FAST IGNITION LASER FUSION ENERGY RESEARCH IN JAPAN

- Summary of the progress of laser fusion research in Japan
- Novel approach of the implosion for the Fast Ignition scheme
- Physics of Isochoric Heating of the imploded plasma
- Prospects for the next stage of laser fusion research in Japan
- Summary

Ryosuke KODAMA
Institute of Laser Engineering, Osaka University

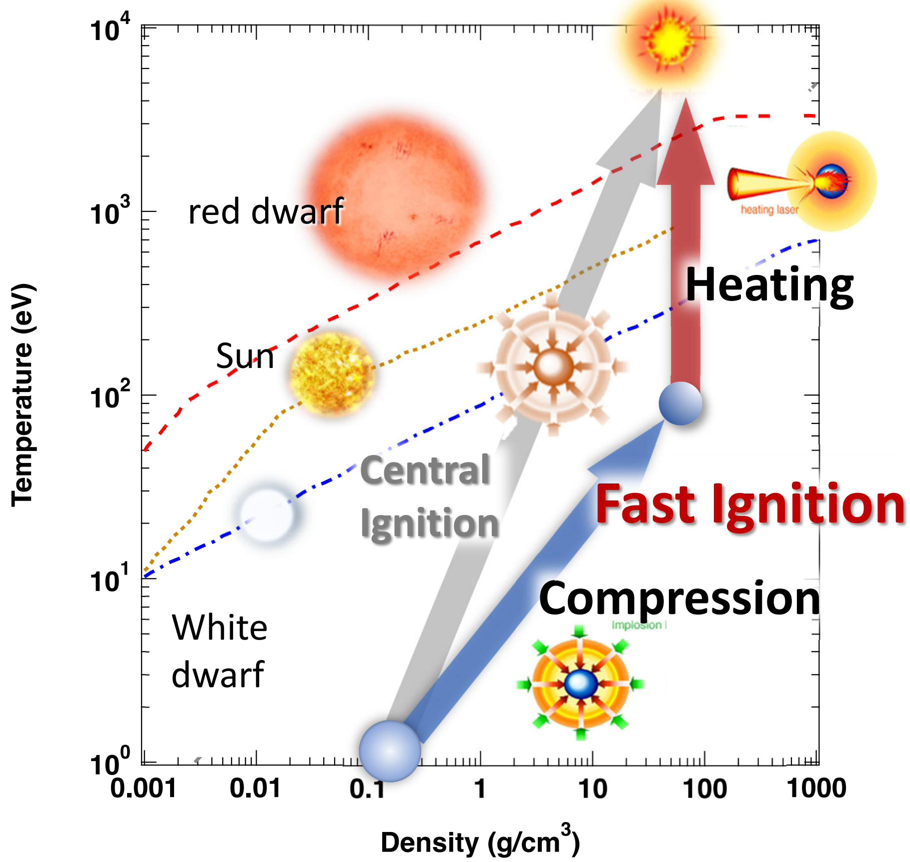
Summary of Laser Fusion Research Achievement in Japan

- ✓ At ILE Osaka, the required temperature and density conditions have been achieved individually with a central ignition scheme.

1986 High Temperature Implosion for fusion
(**10keV**)
(C.Yamanaka et al., Nature 1986)

1991 High Density Implosion for fusion
(**600 to 1000 times** the solid density)
(H. Azechi et al., Laser Part. Beams 1991)

➢ **Approaching with a Fast Ignition Scheme for opt. of the density and the temperature**



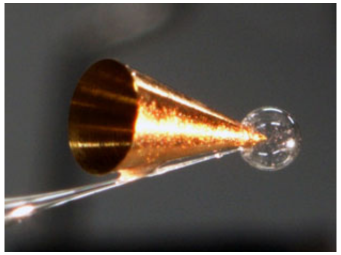
FIREX campaign FIREX: Fast Ignition Realization Experiment

2001 Proof of principle for the Fast Ignition Scheme
(e.g. R. Kodama et al., Nature 2001)

2020 Investigation of the heating Physics and demonstration of >10 times high efficiency than the central scheme
(e.g. K Matsuo, et al., Phys. Rev. Lett. 2020)

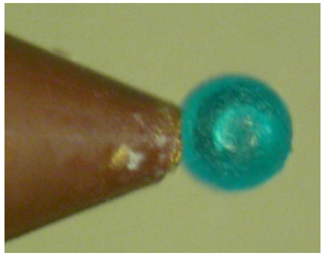
Fast Ignition scheme has achieved the same level of Fusion Product with less than 1/10 of the energy of the Central Ignition Scheme.

Advanced and unique target design



Efficient heating
with an entrant cone target

R. Kodama et al., Nature (2001)
S. Sakata et al., Nature Commun. (2018)
K. Matsuo et al., Phys. Rev. Lett (2020)



Stable implosion
With a solid ball target

S. Fujioka et al, Phys. Rev. E, (2015)
H. Sawada *et al.,* APL (2016)

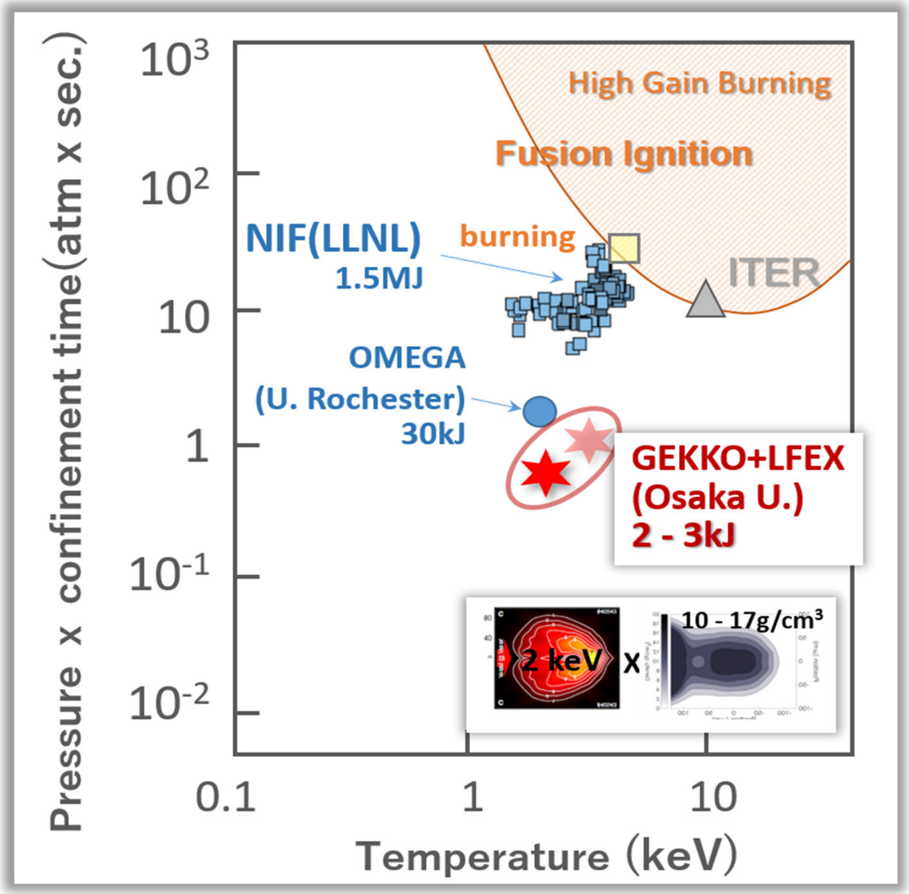
Laser Facility for Fusion Research in Japan

Multi-kJ/ns laser **GEKKO-XII**

+

kJ/short pulse laser **LFEX**

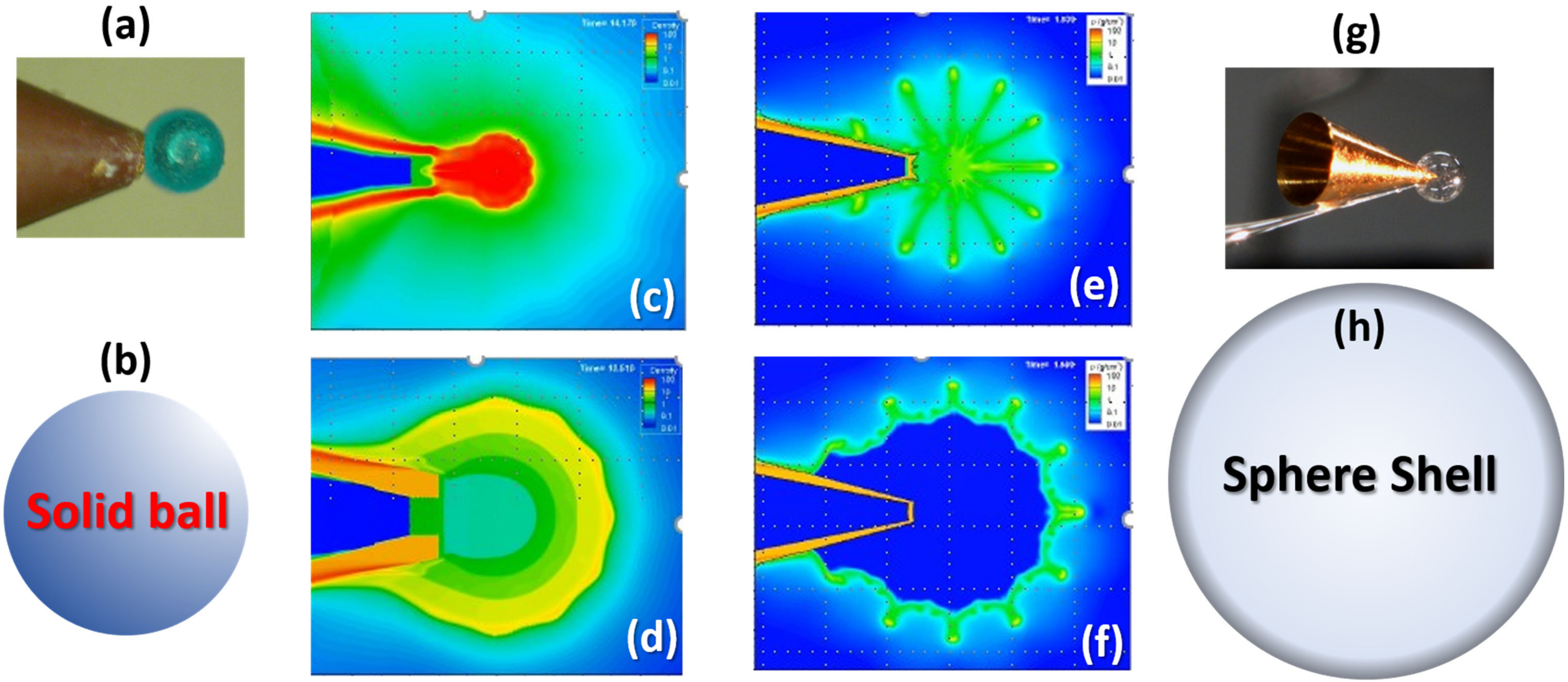
Investigation of detailed physics and demonstration of efficient heating



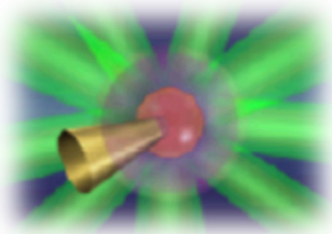
K Matsuo, *et al.,* Phys. Rev. Lett. 124, (2020) 035001

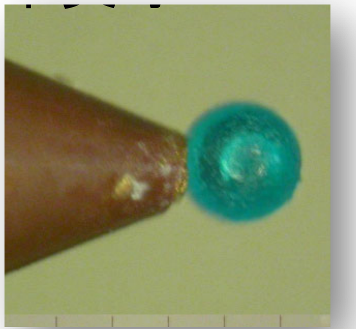
Stable implosion that can only be achieved with a Fast Ignition Scheme! -Implosion of a solid sphere -

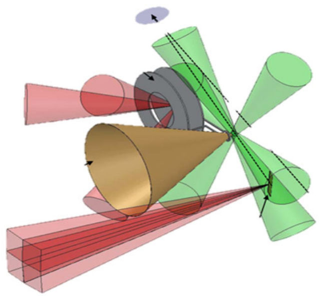
- **Hydrodynamically stable fuel implosion (free from one of the difficulties of laser fusion)**
- **Insensitive to beam balance (timing), stable implosion can be expected.**
- **Target design allows for efficient diffusive heating**
- Relatively easy fabrication of fuel spheres

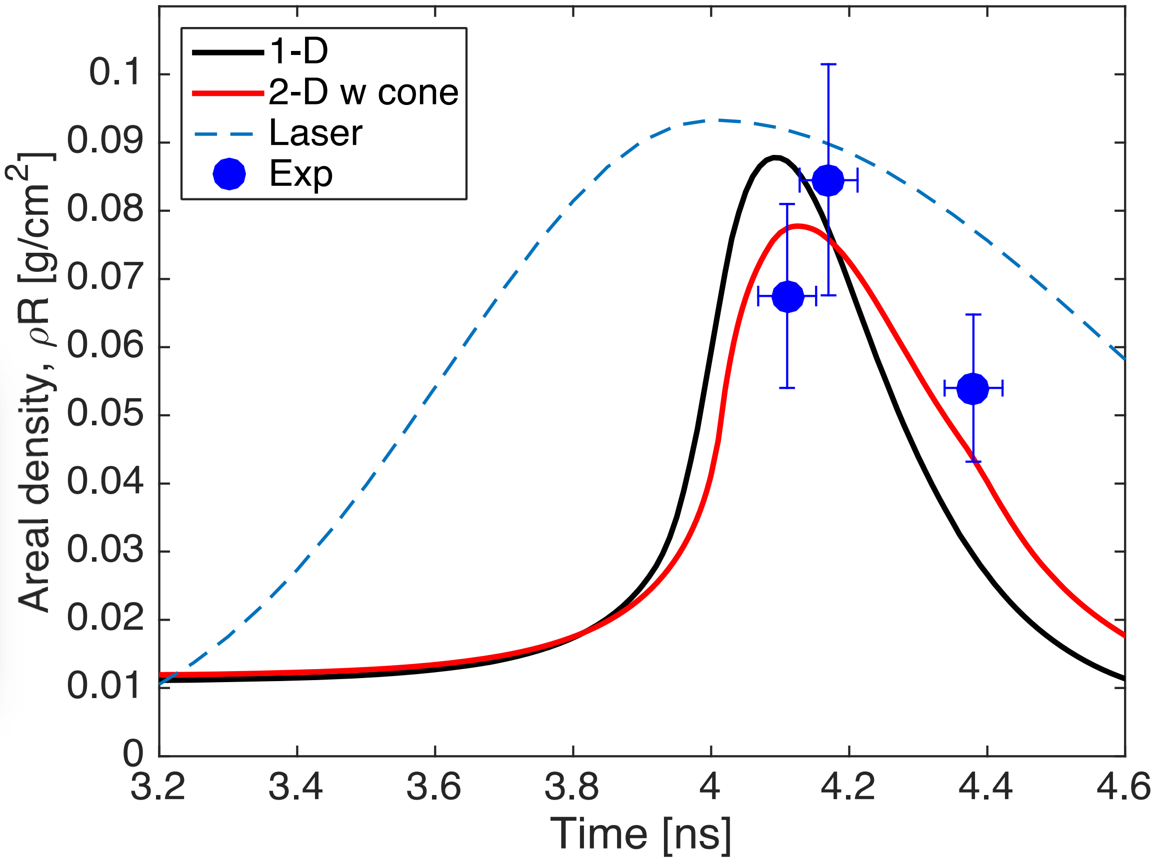


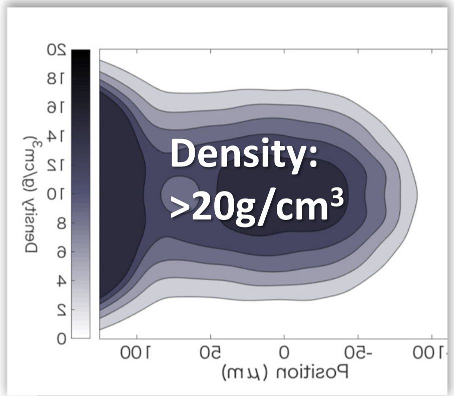
The solid sphere demonstrated much more stable implosion compared to the shell.

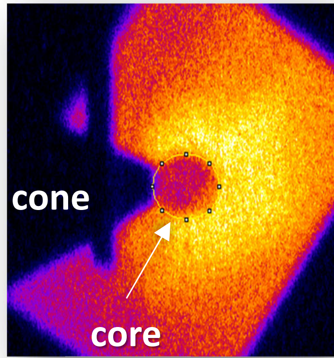


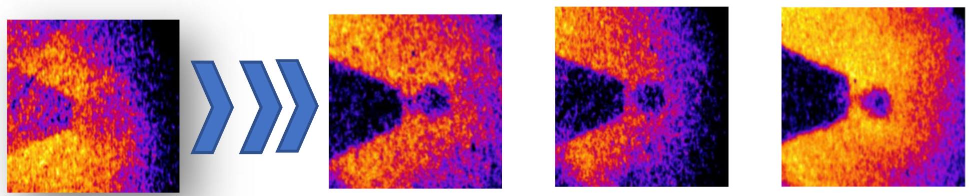






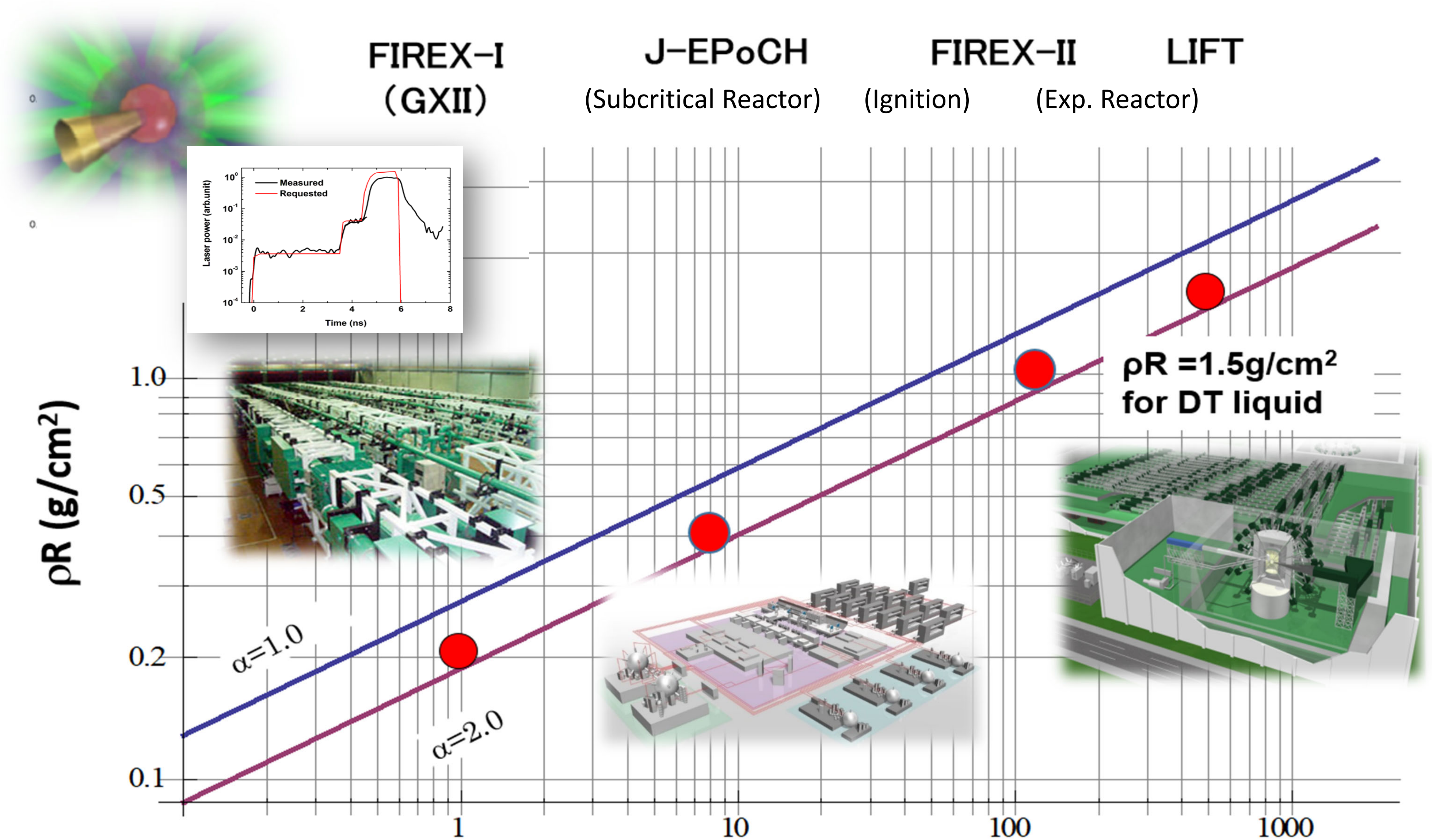






H. Sawada et al., *Appl. Phys. Lett.* **108**, (2016) 254101

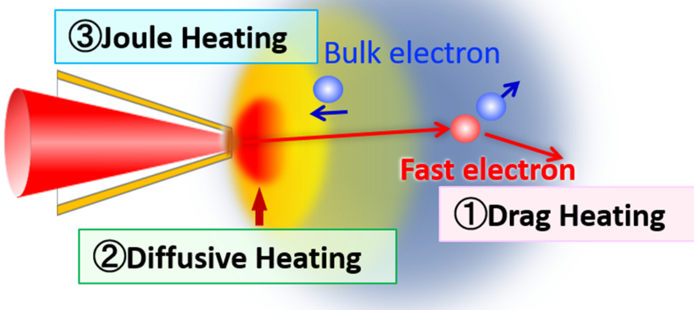
Laser fusion reactor with the fast ignition scheme will be feasible with the solid sphere target (2D simulation)



H. Nagatomo et al., *Nuclear Fusion* **59**, 106055 (2019)

Drag heating efficiently heats the dense area, while diffusive heating heats the area close to the laser irradiation.

Heating mechanism is not simple, nor is it a unique process.



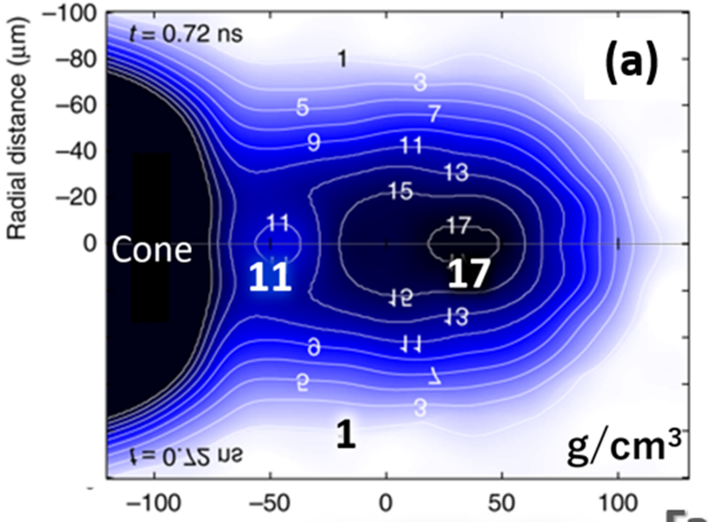
$$\frac{3}{2} n_e \frac{\partial T_e}{\partial t} = \underbrace{\frac{3}{2}\frac{n_h T_h}{\tau_e(T_h)}}_{①} + \underbrace{\frac{\partial}{\partial x}\left(\kappa(T_e)\frac{\partial T_e}{\partial x}\right)}_{②} + \underbrace{\frac{{j_h}^2}{\sigma(T_e)}}_{③}$$

① Increase in the coupling efficiency with the density of the compressed plasmas
② Increase in the coupling efficiency with the pulse duration of heating
③ Insufficient range for compressed-plasma heating

J. Kemp, Y. Sentoku et al., Phys. Rev. Lett. **97**, 235001(2006)

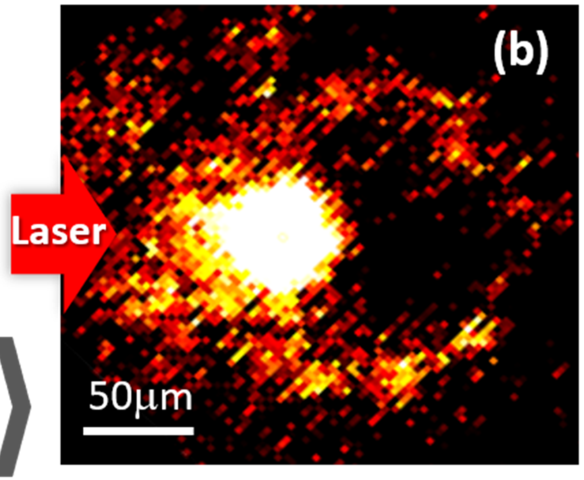
at Max. Implosion

Density contour



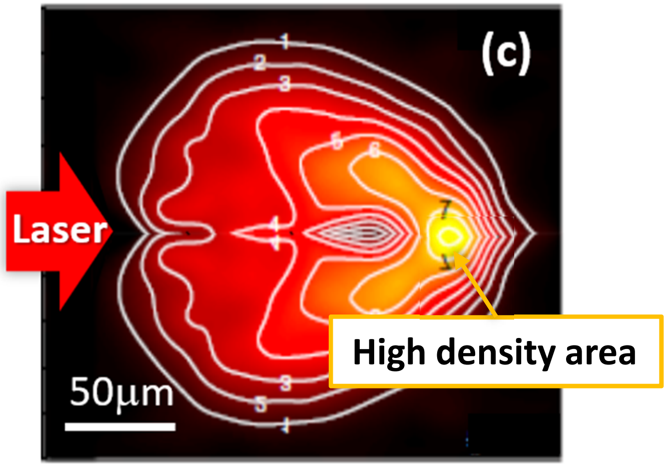
Diffusive heating area

Cu-Heα & Lyα lines



Drag heating area

Cu Kα



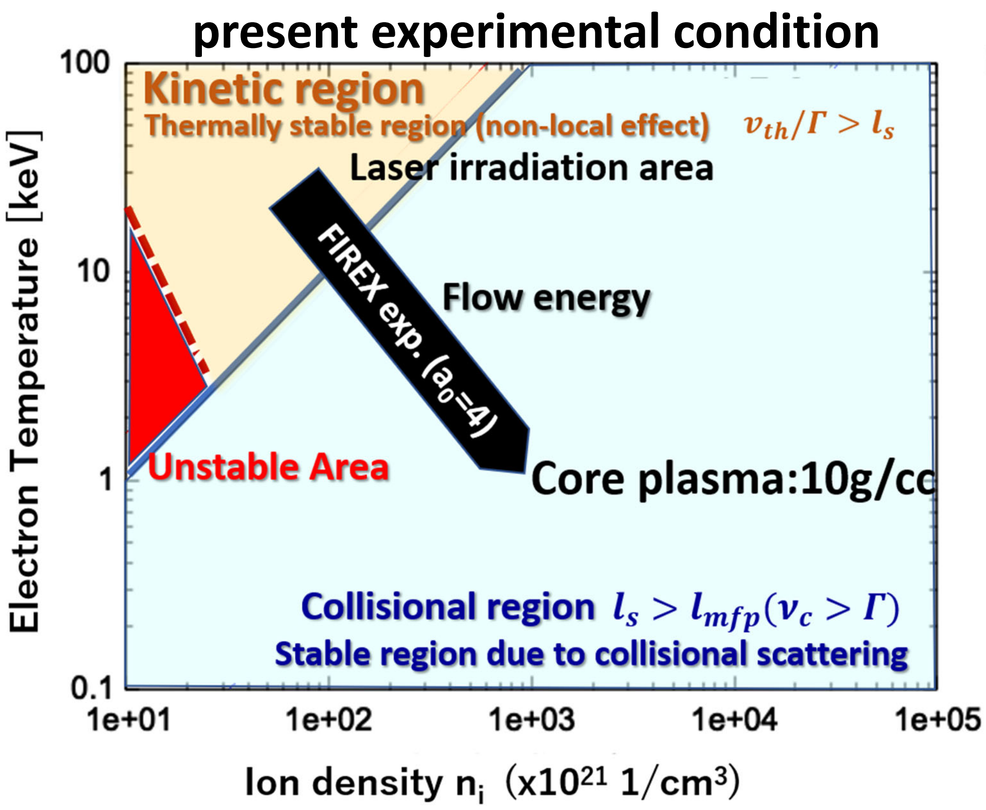
Fast heating

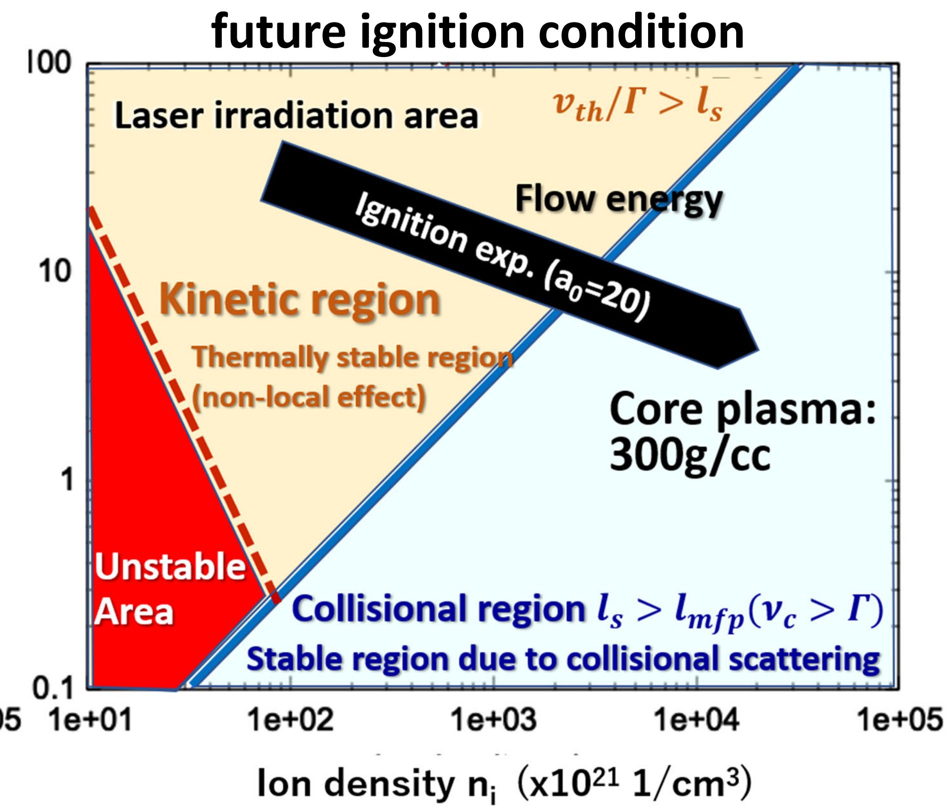
implosion

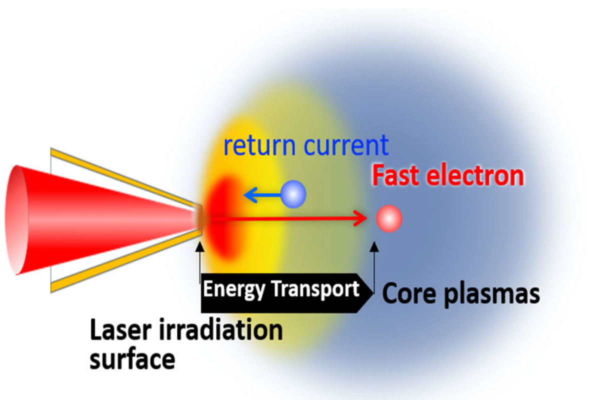
heating

Energy Density Map given by Temp. vs Density showing the Area of Stable and Unstable Electron Transport for present and future ignition conditions.

The black arrow gives a rough indication of the trajectory of electron transport from the laser surface to the point where the core density is maximum.







Light blue area: stable region dominated by collision; yellowish area: stable region due to electrons nonlocally diffused; red area: unstable region where the density is not high and temperature is below a certain level.

Γ : growth rate of beam instability [1/s]
l_s ; plasma skin depth [m]
l_{mfp} : mean free path [m]
v_{th} : thermal velocity[m/s]

Progresses and Prospects as the next step of Laser Fusion Research in Japan

2022-2026 For the Next 50 YEARS

Milestones of laser fusion research ILE Osaka,

- ✓ the required temperature and density conditions have been achieved individually with a central ignition scheme.
- ✓ The effectiveness of the Fast ignition schemes has been demonstrated.

1986 High Temperature Implosion for fusion （**10keV**）
(C.Yamanaka et al., Nature 1986)

1991 High Density Implosion for fusion (**600 to 1000 times** the solid density)
(H. Azechi et al., Laser Part. Beams 1991)

Fast Ignition research

2001 Proof of principle for the Fast Ignition Scheme
(e.g. R. Kodama et al., Nature 2001)

2020 Investigation of the heating Physics and demonstration of >10 times high efficiency than the central scheme
(e.g. K Matsuo, et al., Phys. Rev. Lett. 2020)

What is the next stage？

① Study of Burning Physics:

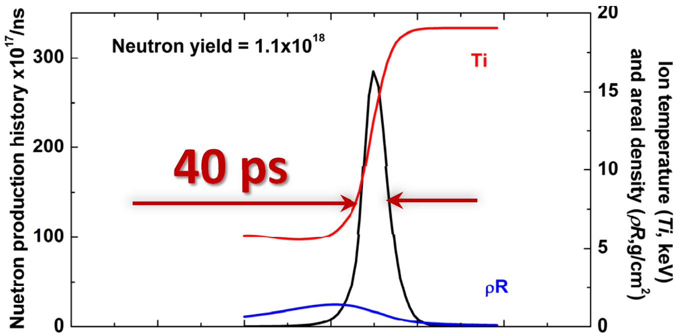
New Diagnostics and International Collaboration

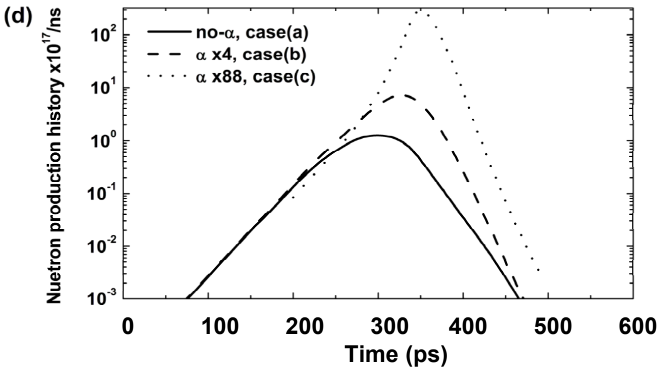
② Demonstration of Repetitive Laser Fusion Reaction:

Subcritical Fusion Reactor with J-E-PoCH

To study the Burning physics as the next step, Pico second time-resolved neutron diagnostics has been developed

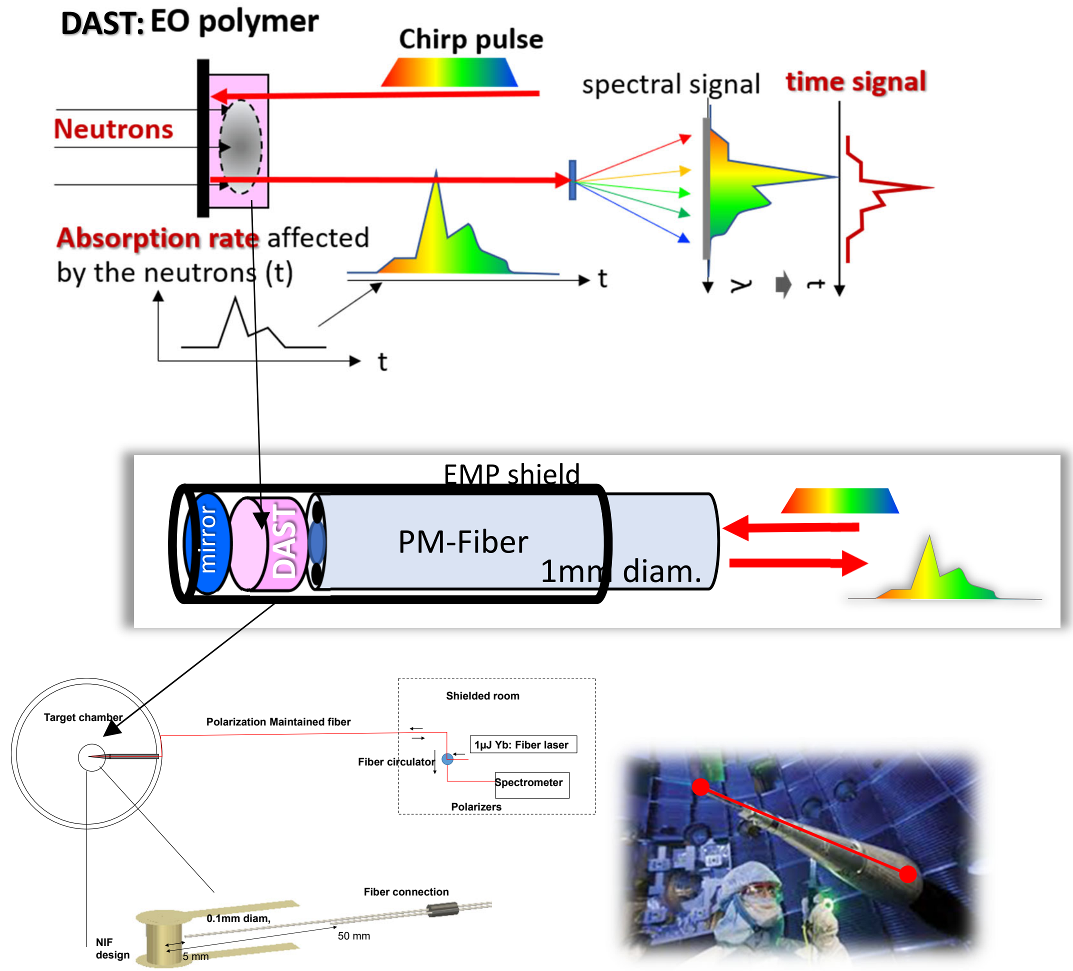
Laser fusion burn time could be a few 10ps and ps time resolution would be required to measure the burning properties.





J. Frenje, et al., Rev. Sci. Instrum. **87**, 11D806(2016)

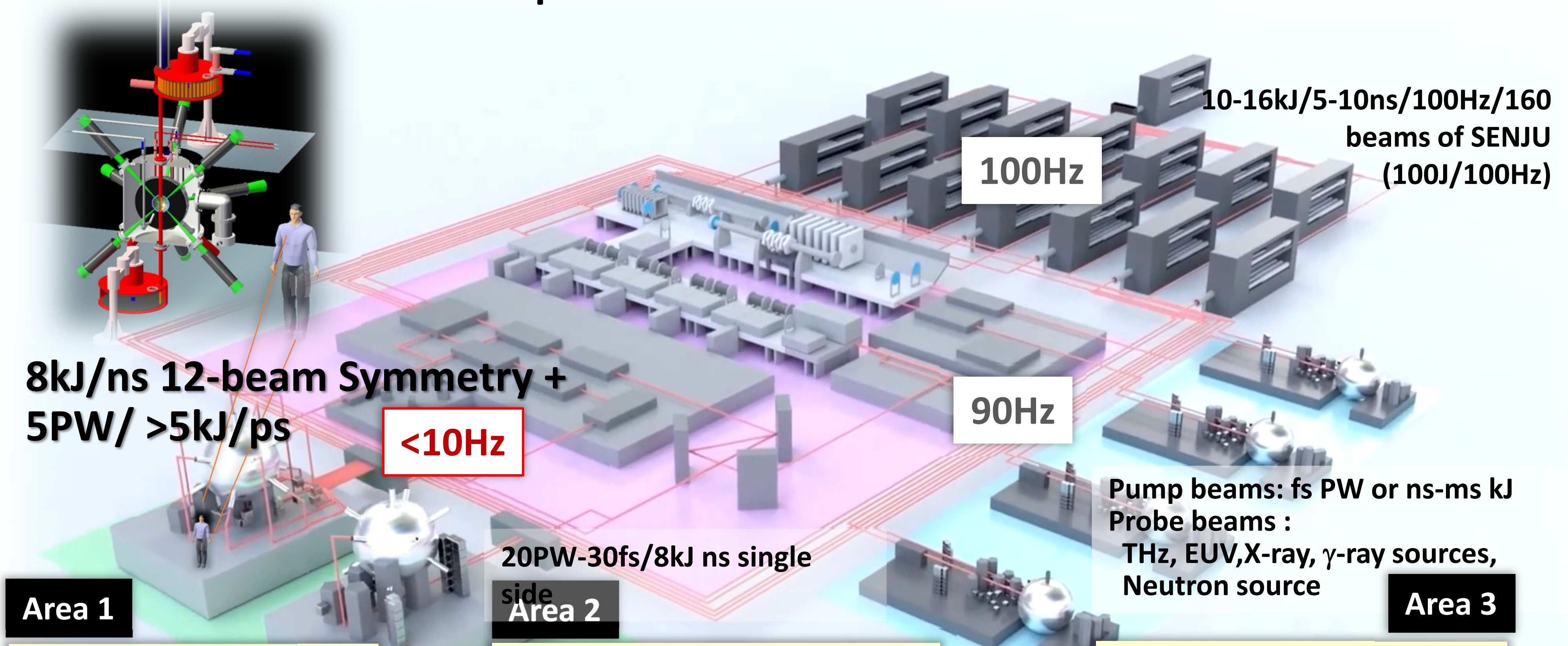
Y. Arikawa et al., Rev. Sci. Instrum. **91**, 063304 (2020)



Demonstration of Repetitive Laser Fusion Reaction as the Next Step Requires High Repetition Power Laser system

- High-repetition, high-power laser facility: **J-EPoCH** has been proposed for multiple purposes in high energy density science, including laser fusion research in Japan.
- J-EPoCH would realize the first laser fusion subcritical reactor for the fusion engineering.

◆ Laser fusion subcritical power reactor with J-EPoCH



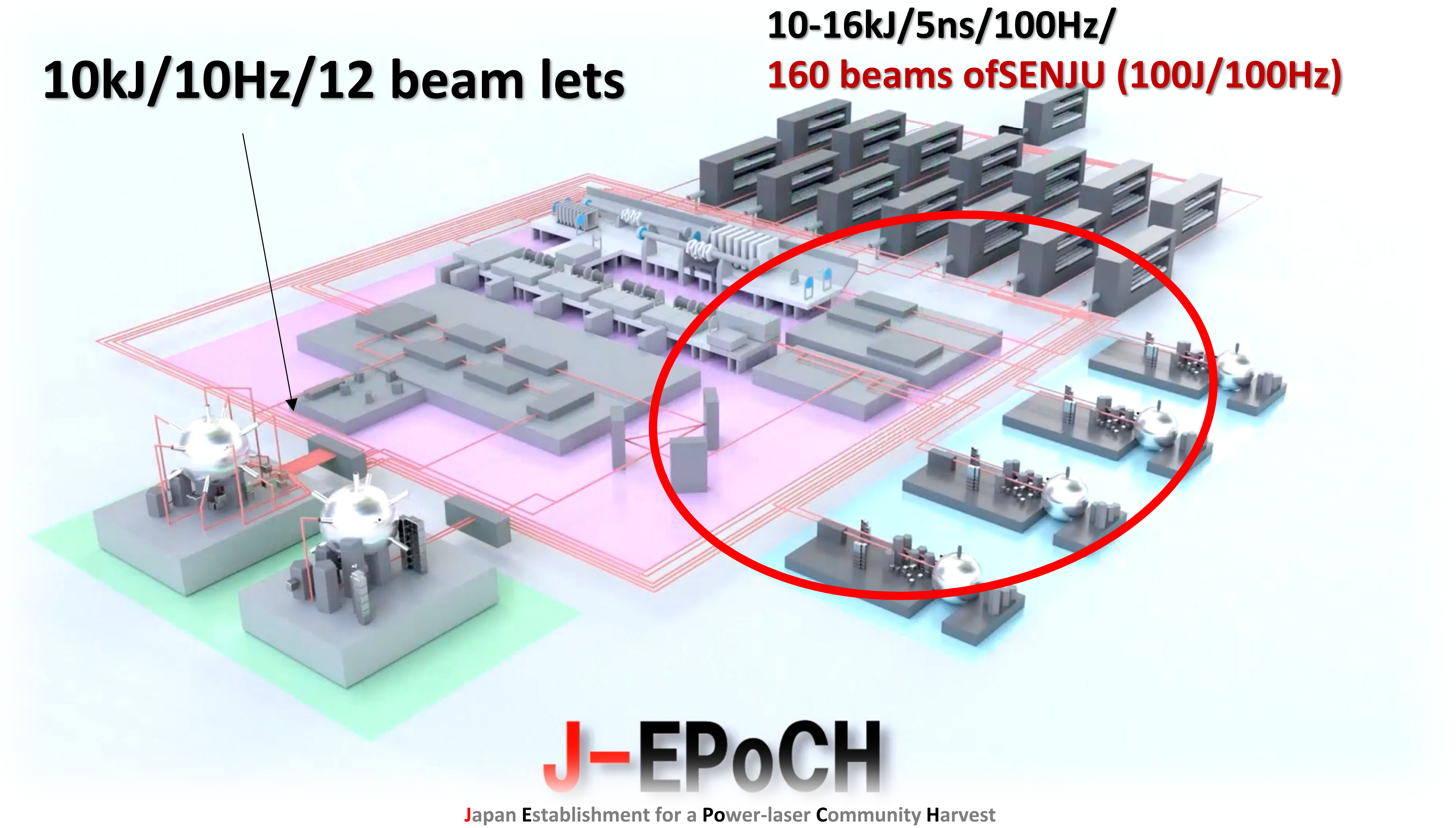
Area 1: High density
- Ultra High-Density Phys.
- **Laser Fusion Plasma Phys.**
- **Laser Fusion Reactor Eng.**
- Laser Astro Phys.
- Laser Nuclear Physics

Area 2: High field & pressure
- Quantum Vacuum Phys.
- Laser Nuclear Phys.
- Ultra High-Field Phys.
- Laser Astro-Phys.
- Ultra High-Pressure Phys. and Chem.

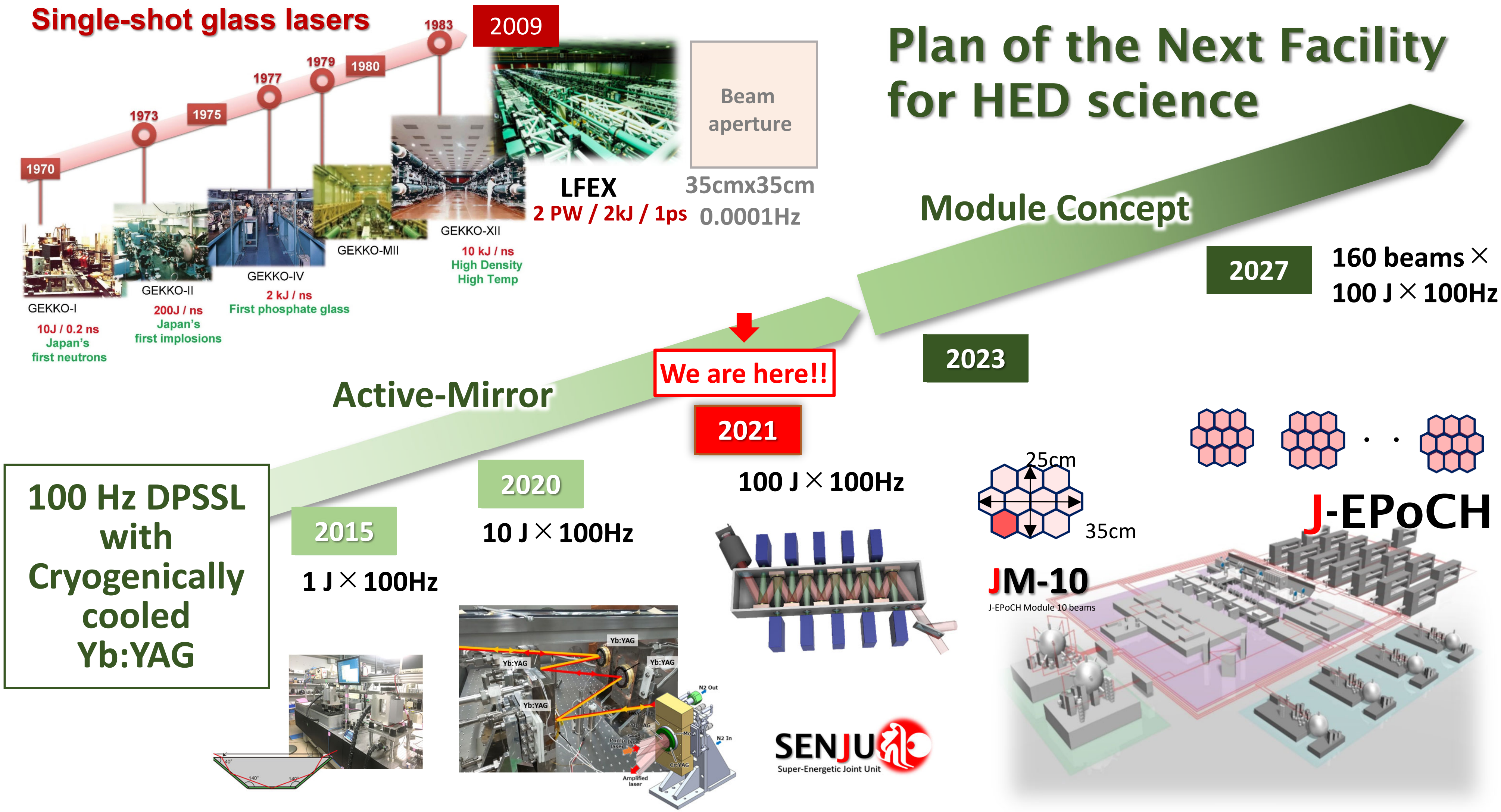
Area 3:Diversity
- Material Science
- Condensed Matter Physics and Chemistry
- Life Science
- Beam Sci. and Nuclear Photo.

One of the most important key technologies in the J-EPoCH is a 100J/100Hz laser, named SENJU

because the J-EPoCH is based on the 160 beams of the SENJU



Progress and Future Plan of Development of the Large-Scale High-Power Laser System: J-EPoCH

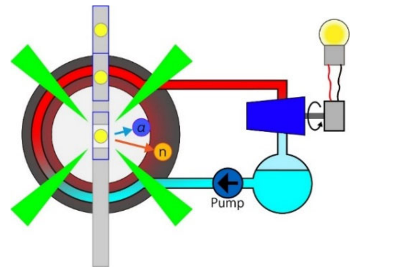


Laser fusion subcritical power reactor with J-EPoCH

- various applications other than the demonstration of power generation-

A. Iwamoto and R. Kodama, *High Energ. Dens. Phys.*, **36** (2020), 100842.

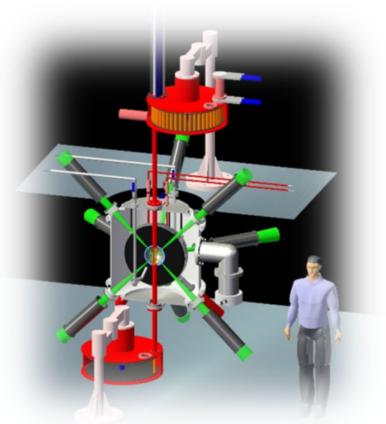
■ Steady-state Power Generation Experiment: Neutron energy conversion technology



- ➢ 1～100 Hz/8kJ → thermal energy 14 ～ 1,400 W ; electric power: a few w
  - Nuclear fusion energy : 22.4 J/shot ; total thermal energy : 14.0 J/shot Q = 0.002（14 J / 8 kJ）

■ Neutron Applications: Fusion reactor material technology

- ➢ 1～100 Hz/8kJ → 10^{13}～10^{15} n/sec ; 6.6 x 10^{13} ～ 10^{15} n/m^2 sec @10cm
  - Neutron production : 10^{13} /shot



■ Tritium Breeding: Fusion fuel breeding technology

- ➢ **Tritium Breeding Ratio : 6.8 x 10^{-6} (3.8 x 10^{11} /5.6 x 10^{16} [/LHART])**
  - Tritium products : 3.8 x 10^{13} /100 shots; Radioactivity ; 6.8 x 10^{4} Bq

☐ Reproduction of laser fusion reactor systems
☐ Development of reactor material
☐ Neutron thermal load test of a diverter in a magnetic fusion reactor

Summary of FI research in Japan

■ Fusion Product

- Demonstrated higher efficient fusion product of FI scheme than the conventional center ignition scheme.

■ High Density Implosion

- Invented a stable fusion fuel implosion method suitable for the fast ignition scheme: the solid sphere implosion method, and demonstrated the implosion performance that can be reproduced as compared with the 2D simulation.
- Almost free from fluid instability and little effect of laser non-uniform irradiation such as timing deviation.
- The density required for the fusion ignition and experimental reactors will be achieved with this solid sphere implosion from the prediction by 2D simulations that were consistent with experiments.

■ Heating of the Compressed Core Plasmas

- Success in efficient heating under fusion ignition conditions considering the heating physics mechanism
- Investigation of the physical mechanism of high-density plasma heating by hot electrons generated by short pulse lasers

■ Next new stage

- **Development of the High –Rep. Laser as advance technologies for fusion engineering: J-EPoCH as well as advance neutron diagnostics**