EUROfusion Science Meeting on results of Enabling Research Projects 2021-2024

Inertial Fusion Project:

Advancing shock ignition for direct-drive inertial fusion

ENR-IFE.01.CEA

Dimitri Batani
University of Bordeaux, France
dimitri.batani@u-bordeaux.fr

Plan of Presentation

- The Project
- Examples of performed work
- The HiPER+ proposal

I believe we did a lot of work: this presentation is not exhaustive of all what has been done but rather just presents some significant examples

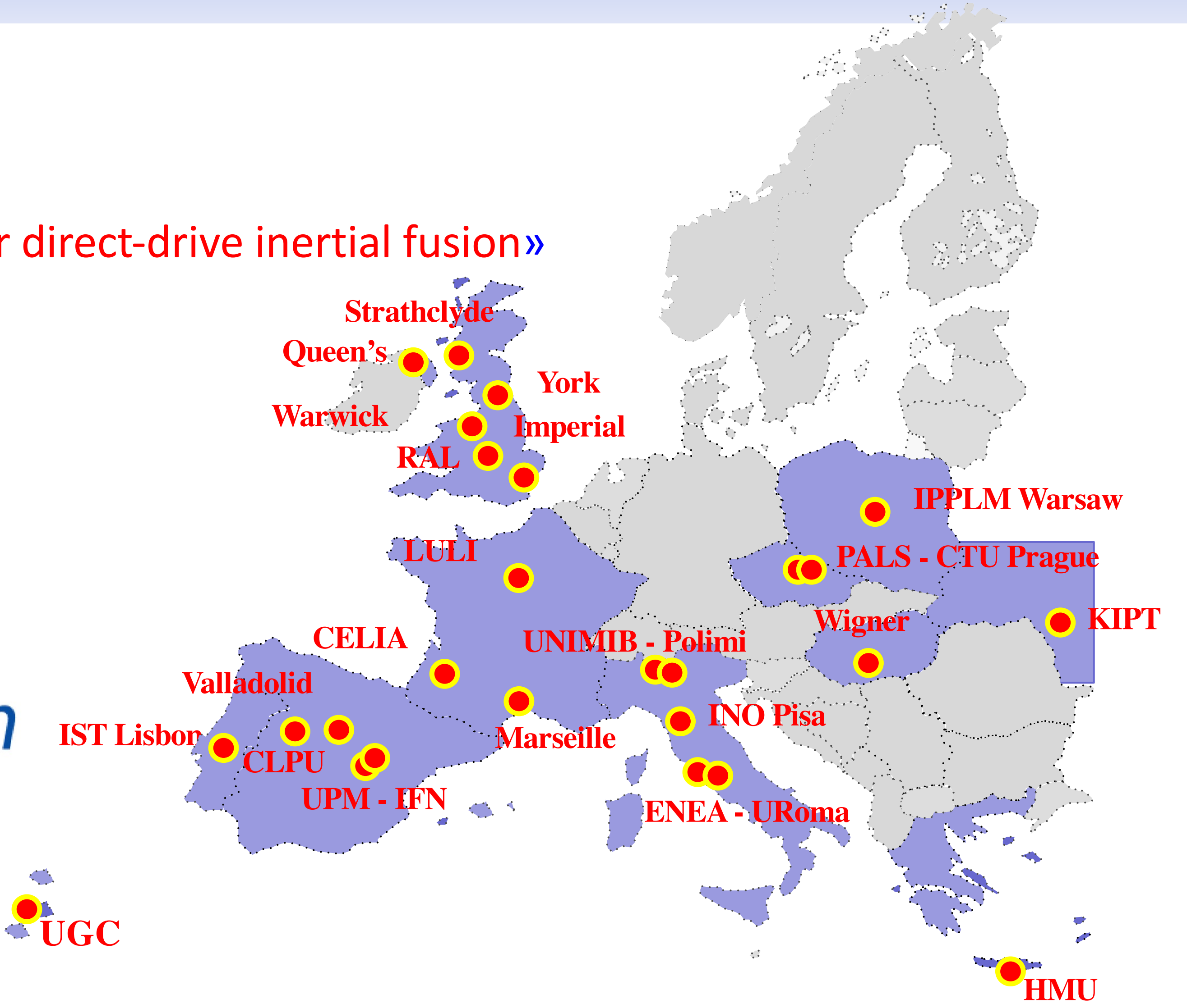
Only one IFE project has been supported by EUROFusion in 2021-2024

Enabling Research project
«Advancing shock ignition for direct-drive inertial fusion»

April 2021 – March 2024

PI Dimitri Batani

EUROfusion



10 countries, 24 groups, and 99 researchers involved in the project with about 70% "in kind" contributions in terms of PM

Large impact of NIF results

NIF results provide a validation of the Inertial Fusion concept, achieving ignition beyond breakeven, and opening the pathway to gain.

For the first time in the U.S., they think on the possibility of developing national projects on Inertial Fusion Energy (IFE) as a future source of energy

- **Basic Research Needs** report: a foundational guide for DOE to establish a national IFE program in the USA

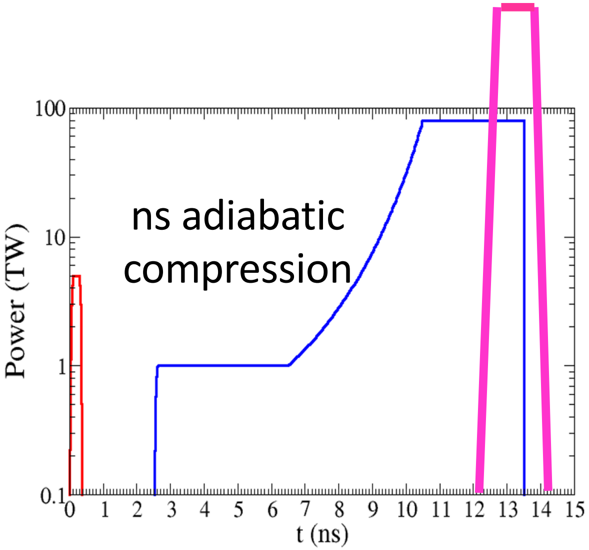
Germany has suddenly changed its attitude towards IFE

- **Memorandum** on laser IFE for the federal ministry of education and research of Germany (May 2023) and more recently statement of allocation of 1 B€ to fusion research

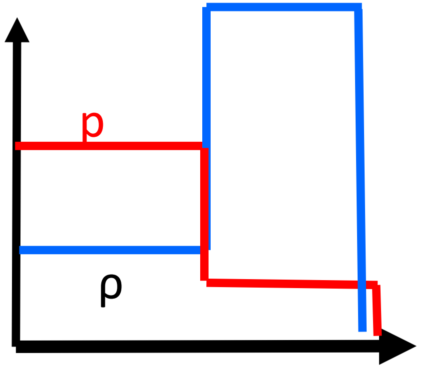
A big shift from defense-driven research to energy-oriented research

Shock Ignition

- Scheme proposed by R. Betti, J.Perkins et al. [PRL 98 (2007)] and anticipated by V.A.Shcherbakov [Sov.J. Plasma Phys. 9, 240 (1983)]
- Thicker and more massive target at lower implosion velocity V ≈ 240 km/s are intrinsically more resistant against the effect of hydro instabilities
- A final laser spike launches a strong converging shock (≥ 300 Mbar at the ablation front). This requires laser intensities $\approx 10^{16}\, W/cm^2$



Ignition spike (a few 100 ps)



- Shock Ignition is compatible with present-day laser technology ☺

Unknowns of Shock Ignition

- Effect of laser-plasma instabilities at intensities up to ≈ 10^{16} W/cm^2. SRS, SBS and TPD. How they develop? How much light do they reflect?

- Are there many hot electrons and at what energy? What is their effect? *(usually in ICF hot electrons are dangerous since they preheat the target… Here they came at late times, large fuel ρr, so they could indeed be not harmful or even beneficial, increasing laser-target coupling in presence of a very extended plasma corona…)*

- Are we really able to couple the high-intensity laser beam to the payload through an extended plasma corona? Are we really able to create a strong shock? (P ≥300 Mbar)

Our project was organized in 5 work packages

- WP1: characterization of hot electrons and hot-electron-driven SI
- WP2: hydrodynamic instabilities and mitigation strategies in DD-SI, including use of foams
- WP3: bipolar SI: direct drive compression and bipolar spike irradiation, new approaches to DD SI, advanced concepts & advanced fuels
- WP4: parametric instabilities and cross beam energy transfer, mitigation using broadband lasers
- WP5: magnetic-field-assisted inertial fusion implosion and ignition.

Achievement of scientific deliverables

Scientific deliverable *(annual scientific deliverables as specified in the Task Agreement)*	**Achieved: Fully/Partly/Not**	**Evidence for achievement, brief reason for partial or non-achievement**
D1.2 Report on HE effects in SI-designed targets (WP1)	Fully	See paper 10 , 18, 19
D2.2 Report on the evaluation on the impact of RT for SI-designed targets (WP2)	Partly	See paper 20, also paper in preparation as result of the PhD thesis of Diego Viala (supervisors A.Colaitis, D.Batani)
D2.3 Report on using foams to mitigate hydro instabilities growth (WP2)	Fully	See papers 7, 9, 16
D3.1 Report on feasibility of bipolar shock ignition and proposal for experiments on LMJ/NIF (WP3)	Fully	See papers 1, 21, 22
D4.1 Report on LPI and CBET in SI conditions (WP4)	Fully	See paper 10, 14, 21
D5.2 Report on the characterization of magnetized HED plasmas over the implosion and at stagnation (WP5)	Fully	See papers 5, 6, 12, 22, 29
D1.1 Report on measurements of HE distribution and HE tail in SI conditions. Optimization of bremsstrahlung cannon, correlation among different diagnostics (WP1)	Fully	See papers 10, 20, 25
D5.1 Design of a magnetized implosion experiment at MJ scale at LMJ or NIF (WP5)	Fully	See papers 5, 6, 22

2023: 32 papers uploaded in the Eurofusion PINBOARD

	First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
1	Barlow	D	A New Optimization Methodology for Polar Direct Drive Illuminations at the National Ignition Facility	Physical Review Letters	Paper	submitted	932
2	Ehret	M	High-repetition-rate source of nanosecond duration kA-current pulses driven by relativistic laser pulses	High Power Laser Science and Engineering	Paper	submitted	900
3	Nikl	J	High-order curvilinear finite element magneto-hydrodynamics I: A conservative Lagrangian scheme	Journal of Computational Physics	Paper	https://doi.org/10.1016/j.jcp.2022.111158	897
4	Hadjikyriacou	A	Novel approach to TNSA enhancement using multi-layered targets a numerical study	Plasma Physics and Controlled Fusion	Paper	DOI 10.1088/1361-6587/acdc51	896
5	Vlachos	C	Laser-driven quasi-static B-fields for magnetized high energy-density experiments	Physics of Plasmas	Paper	submitted	895
6	Bailly-Grandvaux	M.	Impact of strong magnetization in cylindrical plasma implosions with applied B-field measured via X-ray emission spectroscopy	Physical Review Research	Paper	DOI: 10.1103/PhysRevResearch.6.L012018	894
7	Paddock	R	Measuring the principal Hugoniot of ICF-relevant TMPTA plastic foams	Physical Review E	Paper	https://doi.org/10.1103/PhysRevE.107.025206	858
8	Barbato	F	Feasibility study of an XPCI diagnostic to observe the evolution of micro-voids in an ICF target	Plasma Physics and Controlled Fusion	Paper	DOI 10.1088/1361-6587/ad1a42	839
9	Maffini	M	Numerical Study of Carbon Nanofoam Targets for Laser-Driven Inertial Fusion Experiments	Laser and Particle Beams	Paper	https://doi.org/10.1155/2023/1214430	837
10	Cristoforetti	G.	Investigation on the origin of hot electrons in laser plasma interaction at shock ignition intensities	Scientific Reports	Paper	https://doi.org/10.1038/s41598-023-46189-7	782
11	Chrisment	A	Analysis of a kinetic model for electron heat transport in inertial confinement fusion plasmas	Physics of Plasmas	Paper	DOI: 10.1063/5.0107034	307
12	Pisarczyk	T	Strongly magnetized plasma produced by interaction of nanosecond kJ-class laser with snail targets	Plasma Physics and Controlled Fusion	Paper	DOI: 10.1088/1361-6587/acc421	203
13	Igumenshchev	I	Proof-of-Principle Experiment on the Dynamic Shell Formation for Inertial Confinement Fusion	Physical Review Letters	Paper	DOI: 10.1103/PhysRevLett.131.015102	107
14	Cristoforetti	G	Multibeam Laser Plasma Interaction at Gekko XII laser facility in conditions relevant for Direct-Drive Inertial Confinement Fusion	High Power Laser Science and Engineering	Paper	DOI: 10.1017/hpl.2023.13	84
15	Perez-Callejo	G	X-ray imaging and radiation transport effects on cylindrical implosions	Review of Scientific Instruments	Paper	DOI: 10.1063/5.0099180	78
16	Hudec	L	Hybrid ablation-expansion model for laser interaction with low-density foams	Physics of Plasmas	Paper	DOI: 10.1063/5.0139488	61
17	Papadogiannis	N	Pump-probe reflectivity studies of ultrashort laser-induced acousto-mechanical strains in ZnO films	Applied Physics A	Paper	DOI: 10.1007/s00339-023-06837-1	57
18	Tentori	A	3D Monte-Carlo model to study the transport of hot electrons in the context of Inertial Confinement Fusion: Part II	Matter and Radiation at Extremes	Paper	DOI: 10.1063/5.0103632	32
19	Tentori	A	3D Monte-Carlo model to study the transport of hot electrons in the context of Inertial Confinement Fusion: Part I	Matter and Radiation at Extremes	Paper	DOI: 10.1063/5.0103631	32
20	Colaitis	A	3D simulations of Inertial Confinement Fusion implosions part 2: systematic flow anomalies and impact of low modes on performances in OMEGA experiments	Plasma Physics and Controlled Fusion	paper	DOI: 10.1088/1361-6587/aca78d	382 (2022)
21	Colaitis	A	3D simulations of Inertial Confinement Fusion implosions part 1: inline modeling of polarized cross beam energy transfer and subsequent drive anomalies on OMEGA and NIF	Plasma Physics and Controlled Fusion	paper	DOI 10.1088/1361-6587/aca78e	381 (2022)
22	Perez-Callejo	G	A cylindrical implosion platform for the study of highly magnetized plasmas at LMJ	Physical Review E	paper	DOI: 10.1103/PhysRevE.106.035206	218 (2022)
23	Savino	L	Studies on dynamical shell formation for direct-drive laser fusion	Il Nuovo Cimento C	paper	DOI: 10.1393/ncc/i2022-22180-x	97 (2022)
24	Atzeni	S	Breakthrough at the NIF paves the way to inertial fusion energy	Europhysics News	paper	DOI: https://doi.org/10.1051/epn/2022106	54 (2024)
25	Batani	D	Advances in the Study of Laser-Driven Proton-Boron Fusion	Laser and Particle Beams	paper	doi.org/10.1155/2023/9824024	55 (2024)
26	Filippov	E	Characterization of hot electrons generated by laser-plasma interaction at Shock Ignition intensities	Matter and Radiation at Extremes	paper	https://doi.org/10.1063/5.0157168	53 (2024)
27	Batani	D	Future for Inertial Fusion Energy in Europe: A roadmap	High Power Laser Science and Engineering	paper	10.1017/hpl.2023.80	52 (2024)
28	Kawasaki	K	Effects of hydrogen concentration in ablator material on stimulated Raman scattering, two-plasmon decay, and hot electrons for direct-drive inertial confinement fusion	PHYSICAL REVIEW RESEARCH	paper	https://doi.org/10.1103/PhysRevResearch.5.033051	50 (2024)
29	Pisarczyk	T	Influence of the magnetic field on properties of hot electron emission from ablative plasma produced at laser irradiation of a disc-coil target	Plasma Physics and Controlled Fusion	paper	DOI 10.1088/1361-6587/ac95c4	469 (2022)
30	Tamagawa	T	Development of an experimental platform for the investigation of laser–plasma interaction in conditions relevant to shock ignition regime	Rev. Sci. Instrum	paper	doi: 10.1063/5.0089969	49 (2024)
31	Salvadori	M	Univocal discrimination of alpha particles produced by 11B(p,alpha)2alpha fusions in laser-matter experiments by advanced Thomson Spectrometry	Laser and Particle Beams	paper	DOI: 10.1155/2023/7831712	360 (2022)
32	Sciscio	M	High sensitivity Thomson spectrometry in experiments of laser-driven low-rate neutron-less fusion reactions	Laser and Particle Beams	paper	DOI: 10.1155/2023/3531875	423 (2022)

2024: 12 papers uploaded in the Eurofusion PINBOARD

874 D Batani et al. "Equation of state for boron nitride along the principal Hugoniot to 16 Mbar" Matter and Radiation at Extremes

863 M Sciscio et al. "Laser initiated p-11B fusion reactions in petawatt high-repetition-rates laser facilities" Matter and Radiation at Extremes

844 D Viala et al. "Comparison of chamber beam geometry robustness to mispointing, imbalance and target offset for direct-drive laser fusion facilities" Nuclear Fusion

174 A. Zaras-Szydlowska et al. "Interferometric measurements of plasma expansion induced by the interaction of a femtosecond laser pulse with a solid Al target, performed at the High Power Laser Laboratory at IPPLM" Physics of Plasmas

62 S. Singh et al. "Hot electron emission characteristics from thin metal foil targets irradiated by terawatt laser" Laser and Particle Beams

61 S. Singh et al. "Hot electron and x-ray generation by sub-ns kJ-class laser-produced tantalum plasma" Plasma Physics and Controlled Fusion

55 D Batani et al."Advances in the Study of Laser-Driven Proton-Boron Fusion" Laser and Particle Beams

54 S Atzeni et al."Breakthrough at the NIF paves the way to inertial fusion energy" Europhysics News

53 E Fillipov et al. "Characterization of hot electrons generated by laser-plasma interaction at Shock Ignition intensities" Matter and Radiation at Extremes

52 D Batani et al. "Future for Inertial Fusion Energy in Europe: A roadmap" High Power Laser Science and Engineering

50 K Kawasaki et al. "Effects of hydrogen concentration in ablator material on stimulated Raman scattering, two-plasmon decay, and hot electrons for direct-drive inertial confinement fusion" Physical Review Research

48 T Tamagawa et al. "Development of an experimental platform for the investigation of laser-plasma interaction in conditions relevant to shock ignition regime" Review of Scientific Instruments

Plan of Presentation

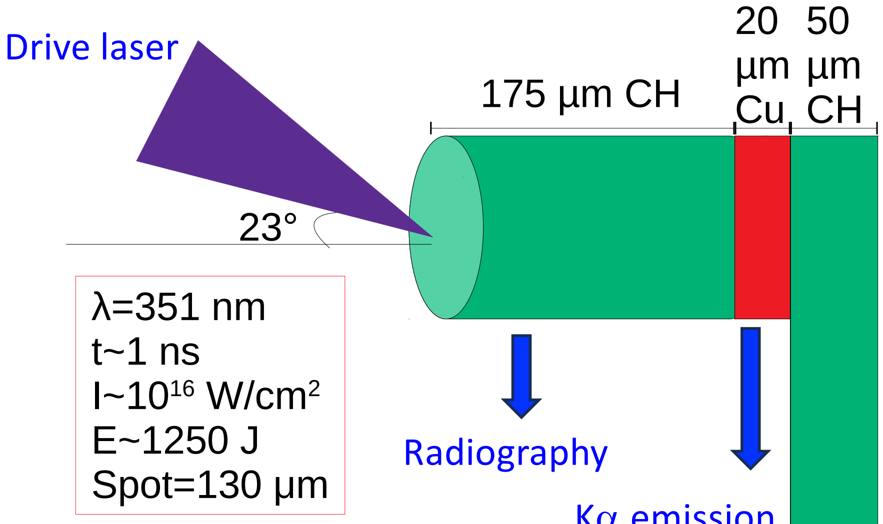
- The Project
- Examples of performed work
- The HiPER+ proposal

Some examples of recent research work

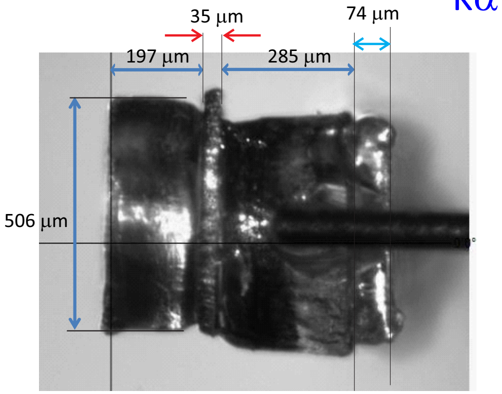
Collaboration with the Omega laser facility

- *Experiment directly supported by the EUROFusion Enabling Research Project on Shock Ignition*

Omega Experiment: Laser beam with characteristics relevant to SI scheme focused on multi-layer planar target to produce a strong shock and hot electrons

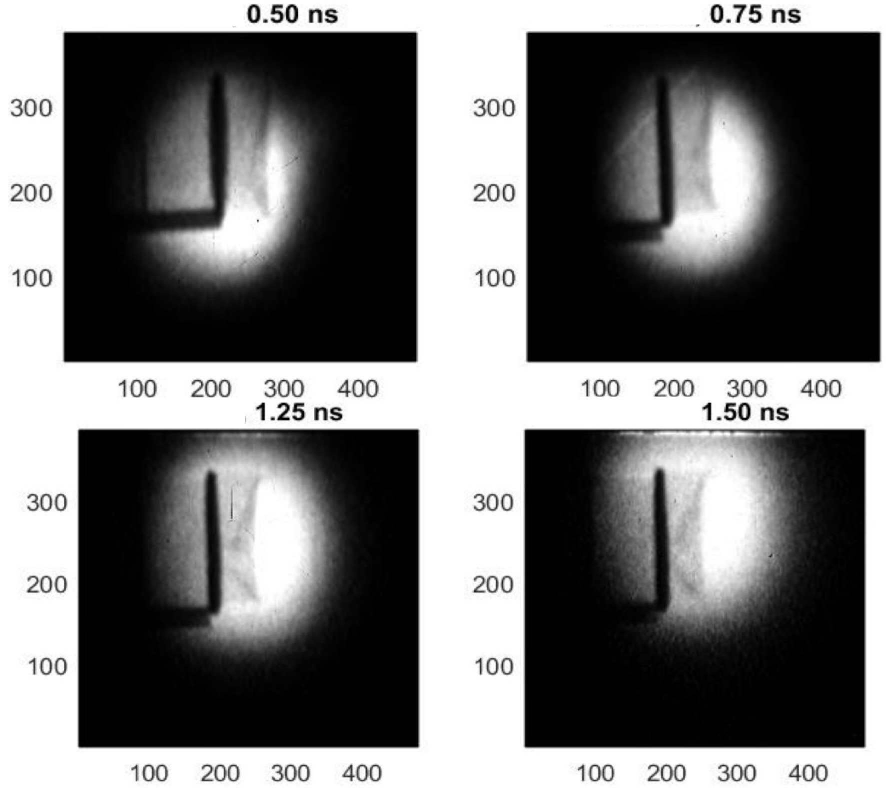


λ=351 nm
t~1 ns
I~10^{16} W/cm^2
E~1250 J
Spot=130 µm



Shock propagation:

Time resolved X-ray radiography

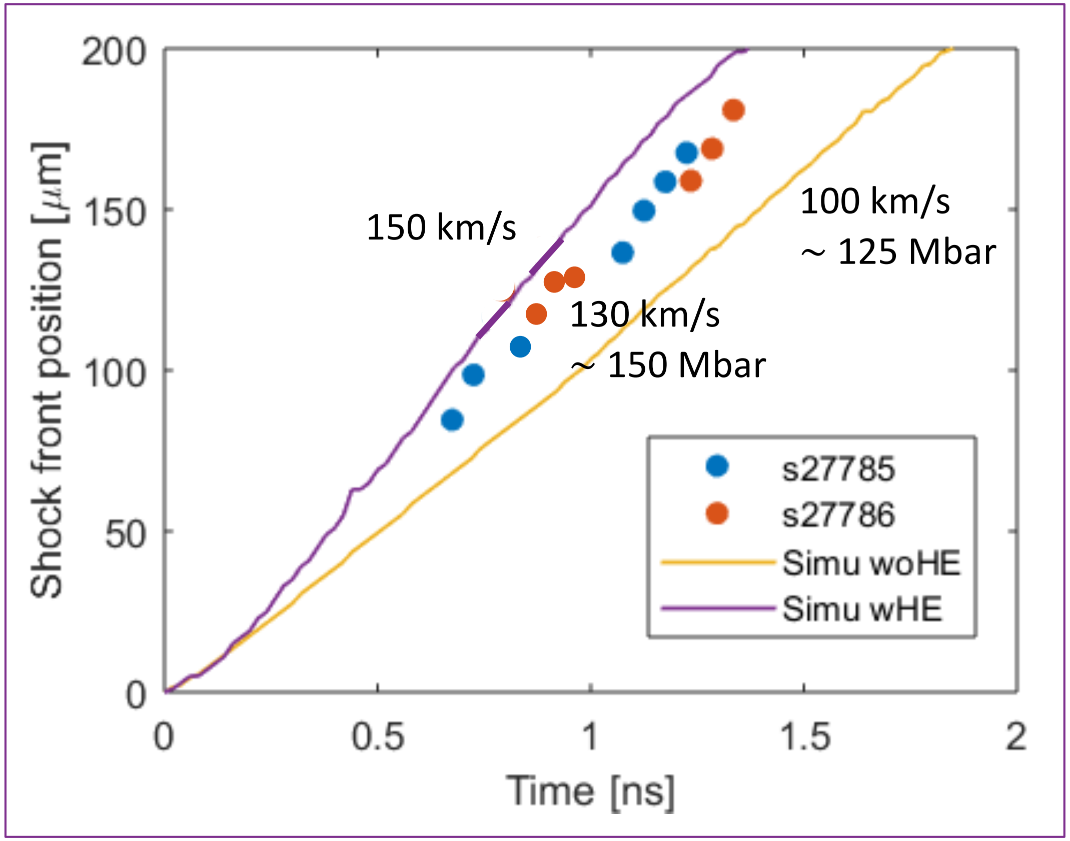


Shock Velocity and Pressure: effect of hot electrons

Hot electrons: were characterized using bremsstrahlung and K$_\alpha$ emission on spectrometers

Two diagnostics measure the K_α emission from copper: ZNVH: Zinc Von Hamos, crystal reflection recorded on IP.
HRS: High Resolution Spectrometer, recorded on CCD.

One diagnostic (BMXS) measured bremsstrahlung emission



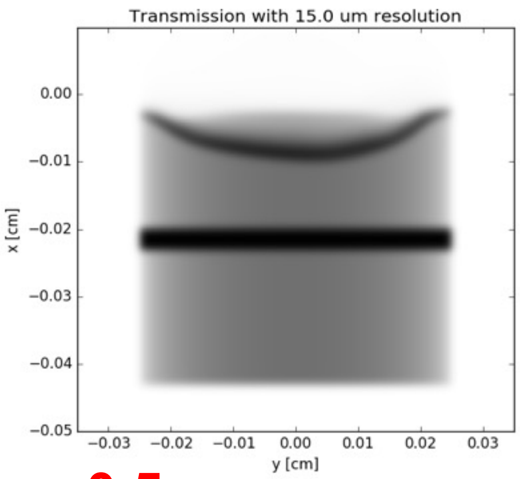
A. Tentori et al. Physics of Plasmas 28, 103302 (2021)

- **Hot electron temperature ≈25 keV (*good news for shock ignition*) and energy conversion of 10%, i.e. a total energy of ≈ 60 J**
- **Pressure increases from 125 to 150 Mbar and shock velocity from 100 to 130 km/s**

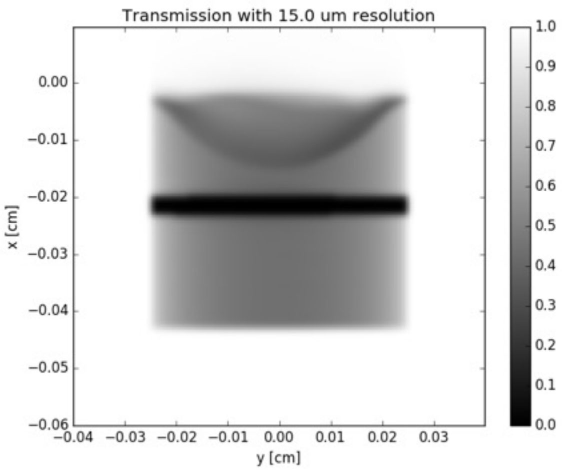
Experimental results reproduced only taking hot electrons into account

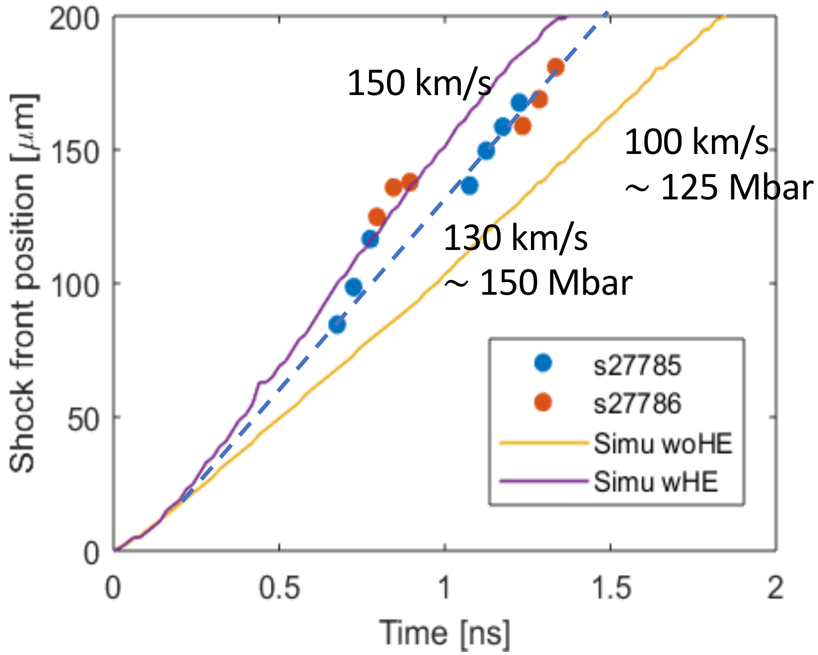
Hot electrons measurement by Bremsstrahlung and K_α must be compared to hydro results to completely constraint the HE distribution. In our experiment $T_{hot} \sim 26$ keV with an energy conversion of 11% *(good news for Shock Ignition)*

Simulation woHE

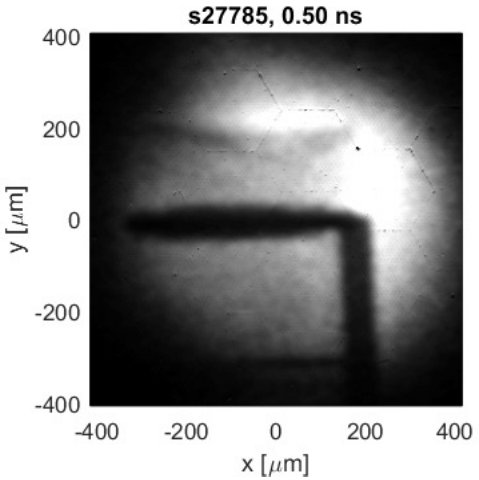


Simulation wHE





0.5 ns

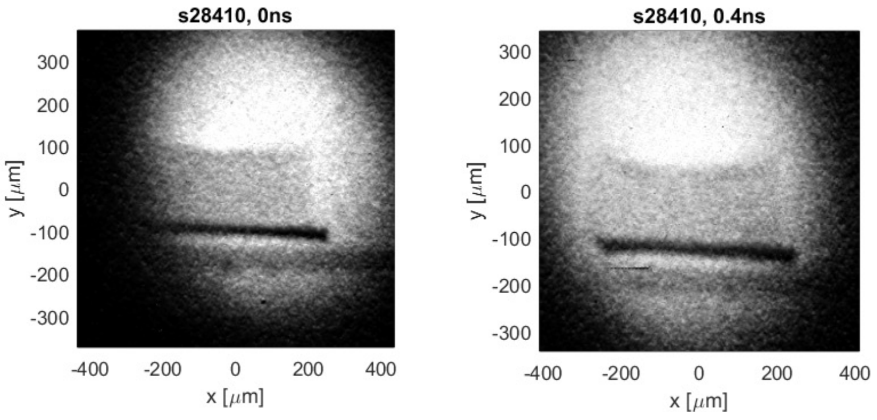


Experiment

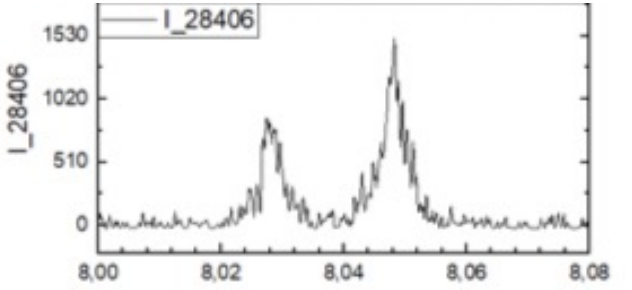
Effect of the HE on the hydrodynamic:

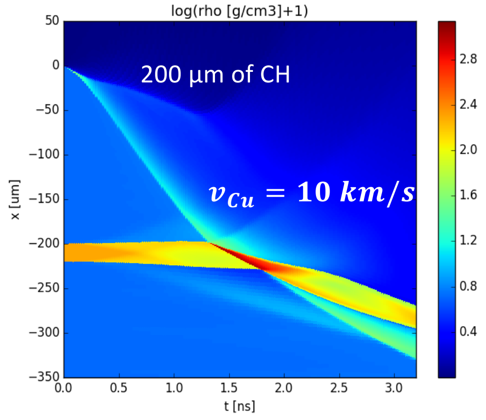
- **Faster shock**
- **Expansion of shocked CH**
- **Expansion of the Cu layer**

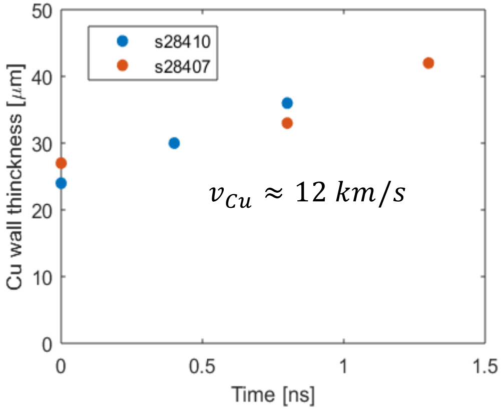
Heating and expansion of Cu layer due to hot electrons



Kα spectra: PrismSpect modeling

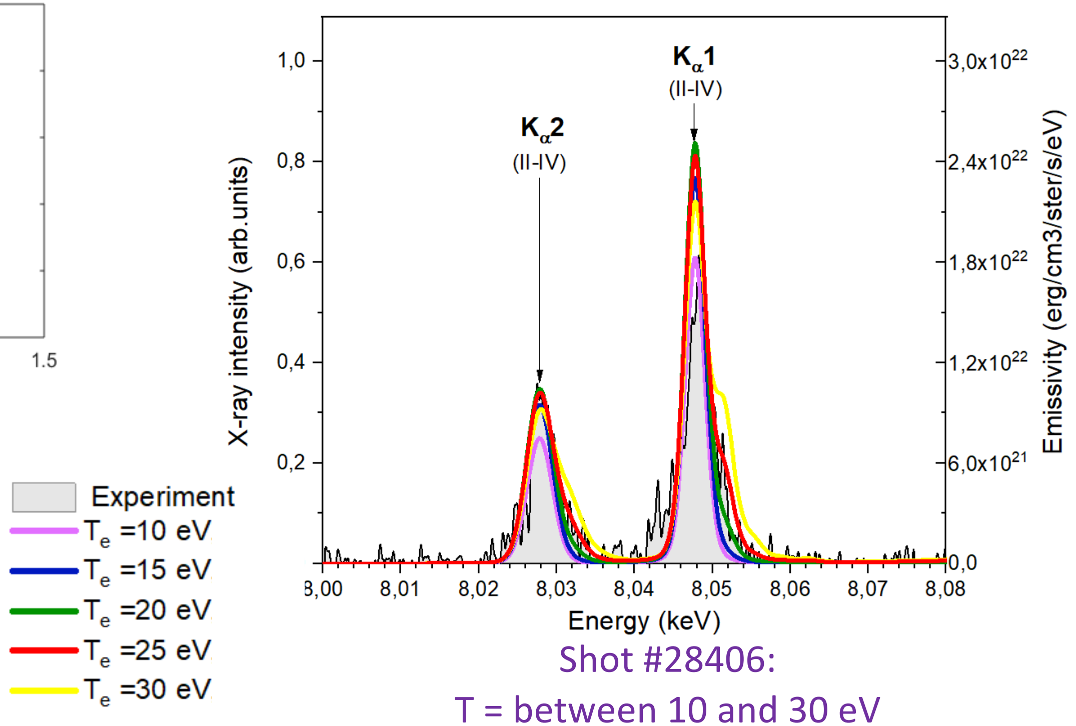






T = ≥ 10 eV

Fair agreement between
hydrodynamic and spectroscopic data
Cu is driven to WDM state

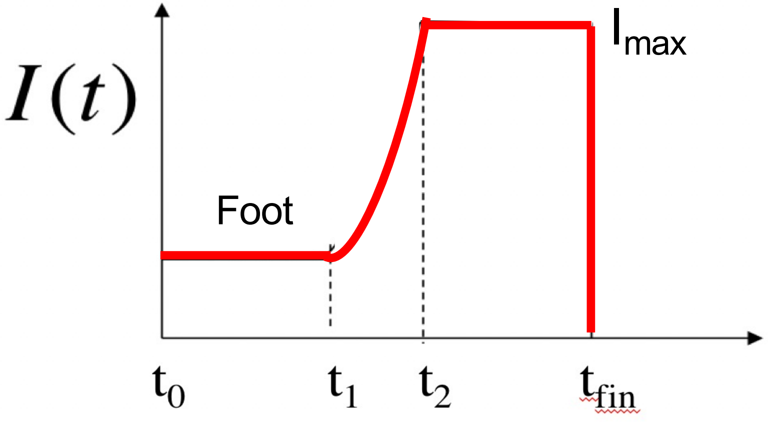


Shot #28406:
T = between 10 and 30 eV

Collaboration with China (PKU, IAPCM, LFRC)

To get high gain we need quasi-isentropic compression

$$\alpha \equiv \frac{p}{p_F} \quad \Rightarrow \text{(for DT plasma)} \quad \alpha_{DT} \equiv \frac{p(Mb)}{2.2\rho(g/cc)^{5/3}}$$



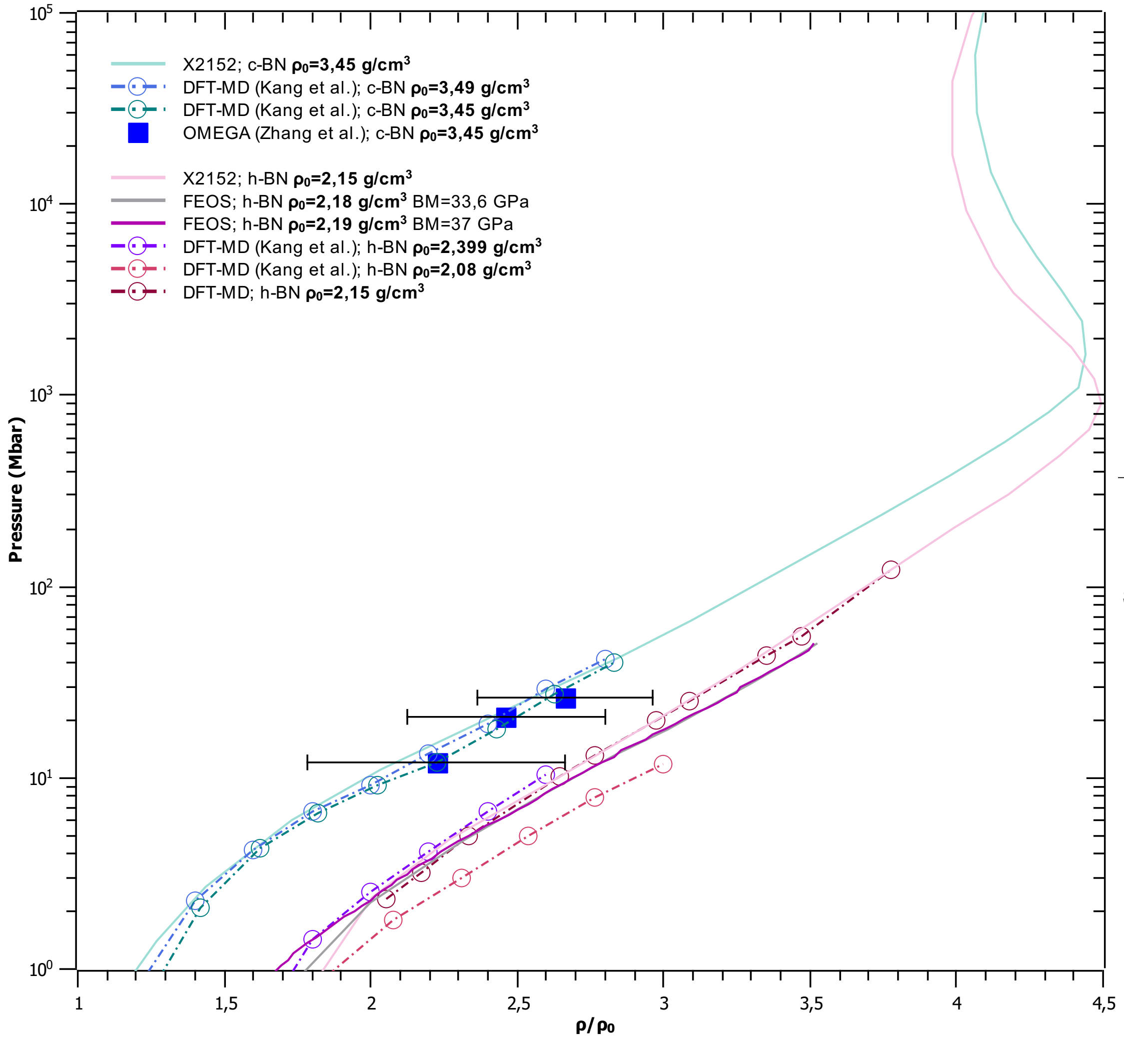
The use of diamond ablator has been a key ingredient in achieving gain.

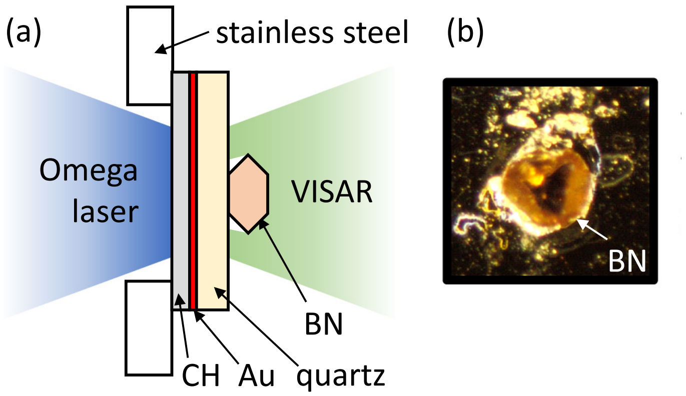
However, in current experiments the first shock is set at 12 Mbar, above the HDC melting point. In other words, the high bulk modulus and high melting temperature of diamond imply that we cannot go to low entropy parameters α

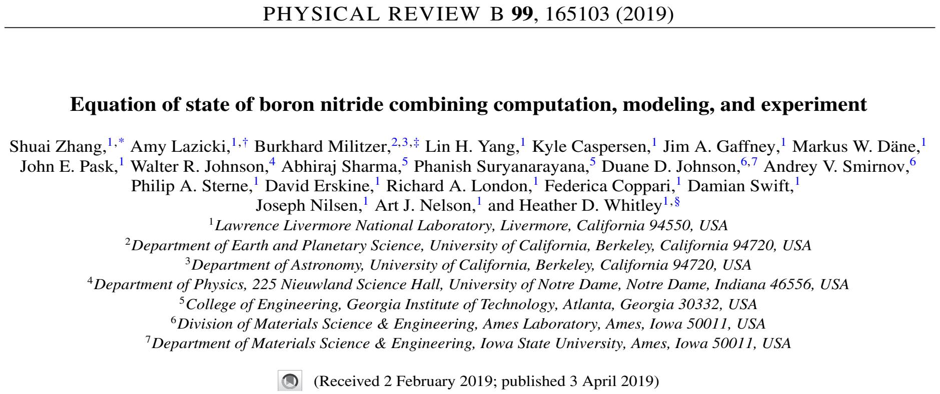
⇨ ***Looking for new ablators***

Bulk modulus hexagonal BN 37 Gpa
Bulk modulus cubic BN 369 Gpa
Bulk modulus diamond 530 GPa

EoS data for BN (laser Omega)






PHYSICAL REVIEW B **99**, 165103 (2019)

Equation of state of boron nitride combining computation, modeling, and experiment

Shuai Zhang,[1,*] Amy Lazicki,[1,†] Burkhard Militzer,[2,3,‡] Lin H. Yang,[1] Kyle Caspersen,[1] Jim A. Gaffney,[1] Markus W. Däne,[1]
John E. Pask,[1] Walter R. Johnson,[4] Abhiraj Sharma,[5] Phanish Suryanarayana,[5] Duane D. Johnson,[6,7] Andrey V. Smirnov,[6]
Philip A. Sterne,[1] David Erskine,[1] Richard A. London,[1] Federica Coppari,[1] Damian Swift,[1]
Joseph Nilsen,[1] Art J. Nelson,[1] and Heather D. Whitley[1,§]
[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[2]*Department of Earth and Planetary Science, University of California, Berkeley, California 94720, USA*
[3]*Department of Astronomy, University of California, Berkeley, California 94720, USA*
[4]*Department of Physics, 225 Nieuwland Science Hall, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[5]*College of Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
[6]*Division of Materials Science & Engineering, Ames Laboratory, Ames, Iowa 50011, USA*
[7]*Department of Materials Science & Engineering, Iowa State University, Ames, Iowa 50011, USA*

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EoS platform at SG-III prototype

- 8 beams/1~3ns/351nm-1200J/beam, 500-2000um/CPP+SSD
- 9th beam-4kJ/5ns, 20ns pulse shaping ability

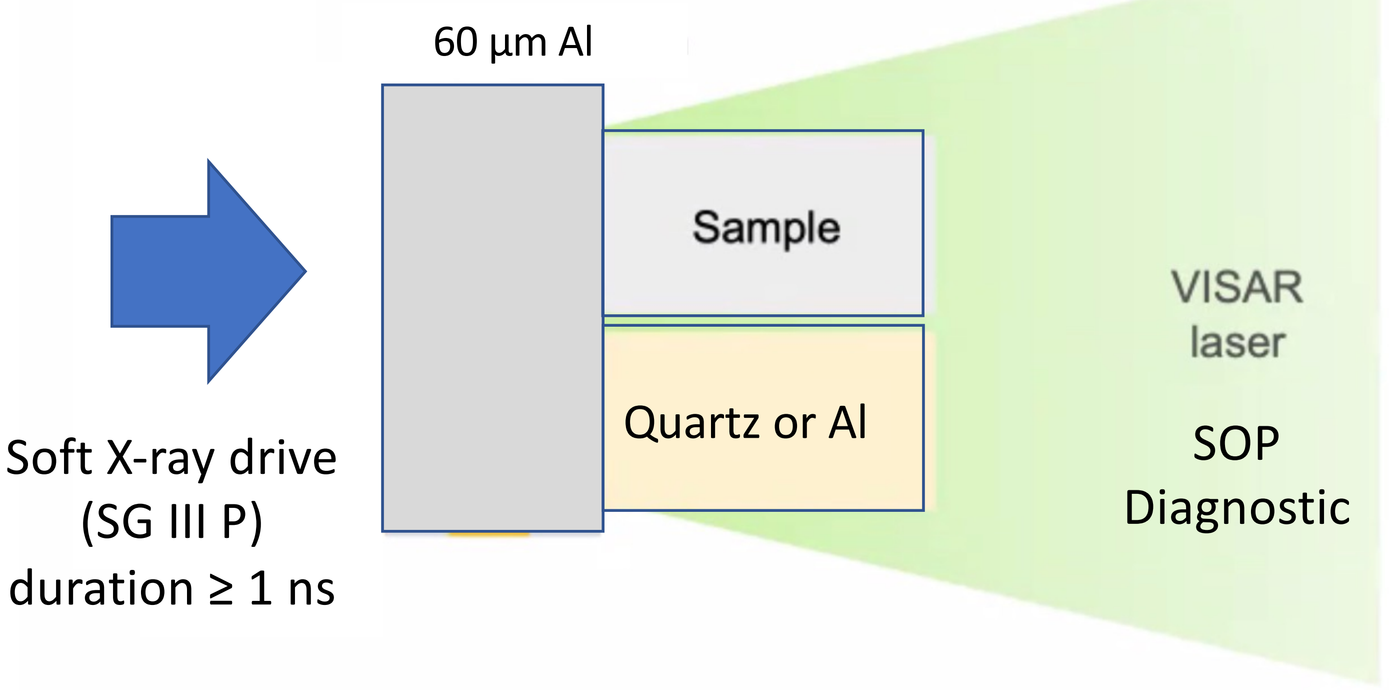
- Diagnostic: VISAR(2 legs at 532nm 10-50km/s), SOP(calibrated), XRD, XPHC

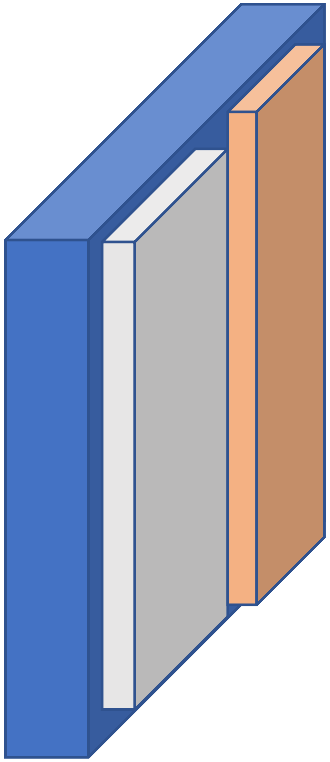
Indirect Drive (SG III P)

Al substrate (1 mm X 1 mm X 60 µm)

BN Parallelepiped (0.8 mm X 0.4 mm X 60 µm)

Reference material Parallelepiped (0.8 mm X 0.4 mm)





Type of targets:

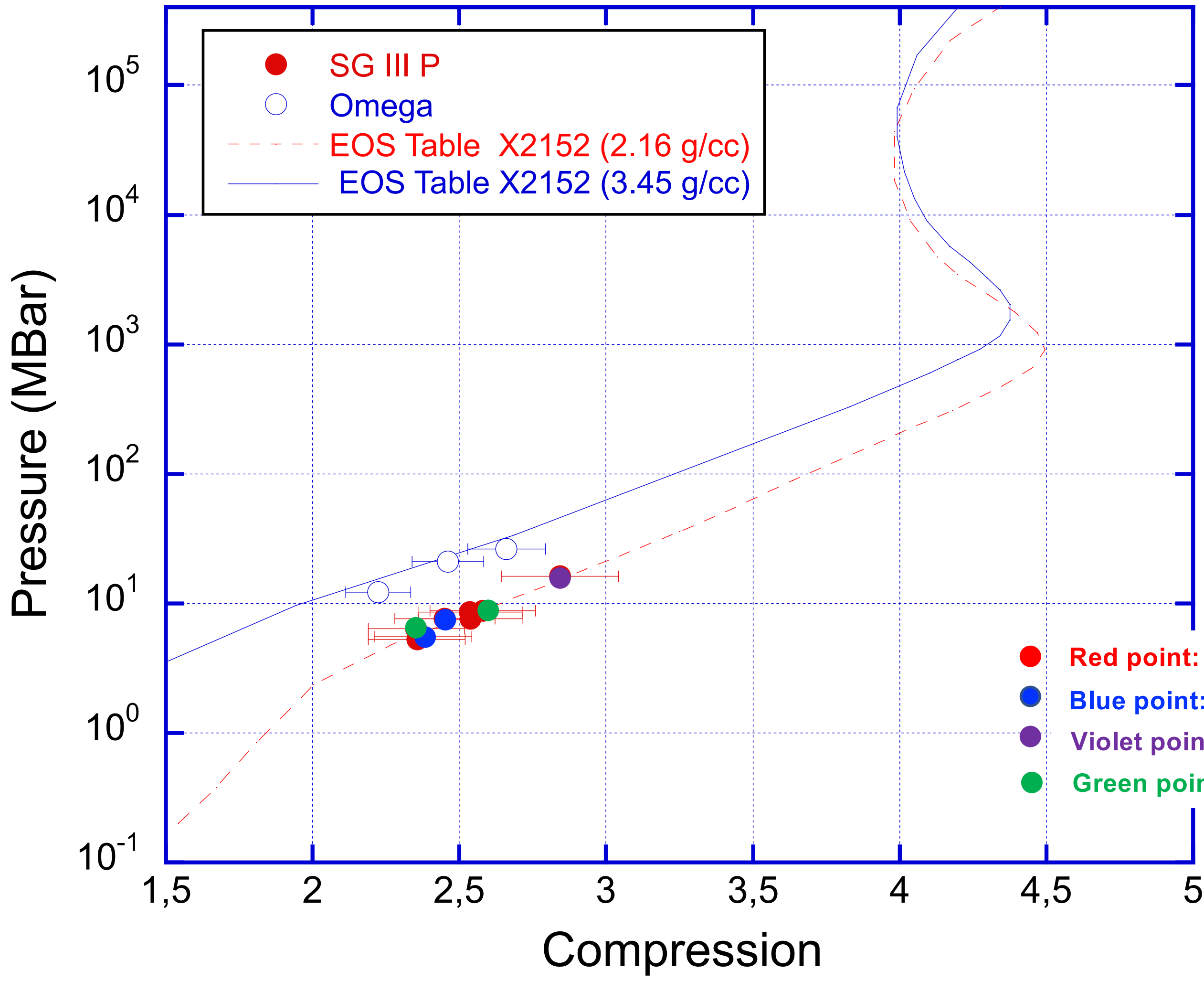
1) UK targets with 100 µm quartz
2) Chinese targets with 200 µm quartz
3) Chinese targets with Al as reference

Type of hohlraums:

1) Big hohlraum ($T_r \approx$ 130 eV)
2) Small hohlraum ($T_r \approx$ 170 eV)

10 shots- 8 successful shots

EoS data for BN (laser SG III P)



● **Red point: 2.04 g/cm^3 (Q-Al-BN) Chinese target**

● **Blue point: 2.05 g/cm^3 (Q-Al-BN) UK target**

● **Violet point: 2.04 g/cm^3 (Q-Al-BN) Small hohlraum**

● **Green point: 2.04g/cm^3 (Al-BN)**

LFRC 激光聚变研究中心
LASER FUSION RESEARCH CENTER

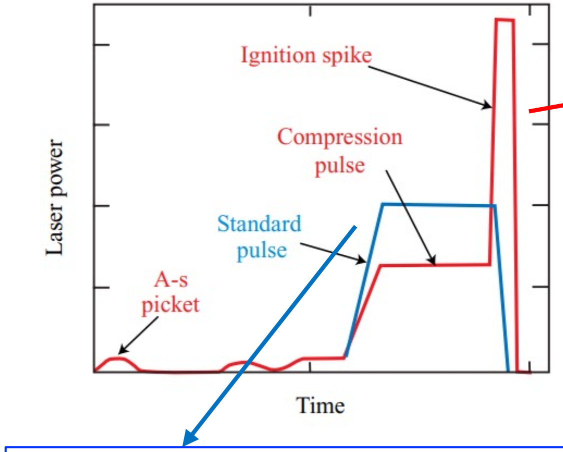
CAPT, Peking University

北京应用物理与计算数学研究所
Institute of Applied Physics and Computational Mathematics

université de BORDEAUX

Huan Zhang, Yutong Yang, Zanyang Guan, Xiaoxi Duan, Mengsheng Yang, Weimin Yang, Yonggang Liu, Jingxiang Shen, Katarzyna Batani, Diluka Singappuli, Yongsheng Li, Wenyi Huo, Ke Lan, Hao Liu, Yulong Li, Dong Yang, Sanwei Li, Zhebin Wang, Jiamin Yang, Zongqing Zhao, Weiyan Zhang, Liang Sun, Wei Kang, and Dimitri Batani "Equation of state of for boron nitride along the principal Hugoniot to 16 Mbar" *Matter Radiat. Extremes* (2024)

LPI: Classical Direct Drive vs. Shock Ignition



Shock Ignition

I ≈ 10^{16} W/cm^2
implosion velocity ~240 km/s
T ≈ 5 keV
L_n ≈ 500 μm

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

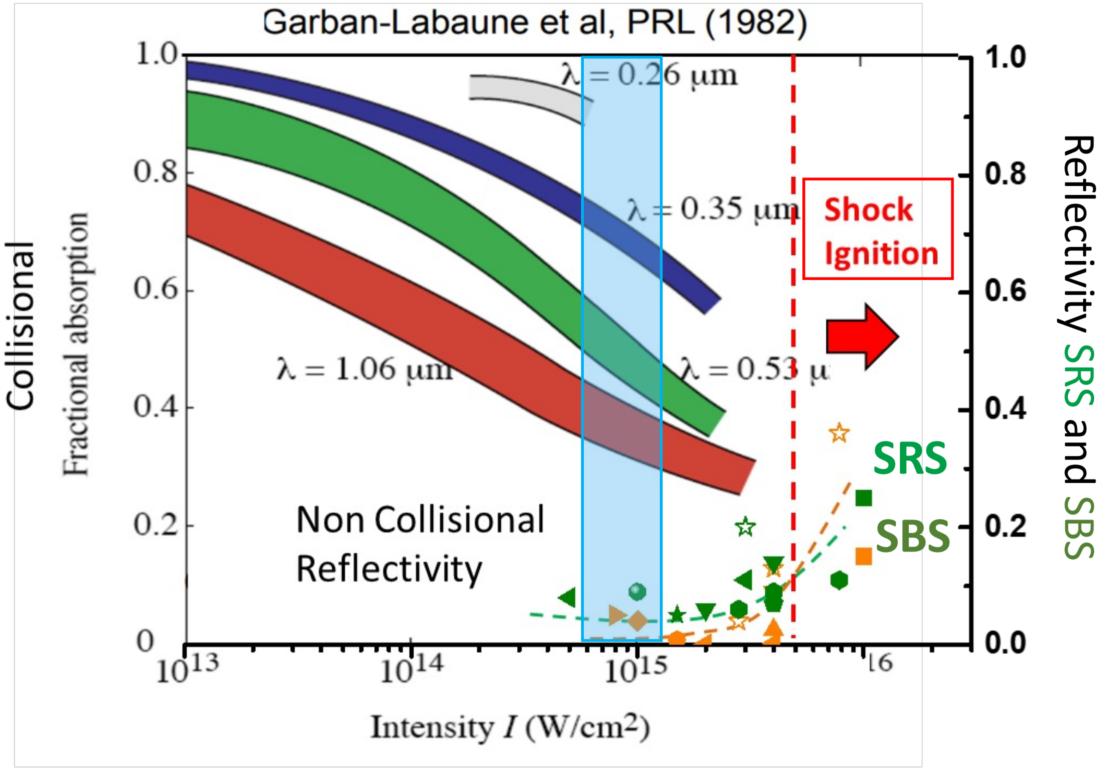
SBS, SRS, (TPD)

HE mainly driven by SRS

Classical Direct Drive

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

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


Garban-Labaune et al, PRL (1982)

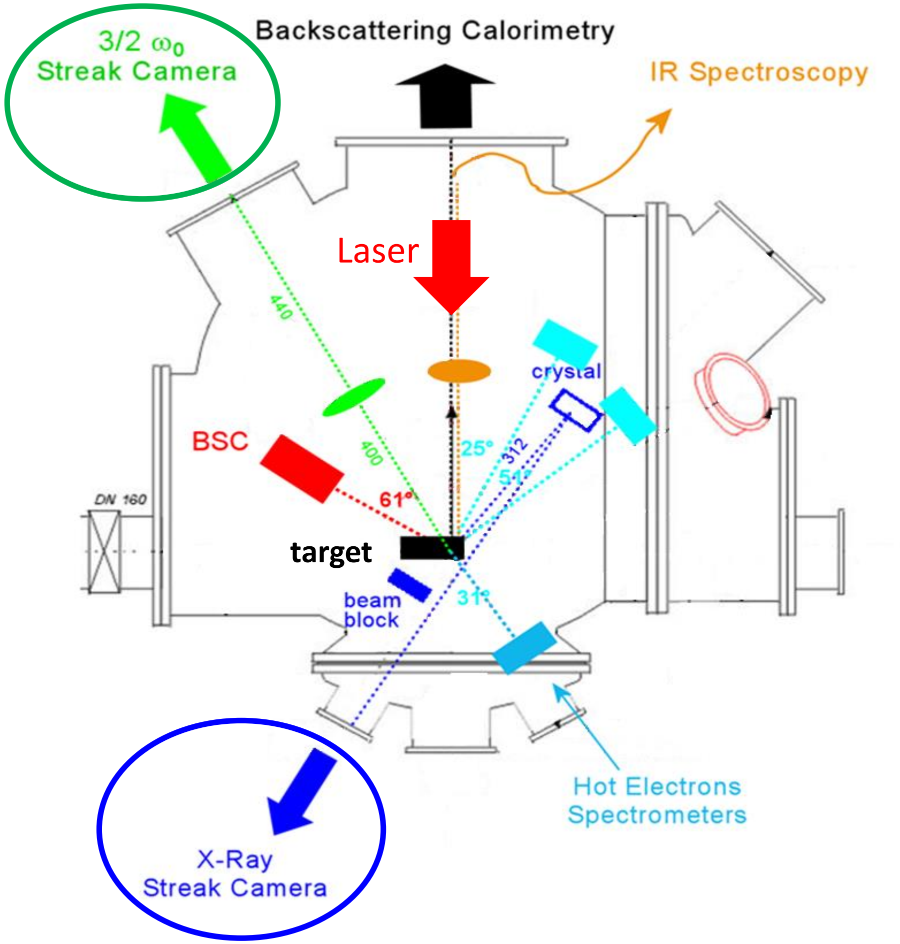
Work on Parametric Instabilities and hot electrons

An example: experiments at the PALS laser Prague

The PALS Iodine Laser

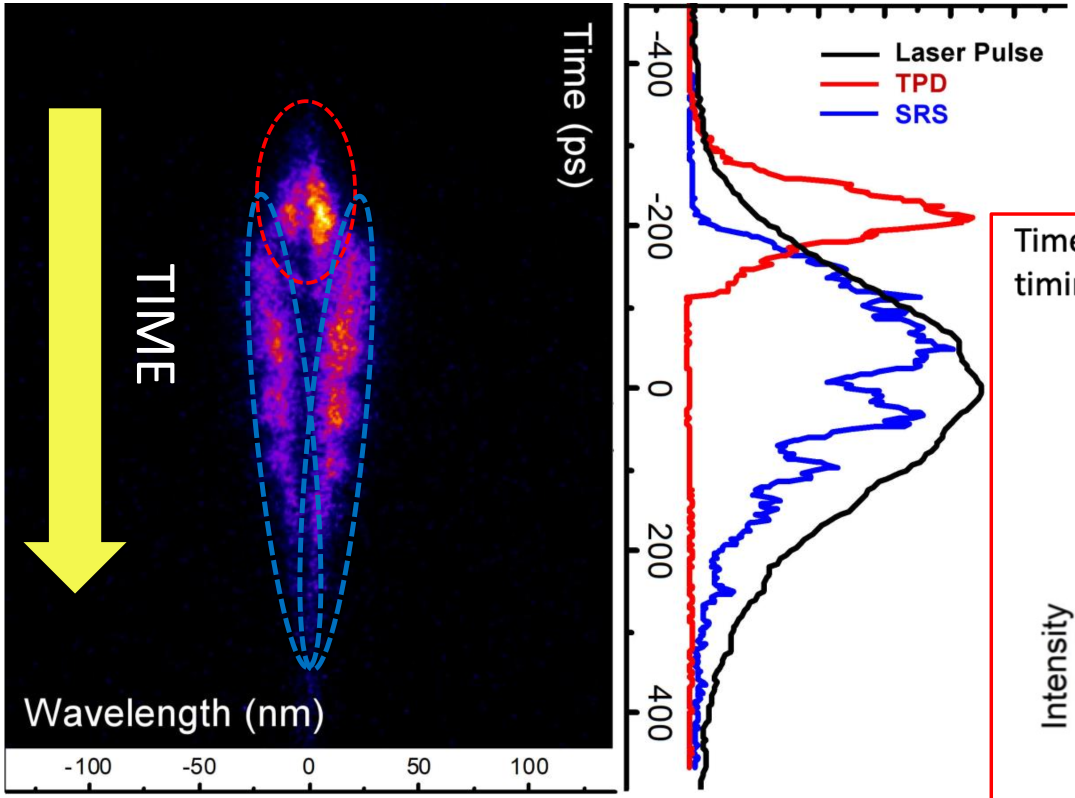
λ =1.3 μm τ = 300 ps E = 1500 J

3ω λ =0.44 μm E ≤ 500 J



Work on Parametric Instabilities and hot electrons

Timing of parametric instabilities and HE

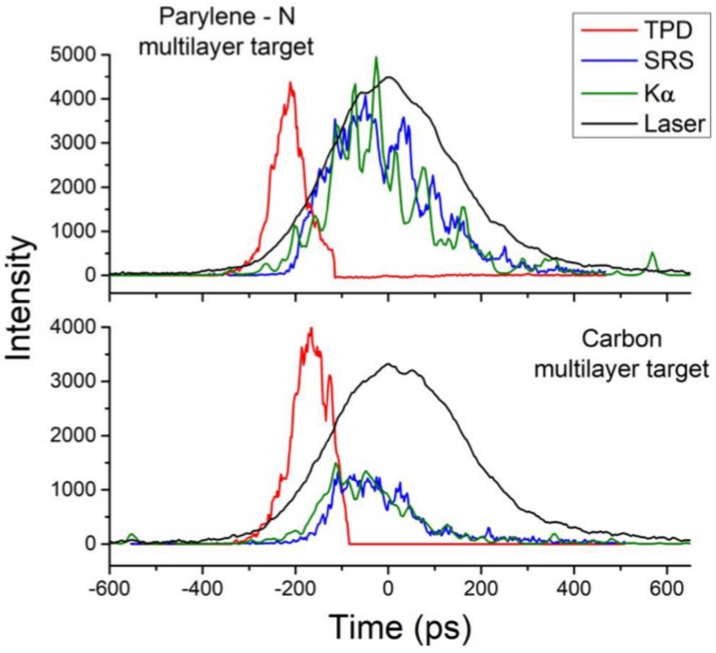


All data suggest that HE are produced by SRS

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

At high temperature (laser peak), TPD is damped

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

Approaching Shock Ignition conditions

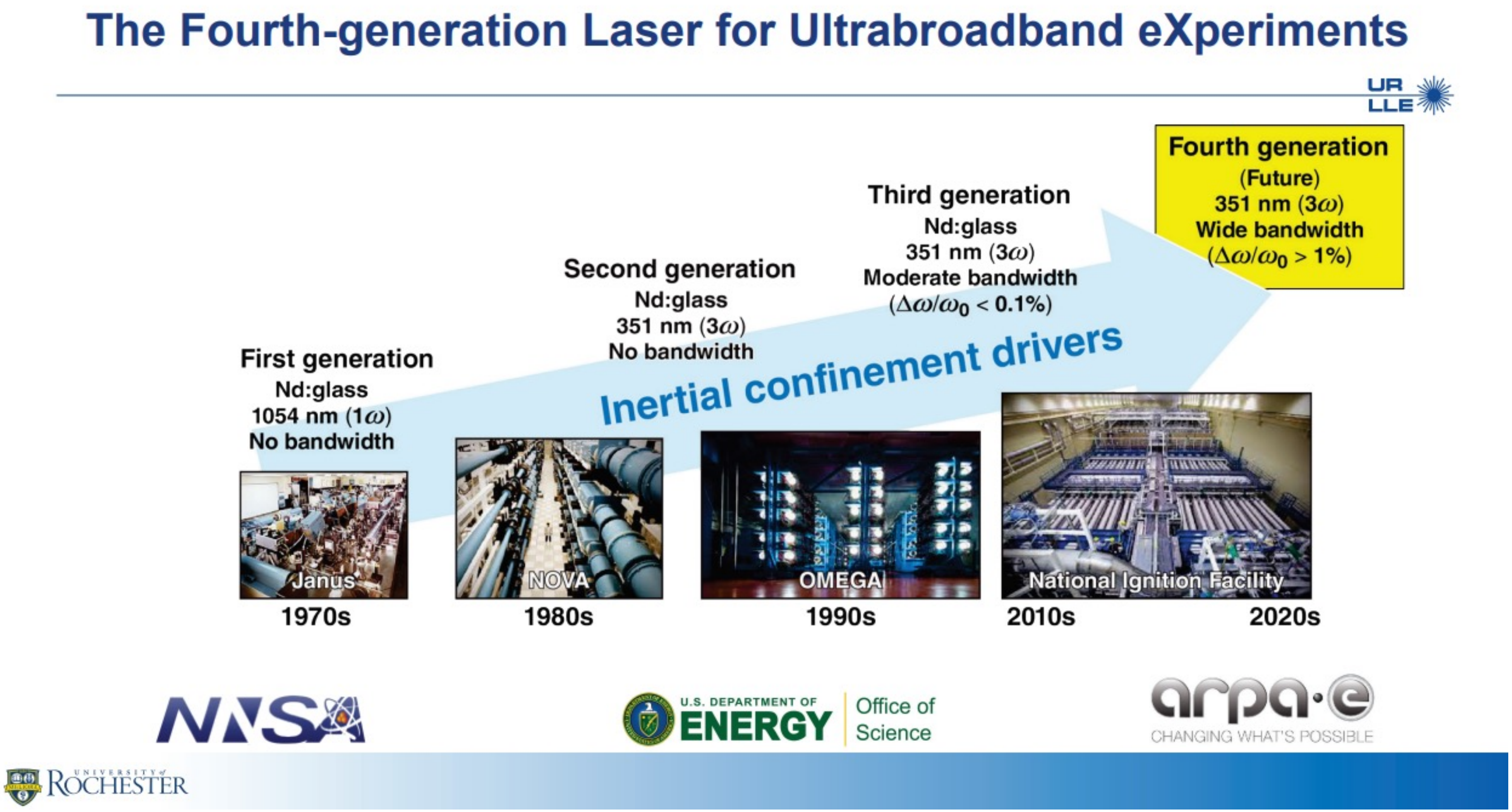
	Multi beam	**Lambda** (nm)	**Intensity** (W/cm^2)	**Iλ^2** (Wμm^2/cm^2)	**L** (μm)	**T** (keV)	**Bandwidth / Chirp**
GEKKO XII	YES	351	1.5x10^{15}	2x10^{14}	100	1-2	NO/NO
PALS	NO	438 1314	5x10^{15} 1.5x10^{16}	1x10^{15} 2.5x10^{16}	100 100	1-2 3-4	NO/NO
ELI-BL	NO	532	10^{14} - 10^{15}	3x(10^{13}-10^{14})	100	1	NO/YES
Vulcan	NO	532	1x10^{16}	3x10^{15}	400	1-2	NO/YES
LMJ	YES	351	3.5x10^{15}	4.3x10^{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

Broadband effects on LPI



The Fourth-generation Laser for Ultrabroadband eXperiments

UR LLE

First generation
Nd:glass
1054 nm (1ω)
No bandwidth

Second generation
Nd:glass
351 nm (3ω)
No bandwidth

Third generation
Nd:glass
351 nm (3ω)
Moderate bandwidth
($\Delta\omega/\omega_0 < 0.1\%$)

Fourth generation
(Future)
351 nm (3ω)
Wide bandwidth
($\Delta\omega/\omega_0 > 1\%$)

Inertial confinement drivers

Janus
1970s

NOVA
1980s

OMEGA
1990s

National Ignition Facility
2010s 2020s

NNSA

U.S. DEPARTMENT OF ENERGY | Office of Science

arpa·e
CHANGING WHAT'S POSSIBLE

UNIVERSITY of ROCHESTER

Experiments at ELI–L4 laser, Vulcan, Phelix, and in the future at the Chinese laser installation Kunwu in the Shanghai Institute of Laser Plasma ($\Delta\omega/\omega_0 \sim 0.55\%$)

Broadband effects on LPI: Vulcan experiment

LASER IRRADIATION DESIGN (PLANAR)

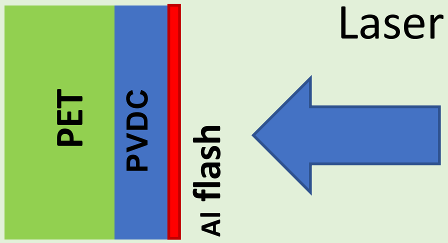
4 driver/heating beams (long beams)
E=250 J x 4, λ=1053 nm, 3 ns
FWHM=800 μm, I ≈ 3x10^{13} W/cm^2

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

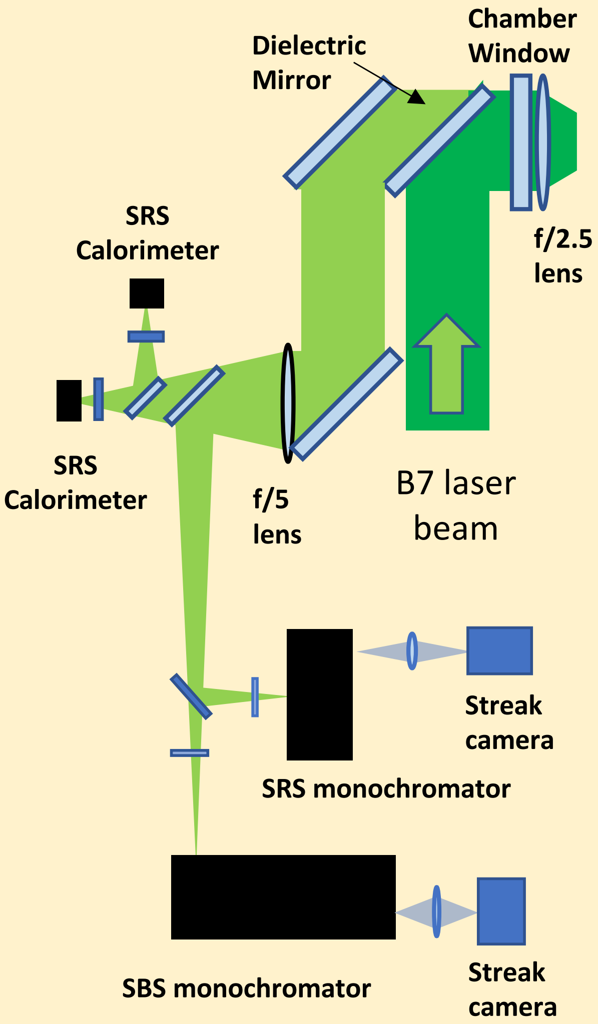
3 oscillators:

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

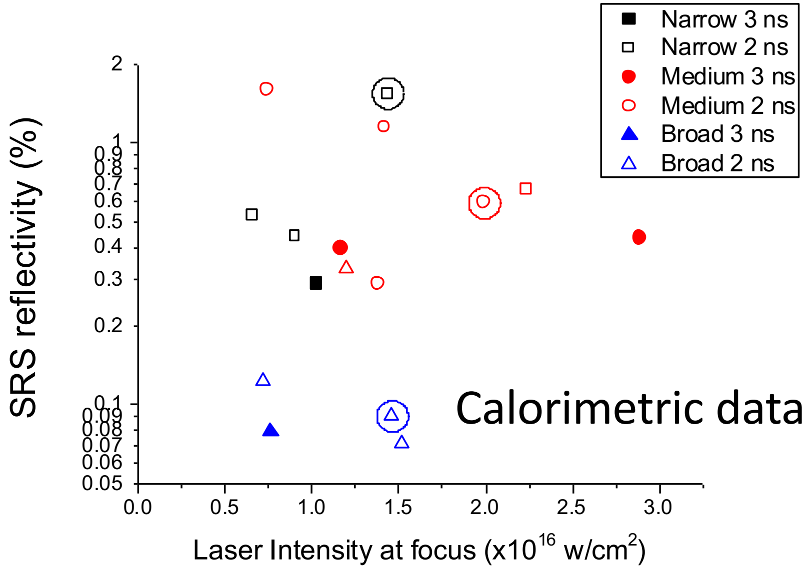


BACKSCATTERING DIAGNOSTICS

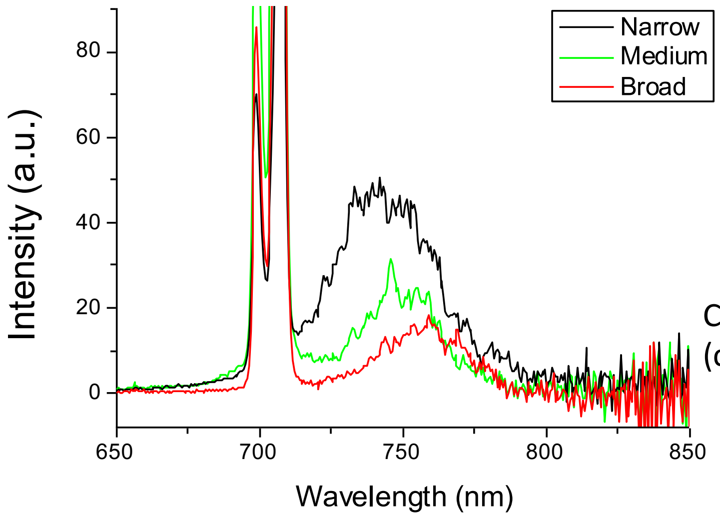


Preliminary results from Vulcan experiment

Stimulated Raman Scattering

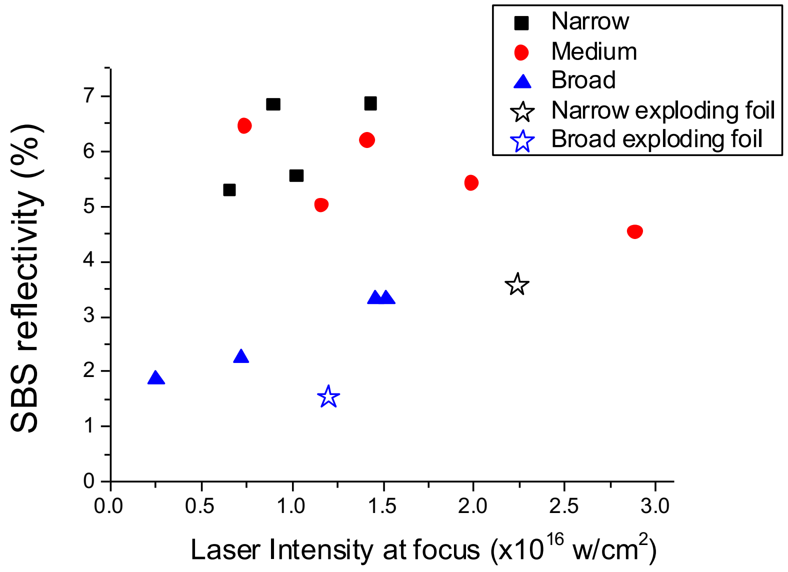


Calorimetric data



SRS spectra

Comparable shots (circles above)

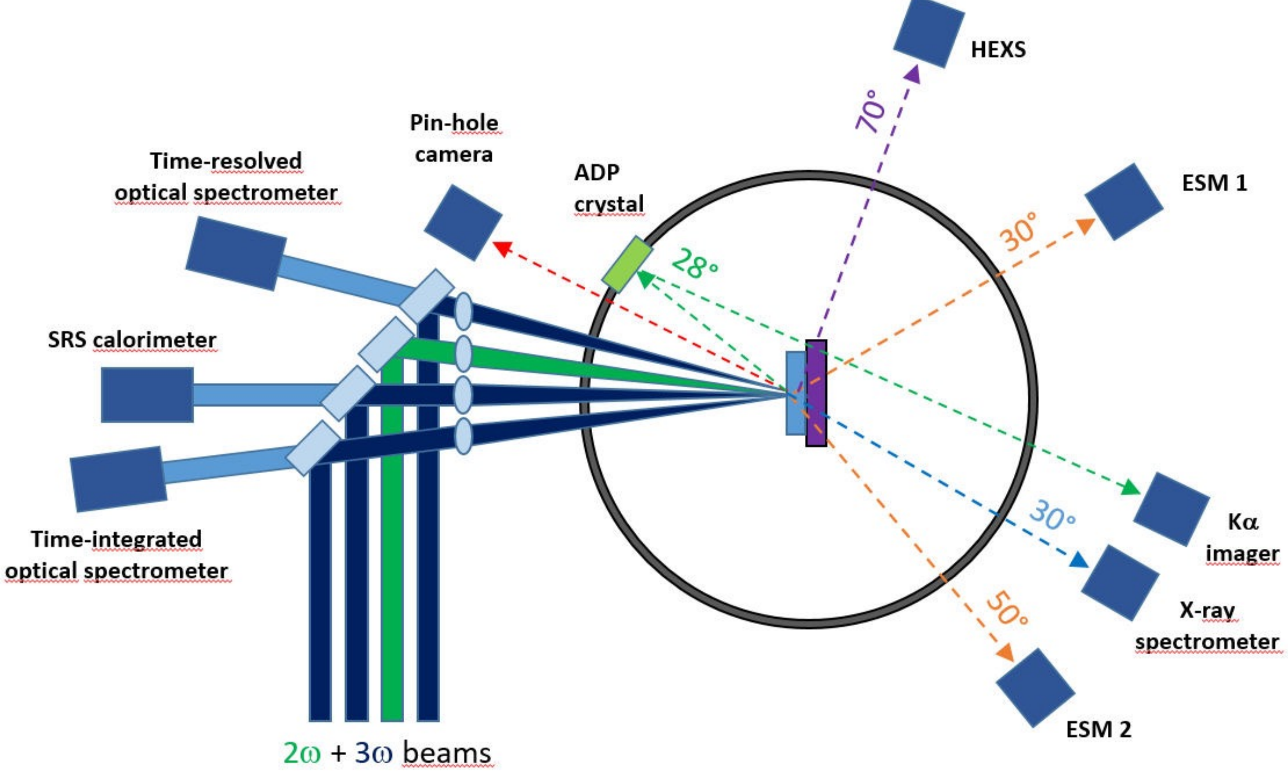


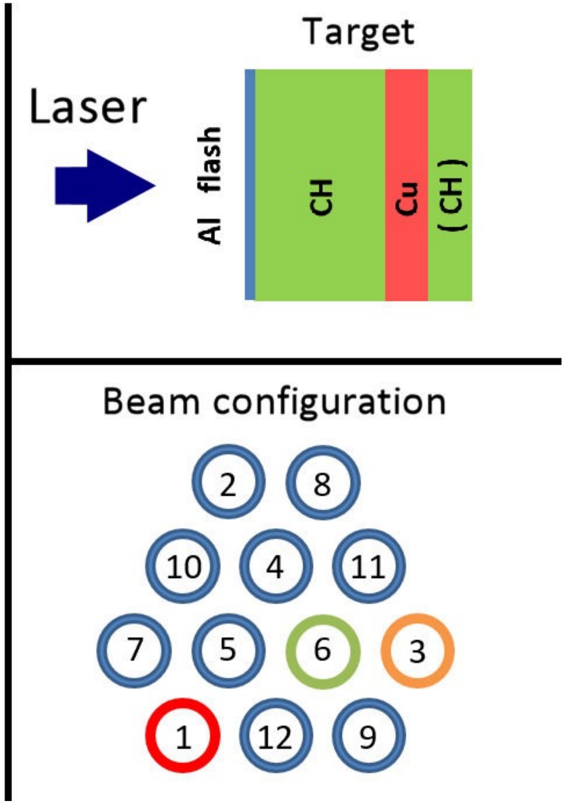
Narrowband and medium band/chirp pulses provide similar results, while large band/chirp pulses provide a fall of SRS and SBS

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





3 Heating beams @ 2ω

120 J /beam / 300 ps + KPP

FWHM spot = 850 μm

$I = 1.5 \times 10^{14}$ W/cm^2

9 interaction beams @ 3ω

80 J/beam /300 ps + RPP

FWHM/beam = 150 μm

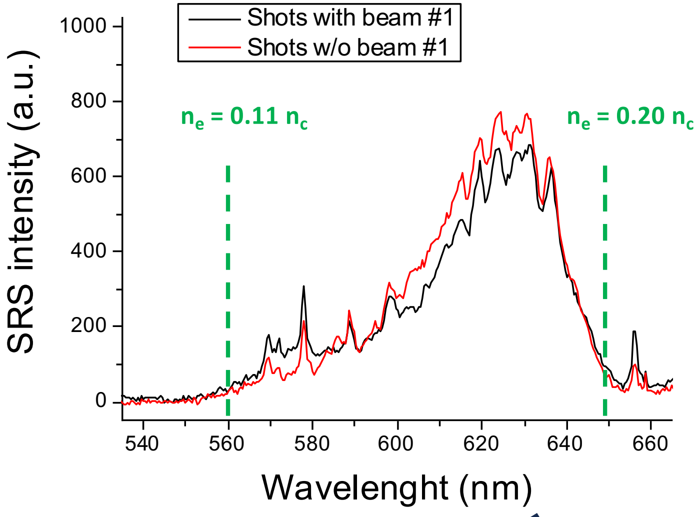
$I_{\text{beam}} = (0.7\text{-}1.2)\cdot 10^{15}$

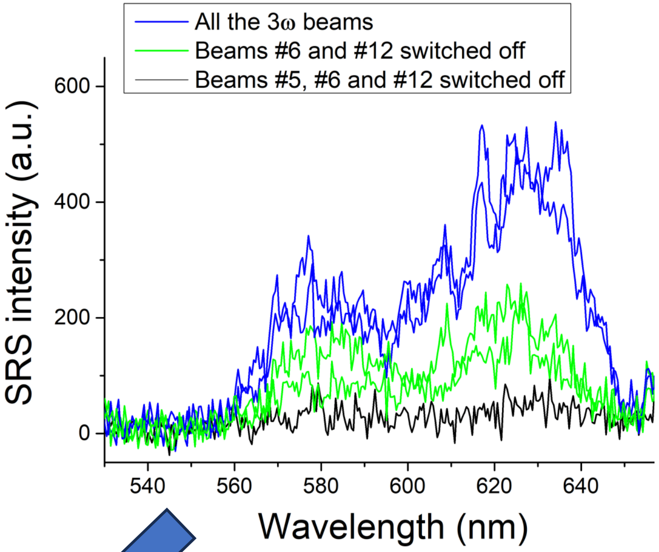
FWHM/bundle = 300 μm

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

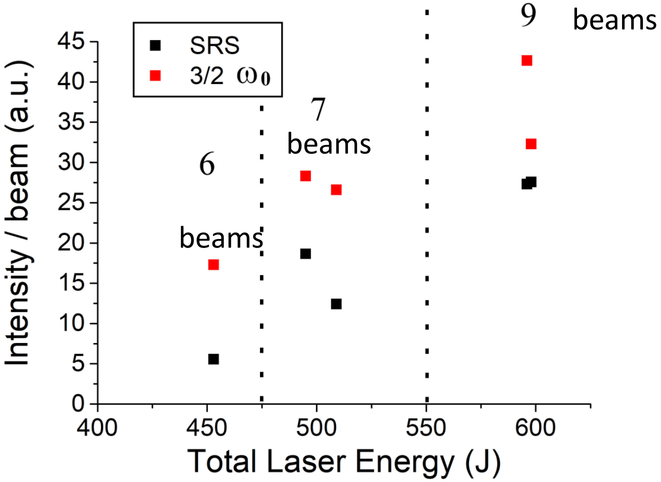
$I\lambda^2 = (1\text{-}3)\cdot 10^{14}$ W μm^2/cm^2

Multibeam effects - SRS





Intensity of SRS and TPD divided per the number of laser beams



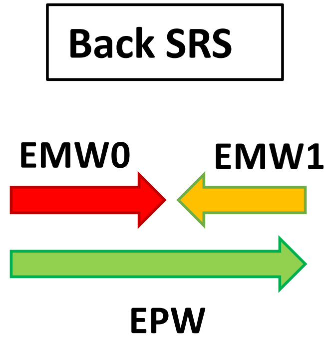
Spectrometer located behind the last mirror of beam #1

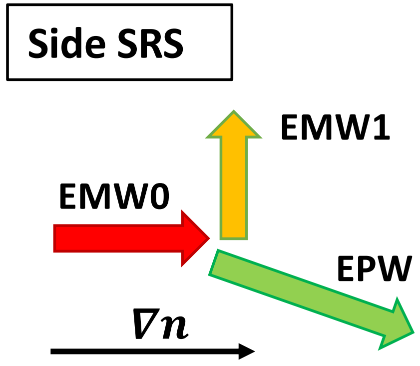
SRS scattered light is not purely backscattered but affected by other laser beams

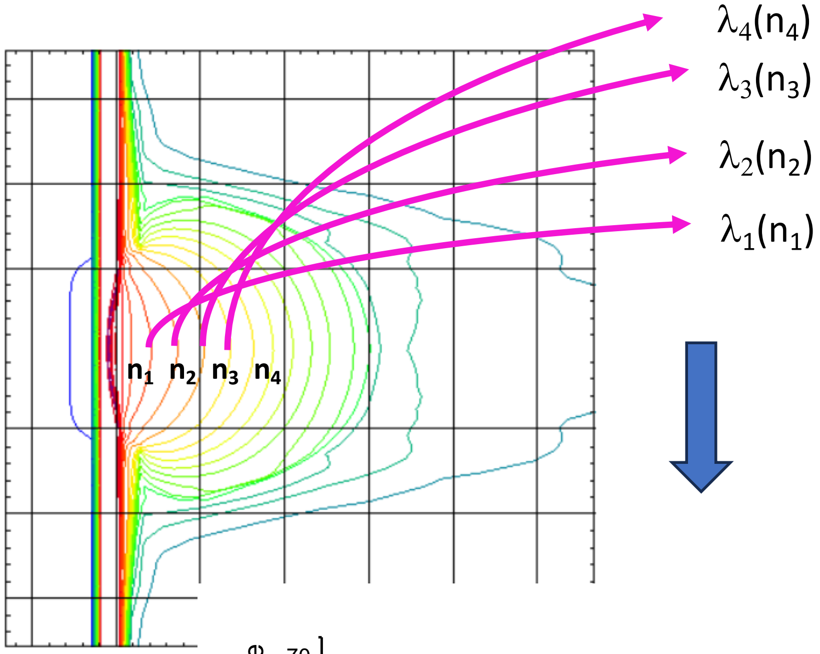
Both SRS and 3/2ω intensity scales with overall energy/intensity and not with single beam intensity.

These results are an evidence of collective growth of SRS and TPD

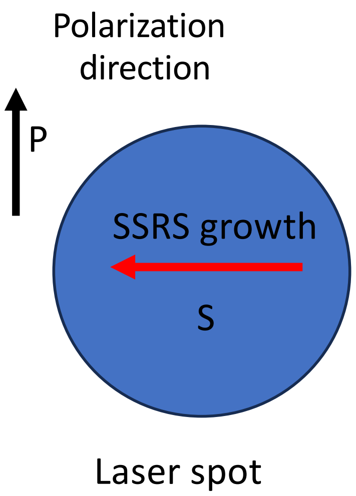
Impact of Side SRS

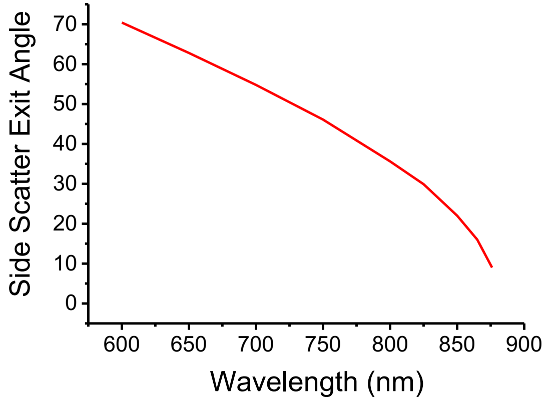






- The exit angle depends only on the density where SSRS is driven and on the density profile
- Light preferentially scattered in the S plane
- SSRS grows more strongly along the spot in the S-direction
- SSRS growth can be limited by the spot size or the density scalelength





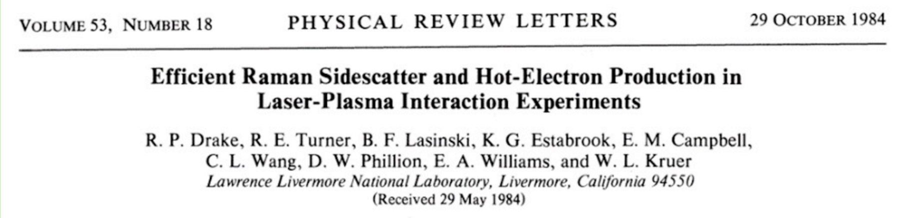
Impact of Side SRS

Early studied in the 70s: SSRS can have a dramatic impact on ICF performance

Very few observations in the 80s

Drake, PRL 53, 1739, 1984; Phy. Fluids, 31, 3130, 1988; Phys. Fluids B 1, 1082, 1989

I = 10^{14} – $2\mathrm{x}10^{16}$ W/cm^2 no RPP $E_{SRSS} \approx 1/2\ E_{BRS}$



VOLUME 53, NUMBER 18 PHYSICAL REVIEW LETTERS 29 OCTOBER 1984

Efficient Raman Sidescatter and Hot-Electron Production in Laser-Plasma Interaction Experiments

R. P. Drake, R. E. Turner, B. F. Lasinski, K. G. Estabrook, E. M. Campbell, C. L. Wang, D. W. Phillion, E. A. Williams, and W. L. Kruer

Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 29 May 1984)

No more investigation

Why few observations ?

Observation limited by collisional absorption of scattered light

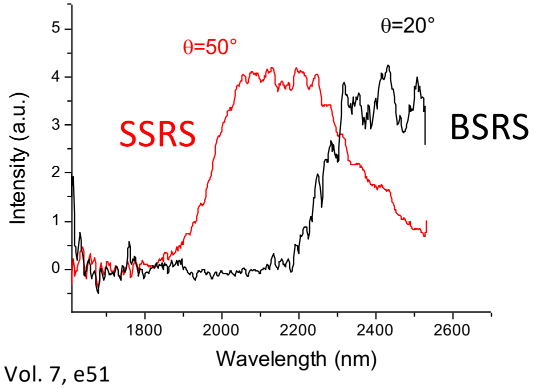
Intrinsic difficulty to measure and quantify light scattered in the whole solid angle

Recent experiments at Omega and NIF identify SSRS to be relevant and maybe dominant

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

TODAY

Our experiment at PALS in 2019



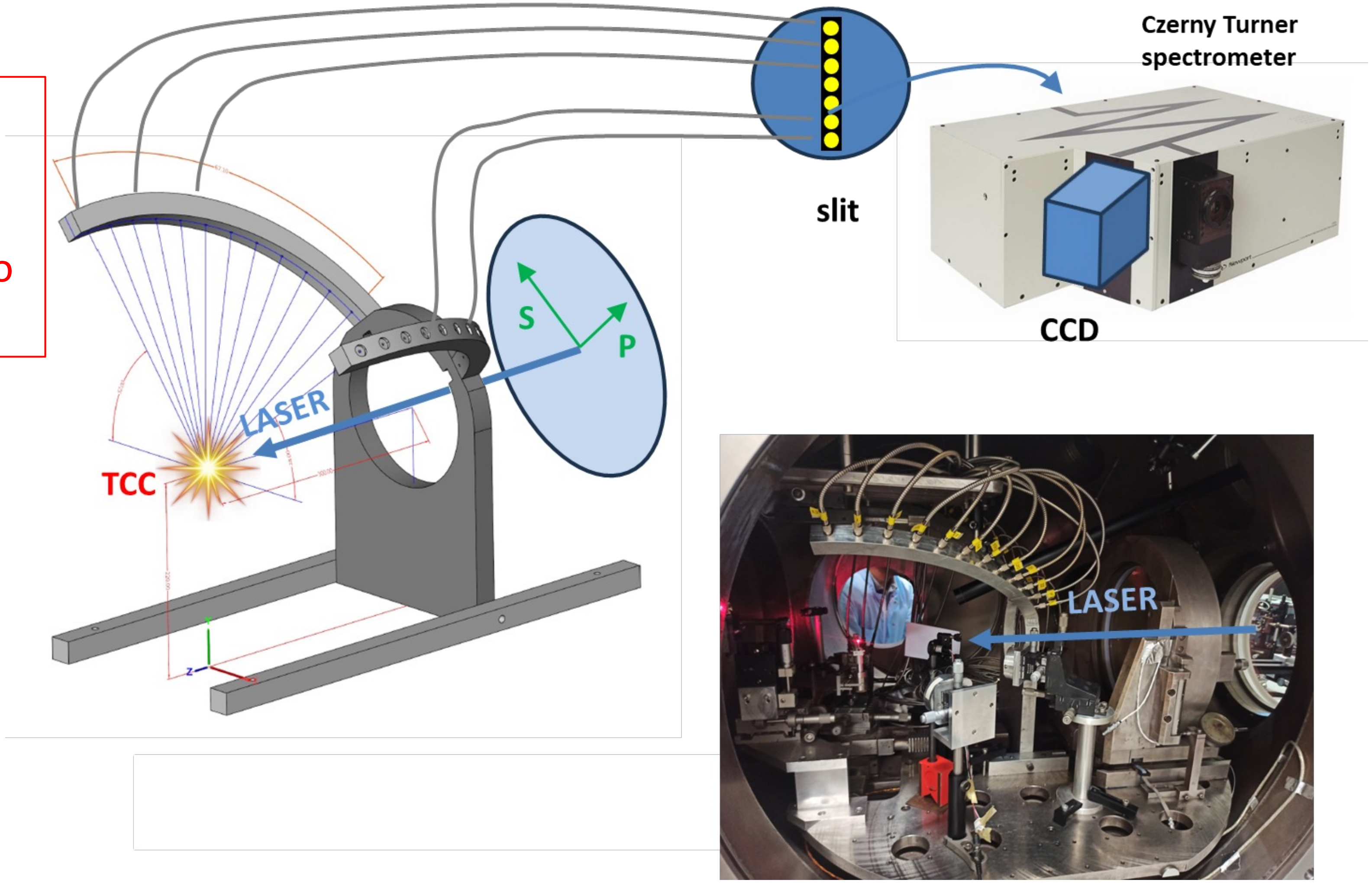
G. Cristoforetti et al., HPLSE, (2019), Vol. 7, e51

Side SRS: PALS 2023 experiment

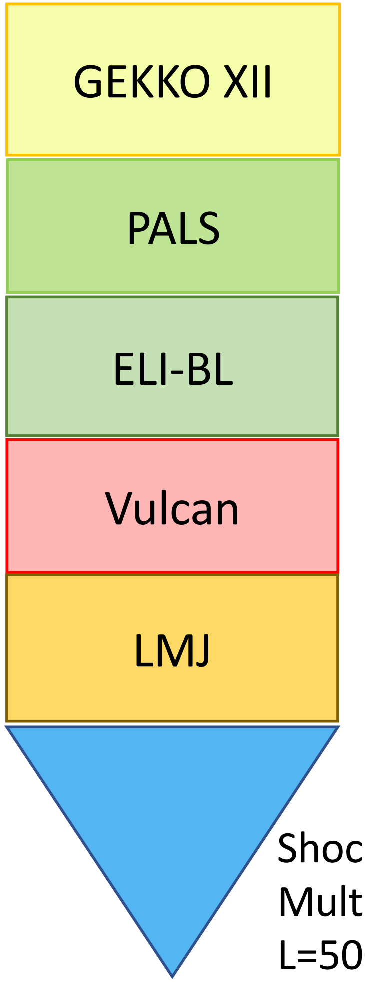
G. Cristoforetti, S. Agarwal, D.Batani, M. Cervenak, P. Devi, R. Dudzak, D. Ettel, P. Gajdos, K. Glize, E. Hume, S. Jelinek, L. Juha, P.Koester, M. Krupka, M. Krus, H. Larreur, G. Malka, D. Mancelli, A. Morace, P. Nicolai, O. Renner, D. Singapulli, S. Singh, M. Tatarakis, Y. Wang, N. Woolsey, X. Zhao,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

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)



Approaching Shock Ignition conditions



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

G. Cristoforetti et al., Euro Phys. Lett., 117, 35001, 2017
G. Cristoforetti et al., Phys. Plasmas 25, 012702, 2018
D. Batani et al., Nucl. Fusion, 59, 032012, 2019
G. Cristoforetti et al., HPLSE, (2019), Vol. 7, e51
S. Baton et al., High Energy Density Physics 36, 100796, 2020
P. Koester et al., Review of Scientific Instruments 92, 013501, 2021
G. Cristoforetti et al., HPLSE, (2021), Vol. 9, e60
T. Tamagawa et al., Rev. Sci. Instrum., 93, 063505, 2022
G. Cristoforetti et al., HPLSE, Vol. 11, e24, 2023
K Kawasaki, Phys. Rev. Research 5, 033051, 2023
F. Wasser et al., *Rev. Sci. Instrum.* 94, 093503, 2023
E. Filippov et al., MRE 8 (6), 065602, 2023
G. Cristoforetti et al, Sci. Rep., 13, 20681, 2023
F. Wasser et al., *Phys. Plasmas* 31, 022107, 2024

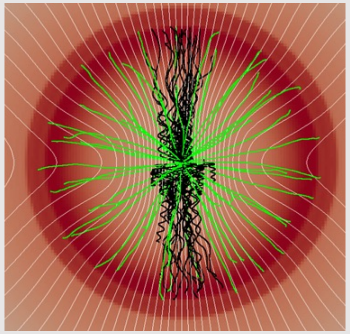
Different facilities can be used to investigate the role of different parameters

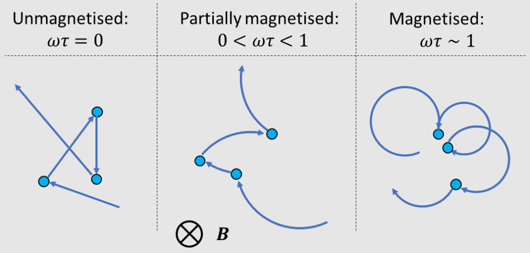
Lack of dedicated facility in Europe

Design of Magneto-Inertial Fusion Experiments

Magnetised ICF

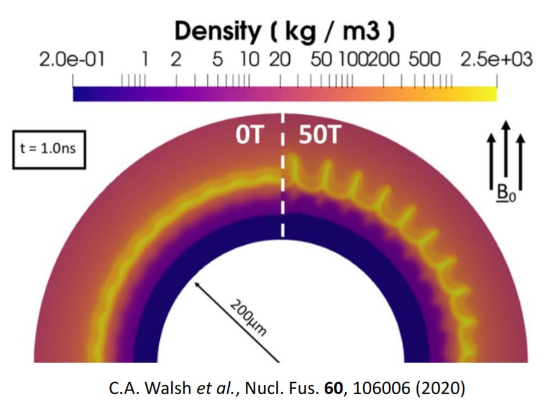
***Magnetised** & **Unmagnetized** α trajectories*





Magnetization reduces thermal conduction losses from the hotspot.

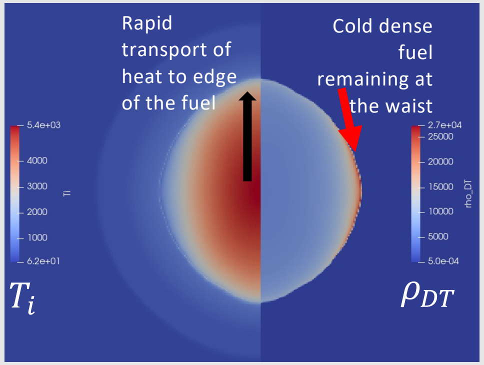
Magnetised Direct Drive



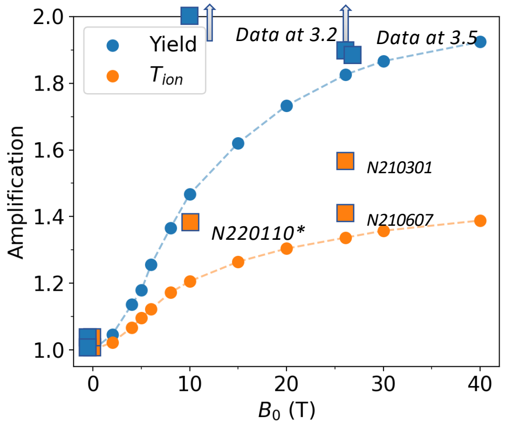
C.A. Walsh *et al.*, Nucl. Fus. **60**, 106006 (2020)

Enhanced ablation surface instability growth at poles of the capsule.

Magnetised Indirect Drive



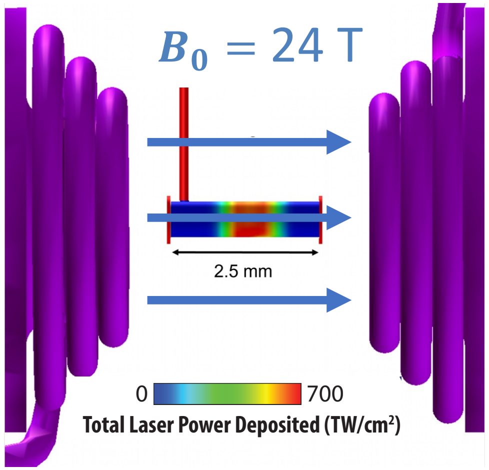
Hotspot thermal conduction suppressed along waist leading to elongated hotspot



Up to 2 times yield enhancement from initial 40T field predicted.

Experiment at OMEGA

Seed B-field driven externally by a **capacitor bank discharge** (stable over ~μs)

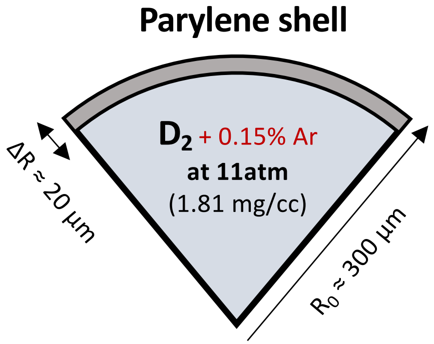


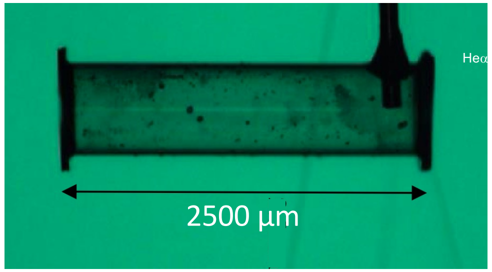
Laser drive: 40 UV beams, 1.5 ns, total energy of 14.5 kJ, > 5x10^{14} W/cm^2 across 650 μm

Implosions at OMEGA with seed B-fields

Experimental setup

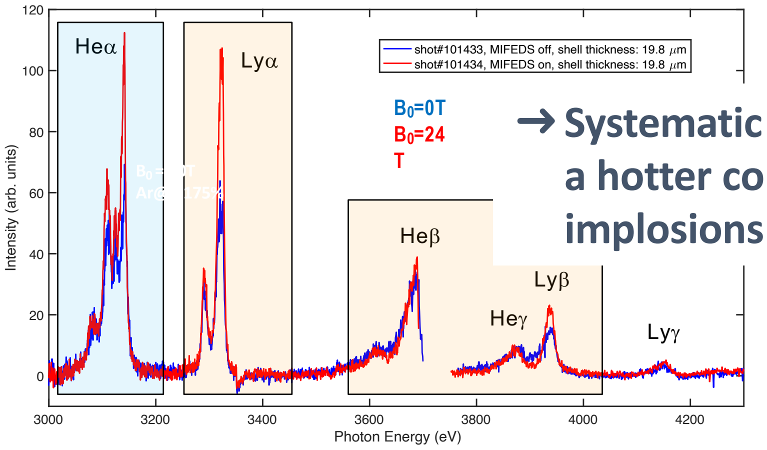
Cylindric plastic shells filled with D_2 at 11 atm with 0.15% atomic concentration of Ar doping for spectroscopic tracing





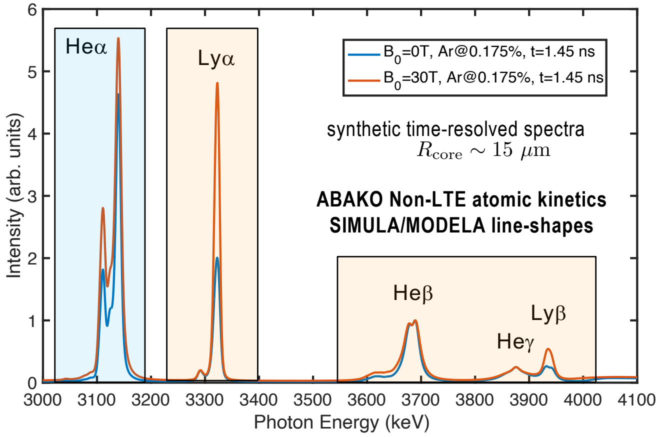
Ar K-shell spectra characterize core plasma conditions

Experimental time-integrated Ar K-shell emission



→ **Systematic intensity ratios suggest a hotter core for the magnetized implosions**

Modelled Ar K-shell emission

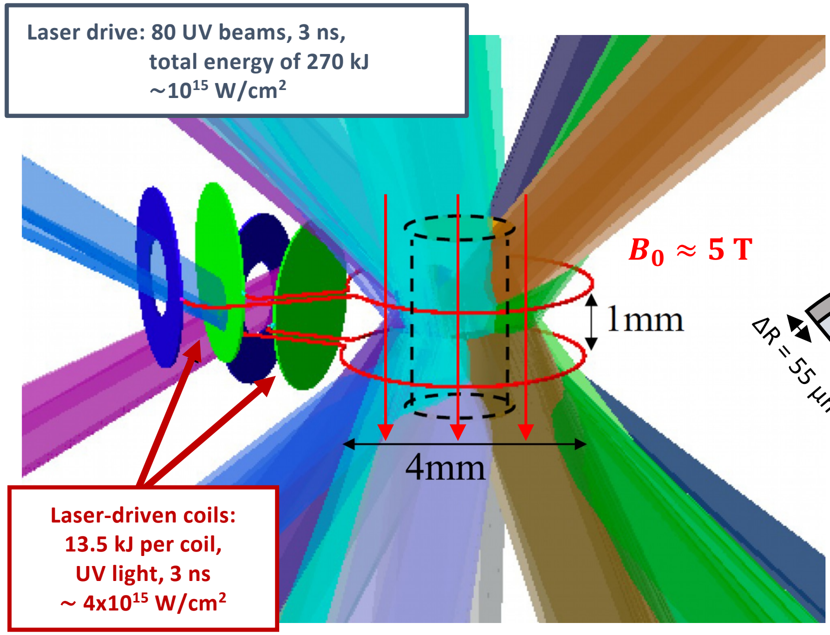


→ **Observations qualitatively predicted by synthetic spectra simulations**

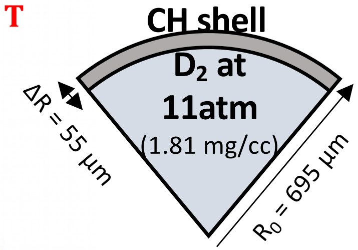
Extension to LMJ with 20x higher drive energy

Setup at LMJ *– shots scheduled in 2024 - 2026*

Laser drive: 80 UV beams, 3 ns, total energy of 270 kJ ~10^{15} W/cm^2



Laser-driven coils: 13.5 kJ per coil, UV light, 3 ns ~ 4x10^{15} W/cm^2

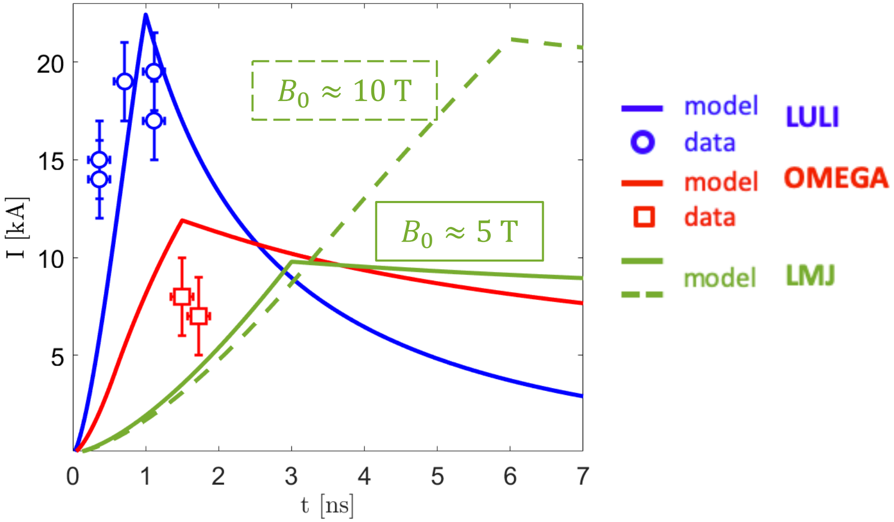


Compared to OMEGA :

- 20x more laser-drive energy
- 2.3x larger targets

→ **Greater compression ratio and larger core**

Current evolution in laser-driven coils from ***<u>model</u>*** *(curves)* ***and <u>benchmarking data</u> from preparatory experiments*** *(symbols)*



G.Pérez-Callejo et al., Phys. Rev. E, 106, 035206 (2022)

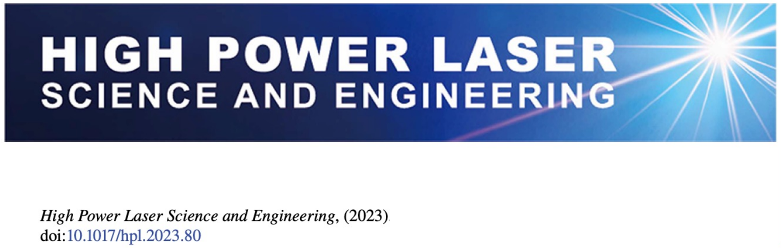
- External pulsed power for B-field unavailable at LMJ
  - **Alternative use of laser-driven coils with predicted seed B-field in the 5 to 10 T range**
- Preliminary shots done in 2022 to characterize magnetic field generation

Plan of Presentation

- The Project
- Examples of performed work
- The HiPER+ proposal

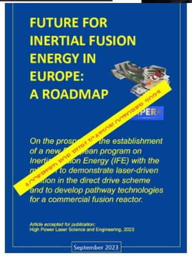
HIPER+ initiative

- In September 2021 a group of scientist started the **HiPER+** Initiative
- Today HiPER+ group is composed by a nucleus of 15 scientist supported by more than 100 scientists from EU.



HIGH POWER LASER
SCIENCE AND ENGINEERING

High Power Laser Science and Engineering, (2023)
doi:10.1017/hpl.2023.80

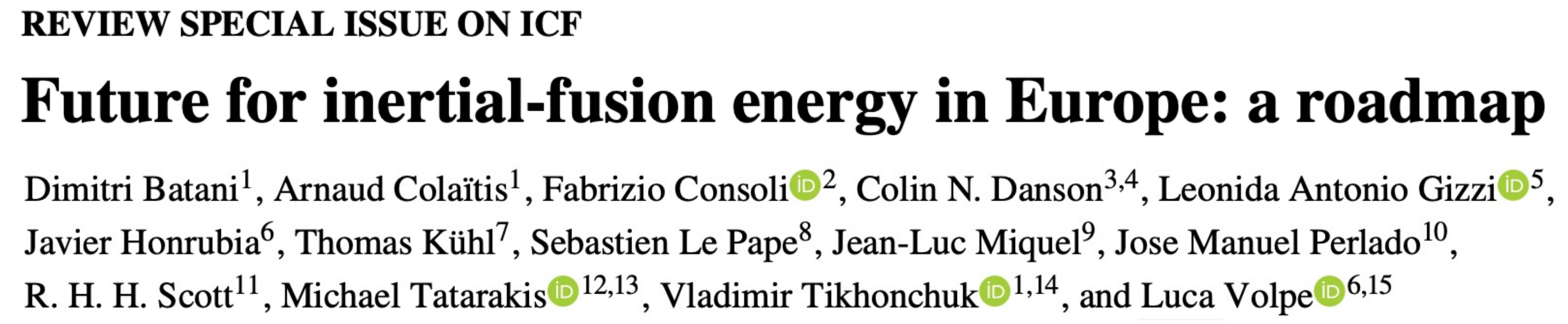


FUTURE FOR
INERTIAL FUSION
ENERGY IN
EUROPE:
A ROADMAP

On the prosp[illegible] the establishment of a new E[illegible]pean program on Inerti[illegible]sion Energy (IFE) with the mi[illegible] to demonstrate laser-driven [illegible]ition in the direct drive scheme and to develop pathway technologies for a commercial fusion reactor.

Article accepted for publication:
High Power Laser Science and Engineering, 2023

September 2023



REVIEW SPECIAL ISSUE ON ICF

Future for inertial-fusion energy in Europe: a roadmap

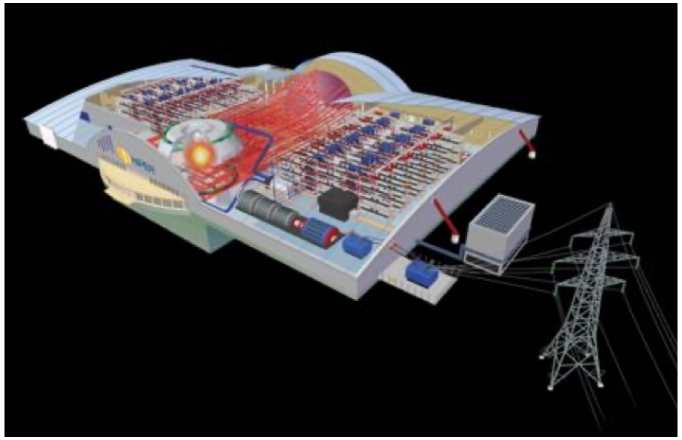
Dimitri Batani[1], Arnaud Colaïtis[1], Fabrizio Consoli[2], Colin N. Danson[3,4], Leonida Antonio Gizzi[5], Javier Honrubia[6], Thomas Kühl[7], Sebastien Le Pape[8], Jean-Luc Miquel[9], Jose Manuel Perlado[10], R. H. H. Scott[11], Michael Tatarakis[12,13], Vladimir Tikhonchuk[1,14], and Luca Volpe[6,15]

On what we build: The EU IFE community

2005-2014 European Project “HIPER” (High Power Laser Energy Research Facility)

European Strategy Forum on Research Infrastructures
ESFRI

EUROPEAN ROADMAP FOR RESEARCH INFRASTRUCTURES
Report 2006



HiPER

HiPER, conceived as a large-scale laser system designed to demonstrate significant energy production form ICF, was listed on the ESFRI large scale facility roadmap and awarded preparatory phase funding (~2 M€) by the EU with additional funding from STFC, UK, and the Ministry of Education, Czech Republic, and work in-kind from many other partners

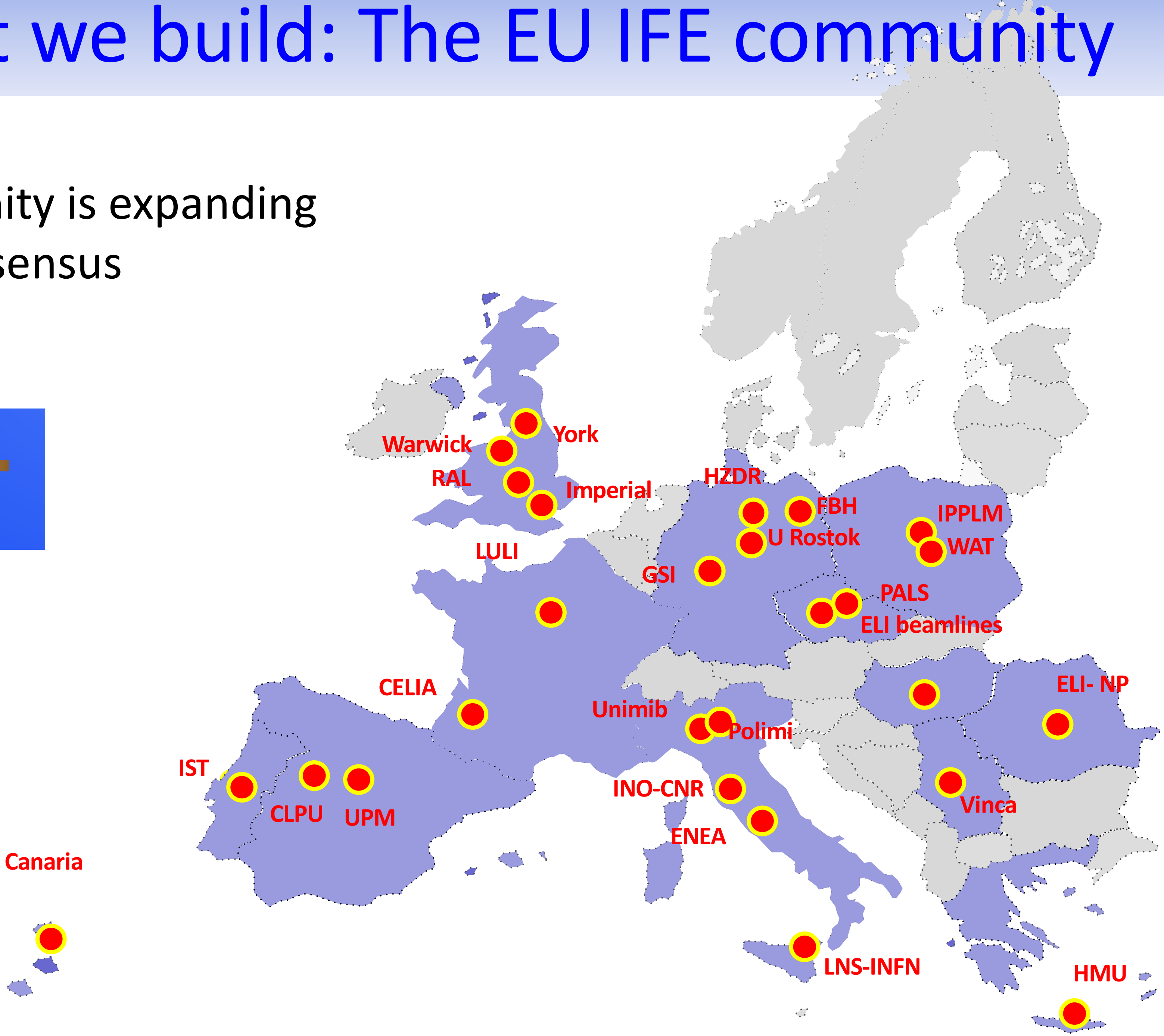
The project was based on the assumption that NIF would ignite during the National ignition Campaign (2009-2012)

www.hiper-laser.org

On what we build: The EU IFE community

HiPER+ community is expanding and gaining consensus

HiPER+
EUROPEAN LASER FUSION ENERGY



HiPER+ timeline

3 major steps of 10 years each: produce knowledge, build the machine, produce and analyze results for the technology transfer

Years 1-10	Years 11-20	Years 21-30
R&D	**Pilot IFE reactor**	**DEMO-IFE reactor**

Synergies with companies and national projects can somewhat accelerate this time scale…

Major axes of research & technology development

- **A: physics & technology for IFE**
- **B: development of IFE laser technology**
- **C: material science & reactor technology**
- **D: development of community, coordination & management**

Next steps: Applications for MSCA Doctoral network, COST Actions, Europena Innovation Council, ERC Synergy Grants, finally proposal to be submitted to ESFRI

For comparison:
NIF high gain expected in 2028   (G~20 ?)
LMJ full operation at 1.3 MJ expected in 2027
First plasma in ITER expected not before ~2025 (?)

Important "side" activities from our network

Strong activity on summer schools

- *"Plasmas in Superstrong Fields" Erice, Sicily, July 2022*
- *LaPlaSS "Experimental methods in high-intensity laser-plasma processes"*
  Salamanca, Spain, September 2020
- *LaPlaSS "High-intensity laser-plasma processes for laser fusion and related applications"*
  Salamanca, Spain, September 2023
- *Intensive School on Laser, Plasma and Fusion, Rethymno, Crete, September 2024*

Collaboration with the Coordinated Research Project of IAEA on "Pathways to Inertial Fusion Energy"

Collaboration in organizing the ELI "Laser-induced Fusion Meeting" Prague, 28-29 November 2023

Collaboration with the LASERLAB expert groups on "Micro- and nano-structured materials for experiments with high-power lasers" and on "Inertial Confinement Fusion / Inertial Fusion Energy"

Collaboration with the (approved) COST project ProBoNo «PROton BOron Nuclear fusion: from energy production to medical applicatiOns"

Attention to the new "industrial environment" for Nuclear Fusion

Thank you for your attention !