology **31** (7), 407 (2019).
Front Oncol. **9**, 1563 (2019).
Proc. Natl. Acad. Sci. USA **116** (22), 10943 (2019).

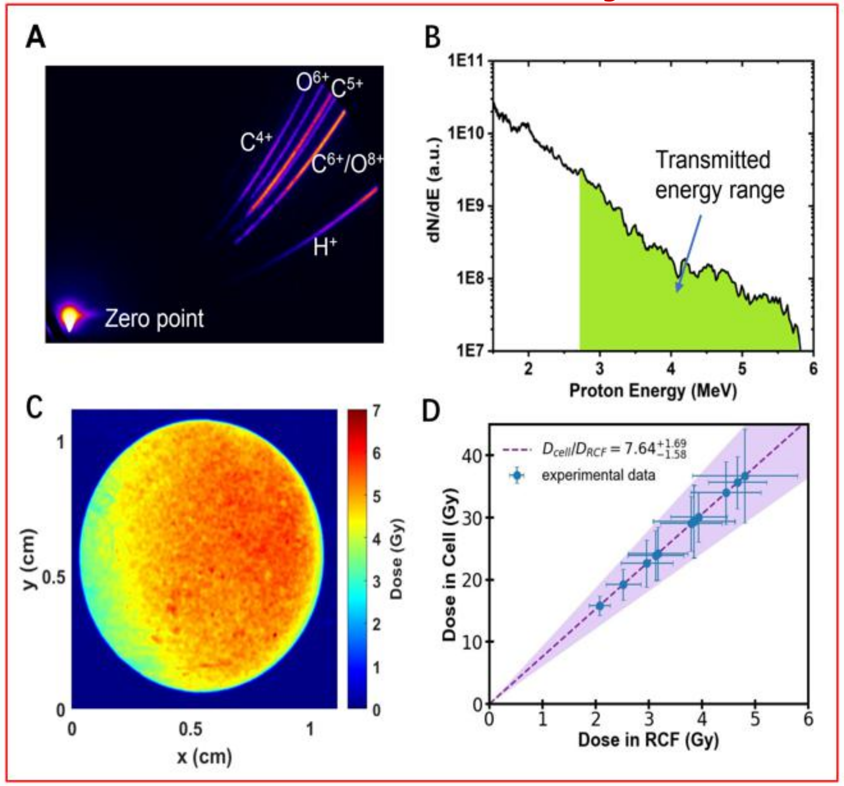
The oxygen effect hypothesis :
FLASH with high total dose rate depletes oxygen within ultra-short time, and it is too quickly for diffusion and reoxygenation, so the normal tissue show radiation resistance as hypoxic tissue.

Ultra-high Dose FLASH Irradiation with Laser Protons

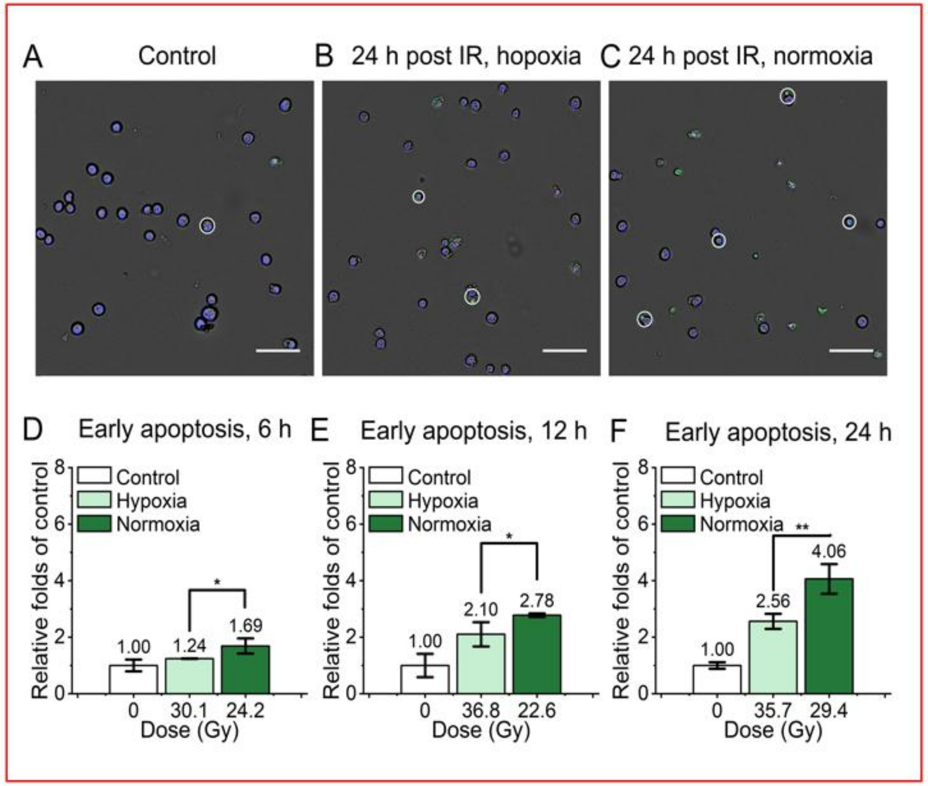
Dose rate 10^9 Gy/s !



Experimental setup for FLASH irradiation



Dose and dose rate calculation



Early apoptosis of irradiated normal fibroblast cells

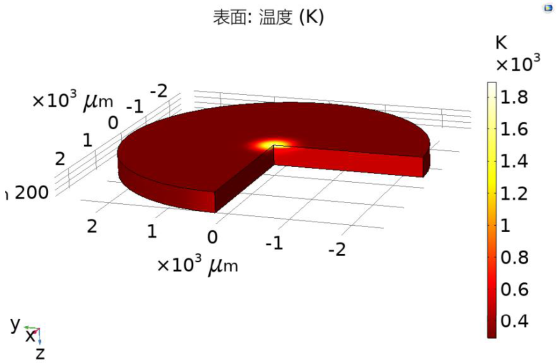
Radio-resistance of normal fibroblast cells under FLASH-IR can be enhanced by hypoxia.

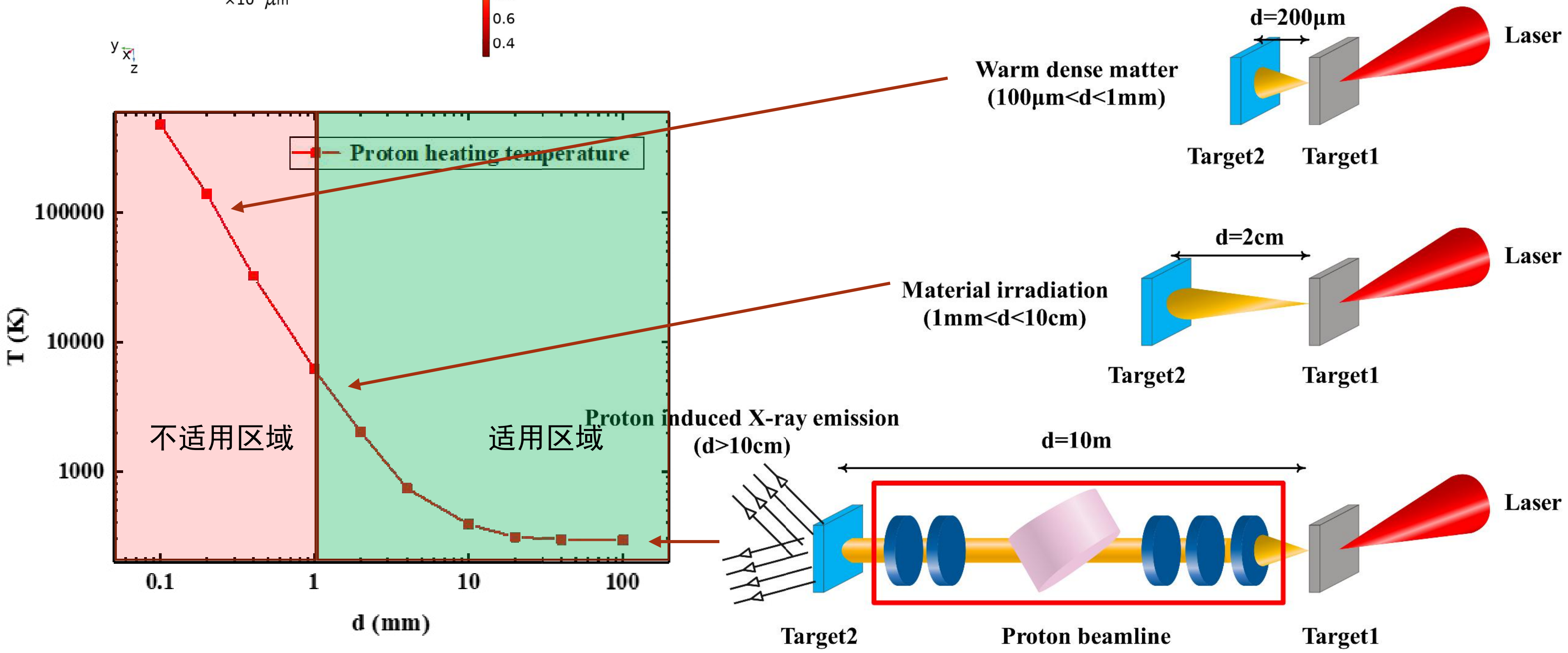
Jintao Han,… Xueqing Yan*, Wenjun Ma*, Gen Yang*, Frontiers in Cell and Developmental Biology (2021)

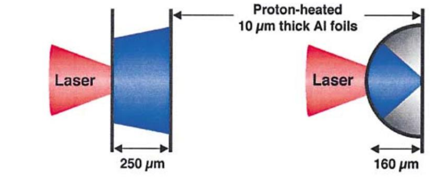
Transient Heat Flux Irradiation

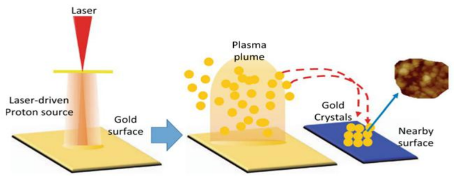
Temperature effect of LIBs irradiation

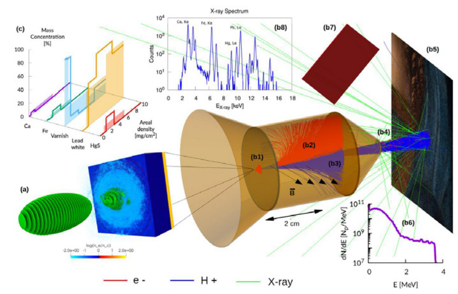
With the decrease of irradiation distance, the temperature of the sample heated by LIBs rises sharply from room temperature to tens of eV. The research field can transit from normal material irradiation to warm dense matter.





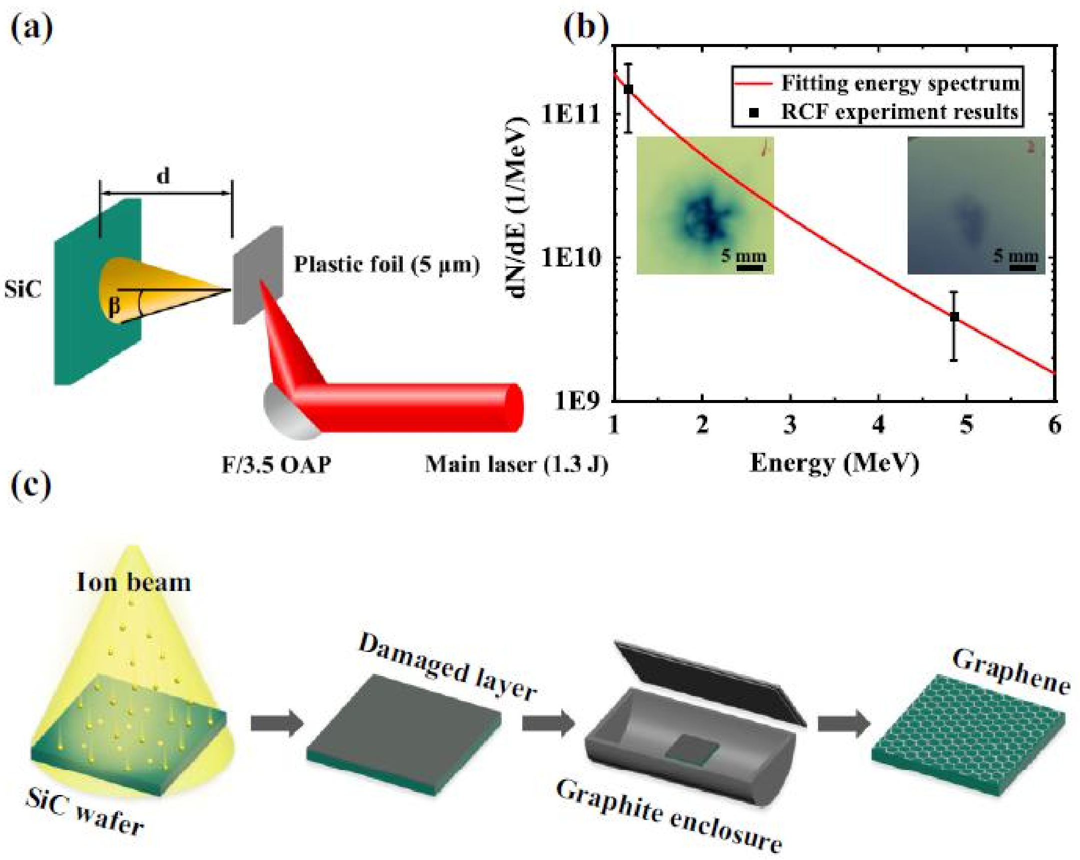


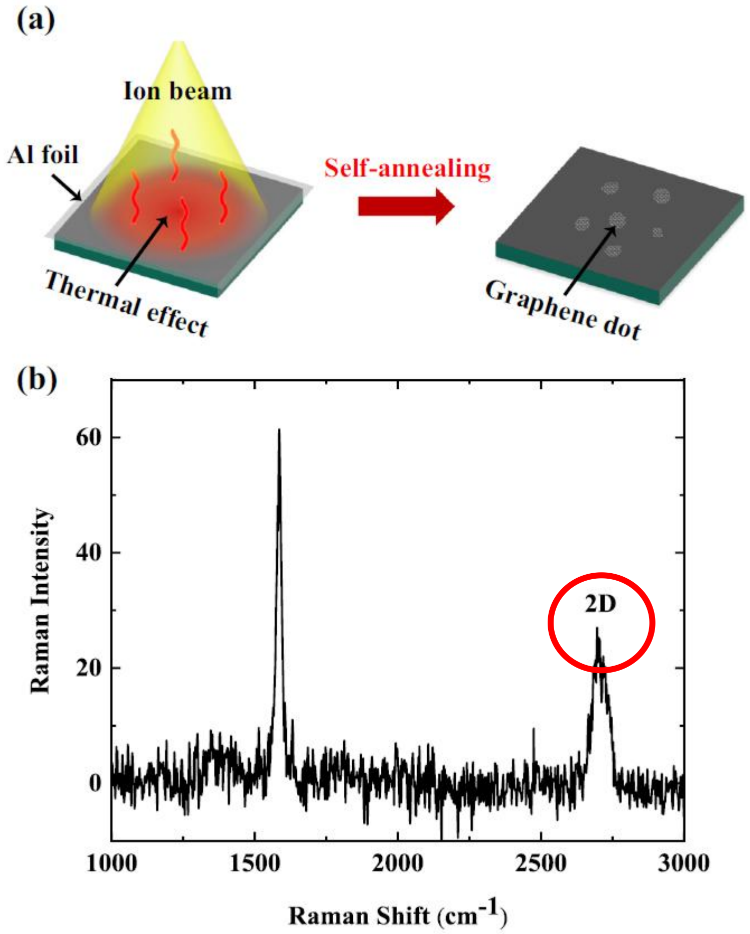




Phys. Rev. Lett. **19**, 125004 (2003).
Nature Communications, s41467-017-02675-x (2018).
Scientific Reports **7**: 12522 (2017) *Scientific Reports*, **7**: 40415 (2017).

Preparation of Graphene on SiC





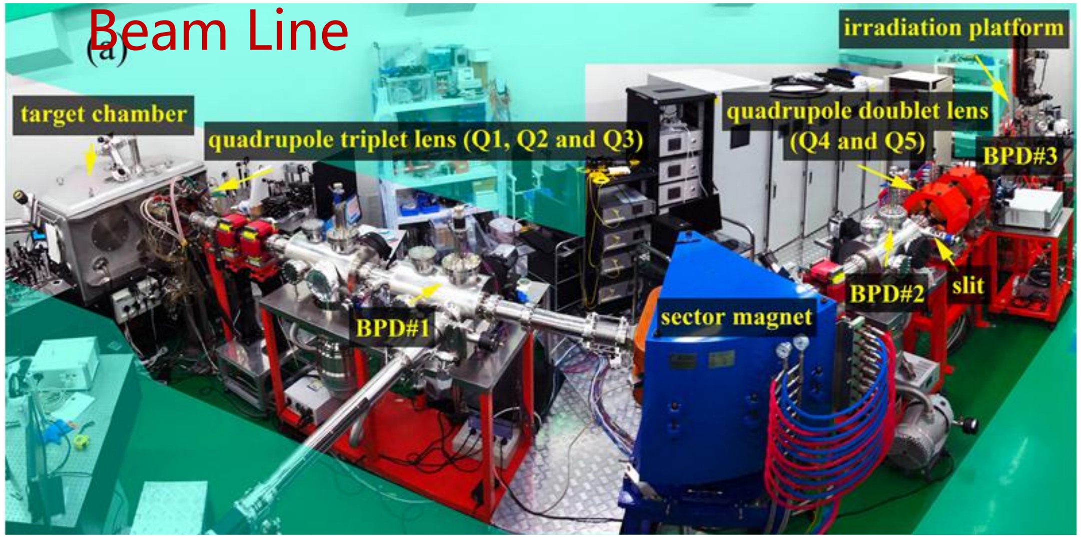
- After irradiated by the laser-accelerated ions, the SiC sample is annealed at 1100℃, the characteristic 2D peak of graphene appears in the Raman spectroscopy indicating that LIBs irradiating SiC can prepare graphene like the ion beam of a traditional accelerator.
- Significant thermal effect was induced when irradiation distance reduced to less than 1 cm, which could make partial SiC self-annealing to prepare graphene dots directly.

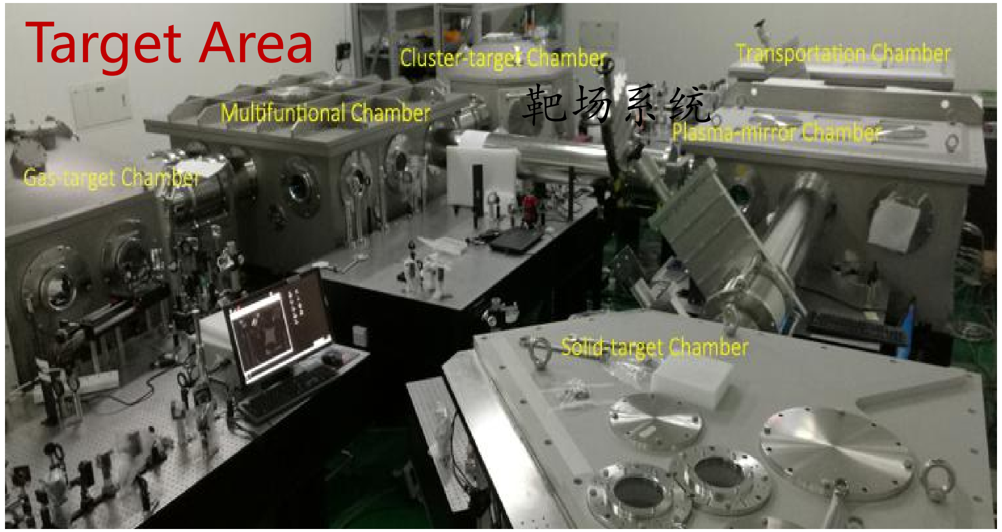
PART 03

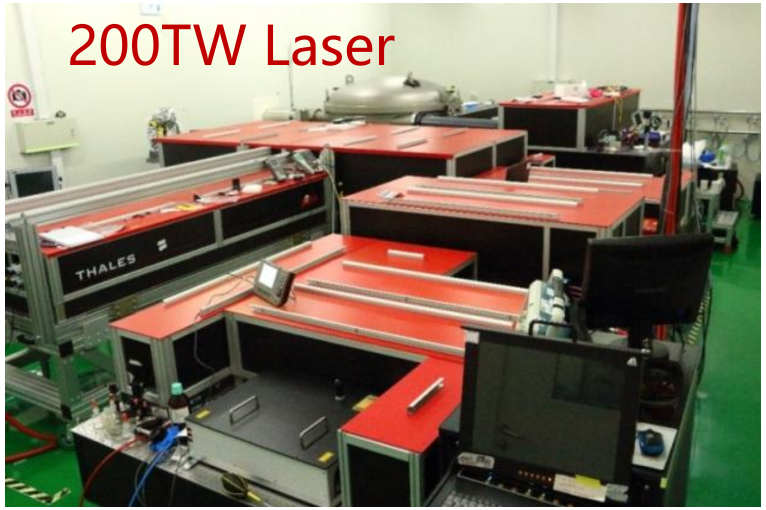
Compact LAser Plasma Accelerator at Peking University

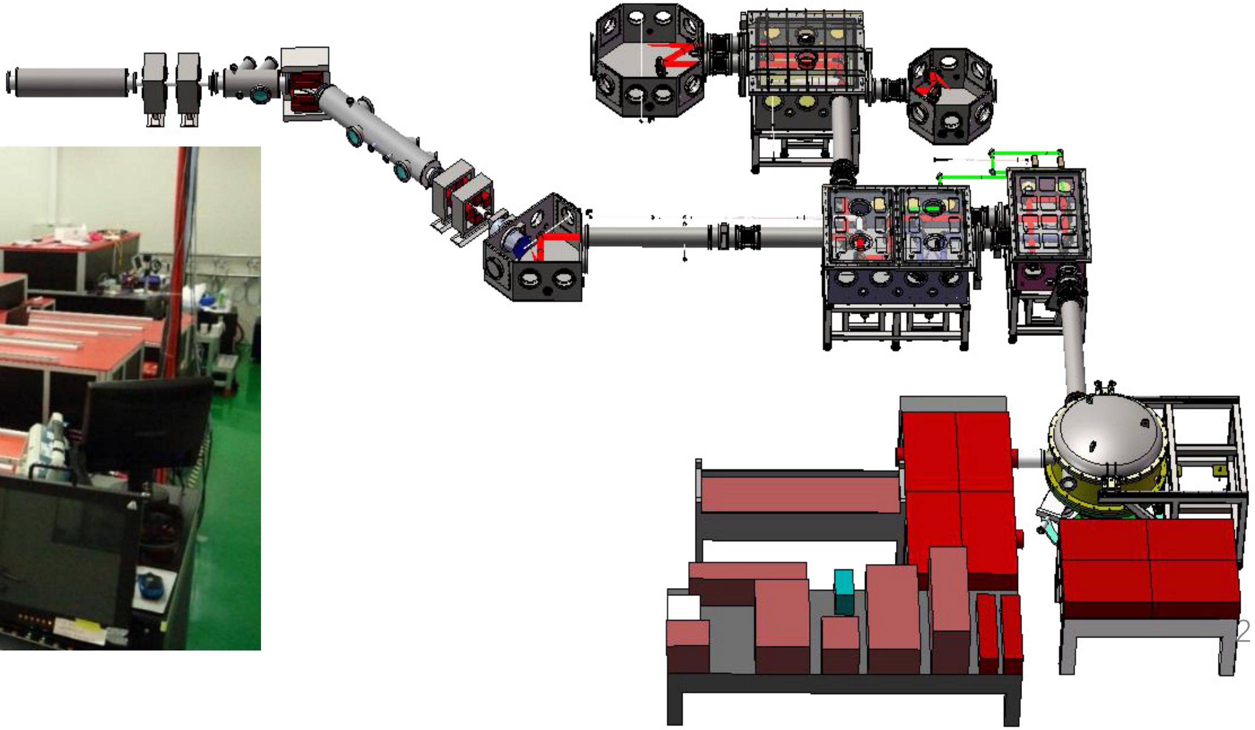
- CLAPA I : 200TW laser accelerator
- CPALA II: 2PW laser accelerator

CLAPA I (2013-2018)

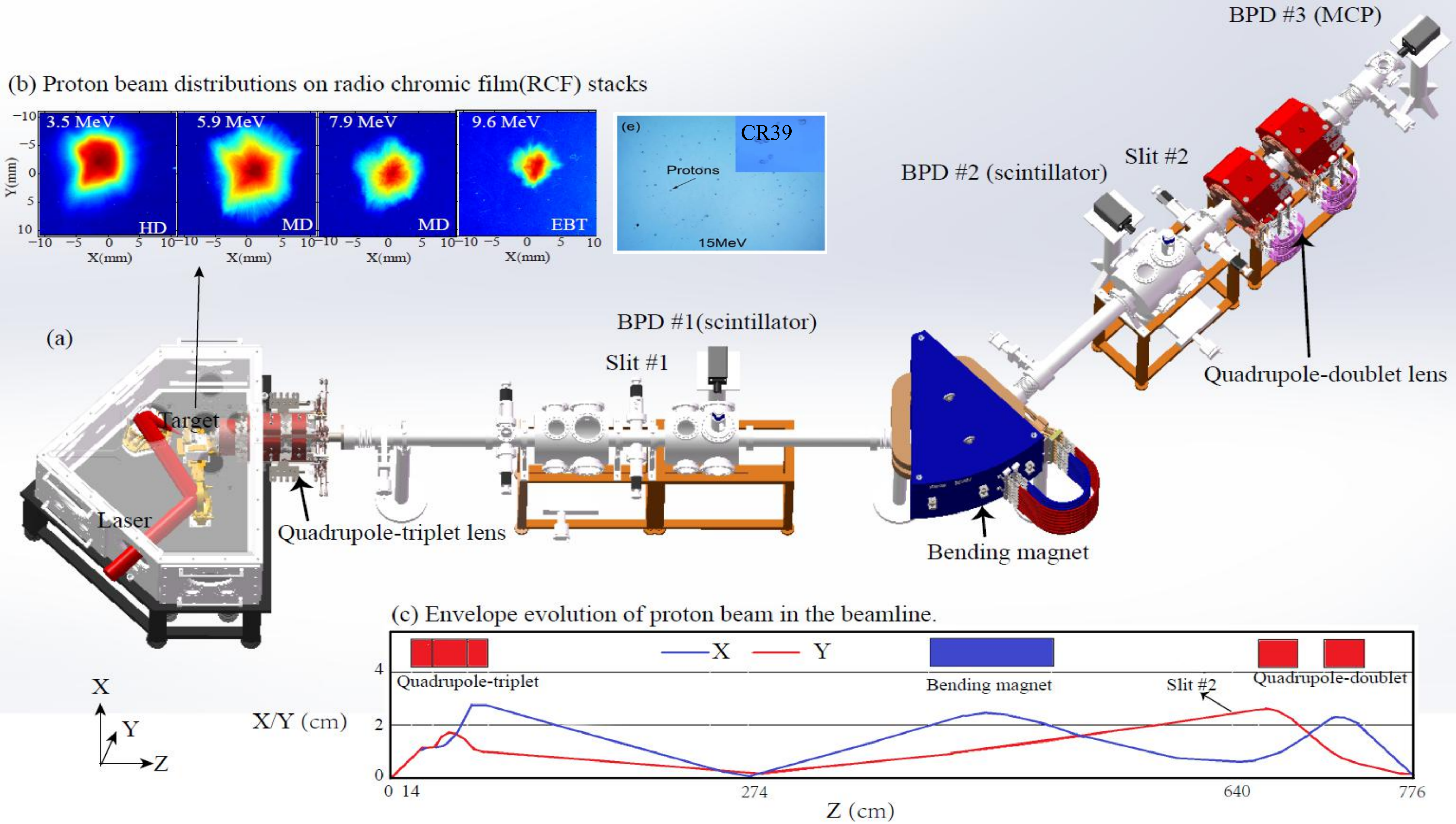






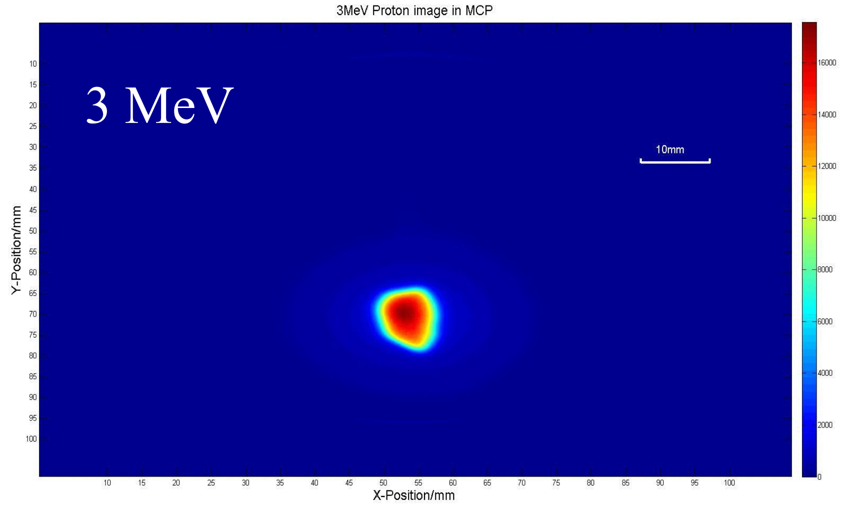


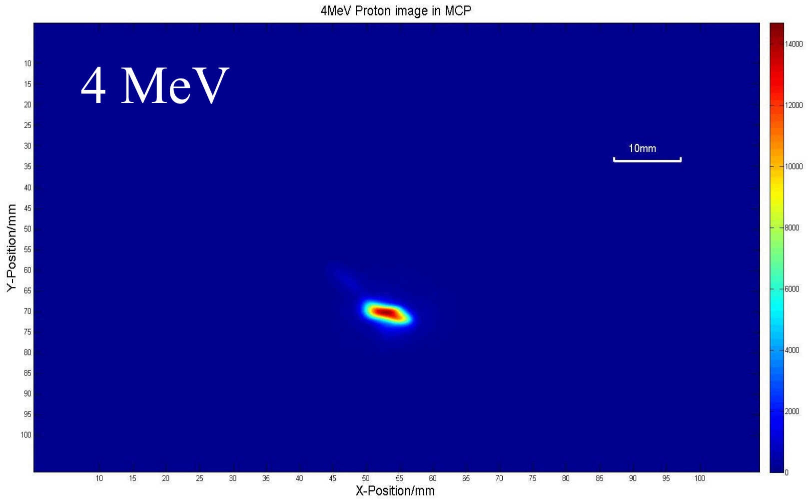
Beamline of CLAPA I

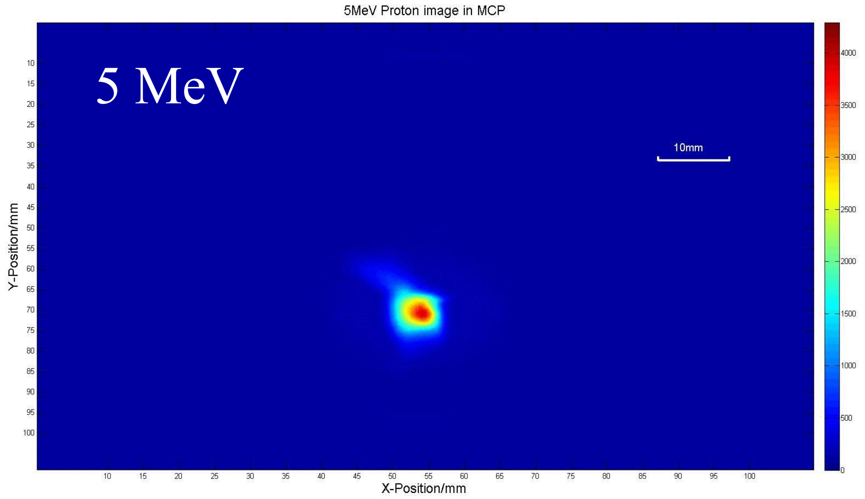


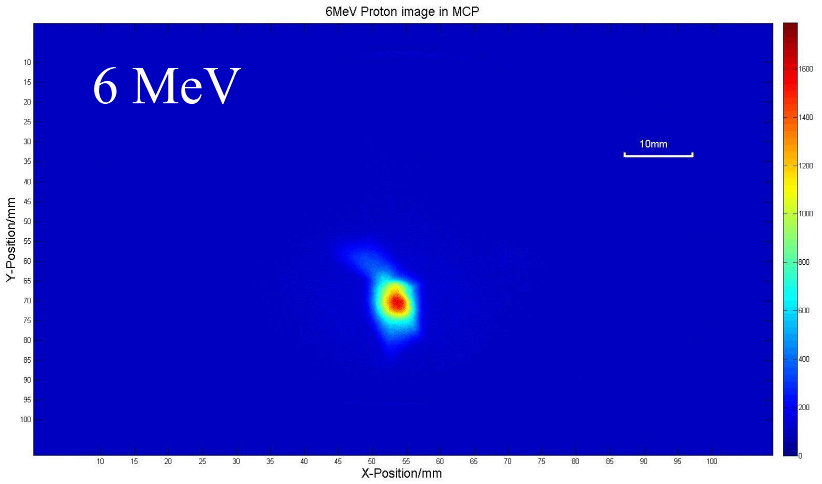
Physical Review Accelerators and Beams **22**, 061302 (2019).

Proton beam with 1%energy spread



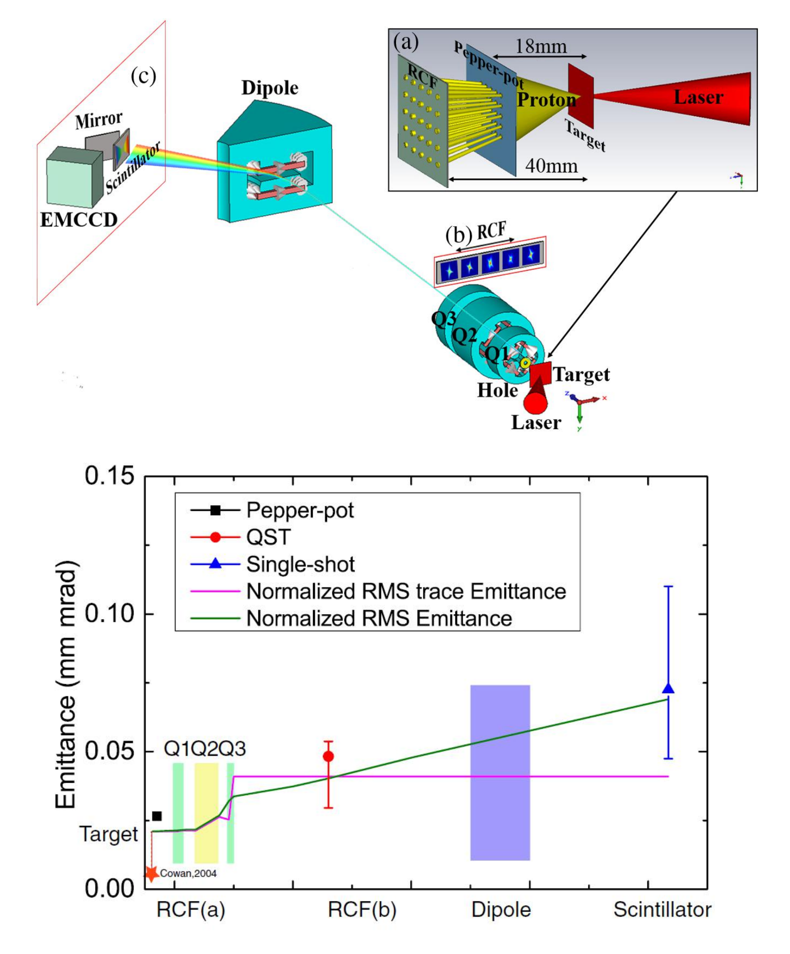




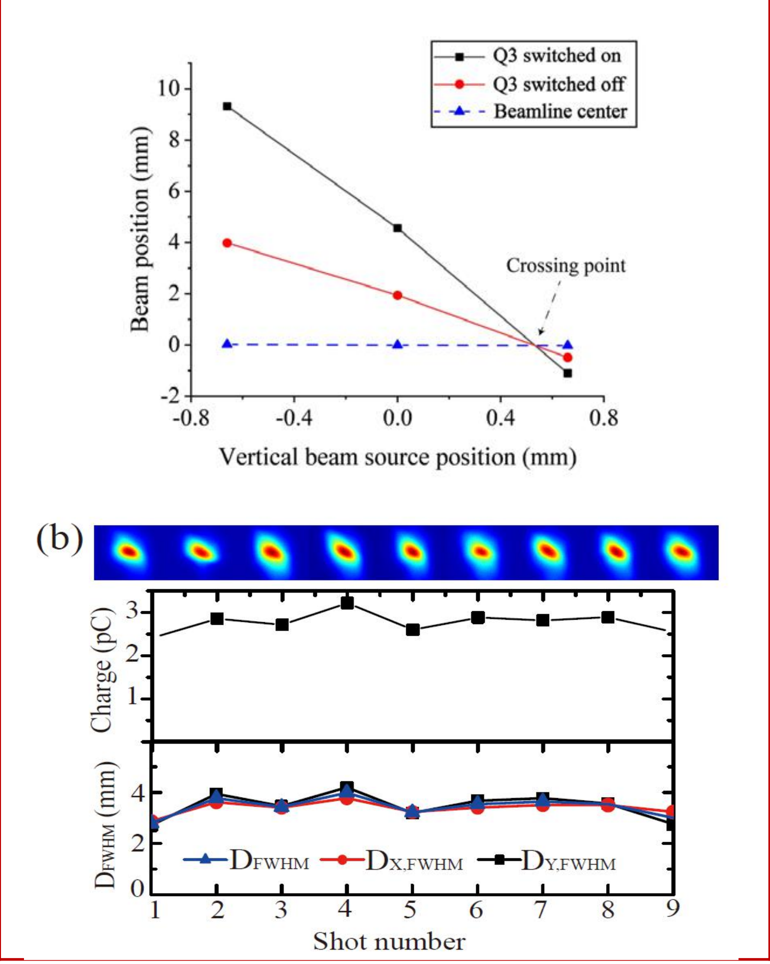


Experiments on CLAPAI beamline

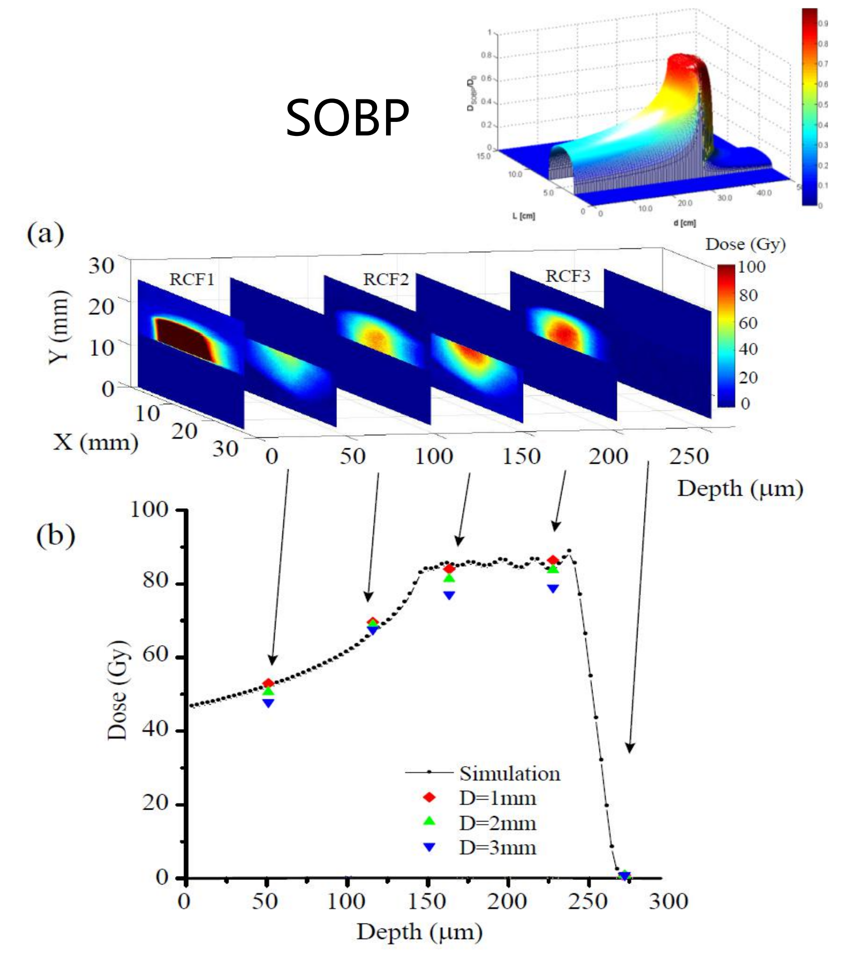
Accurate emittance measurement along the beamline



The key technology of beam regulation



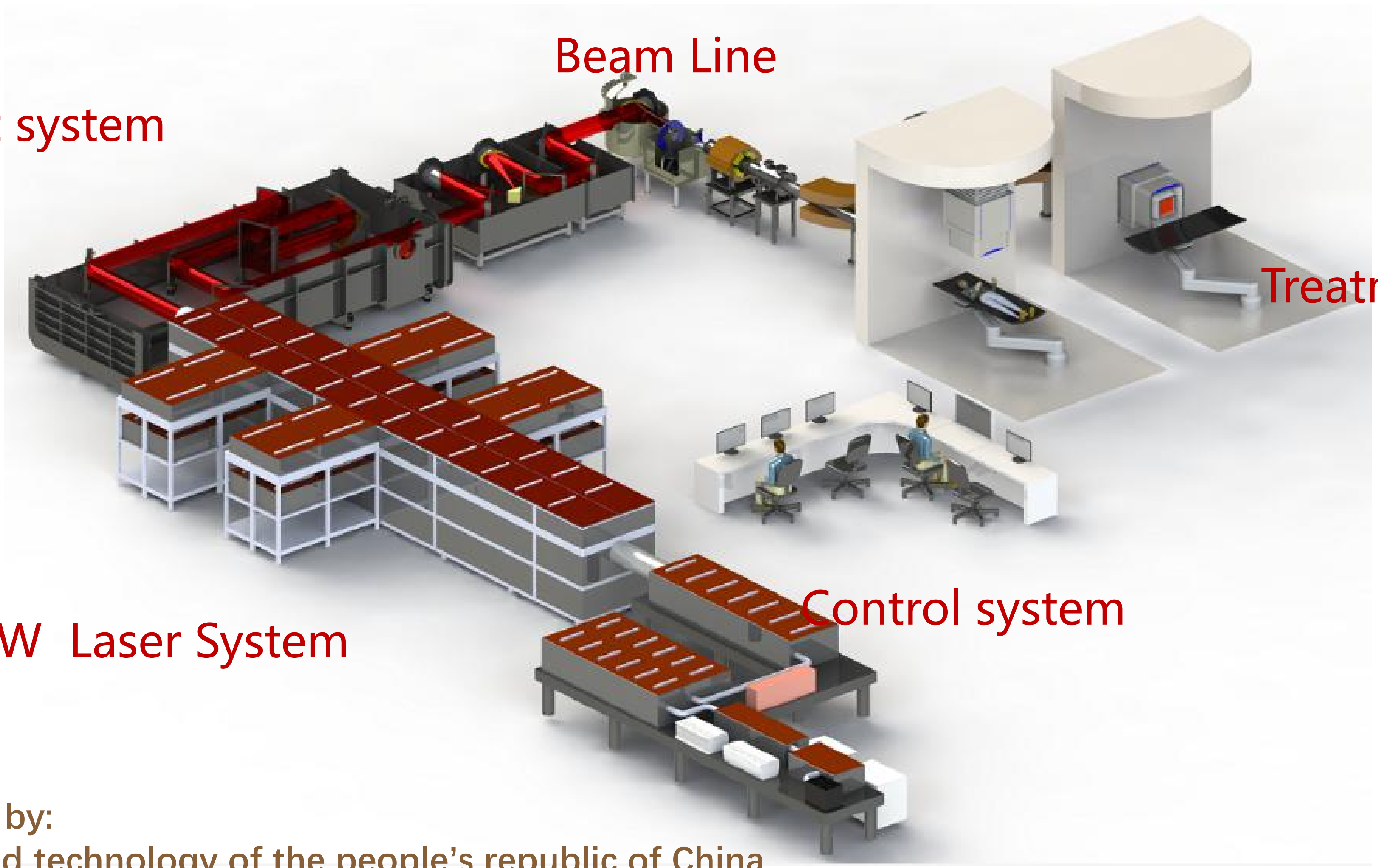
Tailored energy deposition with 3% energy spread beams



Physical Review Accelerators and Beams **23**,031302 (2020). *Physical Review Accelerators and Beams* **23**, 121304 (2020).

CLAPA II (2020-2025)

CLAPAII is a new laser-driven proton therapy facility under construction at Beijing Laser Acceleration Innovation center (BLAIC).

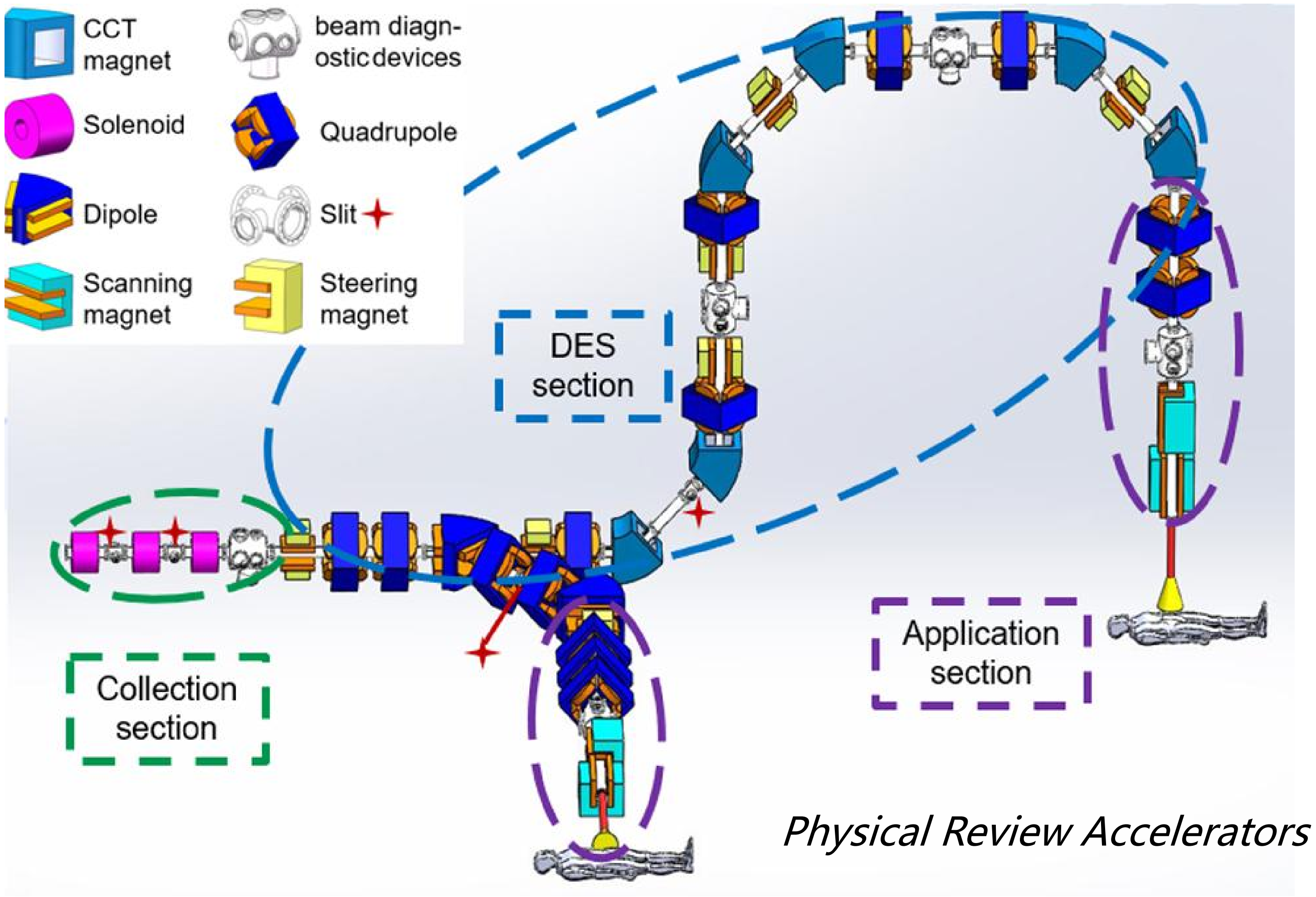


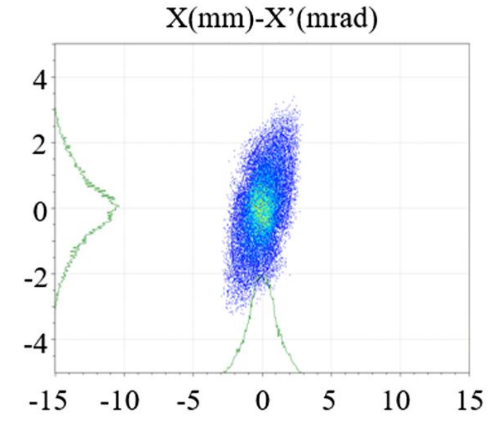
The project is supported by:

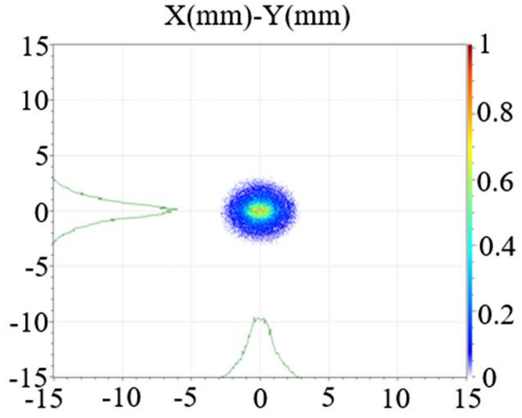
- Ministry of science and technology of the people's republic of China
- Beijing municipal commission of development and reform

Achromatic beamline of CLAPA II

- The beamline is designed with two transport lines to provide both horizontal and vertical irradiation modes with 40–100 MeV central energy protons.
- It can mitigate the negative effects of large energy spread up to 5% , and to reduce the overall weight of the vertical beamline.



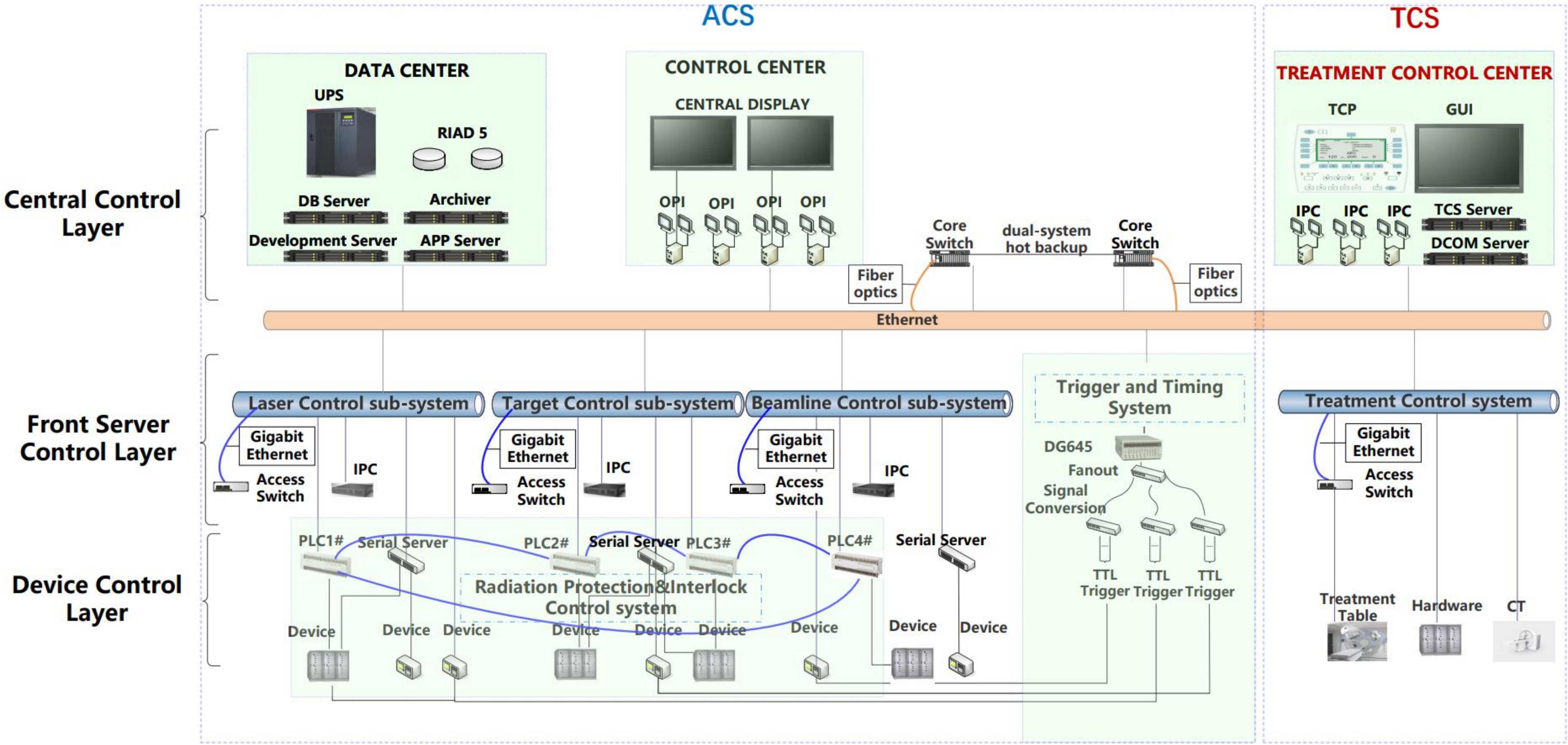




Physical Review Accelerators and Beams **23,** 111302 (2020).

Control system Of CLAPA II

- Fully functional automatic accelerator control system and treatment control system can meet the requirements of medical device certification.



PART 04

Summary

Summary

✓Laser plasma accelerator with ultra-high gradient is a promising candidate for future compact accelerator.

✓Laser accelerated protons have many potential applications, such as be applied to Ultra-high dose rate FLASH irradiation of biological samples and transient heat load testing of materials.

✓CLAPAI is a compact 200TW laser plasma accelerator at PKU. Laser accelerator of 3-9 MeV proton beams with 1% energy spread have been achieved on CLAPAI.

✓CLAPAII will be a new 2PW laser-driven proton therapy facility at Beijing Laser Acceleration Innovation center (BLAIC). A 2PW laser system, a fully functional target system, an achromatic beamline and an automatic control system are under research and development.

Thanks for your attention！
谢谢！敬请指正！