New challenges in Laser-Plasma Interaction research for Inertial Fusion Energy

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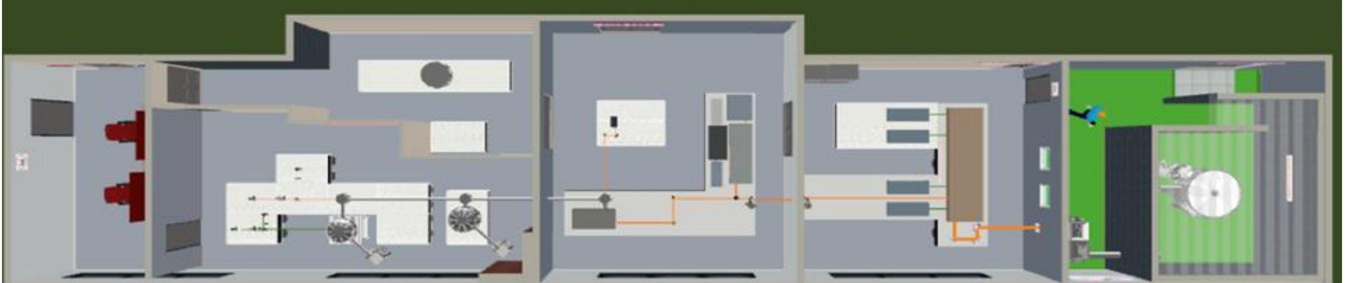
TOPICS

- New laser sources and technology for ultraintense lasers
- Laser-plasma acceleration
- Flash radiotherapy research
- Laser-plasma interaction for direct drive schemes of Inertial Confinement Fusion

Sub-PW Experimental Laser Facility



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Outline

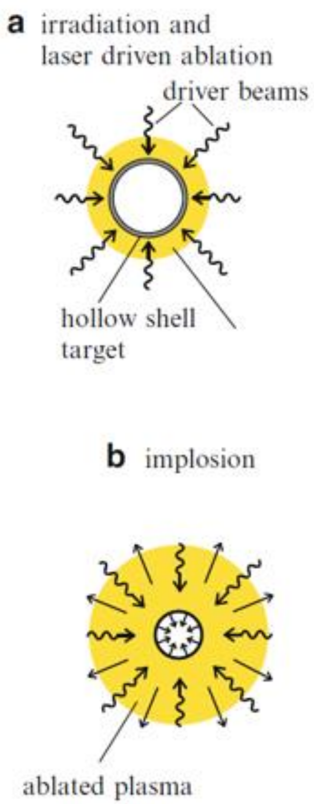
- Introduction to LPI and basic processes
  - SBS
  - SRS, TPD
  - CBET
  - Filamentation
  - Speckles

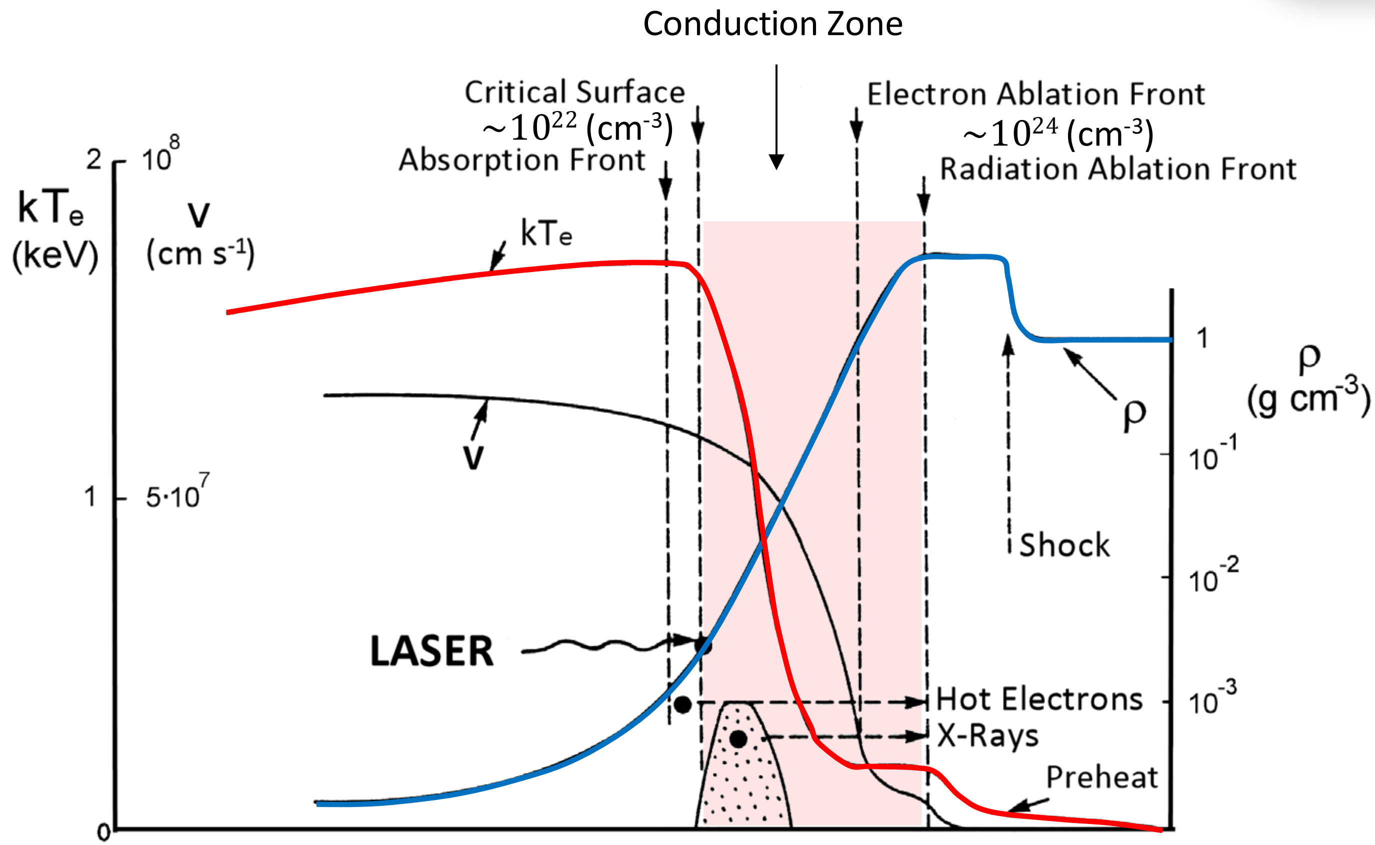
- Some Hot Topics

multiple beam irradiation
broadband and chirped beams
side SRS
Shock Ignition and HE

- Conclusions

Laser Collisional Absorption

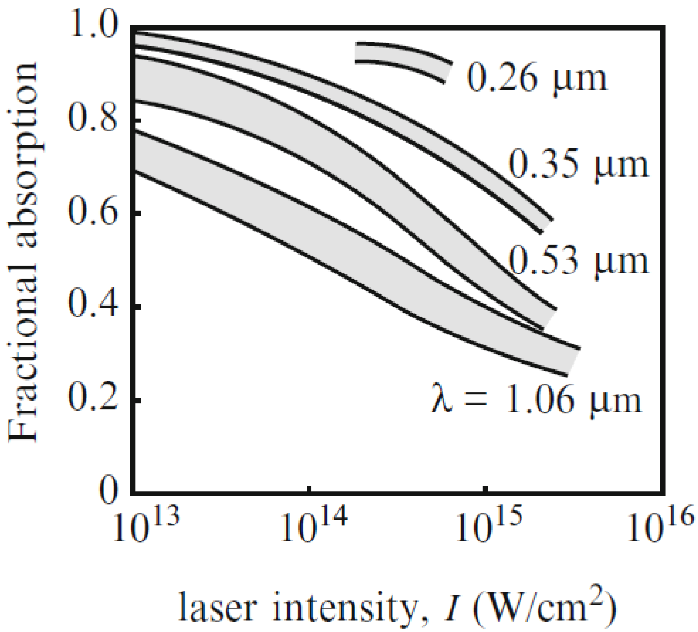


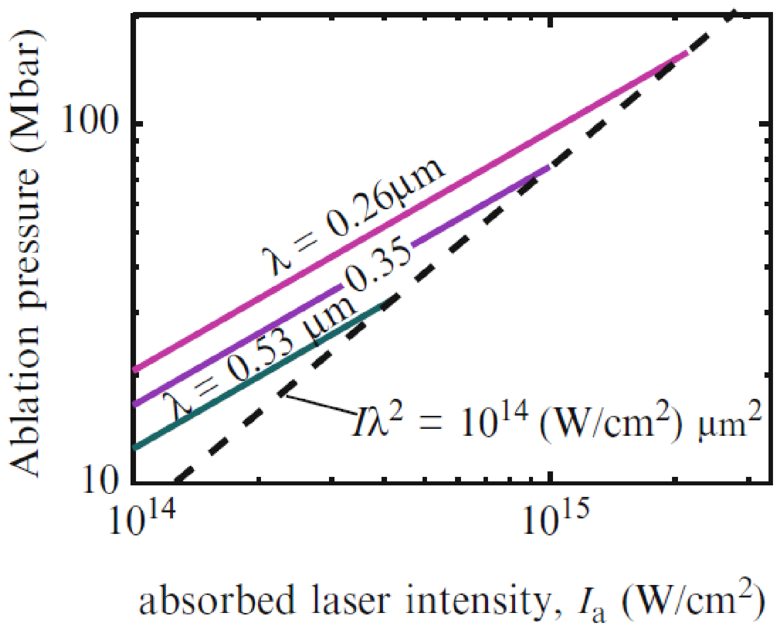


In a idealized ICF situation, laser light is absorbed by collisional absorption (inverse Bremsstrahlung) near the critical density surface $n_c(cm^{-3}) = 1.1 \cdot 10^{21}/\lambda_{\mu m}^2$ (where $\omega_0 = \omega_p = 4\pi e^2 n_e/m_e$) and successively the energy is transported to the the ablation front mainly via thermal electrons through the conduction zone.

$$\frac{dI_L}{dz} = -k_{IB} I_L \qquad\qquad k_{IB} \propto \frac{Z(n_e/n_c)^2}{T_e^{3/2}(1-n_e/n_c)^{1/2}}$$

UV irradiation





S. Atzeni, Chapter 10, Laser Plasma Interaction and Application

$$\nu_{eff} \approx \nu_c \frac{v_{th}^3}{(v_{osc}^2 + v_{th}^2)^{3/2}}$$

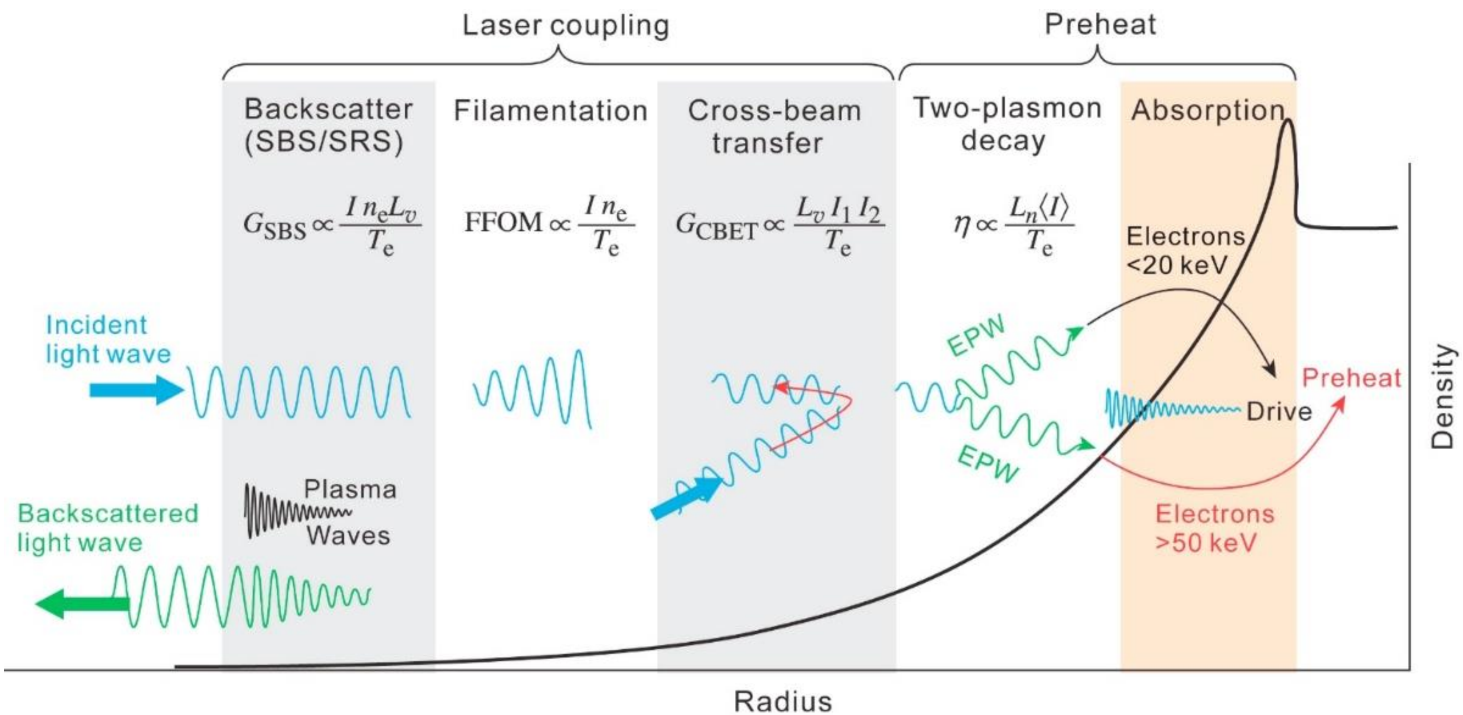
$$v_{osc}/c \approx 0.85\lambda_{\mu m} I_L^{1/2}$$

$$P_{abl} \approx 57\left(\eta_{abs} I_L / \lambda_{L\mu m}\right)^{2/3} MBar$$

- At higher laser intensities the effective collision frequency I is reduced by quiver motion in laser field
- UV light is more efficiently absorbed because it propagates to higher densities

The ablation pressure obtained is larger for UV laser light due to a shorter conduction zone

Laser Plasma Interaction



Froula et al., Plasma Phys. Control. Fusion 54 (2012) 124016

In real ICF conditions, for $I\lambda^2_{\mu m} > 10^{14} W cm^{-2}$, many «non collisional» mechanisms – or parametric instabilities - are driven in the plasma corona, producing:

- the scattering of a significant percentage of laser energy (SRS, SBS)
- the unbalance of multiple laser beams irradiation (CBET)
- Small scale modulation of beam irradiation (filamentation)
- Suprathermal (or hot) electrons, produced by damping of SRS and TPD plasma waves, prehating the fuel

Parametric instabilities

- Parametric Instabilities are 3-waves coupling processes where the e.m. laser excites ion-acoustic or electron plasma waves

$$\omega_1 = \omega_2 + \omega_3$$
$$\vec{k}_1 = \vec{k}_2 + \vec{k}_3$$

- Thresholds are given by the damping of daughter waves

$$\gamma_0^2 > \nu_1 \nu_2$$

- In inhomogeneous plasmas, the threshold of convective instabilities depends on the resonance region (∇n, ∇v)

$$\gamma_0^2 > K' v_1\ v_2$$
$$K' = d\big(k_0(x) - k_1(x) - k_2(x)\big)/dx$$

Stimulated Raman Scattering (SRS)

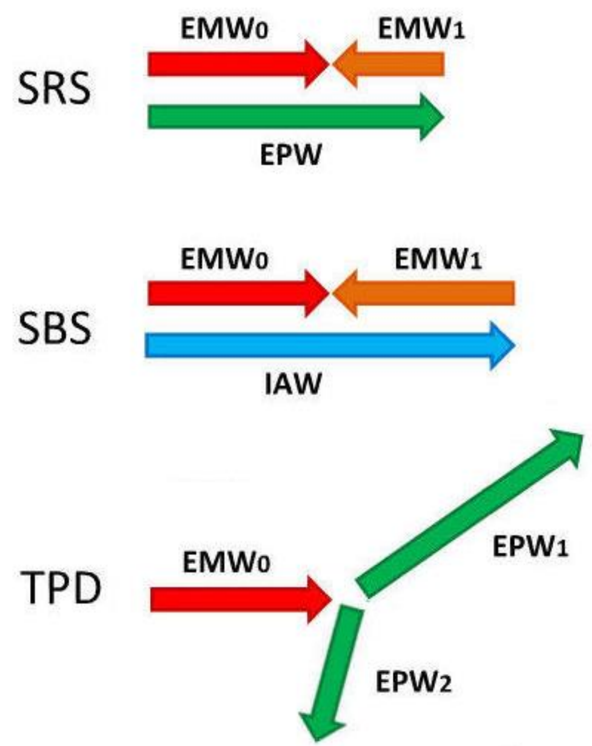
absolute	convective
~10^{14} W/cm^2	~10^{15} W/cm^2

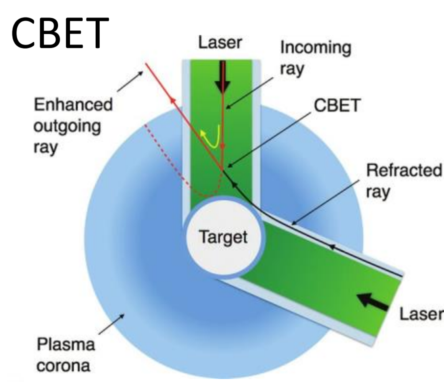
Stimulated Brillouin Scattering (SBS) & Cross Beam Energy Transfer (CBET)

~10^{14} W/cm^2

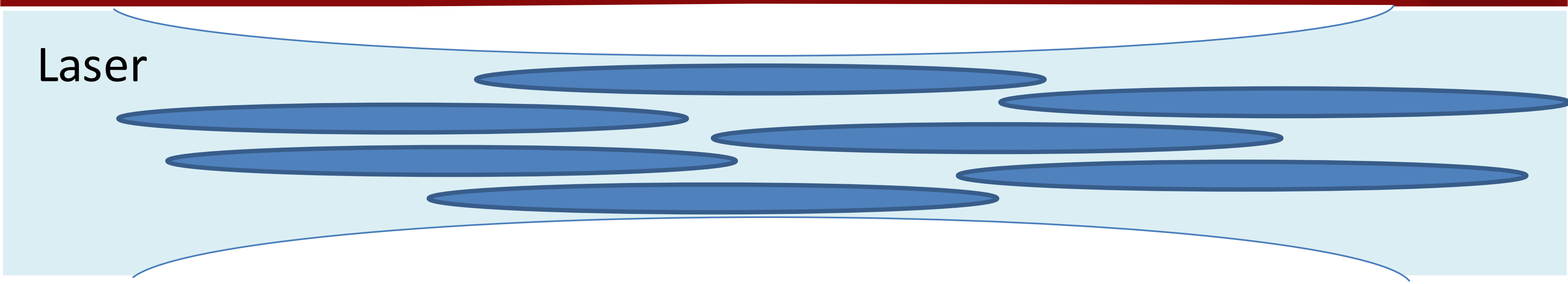
Two Plasmon Decay

~10^{14} W/cm^2





Speckles and local conditions



Speckle size

$\lambda_{\perp} \approx 1.2F\lambda_0 \quad \lambda_{\parallel} \approx 8F^2\lambda_0$

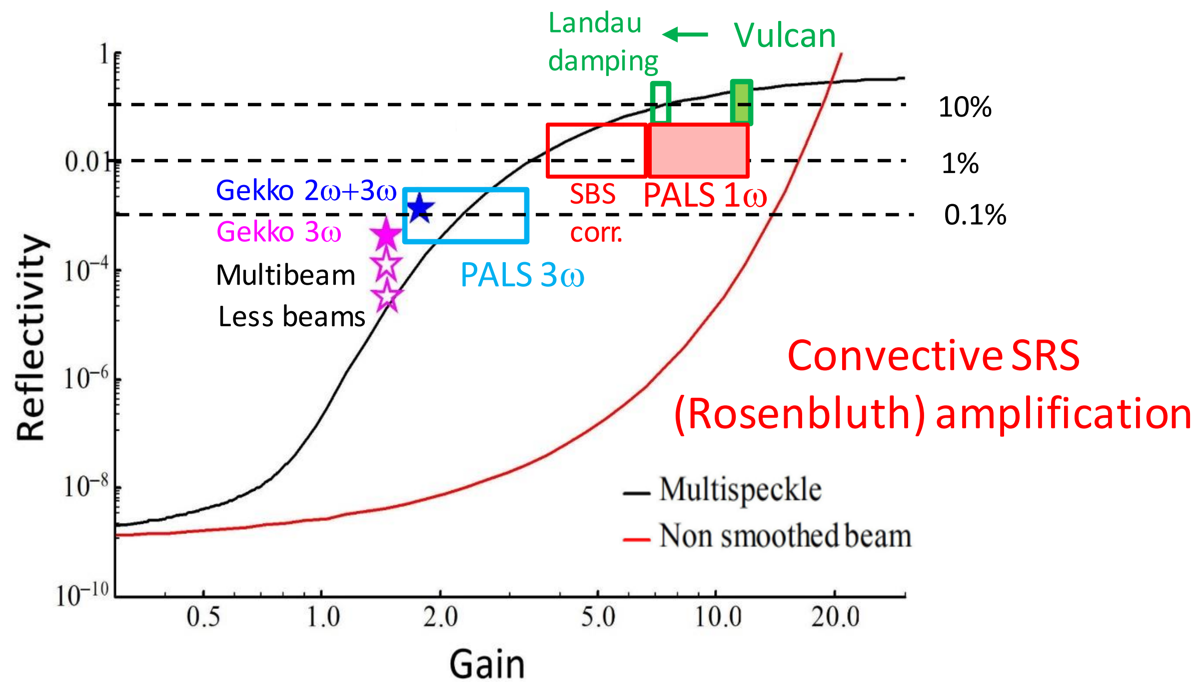
for F=10 and λ=0.355 nm

$\lambda_{\perp} \approx 4.2\ \mu m \ \lambda_{\parallel} \approx 280\ \mu m$

Intensity distribution

$u = I_{sp}/\langle I \rangle \qquad f(u) \propto ue^{-u}$

High-energy tail up to $\approx 10\langle I \rangle$



We need a multispeckle model, including local intensity and saturation

For more info see *G. Cristoforetti et al., High Power Laser Science and Engineering*, (2021), Vol. 9, e60

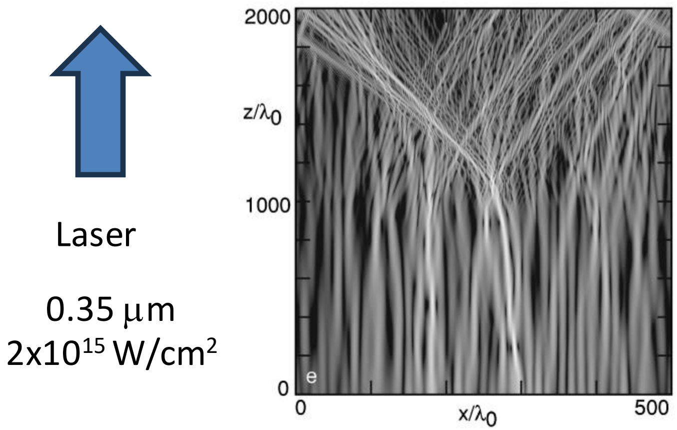
Self focussing and beam filamentation

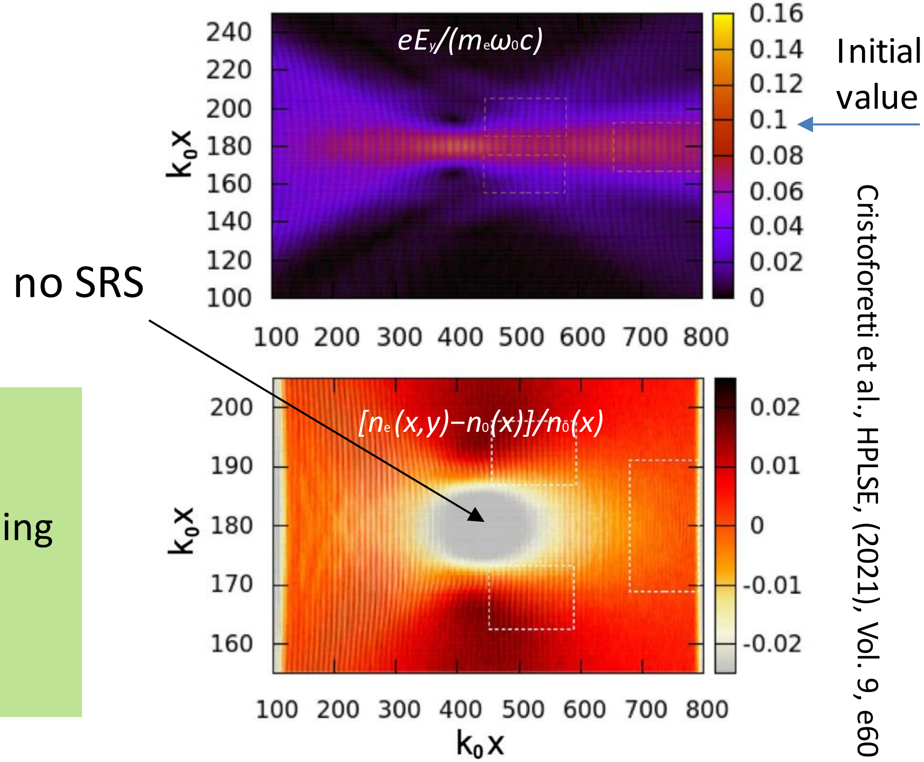
Self focusing of laser light can amplify intensity perturbations and induce filamentation

- Thermal effects → the rise in temperature induces a hydrodynamic expansion which leads to an increase of the index of refraction
- Ponderomotive effects → ponderomotive force pushes electrons away from the region where the laser beam is more intense, therefore increasing the refractive index

$$P > P_c \approx 32 T_{keV} \frac{\sqrt{1 - n_e/n_c}}{n_e/n_c}$$

Schmitt and Afeyan, PoP 1998



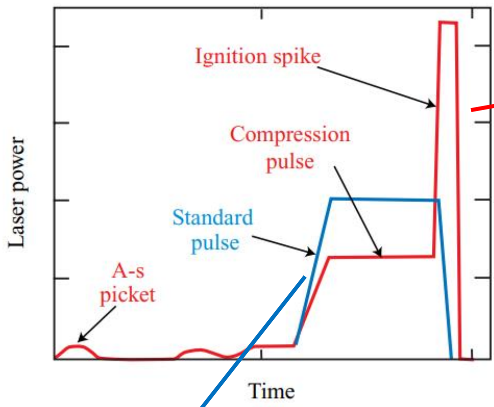


Cristoforetti et al., HPLSE, (2021), Vol. 9, e60

Filamentation can produce:

- local higher intensity but also plasma smoothing
- density depletion and profile modification
- Laser angular spreading
- Laser spectral broadening

LPI: Classical Direct Drive vs. Shock Ignition



Shock Ignition

$I \approx 10^{16}$ W/cm^2
implosion velocity ~240 km/s
T ≈ 5 keV
$L_n \approx 500\ \mu$m

Regime dominated by parametric instabilities in kinetic regime (R= 40-50%) and HE generation.

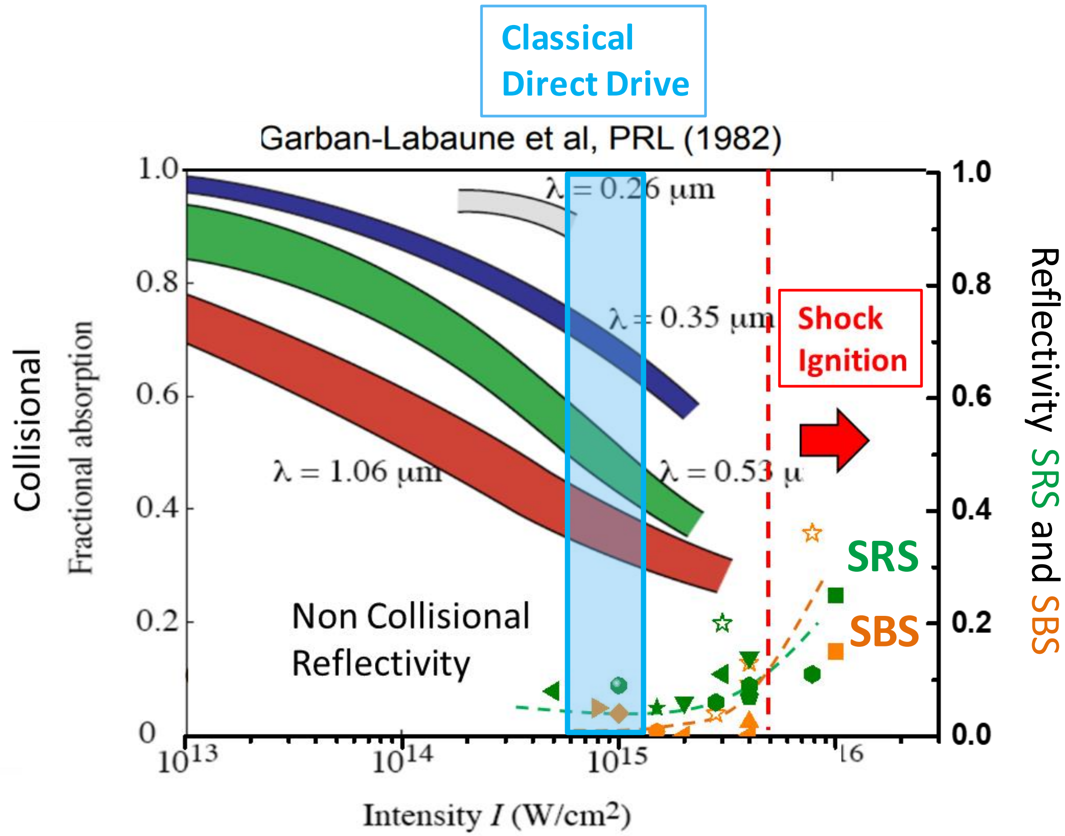
SBS, SRS, (TPD)
HE mainly driven by SRS

Classical Direct Drive

$I \approx 10^{15}$ W/cm^2
implosion velocity ~350-400 km/s
T ≈ 5 keV
$L_n \approx 500\ \mu$m

SBS, TPD, (SRS)

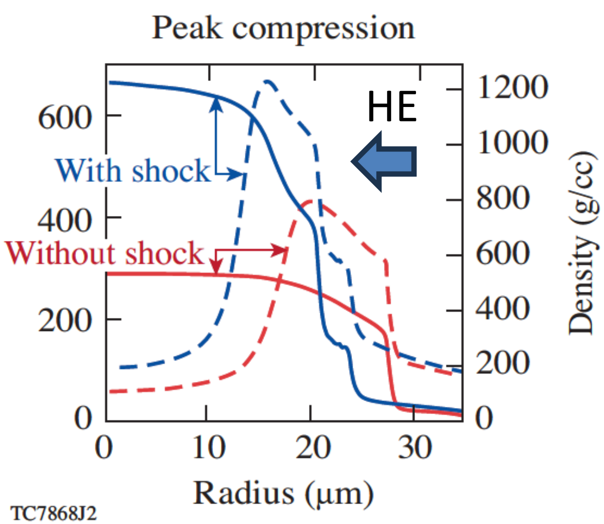
HE mainly driven by collective TPD at OMEGA (NIF?)

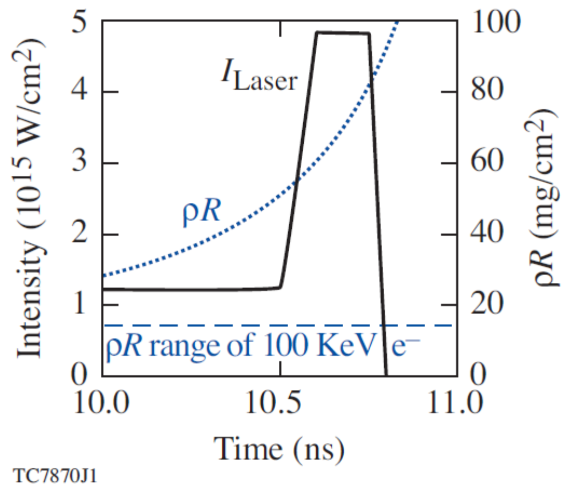


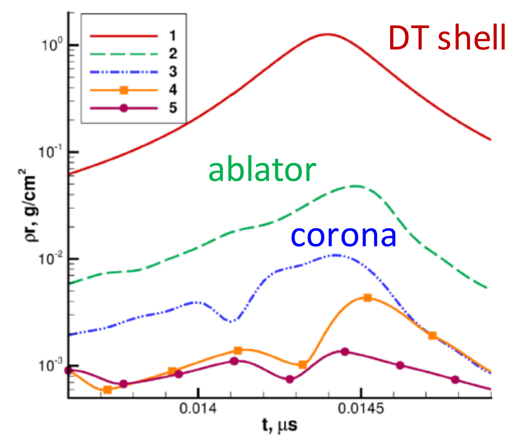
Shock Ignition: Hot Electrons

Differently from classical Direct-Drive ICF, in Shock Ignition scheme the effect of hot electrons (HE) could be beneficial increasing the ignitor pressure since they are expected to stop in the high-ρR shell.
e.g. for $E_{hot} \approx 80$ keV → range 0.01 g/cm^2

Betti et al., J. of Phys. Conf. Ser. 112, 022024, 2008







Gus'kov et al., HEDP 36, 022024, 2008

We expect the positive effect is dominant for HE temperatures lower than 60 keV

It is important

- Characterize HE in conditions as much as possible close to SI
- Understand the source of HE (SRS, TPD, other)

Approaching Shock Ignition

	Multi beam	Lambda (nm)	Intensity (W/cm^2)	$I\lambda^2$ ($W\mu m^2/cm^2$)	L (μm)	T (keV)	Bandwidth / Chirp
GEKKO XII	YES	351	1.5×10^{15}	2×10^{14}	100	1-2	NO/NO
PALS	NO	438 1314	5×10^{15} 1.5×10^{16}	1×10^{15} 2.5×10^{16}	100 100	1-2 3-4	NO/NO
ELI-BL	NO	532	10^{14} - 10^{15}	$3\times(10^{13}$-$10^{14})$	100	1	NO/YES
Vulcan	NO	532	1×10^{16}	3×10^{15}	400	1-2	NO/YES
LMJ	YES	351	3.5×10^{15}	4.3×10^{14}	480	4.5	NO/NO

Shock Ignition regime
Multibeam 3ω, $I = 10^{16}$ W/cm^2
$L=500$ μm, $T=3$-5 keV

Different facilities can be used to investigate the role of different parameters

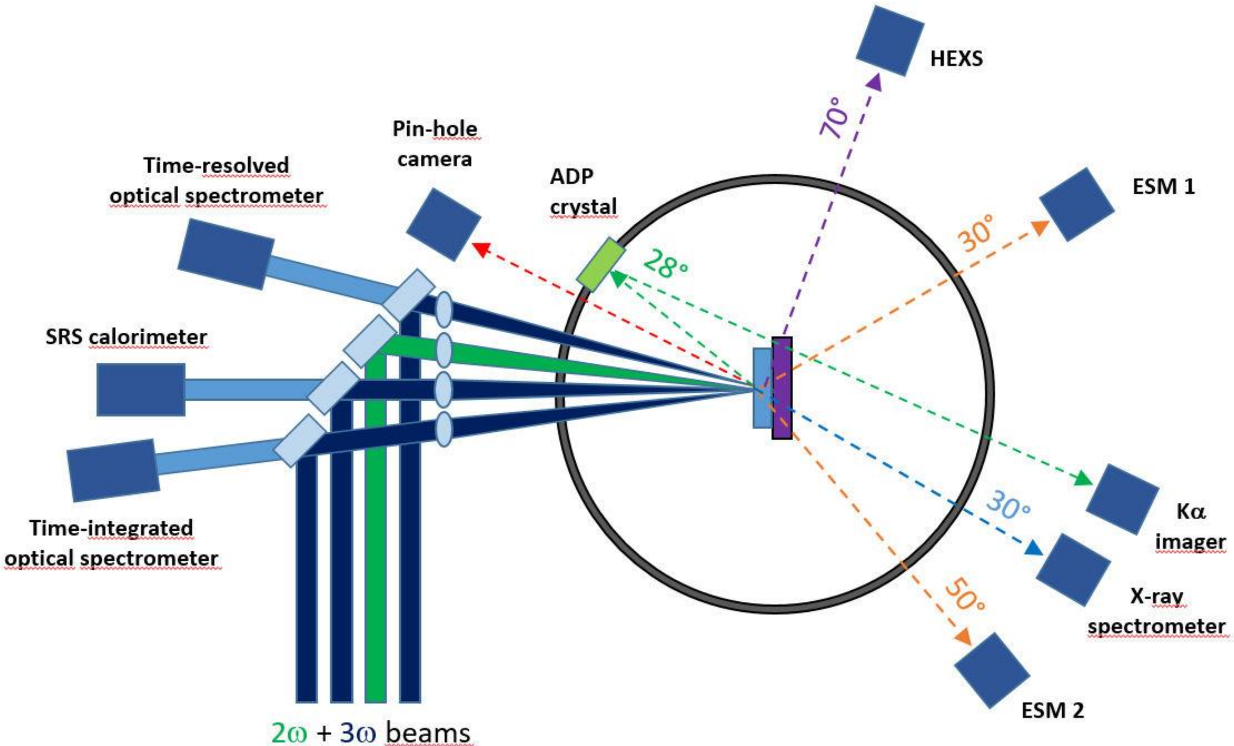
Lack of dedicated facility in Europe

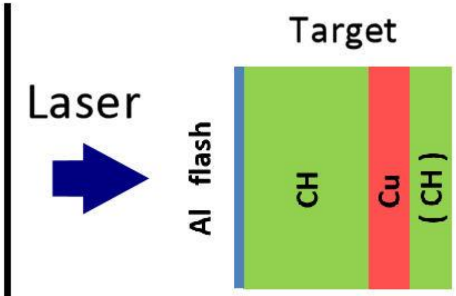
Multibeam effects

Multibeams effects on LPI: *GEKKO XII experiment*

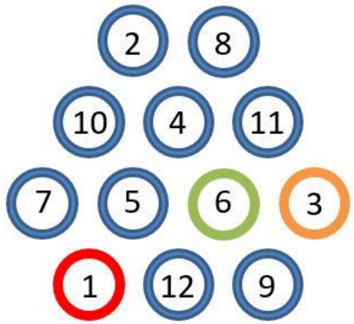
G. Cristoforetti, P. Koester, S. Atzeni, D. Batani, S. Fujioka, Y. Hironaka, S. Hüller, T. Idesaka, K. Katagiri, K. Kawasaki, R. Kodama, D. Mancelli, Ph. Nicolai, N. Ozaki, A. Schiavi, K. Shigemori , R. Takizawa, T. Tamagawa, D. Tanaka, A. Tentori, Y. Umeda, A. Yogo, and L. A. Gizzi

G. Cristoforetti et al., HPLSE, Vol. 11, e24, 2023





Beam configuration



3 Heating beams @ 2ω

120 J /beam / 300 ps + KPP

FWHM spot = 850 μm

I= 1.5 x 10^{14} W/cm^2

9 interaction beams @ 3ω

80 J/beam /300 ps + RPP

FWHM/beam = 150 μm

FWHM/bundle = 300 μm

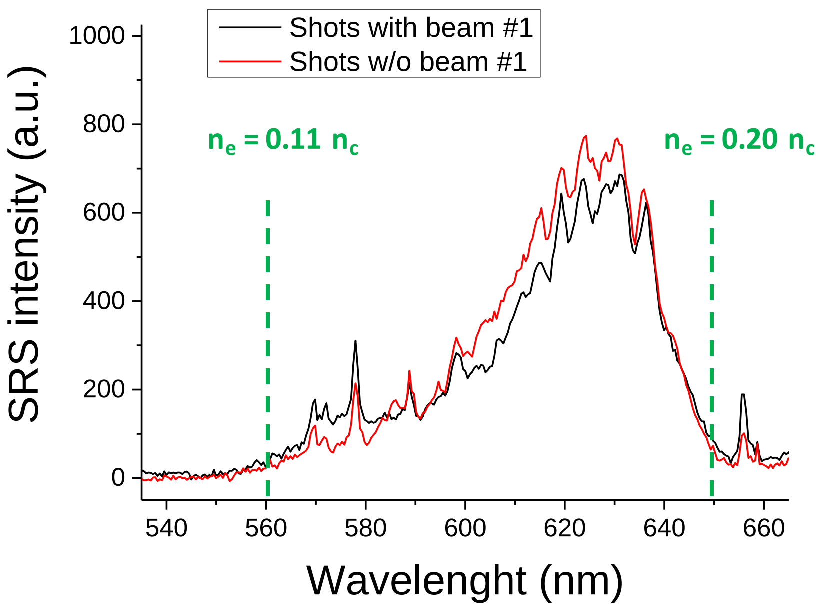
$I_{beam} = (0.7\text{-}1.2)\cdot 10^{15}$ $I_{bundle} = (1.5\text{-}2.3)\cdot 10^{15}$ W/cm^2

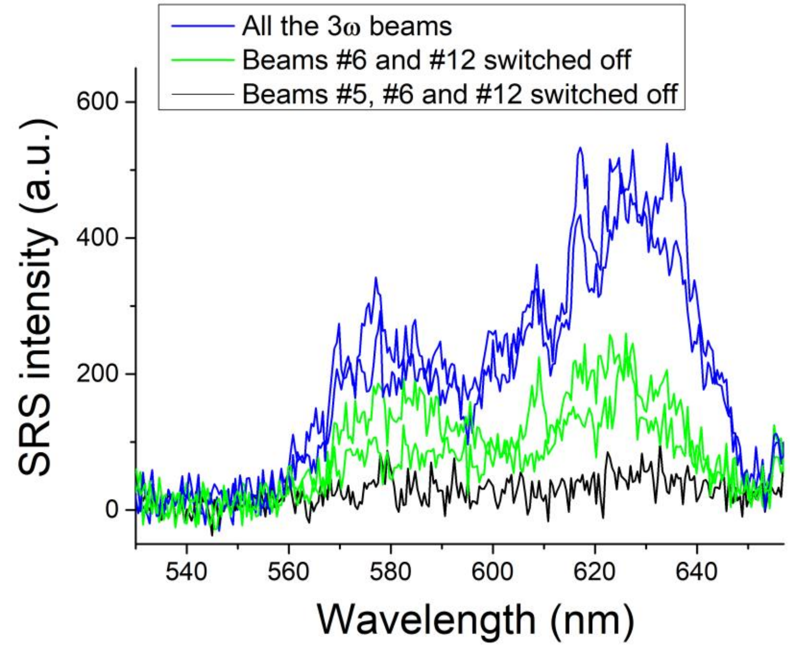
$I\lambda^2 = (1\text{-}3)\cdot 10^{14}$ W μm^2/cm^2

Multibeam effects - SRS

Spectrometer located behind the last mirror of beam #1

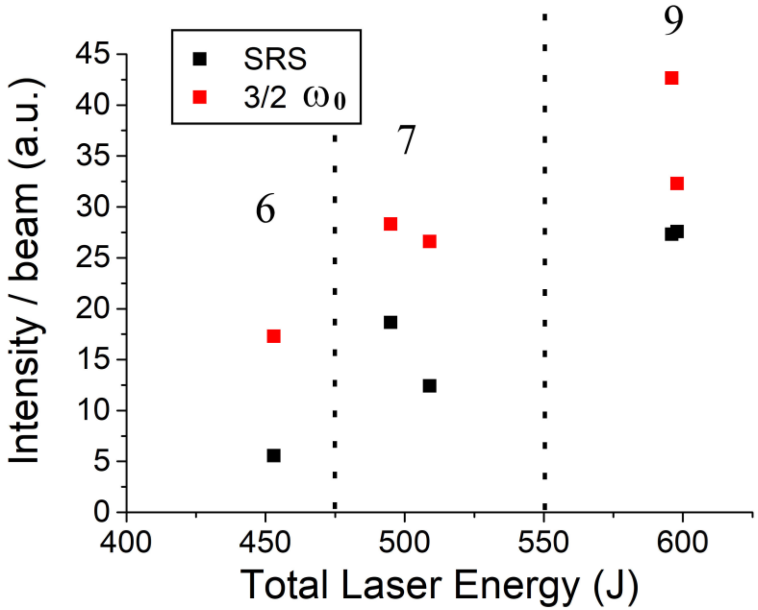
R_{SRS} = 0.03-0.15 %

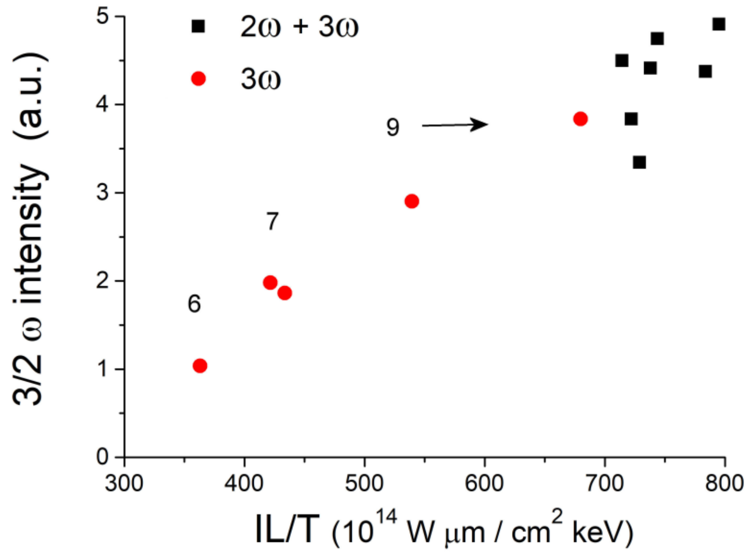




SRS scattered light is not purely backscattered but affected by other laser beams

Multibeam effects - TPD





TPD scales as $I_{ov}L/T$

Both SRS and 3/2ω intensity scales with overall energy/intensity and not with single beam intensity

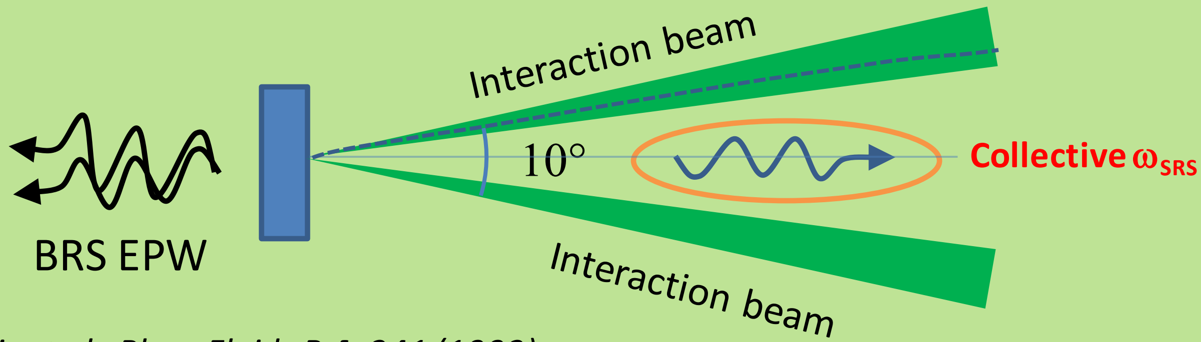
According to OMEGA results, TPD is in saturated regime for $I_{ov}L/T > (350\text{-}400)\cdot 10^{14}$ W μm / cm² keV

We need to...

Configuration with
common scattered e.m. wave

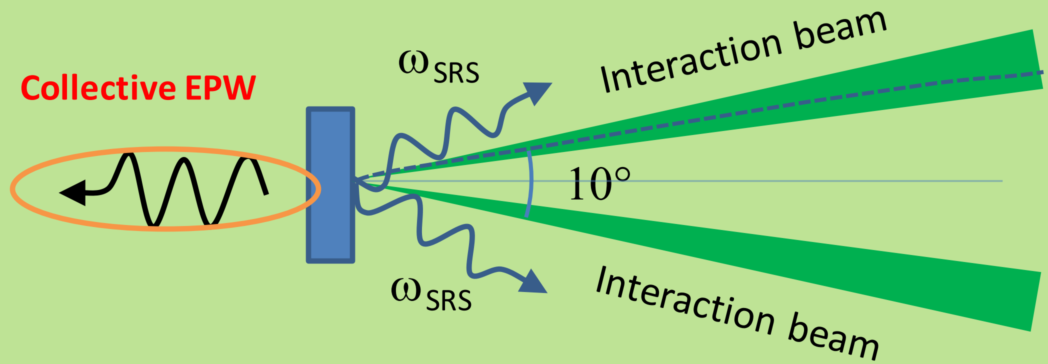
has the lowest threshold

$$I^{th}_{coll} = \frac{1}{N}\, I^{th}_{SB}$$



DuBois et al., Phys. Fluids B ***4****, 241 (1992)*

Configuration with
common scattered plasma wave



Large effort at NIF for CBET
Abd at OMEGA for TPD

Difficult in Europe !

- Investigate the thresholds and scaling
- configurations of common wave (EPW or e.m.)
- HE energy and angular distribution in particular on SRS

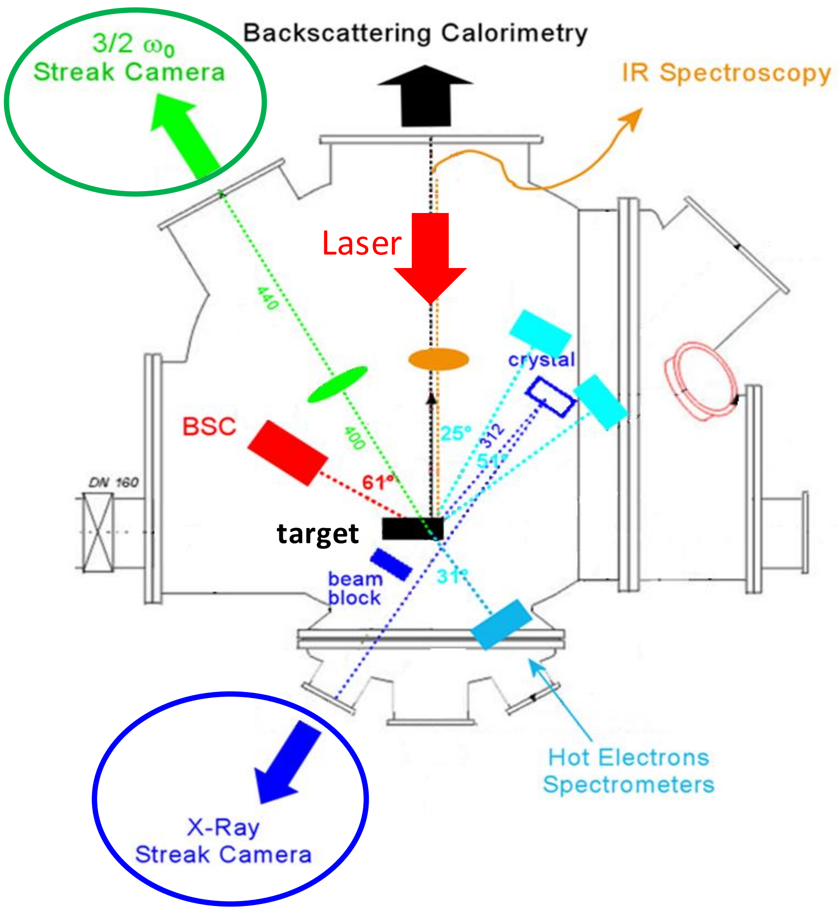
HE origin at SI intensity

2 - Origin of HE at high T and intensity: *PALS 2020 experiment*

G. Cristoforetti, F. Baffigi, D. Batani, R. Dudzak, R. Fedosejevs, E.D. Filippov, P. Gajdos, L. Juha, M. Khan, P. Koester, M. Krus, D. Mancelli, A.S. Martynenko, Ph. Nicolai, S.A. Pikuz, O. Renner, A. Tentori, L.Volpe, N. Woolsey, G. Zeraouli, L.A. Gizzi

G. Cristoforetti et al, Sci. Rep., 13, 20681, 2023

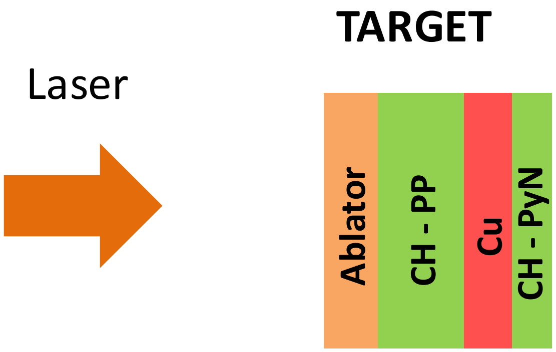
Recent ENR-IFE projects (D.Batani)



Shots @ 1ω

λ = 1.314 μm
Laser Energy : 200 – 600 J
Duration : 280 – 400 ps

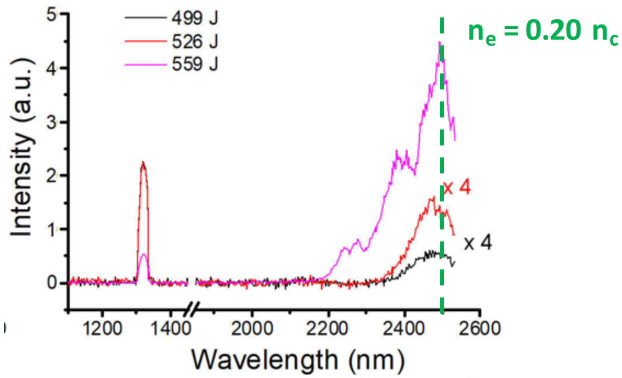
Intensity : (5 – 10) x 10^{15} W/cm^2
$I\lambda^2 = (0.9\text{-}1.5)\cdot 10^{16}$ W μm^2/cm^2

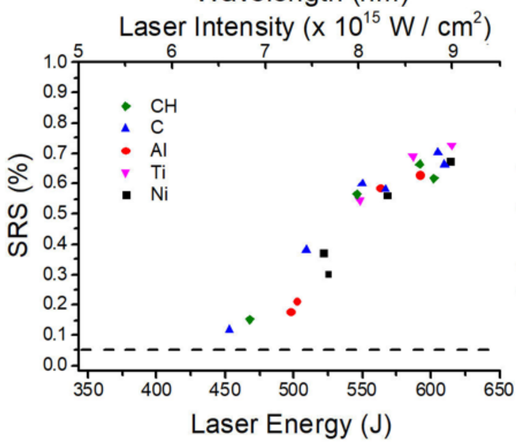


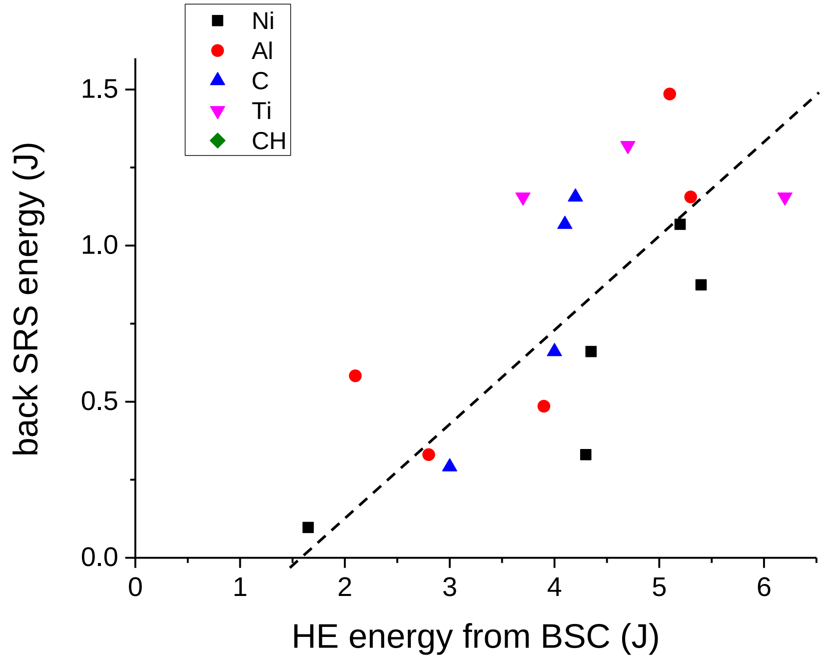
PP – Polypropylene
PyN – Parylene N
Ablator – PyN, C, Al, Ti, Ni
+ bulk Cu

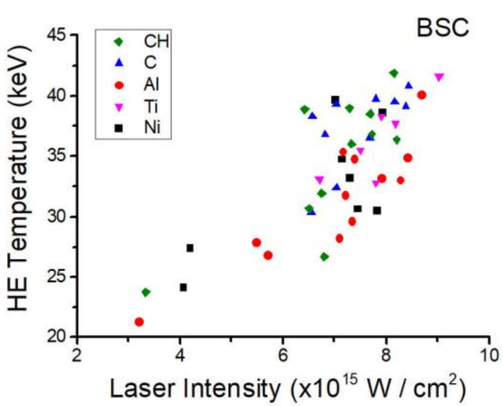
HE origin

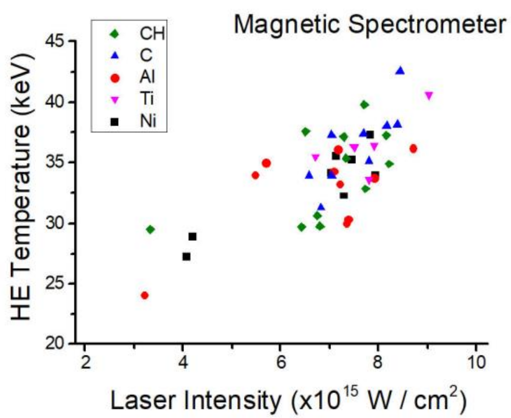
HE and SRS





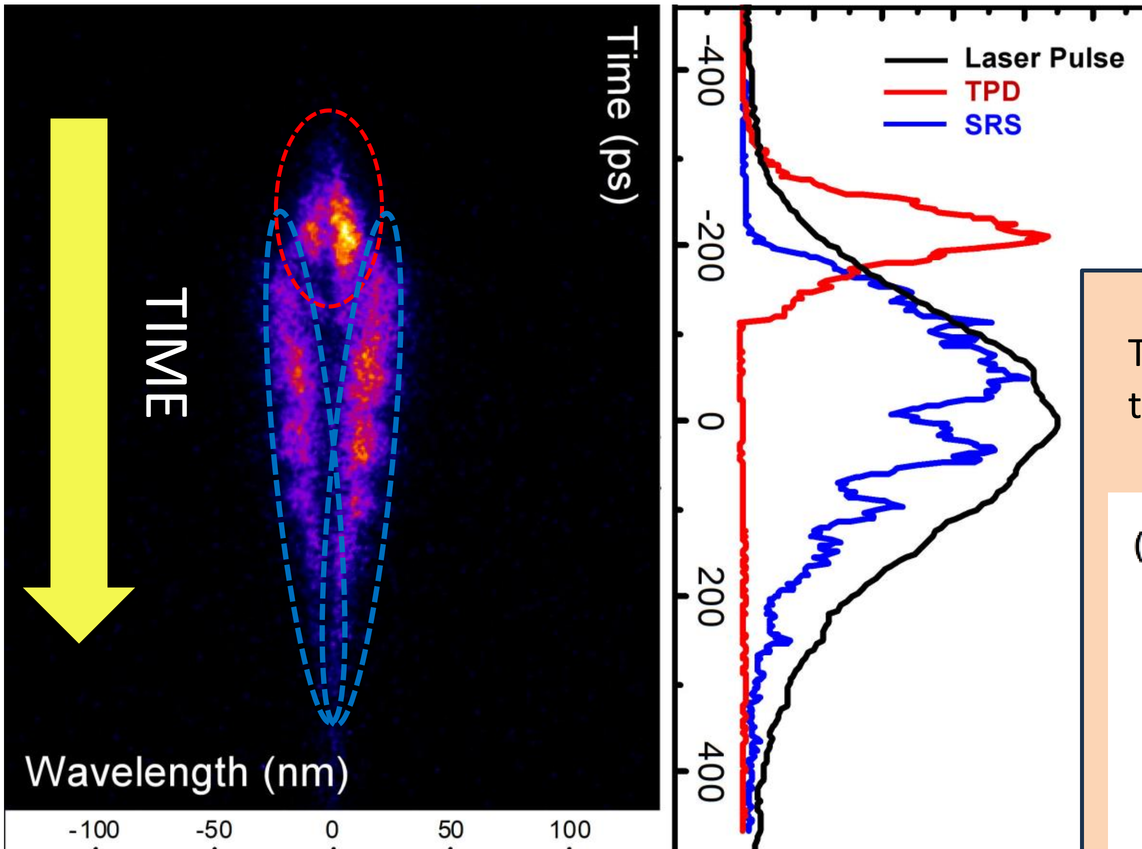






- HE energy is correlated to SRS energy
- HE temperature rises with laser intensity in the range 25-45 keV and phase velocity of EPW with SRS at 2450 nm corresponds to 40 keV
- HE conversion efficiency is 1-2%, of the order of SRS reflectivity
- The divergence of HE is ≈10°, in agreement with back SRS

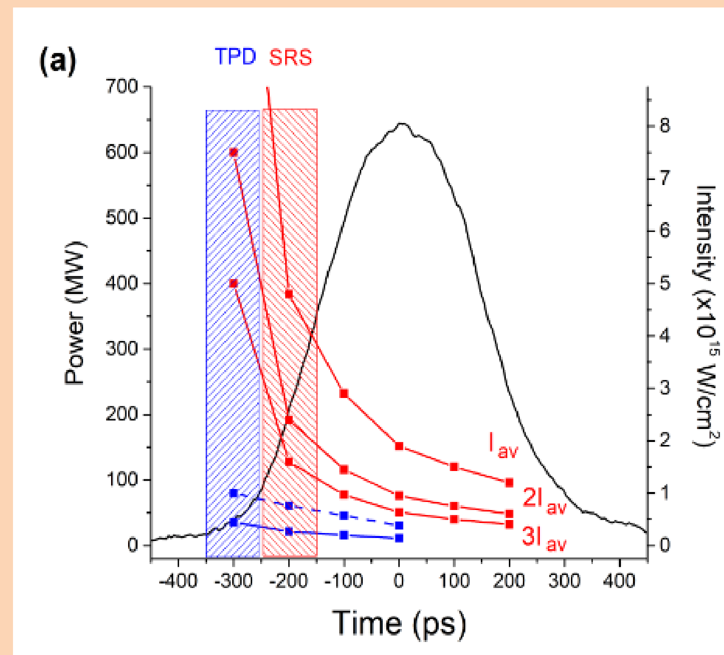
LPI timing



TPD well before the laser peak
SRS peaks 50-100 ps before the laser peak

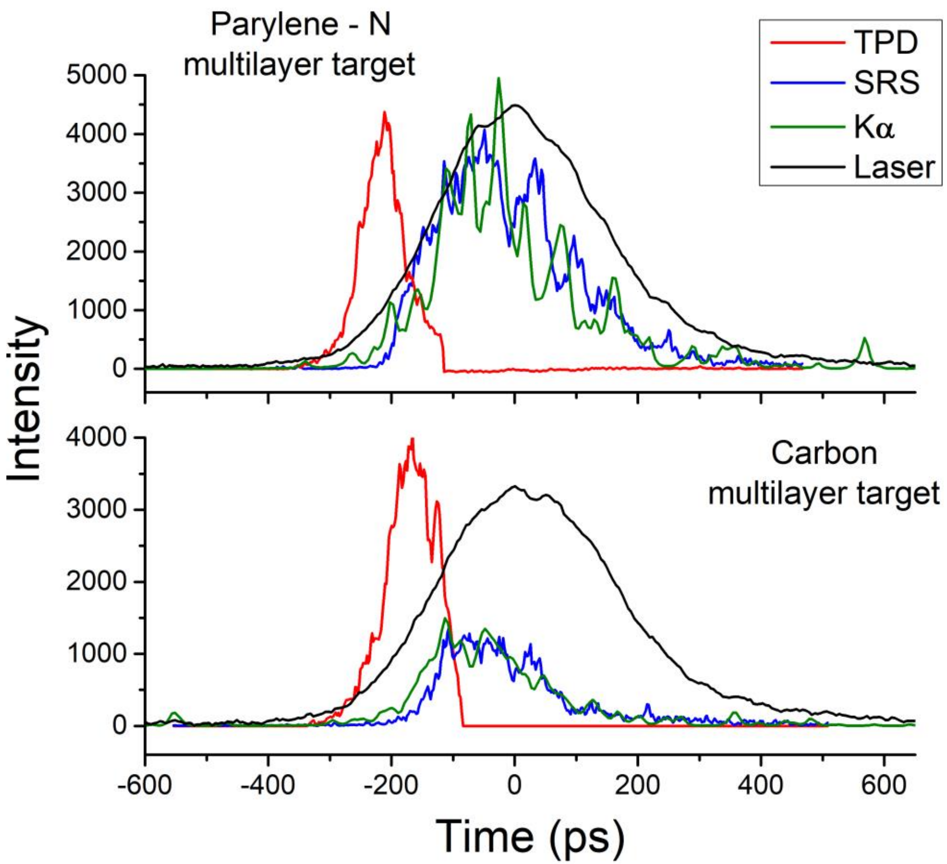
At high temperature, TPD is damped

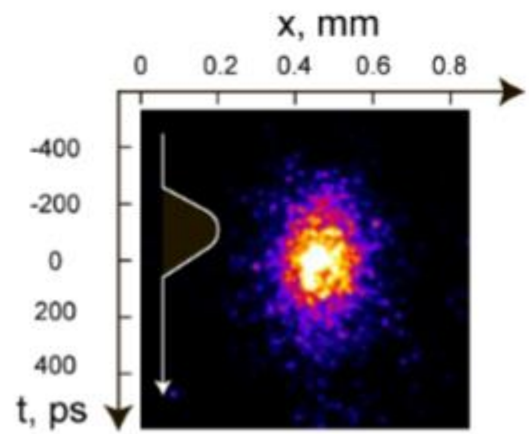
The ignition of the two signals confirms that they originate from TPD and SRS

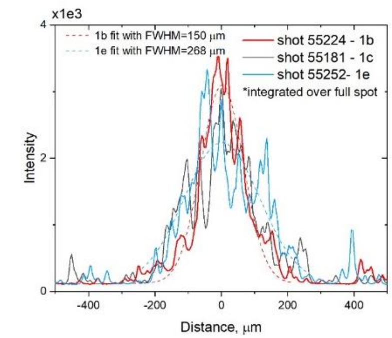


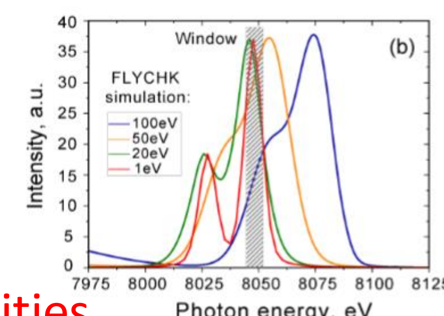
SRS, TPD and K_α timing

Time-resolved Kα Cu imager where the absolute timing of X-ray Streak camera is given by a 3ω fiducial









Kα is overlapped with SRS in all the shots

So, all data suggest that HE are produced by SRS at SI intensities

3 - Competition SRS/TPD in long plasmas:
Vulcan experiment 2018

Long Plasmas at SI intensity

G. Cristoforetti, S. Hüller, P. Koester, L. Antonelli, S. Atzeni, F. Baffigi, D. Batani, C. Baird, N. Booth, M. Galimberti, K. Glize, A. Héron, M. Khan, P. Loiseau, D. Mancelli , M. Notley, P. Oliveira, O. Renner, M. Smid, A. Schiavi, G. Tran, N. C. Woolsey, L. A. Gizzi

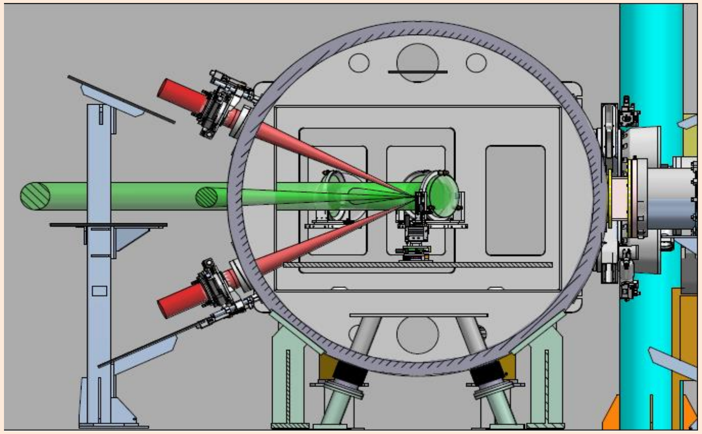
Recent ENR-IFE projects (D.Batani)

G. Cristoforetti et al., HPLSE, (2021), Vol. 9, e60

LASER IRRADIATION DESIGN (PLANAR GEOMETRY)

4 driver/heating beams (long beams)
E=250 J x 4, λ=1053 nm, 3 ns
FWHM=800 μm, I ≈ 3x10^{13} W/cm^2

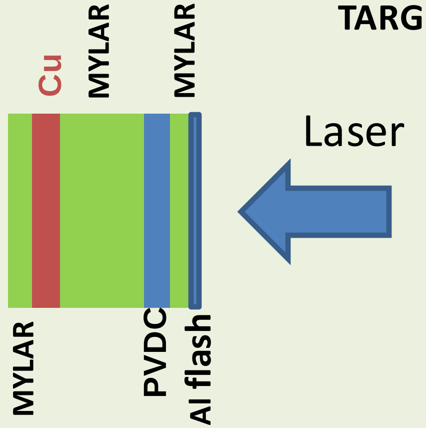
interaction beam B8 bypassing compressor
E≈85 J, λ=527 nm, 0.7 ns, RPP
FWHM ≈ 40 μm, I ≈ 10^{16} W/cm^2
f/# ≈2.5



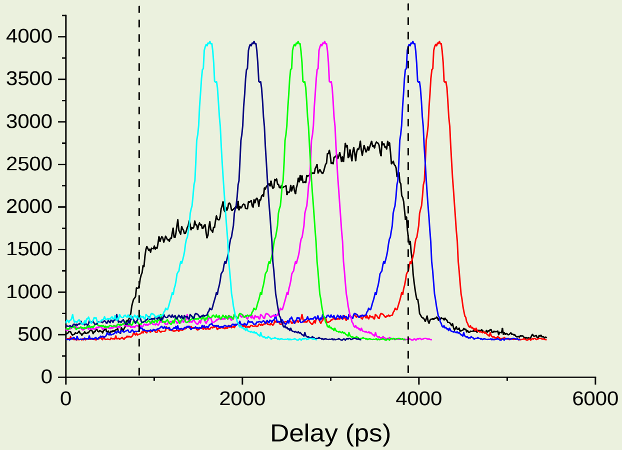
Interaction beams

Heating beams

TARGET DESIGN

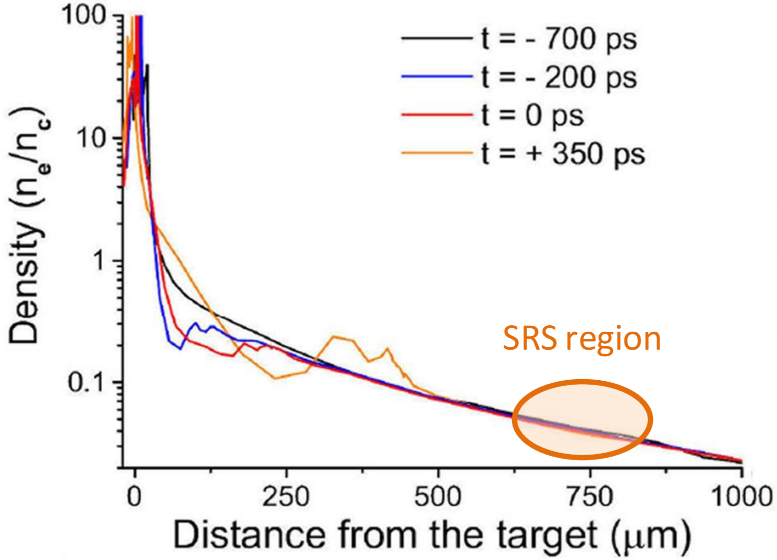


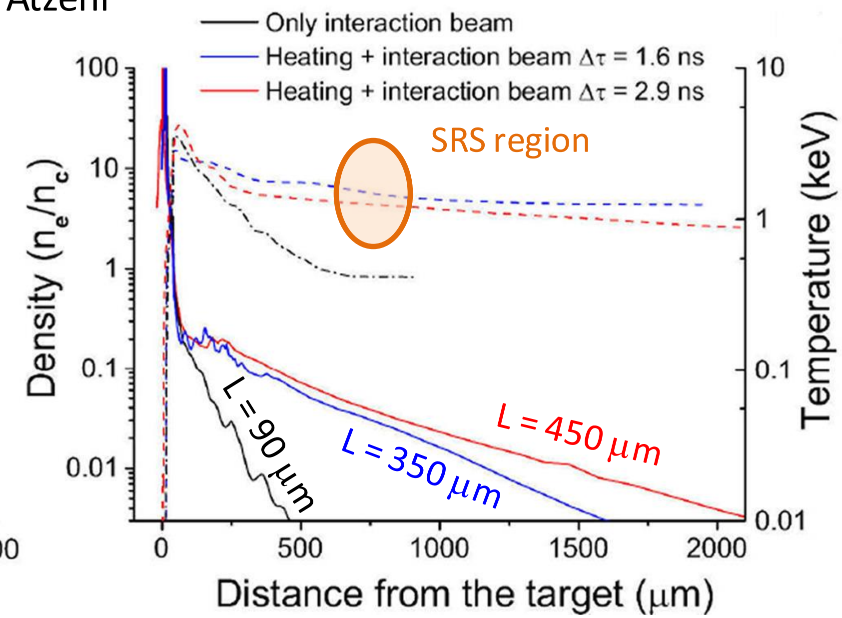
TIMING OF THE PULSES



Interaction conditions

DUED hydrodyamic simulations by. A. Schiavi and S. Atzeni



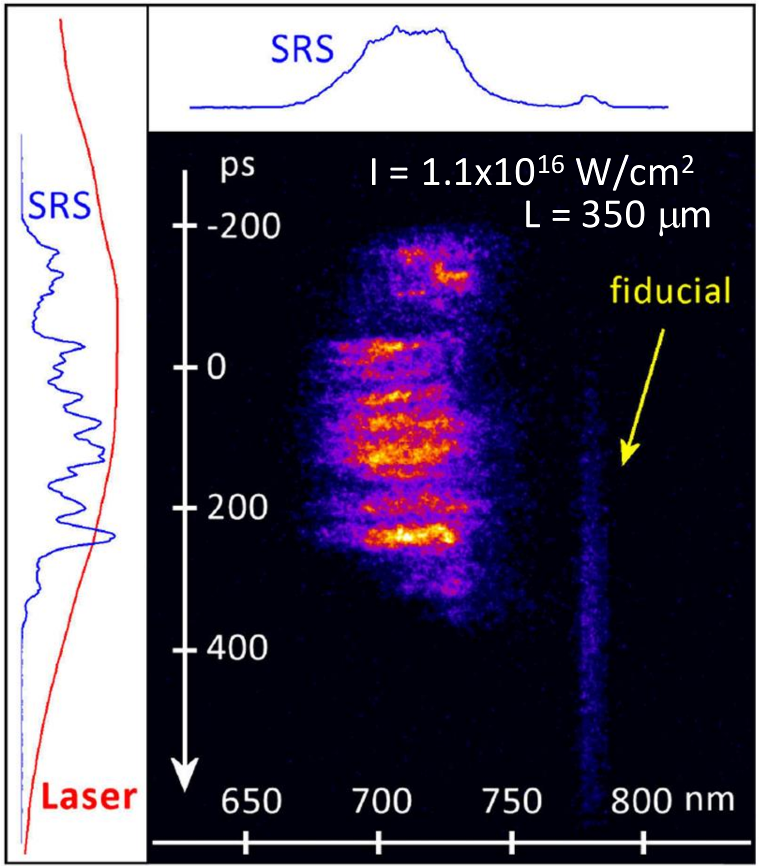


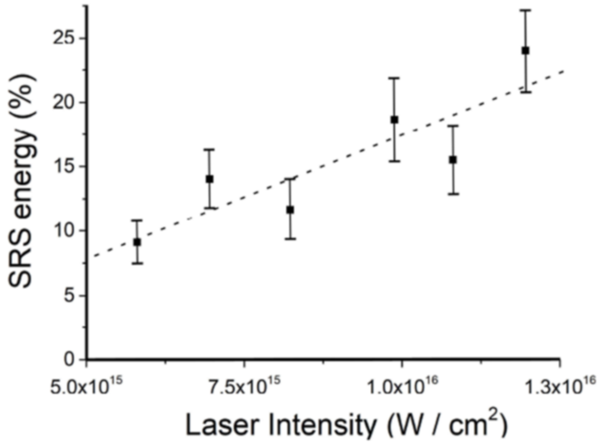
In SRS region

T ≈ 1 keV
L = 90 – 450 μm

depending on the delay of the main pulse

Stimulated Raman Scattering





SRS driven in bursts at low densities $n = 0.03\text{-}0.07\ n_c$

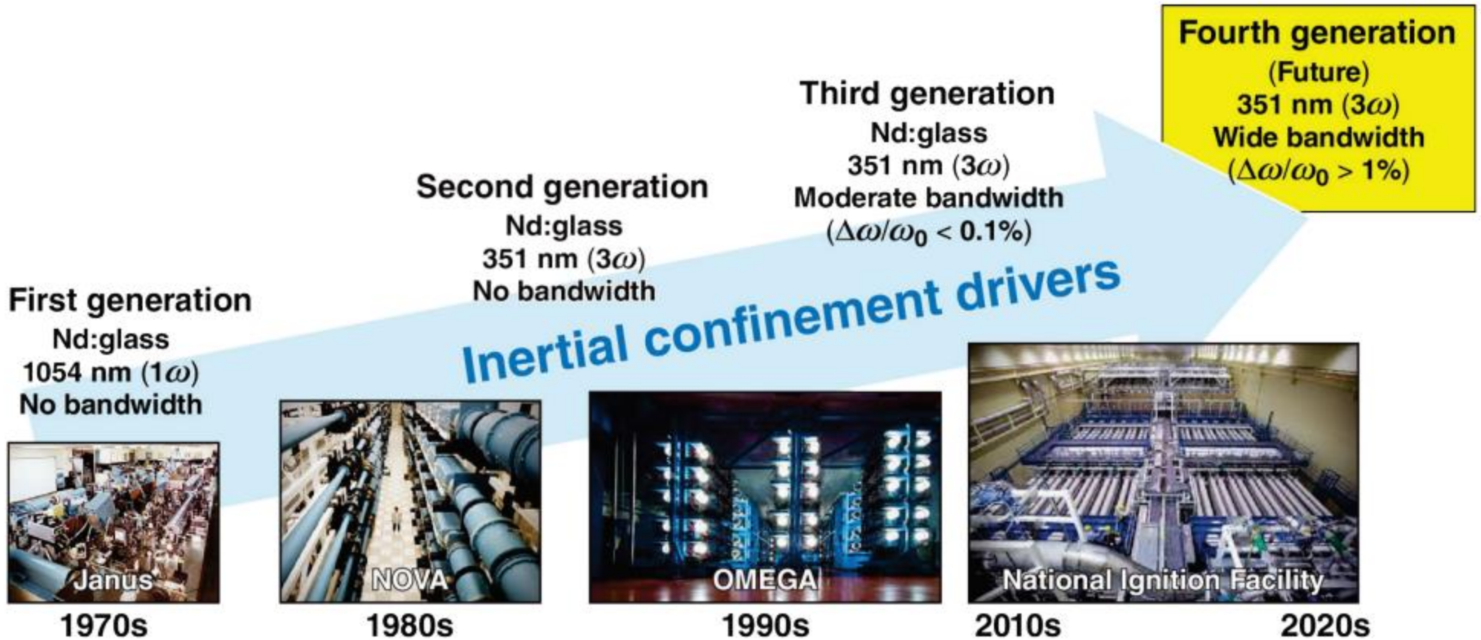
$k_e\lambda_D = 0.3\text{-}0.5$ Strongly kinetic regime

- In long scale plasmas and SI intensities, SRS is driven in filaments at low densities in strong kinetic regime and can reach 40-50% instantaneous reflectivities
- TPD and high-density SRS are not observed, for pump depletion and plasma-induced smoothing after a few speckles layer.

Broadband effects on LPI

The Fourth-generation Laser for Ultrabroadband eXperiments

UR LLE



NNSA

U.S. DEPARTMENT OF ENERGY | Office of Science

arpa·e CHANGING WHAT'S POSSIBLE

UNIVERSITY of ROCHESTER

Broadband effects on SRS

In direct-drive inertial confinement fusion, the laser bandwidth reduces the laser imprinting seed of hydrodynamic instabilities

Patel, PRL 131, 105101 (2023)

In homogeneous plasmas, inserting a bandwidth Δω the growth rate $\gamma_0 \rightarrow \frac{\gamma_0^2}{\Delta\omega}$, so it is reduced for $\Delta\omega > \gamma_0$. Basically, the laser intensity is distributed at frequencies larger than the resonant on, so the effective intensity is smaller.

Thomson 1975 Nucl. Fusion 15 237

For absolute SRS (and TPD) in inhomogeneous plasmas, where the bandwidth enchances the instability threshold $\Delta\omega \sim 1 - 2\%$.

Bates 2023 Physics of Plasmas 30, 052703

For convective amplification in inhomogeneous plasmas, however, the lower growth rate is compensated by a longer interaction length. Basically **the coupling conditions are satisfied in a larger resonance region**.

Gudzar 1991 Physics of Fluids B 3, 2882

The effect of bandwidth on LPI needs to be investigated

Recent experiment at Kunwu laser facility of Shanghai Institute of Laser Plasma $\Delta\omega/\omega = 0.6\%$
Lei et al., PRL, in press 2024

Bandwidth/Chirp

New Vulcan TAW experiment

Sep/Oct 2022

PI : L.A. Gizzi   **INO-CNR (Italy), York Univ. and CLF (UK), Hellenic Mediterranean Univ. (Greece), Celia (France), Focussed Energy**

LASER IRRADIATION DESIGN (PLANAR)

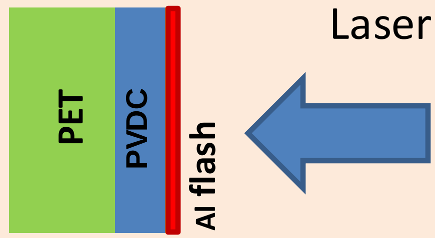
4 driver/heating beams (long beams)
E=250 J x 4, λ=1053 nm, 3 ns
FWHM=800 μm, I $\approx$ 3x10^{13} W/cm^2

interaction beam B8 bypassing compressor
E= 100-150 J, λ=527 nm, 0.7-1.0 ns, RPP
FWHM $\approx$ 40 μm, I $\approx$ 10^{16} W/cm^2 , f/# $\approx$2.5

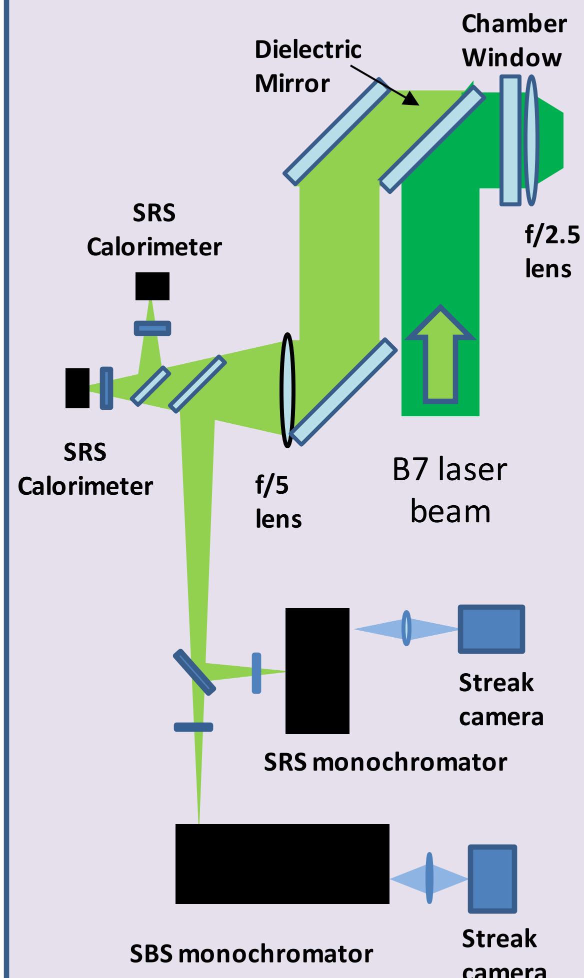
3 oscillators:

Option	SHG Duration (ps)	SHG Bandwidth (nm) (%)	Chirp Rate (nm/ns)
Narrowband	770	Fourier limited	0
OPO phosphate amp.	680	0.77 nm 0.15%	0.95
OPCPA Silicate amp.	1100	1.77 nm 0.34%	1.22

TARGET DESIGN

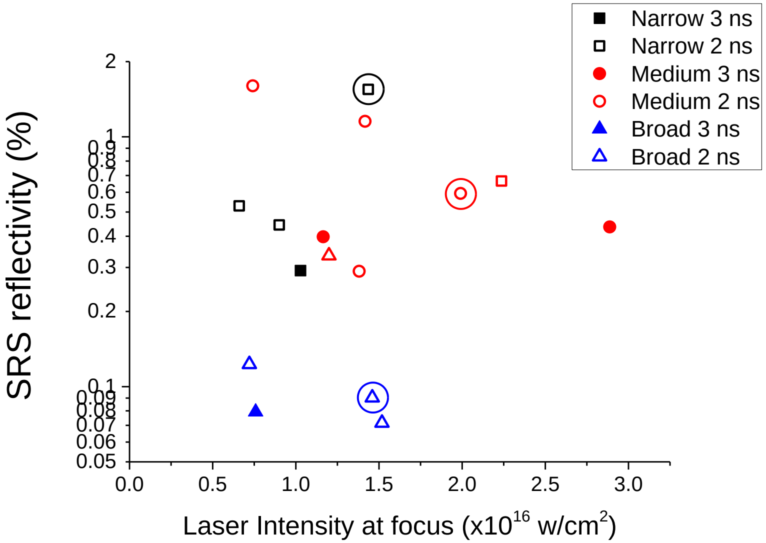


BACKSCATTERING DIAGNOSTICS

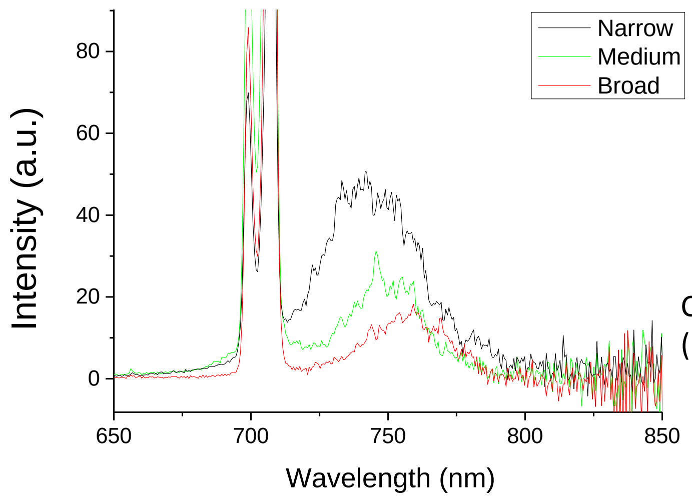


Preliminary results from TAW 2022 experiment
Stimulated Raman Scattering

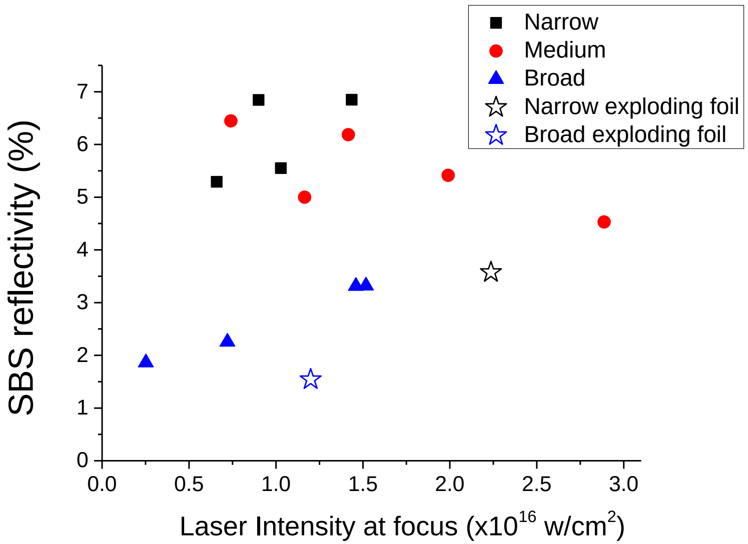
Calorimetric data



SRS spectra



Comparable shots (circles above)



Narrowband and medium band/chirp pulses provide similar results, while large band/chirp pulses provide a fall of SRS and SBS

Bandwidth/Chirp

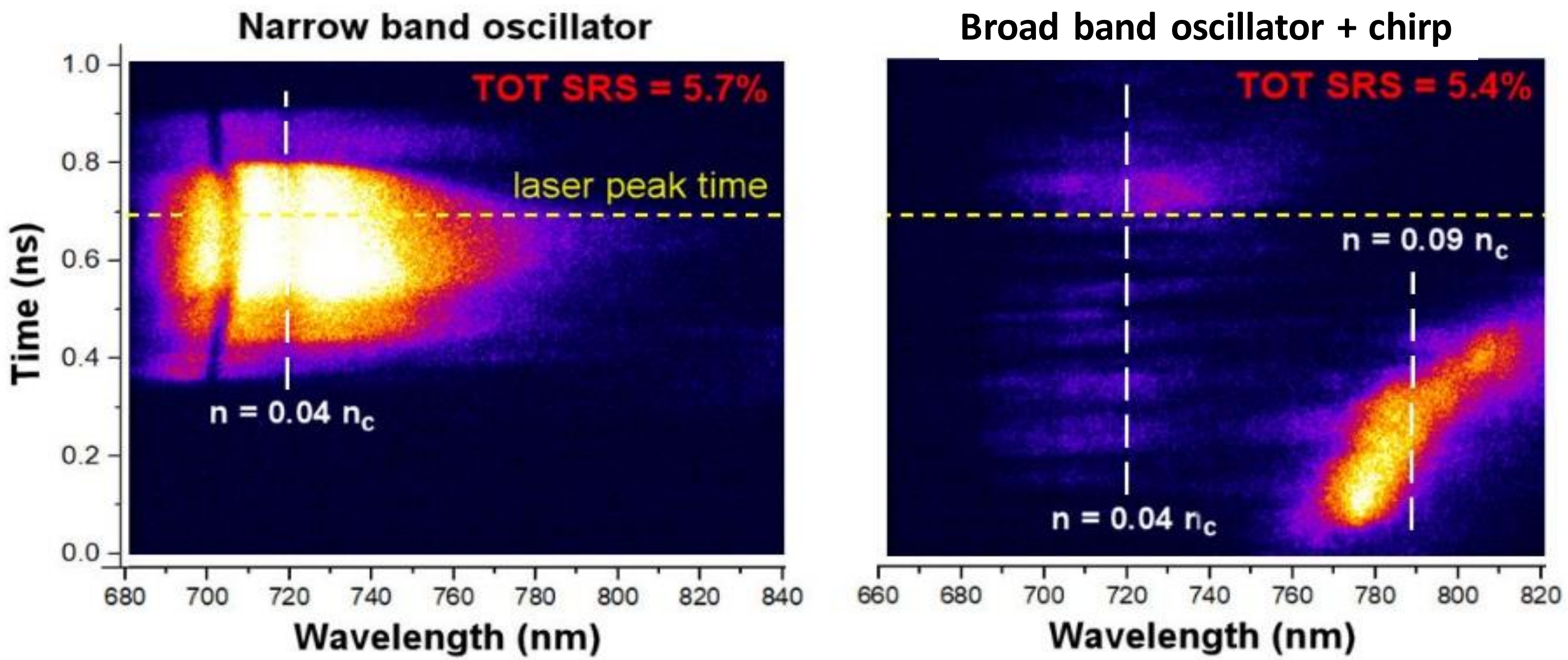
Final shots from TAW 2018 experiment

Pulse length = 700 ps

$I \approx 10^{16}$ W/cm^2

$\Delta\lambda/\lambda \sim 10^{-4}$ %

$\Delta\lambda_{TOT} \sim 0.7$ nm $\Delta\lambda_{TOT}/\lambda \sim 0.13$ % $d\lambda/dt = 0.95$ nm/ns

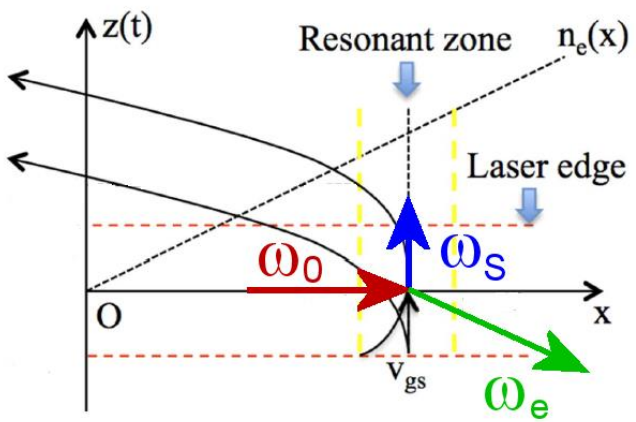


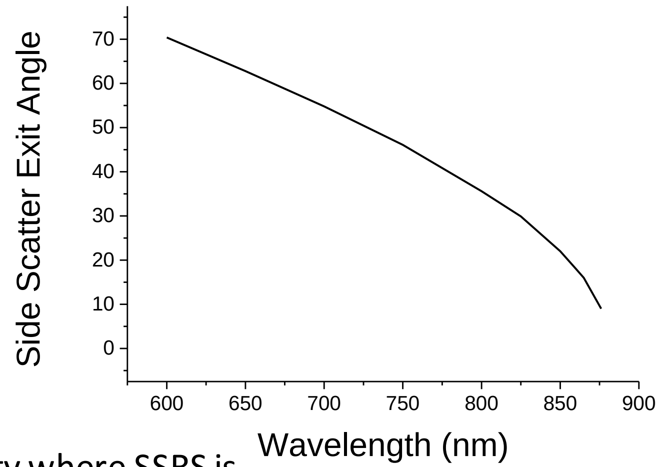
Broadband Chirped Oscillator leads to

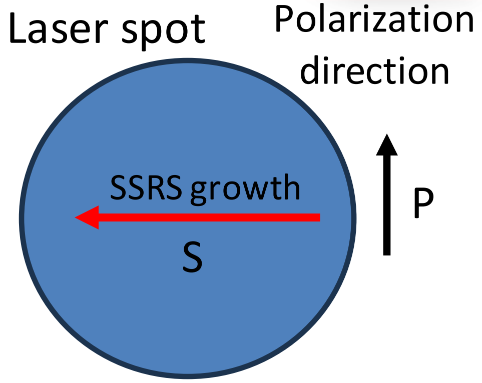
- a stronger growth of SRS at higher density, and
- a reduction of SRS at lower densities

Preliminary 2D simulations with a wave-coupling code (S.Huller) suggest that the chirp inhibits filamentation by shifting the speckles in time, reducing plasma smoothing

What we expect for Side SRS







- The exit angle depends only on the density where SSRS is driven and on the density profile.

We expect light emerging at 45-65°

- Light preferentially scattered out of polarization plane
- SSRS grows more strongly along the spot in the S-plane direction
- SSRS growth can be limited by the spot size or the density scalelength, depending on the conditions, while BSRS is usually limited by the density scalelength.

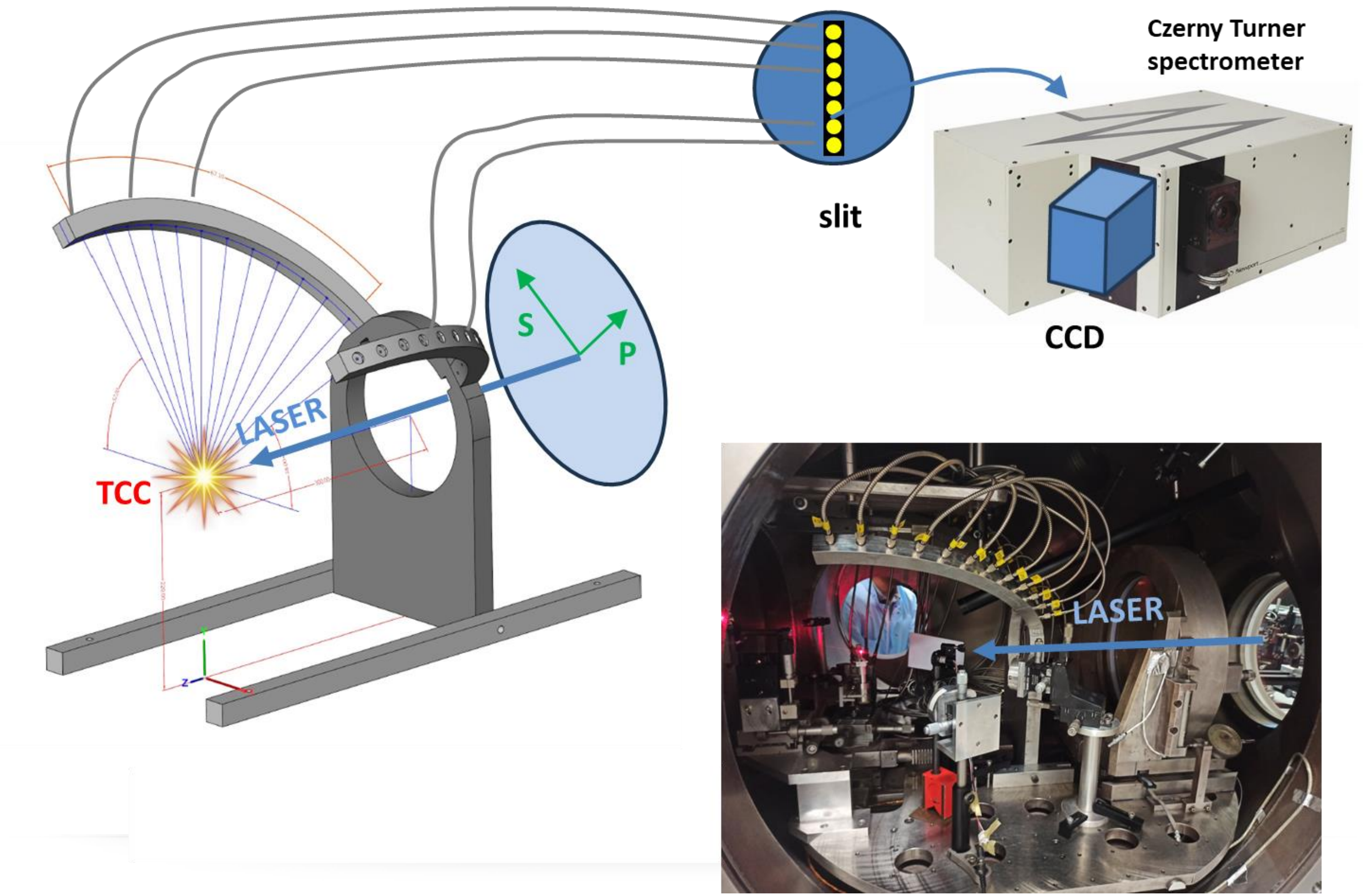
Recent experiments at Omega and NIF identify side SRS to be relevant

Michel et al., Phys. Rev. E **99**, 033203 (2019)
Rosenberg et al., Phys. Plasmas **27**, 042705 (2020)
Hironaka et al., Phys. Plasmas **30**, 022708 (2023)

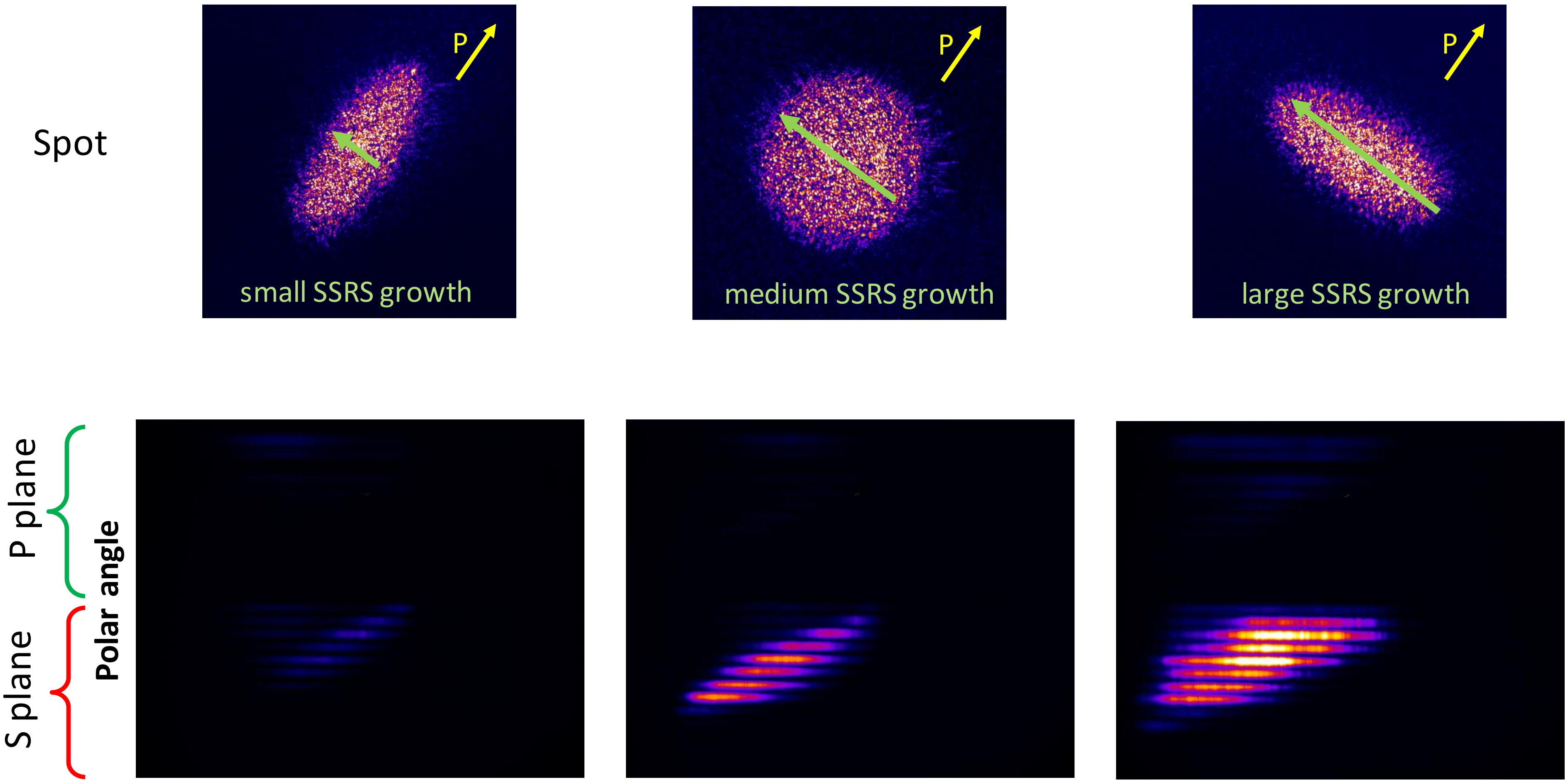
Side SRS

Side SRS: PALS 2023 experiment

G. Cristoforetti, S. Agarwal, D.Batani, M. Cervenak, P. Devi, R. Dudzak, D. Ettel, P. Gajdos, K. Glize, E. Hume, S. Jelinek, L. Juha, P.Koester, M. Krupka, M. Krus, H. Larreur, G. Malka, D. Mancelli, A. Morace, P. Nicolai, O. Renner, D. Singapulli, S. Singh, M. Tatarakis, Y. Wang, N. Woolsey, X. Zhao, L.A. Gizzi



Effect of spot size on SSRS



- The SSRS growth is here clearly limited by the spot size
- By modifying the density scalelength we observe a different dependence SSRS vs. BSRS

Conclusions

- Knowledge of LPI processes is crucial for the success of ICF. We can not skip plasma physics.

- In Europe we have a large expertise in the field. High level papers are published each year, both experimental and theoretical.

- However an European international roadmap and a dedicated facility is necessary to address and coordinate the research of ICF, and also LPI investigation and mitigation

THANK YOU FOR YOUR ATTENTION !

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More info at www.ilil.ino.cnr.it

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