Theory and Simulation of Photon-Matter Interaction
01 - 05 July 2018, ELI-ALPS, Szeged, Hungary

COLLIDING LASER-PRODUCED PLASMA (CLPP) AS TARGETS FOR LASER-GENERATED EXTREME ULTRAVIOLET SOURCES

Haider M. Al-Juboori

SpacLab, University College Dublin (UCD), Dublin, Ireland

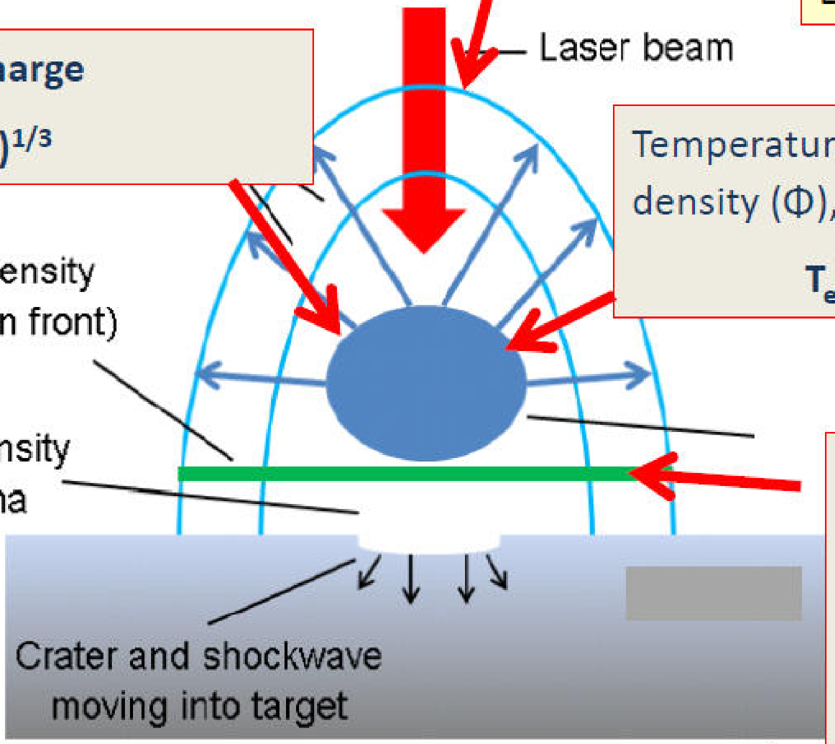
haider.al-juboori@ucd.ie

5th July 2018

Layout

- Laser Produced Plasma– Orientation.
  - Principles.
  - Properties.
  - Applications.
- Colliding Laser Produced Plasma (CLPP)- key points.
- CLPP: Target geometry and stagnation layer.
- Conversion Efficiency (CE).
- Summary

Laser Produced Plasma– Orientation



Expansion velocity ≈ 10^6 - 10^7 cms^{-1}

For ns duration plasmas
Collisional Radiative (CR)
Equilibrium assumed

Average charge

≈ 0.67 $(ZT_e)^{1/3}$

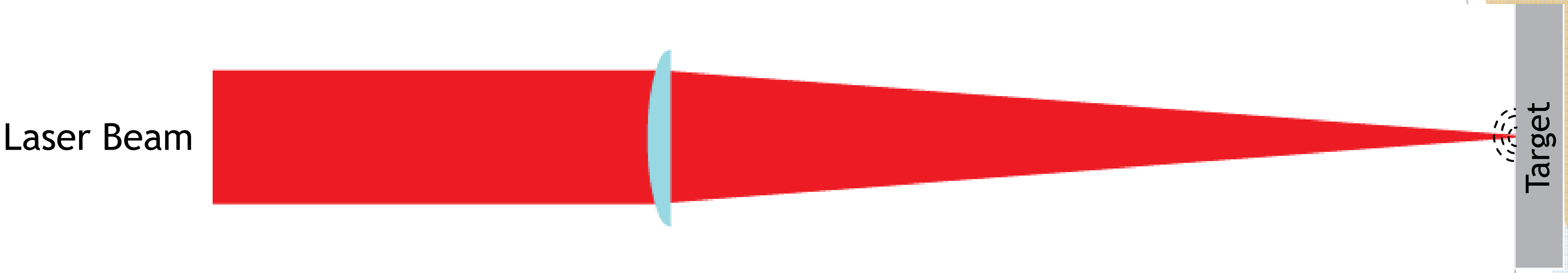
Temperature depends on laser power density (Φ),

T_e(eV) α $(\lambda^2\Phi)^{3/5}$ …CR model

Critical electron density, **n_{ec}** $=10^{19} – 10^{21}$ cm^{-3} depends on laser wavelength **(n_{ec}~$[10^{21}/\lambda(\mu m)^2]$ cm^{-3})**

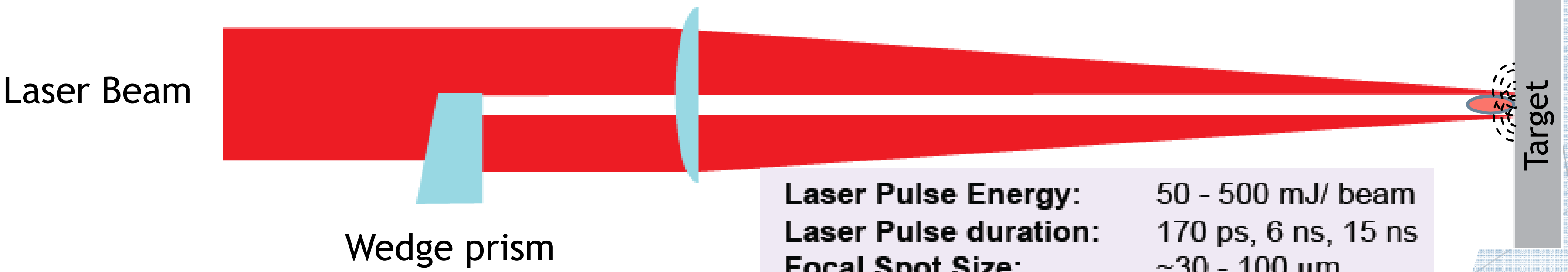
To conserve momentum, plasma expands perpendicular to target surface

Colliding Plasmas – Orientation



$$d = \gamma f\left(n-1\right)$$

Making Stagnation layers



Laser Pulse Energy:	50 - 500 mJ/ beam
Laser Pulse duration:	170 ps, 6 ns, 15 ns
Focal Spot Size:	~30 - 100 μm
Irradiance:	10^9 - 10^{11} W.cm^{-2}

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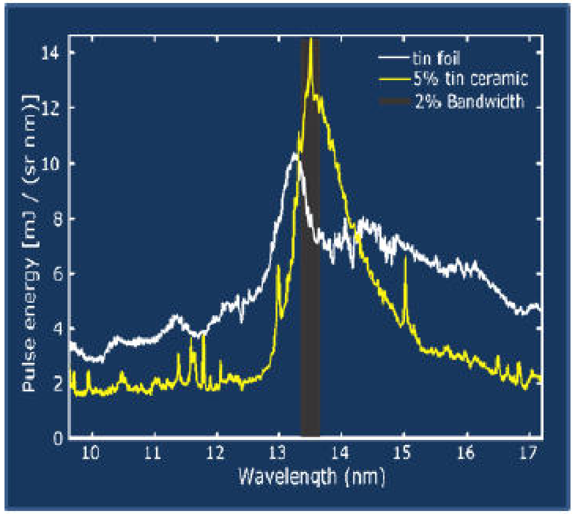
In-Band Conversion Efficiency (CE)

Slab Targets

Nd:YAG plasmas: 2%<CE<3%

e.g. CE~2.3% /2π sr for 100% Sn @Φ= 1.6x10^{11}Wcm^{-2}
CE~2.9% /2π sr for 5% Sn @Φ= 2x10^{11}Wcm^{-2}

(Hayden et al. 2006 , JAP 99, 9)

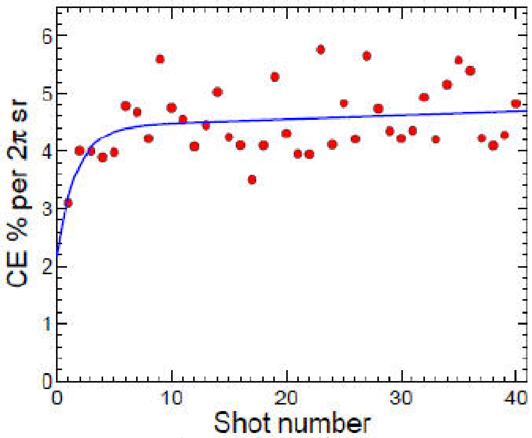


CO_2 plasmas: 2%<CE<3%

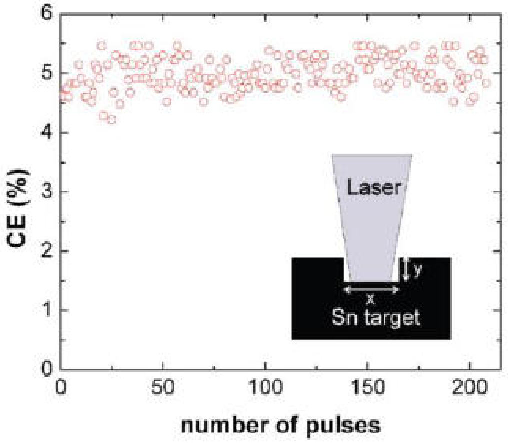
CE ~ 2.6% for 100% Sn @Φ= 1.6x10^{11}Wcm^{-2}

(Tao et al. 2008, APL 92, 251501)

CE increased after multiple shots on same target position to ~4.5%.
Lateral expansion reduced.

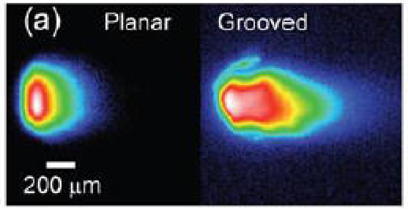


Grooved Targets:

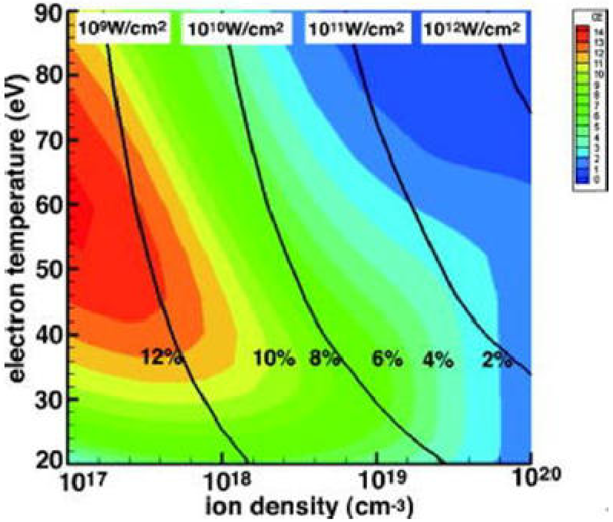


CO_2 pulse with τ = 25 - 55ns, typically FWHM = 30 ns
Φ = 6 x 10^9 Wcm^{-2}

(Harilal et al. 2010 APL 96, 111503)



Optimized In-Band CE



(Nishihara et al 2008 Phys. Plasmas 15, 056708)

Maximum CE in a mass limited droplet ~6-7% allowing for -10 excitation emission cycles/ion.

If kinetic losses are supressed, CE ~20% at $25 \leq T_e \leq 32$ eV.
CE values of 11.5% under optimised conditions

(Basko (2016) Phys. Plasmas 23, 083114)

To optimise CE :

- Minimise kinetic losses → low target density
- Minimise opacity effects → ion density $<10^{18}$ $\mathrm{Wcm^{-2}}$
- Mist or vapour target → dual pulse irradiation
- Laser wavelength should be long to optimise laser plasma coupling → CO_2 laser
- Low density implies large plasma scale length and gentle gradients → reflection losses reduced

Colliding Plasma Target

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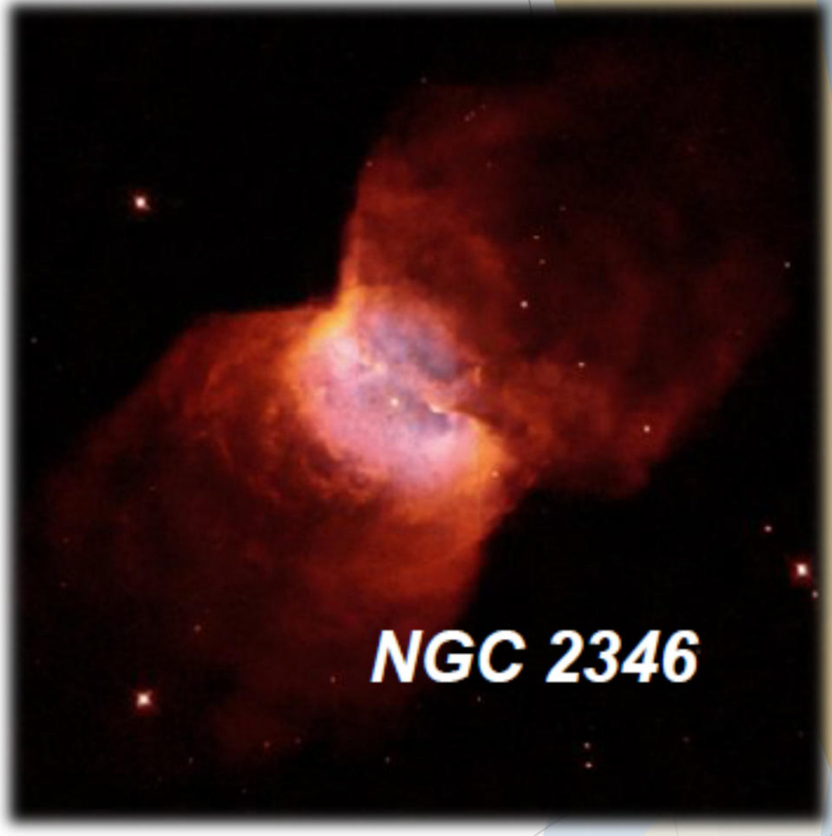
Colliding Plasmas – Orientation

‘From the very BIG’

NGC2346 -
Planetary Nebula
Distance - 2,000 light years
Extent ~ 0.4 light years

Result of the collision of two stars – believed that one became a red giant and started to swallowed its partner in the binary system.



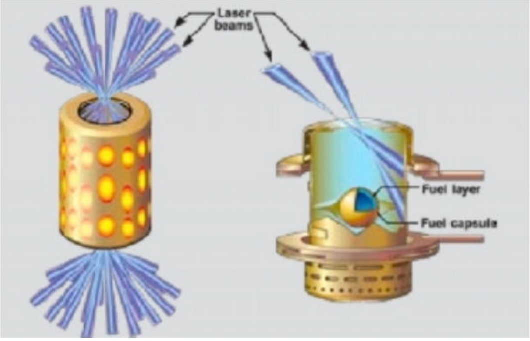
Credit: Hubble Wide Field & Planeary Camera - Massimo Stiavelli (NASA)

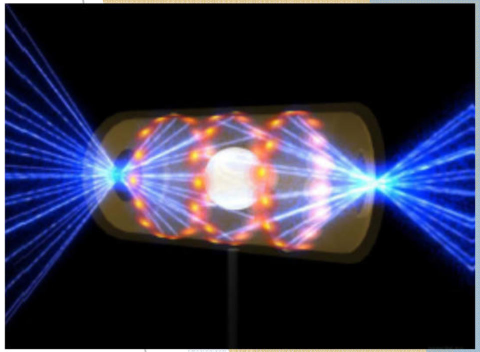
Colliding Plasmas – Orientation

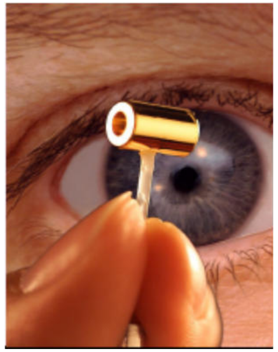
‘To the very small’

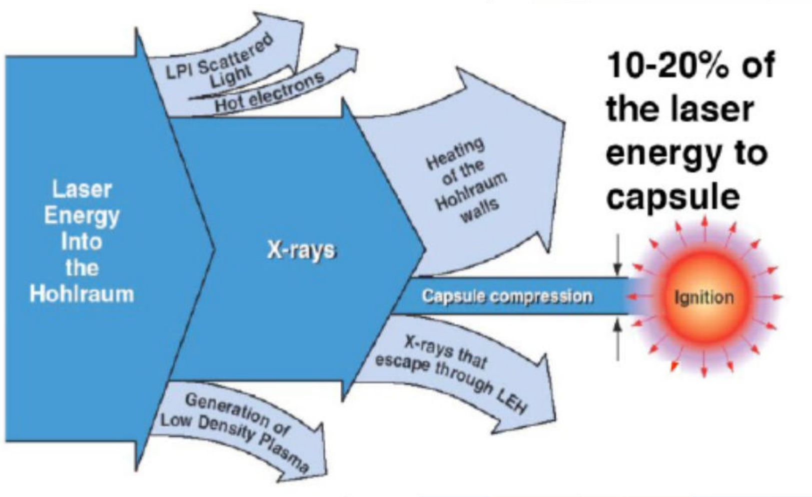
‘Hohlraums – Fusion energy generation’

Multiple laser plasmas formed inside a single high-Z cavity e.g., Au) which provide an array of extremely bright X-ray sources. The fuel pellet is compressed by the X-ray radiation pressure. Advantage is more uniform compression with concomitant amelioration of instabilities…









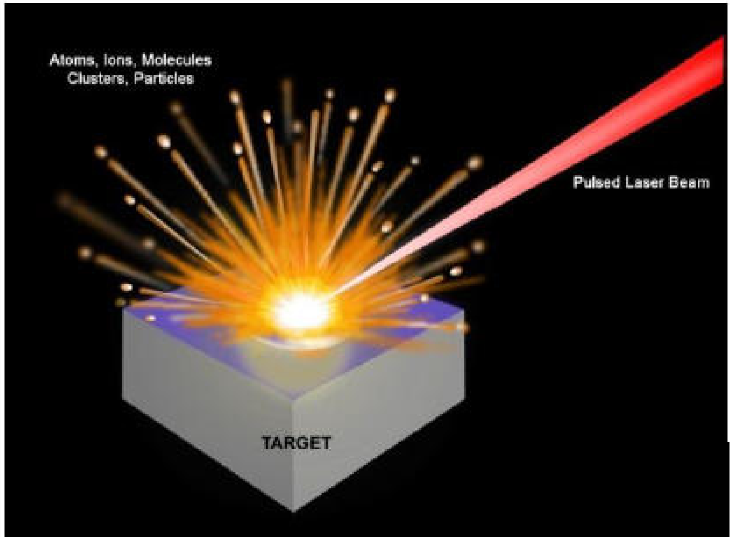
10-20% of the laser energy to capsule

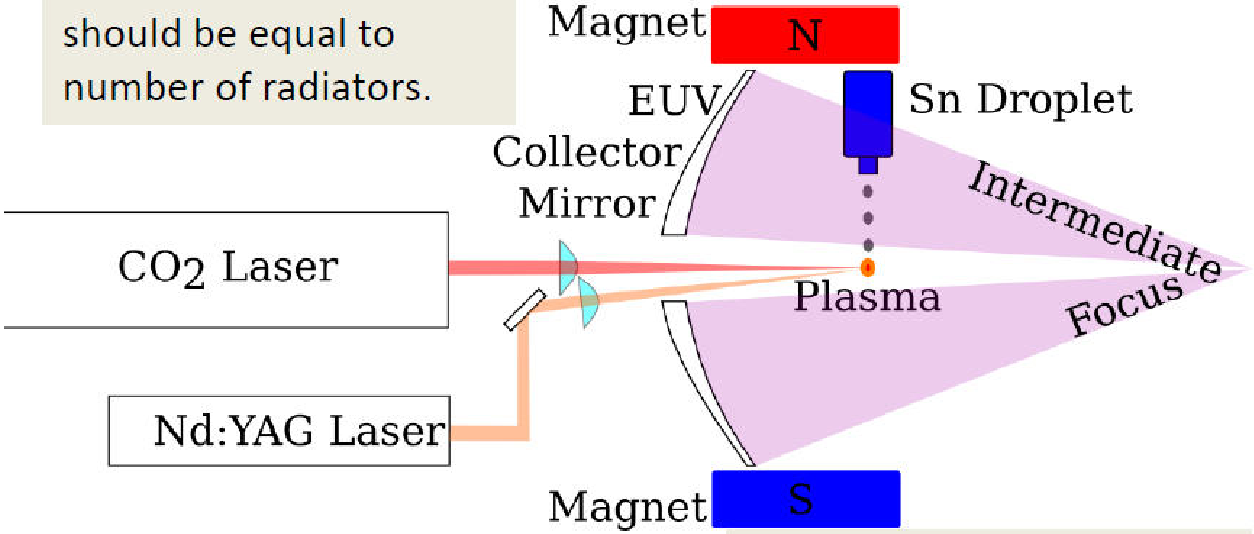
Target Geometry for HVM of EUVL

At high repetition rates, it is not possible to use solid (slab) targets.

For EUV, rep. rate =10^5 Hz

Low mass Sn content. number of Sn atoms should be equal to number of radiators.





To minimise debris, target should be fully ionized by end of laser pulse.

- Gigaphoton and CYMER have obtained > 200 W at Intermediate focus. Maximum CE ~ 5%.
- Gigaphoton: Nd:YAG prepulse, CO_2 main pulse, Cymer: CO_2 main and pre-pulses.

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Colliding Plasmas

When two plasmas collide one observes:

1- Interpenetration -counter streaming plasmas pass through each other.

2. Stagnation -plasmas collide but do not inter-penetrate and form a 'stagnation layer'. Here the local density and temperature rise rapidly.

Could a plasma stagnation layer provide a suitable target for an EUV or BEUV source?

If n_e~10^{19} cm^{-3} and the stagnation layer persisted for an interaction time matched to CO_2 pulse duration, perhaps a high CE could be attained.

Colliding Plasmas

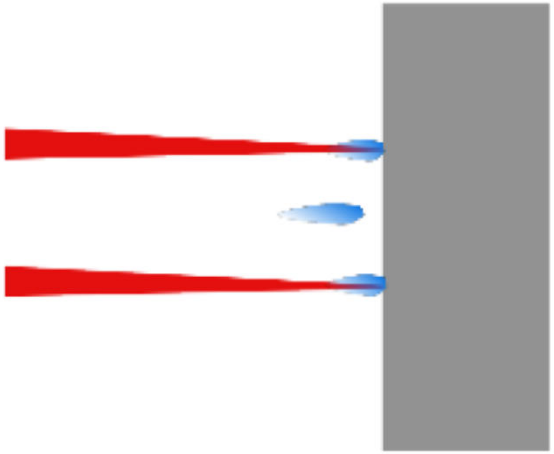
- Collisionality (ξ) is determined by both the mean free path (λ_{ii}) and colliding plasma separation (***D***).

Collisionality Parameter: $\xi = \frac{D}{\lambda_{ii}}$

Large ξ , interpenetrate,
Small ξ , stagnate

$$\lambda_{ii} = \frac{m_i^2 v_{12}^4}{4\pi e^4 Z^4 n_i ln\Lambda_{12}}$$

- υ is the ion velocity -laser power density
- Z is the average ionisation -laser power density
- n_i is the ion density
- Λ_{12} Coulomb logarithm –10 to 30 for lab plasmas



Colliding Plasmas

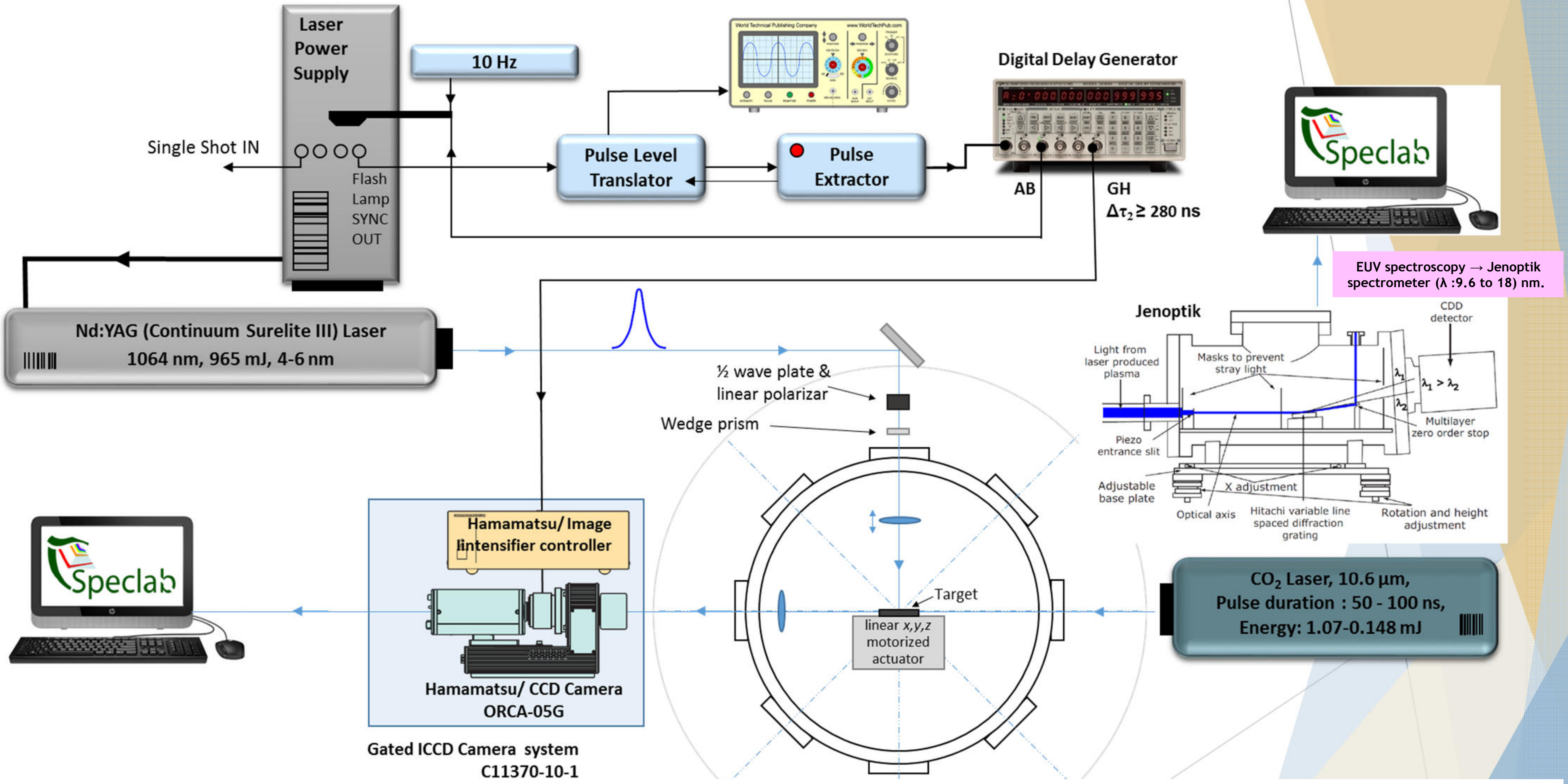


Figure: the apparatus used in the colliding plasma experiments at UCD-Spaclab with external triggering set-up for Nd:YAG laser pulse experiments.

Colliding Plasmas

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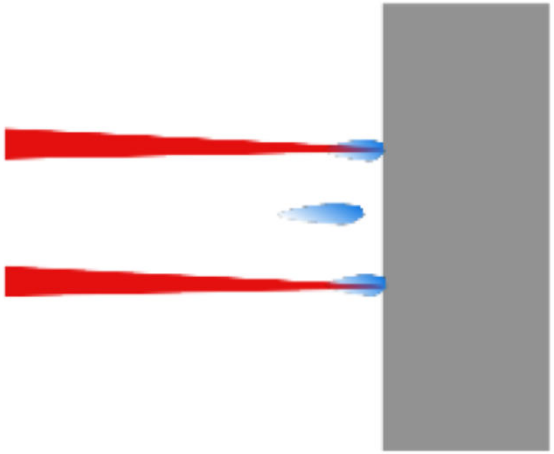
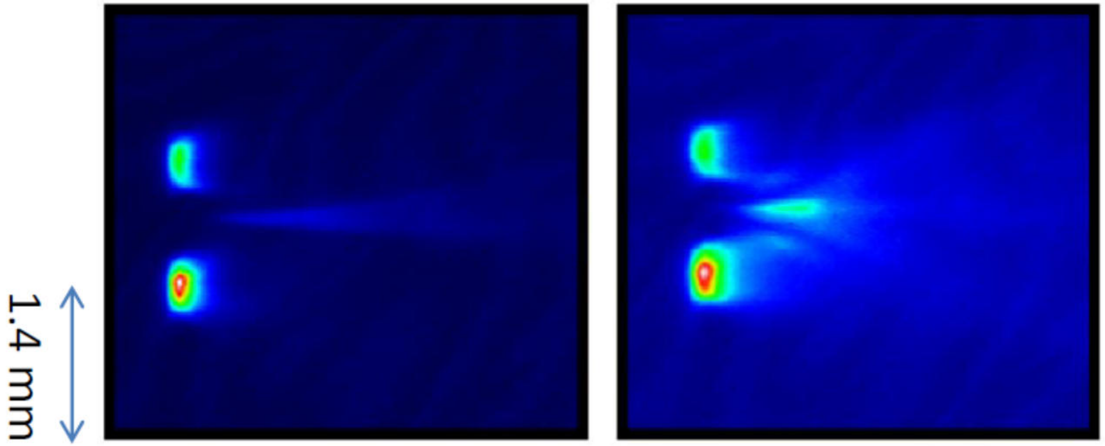


Key point:
One can engineer stagnation layer characteristics; → shape, temperature , density, ..etc ***for specific application***, by:

- varying geometry (D) and,
- laser-target interaction physics (mfp, λ_{ii}).

Flat Target Colliding Plasma

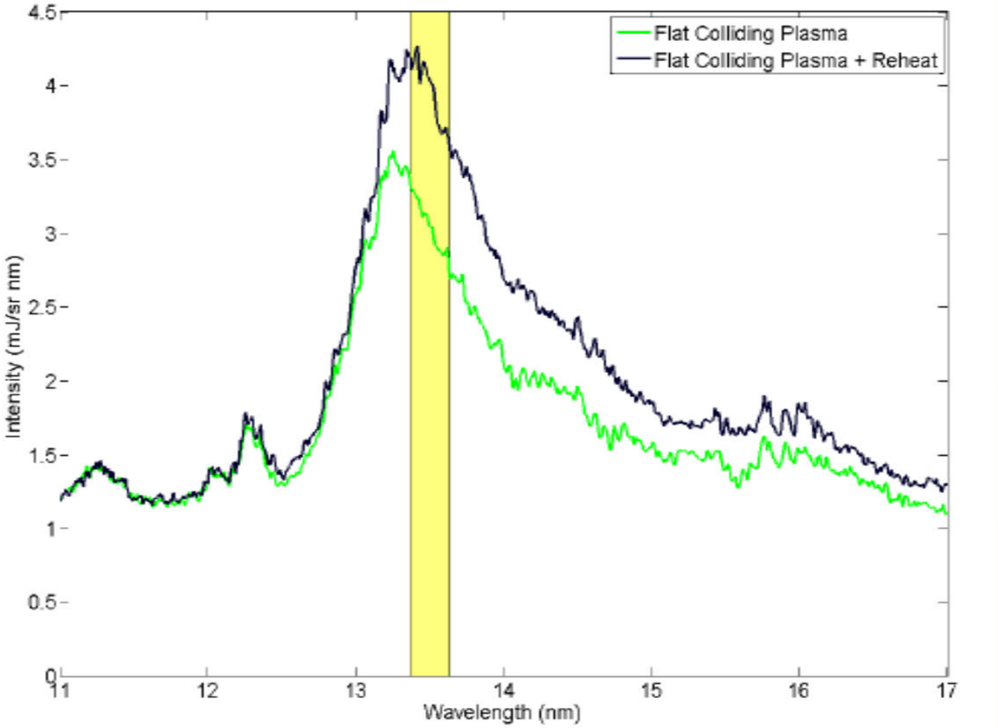
Visible imaging


Nd:YAG Colliding plasma

Nd:YAG CP + CO_2 reheat

Imaging system sensitive to light in 400 –500 nm range.

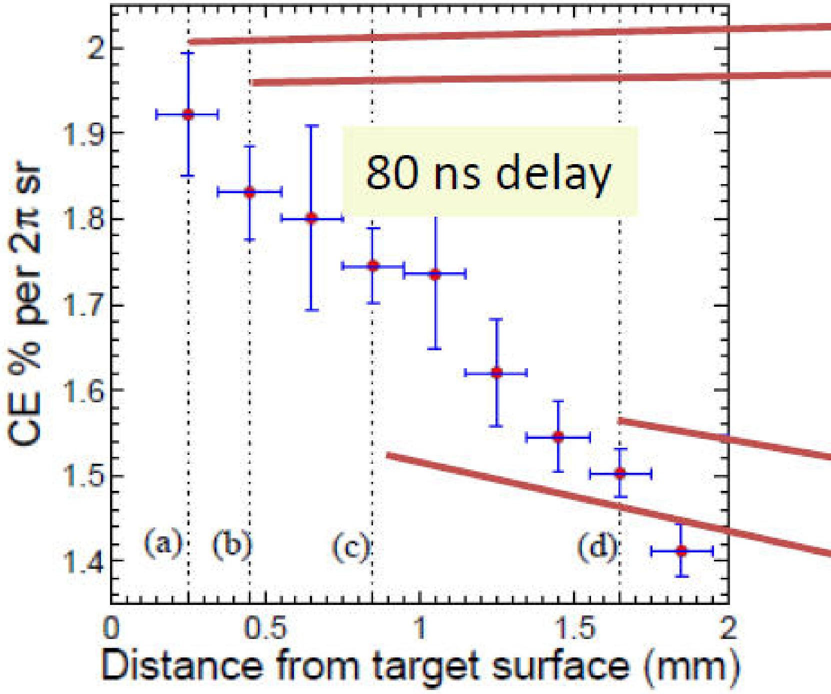
Flat CP and reheat spectra

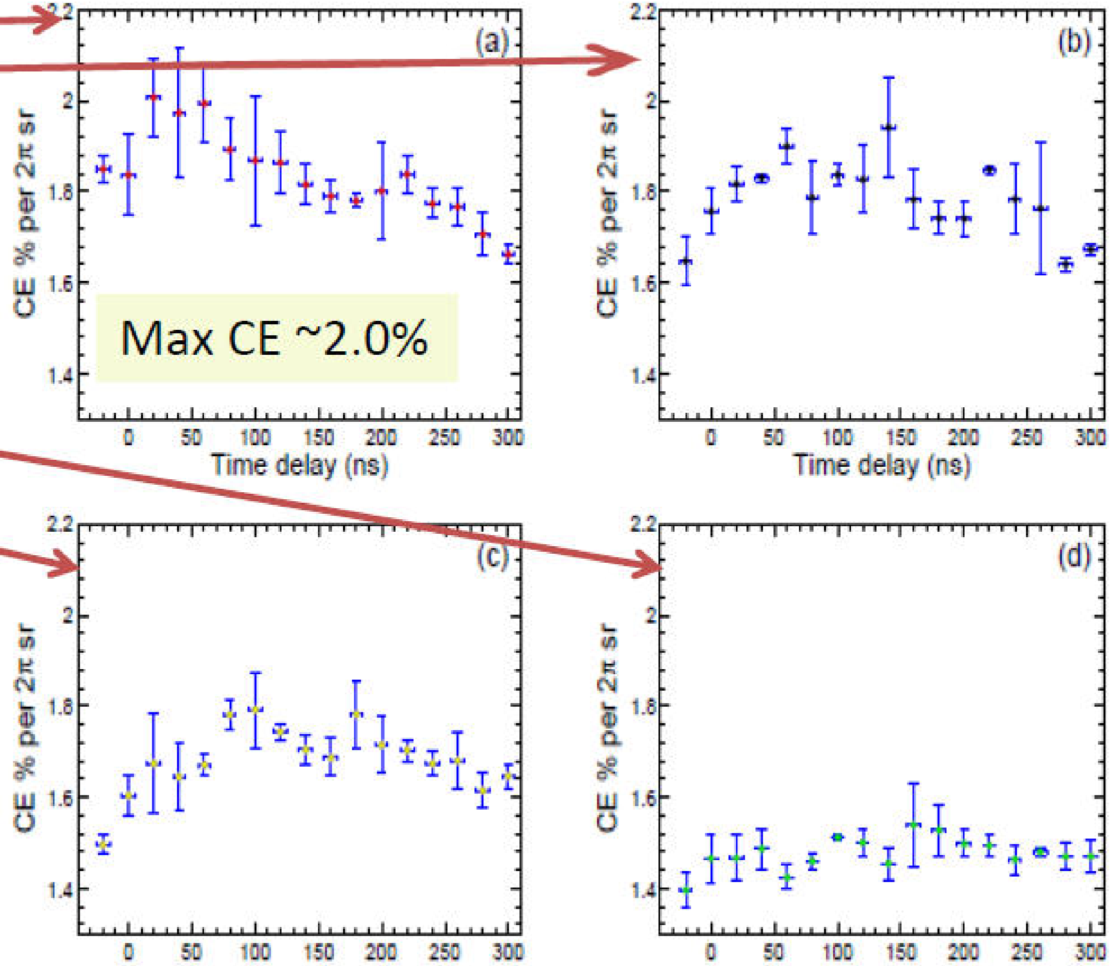


- Highest ion stages emitted along target normal
- Highest ion KE is along target normal ($v_{\text{normal}} \sim 10\, v_{\text{lateral}}$) $\leftrightarrow$ λ_{ii} is ~ 100 times greater and ξ ~ 100 times less

$\rightarrow$ Sharply defined stagnation layer

Flat Target Colliding Plasma

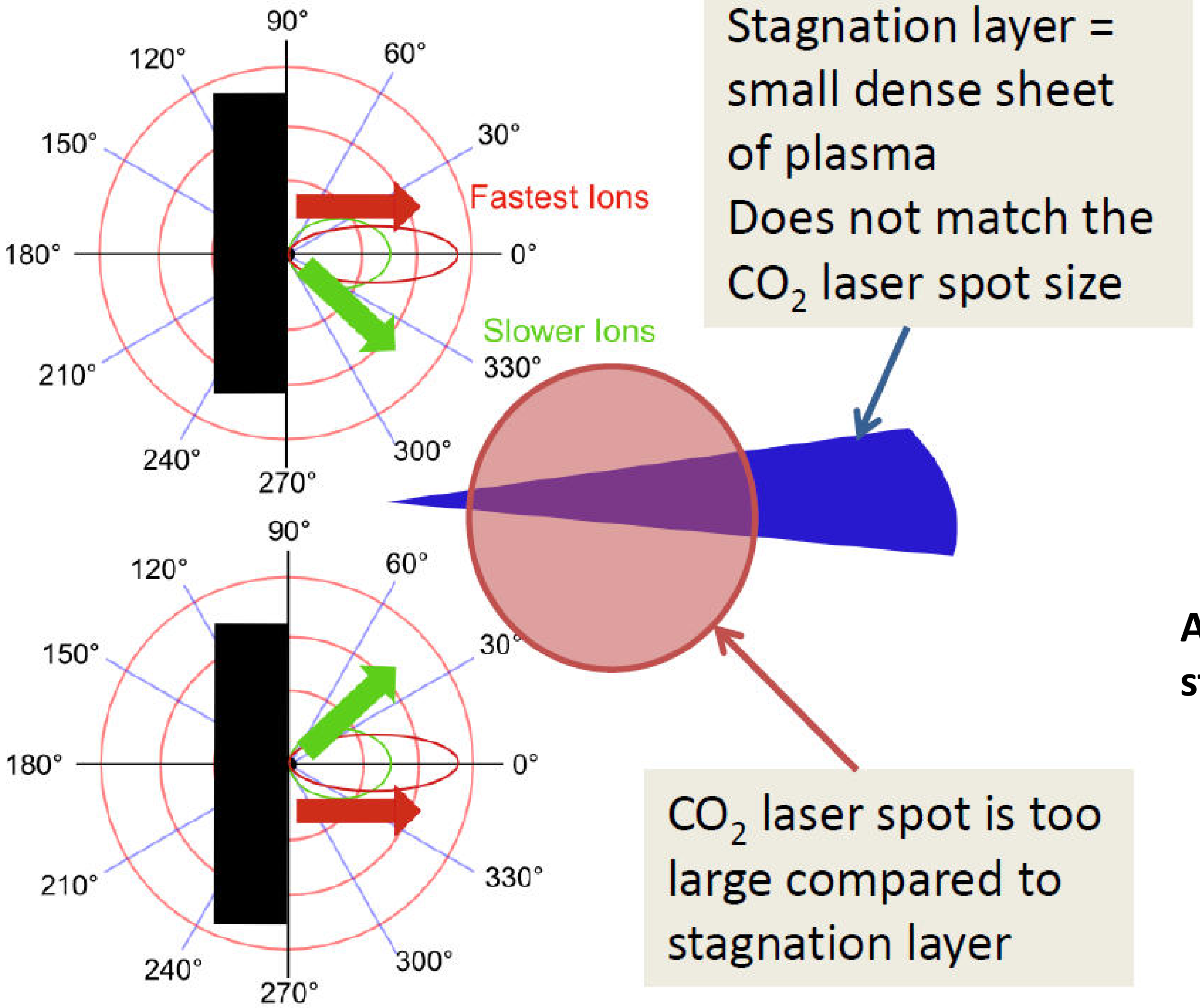




Max CE approx. 1.9%@ 80 ns delay close to target surface, CE decreases with distance. Also max CE at increasing distances generally reached at later times

Gerry O'Sullivan, et al, International Workshop on EUV and Soft X-Ray Sources (2016 Source Workshop) , Amsterdam, November 8th 2016

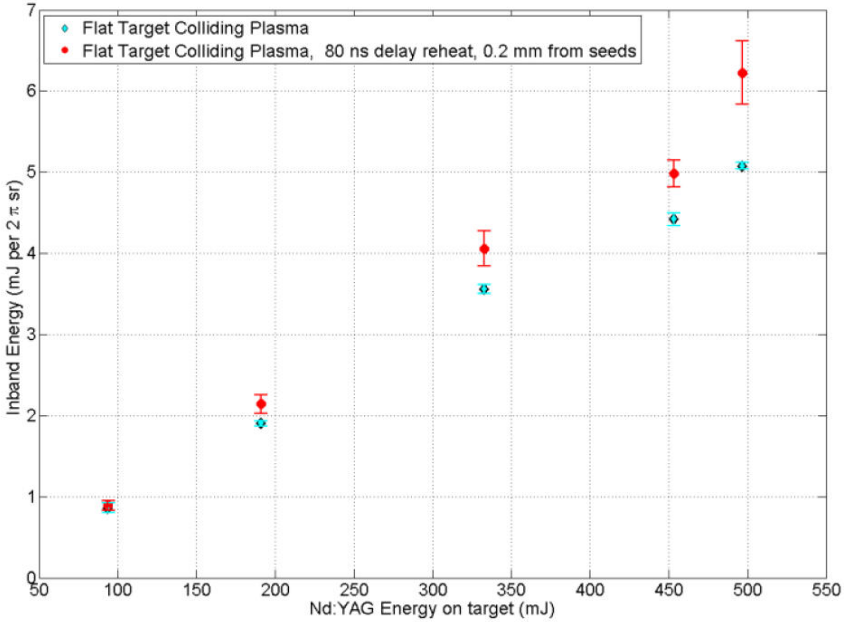
Why Low Efficiency!



Stagnation layer = small dense sheet of plasma

Does not match the CO_2 laser spot size

CO_2 laser spot is too large compared to stagnation layer



As Nd:YAG energy increases – Larger stagnation layer better matched to CO_2 pulse.

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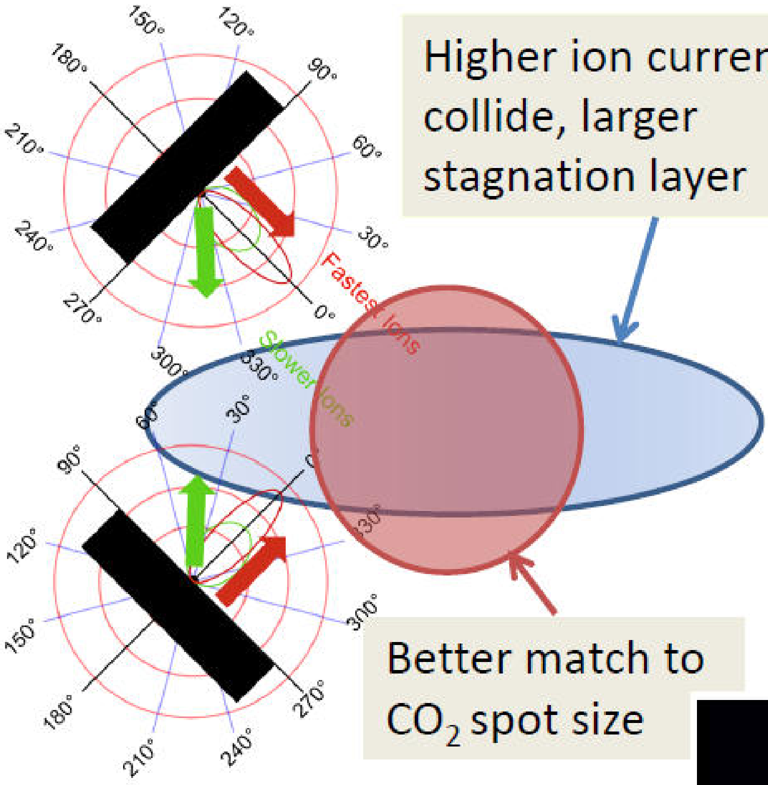
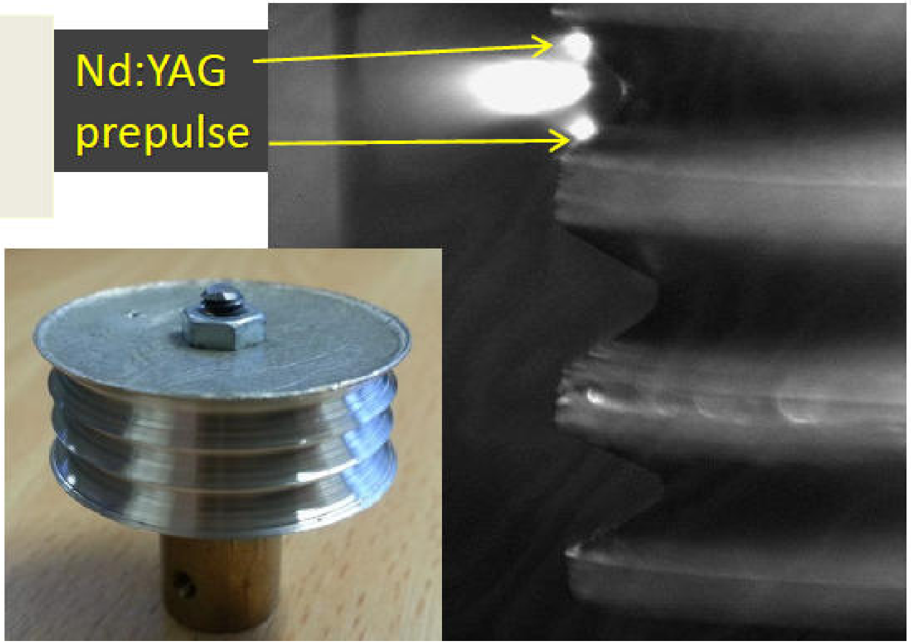
To make a bigger stagnation layer –need more material and more interpenetration

Wedge Target

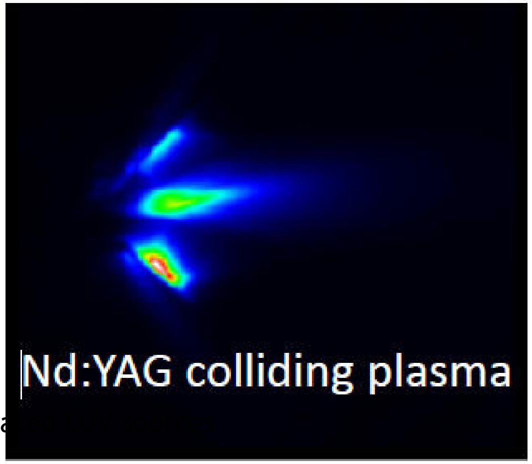


Higher ion currents collide, larger stagnation layer

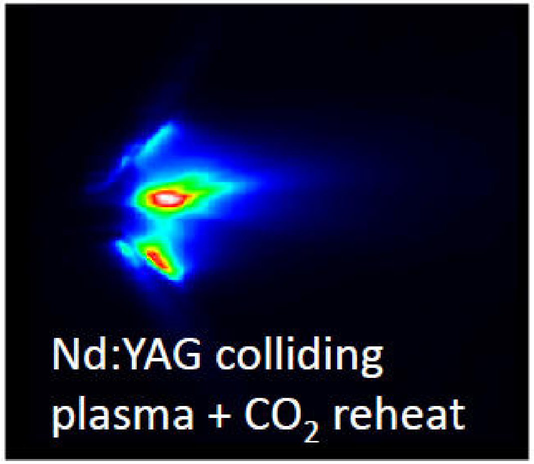
Better match to CO_2 spot size



Visible Imaging system sensitive to λ ~400 – 500 nm

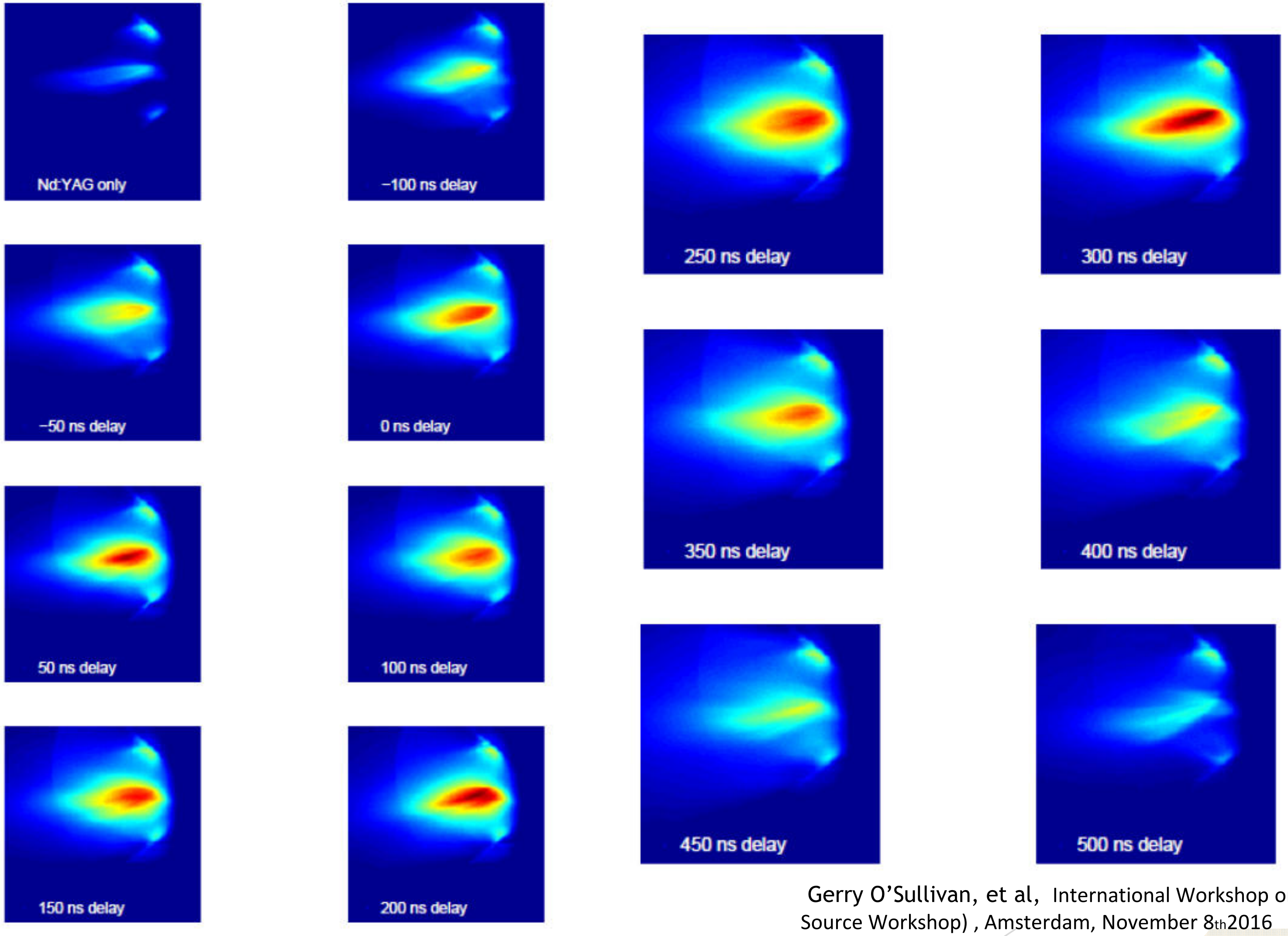


Nd:YAG colliding plasma



Nd:YAG colliding plasma + CO_2 reheat

Colliding Plasma images at Different $\Delta\tau$



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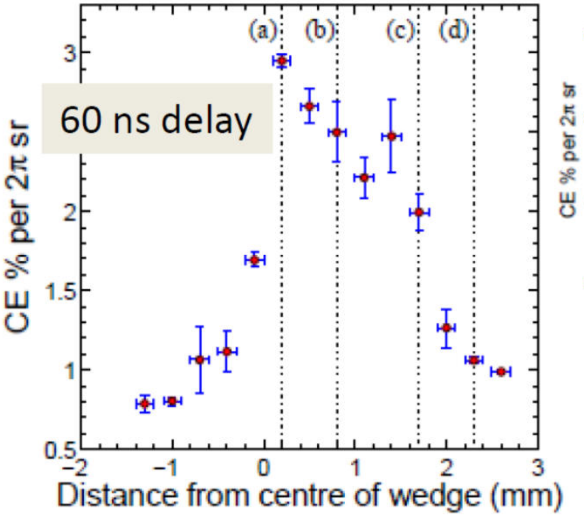
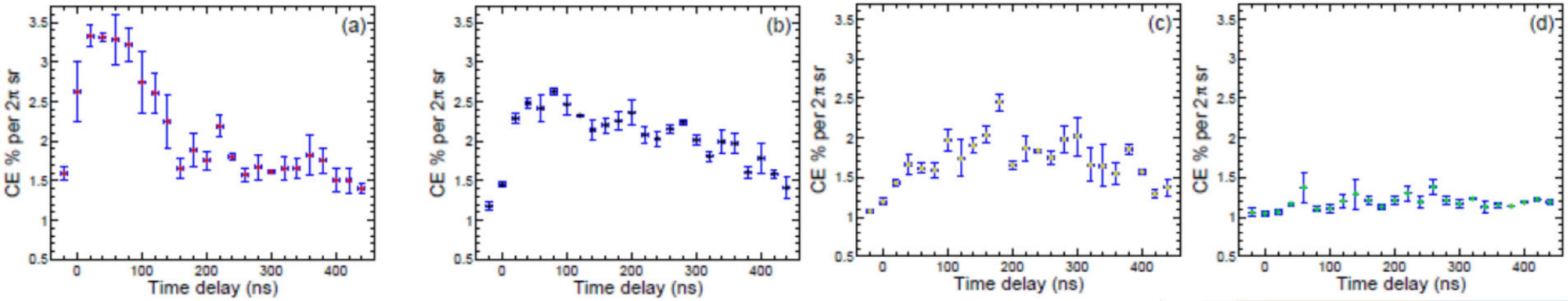
Reheating along wedge target stagnation layer





Max CE @ 60 ns delay close to wedge centre

Nd:YAG, E~ 135 mJ in each pulse,

Φ ~ 1.0x10^{11} Wcm^{-2}

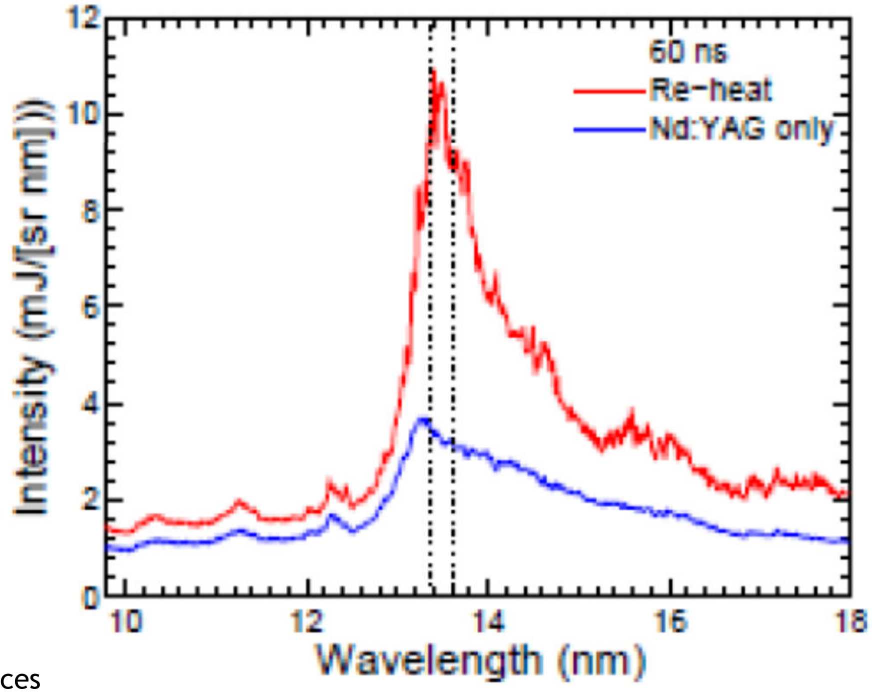
CO_2: E~ 250 mJ, Φ = 1.7x10^9 Wcm^{-2}

CE = 3.3±0.2%

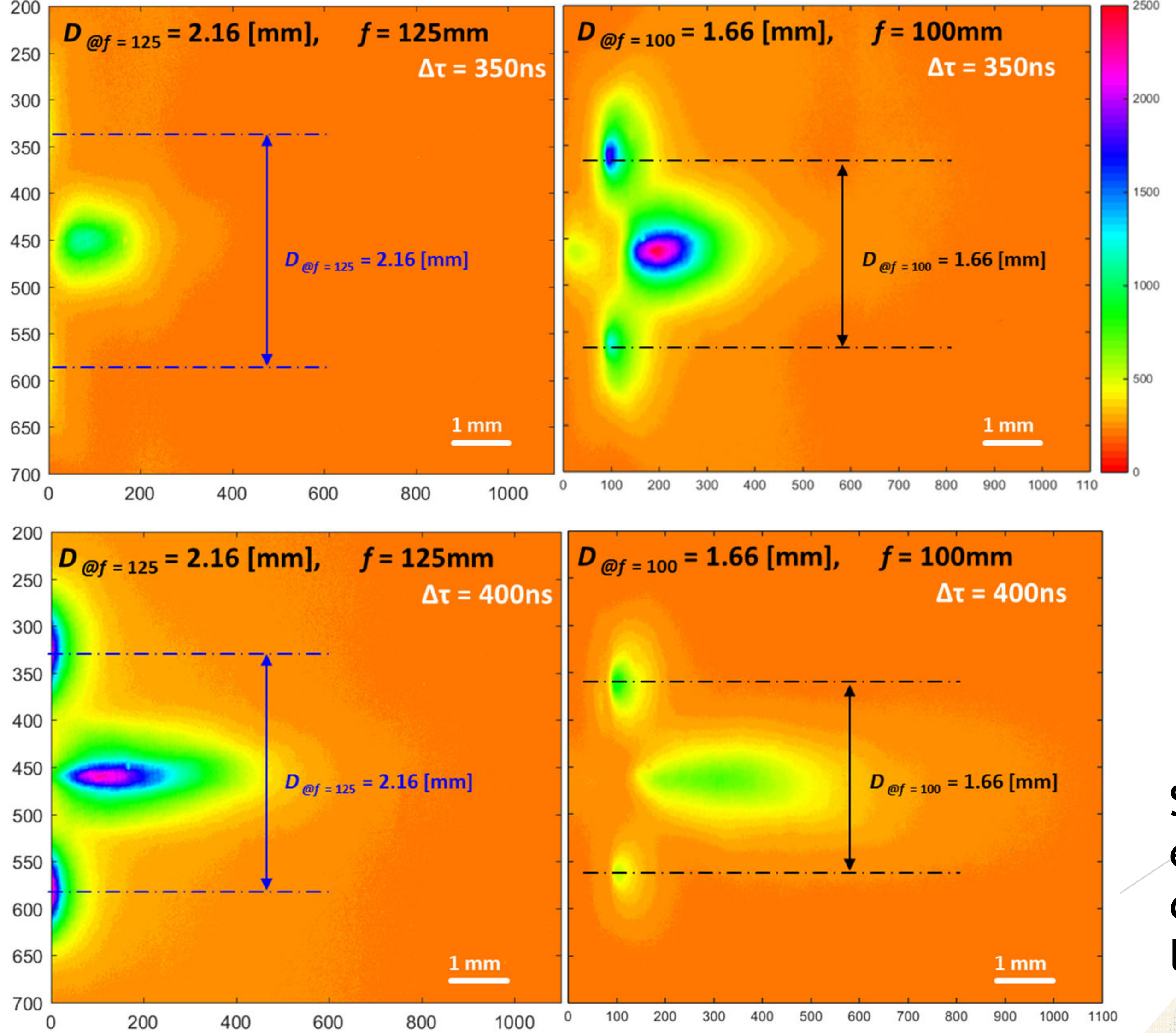
For CO_2 only, CE = 5.1±0.10%

Allowing for overfilling of plasma by

CO_2 CE approximately 7%

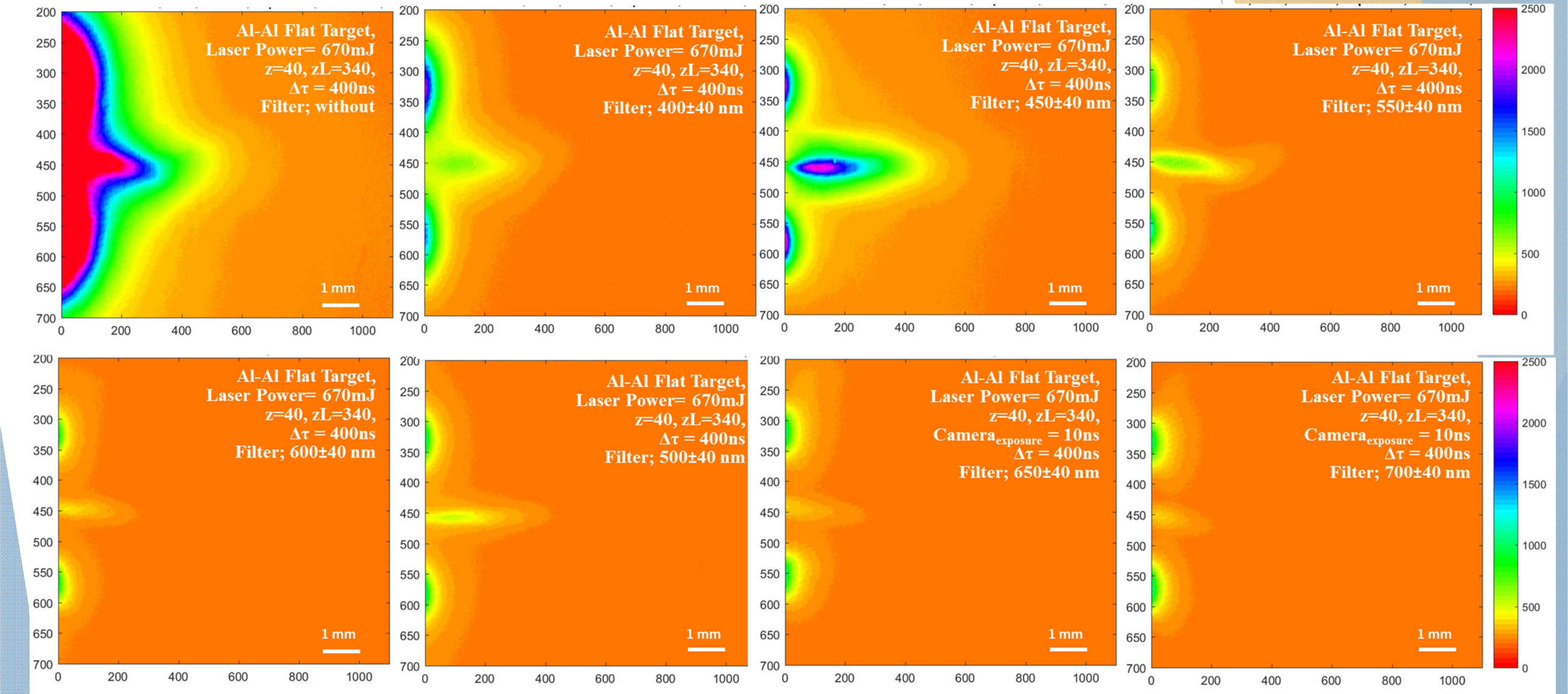


Time Dynamics Imaging of Al-CLPP Al-Plasma, Diff. Dist.



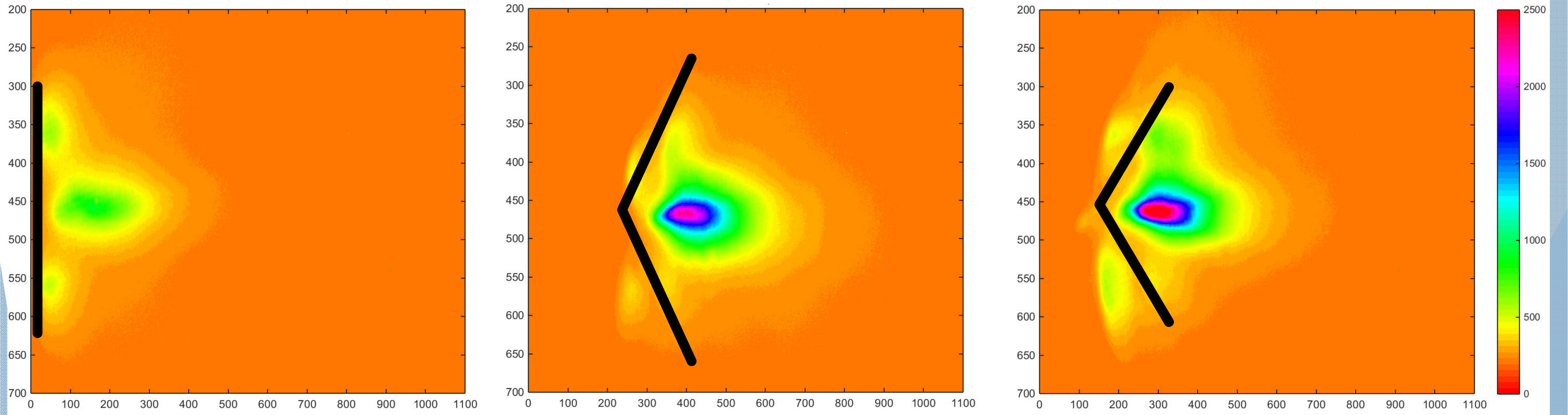
Stagnation layer evolution at two different focusing lenses.

Time Dynamics Imaging: Filter Sensitive Technique



Stagnation layer emission at different visible filters.

Time Dynamics Imaging: Diff. Target Geometry



Si-Si Flat,
laser power at θ=-10
Camera Exposure time = 10ns
Δτ = 340 ns,
Filter = 450 nm

Si-Si , V-120,
laser power at θ=-10
Camera Exposure time = 10ns
Δτ = 340 ns,
Filter = 450 nm

Si-Si , V-80,
laser power at θ=-10
Camera Exposure time = 10ns
Δτ = 340 ns,
Filter = 450 nm

Stagnation layer emission at Diff Target Geometry.

Summary

- Wedge target colliding plasma better matched to CO_2
- Better control of initial conditions could give even higher CE.
- Shows good energy scaling, energy out increases as input energy increases.
- Indicates that with optimum control of pre-pulse conditions, and CE>5% is possible


ngiyabonga
рахмат
danke
謝謝
spas
teşekkür ederim
Баярлалаа
mersi
kia ora
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tapadh leat
спасибо
faafetai lava
vinaka
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blagodaram
dank je
misaotra
matondo
paldies
grazzi
kiitos
dankie
nanni
nandri
dhanyavad
mauruuru
köszönöm
thank you
gracias
хвала
asante
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