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Recent Progress of Compact Laser Proton Accelerator at PKU

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13/06/2022

Outline

- **Research Background**
- **Compact laser plasma accelerator at PKU**
  - CLAPAI
  - CLAPAII
- **Applications of laser accelerated proton beam**
  - Flash irradiation
  - Material irradiation
  - …
- **Summary**

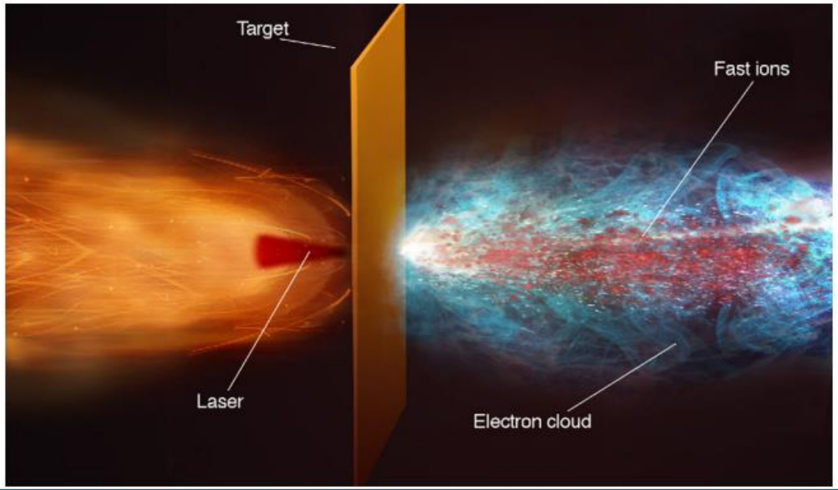
PART 01

Research background

Laser driven ion acceleration

- Acceleration gradient **GV/m-TV/m!!!**
- Acceleration distance ~ few mm -few microns
- Have obtained 7.8 GeV e-, 94 MeV p+

PRL 122.084801(2019)
NC 9： 724 (2018)



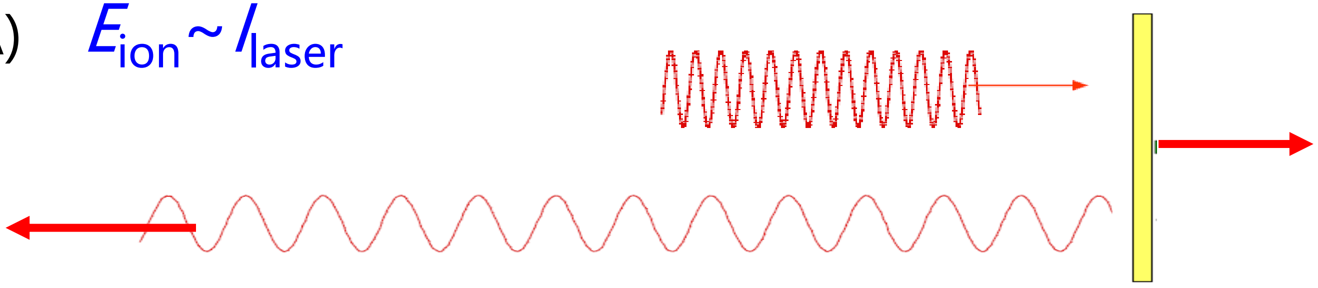
Energy?
Charge?
Energy spread?
Stability?
Reliability?...

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].

Radiation Pressure acceleration：Phase stable acceleration

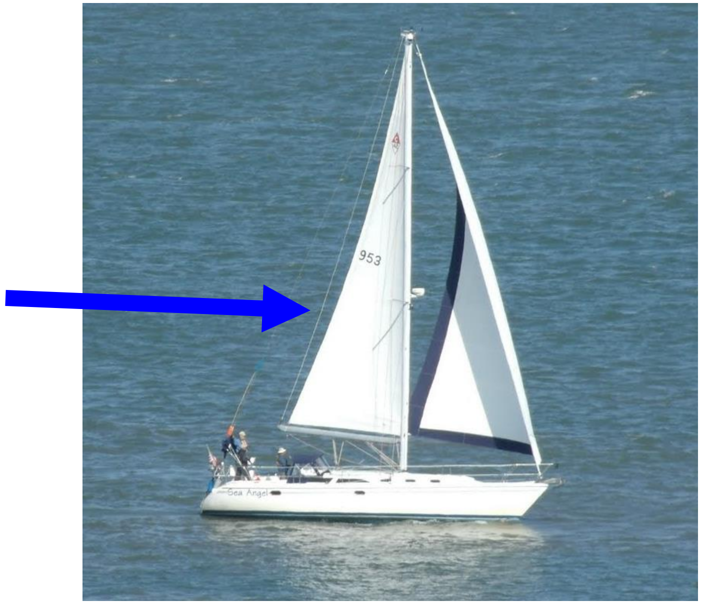
Target normal sheath acceleration (TNSA) $E_{ion} \sim I_{laser}^{1/2}$

Radiation pressure acceleration(RPA) $E_{ion} \sim I_{laser}$

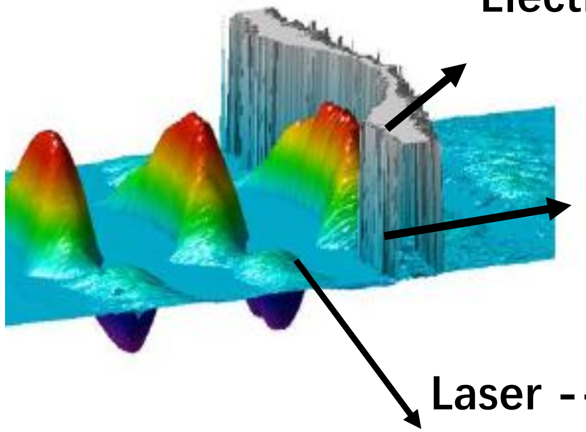


$$\mathrm{CE} = 1 - \frac{1}{4\gamma^2} \approx 100\%$$

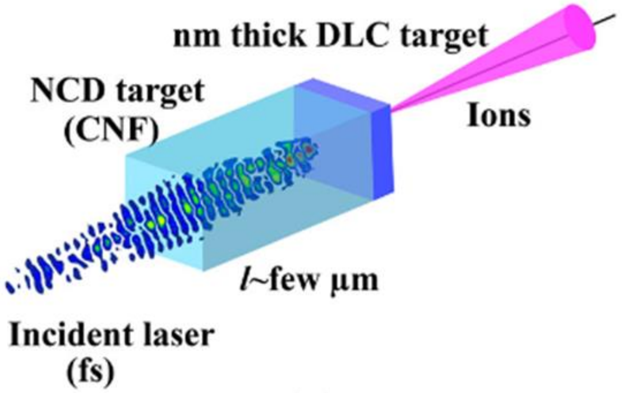
Sailboat



PSA



X.Q.Yan, C.Lin, et al., PRL 100 135003(2008)



PRL 115.064801(2015)

Experimental results for proton energy

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

Nobel Lecture: Extreme light physics and application*

Gerard Mourou†

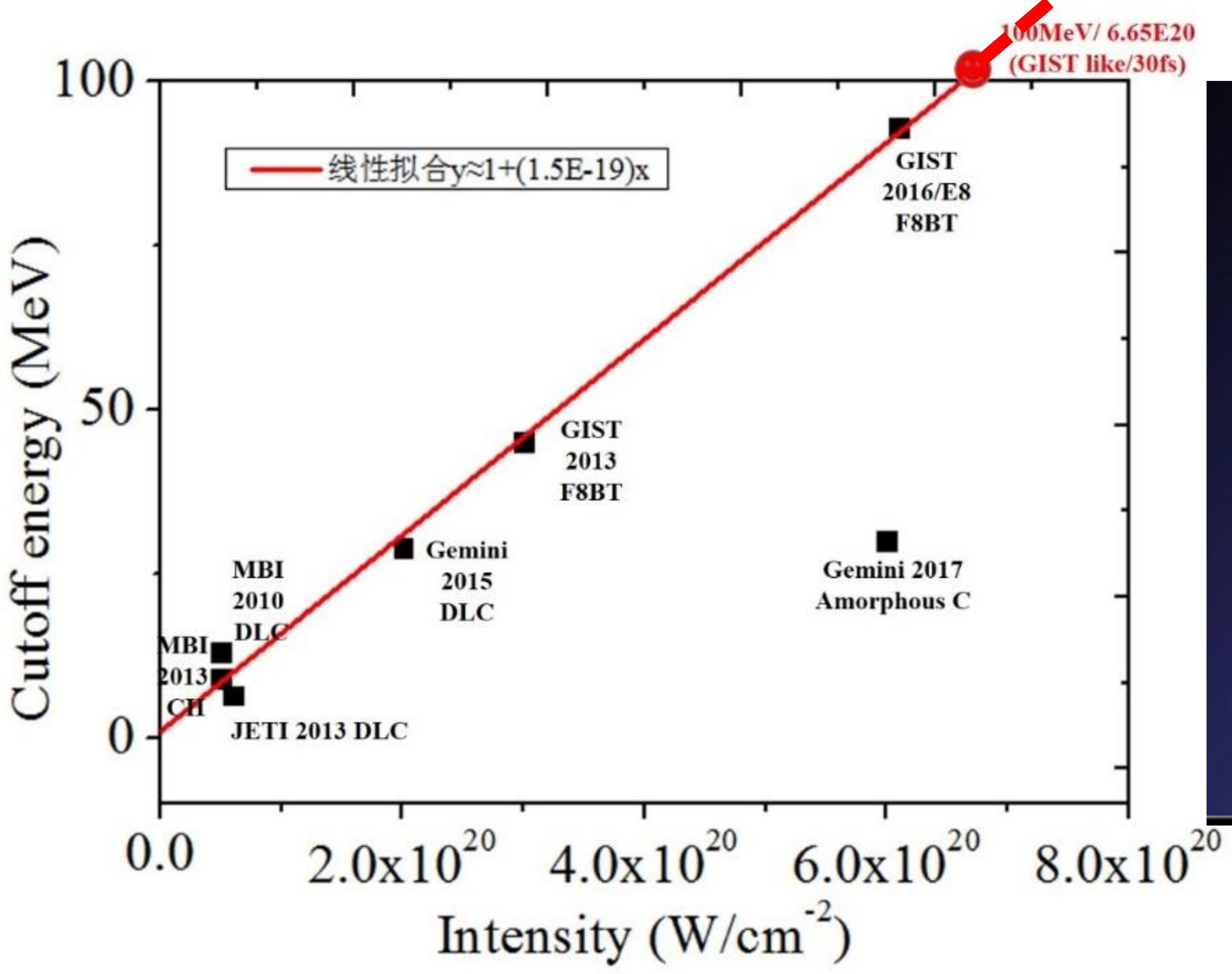
École Polytechnique, 91128 Palaiseau Cedex, France

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],

200MeV@2*10^21 W/cm2



>20 in operation or under construction worldwide.

>5 under construction in China.

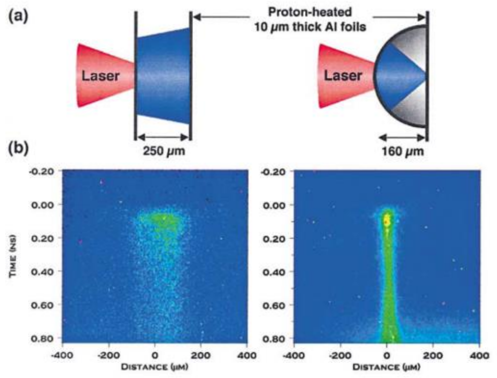
(China has seen the greatest growth internationally in the development of ultra-high-power lasers and in their applications.)

Application of laser driven proton beam

Short!

pulse duration ~ ps to ns

WDM

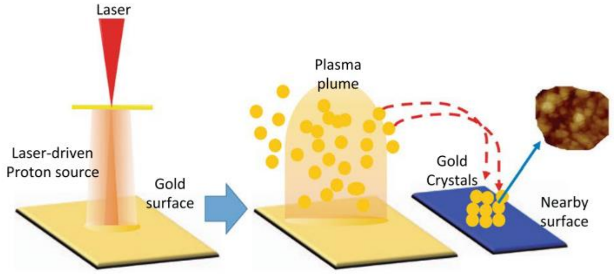


PRL, 2003, 91(12):125004.

Intense!

peak current ~ 10^9-10^{11} ppp ~ KA

Material irradiation



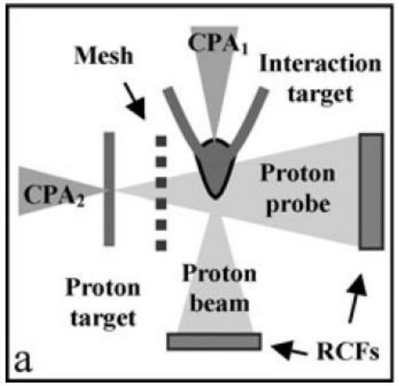
SR, 2017, 7(1):1-9.

Small!

initial spot source ~ 5μm

emittance ~ 0.1 π mm mrad

Proton radiograph



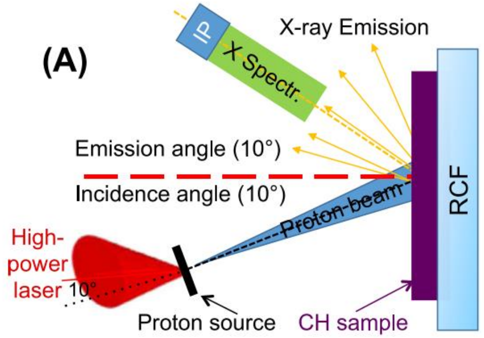
LPB, 2008, 26, 241–248.

Wide!

energy spread ~ 100%

divergence angle ~ 10°

Ion beam analysis



SR, 2017, 7:40415.

✓ Laser accelerated proton beams have unique beam characteristics, which provide new opportunities for scientific research and potential applications in many fields.

✓ These new features also bring new challenges to the beam-line technology.

Beam Line of Laser Driven Protons

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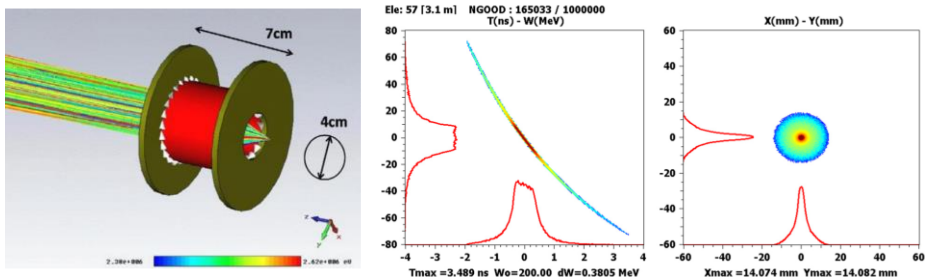
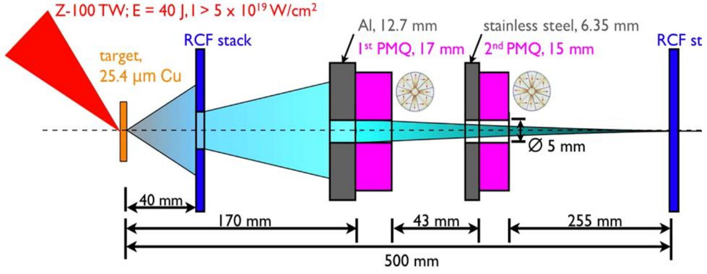
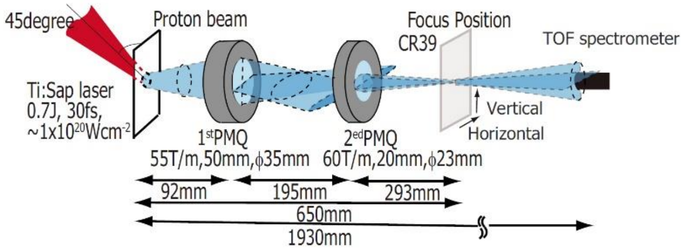
Pulsed solenoid



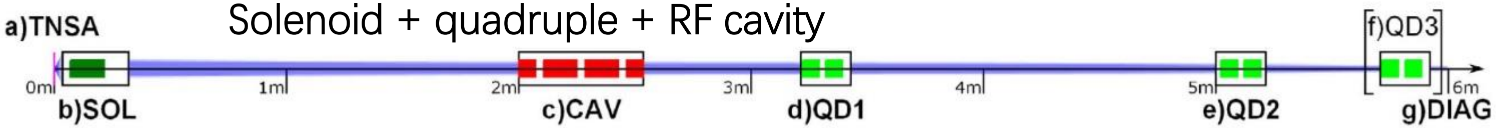
Electronic Quadruple



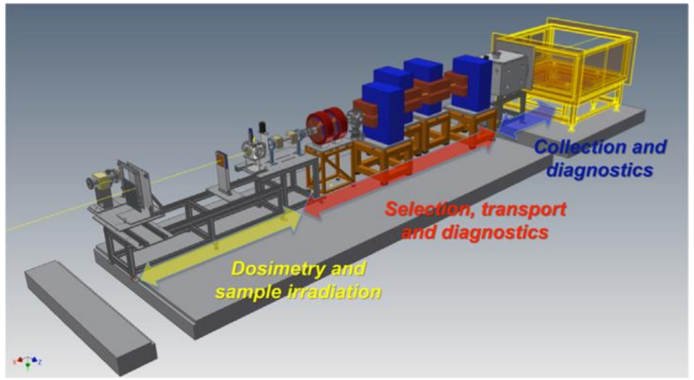
Permanent Quadruple



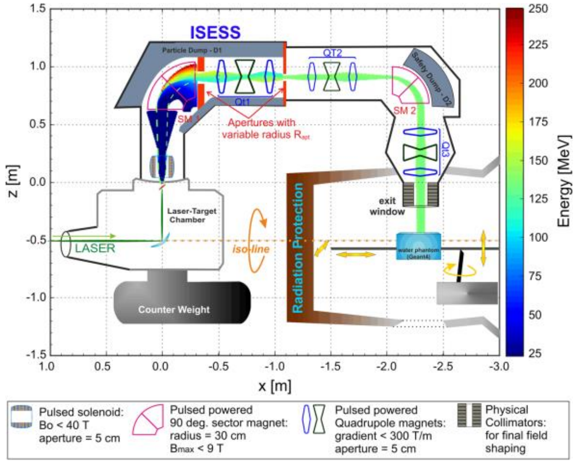
Solenoid + quadruple + RF cavity



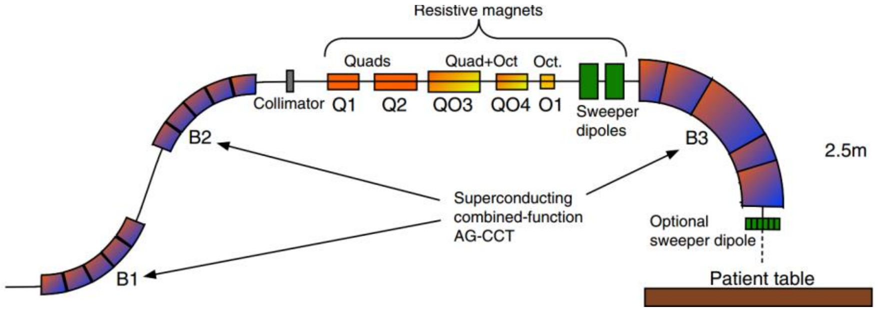
ELI beam line design



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).

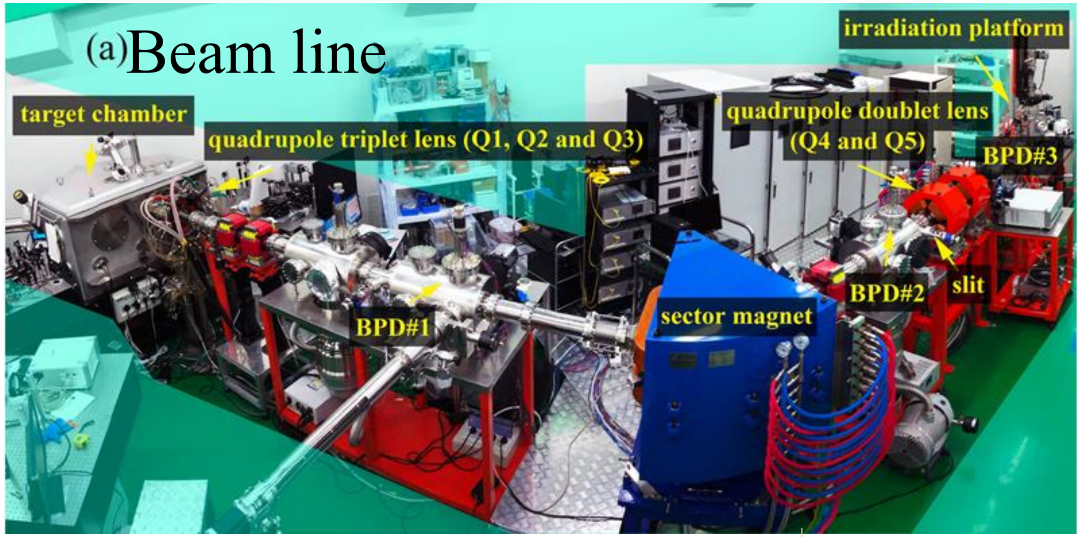
S. Busold *et al.*, *Scientific Reports* **5**, 12459 (2015).
F. Romano *et al.*, *NIM-A* **829**, 153 (2016).
U. Masood et al., Applied Physics B **117**, pages41–52 (2014).
U. Masood *et al.*, *Physics in Medicine & Biology* **62**, 5531 (2017).
J. G. ZHU *et al.*, *Phys. Rev. ST Accel. Beams* **22**, 061302 (2019).

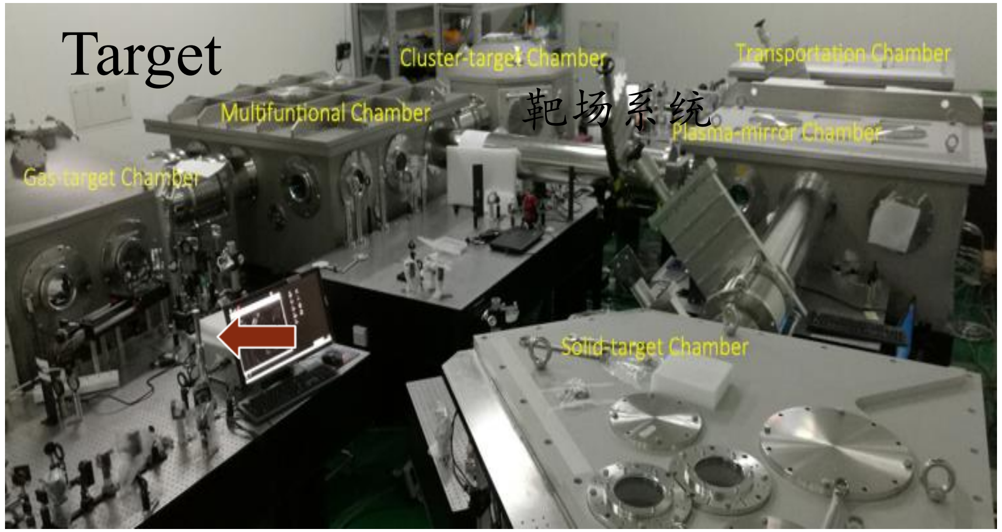
PART 02

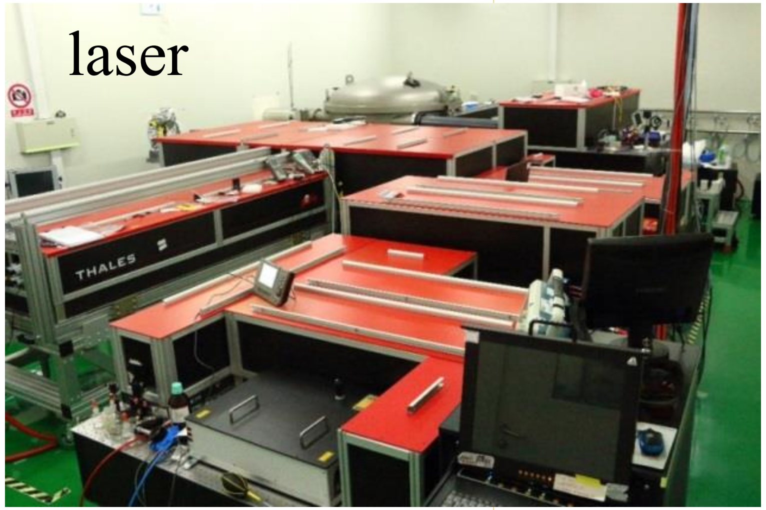
Compact laser plasma accelerator at PKU

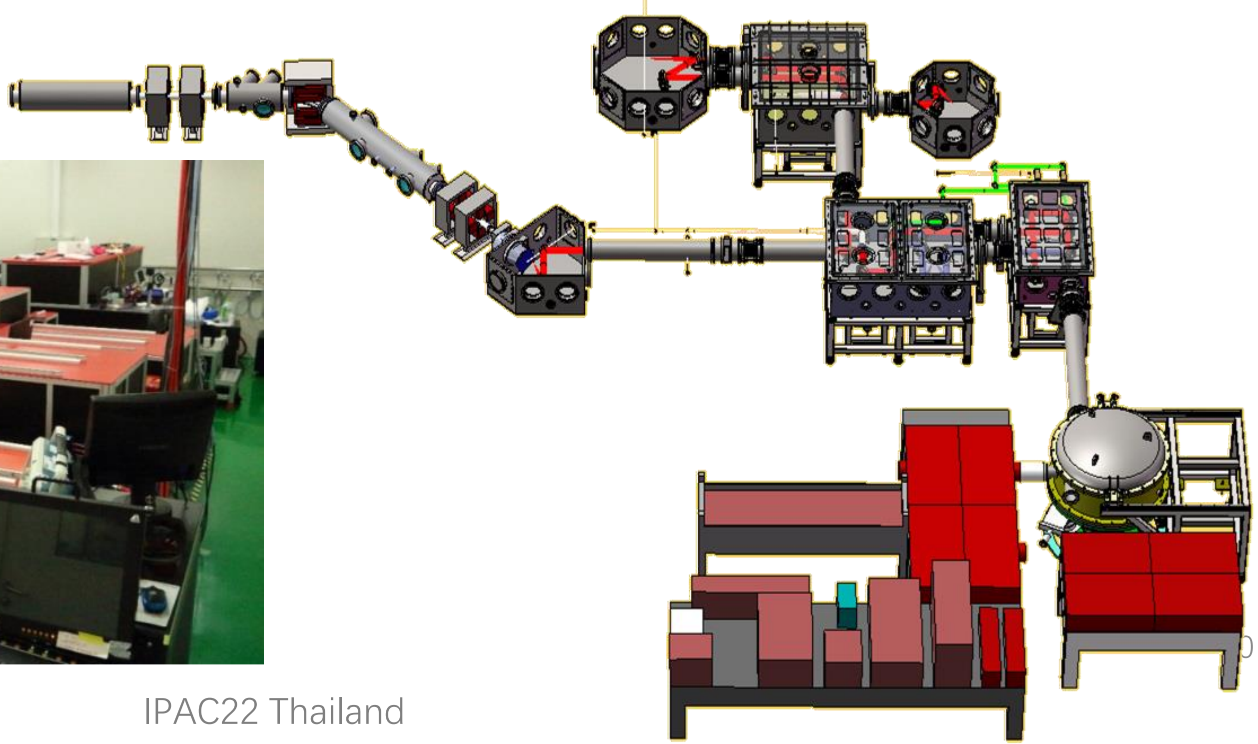
- CLAPA I : 200TW laser accelerator
- CPALA II: 2PW laser accelerator

CLAPA I (2013-2018)

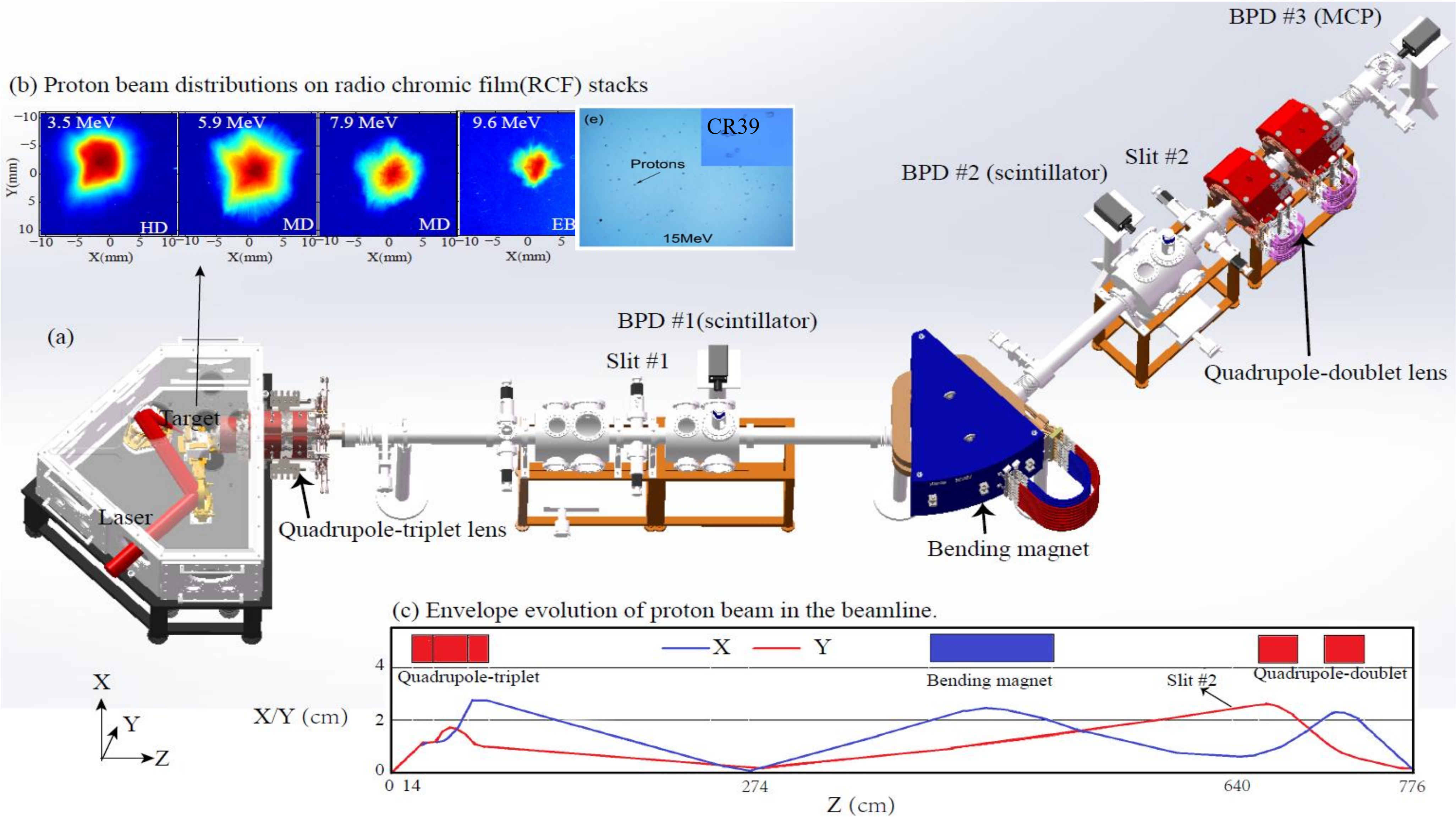






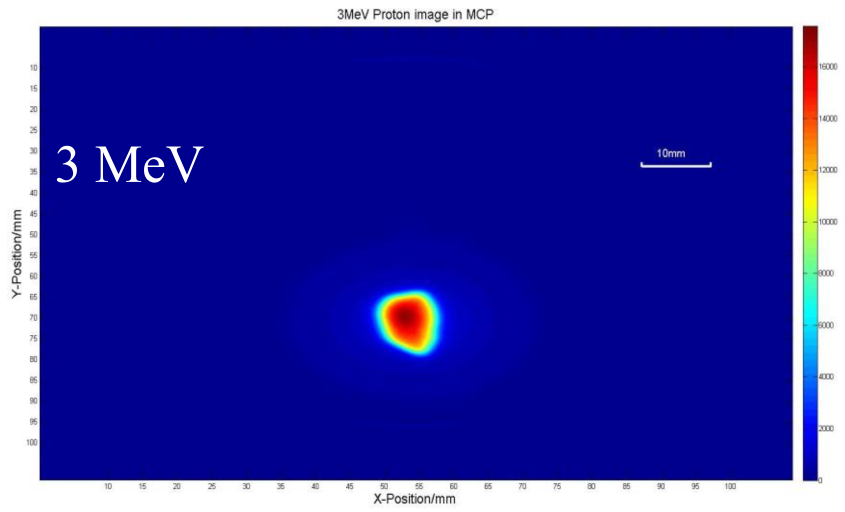


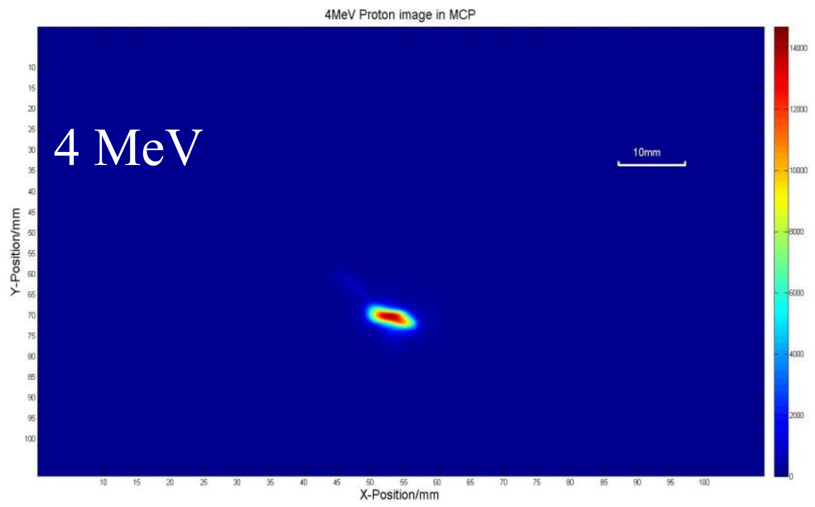
Beamline of CLAPA I

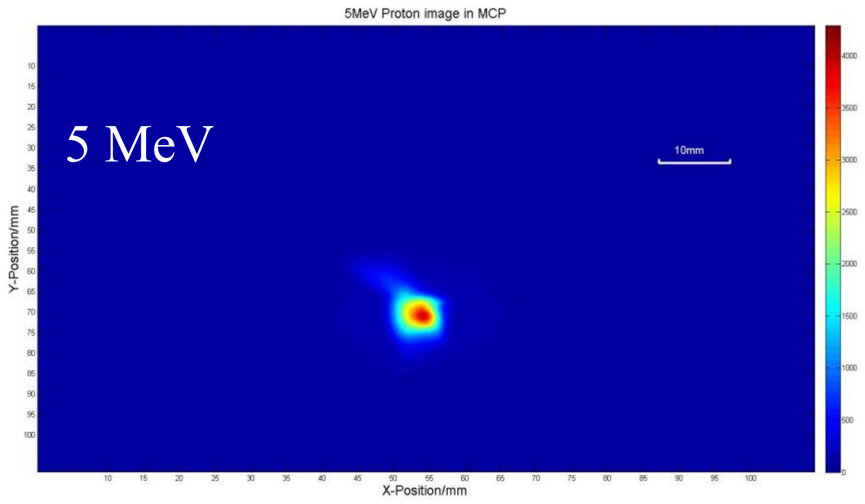


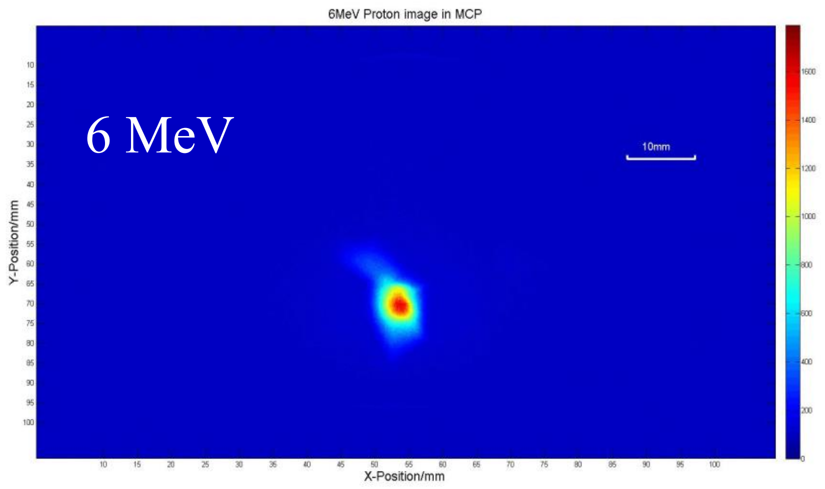
J.G.Zhu,…, C.Lin*, X.Q.Yan* PRAB 22, 061302 (2019).

Proton beam with 1%energy spread







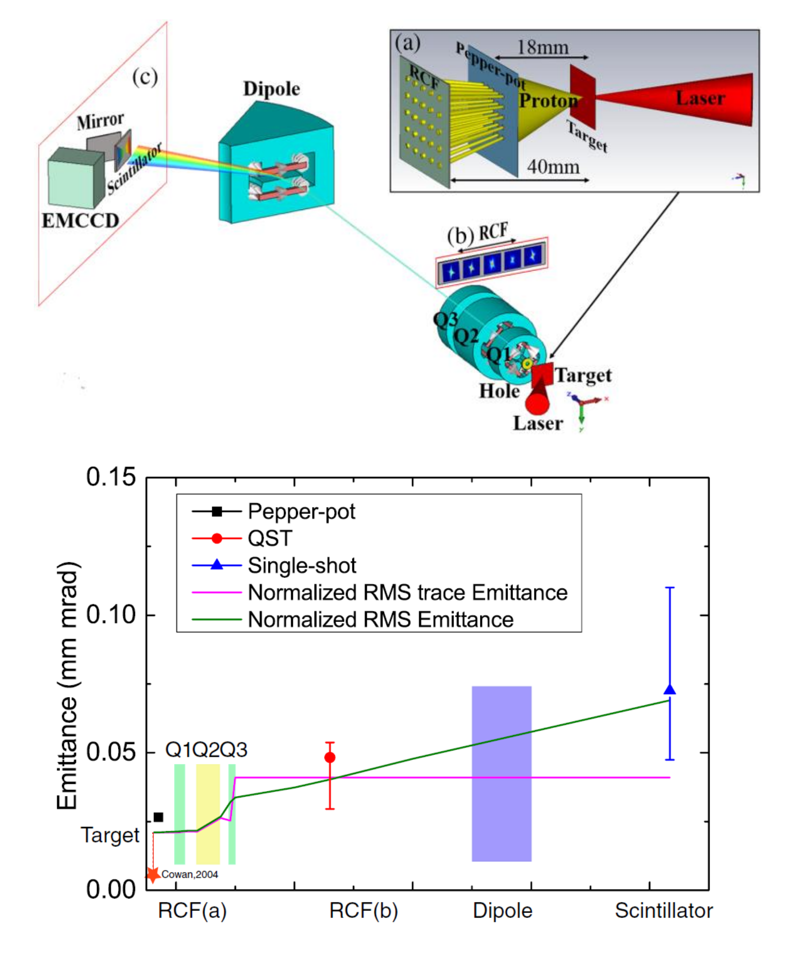


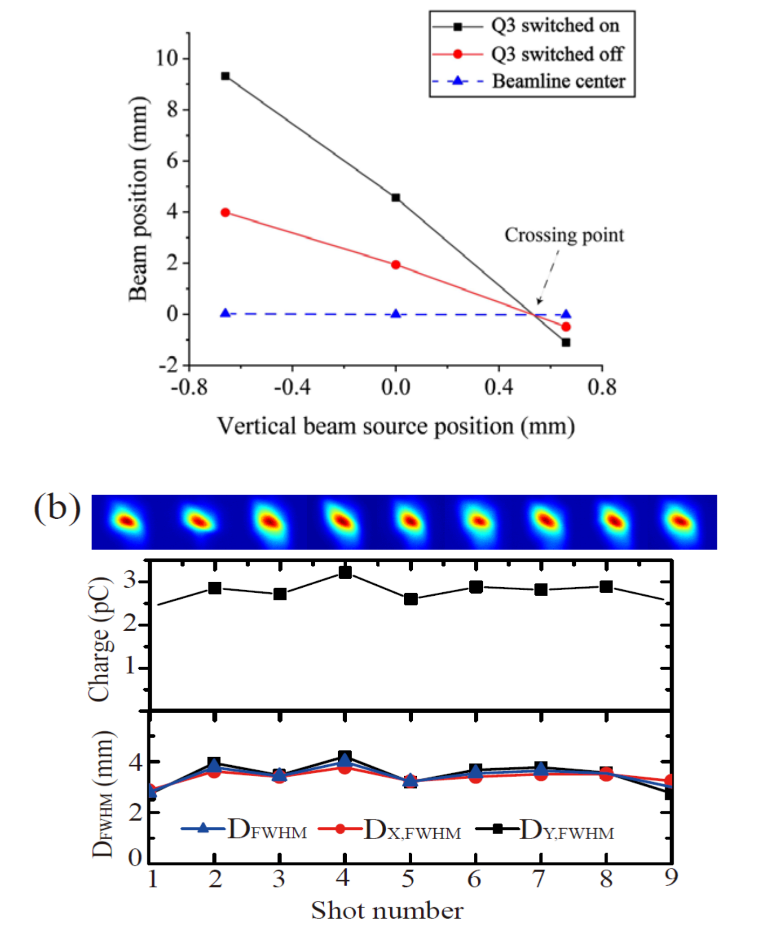
Experiments on CLAPAI beamline

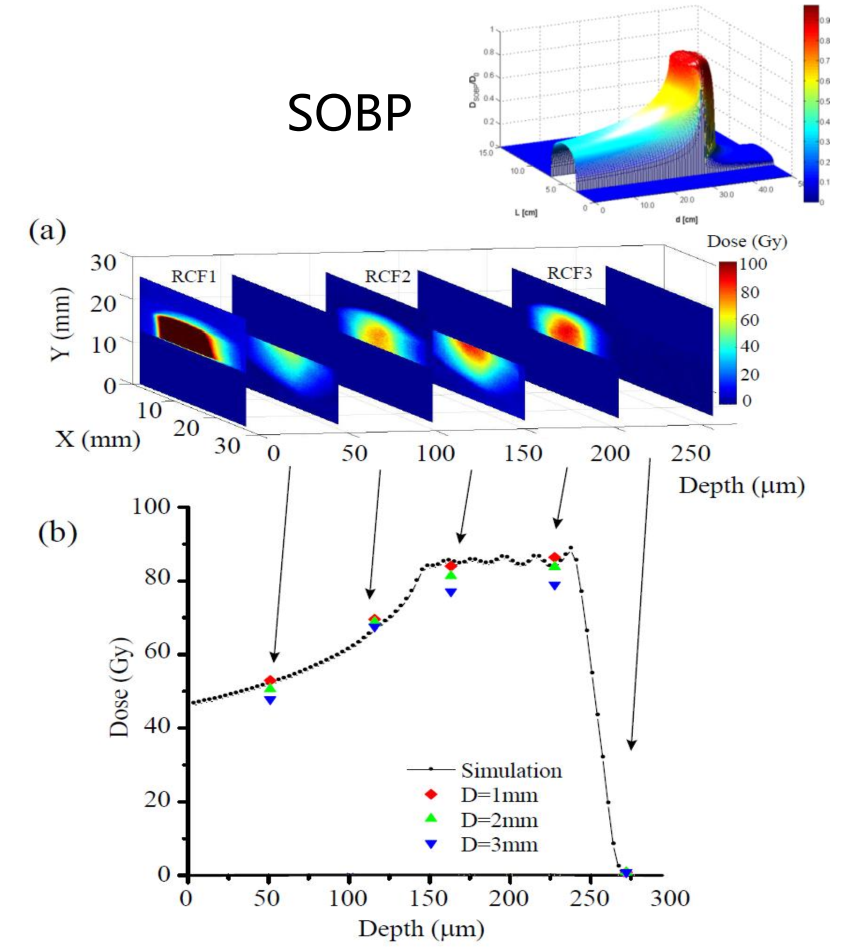
Accurate emittance measurement along the beamline

The key technology of beam regulation

Tailored energy deposition with 3% energy spread beams



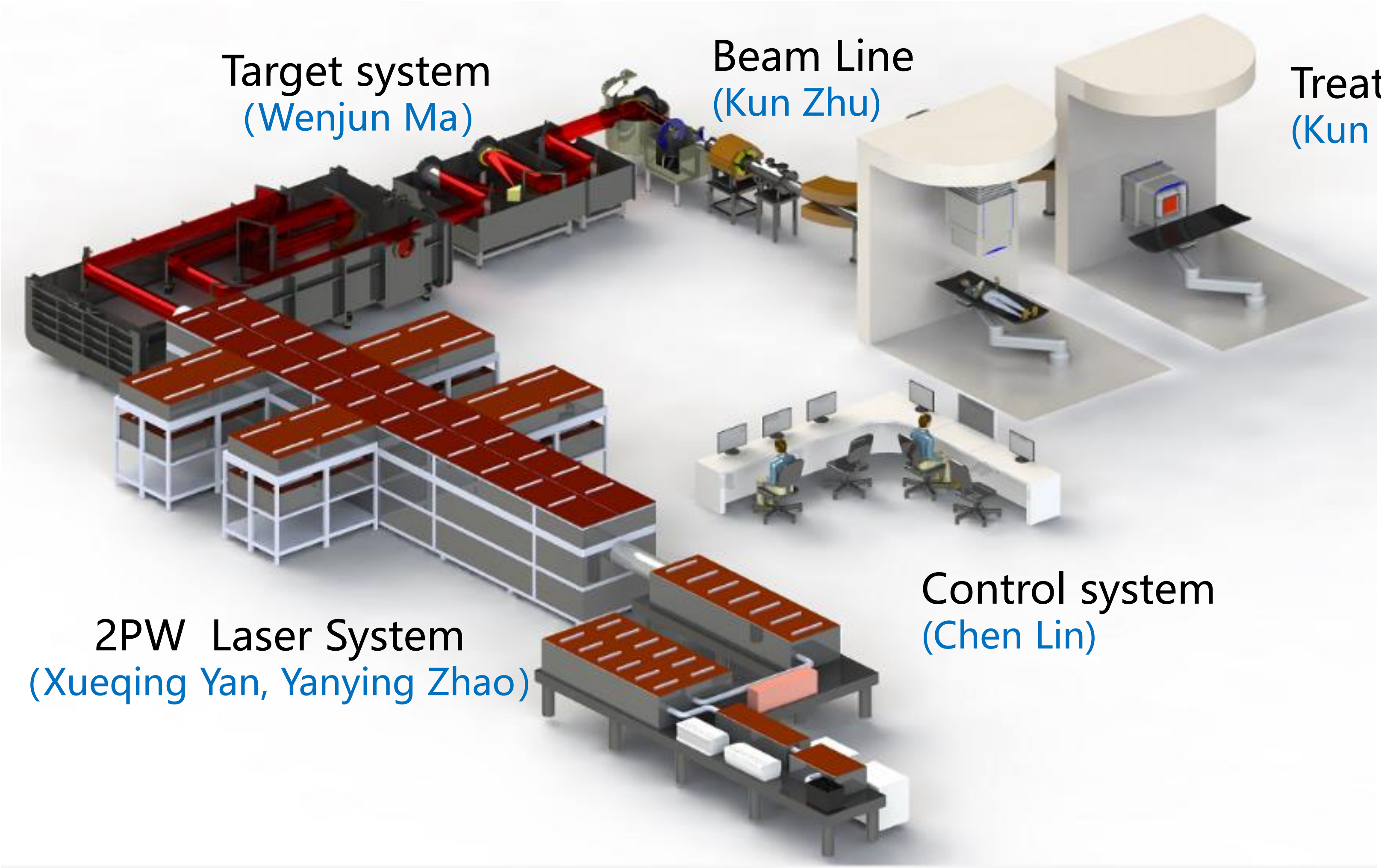


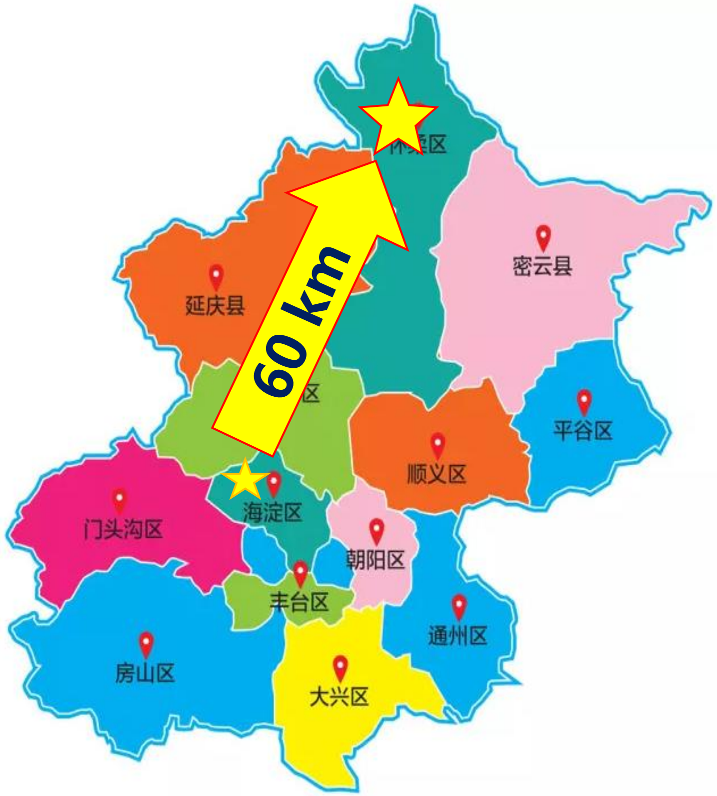


M. J. Wu,…, C.Lin*, X.Q.Yan*, PRAB 23,031302 (2020). J.G.Zhu,…, C.Lin*, X.Q.Yan*, PRAB 23, 121304 (2020).

CLAPA II

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



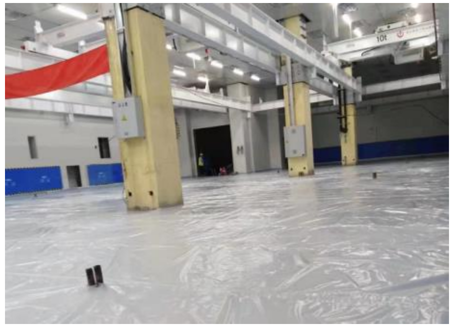


Beijing laser acceleration Innovation Center

Beijing laser acceleration innovation center (BLAIC) covers an area of 30000 square meters, including 13 scientific laser accelerator R & D platforms and technical support platforms. BLAIC will be in operation by the middle of 2023.

(1) Application object: proton radiotherapy device based on laser accelerator

(2) Scientific object : laser driven high brightness light source



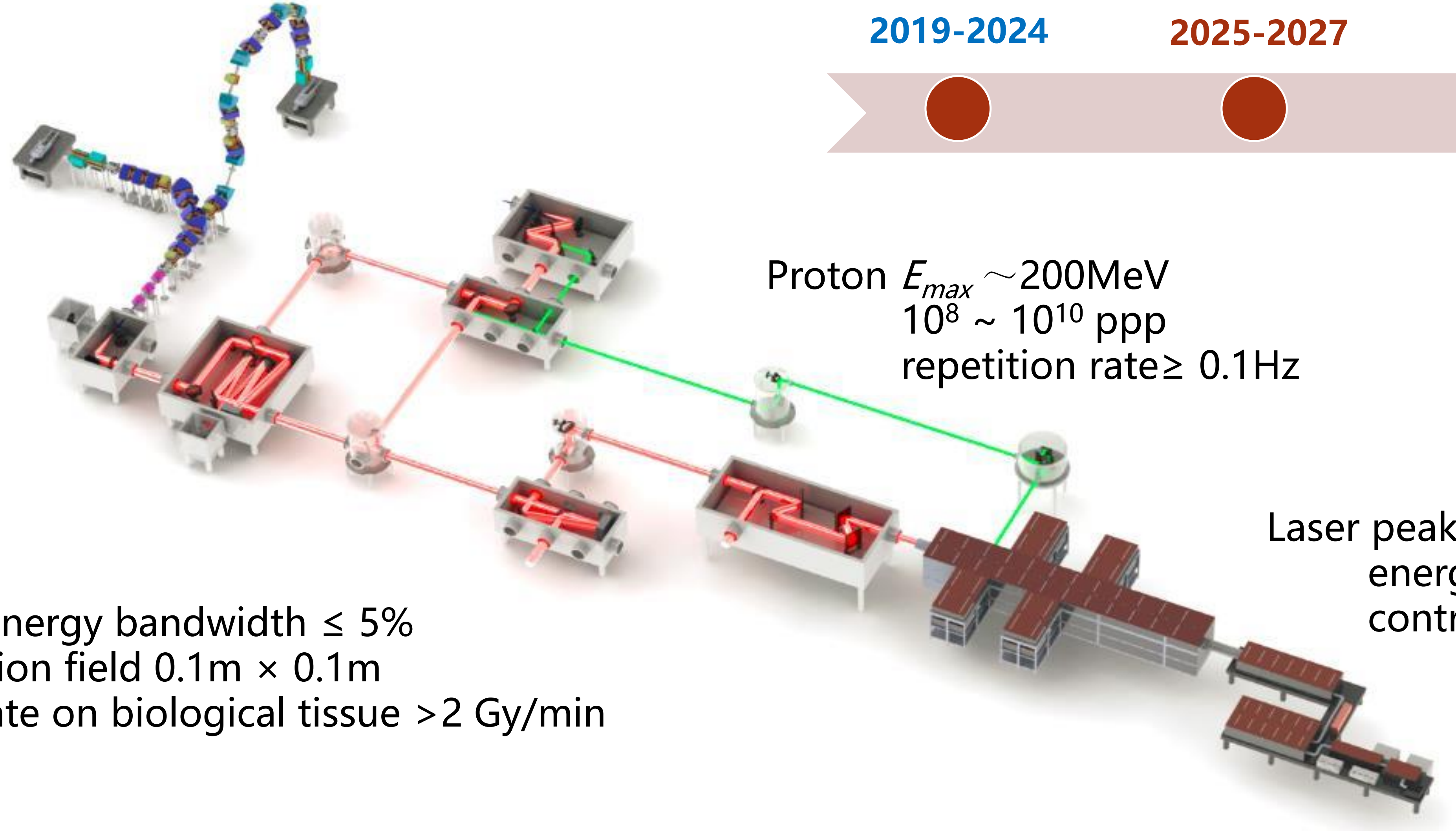

Technical route of CLAPAII

Technical readiness: level 9
MTBF≥1000h

Experimental prototype: 2019-2024

Engineering prototype: 2025-2027

Product prototype: 2028-2030



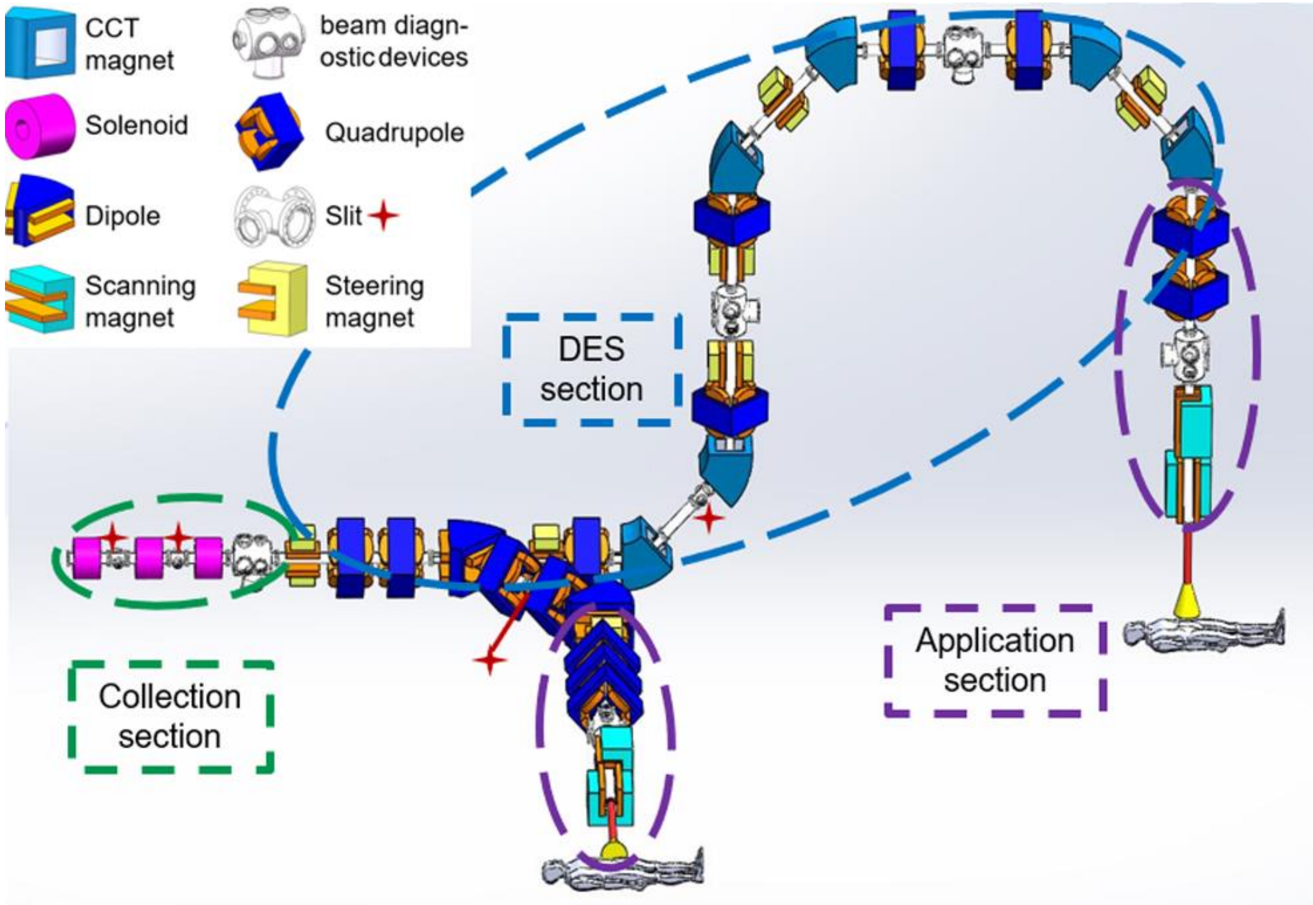
Proton E_{max} ~200MeV
10^8 ~ 10^{10} ppp
repetition rate≥ 0.1Hz

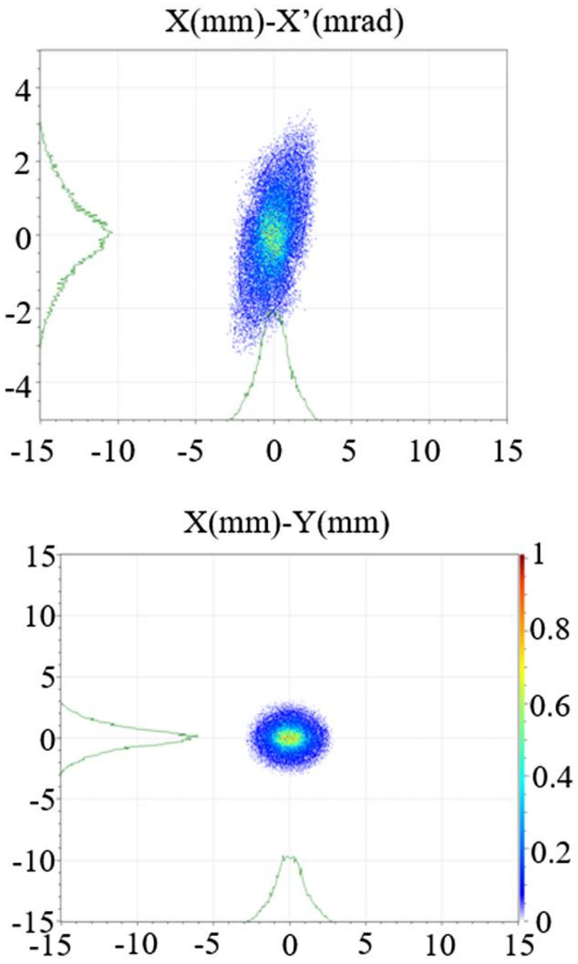
Laser peak power ≥ 2pw
energy on target ≥ 25J
contrast ≥ 10^{10}

Beam energy bandwidth ≤ 5%
irradiation field 0.1m × 0.1m
Dose rate on biological tissue >2 Gy/min

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.

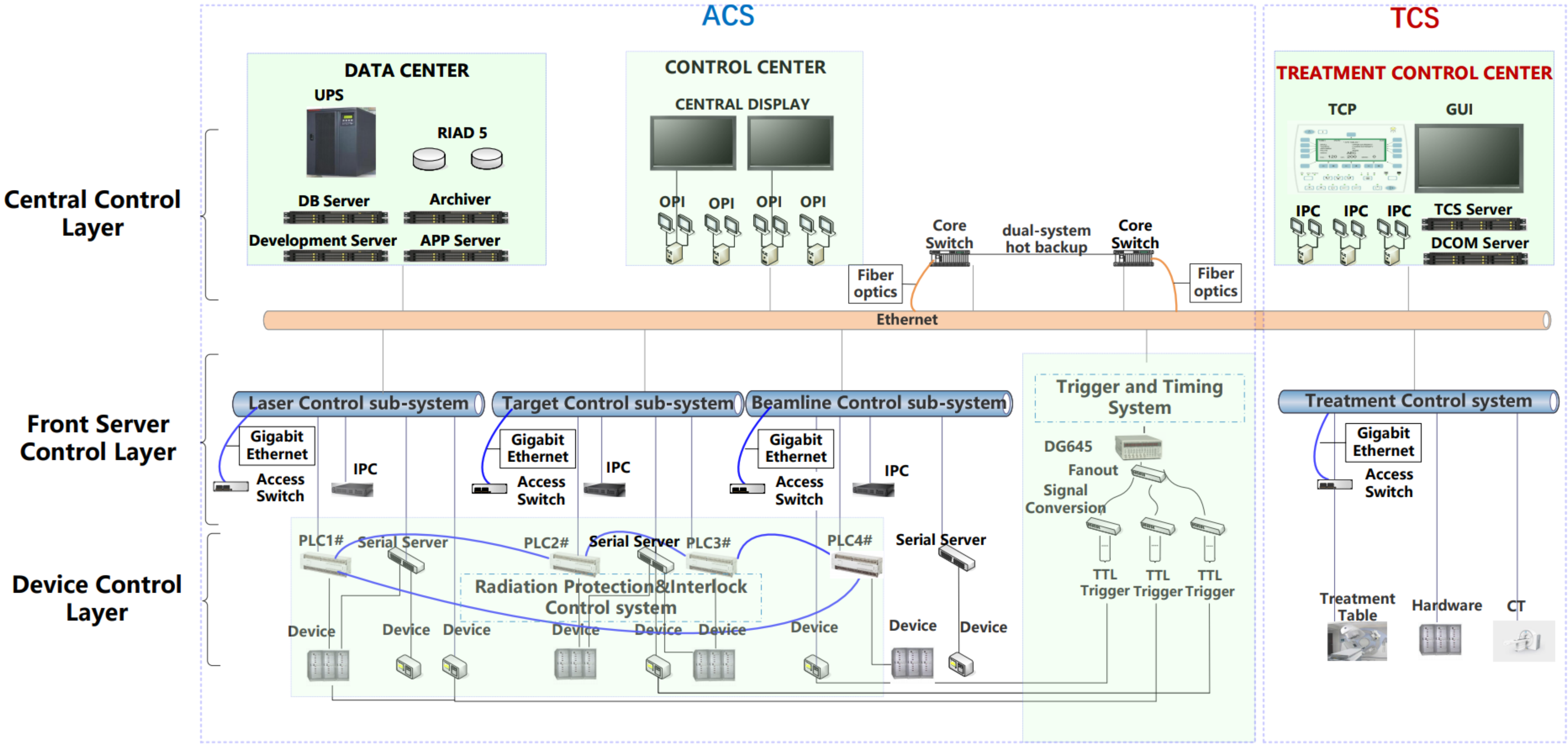




K. D. Wang, K. Zhu*,… X.Q.Yan*, PRAB 23, 111302 (2020).

Control system Of CLAPA II

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



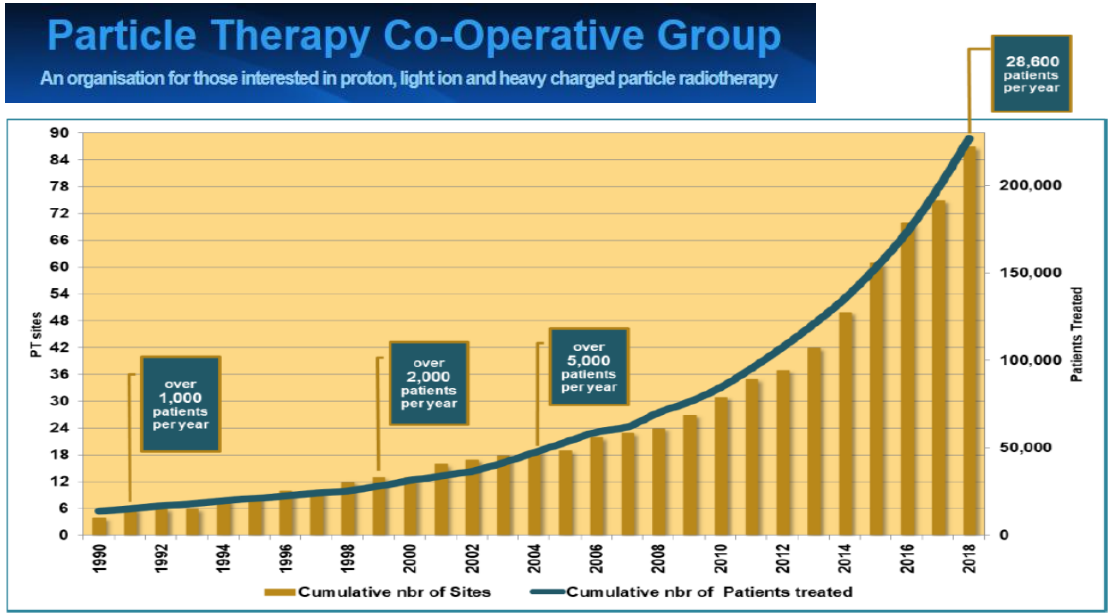
PART 03

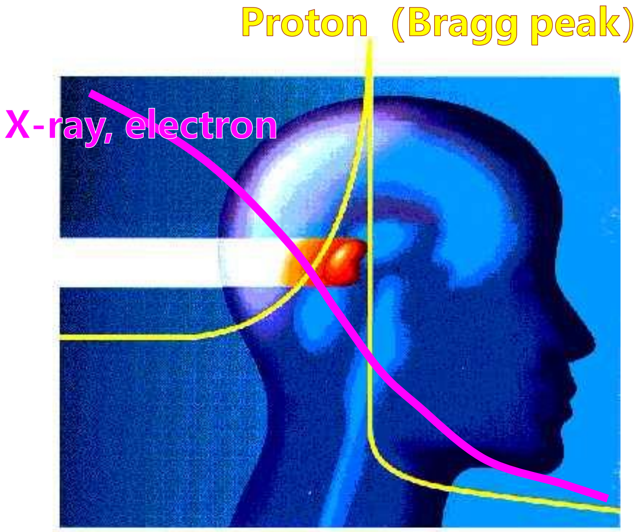
Applications of laser accelerated proton beam

- Flash irradiation (FLASH-IR)
- Material irradiation

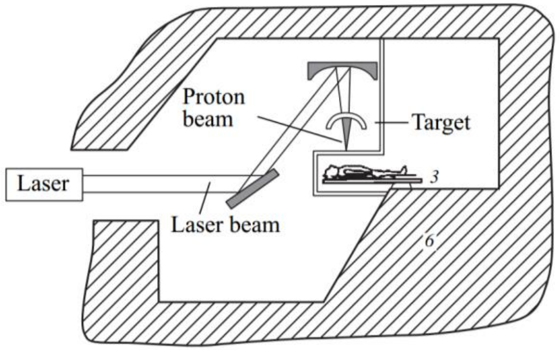
Advantages of Proton Radiotherapy

- 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.





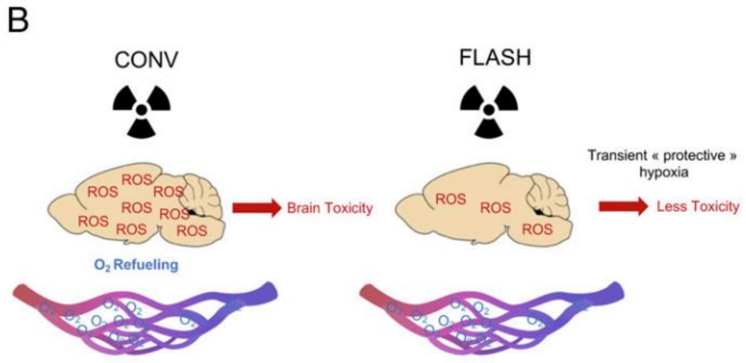
Laser accelerated protons was first proposed for radiotherapy in 2002!

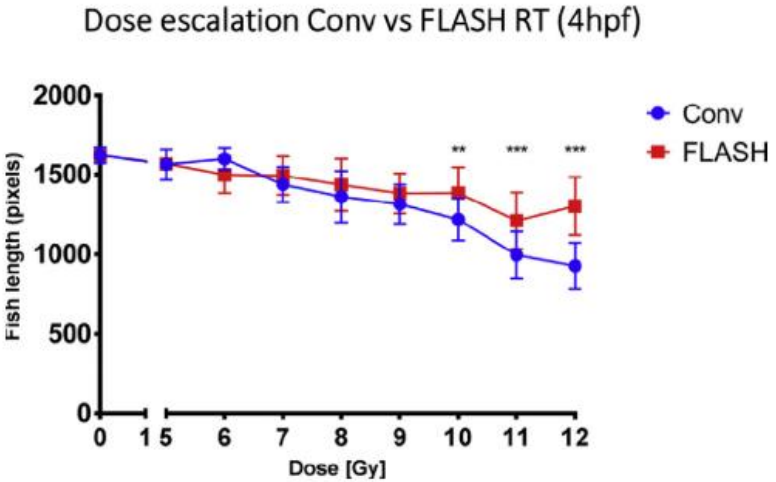


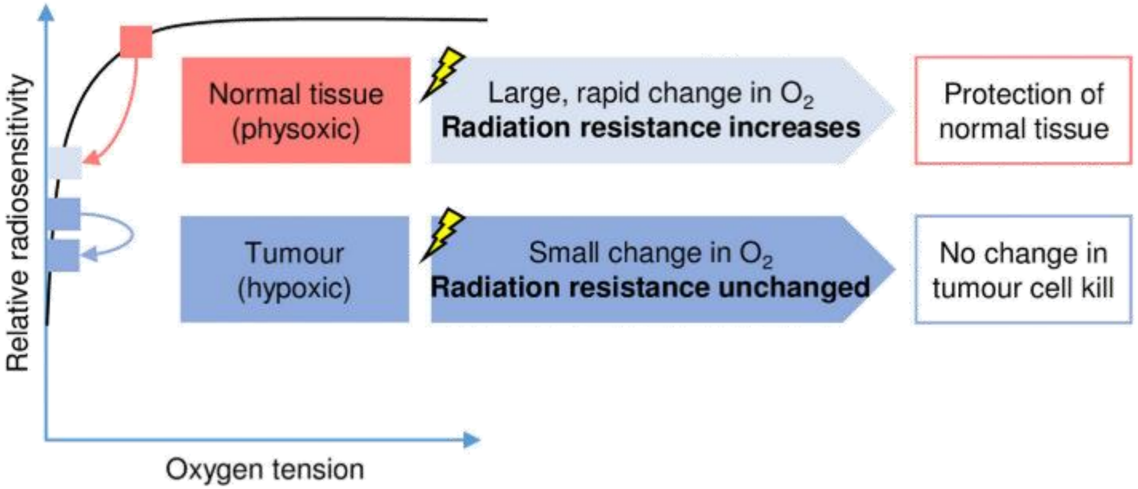
Plasma Physics Reports **28** (5), 453 (2002).

Ultra-high Dose Flash Irradiation (FLASH-IR)

- 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







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.

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

Ultra-high dose FLASH irradiation (10^9Gy/s)

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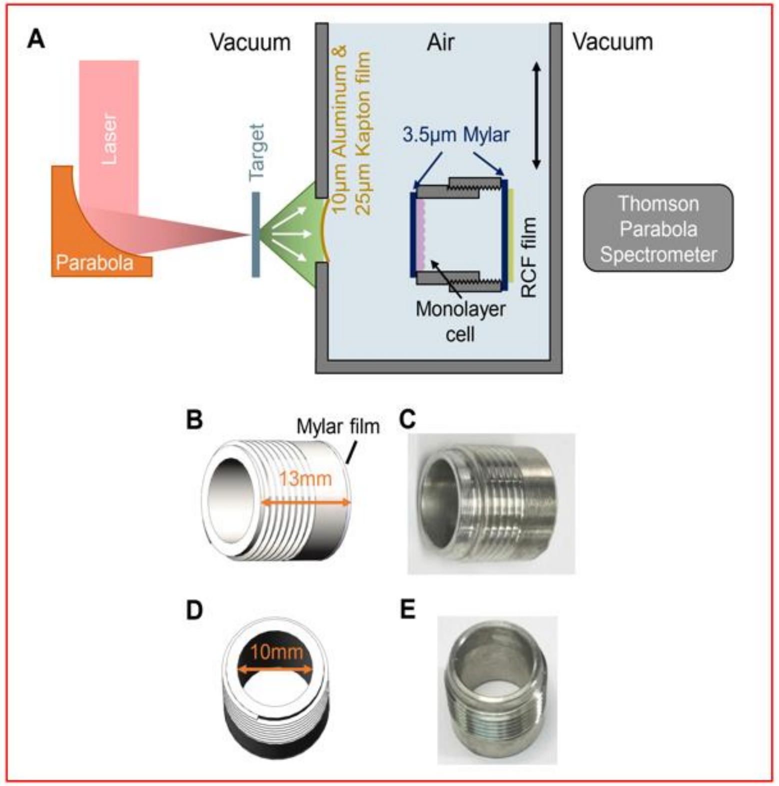
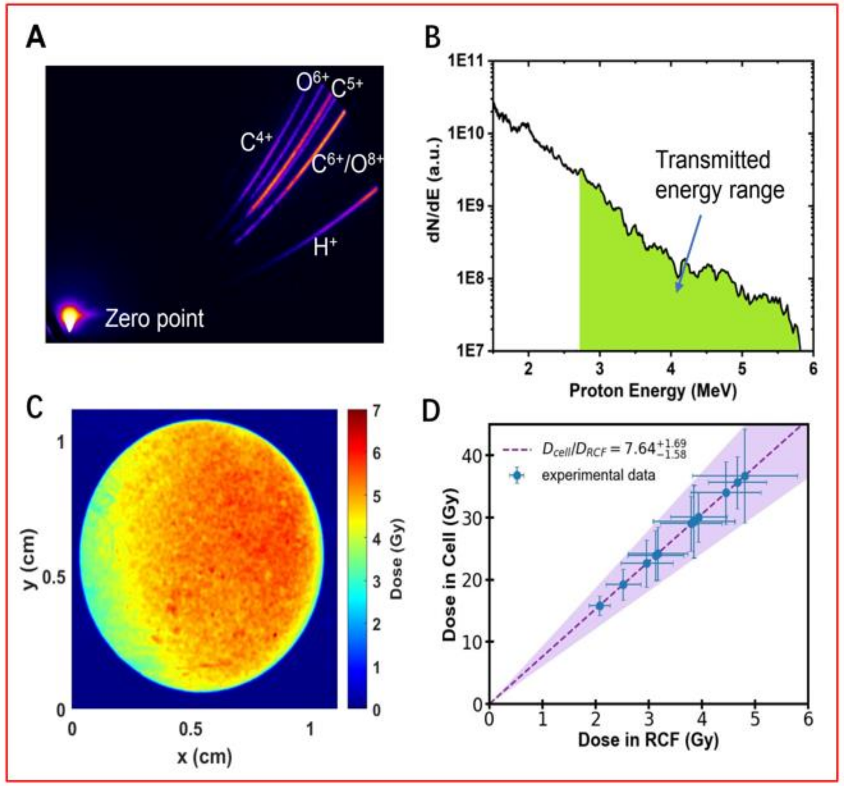
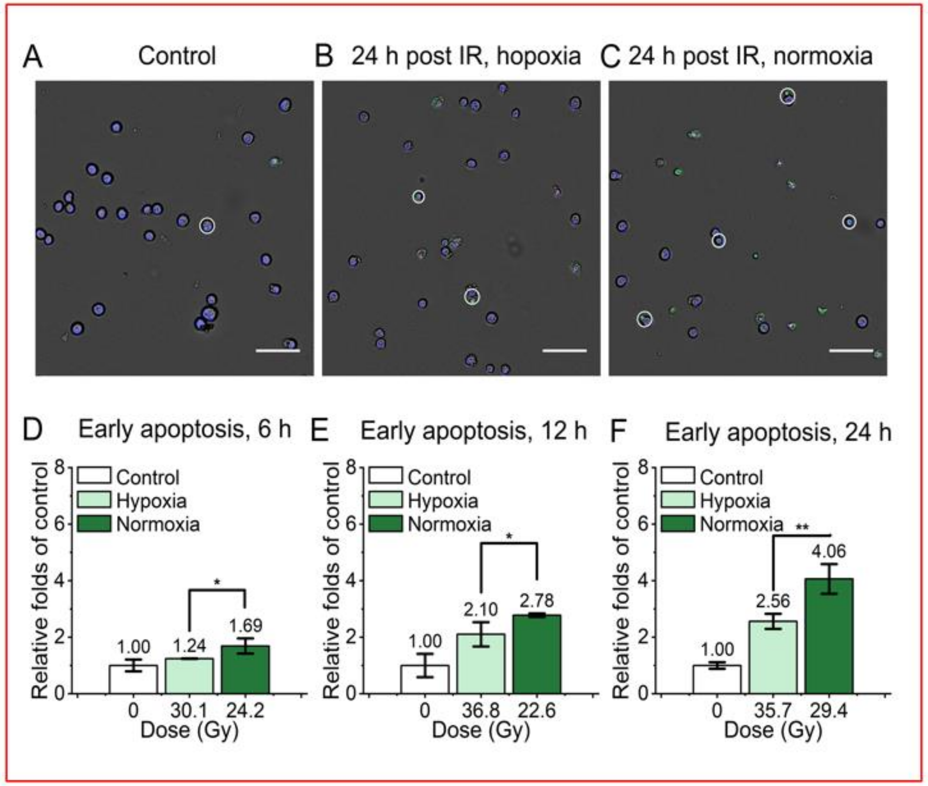


Experimental setup for FLASH irradiation



Dose and dose rate calculation

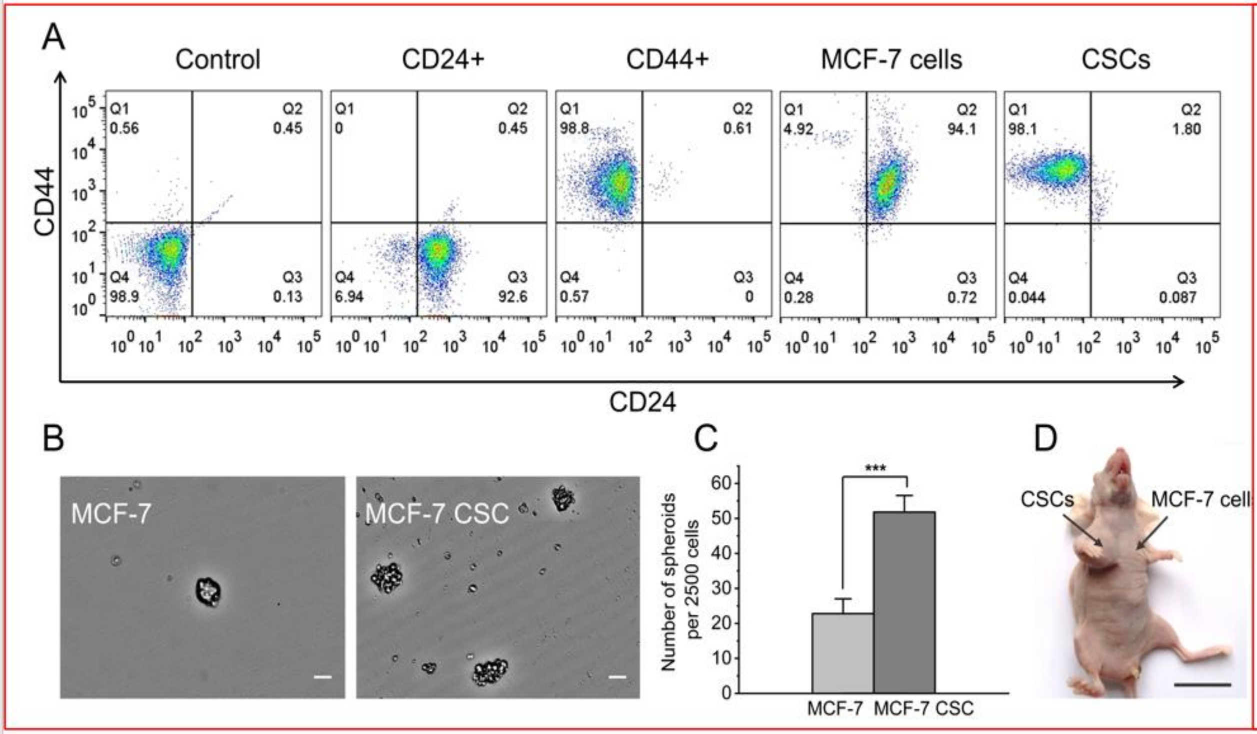


Early apoptosis of irradiated normal fibroblast cells

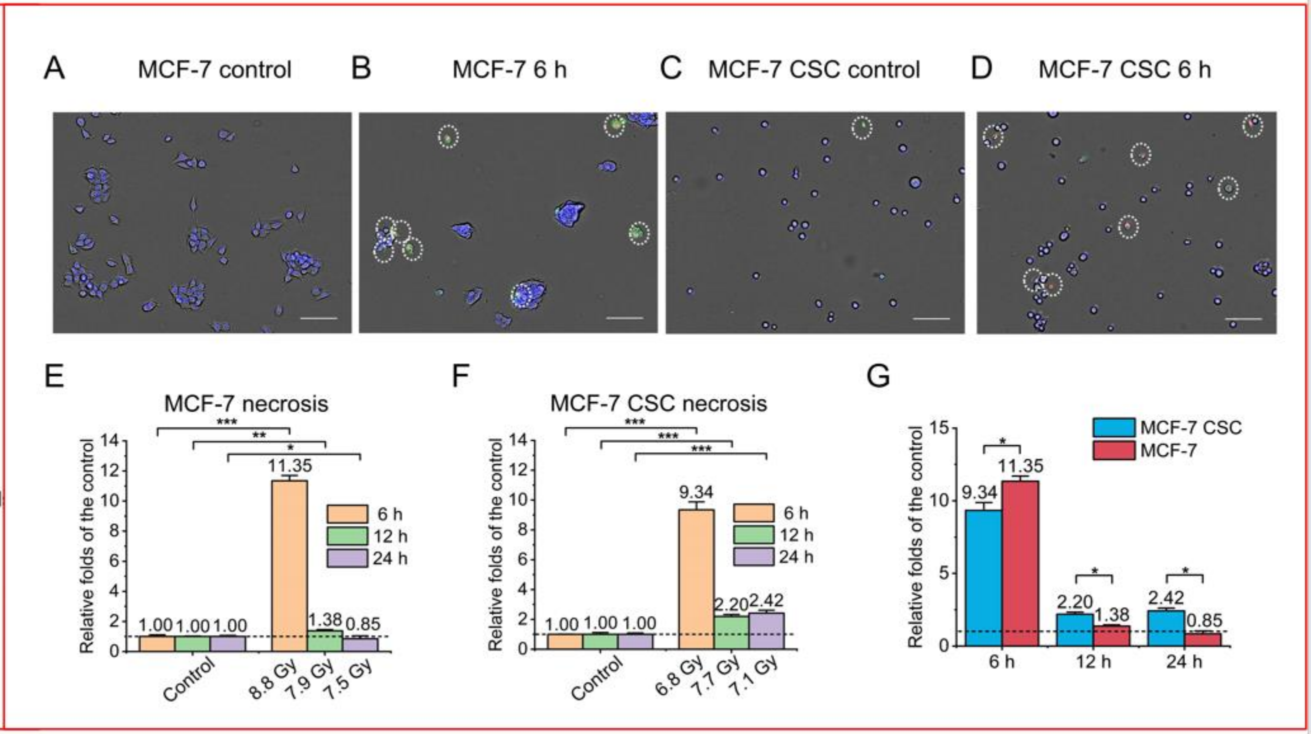
Radio-resistance of normal fibroblast cells under FLASH-IR can be enhanced by hypoxia

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

FLASH irradiation effects in cancer cells



Cancer stem cell sorting and validation

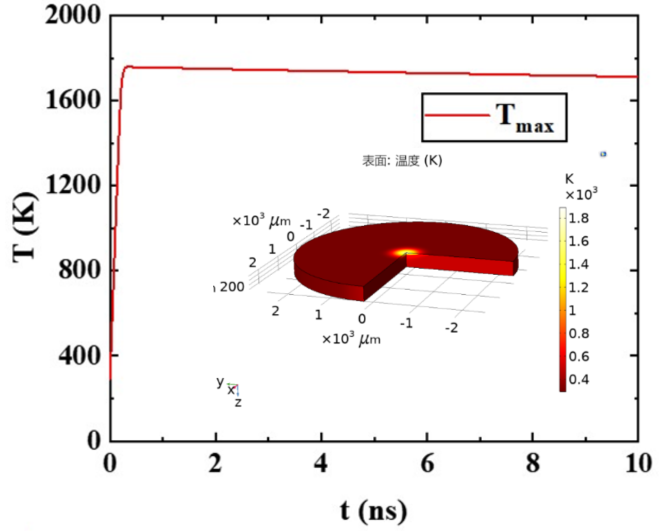


Necrosis of MCF-7 cells and MCF-7 CSCs

Cancer stem cells are more resistant to radiation than normal cancer cells under FLASH-IR

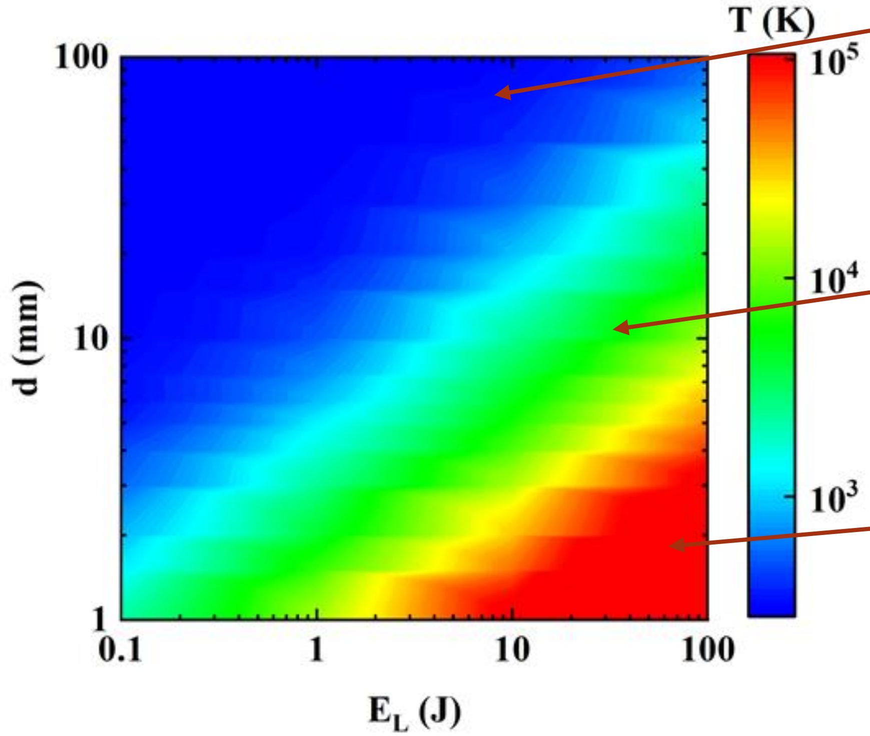
Gen Yang*,... Xueqing Yan*, Wenjun Ma*,Frontiers in Cell and Developmental Biology (2021)

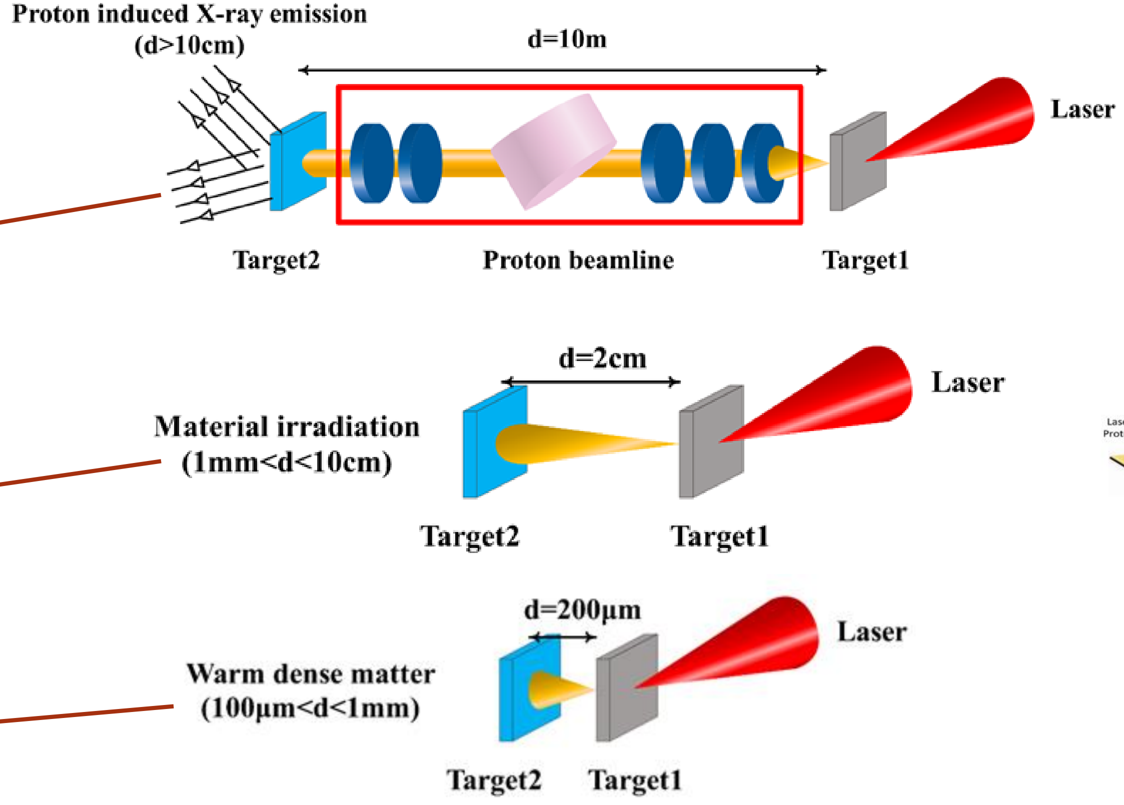
Transient Heat Flux Irradiation

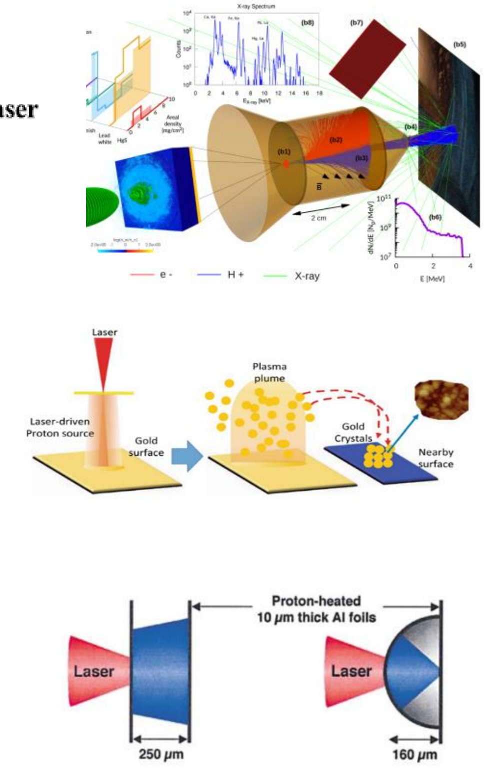


Temperature effect of LIBs irradiation

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.



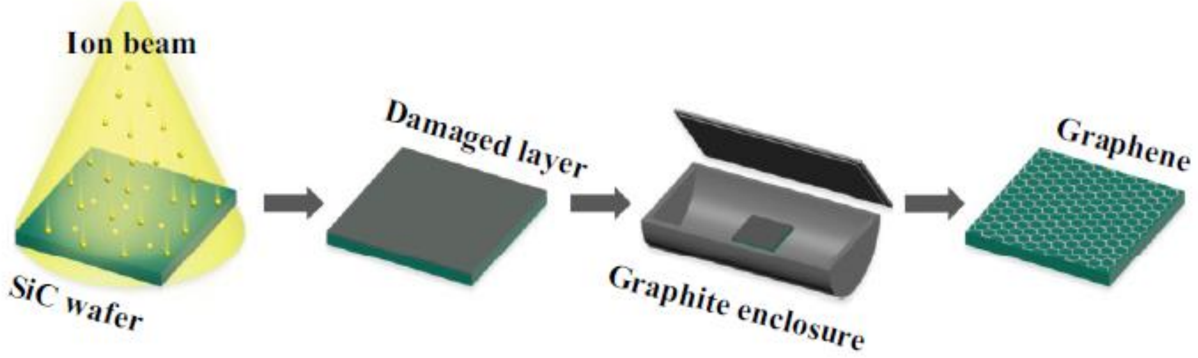




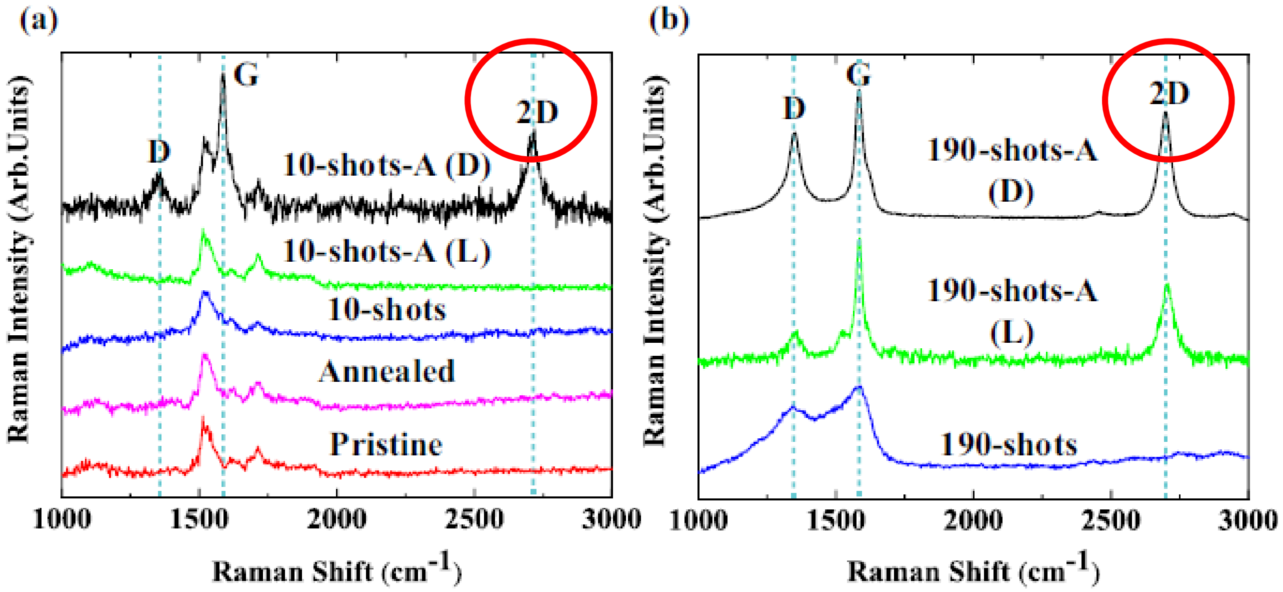
Phys. Rev. Lett. **19**, 125004 (2003). Nature Communications, s41467-017-02675-x (2018).
Scientific Reports **7**: 12522 (2017) Scientific Reports, **7**: 40415 (2017).

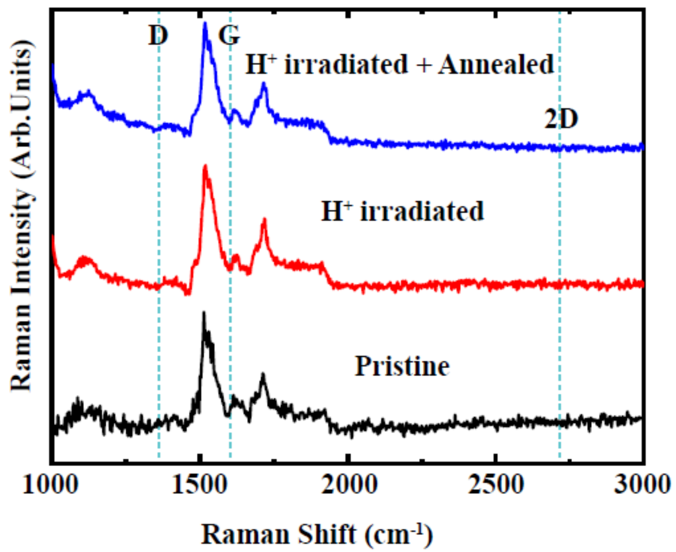
Growth of graphene from silicon carbide

- Laser driven proton beam breaks the C-Si chemical bond. In the process of annealing at 1100℃, silicon atoms sublimate before carbon atoms and desorb from the surface, and the enriched carbon atoms recombine to form graphene films. The characteristic 2D peak of graphene appears in the Raman spectroscopy.
- At the same irradiation dose, there is no 2D peak in SiC annealing after continuous beam irradiation with traditional accelerator, which indicates that the short pulse characteristics play an important role.



Chinese Physics B, 2021, 30(11): 116106.





2×1.7MVTandem

北京大学
PEKING UNIVERSITY

PART 04

Summary

Summary

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

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

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

Thanks for listening！

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