Collisionless shocks in the laboratory

A focus on collisionless shocks generated by high power lasers

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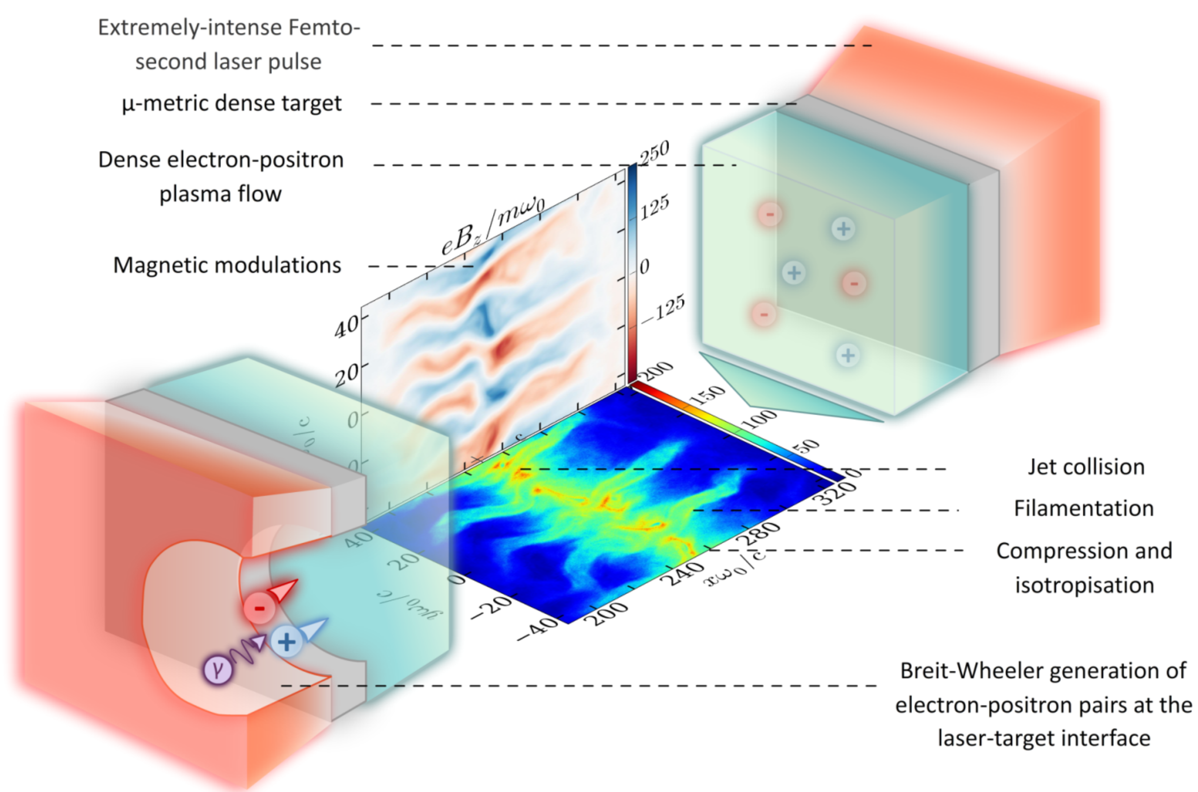

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Outline

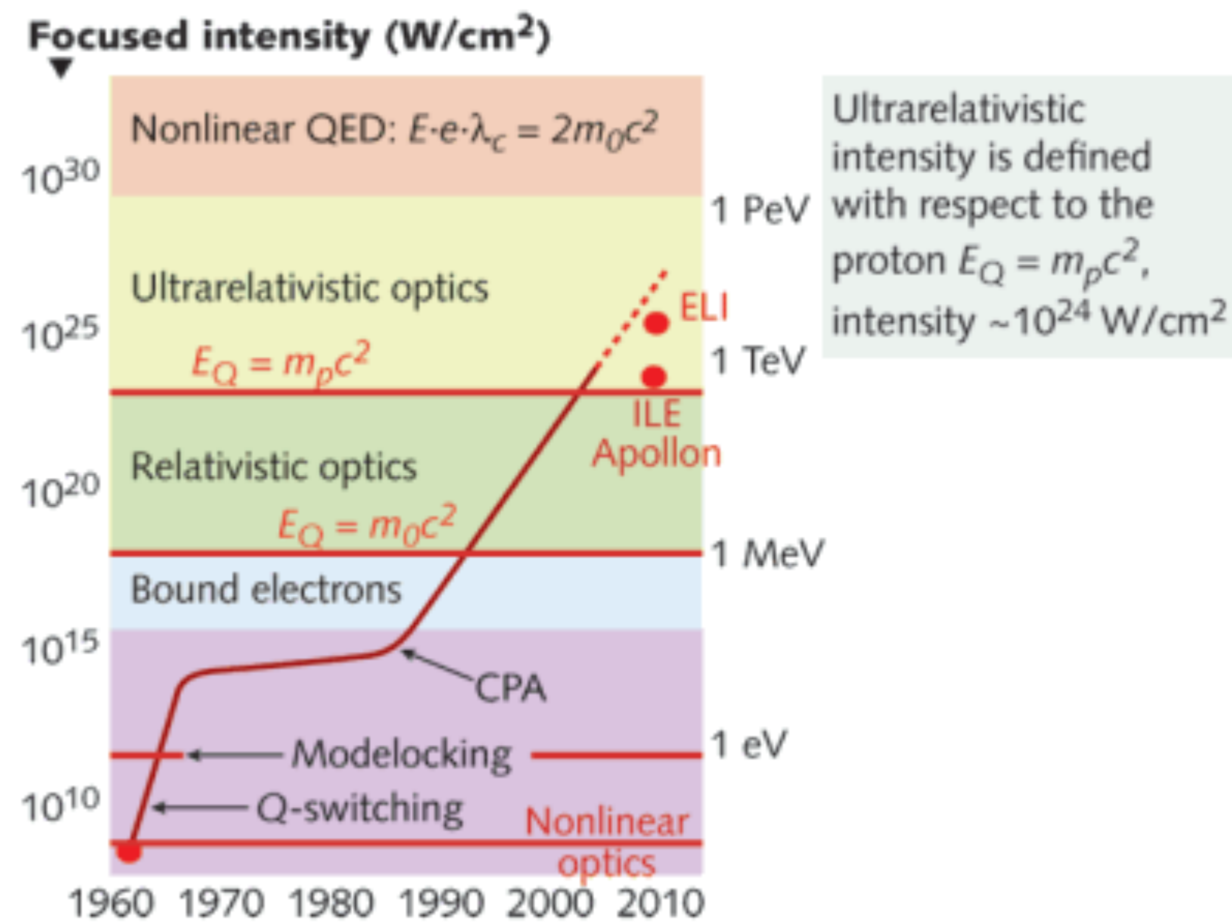
- High power laser systems and applications
- Experimental studies of collisionless shocks of interest for astrophysics
- Collision of plasmas in an external magnetic field as a platform to study magnetized collisionless shocks
- Collisionless shocks in electron-positron plasmas using extreme-light laser pulses
- Conclusions and perspectives

A brief history of lasers for controlled fusion From 1962 to the present day

- **1960s:** first proposals and first experiments (USA, France, Russia)
- **1970s:** de-classification in 1971 and first steps of systematic research, multibeam lasers (Janus, Shivas, Kalmar), neutrons (1968, 10^{13} in 1988), compression (20 g/cc in 1979, 600 g/cc in 1991). Understanding of physical and technical problems (instabilities, transport)
- **1980s:** progress in power and energy: transition from CO_2 (Helios) to 3ω Nd (Nova, Phébus, Vulcan, Gekko), excimer lasers, CPA lasers
- **1990s:** instability control, smoothing, large NIF and LMJ projects, Omega laser, first PW laser, Centurion program (indirect attack), acceleration of particles
- **2000s:** NIF and LMJ lasers, new ignition schemes, applications outside the FCI (accelerators, radiography, medicine, astrophysics), new projects (ELI, HiPER)
- **2009:** construction of NIF is completed
- **After 2010:** multiplication of PW systems (Berkeley, GIST, CLPU, HZDR, INRS…)
- **2014:** construction of LMJ is completed
- **2017:** ARC and PETAL will operate
- **2018:** Apollon and ELI first experiments

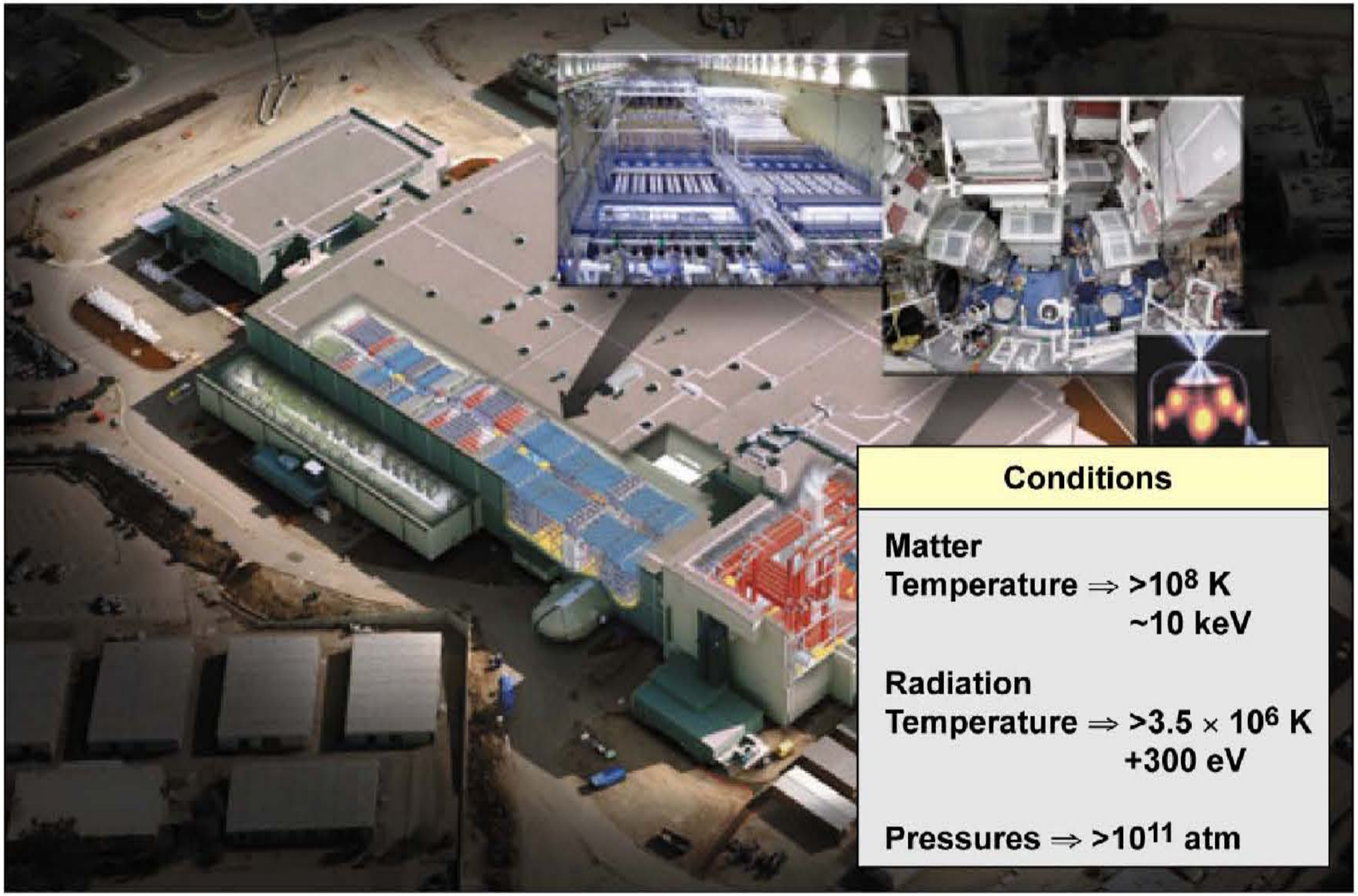
High power laser facilities in the world

- USA: Livermore (LLNL), Los Alamos (LANL), Rochester (LLE), Berkeley, UT, Michigan
- UK: Didcot (Rutherford lab), Aldermaston (AWE)
- France: CEA (CESTA, Saclay), Ecole Polytechnique (LULI, LOA), CELIA
- Germany: Garching, Jena, Munich, Dresden, Dusseldorf
- Czech Republic: PALS
- Japon: Osaka (ILE), Kyoto (JAERI)
- South Korea: GIST
- Russia: Moscou (Lebedev, MEPHI), Arsamas
- China: Pekin, Shanghai



The National Ignition Facility concentrates all the energy in a football stadium-sized facility into a mm^3

The National Ignition Facility

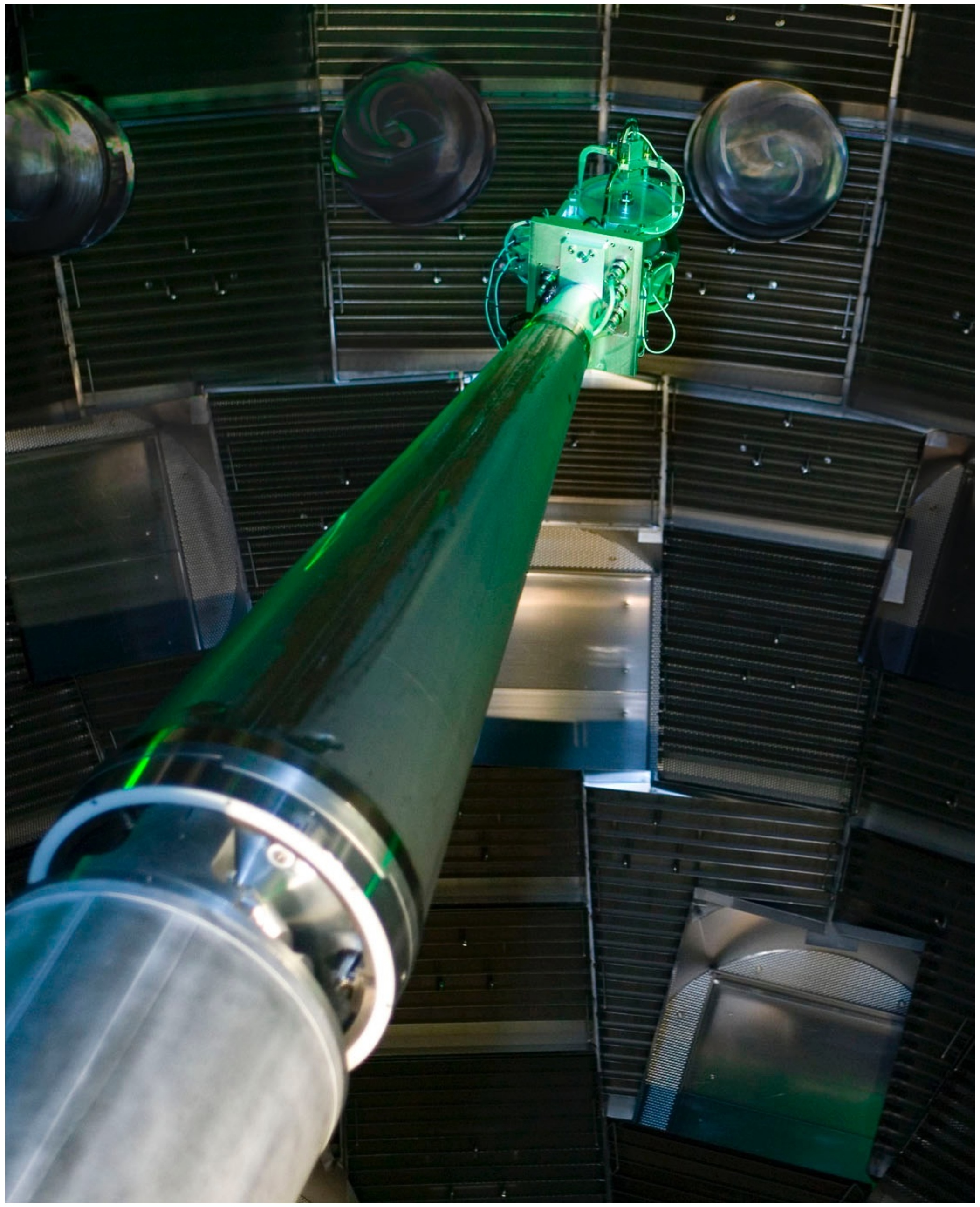


Conditions
Matter Temperature ⇒ >10^8 K ~10 keV
Radiation Temperature ⇒ >3.5×10^6 K +300 eV
Pressures ⇒ >10^{11} atm

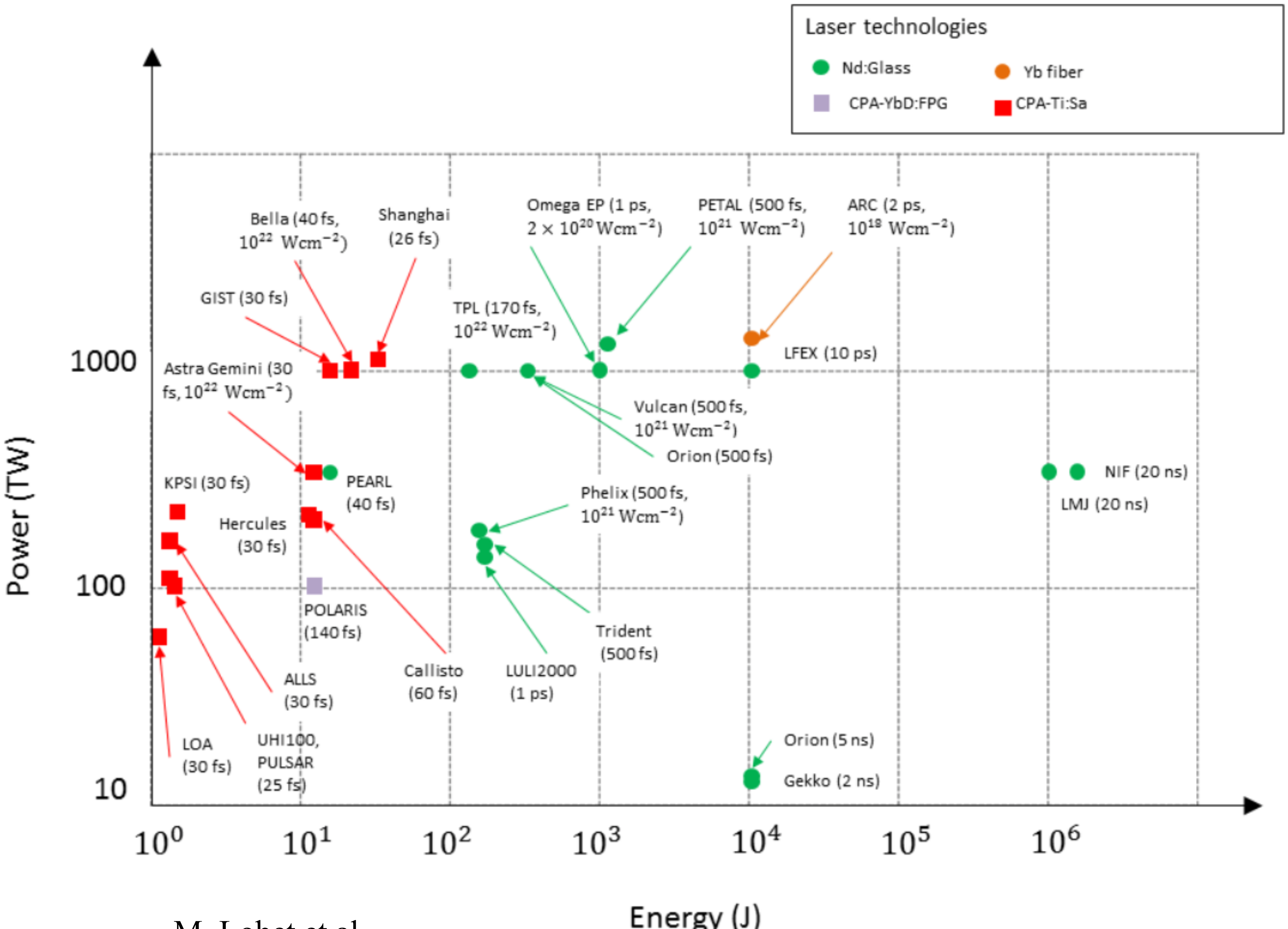
March 2009 : 192 beams delivered 1.1 MJ in 3w

Photos from NIF: interaction chamber

https://lasers.llnl.gov/multimedia/photo_gallery



Laser facilities of power above 100 terawatts (TW) in the world as a function of their power and energy



M. Lobet et al.

Plasma parameters in high power laser experiments

Velocities: 100-1000 km/s (high energy facilities), 0.1-0.3 c (high intensity facilities)

Magnetic fields: up to 100 T with non explosive coils, ~kT with laser assisted B field generation

Densities: 10^{17} cm^{-3} to 10^{24} cm^{-3} (in ICF experiments)

Temperatures: eV to 100s of eV, MeV supra thermal populations can be obtained

Maximum energies in high intensity experiments: 6 GeV for electrons (laser-wakefield acceleration), ~100 MeV for protons and GeV C ions (with thin solid foils)

Most plasma processes can be scaled from the laboratory to other contexts using scaling laws and plasma parameters (Debye length, plasma frequency, magnetization, Mach number, Alfven Mach number, Larmor radius…).

LAPD
UCLA

	Exp. 1	Exp. 2
E_0 (J)	1	20
I_0 (W/cm^2)	0.6×10^{11}	4.7×10^{11}
Piston ions	C^{+4}	C^{+4}
Ambient ions	He^{+1}	H^{+1}
v_0 (km/s)	150	410
B_0 (G)	600	275
n_a (cm^{-3})	2×10^{12}	2×10^{12}
D_0 (cm)	40	35
M_A	0.3	1.0
λ_{ii}/D_0	>100	>100
ρ_p/R_m	0.8	1.6
ρ_a/R_*	0.8	0.8
ρ_i/D_0	0.3	1.3

JLF-Titan
LLNL

Early Time	B = 20 T	B = 500 T	
P, Thermal	4×10^{10}	4×10^{10}	Pa
P, Magnetic	2×10^{8}	1×10^{11}	Pa
Beta	4×10^{-3}	2.4	
Ion r_L	13000	520	μm
Electron r_L	75	3	μm
Mid Time			
P, Thermal	1×10^{9}	1×10^{9}	Pa
P, Magnetic	2×10^{8}	1×10^{11}	Pa
Beta	1×10^{-1}	68	
Ion r_L	4300	180	μm
Electron r_L	24	1.0	μm
Late Time			
P, Thermal	8×10^{6}	8×10^{6}	Pa
P, Magnetic	2×10^{8}	1×10^{11}	Pa
Beta	20	1×10^{4}	
Ion r_L	1100	44	μm
Electron r_L	6.3	0.25	μm

Plasma diagnostics in high power laser experiments

Velocities: particle diagnostics (spectrometers, Thomson parabola), Doppler

Magnetic fields: proton radiography, polarimetry, faraday rotation, B dots

Densities: interferometry, X-ray radiography, shadowgraphy

Temperatures: spectroscopy, Thomson scattering

Maximum energies in high intensity experiments: particle diagnostics (spectrometers, Thomson parabola)

Other diagnostics: neutron measurements, harmonic imaging

Collisionless shocks in high power laser experiments

Significant questions for collisionless shocks (Fox et al. 2015):

- What is the efficiency of the Weibel mechanism vs. compression of upstream magnetic field?
- Can the Fermi or DSA process be verified and if so what is its efficiency?
- How does this depend on the parameters and magnetization of the shock?

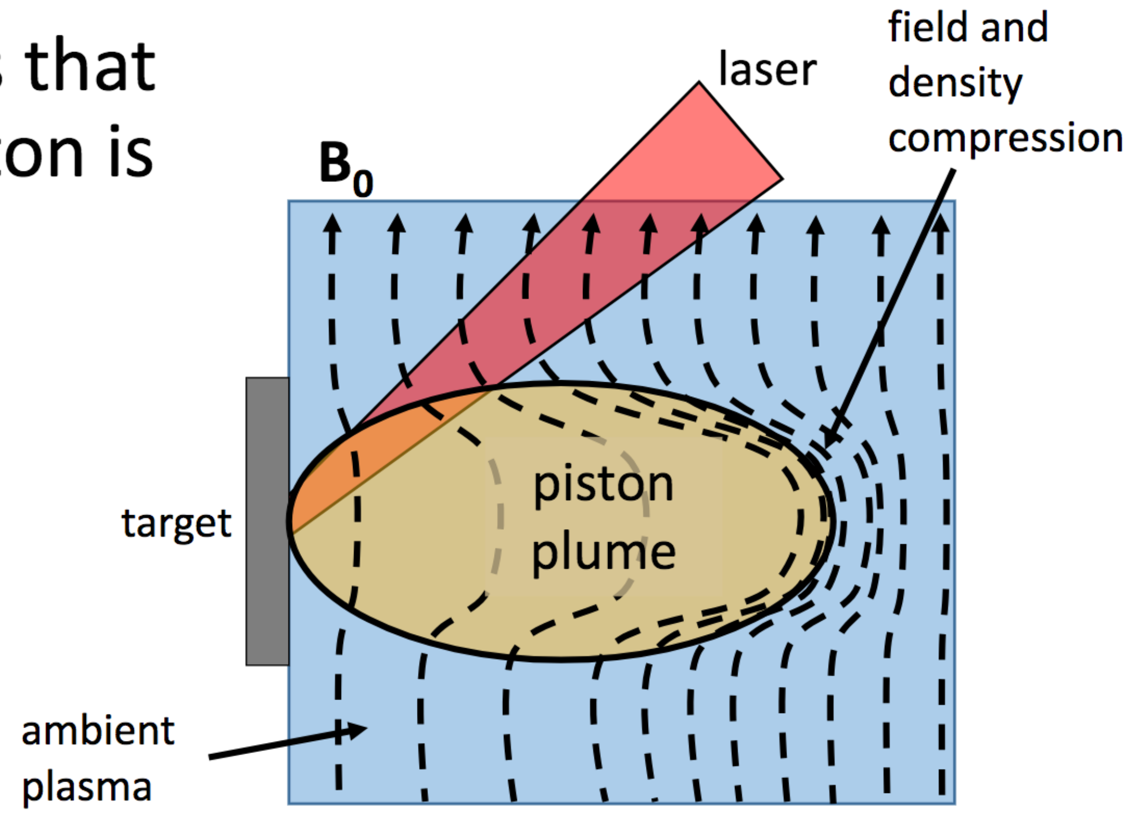
Recent experiments and associated modeling have demonstrated magnetic field generation by the ion-driven Weibel instability between colliding flows for the first time [Fox et al. PRL 2013, Huntington et al. Nat. Phys. 2015].This is the first ingredient required to form a Weibel mediated shock and indicates that at sufficiently large and high temperature it may indeed be possible to demonstrate it in the lab. Recent experiments have also demonstrated magnetized shock formation [Niemann et al. GRL 2014].

Laboratory Experiments can Reproduce the Physics of Space and Astrophysical Collisionless Shocks in a Controlled Setting

- Collisionless shocks are an active area of research
  - Electrostatic
  - Weibel-mediated
  - Magnetized

Romagnani, et al., PRL, 2008
Kuramitsu, et al., PRL, 2011
Haberberger, et al., Nature, 2011
Fox, et al., PRL, 2013
Huntington, et al., Nature, 2015
Niemann, et. al., GRL 2014

- A new class of collisionless shocks experiments that utilize a laser-driven, magnetically-coupled piston is now available
  - Wide range of Mach numbers (M_A<40)
  - 2D and 3D datasets
  - Quasi-perpendicular and quasi-parallel magnetic geometries



Courtesy of Schaeffer et al.

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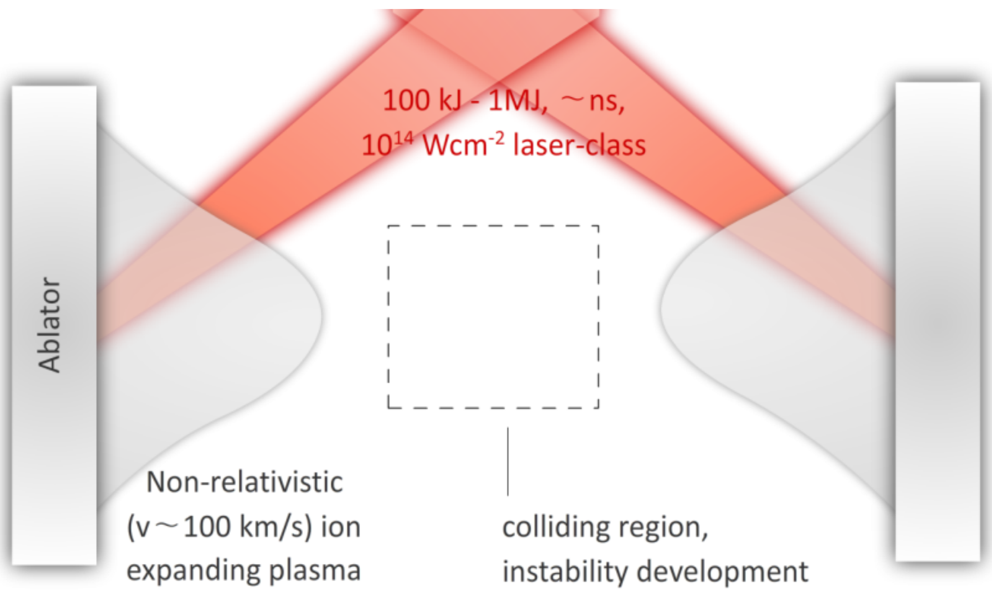
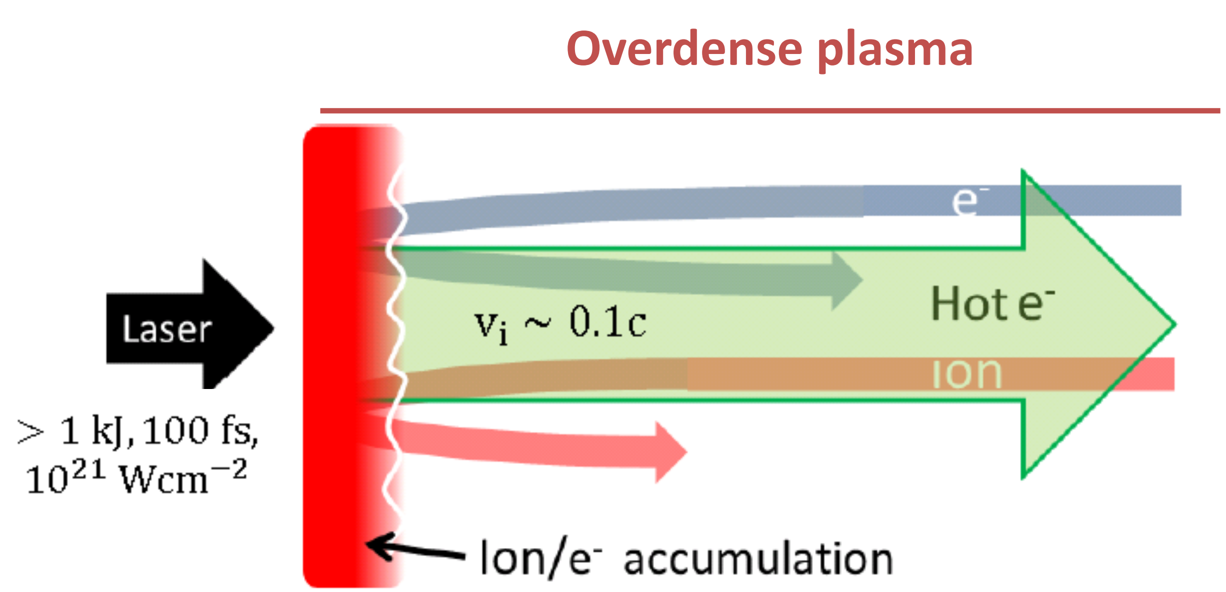
Different scenarii of laser-induced unmagnetized collisionless shocks



Non-relativistic regime: **Shocks between electron-ion *ablated* plasmas [1]**

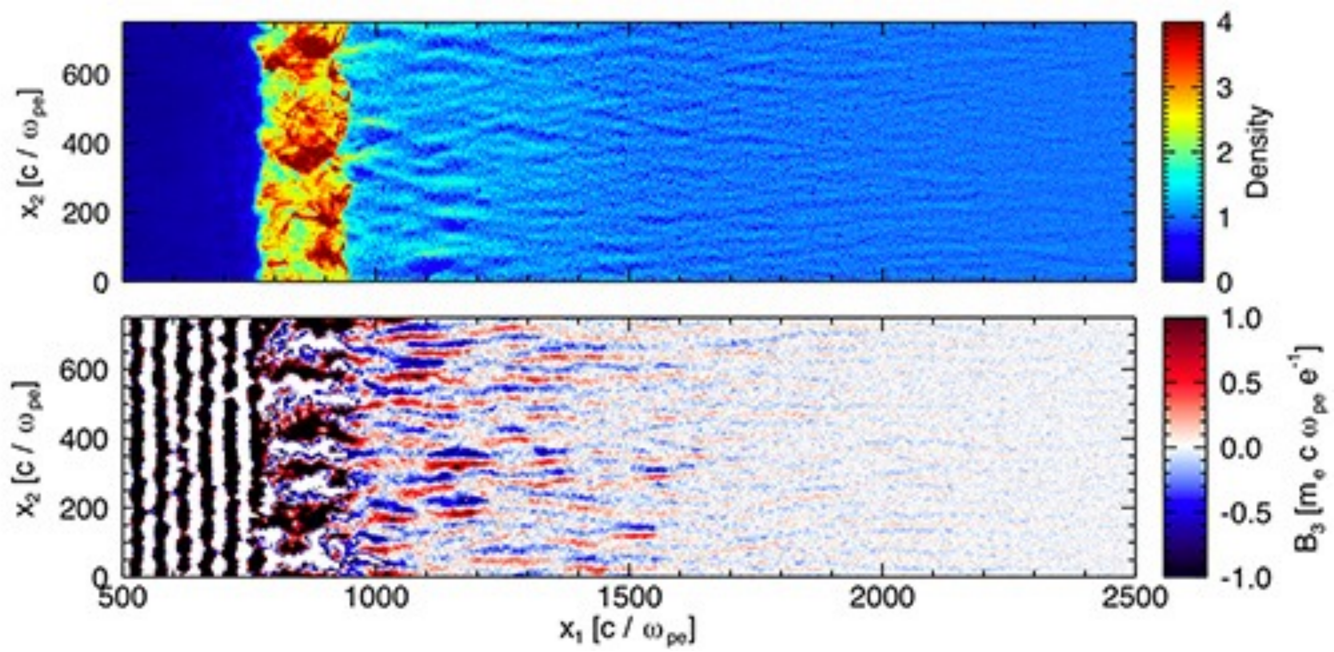


Relativistic regime: **Shocks induced by laser *radiation pressure* in overdense plasmas [2]**

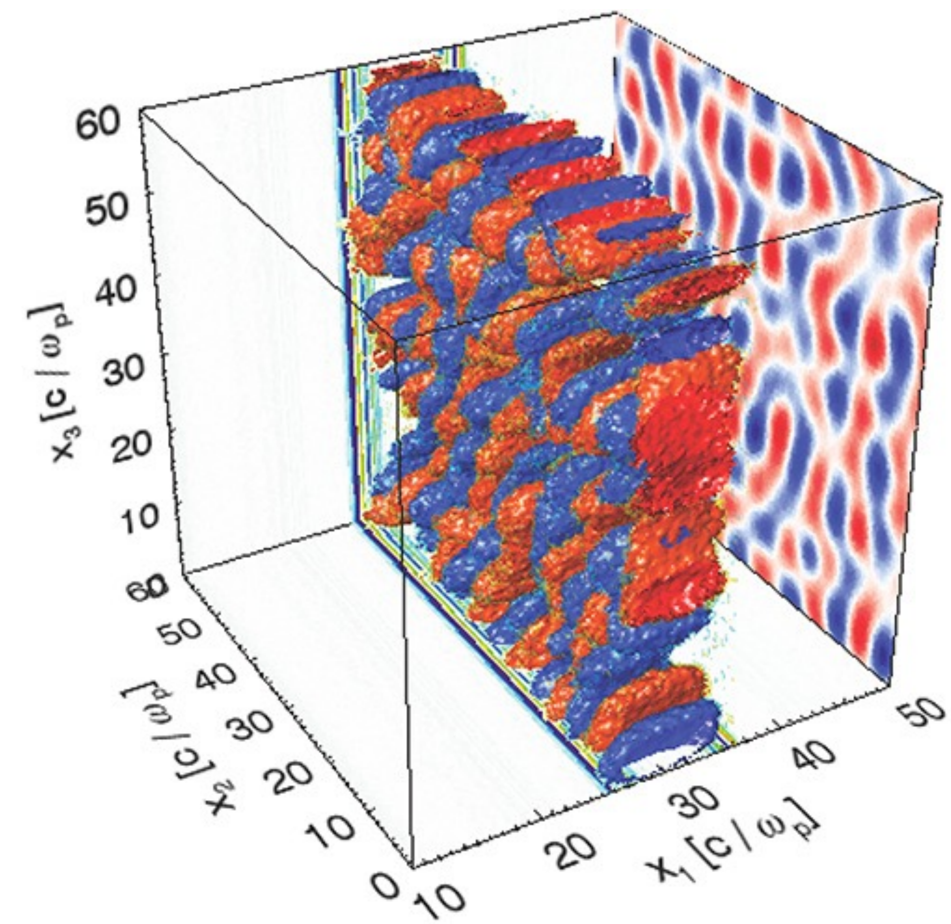
Difficult to diagnose: not considered for laboratory astrophysics experiments yet

[1] – R. Drake *et al.,* AP **749**, 171 (2012), Fox *et al.,* PRL **111**, 225002 (2013)
[2] – F. Fiuza *et al.*, PRL **108**, 235004 (2012);

Weibel mediated shocks with high intensity lasers and dense targets



Structure of Weibel-mediated shock driven by the interaction of an intense laser with an overcritical target. The top panel shows the density compression behind the shock and the filamentary structure ahead of it. The bottom panel shows the strong filamentary magnetic fields associated with the Weibel instability



Perpendicular electromagnetic field in the course of shock formation. 2D projections show the electrostatic field in the planes parallel to shock propagation and the magnetic field projection in the perpendicular plane.

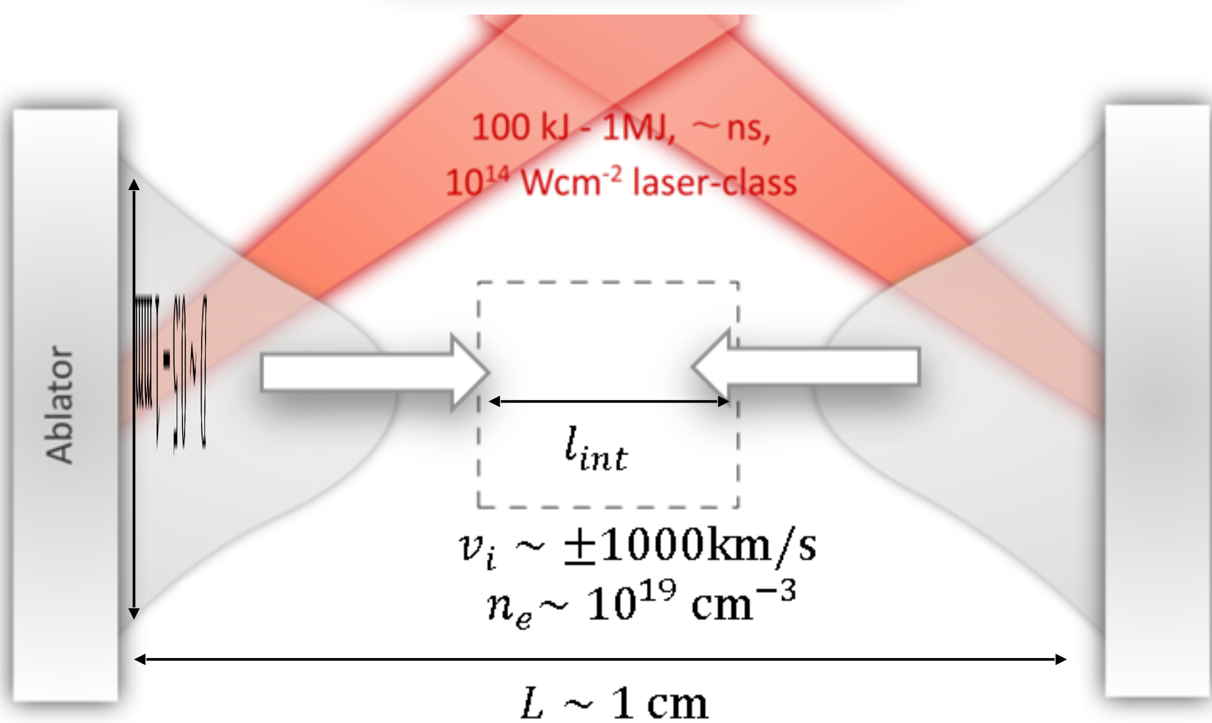
More aimed at particle acceleration on future UHI facilities

F. Fiuza et al., Physical Review Letters 108, 235004 (2012)
A. Stockem et al., Physical Review Letters 113, 105002 (2014)

The experimental investigation of Weibel-mediated plasma collisions is becoming accessible to high-power lasers

- High-power lasers have the unique capability of driving high-velocity ($v_i \sim 0.005 - 0.1c$), high-density ($n_e > 10^{18}$ cm^{-3}) electron-ion plasmas from their interaction with solid targets.
- The simplest scheme consists in making collide two ablative plasma flows[1-3].

High-energy, long-pulse laser scheme[1-3]



- The experimental generation of a Weibel-mediated shock implies:

$$c/\omega_{pi} \ll (D, l_{int}) \ll \lambda_{ii}$$

- For CH plasmas with $n_e = 10^{19}$ cm^{-3}, $v_i = \pm 1000$ km/s, $(T_e, T_i) \sim 1$ keV, one has
  - $M_s \sim 5 \Rightarrow$ Weibel-dominated
  - $c/\omega_{pi} \sim 0.1$ mm
  - $\boldsymbol{l_{int}} = ?$
  - $\lambda_{ee} \sim 2$ mm $\Rightarrow$ collisional electrons?
  - $\lambda_{Ce} \sim 7$ cm
  - $\lambda_{CC} \sim 70$ cm
  - $\lambda_{CH} \sim 300$ cm
  - $\lambda_{HH} \sim 400$ cm

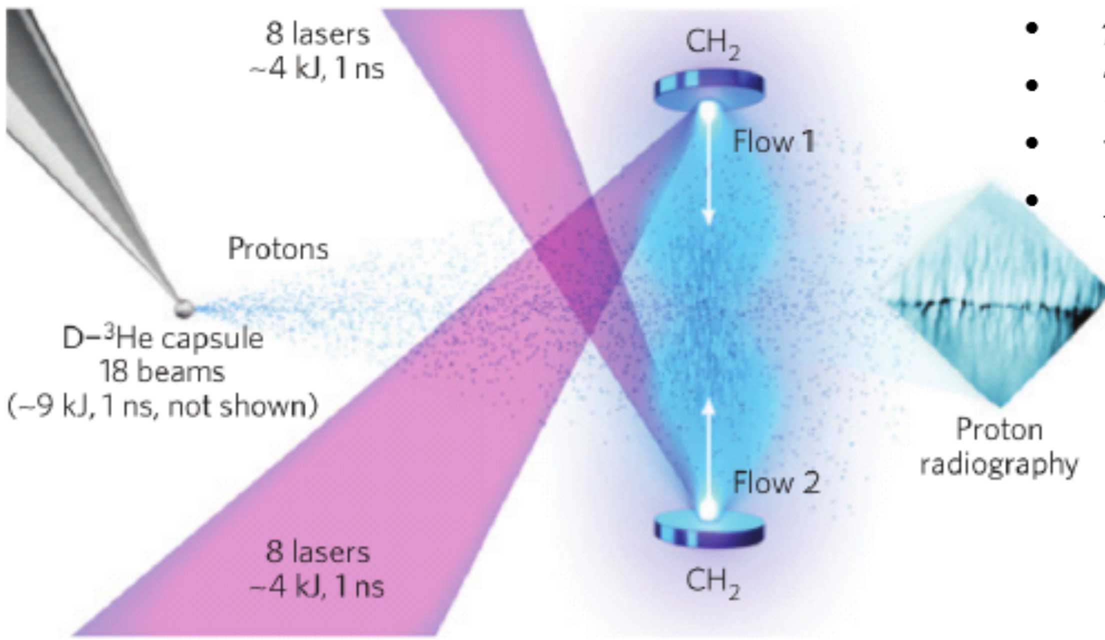
  (λ_{Ce}, λ_{CC}, λ_{CH}, λ_{HH}) $\Rightarrow$ collisionless ions

[1]Kuramitsu et al., PRL. **106**, 175002 (2011); PRL **108**, 195004 (2012)
[2]W. Fox *et al.,* PRL **111**, 225002 (2013)
[3]C.M. Huntington *et al*., Nat. Phys. **11**, 173 (2015)

Courtesy of Laurent Gremillet

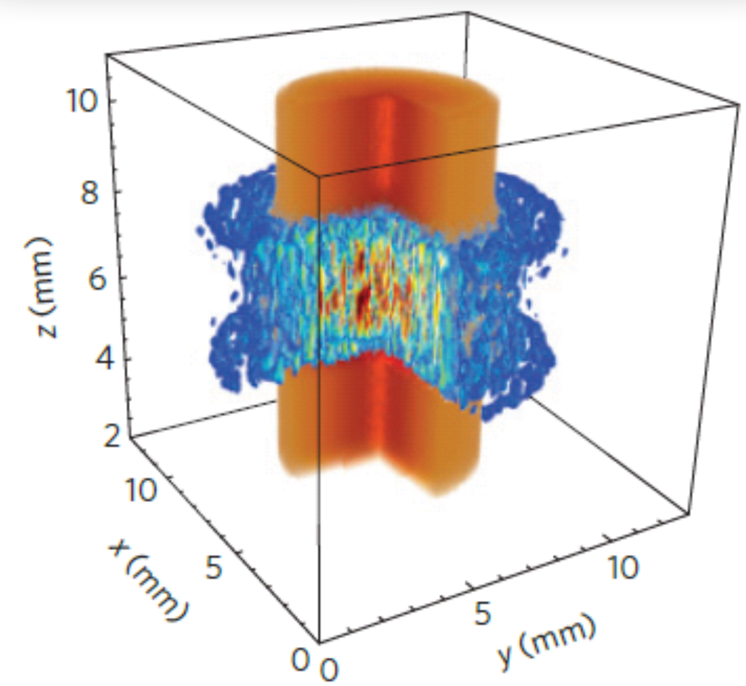
Formation and early nonlinear evolution of Weibel ion filaments recently observed in plasma-collision experiments[1,2]

(a) Experimental setup[1] (OMEGA 2.2kJ, 3ns)



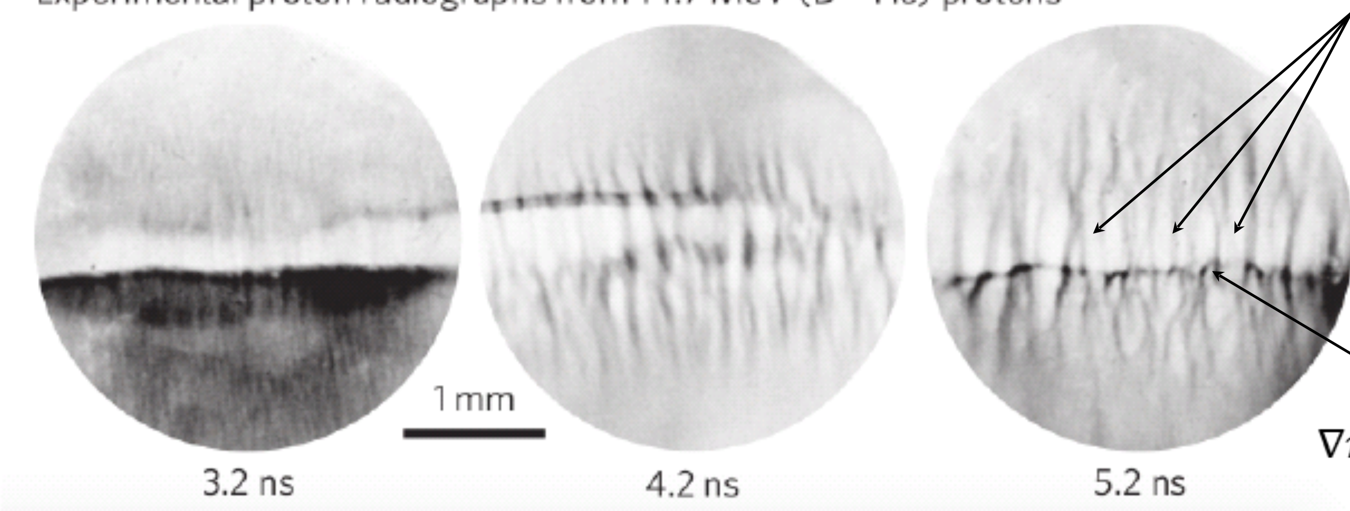
- $n_e \sim 5 \times 10^{18}$ cm^{-3}
- $T_e \sim 0.2$ keV
- $v_i \sim 2000$ kms^{-1} ($M_s \sim 20$)
- $L_{int} \sim 1$ cm $\sim 50c/\omega_{pi}$

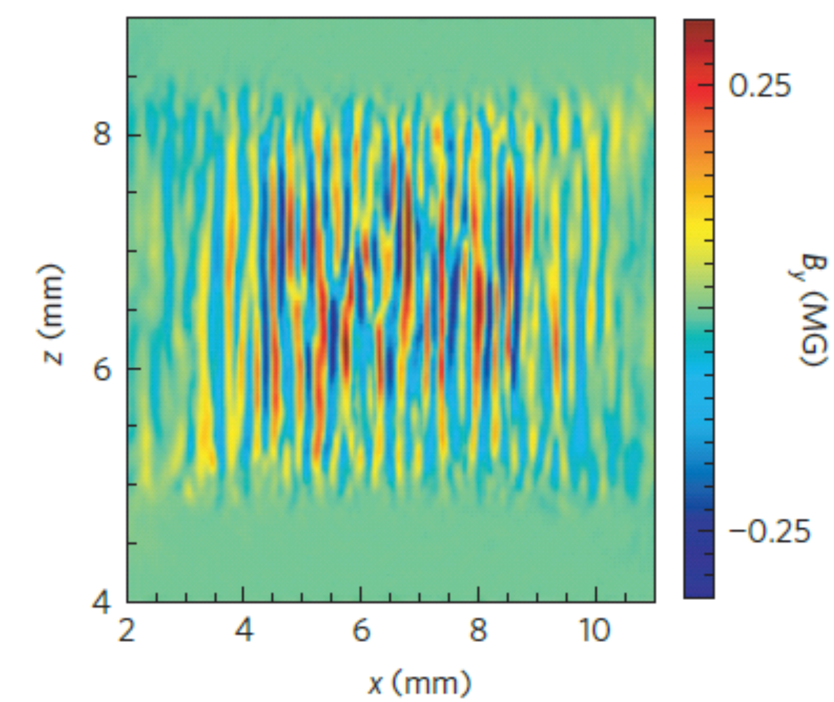
3D PIC (OSIRIS) simulation at $t = 1$ **ns**:
Isosurfaces of n_e(orange) and B (blue-red)



(b) Proton radiograpy diagnostic[1]

Experimental proton radiographs from 14.7 MeV (D–^{3}He) protons





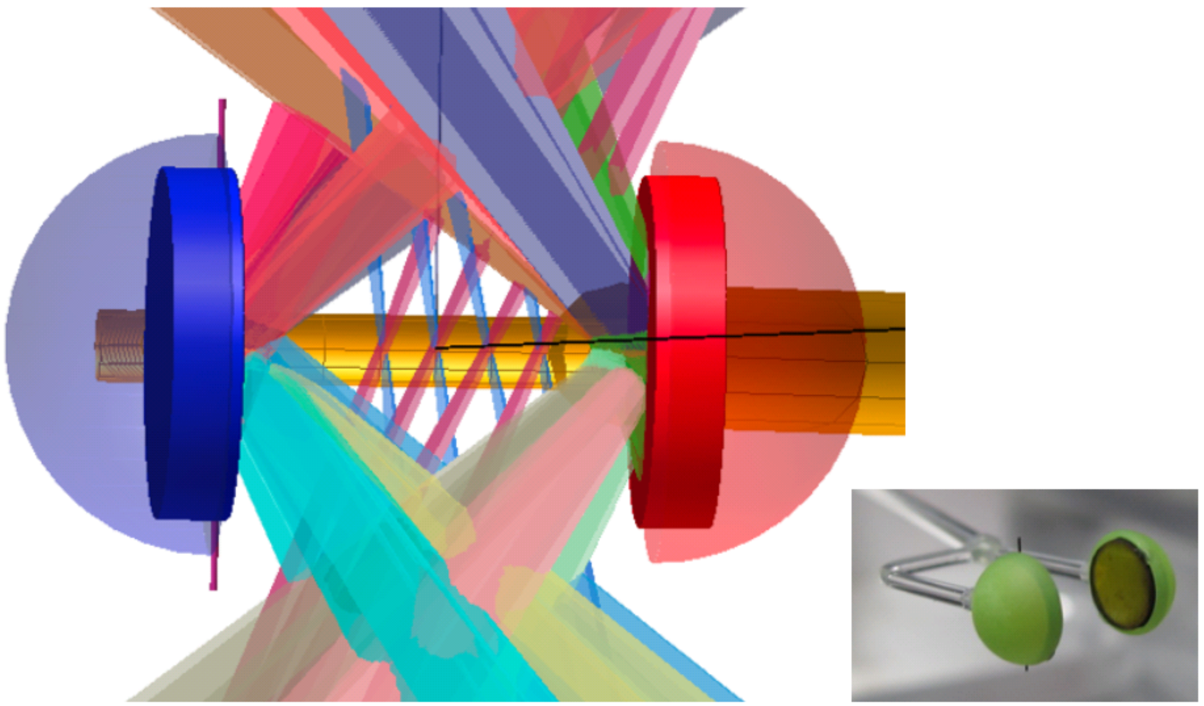
[1]C.M. Huntington *et al.*, Nat. Phys. **11**, 173 (2015)
[2]W. Fox et al., Phys. Rev. Lett. **111**, 225002 (2013)

Courtesy of Laurent Gremillet

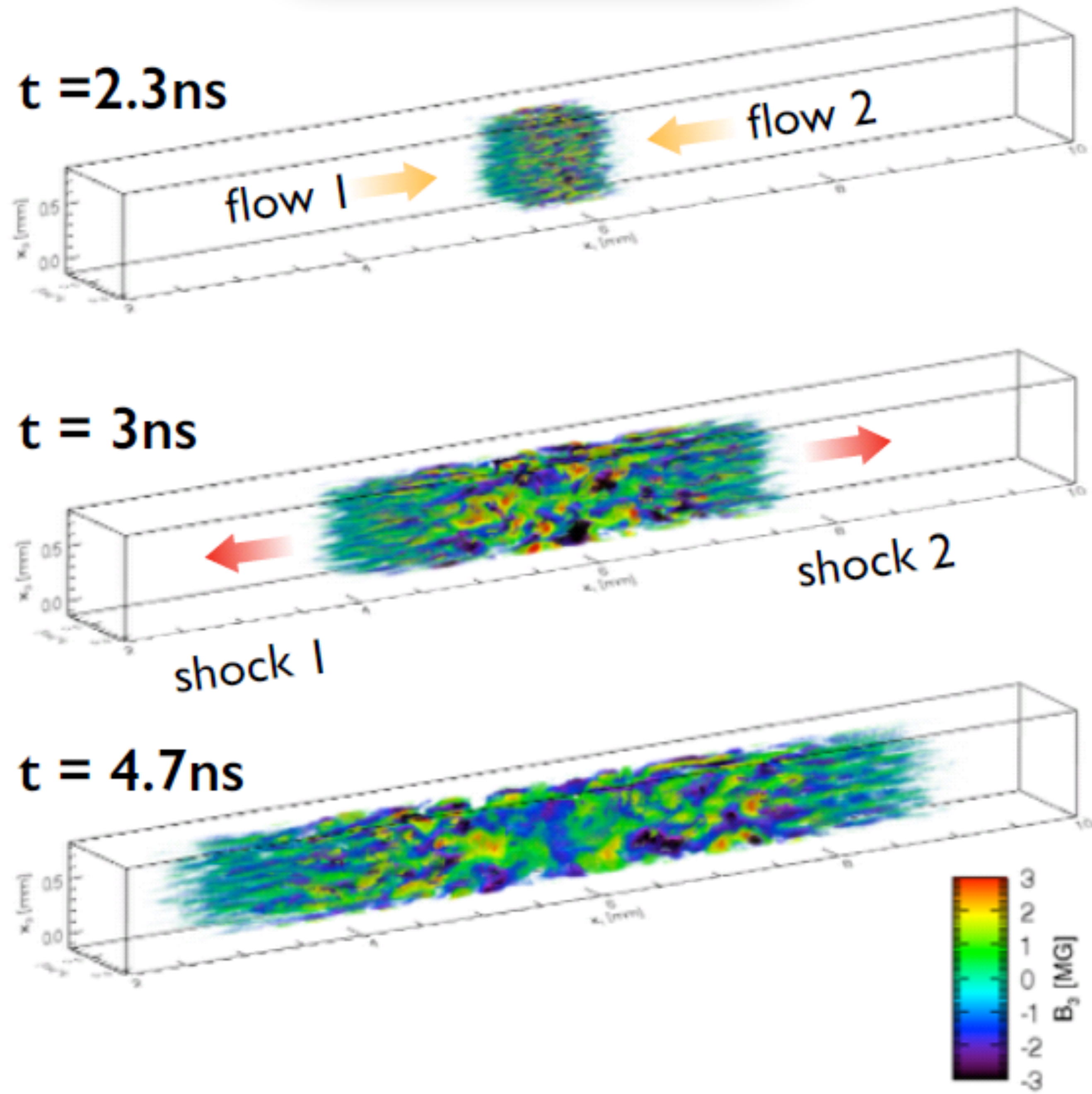
Shock formation expected to be within the reach of the National Ignition Facility

NIF target design[1]

150 - 250 kJ per target
6 mm apart
Fe/Ni (0.1%) doped CD/CH foils



3D PIC (OSIRIS) simulation[1]



- Larger plasma densities ($\sim 2\times10^{20}$ cm^{-3}) are expected $\Rightarrow$ longer effective interaction length ($\sim 500c/\omega_{pi}$), yet instability development may be affected by Coulomb collisions.
- PIC simulations performed with 'heavy' electrons ($m_{e,PIC} = 28m_e$) to reduce computing time.

[1]F. Fiuza, NIF/JLF Users Meeting 2015

Courtesy of Laurent Gremillet

Conclusions on unmagnetized collisions

- Diagnostics of instability developments
- No fully formed shocks even on NIF
- But important progresses on diagnostics and simulations: development of a platform
- Role of collisions is still debated

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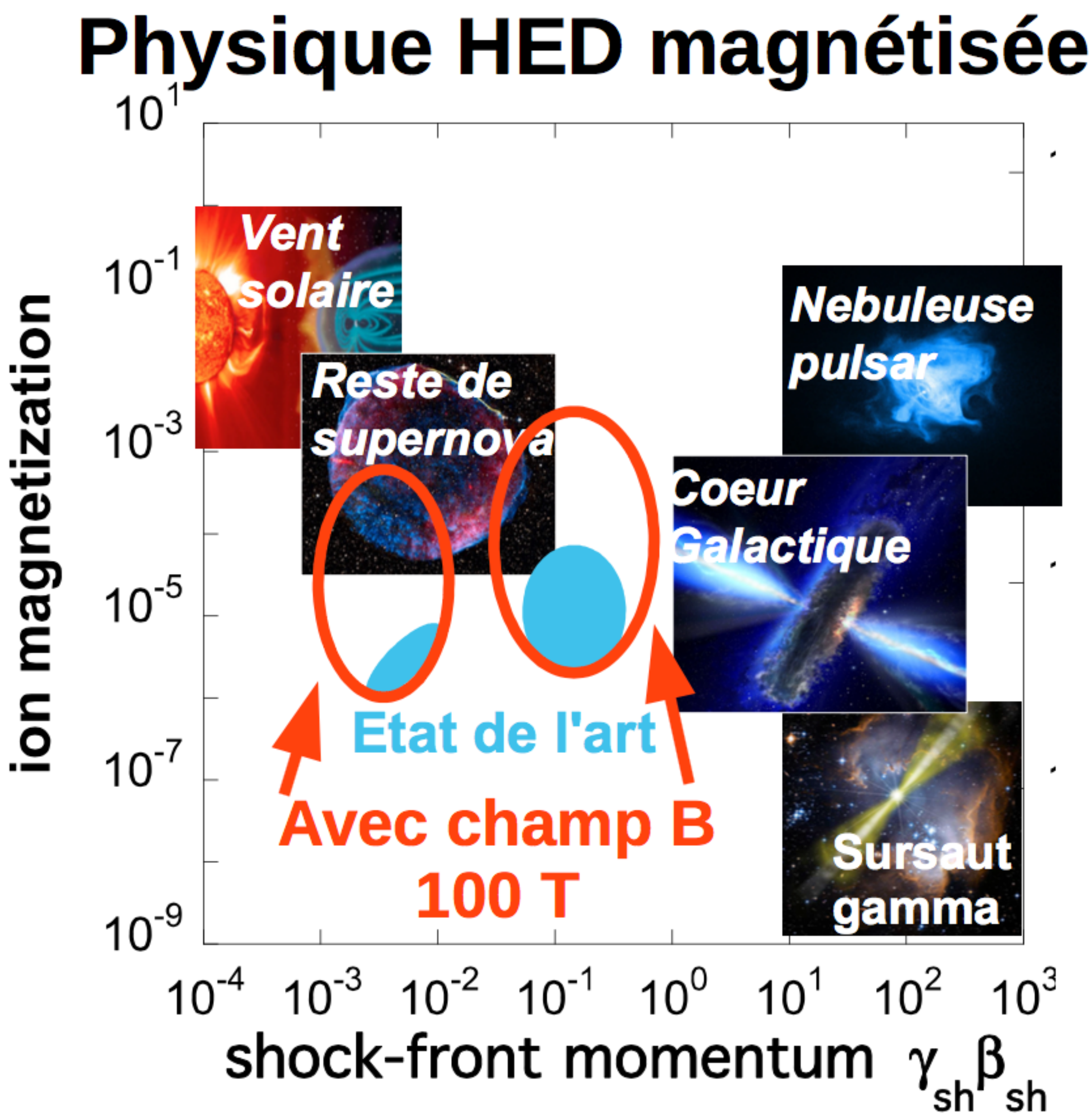
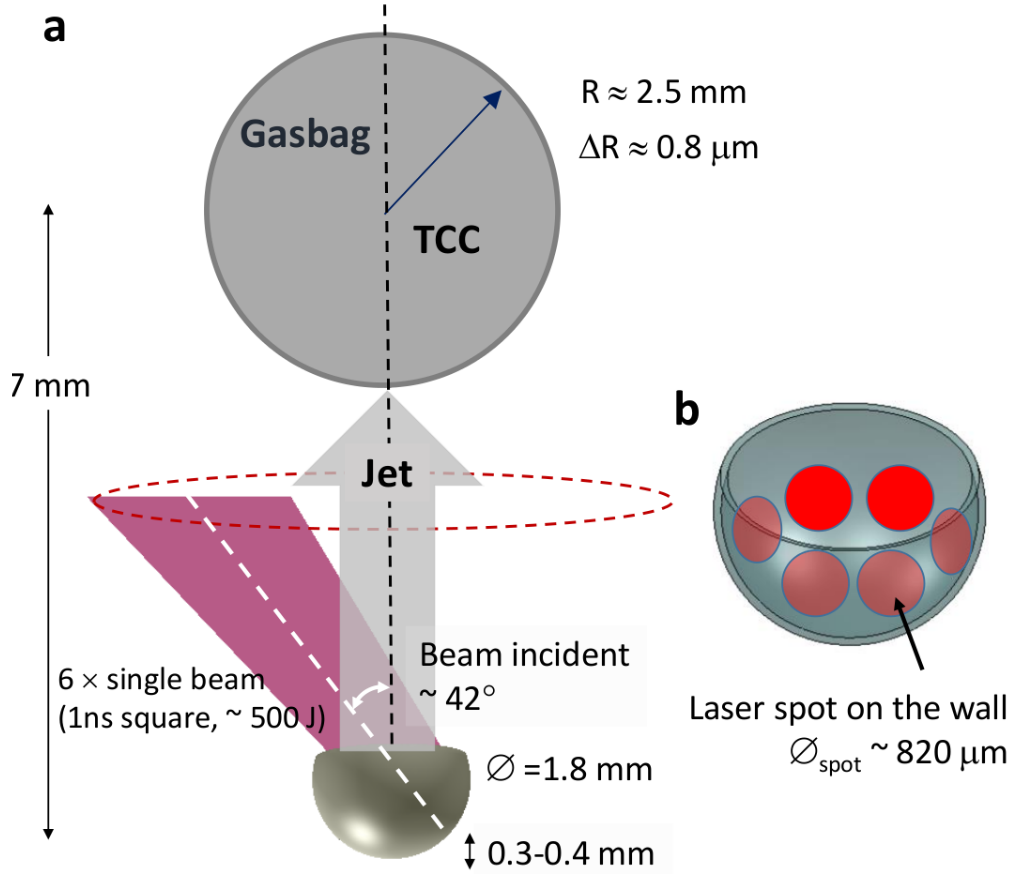
Magnetized laboratory astrophysics



Crucial need to increase collision velocities
and magnetic field amplitudes

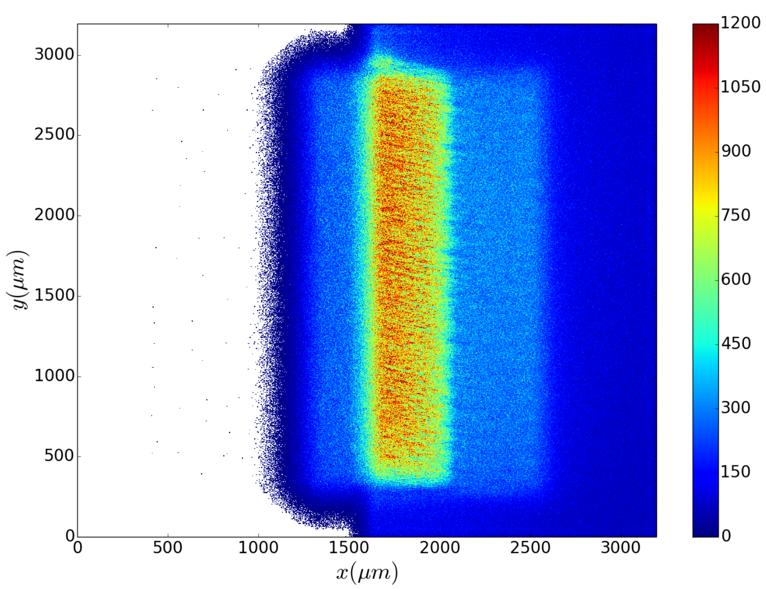
Courtesy of J. Santos

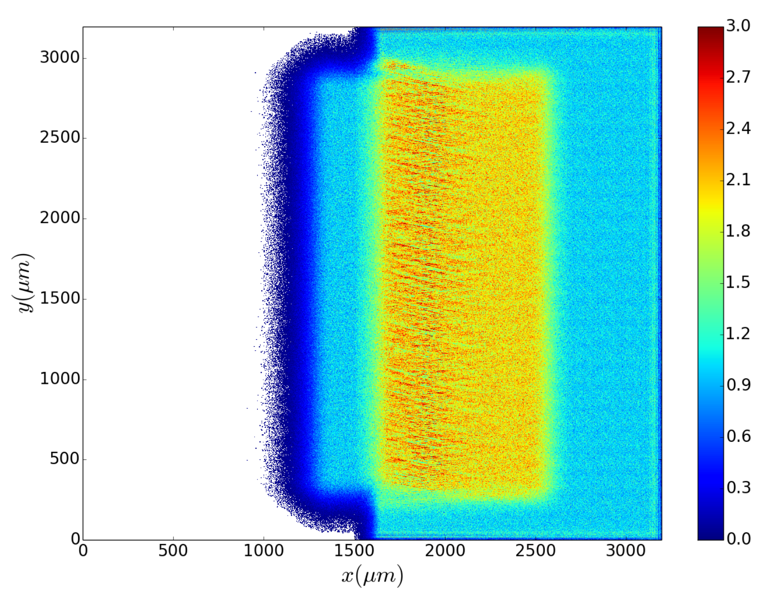
Omega experiments of Chikang Li (MIT) et al.

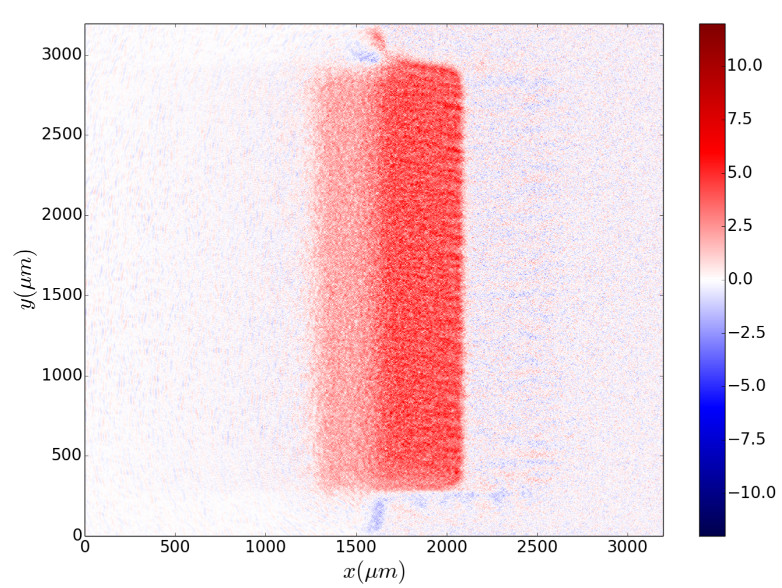


+ electron energization

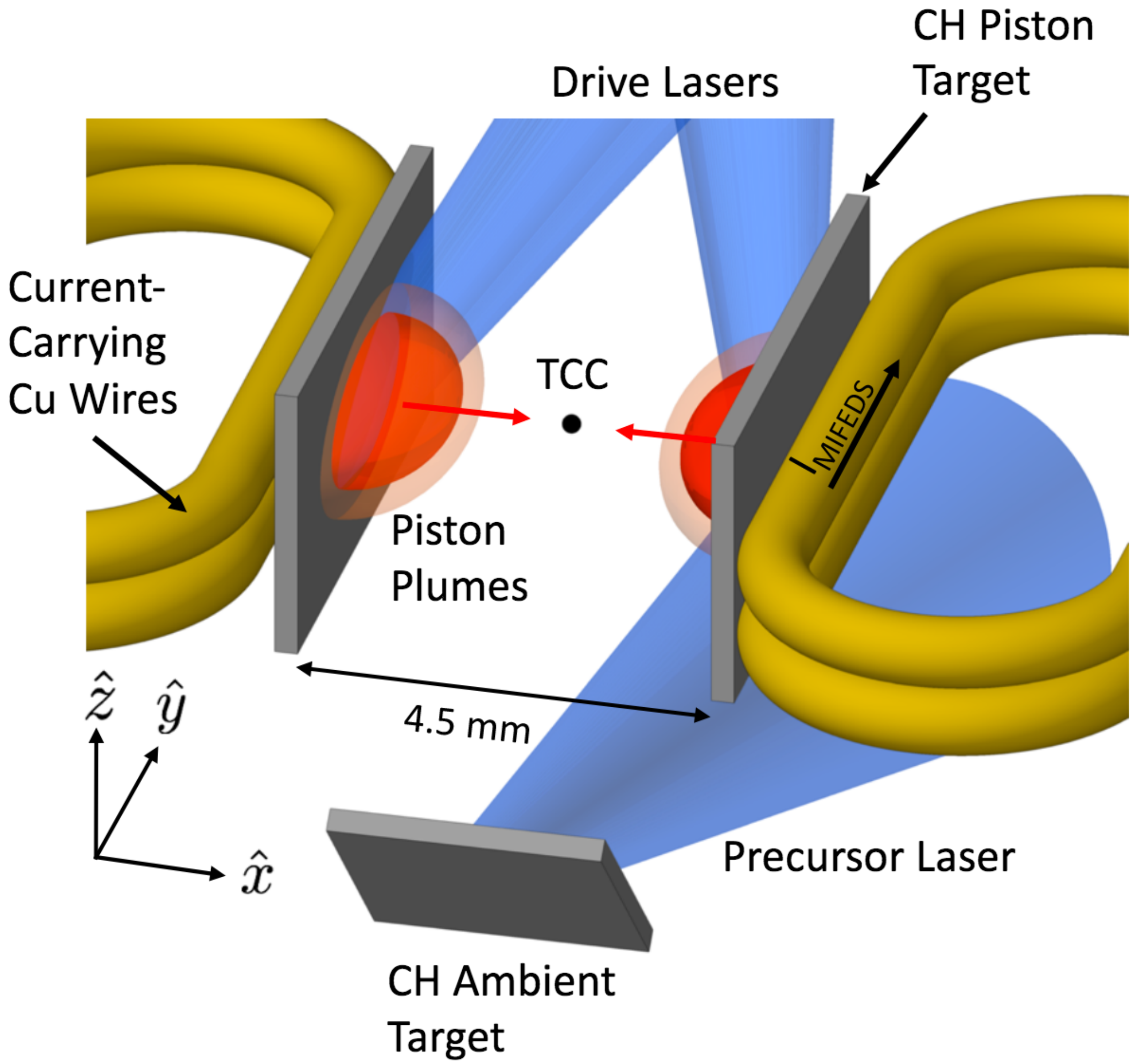
$T_e(eV)$ $n_i(n_0)$ $B_z(T)$







Experimental Setup for Quasi-Perpendicular Shocks on Omega EP

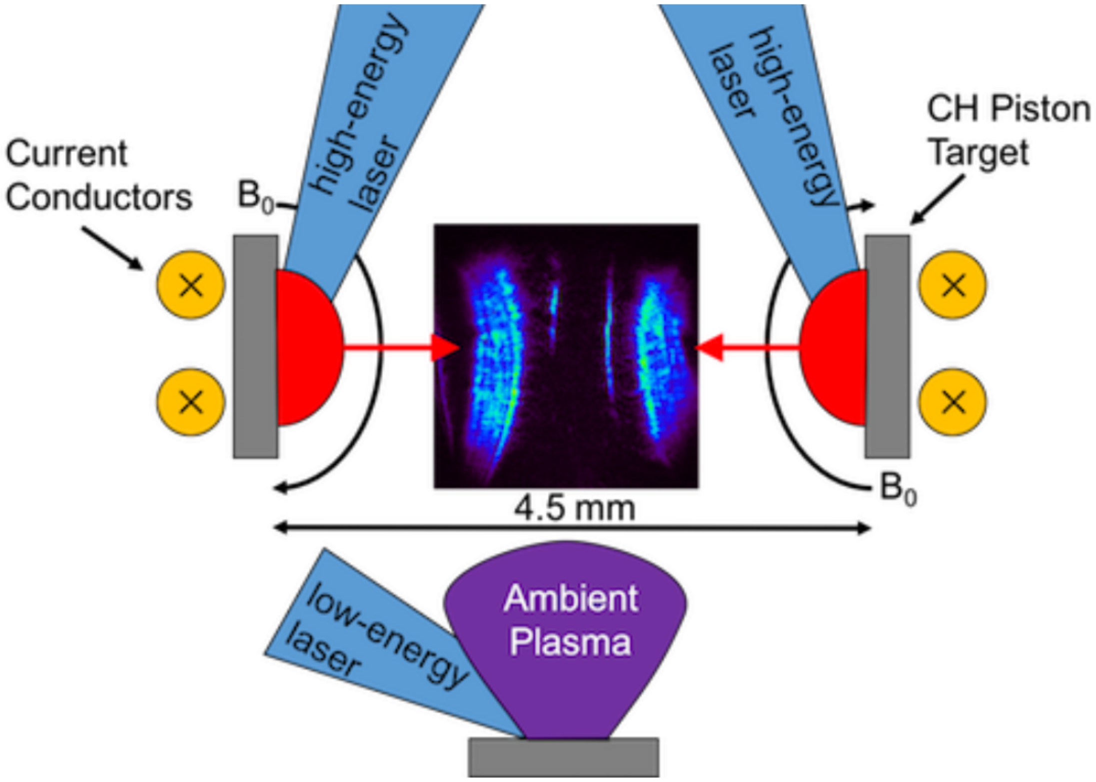


- MIFEDS coils provide background magnetic field ~ 8T
- Heater beam ablates ambient plasma ($n_{i,0} \approx 10^{18}$ cm^{-3}) 12 ns before drive beams
- Drive beams create supersonic piston plumes that expand into ambient plasma
- Diagnostics:
  - Angular Filter Refractometry (AFR)
  - Shadowgraphy
  - Proton radiography

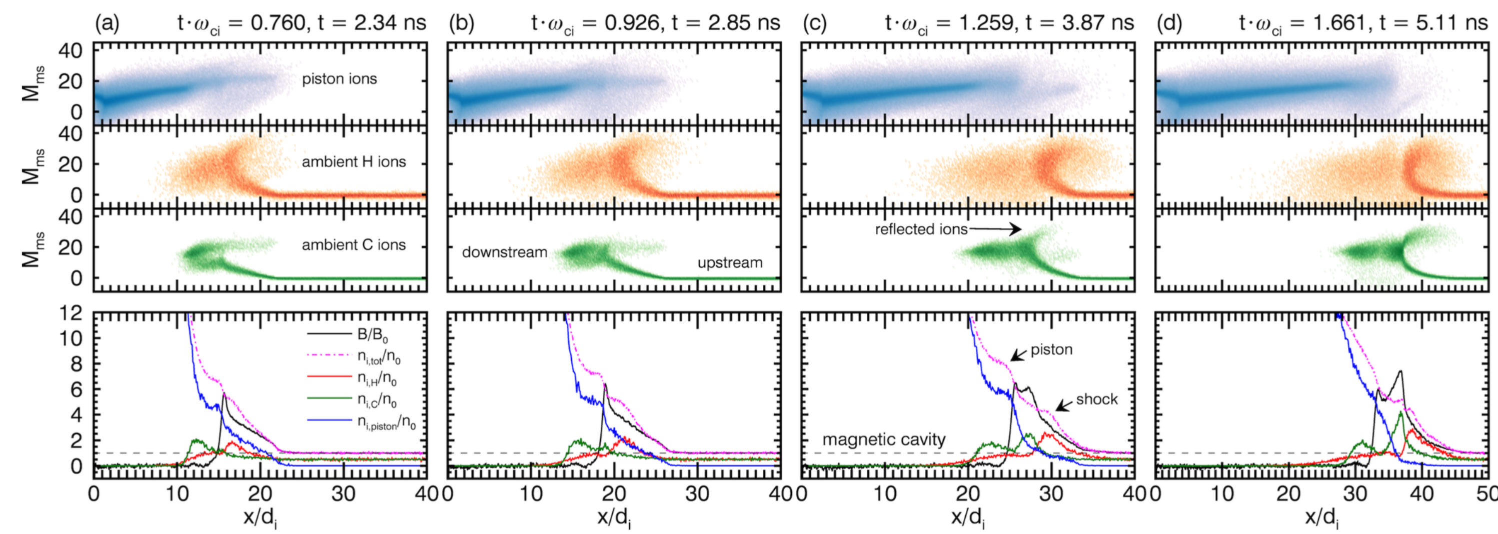
Experiments on the generation and Evolution of High-Mach Number, Laser-Driven Magnetized Collisionless Shocks in the Laboratory

Schaeffer et al. arXiv:1610.06533

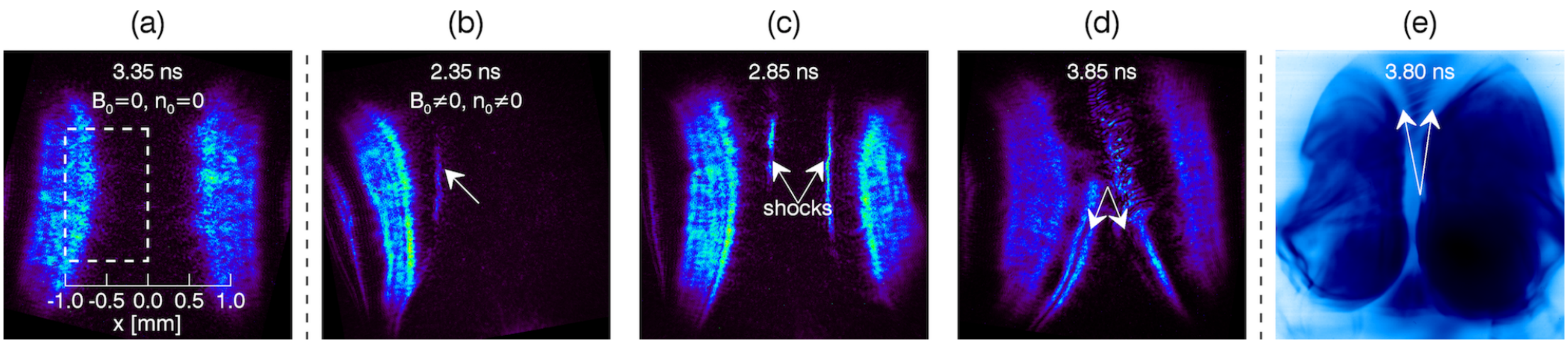
PRINCETON UNIVERSITY



Experimental setup. An external magnetic field (B_0 = 8 T) in an anti-parallel geometry was applied by pulsing current through conductors located behind opposing plastic (CH) piston targets.



Results from 2D particle-in-cell simulations that show the formation of a high-Mach number, magnetized collisionless shock



Refractive and proton radiographic images of collisionless shock evolution

Central Question: How is the Energy Transferred to the Particles?

➢Diffusion by shocks may be the energy source for cosmic ray acceleration

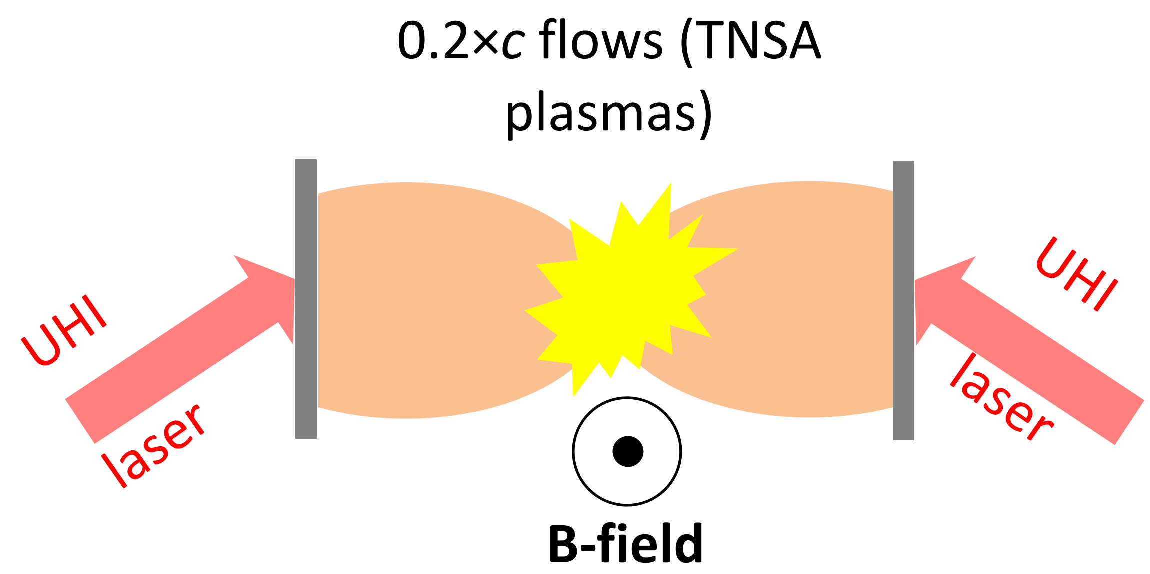
➢Instabilities that produce large amplitude current filaments and amplified magnetic fields can induce acceleration of ions through reflections on the fields

➢Experiments using high-power long –pulse lasers have been performed to investigate such instabilities

Our focus:

1. **Exploit high-velocity colliding flows**
2. **Add an ambient magnetic field (transverse to the flows)**

➡ Allows to move closer to astrophysical situations



E. S. Weibel, Phys. Rev. Lett. **2,** 83 (1959)
A. Bret, The Astrophys. J. **699**, 990 (2009)
S. Davis et al., High Energy Density Physics **9**, 231 (2013)

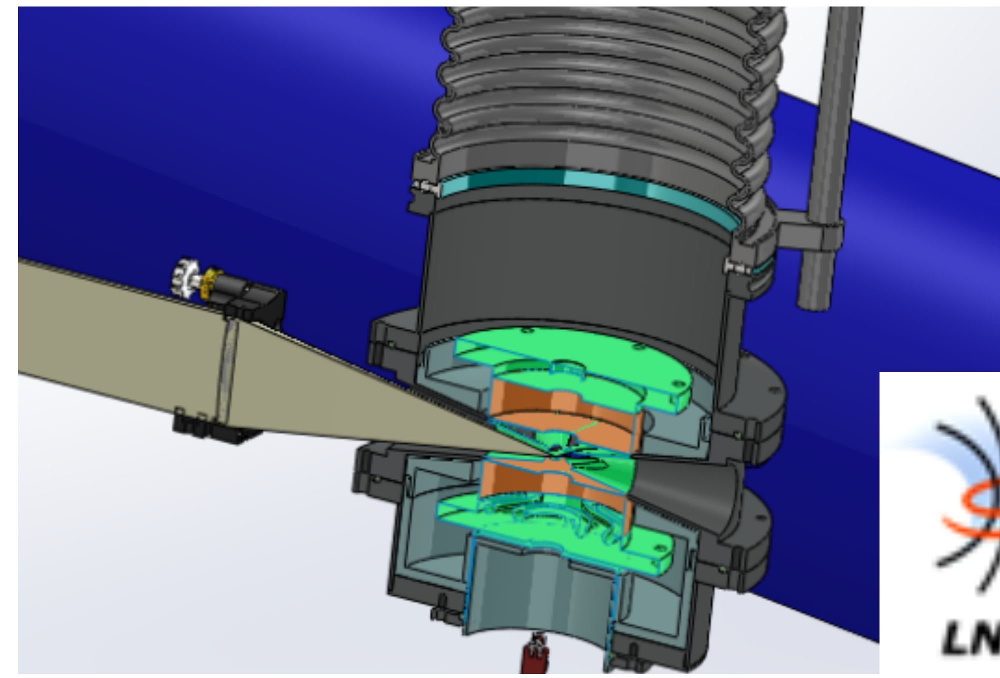
Y. Kuramitsu et al., Phys. Rev. Lett. **106**, 175002 (2011); C. M. Huntington et al., Nat. Phys. **11**, 173 (2015)

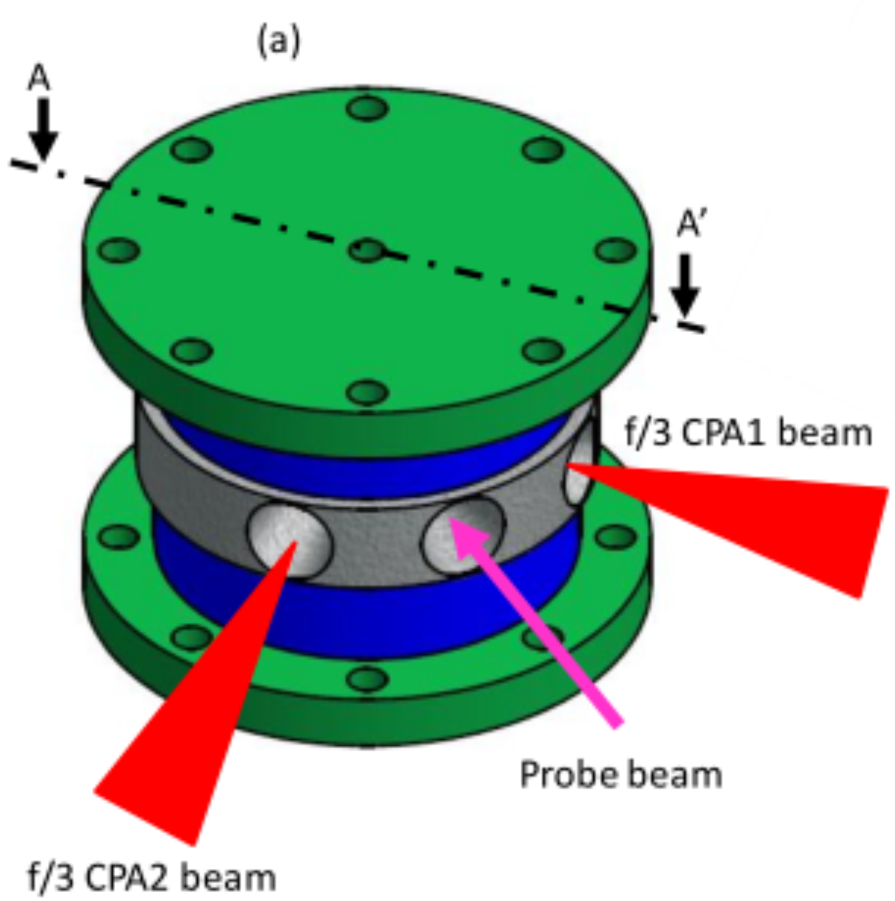
Coil Developed at LNCMI for Titan Geometry

Coil provides **20 T external fields** which are constant in time (many μsec) and space (many mm).

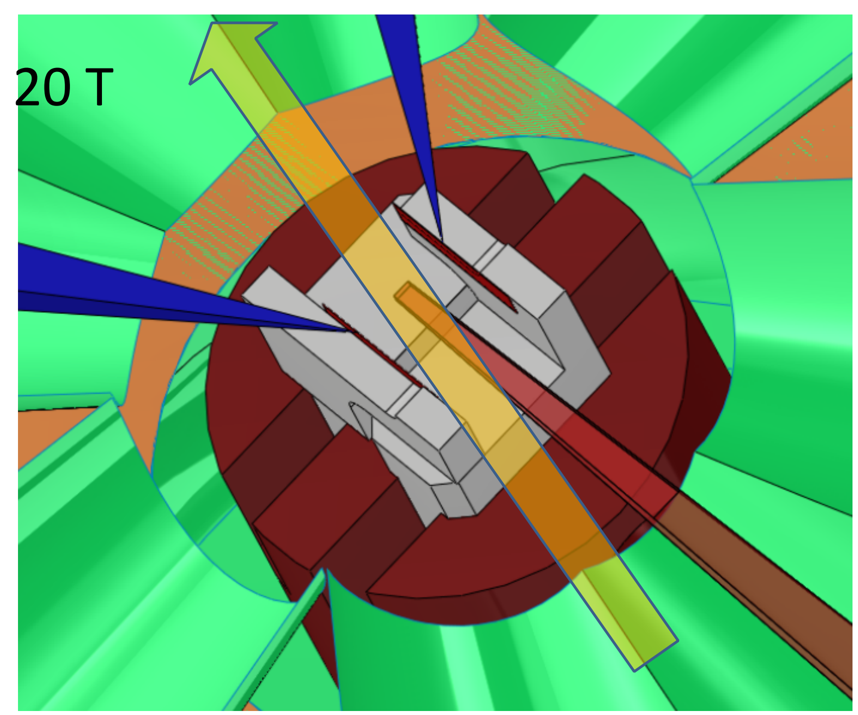
The coil allows the f/3 short-pulse laser beams driving the TNSA plasmas to access the central magnetized zone

D. Higginson et al. HEDP 2015



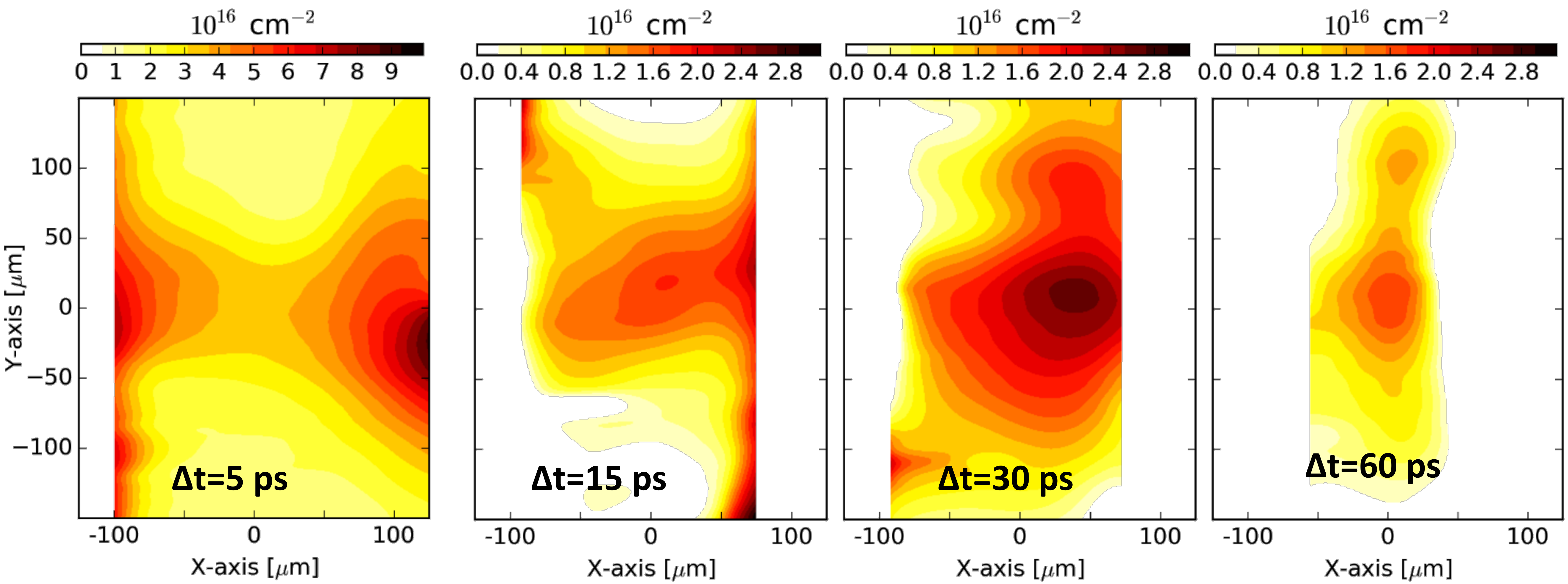


B = 20 T



First signature produced by colliding the plasmas within the B-field: density increase of the center

B=20T, thickness=4.5 µm and separation=250 µm

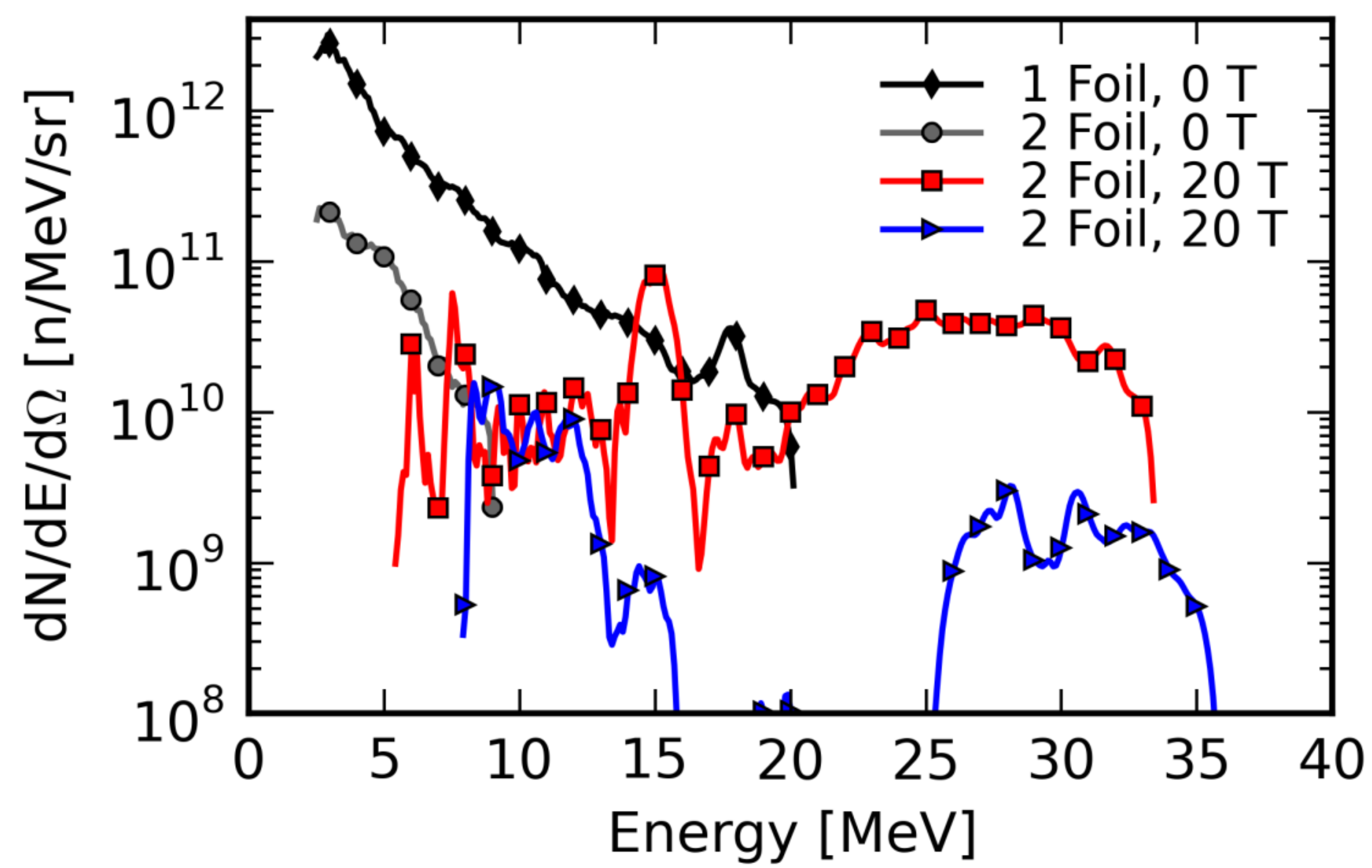


- Density bump cannot result from linear overlap of TNSA beams
- Density bump is not observed w/o B-field
- Closer distance leads to higher densities, and thus a stronger bump.
- When separating the targets by 500 µm, bump creation time is increased by about 2x, as expected from the change in distance.

D. Higginson et al.

Second signature: protons resulting from the magnetized collision emerge with higher energy

- For a single foil shot (no B-field) the maximum energy is 20 MeV.
- For a double foil shot (no B-field) the signal is reduced on the TP due to scattering in the foil. (We have verified this with TRIM).
- For a double foil shot (w/ B-field) the maximum energy increases up to 35 MeV.
- This shows that the protons have gained energy in the process



D. Higginson et al.

Conclusions on magnetized collisions

- First observations of formed magnetized collisionless shocks
- First hints at particle energization
- More experiments are on the way
- Possibility to use higher magnetic fields on MJ facilities
- Higher collision velocities will be explored in the future

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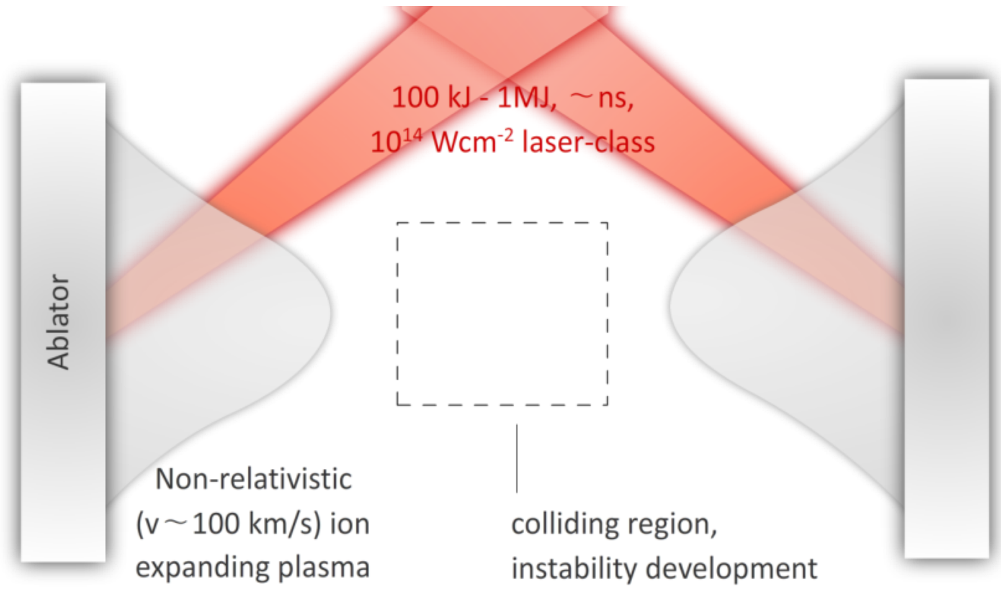
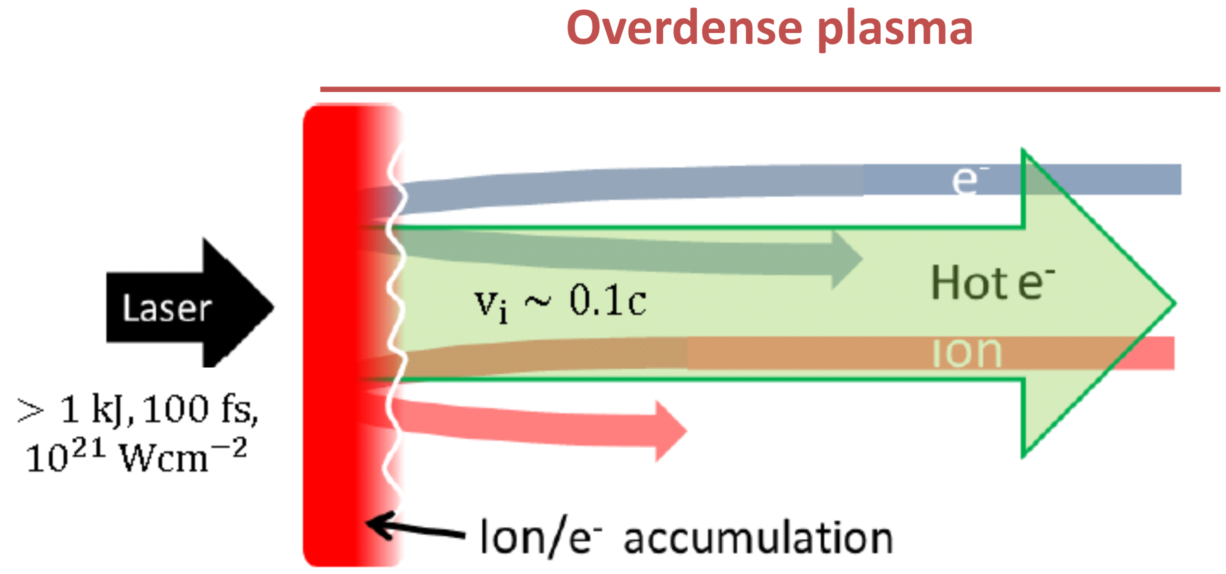
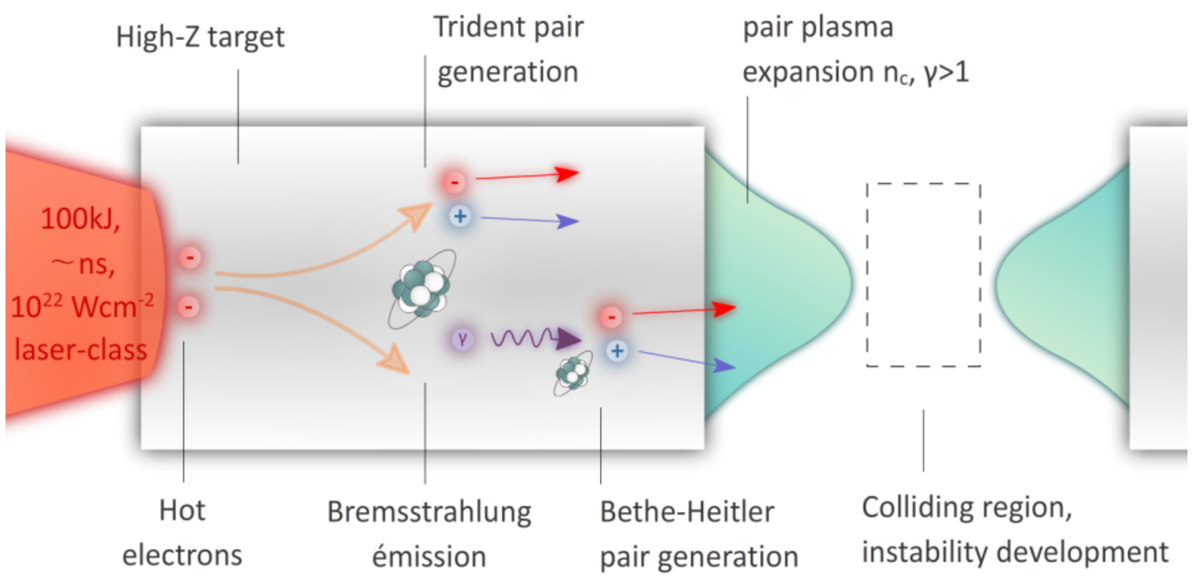


Non-relativistic regime: Shocks between electron-ion *ablated* plasmas [1]



Relativistic regime: **Shocks induced by laser *radiation pressure* in overdense plasmas [2]**



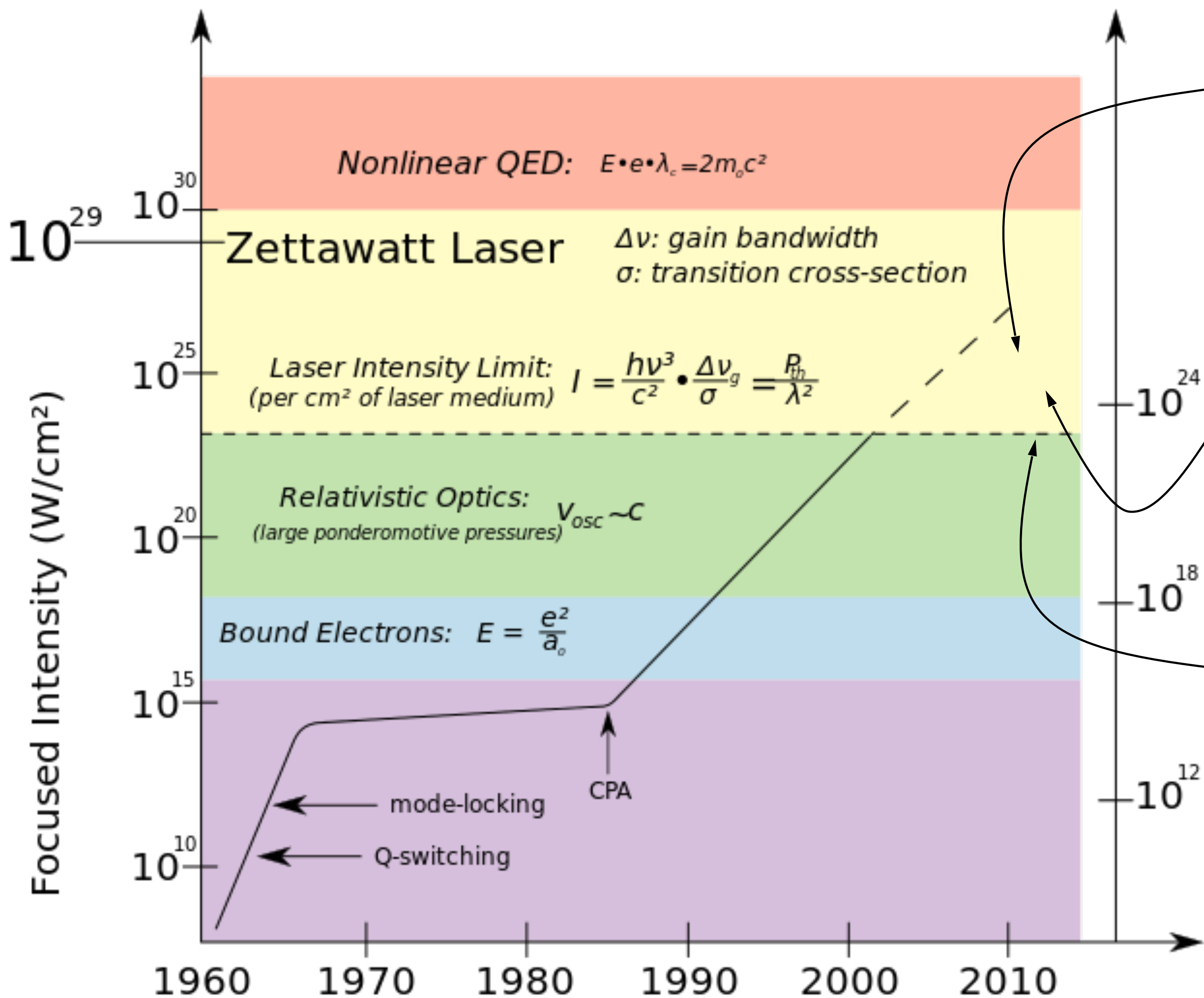
Relativistic regime: **Shocks between e^-e^+ plasma flows [3]**

Experimental study of e^-e^+ instabilities, let alone e^-e^+ shocks, is impaired by difficulty of creating dense enough pair plasmas:

- Previously proposed schemes are based on Bremsstrahlung/Bethe-Heither processes in thick (mm) high-Z targets.
- Here, we study an alternative setup based on synchrotron/Breit-Wheeler processes in thin (μm) targets.

[1] – R. Drake *et al.,* AP **749**, 171 (2012), Fox *et al.,* PRL **111**, 225002 (2013)
[2] – F. Fiuza *et al.*, PRL **108**, 235004 (2012); Poster of C. Ruyer *et al.*
[3] – Myatt *et al.,* PRE **79**, 066409 (2009) ; Chen et *al.*, HEDP **7**, 225-229 (2011)

Future high-power short-pulse laser facilities [1]



EXASCALE: IZEST
(compressed LMJ, NIF-class lasers?)

100 PW: ELI upgrade, XCELS
(10^{23}- 10^{24} Wcm^{-2}, 10x10 PW beams)

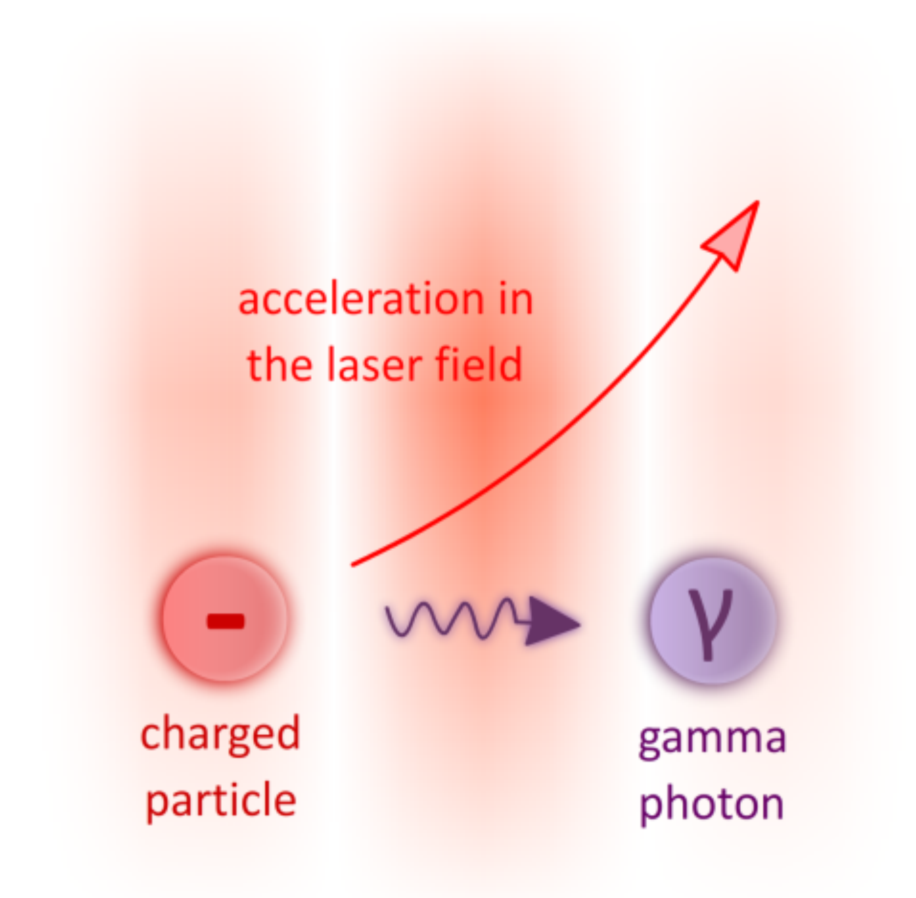
10 PW: Apollon, Vulcan, ELI
(10^{22}- 10^{23} Wcm^{-2}, 150-300 J, 15-30 fs)

1 PW: State of the art facilites
10^{21} Wcm^{-2}, 30 J, 30 fs

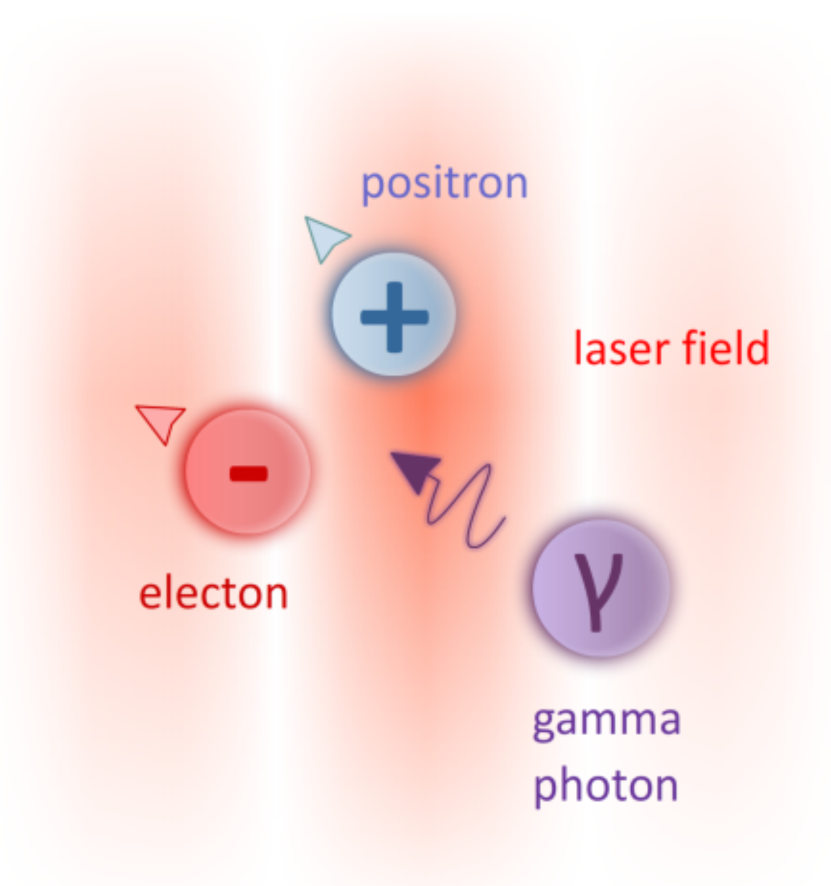
[1] A. Di Piazza *et al.*, Rev. Mod. Phys. **84**, 1177 (2012)

Radiative and QED effects[1] in ultra-intense laser plasma interaction[2,3]

Apollon (10 PW, 100J, 15 fs) → **ELI** (100 PW) → **IZEST** (> 1EW)



Non-linear Compton scattering: high-frequency photon emission in the laser field



Multiphoton Breit-Wheeler: $e^{-}e^{+}$ pair generation in the laser field ($I > 10^{23}$ Wcm^{-2})

And competition with Bethe-Heitler and Trident processes when using solid foils

- Implementation of these mechanisms in the PIC code CALDER [M. Lobet et al. arXiv.1311.1107v2]

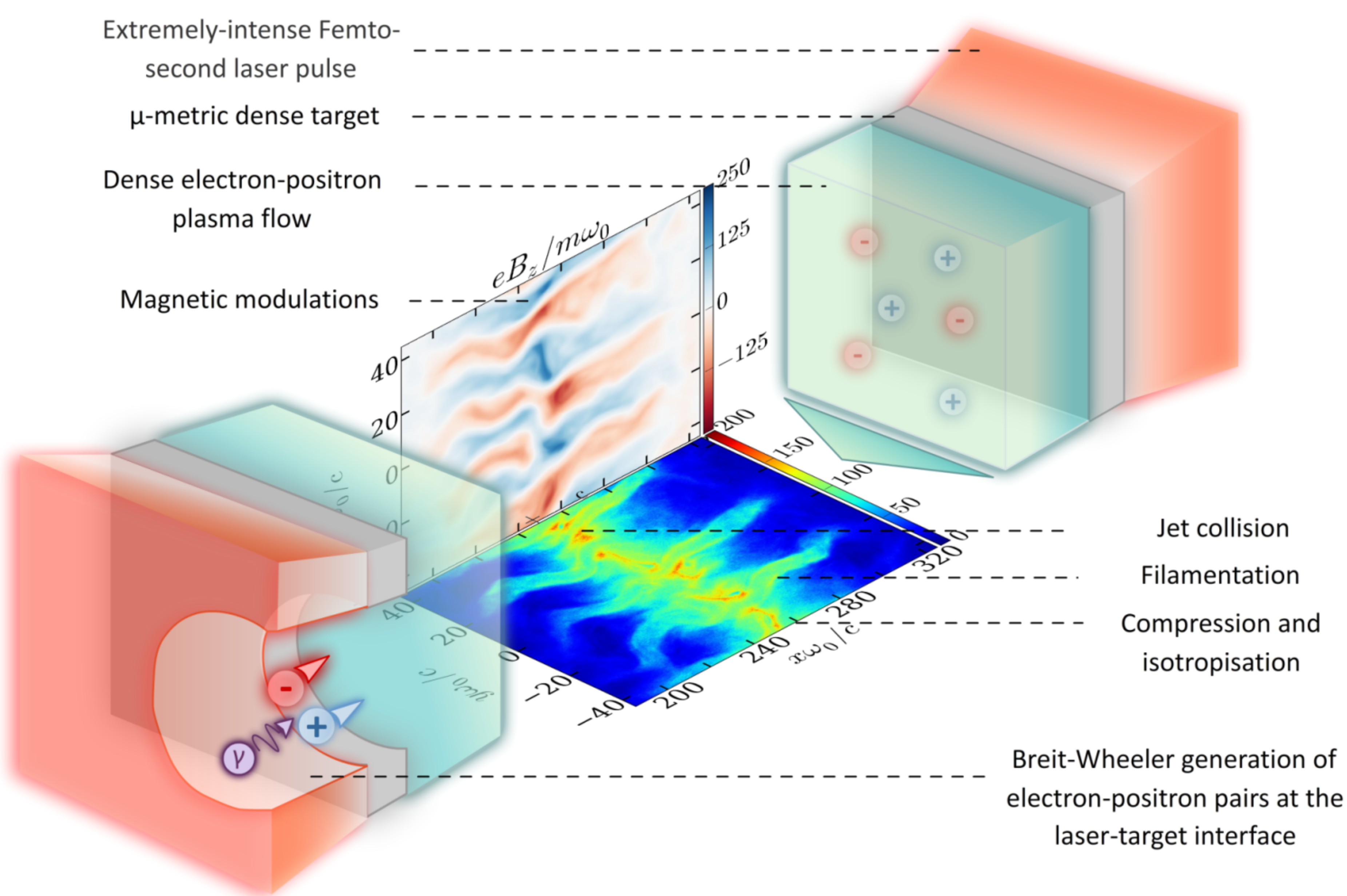
[1] – A. Di Piazza *et al.*, Rev. Mod. Phys. **84**, 1177 (2012) – A. Bell *et al.*, Phys. Rev. Lett. **101**, 200403 (2008).
[2] – A. Zhidkov *et al*, PRL **88**, 185002 (2002) – M. Tamburini *et al*, NJP **12**, 123005 (2010) – R. Capdessus *et al*, PRL **110**, 215003 (2013)
[3] – C. P. Ridgers *et al*, PoP **20**, 056701 (2013) – C. S. Brady *et al*, arXiv preprint 1311.5313 (2013) – L. L. Ji *et al*, PoP **21**, 023109 (2014)

Two-target configuration for the study of the Weibel instability in colliding e^-e^+ jets

Could be transposed to e^-p plasma collisions using low density targets

- High laser intensity necessary to generate sufficiently dense pair plasmas
- Large focal spot necessary to minimize transverse spreading of pair plasma and generate many filaments

⇒ Total laser energy > 200 kJ



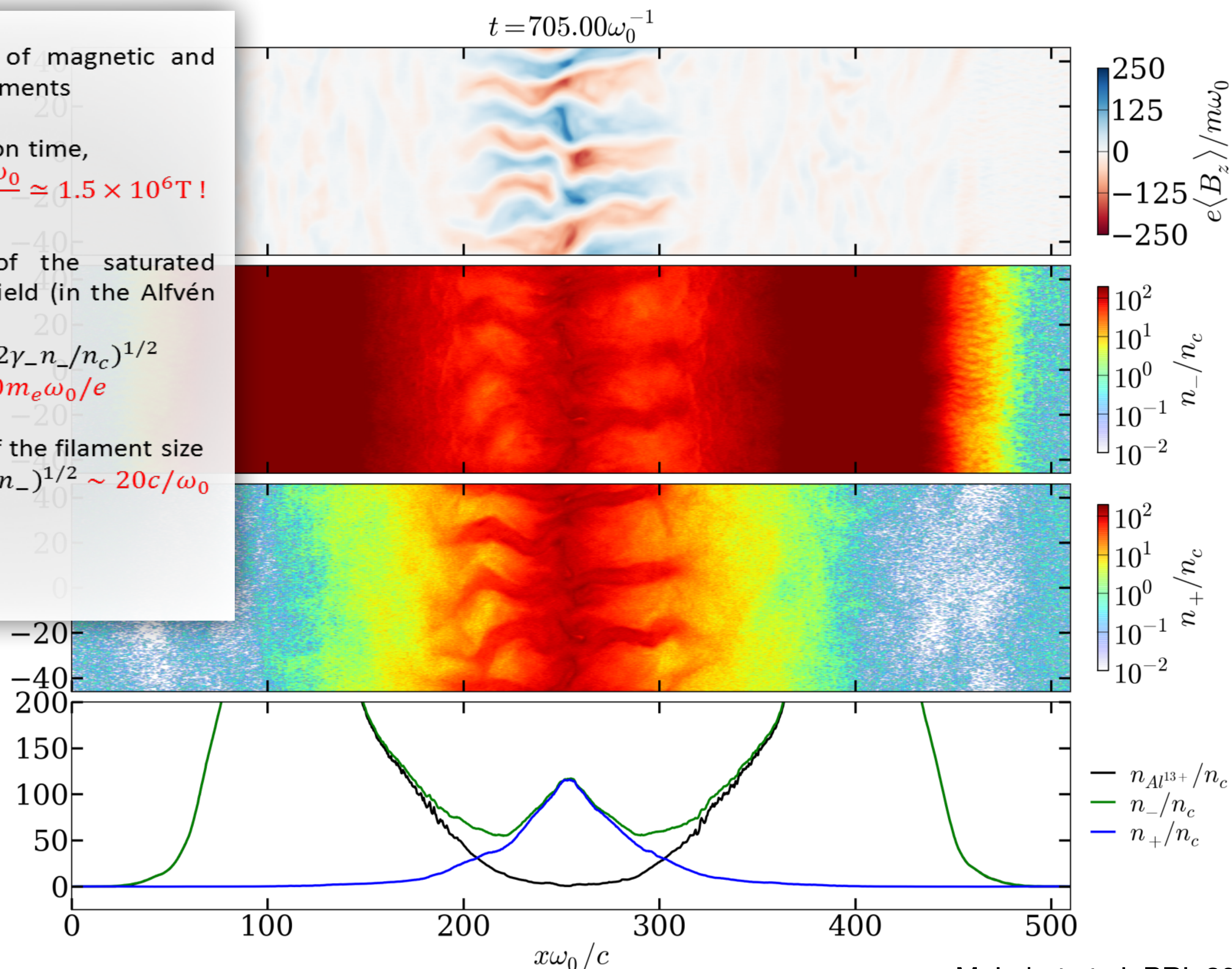
CALDER PIC Simulation

- **Laser:** plane wave, wavelength $\lambda_0 = 1\ \mu m$, Gaussian profile of $125\omega_0^{-1}$ (65 fs) FWHM, linear polarization, amplitude $a_0 = 800$ ($I \sim 8.9 \times 10^{23}\ \mathrm{Wcm^{-2}}$)
- **Target:** fully-ionized Al^{13+} slab of $32c\omega_0^{-1}$ ($5\ \mu m$) thickness + preplasma of $12.5c\omega_0^{-1}$ ($2\ \mu m$) thickness

M. Lobet et al. PRL 2015

Saturated magnetic fluctuations exceed 10^6 T!

- Formation of magnetic and density filaments
- At saturation time,
  $B_z \simeq 150 \frac{m_e \omega_0}{e} \simeq 1.5 \times 10^6 \text{T}$!
- Estimate of the saturated magnetic field (in the Alfvén limit)
  $B_{z,sat} = (2\gamma_- n_-/n_c)^{1/2} \sim 100 m_e \omega_0 / e$
- Estimate of the filament size
  $\lambda \sim 2\pi(n_c \gamma_-/n_-)^{1/2} \sim 20 c/\omega_0$



M. Lobet et al. PRL 2015

Outline

- High power laser systems and applications
- Experimental studies of collisionless shocks of interest for astrophysics
- Collision of plasmas in an external magnetic field as a platform to study magnetized collisionless shocks
- Collisionless shocks in electron-positron plasmas using extreme-light laser pulses
- **Conclusions and perspectives**

Conclusions and perspectives

- Steady progress in the development of high power laser systems and their applications
- Laboratory astrophysics experiments on MJ-scale facilities are still in their infancy but with progresses in diagnostics and simulations they should allow to test astrophysical models of collisionless shocks
- With the construction of UHI laser facilities it should be possible to achieve pair plasma collisions in the laboratory.
- Still a lot of open questions !

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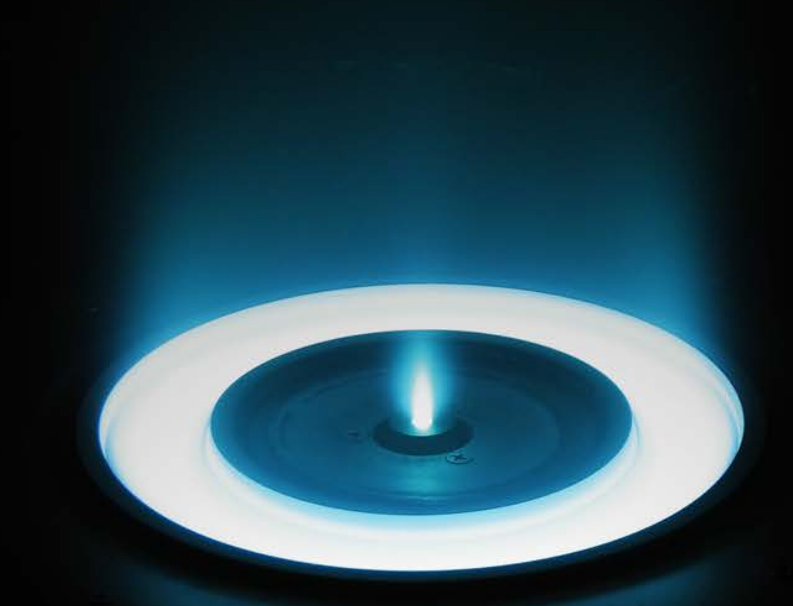

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