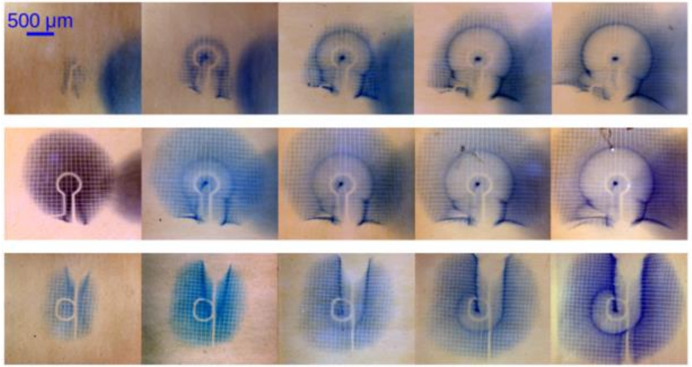
Dispersion Relation and Pulse Shaping of Femtosecond Laser-Driven Transient Pulsed Electromagnetic Fields



Principal Investigators:
P. Bradford, M. Ehret

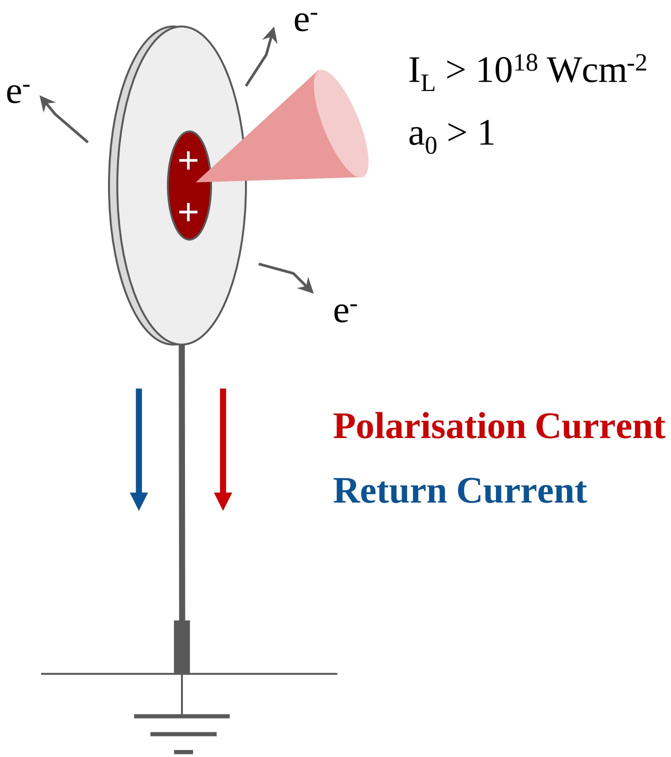
Expert technical support and physical oversight:
C. Vlachos, M. Krupka, Ph. Korneev, G. Gatti, T. Pisarczyk, J. J. Santos

1. **Introduction to laser-driven EM discharges**

2. Our work on fast polarisation pulses driven by relativistic lasers

3. Our experiment on ELI-NP

Relativistic laser-solid interactions produce **electromagnetic pulses (EMP)** that propagate in "vacuum" and along the surface of the target



- Hot electrons ejected by the laser polarise the target
  [A. Brantov *et al*. PRE 2020]
- Polarisation pulse propagates over target surface and EM pulse in free space
  [K. Quinn *et al*. PRL 2009] [M. Ehret *et al*. PoP *submitted*]
  [S. Kar *et al*. Nat. Comm. 2016]
- A return current is drawn when the polarisation wave reaches the ground
  [F. Consoli *et al*. HPLSE 2020]
- Antenna radiation is emitted when the return current passes along the target support
  [J.-L. Dubois *et al*. PRE 2014]
  [A. Poyé *et al*. PRE 2015]

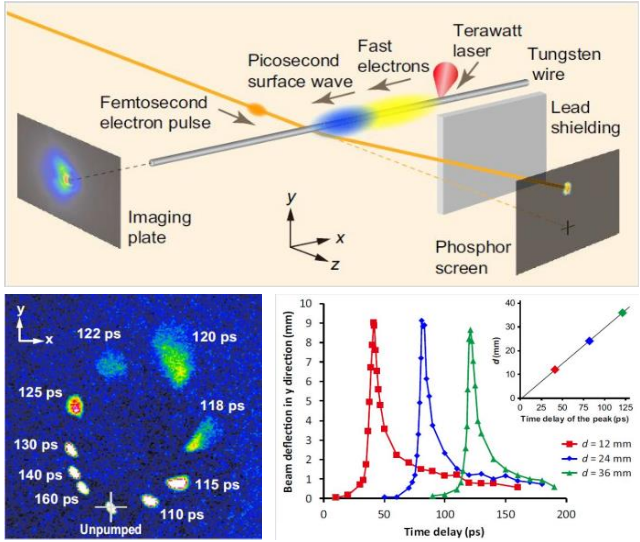
The fast polarisation pulse (t ≲ 50 ps)

As hot e$^-$s cross target-vacuum boundary they excite an EM pulse that propagates in the skin-layer of the target at v ~ *c*

[K. Quinn *et al.* PRL 2009]

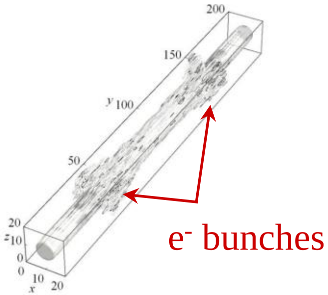
τ ~10 ps Sommerfeld-type EM surface wave

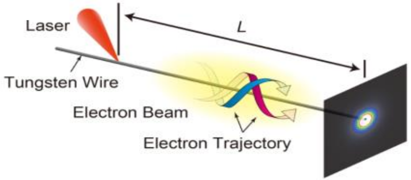
Low dispersion over cm-distances



[S. Tokita *et al.* Sci. Rep. 2015]

Relativistic e$^-$s can be entrained within the surface wave

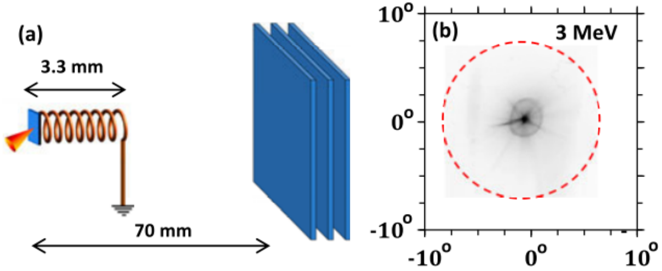




[H. Nakajima *et al.* PRL 2013]

[A. Brantov *et al.* EPJ Web of Conferences 2018]

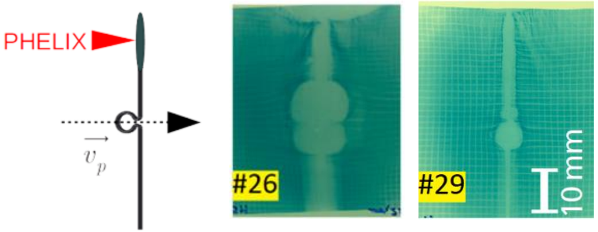
Electric fields for lensing of charged particle beams



[H. Ahmed *et al.* HPLSE 2017]

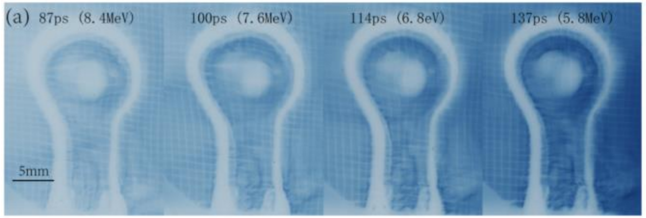
The Return Current (t ≳ 100 ps)

500 fs laser @ 5 x 10^{18} Wcm^{-2} => ~ few kA / tesla in coil



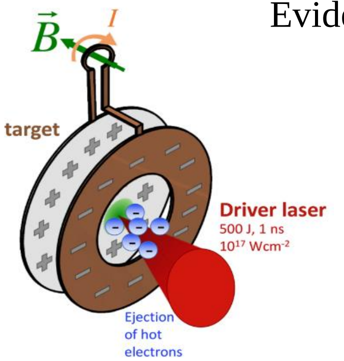
[M. Ehret *et al.* PoP submitted]

30 fs laser @ 10^{18} Wcm^{-2} => 20 T coil field



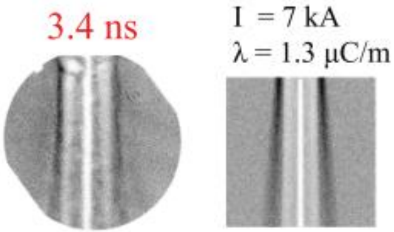
[W. Wang *et al.* PoP 2018]

A similar phenomenon is observed at lower intensity (≲10^{17} Wcm^{-2}) and longer pulse duration (t_{las}~ ns), where the return current can produce quasi-static B-fields



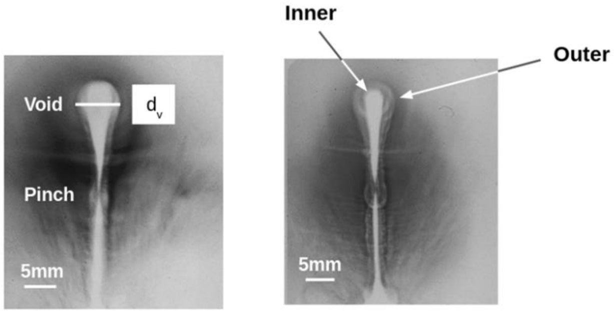
[J. J. Santos *et al.* PoP 2018]

Evidence of multi-kA currents, wire plasma…



[M. Manuel *et al.* APL 2012]

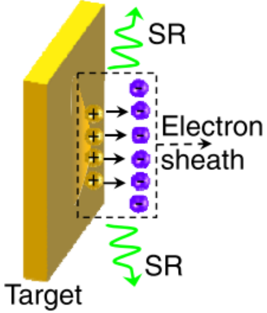
…and long-lived GV/m E-fields



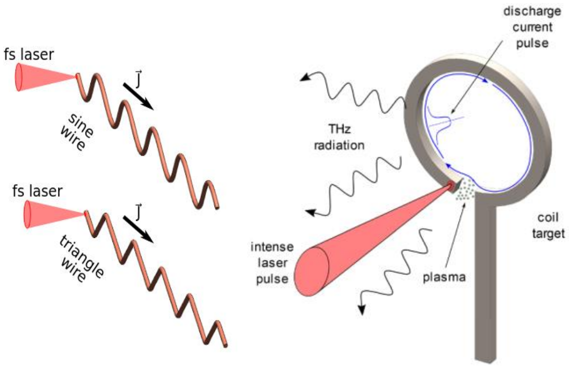
[P. Bradford *et al.* PPCF 2021]

Discharge currents as **secondary sources of radiation**

Bright THz sources

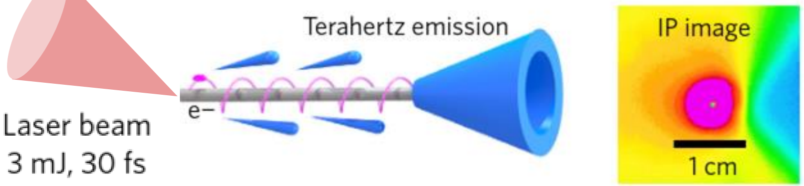


[G.-Q. Liao *et al*. PRX 2020]



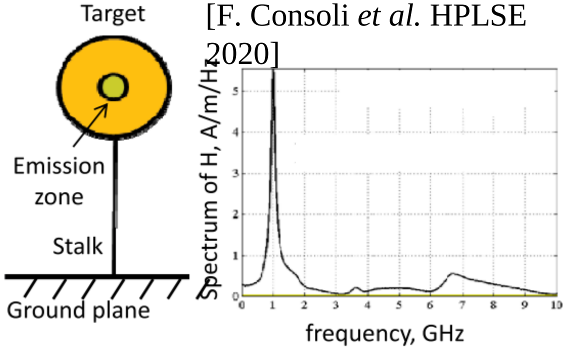
[N. Bukharskii *et al*. APL 2022]

[N. Bukharskii and Ph. Korneev ArXiV 2022]



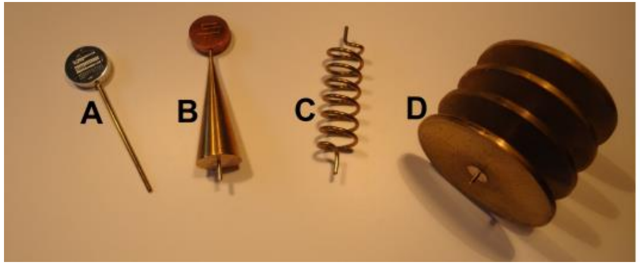
[Y. Tian *et al*. Nat. Phot. 2017]

GHz EMP

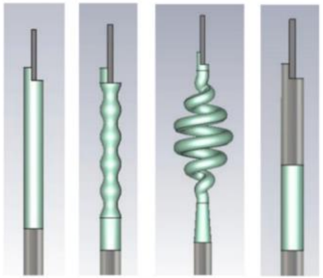


[F. Consoli *et al*. HPLSE 2020]

[D. Minenna *et al*. PoP 2020]



[P. Bradford *et al*. HPLSE 2018]

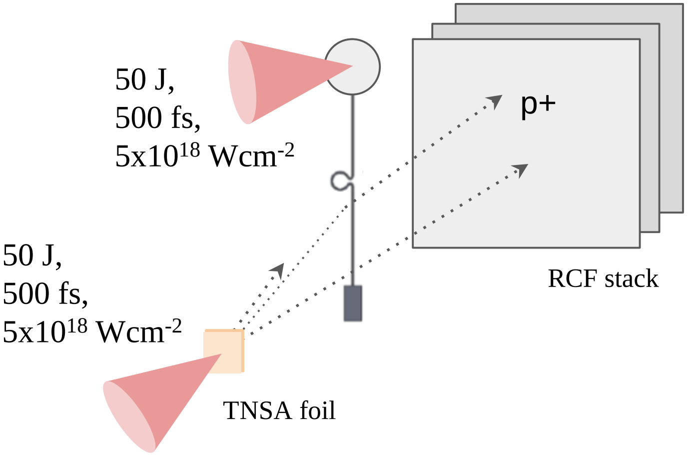


1. Introduction to laser-driven EM discharges

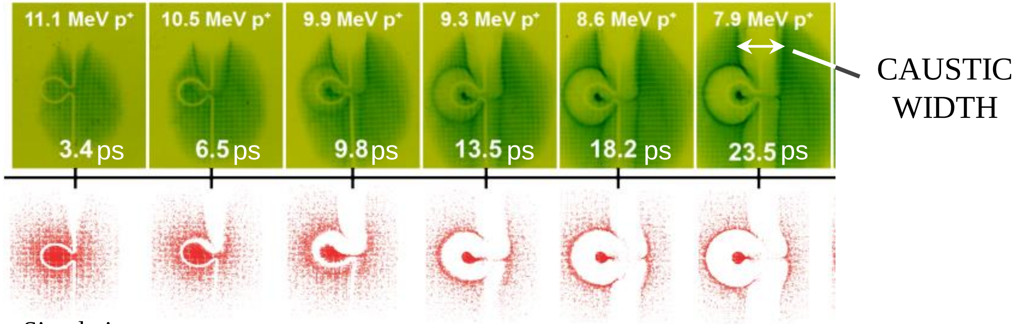
2. **Our work on fast polarisation pulses driven by relativistic lasers**

3. Our experiment on ELI-NP

Sub-*c* group velocity and Weibull-like "shape" of fast discharges measured with proton radiography



PHELIX experiment [M. Ehret *et al.* PoP *submitted*]

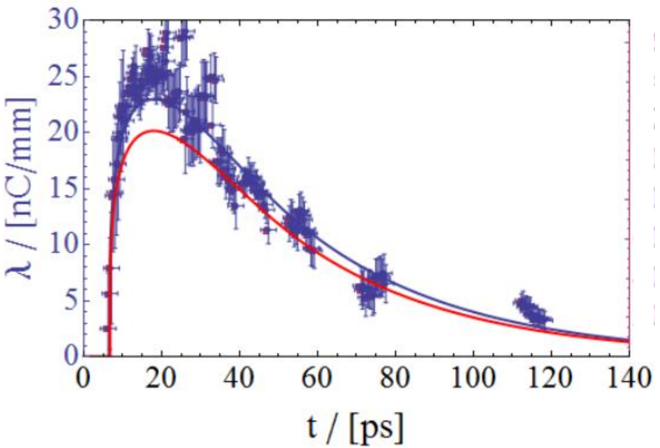


Simulation

1. Analytical deflections dominated by radial E-field:
Caustic width => Weibull-like shape

2. **Electrodynamic p+ tracing simulation** => amplitude, Q = 300 nC

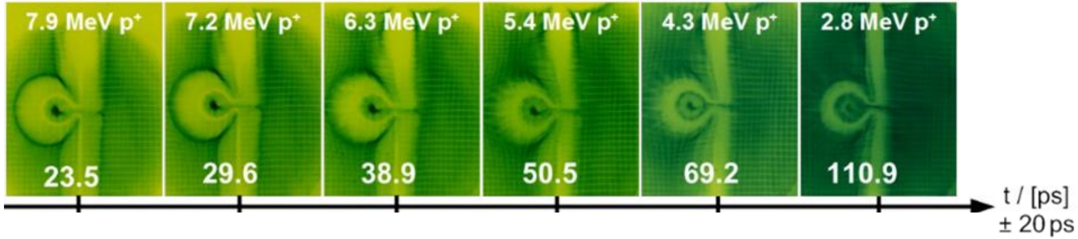
3. Group velocity, $v_g \sim 0.8 - 1$ c



Proton lensing platform provokes interesting questions about the discharge mechanism…

Focusing at coil centre

[M. Ehret *et al.* PoP *submitted*]



Why is the rise and decay >> t_{las} ?

Why is $v_g < c$ on several shots ?

Pulse Characteristics

Rise time, $\tau \sim 10$ ps	E ~ 10 GV/m
FWHM ~ 50 ps	B ~ 1 - 10 T
$v_g = 0.8 - 1\ c$	I ~ 1 - 10 kA

… that are <u>important to answer</u> if we are to develop EM lenses or secondary sources of x-rays, GHz and THz radiation

"Sun-rays" and sub-*c* group velocities indicative of plasma formation on the wire surface?

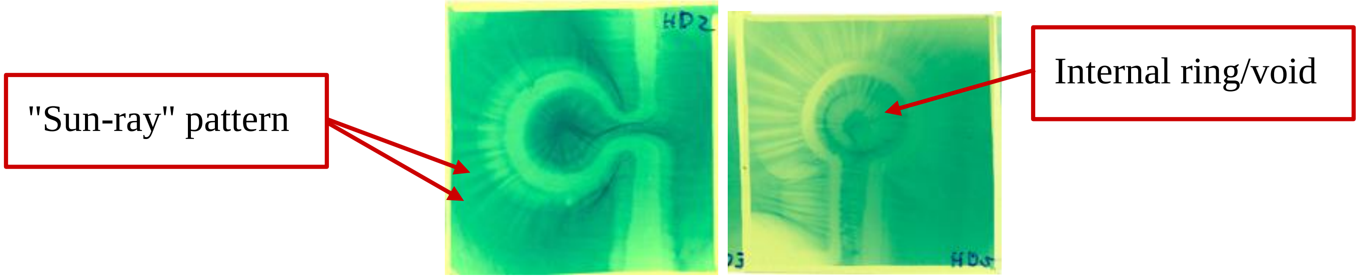
Conjecture 1

For a Sommerfeld wave propagating along a solid conductor, have $v_g \sim c$

Sub-*c* velocity ⇒ plasma formation on wire surface?

Conjecture 2

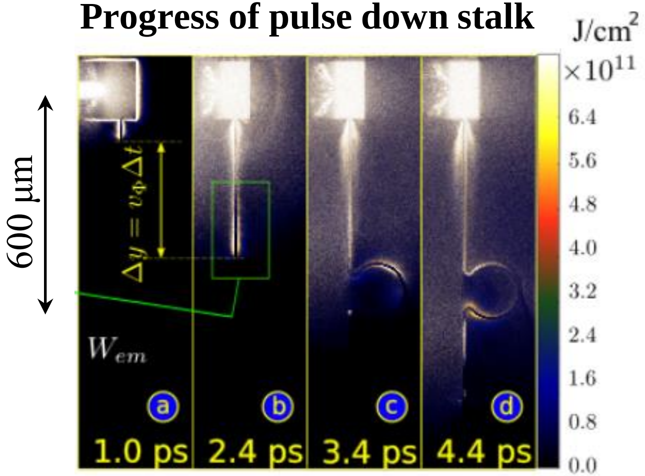
Potential modulations in p+ radiography ⇒ surface roughness can modify wave propagation speed and phase?



PIC sims reveal sub-*c* group velocity of discharge and possible plasma formation on wire

$$w_{em} = B_\perp^2/2\mu_0 + \varepsilon_0 E_\parallel^2/2$$

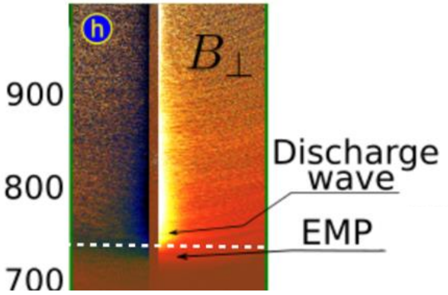
Progress of pulse down stalk



[M. Ehret *et al.* PoP *submitted*]

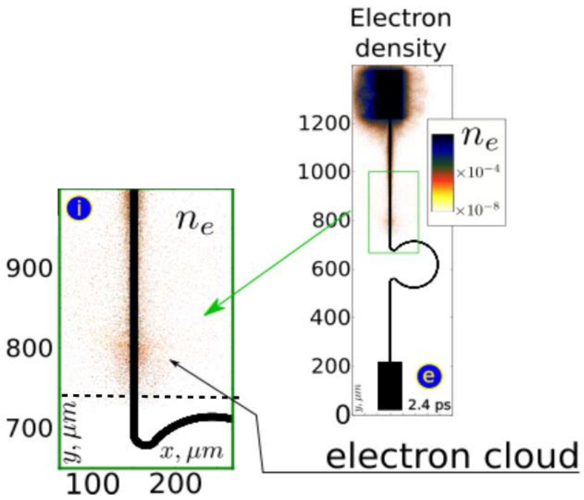
Laser drive
λ = 800 nm,
τ = 1300 fs,
I = 10^{19} Wcm^{-2}

Surface EM pulse propagates more slowly than the airborne EMP



B-field/current rise-time τ ~ 1 ps is <u>too fast</u> to probe with p+ radiography

Plasma formation on wire and/or directly accelerated e$^-$s?



ChoCoLaTII: Simplified Numerical Modelling of Target Charging

[A. Poyé *et al.* PRE 2018]

Target charging is governed by competition between the hot electron temperature T_e and target potential $\Delta\Phi$

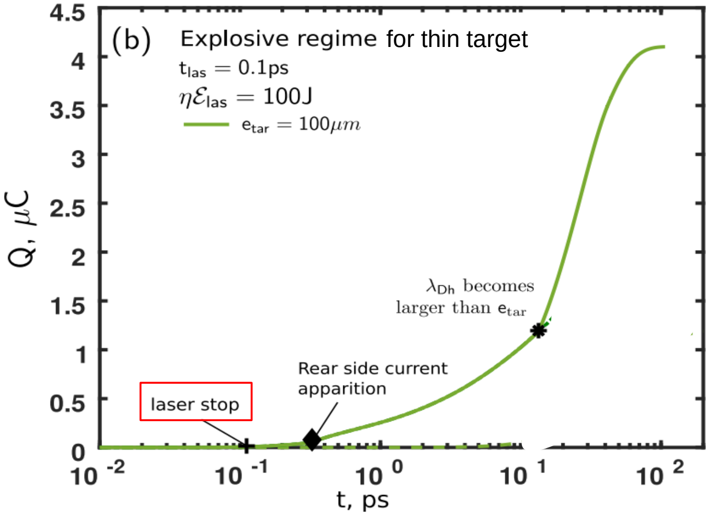
average vel. of electrons that escape the barrier $\Delta\Phi$

$$I_h = e\Omega_b \underbrace{\left(\frac{\eta_\Phi N_h}{V_h}\right)}\pi R_h^2 \overbrace{\int_{\Delta\Phi}^{\infty} f_h(\epsilon) v_h d\epsilon}$$

density of electrons with energy > $\Delta\Phi$

Target potential $\Delta\Phi$ can be divided into thermal (from sheath) and electrostatic (from accumulated charge) components

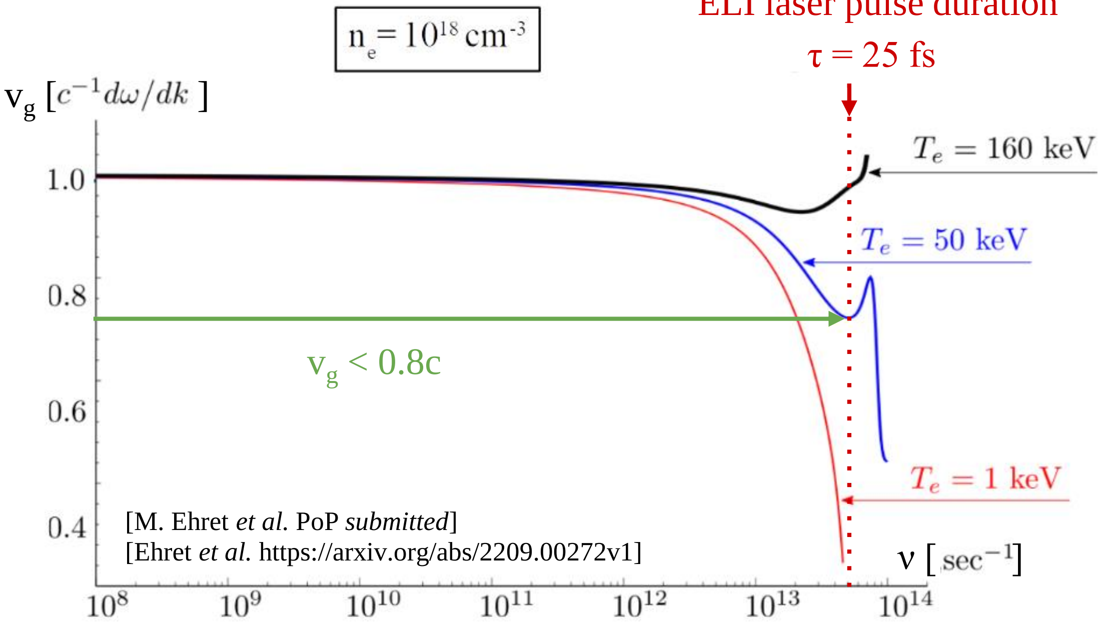
ChoCoLaTII: At high intensity, the rise time of the charge profile can be >> t_{las}



This is principally due to a long hot e[-] collisional cooling time

Analytic modelling of EM wave propagating in wire surface plasma suggests we may be able to tune pulse velocity and shape

Plasma Dispersion Relation: Frequency of polarisation pulse envelope related to plasma (n_e , T_e)



We can estimate the **frequency ν** of the pulse by measuring:

plasma (n_e , T_e)

group velocity, v_g

This allows us to discriminate between:

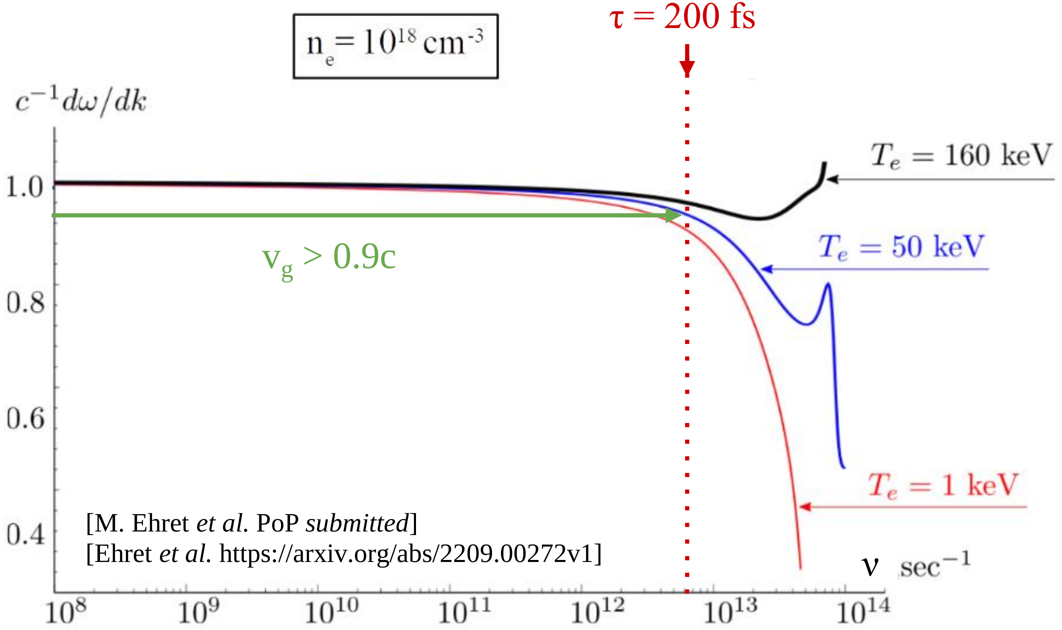
- Expanding surface charge (ChoCoLaTII - long rise-time)
- Sommerfeld wave induced by e^- ejection from target ($\tau_{pulse} \simeq$ laser pulse duration)

Analytic modelling of EM wave propagating in wire surface plasma suggests we may be able to tune pulse velocity and shape

Plasma Dispersion Relation: Frequency of pulse envelope is related to plasma (n_e , T_e)

ELI laser pulse duration

τ = 200 fs



We can estimate the **frequency ν** of the pulse by measuring:

plasma (n_e , T_e)

group velocity, v_g

This allows us to discriminate between:

- Expanding surface charge (ChoCoLaTII - long rise-time)
- Sommerfeld wave induced by e^- ejection from target ($\tau_{pulse} \simeq$ laser pulse duration)

1. Introduction to laser-driven EM discharges

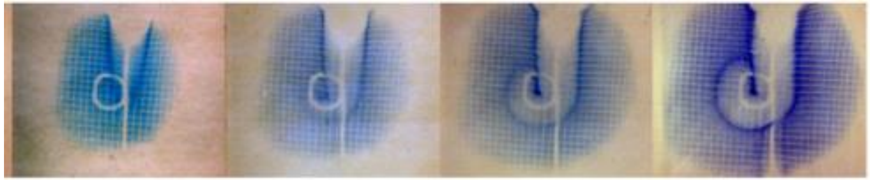
2. Our work on fast polarisation pulses driven by relativistic lasers

3. Our experiment on ELI-NP

ELI-NP is needed to definitively answer the physics of target discharging

We have seen: p+ radiography is limited to ~1-10 ps resolution

Need **sub-ps resolution** (of order t_{las}) to observe if the current rise time is >> t_{las}



Quantify impact of E_{las}, t_{las} and focal spot size on the shape (spatial and temporal) of the discharge pulse
(ELI-NP ESSENTIAL)

Focal spot scan $\Rightarrow T_h \overset{?}{\Rightarrow} Q$

Study the impact of plasma formation on v_g of polarisation pulse

E_{las} scan (fixed I_{las}) $\overset{?}{\Rightarrow}$ impact on Q and T_e via N_h

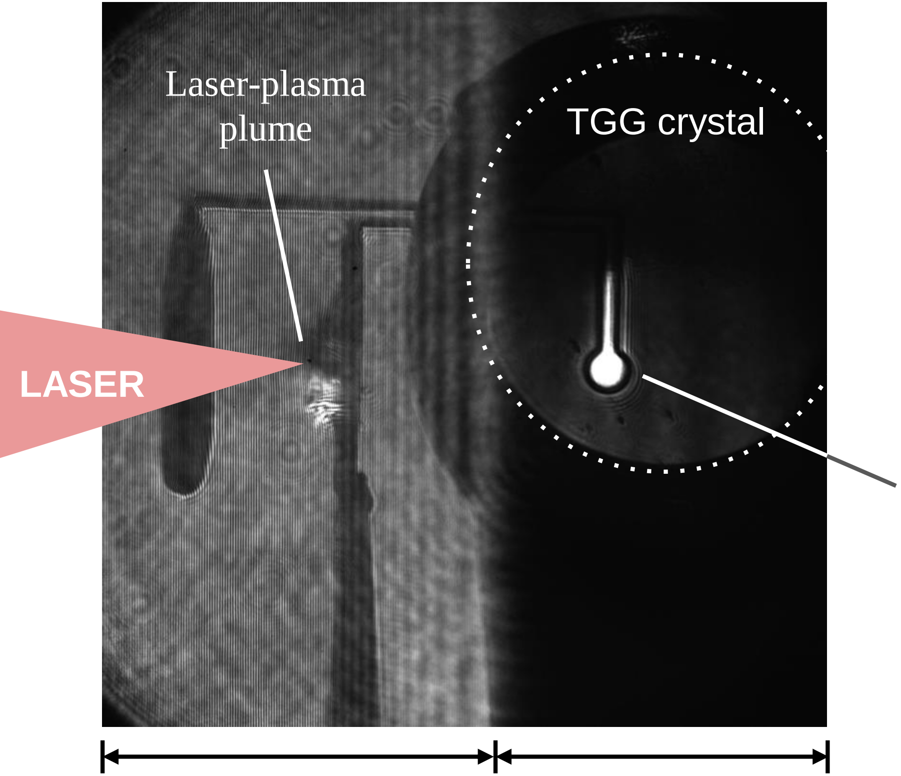
Study the effect of wire thickness, conductivity and roughness on v_g and phase

t_{las} (fixed I_{las} or fixed E_{las}) $\overset{?}{\Rightarrow}$ effect on current and t_{pulse}

Develop pulse trains for selective focusing

Using **optical probing** to diagnose wire currents and plasma conditions at sub-ps resolution

[T. Pisarczyk *et al.* in prep.]



Coil Reference Image

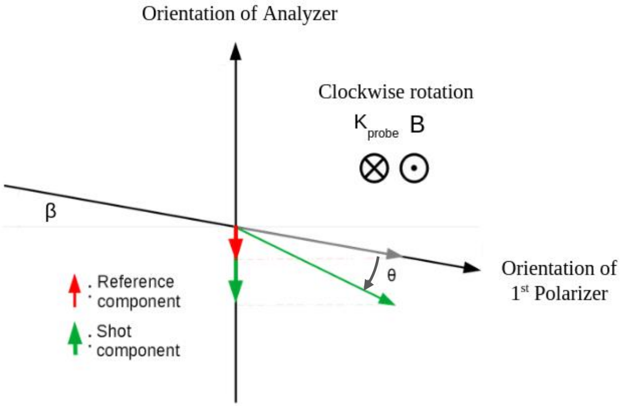
Coil B-field induces polarisation rotation of probe beam

$E_{probe} = 10$ mJ

$\tau_{probe} \sim 40$ fs

$\lambda = 800$ nm

Faraday Rotation Scheme



[T. Pisarczyk *et al.* J. Inst, 2019]

[C. Vlachos *et al.* in prep]

ELI-NP Proposal: First fully-resolved measurement of polarisation pulse and return current

Primary Diagnostics

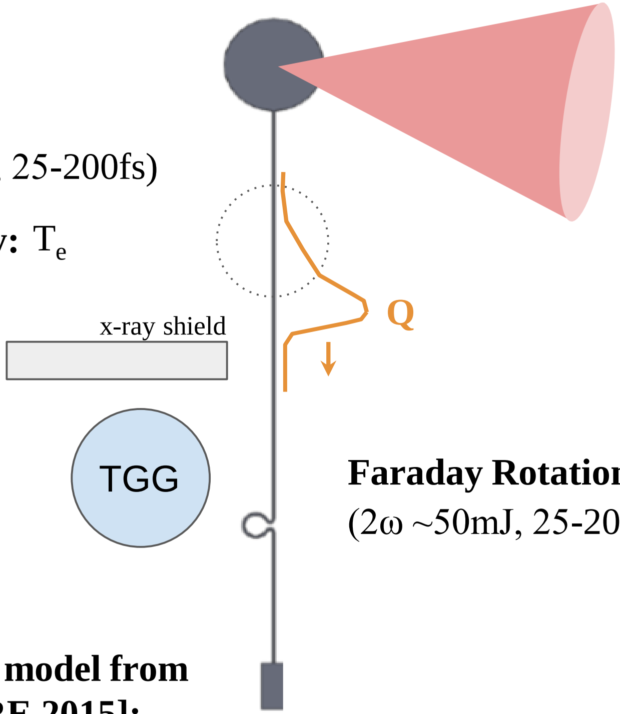
Interferometry and **x-ray spectroscopy** to infer plasma n_e and T_e

Faraday rotation measurement of polarisation/return currents

Interferometry:

n_e probe (2ω ~50mJ, 25-200fs)

X-ray spectroscopy: T_e



4-20μm FWHM
2-24J
25-200fs

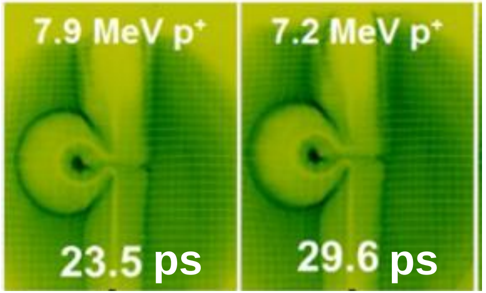
Faraday Rotation:

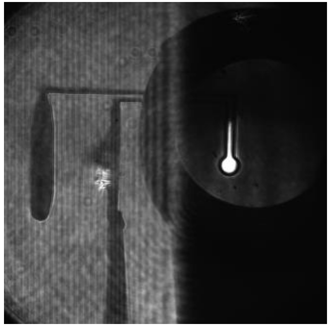
(2ω ~50mJ, 25-200fs)

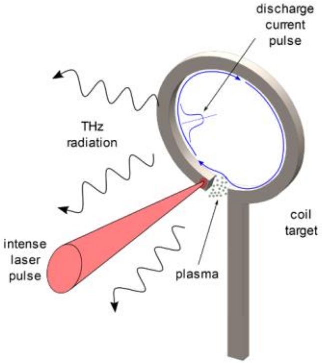
Test charging model from [Poyé *et al.* PRE 2015]:

Conclusions

There remain important questions about the velocity, amplitude and shape of laser-driven currents…







[N. Bukharskii *et al.* APL 2022]

On ELI-NP:

Our experiment will measure the current evolution at **>10x better temporal resolution** than p+ radiography

We will examine how the discharge current is affected by the **plasma dispersion relation** of the wire

We want to use laser/target parameters to produce **shaped kA current pulses and pulse trains**