ITALIAN NATIONAL AGENCY FOR
NEW TECHNOLOGIES, ENERGY AND
SUSTAINABLE ECONOMIC DEVELOPMENT

Advanced diagnostic methodologies for laser-generated electromagnetic fields in experiments of Inertial Confinement Fusion

ICFDT7 - 7th International Conference on Frontier in Diagnostic Technologies

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Massimiliano Scisciò – ENEA Nuclear Dept.

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Outline

- Context: laser-driven pulsed electromagnetic fields (EMPs) and their generation
- EMP probes: established and upcoming technology, challenges and techniques
- EMP measurements with conductive and novel dielectric probes

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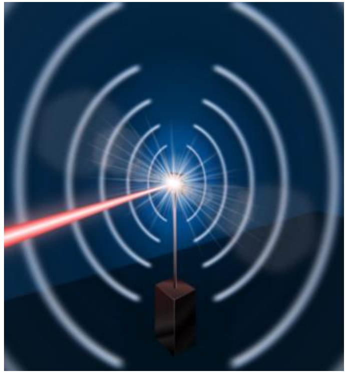
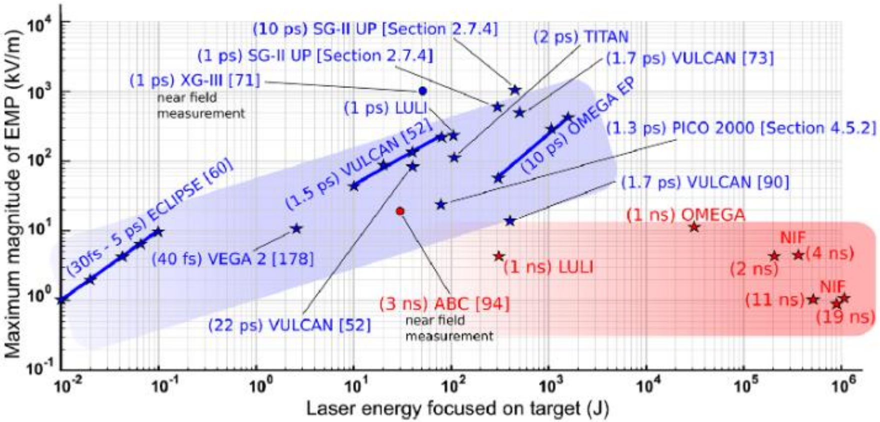
EMPs: when do they occur?

- Transient electromagnetic pulses (EMPs) are regularly detected in laser–target interactions with laser pulses from the femtosecond to the nanosecond range. They occur whenever a displacement of charges is induced.
  - ICF experiments
  - Laser-plasma acceleration
  - Under-dense targets (e.g. foams)
  - Gas-jet targets

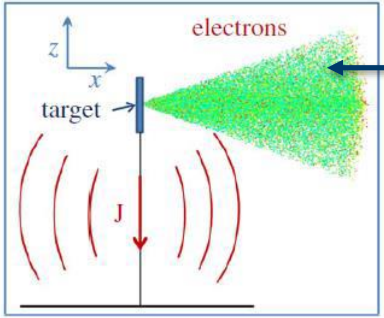
- Remarkable intensity (up to the MV/m order and beyond) and broad frequency range from MHz to THz.

- EMPs scale with laser energy and mostly with laser intensity





EMP sources and generation mechanisms



field source	distribution	intensity decreasing from	max fields	max temporal duration	max frequency range
neutralization current	vertical monopolar antenna	target $\sim r^{-\alpha}$ with $\alpha < 2$	Several MV m^{-1}	100s ns	10s GHz

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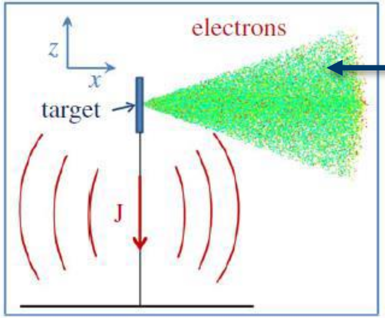
EMP sources and generation mechanisms



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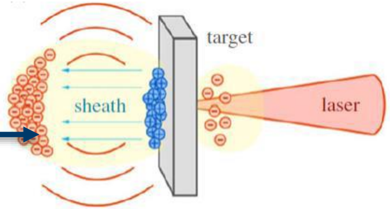
surface-sheath oscillations	horizontal dipolar antenna	target $\sim r^{-2}$	MV m^{-1}	some ps	10s GHz to THz



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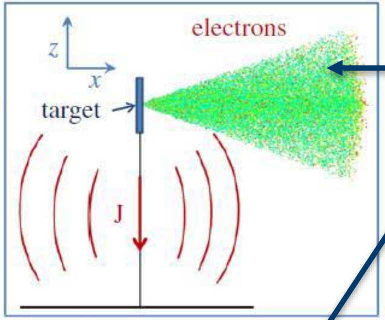

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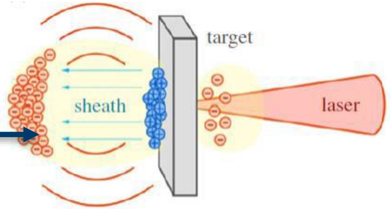

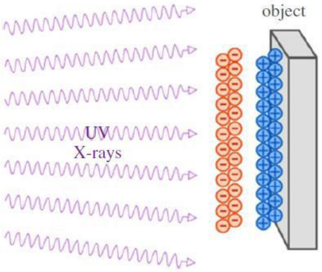

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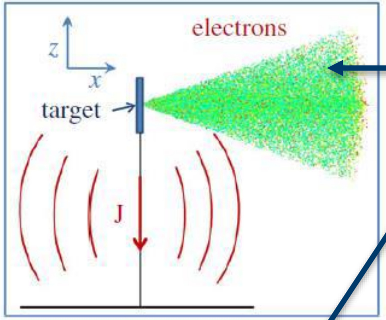

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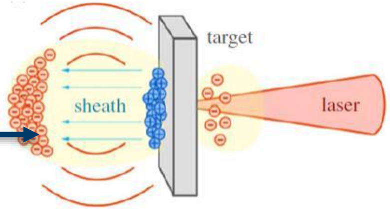
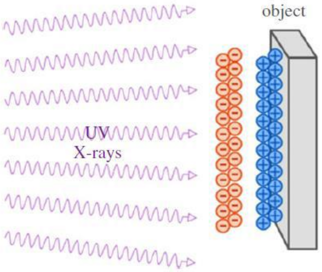
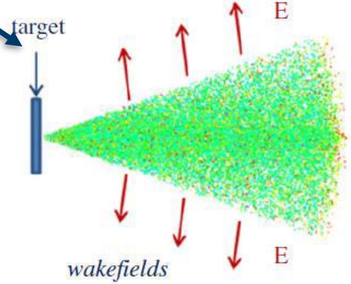
wakefields of accelerated charges	close to the charged particle beams	charged particle beams and target	$\sim$MV m^{-1}	10s ns	100s GHz







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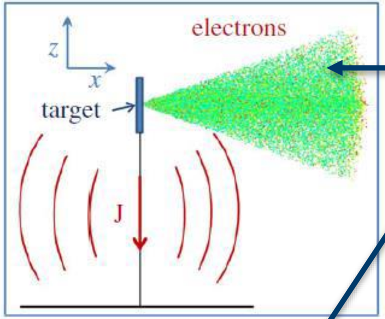

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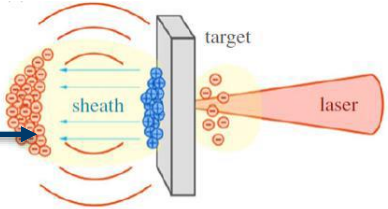
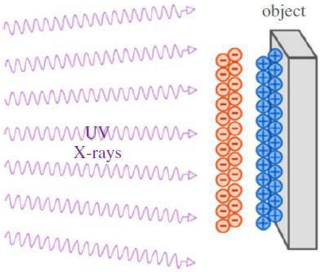
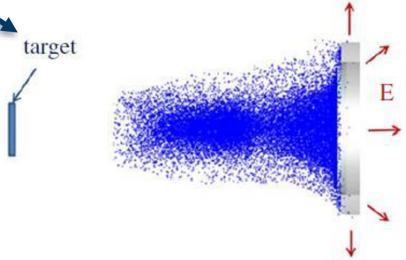
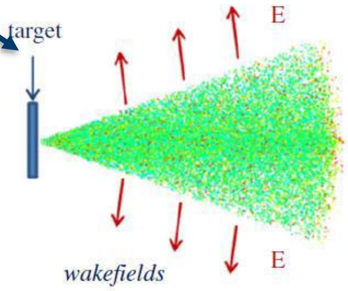
wakefields of accelerated charges	close to the charged particle beams	charged particle beams and target	$\sim$MV m^{-1}	10s ns	100s GHz
particles on surfaces	close to surfaces, even far from the target	exposed surfaces and target	MV m^{-1}	10s ns	approximately 10s MHz to GHz









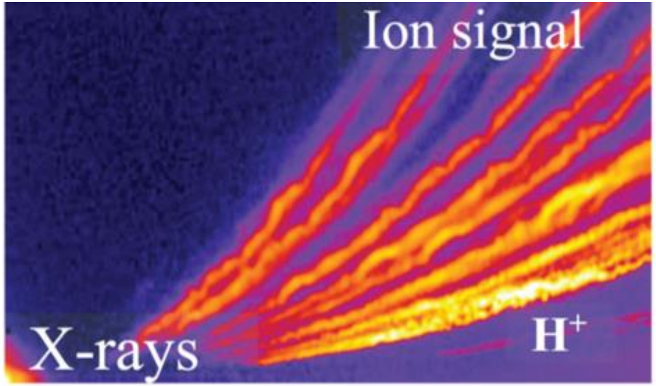
F.Consoli et al., Phil. Trans. Royal Soc. A379, 20200022 (2021)
F. Consoli et al., High Power Laser Science and Engineering 8, e22 (2020)

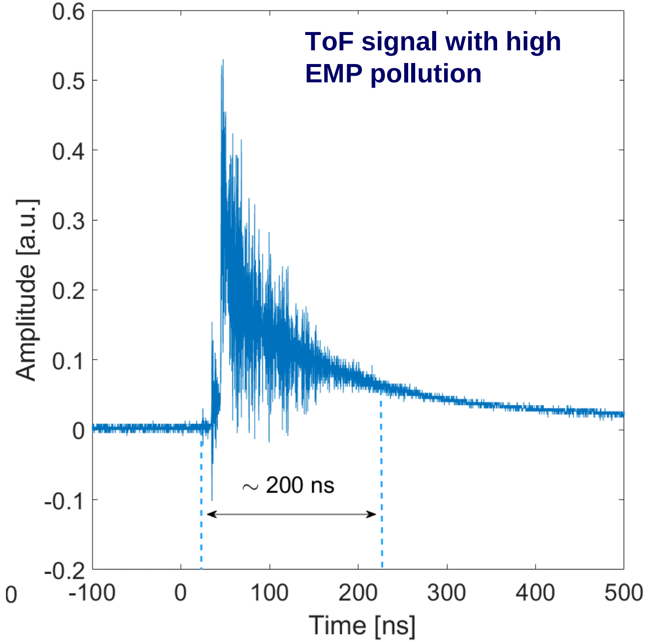
EMPs: hazardous or beneficial?

The EMP associated electric fields can reach the MV/m order.

- saturation/damaging of electronic equipment inside/outside the interaction chamber
- interference with experimental measurements
- background noise affecting signal transmission

➢ **Mitigation techniques are a trending research topic**





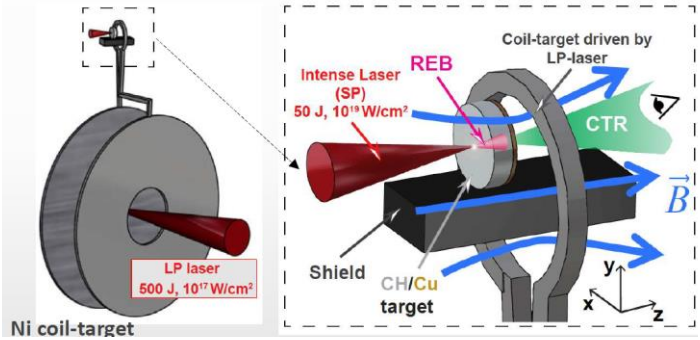
M. Salvadori et al., JINST 15 C10002, 2020
L. Giuffrida et al., Phys. Rev. E 101, 013204 (2013)

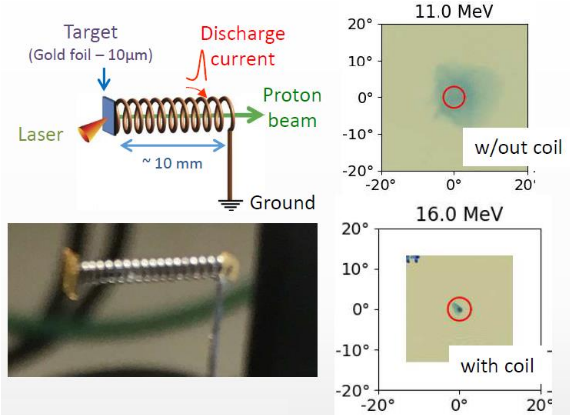
EMPs: hazardous or beneficial?

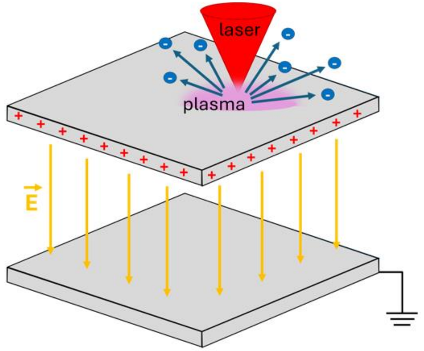
Intense electromagnetic fields produced by laser-matter interaction can be used for as diagnostic instrument and can be used for applications.

- provide a “signature” of the laser-matter interaction
- manipulation of accelerated charged particles
- medical, biological, astrophysical and material studies
- Source of intense fields (tens of kA currents, hundreds of T magnetic field, several MV/m electric field)

➢ **Techniques for accurately measuring, controlling and tuning EMPs are being investigated**







S. Kar et al., Nat. Comm. 2016
M. Bardon et al., PPCF 2020

J. Santos et al., NJP 2015
M. Bailly-Grandvaux et al. Nat. Comm. 2018

Research on EMPs: a growing community

Most recent review about EMP research on HPLSE

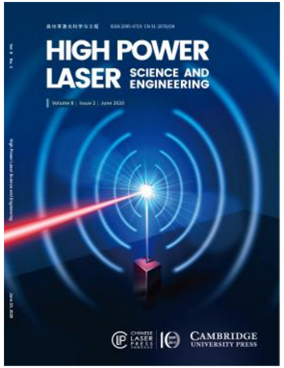
High Power Laser Science and Engineering, (2020), Vol. 8, e22, 59 pages.
doi:10.1017/hpl.2020.13

HIGH POWER LASER SCIENCE AND ENGINEERING

REVIEW

Laser produced electromagnetic pulses: generation, detection and mitigation

Fabrizio Consoli[1], Vladimir T. Tikhonchuk[2,3], Matthieu Bardon[4], Philip Bradford[5], David C. Carroll[6], Jakub Cikhardt[7,8], Mattia Cipriani[1], Robert J. Clarke[6], Thomas E. Cowan[9], Colin N. Danson[10,11,12], Riccardo De Angelis[1], Massimo De Marco[13], Jean-Luc Dubois[2], Bertrand Etchessahar[4], Alejandro Laso Garcia[9], David I. Hillier[10,12], Ales Honsa[3], Weiman Jiang[14], Viliam Kmetik[3], Josef Krása[15], Yutong Li[14,16], Frédéric Lubrano[4], Paul McKenna[17], Josefine Metzkes-Ng[9], Alexandre Poyé[18], Irene Prencipe[9], Piotr Rączka[19], Roland A. Smith[20], Roman Vrana[3], Nigel C. Woolsey[5], Egle Zemaityte[17], Yihang Zhang[14,16], Zhe Zhang[14], Bernhard Zielbauer[21], and David Neely[6,10,17]



Laserlab-Europe AISBL, Interest/Expert group on «Laser-generated electromagnetic pulses»:

https://www.laserlab-europe.eu/aisbl/expert-groups/laser-generated-electromagnetic-pulses

Laserlab Europe

Laser-generated electromagnetic pulses

The interaction of high-energy and high-power laser pulses with matter produces broadband particle and electromagnetic radiation. In particular, a significant portion of the incoming laser energy is transformed to powerful transient electromagnetic pulses (EMPs) in a broad range of radiofrequencies, microwaves and THz radiation. Such fields depend on laser energy and intensity and can easily exceed the MV/m magnitude - strong enough to represent a significant danger for any electronic device placed inside or outside the experimental vacuum chamber. This has been observed worldwide in experiments with high power lasers.

EMPs pose a very important limitation on the performance of high-power laser facilities for applications as diverse as inertial confinement fusion and laser–plasma acceleration. More severe issues are expected for the upcoming PW-scale lasers. The increase of the repetition rate needed to transition processes such as laser acceleration from scientific proof of principle to "real world" applications, e.g. for hadron therapy, also creates the need for more reliable and efficient EMP protection and mitigation techniques.

Understanding the origin of EMP and the complex temporal and spatial distribution of these electromagnetic fields is of key importance for the development of suitable EMP mitigation schemes for safe facility operation. This is constrained by the development of quantitative EMP diagnostic methods and devices that are capable of operating in the harsh conditions of high-power laser experiments.

The members of the present expert group have strong common research interests and extensive expertise on the research activities of laser-generated electromagnetic pulses in the whole RF-μw-THz band, including modeling, diagnostics, mitigation and applications. This will be of direct applicability to all modern laser plasma facilities and importantly to future laser-plasma acceleration and inertial-confinement-fusion plants, and potentially to next generation laser-driven hadron therapy systems. The expert group will promote and focus the activities of each institution to define mutual collaborations and prepare joint experimental campaigns.

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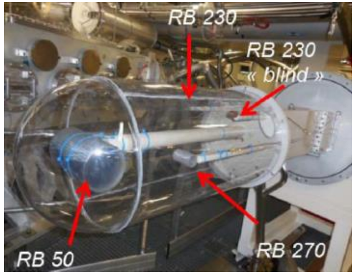
- Context: laser-driven pulsed electromagnetic fields (EMPs) and their generation
- EMP probes: established and upcoming technology, challenges and techniques
- EMP measurements with conductive and novel dielectric probes

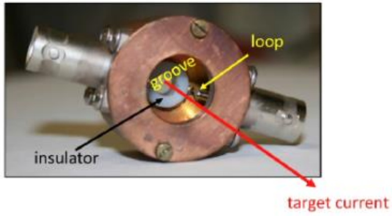
EMP probes for field sensing

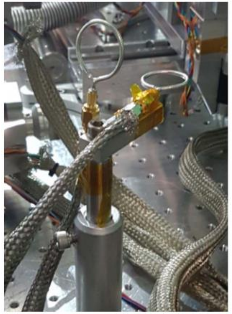
<u>Conductive Probes</u>

- B-Dot, Moebious loops, for B fields
- D-Dot, antennas for E fields
- Calibrated loops for neutralization current



- ➢ Robust, versatile and well-known behavior
- ➢ Information on EMPs is in terms of electrical current, in environments heavily affected by ionizing radiation
- ➢ Sensitive to the time derivative of fields: low noise amplified in signal riconstruction
- ➢ Problems of electromagnetic coupling to the conductors nearby

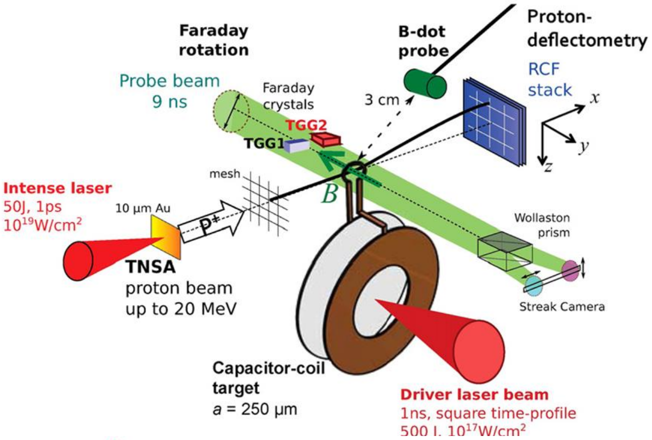




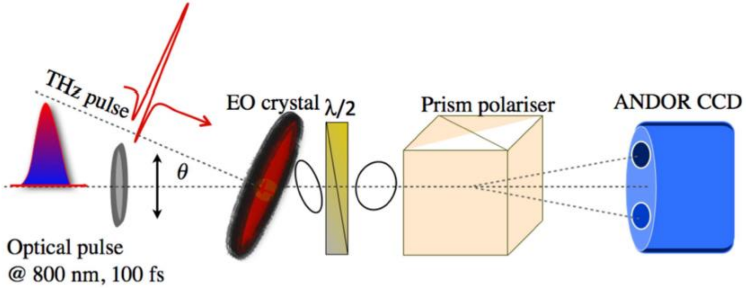
EMP probes for field sensing

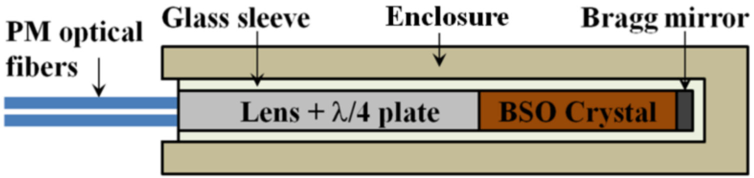
<u>Dielectric probes</u>

- Linear electro-optic (Pockels) effect in dielectric crystals for E field measurements
- Crystals inducing Faraday effect for B field measurements



- ➢ Direct access to the field, rather than to its derivative
- ➢ High selectivity of field components
- ➢ High spatial resolution
- ➢ High frequency, up to the THz level
- ➢ Sensitivity and bandwidth issues





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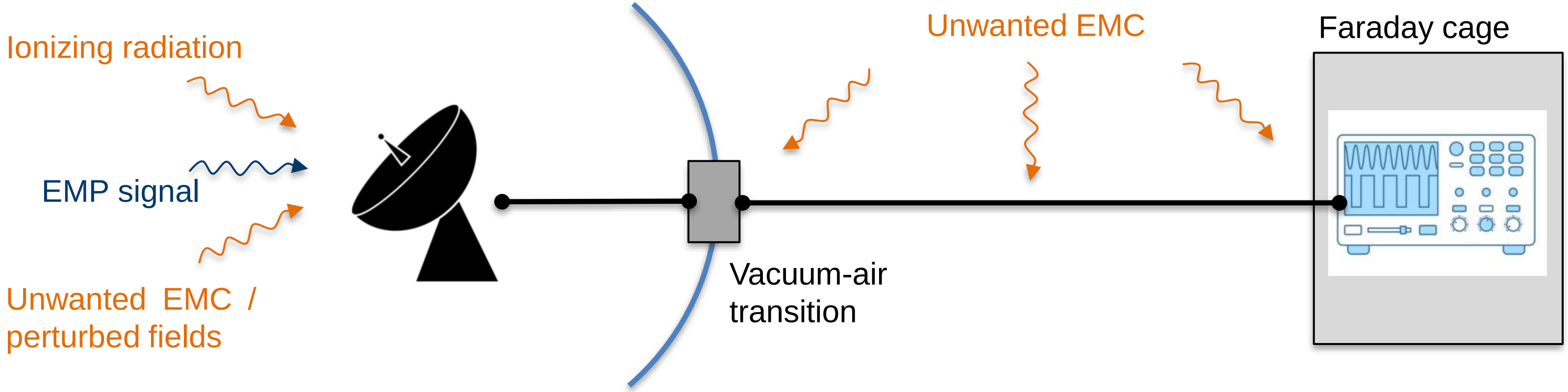
F. Consoli et al, Sci. Rep. 2016
S. Herzer et al. NJP 2018
R. Pompili et al, Sci. Rep 2016

EMP measurements: multiple sources of noise or “artifact” signal



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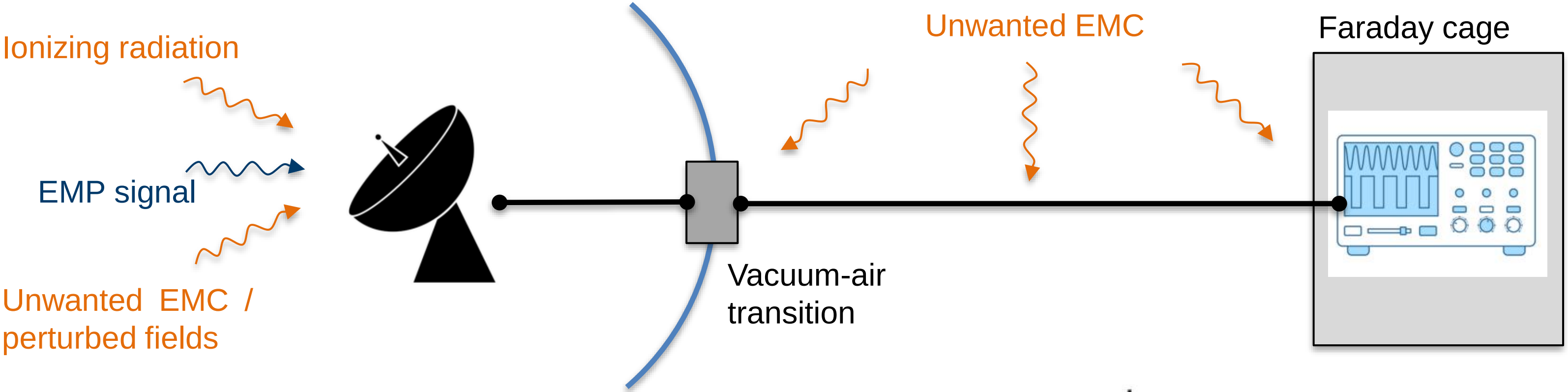
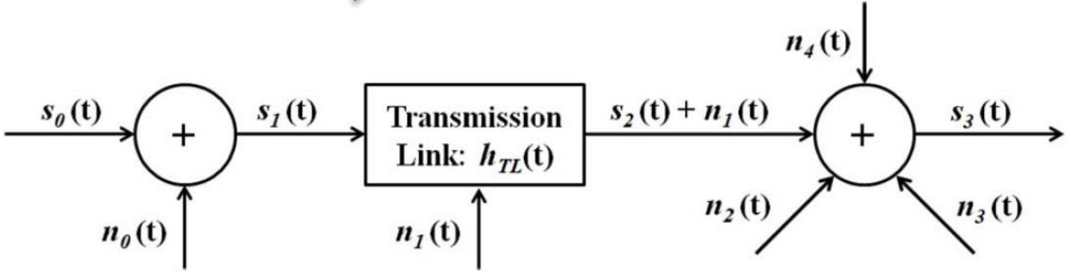
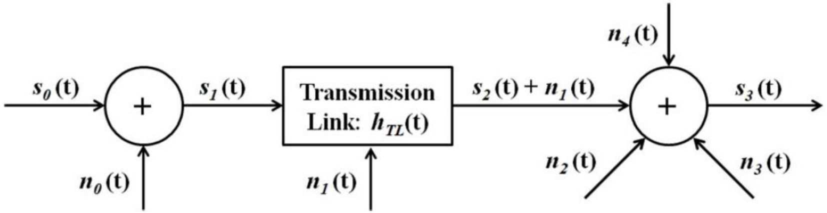




$$s_3(t) = s_2(t) + n_1(t) + n_2(t) + n_3(t) + n_4(t)$$
$$= h_{\mathrm{TL}}(t) \circledast [s_0(t) + n_0(t)] + n_{\mathrm{ext}}(t),$$
$$n_{\mathrm{ext}}(t) = n_1(t) + n_2(t) + n_3(t) + n_4(t)$$

- n_0: noise on the detector due to ionizing radiation
- n_1: EMP noise penetrating the transmission link
- n_3: direct coupling of EMP fields with the scope
- n_4: noise on the scope due to currents flowing on the outer conductor of the cables

EMP measurements: multiple sources of noise or “artifact” signal



$$
\begin{aligned}
s_3(t) &= s_2(t) + n_1(t) + n_2(t) + n_3(t) + n_4(t) \\
&= h_{\mathrm{TL}}(t) \circledast [s_0(t) + n_0(t)] + n_{\mathrm{ext}}(t),
\end{aligned}
$$

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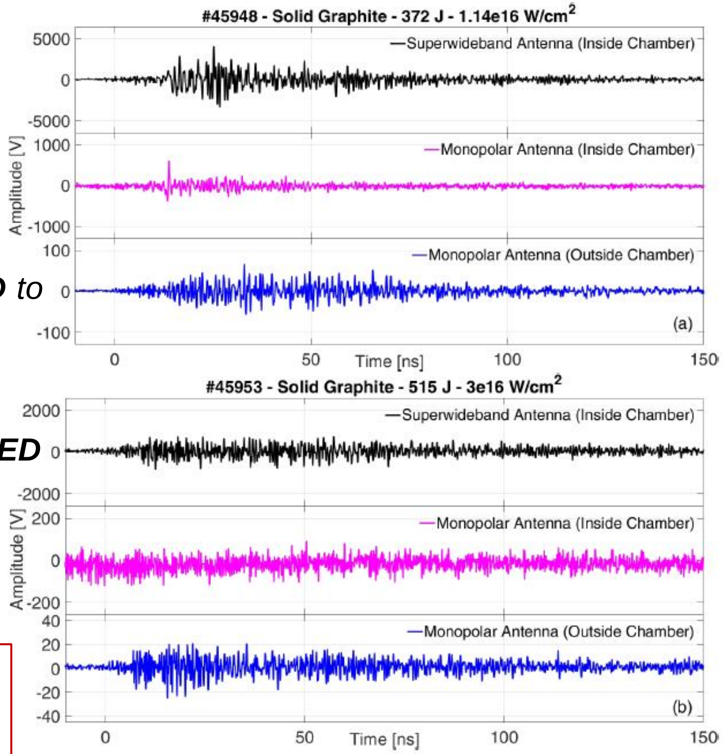
PALS laser: 600 J Energy, 350 ps

Antennas ***CONNECTED*** *to the scope*

Antennas ***DISCONNECTED*** *from the scope*



Signal-to-Noise ratio between 2 and 5. Rather poor.

F. Consoli et al., PPCF 60, 105006 (2018)

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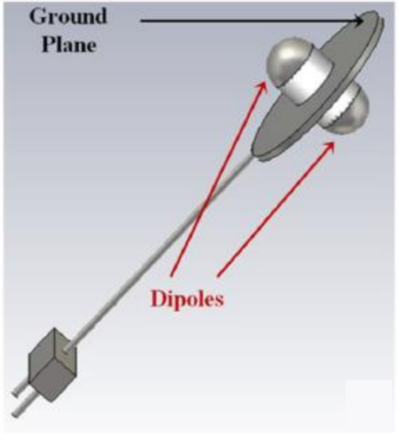
EMP probes: D-dot



~5 cm

Differential conductive probe, retrieving the D-field derivative.

$$E_n(t) = K_{DDOT-B} \int_0^t V_{DDOT-B}(\tau)d\tau$$

$$K_{DDOT\text{-}B} = 9.5 \times 10^{12}\,\mathrm{m}^{-1}\mathrm{s}^{-1}$$

SPECIFICATIONS

Electrical		AD-80(R)
Equiv. Area (A_{eq})		3×10^{-4} m²
Freq. Resp. (3db pt.)		>5.5 GHz
Risetime (t_r 10-90)		<.064 ns
Capitance (F)		2.91×10^{-13}
Max Output (peak)		± 1 kV
Output Connector (s)		SMA (male)*
Physical		
Mass		260g
Dimensions	A	17.78
(cm)	B	5.08
	C	1.95
	D	0.32

- Compact and versatile
- Up to several GHz band
- Rejects common mode signal coming from ionizing radiation

The noise level and the oscilloscope resolution/sensitivity limit the minimum value of measured signal V_{DDOT} and, as a direct consequence, the accuracy of $E_n(t)$.

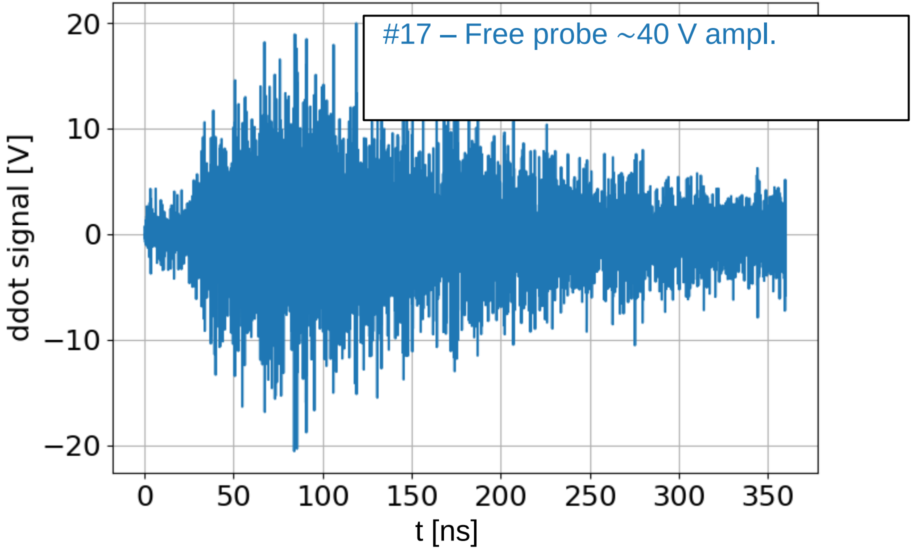
➢ Important to assess noise level for avoiding error-amplification when numerically integrating.

EMP measurement with D-dot: assessment of signal-to-noise ratio

Vulcan Petawatt laser

600 J , 1 ps

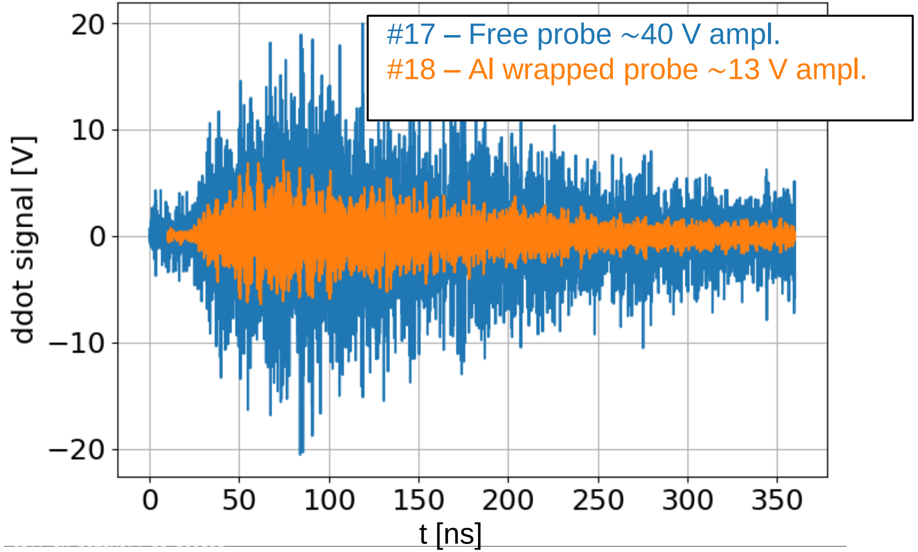
Distance probe-TCC : 190 cm



EMP measurement with D-dot: assessment of signal-to-noise ratio

The noise level along the connection link can be estimated by
i) wrapping the probe with conductive foil

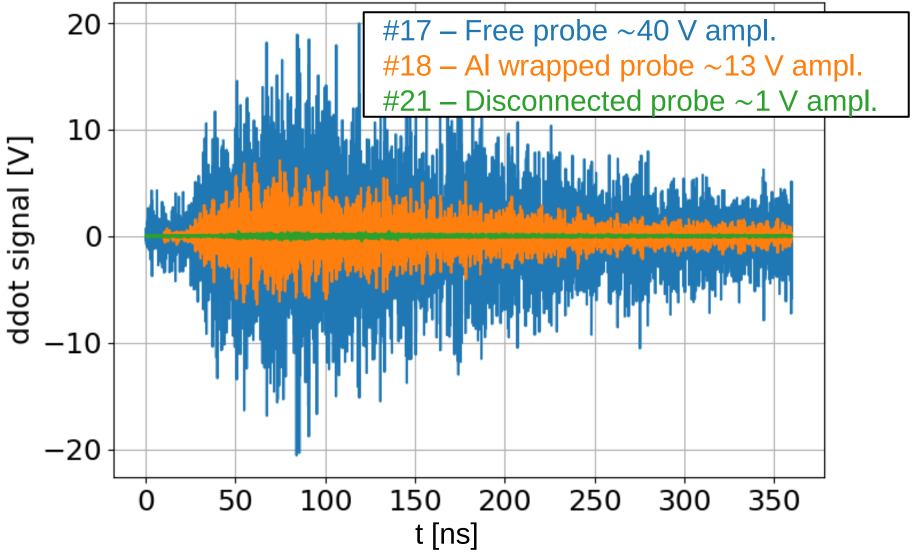
➢ $SNR \approx 3$



EMP measurement with D-dot: assessment of signal-to-noise ratio

The noise level along the connection link can be estimated by
i) wrapping the probe with conductive foil
ii) disconnect the probe from the scope

- $SNR \approx 3$
- $SNR \approx 40$



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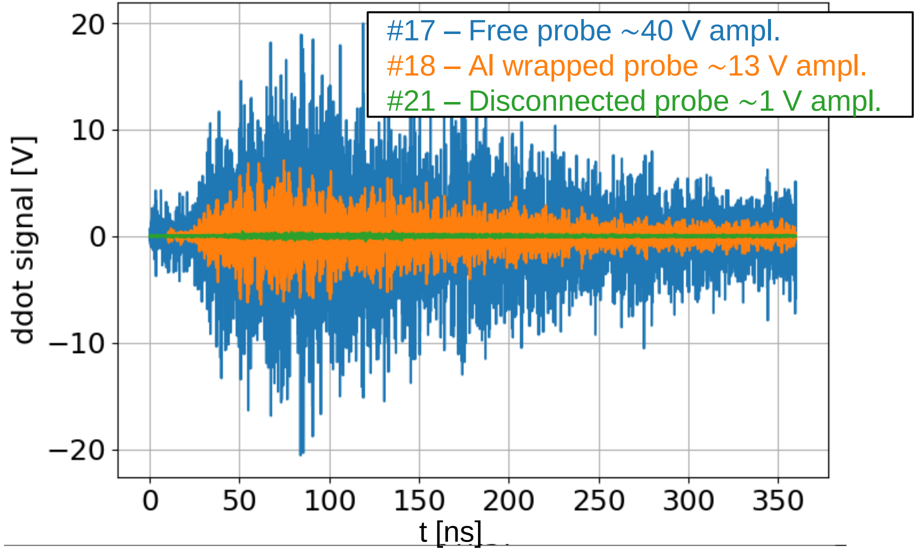
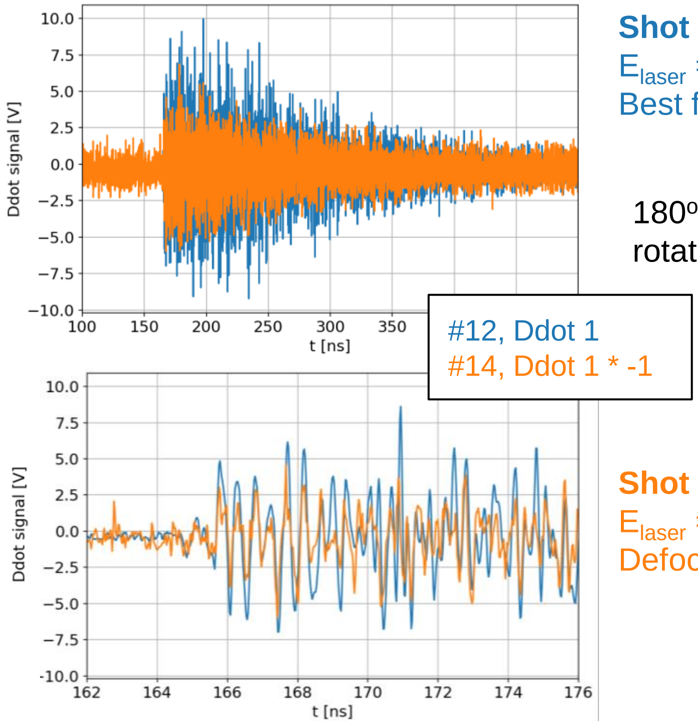


EMP signals well repeatable for similar interaction parameters: turning the probe by 180º Leads to a signal inversion if no significant noise is added to the signal.



Shot #12
E_{laser} = 80.4 J
Best focus

180º probe rotation

Shot #14
E_{laser} = 360.3 J
Defoc. 960 µm

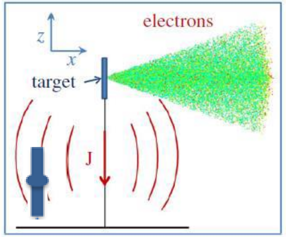
ENEA

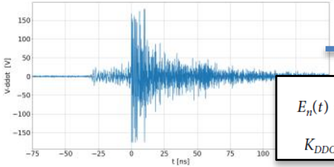
EMP measurements with D-dot

PALS laser

E=600 J
350 ps

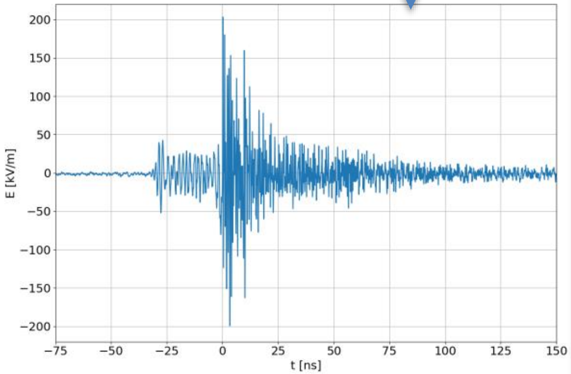
Probe –TCC:
~40 cm





$$E_n(t) = K_{DDOT-B}\int_0^t V_{DDOT-B}(\tau)d\tau$$

$$K_{DDOT-B} = 9.5\times 10^{12}\,\mathrm{m}^{-1}\mathrm{s}^{-1}$$

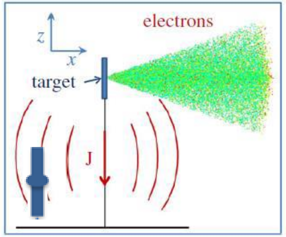


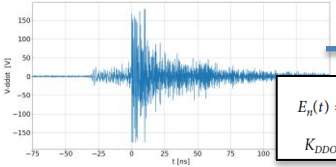
EMP measurements with D-dot

PALS laser

E=600 J
350 ps

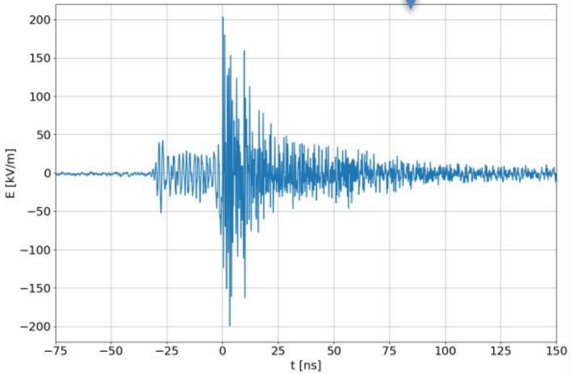
Probe –TCC:
~40 cm





$$E_n(t) = K_{DDOT-B}\int_0^t V_{DDOT-B}(\tau)d\tau$$

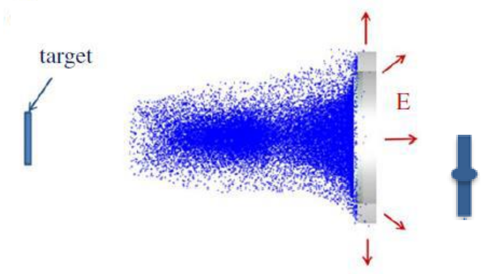
$$K_{DDOT\text{-}B} = 9.5 \times 10^{12}\,\mathrm{m^{-1}s^{-1}}$$

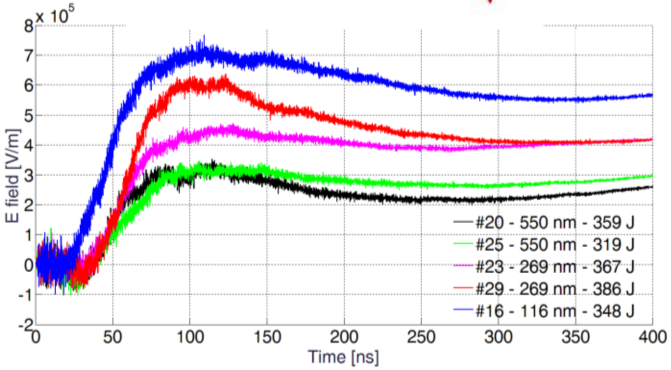


Vulcan Petawatt laser

E=350 J
1 ps

Probe behind
focusing parabola





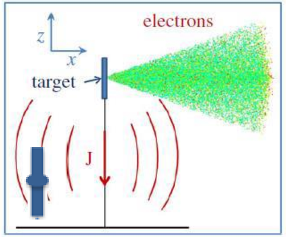
F. Consoli et al., Sci. Rep 9, 8551 (2019)

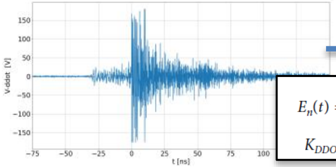
EMP measurements with D-dot

PALS laser

E=600 J
350 ps

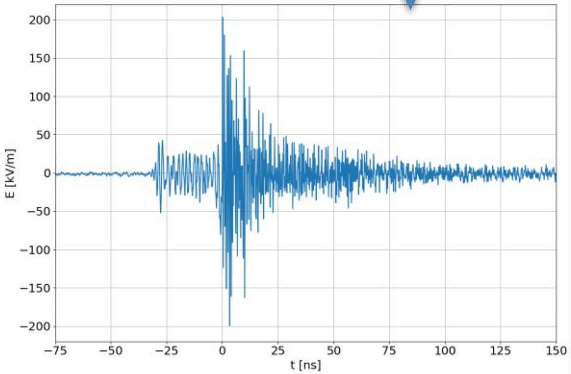
Probe –TCC:
~40 cm





$$E_n(t) = K_{DDOT-B} \int_0^t V_{DDOT-B}(\tau)d\tau$$

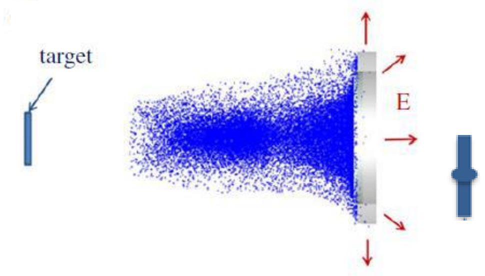
$$K_{DDOT\text{-}B} = 9.5 \times 10^{12}\,\mathrm{m^{-1}s^{-1}}$$

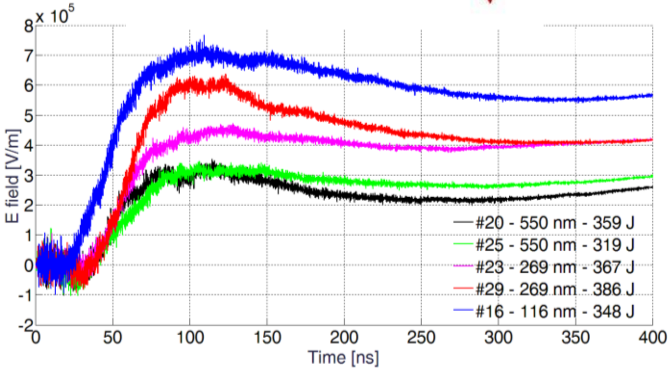


Vulcan Petawatt laser

E=350 J
1 ps

Probe behind focusing parabola



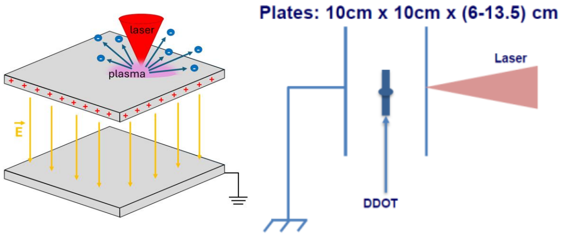


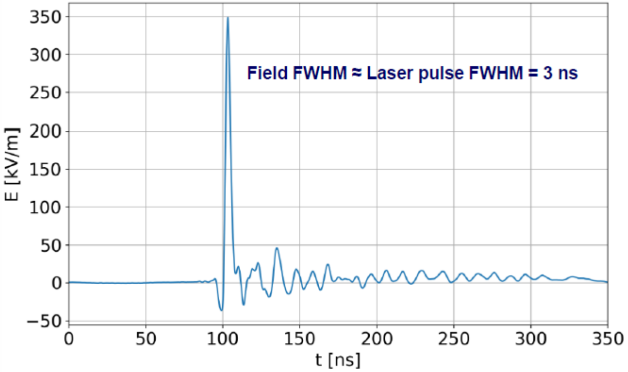
F. Consoli et al., Sci. Rep 9, 8551 (2019)

ABC laser

E=30 J
3 ns

Probe inside capacitor-like structure

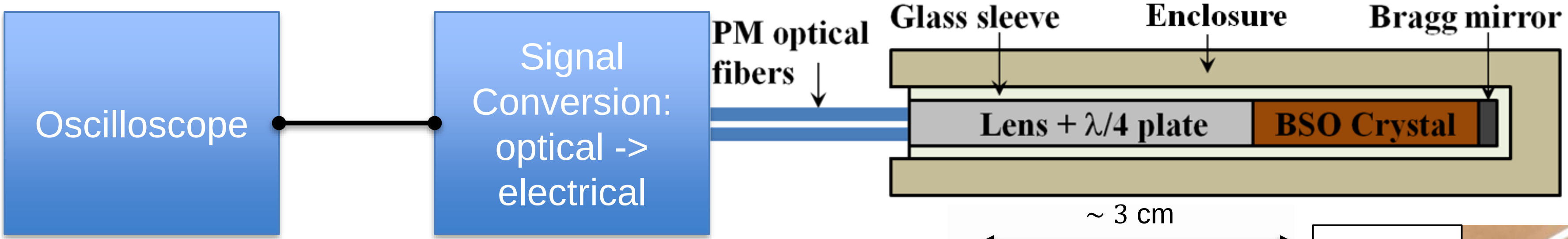


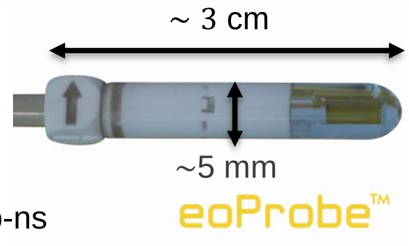


F. Consoli et al., *to be submitted (2024)*

EMP probes: electro-optical probe

The probe is based on the Linear Electro-Optical (Pockels) effect, provided by an isotropic crystal. The crystal changes its refractive index according to the present E-field intensity. *Polarization state modulation* (PSM): the polarization of a Circularly polarized laser probe beam will be modified by birefringence induced on the isotropic crystal.





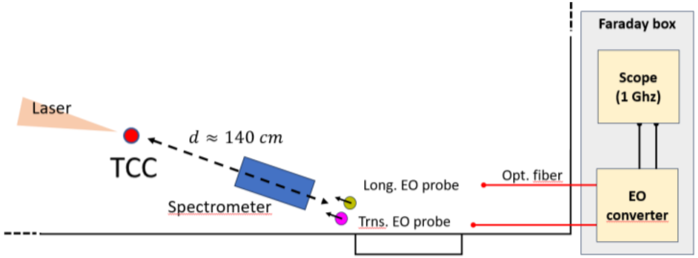
$$E(t)\,[V/m] = AF\,[m^{-1}] \cdot x_{EO}(t)[V]$$

The optical signal is converted to a fully analogue voltage (no sampling). Sub-ns temporal resolution, mm-scale spatial resolution, measurement voxel < mm^3.

➢ Important to assess noise level: typically, low SNR due to low sensitivity

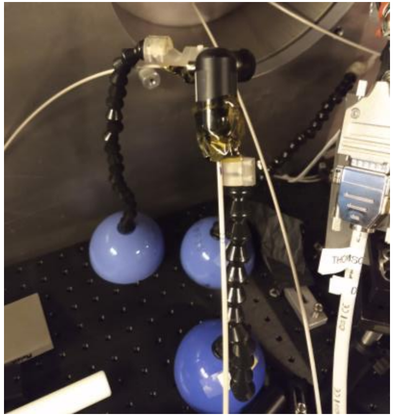
ENEA

EMP EO measurement

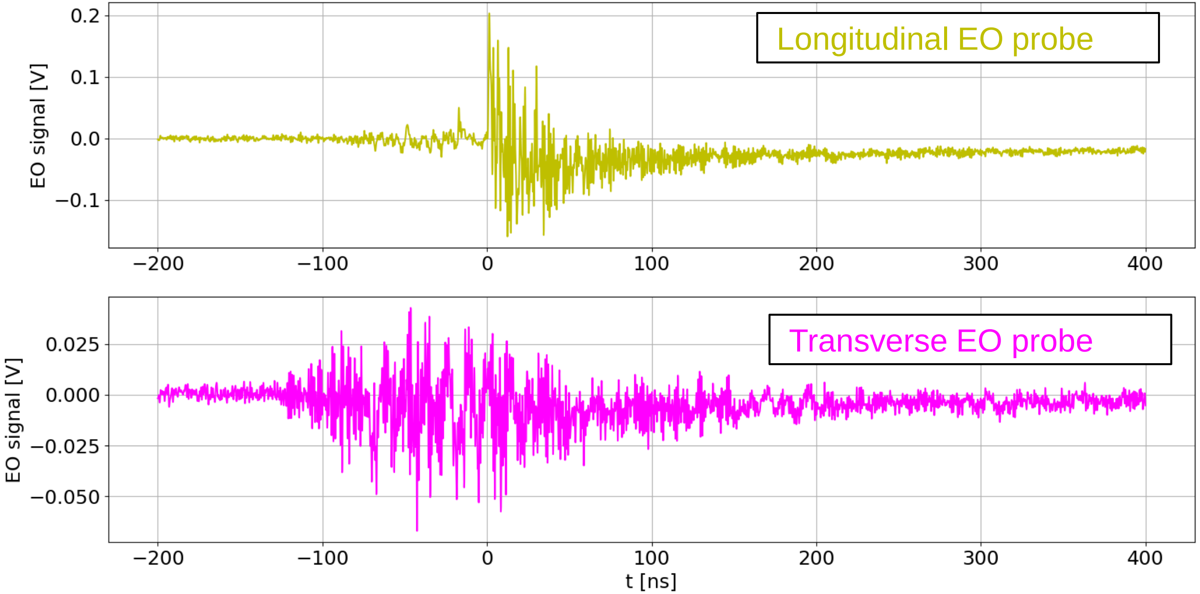


RAL-CLF Vulcan Petawatt Laser

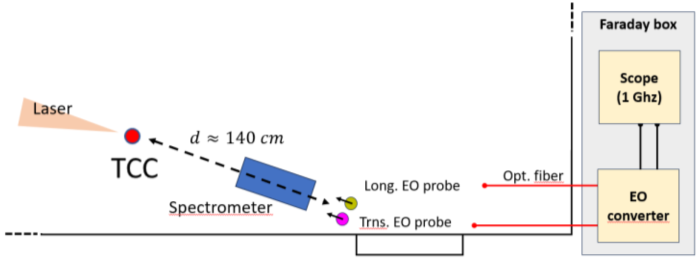
- 360 J on target
- 1 ps pulse duration
- Up to 10^{21} W/cm^2 intensity
- 1054 nm wavelength



Shot #9 E_{laser} = 685 J

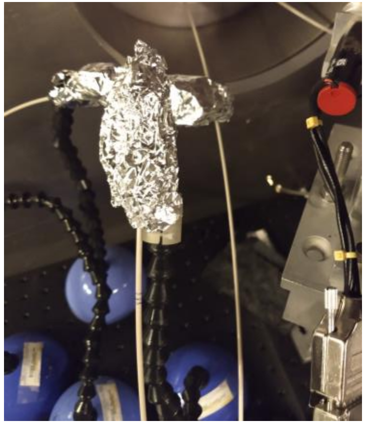


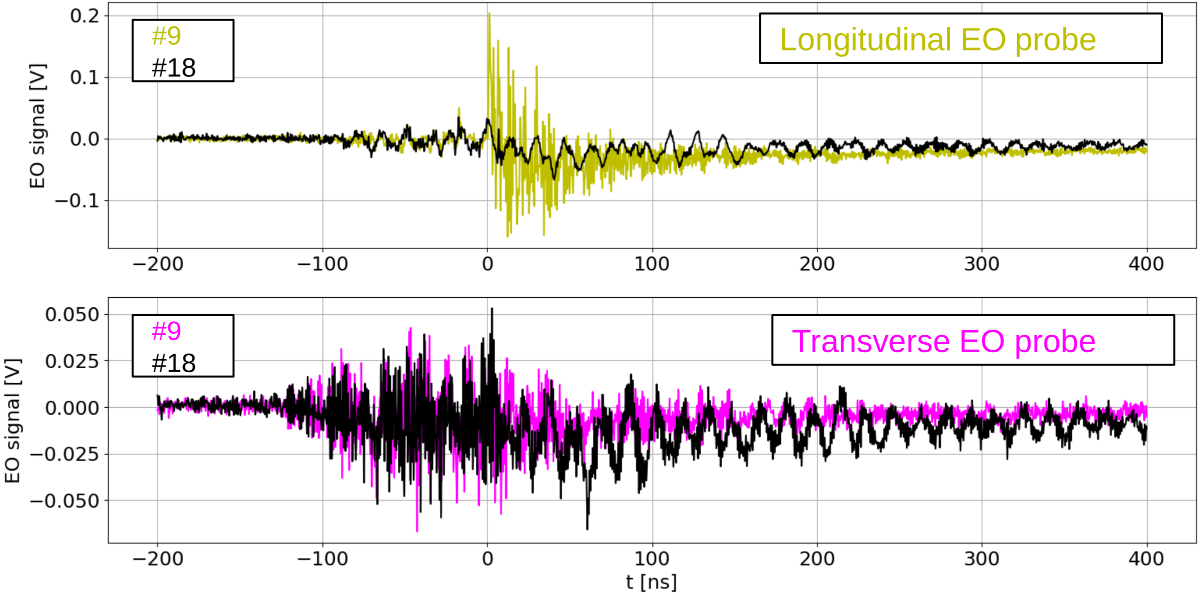
EMP EO measurement



Shot #9 E_{laser} = 685 J

Shot #18 E_{laser} = 683 J "blinded" probes (w. Aluminum foil)





Longitudinal probe:

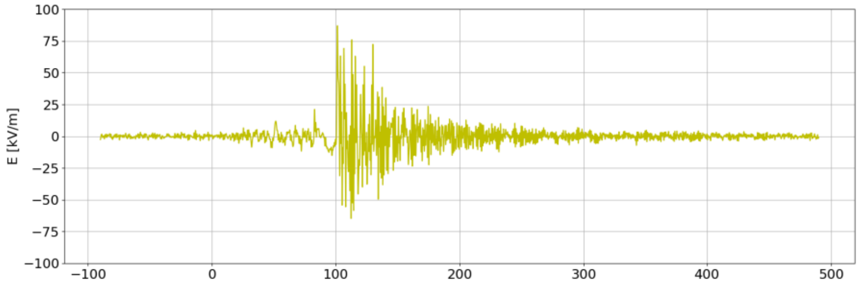
- Up to 0.2 V "real signal" and 0.03 V "noise" signal
- SNR about 7

Transverse probe:

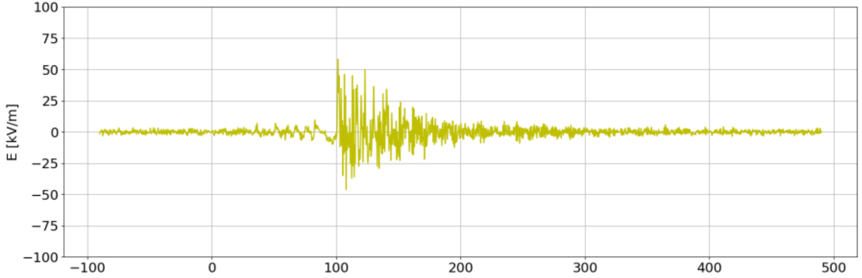
- Noise and signal have the same level

EMP EO meausrement

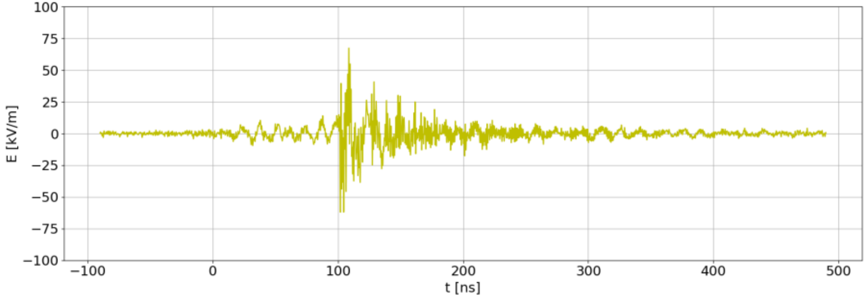
Shot #9
E_{laser} = 685 J



Shot #10
E_{laser} = 318 J



Shot #17
E_{laser} = 566 J ,
60 um defocusing

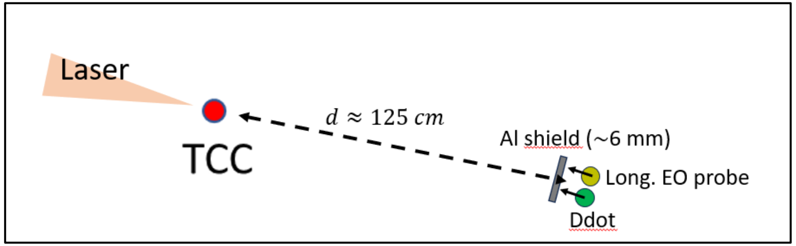


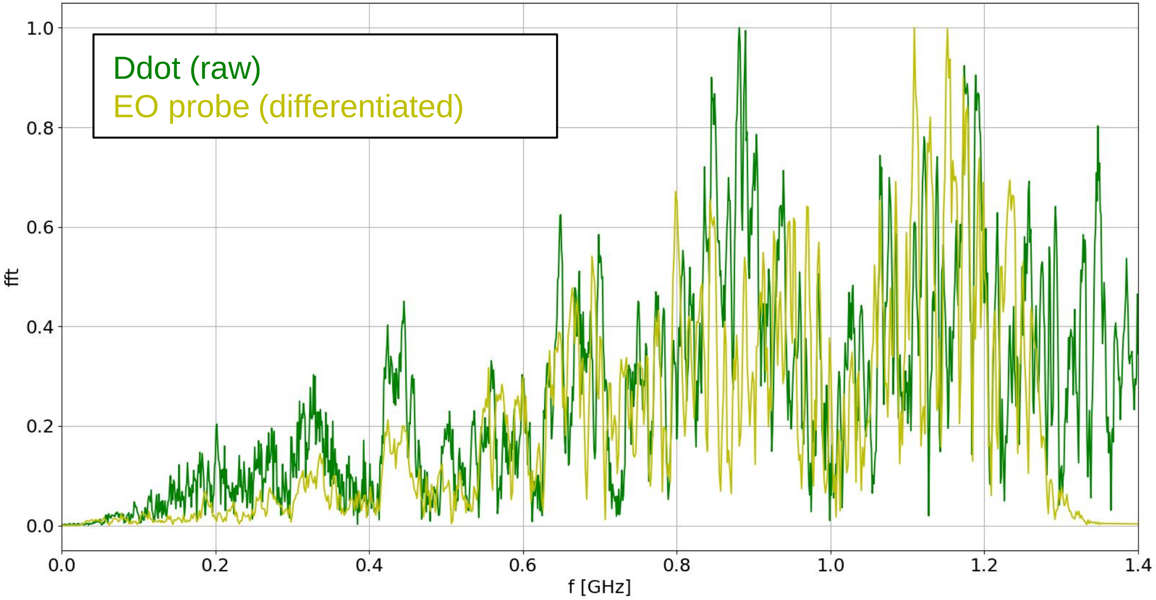
Slow transient component is filtered.

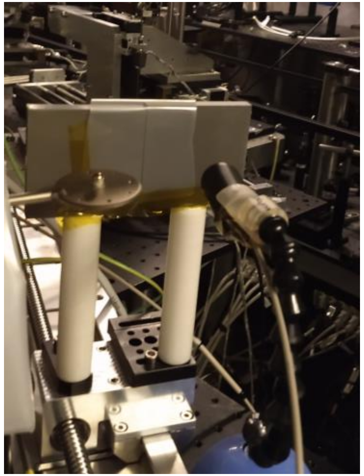
$$E(t)\ [V/m] = AF\ [m^{-1}] \cdot x_{EO}(t)[V]$$

Antenna calibration yields electric field values in the multiple tens of kV/m range.

EO probe vs. D-dot comparison







Shot #31
E_{laser} = 595 J

EO probe vs. Ddot: frequency domain

Conclusions

- Laser-matter interaction of high energy and intensity produce remarkable transient electromagnetic pulses, up to the MV/m order.
- Recognized major source of emission in the MHz-GHz domain is the neutralization current flowing through the target holder.
- Other sources of EMP are identified, but further characterization is needed.
- A large number of promising applications can be enabled by a full comprehension of the physics of EMP generation, of the mechanisms of their operation, and by a suitable characterization of EMP fields.
- Primary requirement is the development and optimization of effective EMP detection methodologies, still an open issue in many conditions.
- Novel electro-optical-based measurement techniques represent the state of the art for novel EMP diagnostics. However, they still require in-detail studies and improvement for an effective use as an alternative to conductive probes.

Thank you for your attention.

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