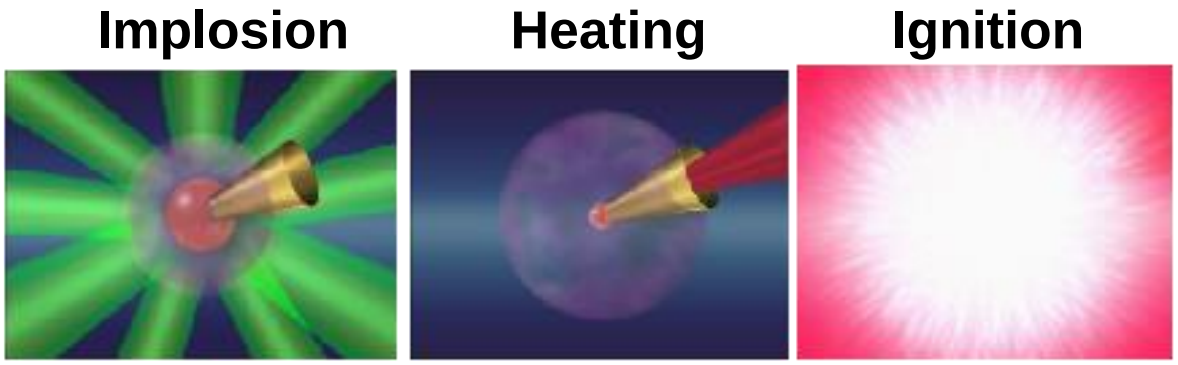
A Pathway to Laser Fusion Energy: Fast Ignition Realization EXperiment (FIREX)



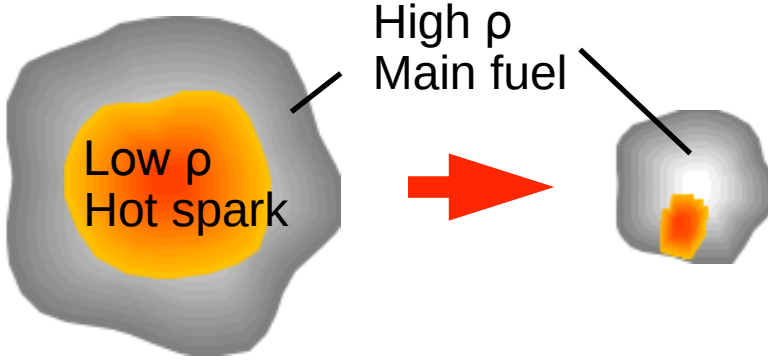
Primitive idea by
T. Yamanaka, int. rep. 83.
N. Basov, J. Sov. Laser Res. 92.
Matured concept by
M. Tabak, PoP 94.

Hiroshi AZECHI
Director, Institute of Laser Engineering, Osaka University
26th IAEA-FEC, 2016. 10. 18
Kyoto, Japan

Fast Ignition: A Compact Root to IFE

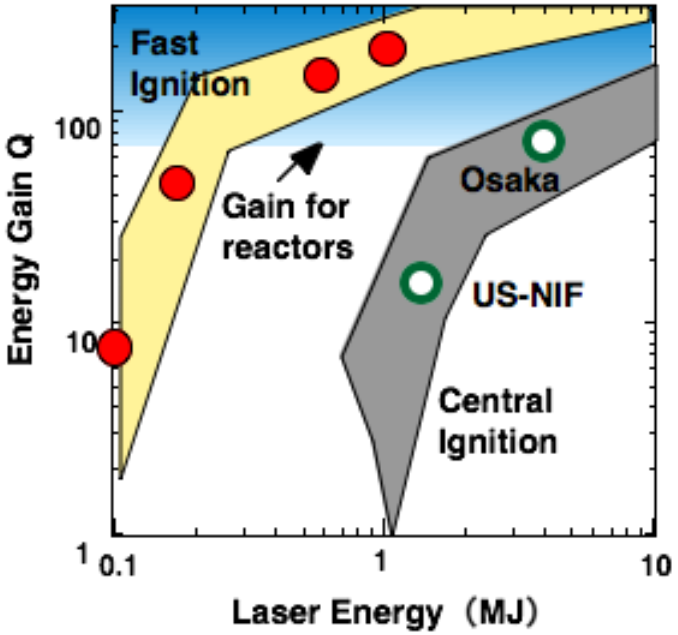
Central ignition (Isobaric)

Fast ignition (Isochoric)



$E_{ignition} \sim \rho R^3 \sim (\rho R)^3/\rho^2$

ρR = alpha particle range



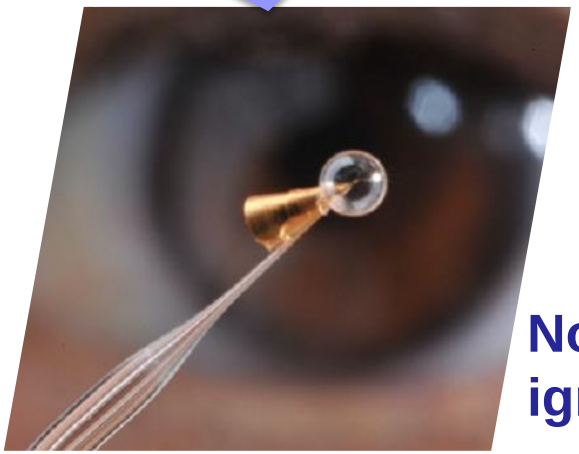
Fast ignition reduces ignition energy.

Compact fusion will accelerate inertial fusion energy development.

FIREX
Fast Ignition Realization EXperiment

Nanosecond Laser
GEKKO-XII for Implosion

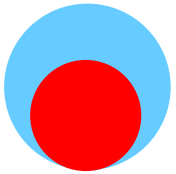
Picosecond Laser
LFEX for Heating



①FIREX-I/5-keV Heating

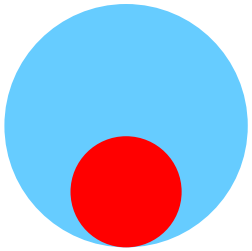
ρR ~ 0.2 g/cm^2

②FIREX-II/Ignition



ρR ~ 1.2 g/cm^2

③Reactor/High Gain



ρR > 2.0 g/cm^2

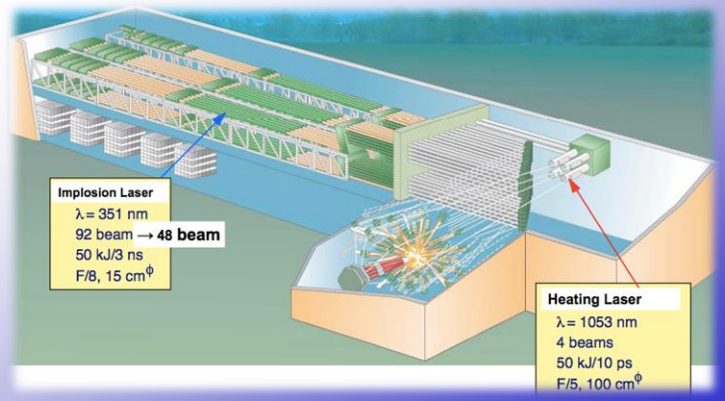
No essential difference between ignitors of FIREX-I and reactor

Roadmap towards Fusion Power Generation

～2016

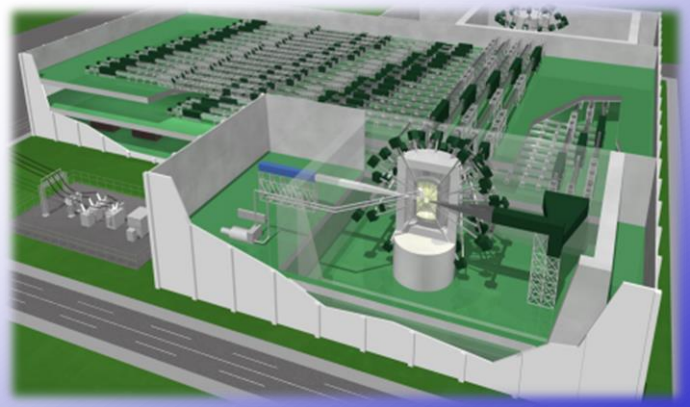
FIREX-I: 5-keV Heating

～2025



FIREX-II: Ignition

～2040



LIFT: Power Generation

Atomic Energy Commission of Japan report (Oct. 2005):

"Based on its (FIREX-I) achievement, it will be decided whether the project should advance to its second-phase which will be aimed at realizing of ignition and burning"

***Laboratory Inertial Fusion Test**

Summary

Critical issues of fast ignition

- ✓ Laser-accelerated Relativistic Electron Beam (REB) is too energetic, and
- ✓ REB is too divergent to couple with a compressed core.

Cool REB Campaign

- ✓ Contrast ratio of LFEX is improved to ten billion.
- ✓ Low energy electrons (<few MeV) increased significantly.

Guiding REB Campaign

- ✓ Kilo-tesla magnetic-field is generated in free space for the first time.
- ✓ Convergence of REB by magnetic-field was demonstrated.

Integration Campaign

- ✓ Cool and Guiding REB are simultaneously implemented.
- ✓ Temperature of ~3keV is demonstrated at a reduced heating energy.

What Next?

- ✓ High energy rep. laser J-EPoCH*
- ✓ International cooperation of FIREX-II.

*Japan Establishment for POwer laser Community Harvest

Heating Laser Development

GEKKO-MII-Short Pulse 1989

30 J / 1 ps

PetaWatt Mod 1996

PetaWatt 2001

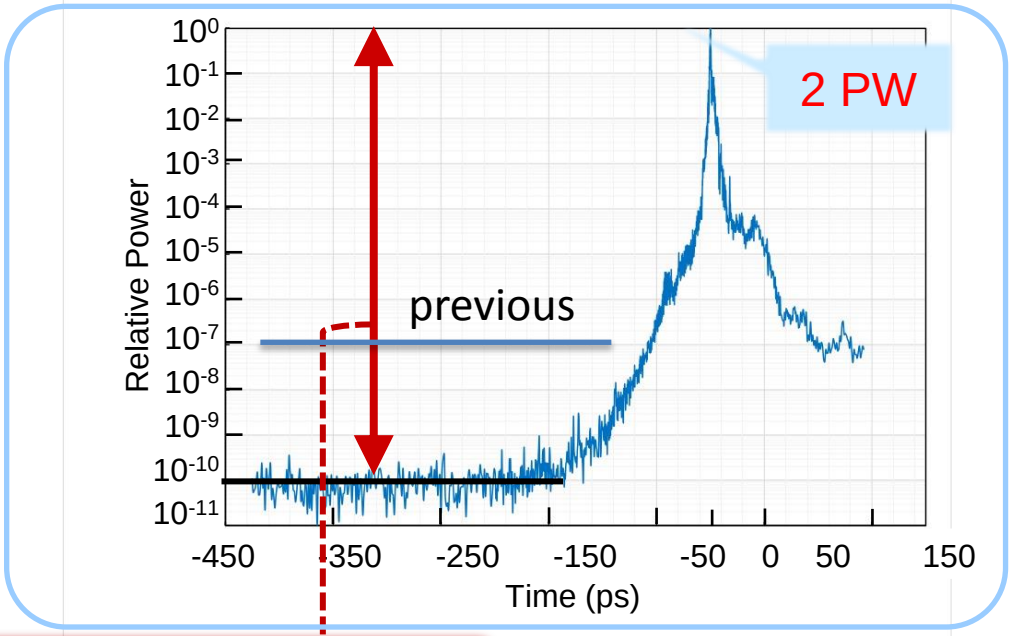
0.5 kJ / 0.5 ps

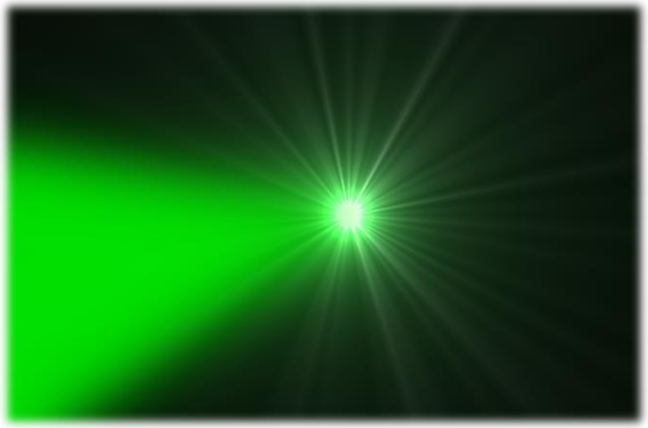
LFEX 1 beam2009

4 beam 2014

2-10 kJ /1-10 ps

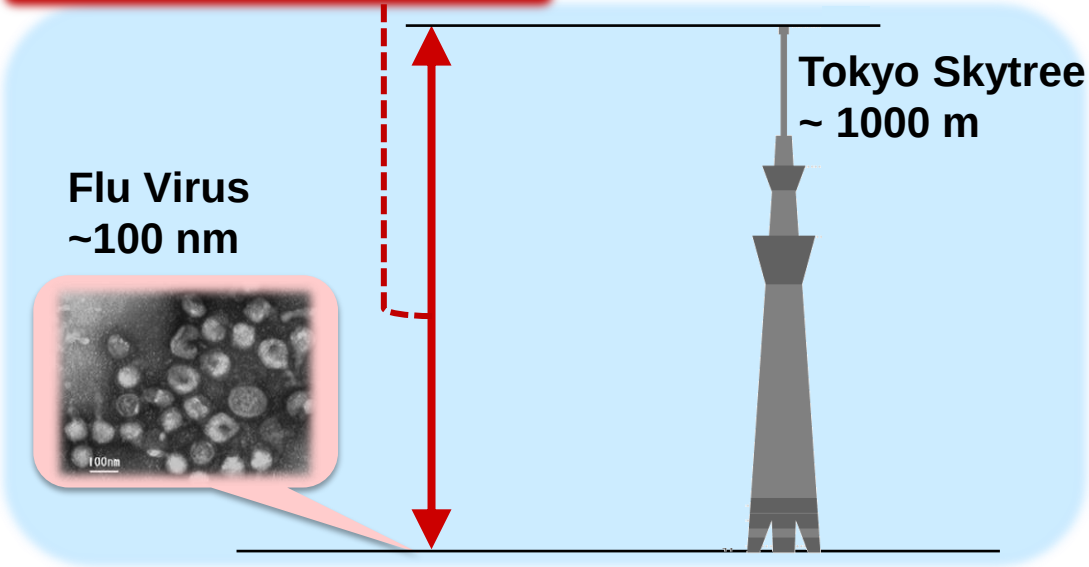
Cool REB Campaign: Highest Contrast





>10 orders of magnitude

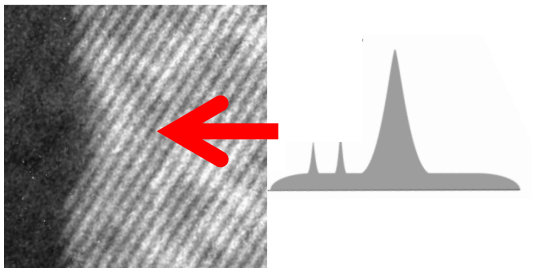
Pedestal : Peak ≈ Virus : Skyscraper



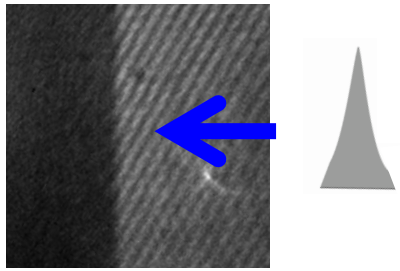
See Kawanaka, Thu. Afternoon

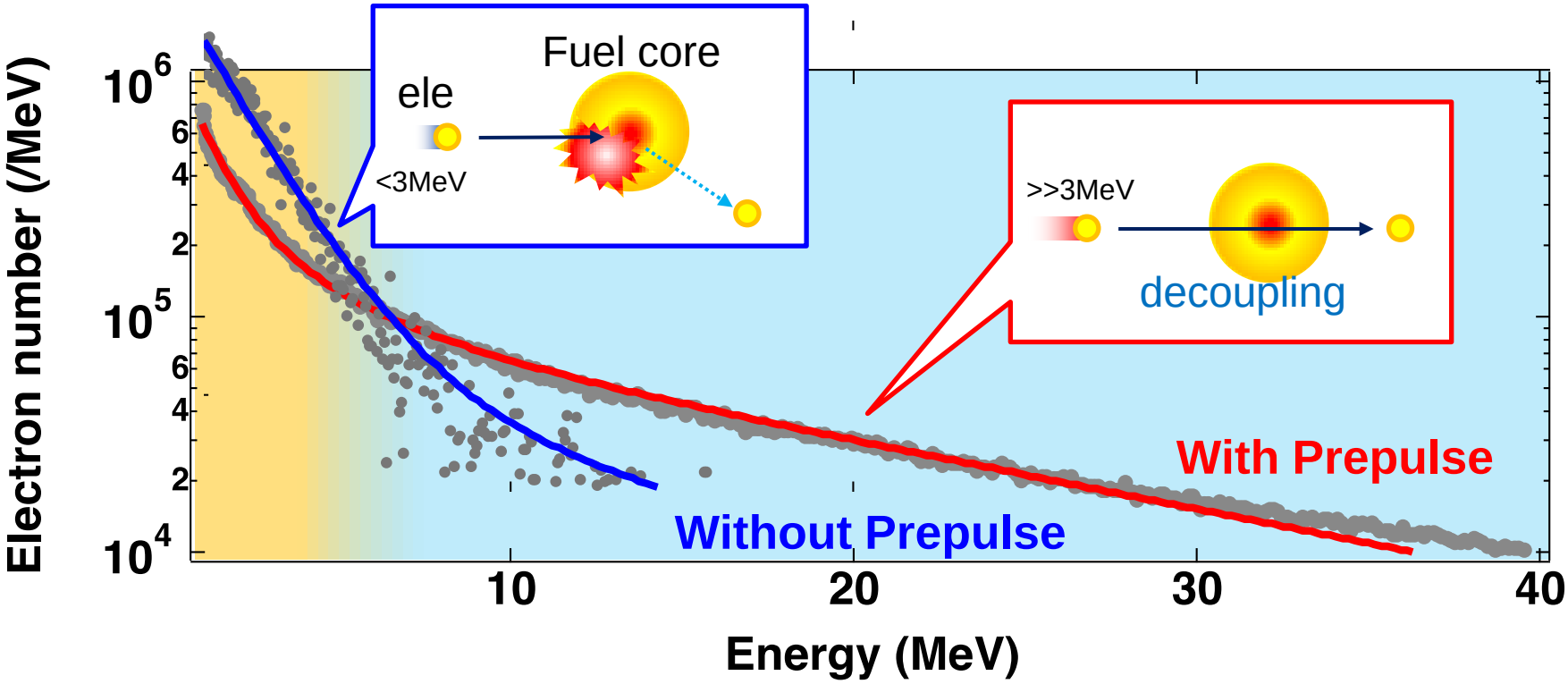
Cool REB Campaign: Results

With Prepulse
@1.5 ns before main pulse



Prepulse Free
@0.15 ns before main pulse

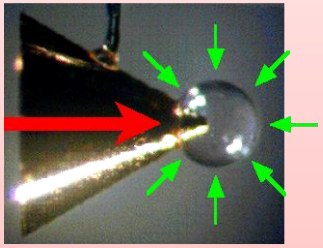




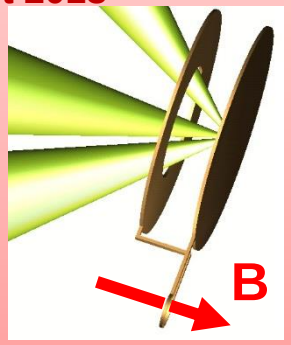
Low energy component of REB increased dramatically.

Guiding REB Campaign: Concept

Fast Ignition Target
Nature 2001, 2002

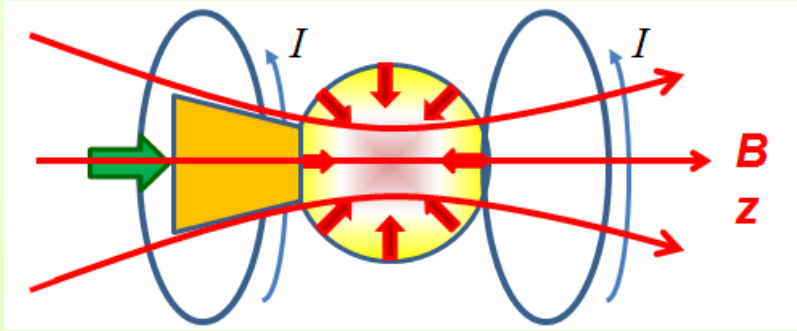


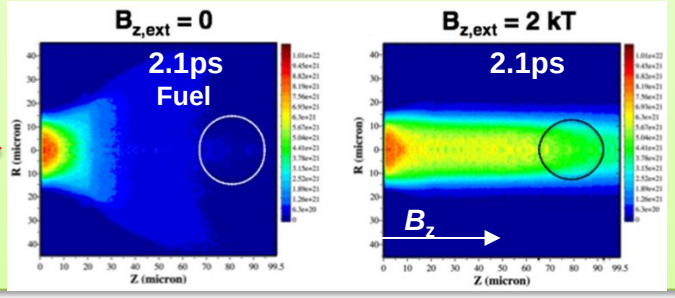
High B Field
Sci. Report 2013



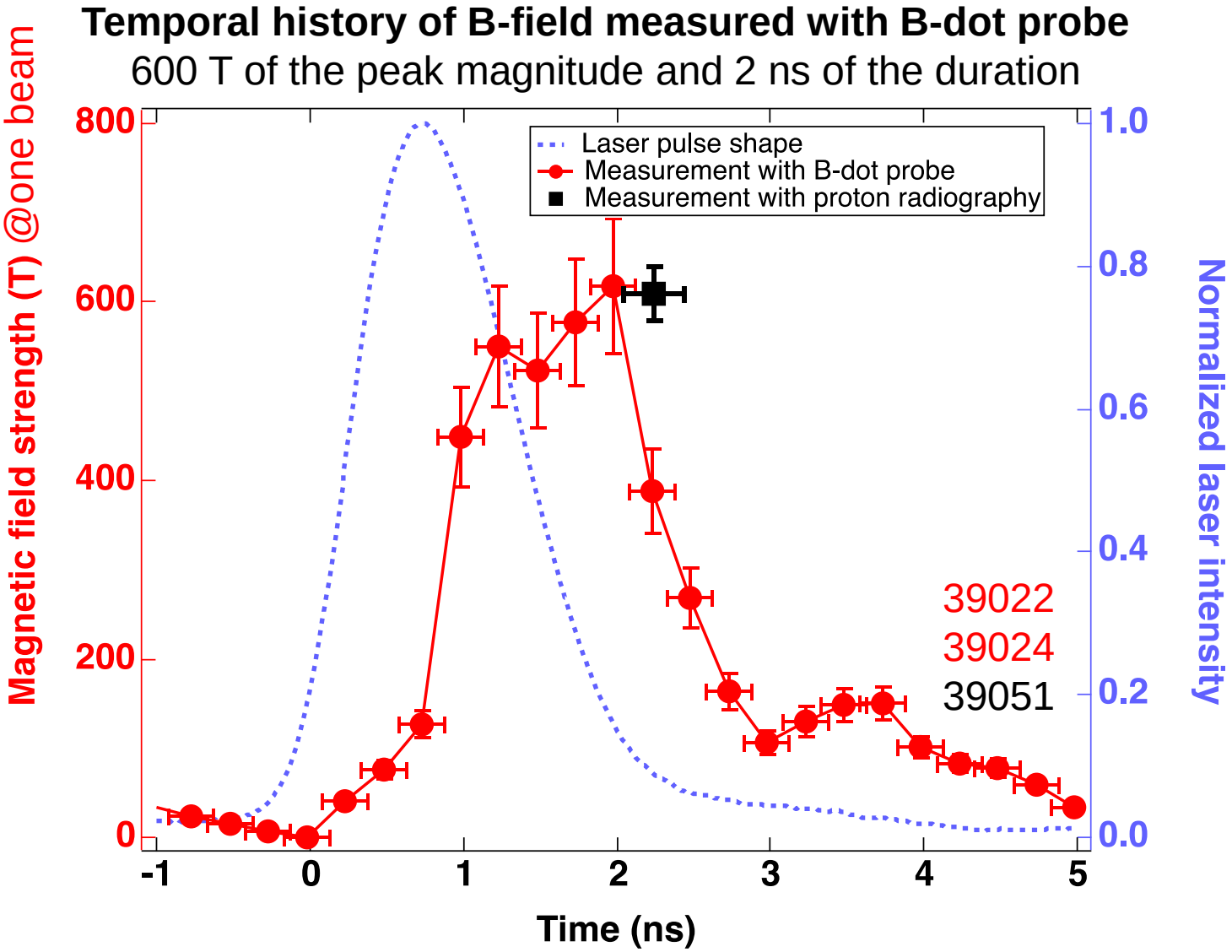
Heating Laser

Fast Electron Guiding by B Field
⇒Efficient heating





Guiding REB Campaign: Mag Field



Laser driven Capacitor-coil target generated strong (kilo Tesla) magnetic field

Guiding REB Campaign: Results

OSAKA UNIVERSITY

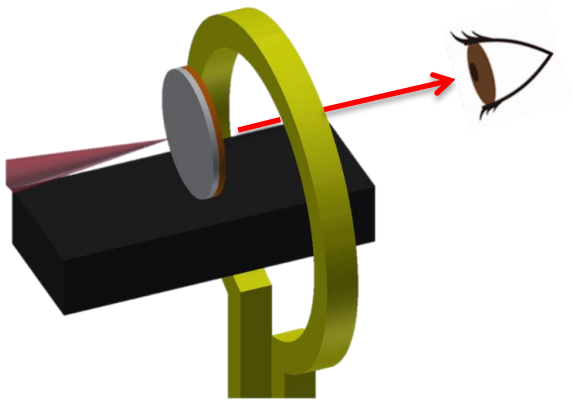
Institute of Laser Engineering

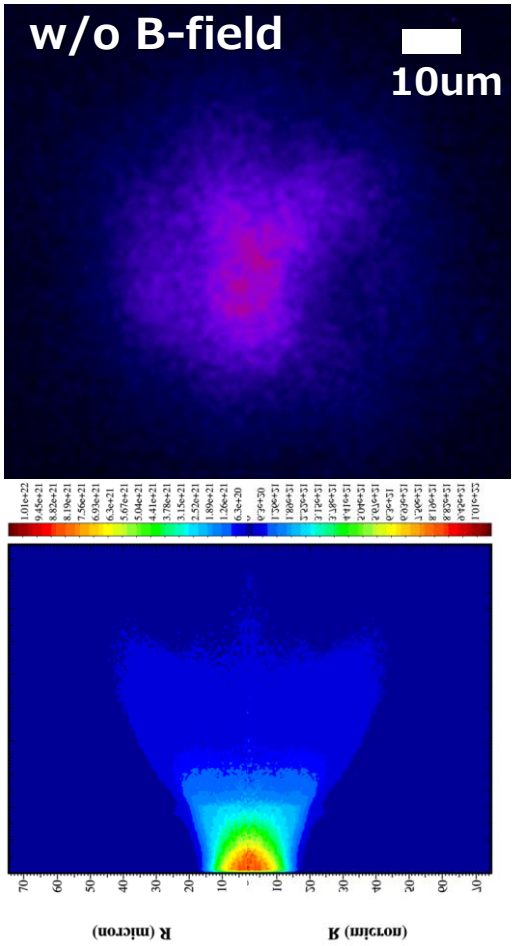
CELIA

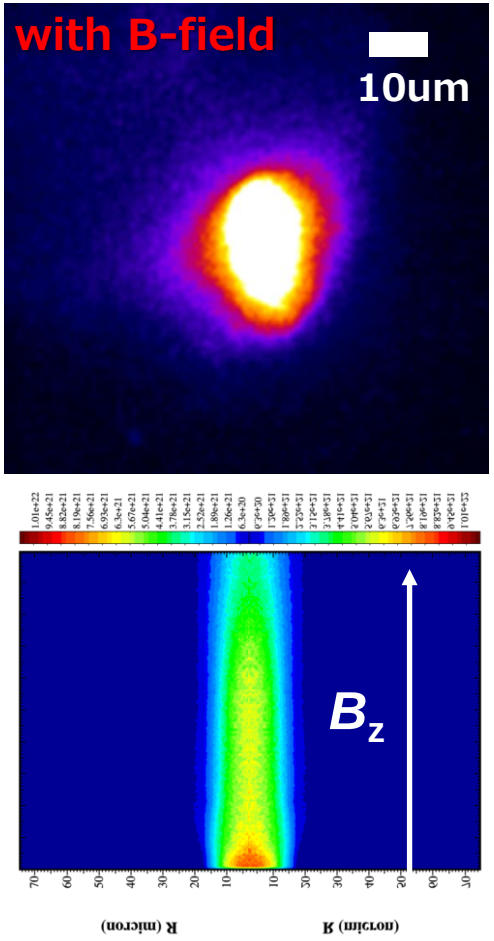
université de BORDEAUX

Spatial spread of REB after long distance traverse

X1/2 size, X8 intensity







Kilo Tesla magnetic field guides relativistic electron beam.

Integration Campaign: Simulation

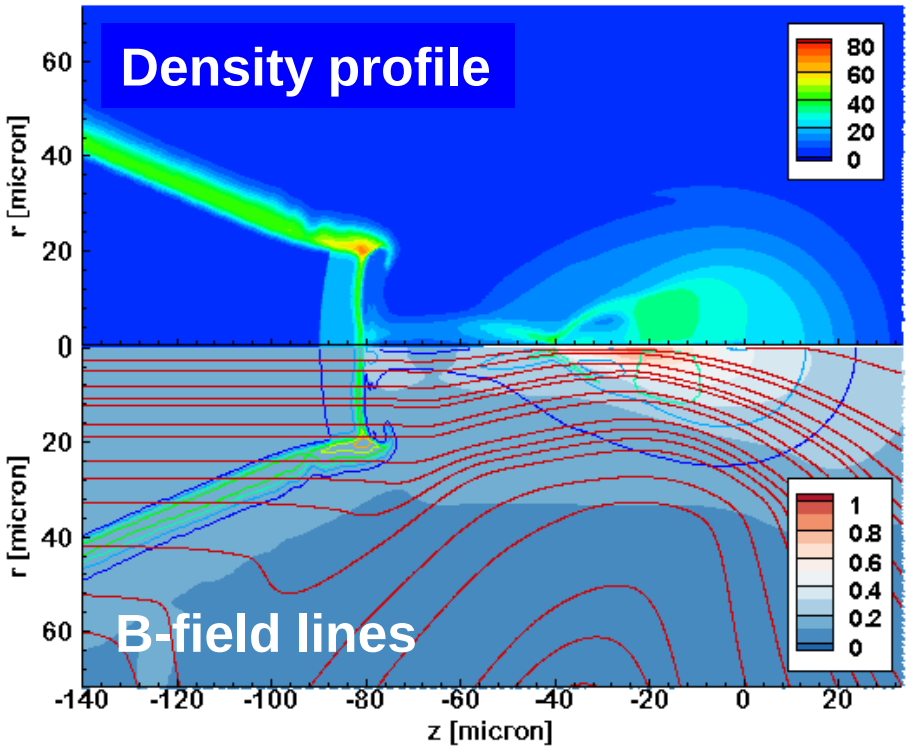
Nagatomo *et al*., NF (2015) & T. Johzaki *et al.,* PPCF (2016).

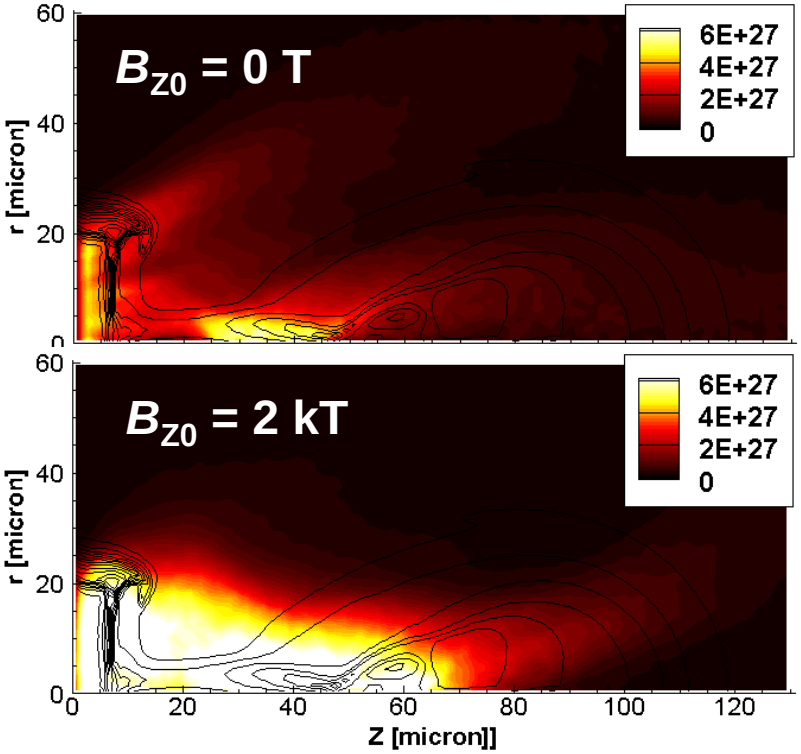
Density & Field line

Mirror ratio is ~4 due to low convergence ratio and large magnetic Reynolds number ($R_m = \tau_{diff}/\tau_{imp} > 1$).

REB energy density [erg/cm^3]

REB is punched by moderately compressed B-field.

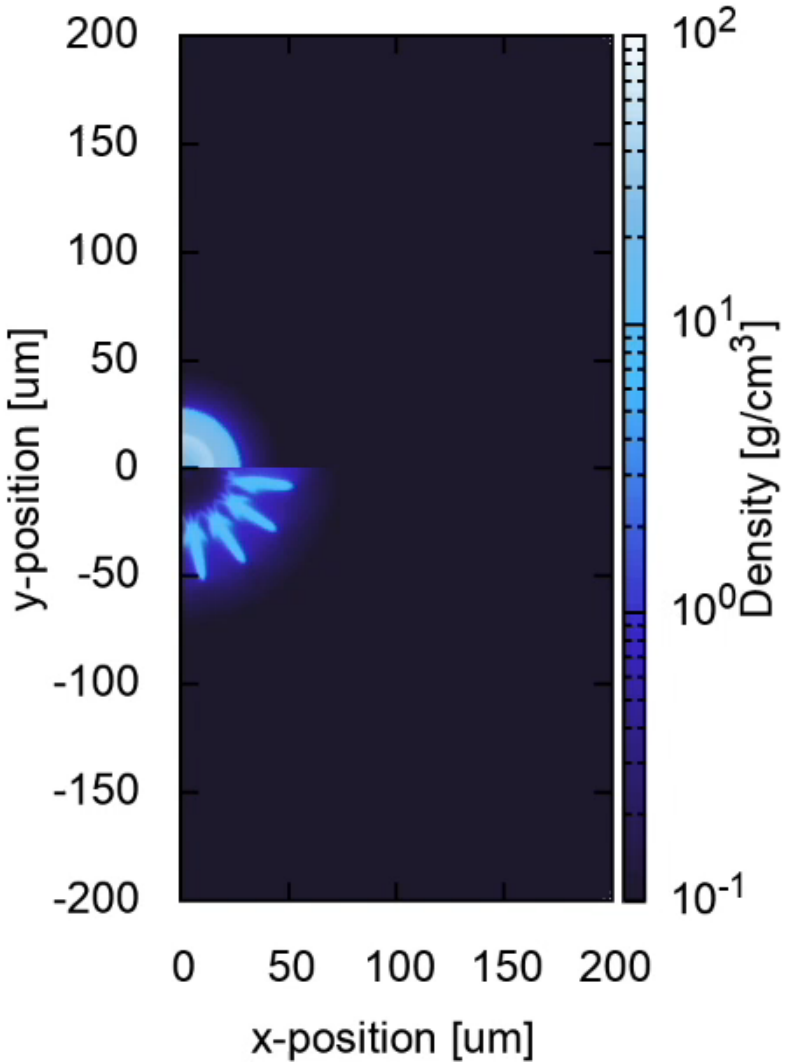




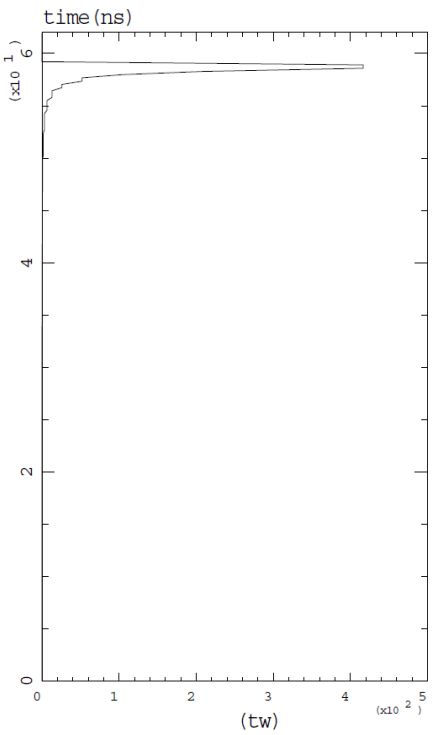
Mirror ratio of ~4 suitable for electron convergence, leading to effective heating of high density plasma

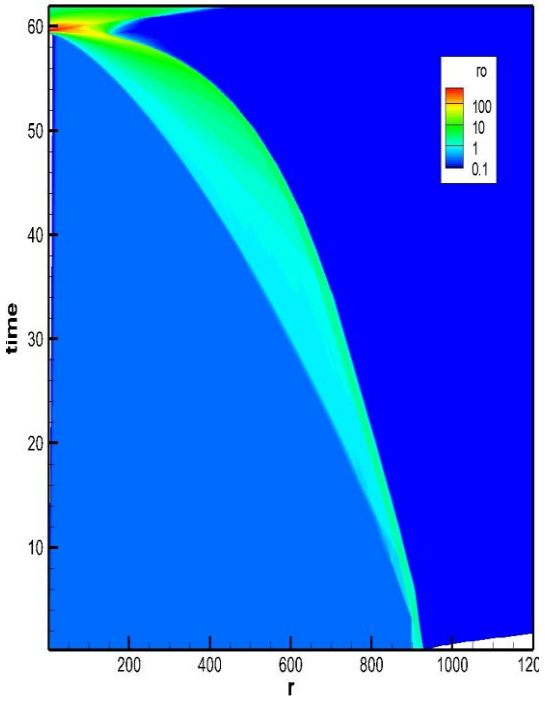
Integration Campaign: Solid Ball Fuel

Growth of surface perturbation Initiated by non-uniform laser drive



High density compression with tailored pulse





ρR achieves 2.7 g/cm^2

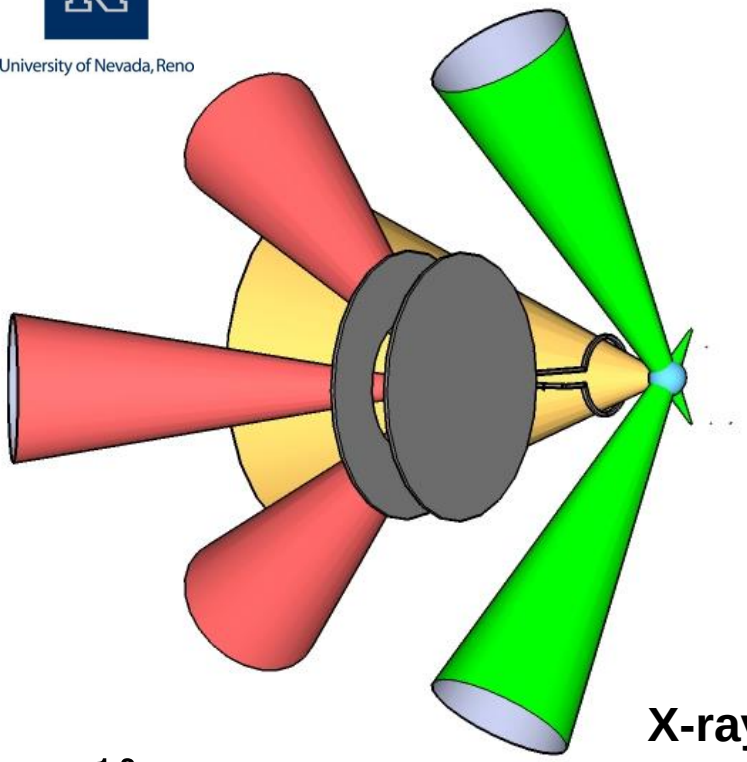
Integration Campaign: Experiment

OSAKA UNIVERSITY

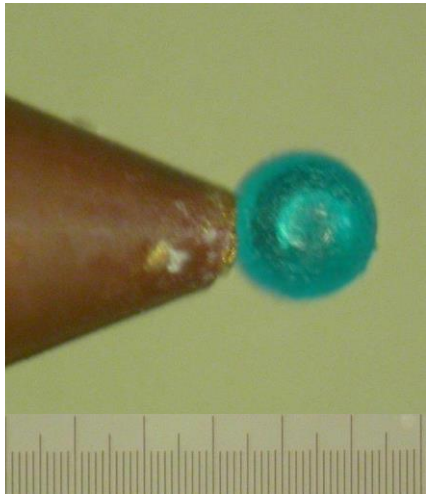
University of Nevada, Reno

Institute of Laser Engineering

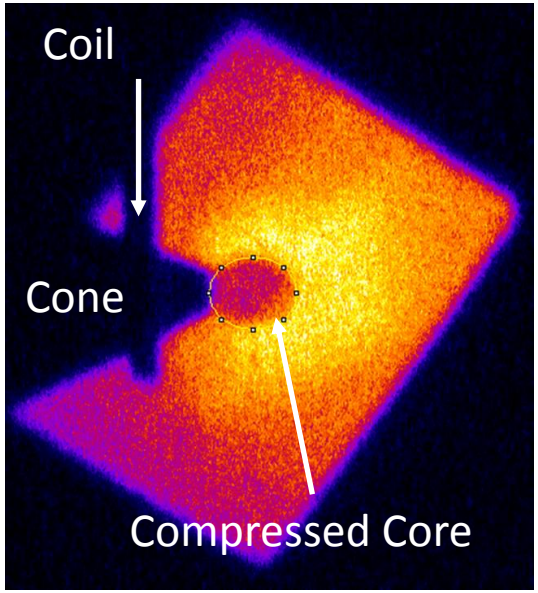
Target layout



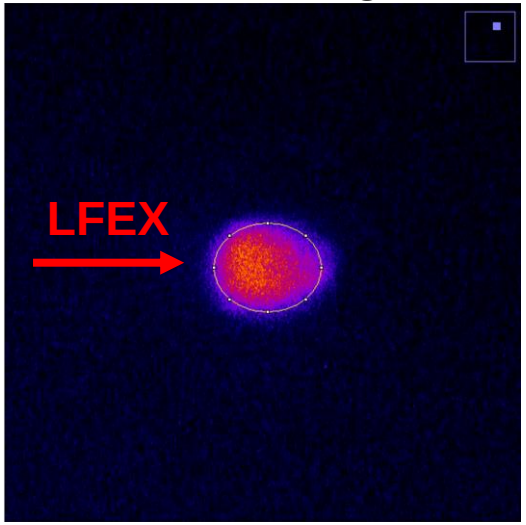
Cu-doped plastic sphere



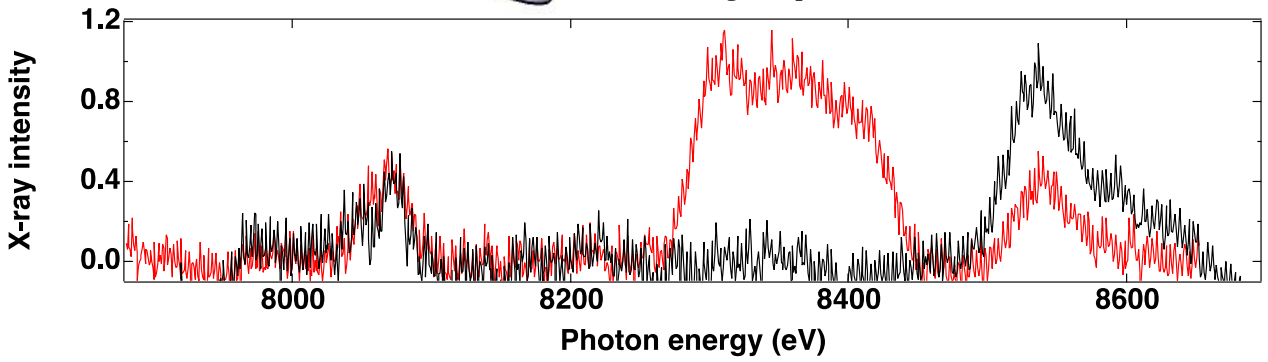
X-ray shadow



Cu-$K\alpha$ image



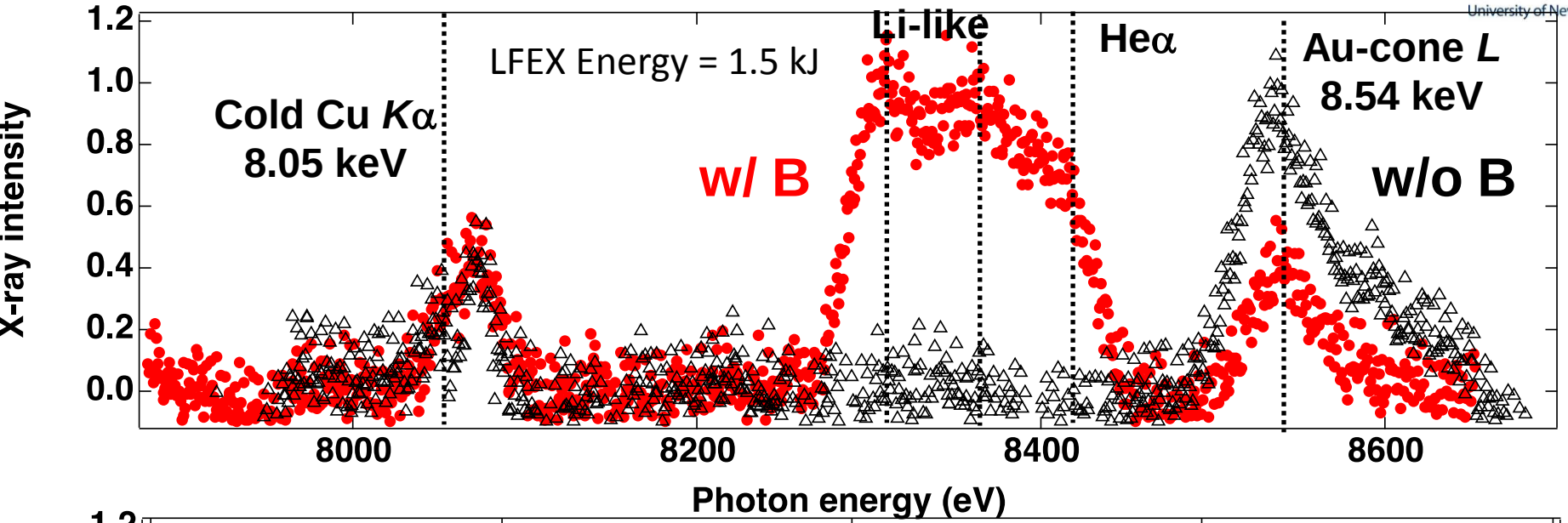
X-ray spectrum

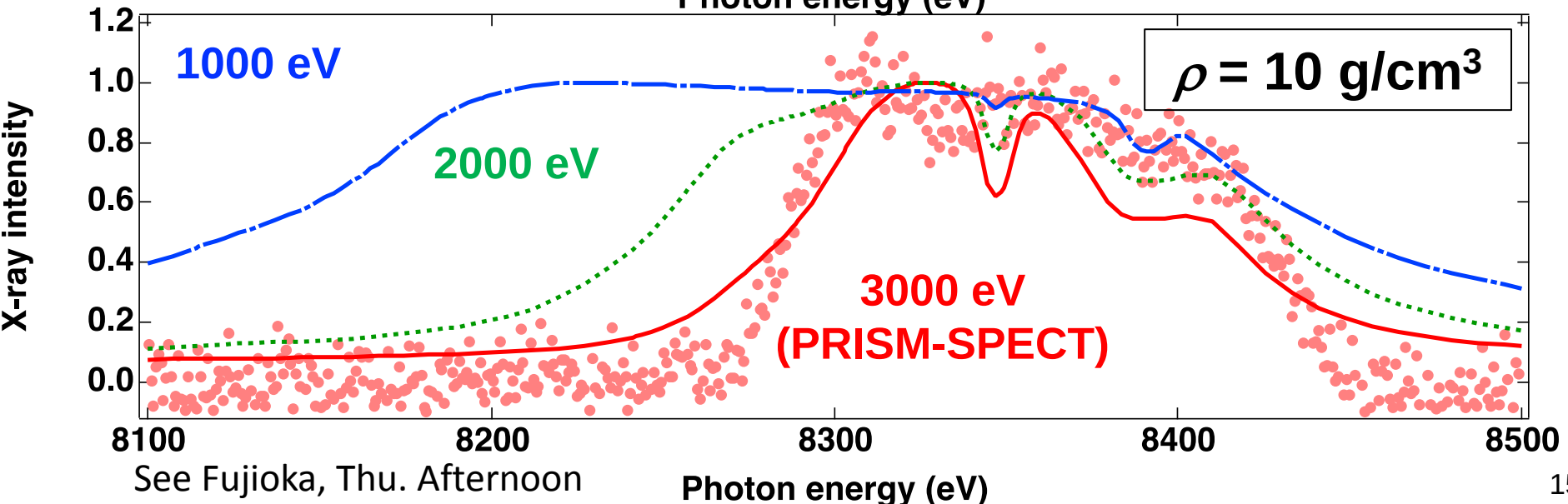


Compressed core is well heated to some keV.

Integration Campaign: 3-keV Heating

K shell emissions of Cu increase with B field.





See Fujioka, Thu. Afternoon

What next?

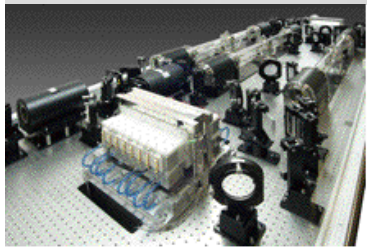
1. Transition from single shot to rep-rate lasers
   (5-10 kJ/0.1-10 Hz)
   - High energy density science
   - Industrial application
   - Fusion basics

2. International Cooperation:
   - Fast ignition demonstration
   - High energy density science with large scale plasma

Three Innovations for High Repetition Laser

From Flush Lamps to Diodes

Flash Lamps
Broad spectra
→Inefficienty

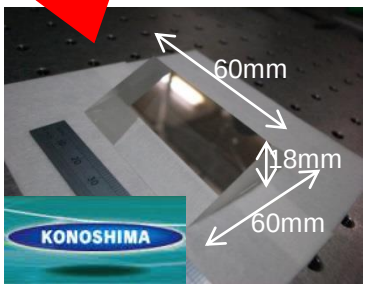


Laser Diodes
Emission lines≈
absorption lines

X100 efficiency

From Glasses to Ceramics

Laser Glasses
- Large optics
- Low thermal conductivity

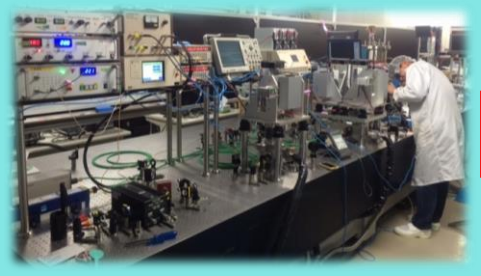


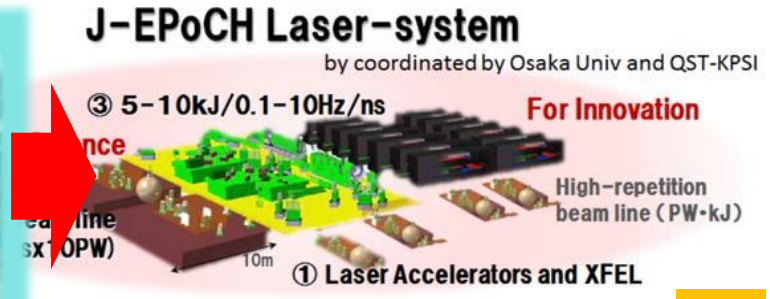
Yb: YAG Cooled Ceramic Crystal
- Large optics
- High thermal conductivity

X100 thermal conductivity

GEMBU Laser 1J, 100Hz

Cooled Ceramic Crystal Laser developed in ILE becomes a Global Standard.

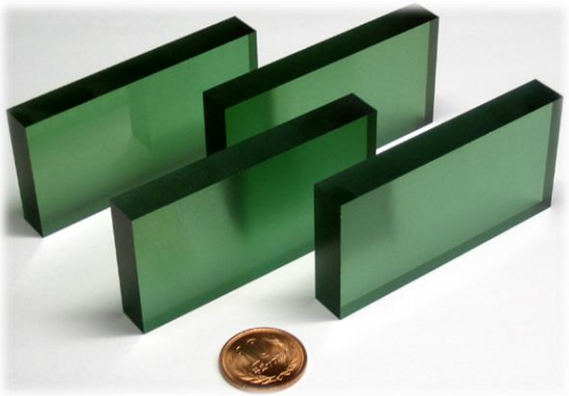


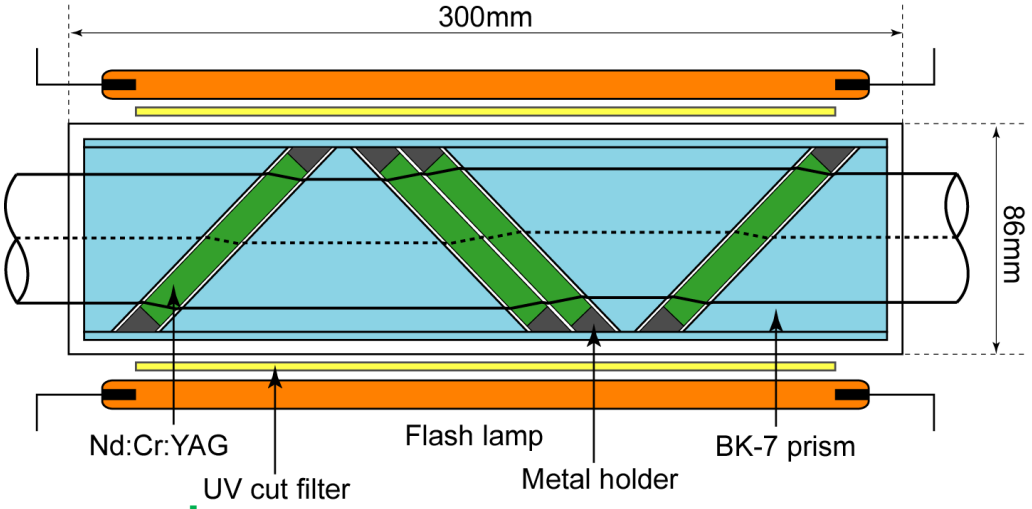


Japan Establishment for POwer laser Community Harvest

Split Disk : a New Breakthrough in Rep-rate High Power Laser

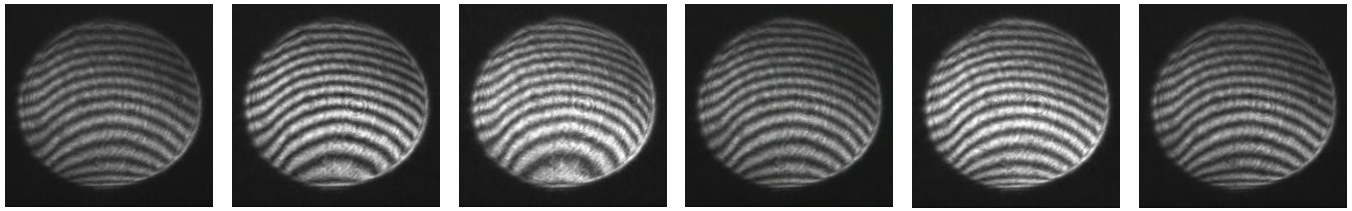
Nd:Glass or
Ceramic Nd:Cr:YAG (Nd: 0.8at% Cr: 0.1at%)





X100 heat removal

10l/min (0.5m/sec), 800J, 10Hz, 100pulse



Interference fringe of water

0s **5s** **10s** **15s** **30s** **40s**

excitation

One million times increase of rep-rate

Next Generation Multi-Purpose Facility

OSAKA UNIVERSITY

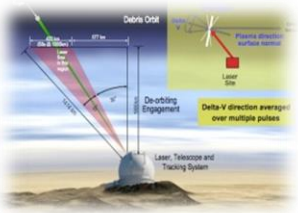
Institute of Laser Engineering

Academic Frontiers

Planetary Science **Astrophysics** **Vacuum Quantum Physics**

Infrastructure

Space debris elimination



Laser Propulsion

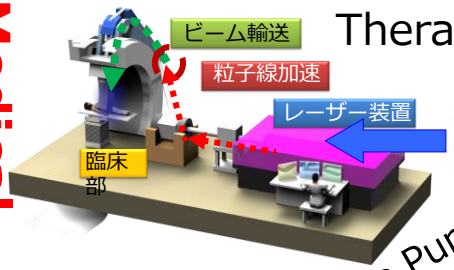
Nondestructive inspection

LIFT: Power Generation

~2040

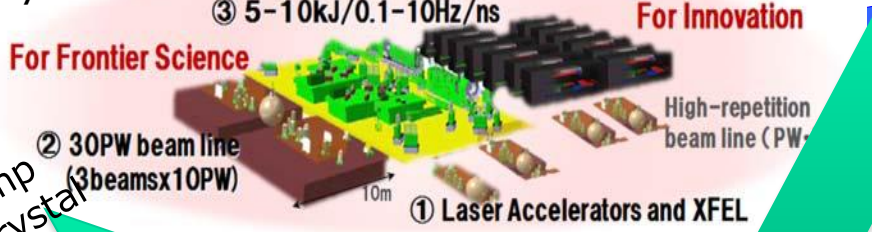
Medical

Radiation Therapy



J-EPoCH Laser-system

by coordinated by Osaka Univ. QST-KPSI



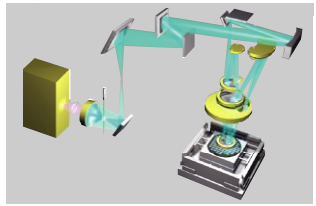
Japan Establishment for POwer laser Community Harvest

Diode Pump

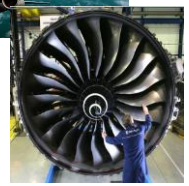
Ceramic Crystal

Industry

Semiconductor manuf.



Laser Machining



Gear

3D Printing

Turbine Brads

Material

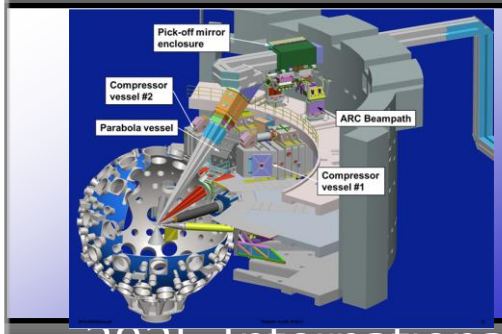
Surface process (a-Si)

Perovskite Ceramic

FIREX-I

~2016

FIREX-II: Ignition



~2025 International

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*Japan Establishment for POwer laser Community Harvest


IFSA
2017
We hope to see you soon in Saint Malo!
10-15 September 2017