Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Characterization of intense electromagnetic fields in the radiofrequency-microwave regime generated by powerful laser-matter interaction

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ICFDT - 3rd-5th October 2018, Frascati

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Introduction

- Intense transient radiofrequency-microwave electromagnetic fields are generated by laser-matter interaction. The associated electric fields can reach the MV/m order, and induce saturation and damaging on electronic equipment nearby.
    - On the other hand, intense electromagnetic fields produced by laser-matter interaction can be used for as diagnostic instrument, but also for several different promising applications [1,2]:
        - conditioning of accelerated charged particles
        - for medical and biological studies
        - radiation hardness experiments
        - studies of processes of astrophysical interest.

- Sources of these ElectroMagnetic Pulses (EMPs) in laser-target experiments are still not completely understood for all the different ranges of laser intensity and duration, and they appear to be dependent on the specific experiment and on laser regime. One of the main problems is their accurate measurement.

[1] S. Kar, et al. Nat. Comm. 7, 10792 (2016). S. Fujioka, Sci. Rep. 3, 1170 (2012). J.J. Santos, New J. Phys. 17, 083051 (2015); P. Korneev, Phys. Rev. E 91, 043107 (2015); V.T. Tikhonchuk, et al. Phys. Rev. E 96, 023202 (2017).
[2] B. Albertazzi, et al. Science 346, 325 (2014).

Introduction

- **Some recent studies [1] on Eclipse laser (~100 mJ, tens of fs pulse, ~10^{18} W/cm^2) showed that in those conditions the main source of EMP is target charging because of electron emission, causing the subsequent neutralization current through the target holder.**

- **They suggested that for long pulses EMP contribution due to neutralization current should be strongly inhibithed. Indeed experiments with PALS laser (300 ps, 600 J, 1315 nm) a current of 4 kA was demonstrated [2].**

- **Further recent experiments on Eclipse laser showed that some effects go beyond the dipole-antenna emission mechanism due to neutralization currents [3].**

- **Other possible sources of EMP for the different regimes, relevant for Inertial confinement fusion and laser-plasma acceleration?**

[1] J.-L. Dubois et al, PRE 89 (2014) 013102; A. Poyé et al, PRE 91 (2015) 043106;
[2] J. Cikhardt et al., Rev. Sci. Instrum. 85 (2014) 103507; J. Krasa, et al, Plasma Phys. And Control. Fusion 59 (2017) 065007
[3] P. Rackza, et al, Laser Part. Beams 35, 677 (2017)

Conductive probes

- The detection of one component of the electromagnetic field is commonly performed by electric or magnetic conductive probes [1-6] and by broadband antennas [7-12].

- The use of conductive probes for EMP measurements shows many problems, because information on fields is in terms of electrical current. This causes
  - detection of spurious signals
  - impossibility to perform measurements at direct sight of target and at close proximity. Their use requires effective shielding against direct and indirect (generated on surfaces of objects in the vacuum chamber: bremsstrahlung, recombination of photo-emitted electrons) ionizing radiation coming from laser-plasma
  - access only to the time derivative of the signal sensitive to dD/dt or dB/dt. Limitations due to the finite resolution of oscilloscopes.
  - reduced bandwidth especially at the lowest frequencies
  - detection of only one component for a given place

[1] A. V. Kabashin, et al., Appl. Phys. Lett. 73 (1998) 25;
[2] J. Raimbourg, Rev. Sci. Instrum. 75 (2004) 4234;
[3] D. C. Eder, et al., LLNL-TR-411183, Technical Report, LLNL (2009);
[4] J. J. Santos et al, New J. Phys. 17 (2015) 083051;
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[9] F. Consoli, R. De Angelis et al, NIMA 720 (2013) 149;
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[11] F. Consoli, R. De Angelis et al, 33rd ECLIM, 2014, Paris, France.
[12] F. Consoli, R. De Angelis et al, Proc. 15th IEEE-EEEIC, 2015, Rome, Italy.

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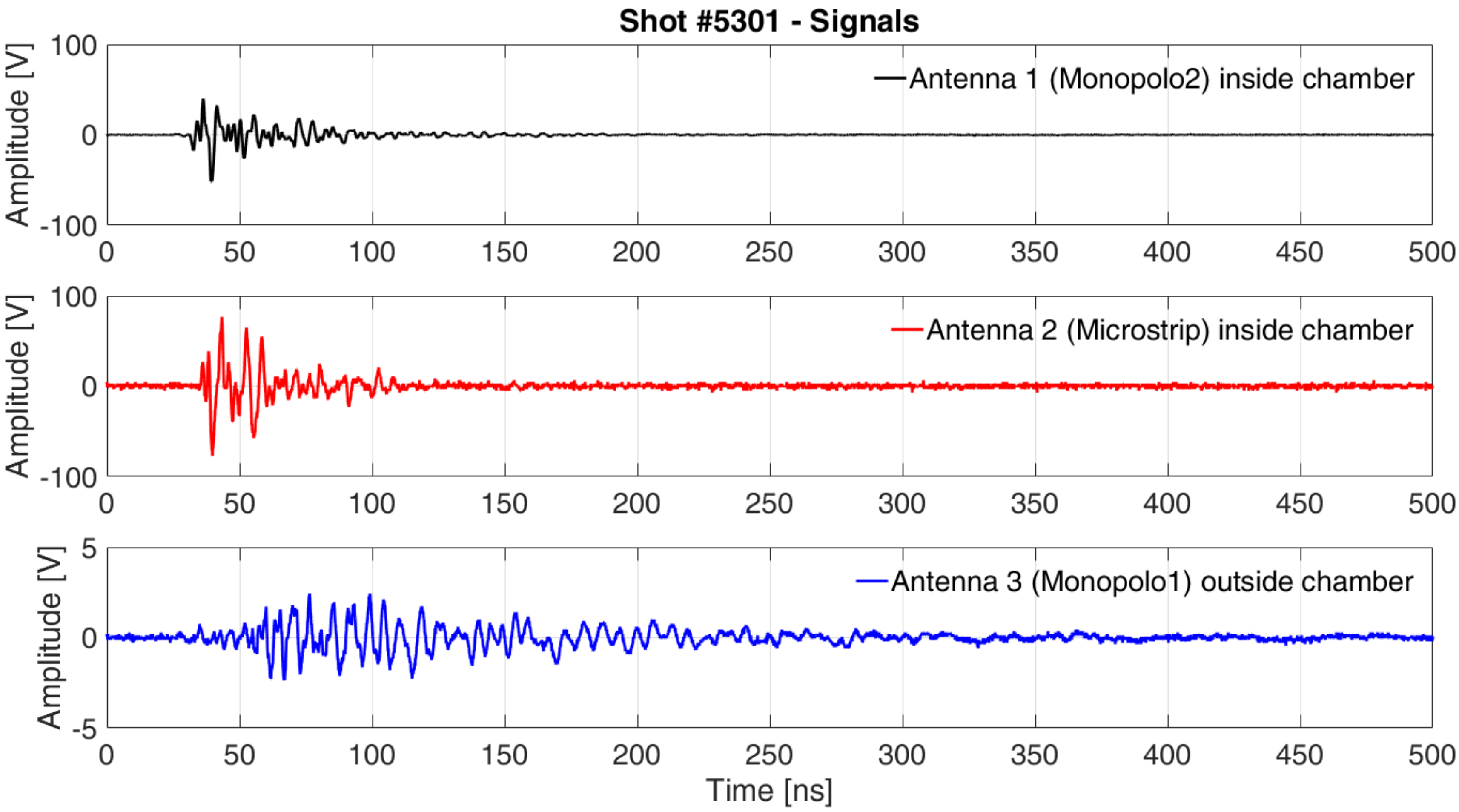
Conductive probes

- **Examples of signals detected by conductive probes**



Dielectric Electro-Optical Probe

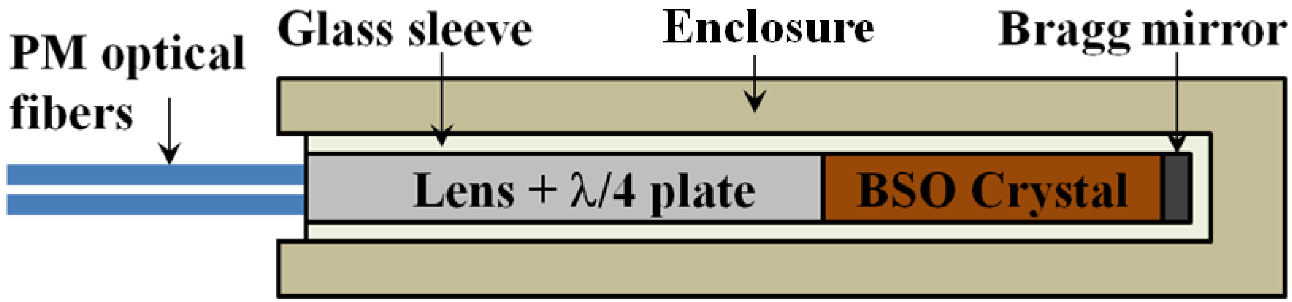
- Linear Electro-Optical (Pockels) effect – isotropic BSO crystal
- Circularly polarized laser probe beam, λ = 1550 nm
- *__Polarization state modulation__* (PSM): polarization modified by birefringence induced on the isotropic crystal
- Propagation vector $\vec{k}$ ~ <111> direction of the crystal – Measurements of $\vec{E}_{\perp}$ orthogonal to $\vec{k}$. Generated elliptical polarization containing information on:

  1) ellipticity and 2) $\xi_{\pm}$ orientation of the eigendielectric axes with respect to the <11$\bar{2}$> optical axis

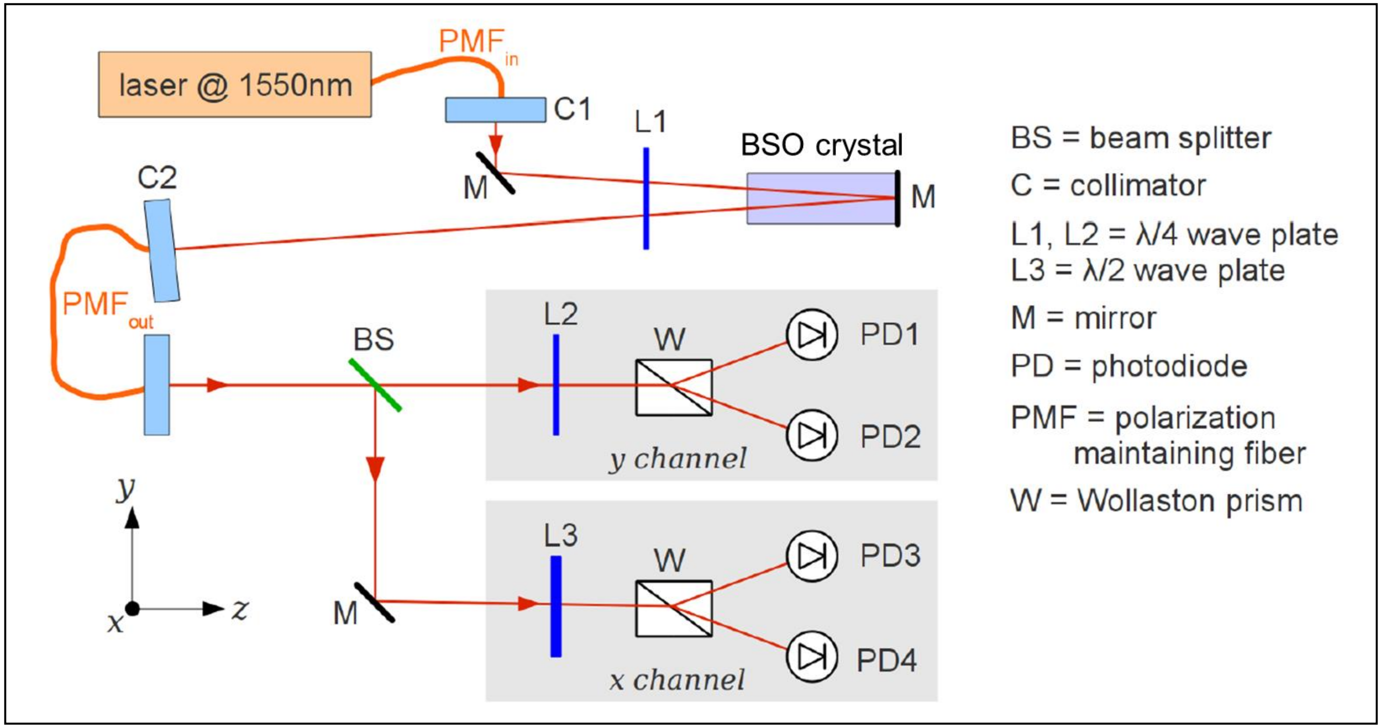
$$\Delta\varphi \propto |\vec{E}_{\perp}|; \qquad \xi_{\pm} = \frac{\pi(3 \pm 1) - 2\alpha_E}{4}$$

being $\Delta\varphi$ the induced phase between the two transverse components, and α_E the angle between $\vec{E}_{\perp}$ and the <11$\bar{2}$> direction.

- Propagation vector $\vec{k}$ ~ <100> direction of the crystal – Measurements of $\vec{E}$ component parallel to $\vec{k}$.



Dielectric Electro-Optical Probe



- **Calibration by a TEM cell provided precise data on orientation of crystal axes and sensitivity.**

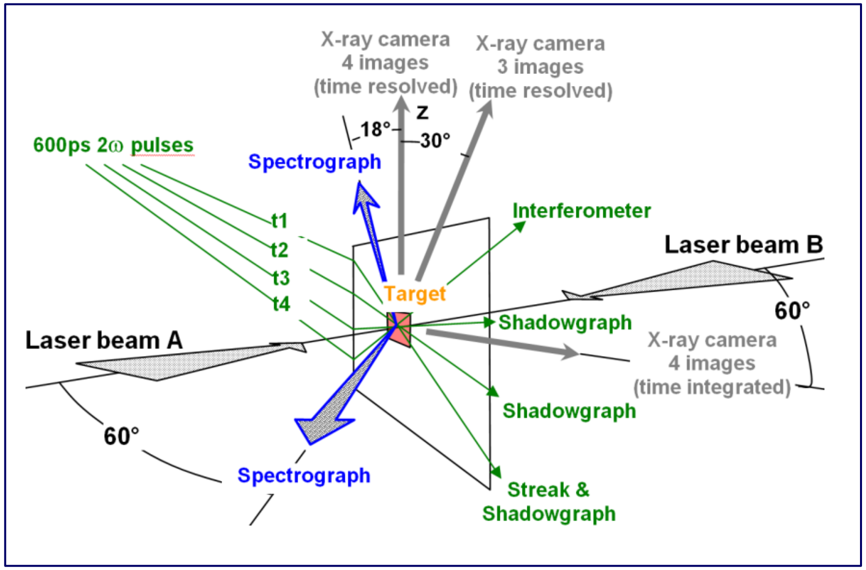
Dielectric Electro-Optical Probe

Advantages with respect to classical conductive probes

- **Direct and linear access to the electric field, without any time integration, as instead done for electric and magnetic conductive probes (sensitive to dD/dt or dB/dt). No problem for low frequency components.**
- **Possibility to put the probe close to the target, and at direct sight**
- **Possibility to perform time resolved measurement of multiple components of the electric field simultaneously in the same position**
- **Negligible perturbation of the fields, due to the dielectric nature, and the small dimensions**
- **High space resolution (a few mm)**

EMP Detection by Electro-optical probe - 1

ABC LASER – ENEA Centro Ricerche Frascati



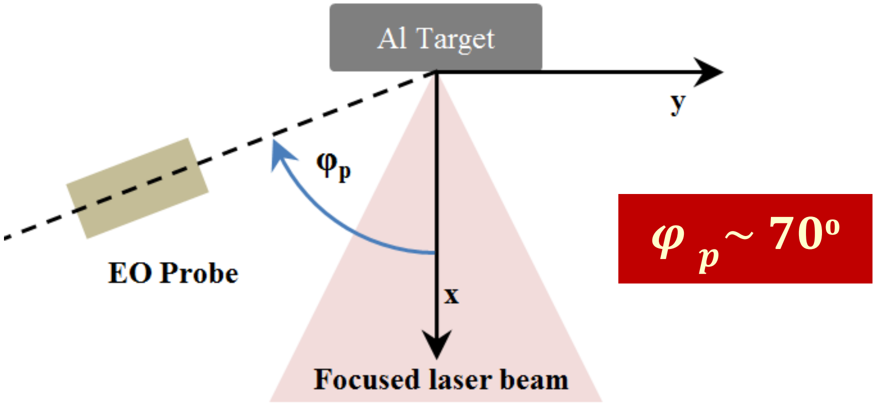
- Nd:phosphate-glass
- λ_0 = 1054 nm
- FWHM = 3 ns
- Two circularly polarized beams
- 100 J maximum energy each, at λ_0
- Possibility to work at $\lambda_0/2$
- 10^{-5} contrast
- F/1 lens up to 50 μm diameter focal spot

Experiment parameters

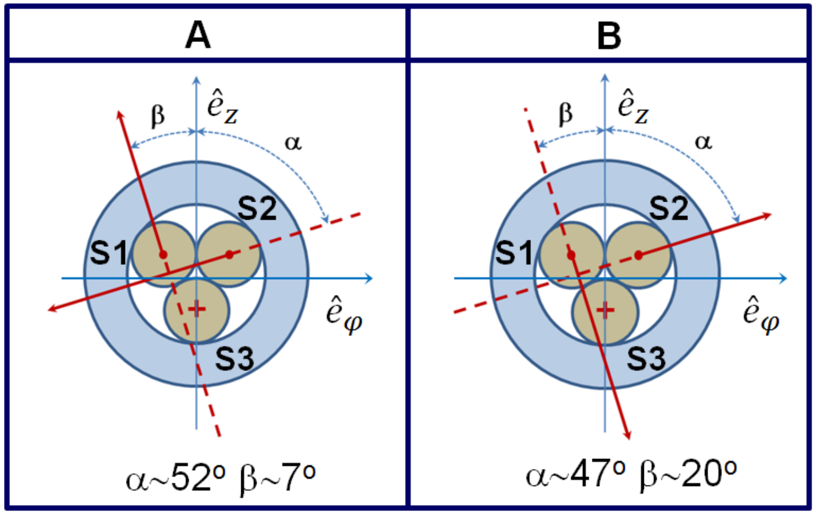
- One beam, 20-30 J; 35-45 J
- $\lambda = \lambda_0$
- Focus: 50 μm diameter
- ~ $5 \cdot 10^{14}$ W/cm^2 intensity
- Normal incidence
- Pure Al target:
  - 1.71-1.79 mm thickness
  - 40 mm^2 plain surface

Measurement setup

- <u>One field component for each probe</u> – BSO crystals for all.
  - Classical transversal configuration for two probes: $\vec{k}$ ~ <111>.
  - Longitudinal configuration for the third probe: $\vec{k}$ ~ <100>
- <u>85 mm</u> distance from target
- The complete structure was enclosed in a 3 mm thick Teflon shield, which
  - protected it from the direct X-ray radiation coming from the LPI
  - improved the overall sensitivity, due to partial impedance matching caused by Teflon ε_r = 2.1, intermediate between the probe effective ε_r ~ 9 and vacuum [2].



$\varphi_p \sim 70^o$



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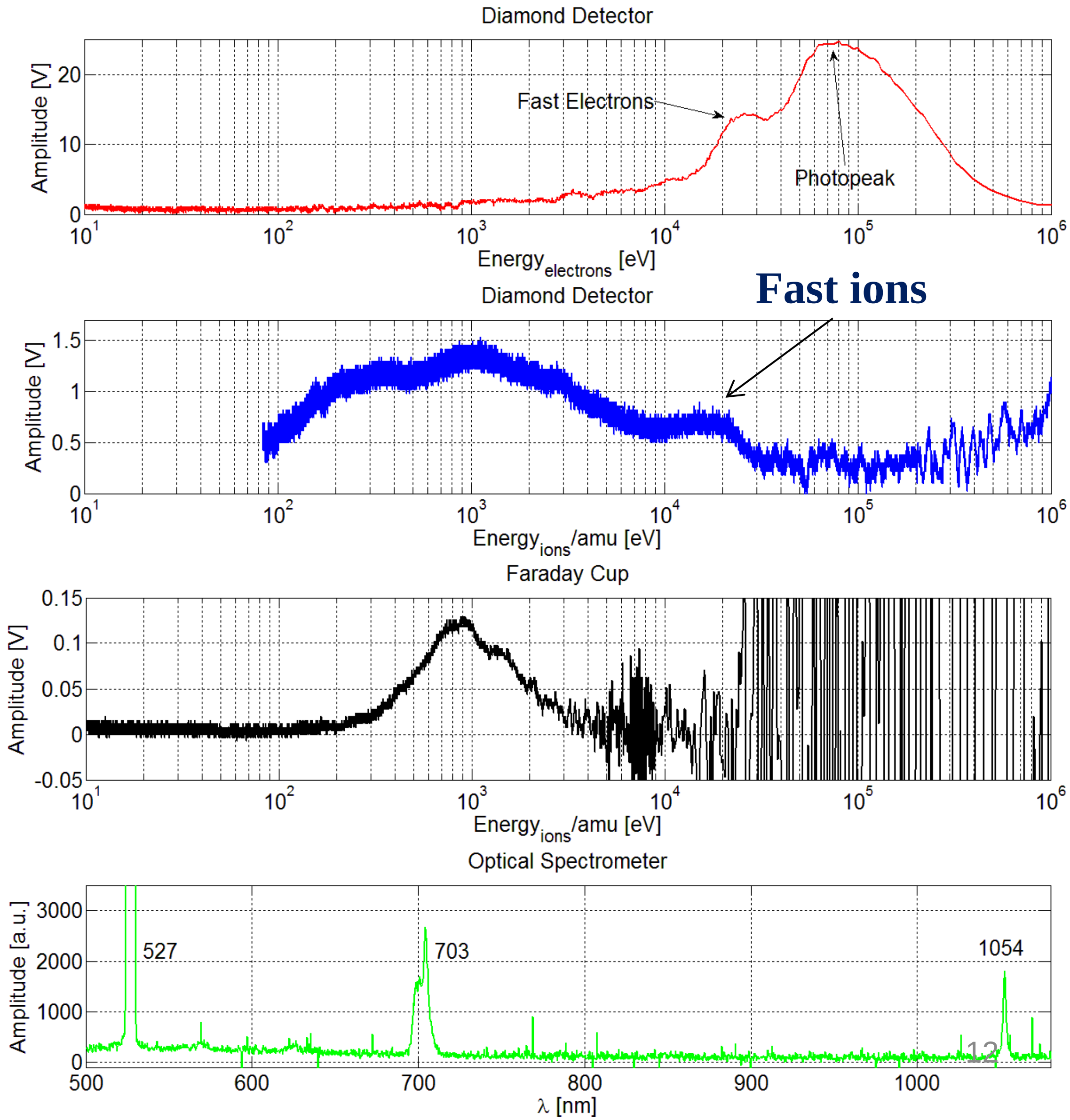
[2] G. Gaborit et al, Appl. Phys. Lett., 90, (2007) 241118 ; IEEE Trans. on Plasma Sci., 41, 10, (2013) 2851; 42, 5, (2014) 1265

Experimental measurements - LPI

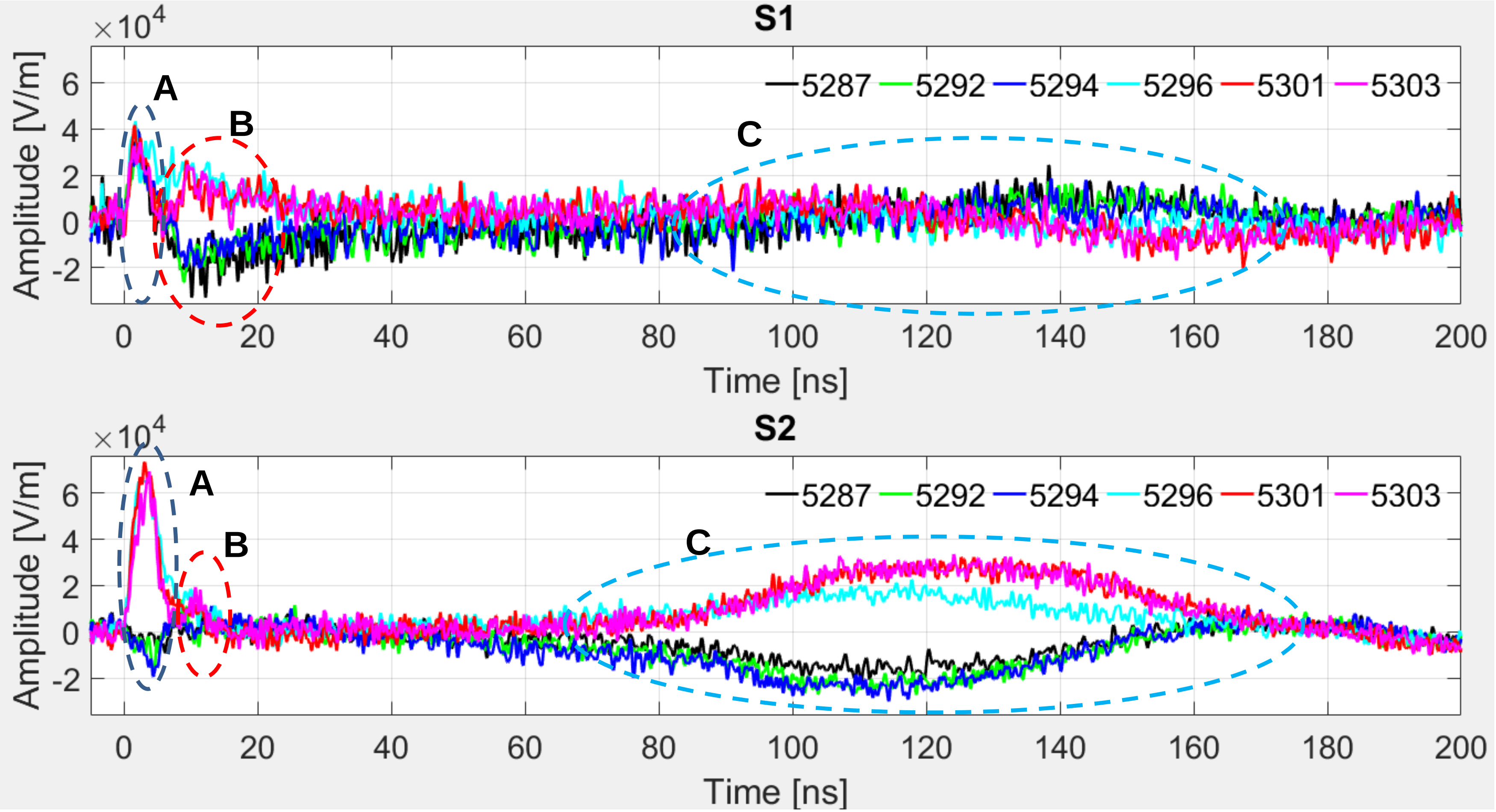
- CVD Diamond Detector:
65º from target normal;
Fast electrons:
peak at 26 keV,
with FWHM = 40%.
Fast ions:
peak at E_{ion}/amu ~ 20 keV
Thermal ion component
peak at E_{ion}/amu ~1 keV

- Faraday Cup:
53º from target normal;
thermal ion component;
~ as CVD Diamond

- Optical spectrometer.
2/3 λ component

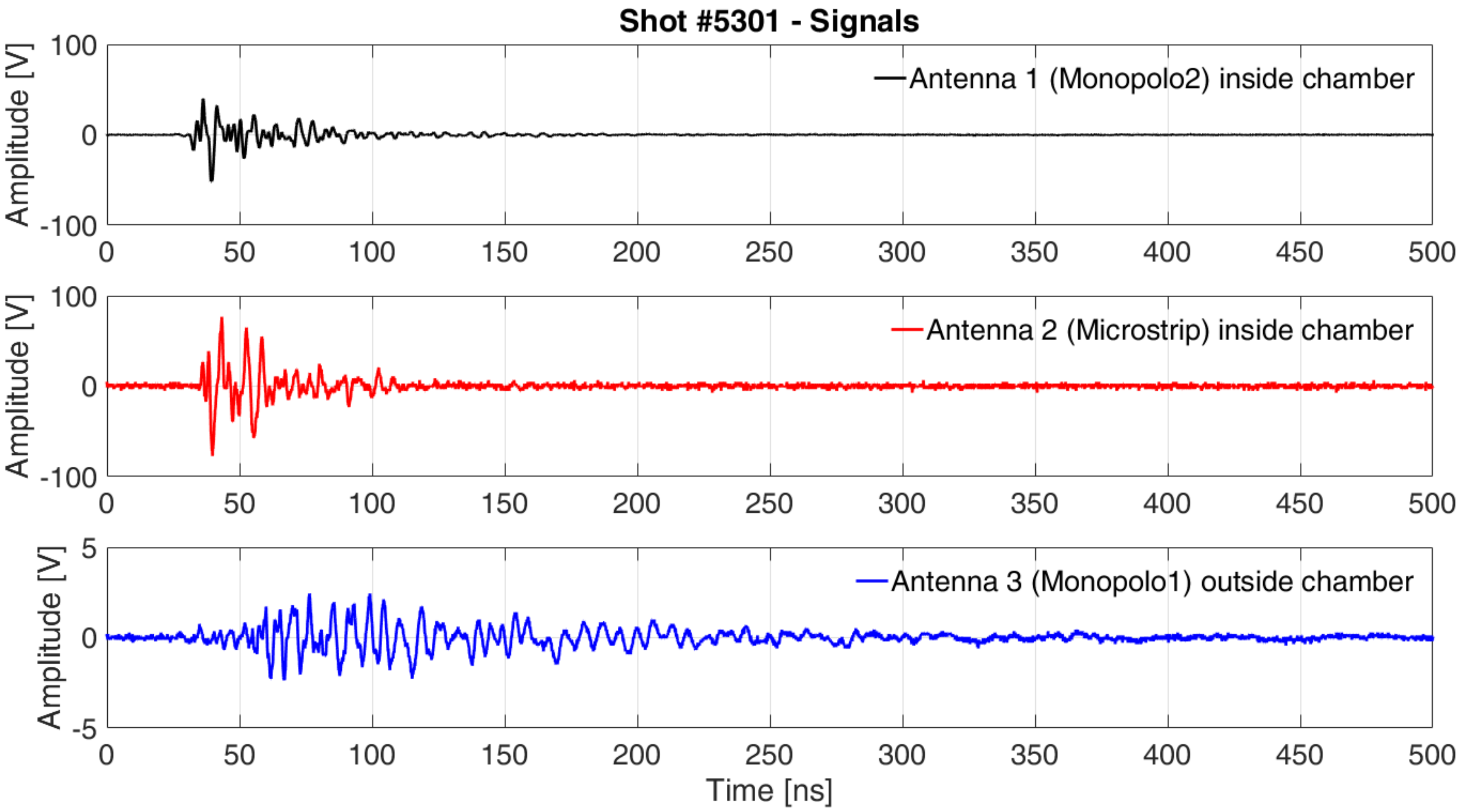


Two-axis E field measurements



Conductive probes

- **Examples of signals detected by conductive probes**



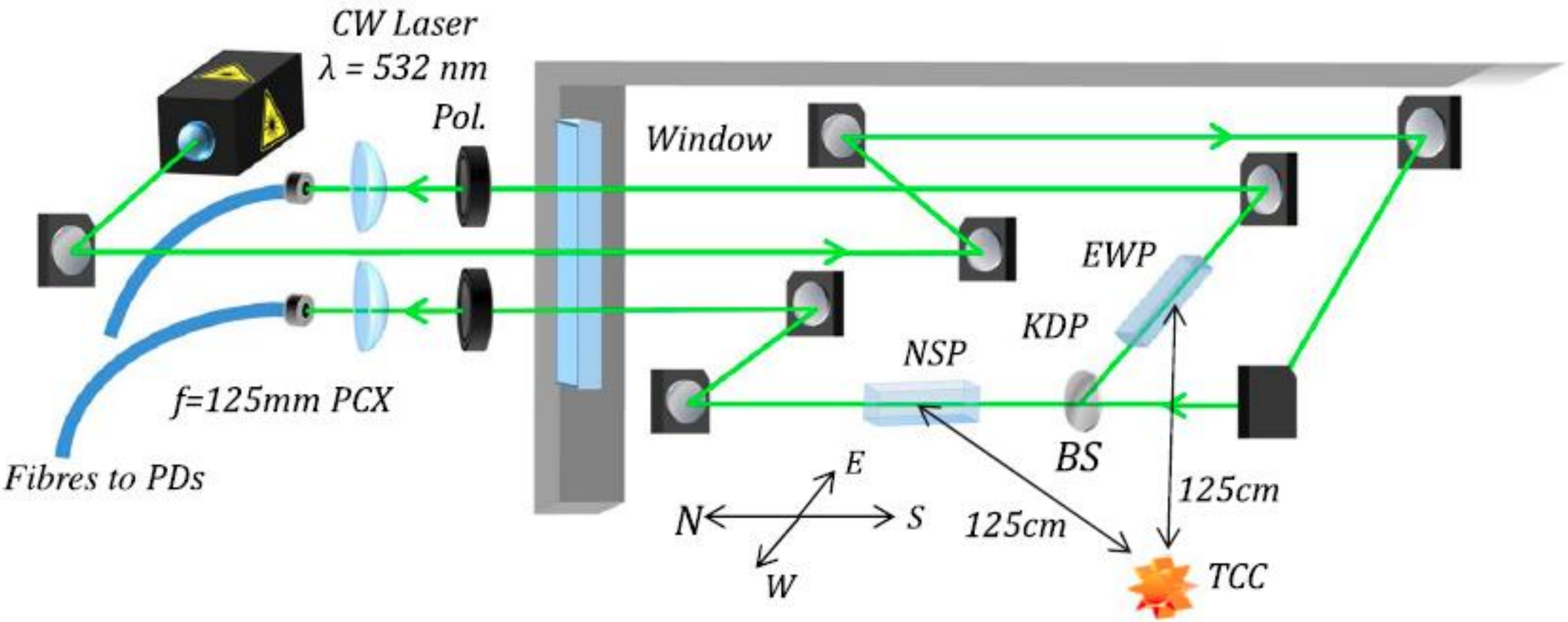
EMP Detection by Electro-optical probe - 2

Vulcan experiment

- **269 nm thick Parylene-N plastic foil target (1.1 g/cm^3)**

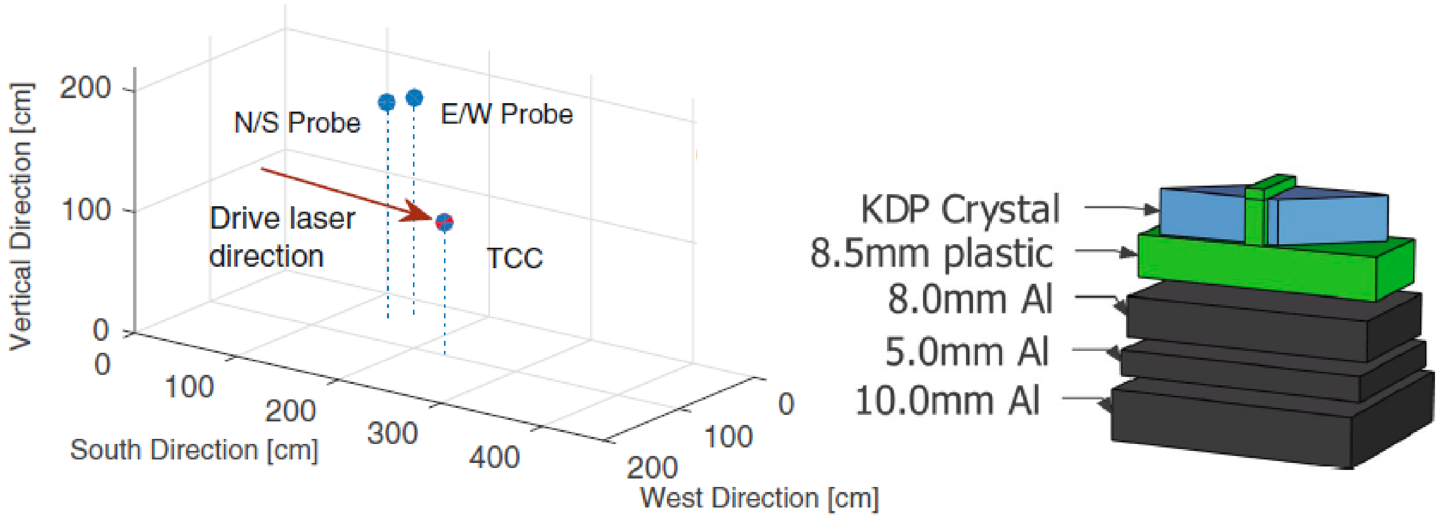
- **Vulcan. Laser: pulse of duration 1.7 ps, centre wavelength 1054 nm, 386 J delivered to target, 227 TW power, peak intensity of 4.8 × 10^{20} W/cm^2.**

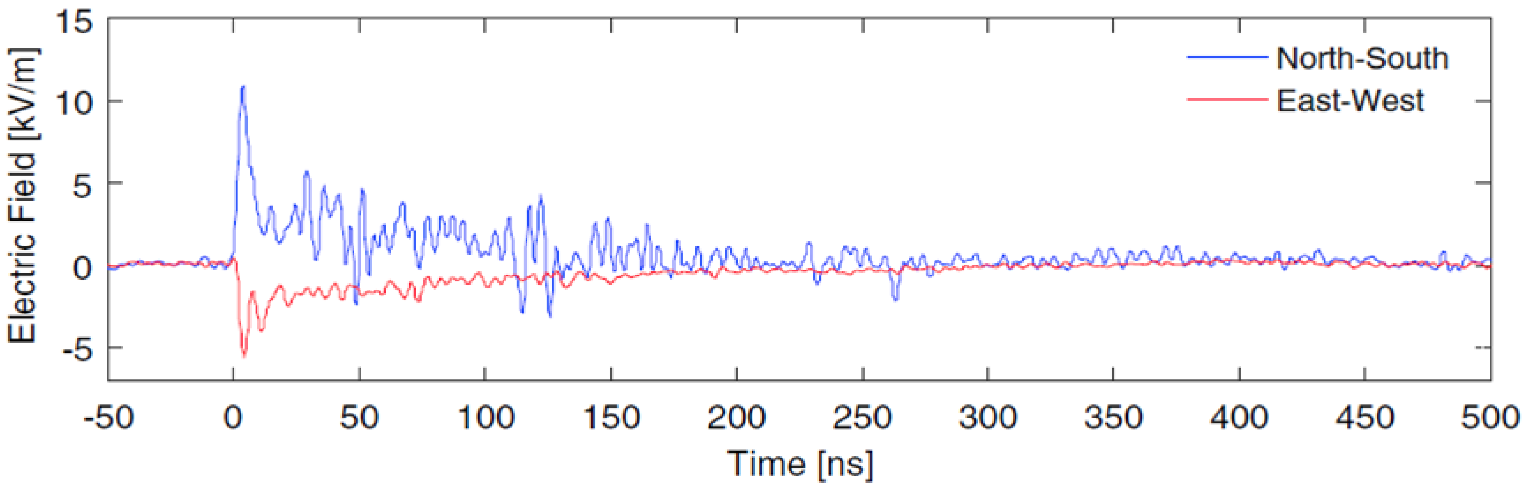
- **KDP crystals used**



T.S. Robinson, F. Consoli, S. Giltrap, S.J. Eardley, G.S. Hicks, E.J. Ditter, O.Ettlinger, N.H. Stuart, M. Notley, R. De Angelis, Z. Najmudin & R.A. Smith, Scientific Reports 16, 42441 (2017)

Vulcan experiment



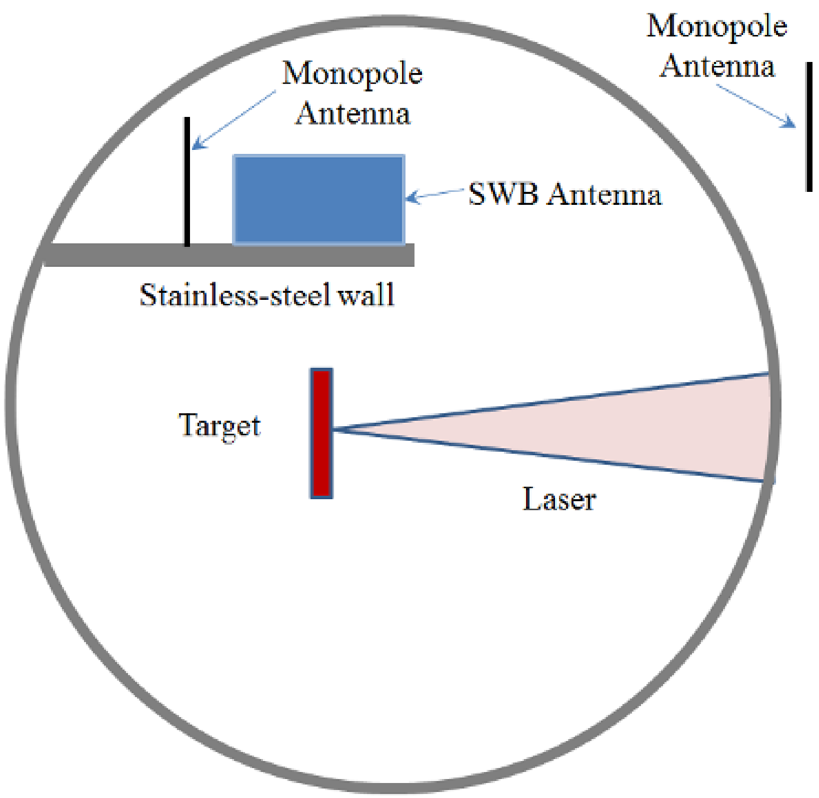


Electro-optical methods efficient even inside the experimental chamber of Vulcan Petawatt experiment at 5 × 10^{20} W/cm^2 intensities.

EMP Detection by conductive probes

PALS Experiment

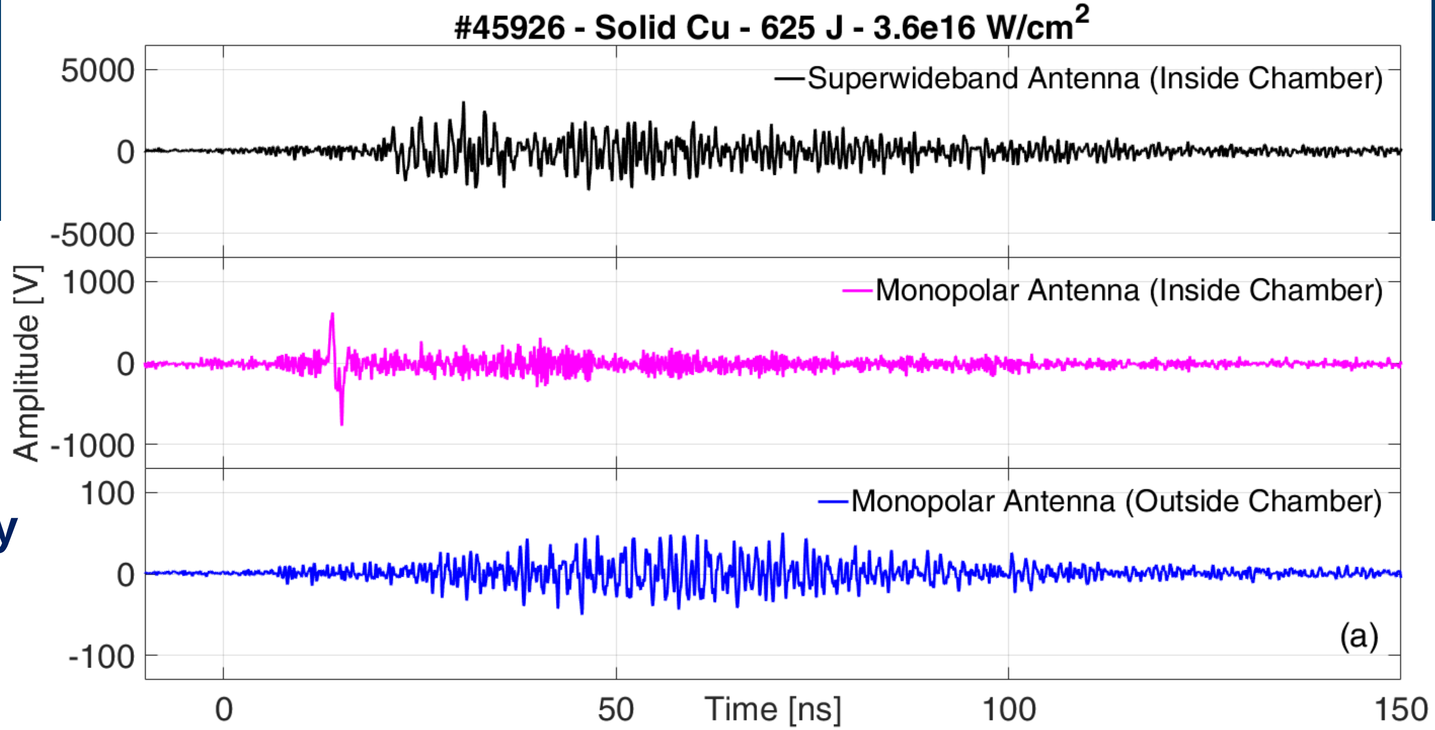
- λ_0 = 1315 nm fundamental wavelength, with ~350 ps pulse duration, energies up to 600 J, intensities up to 10^{16} W/cm^2 on solid targets of different materials

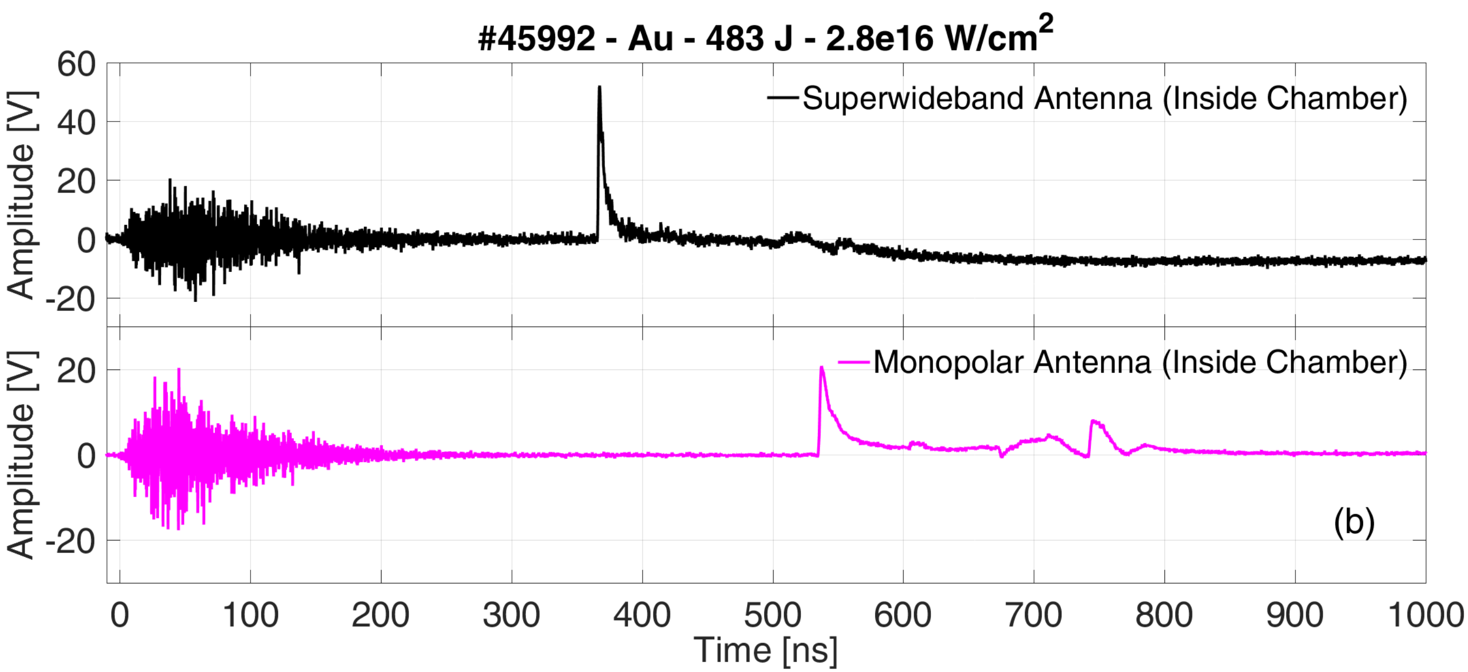


- F. Consoli, R. De Angelis, M. De Marco, J. Krasa, J. Cikhardt, M. Pfeifer, D. Margarone, D. Klir, R. Dudzak, "EMP characterization at PALS on solid-target experiments", Plasma Physics and Controlled Fusion 60, 105006 (2018)
- M. De Marco, J. Krása, J. Cikhardt, F. Consoli, R. De Angelis, M. Pfeifer, M. Krůs, J. Dostál, D. Margarone, A. Picciotto, A. Velyhan, D. Klír, R. Dudžák, J. Limpouch, G. Korn, EPJ Web of Conferences 167, 03009 (2018).

PALS Experiment

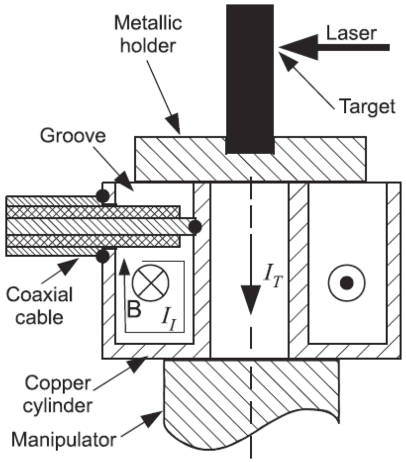
Use of specific delay lines can induce time integration of the signals

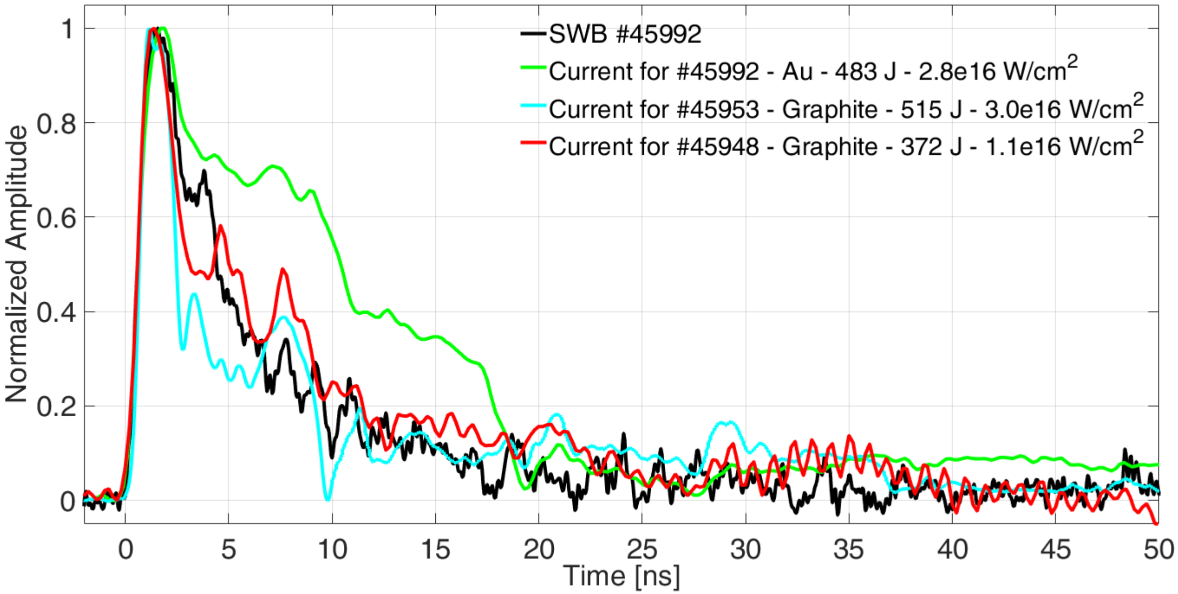


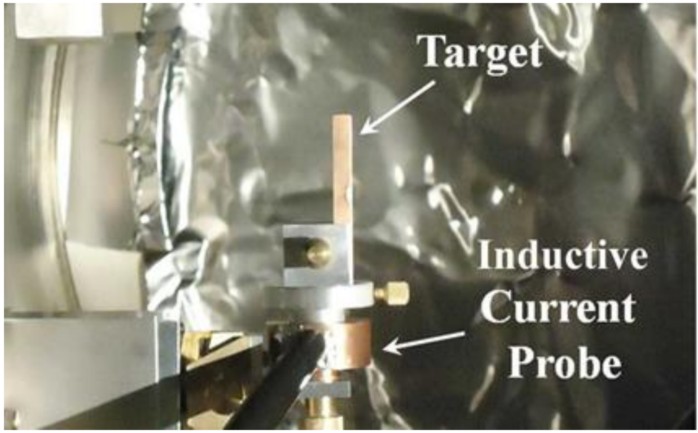


PALS Experiment

- **In the same experiment the neutralization current was measured by means of an inductive T-probe**
- **Antennas are intrinsically time-derivators. The specific integrating delay-line allowed to get the direct measurement of the original time-profile of the detected electric field.**
- **This is <u>the first experiment evidence </u>where both neutralization current and the related clear emitted electromagnetic field are detected.**
- **Remarkable agreement between the two signals was achieved.**







Considerations

- EMP measurements in laboratories around the world, performed by conductive probes (D-dot and B-dot), have the limitation of large distances from target. They showed [1]
  - E-fields up to hundreds kV/m to MV/m for fs-ps pulses; E_{LASER} ~0.1-1 kJ
  - E-fields up to ~1-10 kV/m for ns pulses; E_{LASER} ~0.3 kJ – 1 MJ

- Tailored EMP measurements performed by EO methods were able to measure the E-fields in close proximity of target (~85 mm), and showed [2]
  - E-fields up to ~ 200 kV/m for 3 ns pulses; E_{LASER} ~ 30 J;
  - Estimation of total EMP energy ~ 2% of E_{LASER}

- EO methods have been able to measure of EMPs also in experiments with Vulcan laser at petawatt regimes [3] where EMP are expected to be higher.

- Both neutralization current and associated clear radiated EM field have been measured for the first time in PALS experiment. Suitable delay-line integrators have achieved the analogical conditioning of signals from antennas placed within the experimental chamber [4].

[1] A. Poyé, J.-L. Dubois, F. Lubrano-Lavaderci, E. D'Humières, M. Bardon, S. Hulin, M. Bailly-Grandvaux, J. Ribolzi, D. Raffestin, J. J. Santos, Ph. Nicolai, V. Tikhonchuk, Physical Review E 92, 043107 (2015).
[2] F. Consoli, R. De Angelis, L. Duvillaret, P. L. Andreoli, M. Cipriani, G. Cristofari, G. Di Giorgio, F. Ingenito, C. Verona, Scientific Reports 6, 27889 (2016).
[3] T.S. Robinson, F. Consoli, S. Giltrap, S.J. Eardley, G.S. Hicks, E.J. Ditter, O.Ettlinger, N.H. Stuart, M. Notley, R. De Angelis, Z. Najmudin & R.A. Smith, Scientific Reports 7, 983 (2017).
[4] F. Consoli, R. De Angelis, M. De Marco, J. Krasa, J. Cikhardt, M. Pfeifer, D. Margarone, D. Klir, R. Dudzak, "EMP characterization at PALS on solid-target experiments", Plasma Physics and Controlled Fusion 60, 105006 (2018).

Considerations

- **These measurements of EMP confirm that emitted particles in ns laser experiment are a clear main source of EMP and open to the understanding of further sources of EMPs, <u>important and delicate</u> issue in facilities for inertial confinement fusion and laser-plasma acceleration.**
    - **Induced fields due to particle beam anisotropy**
    - **Charge deposition or implantation on surfaces**
    - **Secondary electron emission, photoemission and recombination**
    - **Possible contribution of X-rays in terms of generation of a transient charged layer around surfaces**

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Acknowledgment

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3rd Working Day – 33d December 2018
ENEA C.R. Frascati

- https://agenda.enea.it/event/139

ENEA 3rd EMP Working Day 3rd December 2018

- Overview
- Topics and Scope
- Committees
- Important Dates
- Call for Abstracts
- Registration
- Participant List
- Agenda
- Social events
- Venue
- Accomodation

The Third EMP Working Day will be held on the 3rd December 2018 at the Frascati Research Center of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in Frascati (Rome). Frascati is a beautiful location, part of the Castelli Romani (Alban Hills) close to Rome and very well connected with it.

As in the previous editions organized by CELIA in Bordeaux in 2016 and by IPPLM in Warsaw in 2017, this one-day meeting is intended to be an informal occasion to discuss about strong electromagnetic pulses (EMPs) generated by laser-matter interactions at high laser energy and intensity, and on related phenomena such as extreme laser-induced currents and ultra-strong quasi-static magnetic and electric fields. Similarly to past editions, it is expected that the meeting would be attended by scientists from major European laboratories: CELIA, CESTA, Rutherford Appleton Laboratory, PALS, ELI, ENEA Frascati, IPPLM, HZDR, CLPU Salamanca, and others.

The meeting will be supported by the ENEA Fusion and Nuclear Safety Department and no fee is required to participate.