From laser acceleration to laser proton accelerator： First step to large-scale user facility

Xueqing Yan, Chen Lin, Wenjun Ma, Haiyang Lu, Yanying Zhao, Jungao Zhu, Kun Zhu, Qing Liao, Minjian Wu, Yixing Geng, Dongyu Li, C.C. Li, A. L. Zhang, Xiaohan Xu, Y.R.Shou, J.Q.Yu, R.H.Hu, Z. Gong, Jiaer Chen

State Key Laboratory of Nuclear Physics and Technology,

CAPT, Peking University, Beijing, China, 100871

2018年9月20日

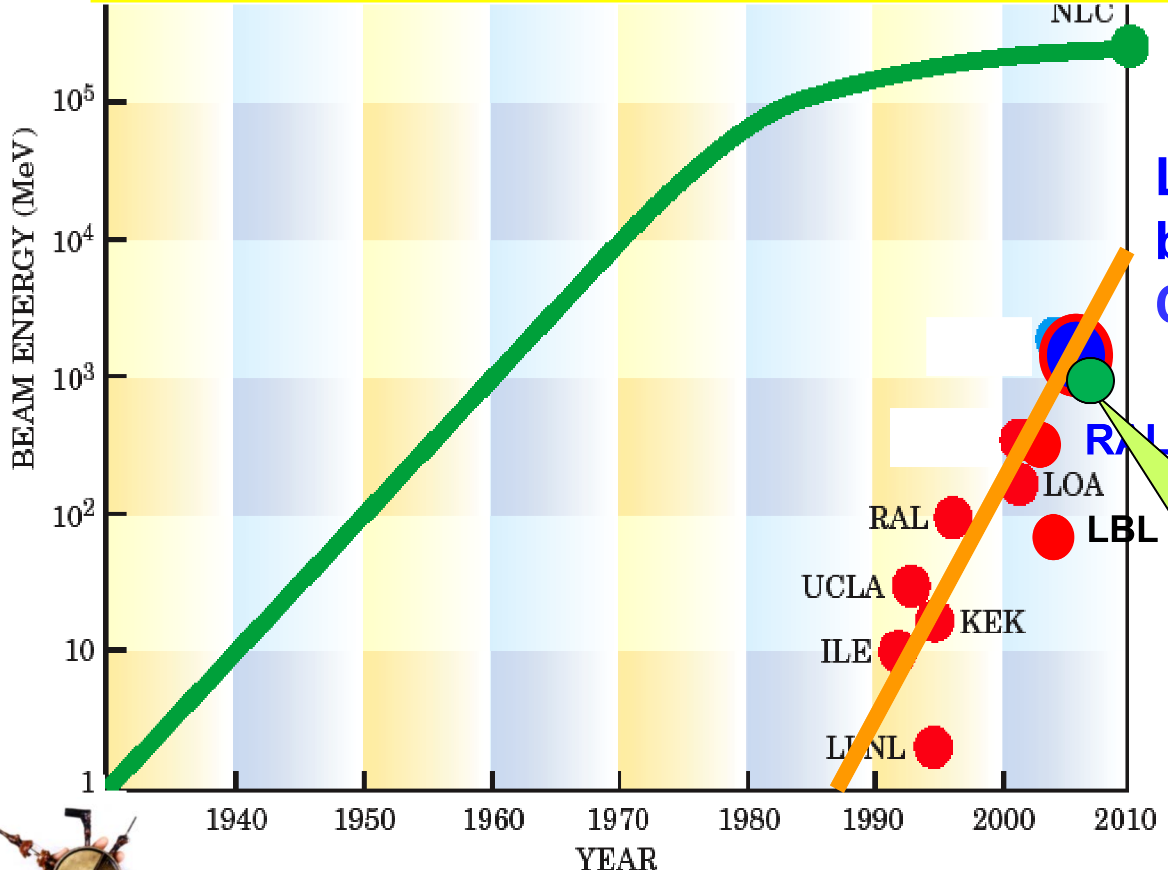
Outline

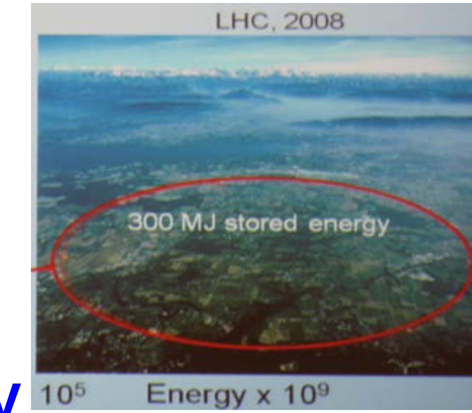
1. Introduction
2. Compact laser plasma accelerator at Peking University
3. LAser Driven multi-beAm FAcility (LADAA)—large-scale user facility planned in future

Laser acceleration and innovation

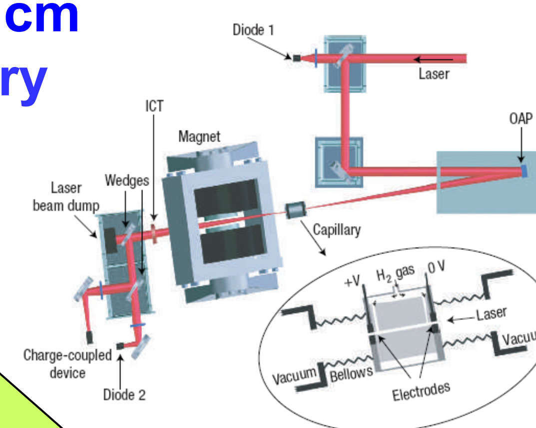
From eV→MeV→GeV → TeV… , RF accelerator ！

常规加速器的能量接近饱和！
激光等离子体加速器发展迅速！





LBL 4GeV by few cm Capillary



加速梯度高 3 个量级的激光等离子体加速发展迅速！

SKL CAPT

Thomas M. Baer 教授
美国斯坦福光子学研究中心主任
2009年美国光学学会主席

Nicholas P. Bigelow 教授
美国罗切斯特大学
物理与天文系主任

《Science》

rrestrial life ... resource. Yet ... ual is not option when it comes to soil, food and pe... It's time for a greener revolution.

Lasers

Thomas M. Baer
Stanford Photonics Rese... Cente...
Nicholas P. Bigelow
Department of Physi... and Astronomy, Univer... of Rochester

to ultrahigh intensities, these lasers will be used as engines to accelerate electrons and protons

Metabolomics

Those who conceived and invented the laser 50 years ago this year could not have predicted the roles that it has had over the past half-century: from communications to environmental monitoring, from manufacturing to medicine, from entertainment to scientific research.

By 2020, lasers will probably emit beams with spot sizes of the order of 1 nanometre — the size of a small molecule. Objects with dimensions less than a wavelength cannot usually be resolved using lasers or microscopy unless the photons are emitted from an aperture smaller than the object. Microscopes that incorporate laser sources with apertures the size of a single molecule will be useful in fast, direct sequencing of biomolecules such as DNA and RNA. These miniature beams will also provide hard-disk storage at densities 100 times greater than those available today — petabytes of storage in a personal computer.

Ultraprecise, laser-based clocks will measure the drift in fundamental constants as the Universe expands, challenging our theories describing the origin and evolution of the cosmos.

Next-generation lasers will allow the cr... ion of new states of matter, compressing a... heating materials to temperatures found o... in the centres of massive stars, and at pressu... that can squeeze hydrogen atoms together... a density 50 times greater than that of le... The resulting fusion reactions may one day harnessed to provide almost limitless carb... free energy. Enough fusion fuel is present... the oceans to supply the current energy ne... of the entire world for longer than the age... the Universe.

By 2020, lasers will generate ultrashort bu... of photons — with pulse widths shorter than the time it takes for light to traverse an atom. These attosecond pulses will allow strobe pictures to be taken of chemical reactions — stop-action pictures of electrons in motion. When amplified

"Ecology viewed inc... as an ess... dimensio... Earth sci...

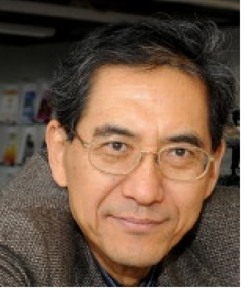
...to look at how species and communities fit into Earth's history. In a decade's time, ecology will be viewed both as a core part of biology, and increasingly as an essential dimension of the Earth sciences.

The conference takes place at the Queen Elizabeth Hall, the Southbank Centre, Belvedere Road, London SE1 8XX, UK. It forms part of a week of celebrations for the Royal Society's 350th anniversary (see go.nature.com/VLSTMT).

Breakthrough in 2020

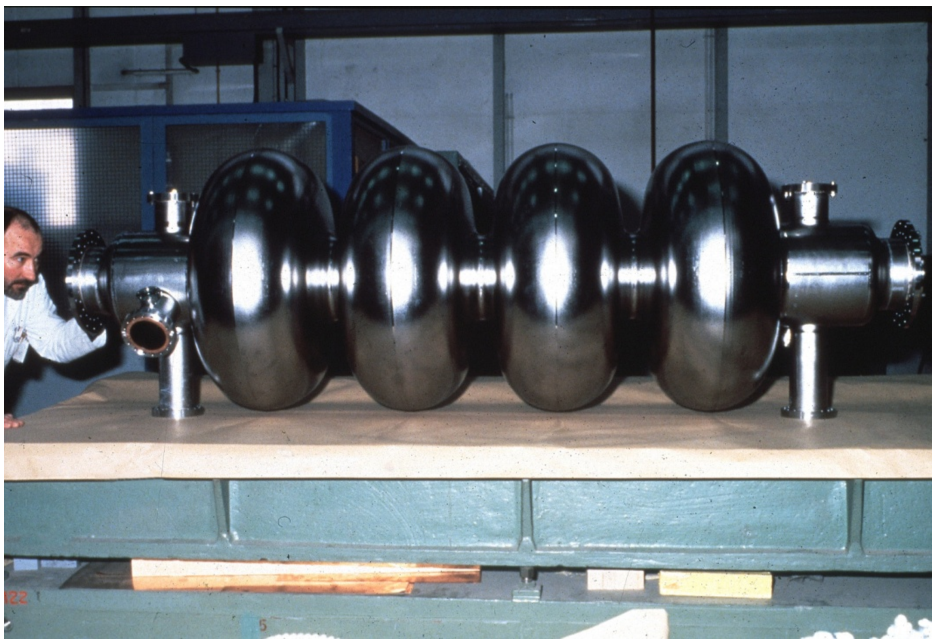
1. 纳米尺度光束应用于显微和存储
2. 基于激光的超精密光钟用于测量宇宙基本常数
3. 激光聚变产生取之不尽的无碳能源
4. 阿秒光脉冲探测电子运动和化学反应
5. 台式化高能电子、质子加速器

超强超短激光相关



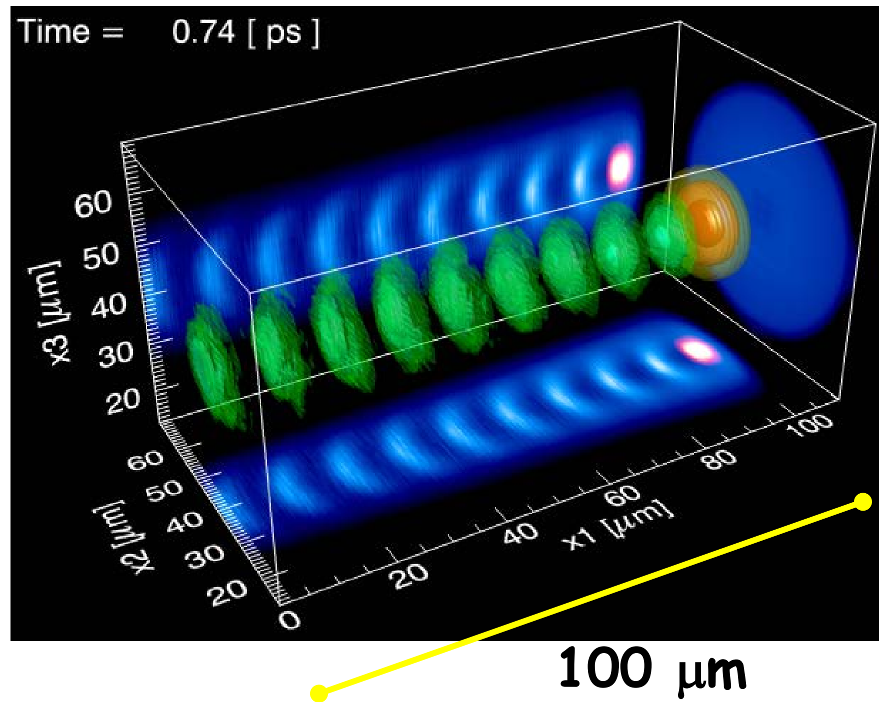
Wakefield acceleration of electrons

LPA is proposed by Tajima & Dawson since 1979, however there is no laser accelerator due to the limitation by the energy spread and stabilities.



1 m

Rf accelerator



100 µm

Wake acceleration

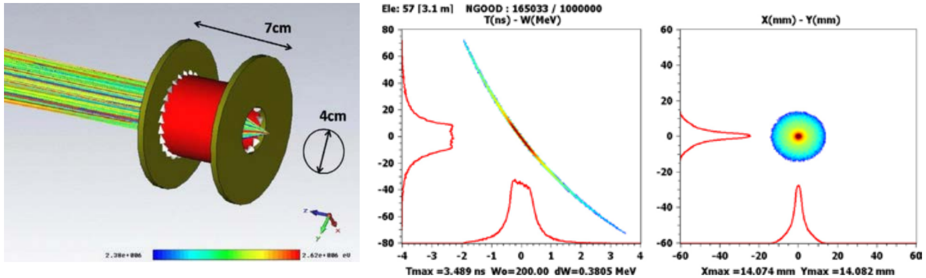
Characteristics of Laser Driven Ion Beam

- Large energy spread~100%
- Large diverge angle~10°
- Small emittance ~0.1 π mm.mrad
- Small initial size, spot source ~5μm
- Short pulse duration ~a few ps
- High peak current ~ 10^9-10^{12}ppp, KA

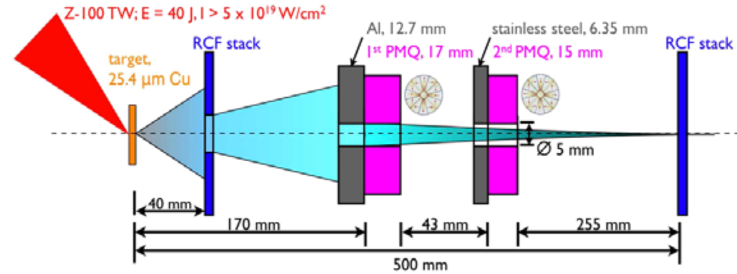
new features for beam optics

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

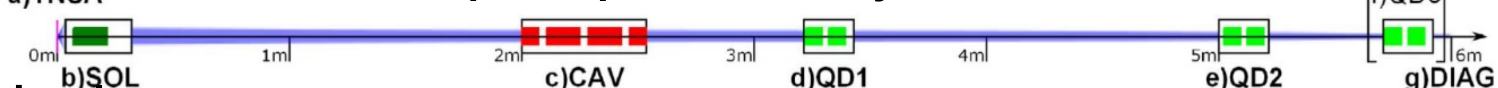
Pulsed solenoid



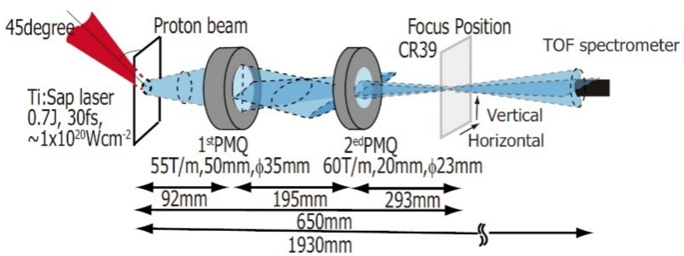
Electronic Quadruple

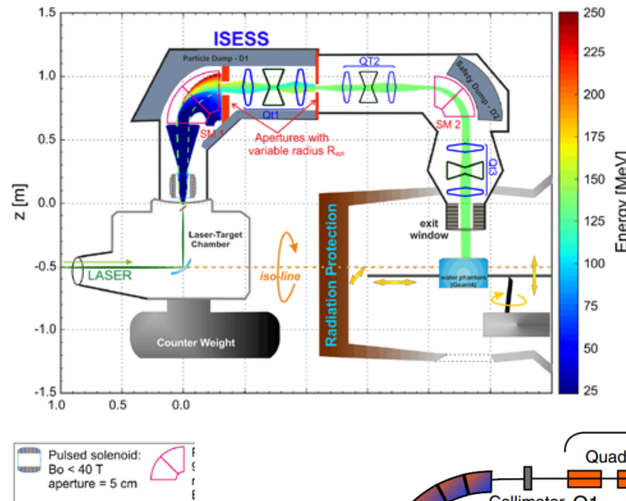


Solenoid + quadruple + RF cavity

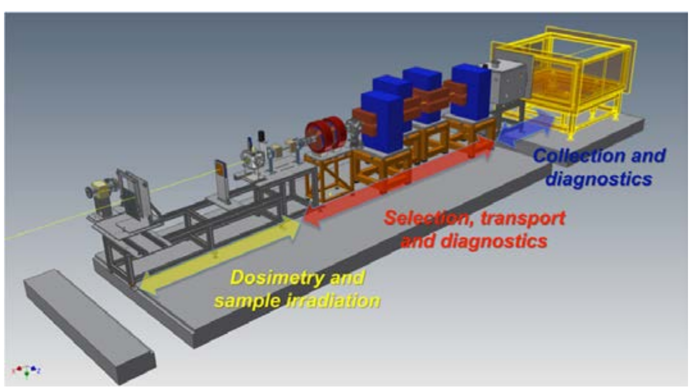


Permanent Quadruple

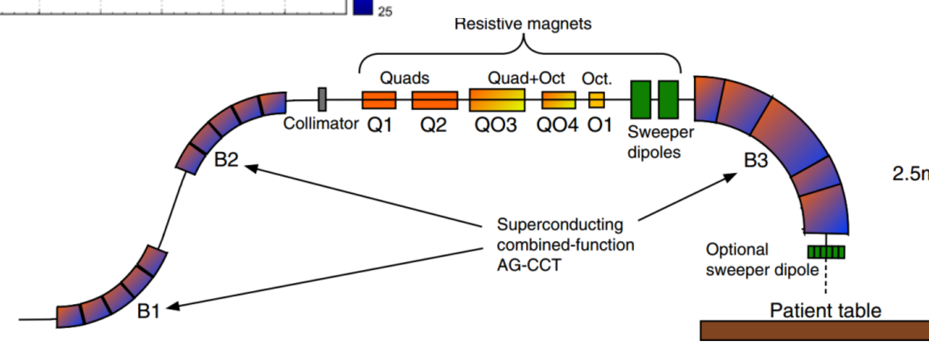




ELI beam line



BELLA beam line



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Phase Stable Acceleration by laser pressure

PRL 100, 135003 (2008) PHYSICAL REVIEW LETTERS week ending 4 APRIL 2008

Generating High-Current Monoenergetic Proton Beams by a Circularly Polarized Laser Pulse in the Phase-Stable Acceleration Regime

X. Q. Yan(颜学庆),[1,5,*] C. Lin(林晨),[1] Z.M. Sheng(盛政明),[1,2,3] Z.Y. Guo(郭之虞),[1] B.C. Liu(刘必成),[1,4] Y.R. Lu(陆元荣),[1] J.X. Fang(方家驯),[1] and J.E. Chen(陈佳洱)[1]

PRL 103, 245003 (2009) PHYSICAL REVIEW LETTERS week ending 11 DECEMBER 2009

Radiation-Pressure Acceleration of Ion Beams Driven by Circularly Polarized Laser Pulses

A. Henig,[1,2,*] S. Steinke,[3] M. Schnürer,[3] T. Sokollik,[3] R. Hörlein,[1,2] D. Kiefer,[1,2] D. Jung,[1,2] J. Schreiber,[1,2,4] B. M. Hegelich,[2,5] X. Q. Yan,[1,6,†] J. Meyer-ter-Vehn,[1] T. Tajima,[2,7] P. V. Nickles,[3] W. Sandner,[3] and D. Habs[1,2]

PRL 103, 135001 (2009) PHYSICAL REVIEW LETTERS 25 SEPT

Self-Organizing GeV, Nanocoulomb, Collimated Proton Beam from Laser Foil Interaction at 7×10^{21} W/cm^2

X. Q. Yan,[1,2,4,*] H. C. Wu,[1] Z. M. Sheng,[3] J.E. Chen,[2] and J. Meyer-ter-Vehn[1]

PRL 107, 115002 (2011) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2011

Monoenergetic Ion Beam Generation by Driving Ion Solitary Waves with Circularly Polarized Laser Light

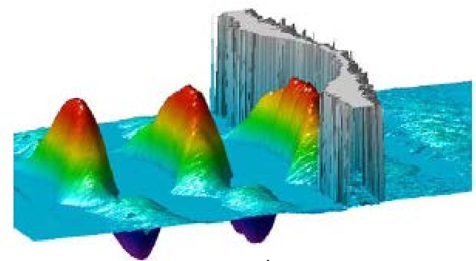
D. Jung,[1,2,3,*] L. Yin,[1] B. J. Albright,[1] D.C. Gautier,[1] R. Hörlein,[2,3] D. Kiefer,[2,3] A. Henig,[2,3] R. Johnson,[1] S. Letzring,[1] S. Palaniyappan,[1] R. Shah,[1] T. Shimada,[1] X. Q. Yan,[3] K.J. Bowers,[1] T. Tajima,[2]

Laser shaping of a relativistic intense, short Gaussian pulse by a plasma lens

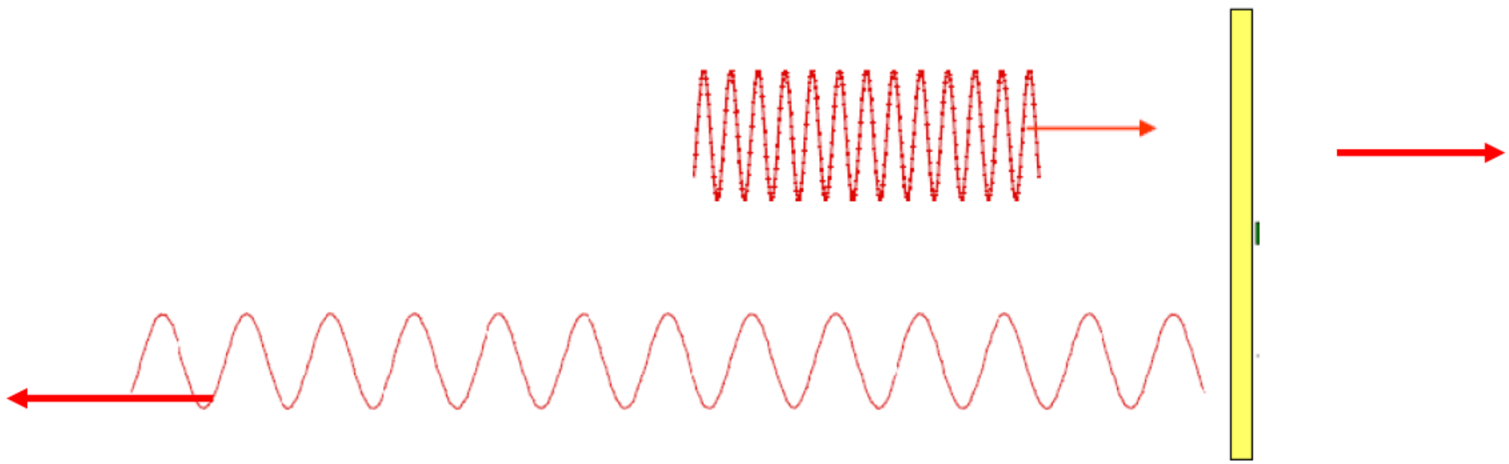
H.Y.Wang,[1] C.Lin,[1,*] Z.M.Sheng,[2] B.Liu,[1] S.Zhao,[1] Z.Y.Guo,[1] Y.R.Lu,[1] X.T.He,[1] J.E.Chen,[1] and X.Q.Yan[1,†]

[1] *State Key Laboratory of Nuclear Physics and Technology, Peking University,*

•解决离子能散大、能量低关键问题！
•可以将离子能量提高二个量级！



Conversion Efficiency

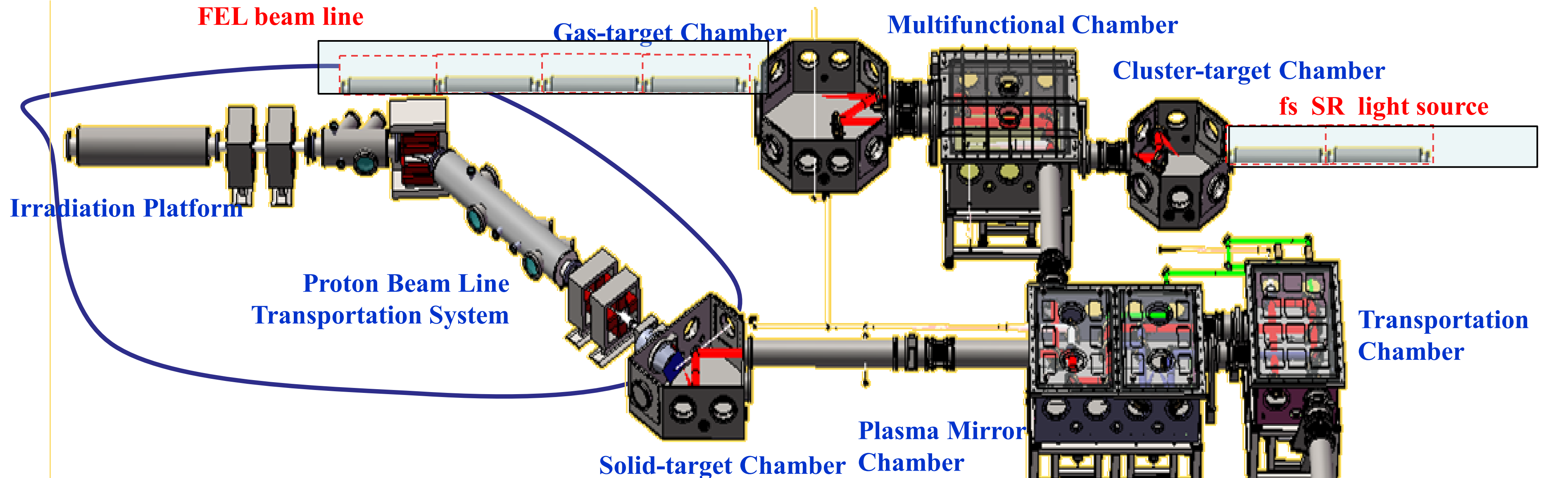


$$CE=1-\frac{1}{4\gamma^2}\sim 100\%$$

A. Einstein, Annalen der Physik 17, 891 (1905)

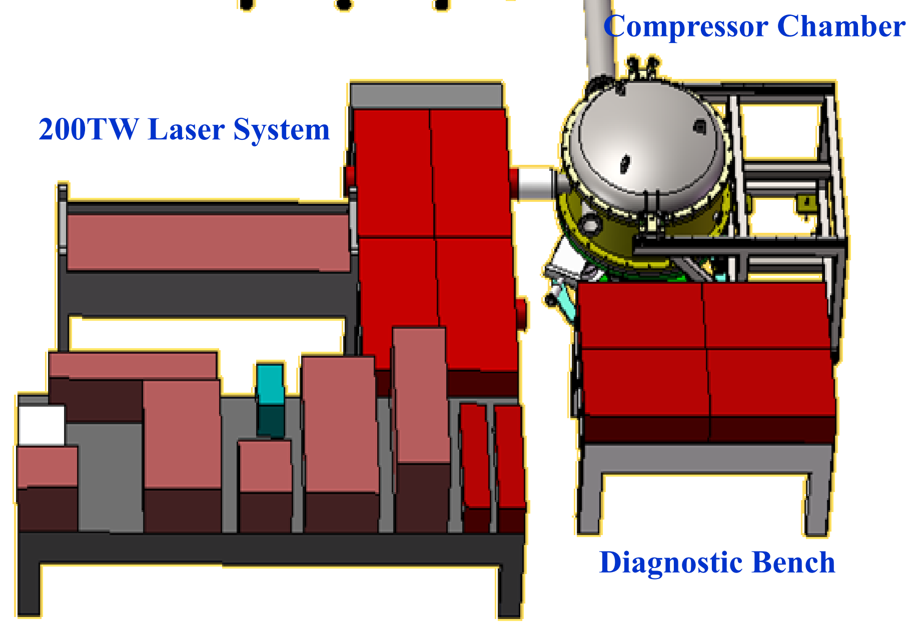
CLAPA at Peking University

(Compact LAser Plasma Accelerator)

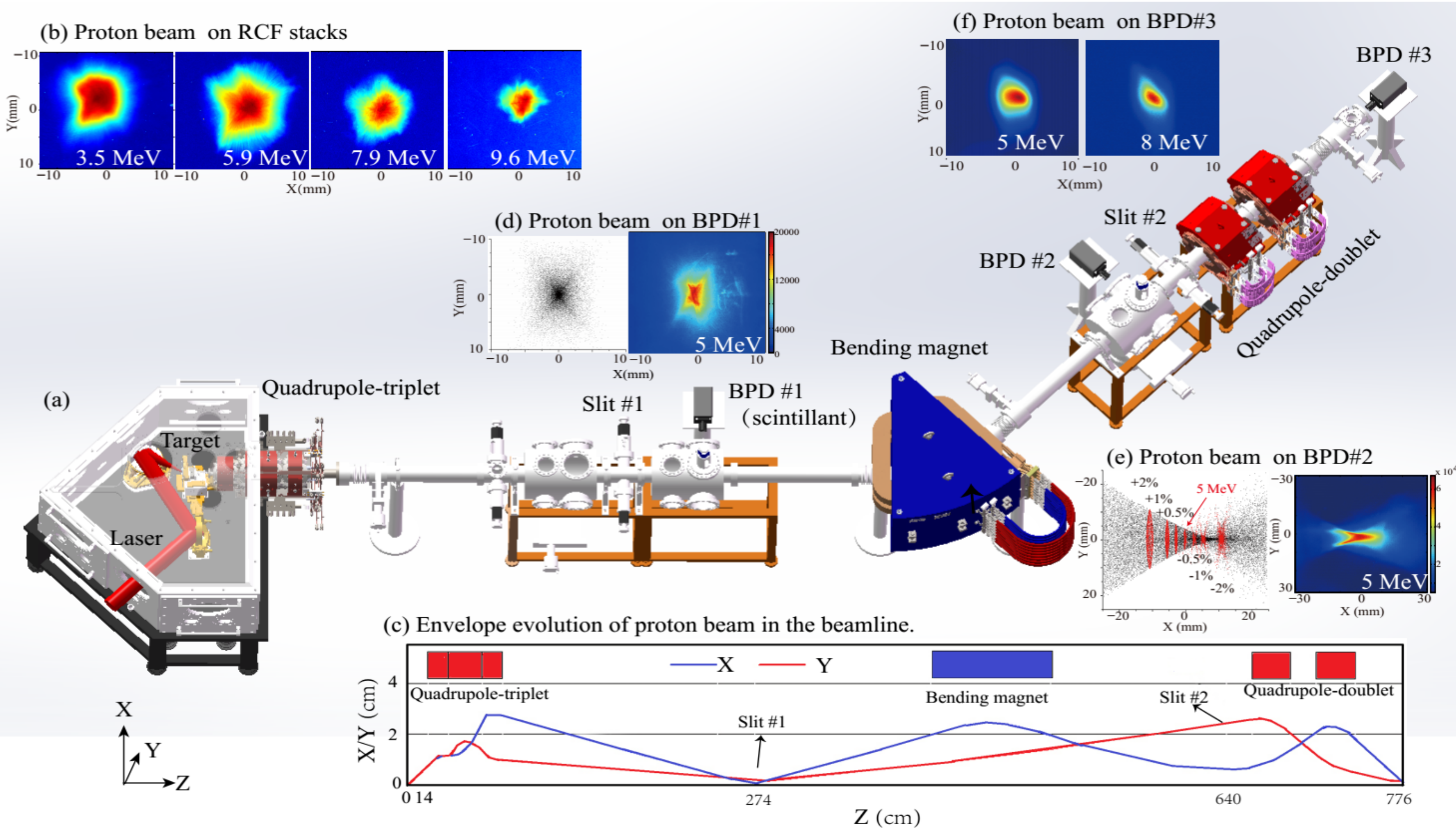


High Contrast 5Hz 200TW Laser System

Pulse Energy	5 J
Duration:	25 fs
Repetition :	5 Hz
Wavelength:	800 nm+/-10 nm
Contrast Ratio:	> 10^{10}:1 @ ~ns
	10^{10}:1 @ 100 ps
	10^{9}:1 @ 20 ps
	10^{6}:1 @ 5 ps
	10^{3}:1 @ 1 ps



Proton beam with 1% energy spread/30pC/10MeV



J.G.Zhu,…, C.Lin, X.Q.Yan, submitted, 2018

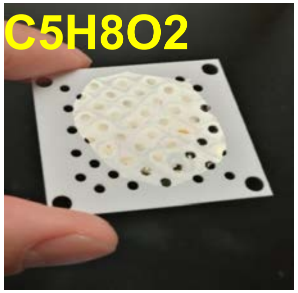
J.G.Zhu,…, X.Q.Yan,*Chin. Phys. C* 41, 097001 (2017)

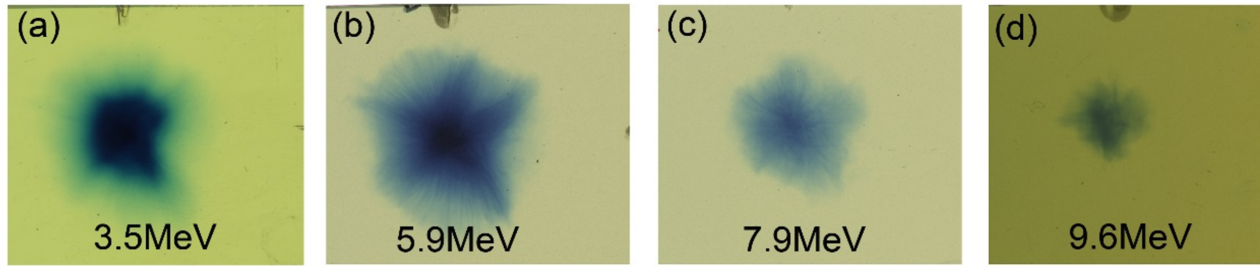
RAMI:

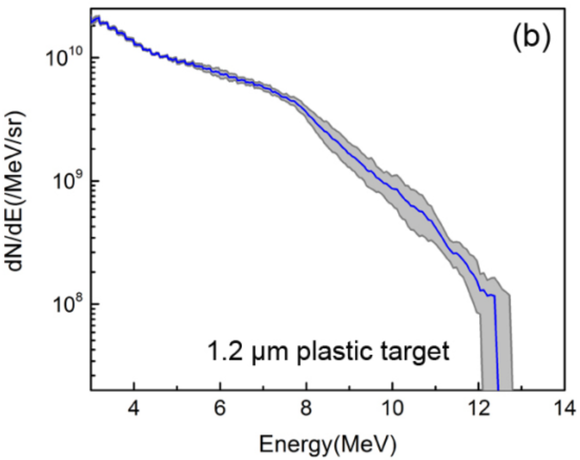
Reliability Availability

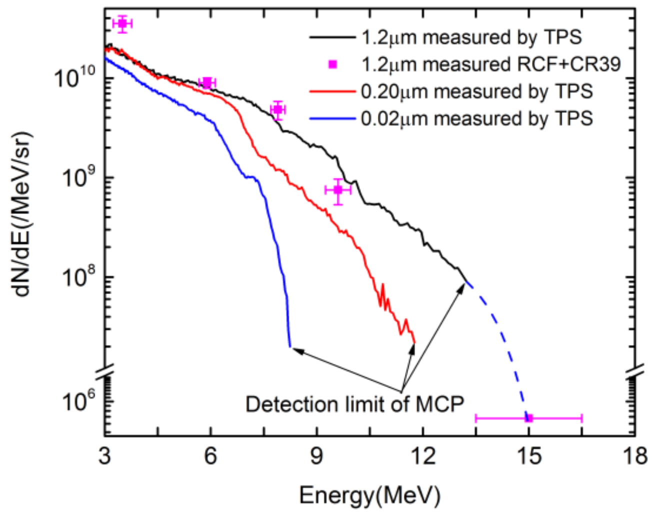
Maintainability Inspectability

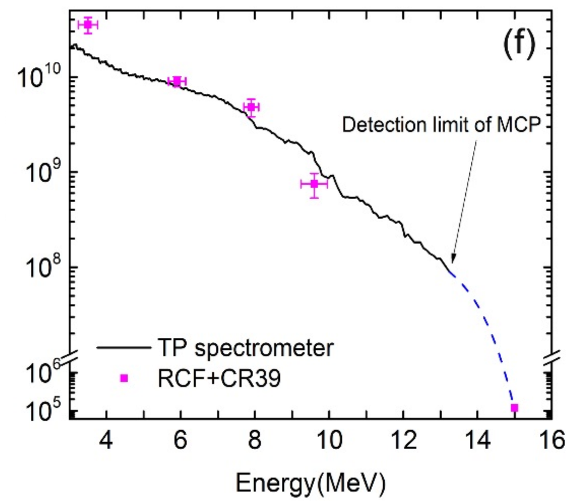
Experiment with plastic target











Plastic targets produced proton beams with good stability and the beam cutoff energy stability better than 3%

Stable protons were generated based on 20nm plastic target without PM.

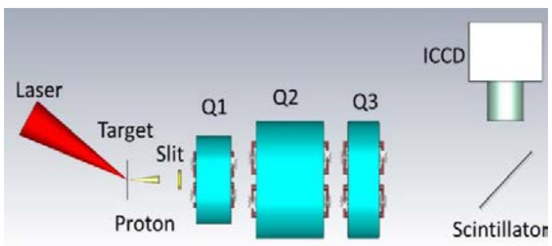
Emittance measurement

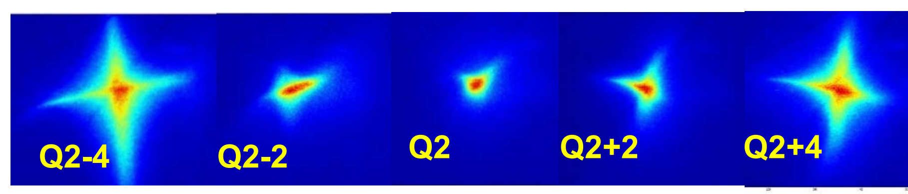
- Emittance of protons from tradiation accelerators： ~ mm·mrad
- Emittance of protons from laser accelerators：

  Pepperpot method (2.8MeV,±50mrad): 7 mm·mrad

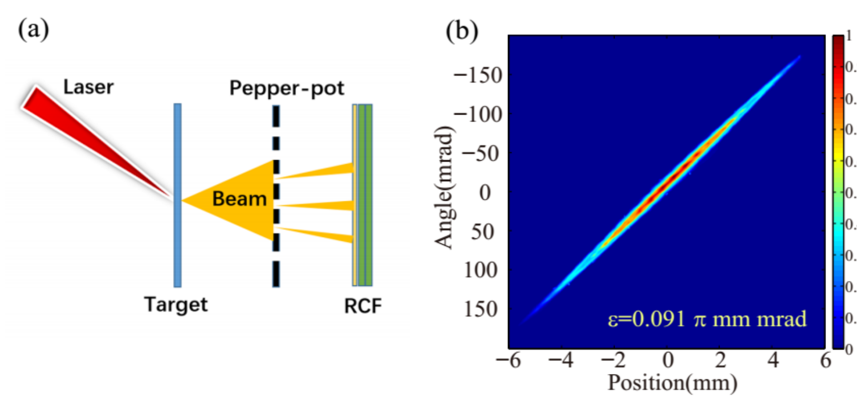
  Magnetic scan method（4-5MeV,±50mrad）:

  5 mm·mrad @ metal target 2 mm·mrad@ plastic target

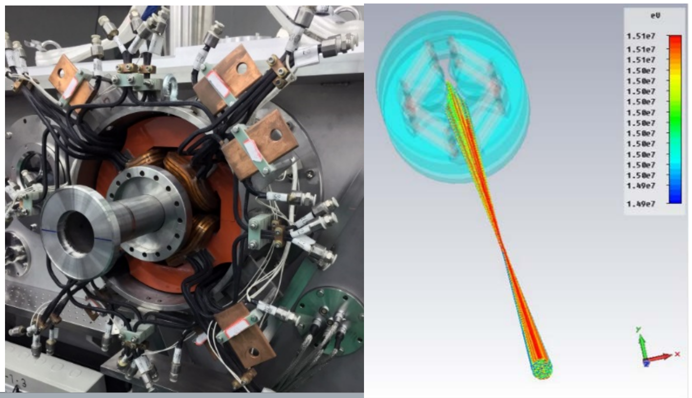


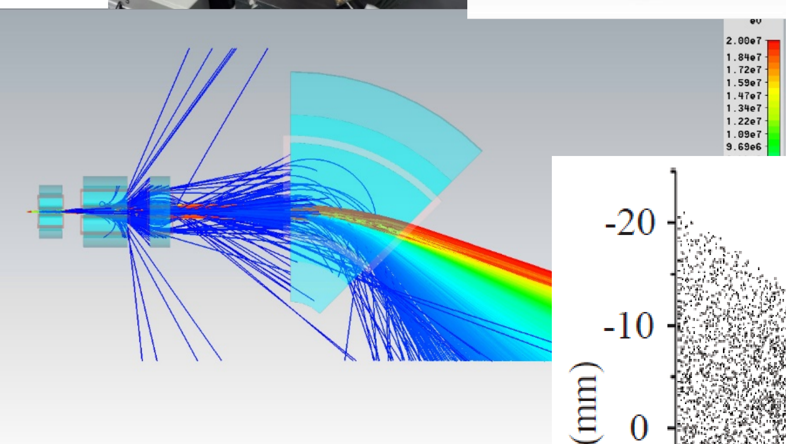


mm*mrad	Emittance(0.576rms)		remarks
	ε_y	ε_x	
1.2um Al	3.21		5.6MeV,±20mrad
1.8um Al	2.93		
2.5um Al	1.37		
2.5um Al	3.22	5.03	5MeV,±50mrad
5um Plastic	2.38	2.04	4MeV,±50[+]mrad

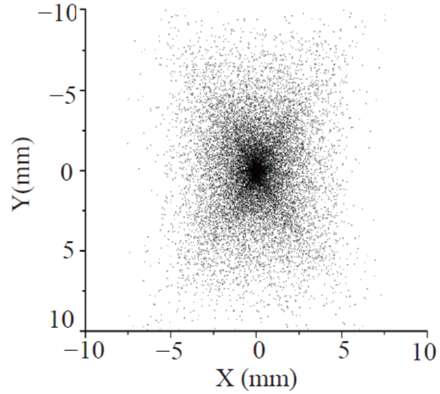


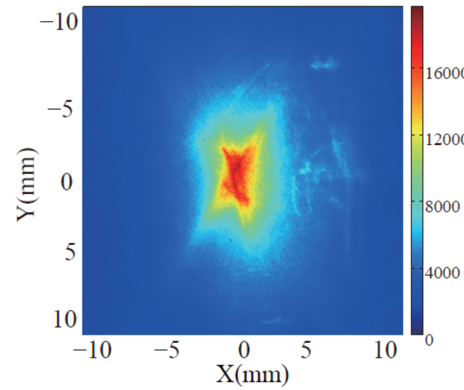
Beam focusing and energy selection



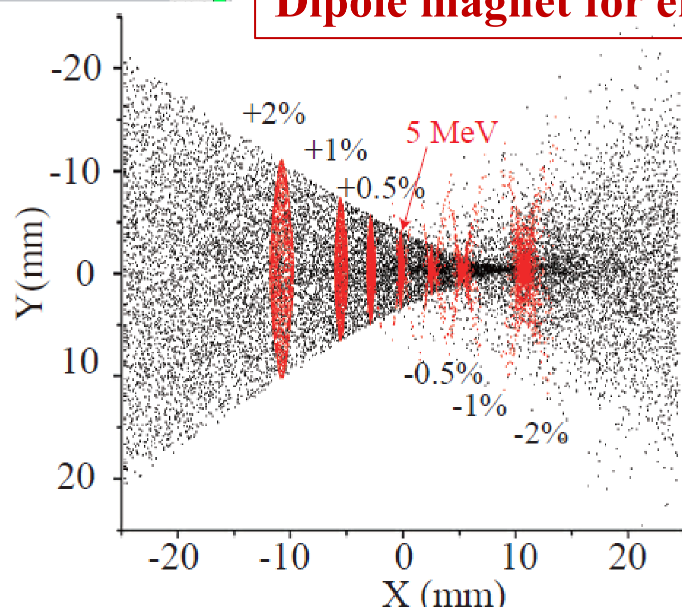


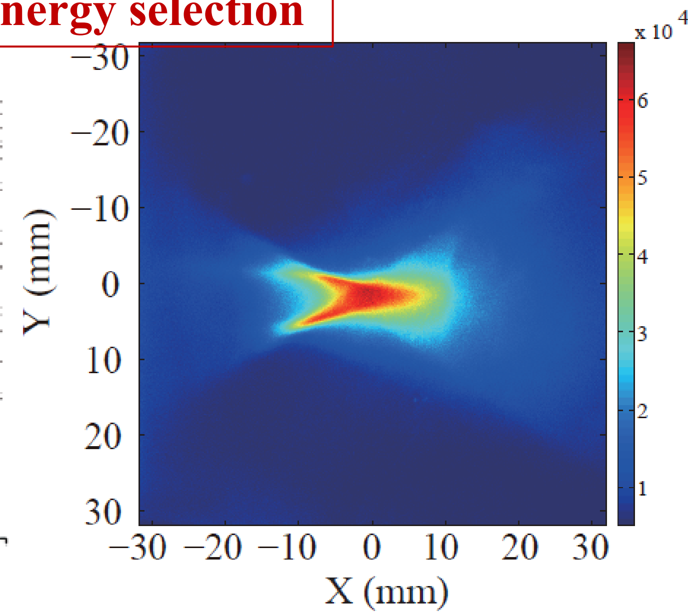
Quadruple triplet magnet lens for focusing



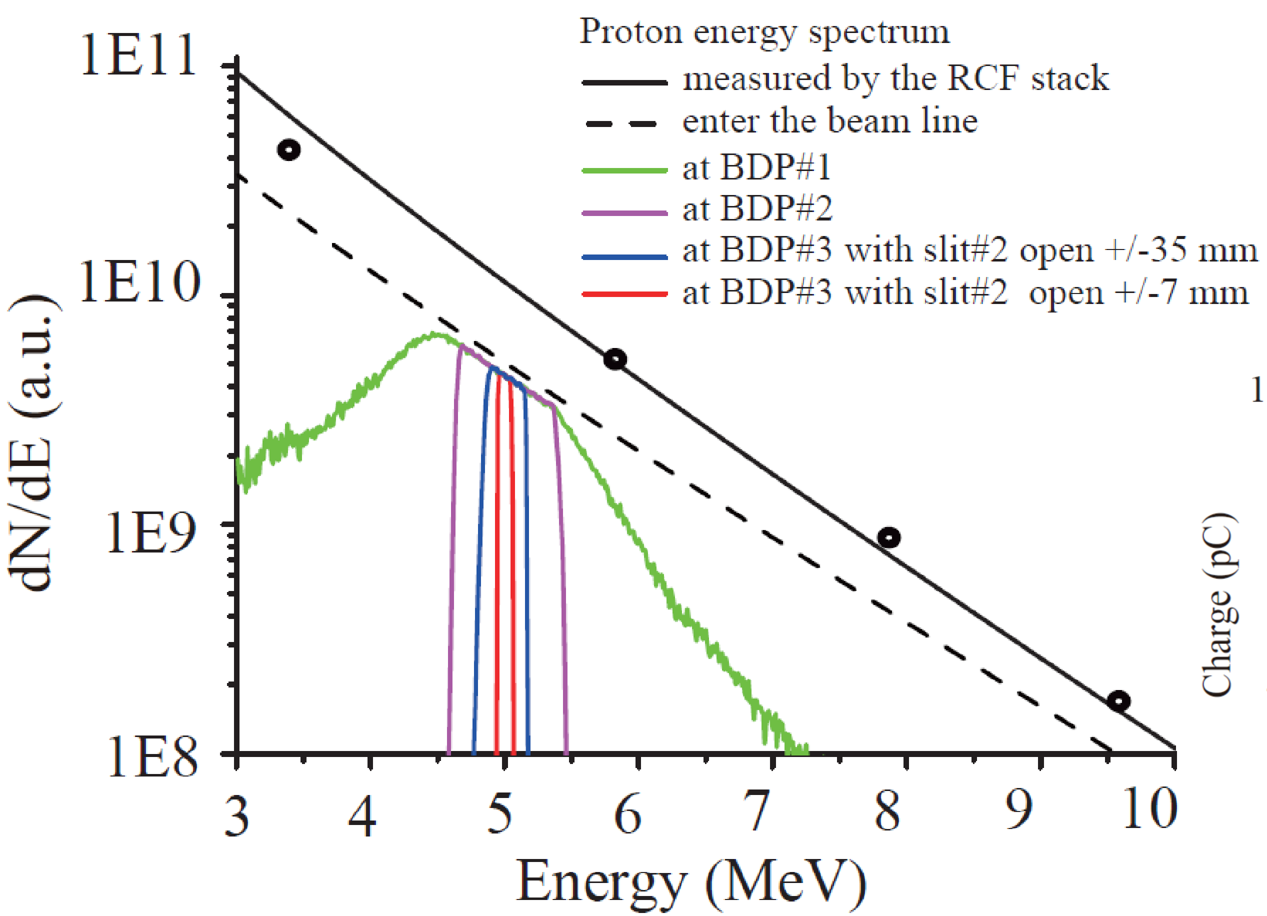


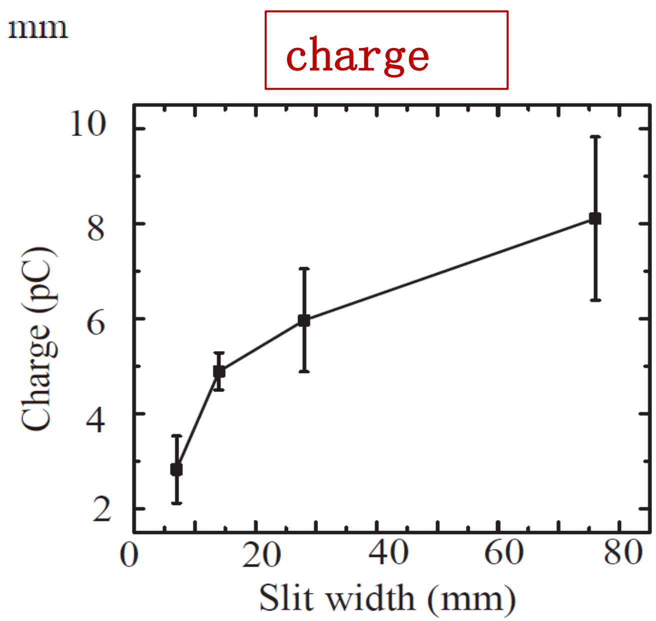
Dipole magnet for energy selection



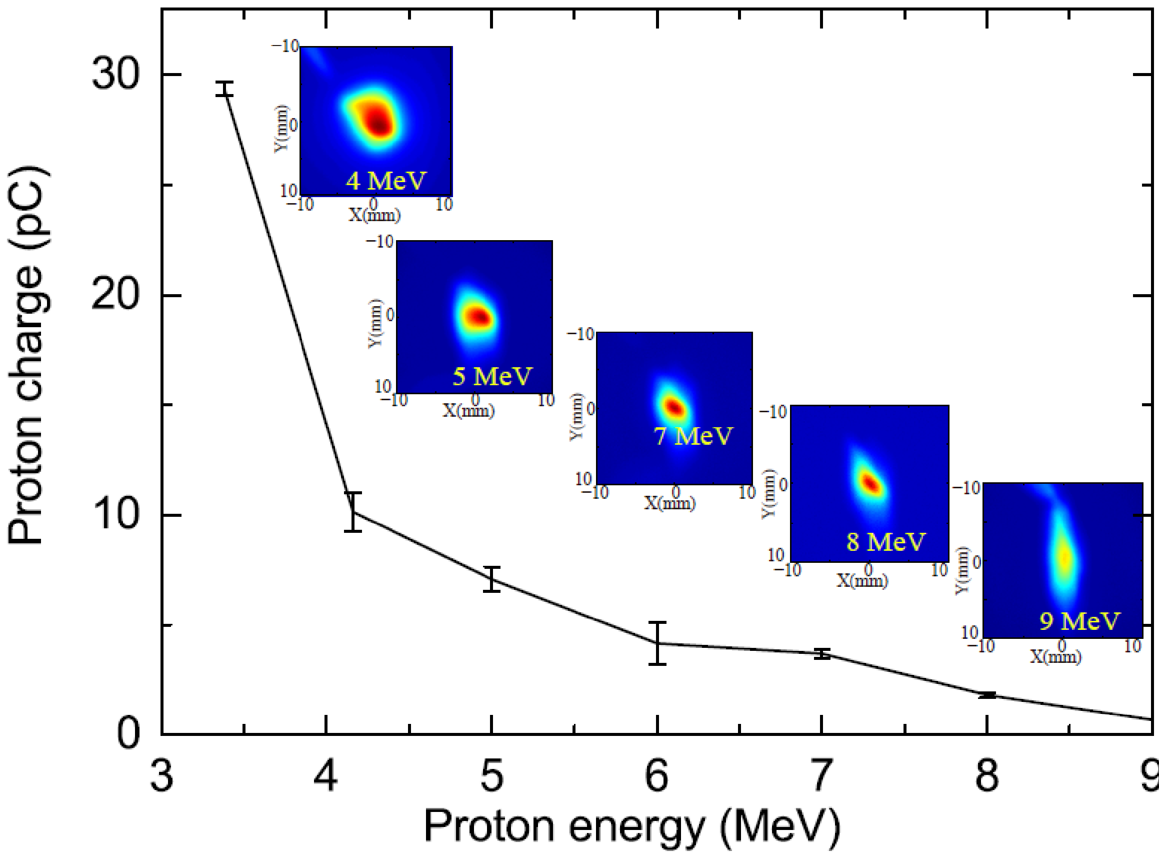


Proton energy and charge control



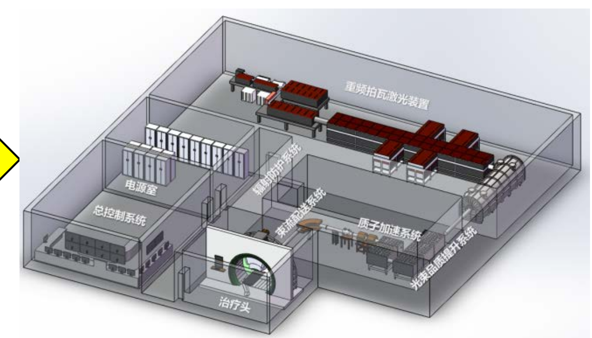


1% energy spread /10pC/<10MeV proton



原始创新与突破点：

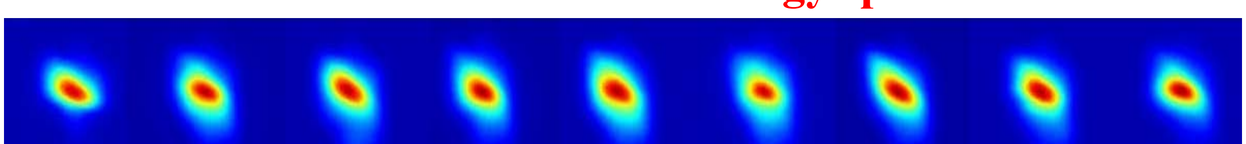
- 提出和证实稳相光压机制
- 采用新型纳米靶材提高离子加速效率和稳定性。
- 提出点点成像电磁铁传输线，解决RAMI问题。



RAMI：

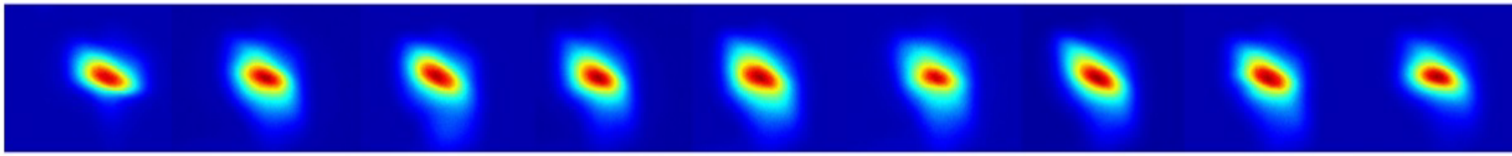
Reliability
Availability
Maintainability
Inspectability

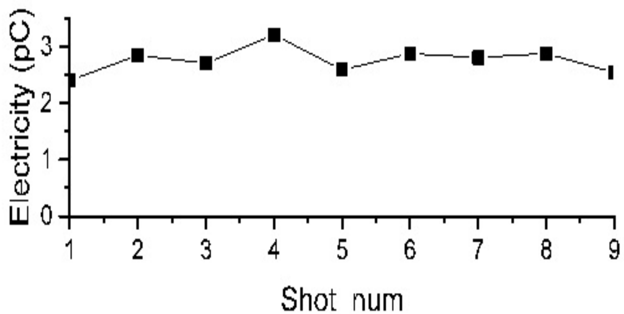
3-9 MeV Proton beam with 1% energy spread

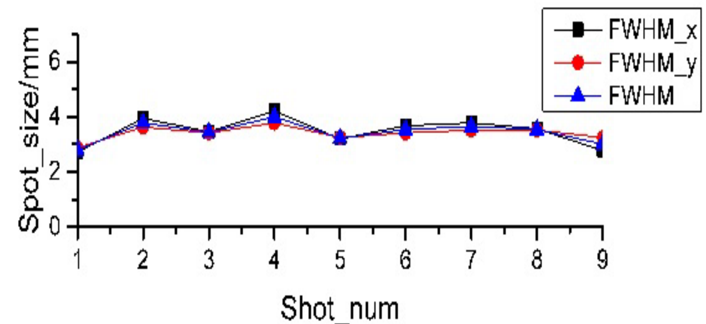


Quadruple doublet lens to refocus the beam (2)

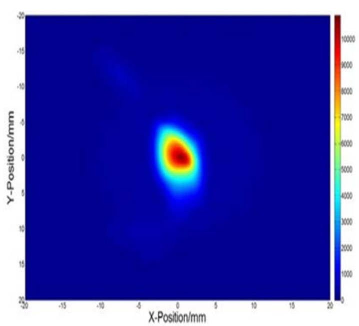
束斑稳定性探测， 5 MeV 1% 能散



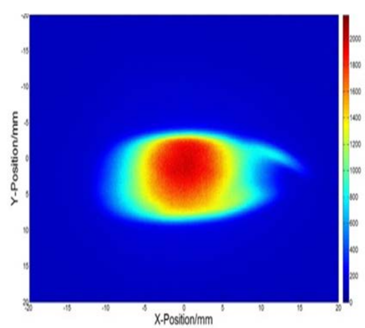




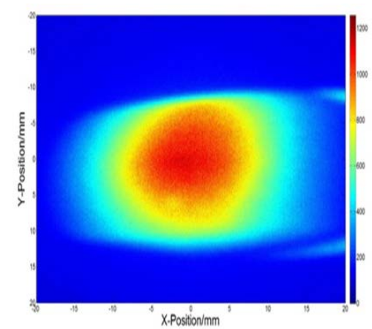
束斑辐照野控制，5 MeV， 1%能散



Spot_size_5mm(5.1182pC)



Spot_size_11mm(4.7914pC)



Spot_size_18mm(5.5565pC)

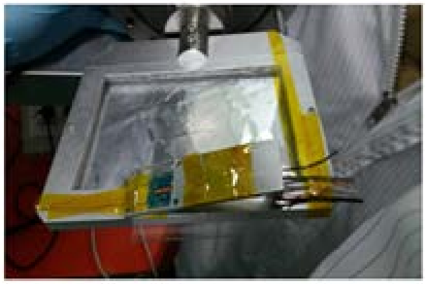
Irradiation platform

- ✓Biological irradiation
- ✓Plasma diagnosis
- ✓Simulation of the space environment
- ✓High energy physics

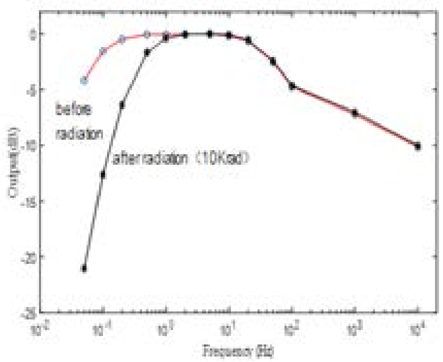
Some Applications at PKU

空间辐射效应分析与评估

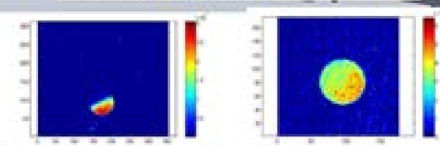
FY3号卫星的AICHI磁场传感器



辐照前后传感器带通变化

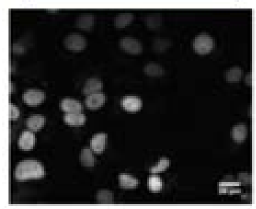


质子束分析及生物辐照效应研究



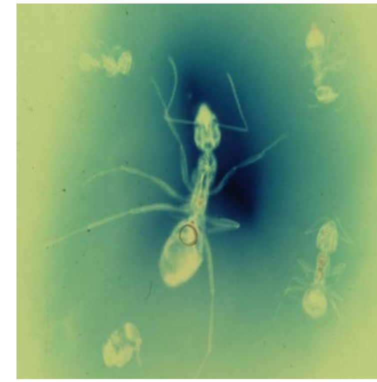
5.0300e+05/shot
6.32 Gy/shot

1.4395e+05/shot
0.77 Gy/shot

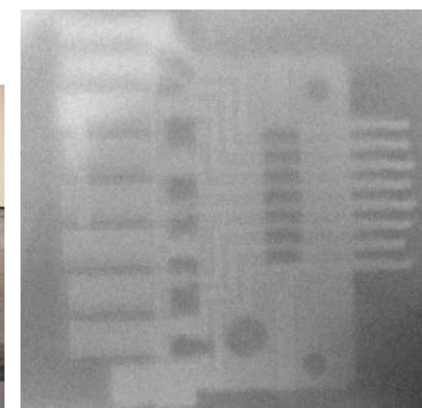


辐照后细胞

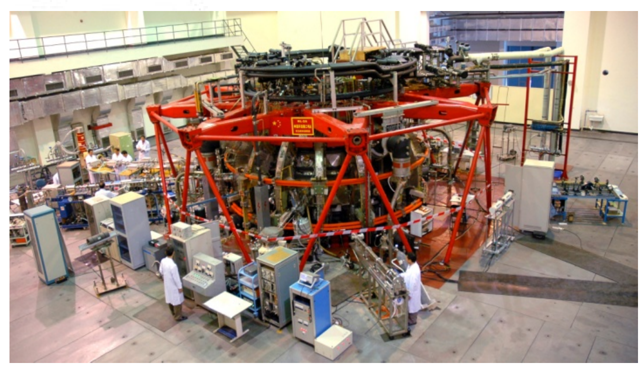
质子生物照相



高能电子&X射线照相

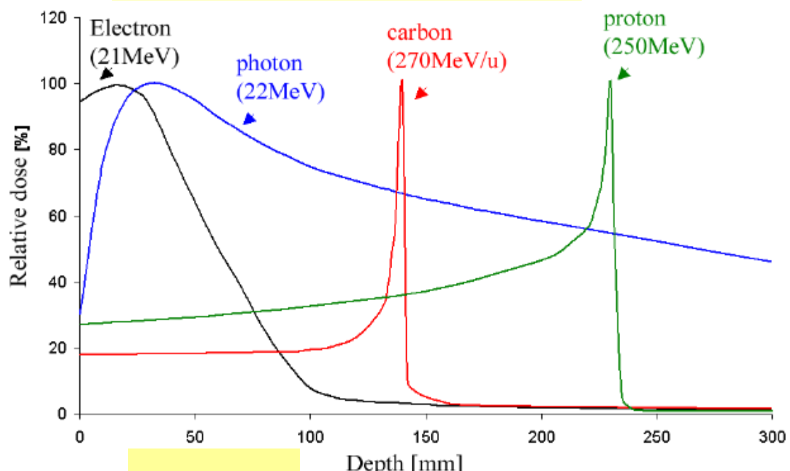


激光离子束轨迹探针（HL-2A成都）

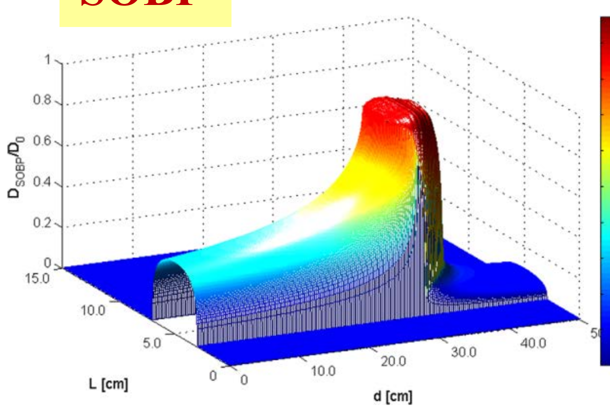


Spread-out Bragg Peak

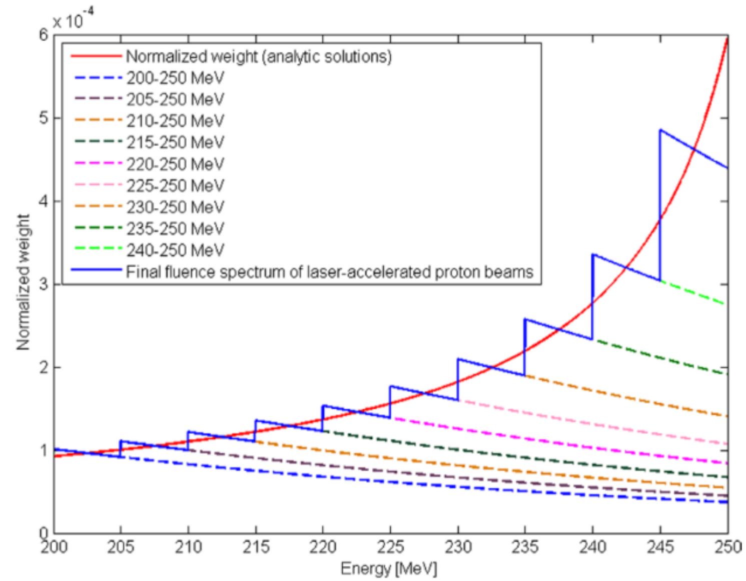
Single Bragg Peak



SOBP



L Tao *et al.* Phys. Med. Biol. 62 (2017) 5200



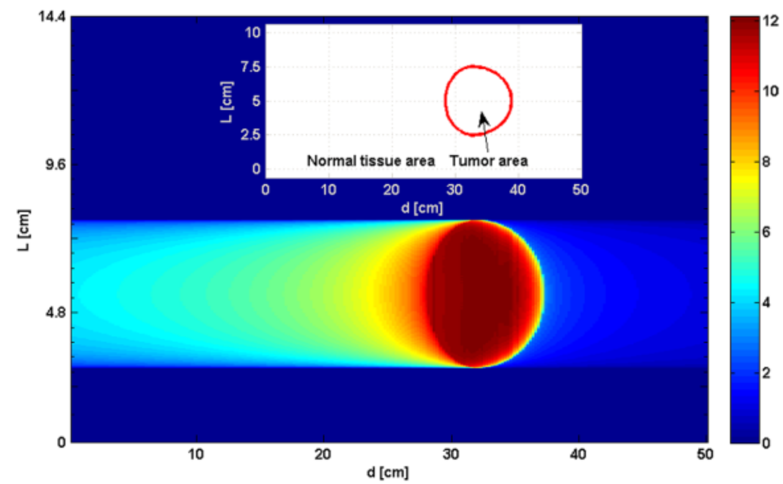
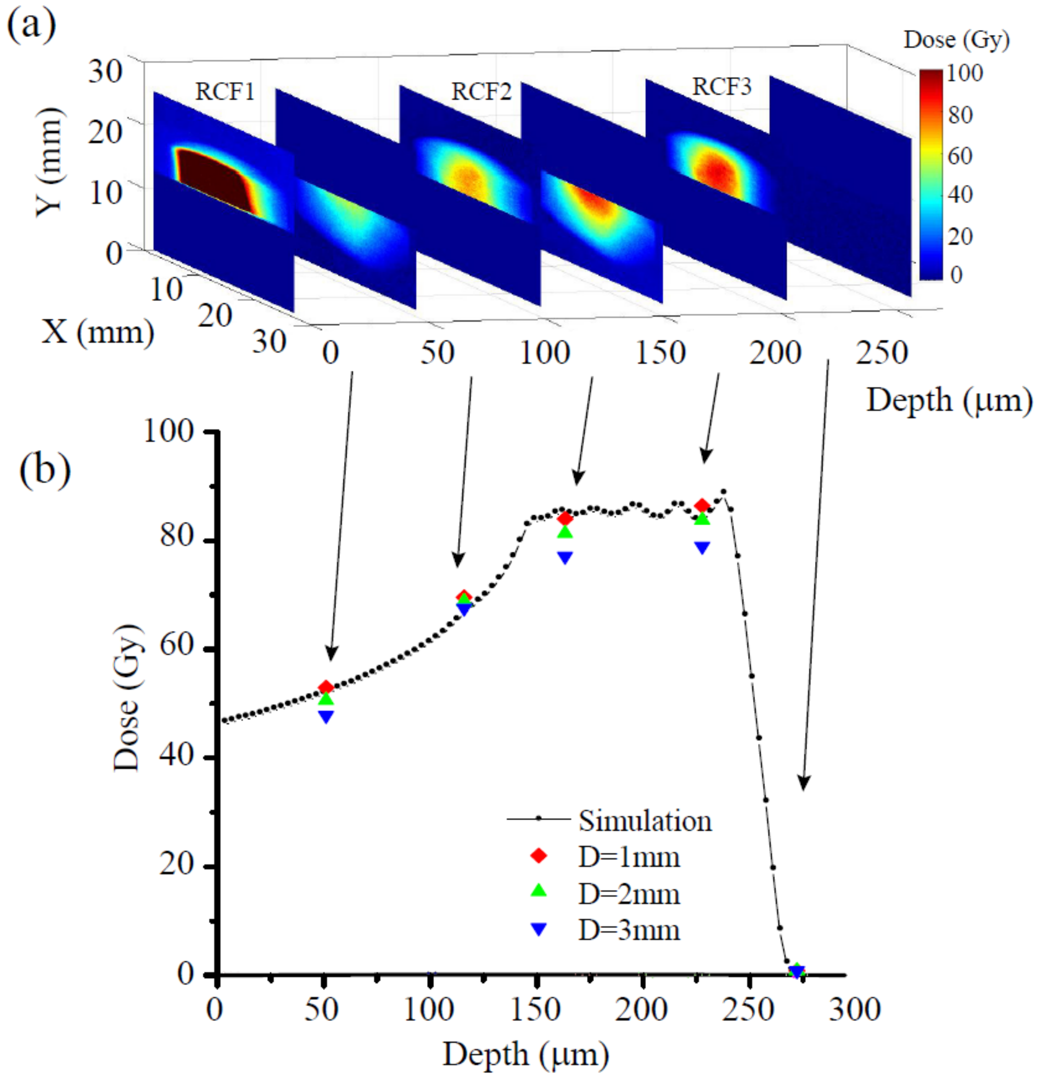


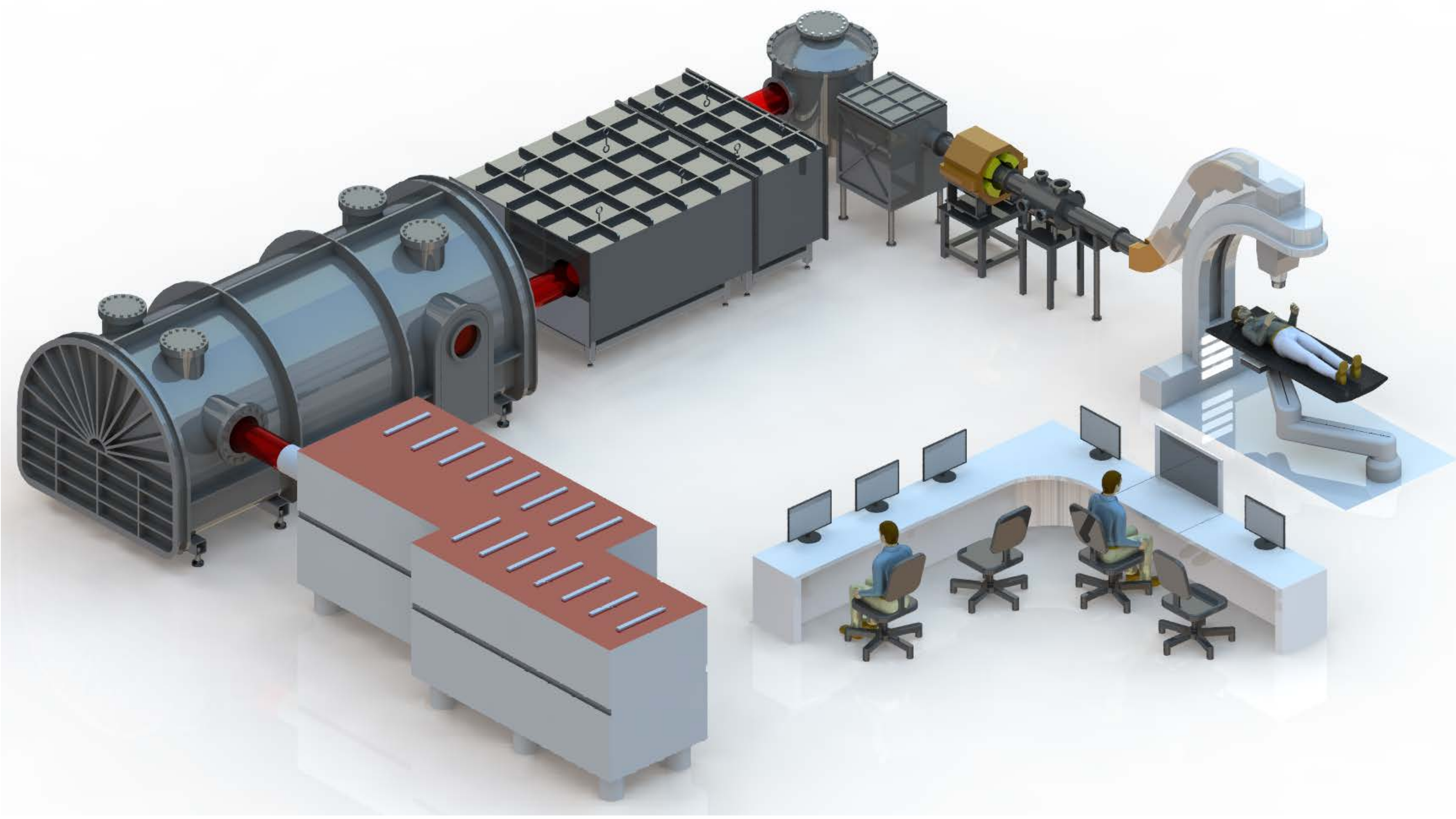
Figure 6. The 2D reconstruction result of the SOBP for an ideal situation with a specific tumor region.

SOBP at CLAPA Beam line

SOBP ,a key technology of proton radiotherapy, is realized with laser accelerator for the first time at PKU.



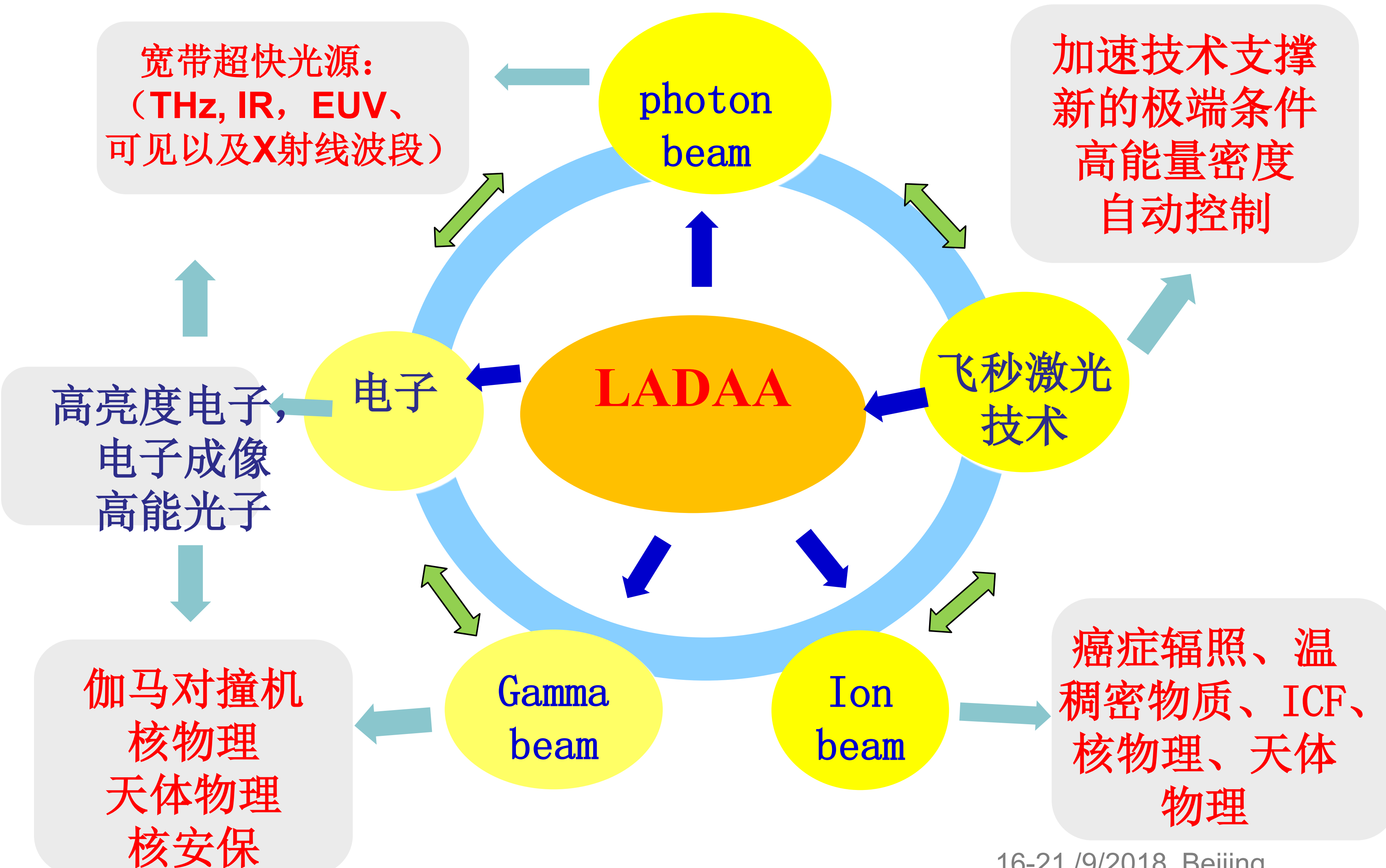
A table-top proton cancer therapy machine



Outline

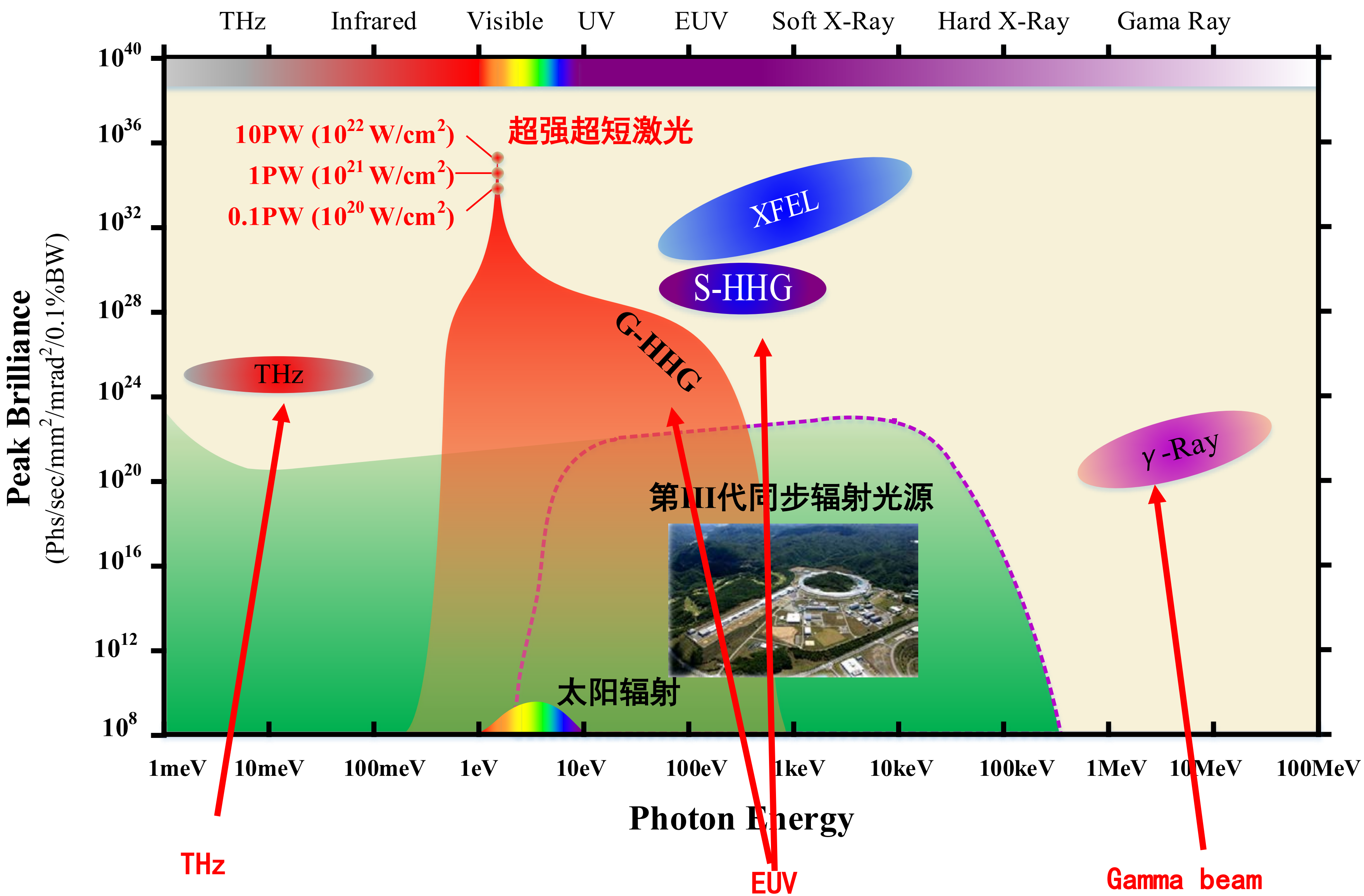
1. Introduction
2. Compact laser plasma accelerator at Peking University
3. LAser Driven multi-beAm FAcility (LADAA)—large-scale user facility planned in future

LAser Driven multi-beAm FAcility



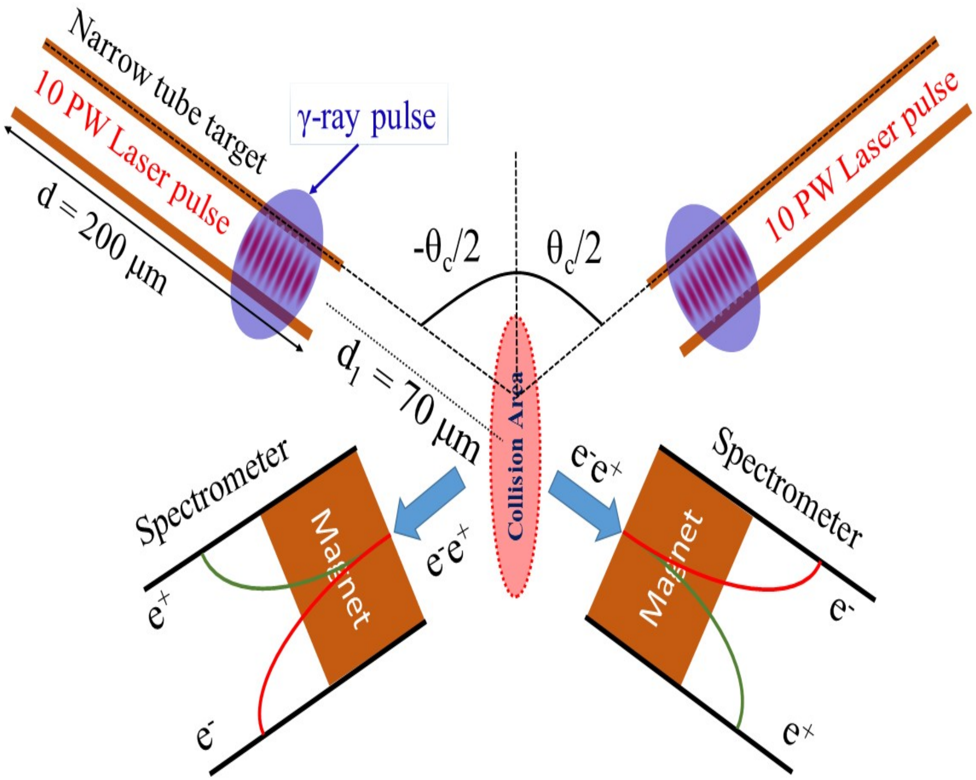
16-21 /9/2018, Beijing

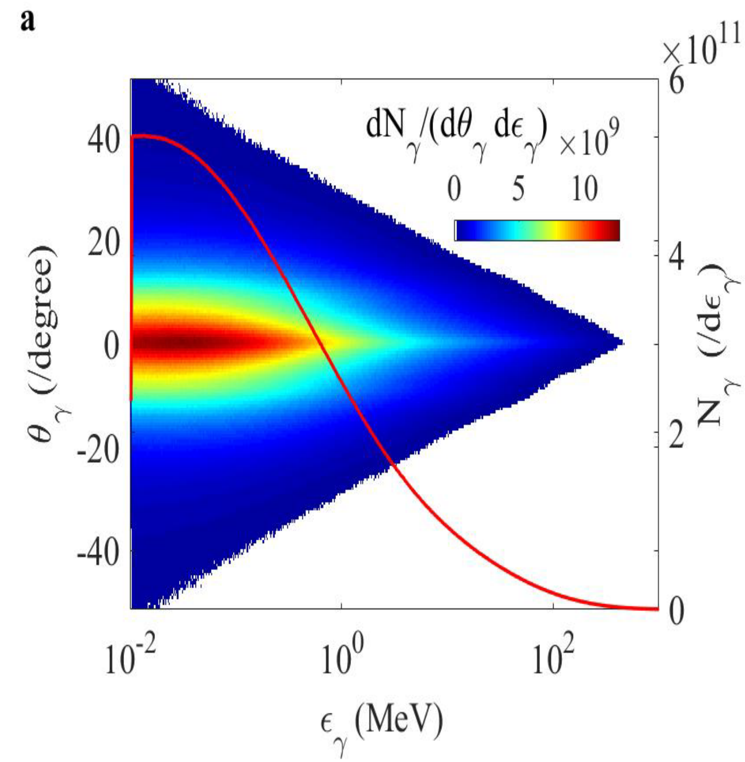
Ultrafast light sources driven by laser



Gamma beam driven by 10-PW laser pulses

Jinqing Yu, et al. APL 2018 **Featured Article**

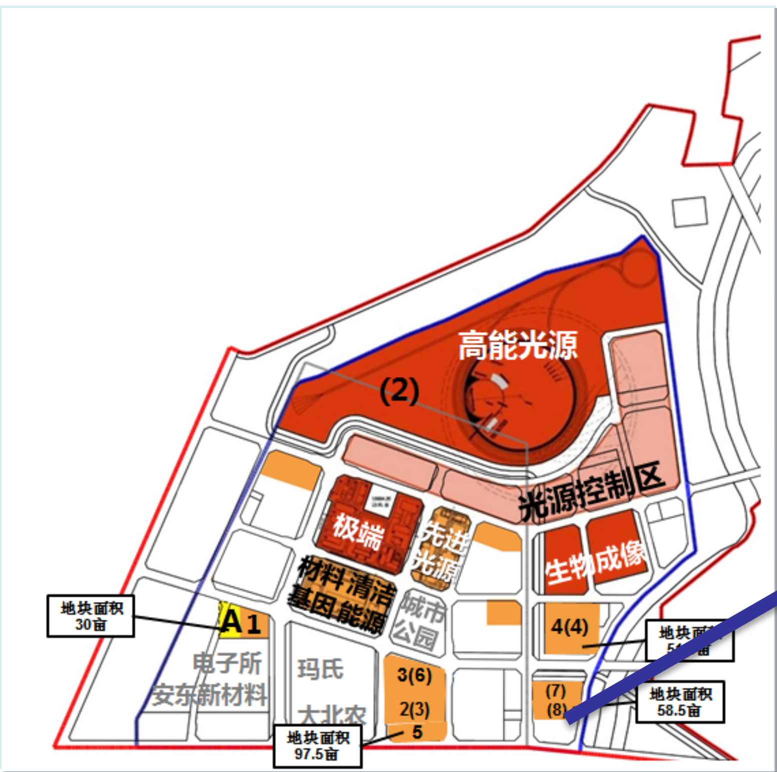


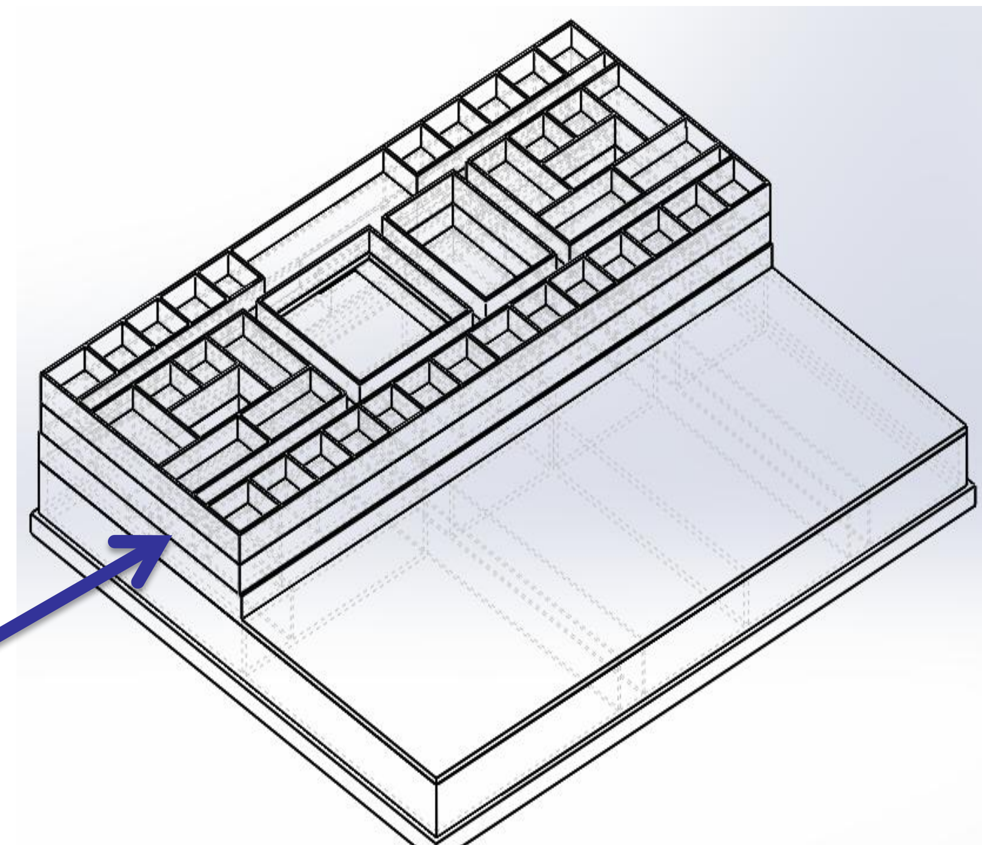


In one pulse, more than 1×10^{14} γ-ray photons with a divergence of 3 degrees. At 0.5 MeV, the brilliance of the γ-ray pulse is about 10^{25} photons·s^{-1}·mm^{-2}·mrad^{-2}·0.1%BW.

Beijing Laser Acceleration Platform

2017.12, LADAA was proposed to MOE
2018.3, LADAA was launched!
2018.8 BLAIC (CDR 0) was approved by Beijing government
100MeV Laser proton accelerator as the first ion beam
2021.9, TDR… …





Huairou National Science and Technology Innovation Center

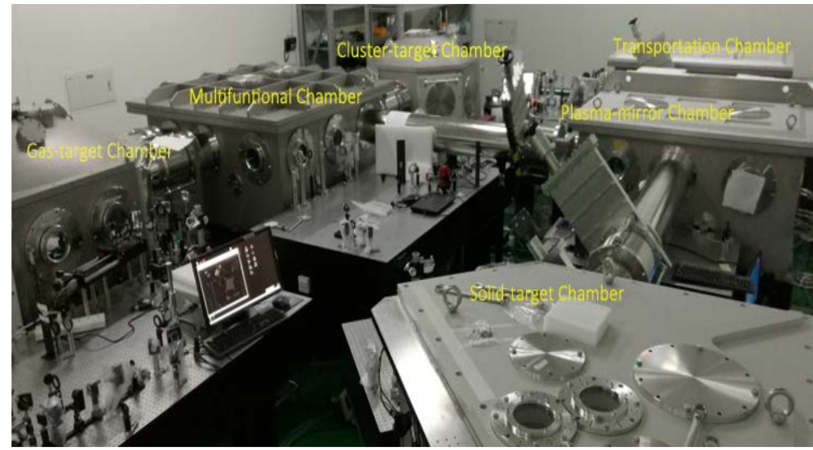
Summary

- ✓A laser proton accelerator (CLAPA) with 1% energy spread and RAMI has been built at Peking University for the first time.
- ✓3-15 MeV proton beams have been generated with stability better than 3% by using plastic targets, proton beams with 1% energy spread and 1-20 pC has been achieved.
- ✓LAser Driven multi-beAm FAcility (LADAA)—large-scale user facility is planned in future

Thanks for your attention!

Peking University Lab Visit
CLAPA

200TW laser system



Target chamber

1% energy spread beam line

Irradiation platform

16-21 /9/2018, Beijing