Development of the laser driven ion injector for the new generation heavy ion cancer therapy

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Asian Forum for Accelerators and Detectors (AFAD) 2018

WG4: Innovative Accelerator Techniques

28- 31 January, 2018

Daejeon Convention Center, Korea

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✓ Summary

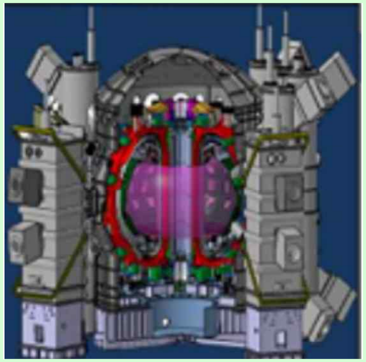
QST has been established at April 2016

QST: National Institutes for **Q**uantum and Radiological **S**cience and **T**echnology

QST can provide a research base on Quantum Science and Technology.

Ion beam

Laser



Fusion

Heavy Ion beam

Takasaki Advanced Radiation Research Institute (TARRI)

Kansai Photon Science Institute (KPSI)

Quantum Beam Science Directorate (QuBS)

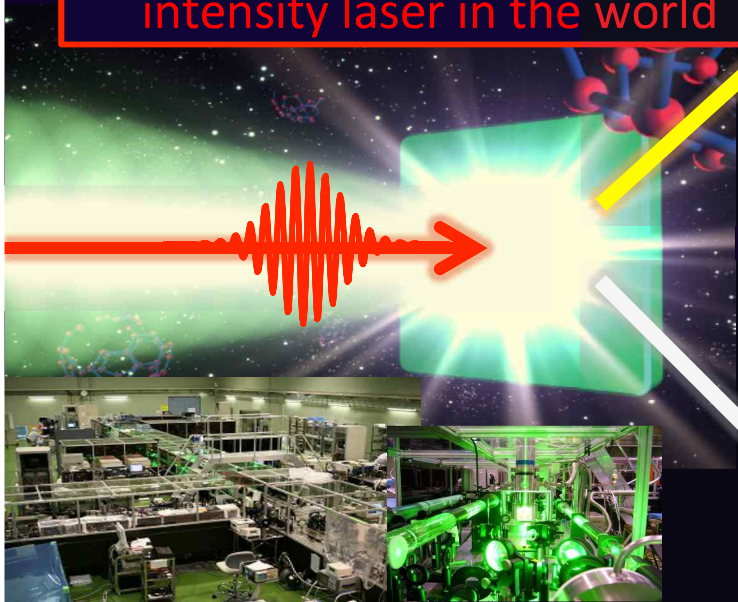
Fusion Energy Research and Development Directorate

National Institute of Radiological Sciences (NIRS)

What is going on at KPSI, Kizu?

With developing a top class laser in the world, we study on the cutting edge science, and promote the industrial and biomedical application for generating the innovation.

Development of a top class high intensity laser in the world

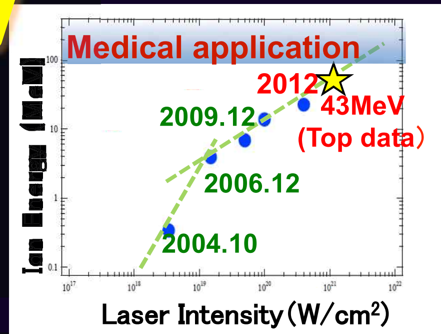


Ultra short high peak power laser in KPSI:

J-KAREN

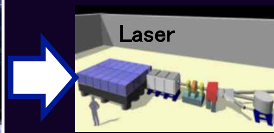
Study on the cutting edge science

Laser driven particle acceleration with intense laser



Big accelerator could be compact in the future.

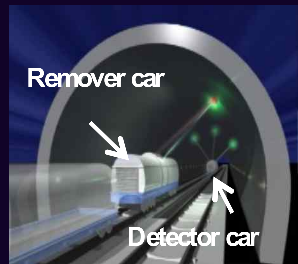
J-PARC



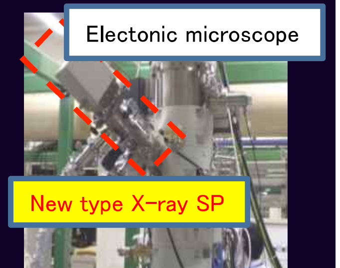
Laser driven particle accelerator

Promotion of the industrial and biomedical application for generating the innovation

Practical realization of non-invasive treatment with optical fiber and laser (venture co. in JAEA)



Tunnel inspection technology by laser light (SIP project)



Development of x-ray analizer with nano-resolution (Market placed by JEOL)

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Particle cancer therapy has been proposed

R.R. Wilson, "Foreword to the Second International Symposium on Hadrontherapy," in Advances in Hadrontherapy, (U. Amaldi, B. Larsson, Y. Lemoigne, Y., Eds.), Excerpta Medica, Elsevier, International Congress Series **1144**: ix-xiii (1997).

Radiological Use of Fast Protons

ROBERT R. WILSON

Research Laboratory of Physics, Harvard University

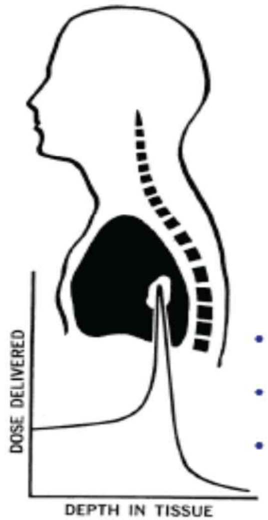
Cambridge, Massachusetts

Except for electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in large part, been due to the very short penetration in tissue of protons, deut... particles from present ...-energy machi... how...

per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

These properties make it possible to irradiate intensely a strictly localized region ...

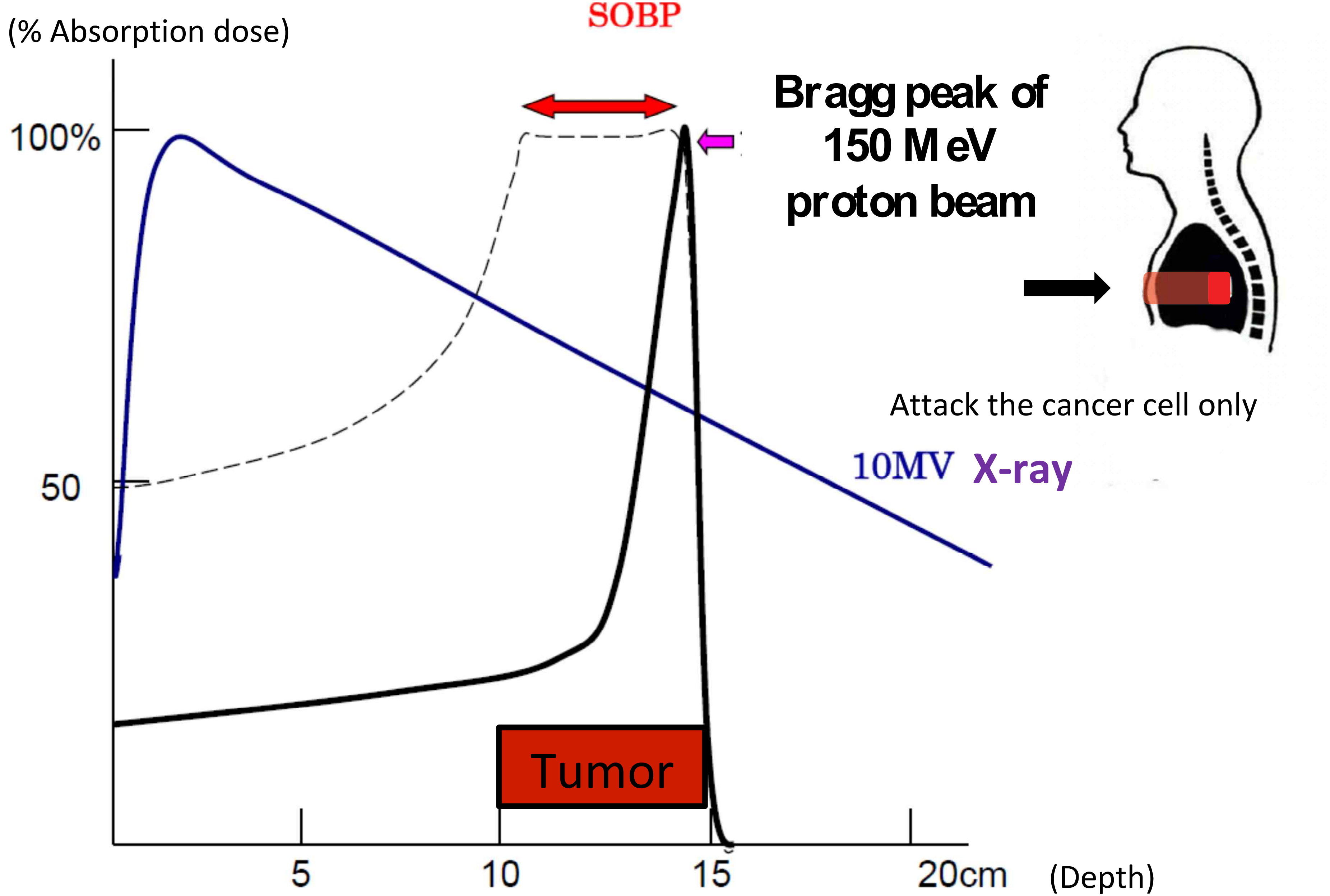
Radiology 47: 487-491, 1946



- Dose localization
- Low entrance dose
- No or low exit dose

In 1946、R. Wilson has proposed a particle cancer therapy, in which a physical property of energetic ions is well applied.

Dose distribution comparison

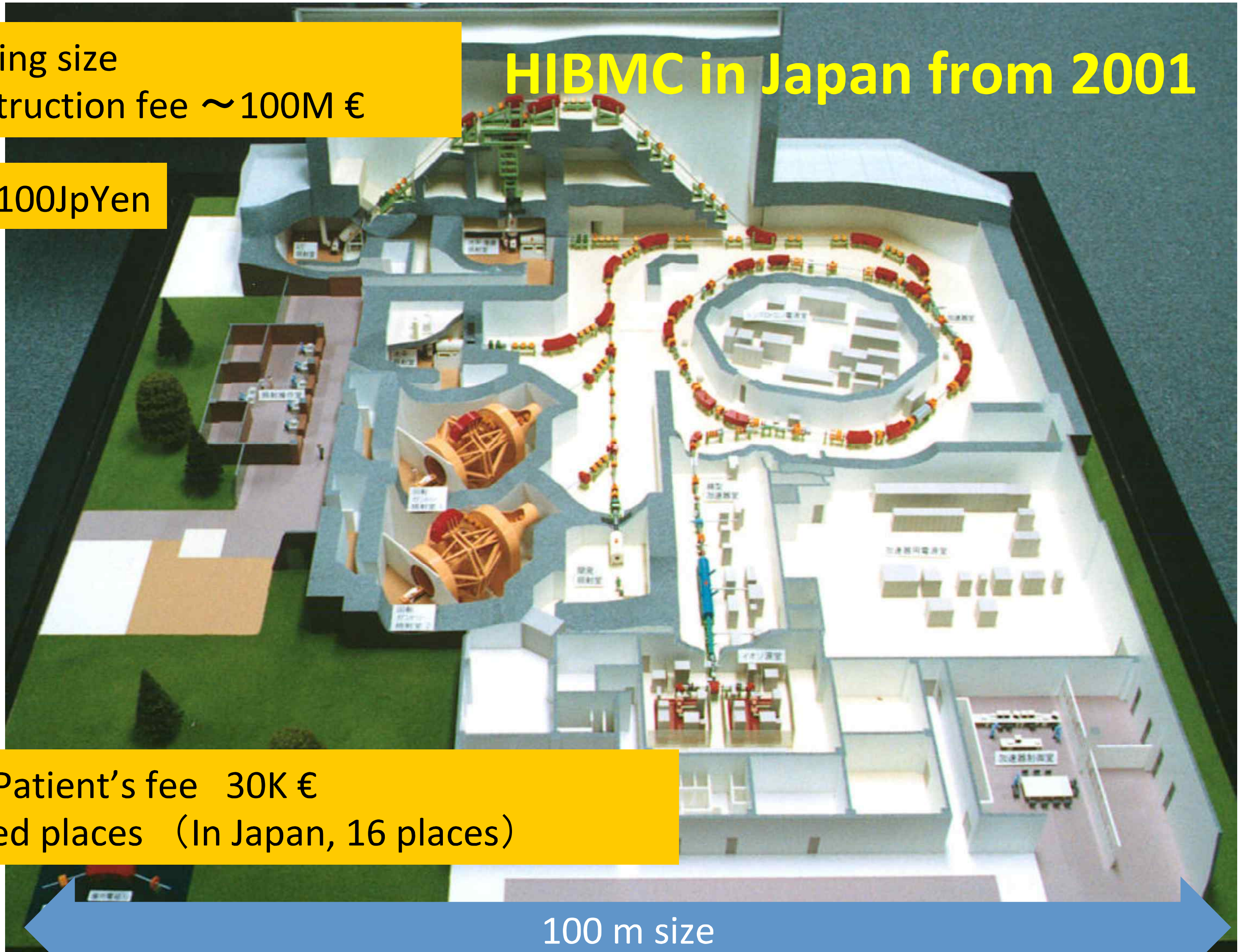


Medical innovation happened!

Particle cancer therapy brought us following innovative matters.

* **High QoL (Quality of Life)**
* **Quick social rehabilitation**
* **Medical treatment as an outpatient**

Particle cancer therapy system was very huge and very expensive



Building size
Construction fee ～100M €

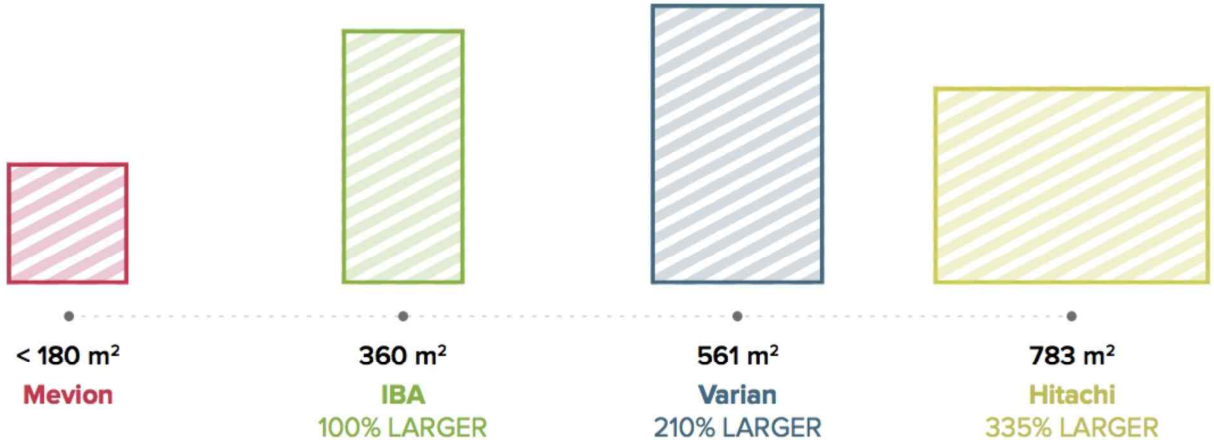
1€ = 100JpYen

HIBMC in Japan from 2001

High Patient's fee 30K €
Limited places （In Japan, 16 places）

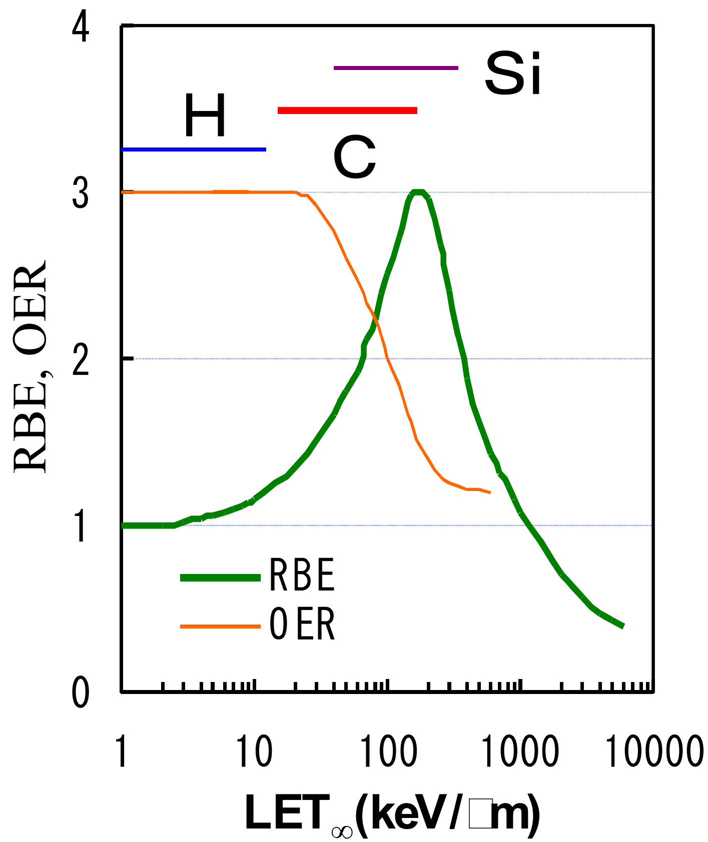
100 m size

Proton machine is becoming smaller with conventional acceleration technology

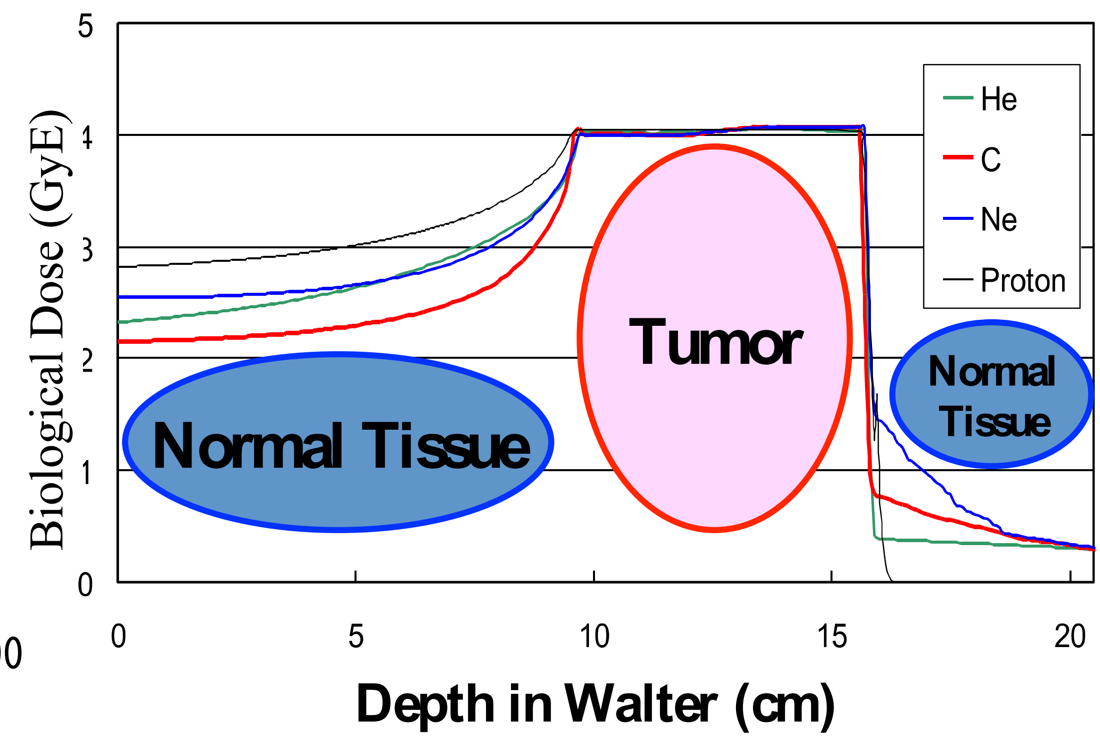


Biological Property of Heavy Ion Beam

High Biological Effect



LET Dependence of RBE □ OER



RBE : Relative Biological Effectiveness　OER : Oxygen Enhancement Ratio

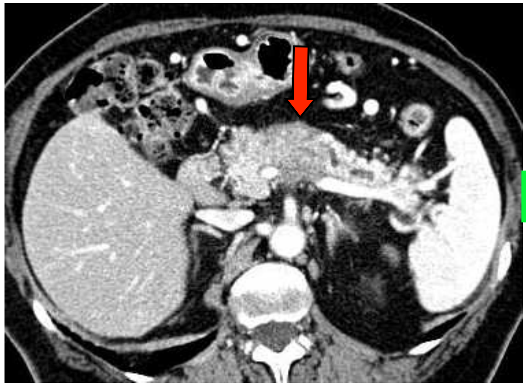
QST

Record of treatment of unresectable pancreatic cancer

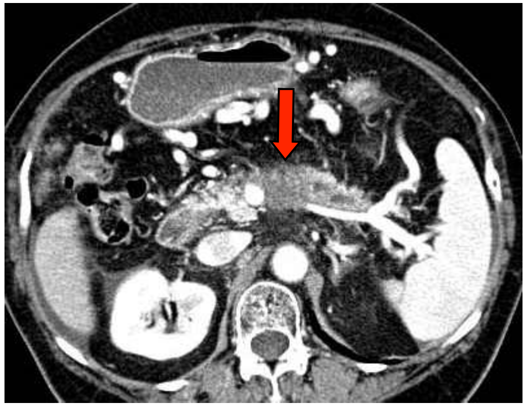
Author	□ear	n	Treatment	Dose	Survival rate	
					1 y	2 y
ECO□	200□	34	□EM□RT	50.4□y	50□	12□
		37	□EM	-	32□	4□
Ishii	2010	50	□EM	-	64□	14□
Sudo	2011	34	S-1□RT	50.4□y	71□	25□
Schellenberg	2011	26	□EM□RT	25□y/1fr	50□	20□
NIRS	2014	52	□EM□CIRT	45.6-55.2□yE	77□	4□□

GEM：Anti-cancer Agent, RT：Radiotherapy、CIRT：Carbon Ion Radiotherapy

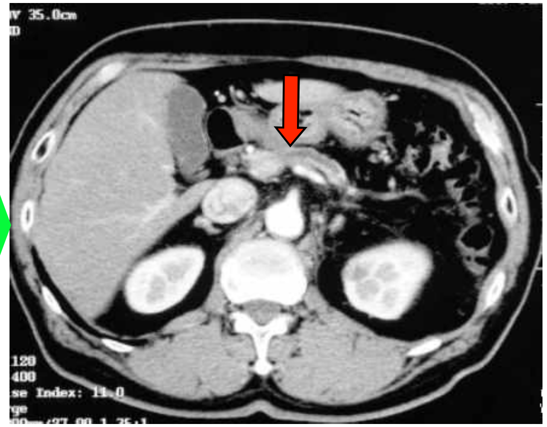
Example of treatment of unresectable pancreatic cancer



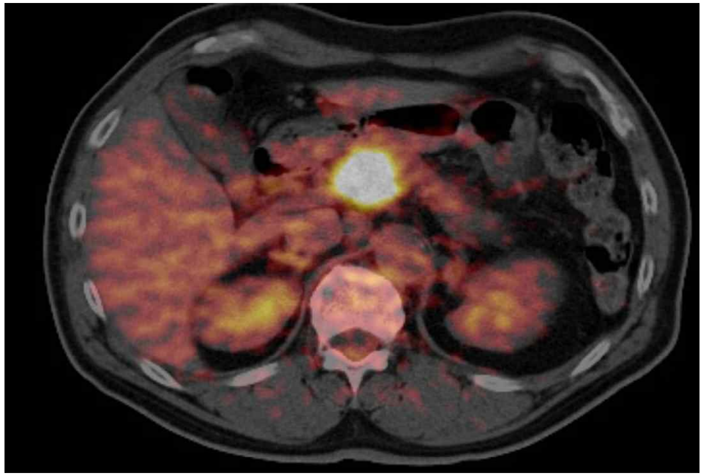
Before



4 Months after

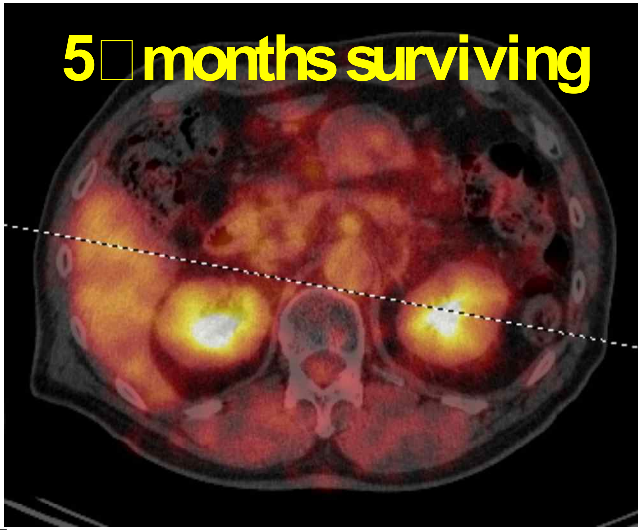


8 Months after



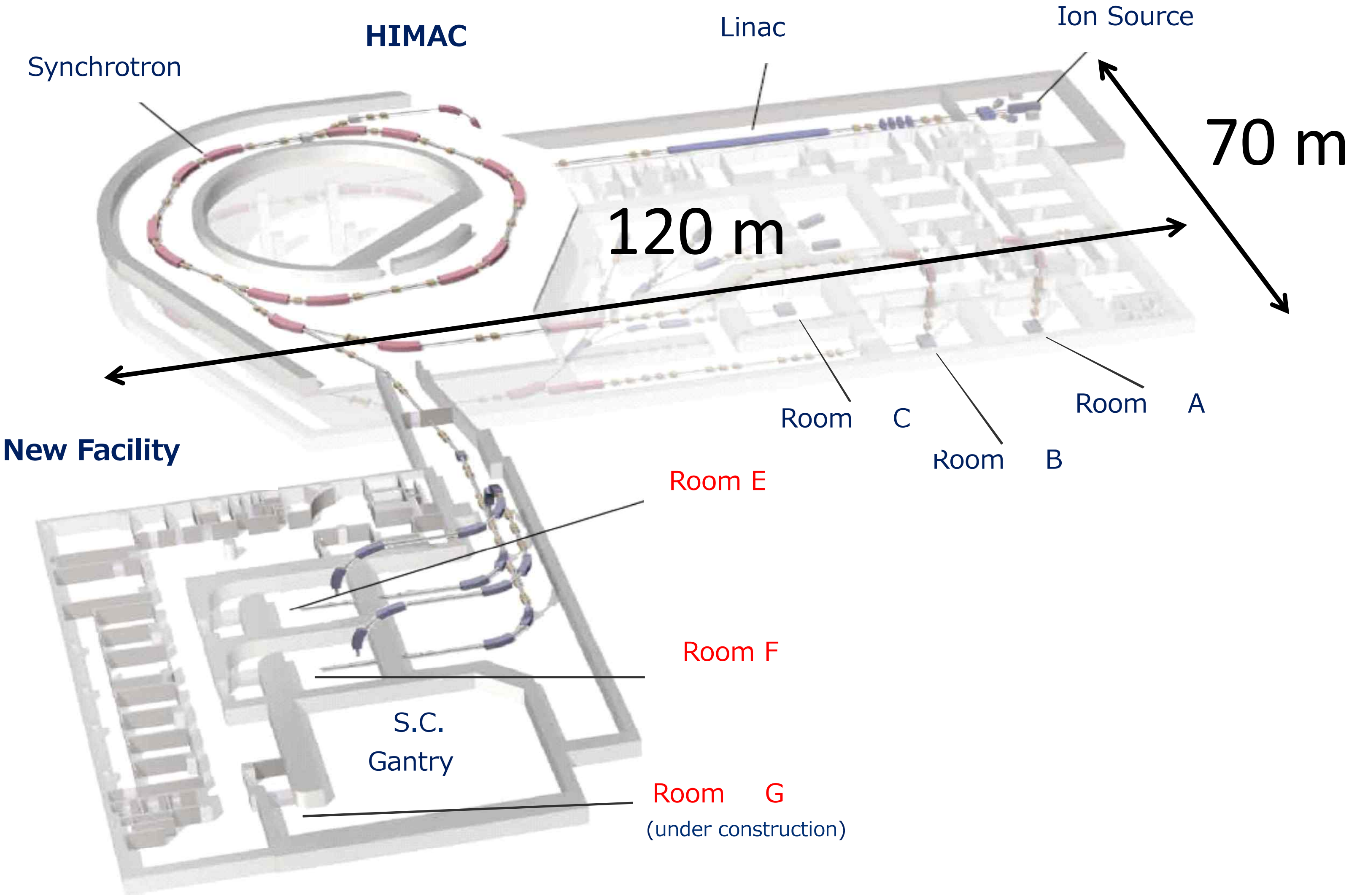
Before

50.4GyE/12Fr

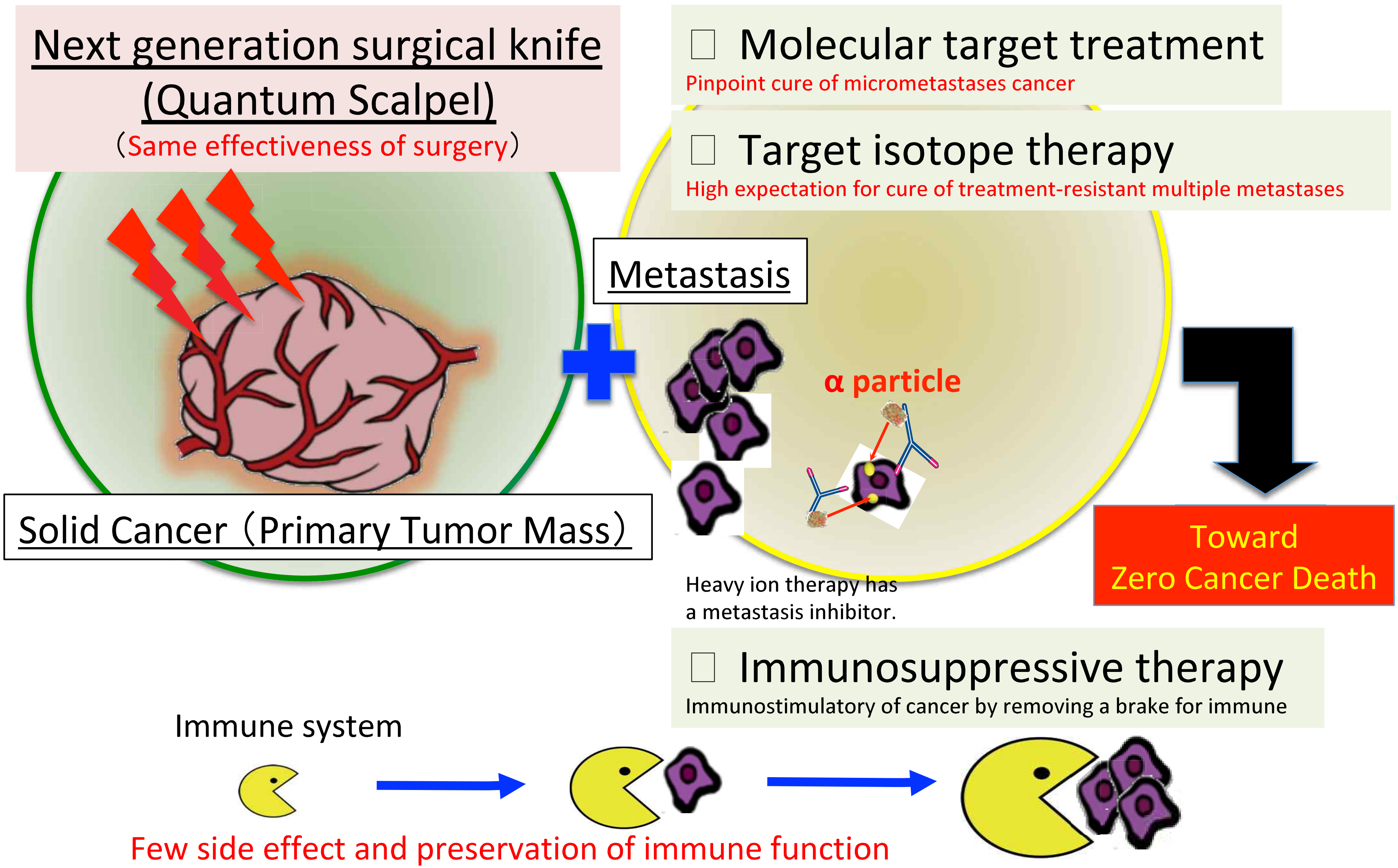


46 Months after

HIMAC in NIRS



Healthy and Longevity Society by Zero Cancer Death



Few side effect and preservation of immune function
Keep a high QoL (Quality of Life)

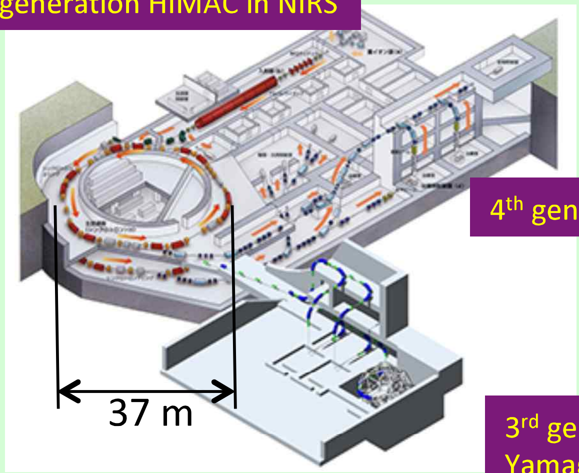
QST Concluded Framework Agreement for Developing □Quantum Scalpel□between 4 Japanese Companies

MITSUBISHI ELECTRIC	HITACH	QST	TOSHIBA	SUMITOMO Heavy Industries, ltd.
President Sakuyama	Nakanishi Chairman	President Hirano	President Tsunakawa	President Betsukawa

5th generation heavy ion cancer therapy machine Ⅰ

QST

1st generation HIMAC in NIRS



37 m

2nd generation: Gunma Univ., Heidelverg Univ.

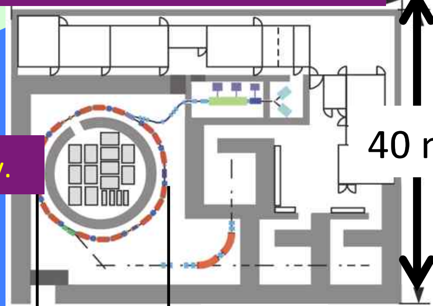
20 m

Present status

NIRS found that there is a positive effect with using multi-ion speices for curing cancer.
→ Multi-ion irradiation cancer therapy

With using a super conducting magnet, it can be packed in 45 m x 34 m size building with a gantry.

3rd generation: Yamagata Univ, Kanagawa, etc.



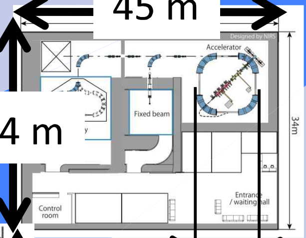
40 m

60 m

10 m

Under development now

4th generation: multi-ion irradiation effect and super conducting magnet tech.



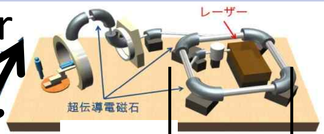
45 m

34 m

8 m

5th generation: using laser driven ion accelerator

10 years after



10 m

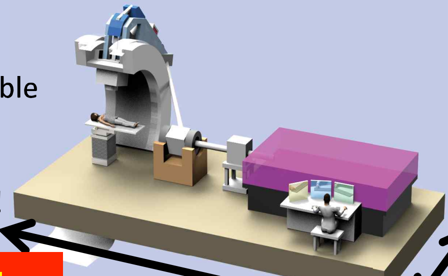
20m

7 m

With using a super conducting strong magnet and **laser driven ion injector**, it can be packed in 20 m x 10 m size building with a gantry.
Laser driven ion injector should be placed inside the main synchrotron accelerator ring.
This machine can be put in a big hospital. → An extra building is not necessary.

Future: Compact inexpensive machine with all optical

Heavy ion cancer therapy available at any time at anywhere, for anybody!
GeV/u accelerator at anywhere!



～10m

～5 m

Generation of Destructive Innovation

Future status

20 years after

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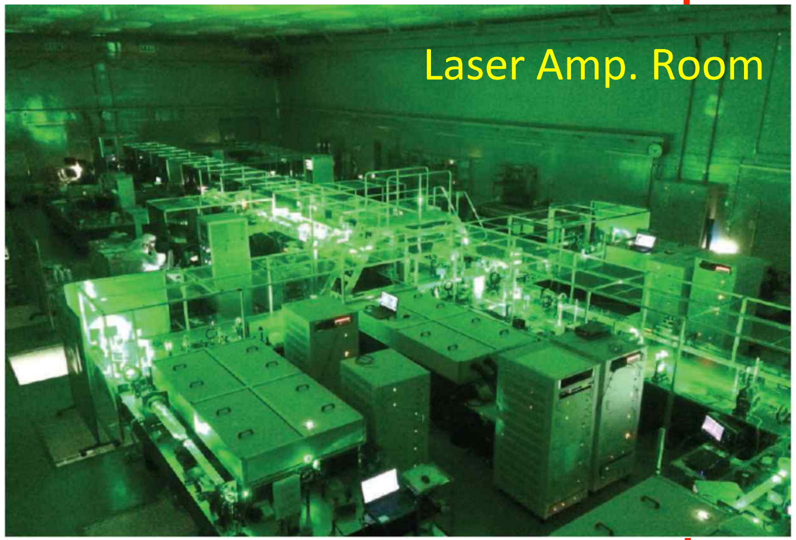
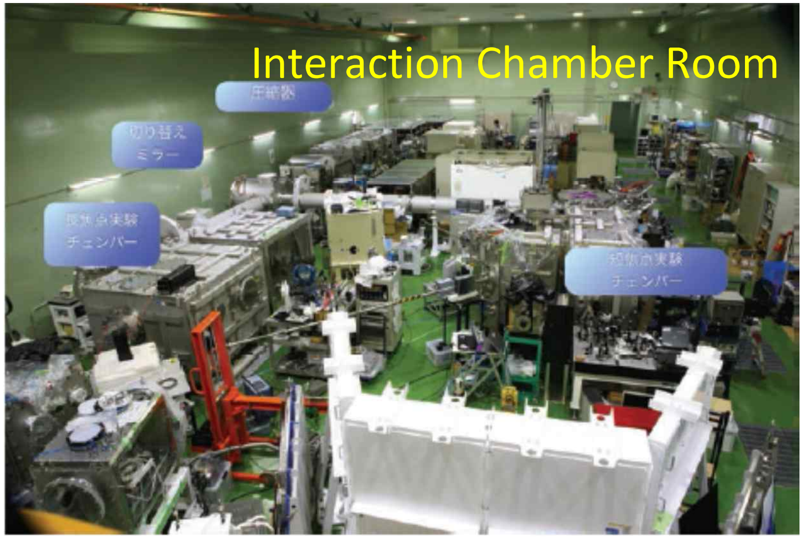
Peta Watt (PW) laser science

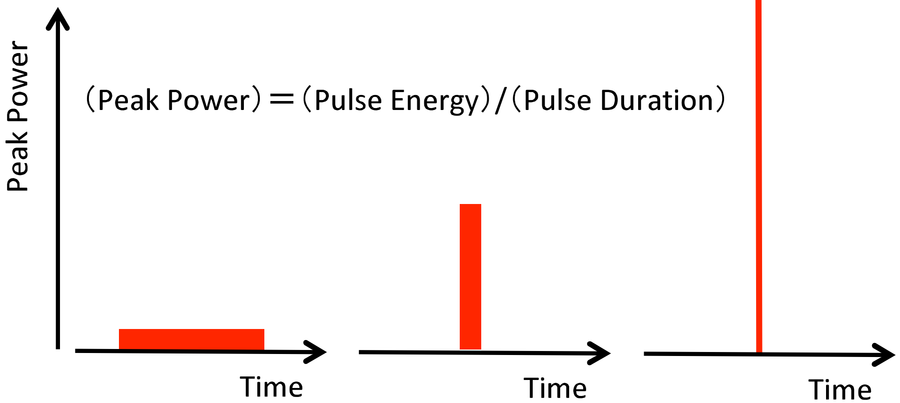
KPSI, QuBS, QST　Kizu area

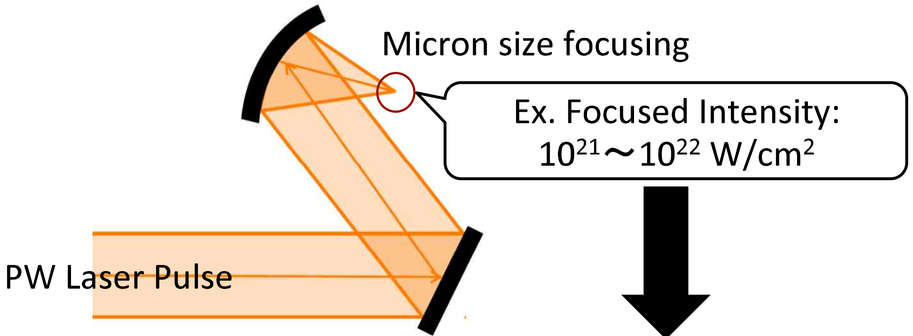
J-KAREN-P　Peak Power: 1 PW　（Peta Watt）

= 1,000 trillion watt　～ 1 trillion hors power









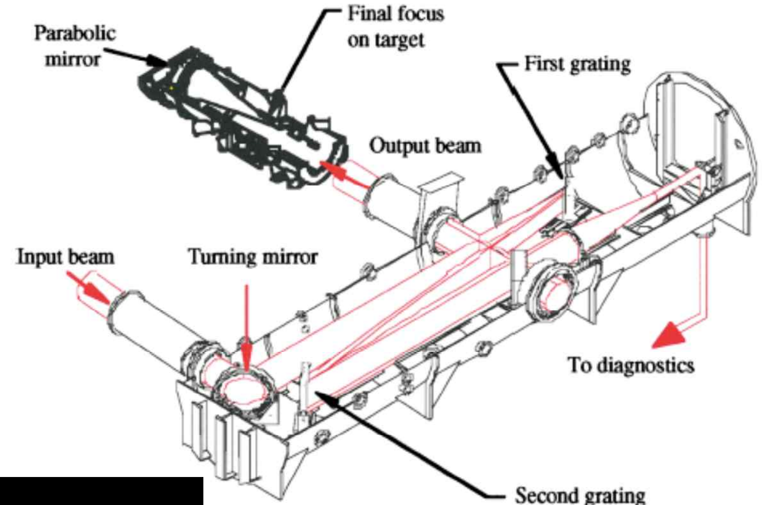
Normalized vector potential: a_0 20～70
→ We can control dense energetic electrons!

10^{15}W (1 PW) peak power was firstly generated with laser system over 10 years ago

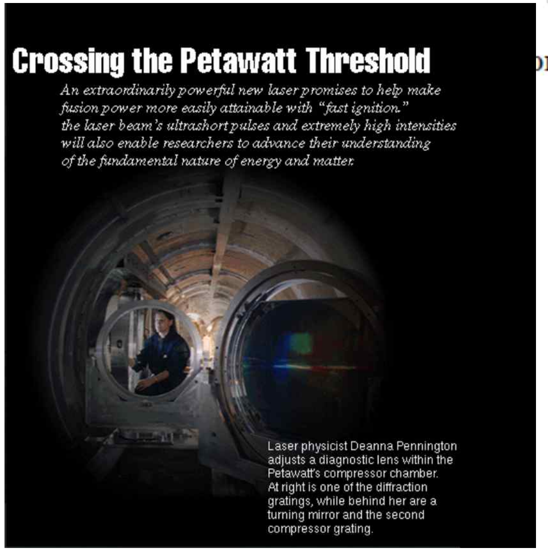
Larence Livermore National Laboratory in USA

M. Perry et al. Opt. Lett. 1999

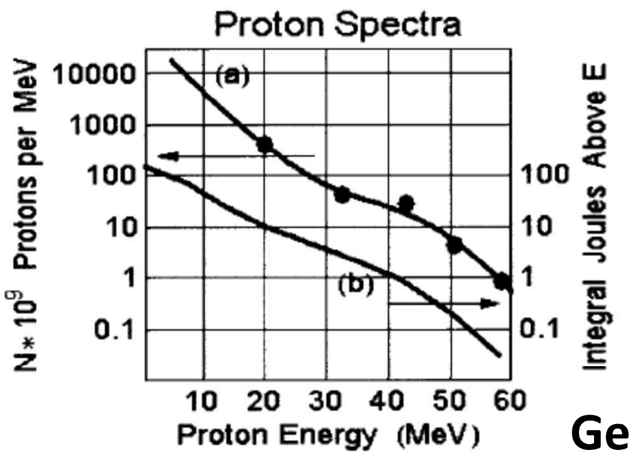
Pulse width : 1 ns → 1ps



ompressor and single-beam target chamber.



Energetic proton beam can be generated with PW laser



R. Snavely et al. Phys Rev. Lett. 2000

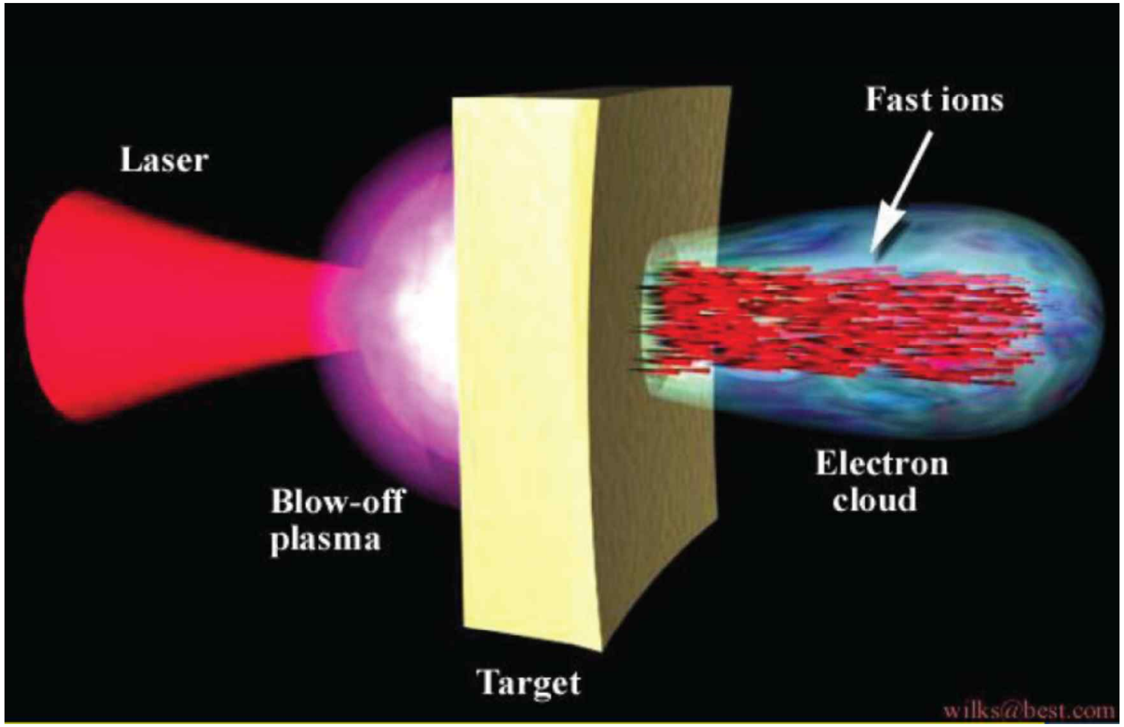
VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids

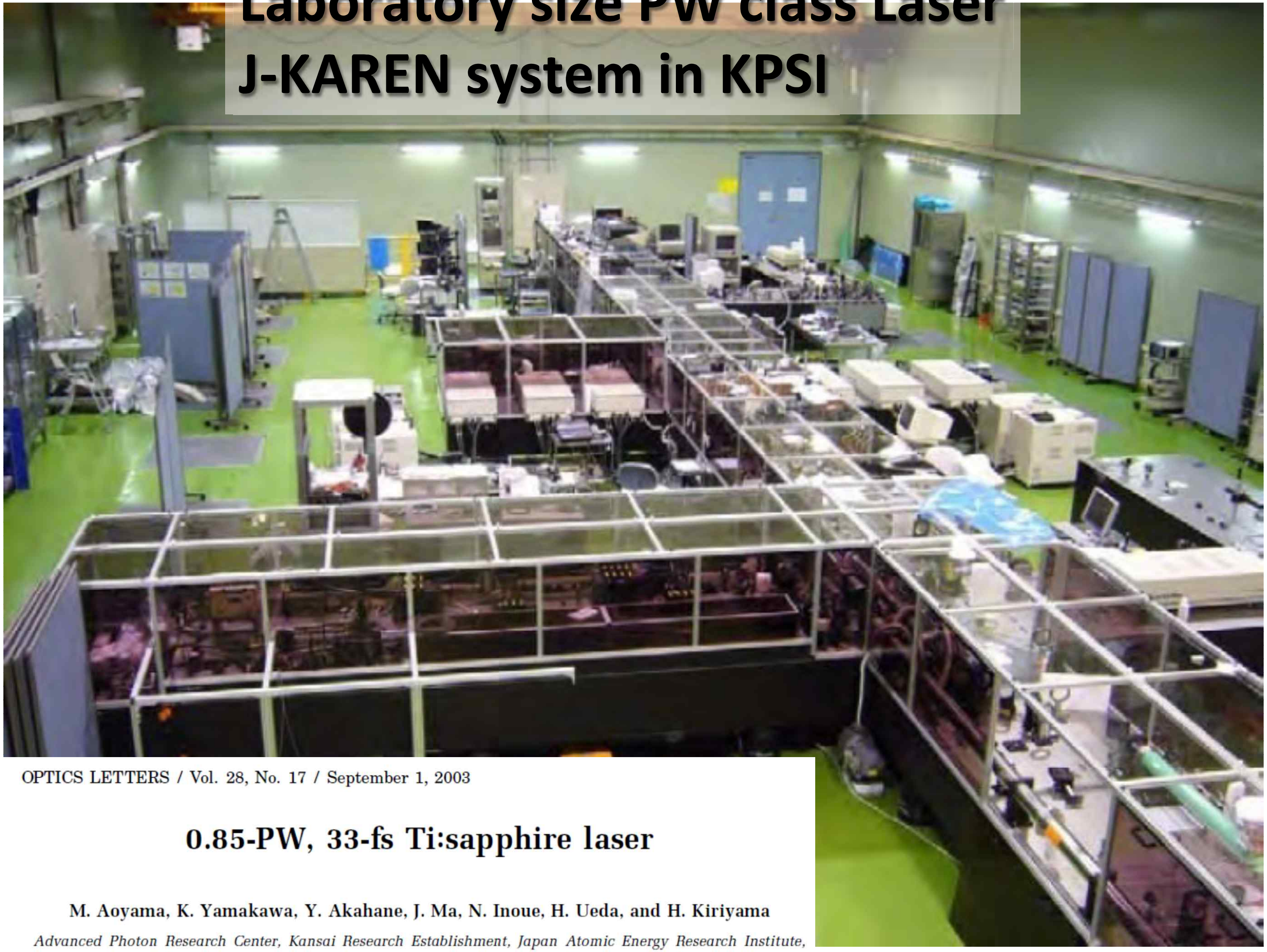
R. A. Snavely,[1,2] M. H. Key,[1] S. P. Hatchett,[1] T. E. Cowan,[1] M. Roth,[3,*] T. W. Phillips,[1] M. A. Stoyer,[1] E. A. Henry,[1] T. C. Sangster,[1] M. S. Singh,[1] S. C. Wilks,[1] A. MacKinnon,[1] A. Offenberger,[4,*] D. M. Pennington,[1] K. Yasuike,[5,*] A. B. Langdon,[1] B. F. Lasinski,[1] J. Johnson,[6] M. D. Perry,[1] and E. M. Campbell[1]

[1] *Lawrence Livermore National Laboratory, University of California, P.O. Box 808, Livermore, California 94550*

Generation of ～60 MeV protons have been observed.



Laboratory size PW class Laser J-KAREN system in KPSI



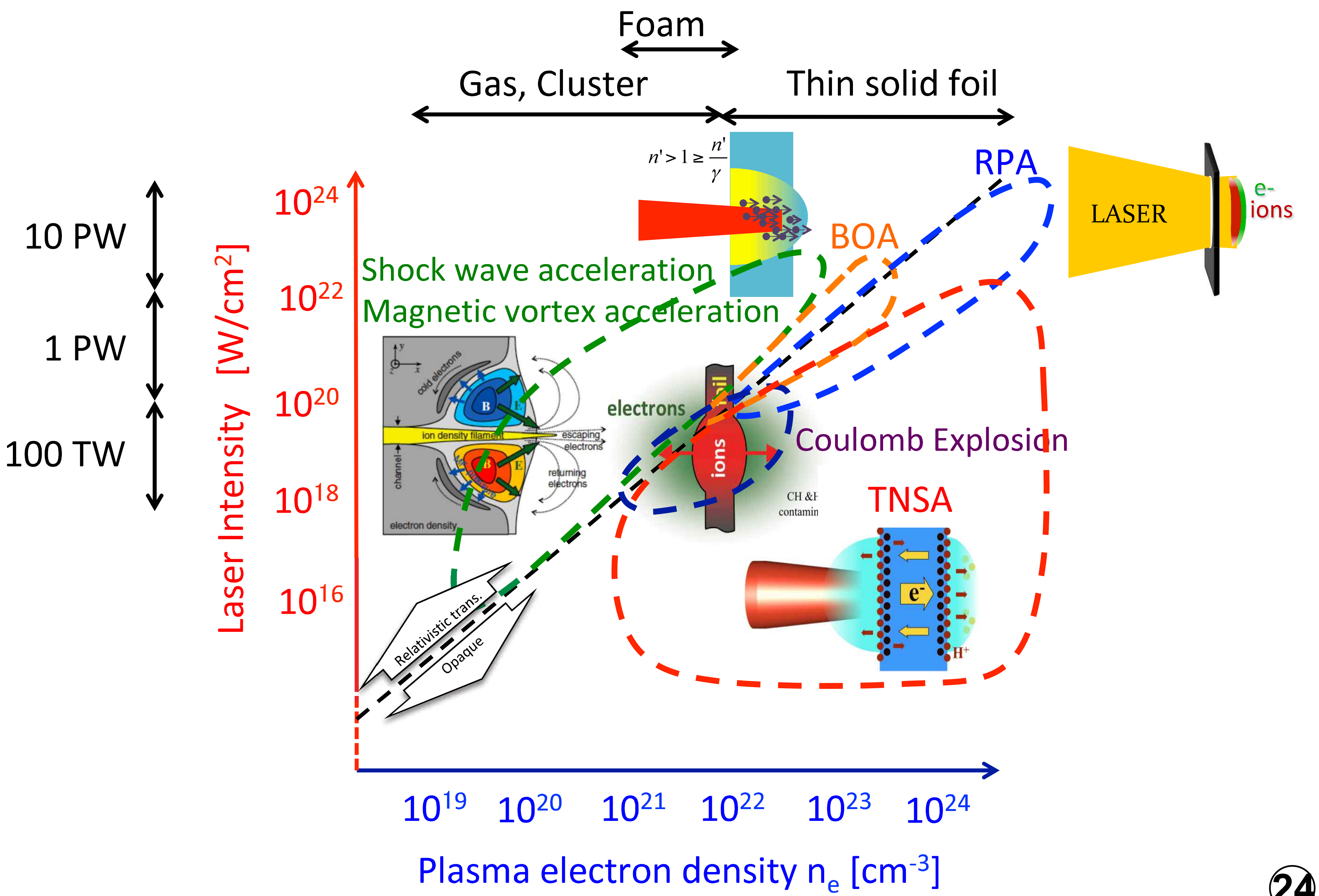
1594 OPTICS LETTERS / Vol. 28, No. 17 / September 1, 2003

0.85-PW, 33-fs Ti:sapphire laser

M. Aoyama, K. Yamakawa, Y. Akahane, J. Ma, N. Inoue, H. Ueda, and H. Kiriyama

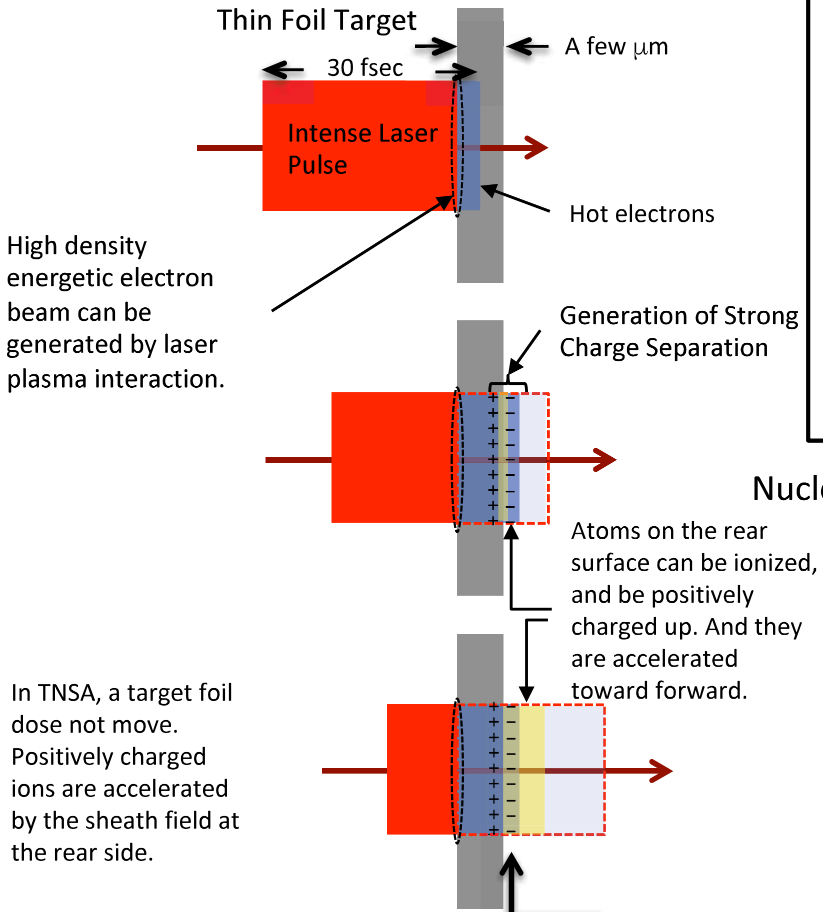
Advanced Photon Research Center, Kansai Research Establishment, Japan Atomic Energy Research Institute, Umemidai 8-1, Kizu-cho, Kyoto, 619-0215, Japan

Laser driven ion acceleration Schemes



Laser driven ion acceleration by TNSA

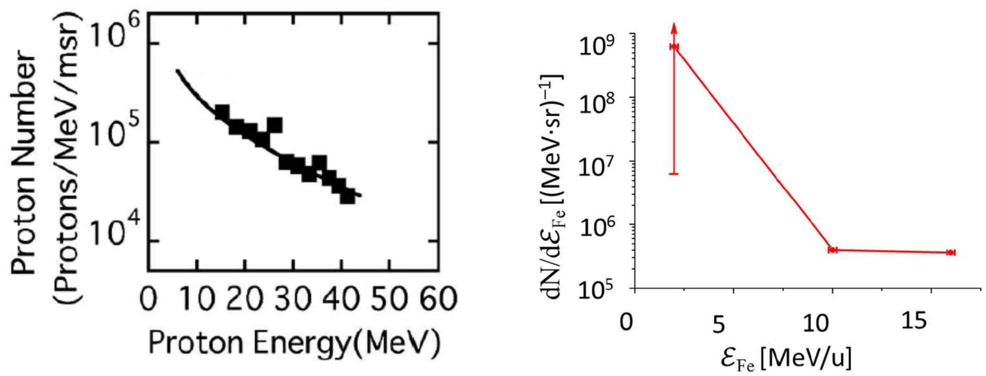
Laser acceleration by TNSA



Old data (0.2 PW、30min. per shot)

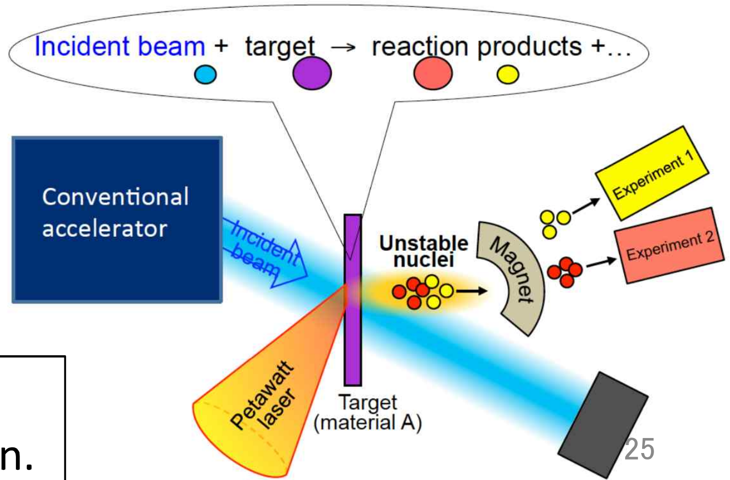
Protons: 2012 OL

Iron ions: 2015 PoP



Nuclear data in a new regime can be obtained with conventional scheme

→ LENex (Laser driven Exotic Nuclei extraction-acceleration method)



100 TV/m class electric field can be generated

→ Heavy ions can be accelerated with highly ionization.

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- ✓ Possibility of the laser acceleration injector for Quantum Scalpel
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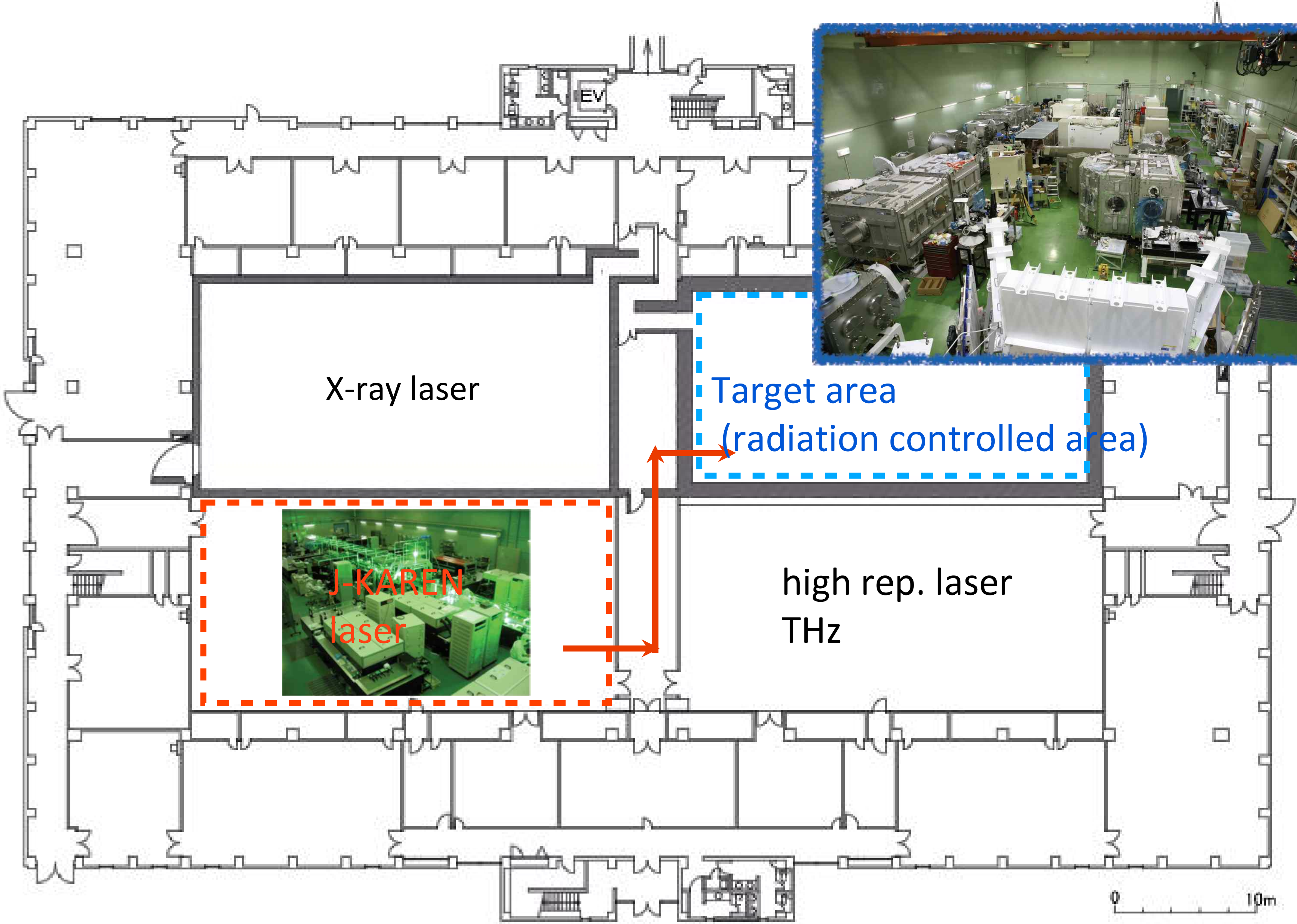
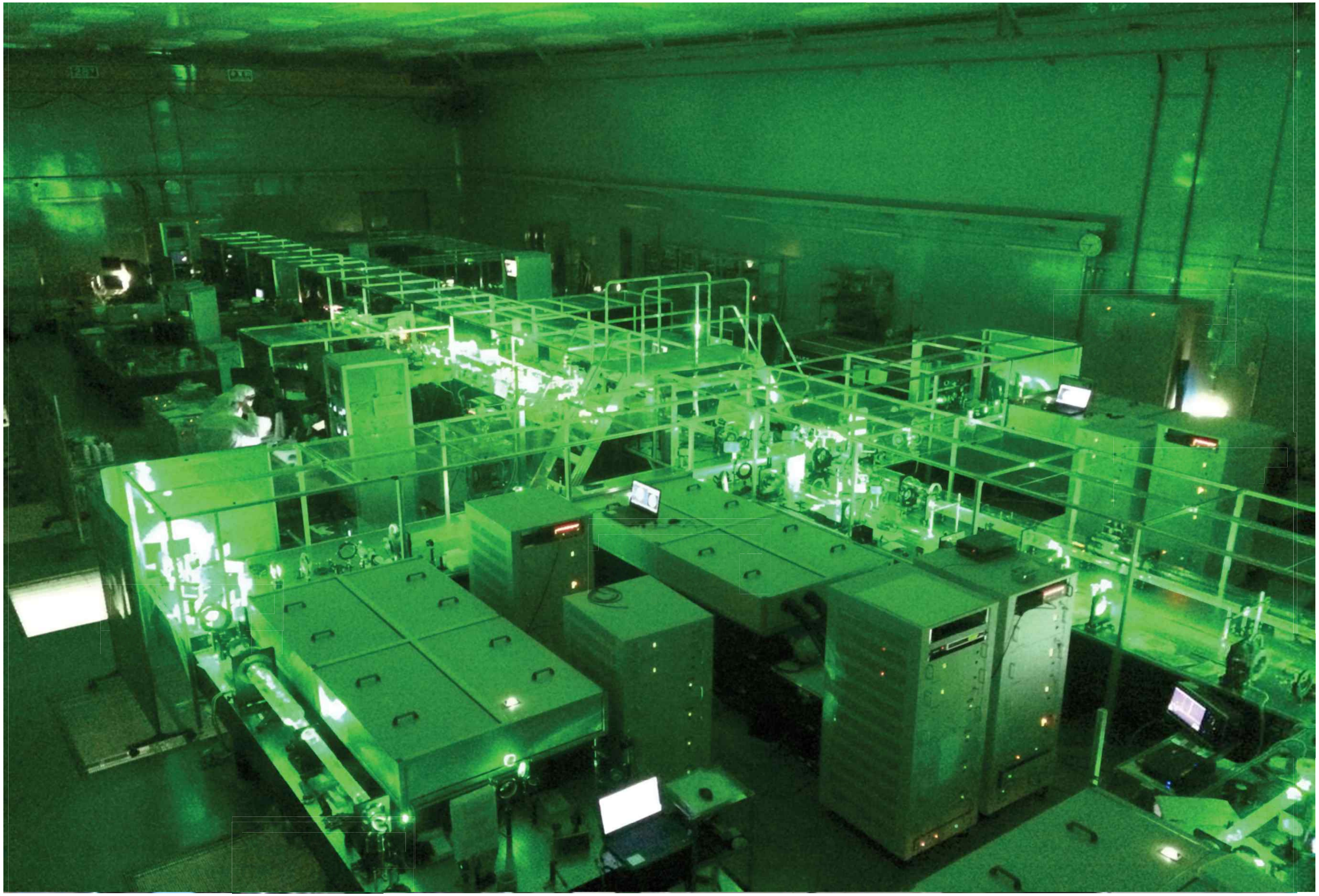
J-KAREN-P

	Previous J-KAREN	**J-KAREN-P**
Peak power on target	200 TW	~ 1 PW
Pulse duration	30 fs	30 fs
repetition rate	0.00056 Hz	0.1 Hz
Contrast ratio	10^{12}	10^{12}
Irradiance on-target	10^{21} W/cm^{2}	10^{22} W/cm^{2}
Beam size	∅150 mm	∅250 mm

Laser and Target rooms at QST



Current view: Laser



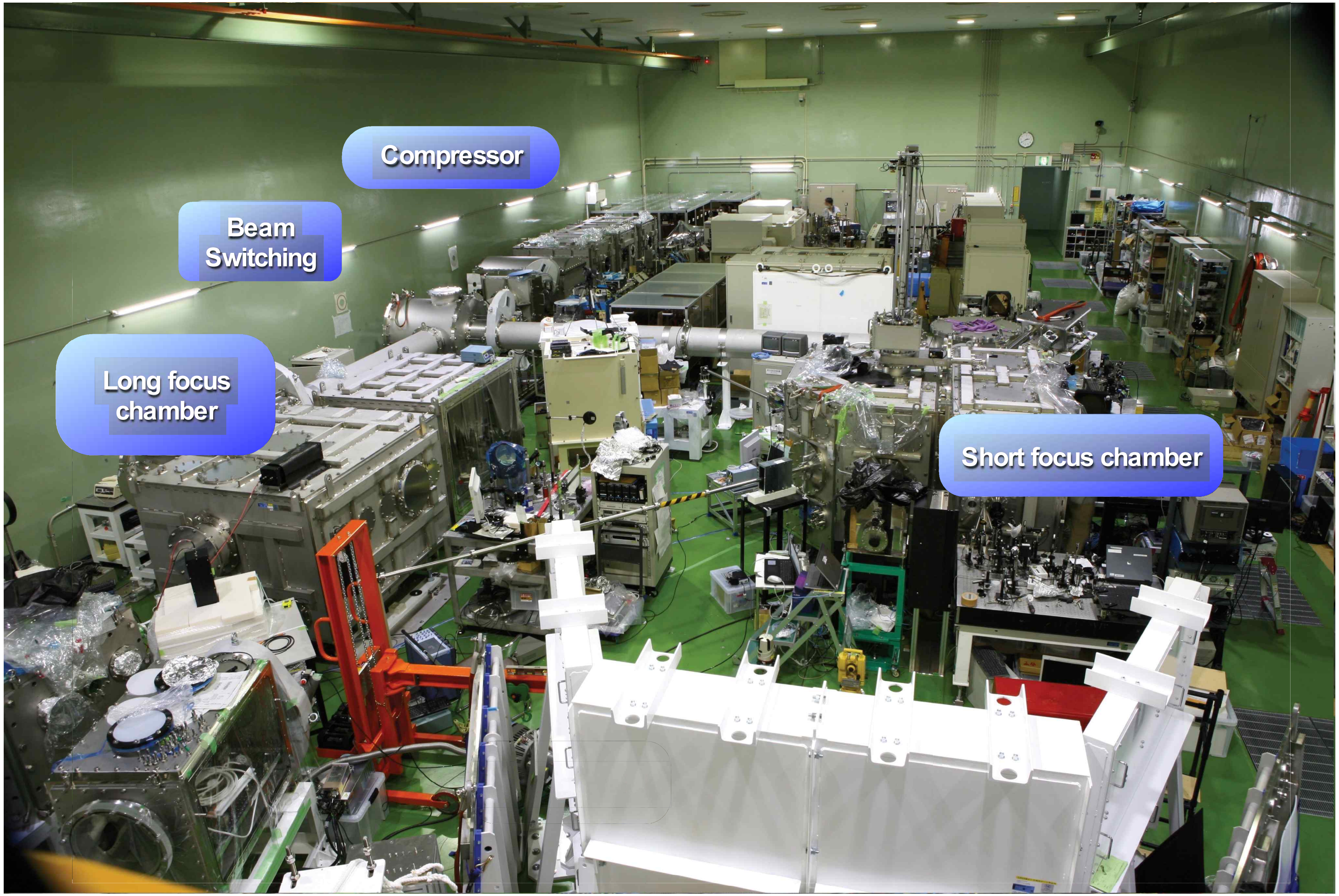
J-KAREN-P

✔ The upgrade of J-KAREN has been started from FY2013. From FY2018, the operation for commissioning and a user mode will be started.

✔ 30 J /30 fsec with 0.1 Hz repetition rate is possible. → 1 Peta Watt

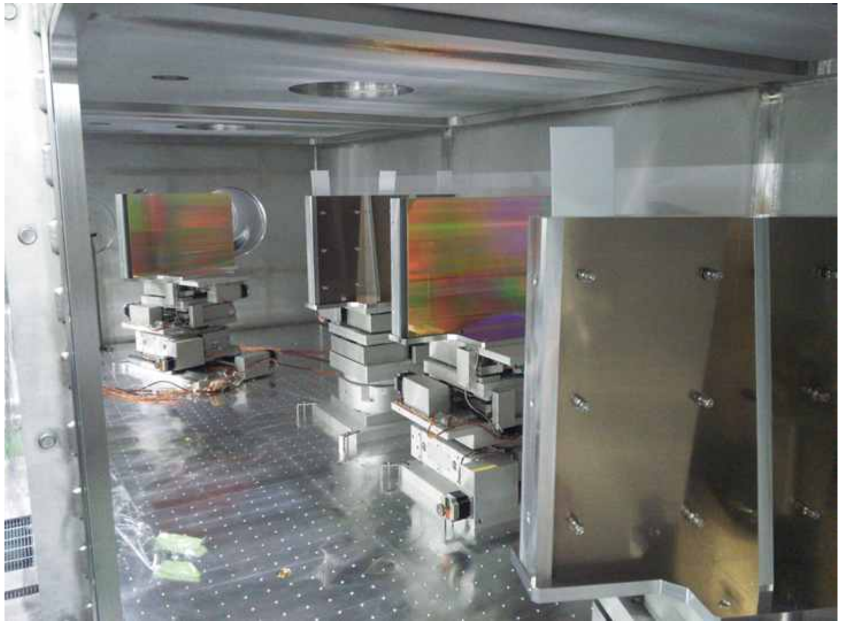
✔ Irradiation intensity of 10^{22} W/cm^2 on target is available.
（Top achievable experimental peak intensity in the world）

Before upgrade G101(2014/March)

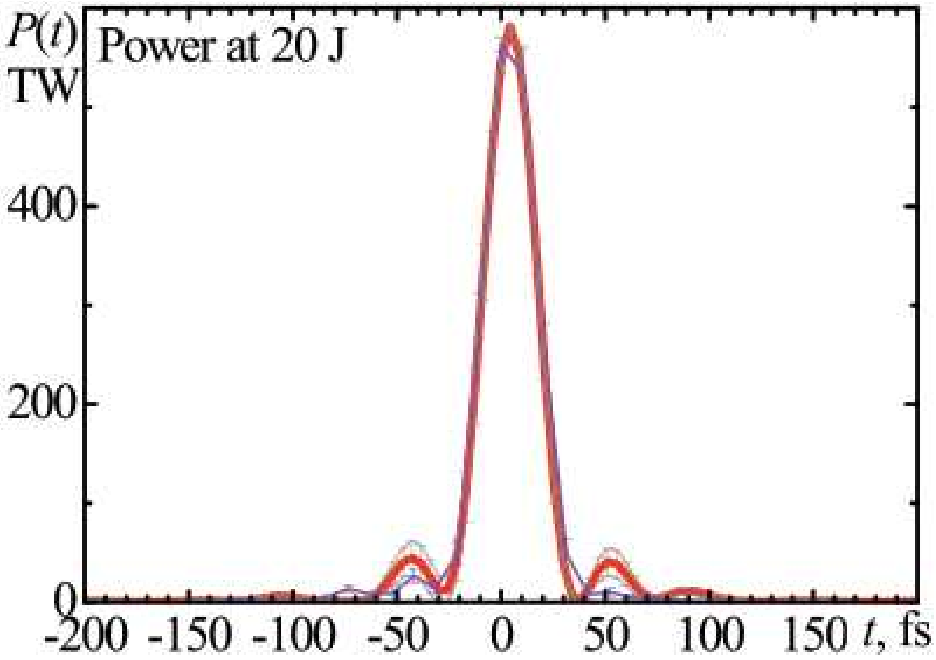


Full system commissioning
Pulse compression

✓ View of the compressor



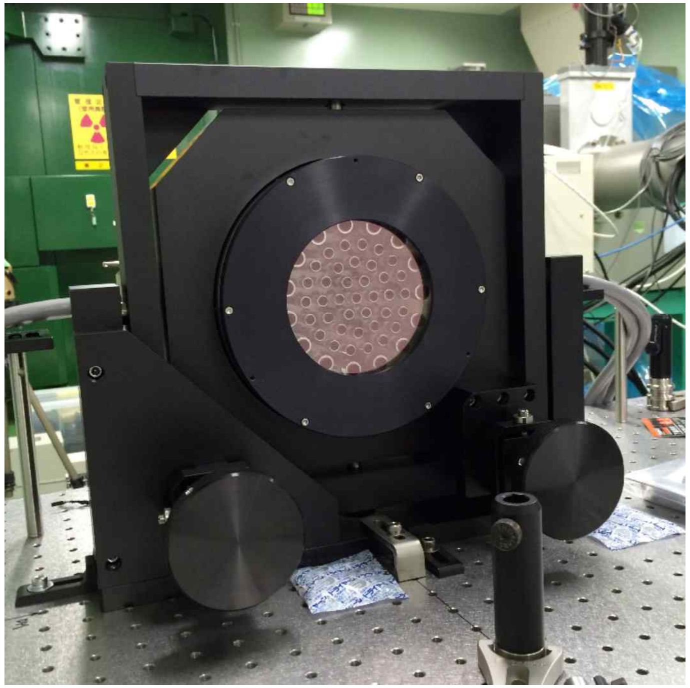
✓ Pulse duration



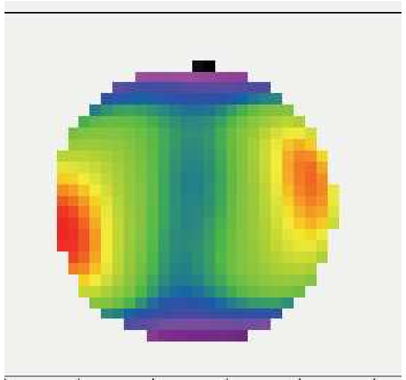
For over 156 single shots, pulses are compressed down to
29.1±0.7 fs (FWHM)
34.3±1.1 fs (Effective width)
,indicating a potential peak power of over PW

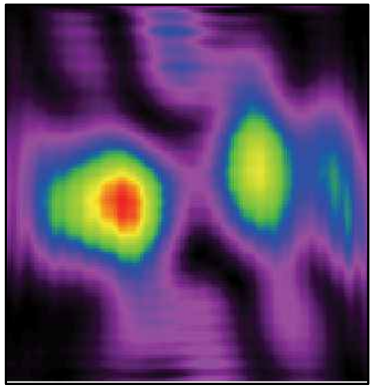
Wavefront correction has been successfully carried out by a 95 mm diameter deformable mirror

✓ View of the deformable mirror



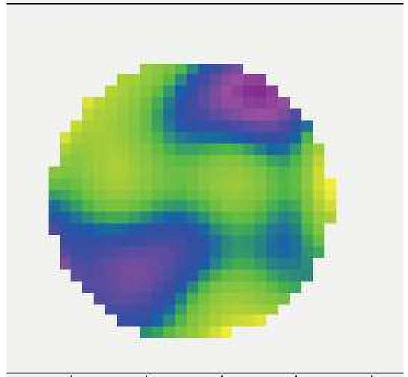
✓ Without correction

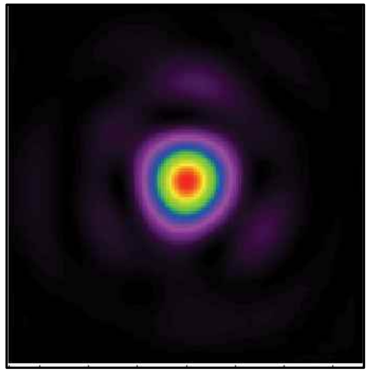




Calculated PSF
Strehl ratio □ 0.12

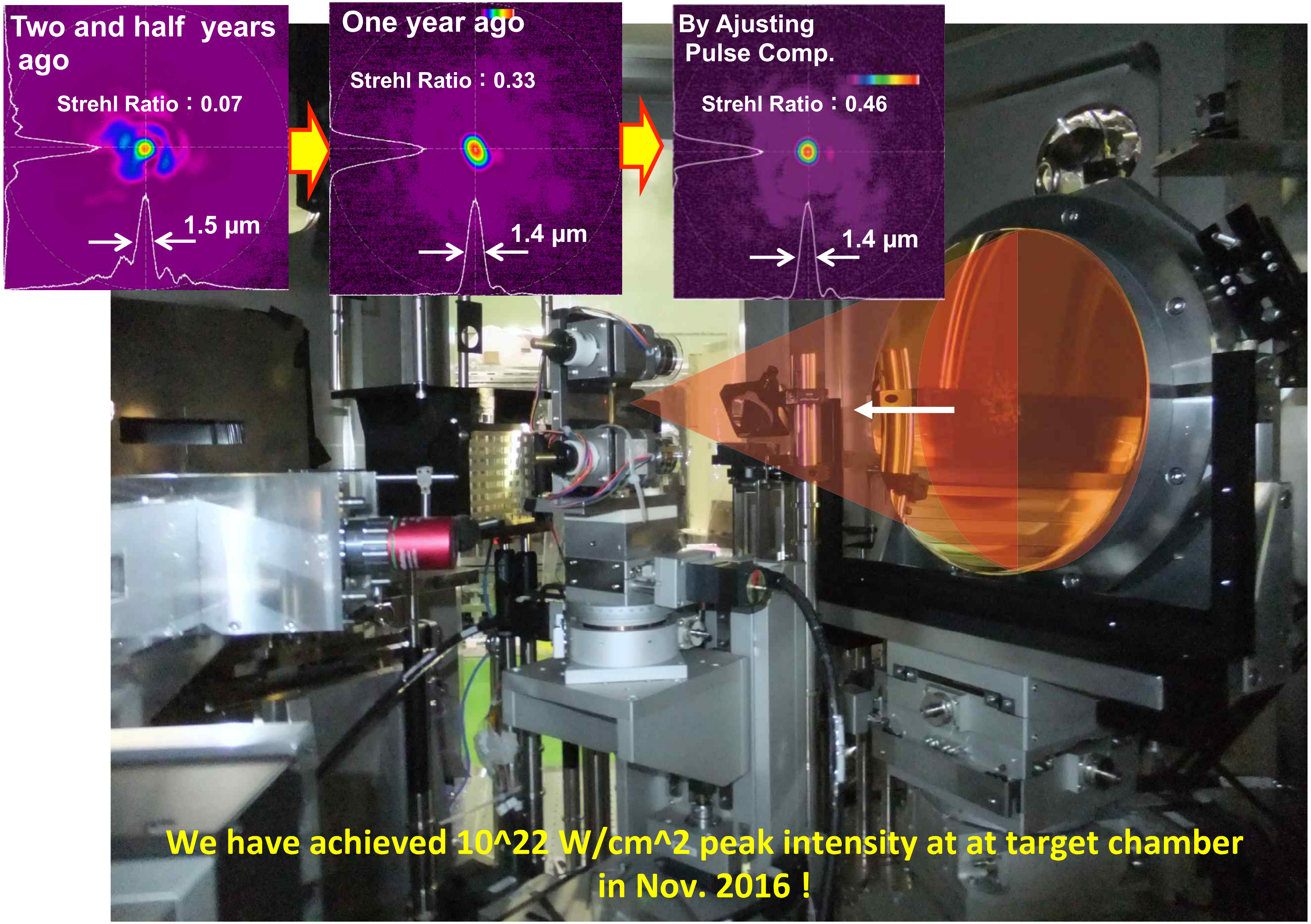
✓ With correction





Calculated PSF
Strehl ratio □ 0.□6

Short-F (F/1.4) target area



Upgrade of J-KAREN-P laser system

goal and achievement of the laser performance on target

	J-KAREN previous	J-KAREN-P Final goal
Peak power on target [PW]	0.2	1
Repetition rate	1shot every 30min.	0.1 Hz
Peak intensity on target [W/cm^2]	10^{21}	10^{22}
Temporal contrast	10^{-11}	10^{-12}

Nov 2016	Mar 2017	Effects on ion acceleration
0.25	0.25	higher max energy
0.1Hz	0.1Hz	Higher flux per unit time
Max $1\text{x}10^{22}$	Max $5\text{x}10^{21}$	higher max energy(higher Z)
10^{-11}	10^{-11}	Achieve shot thin foil (higher efficiency, RPA??)

Used for ion acceleration exp.

Contents

5^{th} generation heavy ion cancer therapy machine Ⅱ

5^{th} generation ion cancer therapy machine（This could be realized 10 years after.）

Compact Quantum Scalpel with a power laser technology which can be placed on one floor in a big hospital.

Ion species： Helium, Nitrogen, Carbon, Oxygen, Neon etc.

Synchrotron： ～7m in dim., Building size： 20m x 20m （in hospital）

Irradiation device： Gantry scanning

Spec requirement to laser driven ion injector

Ex.：Ion energy: > 4 MeV/u

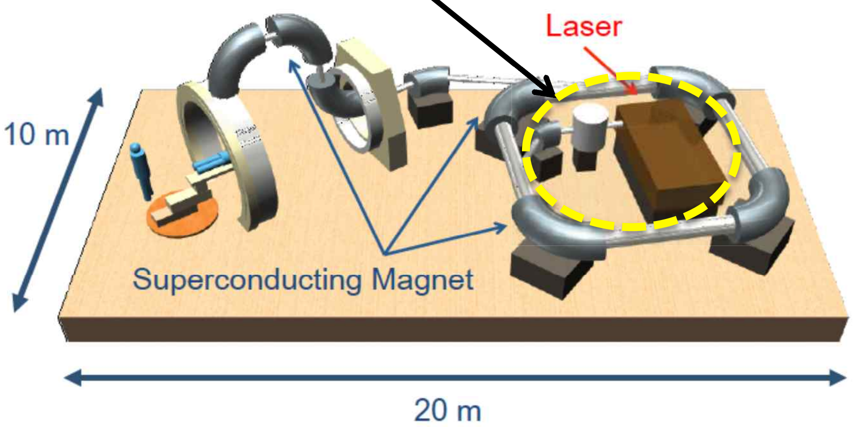
Rep. rate: > 1 Hz, < 1 kHz

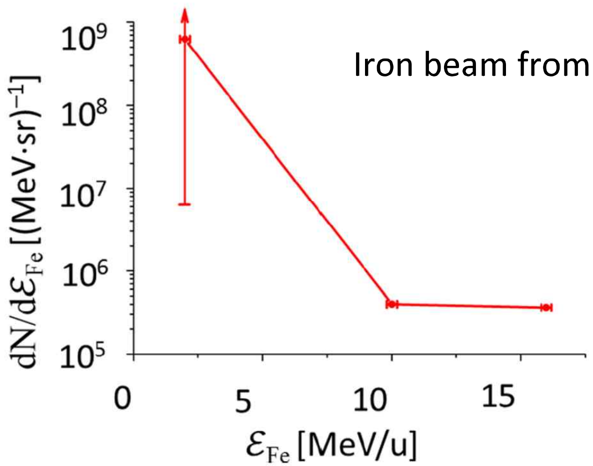
Number in 1 % b.w. : >10^9 in 2 sec

10 Hz → >10^8/shot in 10 % b.w.

→ >10^8/shot in 1 % b.w. with Phase Rotation

Laser driven injector should be placed inside the synchrotron ring.





Scenario of Quantum Scalpel treatment

Laser-acceleration injector

- High rep rate high power laser ← 10 Hz, PW class power laser
- ↓
- High energy highly charged ion generation by LPI ← 2×10^9 Carbons @4 MeV/u in 2sec, ±10%b.w.
- ↓
- Medium energy beam transport section (MEBT) ← With debancha, etc. 2×10^9 Carbons@4 MeV/u, ±1%b.w.

↓

Synchrotron accelerator

Injected 2×10^9 Carbons are accelerated to the necessary energy during 5 sec, and are ejected to gantry.

⇓

Gantry

Spot scanning treatment ～10 sec from laser irradiation（1time）
100 cc class tumor can be treated with 1 time

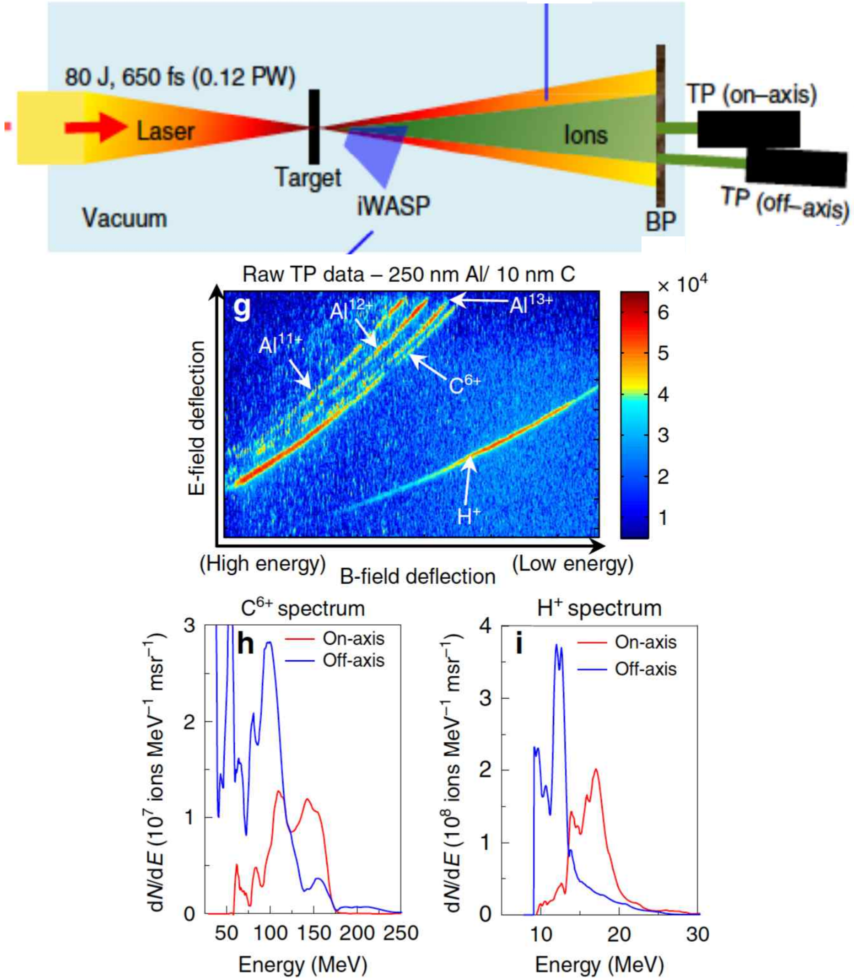
⇓

Patient

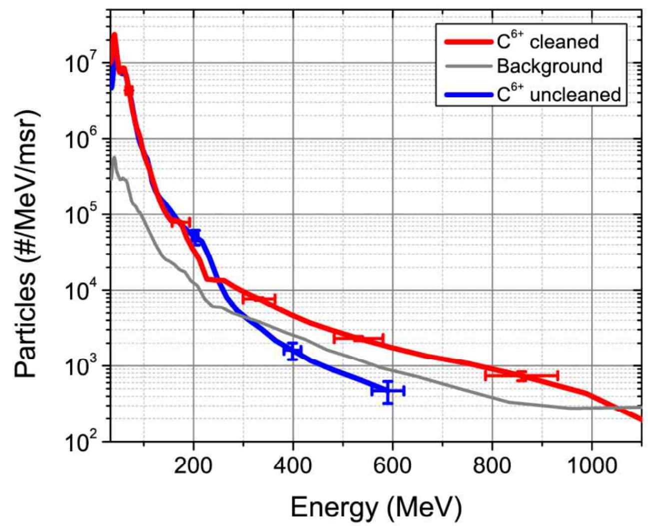
To treat over 100cc tumor, multi-time spot scanning is performed
Ex. One liter tumor: 10 times → 100 sec（～2 min）

High yield experiment for laser driven heavy ion acceleration

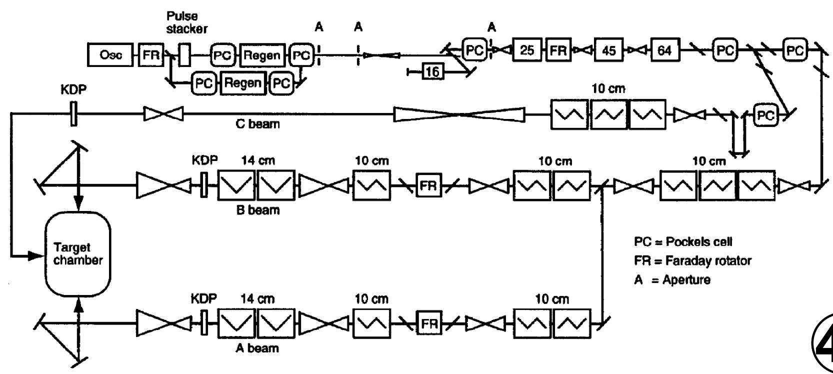
S. Palaniyappan, et al., Nat. Comm., **6** 10170 (2015).
80 J/650 fs Nd: Glass CPA laser @LANL (US)
Max 18 MeV/u Al ion generation
With 5 % energy conversion efficiency



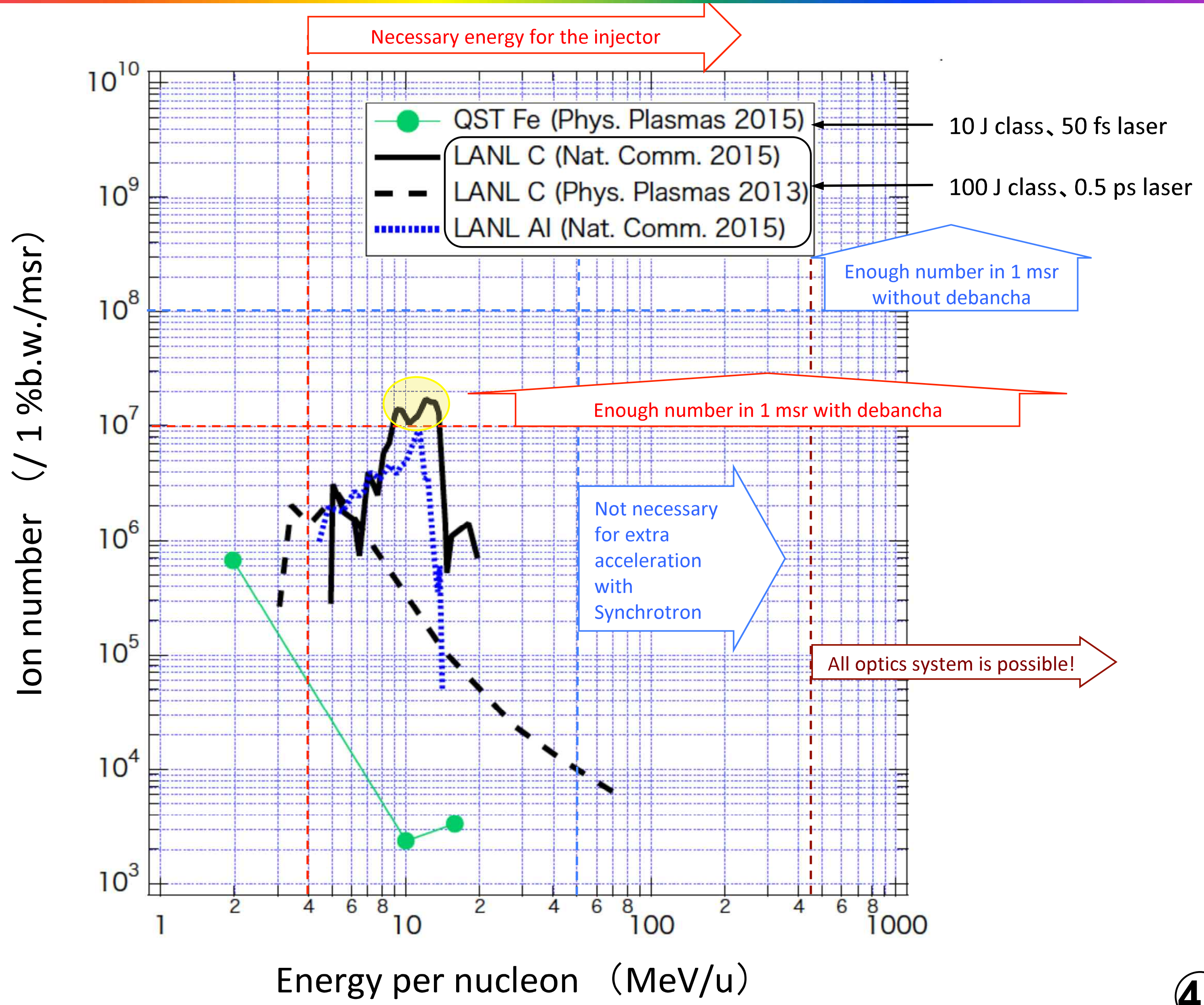
D. Jung, et al., Phys. Plasmas **20**, 083103 (2013).
80 J/650 fs Nd: Glass CPA laser @LANL (US)
1 GeV Carbon acceleration with a heated DLC foil



LANLのTrident Laser 80 J/650 fs



Possibility of the injector for Quantum Scalpel Ⅰ

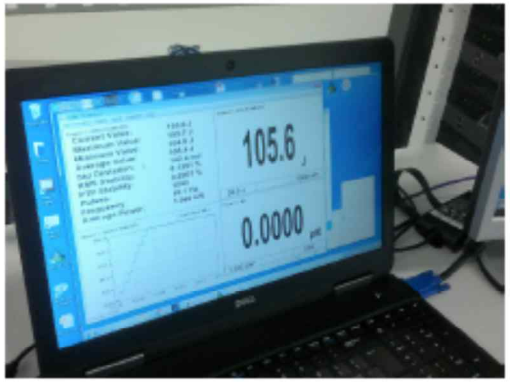


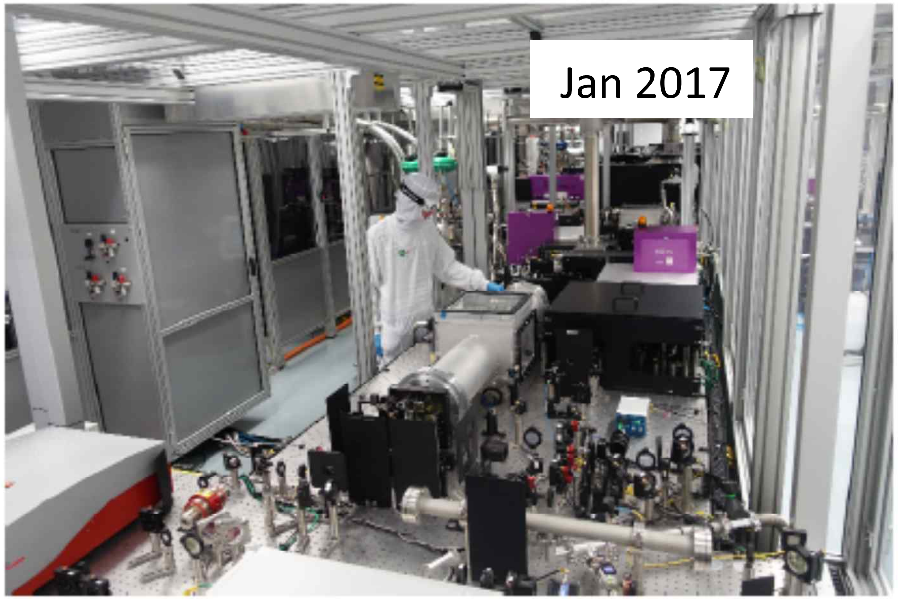
Possibility of the injector for Quantum Scalpel Ⅱ

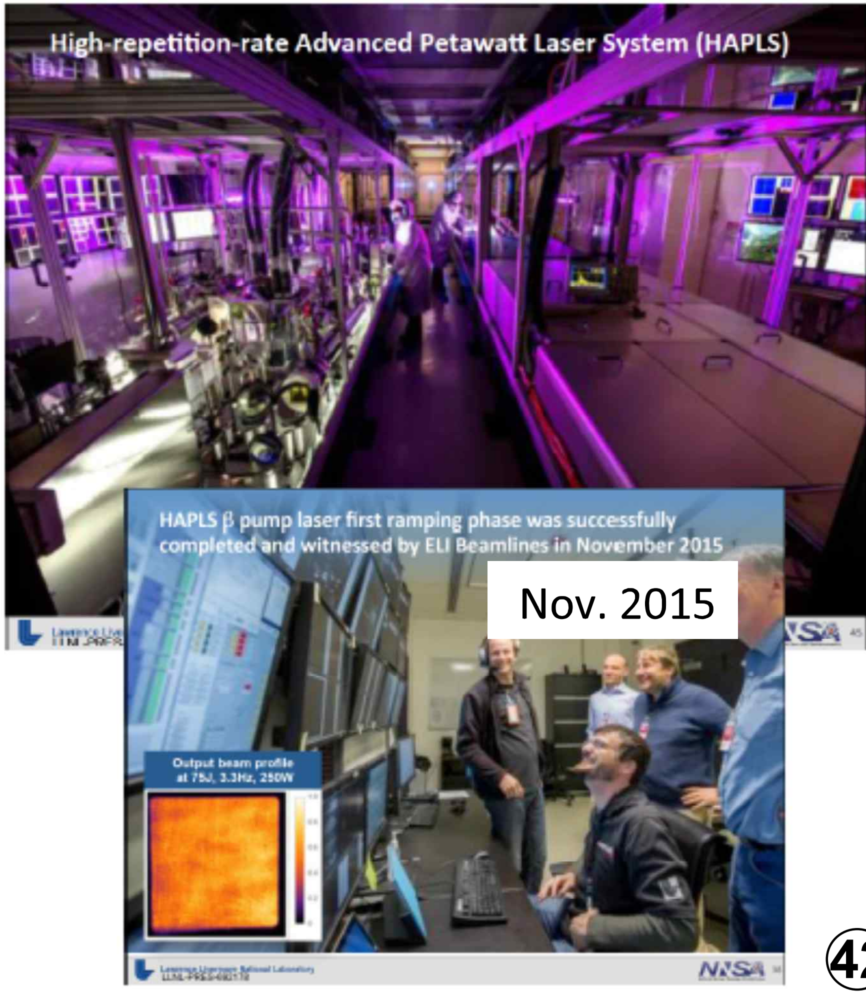
100 J/10 Hz Yb:YAG laser developed in RAL(UK) has been operated at HiLASE (Czech Republic)
→ 1kW

Opt. Lett. **41** 2089 (2017)

Glass laser for pumping 1 PW/3.3 Hz Ti:S laser HAPLS developed in LLNL（US）has been operated with 105 J/3.3 Hz
→ 350 W







A new fund for laser acceleration study has been started from Nov, 2017.

JST-Mirai R&D Program (Large scale Type)

Japan Science and Technology Agency（JST）

5 M€/year x 4 years → stage gate
+(6.6 M€+1.65M€ from companies) x 6 years
→ Total 70 M€ project

This project includes not only ion accelerator development, but also electron accelerator development and power laser development.

Summary

- ✓ In Japan, a new generation heavy ion cancer therapy machine, so called Quantum Scalpel, is started to be developed with 4 big companies by QST.

- ✓ Recent activity of ion acceleration study with upgraded J-KAREN has been introduced.

- ✓ The rough design of the laser acceleration injector for Quantum Scalpel has been shown.

- ✓ For injector development, 70 M€/10 years project has been started from Nov, 2017 for laser accelerator R&D including electron accelerator development and power laser development in Japan.