Relativistic Laser self-focusing

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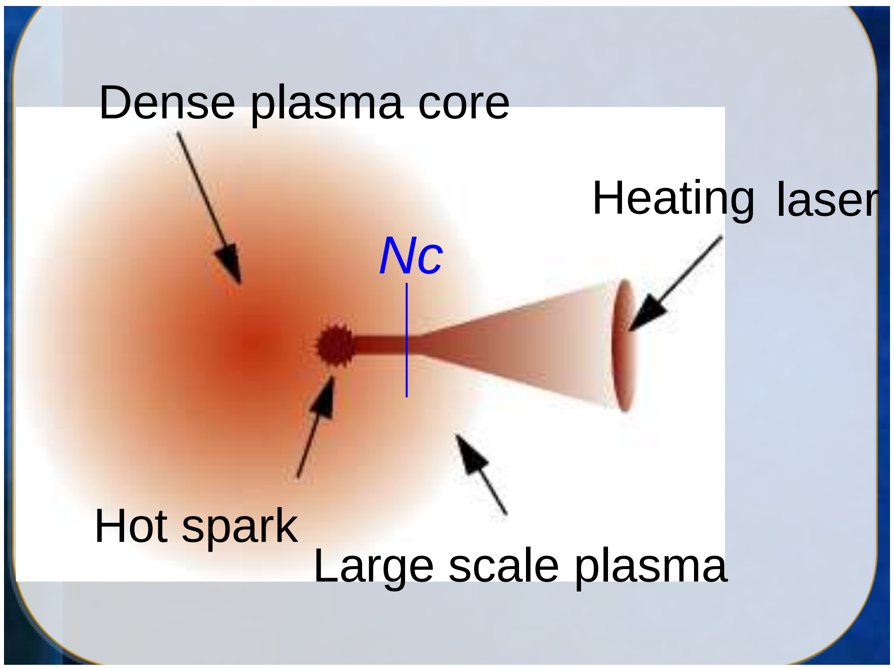
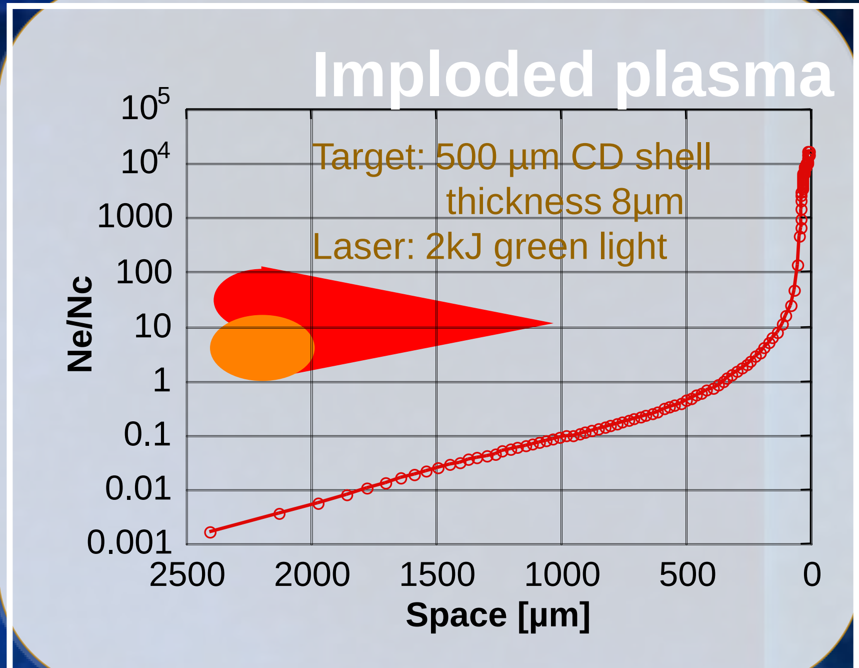
Concept of Fast Ignition with direct heating by ultra-intense laser





1. The imploded plasma has steep density gradient at density higher than 10Nc. For 2kJ implosion, the distance from 50Nc to 1000Nc core plasma is only 40μm.
2. The heating laser is expected to penetrate into 50~100Nc which is close to the core plasma.

We call this particular self-focusing “Super-penetration” since

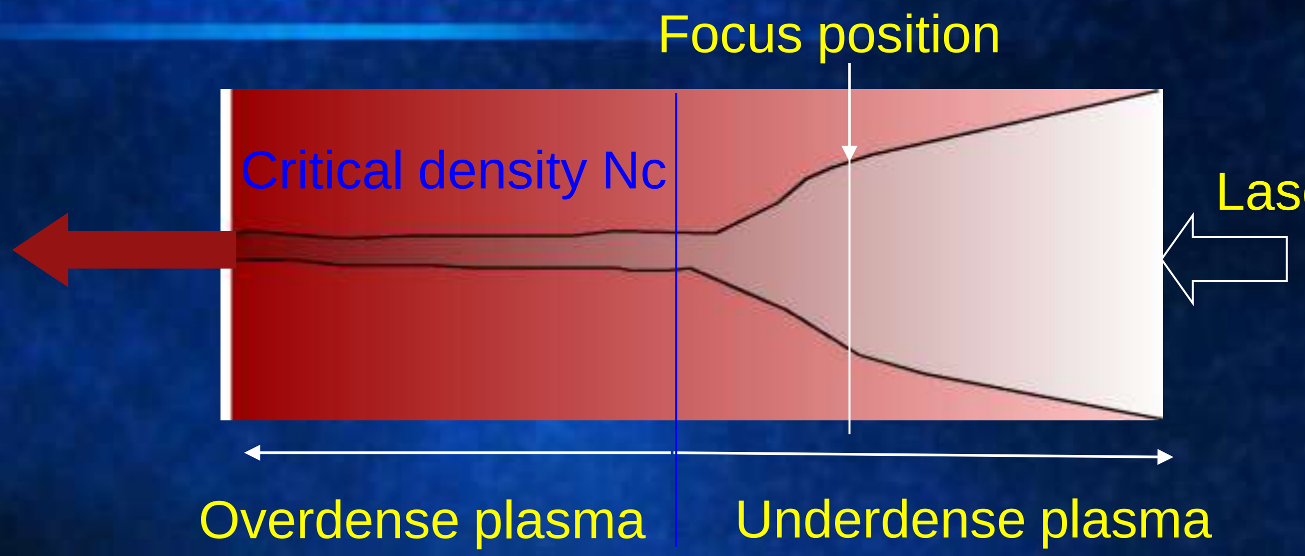
Super-penetration is a relativistic laser self-focusing that penetrates over the critical density with relativistic effects and can be used to fast heat the imploded core if it carry the laser energy close to the vicinity of the core.

Outline

1. Brief Introduction of self-focusing
2. Demonstration of laser propagation in 10x N_c plasmas with 300J/PW laser.
3. Fast electron spectrum through super-penetration
4. Summary

Brief Introduction of self-focusing

What is "Super-penetration" mode of intense laser propagation in plasmas



Relativistic Self-focusing + Relativistic Induced Transparency + hole boring
(RSF) (RIT) (LHB)

Evacuation of electrons

Super-penetration

Concept: Self-focusing, RIT and LHB

1. Self-focusing: in underdense plasma a laser pulse undergoes relativistic self-focusing when its power exceeds the critical value

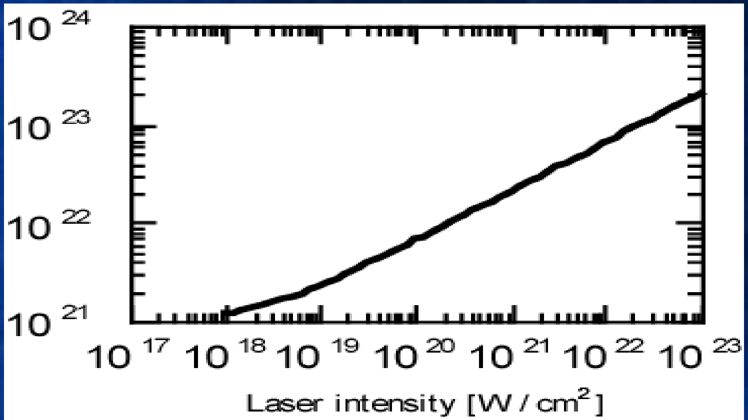
$$P_{cr} \approx 17(\omega / \omega_p)^2$$ GW

2. Relativistic induced transparency (RIT): The relativistic mass increase of plasma electrons leads the effective transparency of plasma with density less than γNc to the laser pulse. This effect is known as RIT. Higher intensity laser can reach denser plasma region via RIT.

10^{22}W/cm^2 laser can reach 70Nc via RIT

$$N_{cr} = \gamma N_c$$

$$\gamma = \sqrt{1 + \frac{a_L^2}{2}}$$



3. Laser hole boring (LHB): The laser light ponderomotive pressure can bore a hole in the over-dense plasmas:

$$u = c\left(\frac{n_c}{2n_e}\frac{Zm_0}{M_0}\frac{I\lambda^2}{1.37\times10^{18}}\right)^{1/2}$$

Demonstration of laser propagation in 10x N_c plasmas with 300J/PW 0.5 psec laser.

Experiments of laser propagation in plasmas: plasma channel formation

- ## Laser condition

GEKKO XII Laser

Wavelength : 0.527 μm
Energy : ~40-48J/beam 2
Pulse duration : 1.3 ns Gaussian
Intensity : 1~2x10^{13}W/cm^2 @500μm

PW Laser

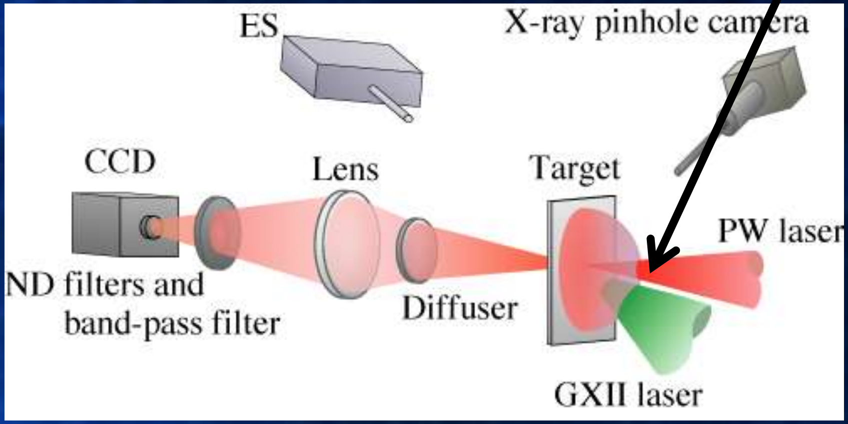
Wavelength : 1.053 μm
Energy : 150~250 J
Pulse duration : 600 fs
Intensity : 5x10^{18}W/cm^2@70μm

- Target: (front)0.1 μm Al+1 μm CD, planar

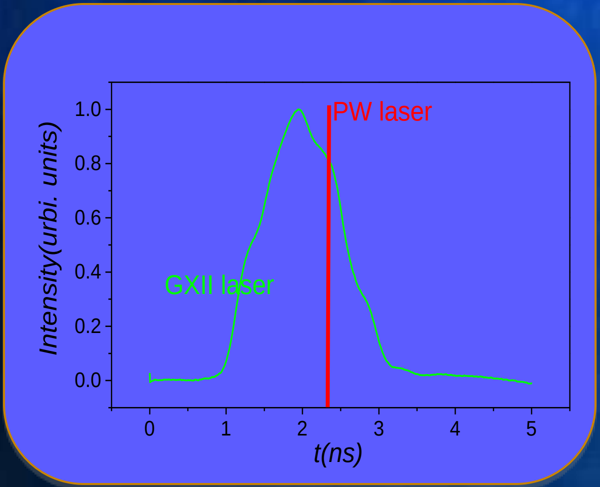
Experiments of plasma channel formation in over-dense (x10 N_c) plasma

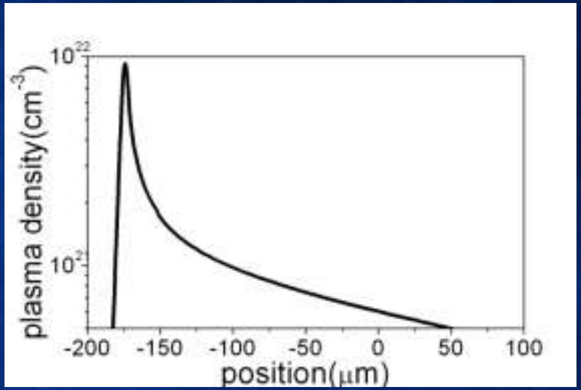
150J/0.6ps

- **Experimental setup**
  - -XPHC: 21deg to GXII PW laser axis
    18 μm pinhole/40 μm Be filter/M~9
    keV x-ray energy range
  - -ESM: 21 deg to GXII PW laser axis
    energy range 1-100MeV
  - -transmittance: along GXII PW laser axis,
    an optical diffuser used



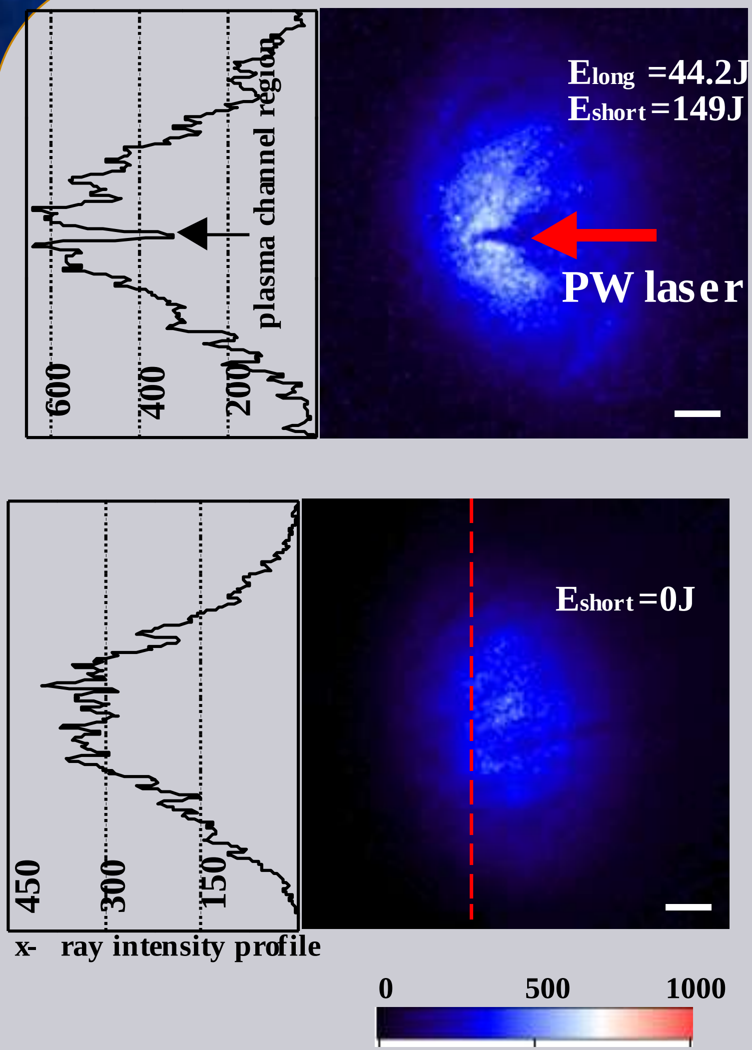
- **Timing: GXII laser pulse peak to GXII PW laser peak 0.15ns**





- **Preformed plasma: at GXII PW laser injection, 80μm thick overdense region with peak density 10Nc based on 1D_ILESTA hydro simulation**

keV x-ray pinhole camera images show clear plasma channel formation and indicate the laser beam pointing is along the laser axis



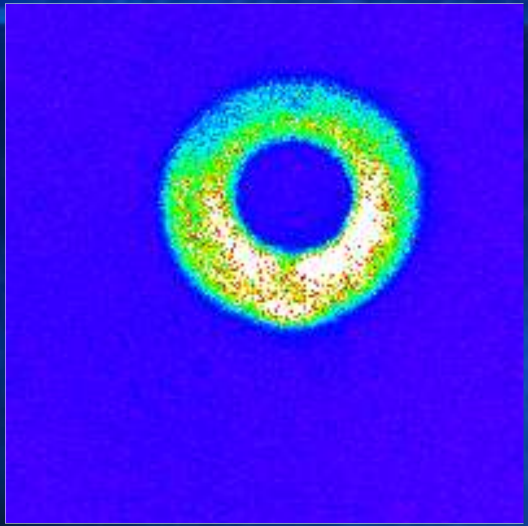
With GXII PW laser
There is clear plasma channel formation

The laser transmittance through the whole plasma suggests the channel length is over 500 µm

Without GXII PW laser
There is no plasma channel formation

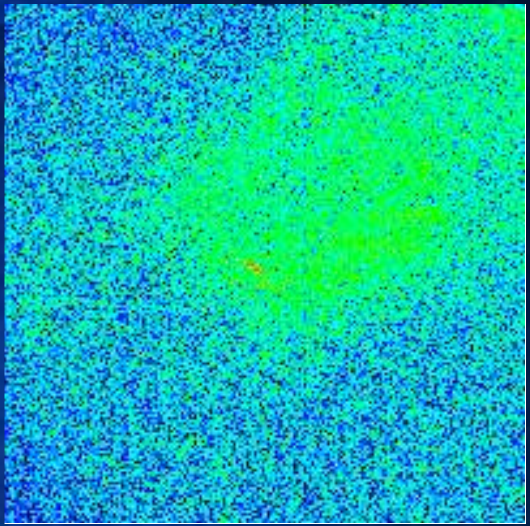
PW laser light transmittance measurement confirms the laser channeling into the high density plasma with self-focusing

a



Without target: Low energy PW laser calibration shot image

b



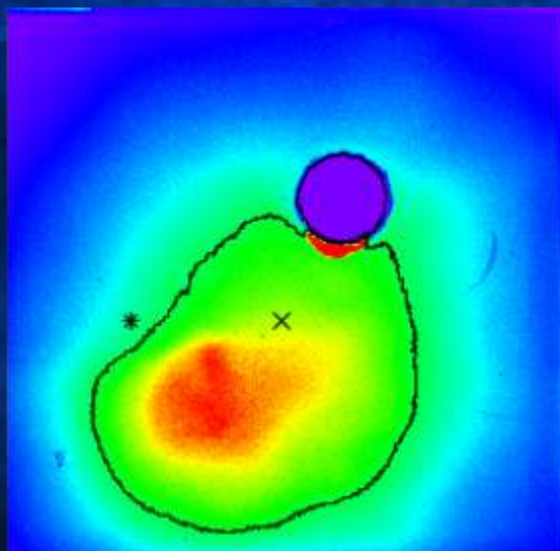
With PW laser injection into the preformed plasma:

4% transmittance

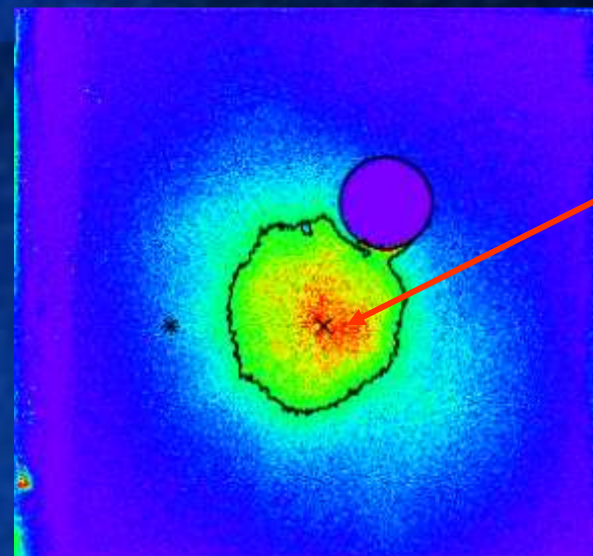
1. **Taking into account of relativistic induced transparency and Wilks's laser hole-boring, we estimate that the GXII PW laser should self-focus down to 20 μm to penetrate through the preformed plasma. The GXII PW laser focus size in vacuum is about 70 μm.**

Hot electron beam divergence

70deg
(FWHM)



Planar Solid target



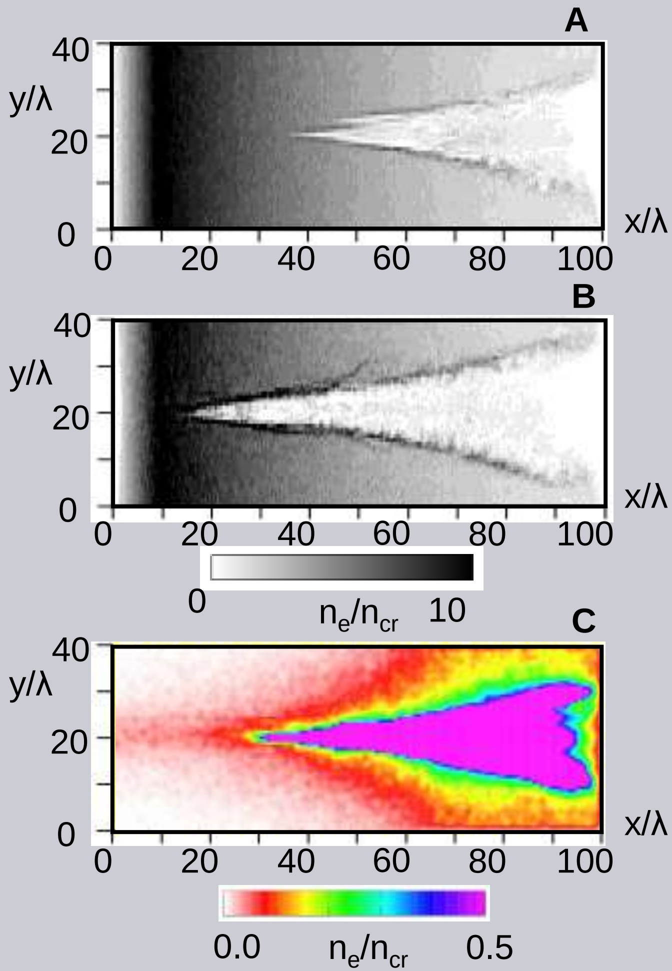
Preformed plasma

PW laser axis

30 deg
(FWHM)

1. **With planar solid targets fast electron emission peaks normal to the target rear surface and shows broader distribution with >40deg.**
2. **With preformed plasmas fast electron emission peaks along the laser axis and shows collimated distribution with 20~30deg.**

PIC simulation indicates collimated and highly directional hot electron generation along the laser axis



Plasma density at time 1

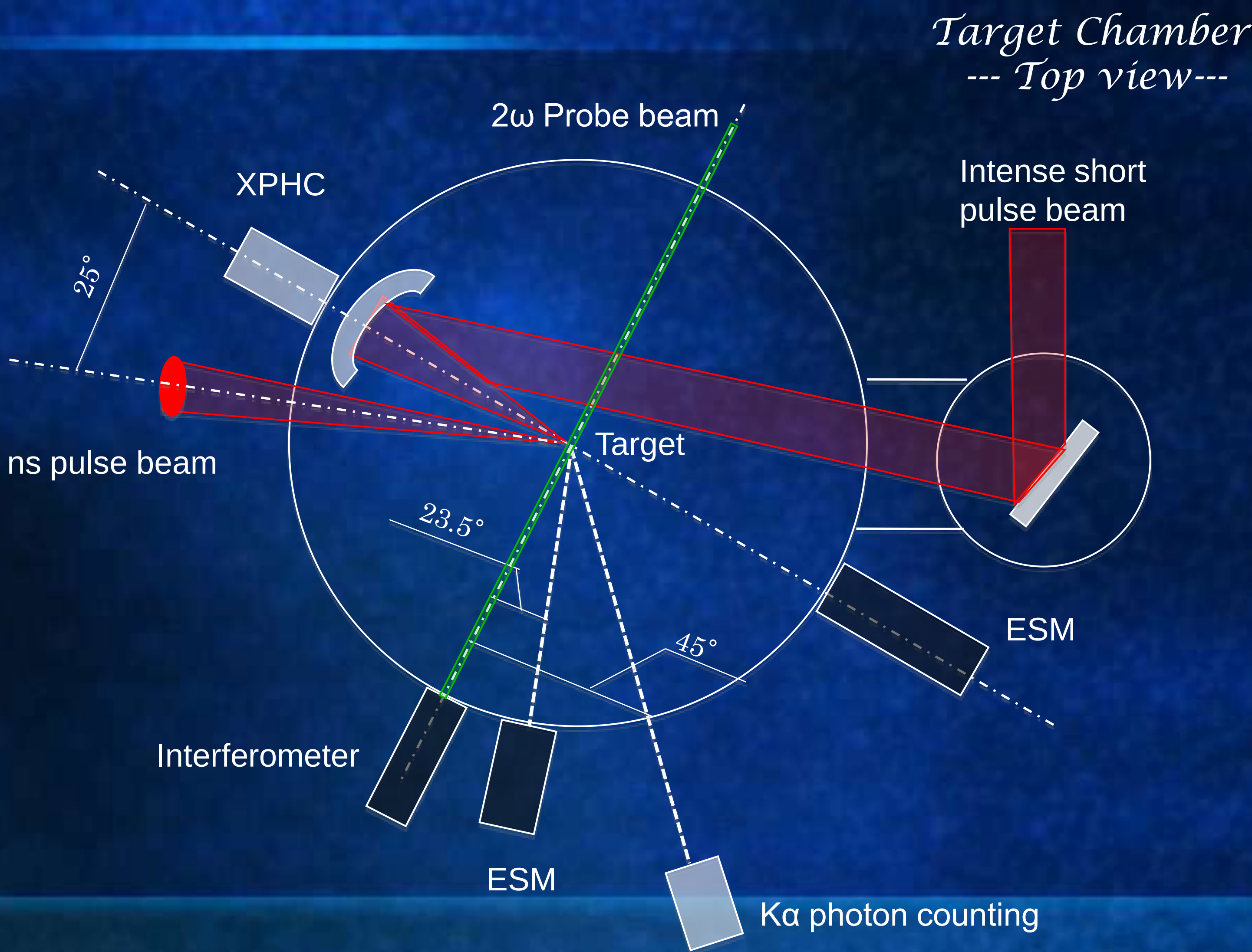
Plasma density at time 2

Hot electron density at time 1

Fast electron spectrum through super-penetration with 60 TW/500 fs laser

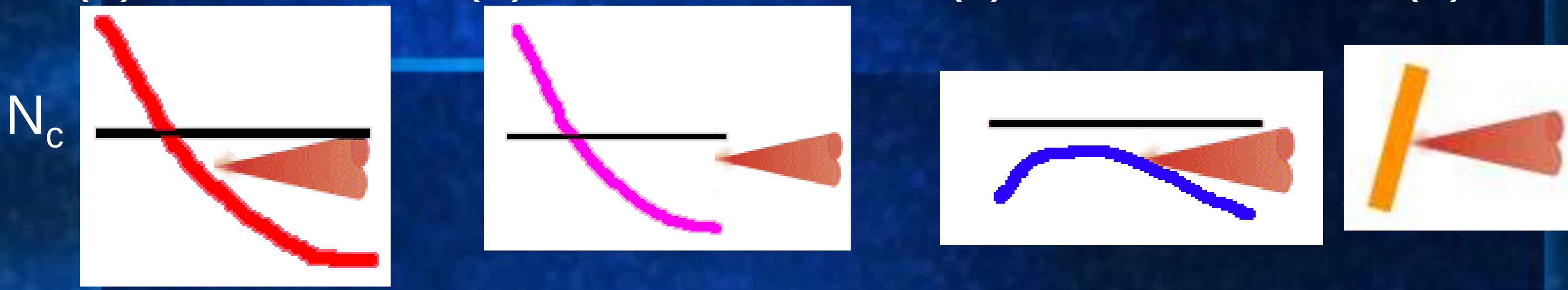
Experimental setup

- GMII 60TW short pulse + 30J ns pulse



4 different conditions are tested.

(a) Overdense (b) Overdense (c) Underdense (d) Solid



Target	Focus wrt Nc	Ne @ Focus
(a)Overdense	120 μm	$3.0*10^{20}$
(b)Overdense	420 μm	$1.9*10^{20}$
(c)Underdense	—	$2.63*10^{20}$
(d)Solid	0 μm	10^{23}

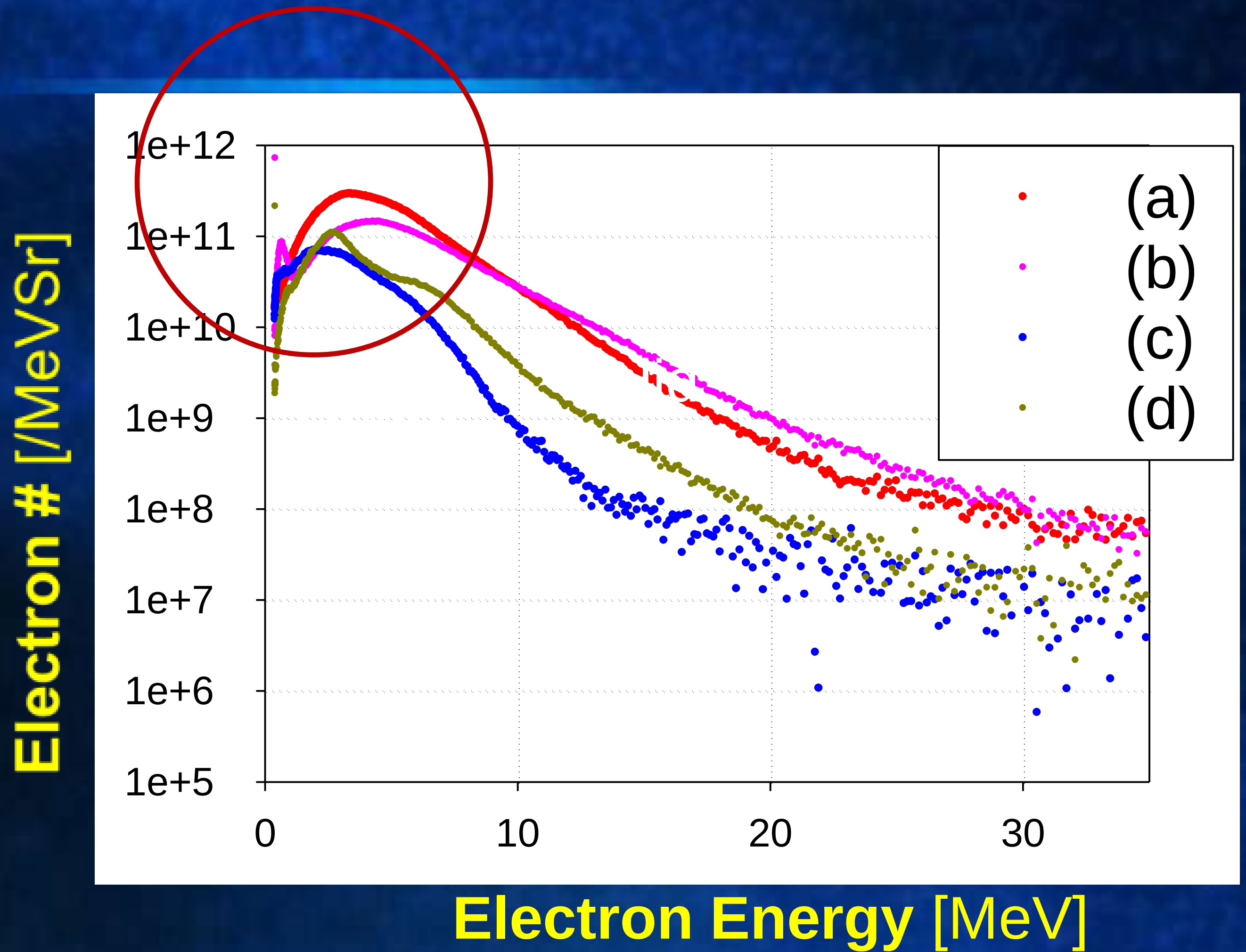
- Large static fields exist at rear side of targets. These affect the escaping fast electrons or trap them within the potential.

- As long as the plasma conditions of target rears are same, we should be able to compare the behaviors of electrons escaping from targets.

- H Habara et al., PRL 104, 055001 (2010); H Habara et al., POP, 17, 0553061(2010).
- T Yabuuchi et al., 14, 040706(2007).

Fast electron generation with different plasmas

Electrons observed on-axis front.



Over@120

Focus Optics F/3.9
(a)Overdense@120um, (b) Overdense@420um
(c) Underdense, (d) Solid

Summary

1. PW laser SPT with peak density 10 Nc has been demonstrated as a single channel formation traveling more than 100 μm.
   Fast electron temperature is about 1.5MeV, higher than that for solid targets (1MeV).
   Fast electron beam divergence appear collimated for SPT to 30º compared to 70º of plane target.
2. SPT produces more than twice fast electrons compared to self-focusing in underdense.

Relevant Works

1. SPT first indication
   KA Tanaka et al.,
   POP 7 2014 (2000)

2. SPT for core heating: x 4 N_y increase.
   Y Kitagawa et al.,
   PRE 71 016403 (2005)

3. SPT focus optimization
   T Matsuoka et al.,
   PPCF 50 105011 (2008)

4. SPT demonstration with 200J PW laser
   A Lei et al.,
   POP 16 056307 2009