Laser-plasmas

– description and diagnostics

Workshop: *Quelles sont les possibilités d’expériences en astrophysique nucléaire avec les lasers?*

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Acknowledgments

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Dimitri Batani, Jérôme Faure, Malte Kaluza,
Victor Malka, Paul Neumayer, Michalis Tatarakis,
Vladimir Tikhonchuk, Luca Volpe

Outline

Description and diagnostics of laser-plasmas

→ What is a plasma?

→ Laser-plasmas

→ Electron acceleration in under-dense plasmas

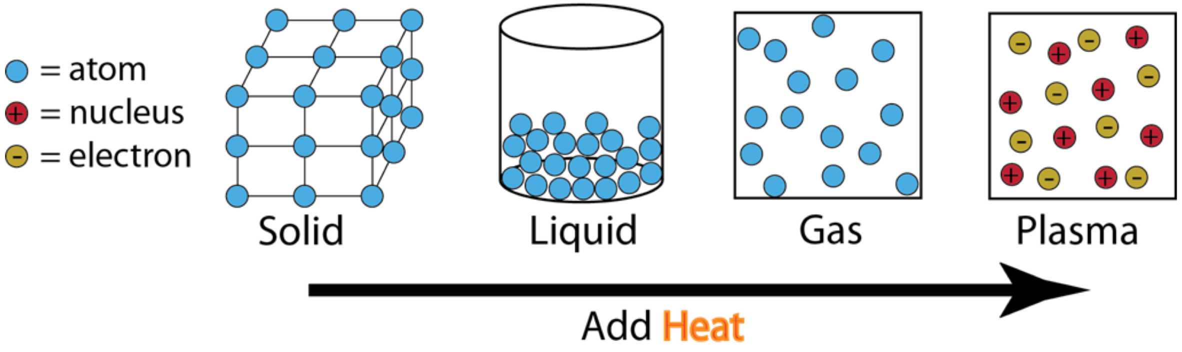
→ Relativistic electrons in dense matter

→ Magnetized high energy-density

What is a plasma ?

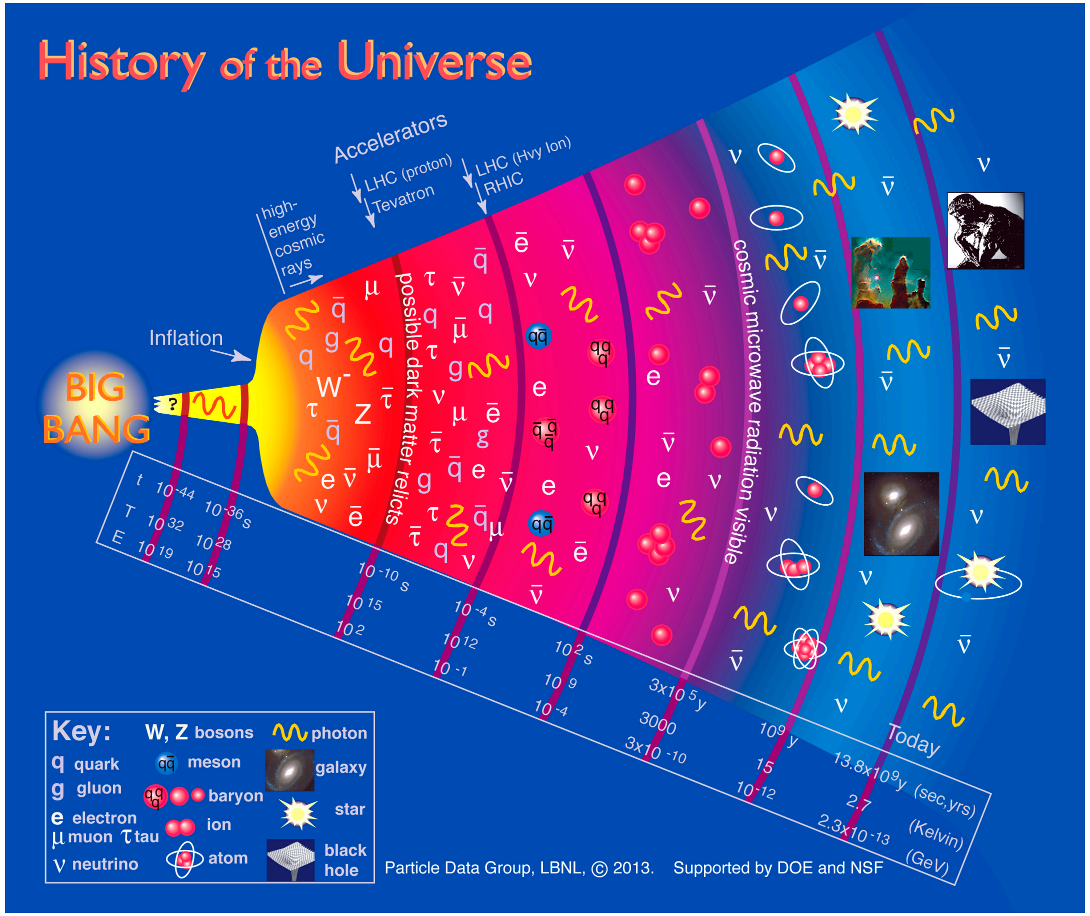
Plasma is a state of matter

→ **The state of matter changes as one adds energy…**



A partially or completely ionized medium

Plasma is the 4th state of matter



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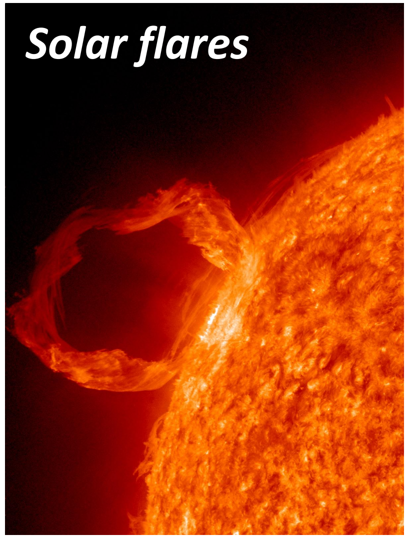
History of the Universe:

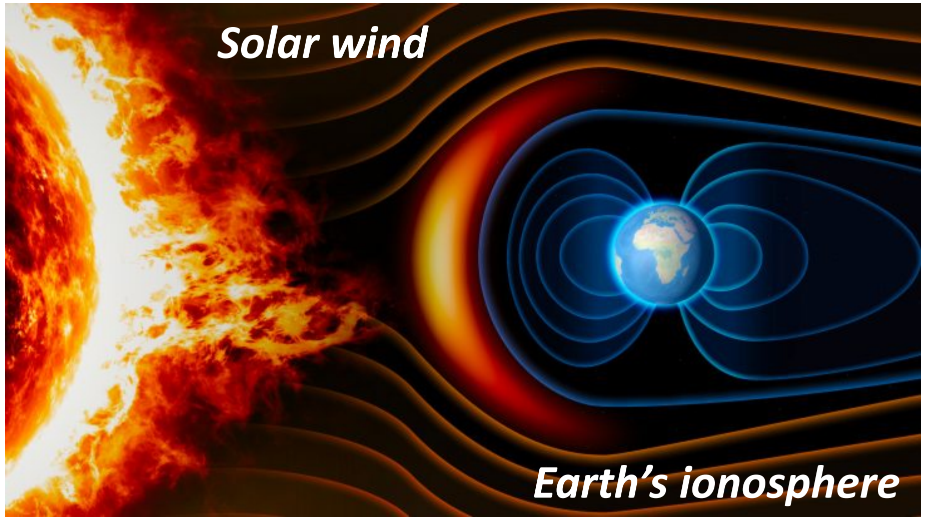
Plasma is the 1st state of matter

99% of matter in the Universe is in plasma state

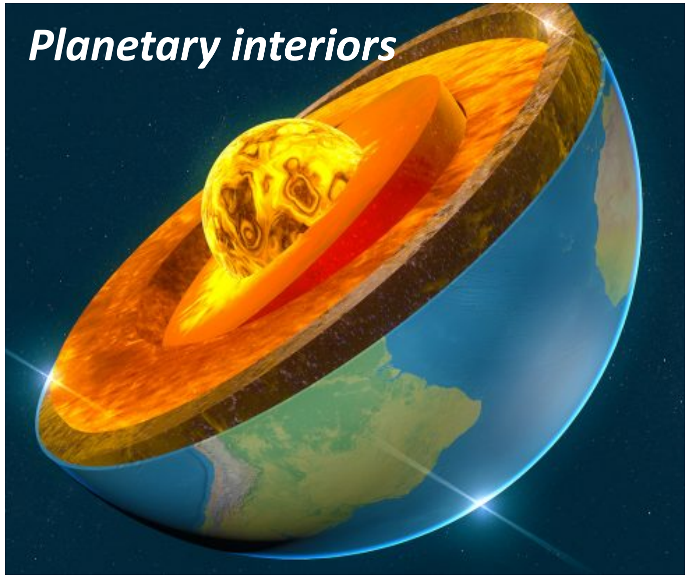

Interstellar space


Solar flares


Aurora borealis


Solar wind

Earth's ionosphere

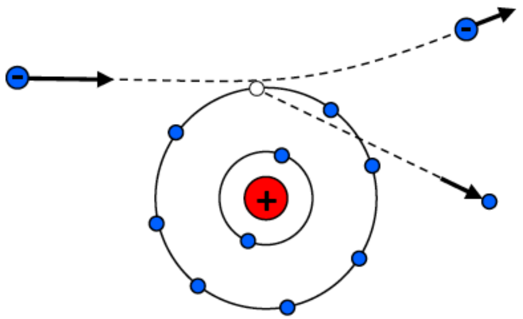

Planetary interiors


Lightning

What is a plasma ?

Matter at very high temperature

→ Temperature corresponds to the mean thermal kinetic energy $\frac{3}{2}k_BT \equiv \frac{1}{2}m\langle v^2\rangle$



Collisional ionization: $A^{n+} + e^- \rightarrow A^{(n+1)+} + 2e^-$

Saha equation (simplified) between A^0 and A^{1+}:

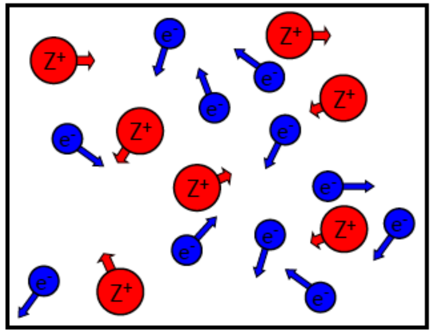
Typical ionization potential ~10 eV

$$\frac{n_1}{n_0} \propto \underbrace{\exp\left(-\frac{I_{\text{ioniz}}}{k_BT}\right)}$$

10^{-145} at room temperature

$\mathcal{O}(1)$ for $k_BT \sim 10$ eV

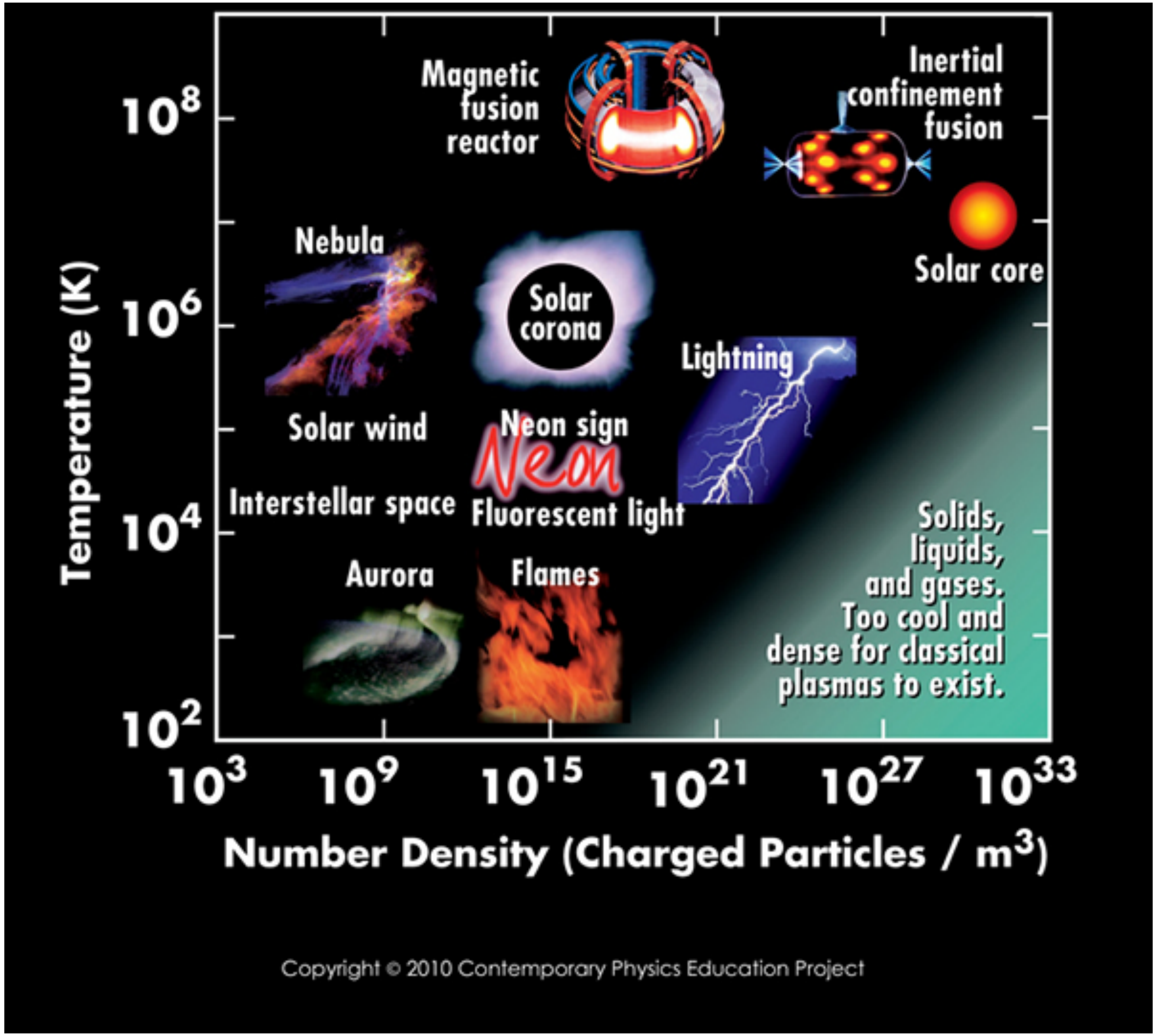
→ Plasma is a mixture of positive ions and electrons
(and maybe a small fraction of neutral atoms and molecules)



Many different kinds of plasma

→ Kind of plasma determined by the thermodynamic parameters

- Temperatures T_e, T_i
- Particle densities n_e, n_i
- Ionization state Z^*



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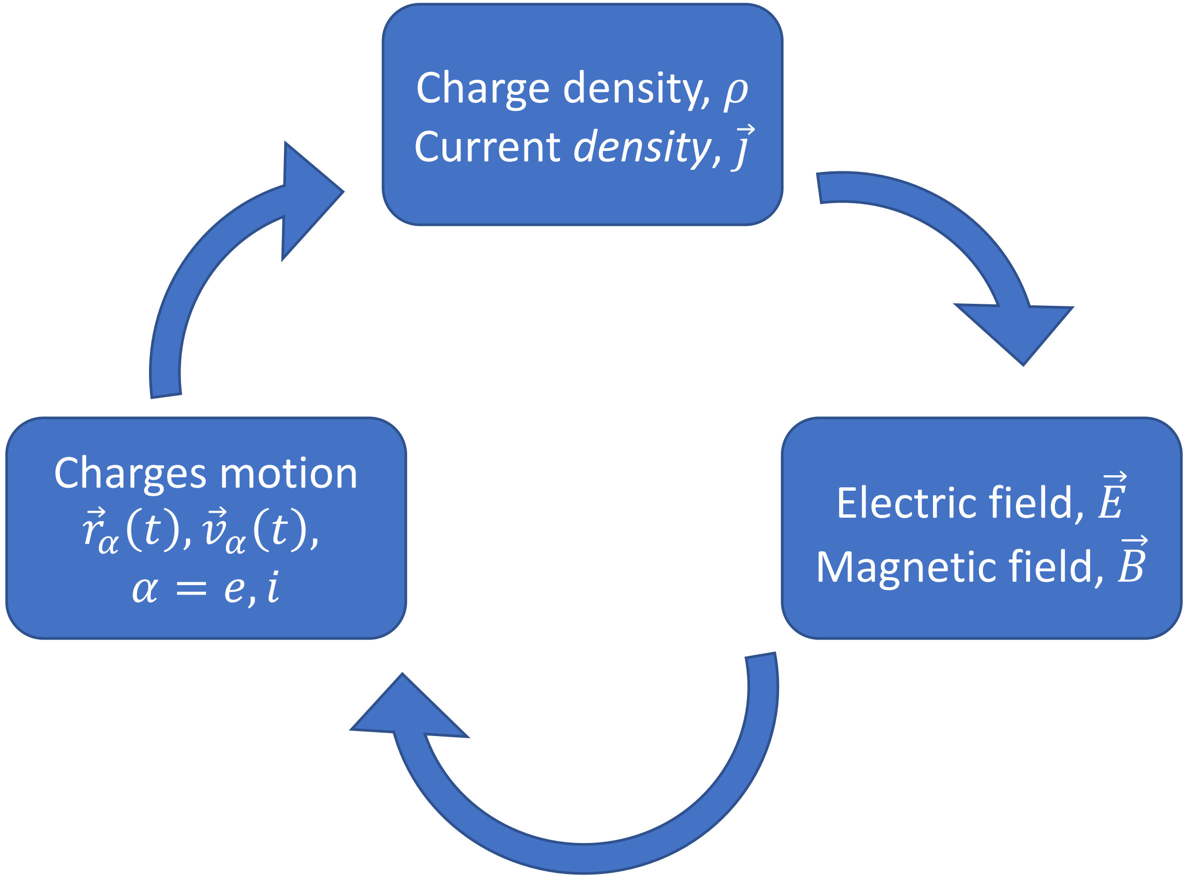
General behavior

→ Plasma: a quasi-neutral gas of charged (electrons + positive ions, $n_i \approx n_e$) and neutral particles which exhibit collective behavior



Charge density, ρ
Current density, $\vec{j}$

Electric field, $\vec{E}$
Magnetic field, $\vec{B}$

Charges motion
$\vec{r}_\alpha(t), \vec{v}_\alpha(t)$,
$\alpha = e, i$

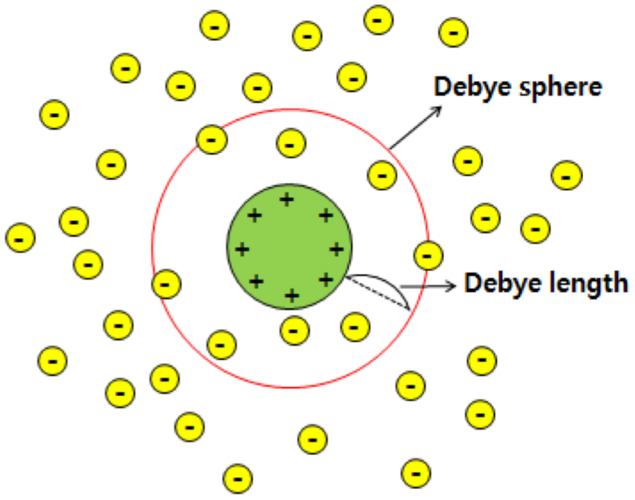
- Charges move and generate local concentration of + or – charge, therefore E-fields.
  Also, motion of charges generates currents, thus B-fields.
- Fields affect motion of other particles far away.
- Plasmas are very good conductors of electricity and are affected by B-field (diamagnetic behavior).
- Particles (charges) exchange momentum and energy through collisions. System tends to converge to equilibrium (Maxwell distributions, thermalization).
- According to temperature, density and the time-scale, plasma dynamics, out-of-equilibrium plasmas are described kinetically (e.g. PIC) and plasmas at equilibrium as fluids (MHD).
- $m_e \ll m_i \;\; \Rightarrow$ much shorter time-scale for electron dynamics.
  Ions follow by electrostatic effect on slower time scale, at the sound speed $c_s = \sqrt{Z^* k_B T_e / m_i}$

What is a plasma ?

Important spatial and time scales

→ Debye length:

Spatial-scale of deviation from electric neutrality



$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{e^2 n_e}}$$

$$\Phi = \Phi_0 \underbrace{\exp(-r/\lambda_D)}_{\text{Plasma screening}}$$

Coulomb potential

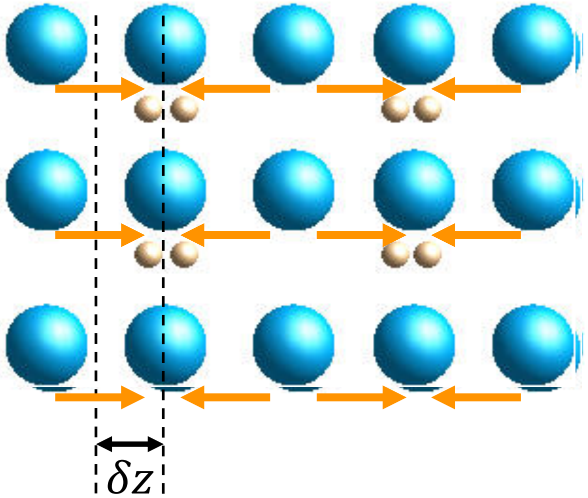
→ Electron thermal velocity:

≈ the mean velocity due to thermal agitation

$$v_{Te} = \lambda_D \omega_{pe} = \sqrt{\frac{k_B T_e}{m_e}}$$

→ Plasma frequency:

(inverse of) time-scale of deviation from electric neutrality



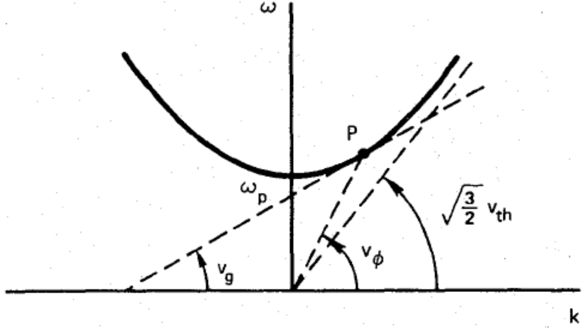
$$E_z \sim e n_e \delta z / \epsilon_0$$

$$\frac{d^2 \delta z}{dt} + \omega_{pe}^2 \delta z = 0$$

$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\epsilon_0 \gamma m_e}}$$

Dispersion due to thermal motion

⇒ electrostatic plasma waves



$$\omega^2 = \omega_{pe}^2 + \frac{3}{2} k^2 v_{Te}^2$$

Criteria for plasma behavior

→ A plasma has *classic* collective behavior if:

$$N_D \gg 1$$

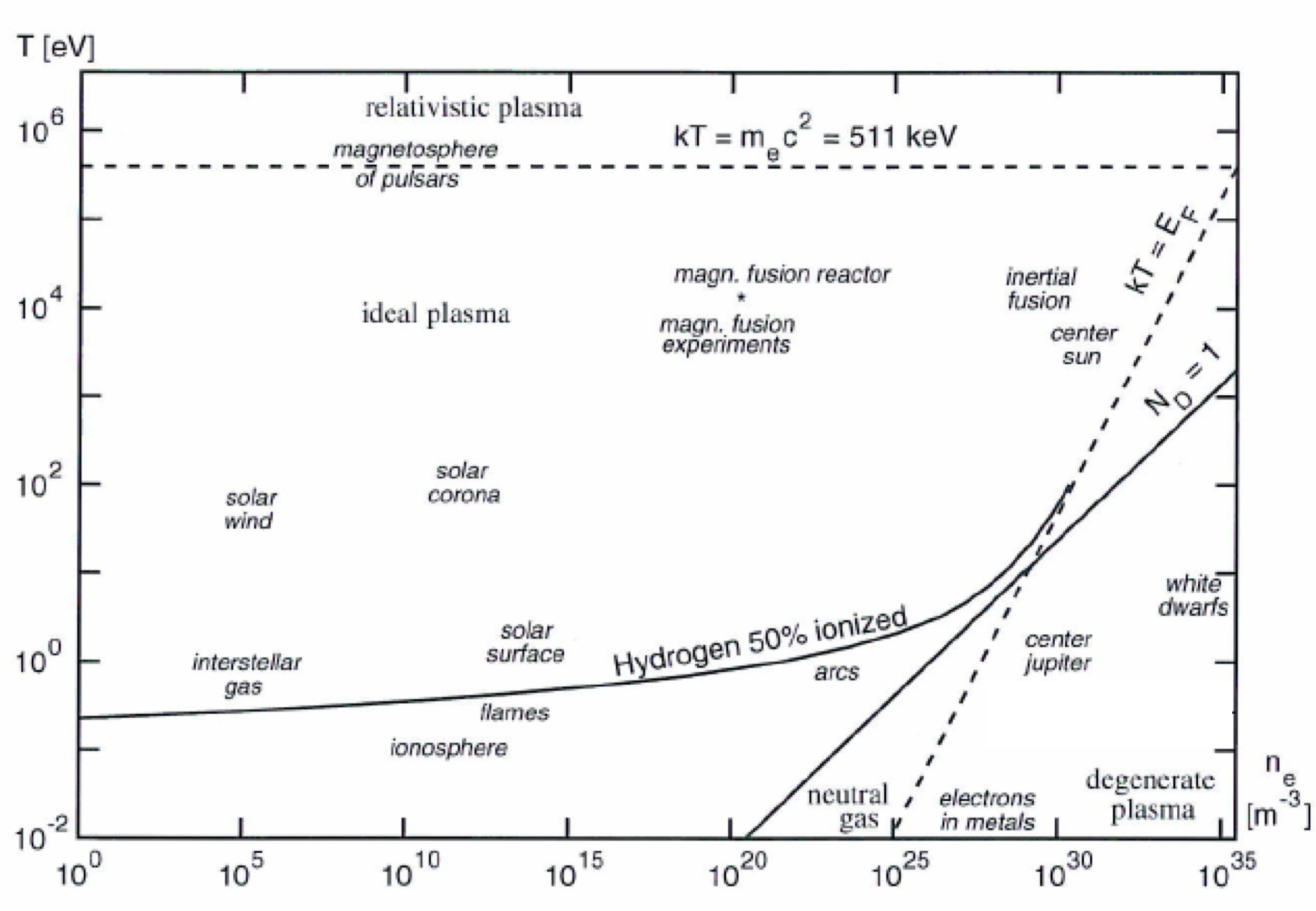
Average number of electrons in the Debye sphere
$N_D = n_e \frac{4}{3}\pi\lambda_D^3$

$$\lambda_D \ll L$$

Characteristic dimension of the system

$$\omega_{pe}\tau_{coll} > 1$$

Mean time between collisions



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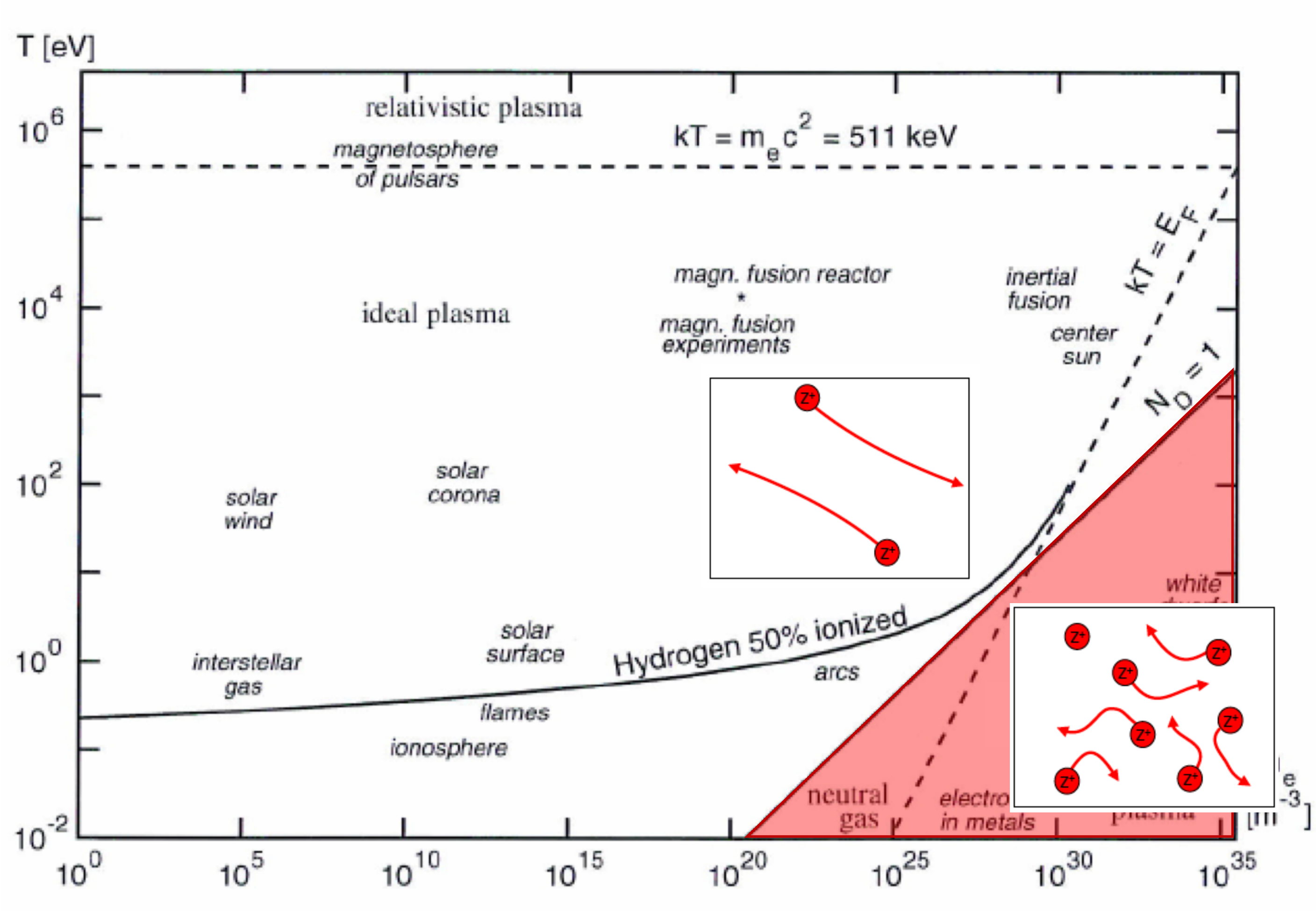

Strongly-coupled plasma if

$N_D < 1$

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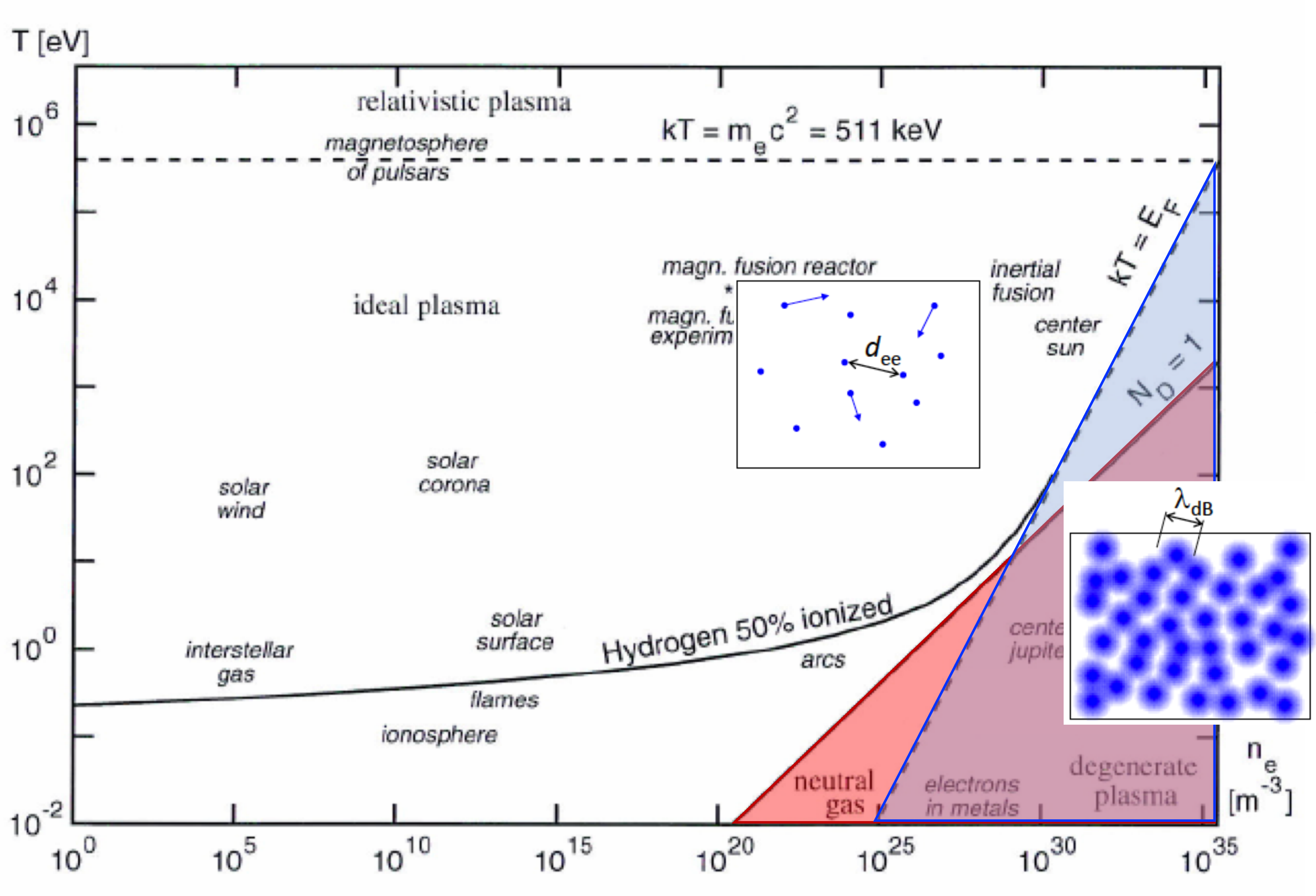


(Partly-)degenerated plasma if

$k_B T < E_F \quad \Leftrightarrow \quad \lambda_{dB} > d_{ee}$

Fermi energy

Strongly-coupled plasma if

$N_D < 1$

What is a plasma ?

Criteria for plasma behavior

→ **A plasma has *classic* collective behavior if:**

$\boldsymbol{N_D \gg 1}$

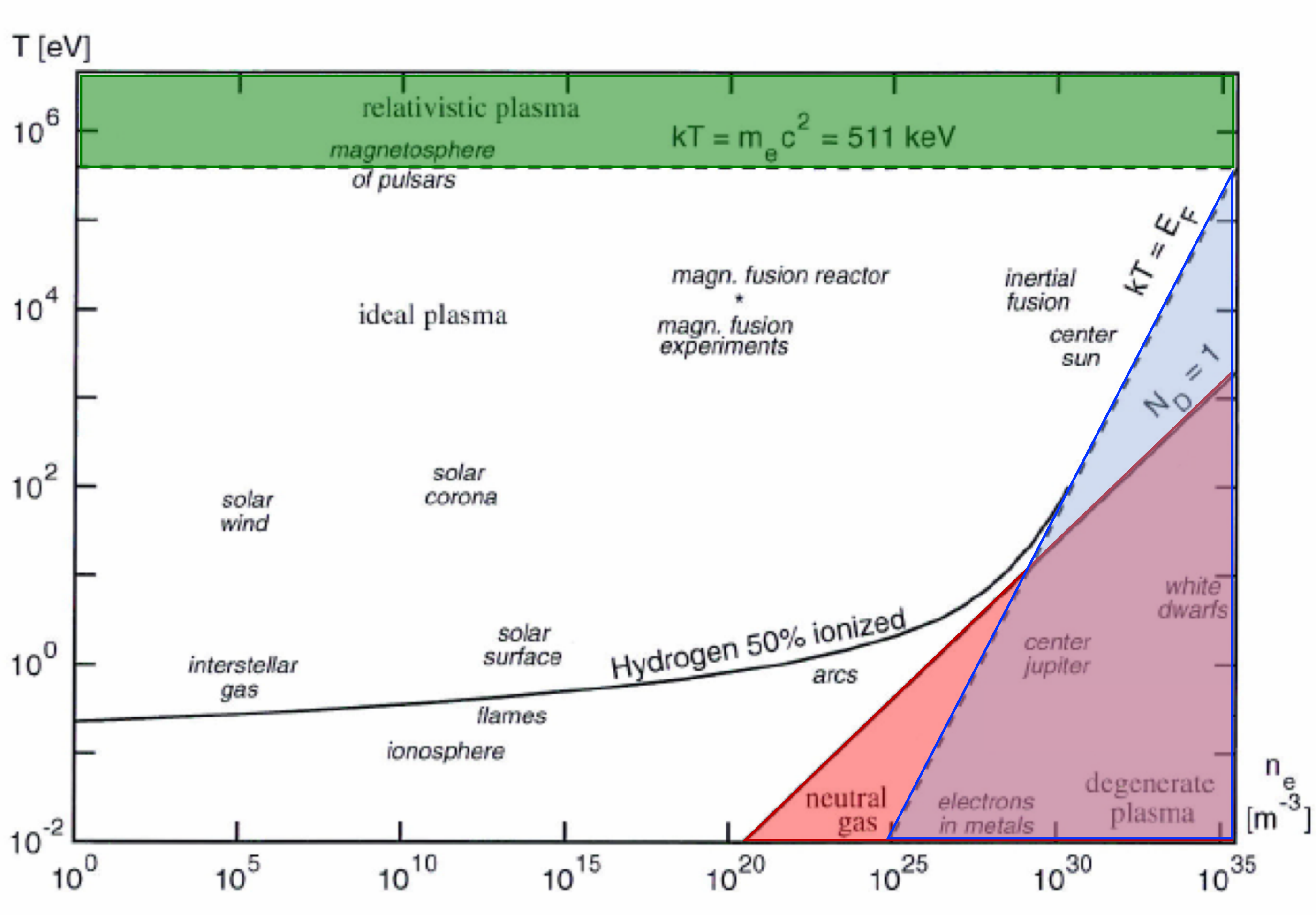
Average number of electrons in the Debye sphere $N_D = n_e \frac{4}{3}\pi\lambda_D^3$

$\boldsymbol{\lambda_D \ll L}$

Characteristic dimension of the system

$\boldsymbol{\omega_{pe}\tau_{coll} > 1}$

Mean time between collisions



Relativistic plasma if

$k_BT > m_ec^2$

(Partly-)degenerated plasma if

$k_BT < E_F \quad \Leftrightarrow \quad \lambda_{dB} > d_{ee}$

Fermi energy

Strongly-coupled plasma if

$N_D < 1$

Outline

Description and diagnostics of laser-plasmas

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- → Relativistic electrons in dense matter
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Electromagnetic waves in plasmas: the critical density

Propagation of electromagnetic (e.m.) waves (of frequency ω) in plasmas:

$$\vec{\nabla}^2\vec{E} - \frac{1}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = \frac{\omega_{pe}^2}{c^2}\vec{E} \qquad \Rightarrow \qquad k = \frac{\sqrt{\omega^2-\omega_{pe}^2}}{c}$$

→ The electron density corresponding to $\omega = \omega_{pe}$ is the **critical (or cutoff) density**

$$n_c = \frac{\epsilon_0 \gamma m_e \omega^2}{e^2} = \frac{\gamma\ 1.11\times 10^{21}\ \mathrm{e/cm^3}}{\lambda^2\ [\mu\mathrm{m}]}$$

→ Plasma refractive index

$$\eta = \sqrt{1-\frac{\omega_{pe}^2}{\omega^2}} = \sqrt{1-\frac{n_e}{n_c}} < 1\ !$$

- k is complex for $\omega < \omega_{pe}$

  The e.m. wave decays exponentially over skin depth $\delta_s \approx c/\omega_{pe}$ (over-dense limit)

- k is real for $\omega > \omega_{pe}$

  The e.m. wave propagates with phase velocity

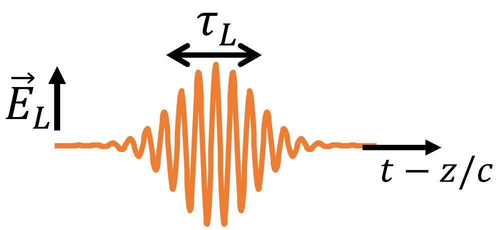
$$v_\varphi = \frac{\omega}{k} = \frac{c}{\sqrt{1-\frac{\omega_{pe}^2}{\omega^2}}} = \frac{c}{\sqrt{1-\frac{n_e}{n_c}}}$$

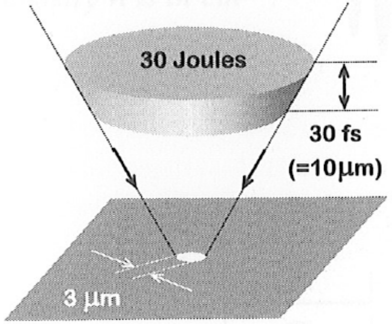
  and group velocity

$$v_g = \frac{\partial\omega}{\partial k} = c\sqrt{1-\frac{\omega_{pe}^2}{\omega^2}} = c\sqrt{1-\frac{n_e}{n_c}}$$

Intense pulsed lasers

→ Laser pulses are bunches of coherent light and the most efficient way to transport energy-density





A significant energy, ε_L, can be delivered in a short pulse of duration τ_L

Pulse power $P_L = \frac{\varepsilon_L}{\tau_L} = \frac{30\ \mathrm{J}}{30\ \mathrm{fs}} = 1\ \mathrm{PW}$

It can be focused onto a small area

Pulse intensity or energy-density flux $I_L = \frac{1}{2}\epsilon_0 c E_L^2 \approx \frac{P_L}{\pi r_L^2} = \frac{30\ \mathrm{J}}{\pi\,(1.5\times10^{-4})^2\ \mathrm{cm}^2} \approx 10^{22}\ \mathrm{W/cm^2}$

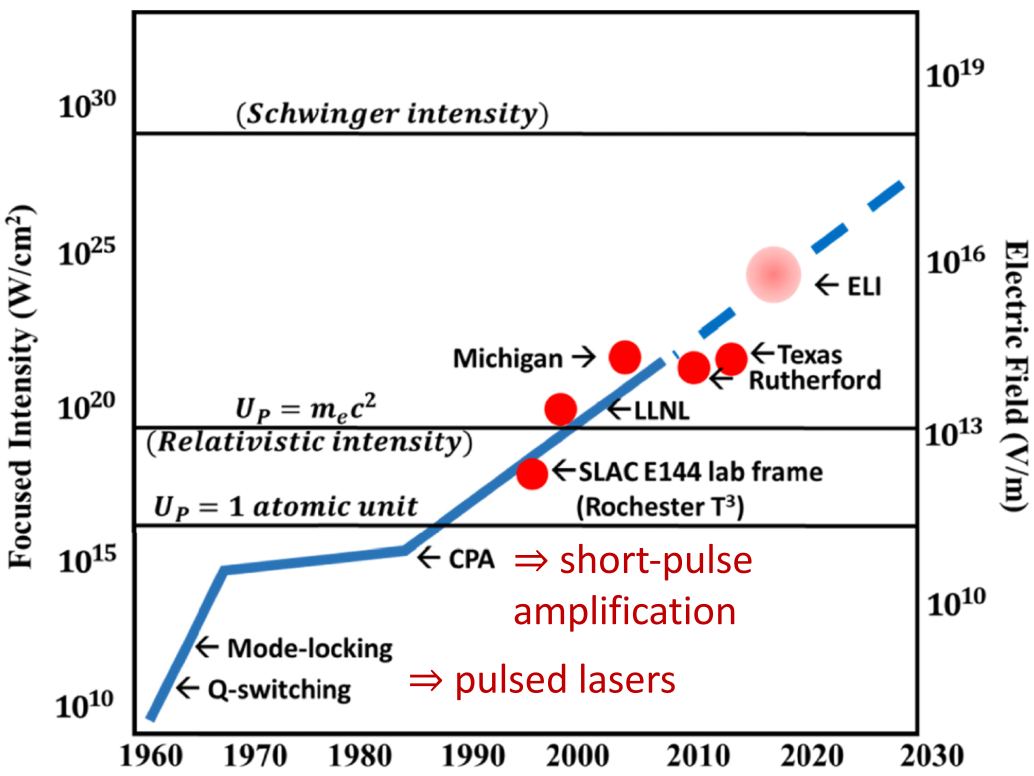
Extreme fields in the laser focus spot:

$$E_L^{\max}[\mathrm{V/m}] = 2.75\times10^{14}\left(\frac{I_L}{10^{22}\ \mathrm{W/cm^2}}\right)^{1/2}$$

$$B_L^{\max}[\mathrm{Tesla}] = 9.2\times10^{5}\left(\frac{I_L}{10^{22}\ \mathrm{W/cm^2}}\right)^{1/2}$$

$$a_0 = \frac{eE_L}{m_e\omega_L c} = 0.85\sqrt{I_{18}\lambda_{\mu\mathrm{m}}^2}$$

Chronologic evolution of laser intensity



⇒ short-pulse amplification

⇒ pulsed lasers

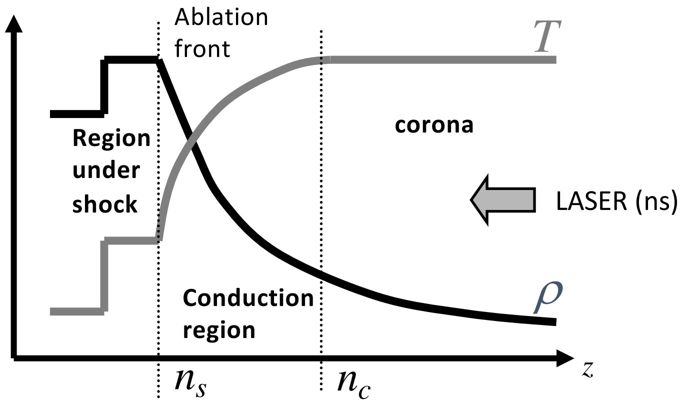
$$\gamma_e = \sqrt{1 + a_0^2/2}$$

Relativistic electron motion for $a_0 > 1$

Laser-plasma interactions in different regimes (with over-critical targets)

→ Long-pulse regime $\tau_L \sim 100\ \mathrm{ps} - 10\ \mathrm{ns}$

$I_L \sim 10^{13} - 10^{17}\ \mathrm{W/cm^2}$



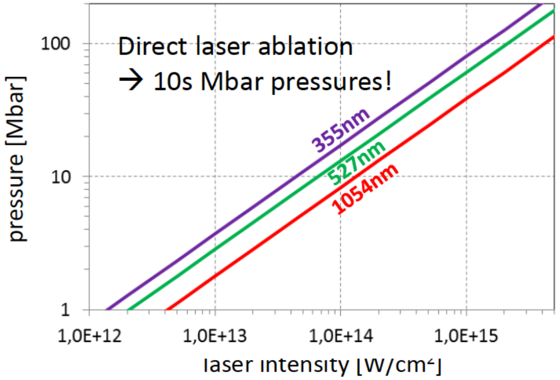
The laser pulse couples with a long density gradient under-dense plasma

Efficient absorption (⇒ heating) by inverse bremsstrahlung (collisional)

$$T \propto (I_L\lambda_L^2)^{2/3} \qquad p \propto \left(\frac{I_L}{\lambda_L}\right)^{2/3}$$

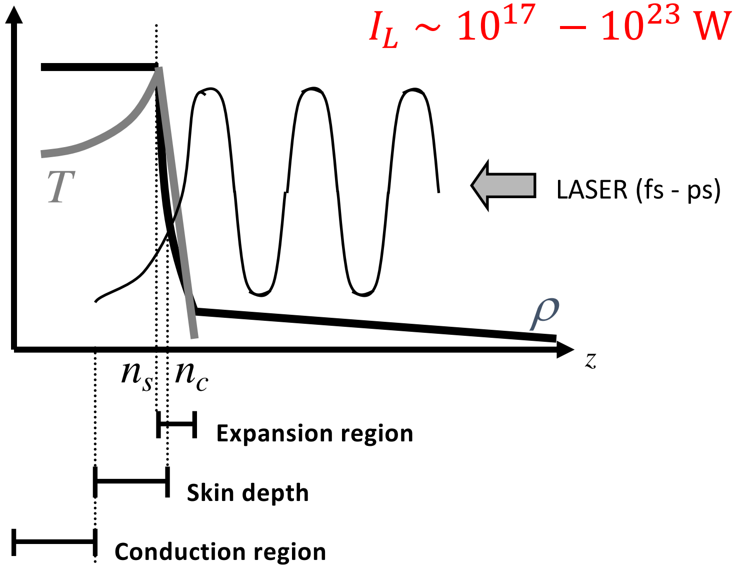
→ Laser-driven shocks

if $\frac{\rho c_s}{\nabla p} \ll \frac{L}{c_s}$



→ Short-pulse regime $\tau_L \sim 10\ \mathrm{fs} - 10\ \mathrm{ps}$

$I_L \sim 10^{17} - 10^{23}\ \mathrm{W/cm^2}$



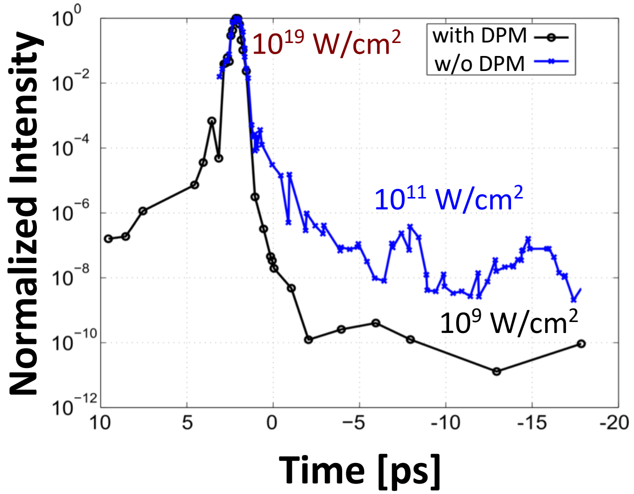
The laser pulse couples with a sharp edge plasma

… unless the target surface is already disturbed by laser ASE pedestal or pre-pulses

Case $a_0 > 1$ (relativistic pulses):

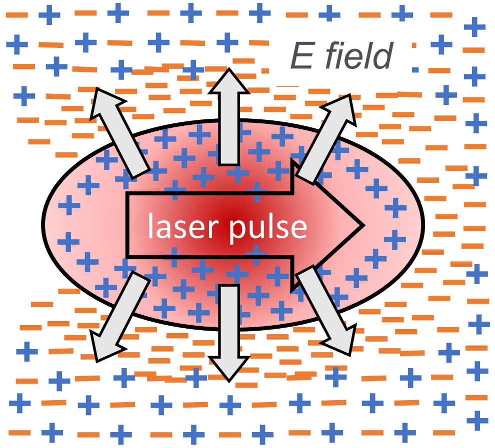
→ Significant fraction of the laser energy transferred into relativistic electrons

→ Isochoric heating by laser-accelerated particles



Laser-plasmas

The ponderomotive force



→ **An intense laser pulse expels electrons**, like a snowplow, **from the regions of higher intensity**

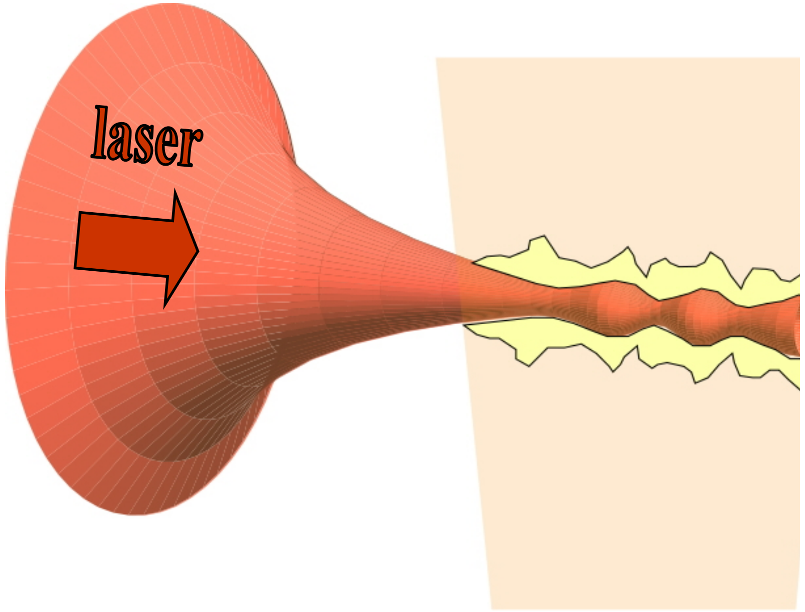
$$\overrightarrow{F_P} \propto -\frac{q^2}{m}\vec{\nabla}\langle I_L\rangle$$

NB *Independent of the charge sign, yet dependent on the particle's mass*

→ At a slower time-scale, ions will follow due to space charge field $E \approx \frac{k_B T_e}{e\lambda_D}$

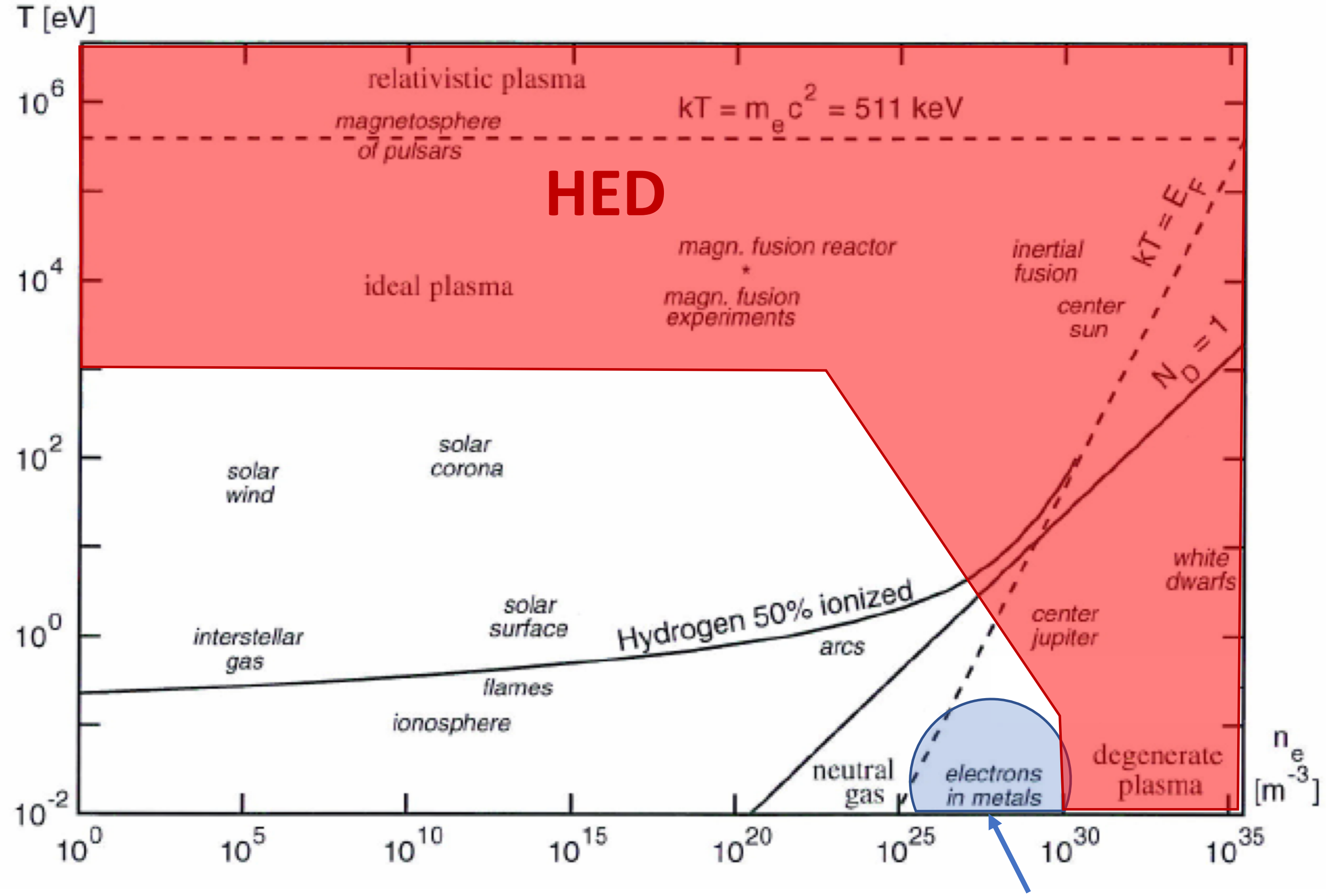
→ Channel hollowing on under-dense plasma

→ Laser-pulse self-focusing if laser power $P_L > 17\,\frac{\omega^2}{\omega_{pe}^2}\,\mathrm{GW}$



Intense lasers drive matter to extreme conditions

→ **High energy-density matter (HED) corresponds to $>10^{11}$ J/cm^3, or a pressure >1 Mbar**
It occurs in planetary interiors, compact stars, supernovae explosions, γ-ray bursts, inertial confinement fusion



Condensed matter

Intense lasers drive matter to extreme conditions

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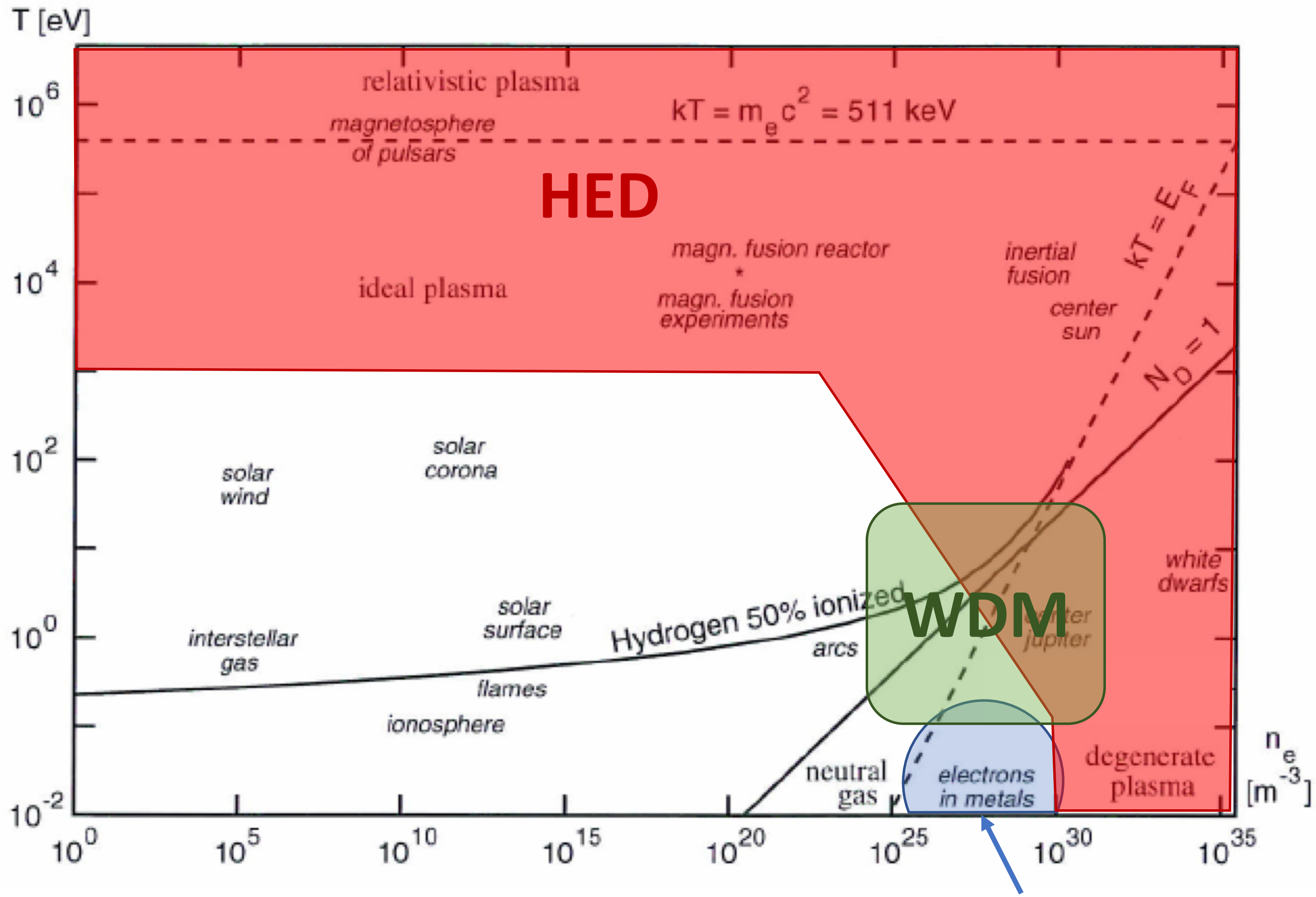


Condensed matter

Warm Dense Matter (WDM):

- Density of 1 – 10x solid density
- Warm temperature (0.1 – 100 eV), *not hot!*

WDM is highly complex:

- Strong ion coupling ($E_{pot} \sim k_BT_i$)
- Electrons partly degenerate ($E_F \sim k_BT_e$)
- Partial ionization
- Chemical bonding
- Phase transitions, phase coexistence, critical points
- Collisions (conductivity, heat transport): $\ln \Lambda_C < 0$
- Radiation transport

It occurs in:

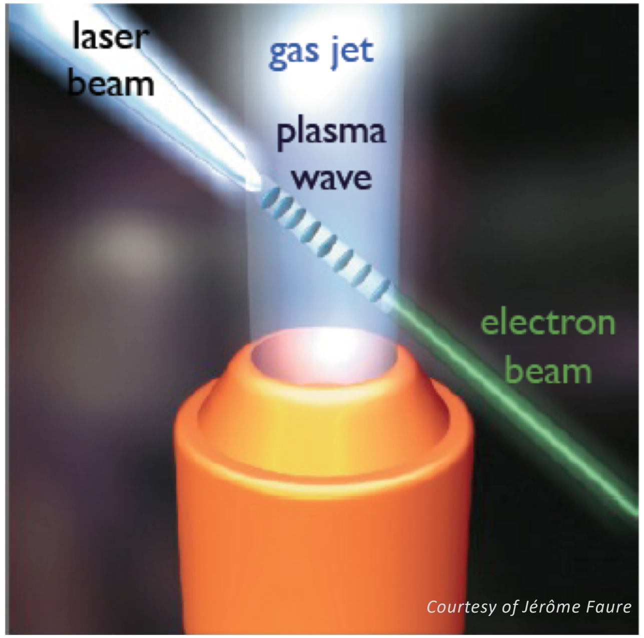
- Transition solid-to-plasma
- Planetary interiors
- Inertial confinement fusion (corona)

Ultra-short, intense and high-energy sources of particles and radiation

→ **Plasmas withstand very high E-fields ~TV/m**

No risk of breakdown in plasma, it is already ionized!

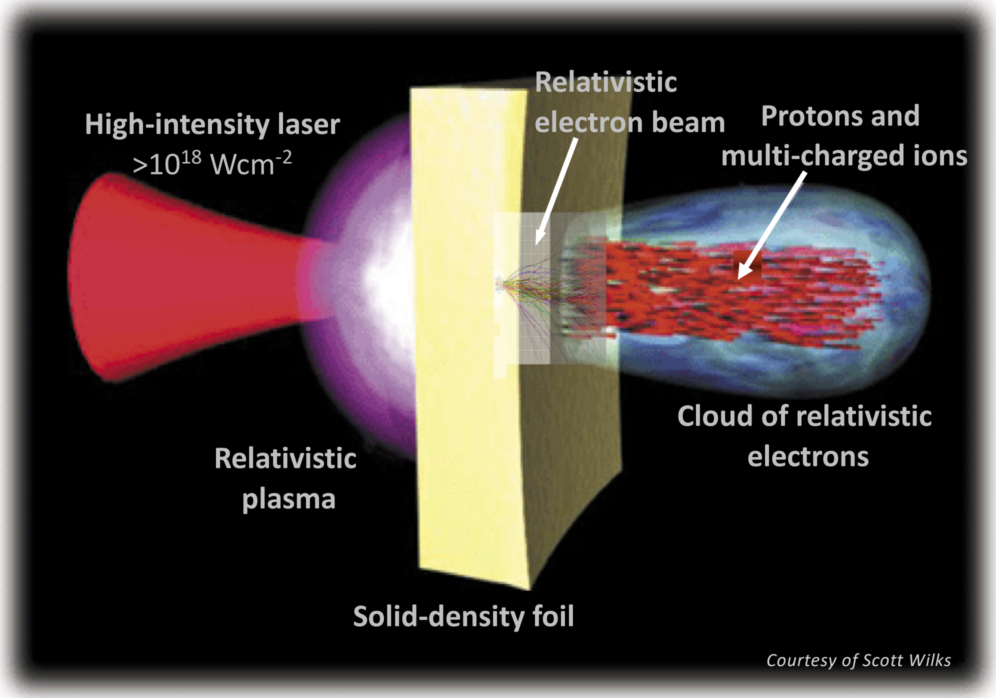
Relativistic laser interactions in under-dense matter…



Courtesy of Jérôme Faure

- ✓ Electrons accelerated up to 10 GeV in the laser pulse wake-field (~100 GV/m over 10 cm)
- ✓ Betatron X-rays issue from the electron undulations

… and in over-dense matter



Courtesy of Scott Wilks

- ✓ MA currents of relativistic (~MeV) electron beams
- ✓ Thermal (100 eV - keV) and hard (keV - MeV) X-rays
- ✓ 10s MeV ion beams accelerated by space charge fields (~1 TV/m over 10 µm)

Relevant parameters and adapted diagnostic techniques

→ How to characterize (and control) a laser-driven plasma?

1. Electric-, $\vec{E}$, and magnetic-field, $\vec{B}$
    - *probing charges (proton deflectometry)*
    - *Faraday rotation of optical probe laser*

2. Charged particles flux
    - *Scintilators, radiochromic films, permanent magnet spectrometers, Thomson parabola*
    - *e.m. emission: cyclotron/synchrotron, bremsstrahlung, Cerenkov, transition radiation, …*

3. Plasma refractive index, electric and thermal conductivity
    - *Absorption and reflection of probe lasers*

4. Over-dense plasma density, ρ, and temperature, T
    - *X-ray emission from partially ionized atoms (spectral lines spectrum)*
    - *Scattering of e.m. waves by plasma particles (e.g. visible and/or X-ray Thomson scattering)*
    - *X-ray radiography (ρ)*

5. Under-dense plasma density, ρ
    - *Optical shadowgraphy, strioscopy, interferometry*

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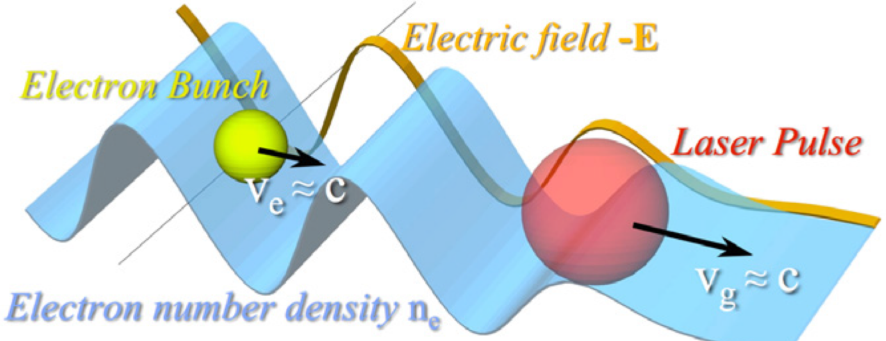
Laser wake-field acceleration

→ Short-pulse laser ponderomotive force excites an electron plasma wave

Wake-field resonance condition: $\tau_L \approx \pi/\omega_{pe}$



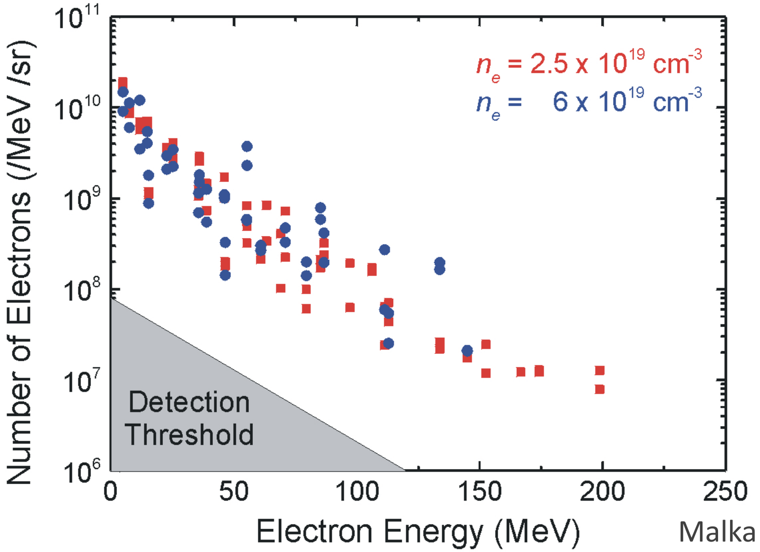
Albert *et al.*, PPCF 2014

$$E_{\text{plasma}} \approx 30\,\frac{\delta n_e}{n_e}\sqrt{\frac{n_e}{10^{17}\,\text{cm}^{-3}}}\ \text{GV/m}$$

≈ 300 GV/m for 100% density perturbation at 10^{19} cm^{-3}

→ Electrons with $v \sim v_\varphi^{\text{plasma}} \approx v_g^{\text{laser}}$ trap the accelerating wave

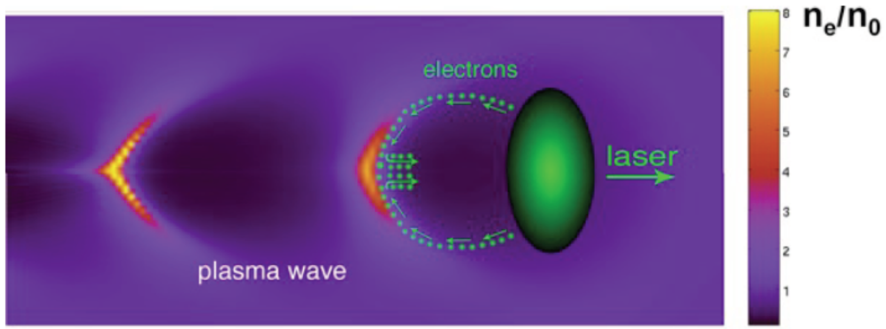
→ Wavebreaking injects electrons, yet also leads to broad electron spectra



Malka *et al.*, Science 2002

The plasma bubble and mono-energetic GeV electron beam acceleration

→ A laser pulse smaller than the plasma wavelength in both longitudinal and transverse directions may lead to a monoenergetic electron beam



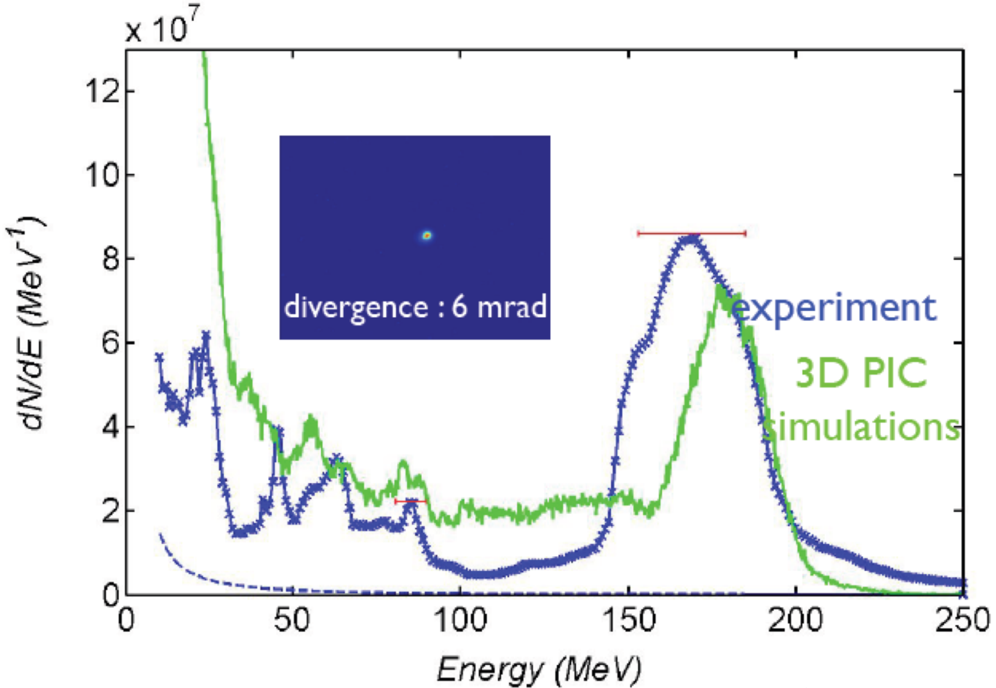
localized self injection in the bubble/
blow-out regime

surfing behind a wake boat

Guiding equilibrium criteria: $k_{pe}\omega_L \approx 2\sqrt{a}$

A. Pukhov & J. Meyer-ter-Vehn, Appl. Phys. B **74**, 355-361 (2002),

Courtesy of Victor Malka

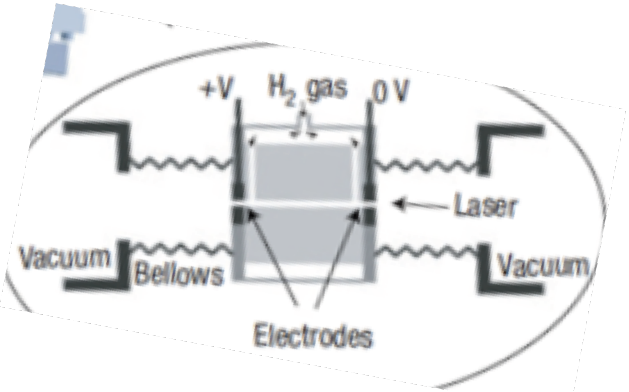


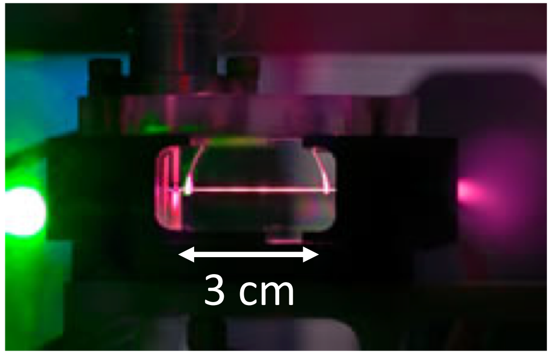
Faure *et* al., Nature 2004

→ Quasi-monoenergetic GeV electron beams from cm-scale capillary discharge accelerators

Leemans *et* al., Nat. Phys. 2006

Current record @ BELLA (LBNL): 8.5 GeV over 9 cm
~10 pC accelerated charge with 0.3 PW laser in <10^{18} cm^{-3} plasma



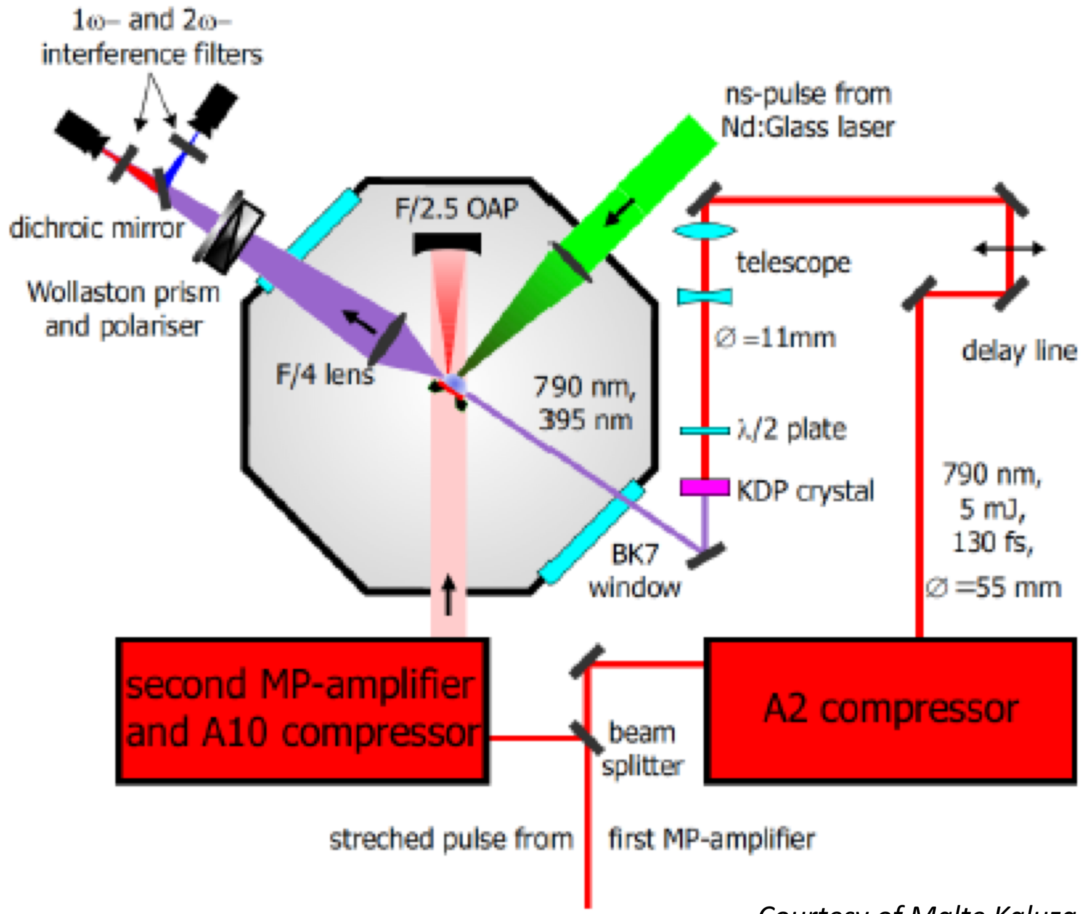


Pump-probe setup

→ **Challenge: probe a tiny** (length $\approx \lambda_p \sim 10\ \mu\text{m}$) **fast moving** ($v_p \sim c$) **laser wake-field feature**

⇒ **pump-probe laser: optical shadowgraphy, interferometry, polarimetry**

Typical setup



Courtesy of Malte Kaluza

Generation of synchronized optical probe pulses :

- split off part of the main pulse
- guide it towards interaction along different path
- adjust temporal delay

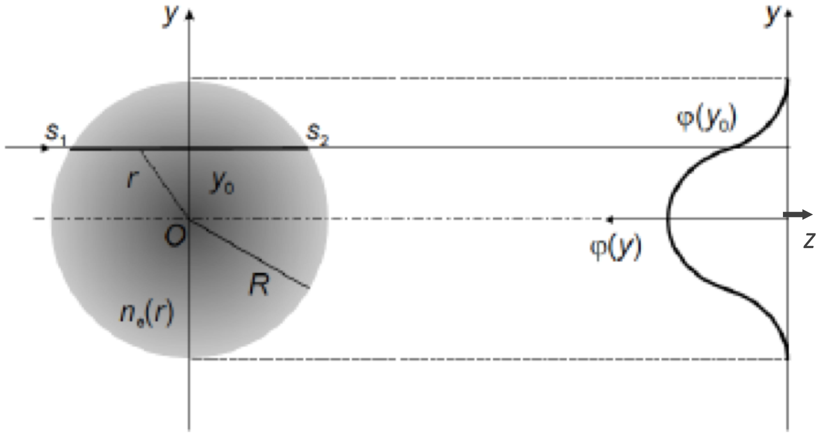
⇒ probe pulse duration similar to main pulse

⇒ perfect synchronization

⇒ record movie from subsequent shots at different delays (requires good shot-to-shot stability)

Interferometry: measurement of the plasma density

➜ An interferometer visualizes phase difference between ray probing the plasma and probe ray going through vacuum

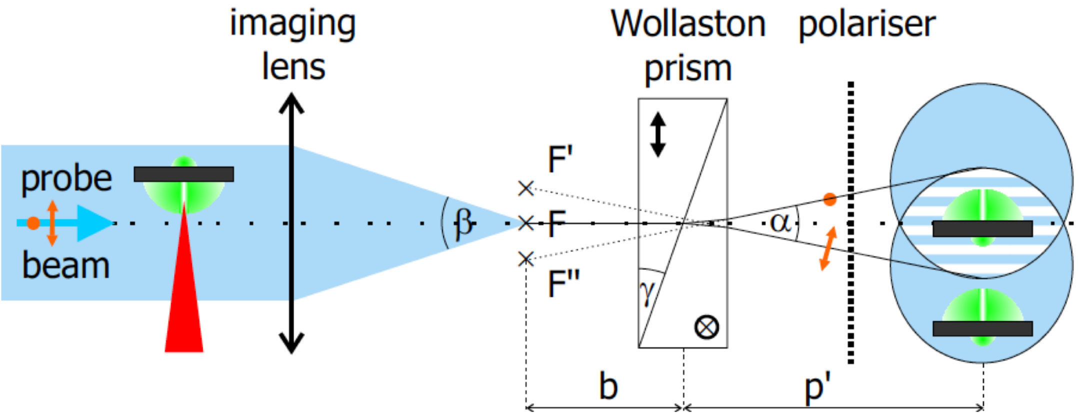


Plasma refractive index

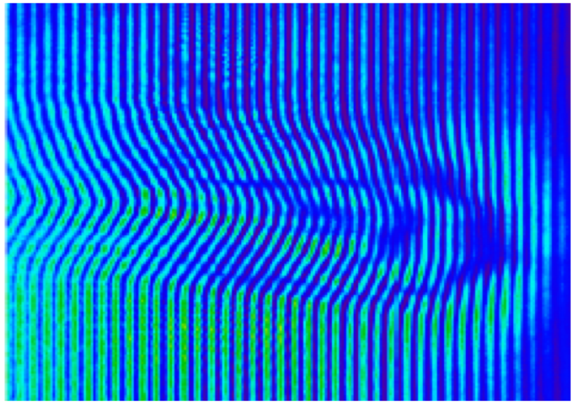
$$\eta = \sqrt{1-\frac{\omega_{pe}^2}{\omega^2}} = \sqrt{1-\frac{n_e}{n_c}}$$

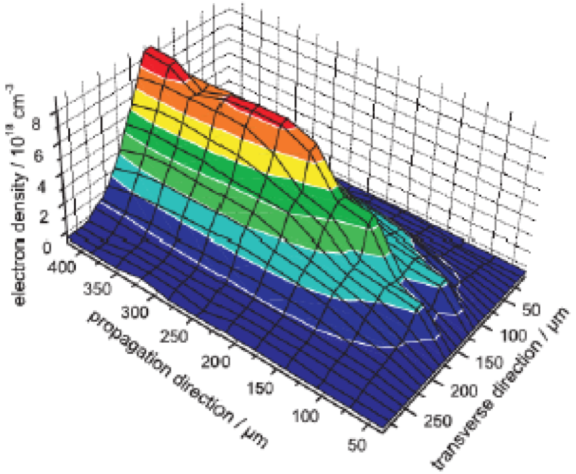
$$\Delta\varphi(y) = \frac{2\pi}{\lambda_{\text{probe}}}\int_{-z_1}^{z_2}\big(1-\eta(y)\big)dz$$

➜ **Nomarski interferometer** facilitates obtaining time-superposition of the plasma and reference short-pulse signals



Cylindrical symmetry is commonly assumed and plasma density map is obtained by Abel inversion of the phase difference map.

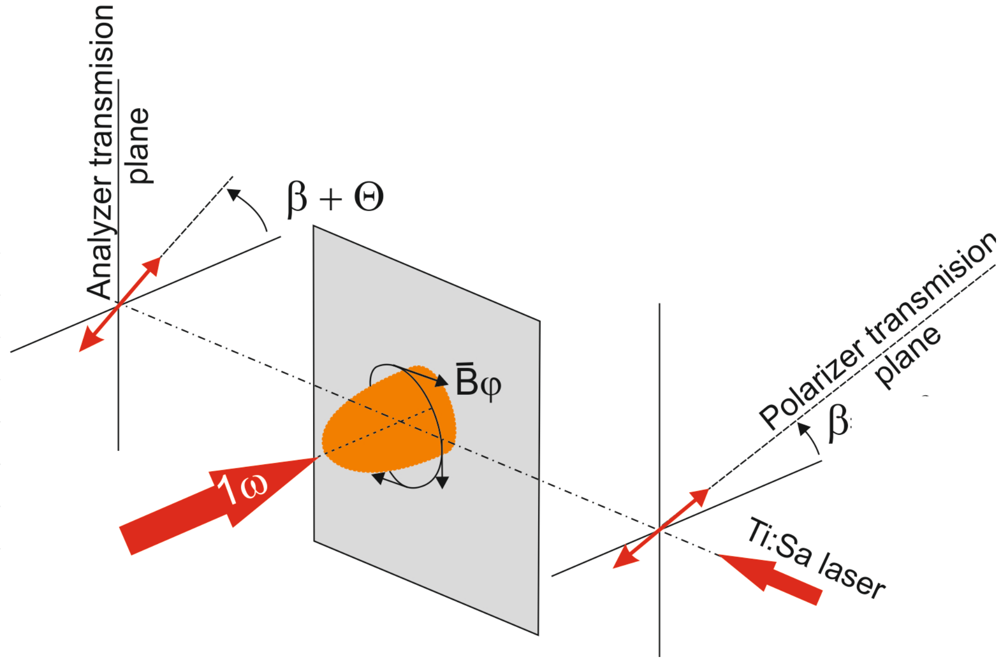


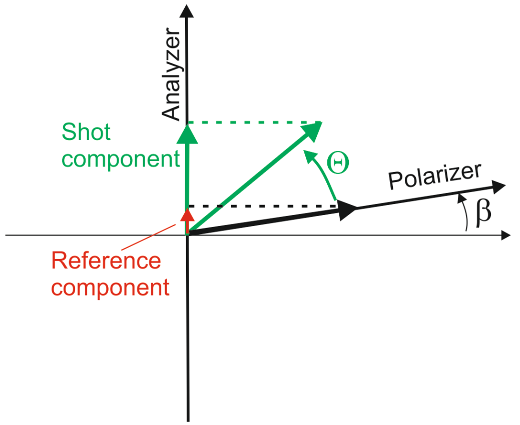


Schlenvoigt, PhD thesis, Univ. Jena 2009

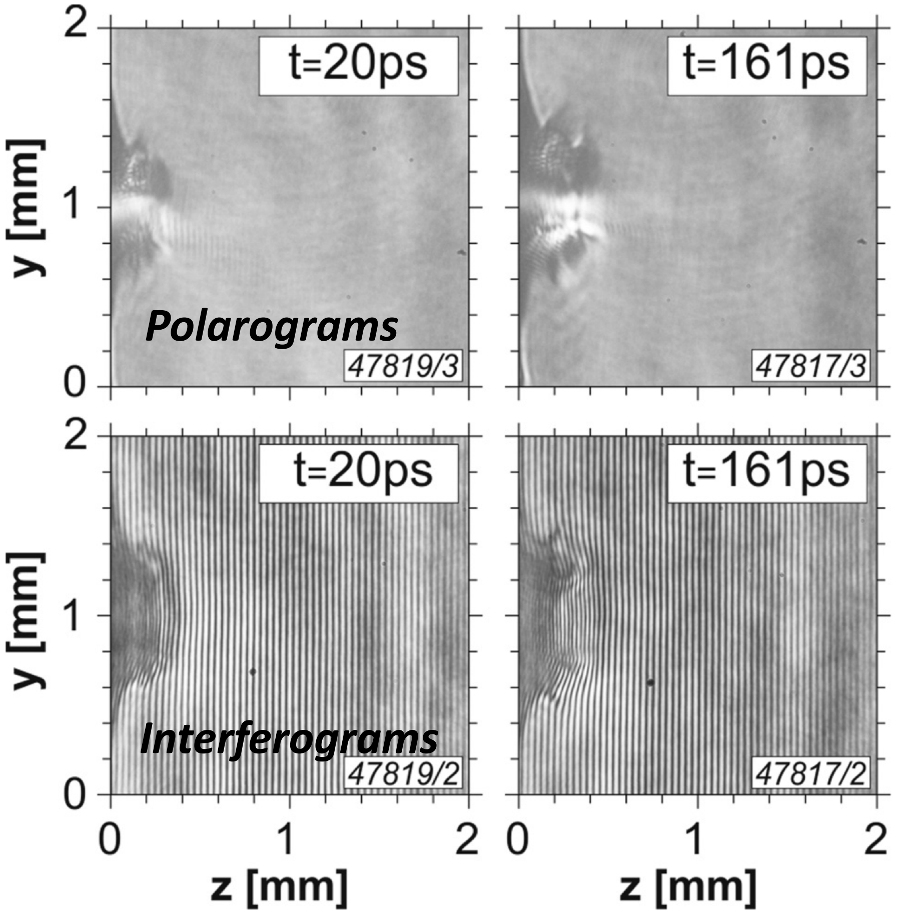
Polarimetry: measurement of the plasma self-generated B-field

→ A polarimeter visualizes the rotation of the polarization of the probing laser pulse due to **Faraday effect** in the plasma





$$\Theta = \text{asin}\left(\sqrt{\frac{I_{\text{shot}}}{I_{\text{ref}}}}\sin\beta\right) - \beta$$



$$\Theta \propto \lambda^2_{\text{probe}} \int \vec{B} \cdot \frac{\vec{k}_{\text{probe}}}{k_{\text{probe}}} n_e(z)dz$$

$\Theta > 0$ if B_φ parallel to $\vec{k}_{\text{probe}}$

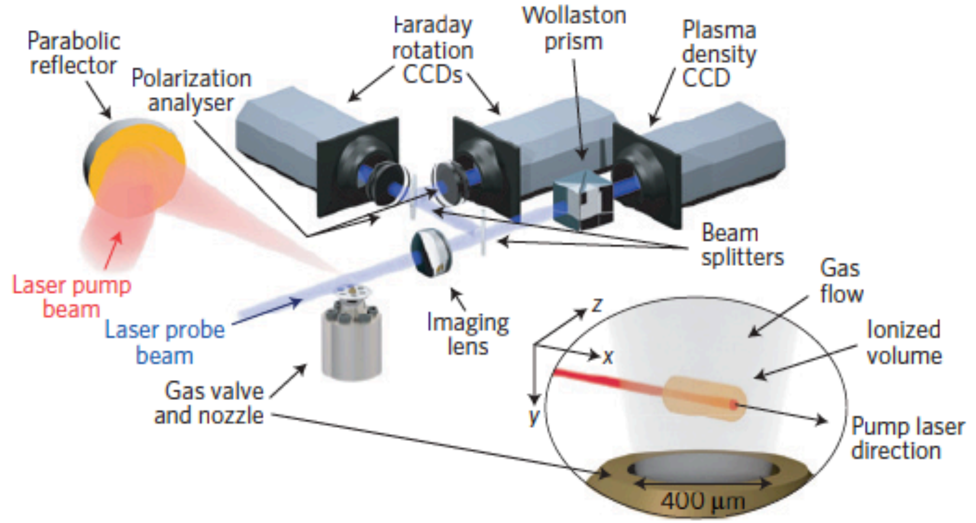
$\Theta < 0$ if B_φ antiparallel to $\vec{k}_{\text{probe}}$

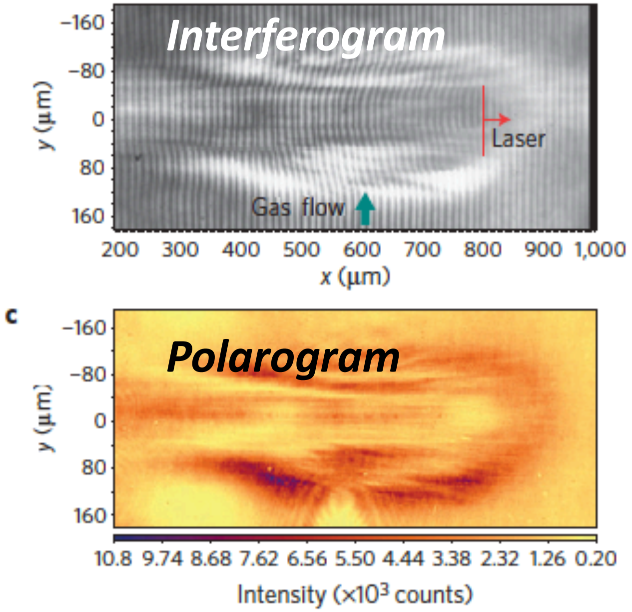
Pisarczyk *et al.*, Phys. Plasmas 2015

Probing of plasma wake-field acceleration

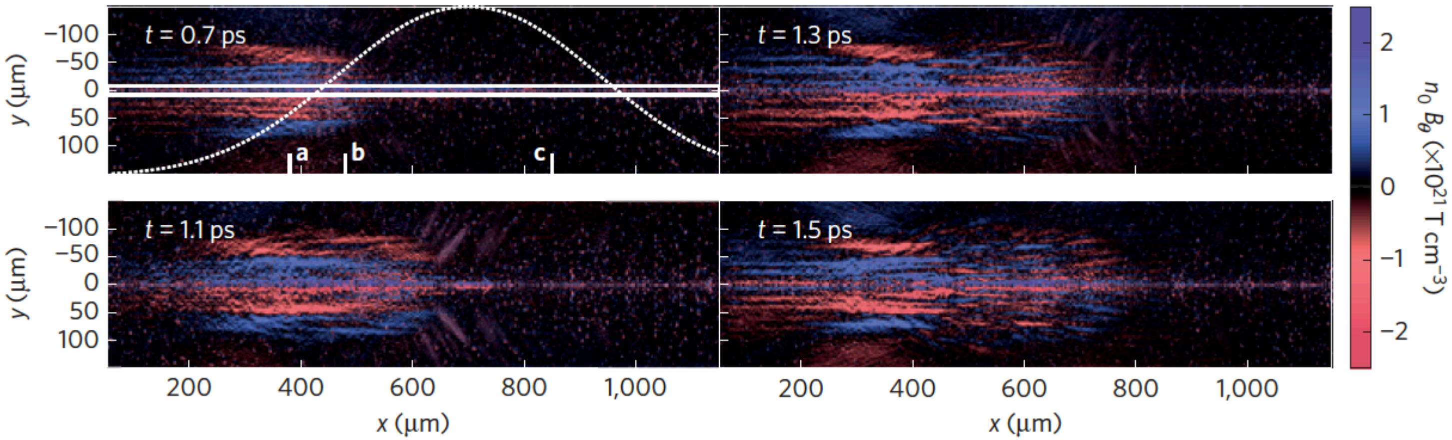
→ Simultaneous measurements of the plasma density (interferometry) and self-generated B-fields (polarimetry)

Flacco *et al.*, Nat. Phys. 2015

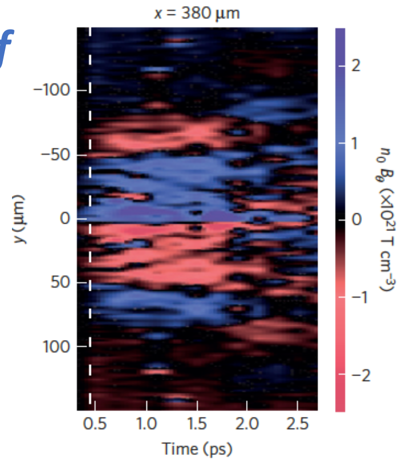




Plasma magnetization at selected times



Evolution in time of the plasma B-field



Outline

Description and diagnostics of laser-plasmas

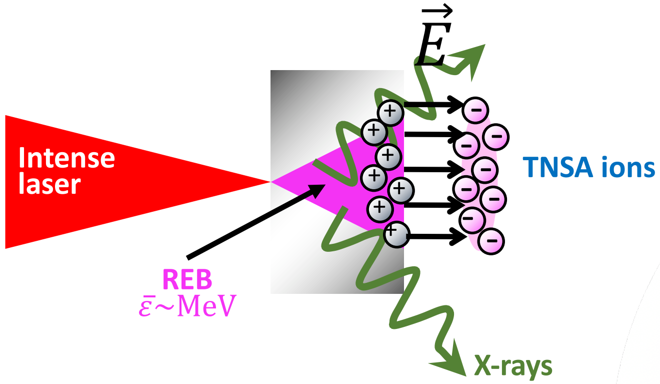
- → What is a plasma?
- → Laser-plasmas
- → Electron acceleration in under-dense plasmas
- → Relativistic electrons in dense matter
- → Magnetized high energy-density

Relativistic electrons in dense matter

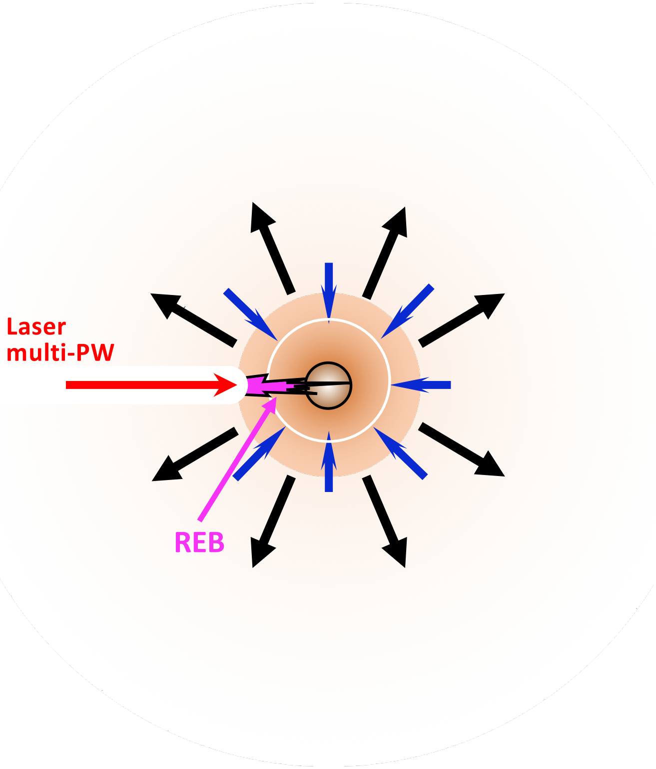
Framework of fast electron beam transport

→ **FEB are generated in relativistic laser (>10^{18} W/cm^2) interactions with dense matter**

→ **REB are powerful energy vectors into dense matter**

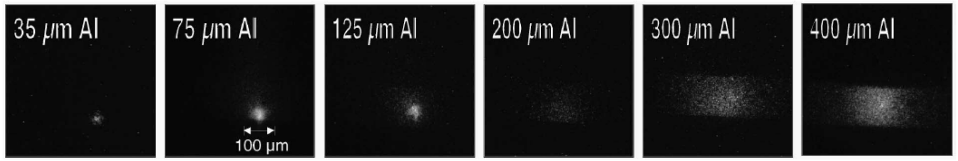


- ❑ **Brief and intense secondary sources**:
  ions, electron-positron pairs, neutrons, photons X and γ
- ❑ **Fast Ignition (FI) in ICF**



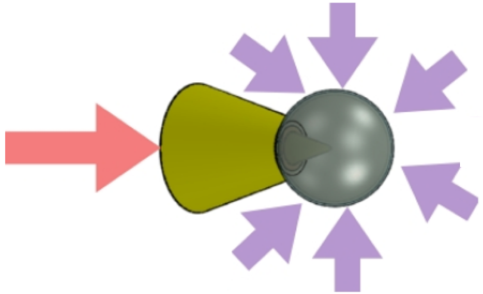
→ **REB observed in solid targets** (by transition radiation) **…**

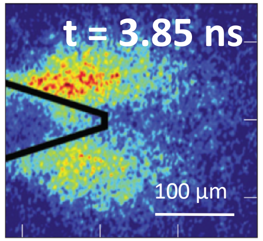
Santos *et al.*, PRL **89** 025001 (2002)



… and in imploded FI-ICF targets
(by X-Kα fluorescence)

Jarrott *et al.*, Nat. Phys. DOI: 10.1038/NPHYS3614 (2016)





⚠ ***REB are intrinsically divergent !***
Non efficient energy transport into dense matter

Driving extreme states of matter

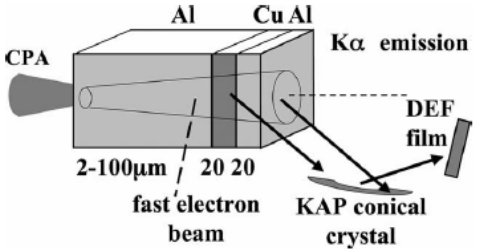
- ☐ **Isochore heating (≈ps) ⇒ high energy-density (HDE) conditions**

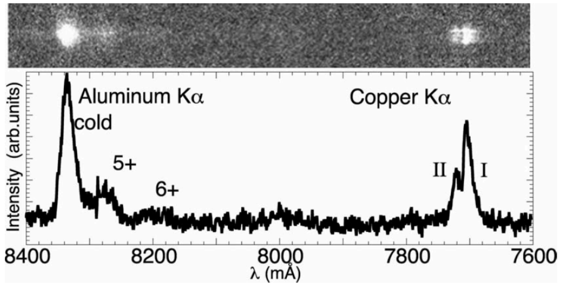
  > 10^{11} J/cm^3, > Mbar

→ Temperature between 1000 and 10 eV over ≈ 100 µm

Martinolli *et al.*, PRE **73**, 046402 (2006)

Kα- fluorescence spectroscopy





PIC-hybrid transport simulations

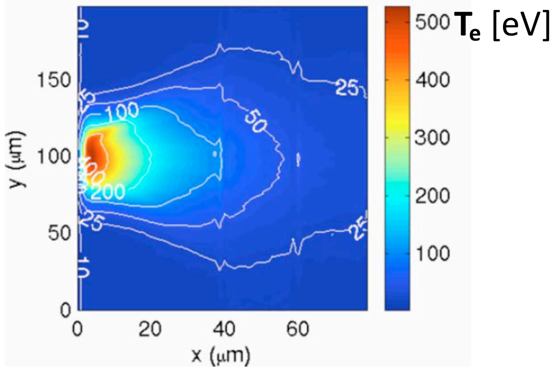
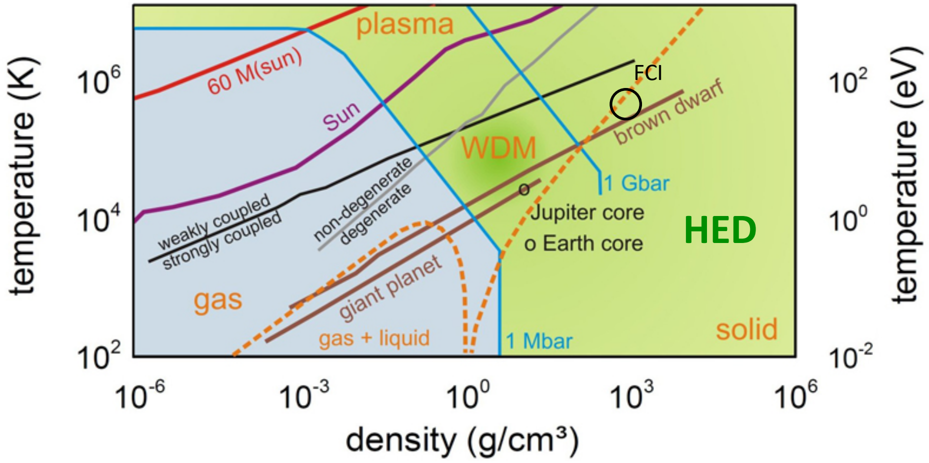


Diagram for the phases of matter



→ Studies of HED matter structure and dynamics, in respect to planetology, astrophysics and ICF

Detection of fast electrons in dense matter

→ FEB characterization is a challenging task

- **Physical inaccessibility to the FEB path**
  Only the relativistic tail of the FEB spectrum overcomes the target potential
- **Very short time-scale (< 20ps)**
  How to isolate FEB transport from target hydrodymanics and related thermal emission?

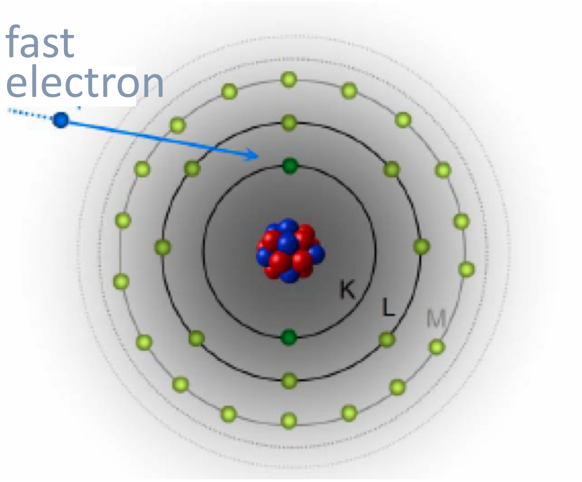
→ Secondary processes (atomic, nuclear or electrodynamic) can yield measurable FEB signatures

- Kα-fluorescence
- Bremsstrahlung
- Coherent Transition Radiation (CTR)
- Thermal emission
- Proton/ion acceleration
- Neutron emission

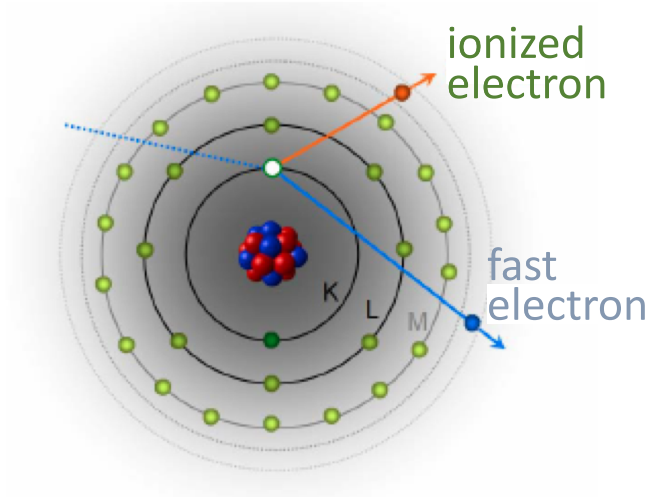
→ Clearly identify mechanisms that are FEB's figures of merit (not related to other plasma components)

Kα-fluorescence

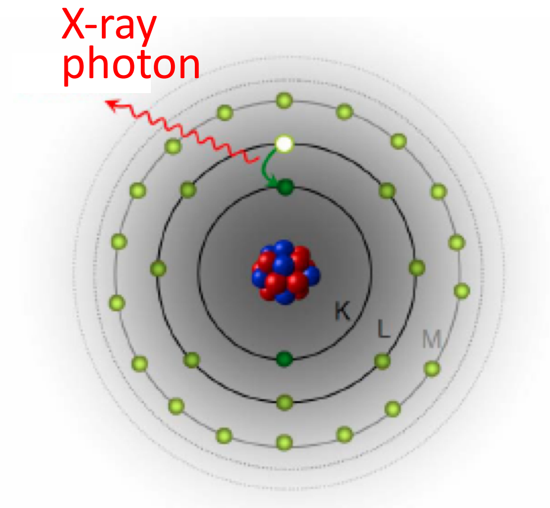
→ Only enough high energy electrons can produce atomic inner-shell ionization



1) Fast electron collides with bound electron



2) Ionisation of a K-shell electron ⇒ atomic gap

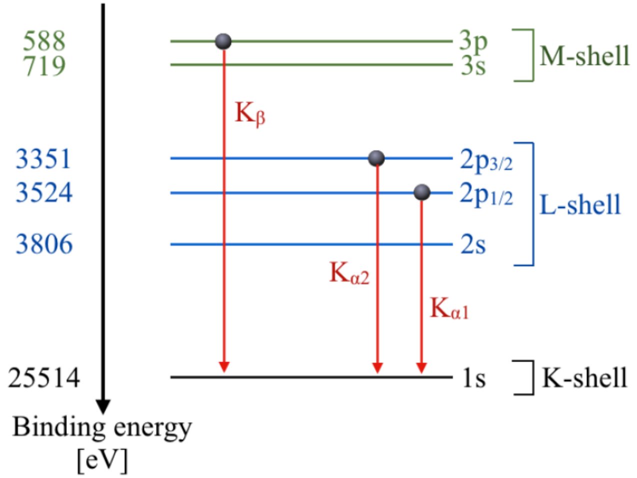


3) Deexcitation ⇒ X-ray emission
⇒ Auger electron

Allowed inner-shell radiative transitions upon inner-shell ionization

(binding energies for Ag)

$$\varepsilon_{K\alpha}[\text{eV}] \approx 10.206(Z-1)^2$$



K-shell emission cross section

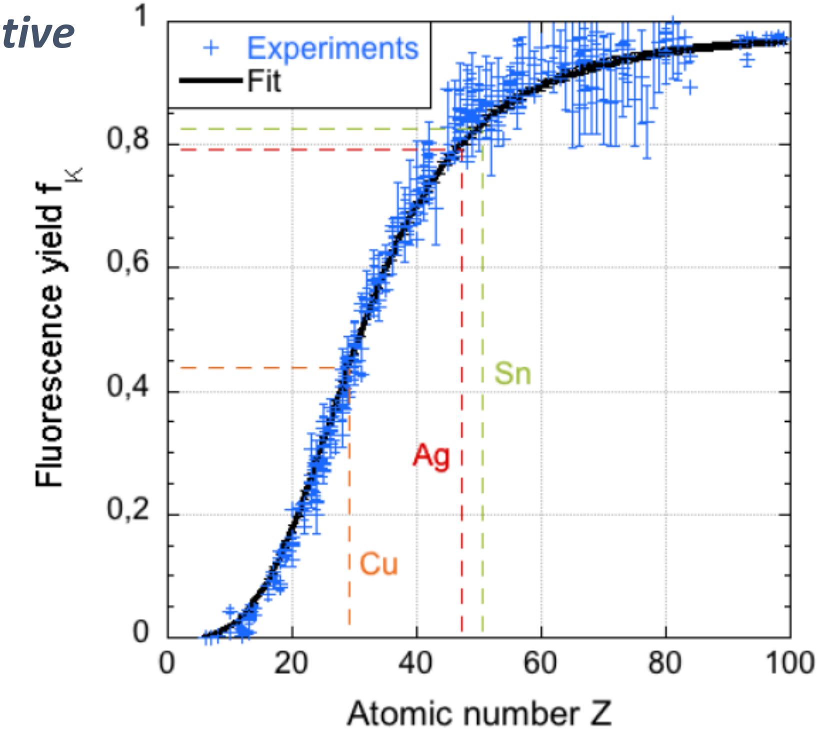
→ **K-shell emission works as FEB *figure of merit***

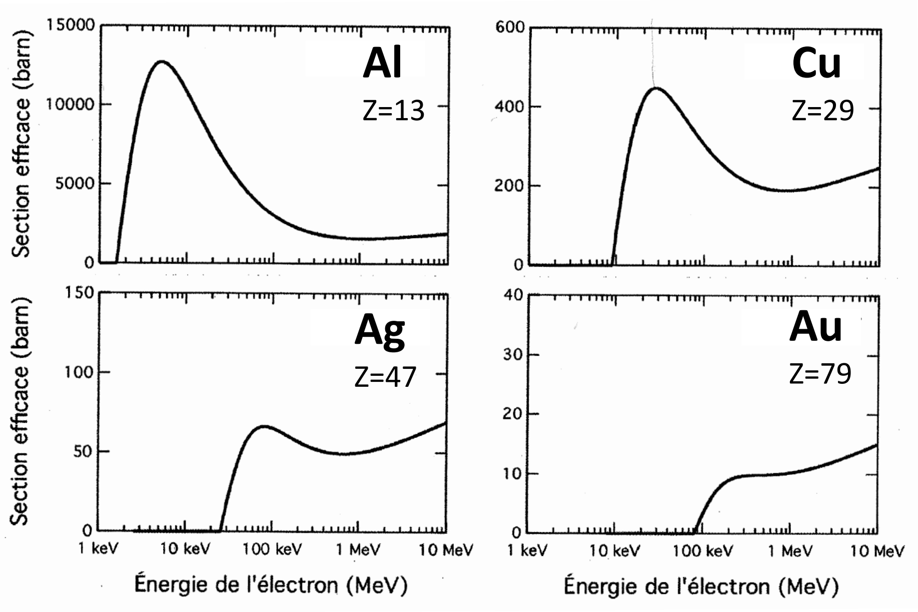
$$\sigma_K = f_K \sigma_{ion}$$

K-shell ionisation cross section for different elements

as a function of the incident electron energy

Probability for radiative de-excitation





- ***Ionisation threshold is the binding energy***

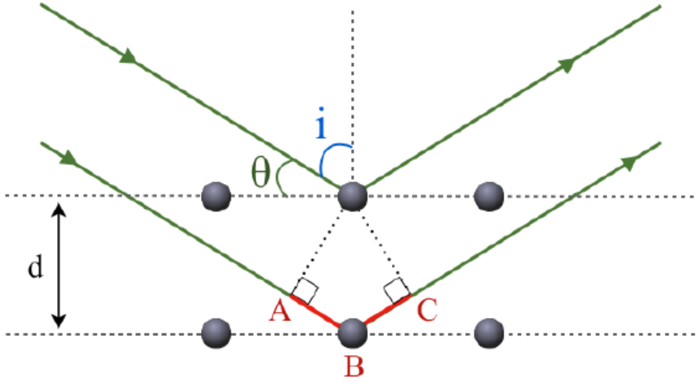
$$I_k[eV] \approx 5.769\, Z^{2.1822}$$

- ***Maximum cross section for ~ 2-3 x I_k***
- ***For mid Z, it doesn't change significantly with ε_h***

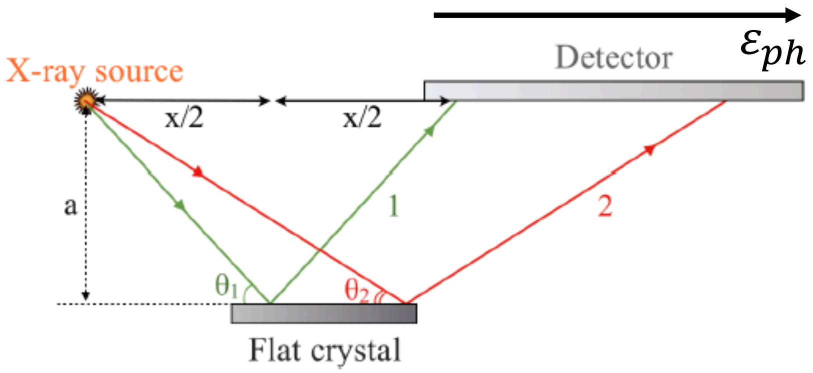
→ **Kα yield roughly counts the number of fast electrons**

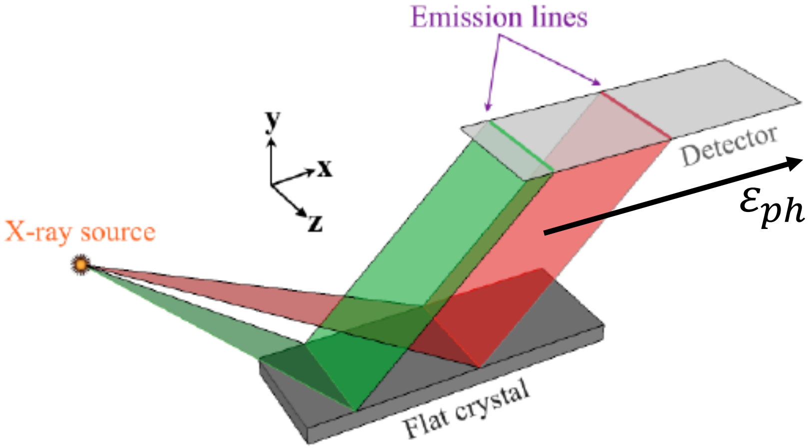
X-ray spectroscopy

→ X-ray dispersion based on Bragg's diffraction



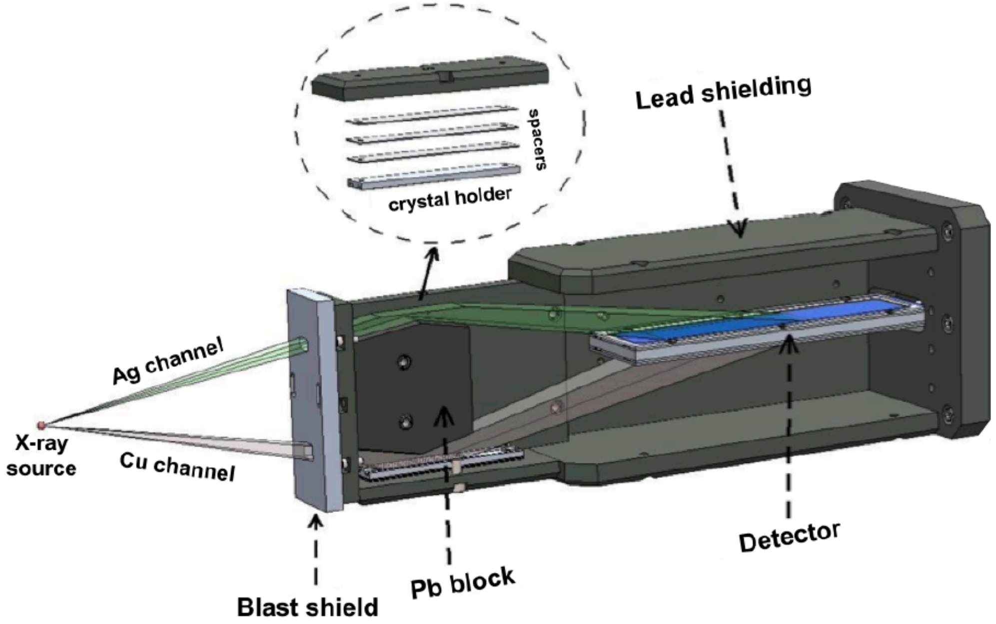
$$2d\ sin\theta = p\lambda = phc/\varepsilon_{ph}$$





Practical implementation with HOPG crystals

Akli *et al.*, JINST **5**, P07008 (2010)



X-ray spectroscopy

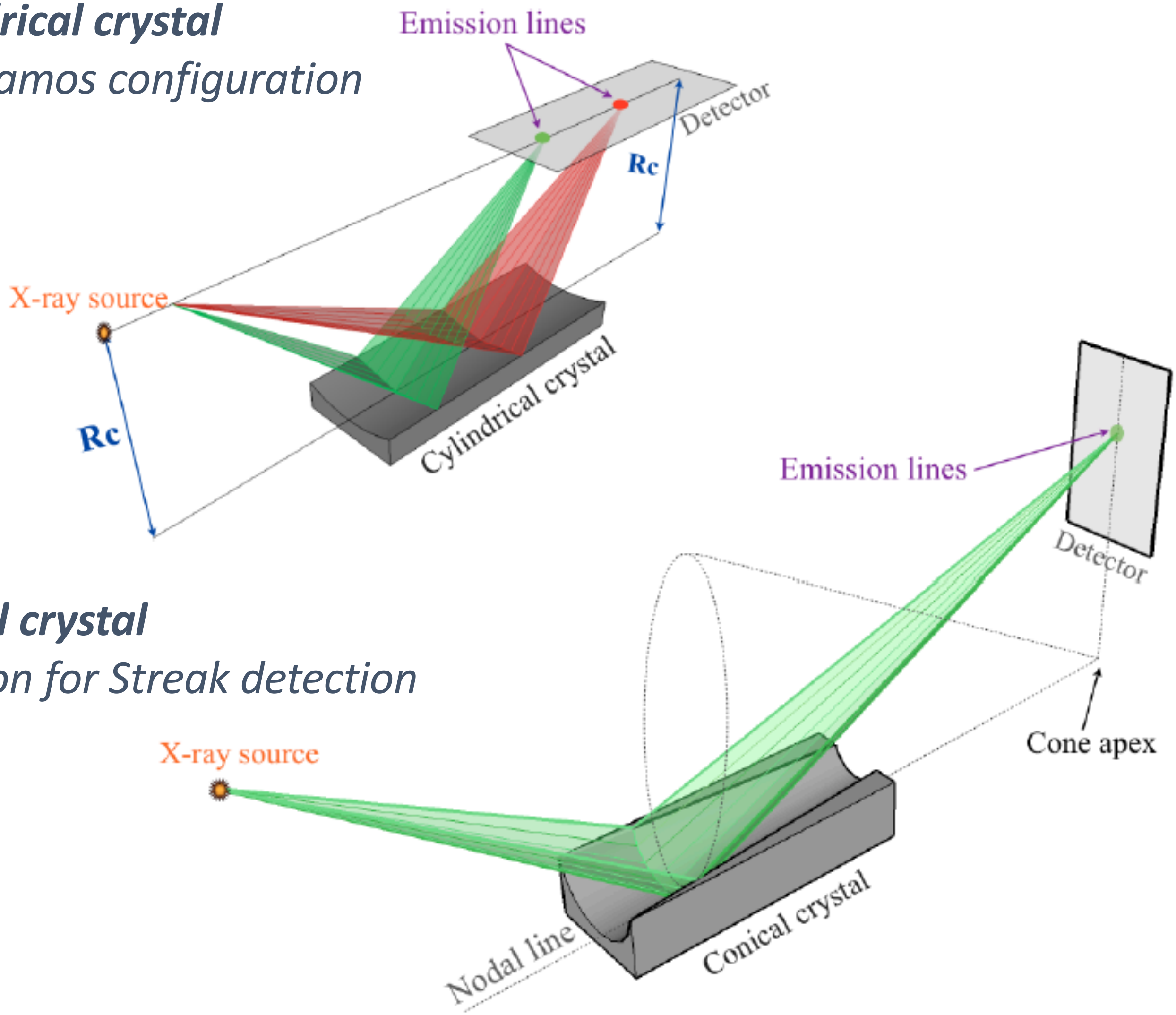
→ Focusing crystals for better signal / noise

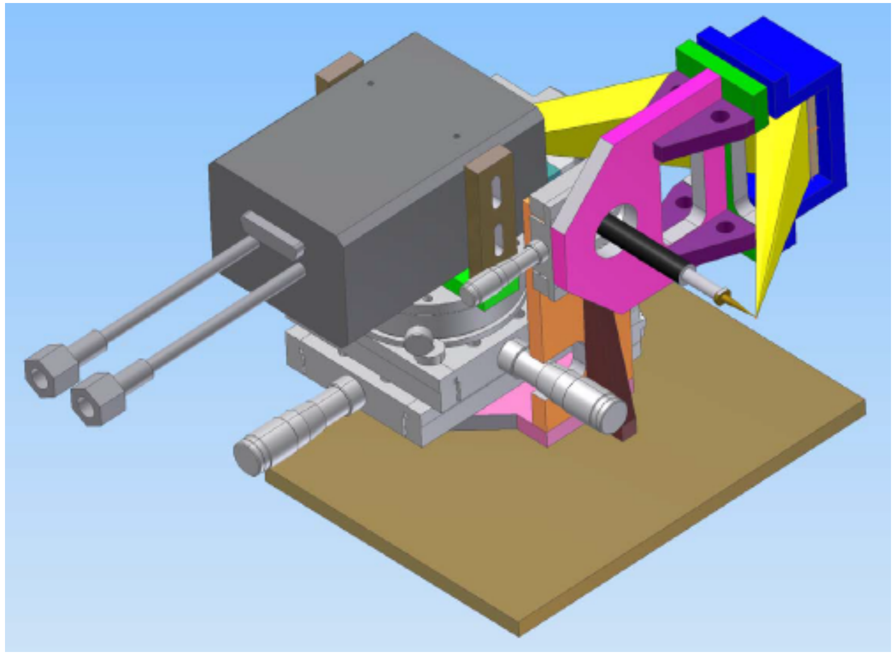
Cylindrical crystal

Von Hamos configuration

Conical crystal

common for Streak detection





$$2d\ sin\theta = p\lambda = phc/\varepsilon_{ph}$$

→ Detection of hard X-rays?

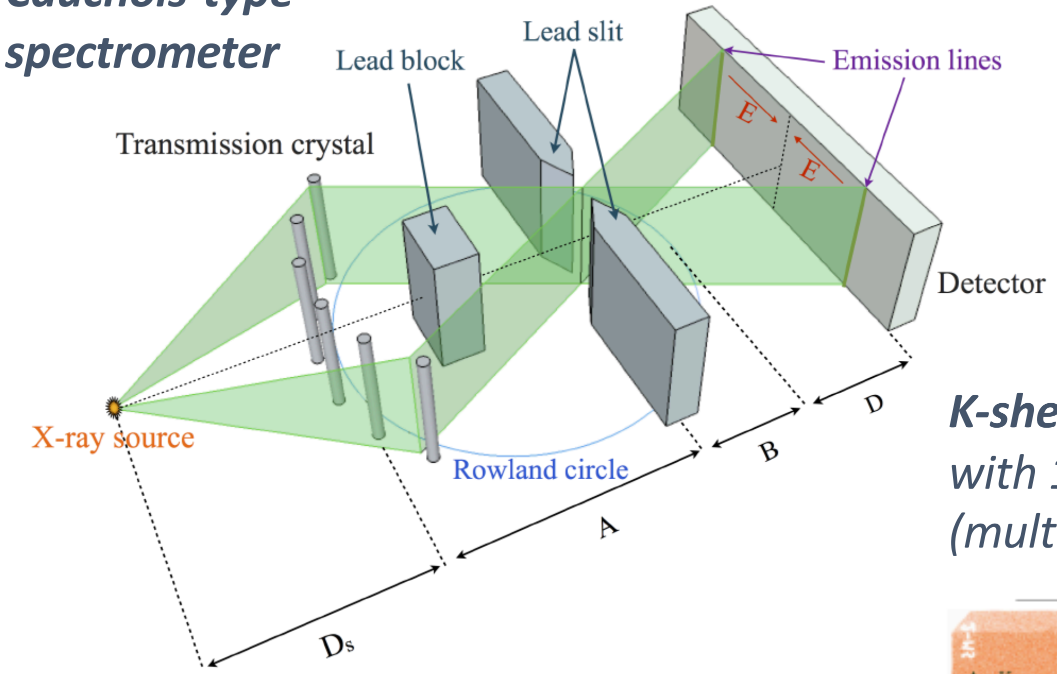
Difficult to produce high quality crystals with small inter-atomic spacing

Relativistic electrons in dense matter

X-ray transmission spectroscopy

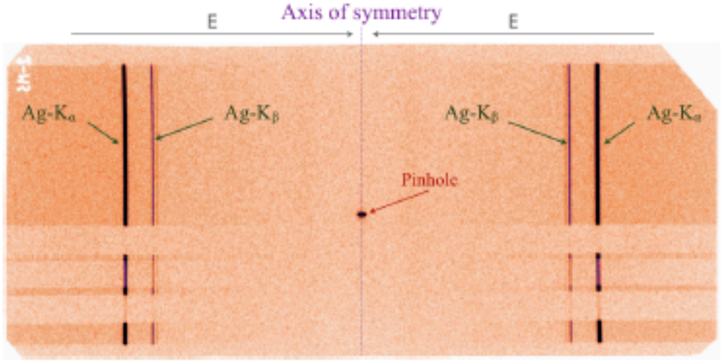
→ Transmission-crystal spectrometers adapted for X-rays up to 80 keV

Cauchois-type spectrometer

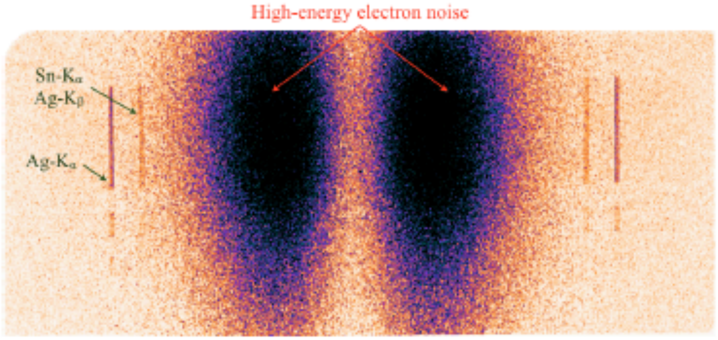


K-shell fluorescence data

with 100 mJ, 30 fs laser (multiple shots)



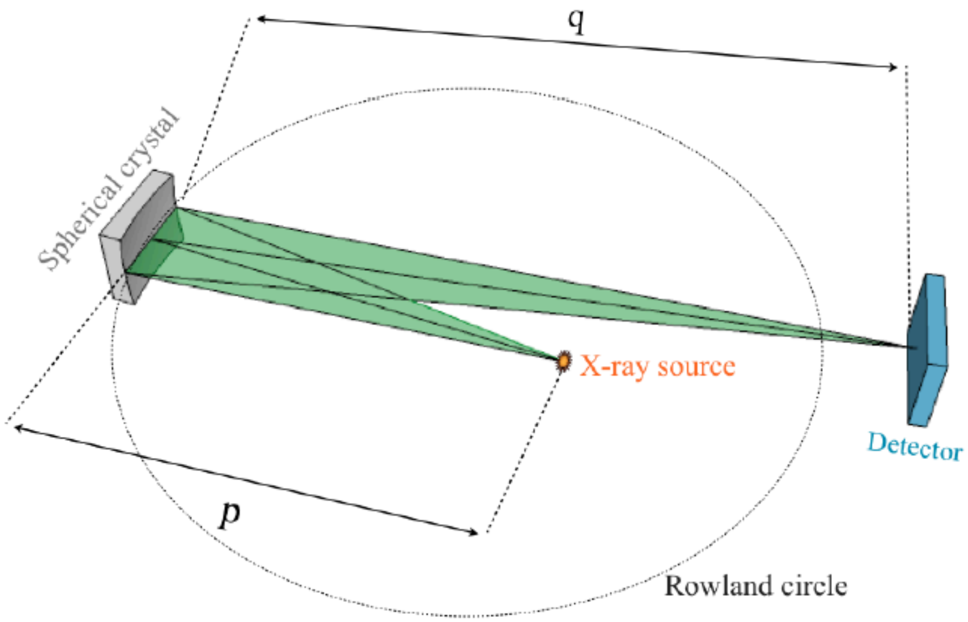
with 100 J, 1 ps laser (single shot)



High-energy electrons can be easily deviated using a ≈ 0.5 T magnet

Kα imaging

→ Spherical crystal imaging combines Bragg diffraction and mirror imaging

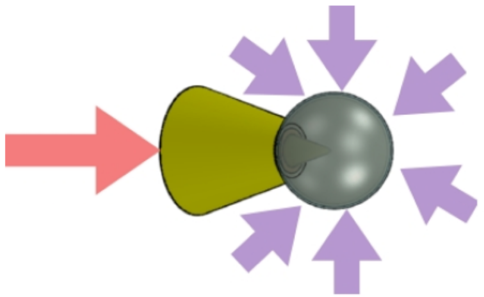


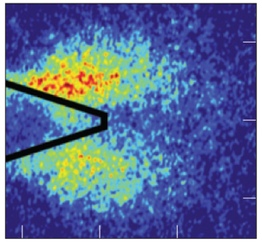
$$2d\,\sin\theta_B = phc/\varepsilon_{ph}$$

$$\frac{1}{p}+\frac{1}{q_t}=\frac{2}{R\sin\theta_B}$$

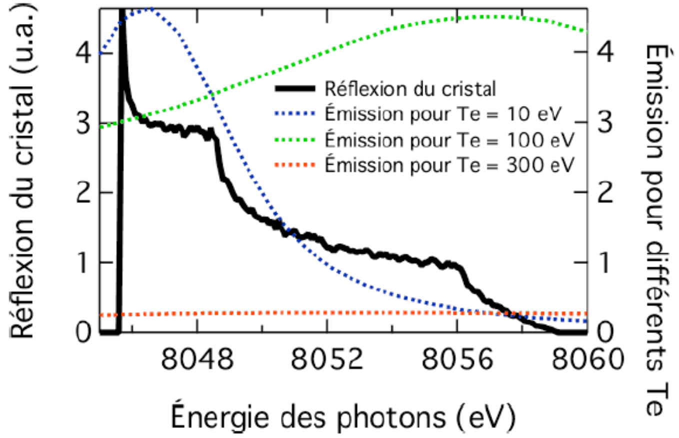
$$\frac{1}{p}+\frac{1}{q_s}=\frac{2\sin\theta_B}{R}$$

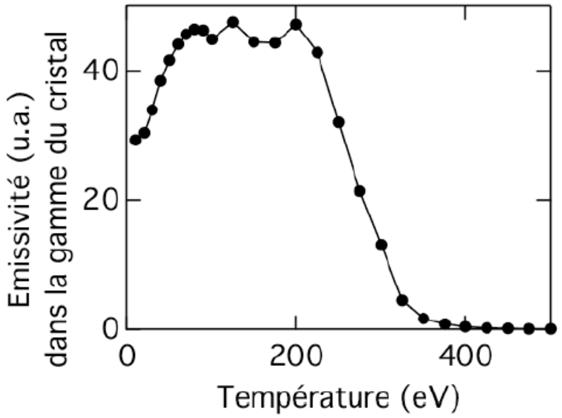
Quasi-paraxial geometry ($\lesssim 90°$) reduces astigmatism,
but limits the range of ε_{ph}





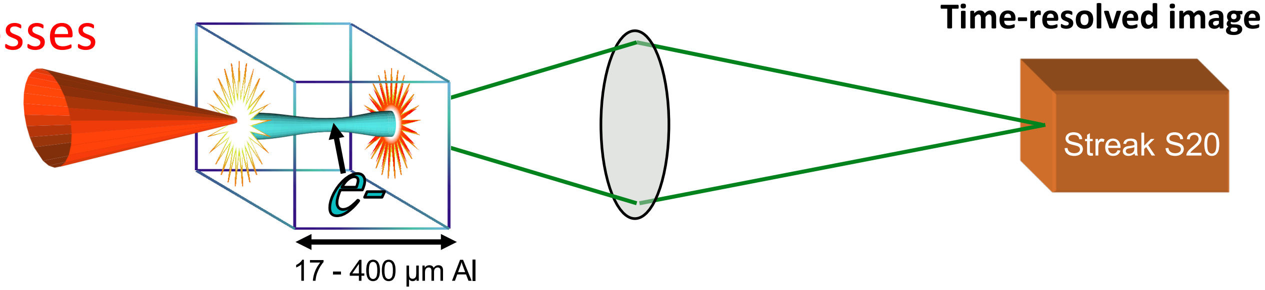
→ Thin crystal bandwidth (≈ 10 eV) explains drop of K*α* reflectivity at high plasma temperature



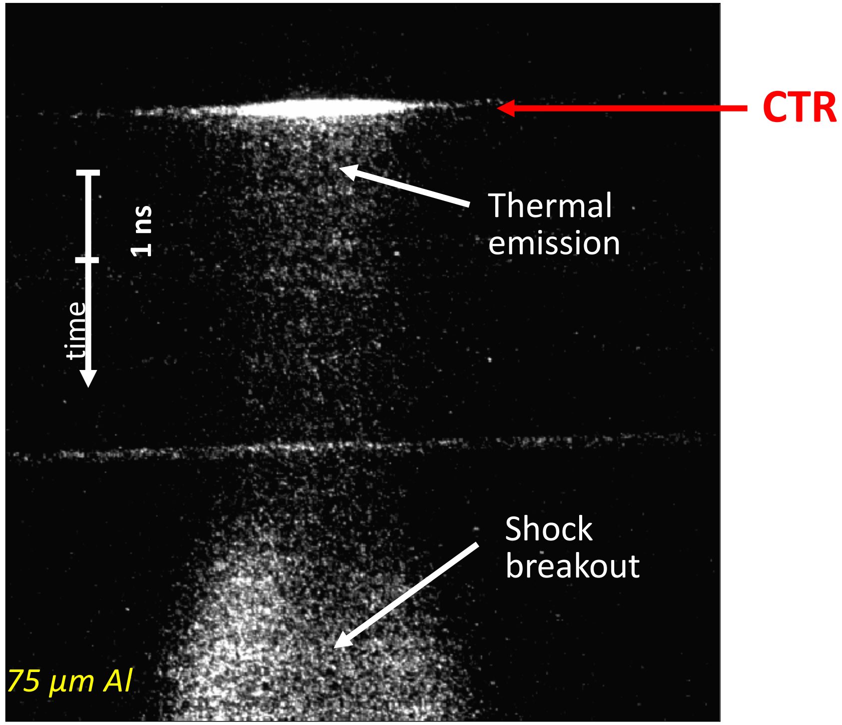


Transition radiation

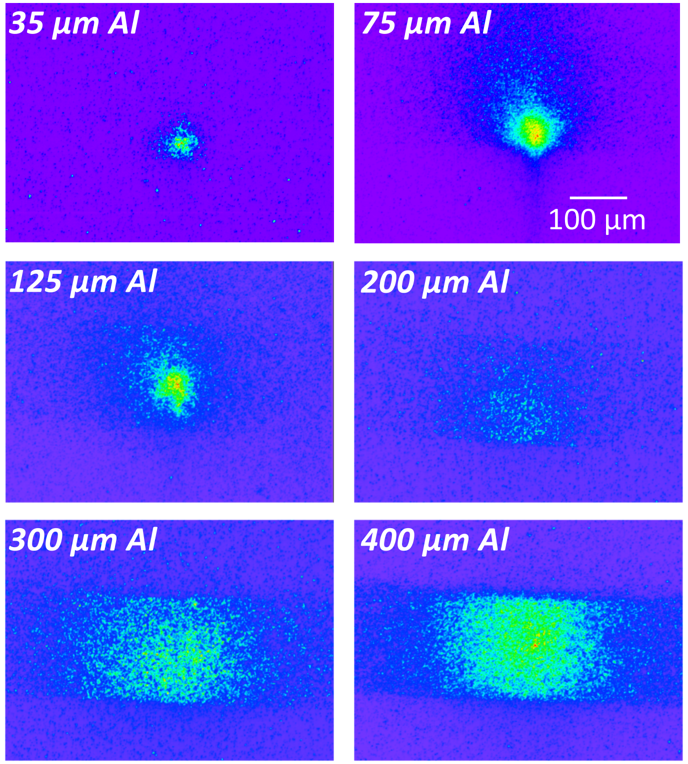
→ **Transition radiation** is emitted when a charge crosses the boundary between two media of different dielectric response



« Slow » streak imaging with narrow slit



Fast streak imaging at full slit aperture



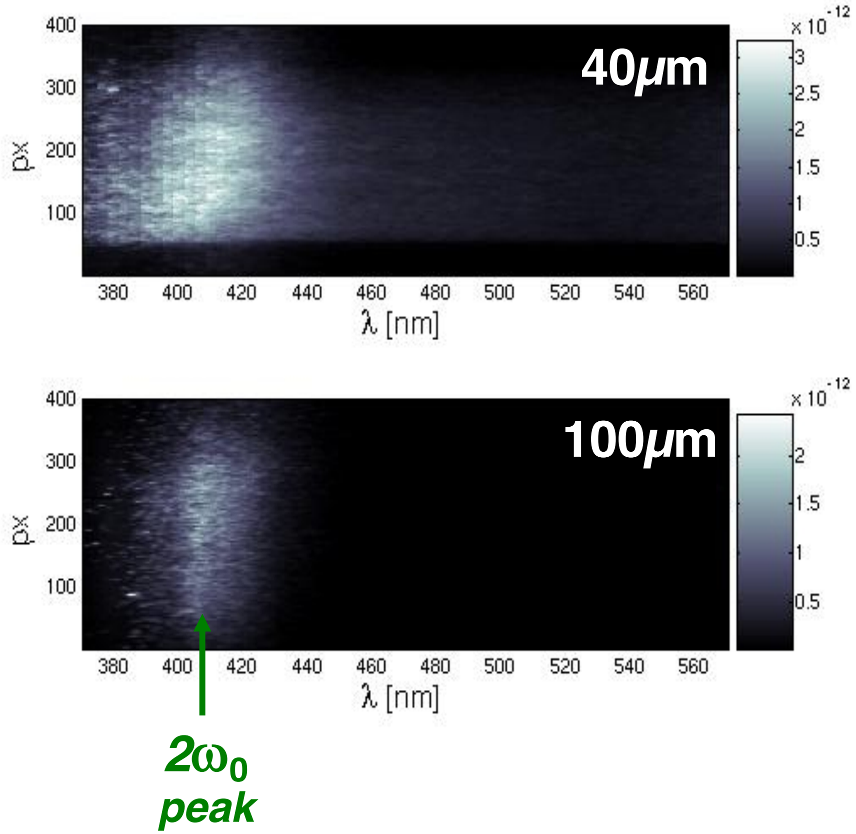
→ **The emission is prompt, same ps-scale of the FEB**

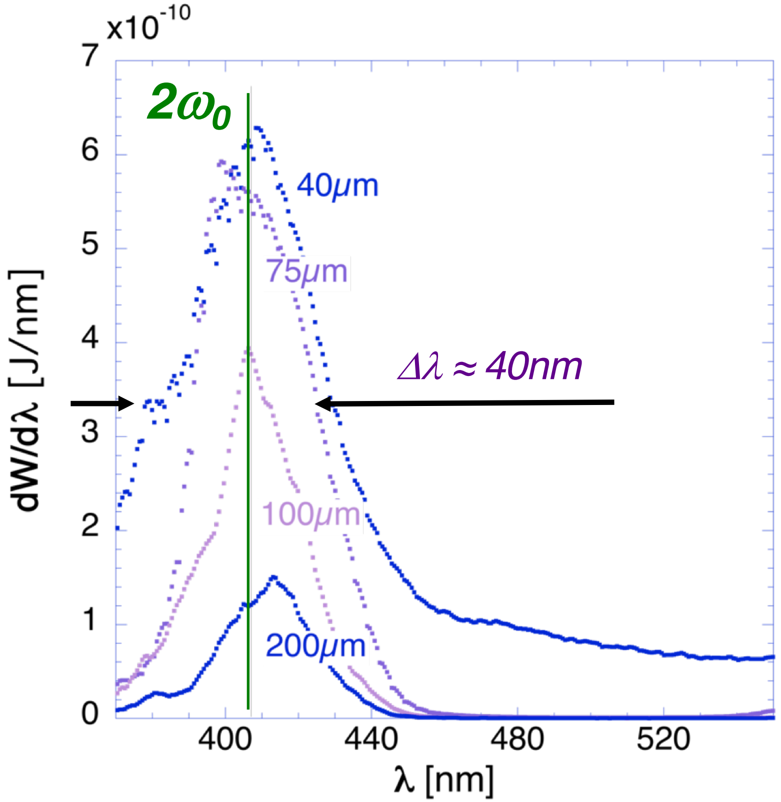
Santos *et al.*, PRL **89** 025001 (2002)

Coherent transition radiation (CTR)

→ **Spectral peak at twice the laser frequency reveals the coherence of the prompt emission**

5ns time-gated spectra



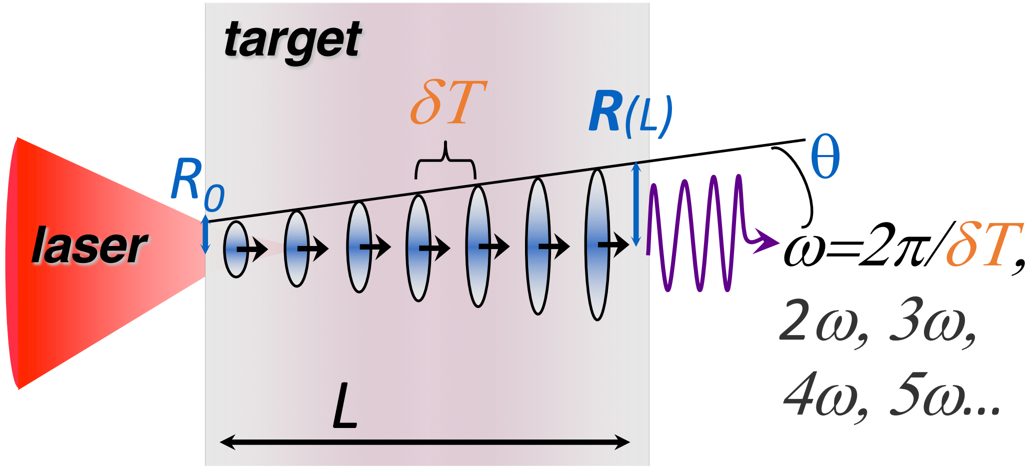


Baton *et al.*, PRL **91** 105001 (2003)

Coherent transition radiation (CTR)

→ FEB is accelerated as a comb of periodic bunches

of sub-micron length l_b, separated by L_b (with $L_b = \lambda_0$ or $\lambda_0/2$)

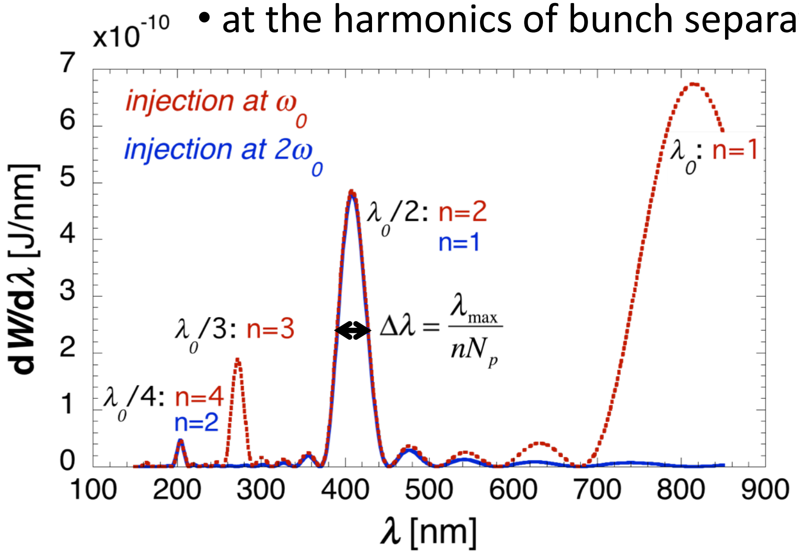


$$f(\varepsilon_h, \theta)\, d\varepsilon_h\, d\theta = j(t)\, dt$$

⇒

Coherent emission

- for $\lambda > l_b$ (bunch length)
- at the harmonics of bunch separation L_b



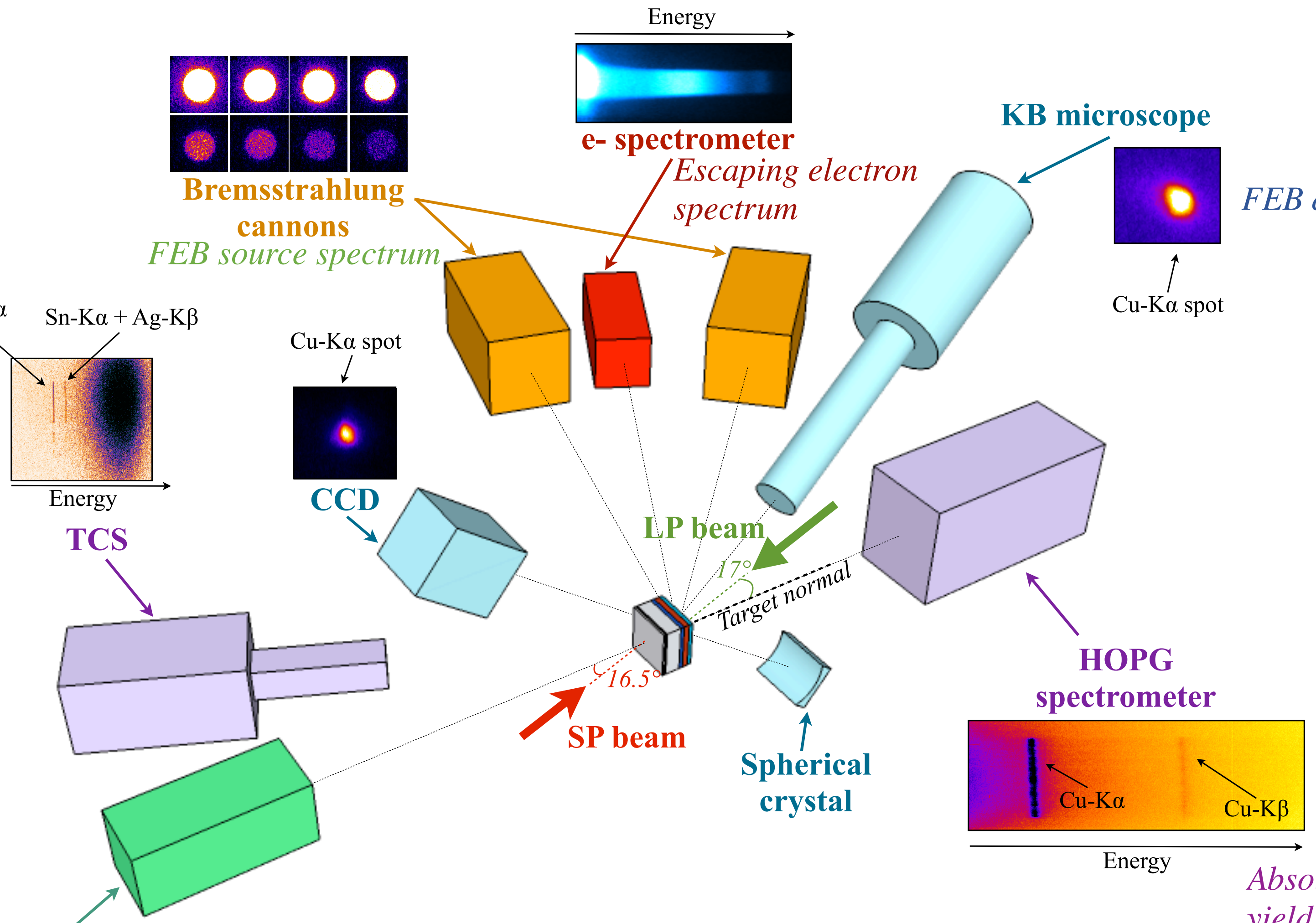
→ The electric fields of each electron add in a coherent way :

$$\left.\frac{dW_{CTR}}{d\lambda}\right|_{N_p\,\text{bunches}} = \left.\frac{dW_{OTR}}{d\lambda}\right|_{1e^-} P^2 \left|\tilde{\rho}_L(\omega)\right|^2 \left|\tilde{\rho}_T(k)\right|^2 \left(\frac{\sin(N_p\omega\delta T/2)}{\sin(\omega\delta T/2)}\right)^2$$

- ***Velocity and angle dispersion*** ⇒ ***time-broadening of the electron bunches***
- ***Growing size of the emitting region***

Lost of coherence with growing crossed thickness

Broad panel of diagnostics for well-characterized experiments



Bremsstrahlung cannons

FEB source spectrum

e- spectrometer

Escaping electron spectrum

KB microscope

FEB divergence

Absolute yields !
Number of fast electrons

TCS

CCD

LP beam

SP beam

Spherical crystal

HOPG spectrometer

Absolute yields !

SOP

shock breakout measurements

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Description and diagnostics of laser-plasmas

- → What is a plasma?
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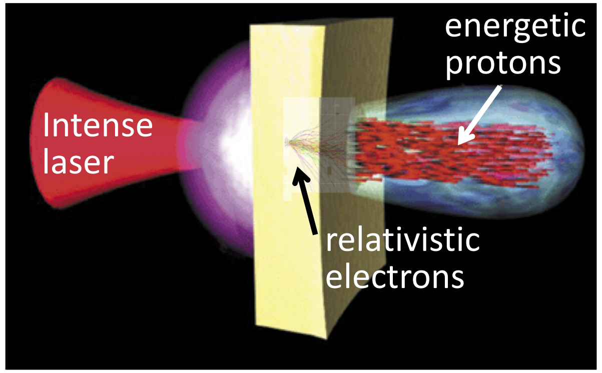
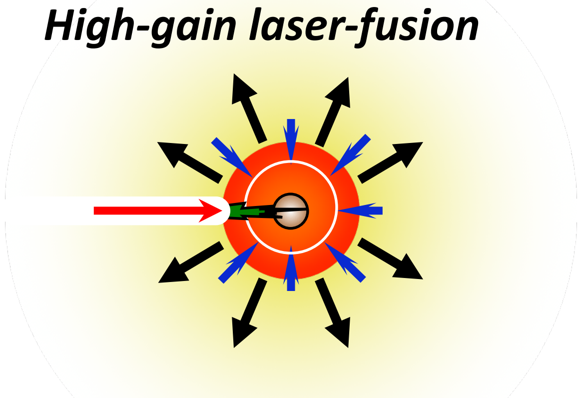
- → Magnetized high energy-density

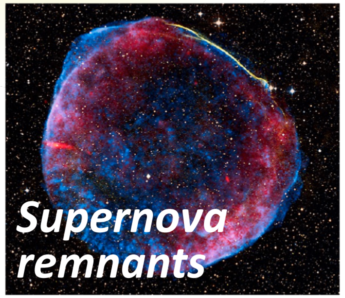
B-fields are ubiquitous in the Universe… and in laser-plasma experiments

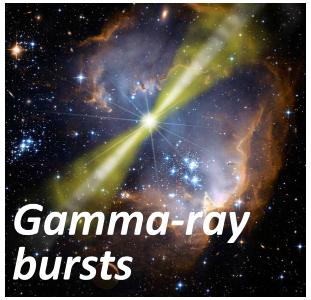
→ *Guiding laser-driven particle beams*



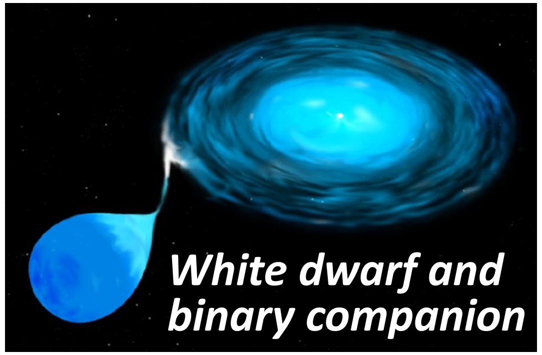


→ *Particle acceleration in turbulent astrophysical plasmas*





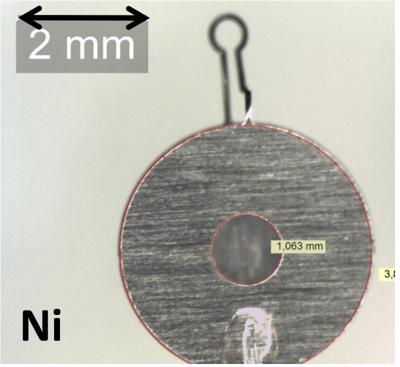
→ *Magnetized atomic physics processes*

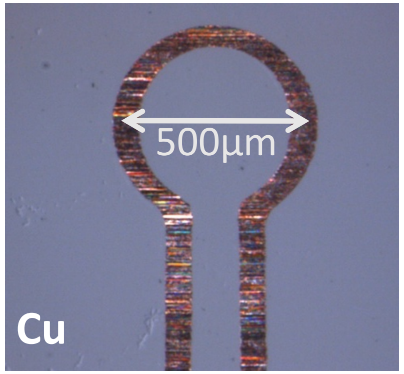


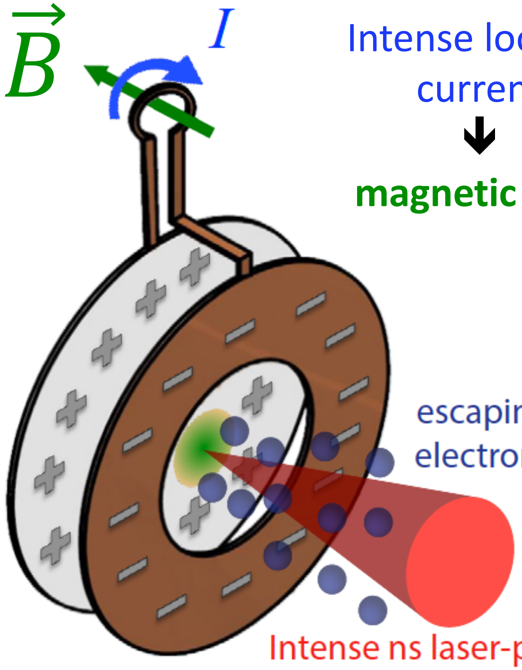
Magneto-static fields driven by ns laser

→ An intense ns laser pulse drives a discharge current over a looped circuit (coil-target), yielding a strong quasi-static magnetic field (B-field)

→ Accurate and reproducible coil-target production







Intense looping current

↓

magnetic field

escaping electrons

Intense ns laser-pulse
500 J, 10^{17} W/cm^2

At the coil centre :

250 kA

$$B_0 \approx \frac{\mu_0 I}{2a} \sim 600\ T$$

coil radius = 250 µm

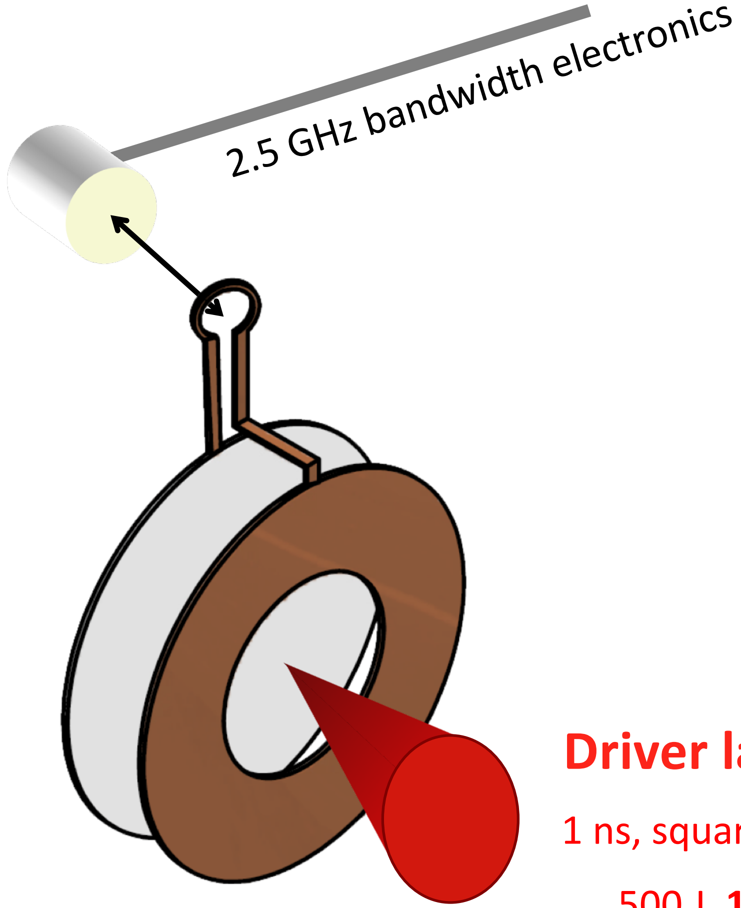
Escaping hot electrons ($T_h \approx 40\ \text{keV}$)
+ small capacitance ($C \approx 0.1\ \text{pF}$)

↓

diode-like current source

B-field measurements: B-dot probing

B-dot probe @ 7cm from coil center



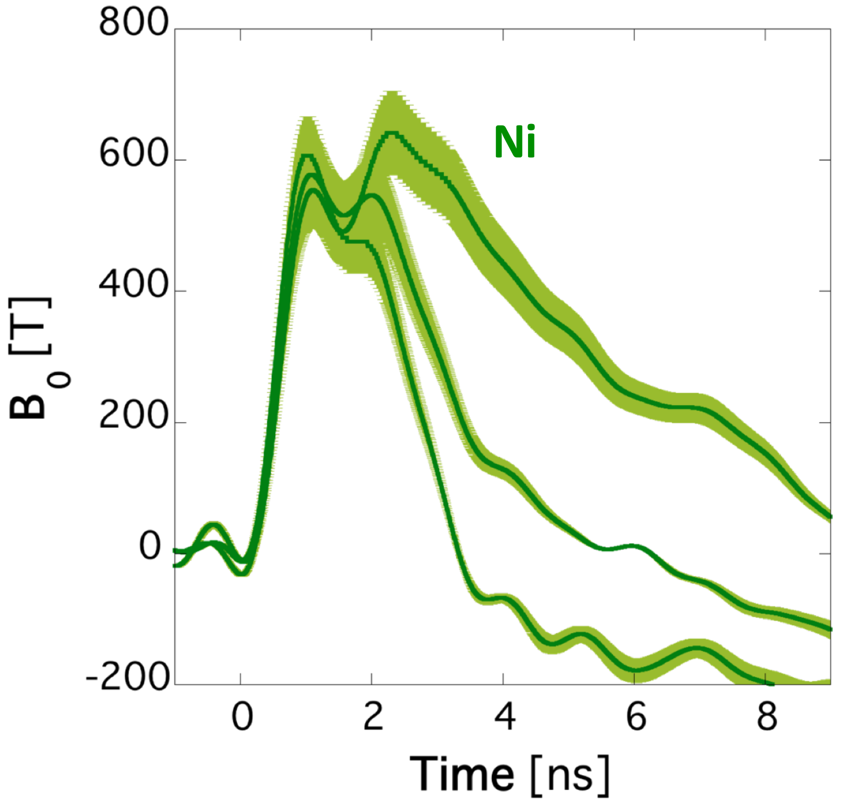
Driver laser beam

1 ns, square time-profile

500 J, **10^{17} W/cm²**

→ **B-fields in the excess of 500 T** and of **ns-scale duration**

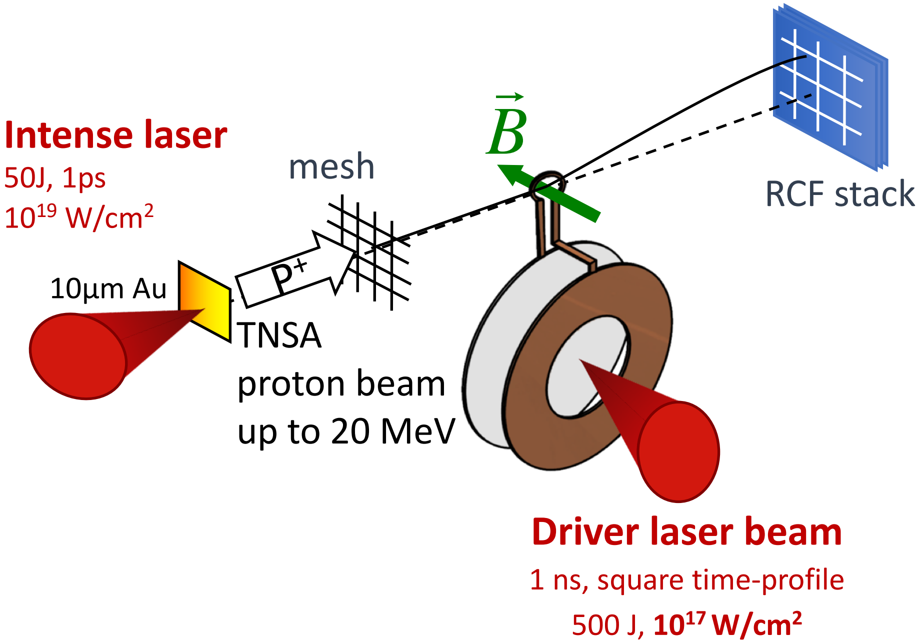
→ **Reproducible peak value and rise time**



J.J. Santos *et al.*, New J. Phys. **17**, 083051 (2015)

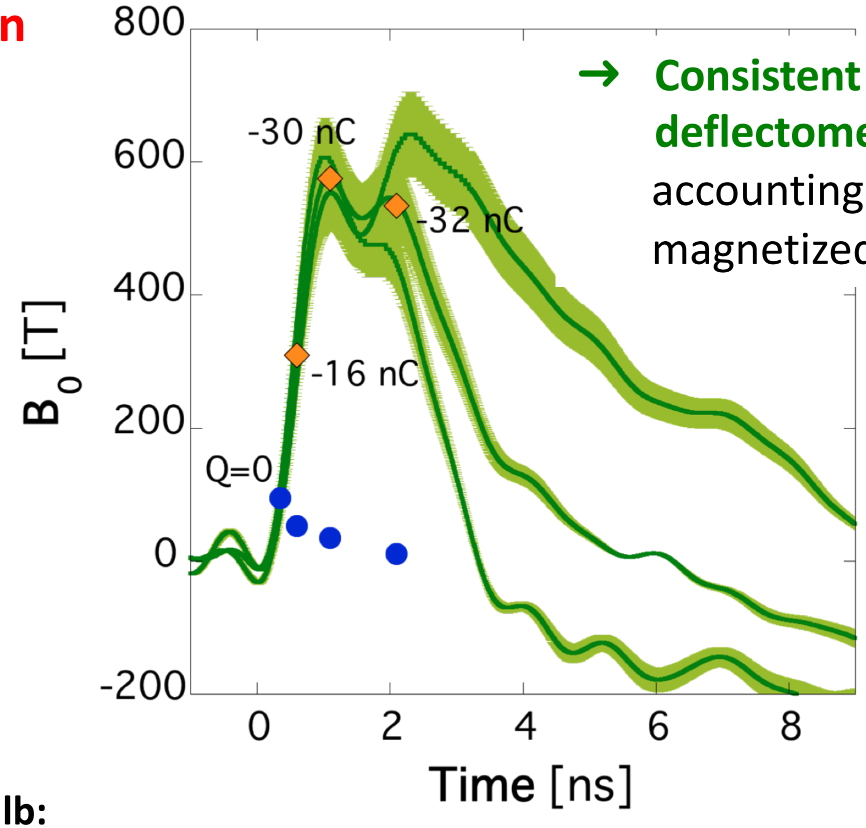
B-field measurements: Proton deflectometry

→ **Protons probe B-field directly at the coil region**

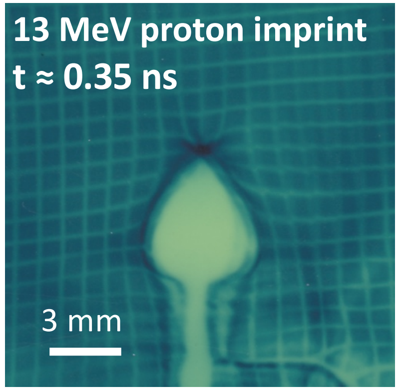


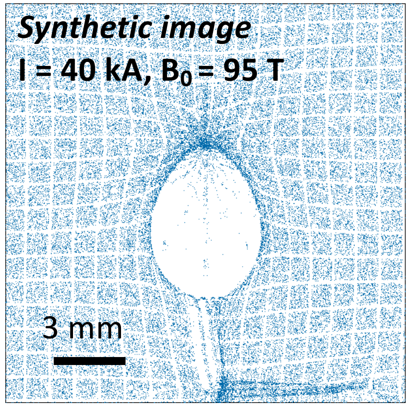
Intense laser
50J, 1ps
10^{19} W/cm^2

Driver laser beam
1 ns, square time-profile
500 J, **10^{17} W/cm²**



→ **Consistent B-dot probing and proton-deflectometry measurements,** accounting as well for E-field effect of magnetized plasma electrons





Void bulb:

→ **protons expelled by strong B-field at the coil region**

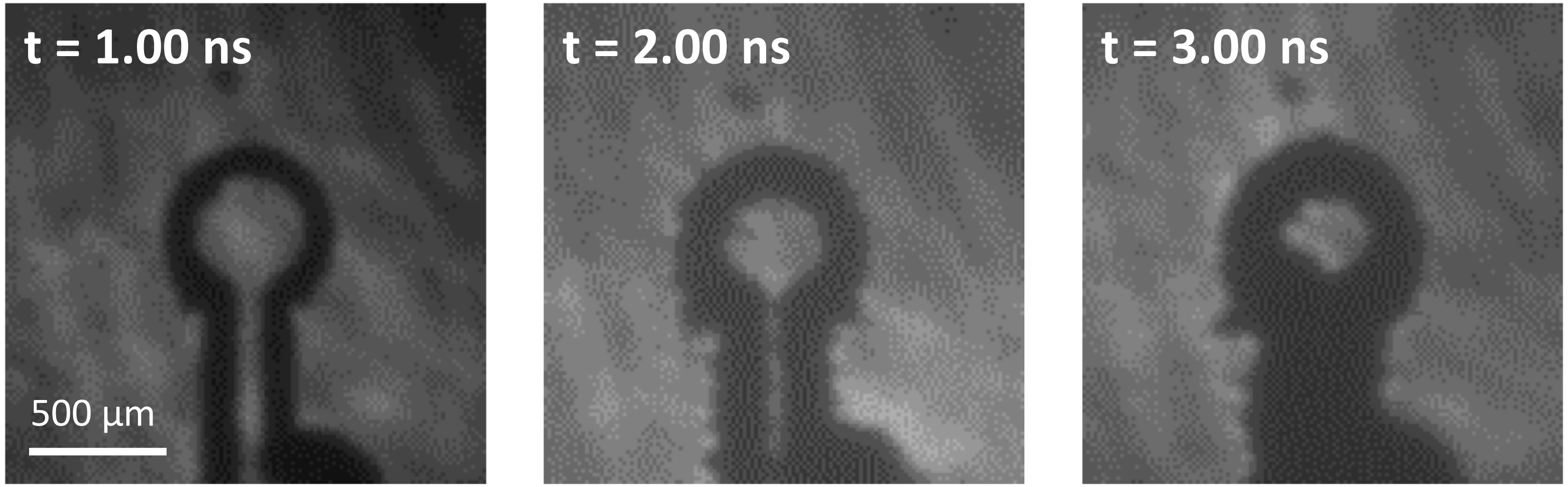
Mesh-imprint deformations:

→ **Dipolar B-field over a range of few mm**

J.J. Santos *et al.*, New J. Phys. **17**, 083051 (2015)

B-field measurements: Optical shadowgraphy

Shadowgraphy data from Ni coils



Wire surface modulation

- wavelength : λ = 110 ± 10 µm
- growth rate : $\gamma \approx 10^9\ \mathrm{s}^{-1}$

Competing thermal and magnetic pressures may drive interchange instability :

$$\gamma \sim \frac{2\pi}{\lambda}\sqrt{B_\varphi^2/\mu_0\rho} \quad \Rightarrow \quad B_\varphi \geq 1800\ \mathrm{T}$$

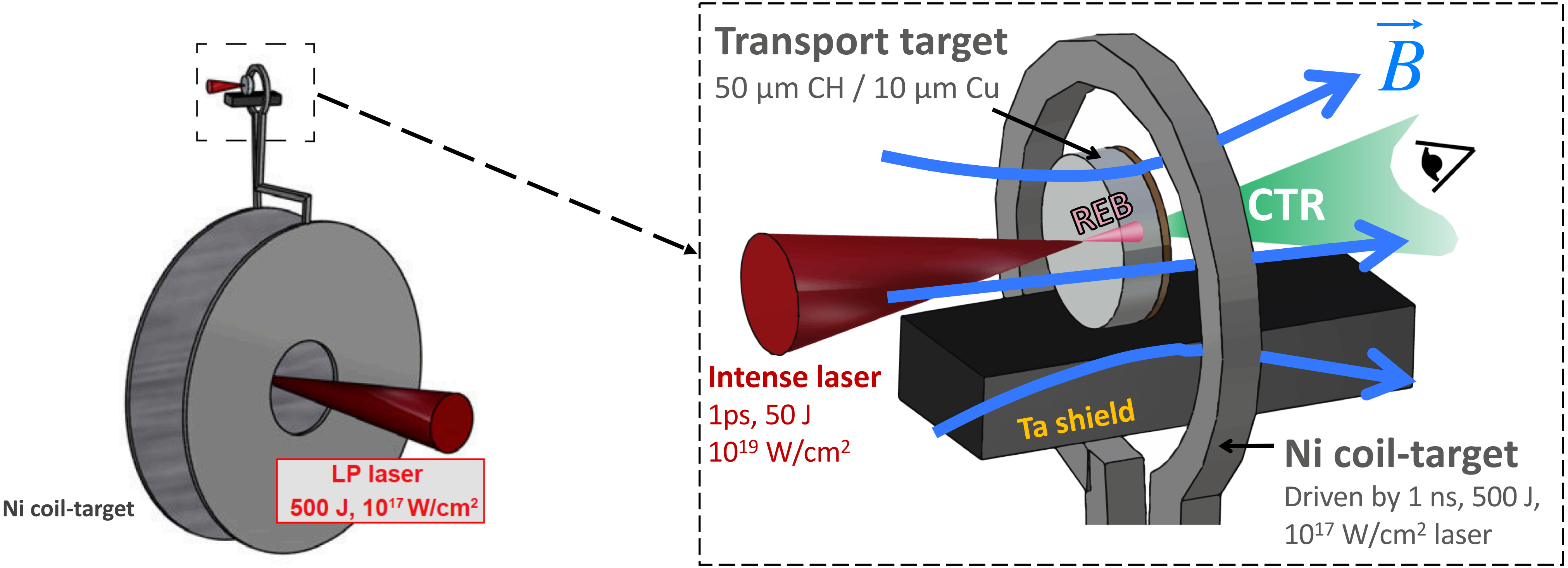
→ **Instability consistent with the 250 kA discharge and 600 T at coil centre**

✓ **Space inside the coil accessible for several ns**

J.J. Santos *et al.*, Phys. Plasmas **25**, 056705 (2018)

Magnetic guiding of relativistic electron beams

Setup at the LULI2000 facility



➜ **REB transverse profile** investigated at the rear of the 60 µm-thick targets by **Coherent Transition Radiation (CTR) at $2\omega_{laser}$**

➜ **Variable target magnetization by scanning :**
- delay between laser pulses
- transport-target position relative to the coil

M. Bailly-Grandvaux *et al.*, Nat. Comm., **9**, 102 (2018)

Enhancement of the REB energy-density-flux

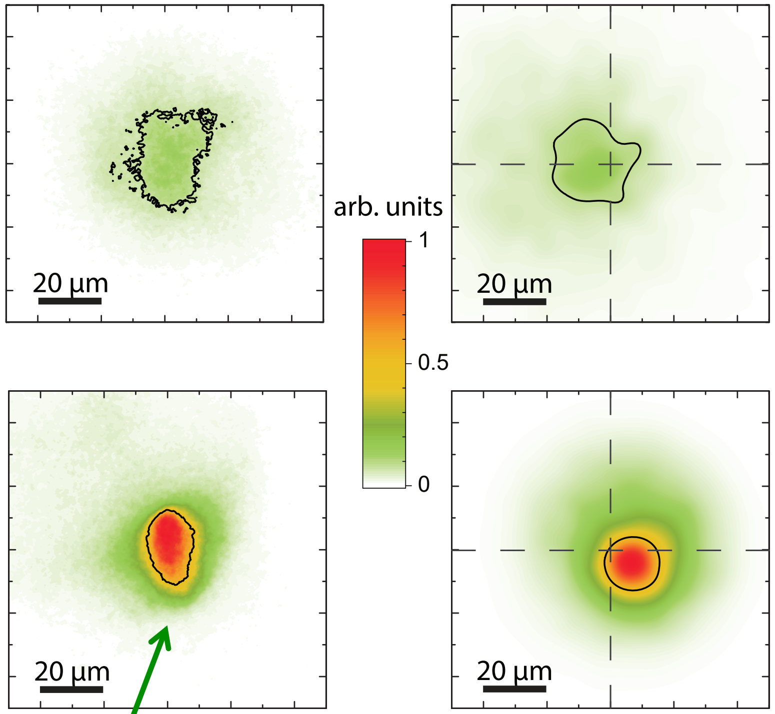
→ **CTR patterns' size, shape and relative yield variations are fairly reproduced by REB transport simulations**

CTR data *Synthetic CTR*

No B-field

With B-field

(Δt = 1 ns, B_0 = 600 T)



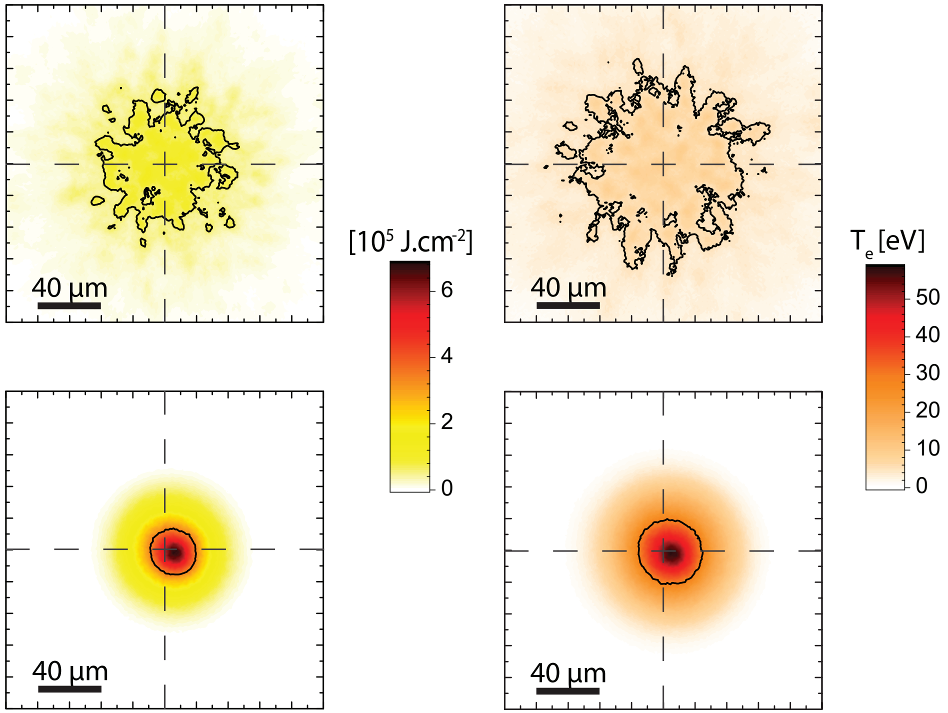
Pinching, 8x times higher CTR yield

→ **REB radial confinement**

M. Bailly-Grandvaux *et al.*, Nat. Comm., **9**, 102 (2018)

Time-integrated rear-side REB energy-density flux

Time-integrated rear-side background electron temp.



→ **5x enhancement on the energy-density flux and induced heating**

(70% of electrons confined in initial radius ; Only 16% w/o B-field)

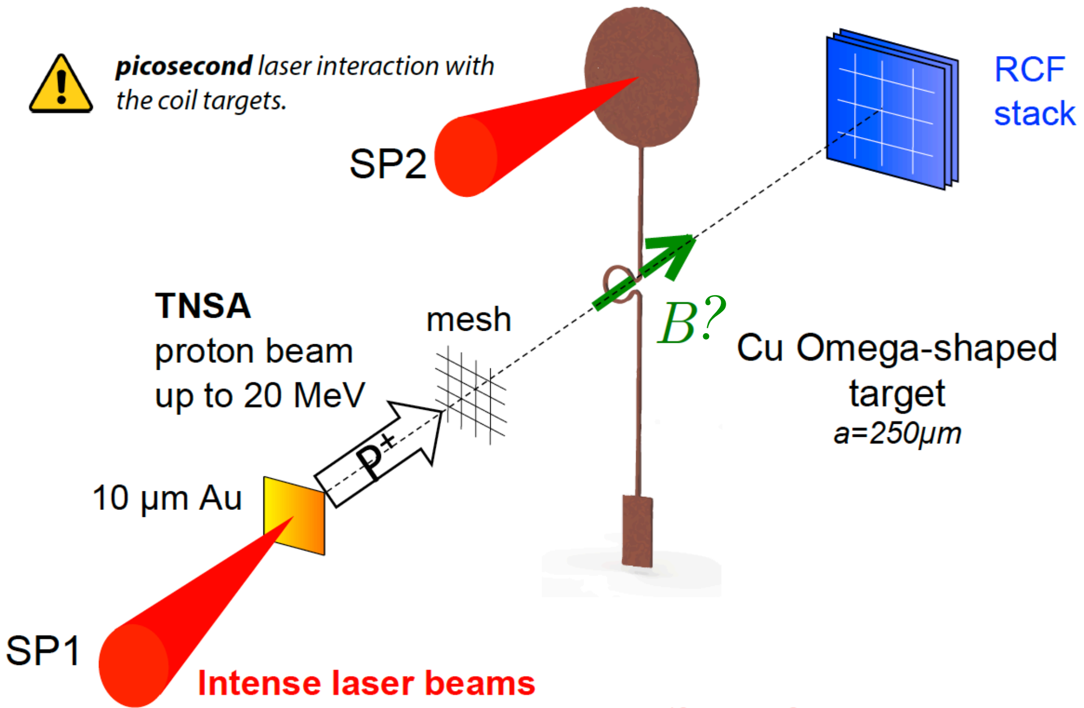
→ **Magnetization of solid targets**

→ **More homogeneous isochoric heating**

Coil-discharges driven in the short-pulse relativistic regime

Setup at the PHELIX laser facility

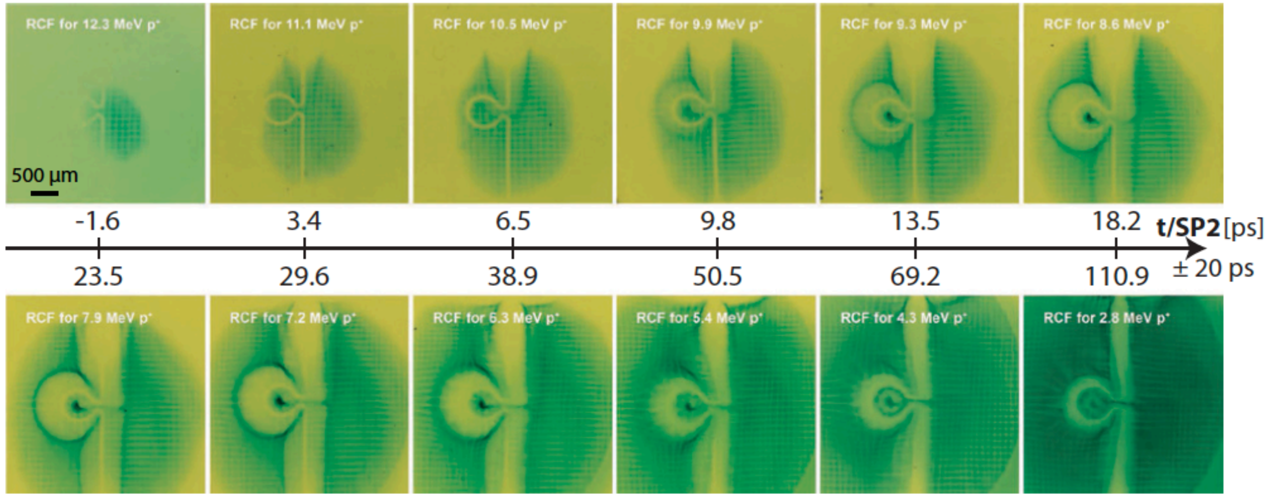
⚠ ***picosecond** laser interaction with the coil targets.*



Intense laser beams
each one : 40 J, 500 fs ; 5×10^{18} W/cm^2

→ Coil-discharge and probing protons driven separately by ps lasers with a controlled delay

→ Electromagnetic lensing of probing protons



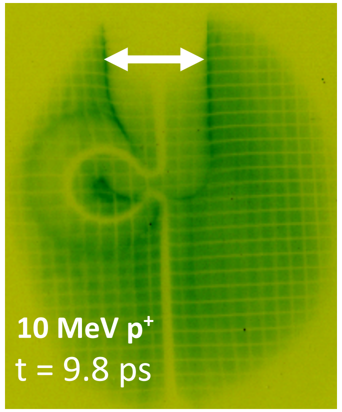
→ **Discharge wave streams along the wire at (0.95 ± 0.02) c**

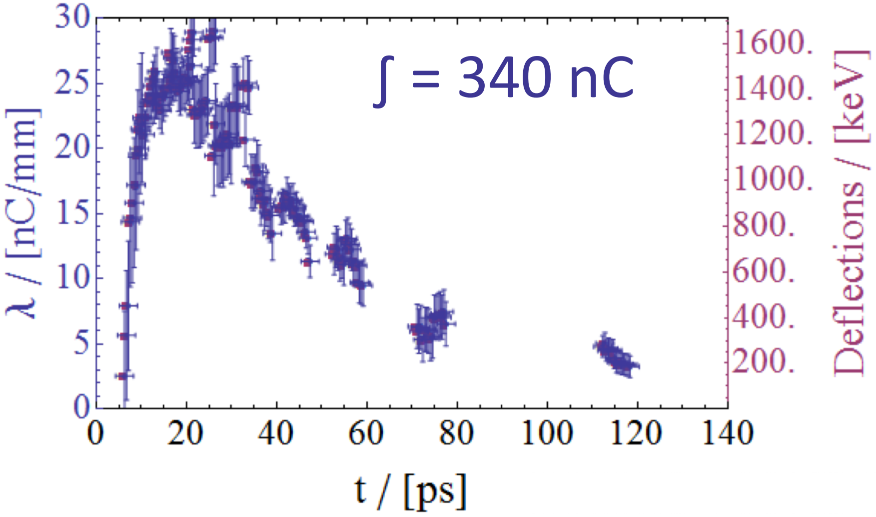
→ **Protons passing inside the coil are focused :** 1.6 ↘ 0.5 mm rad

M. Ehret *et al.*, in preparation

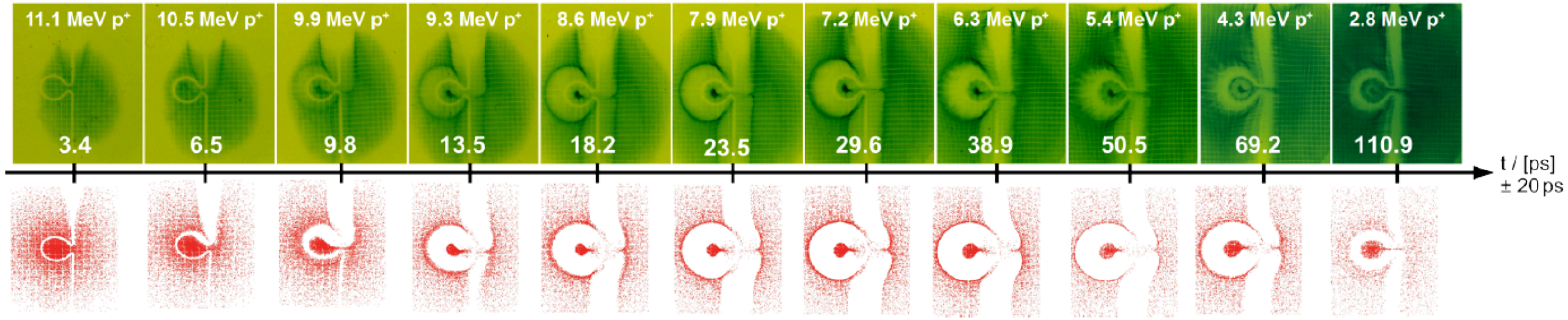
Electromagnetic lensing of TNSA protons

➜ **Streaming pulse shape of positive charge inferred from proton deflections on the straight wire part**



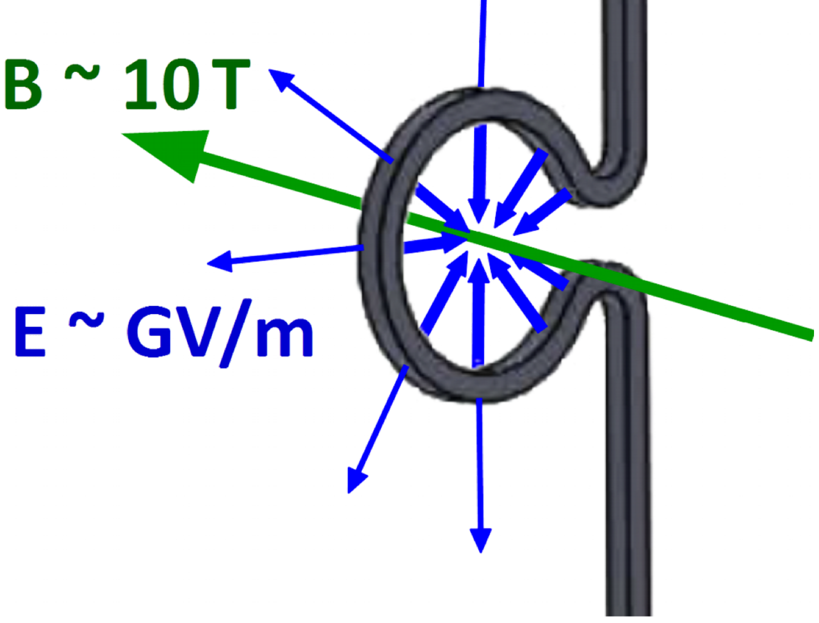


➜ **Synthetic e.m. pulse propagation and proton-deflectometry unfold the fields**



Lens effect lasts < 30 ps

⇒ possible energy selection by tuning the lasers delay



M. Ehret *et al.*, in preparation

Thank you for your attention !