Recent progress of laser proton acceleration at Peking University

Xueqing Yan (颜学庆)

Institute of Heavy Ion Physics
School of physics, Peking University, China

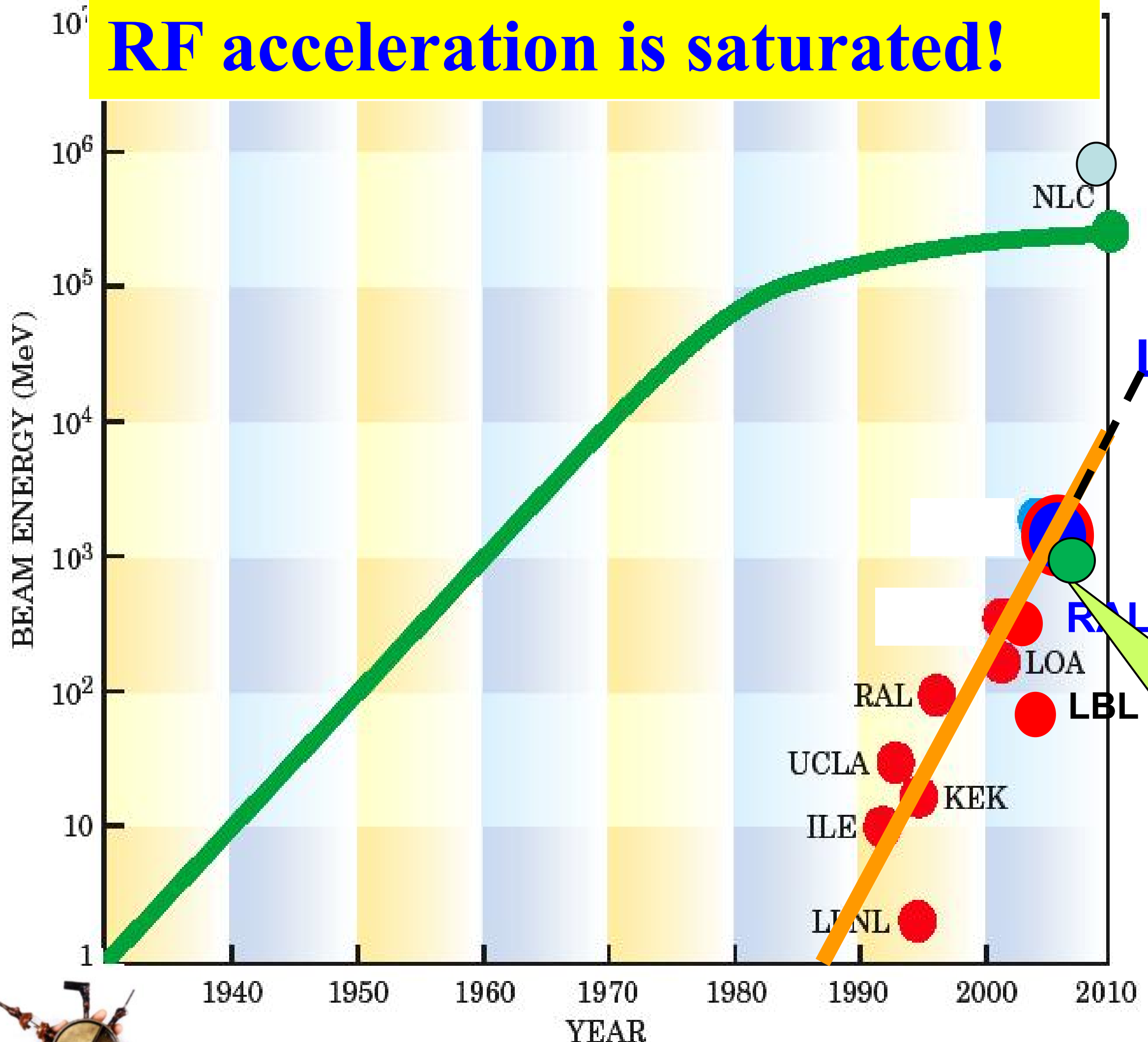
Outline

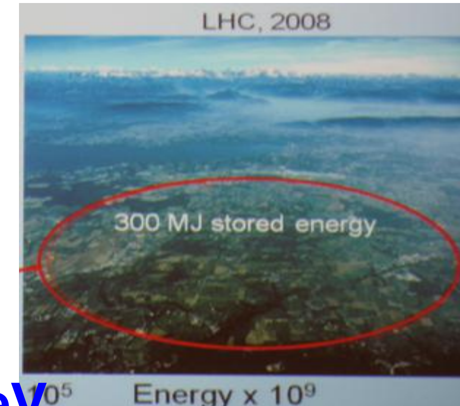
1. Introduction
2. Radiation Pressure Acceleration with Phase stability
3. Compact Laser Proton accelerator with a Beamline
4. summary

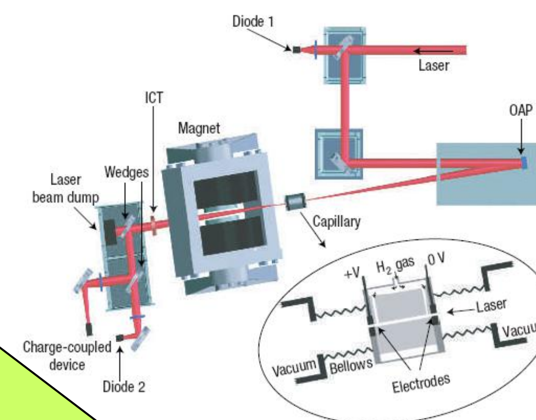
Why and What is laser acceleration?

Particle energy: From eV→MeV→GeV → TeV…

RF acceleration is saturated!







Gradient is thousand
Times higher!

Laser Electron Accelerator

John M Dawson（1930-2001）

Toshiki Tajima

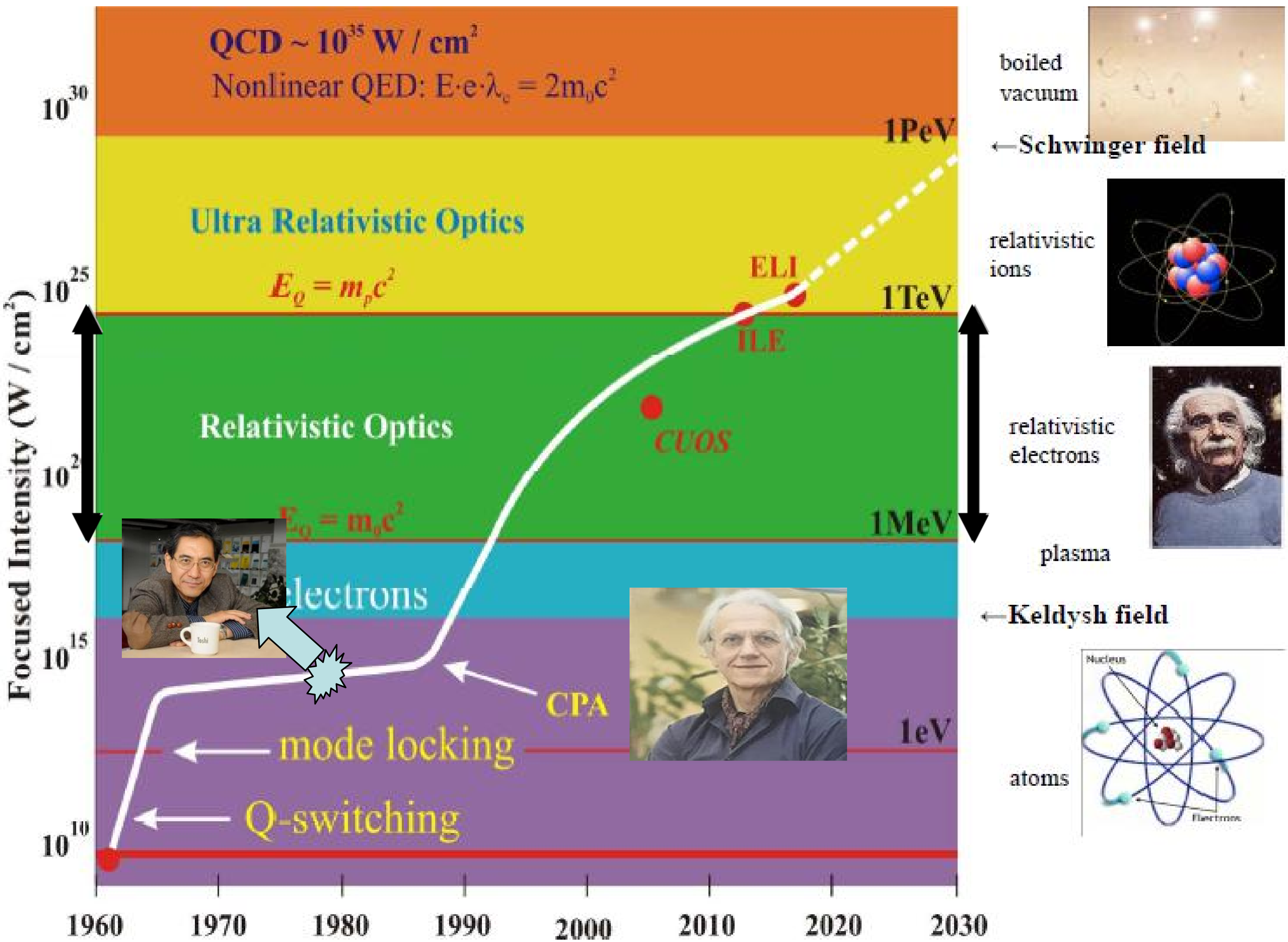
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

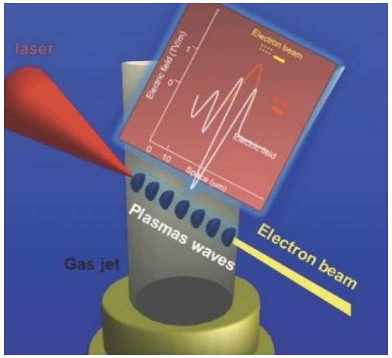
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

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

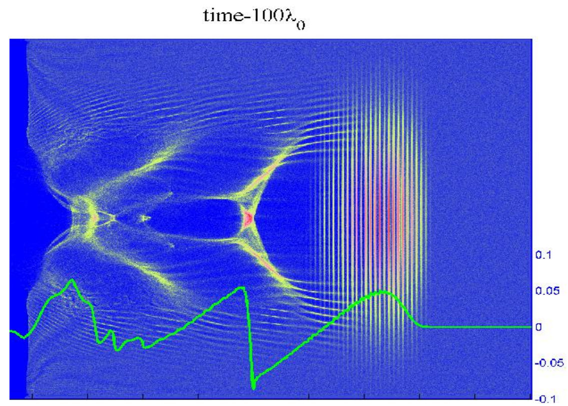
Focused laser Intensity



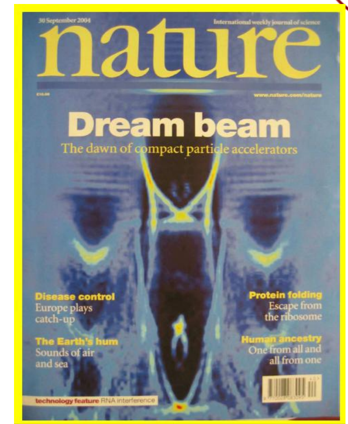
Progress of Laser Electron Acceleration



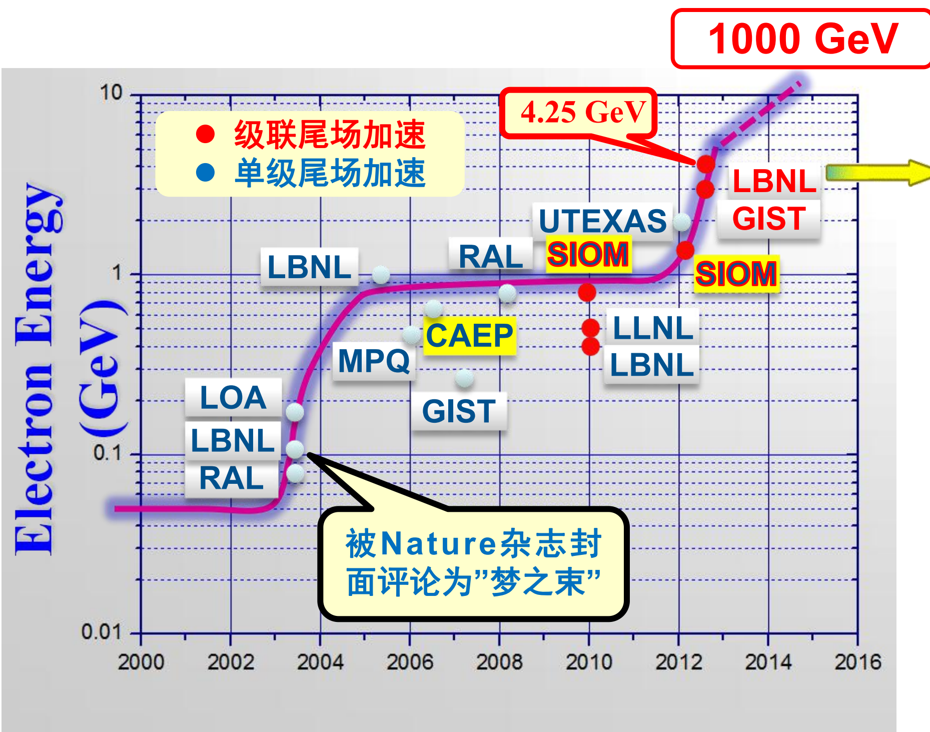
LPA



Gradient ~100 GV/m



Nature,2004



APS physics

Top Ten Physics News Stories in 2014

Tabletop Accelerator

In December, scientists at Lawrence Berkeley National Lab announced a new world record for a compact particle accelerator. The team used a tabletop-sized laser-plasma accelerator to energize electrons up to 4.25 GeV. Though not nearly as powerful as the massive LHC, the tiny BELLA accelerator can do in about one meter what would take CERN 1,000 meters. Physicists hope that this emerging compact accelerator technology will pave the way to new generations of particle colliders.

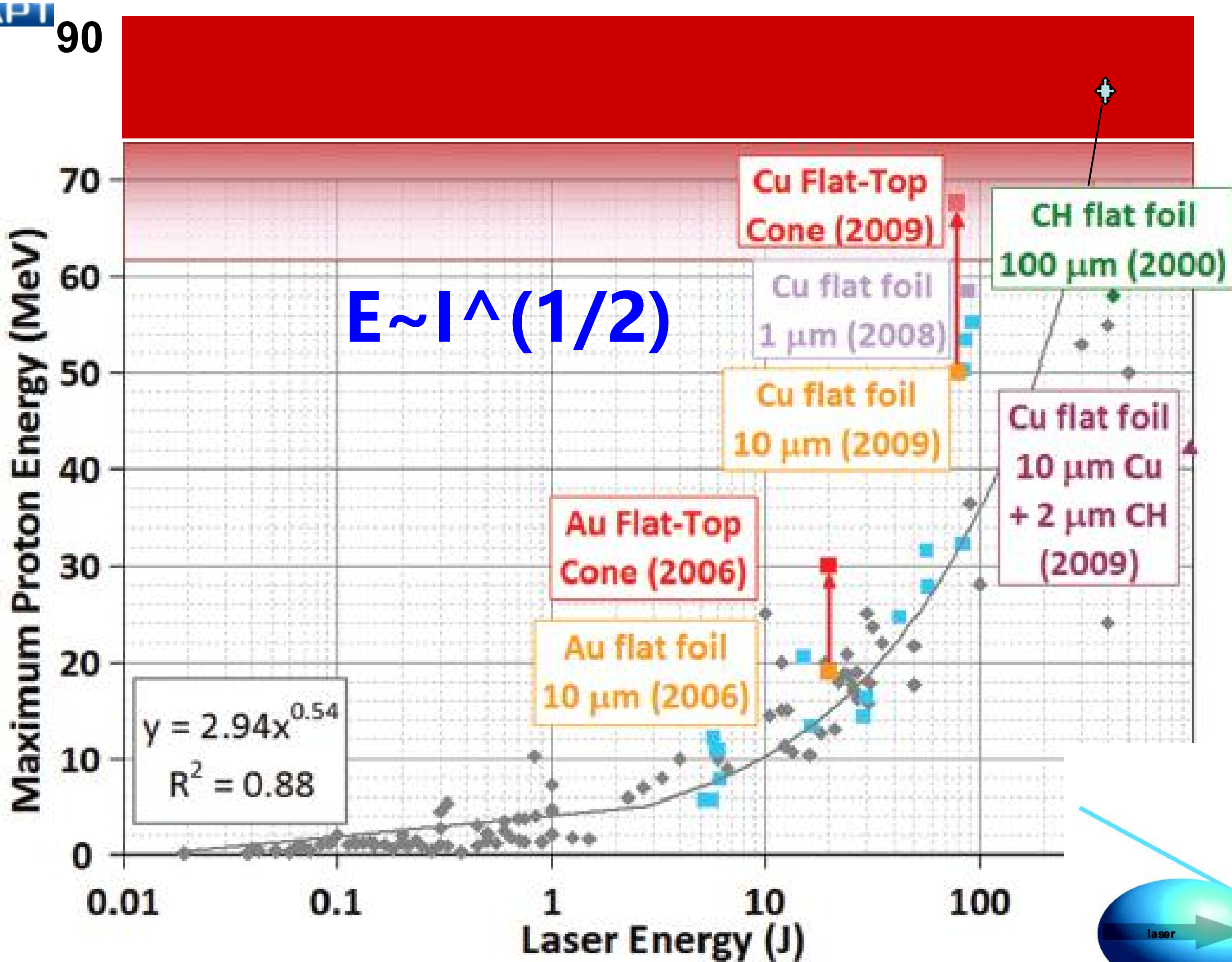
By Prof.R.X.Li

Nobel prize in 2018

Toshiki Tajima

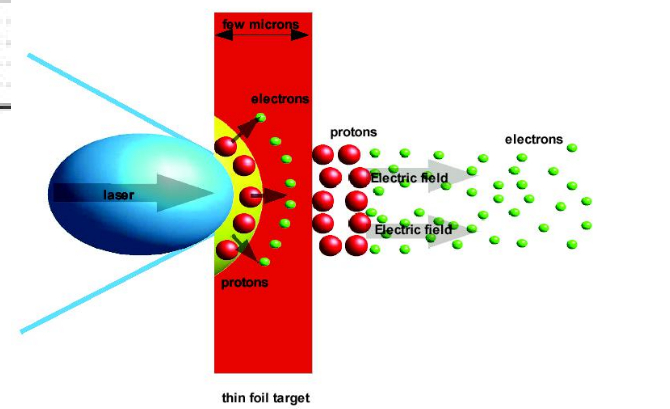
At Lawrence Berkeley National Laboratory in California, a petawatt-class laser at the Berkeley Lab Laser Accelerator (BELLA) facility is used to accelerate electrons to 4.2 GeV over a distance of 9 cm [78]. This is an acceleration gradient of at least two orders of magnitude higher than what can be obtained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

Target Normal Sheath Acceleration for ions



Target Normal Sheath Acceleration

Phys. Rev. Lett. **85**, 2945 (2000).



Maximum proton energy 60 MeV in 2000 and 85 MeV in 2016, moreover the spectrum is still exponential!

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 124802 (2016)

Laser-driven ion accelerators for tumor therapy revisited

Ute Linz[1,*] and Jose Alonso[2,†]
[1] *Forschungszentrum Jülich, D-52425 Jülich, Germany*
[2] *Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 2 August 2016; published 29 December 2016)

Ten years ago, the authors of this report published a first paper on the technical challenges that laser accelerators need to overcome before they could be applied to tumor therapy. Among the major issues were the maximum energy of the accelerated ions and their intensity, control and reproducibility of the laser-pulse output, quality assurance and patient safety. These issues remain today. While theoretical progress has been made for designing transport systems, for tailoring the plumes of laser-generated protons, and for suitable dose delivery, today's best lasers are far from reaching performance levels, in both proton energy and intensity to seriously consider clinical ion beam therapy (IBT) application. This report details these points and substantiates that laser-based IBT is neither superior to IBT with conventional particle accelerators nor ready to replace it.

DOI: 10.1103/PhysRevAccelBeams.19.124802

following challenges:

(1) scaling laws for proton energy with laser power,
(2) shot-to-shot reproducibility to the few-percent level,
(3) improving proton flux by at least an order of magnitude,
(4) development of techniques for accurate dose control and cutoff

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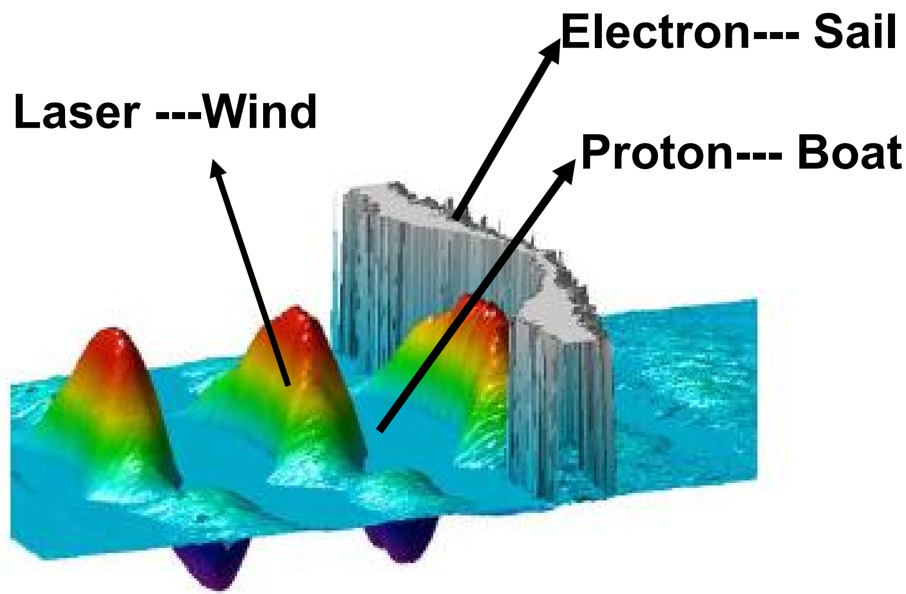
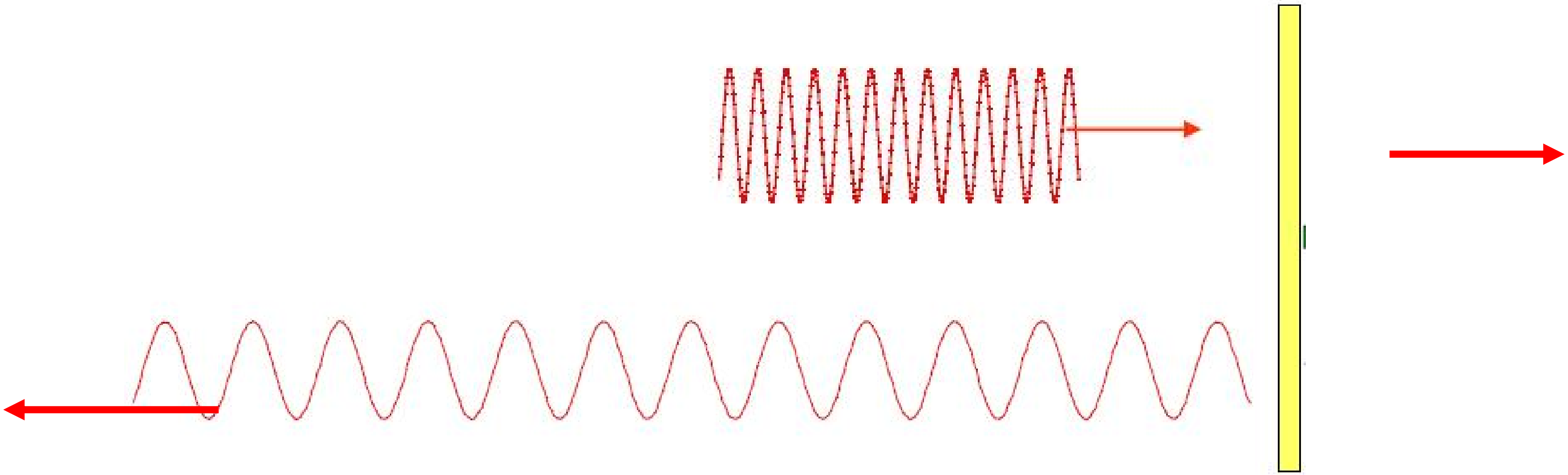
Radiation Pressure Acceleration

Sailboat



X.Q.Yan et al, PRL 100, 135003 (2008)
T.Tajima, D.Habs, X.Q.Yan, RAST, (2009) 1–26

Conversion Efficiency (CE)

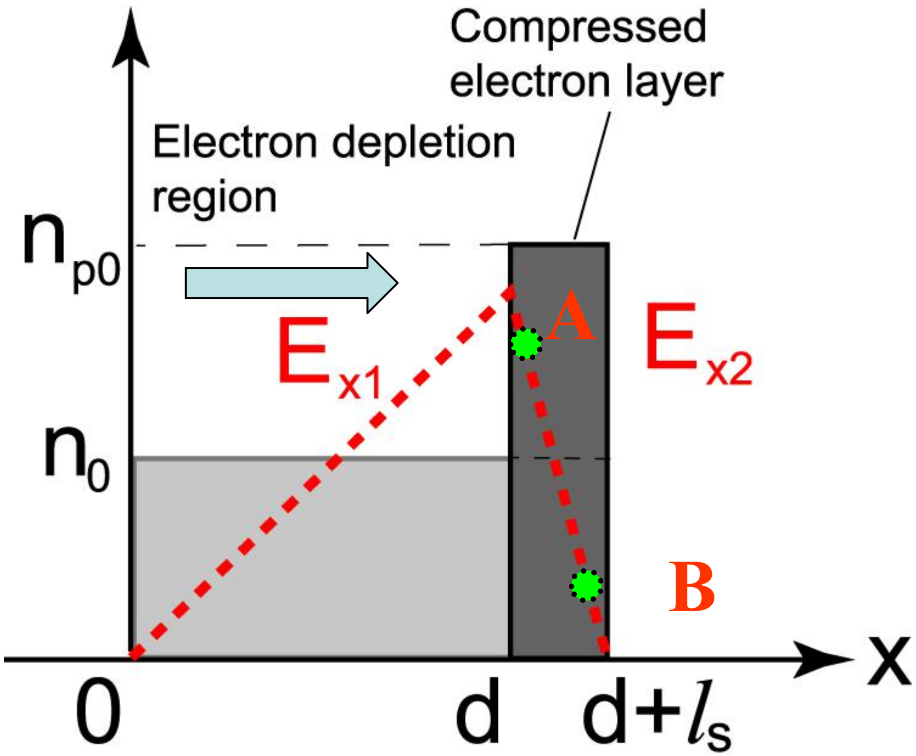


$$CE = 1 - \frac{1}{4\gamma^2} \sim 100\%$$

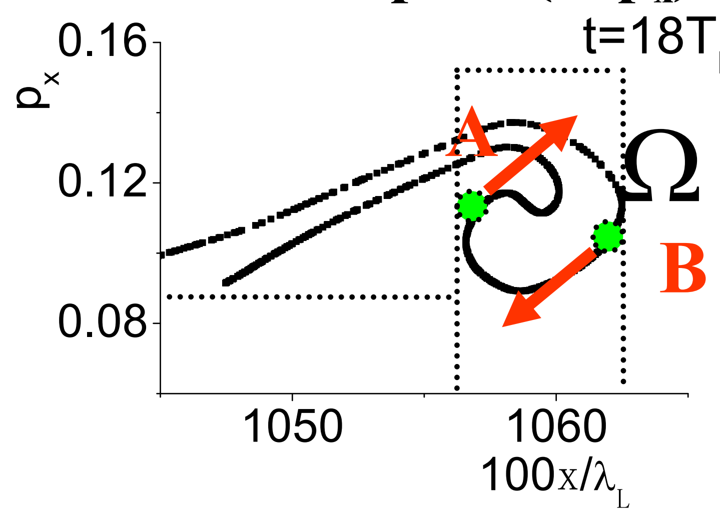
A. Einstein, Annalen der Physik 17, 891 (1905)

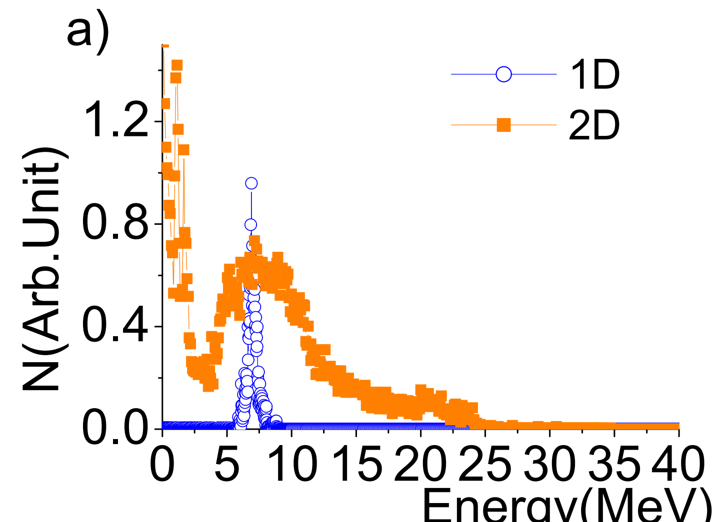
Phase Stability Acceleration when

$$a \sim (n_0 / n_c) D / \lambda_L$$



Phase space (x~p$_x$)





$$E_{x1} = E_0 x / d, (0 < x < d) \qquad E_0 = 4\pi n_0 d$$

$$E_{x2} = E_0 (1 - (x - d)) / l_s, (d < x < d + l_s)$$

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

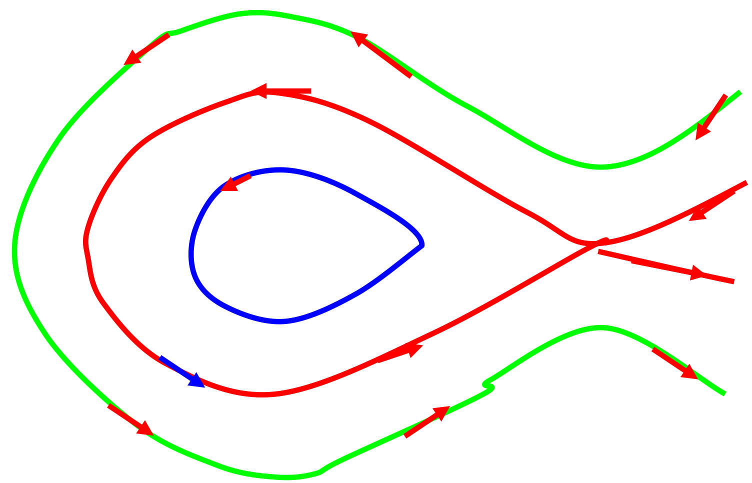
Phase stability

1945: E. McMillan and V.J.Veksler (1944) discover the principle of phase stability

Photo by U. Amaldi

1959: Veksler visits McMilan at Berkeley

$F(\phi_s, \phi)$



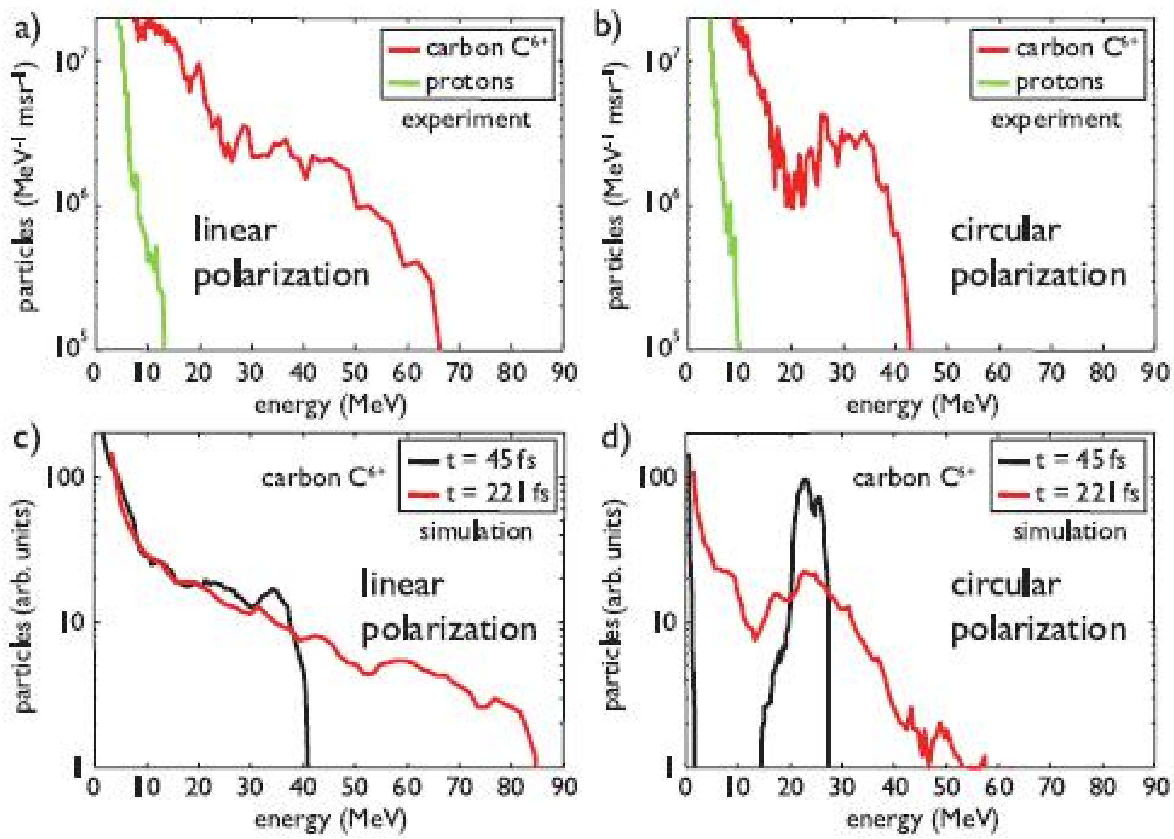
Demonstration of Radiation Pressure Acceleration

PRL **103,** 245003 (2009) PHYSICAL REVIEW LETTERS

$a \sim (n_0 / n_c) D / \lambda_L$

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

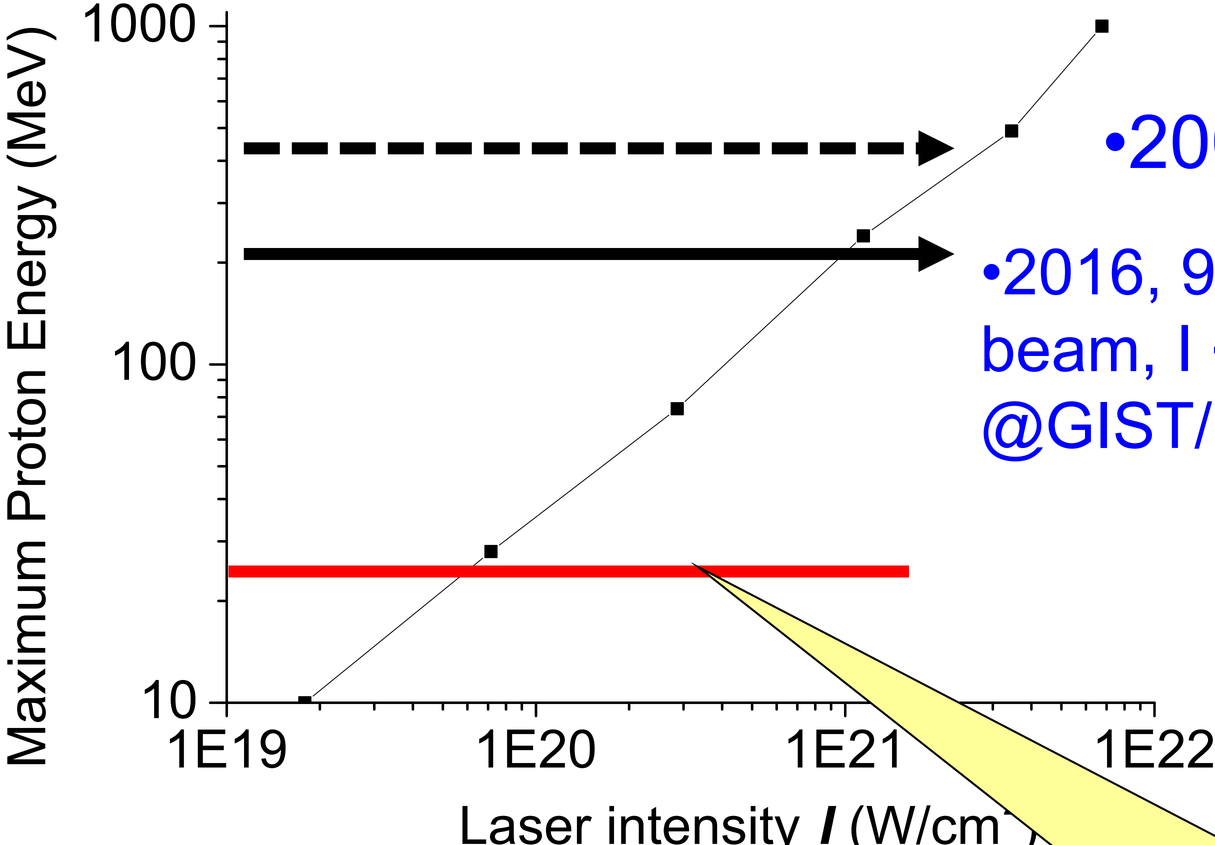
A. Henig,[1,2,*] S. Steinke,[3] M. Schnürer,[3] T. Sokollik,[3] R. Hörlein,[1,2] D. Kiefer,[1,2] D. Jung,[1,2] J. Schreiber,[1,2,4] B. M. Hegelich,[2,5] X. Q. Yan,[1,6,†] J. Meyer-ter-Vehn,[1] T. Tajima,[2,7] P. V. Nickles,[3] W. Sandner,[3] and D. Habs[1,2]
, Germany
748 Garching, Germany
W7 2BZ, United Kingdom
87545, USA
100871, Beijing, China



I~5*10^19W/cm2
5nm DLC foil
13MeV proton
30MeV carbon

Proton energy E ~ I (laser intensity)

T.Tajima, D.Habs, and X.Q.Yan. *Review of Accelerator Science and Technology*, 2(201-228),2009.

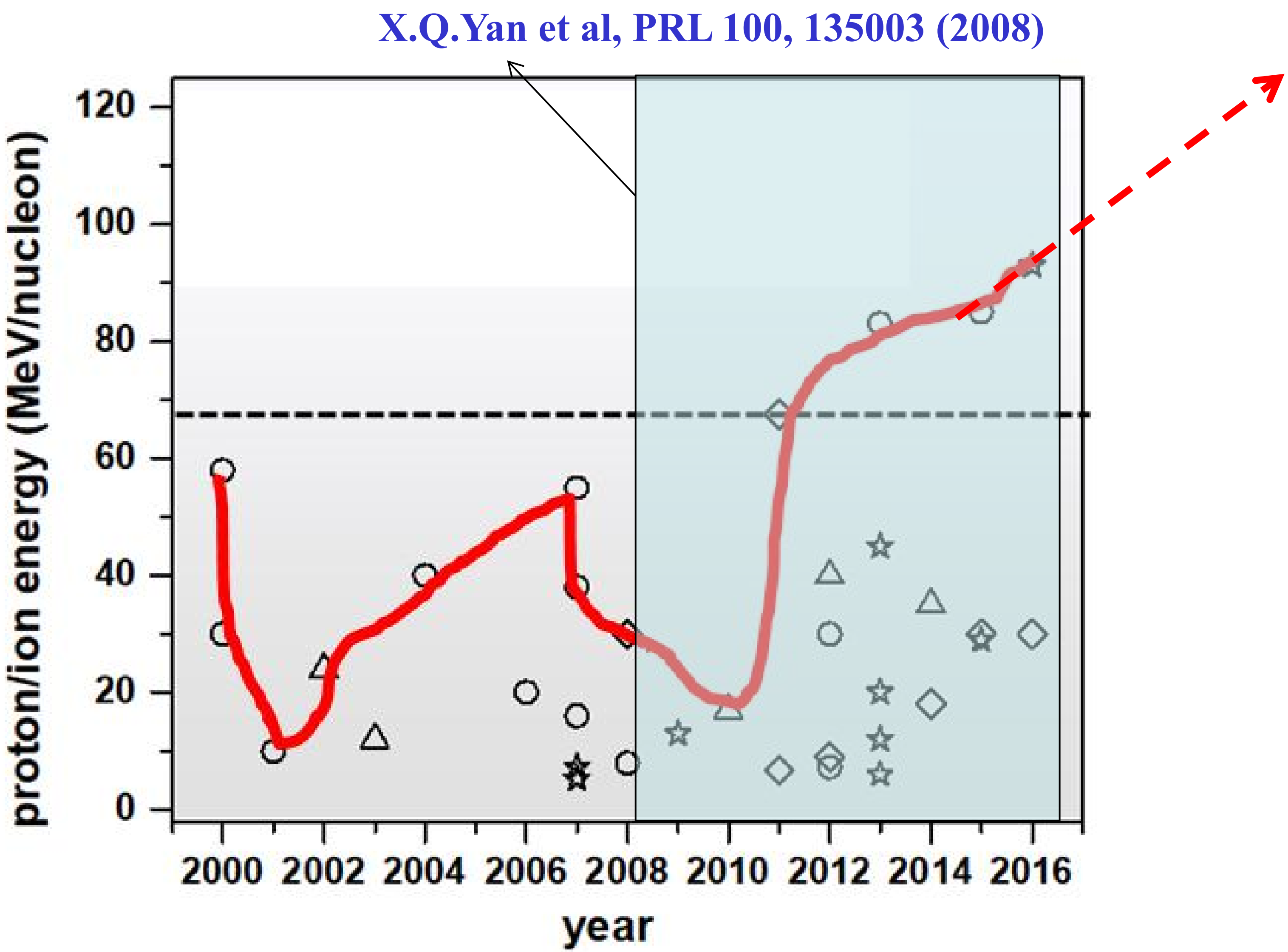


•200MeV?

•2016, 94MeV proton beam, I ~10^21W/cm^2 @GIST/RAL

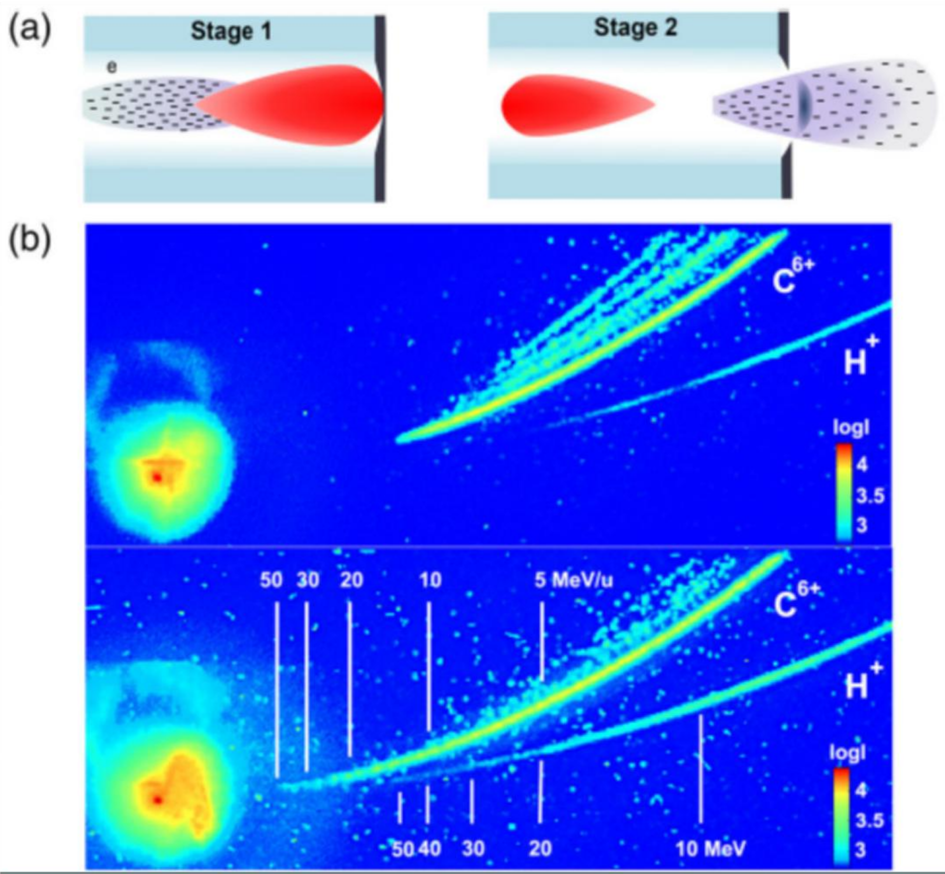
2009, Tens MeV proton@10^20 Experimental demonstration

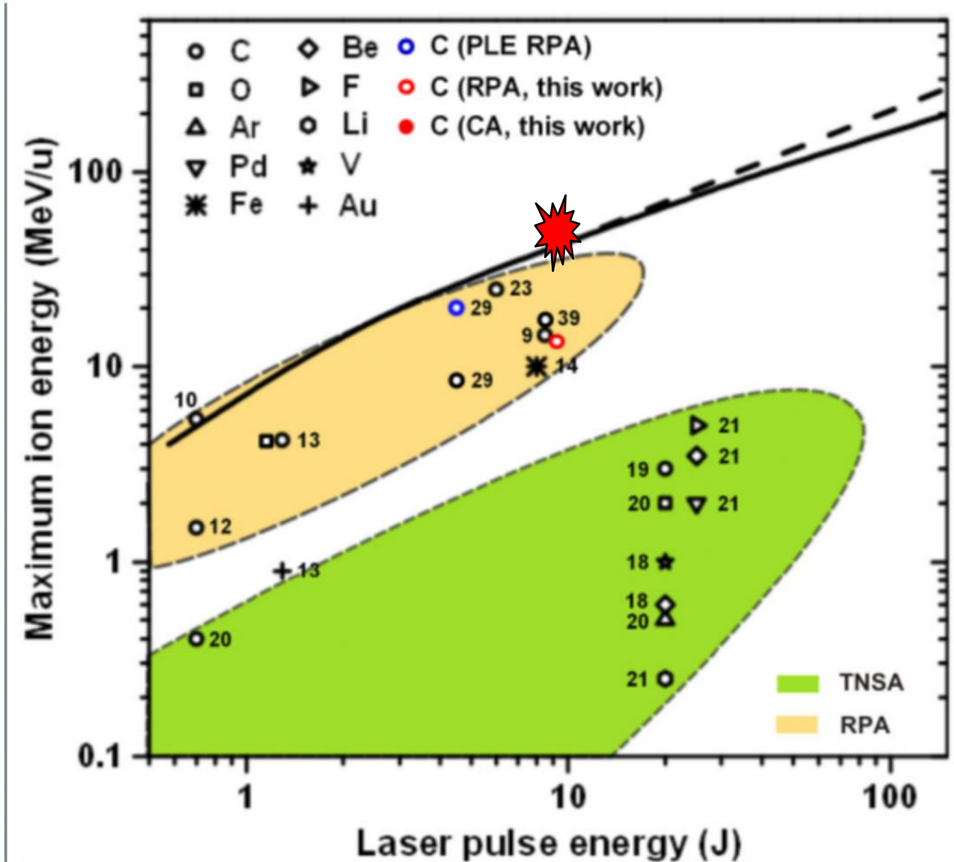
Proton energy in recent experiments



Heavy Ion Acceleration

~600MeV Carbon new record at CoReLS/IBS

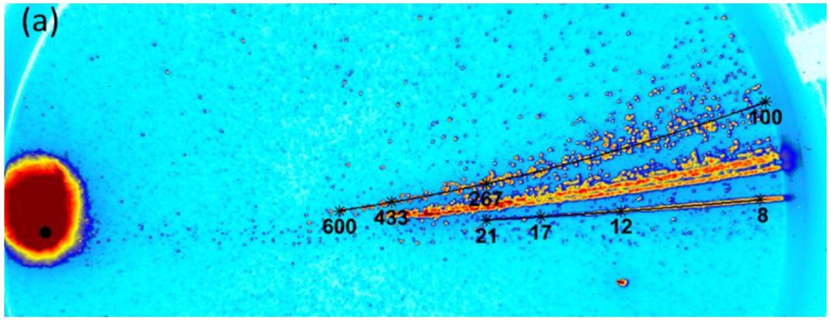




W.J.Ma, et al. , PRL, 122, 014803, 2019

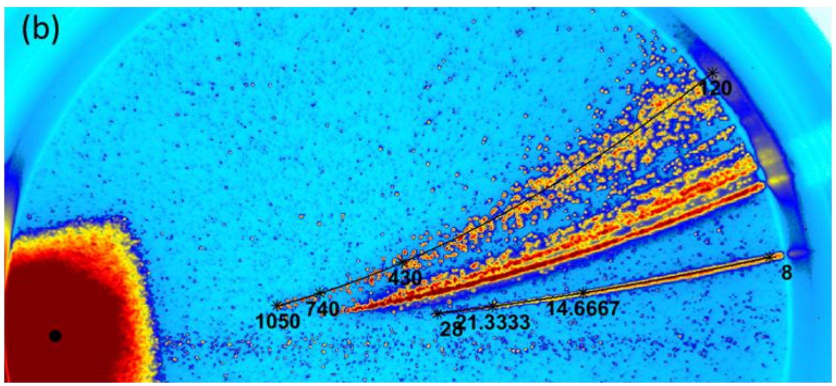
GeV heavy ion acceleration @GIST

B Deflection



E Deflection

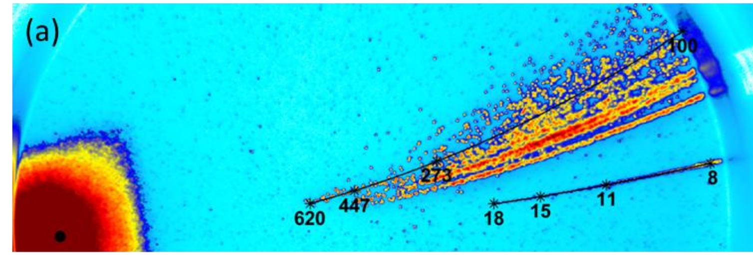
Single-layer 100 nm Au target(100nm):
Max charge state: Au 50+; Max energy: 600 MeV (Au50+)



CNF(0.4nc,80um)+150nm Au target
Max charge state: 56+; Max energy: 1050 MeV(Au50+)

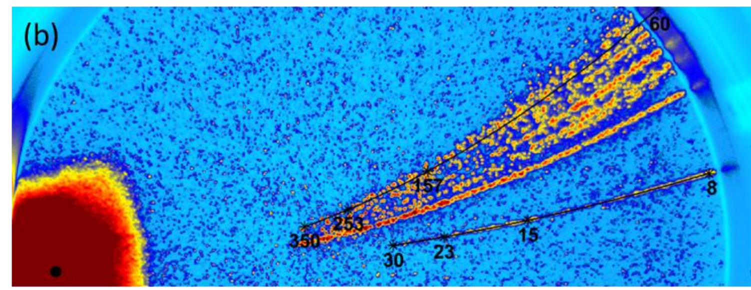
ions	charge	maximum
Gold	50+	1.05GeV
Silver	35+	620MeV
Cu	20+	350MeV
Al	11+	250MeV

B Deflection

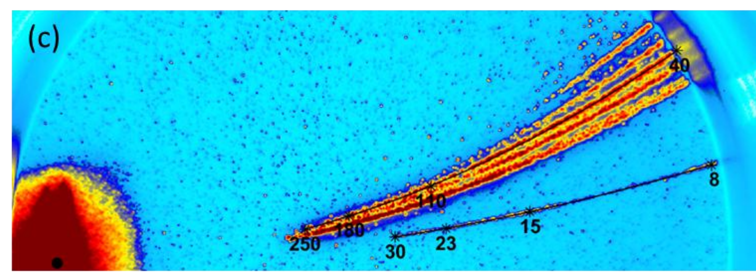


E Deflection

Single layer Ag(100nm)
Max charge state: 38+; Max energy: 620 MeV (Ag35+)



CNF(0.6nc, 80um)+Cu(50nm)
Max charge state: 23+; Max energy: 350 MeV (Cu20+)



CNF(0.6nc, 80um)+Al(20nm)
Max charge state: 13+; Max energy: 250 MeV(Al 11+)

（PRX，2021）

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Characteristics of Laser Driven Ion Beam

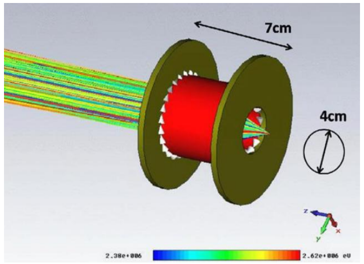
- Large energy spread: 20%~100%
- Large diverge angle~10°
- Small emittance ~0.1 π mm.mrad
- Small initial size, spot source ~5μm
- Short pulse duration ~a few ps
- High peak current ~ 10^9-10^{12}ppp, KA

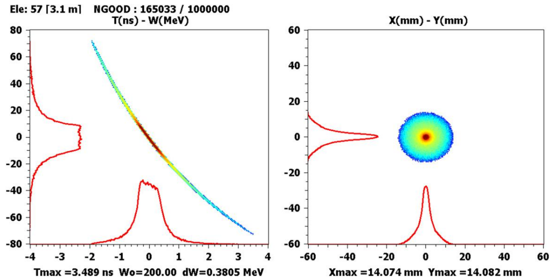
new features for beam optics

From laser acceleration to laser accelerator?

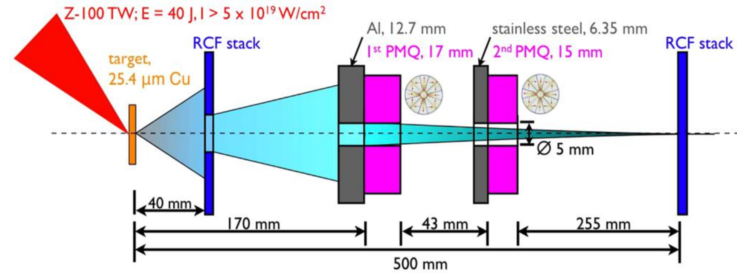
The laser driven ion beams can not be used directly for many applications. **Special designed beam line is necessary!**

Pulsed solenoid

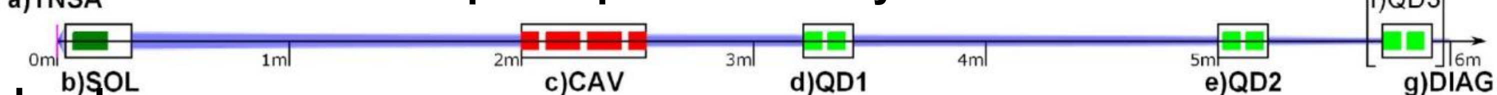




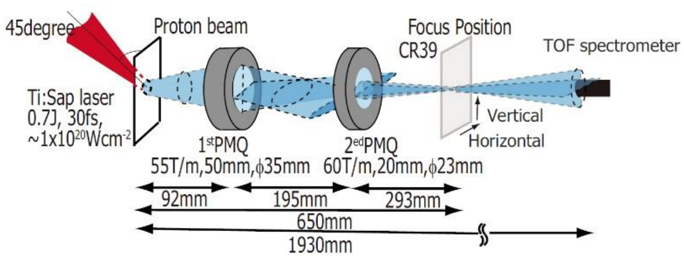
Electronic Quadruple

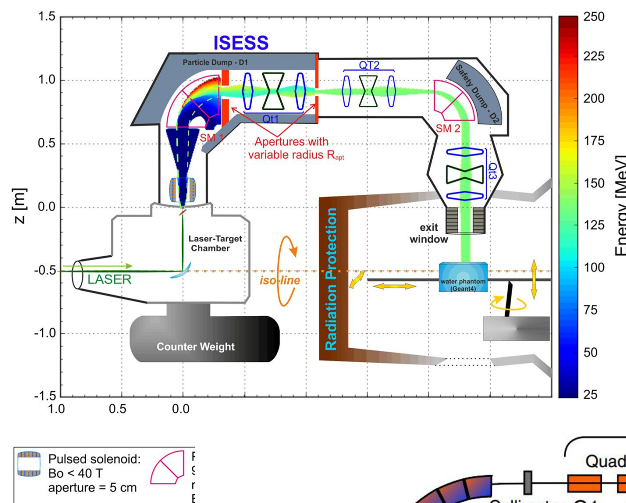


Solenoid + quadruple + RF cavity

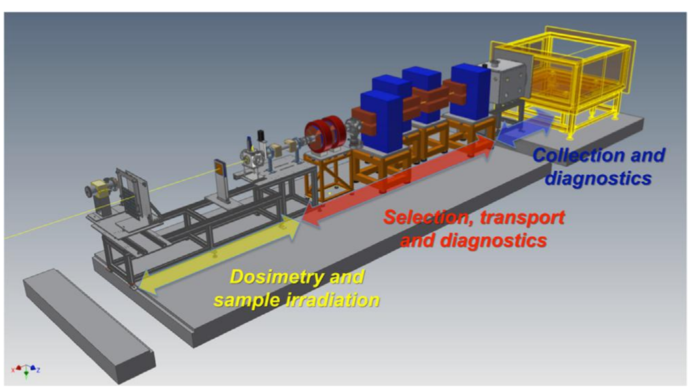


Permanent Quadruple

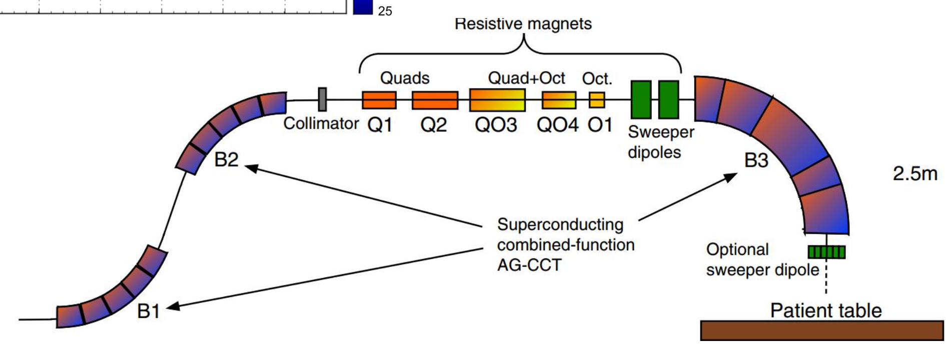




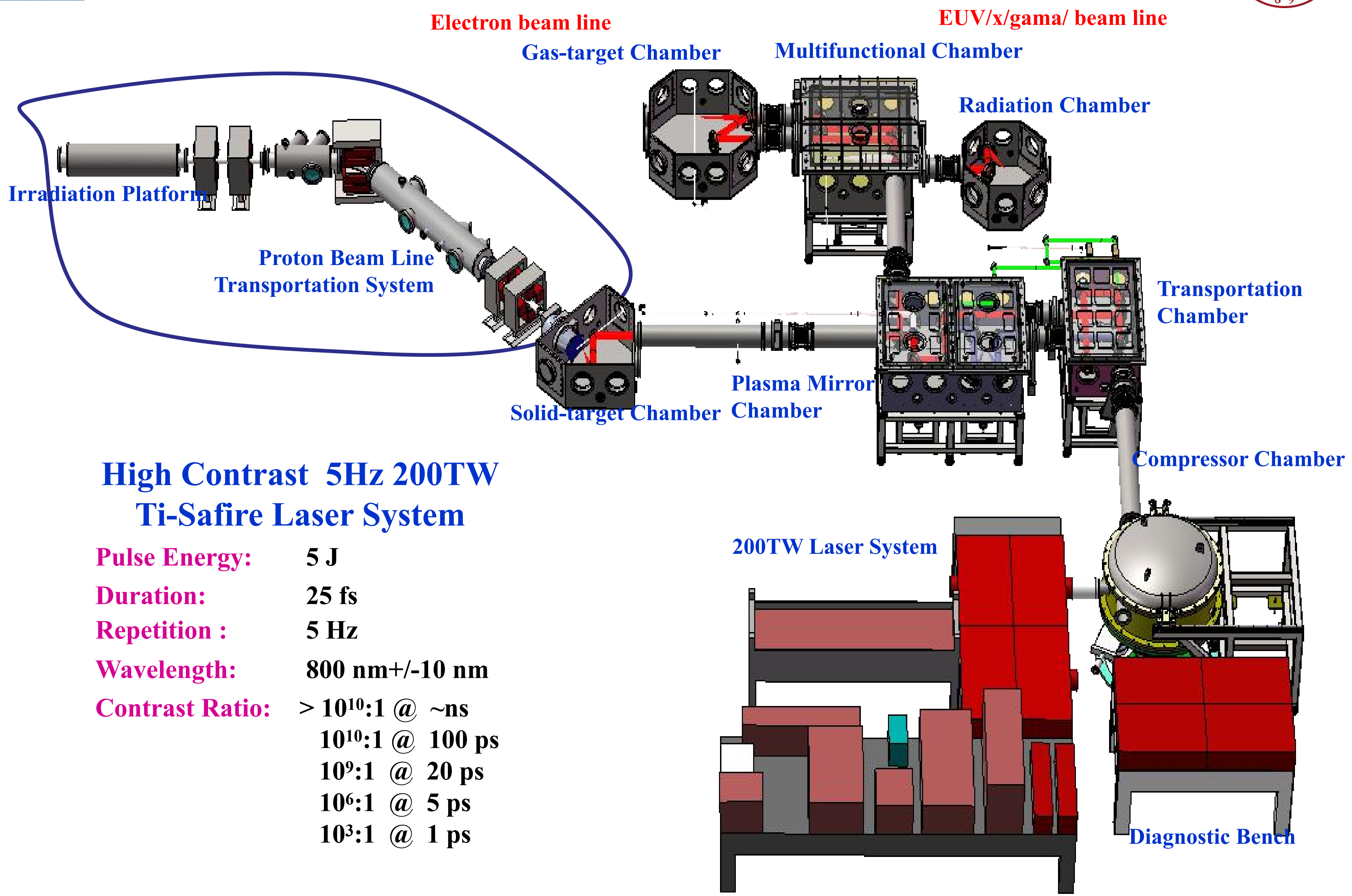
ELI beam line



BELLA beam line



CLAPA (Compact LAser Plasma Accelerator)

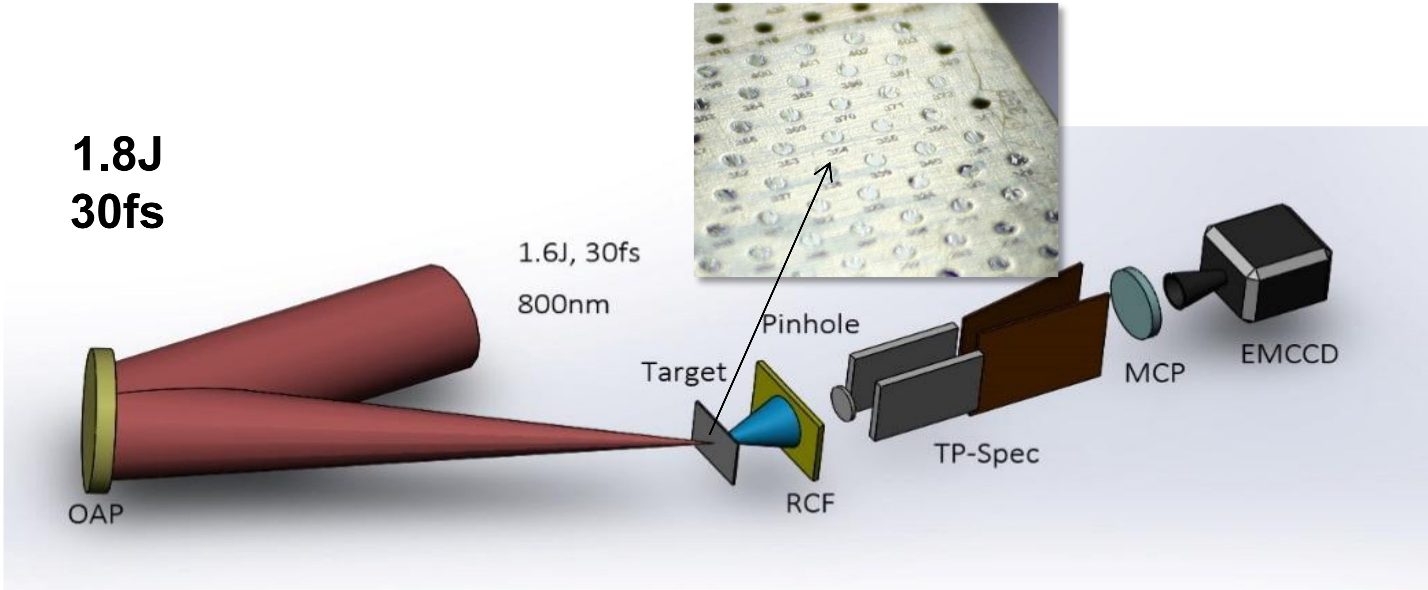


High Contrast 5Hz 200TW Ti-Safire Laser System

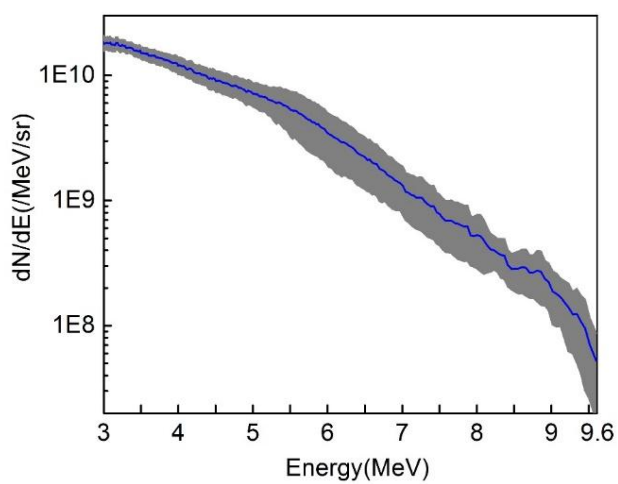
Pulse Energy:	5 J
Duration:	25 fs
Repetition :	5 Hz
Wavelength:	800 nm+/-10 nm
Contrast Ratio:	> 10^{10}:1 @ ~ns
	10^{10}:1 @ 100 ps
	10^{9}:1 @ 20 ps
	10^{6}:1 @ 5 ps
	10^{3}:1 @ 1 ps

Repeatability down to the few-percent level

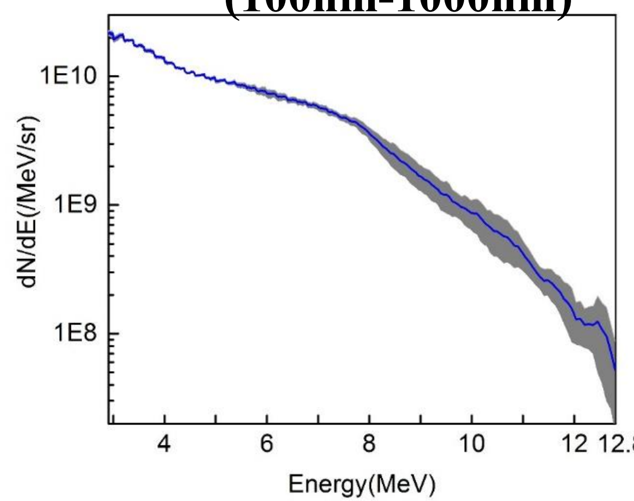
1.8J
30fs



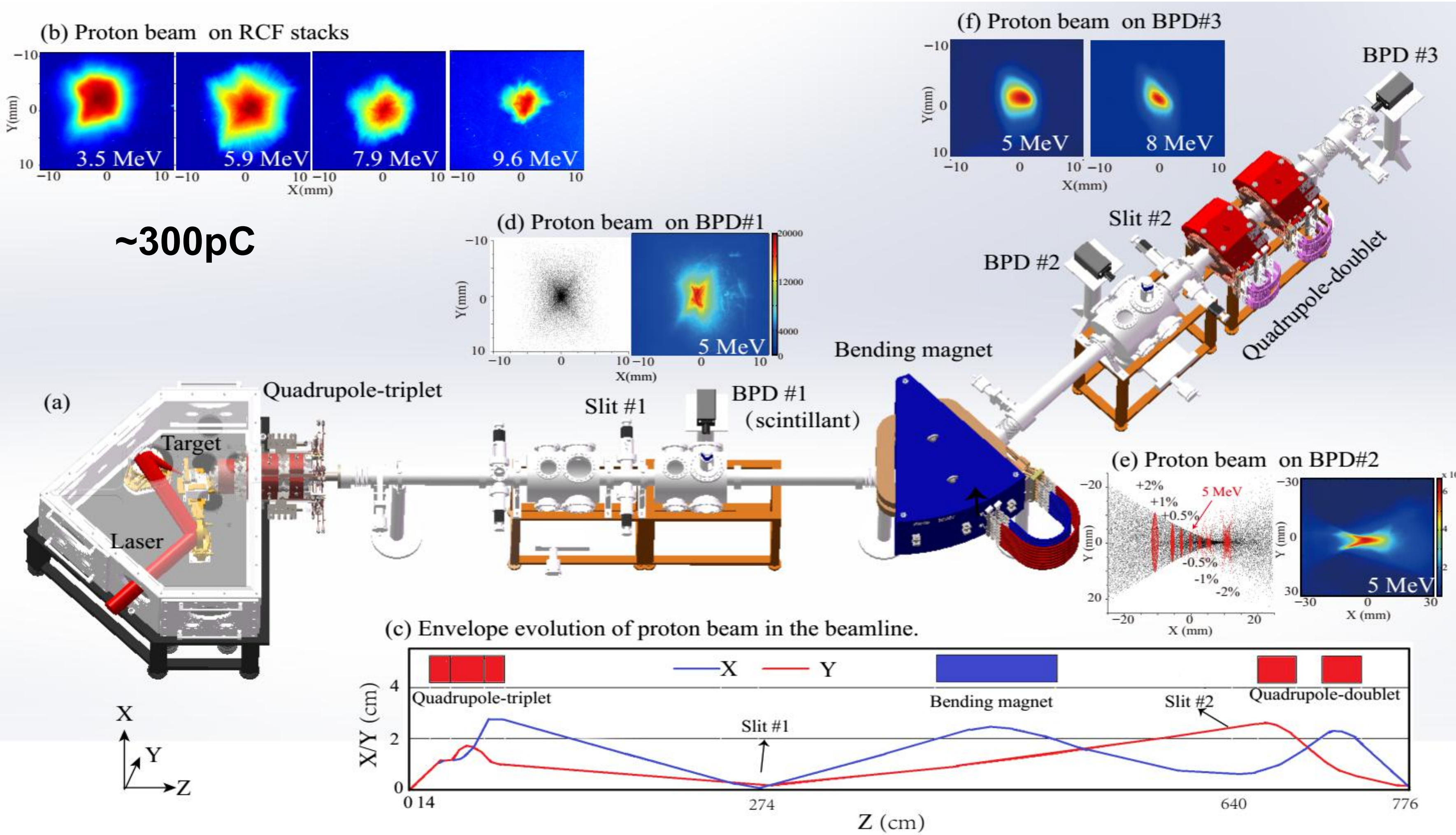
Stability 10% with metal target



Stability 3% with plastic target (100nm-1000nm)



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



~300pC

PRAB，2018,2020

Chin. Phys. C (2017)

RAMI：

Reliability Availability

Maintainability Inspectability

Beam line system

Energy :1-15 MeV； Energy spread: 0.25~±5%

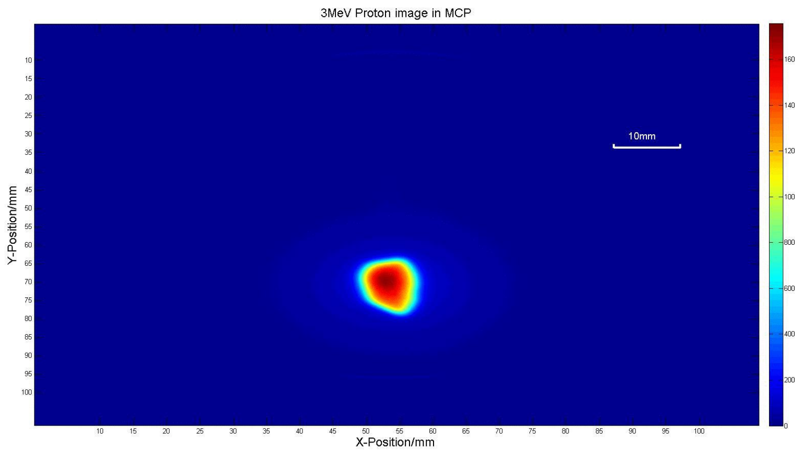
Number: 10^8-10^10

Acceleration chamber **Beamline** **Irradiation platform**

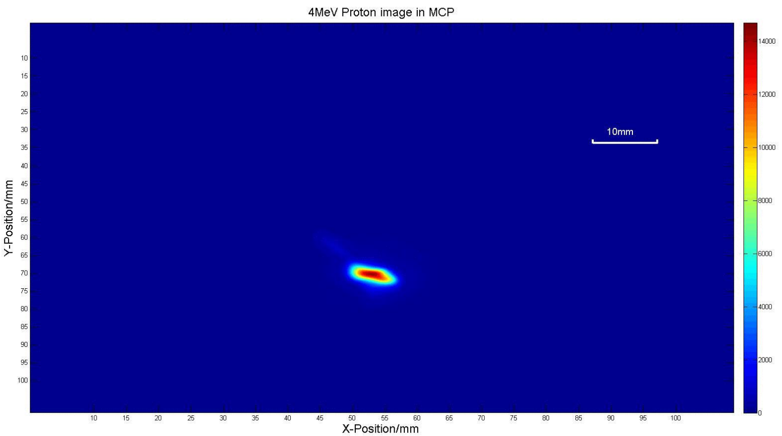
All magnets were made in IMP@Lanzhou

Focusing of the mono-energetic proton beam

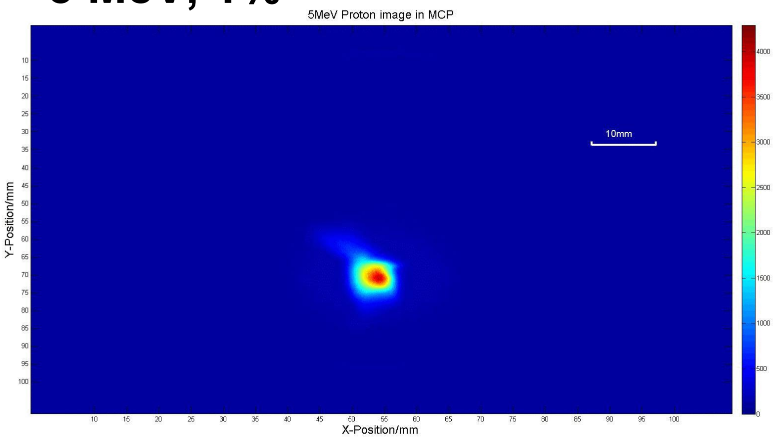
3 MeV, 1%



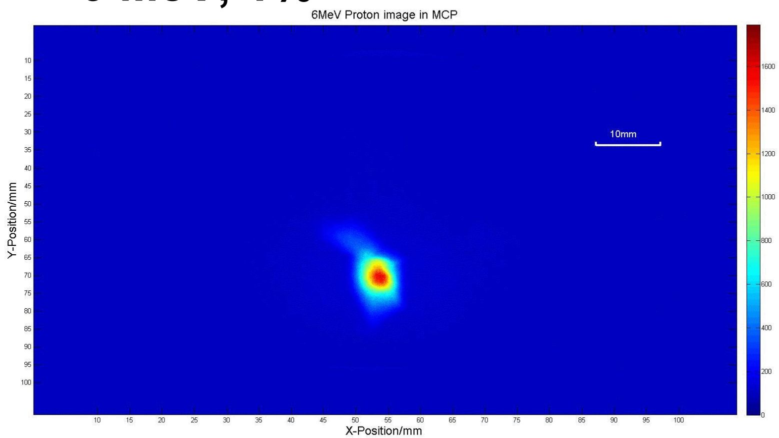
4 MeV, 1%



5 MeV, 1%

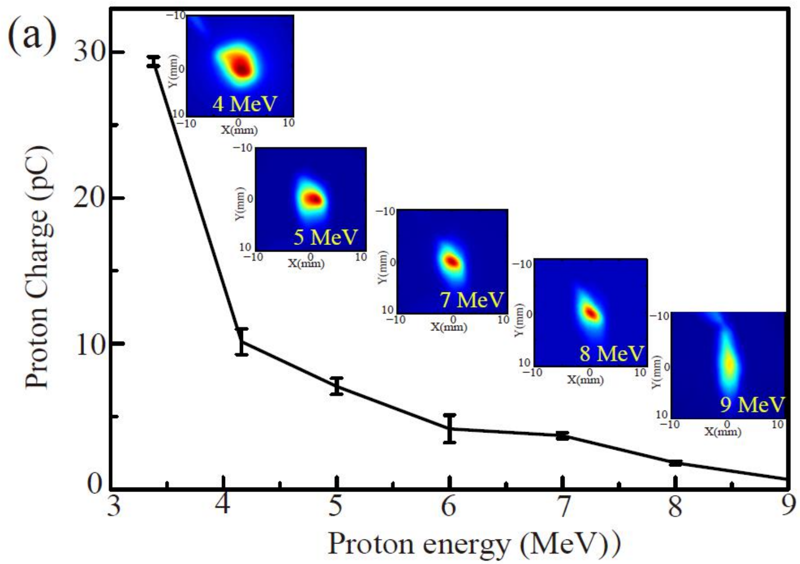


6 MeV, 1%

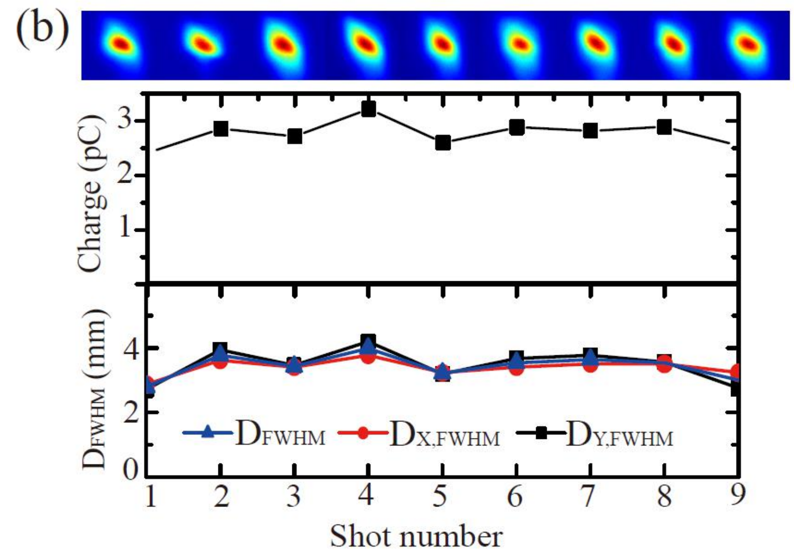


Proton parameter control on the irradiation platform

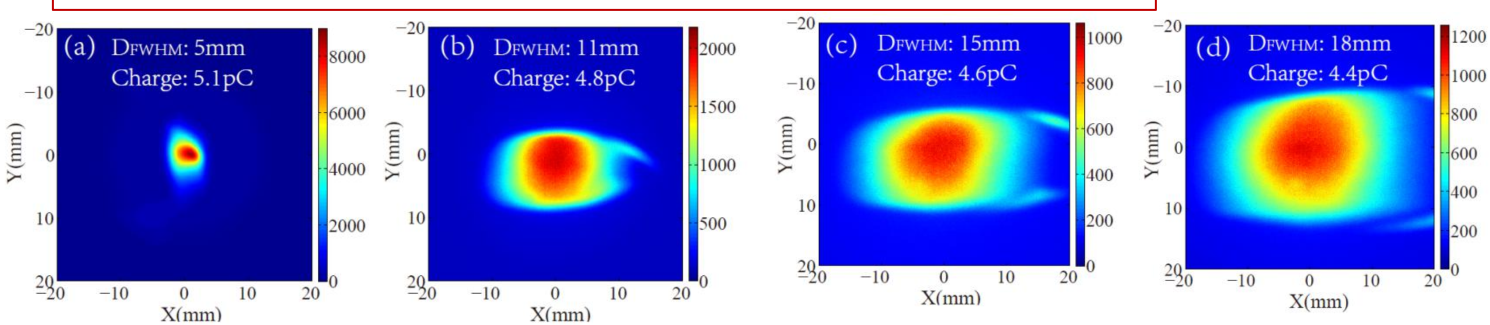
Central Energy 3-9MeV, ΔE=1%



Charge stability 11%， spot stability 8%



Irradiation field and uniformity： 3 mm-20 mm

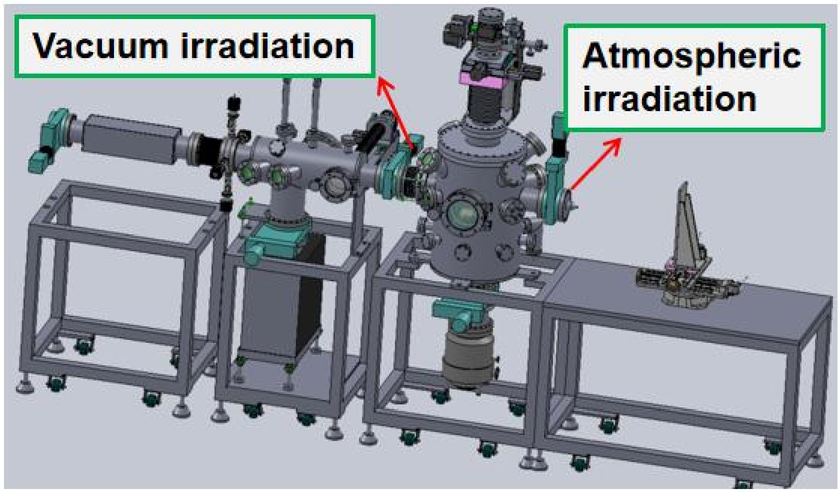


Parameters of laser proton beam

	<100TW	2PW*	Unit
proton energy	15	100-150	MeV
total charge/shot	10^{9-10}	10^{10-11}	n/pulse
beam size	1	1	cm^2
density	10^{11}	10^{13}	n/cm^2
pulse duration	1	1	ns
peak current	100	10^3	A

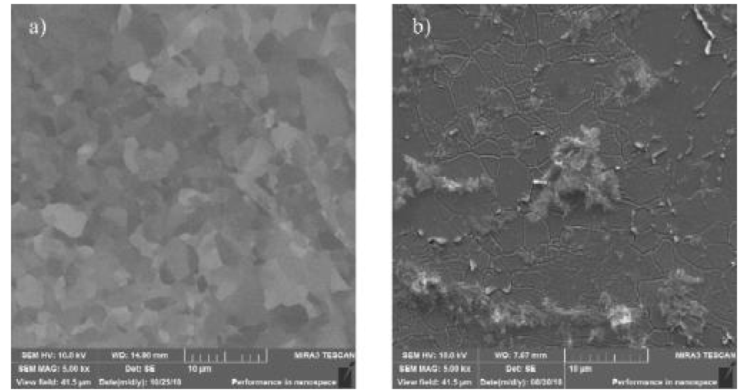
* Theoretical estimation

Irradiation experiments



Made in IMP@Lanzhou

Stress testing for materials



SEM images of the tungsten sample before (a) and after (b) laser accelerated proton irradiation.

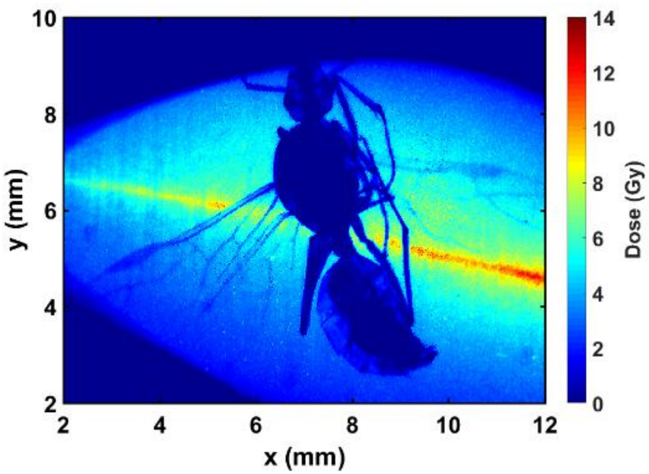
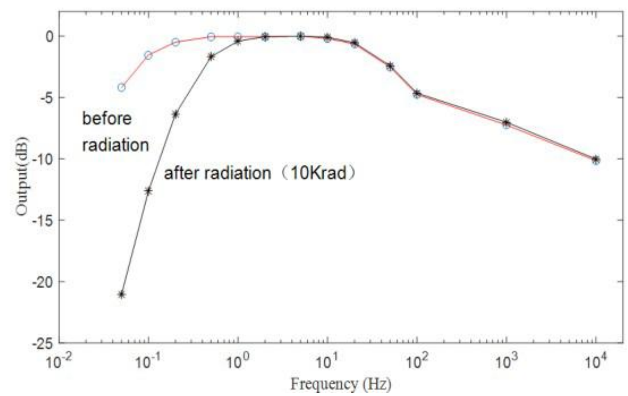
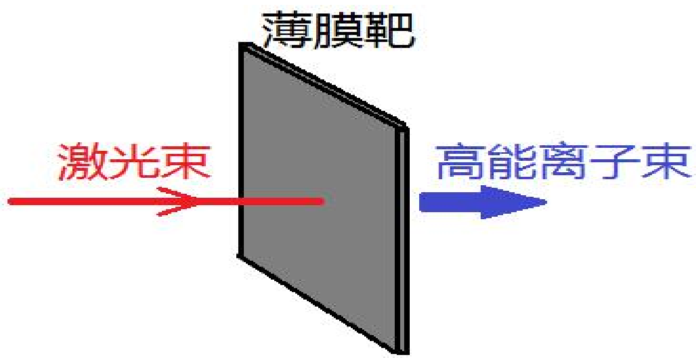


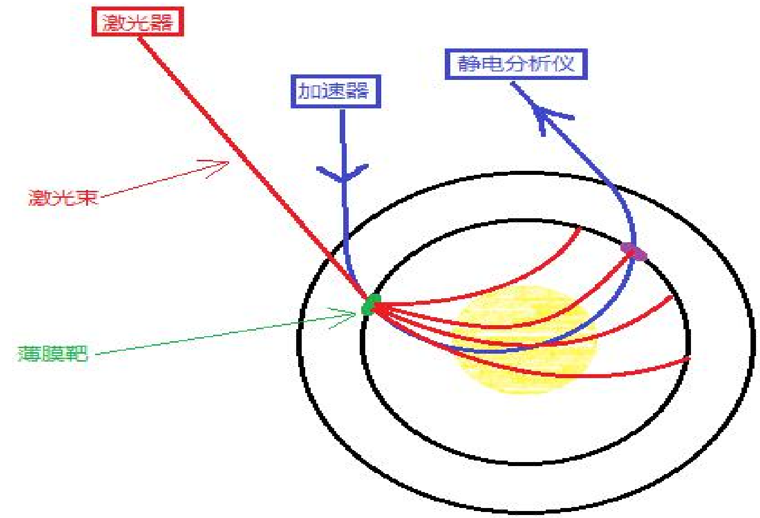
Image of the ant sample on the RCF.



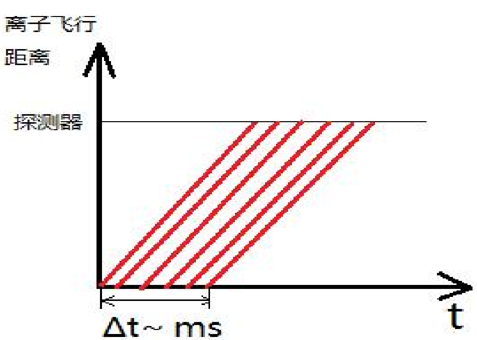
response of semiconductor sensors corresponding to different frequencies

离子束轨道探针(LITP)

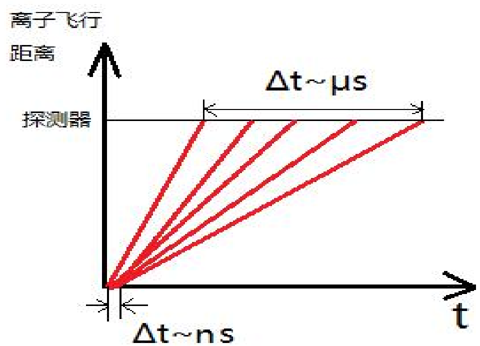




传统加速器



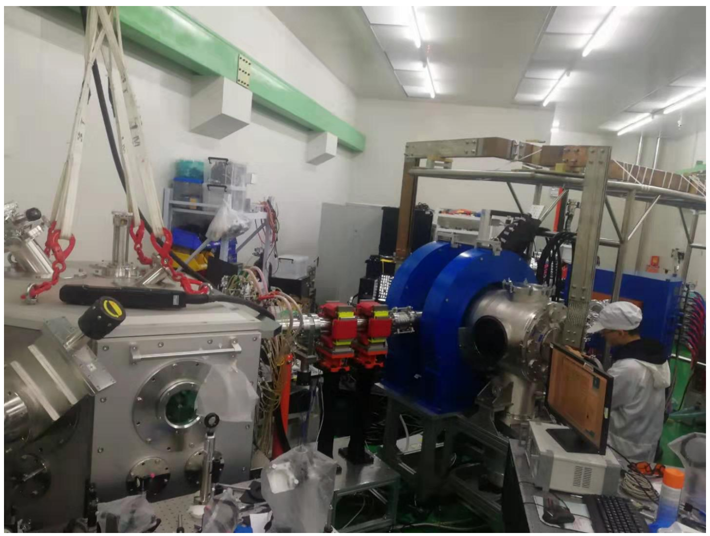
激光加速器

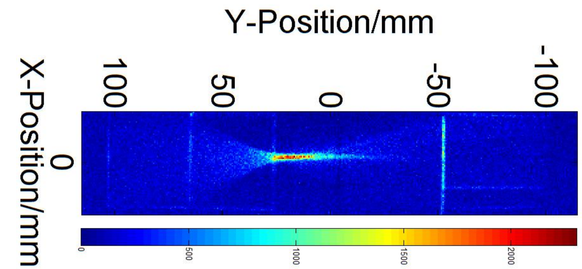


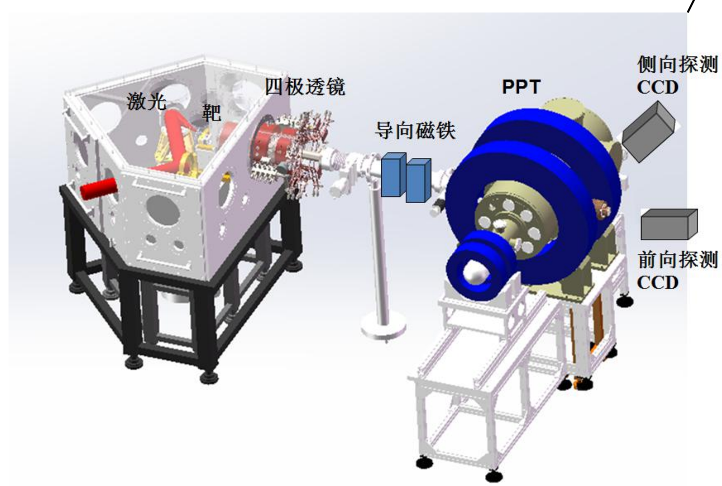
$$m\frac{d\vec{v}_1}{dt} = q\vec{v}_1 \times \vec{B} + q\vec{E}$$

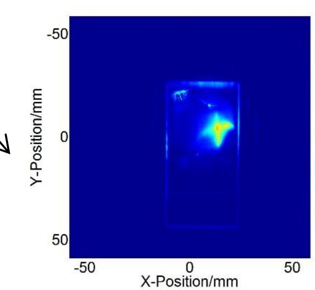
目标：诊断托卡马克的极向磁场和径向电场

CLAPA上完成首次探针(LITP)验证实验



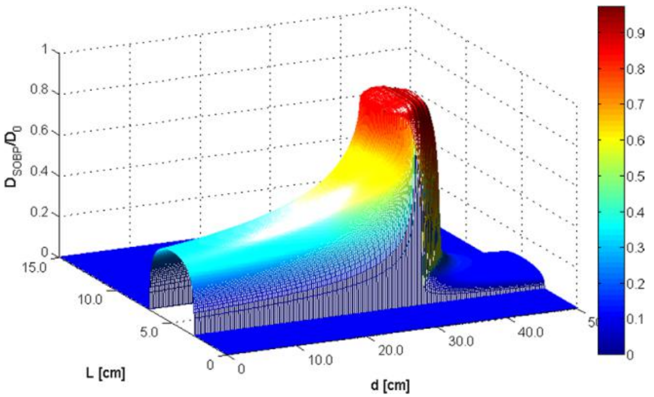


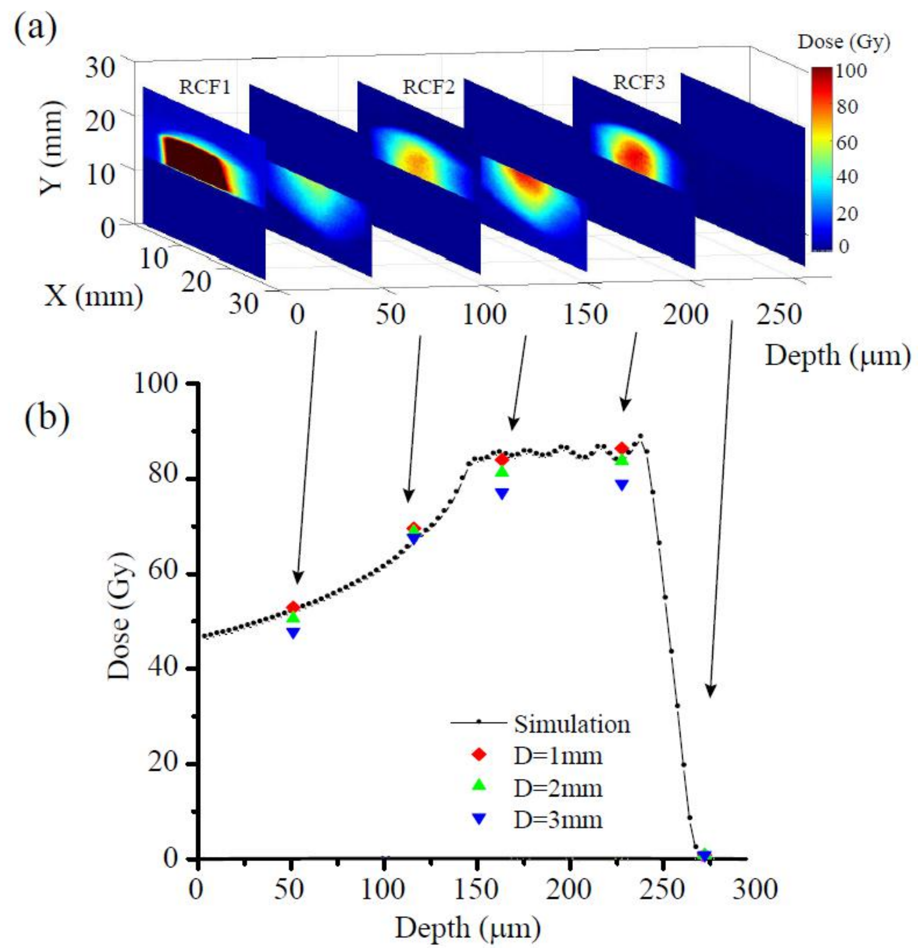




Spread-Out Bragg Peak

First demonstration of laser driven SOBP at Peking University





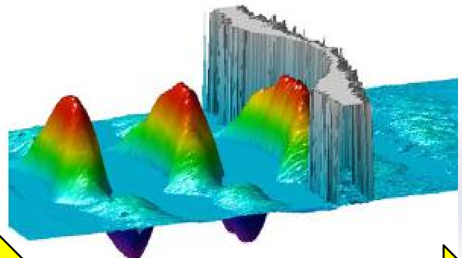
central energy /MeV	weights	shots
3.45	0.107	2.00
3.66	0.143	4.00
3.88	0.179	6.00
4.11	0.246	15.00
4.36	0.346	30.00
4.62	1	146.00

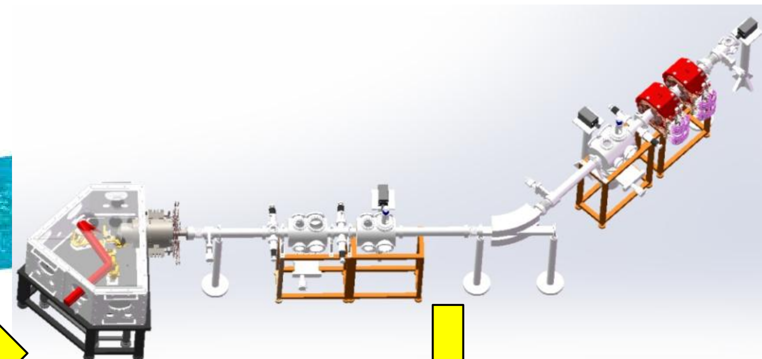
Proton accelerator with 1% energy spread

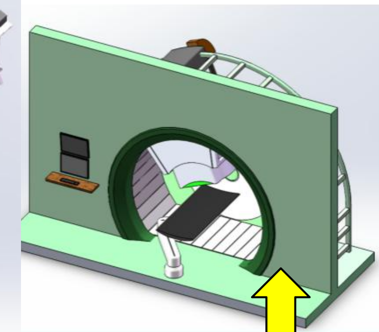
Radiation pressure Acceleration similar to wind sail (PRL 100, 135003,2008)

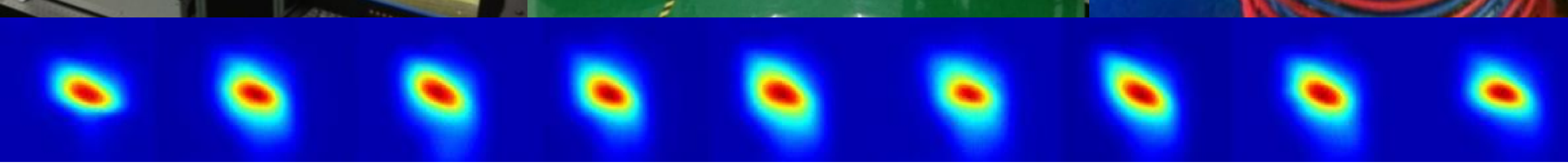
Electromagnet lattice

Laser Proton therapy?



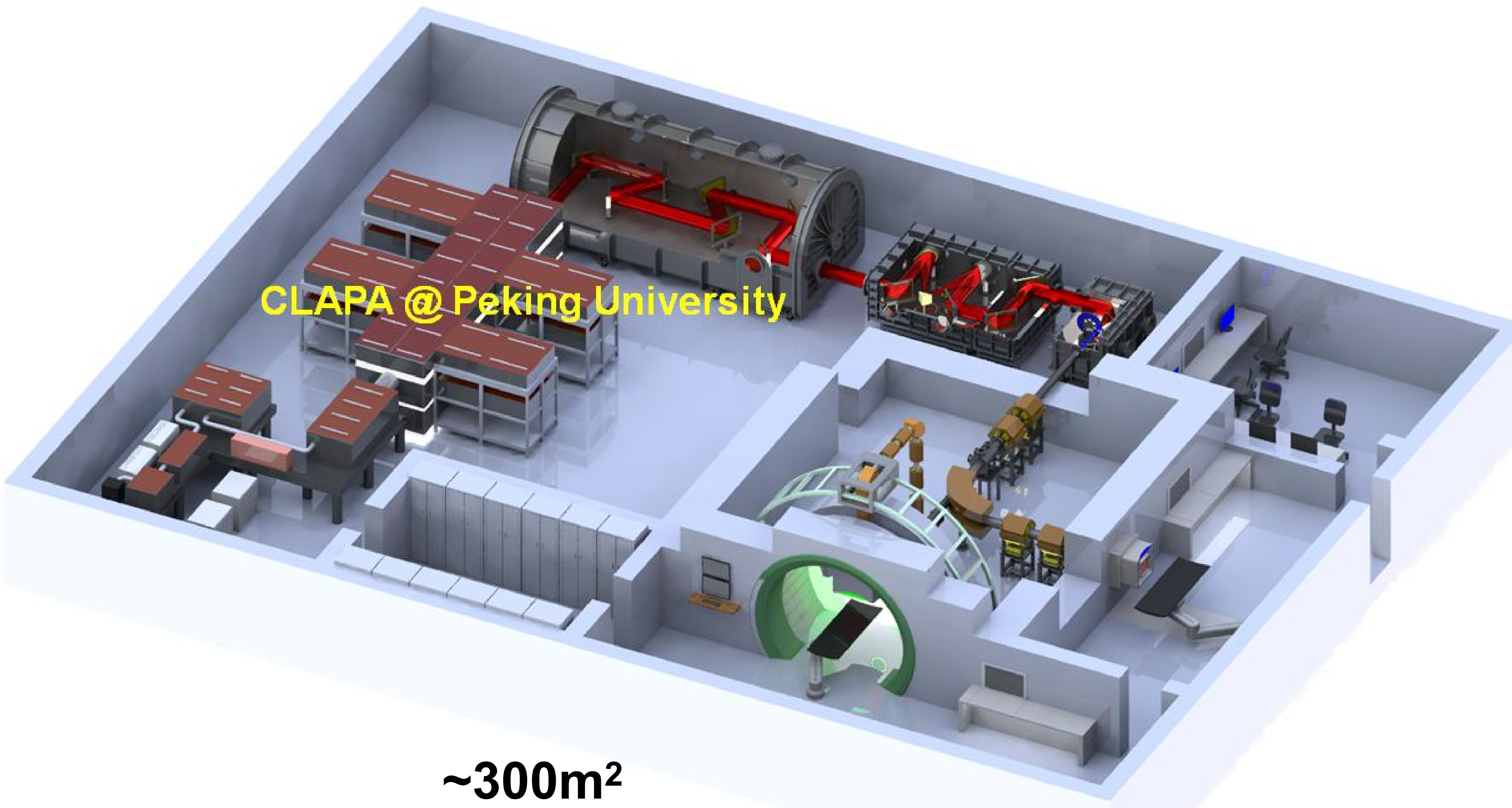






Perspective of Proton cancer therapy

PW/Hz laser



~300m^2

世界上首家激光质子刀医院将落户北京怀柔

~~~感谢倾听！！
~~~

Summary

- ✓ Radiation Pressure Acceleration with phase stability was proposed, it can efficiently accelerate proton/ions.
- ✓ A compact laser plasma accelerator (CLAPA) at Peking University has been built.
- ✓ 3-15 MeV proton beams with 100pC charge have been generated with stability better than 3% by using plastic targets.
- ✓ With the beam line, laser accelerator of <10MeV proton beams with 1% energy spread and 1-30 pC has been achieved.
- ✓ 100MeV proton will be achieved by 2PW laser.

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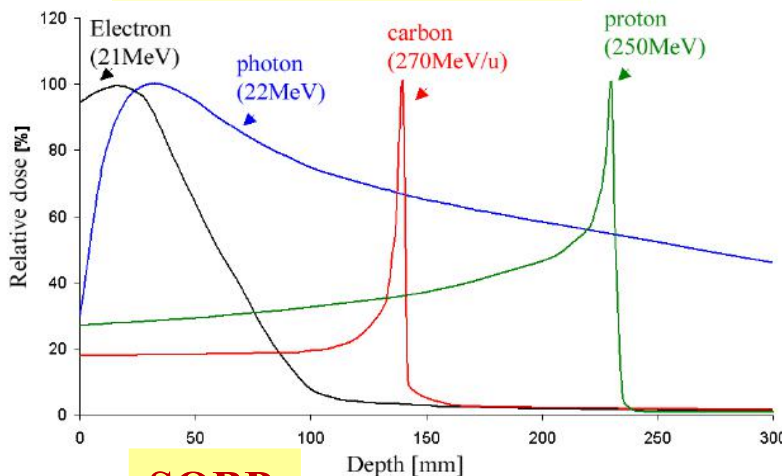
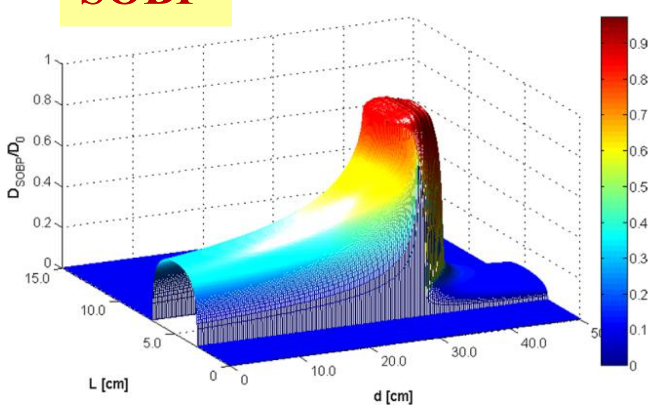
- UCI: T.Tajima
- LOA: G.Mourou
- Shanghai Uni: H.Y.Wang
- SJTU: Z.M.Sheng,M.Chen

Spread-out Bragg Peak using CLAPA Beamline

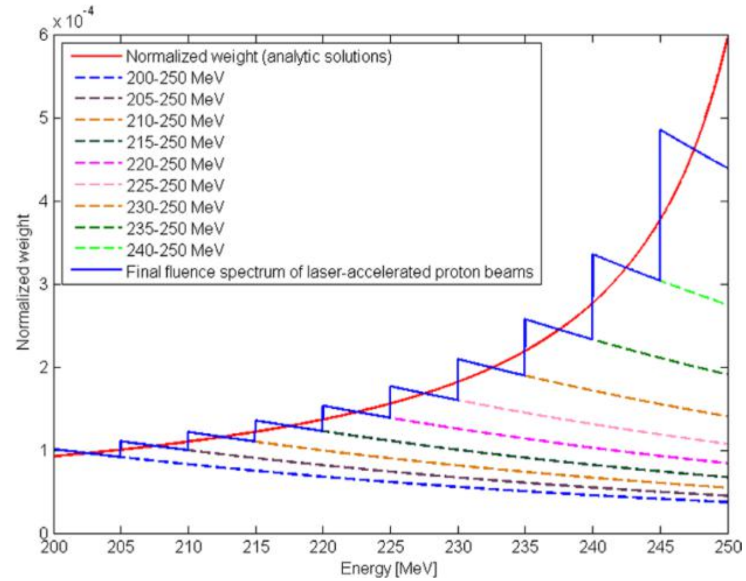
Single Bragg Peak



SOBP



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



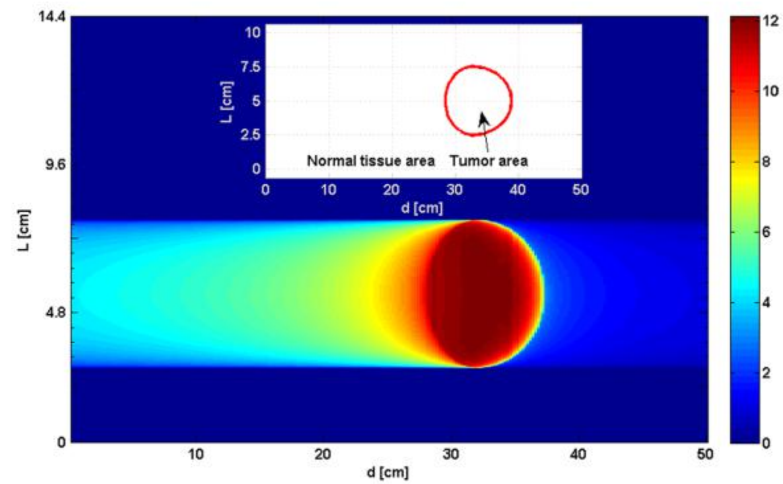
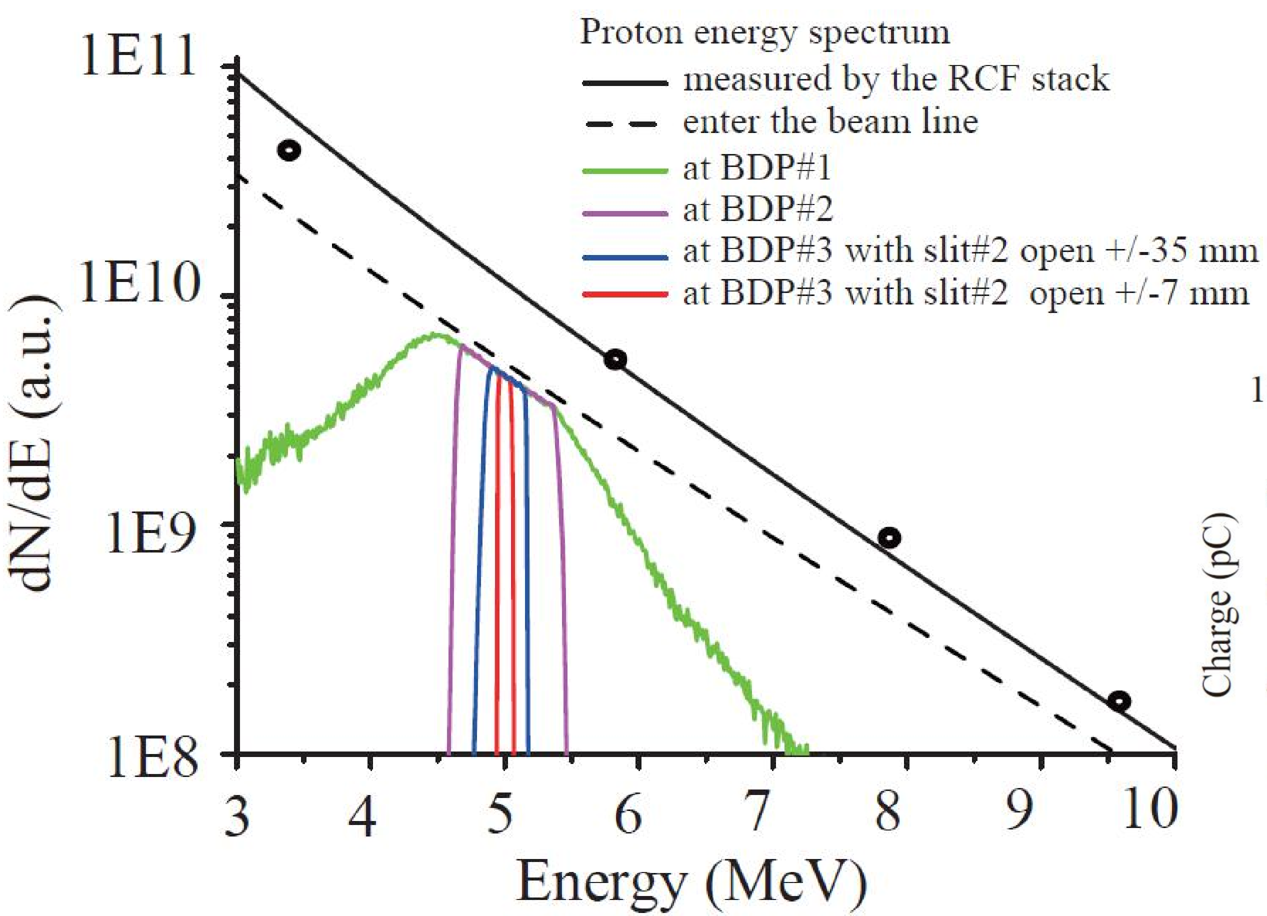


Figure 6. The 2D reconstruction result of the SOBP for an ideal situation with a specific tumor region.

Proton energy and charge control



终端电量