Accelerator activities in Peking University

-laser plasma accelerator and applications

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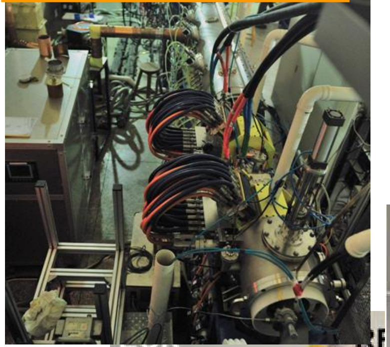
Outline

Institute of Heavy Ion Physics @Peking U. China

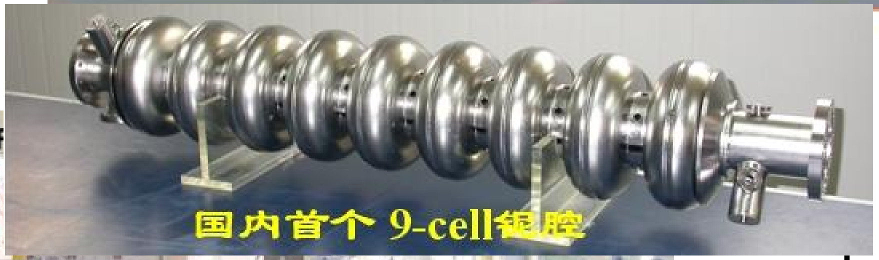
4.5 MV electrostati

AMS facility

RFQ neutron radiography



2*1.7MV tandem



Fou

s

maging

Linac

Ir
S
a

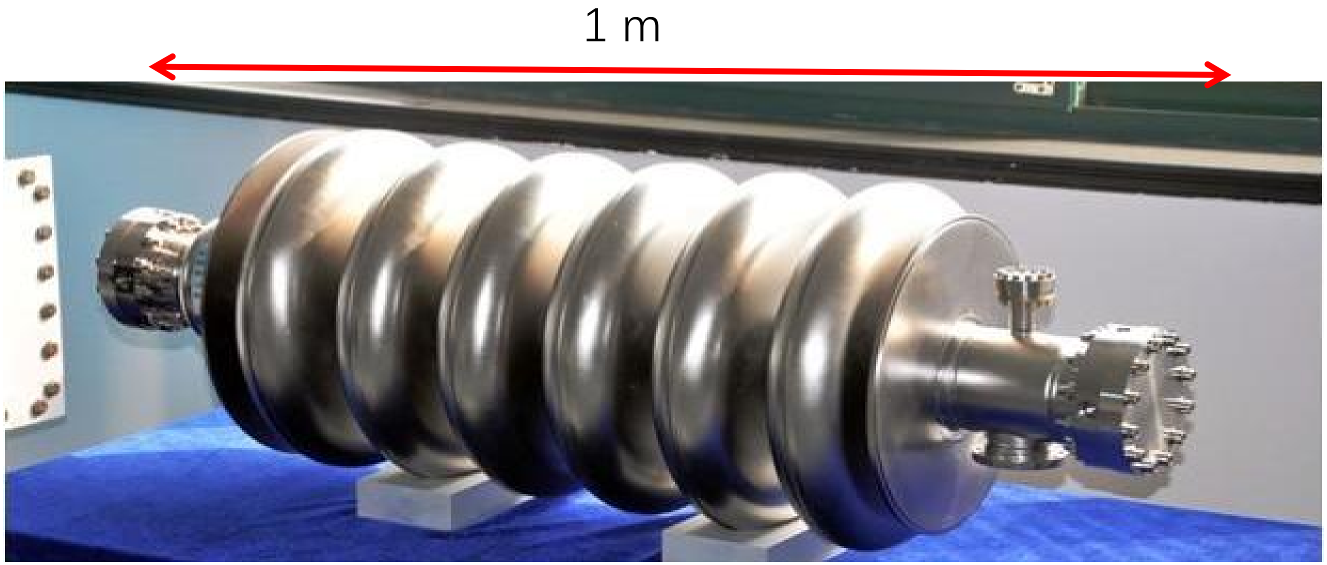
Laser Plasma accelerator

SRF guns worldwide

机构/名称	电子枪能量 (MeV)	束团电荷量 (pC)	Avg current (μA)	暗电流 (nA)	光阴极类型	归一化发射度 (mm-mrad)	状态
北京大学/DC-SRF-II*	1.6 - 2.3	20 - 100	3000	<0.001	CsK_2Sb (绿光光阴极)	0.58 @ 100 pC 0.43 @ 50 pC	运行中
德国亥姆霍兹德累斯顿罗森道夫研究中心(HZDR) /SRF Gun-II	4	50 - 250	62.5	100	Mg, Cs_2Te (紫外光阴极)	2 @ 100 pC	运行中
德国亥姆霍兹柏林中心(HZB) /eERLinPro SRF gun	2.5 - 3	77	-	4.5 (无光阴极时)	CsK_2Sb (绿光光阴极)	0.5 @ 77 pC	研发中
美国海军研究院(NPS)	1.2	78	< 0.001	<20000	Nb (紫外光阴极)	4.9 @ 43 pC	-
美国威斯康星大学(UW)	1.1	100	< 0.1	<0.001	Cu (紫外光阴极)	1 @ 200 pC	-
美国布鲁克海文国家实验室 /CeC SRF gun	1.25 (CeC) - 1.7	100 - 20000 (CeC)	140	<1	CsK_2Sb (绿光光阴极)	0.3 @ 100 pC (束团长达400 ps)	运行中
德国电子同步加速器研究所 (DESY)	>4	20 -100	-	-	Pb或纳米结构金属	-	研发中
美国 SLAC国家加速器实验室 /LCLS-II HE SRF gun	1.8	100	100	<10 (100 MeV 束线末端)	绿光光阴极	-	研发中
日本高能加速器研究机构 /SRF gun #2	2	80	-	-	CsK_2Sb (绿光光阴极)	-	研发中

***The first electron gun that meets the CW X-ray FEL requirements**

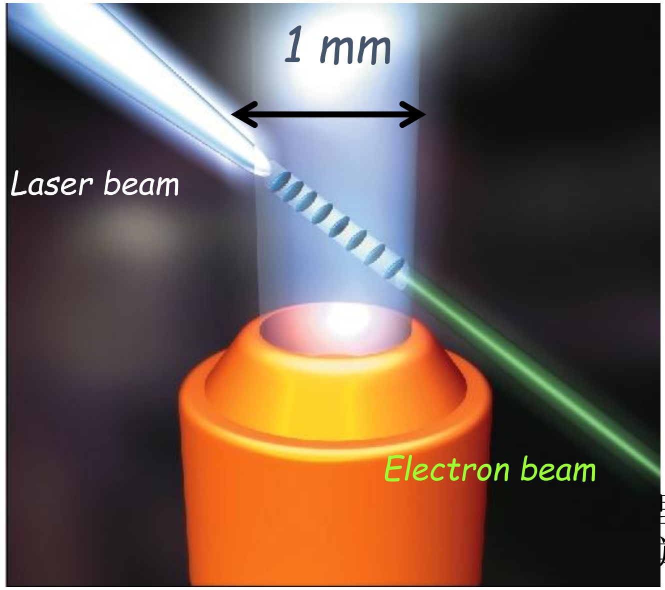
RF accelerator and Laser plasma accelerator

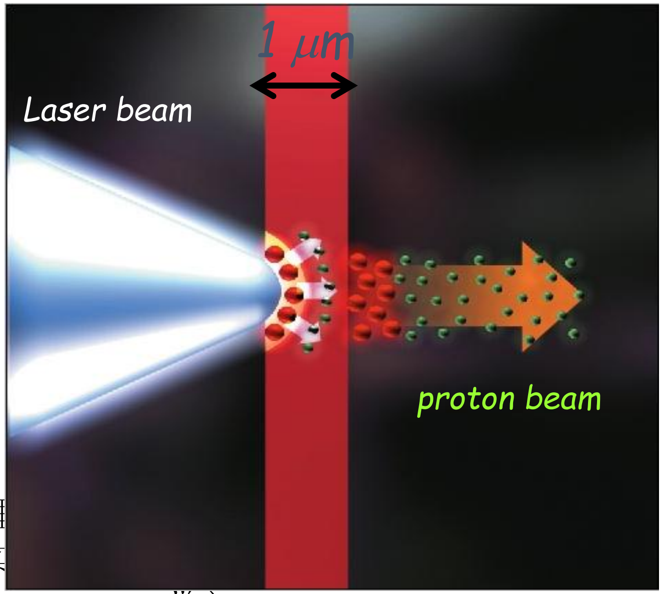


RF accelerator
E = <100MV/m

laser plasma accelerator
E > 100GV/m

1000 times smaller!





LPA was proposed in 1979 by Tajima and Dawson

John M Dawson （1930-2001）

Toshiki Tajima

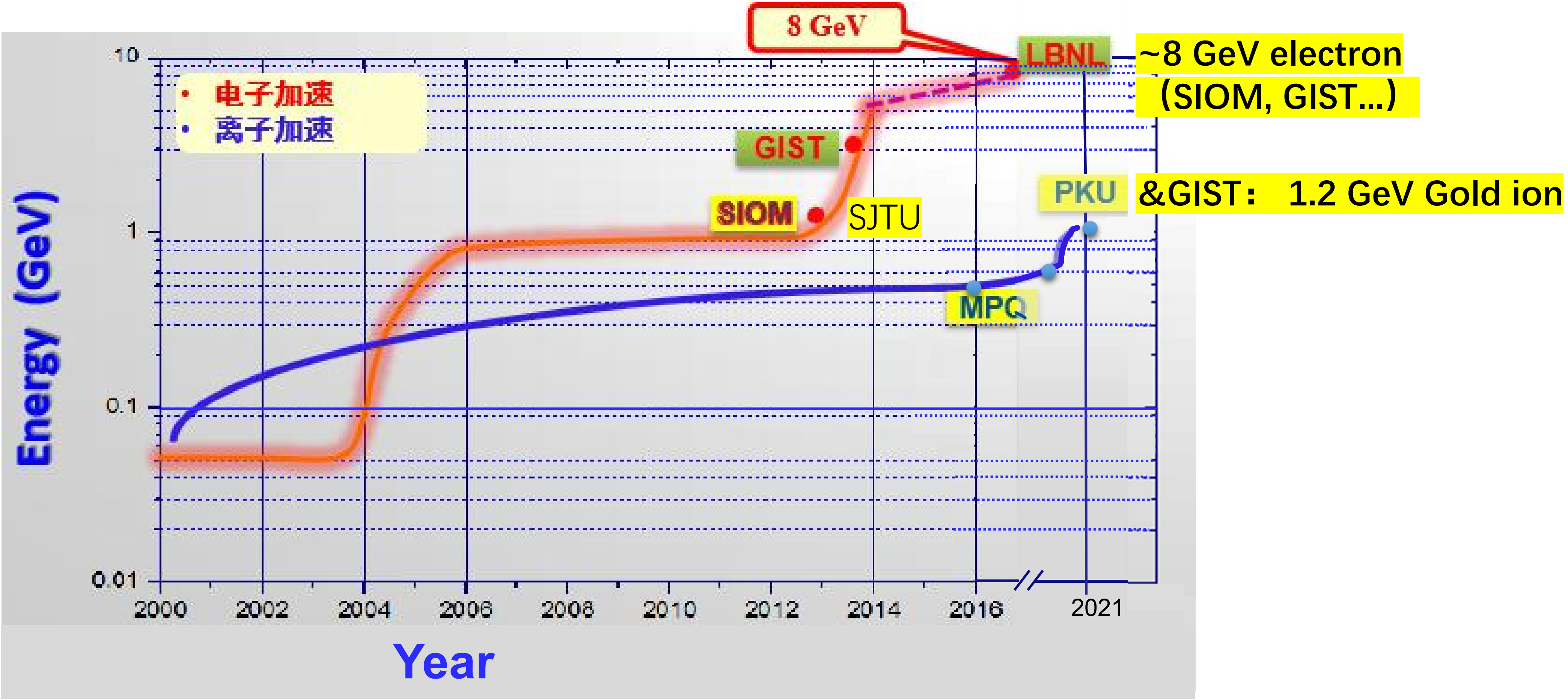
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

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.

Progress of laser plasma acceleration

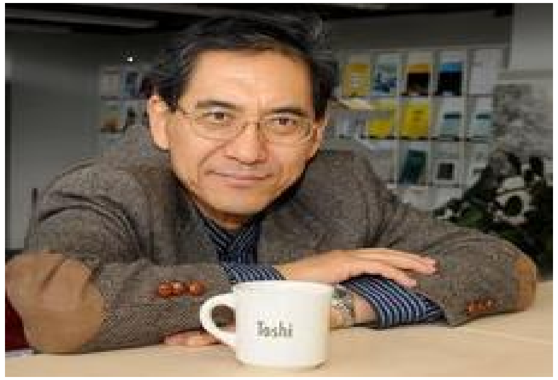


UCLA: Tajima + Dawson 1979

Challenges of laser accelerators

CPA

Inventor of Laser Wake Accelerator



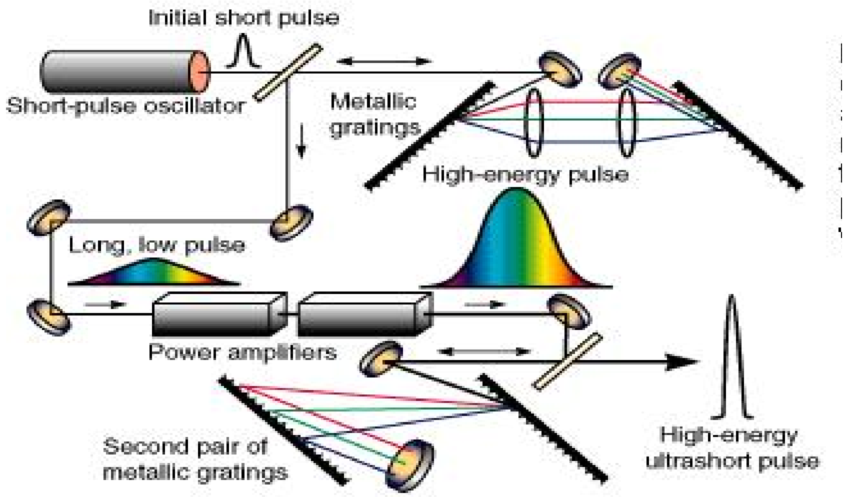
ion energy?
energy spread ?
stability?

Nobel prize report:

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].

Outline

CPA laser technology

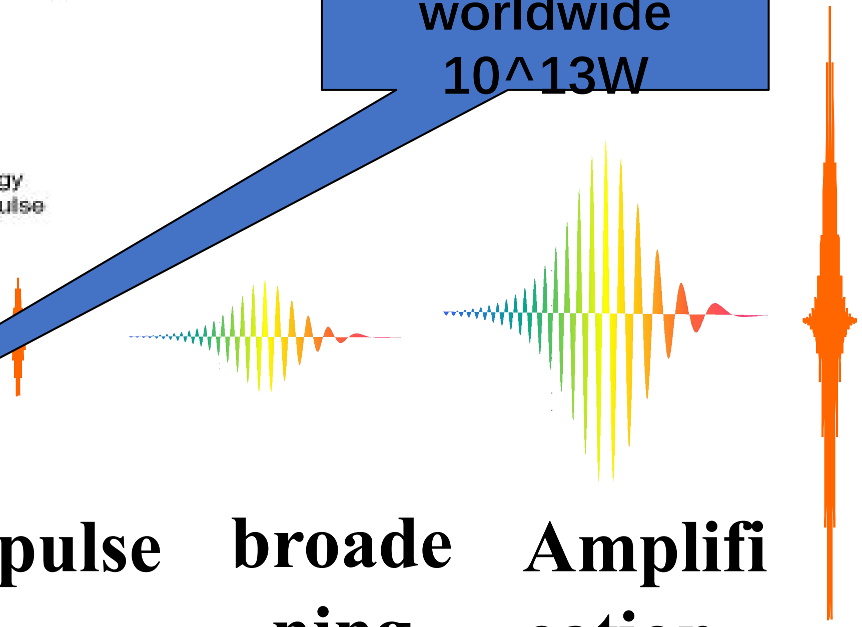


laser power = energy/duration

30J/30fs=10^15W

Electricity power worldwide 10^13W

2013年世界各国发电量排名					
数据来源：《BP世界能源统计年鉴2014》					
排名	国家	大洲	发电量 百万KWH	占全球	增速
	全世界		23,127,009		2.17%
1	中国	亚洲	5,361,620	23.18%	[illegible].50%
2	美国	美洲	4,260,353	18.4[illegible]%	0.27%
3	印度	亚洲	1,102,879	4.77%	4.65%
4	日本	亚洲	1,088,147	4.71%	-1.69%
5	俄罗斯	欧洲	1,060,733	4.59%	-0.80%
6	德国	欧洲	633,600	2.74%	0.60%
7	加拿大	美洲	626,841	2.71%	2.73%
8	法国	欧洲	568,253	2.46%	1.35%
9	巴西	美洲	557,419	2.41%	0.89%
10	韩国	亚洲	534,680	2.31%	0.76%



seed pulse

fs （nJ）

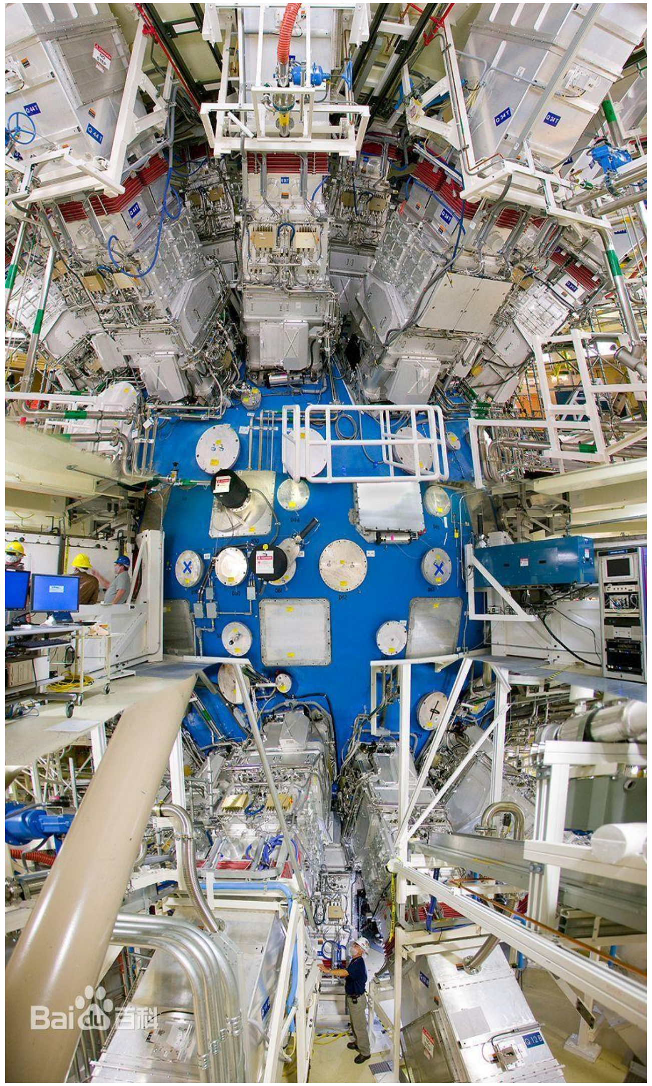
broadening ns

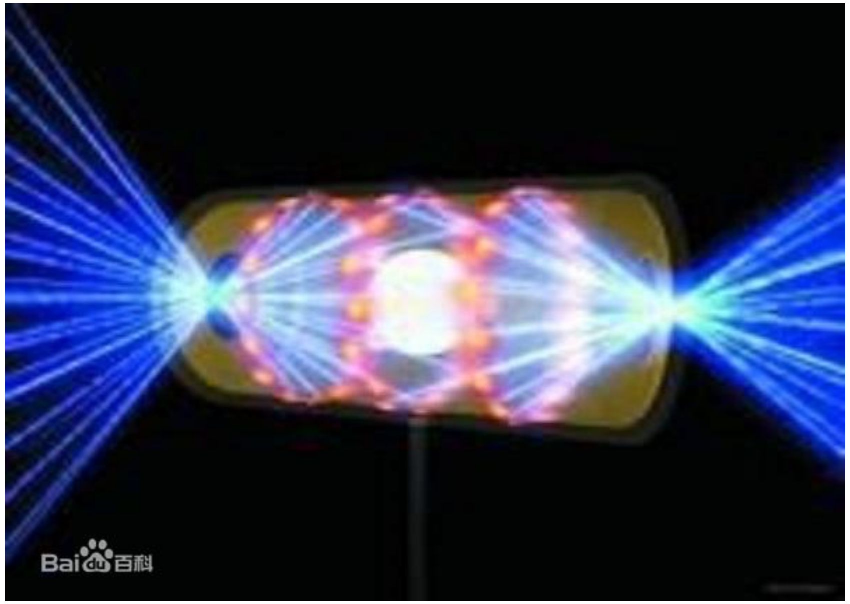
Amplification

~30J

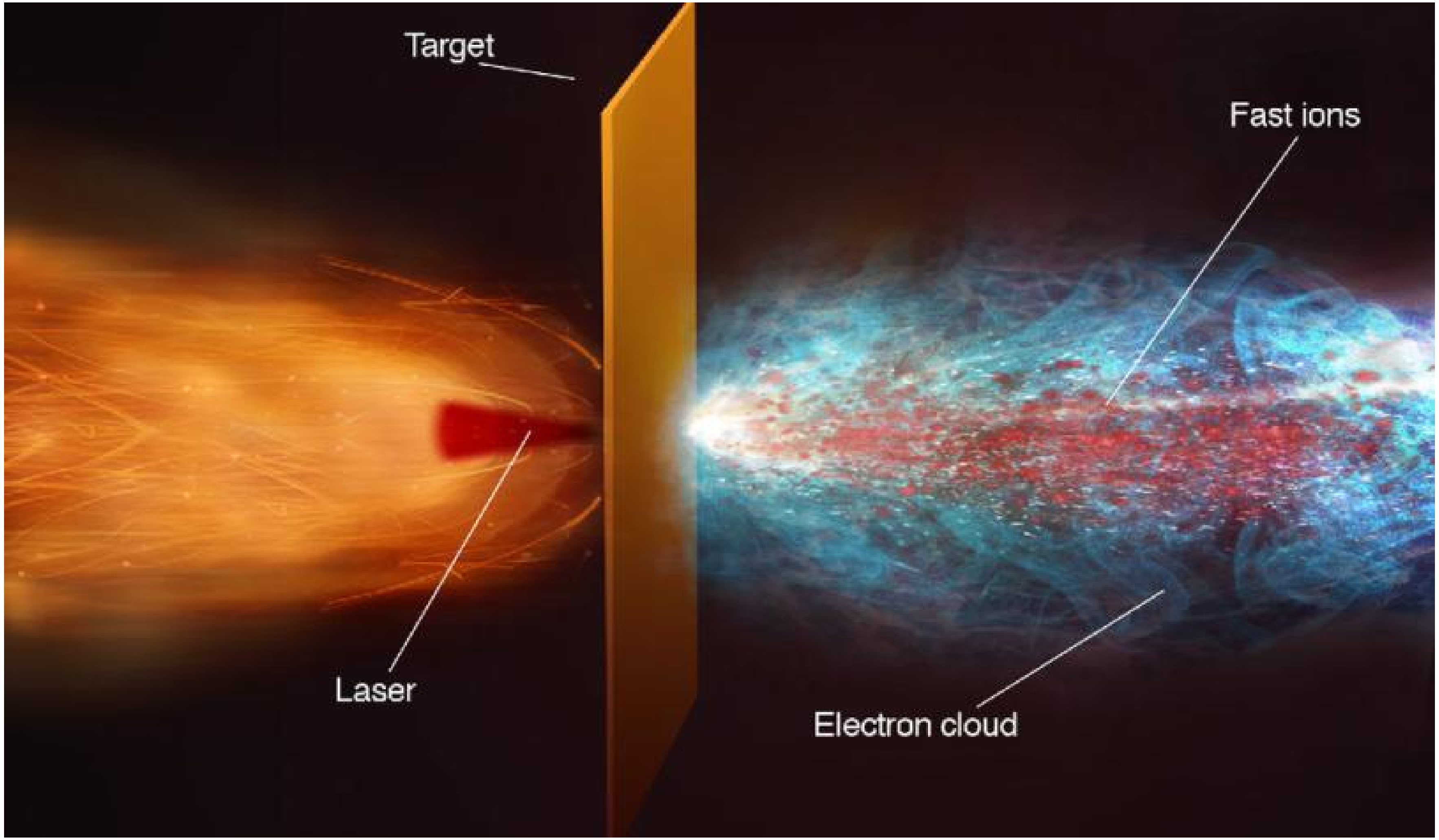
compression (30fs)

NIF facility（MJ/ns~PW)





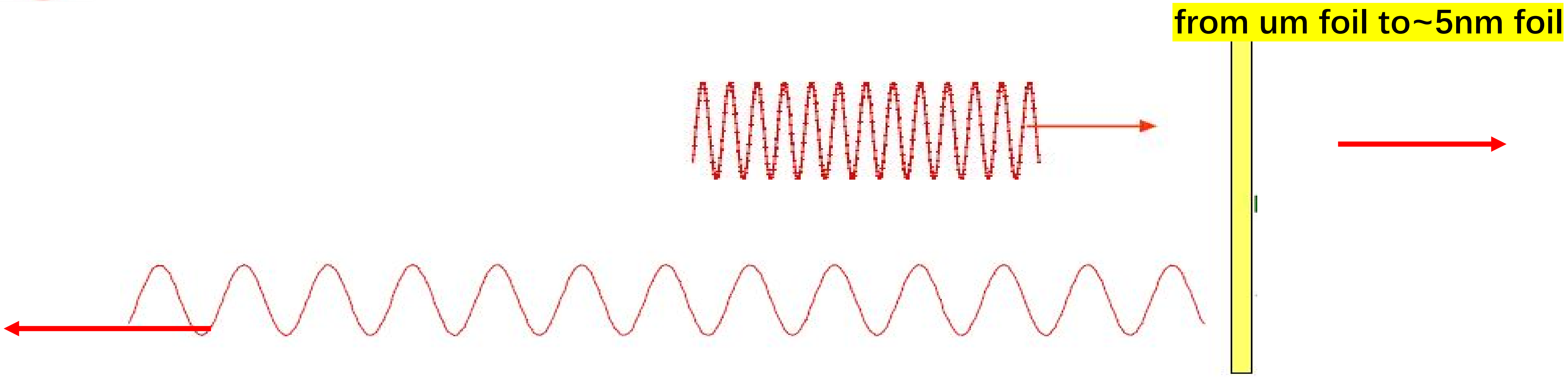
Schematic diagram of laser ion accelerator



In TNSA regime:

- micron thick target
- low efficiency<1%
- duration(ps~ns)
- high current

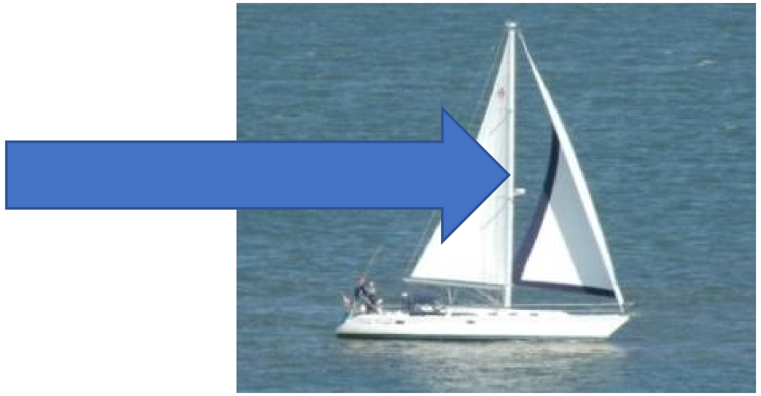
from TNSA to Radiation pressure acceleration

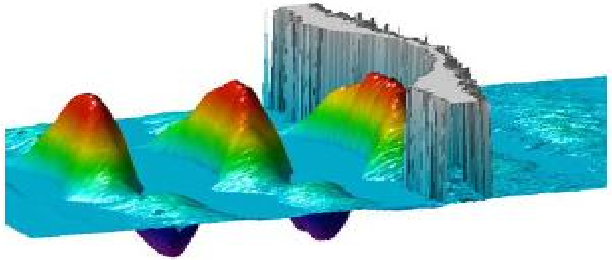


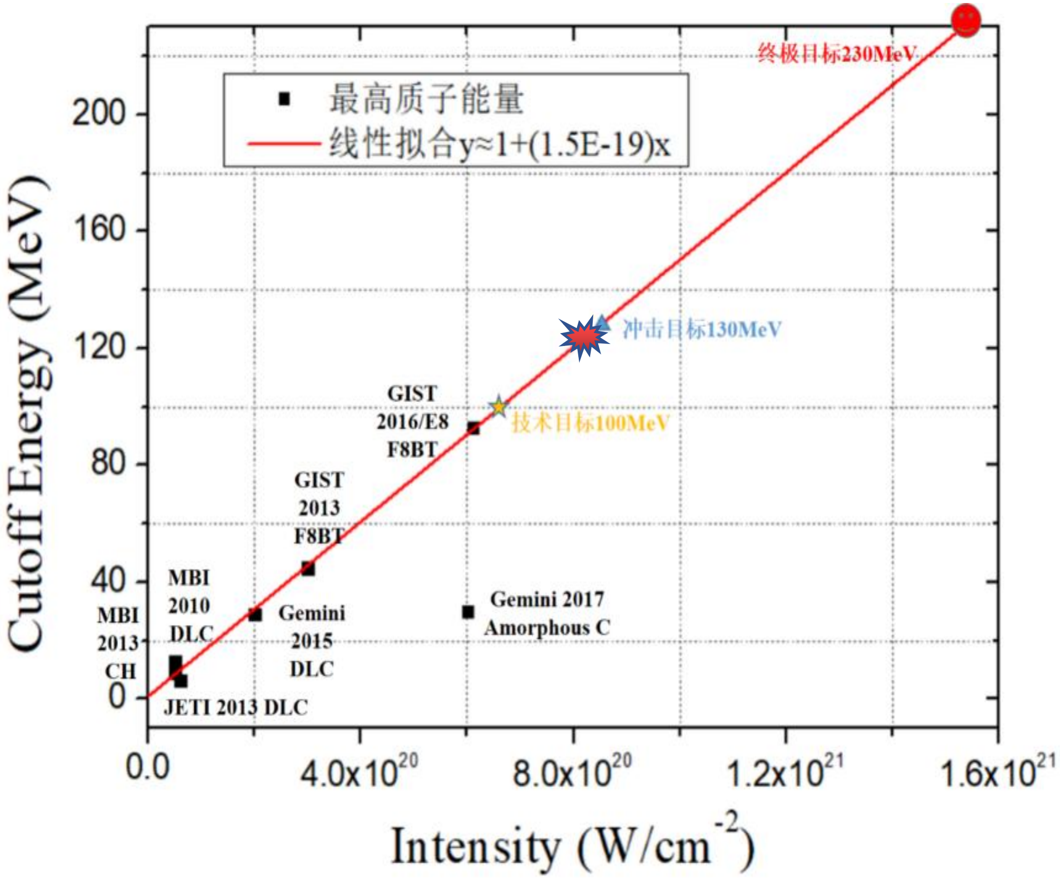
$$CE = 1 - \frac{1}{4\gamma^2} \sim 100\%$$

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

Radiation pressure acceleration in phase stable regime

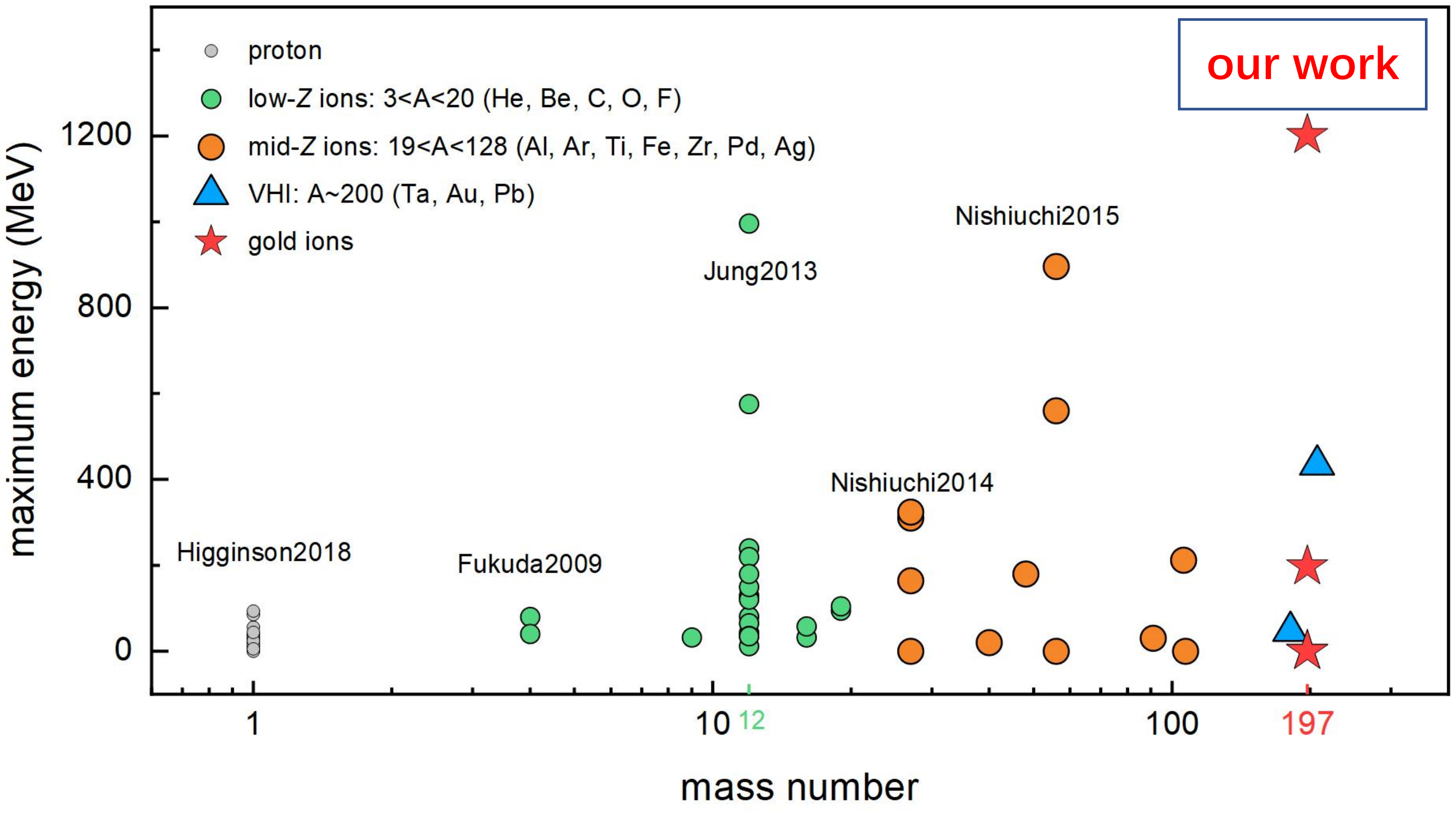






PRL 2008;PRL 2009;PRL 2009

Acceleration of 1.2GeV Au^{61+}



Wang, Phys. Rev. X **11, 021049 (2021); Experiment done in Corels/GIST**

Compact LAser Plasma Accelerator (CLAPA)

beam parameters：

p： 1~15MeV, 10^9/s

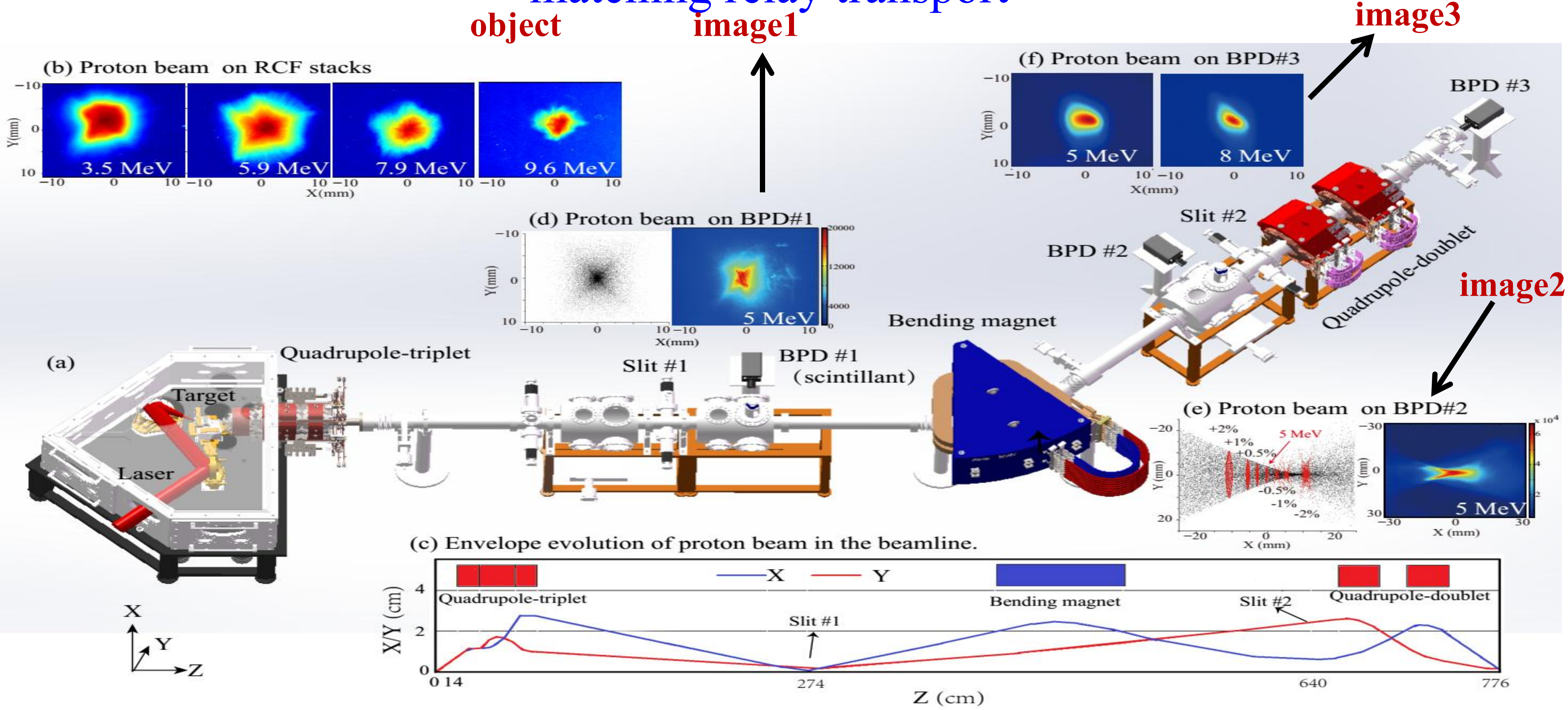
e： 60~300MeV, 10^9/s

γ： 8~100MeV, 10^8/s

duration： [100fs,ns]

CLAPA +magnetic beam line

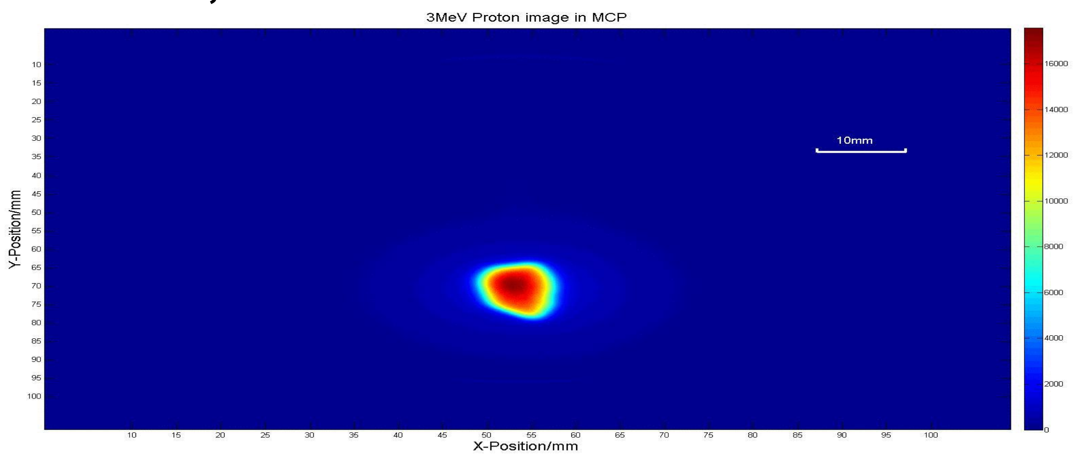
matching relay transport



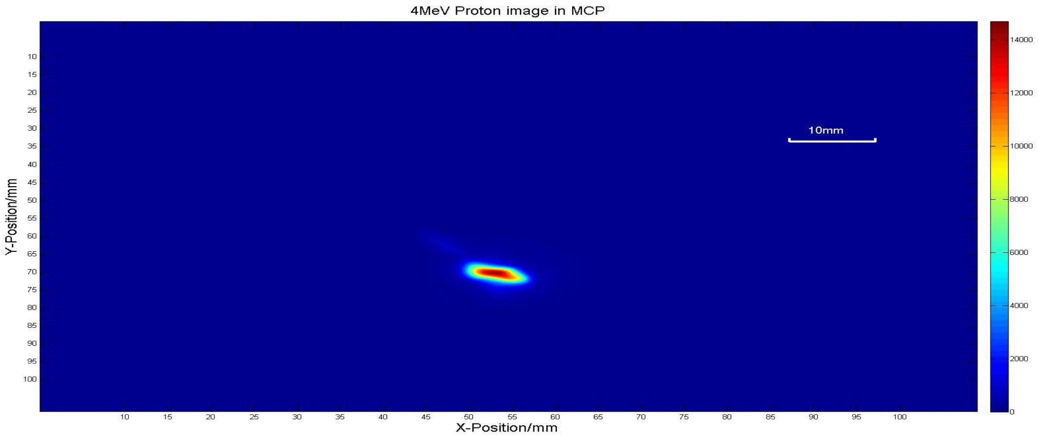
Zhu, et al., PRAB, 2019

Proton beam with 1% energy spread in CLAPA

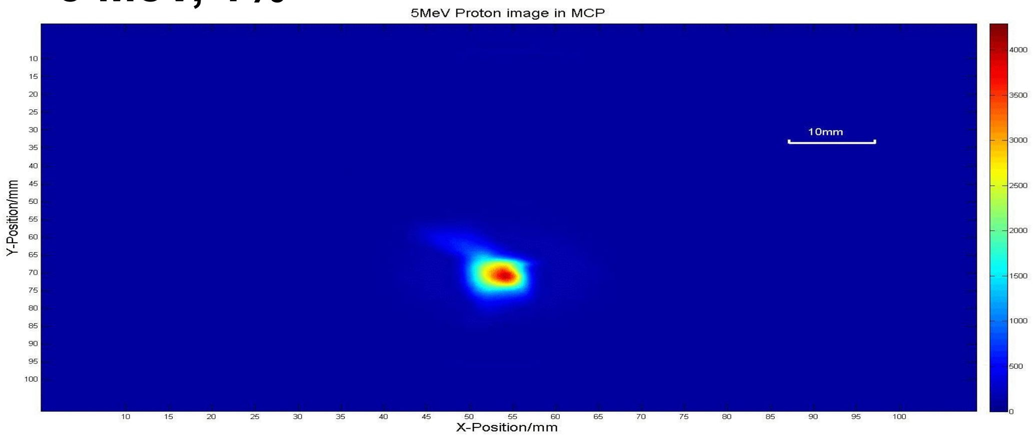
3 MeV, 1%



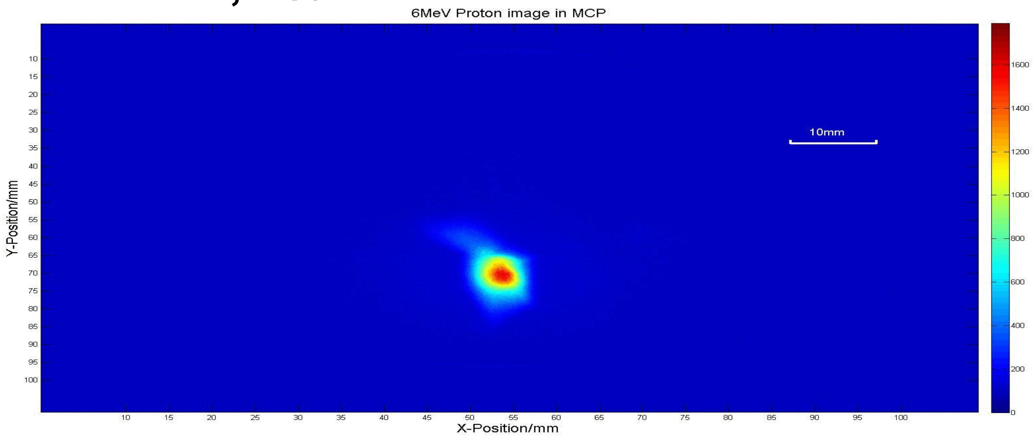
4 MeV, 1%



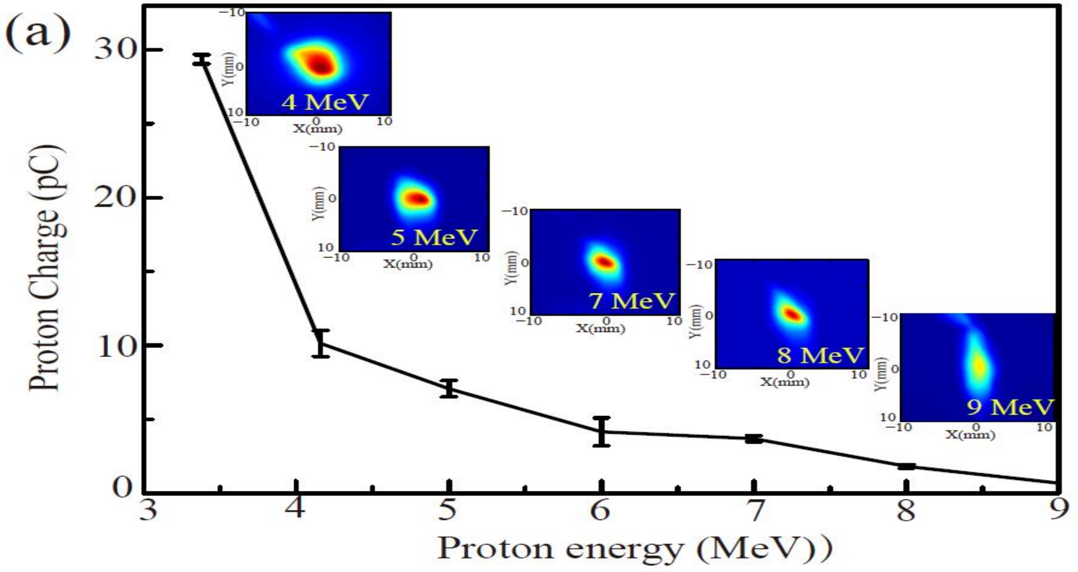
5 MeV, 1%

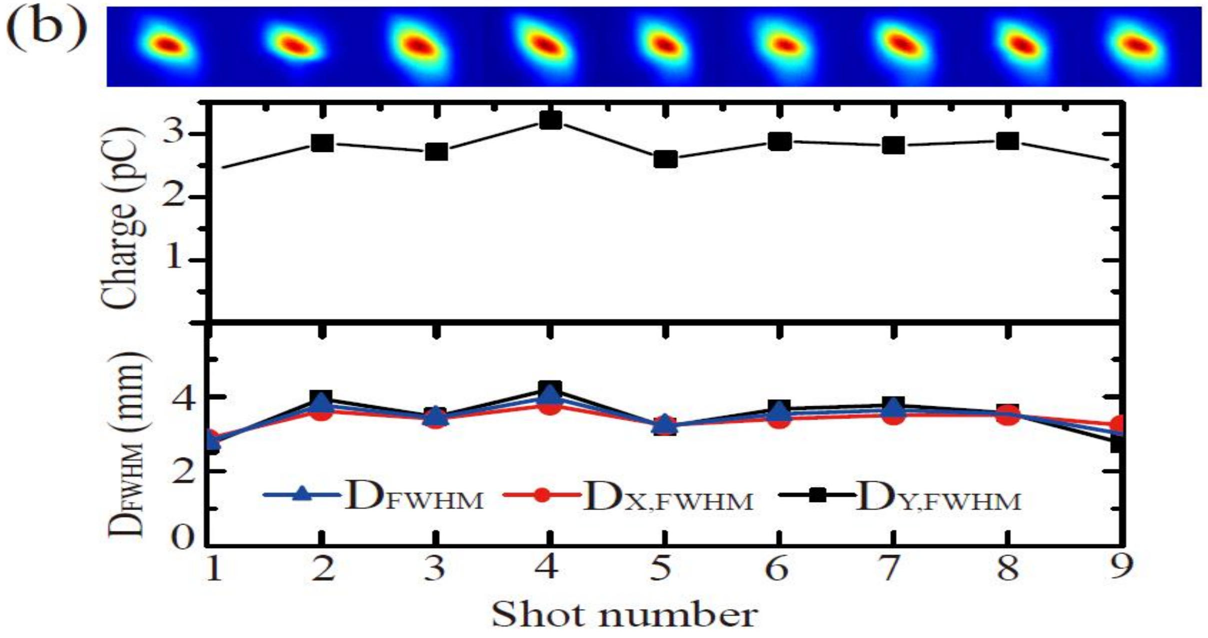


6 MeV, 1%



CLAPA I is under stable operation



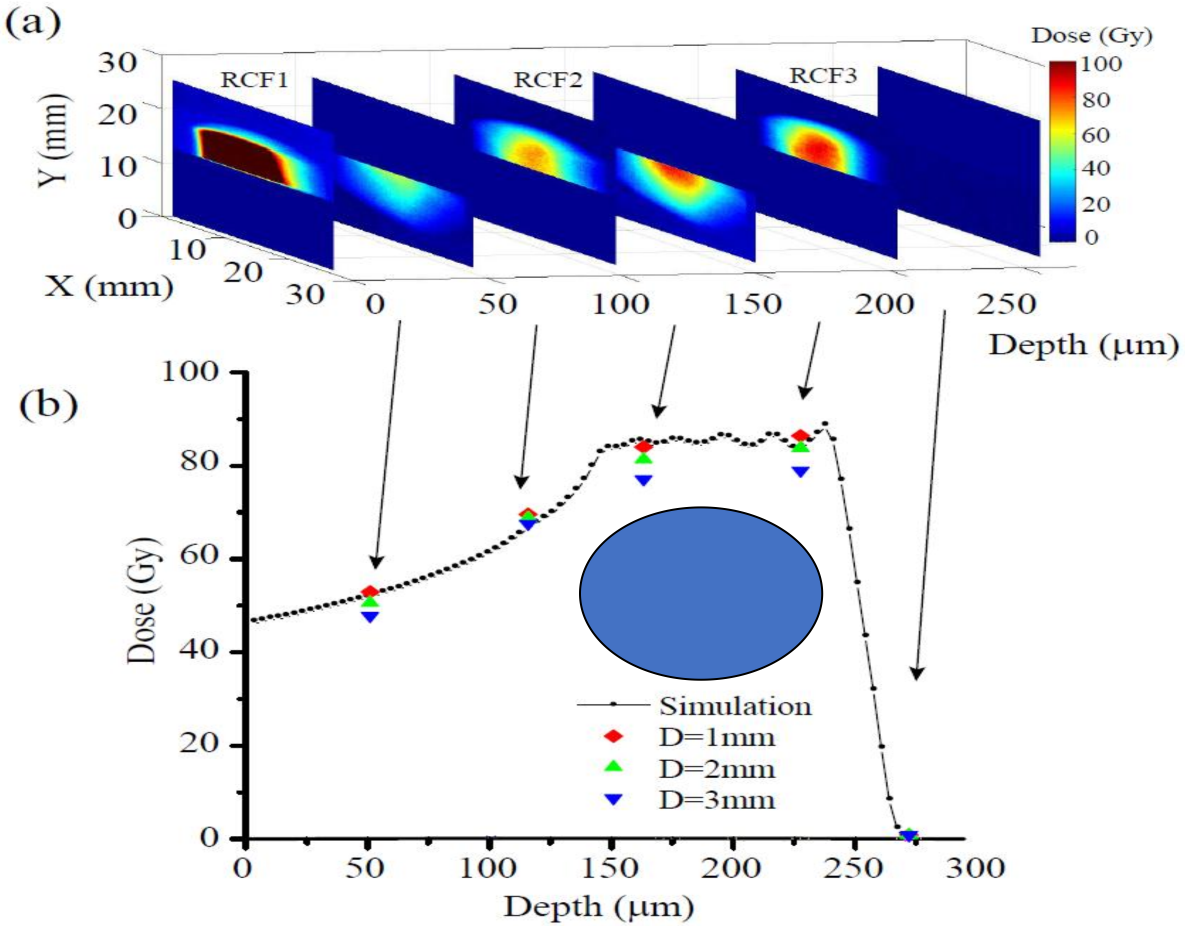


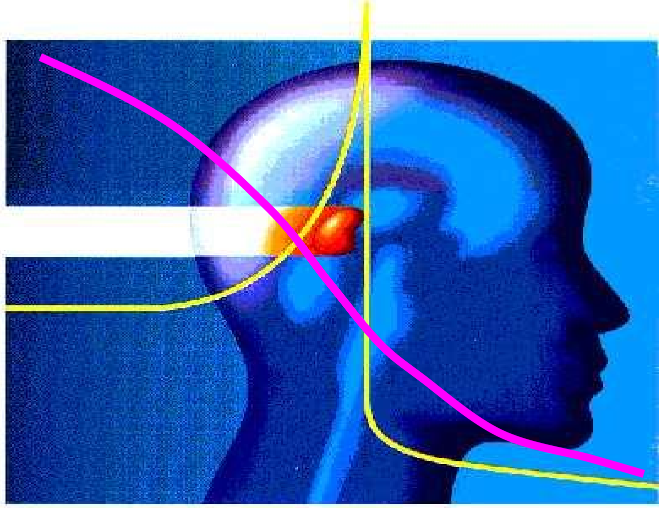
proton beam with 1% energy spread

charge stabillity 11%
spot stablity 8%

PRAB2019

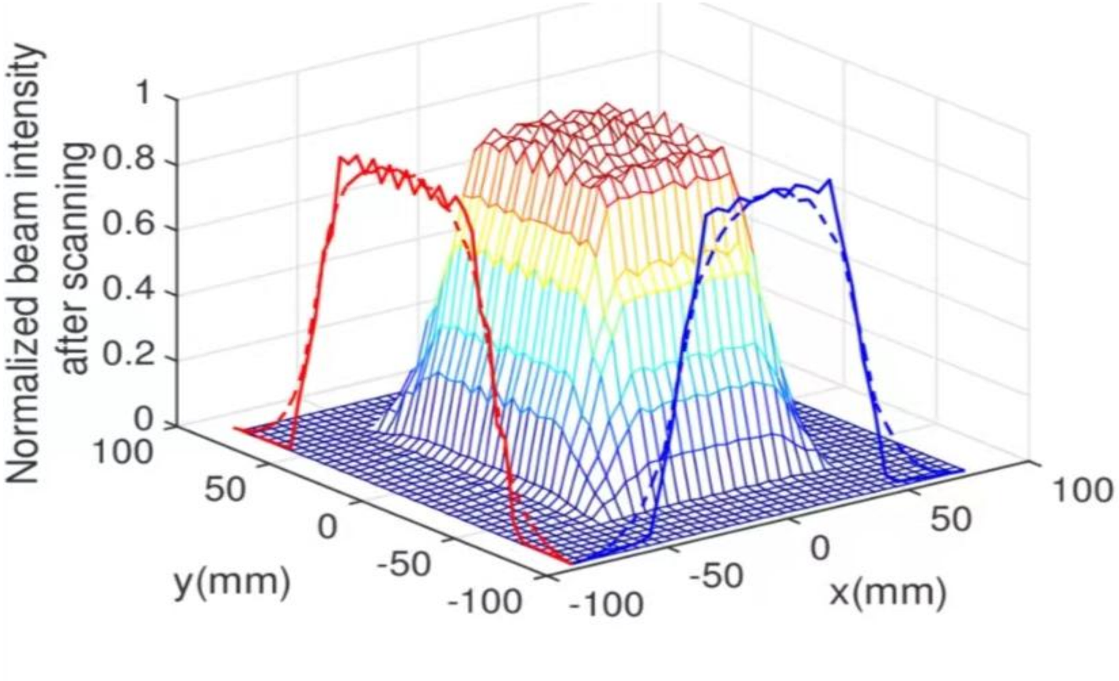
Spread Out Bragg Peak with different proton beams

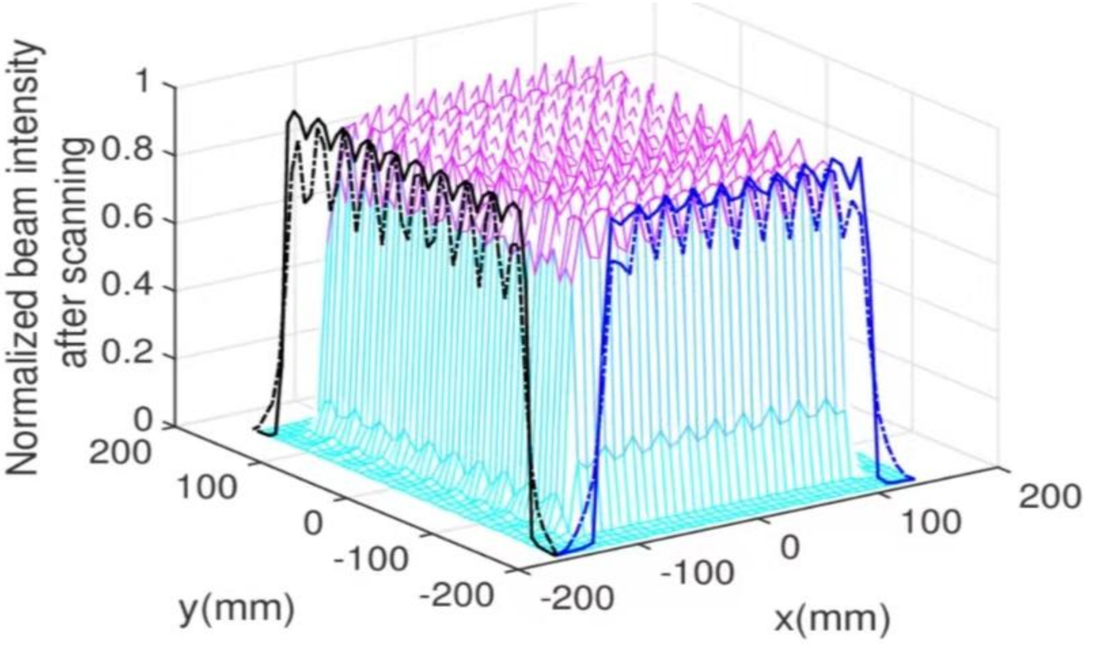




PRAB2019

Pensil beam will be realized in CLAPA II



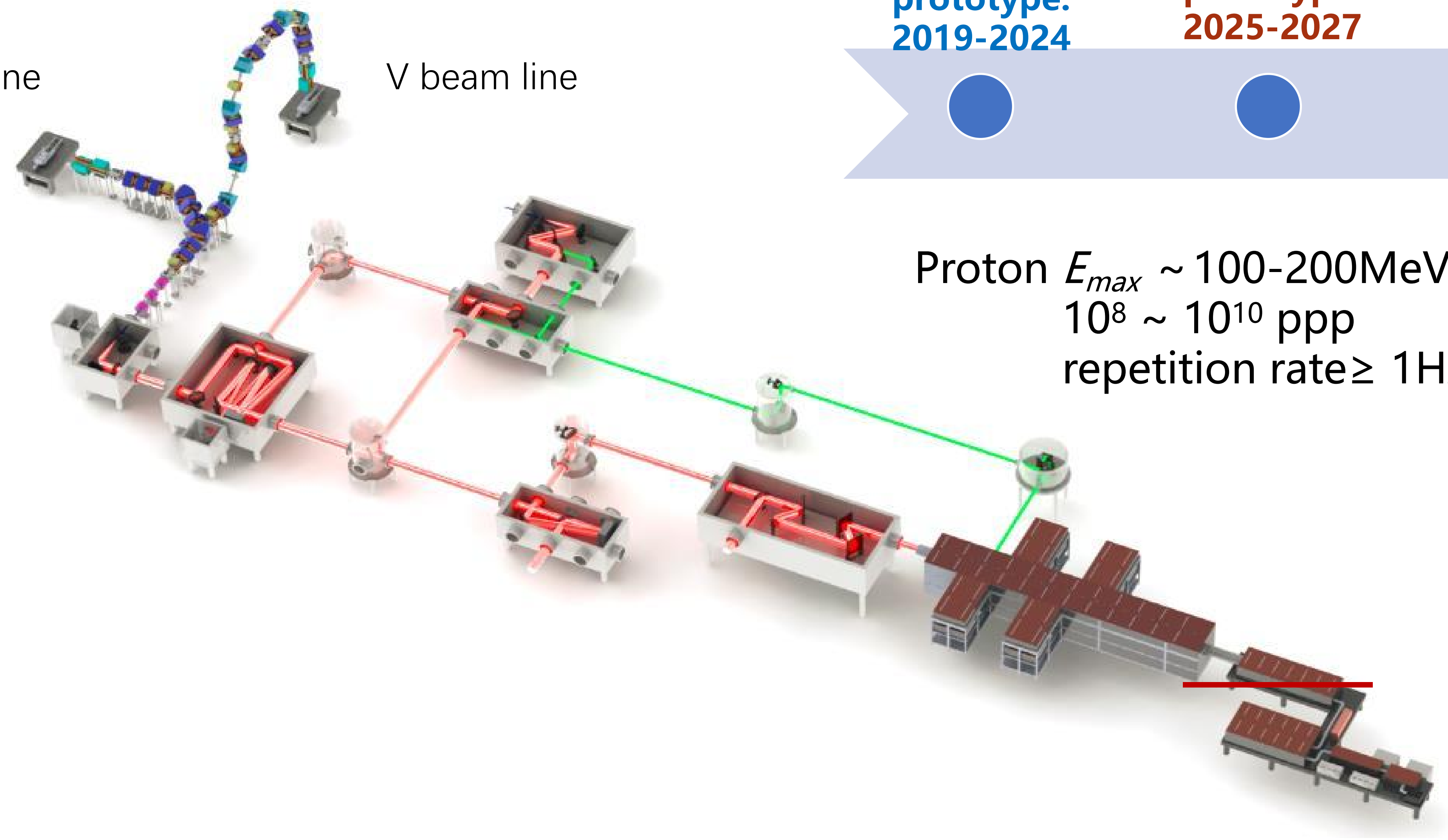


Beam energy bandwidth ≤ 5%
irradiation field 0.1m × 0.1m
Dose rate on biological tissue >2 Gy/min

W.K.Dong, et al., PRAB 2022

Proton therapy facility based on a PW laser

CLAPAII



Experimental prototype: 2019-2024

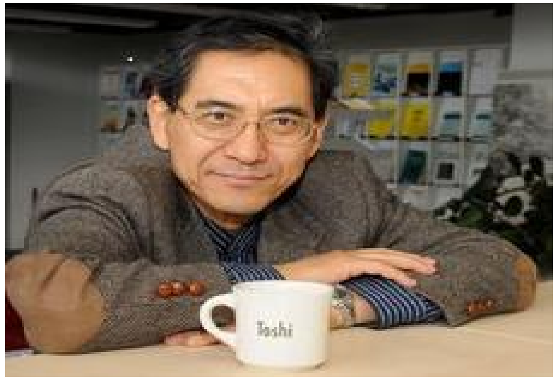
Engineering prototype: 2025-2027

Product prototype: 2028-2030

Proton E_{max} ~ 100-200MeV
10^8 ~ 10^{10} ppp
repetition rate≥ 1Hz

Answer: Challenges of laser accelerators

CPA



energy?	Will be Ok
energy spread ?	OK
stability?	OK
reliability?	OK

Nobel prize report:

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].

Outline

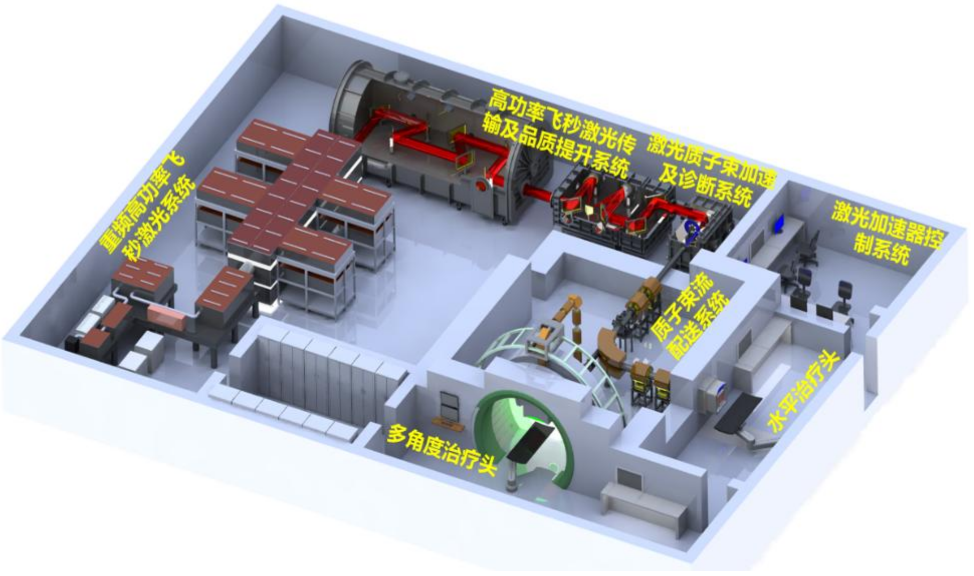
Huairou Science City— National Innovation Center

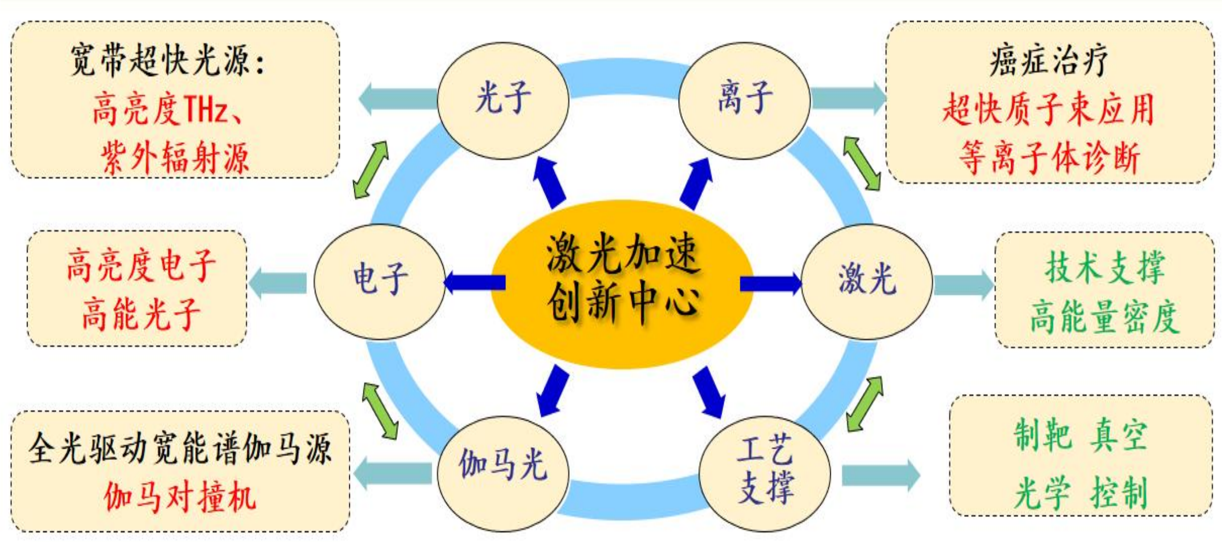
Beijing Laser Acceleration Innovation Center

The advanced laser accelerator research and application research platform:

1) **Immuno-radiotherapy**

2) **Laser driven ultrafast particle beam**

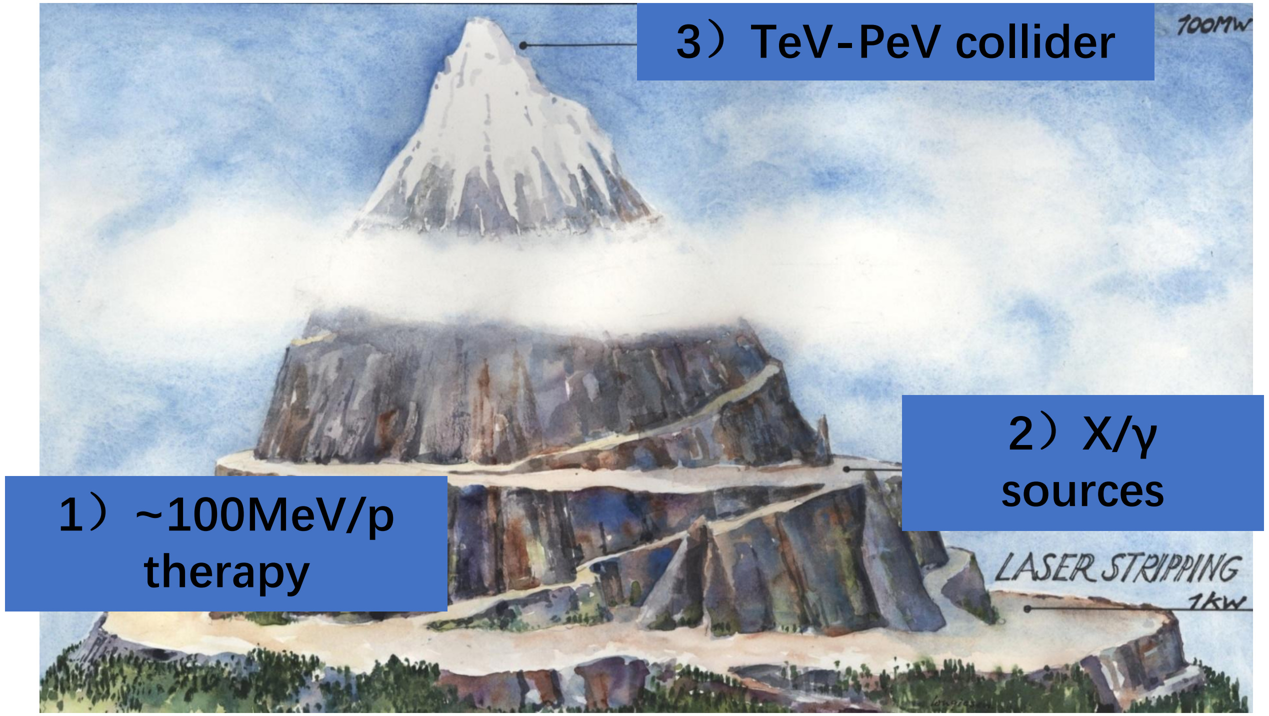




2022年12月入驻，2023年验收

Applications in the future

laser accelerator: 1) ion acceleration; 2) X/γ source;3)collider



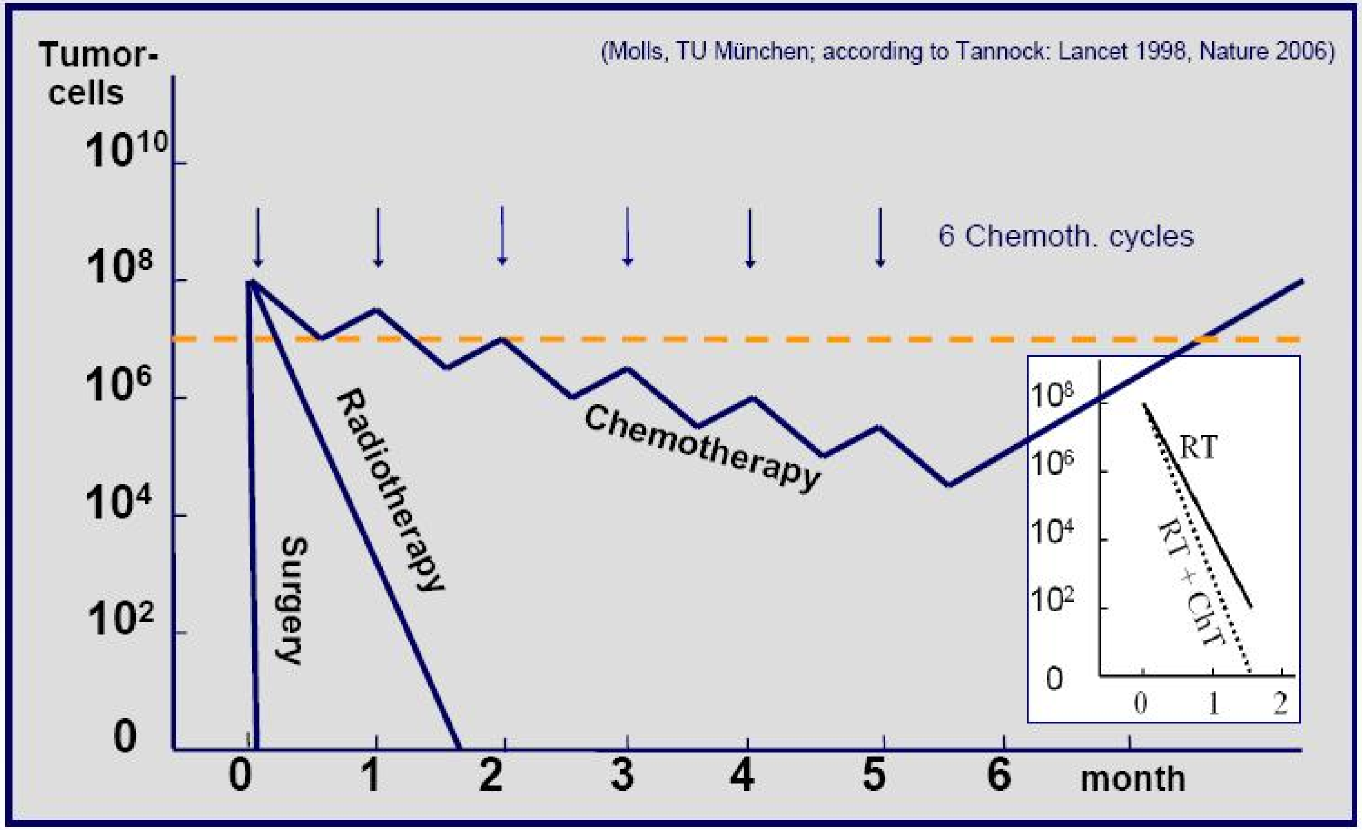
↑ avg power

→rep rate

↗ 脉冲长度

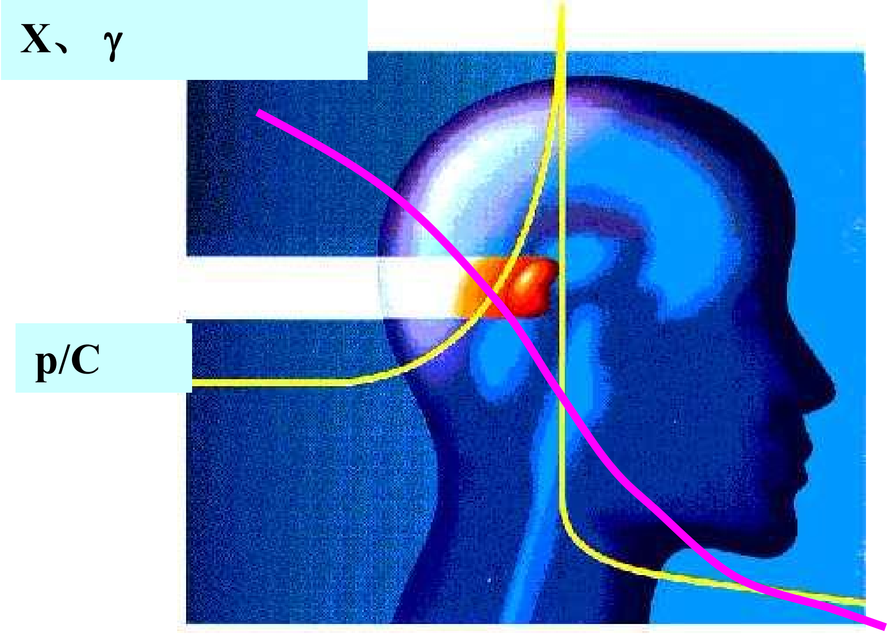
Road map in ICFA+ICUIL joint workshop

Radiotherapy is the one of most effective method for the localized tumor treatment



Macroscopic Tumor: ≥ 5mm (more than 10^7 cells)
Microscopic Tumor: < 5mm (1 – 10^7 cells)

Cell kill after Chemotherapy: only about 3 logarithmic steps (ordinate)

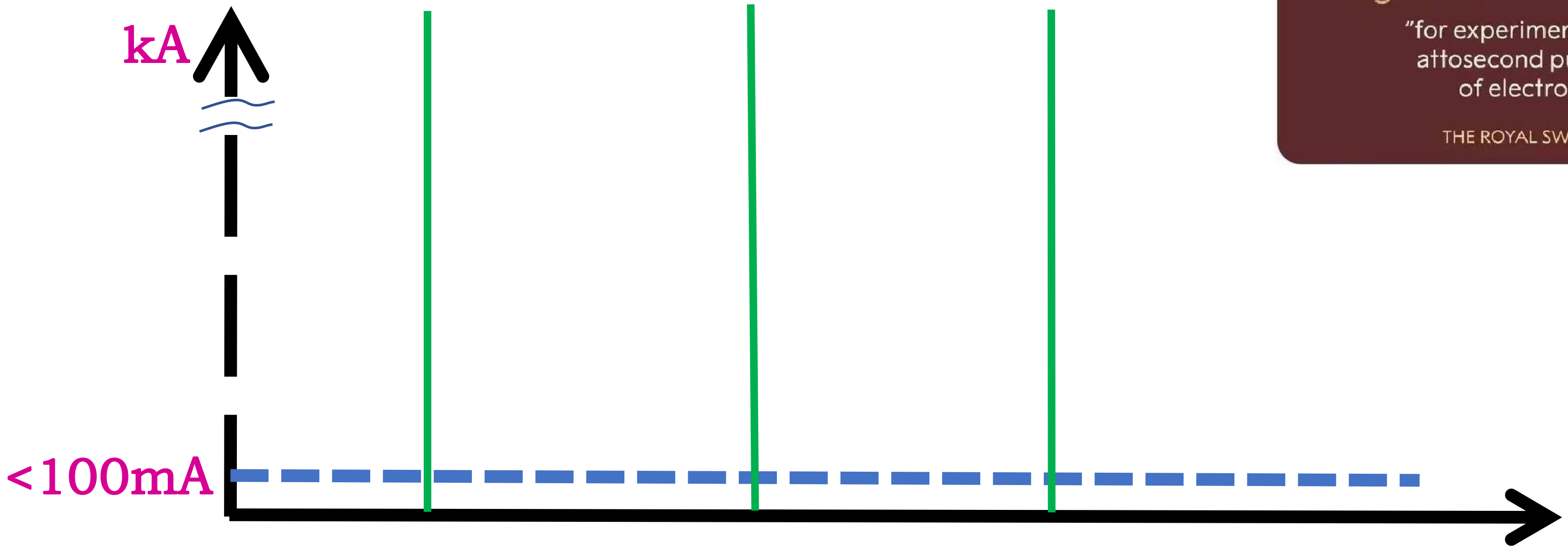


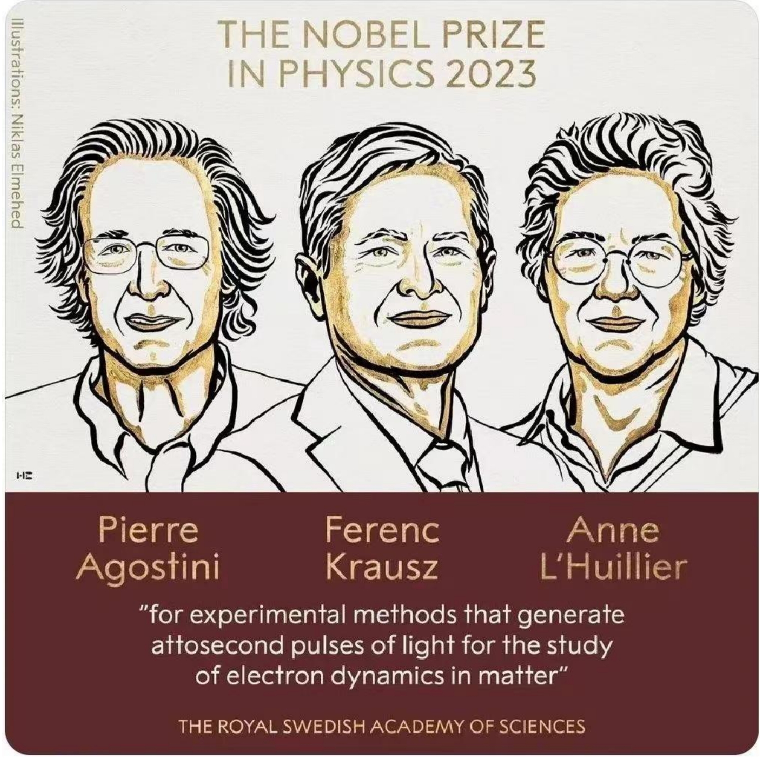
- According to PTCOG statistics, as of the end of 2018, the total number of people receiving particle therapy worldwide exceeded 220000.
- General treatment effectiveness rate above 95%

Advantages of Laser Accelerator Beam: ultrahigh current

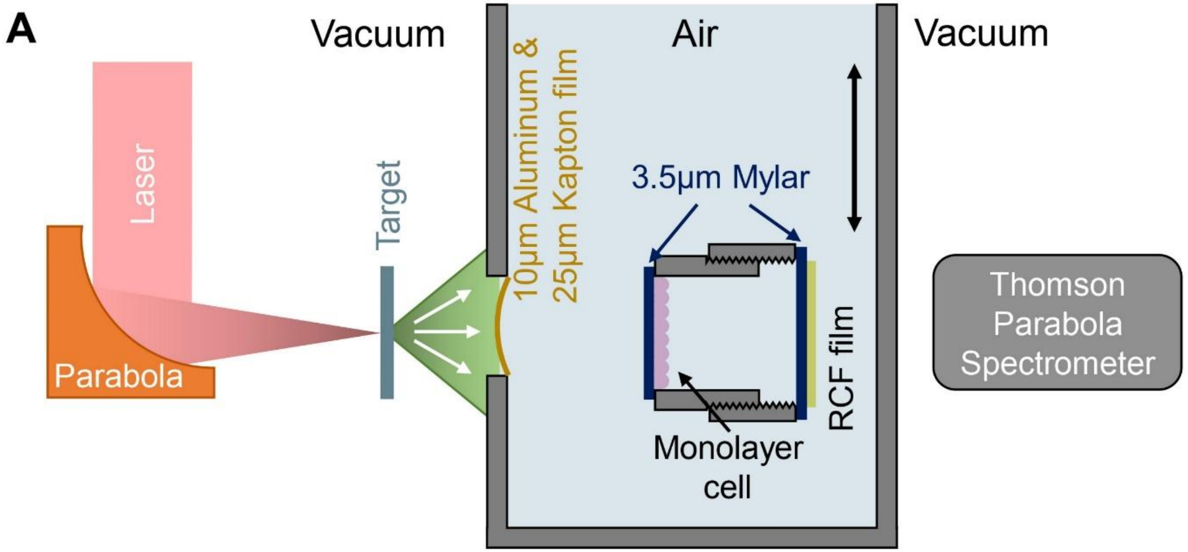
- >10^9 particle/shot
- duration: as~ fs~ ps~ns
- high current: $10^{22\sim23}$/s
- **low backgroud, high contrast**

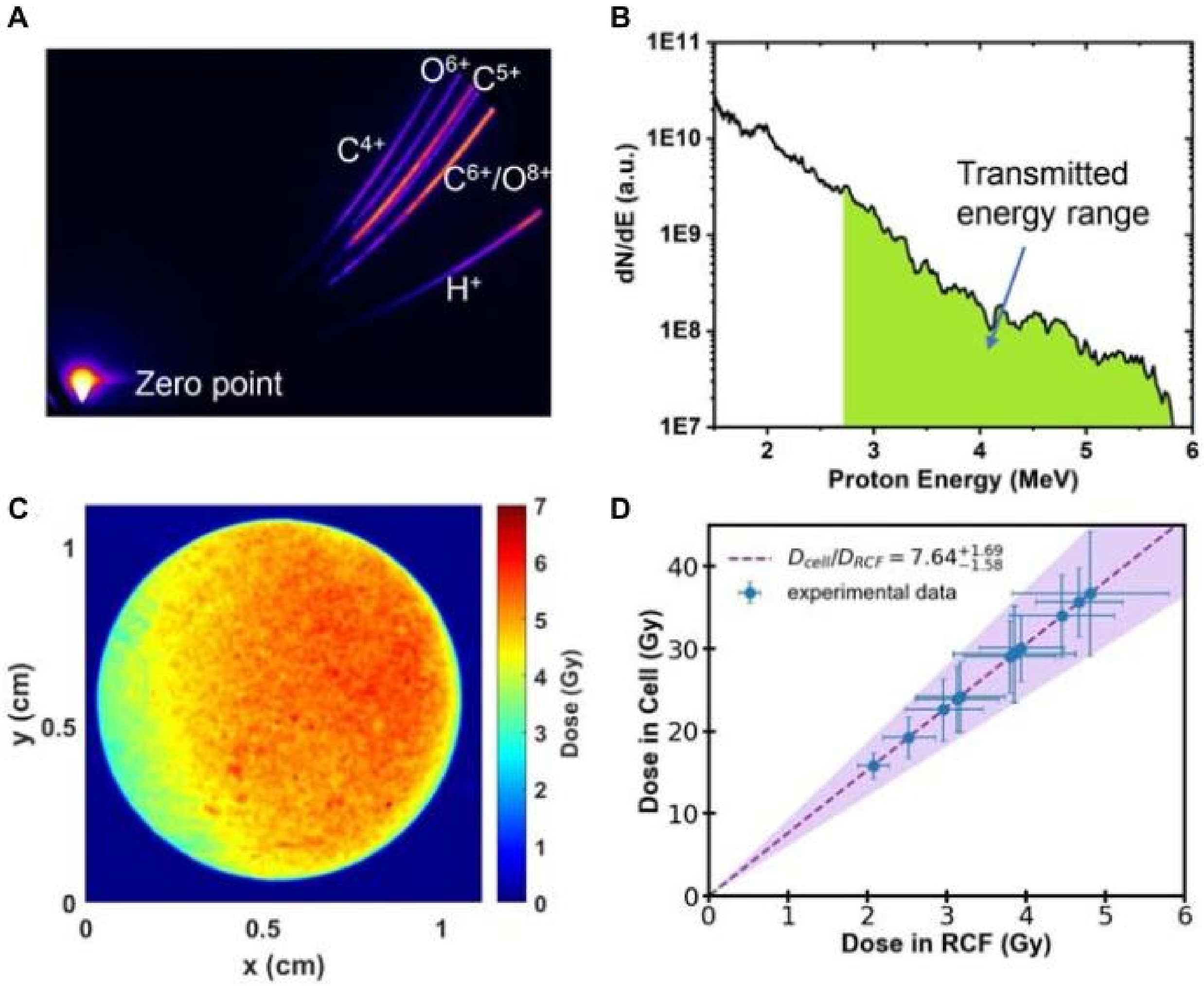
fs beam





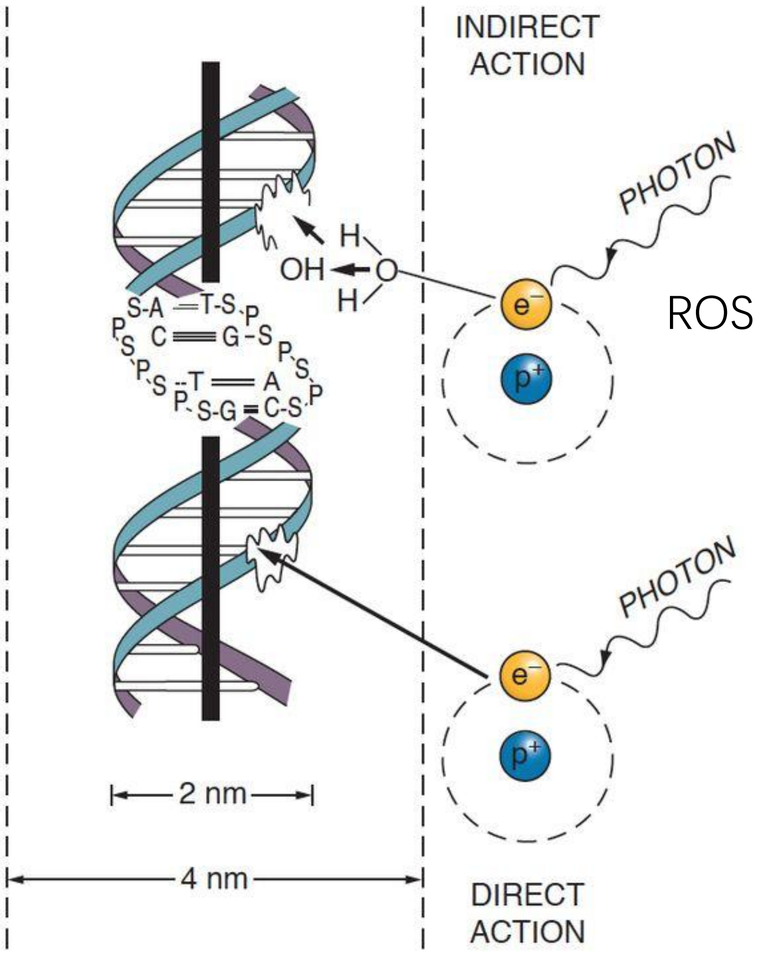
Proton irradiation experiments in CLAPA I

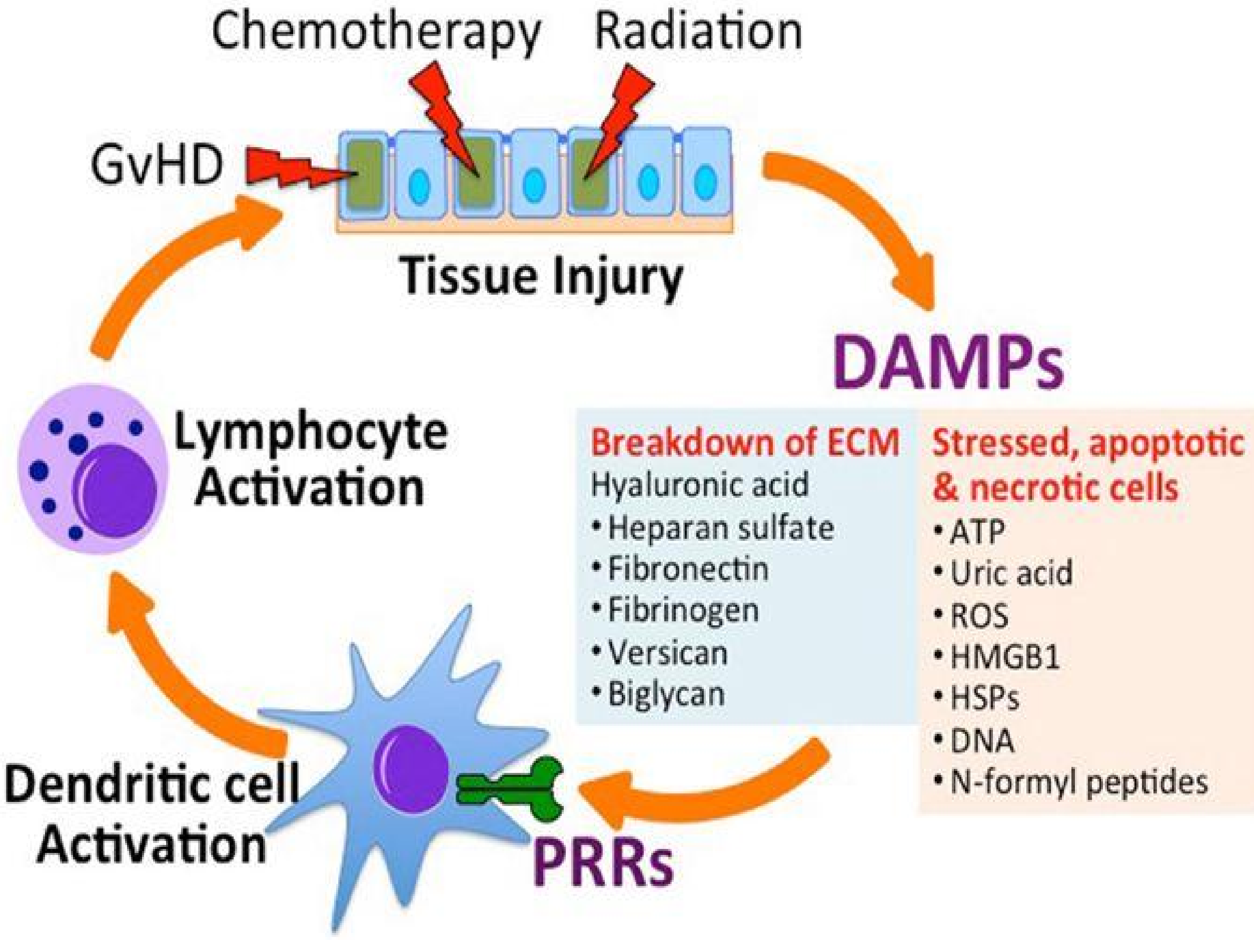




Yang, et al., Frontiers in Cell and Developmental Biology 9: 672693, 2021 A.

Radiation causes immunogenic death (ICD)

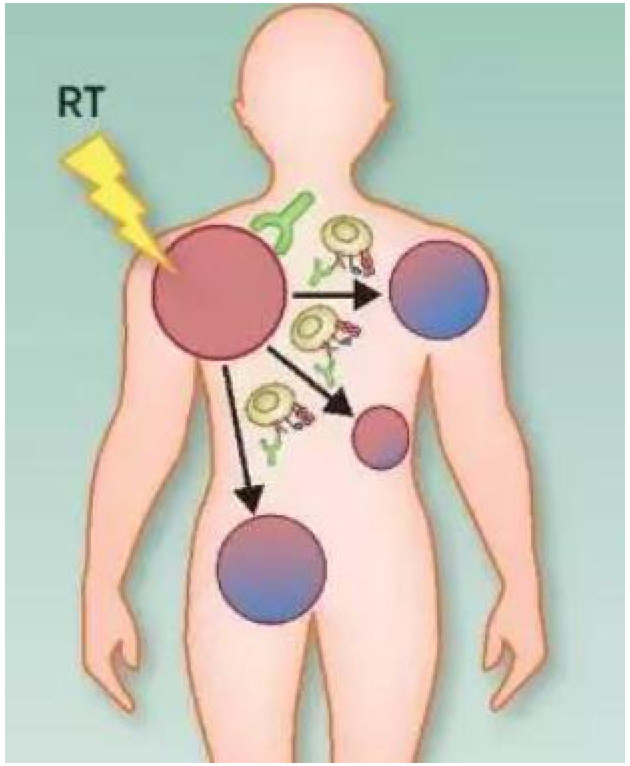


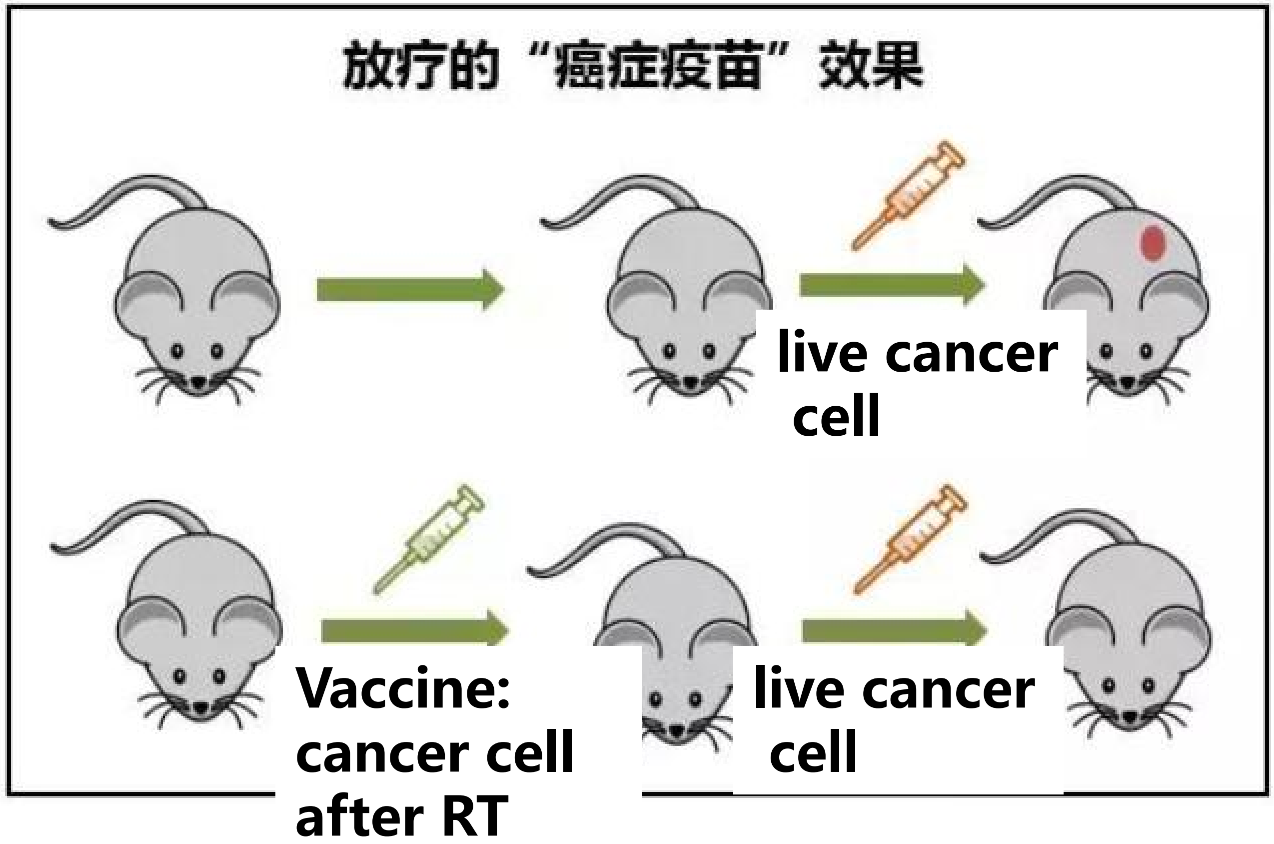


localized tumor damage
DNA bond breaking

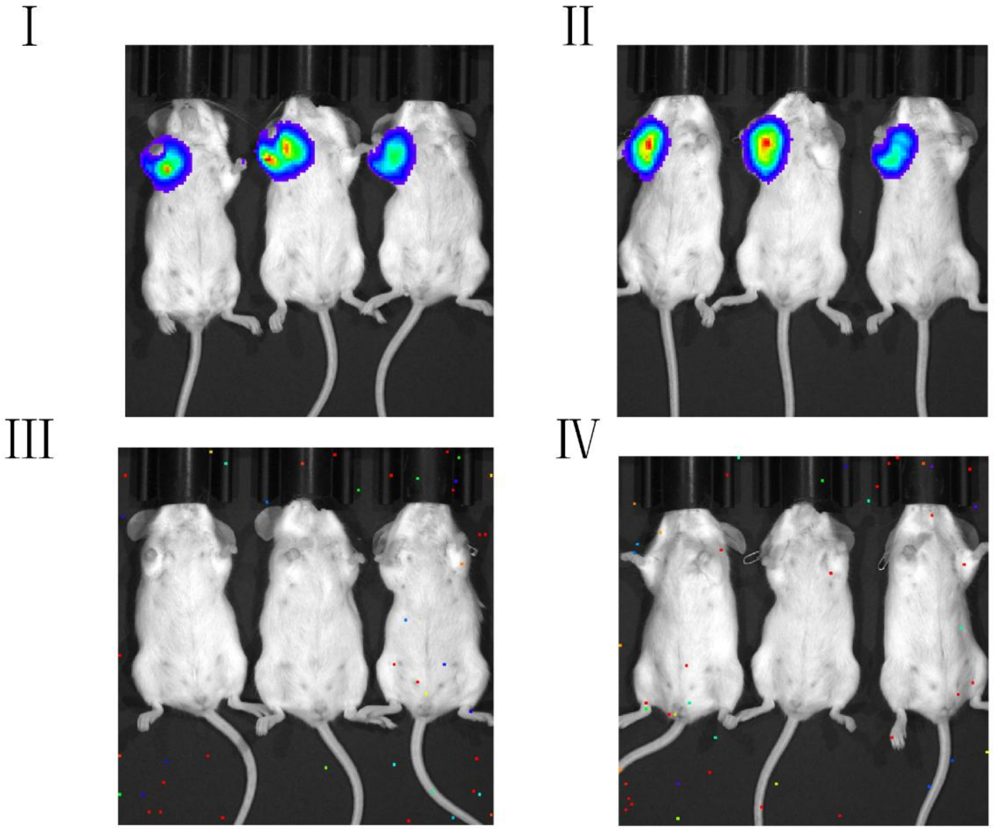
ultrahigh dose rate?
immunity activation

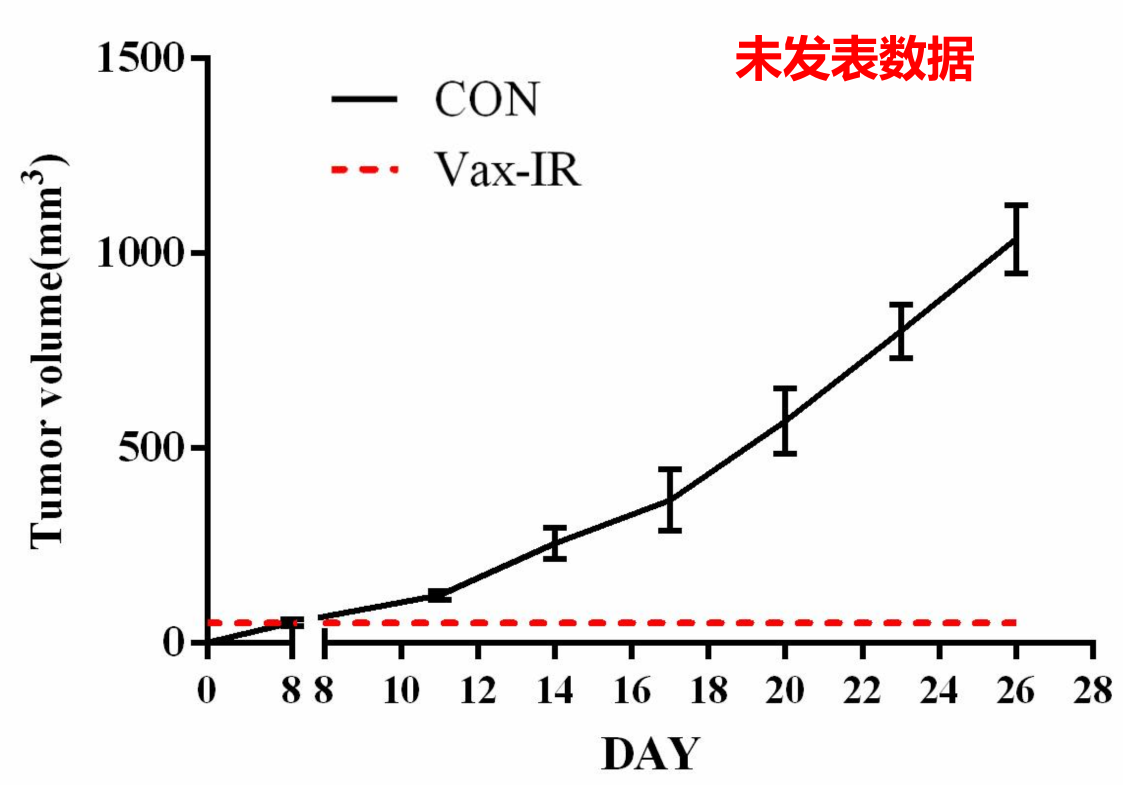
Irradiation immunity?





Radiation induced cancer prevention vaccines





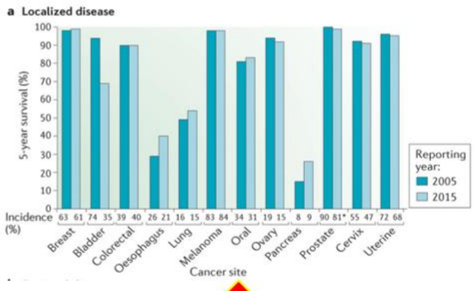
- ➢ **prevention rate**：~100%

Prospects for Laser Accelerator Immunotherapy

localized tumor therapy

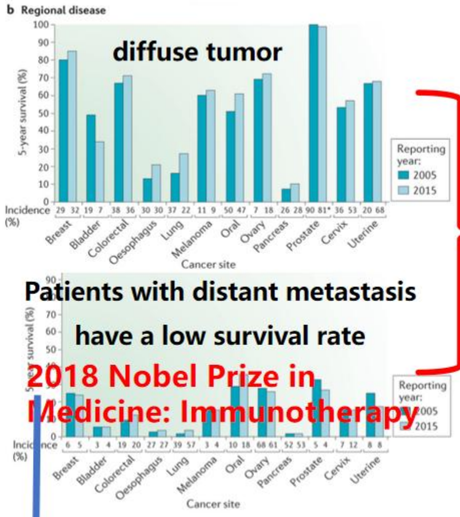
diffuse tumor

~10%



localized tumor patient <10%

5-year survival rate of cancer patients in the United States during 2005~2015



diffuse tumor

Patients with distant metastasis have a low survival rate

2018 Nobel Prize in Medicine: Immunotherapy

>90%

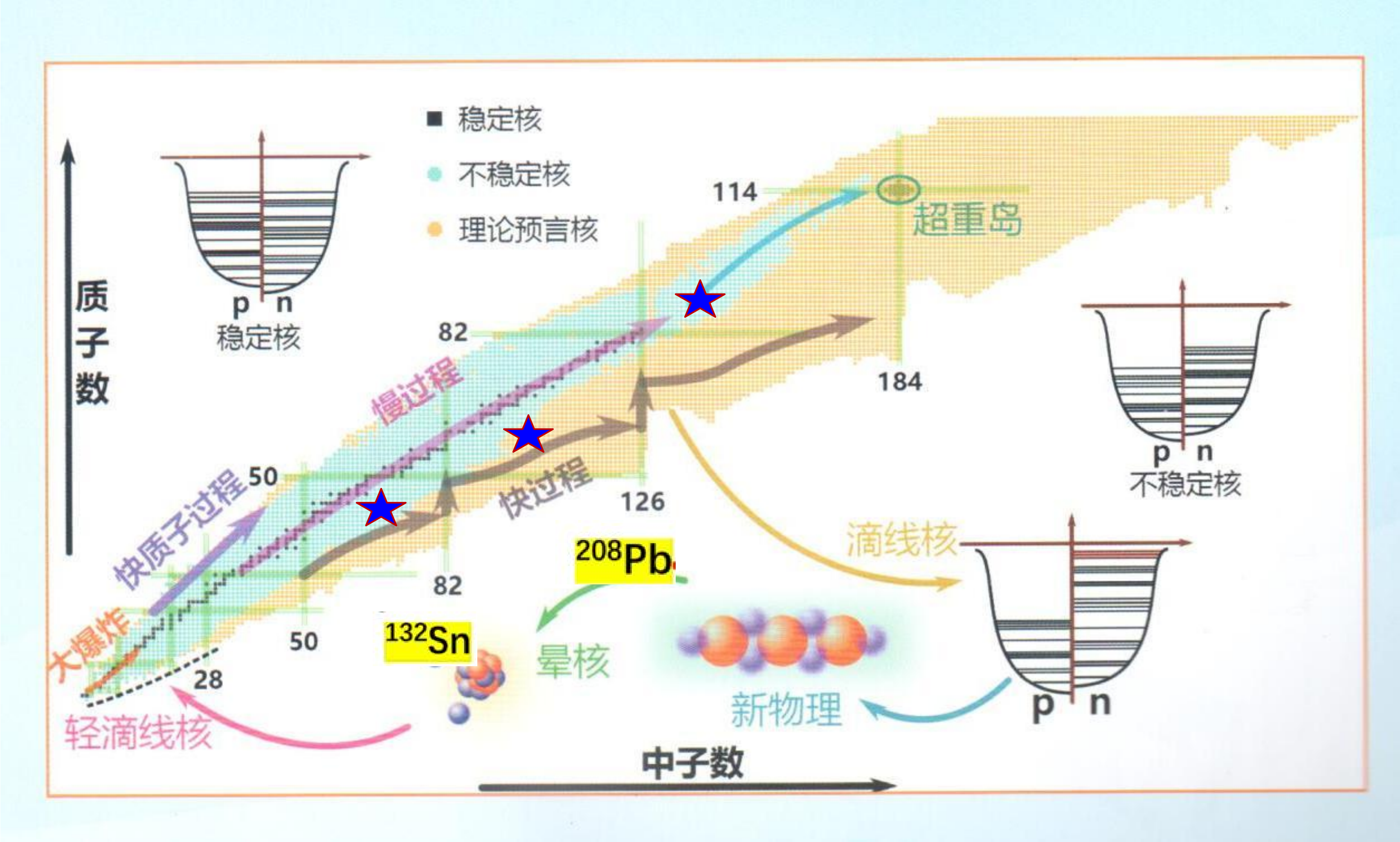
Nature Reviews Cancer 16(4): 201-8, 2016

laser accelerator+immunity =immunoradiotherapy

immuno-radiotherapy

2. γ Source and Heavy element synthesis

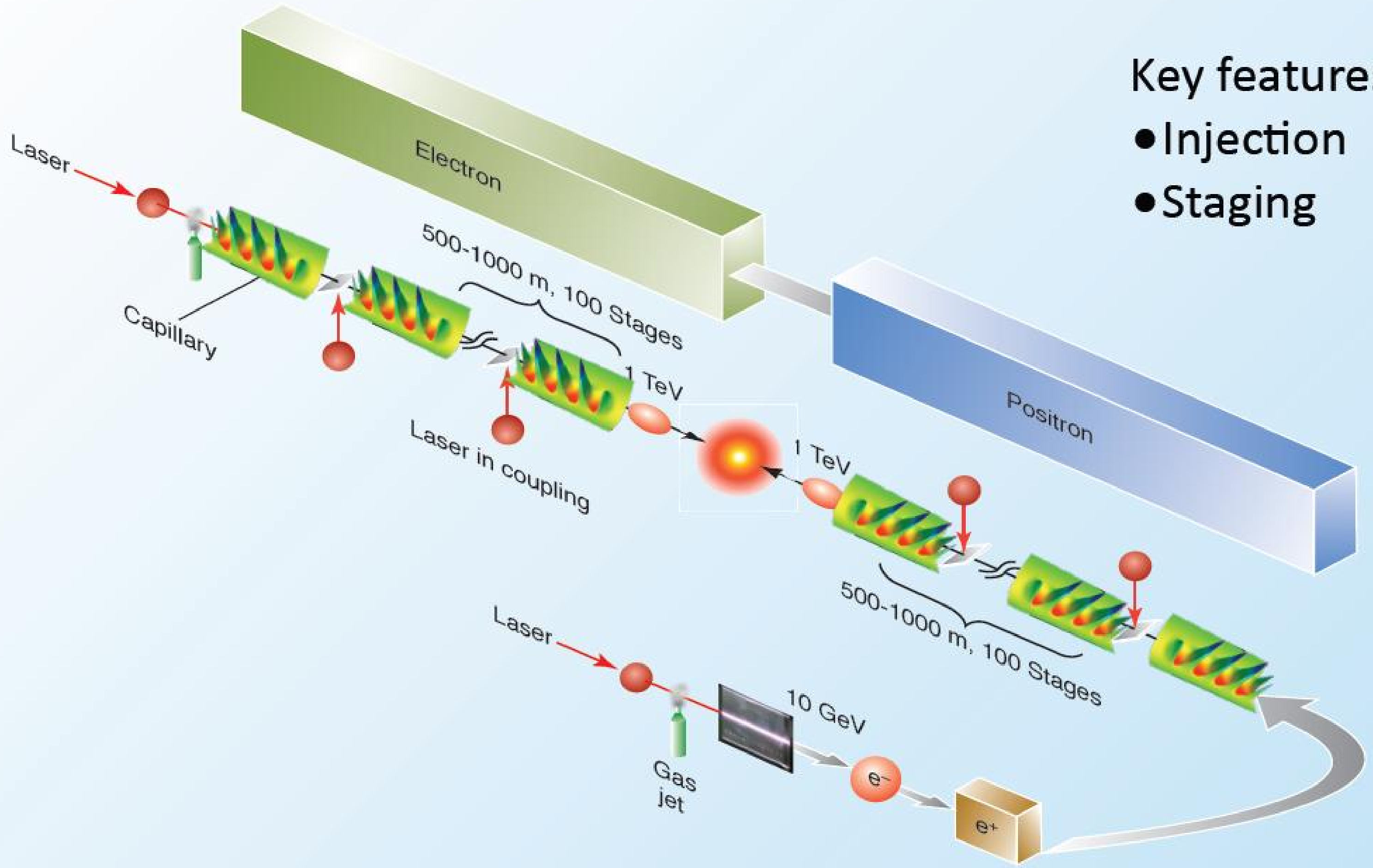
- **Century puzzle r-process (fast neutron process)**



FRIB, FAIR, HIAF, SPIRAL2， RIKEN, BISOL 等聚焦放射性核束物理，人类可研究的核素版图持续扩大

3. Next Generation Collider (Collider?)

Laser Plasma Accelerator Explored For Linear Colliders: Follow Paradigm Of Conventional Accelerators To Increase Beam Energy And Quality



Key features:

- Injection
- Staging

Leemans & Esarey, Physics Today, March 2009; C.B. Schroeder et al., PRST-AB 13 (2010)

3. Next Generation Collider (muon Collider?)

200 times heavier than electrons , suitable for the next generation of high-energy colliders. But short lifestime! Preliminary simulations indicate that TeV protons can drive TeV muon acceleration.

proton energy	μ^+ energy	acceleration time	distance	injected energy	final energy
0.1TeV	7.41GeV	4013ps	1.2m	19.3GeV	26.71GeV
1TeV	74.1GeV	13378ps	4.01m	80.4GeV	154.5GeV
7TeV	519.8GeV	37458ps	11.24m	226.3GeV	746.1GeV

by Prof. Jinqing Yu, Hunan university

Summary

1) The combination of laser acceleration and magnet beam line may overcome the issues faced by laser accelerators in future applications， such as cancer therapy.

2) It will be very interesting to build a laser accelerator for radiation vaccines, short lived isotopes, photonuclear physics, plasma diagnostics and so on .

3) Answer to 2018 Nobel prize report is here.

proton/ion	~100MeV (GeV Au61+)
energy spread	0.1%~1%
stability	<10%

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].

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