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

Electromagnetic pulses from high power lasers: sources, risks and mitigation

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Collaborators

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- **CELIA**, University of Bordeaux, CNRS, CEA, France; **ELI-Beamlines**, Czech Republic
  V.T. Tikhonchuk

- **Central Laser Facility**, Ruth. Appl. Labor., Chilton, Didcot, STFC, UKRI, Oxfordshire, UK;
  P. Bradford, D. Carroll, D. Neely

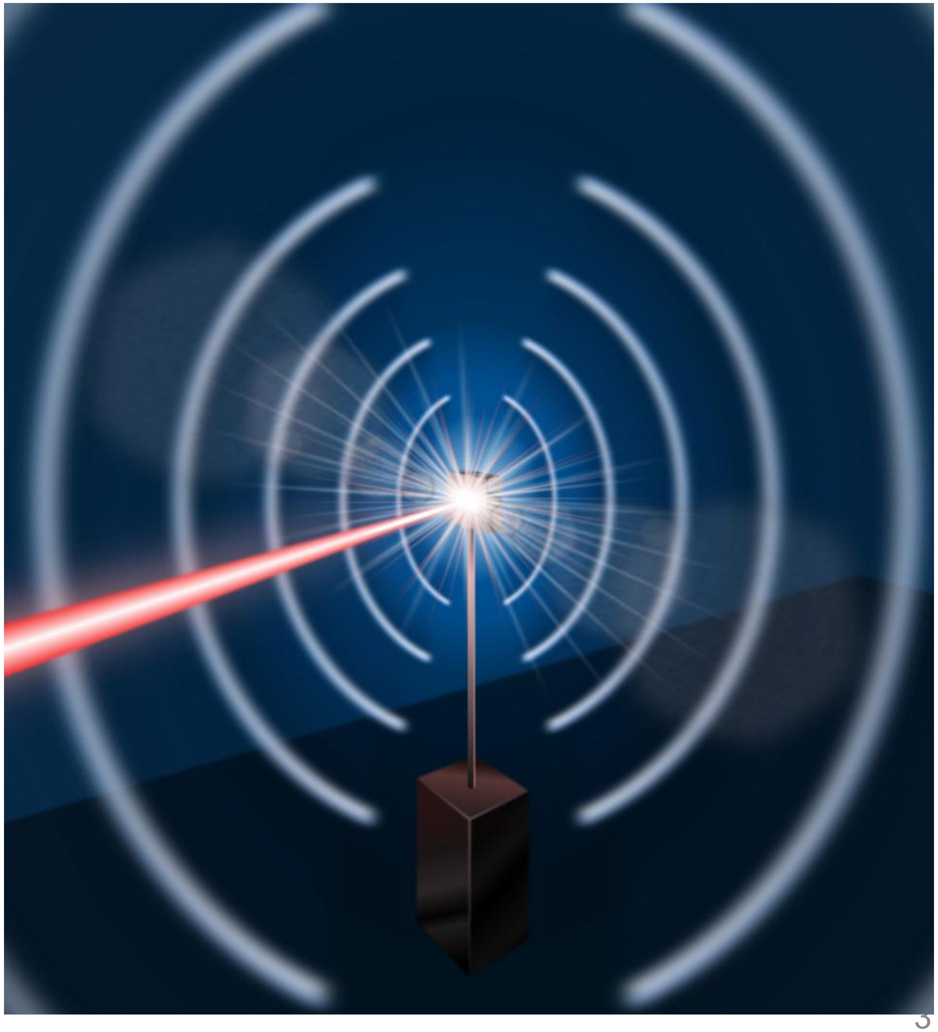
- **Kapteos**, France: L. Duvillaret, G. Gaborit

- **Institute of Physics ASCR**, J. Krása and **Czech Technical University**, J. Cikhardt, Czech Republic:

- **The Blackett Laboratory**, Imperial College London, London, UK: R. A. Smith

Outline

- **Introduction to laser-generated electromagnetic pulses (EMPs)**
- **EMP generation**
- **Methods of EMP diagnostics**
- **Methods of EMP mitigation**
- **EMP applications**



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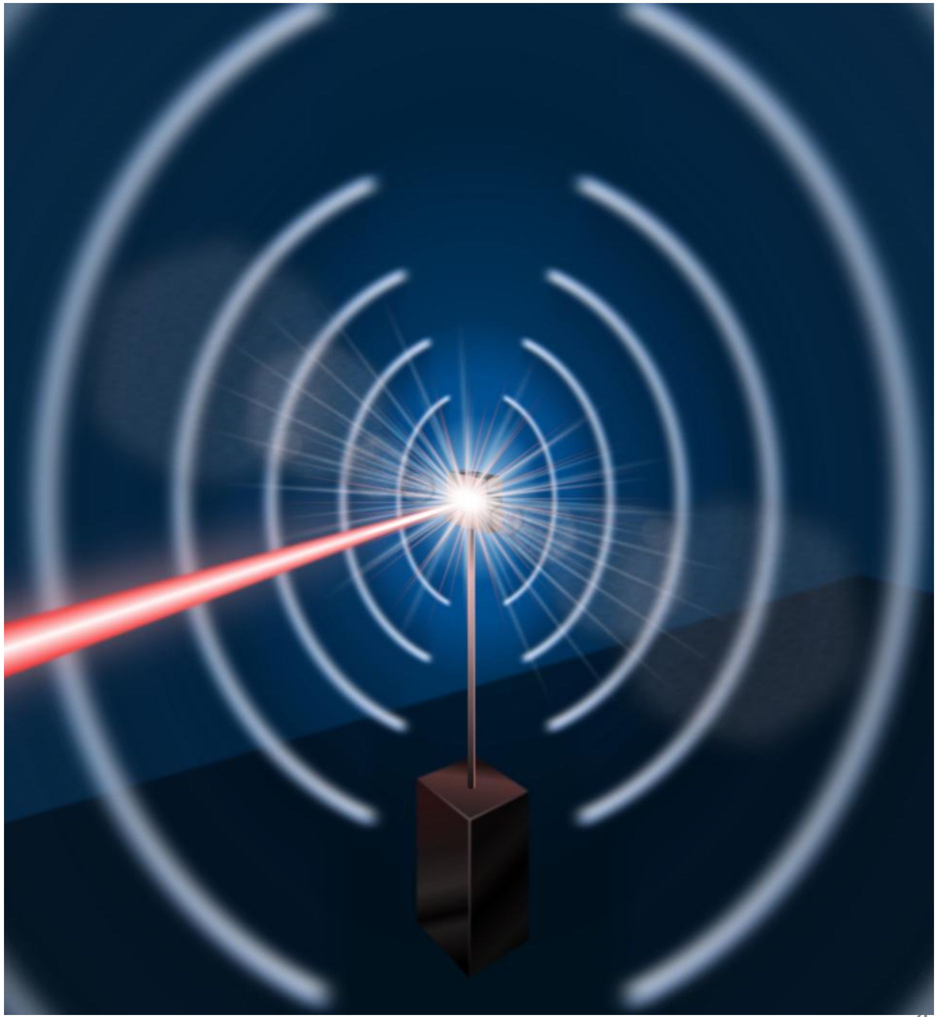


Laser-generated electromagnetic pulses

- **The interaction of high energy and high power laser pulses with matter generates a very wide band of particle and electromagnetic radiation.**

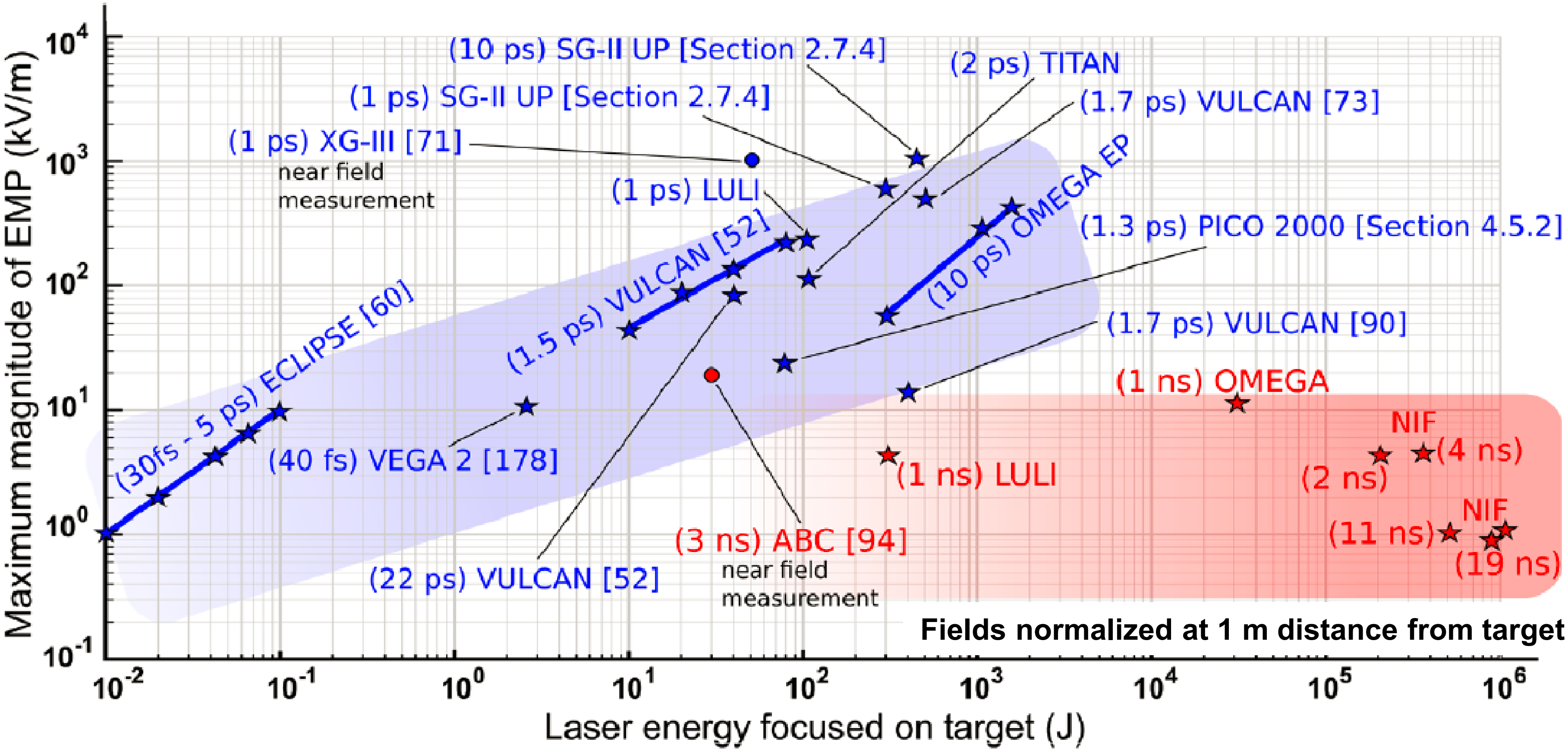
- **The main part of this radiation is ionizing, but there is also a significant portion which is in the radiofrequency-microwave-terahertz frequency range.**

- **Transient electromagnetic pulses (EMPs) are regularly detected in laser–target interactions with laser pulses from the femtosecond to the nanosecond range**

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

Scaling of laser-generated electromagnetic pulses

- **EMPs scale with laser energy and <u>mostly with laser intensity</u>**
- **The different laser pulse regimes determine different band and intensity features of the produced EMPs**



Fields normalized at 1 m distance from target: STRONG NEAR FIELD.
Fields <u>do not scale with 1/r</u> (distance from target)

F. Consoli et al, High Power Laser Science and Engineering 8, e22 (2020)

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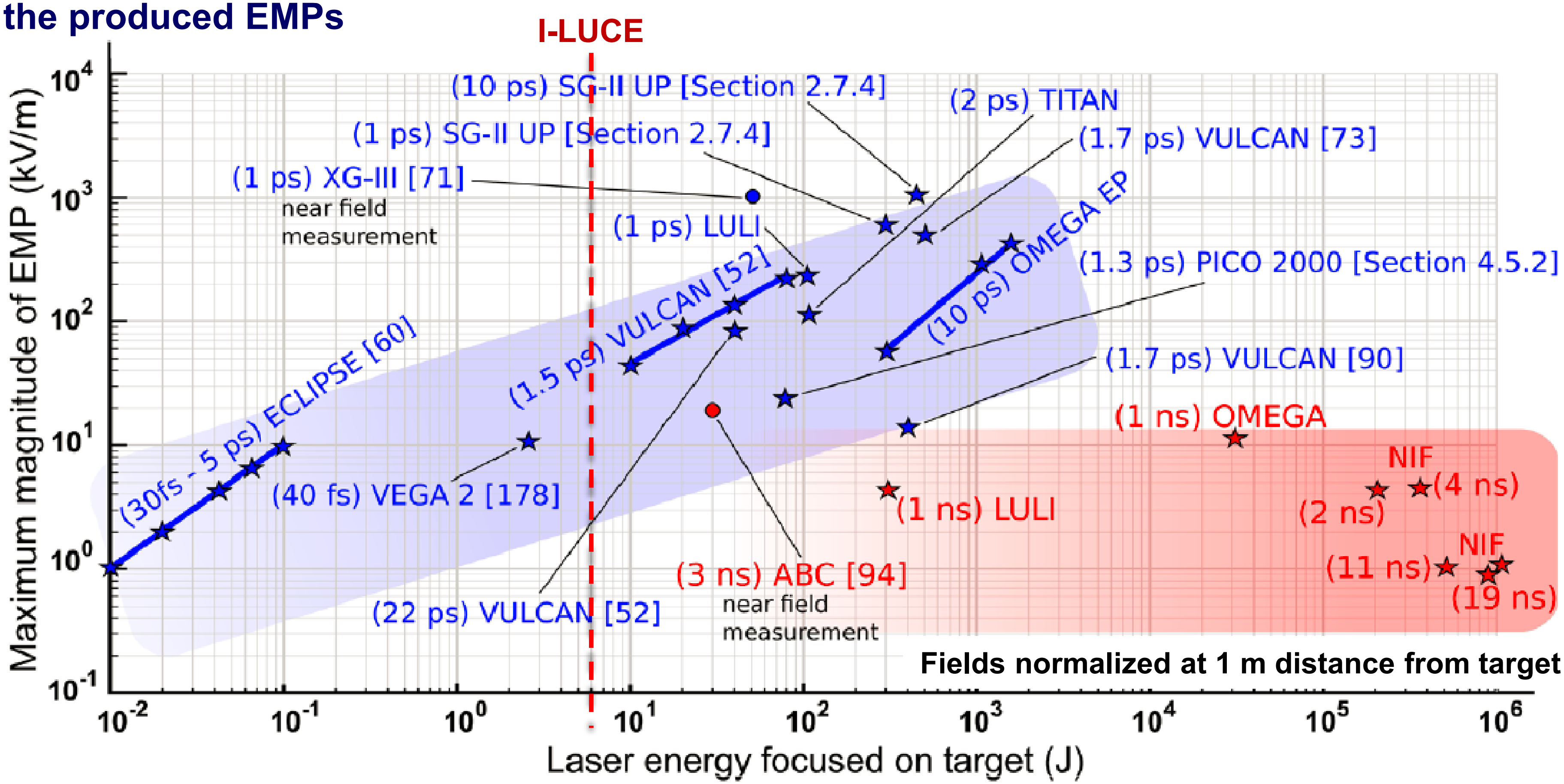

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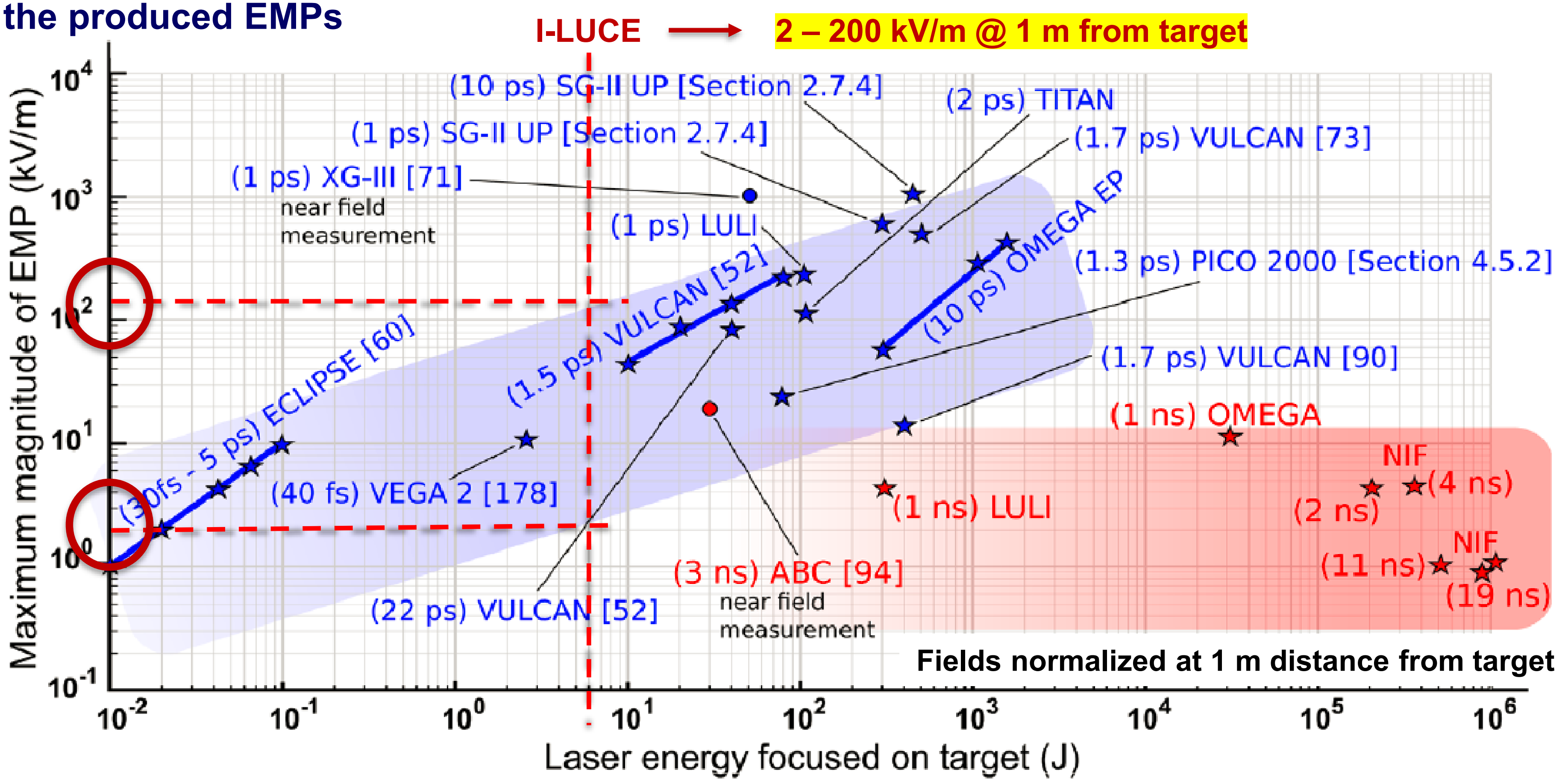

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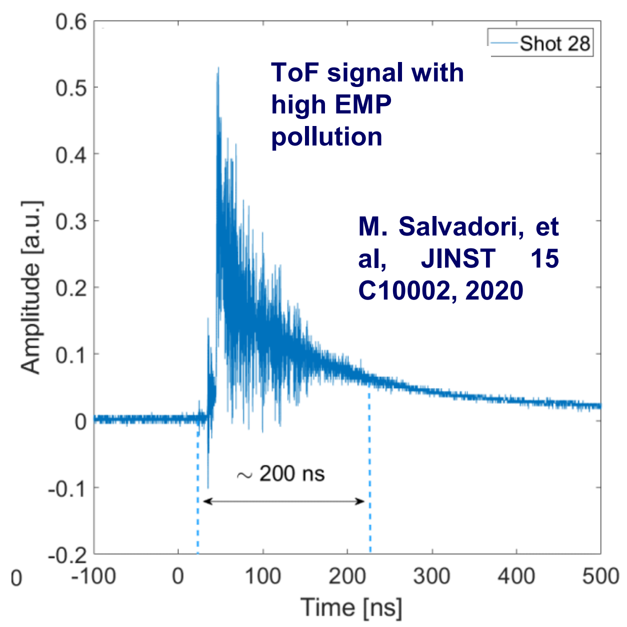
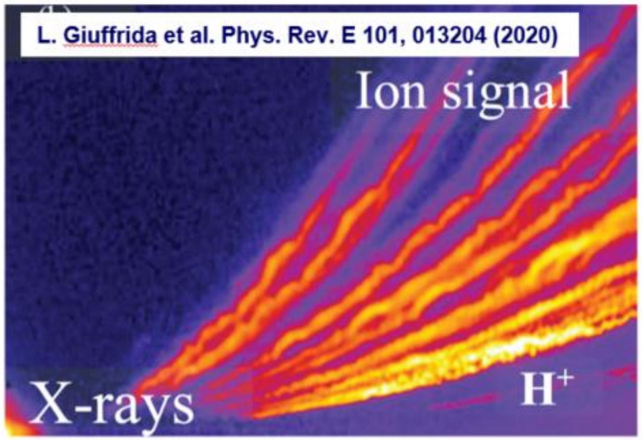
Importance of laser-generated electromagnetic pulses

- **EMPs are recognized as a major threat to electronics, computers, diagnostics and personnel. This requires the development of effective protections.**

- **The new high power and high energy laser facilities that will operate at high-repetition rate will require the development of reliable methods of EMP detection and mitigation**

- **Understanding of EMP physics opens to a wide number of significant applications for these high-intensity fields.**





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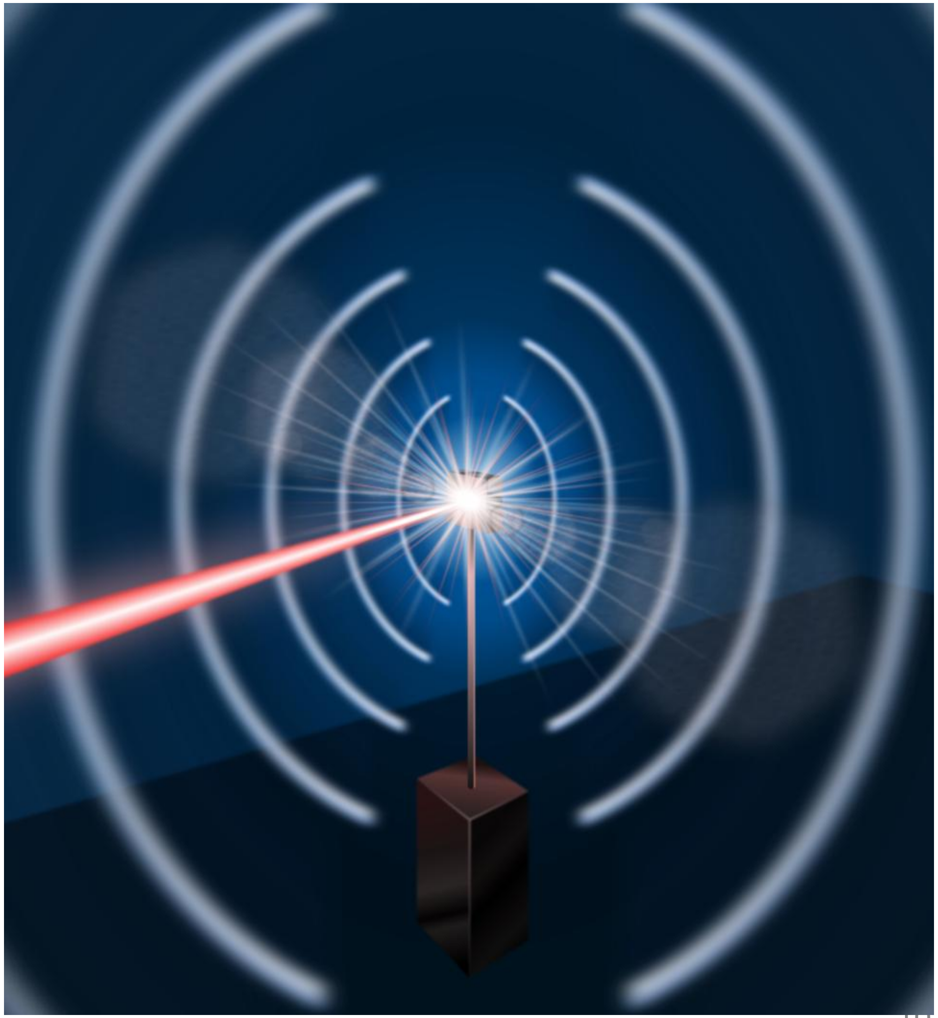
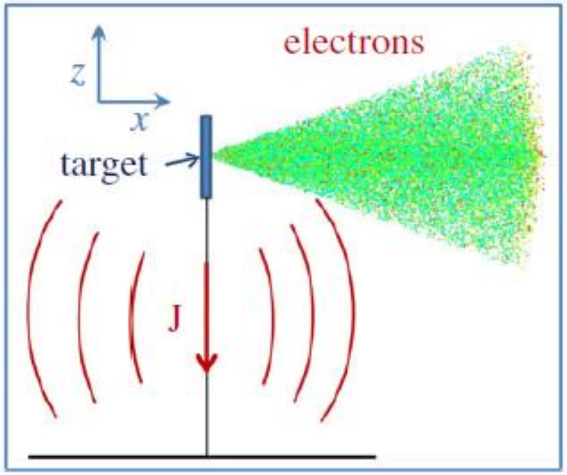


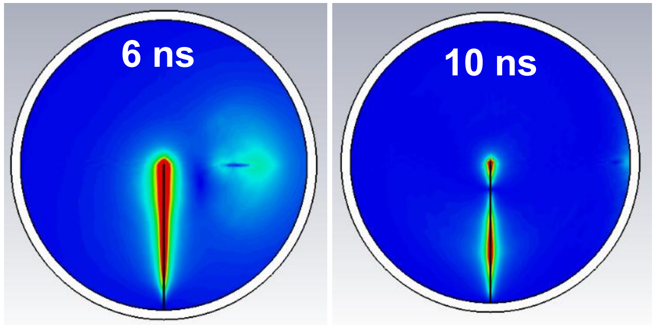
Laser-generated electromagnetic pulses

- **EMP generation is still not completely understood. This is a hot topics of research, since understanding of EMP physics also opens to a wide number of significant applications**

- **One of the recognized main mechanisms of EMP generation is the fast creation of a potential on target, due to the fast emission of electrons.**

- **This potential triggers a neutralization current to ground, that can reach the kA level, showing charges up to μC levels**





F. Consoli, Philosophical Transactions of the Royal Society A - Mathematical, Physical and Engineering Science A 379: 20200022

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Target polarization

- Target charging limited by two characteristic times:
  - laser pulse duration
  - cooling time of hot electrons in the target (up to ~10 ps)

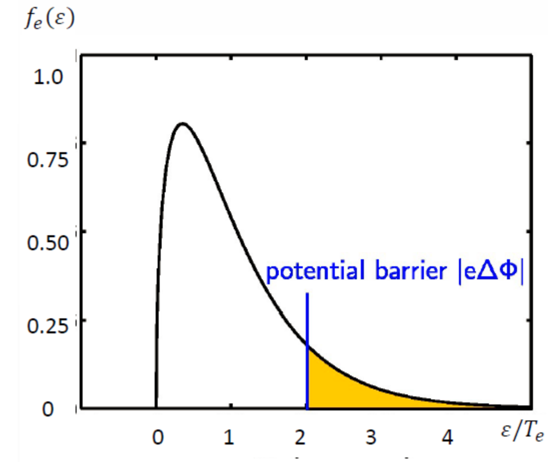
- Discharge time depends instead on the size of target and stalk and on the impedance of the target support.

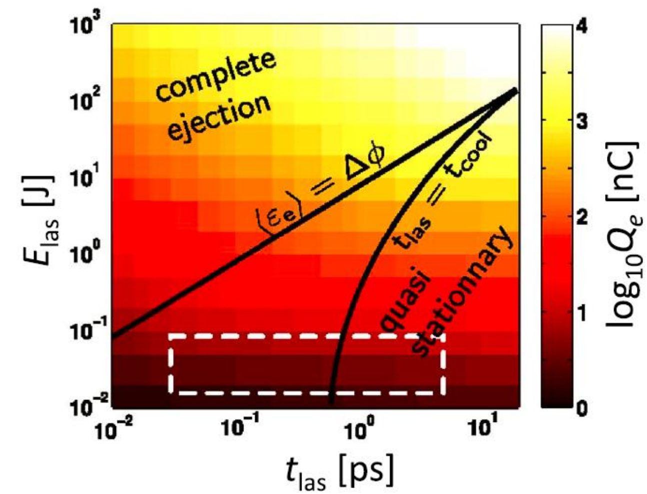
- In typical conditions, for a pulse duration lower than a few ps, the target charging process is temporally separated from the discharge process → charge accumulation

- Target potential defined by the temperature of hot electrons

- Charge depends on target capacitance (fractions of pF)

- Total accumulated charge varies from 10s of nC to a few μC, depending on the laser pulse energy and duration.





J.-L. Dubois et al. Phys. Rev. E 2014
A. Poyé et al. Phys. Rev. E 2015

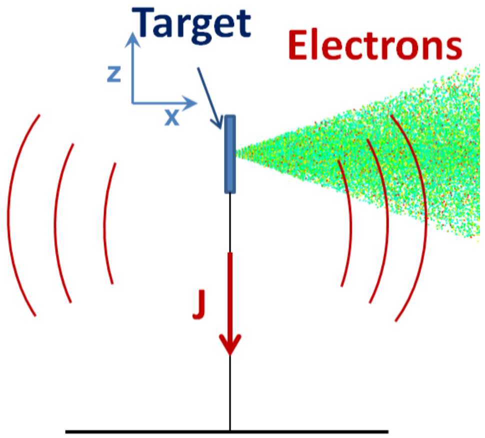
Target polarization

- For longer laser pulses, potential is established by a balance between the rate of electron ejection and the amplitude of the return current through the stalk to the ground.
- For a reasonable stalk length, the discharge time can be estimated of the order of 100's ps and this sets the upper limit of the laser pulse duration that is prone to produce intense EMPs.
- It also explains why the problem of EMP emission is of particular importance for ps and fs pulses and why it has attracted less interest in experiments with longer, ns pulses.
- Nevertheless, since EMP fields scale with both laser intensity and energy, they are still very serious and well-known threats for nanosecond high-energy and high intensity facilities.
- EMP signals can be significantly enhanced if both a long and a short laser pulse interact with the same target.

Mechanisms of electromagnetic emission

- Mechanism of Target Charging: frequencies up to THz domain

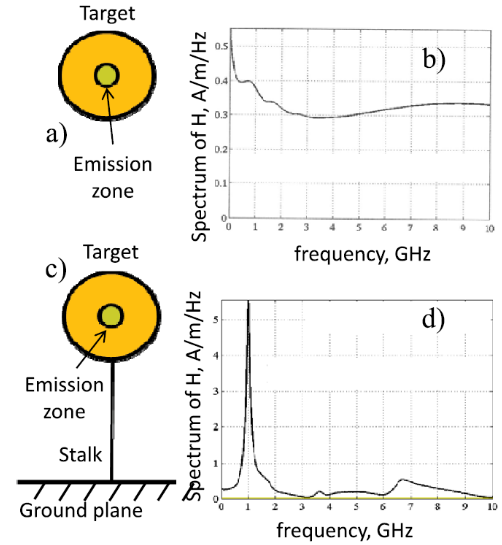
- Two principal sources of EMP emission, associated with the target charging:
  - ejected electrons → up to THz
    - Main emission mechanism: sheath dipolar emission, signicative during the electron ejection time. Coherent transition radiation plays a role but should be at a minor extent [1]
    - coherent process: total energy proportional to the square of electron charge, inversely proportional to the electron ejection time. Most important for the sub-ps lasers.
    - not of primary concern for electronic damage. Many possible applications.
  - produced neutralization current through the target stalk → up to about 100 GHz

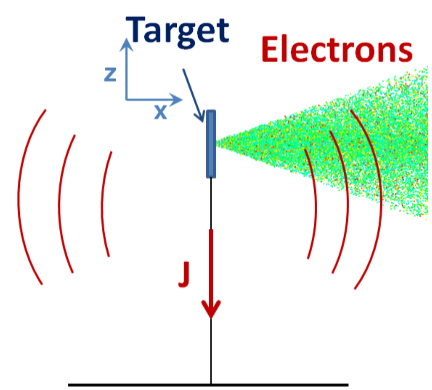


[1] S. Herzer et al. NJP 2018; [2] A. Poyé et al. Phys. Rev. E 2018; [3] G. Liao et al. PNAS 2019; [4] J. Déchard et al Phys Plasmas 2020
[5] V.T. Tikhonchuk et al, Electromagnetic pulse generation in experiments on high power laser facilities, IVth UltraFastLight, Moscow, September 28 - October 2, 2020

Gigahertz emission

- **Relaxation of the charge accumulated on the target during the laser pulse interaction**
- **Current pulse propagation along the holder: resonance emission of the electromagnetic pulse → spectrum is defined by the holder length, as a λ/4 antenna: GHz domain**
- **Pulse duration defined by the target size, kA currents**
- **Small size of the target compared to the emission wavelength → some suppression of emission should happen**



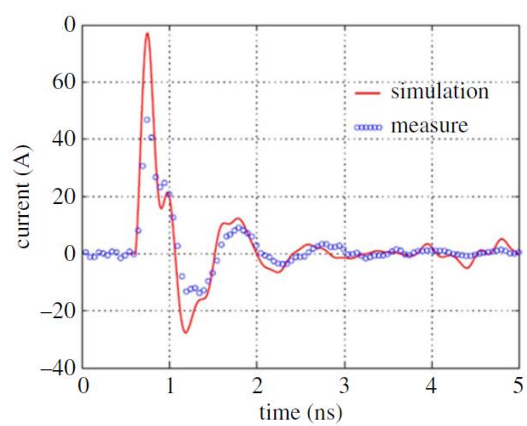


$$P_E = \frac{2.44}{8\pi} Z_0 |J_{\omega_s}|^2 \qquad \mathcal{E}_{\mathrm{GHz}} \simeq 0.1 \frac{c}{d_t} Z_0 Q_e^2$$

J_{ω_s} *Current density of the main harmonic*

Z_0 *Free-space impedance*

d_t *Target diameter*



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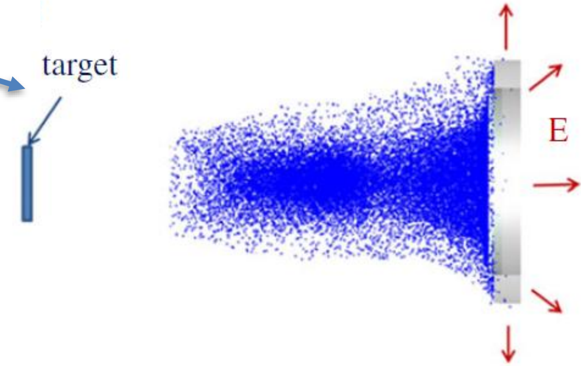
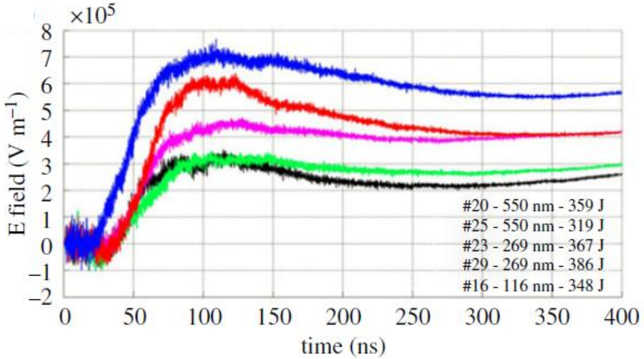
Gigahertz emission – other mechanisms

- **Deposition/secondary emission of particles on surfaces**





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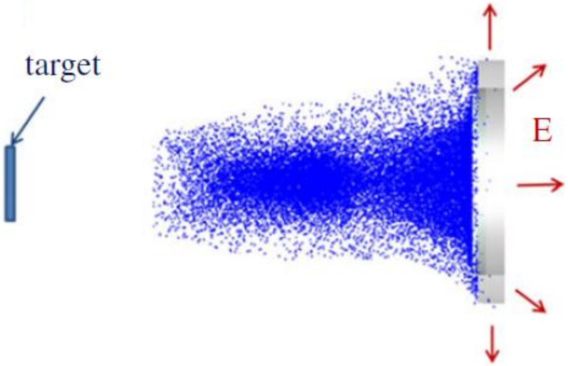

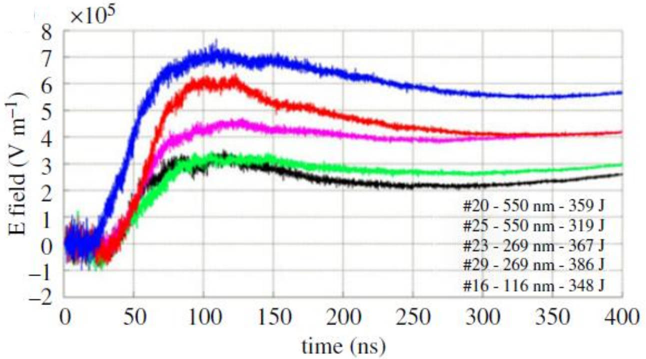

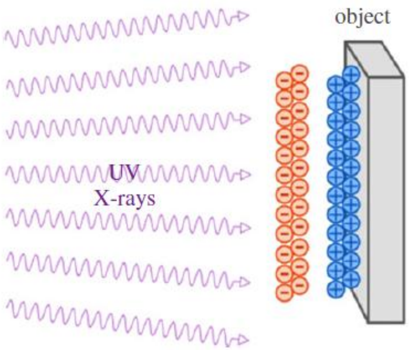

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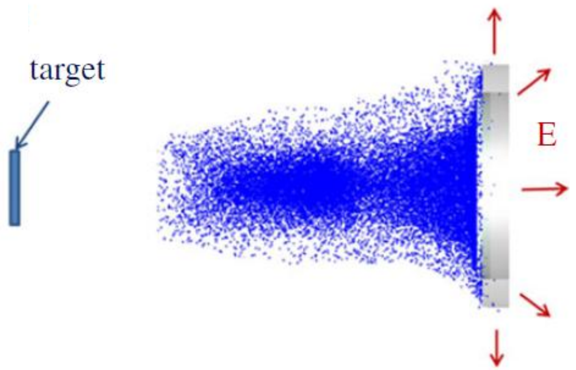

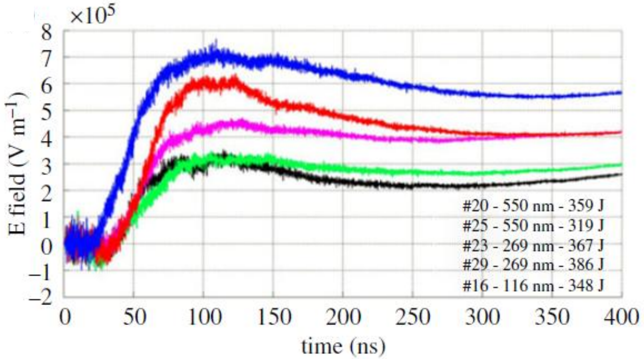

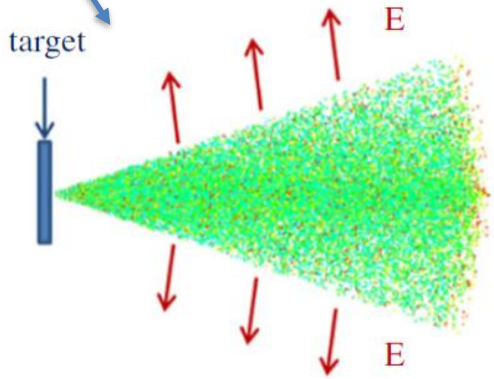

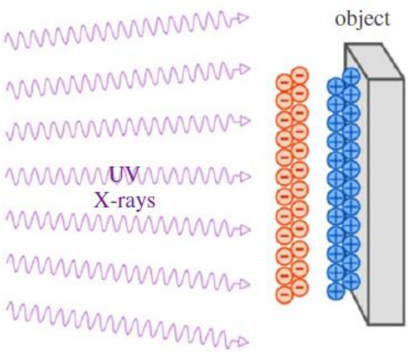

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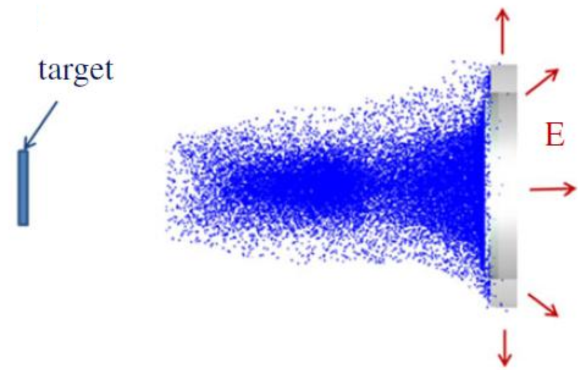
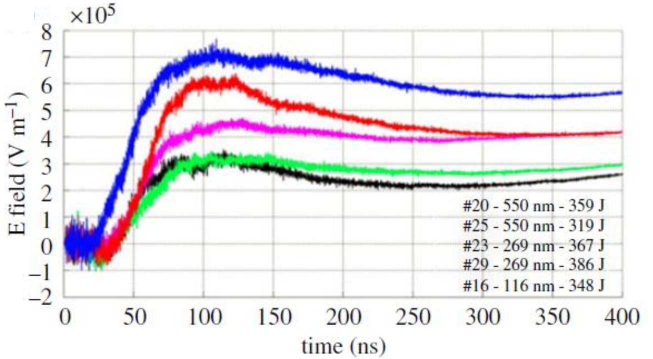
- Transient charged layers due to photoionization
- Quasi-static electric wakefields from charges accelerated by laser–matter interaction
- Among multiple sources of this emission, we mention
  - the secondary currents induced by ejected electrons on the conducting parts of the chamber
  - emission from a toroidal current circulating in the expanding plasma plume
  - plasma recombination after the end of the laser pulse





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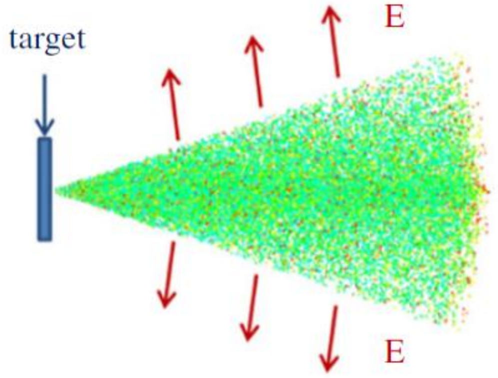

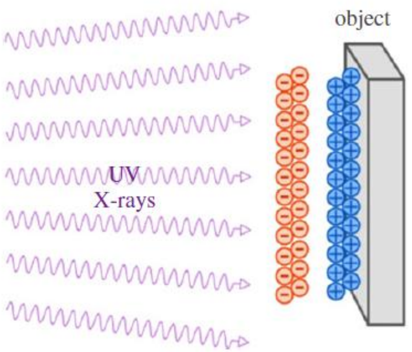

Gigahertz emission – mechanisms comparison

- **As a result, EMP fields can have dependance not monotonically decreasing with radius and be very high also far from the interaction point**

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
surface-sheath oscillations	horizontal dipolar antenna	target $\sim r^{-2}$	MV m^{-1}	some ps	10s GHz to THz
charged layers due to photoionization	close to surfaces exposed to UV-X-γ	target and from exposed surfaces	MV m^{-1}	some ns	10s GHz
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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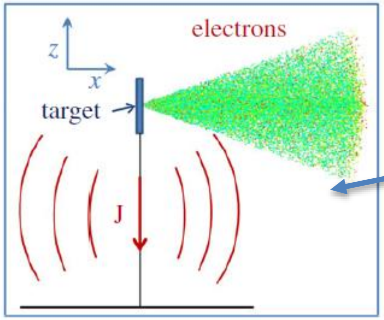

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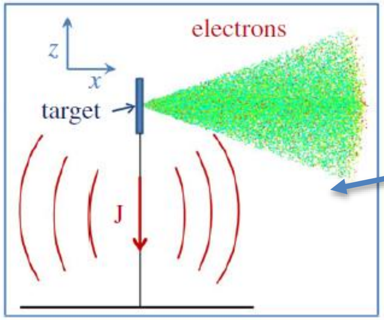

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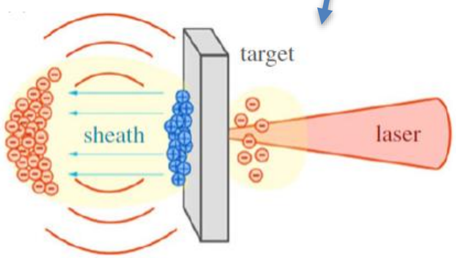

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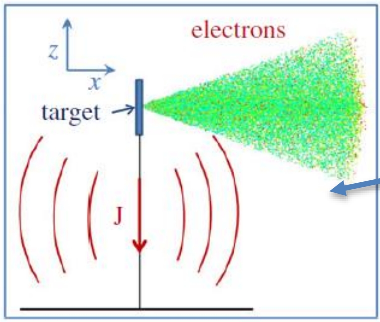

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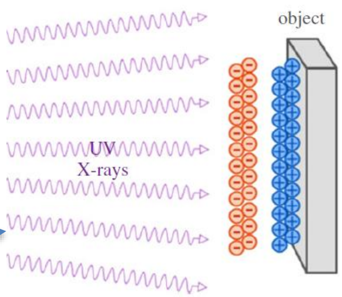

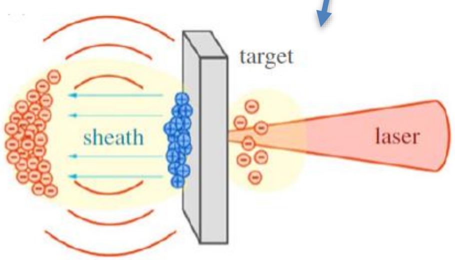

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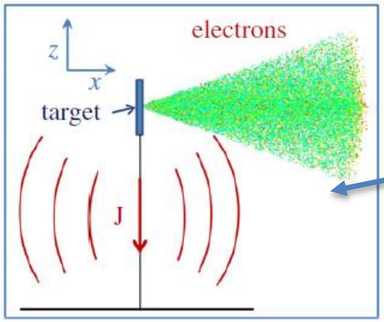

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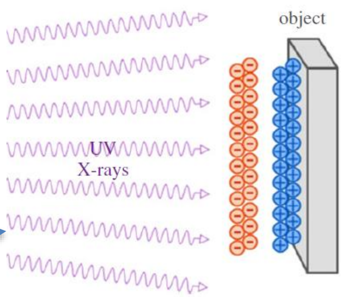
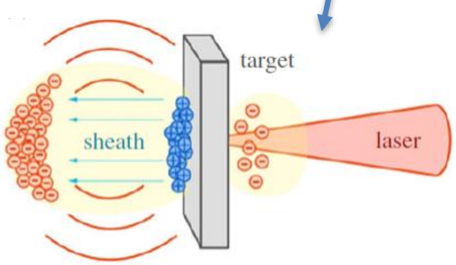
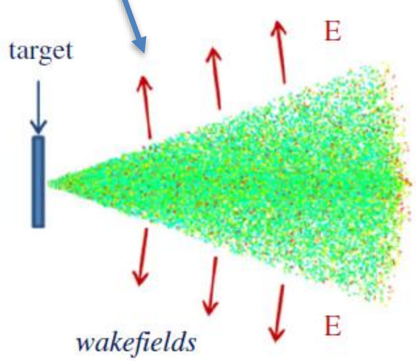


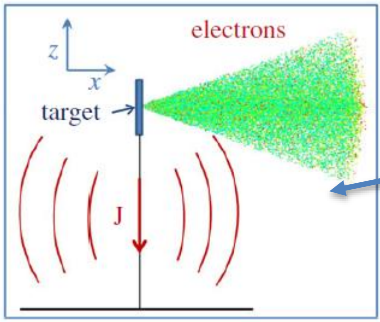




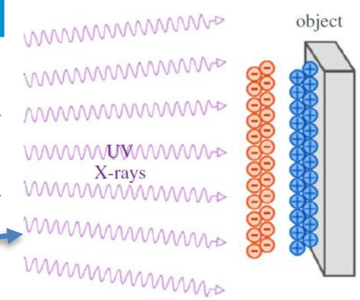
F. Consoli, et al, Phil. Trans. Royal Soc. A 379: 20200022 (2021)

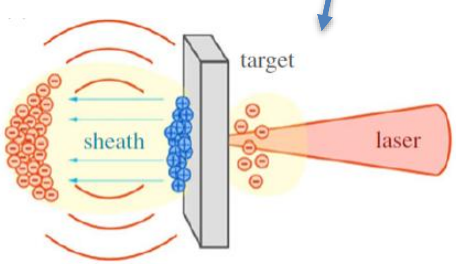
Gigahertz emission – mechanisms comparison

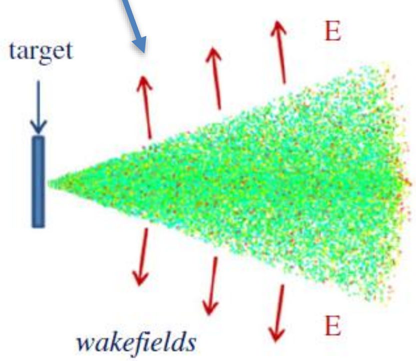
- **As a result, EMP fields can have dependance not monotonically decreasing with radius and be very high also far from the interaction point**

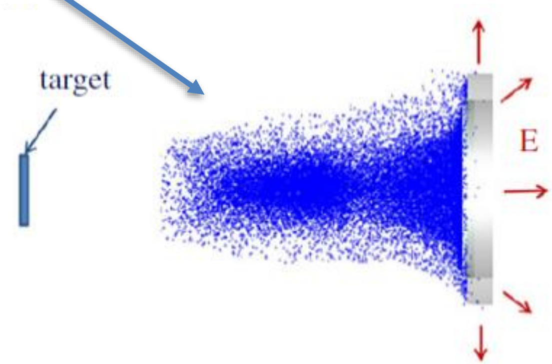


field source	distribution	intensity decreasing from	max fields	max temporal duration	max frequency range
neutralization current	vertical monopolar antenna	target $\sim r^{-\alpha}$ with $\alpha < 2$	Several MV m^{-1}	100s ns	10s GHz
surface-sheath oscillations	horizontal dipolar antenna	target $\sim r^{-2}$	MV m^{-1}	some ps	10s GHz to THz
charged layers due to photoionization	close to surfaces exposed to UV-X-γ	target and from exposed surfaces	MV m^{-1}	some ns	10s GHz
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. A 379: 20200022 (2021)

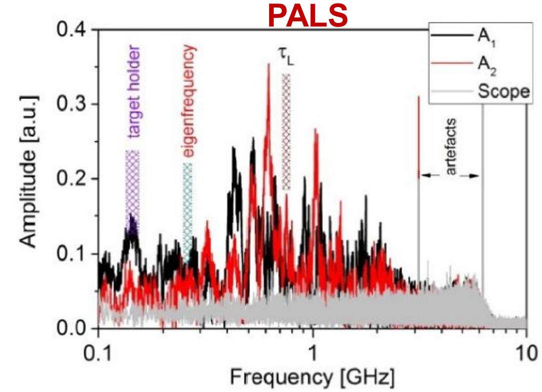
EMP distribution

- **Experimental chamber: electromagnetic resonator with several sources: duration much longher than the neutralization current**
- **Electromagnetic modal expansion, with solenoidal eigenvectors, harmonic and irrotational electric and magnetic eigenvectors.**

$$\mathbf{E} = \sum_{i=1}^{+\infty} A_i \mathbf{E}_i + \sum_{i=1}^{M-1} A_i^0 \mathbf{E}_i^0 + \sum_{i=1}^{+\infty} B_i \mathbf{s}_i ,$$

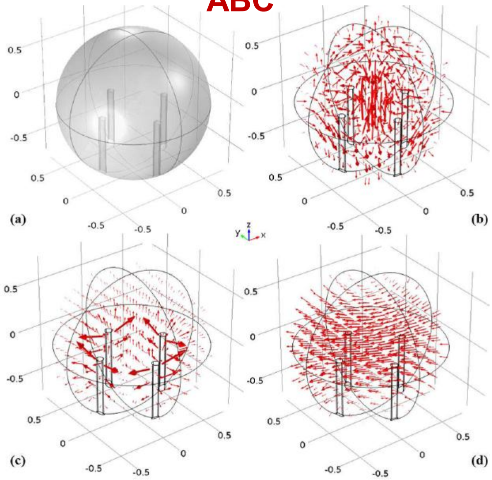
$$\mathbf{H} = \sum_{i=1}^{+\infty} C_i \mathbf{H}_i + \sum_{i=1}^{P-1} C_i^0 \mathbf{H}_i^0 + \sum_{i=1}^{+\infty} D_i \mathbf{g}_i ,$$

PALS

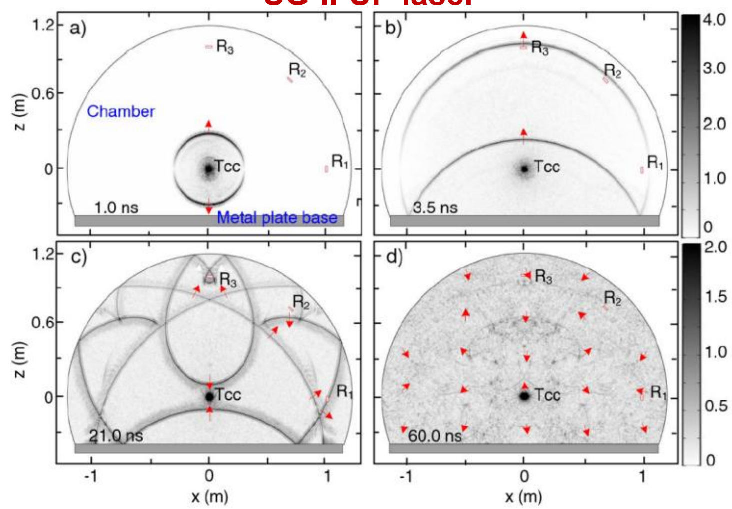


- **Both time-domain and frequency-domain measurements and numerical simulations needed for the EMP field description**

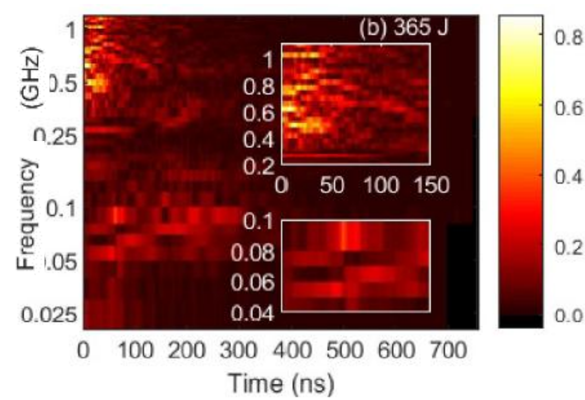
ABC



SG-II-UP laser



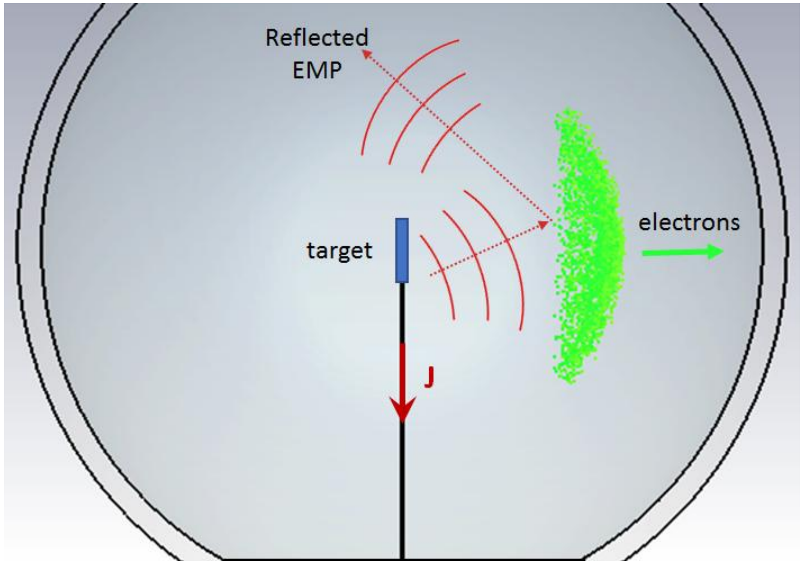
Vulcan



F. Consoli et al, High Pow. Laser Sci.& Engin. 8, e22, 2020
F. Consoli et al. Physics Procedia, 62, 11 (2015).

EMP distribution

- **The modal structure of the electromagnetic fields is also modified by hot electrons and plasma expanding from the target.**
- **They may reflect EMP waves with wavelengths longer than the critical wavelength associated with the electron density in that position.**

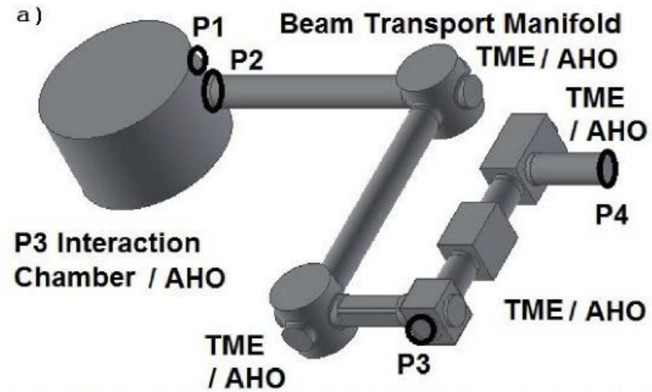


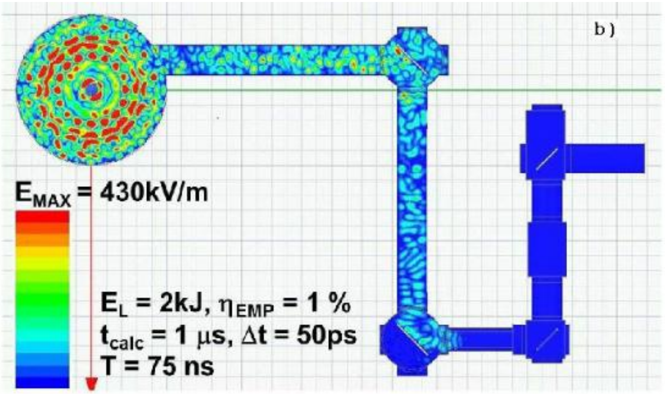
- **Thus, within the experimental chamber, a time-varying volumetric distribution of critical regions may be created for each EMP wavelength.**
- **Detailed analysis requires extended numerical simulations.**

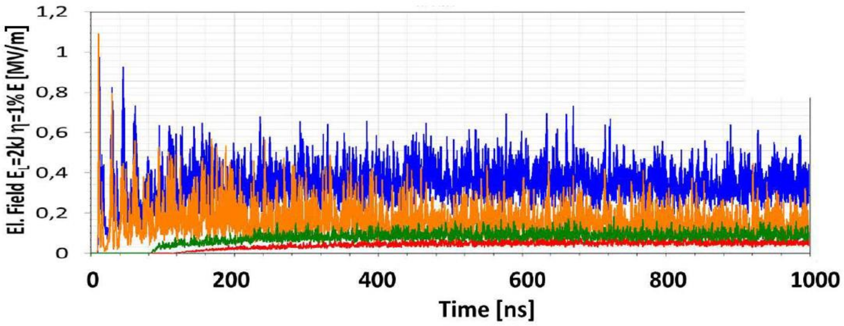
J. Krása et al PPCF 62, 025021 (2020); F. Consoli et al Phil. Trans. R. Soc. A 379, 20200022 (2020)

EMP distribution

- Several **'doors'** lead to the transfer of the EMPs present within the chamber to the outside: dielectric glass windows, vacuum flanges, dialectric vacuum feedthroughs for coaxial cables…
- EMP also **propagates upstream along the tubes of laser guide** and may affect the **beam pointing and compression**
- Study at ELI-Beamlines on EMP tube propagation with ANSYS modeler



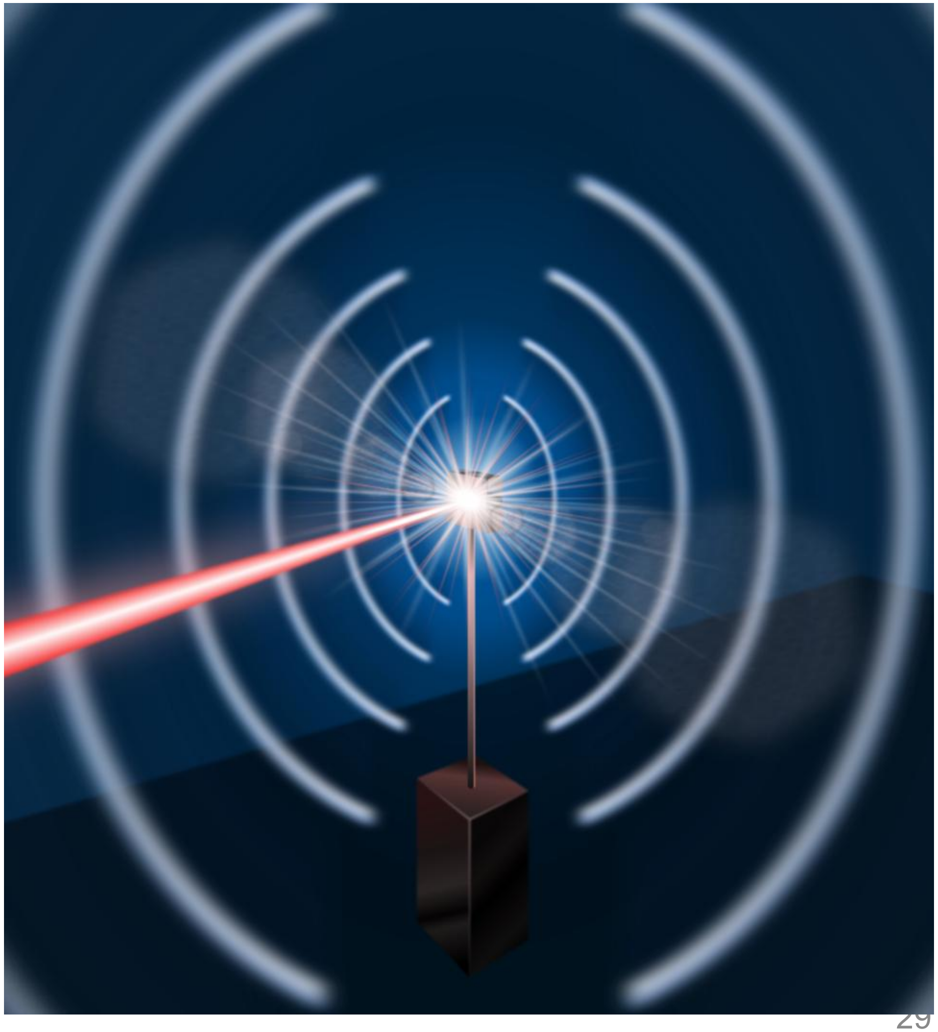




F. Consoli et al, High Pow. Laser Sci.& Engin. 8, e22, 2020;

Outline

- Introduction to laser-generated electromagnetic pulses (EMPs)
- EMP generation
- **Methods of EMP diagnostics**
- Methods of EMP mitigation
- EMP applications

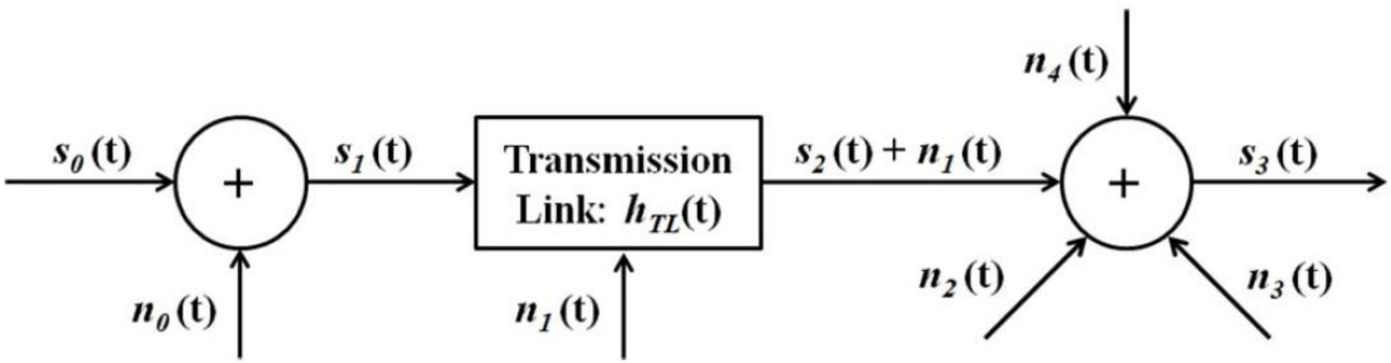


Methods of EMP diagnostics

- **Challenges of measuring EMP fields in laser–matter interaction experiments**
- **Many possible spourious effects on the field measurement and determination**

Functional scheme of contributions for the stored signal in EMP measurements

s_0 EMP signal



s_3 signal actually stored in oscilloscope

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

$$n_{\mathrm{ext}}(t) = n_1(t) + n_2(t) + n_3(t) + n_4(t)$$

- **n_0: noise on the detector because of ionizing radiation**
- **n_1: EMP noise penetrating the whole 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**

F. Consoli et al, High Pow. Laser Sci.& Engin. 8, e22, 2020
F. Consoli et al, PPCF 2018

Methods of EMP diagnostics

- **Challenges of measuring EMP fields in laser–matter interaction experiments**
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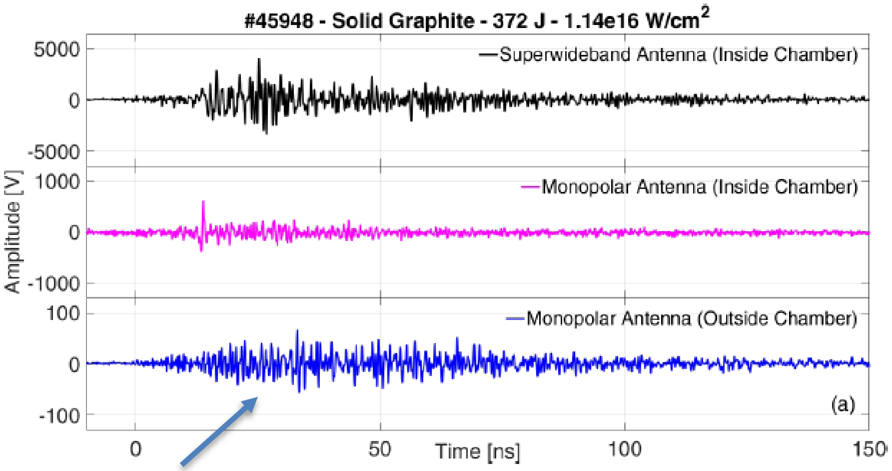
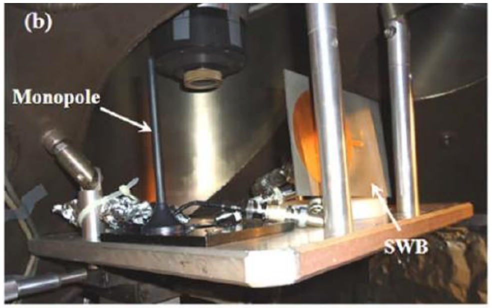
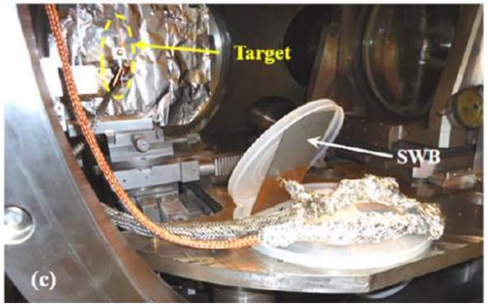
PALS campaign at 600 J Energy, 1 omega, 350 ps



Antennas CONNECTED to the scope





F. Consoli et al, High Pow. Laser Sci.& Engin. 8, e22, 2020
F. Consoli et al, PPCF 2018

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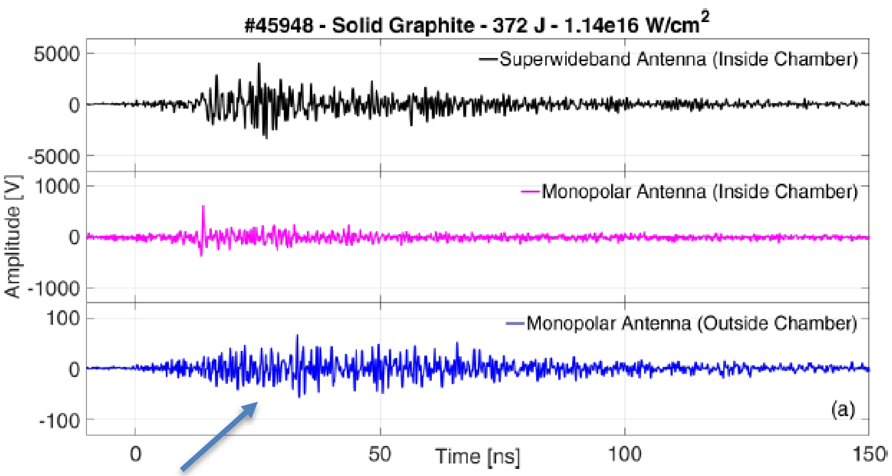
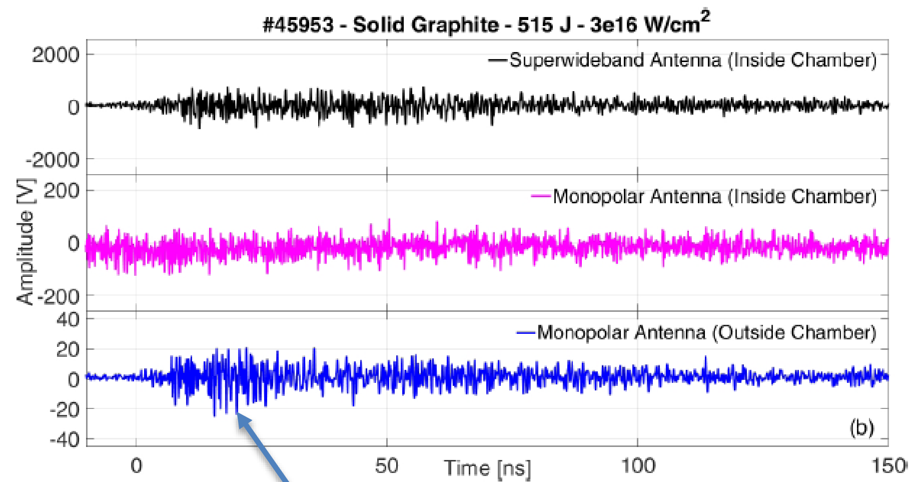
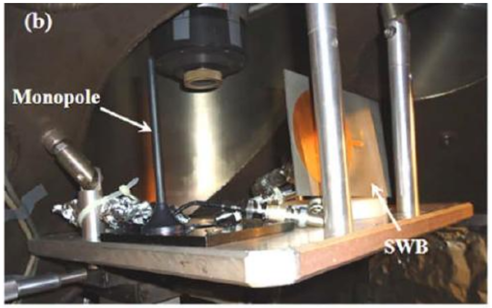
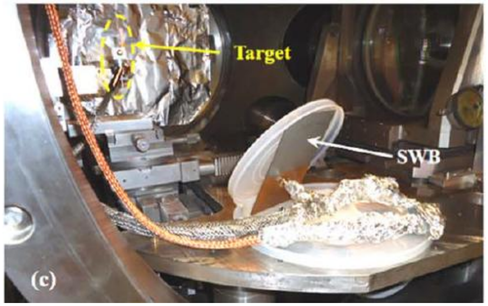




Antennas CONNECTED to the scope

Antennas DISCONNECTED to the scope





F. Consoli et al, High Pow. Laser Sci.& Engin. 8, e22, 2020
F. Consoli et al, PPCF 2018

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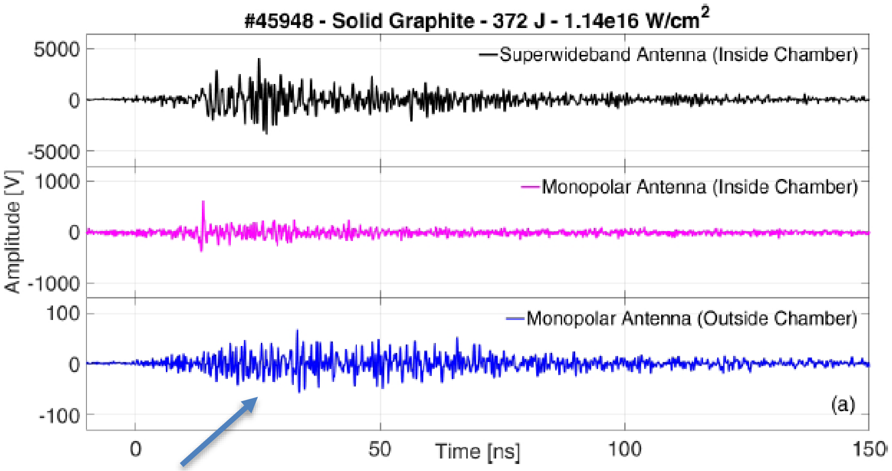
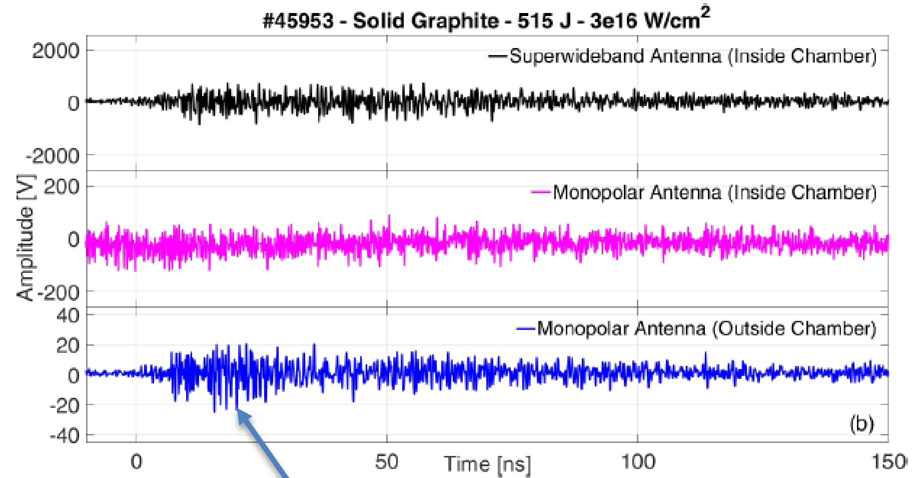
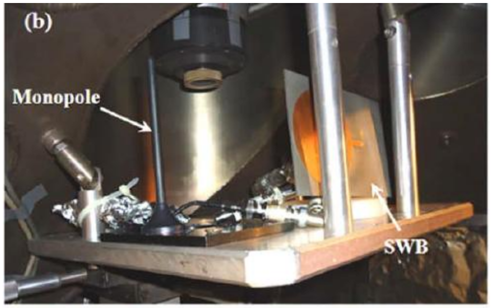


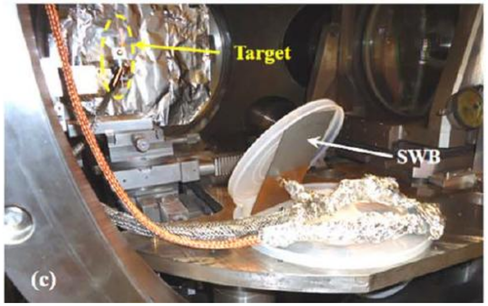


Antennas CONNECTED to the scope

Antennas DISCONNECTED to the scope

Signal-to-Noise ratio between 2 and 5→ rather poor





F. Consoli et al, High Pow. Laser Sci.& Engin. 8, e22, 2020
F. Consoli et al, PPCF 2018

Methods of EMP diagnostics

Conductive Probes

- B-Dot, Moebious loops, for magnetic fields
- D-Dot for electric field
- Calibrated loops for neutralization current
- Antennas

Dielectric probes

- Linear electro-optic (Pockels) effect in dielectric crystals for E field measurements, Faraday effect for B field → High frequency band, up to the THz level

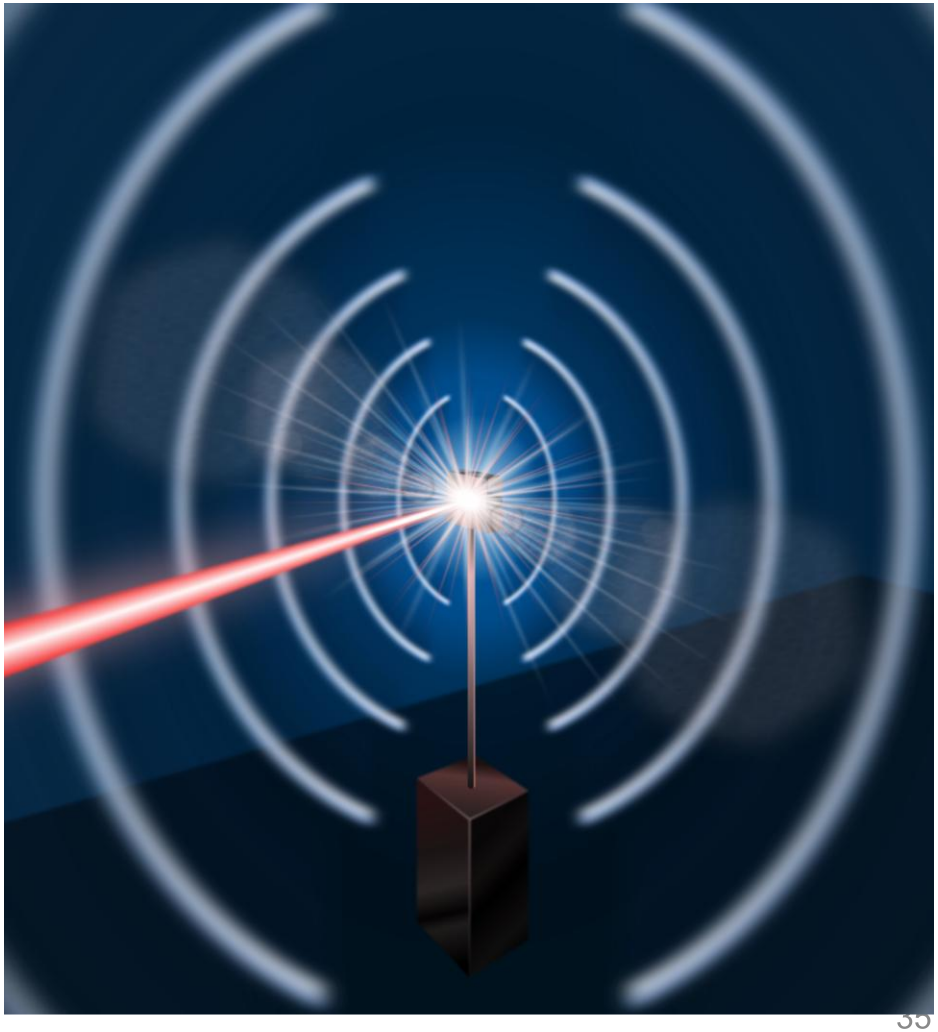
Charged particle deflection for electromagnetic field probing

- Ions
- Electrons

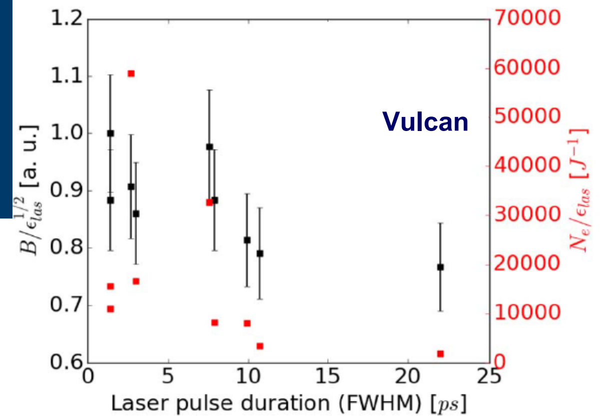
ENEA

Outline

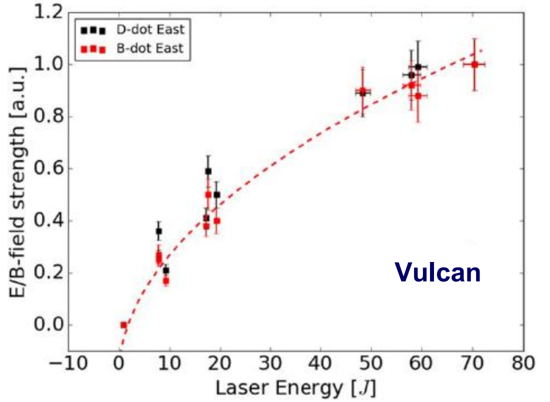
- Introduction to laser-generated electromagnetic pulses (EMPs)
- EMP generation
- Methods of EMP diagnostics
- **Methods of EMP mitigation**
- EMP applications

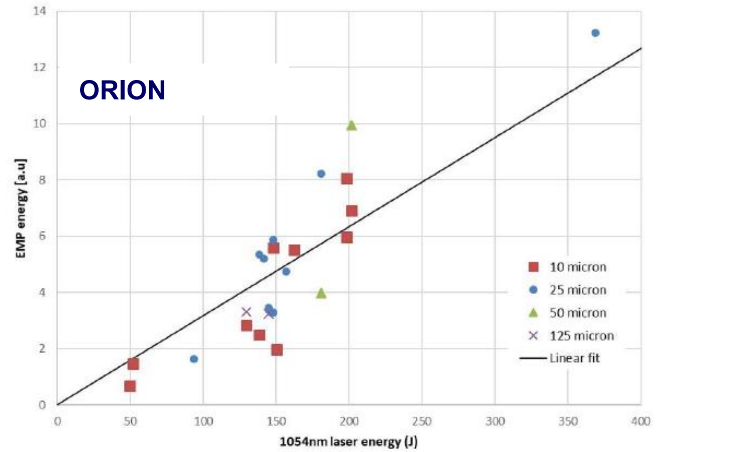


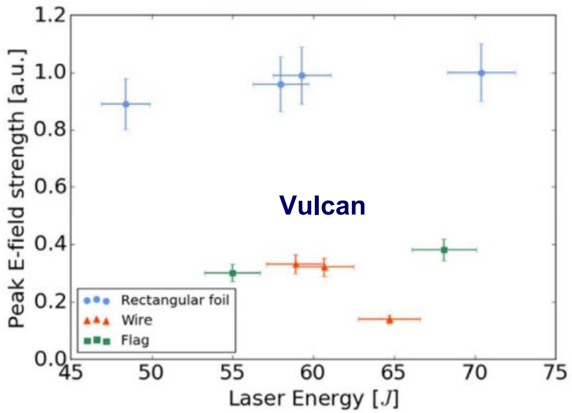
Methods of EMP mitigation: target & interaction

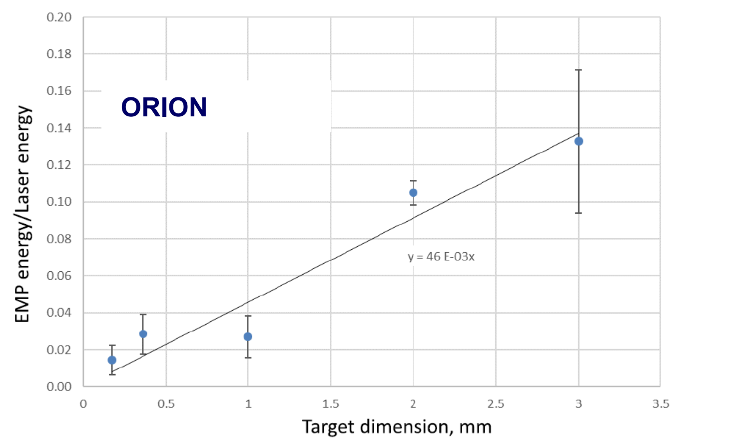


- **EMPs**
  - **Increase with laser energy**
  - **Decrease for longer laser pulses**
  - **Increase for larger targets**
- **Campaigns at Vulcan and Orion, up to 500 J and up to 10^{21} W/cm^2**





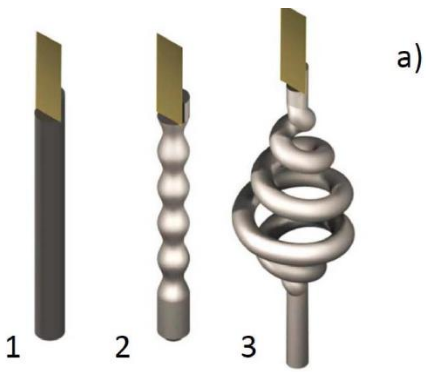


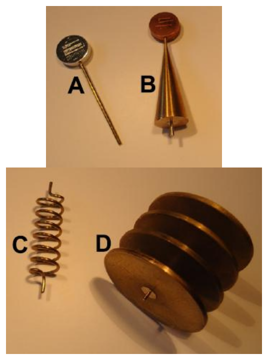


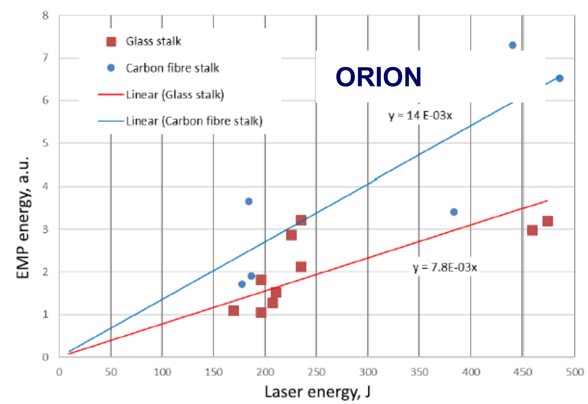
P. Bradford et al, High Power Laser Science & Engin. 2018
F. Consoli et al, High Power Laser Science & Engin. 2020

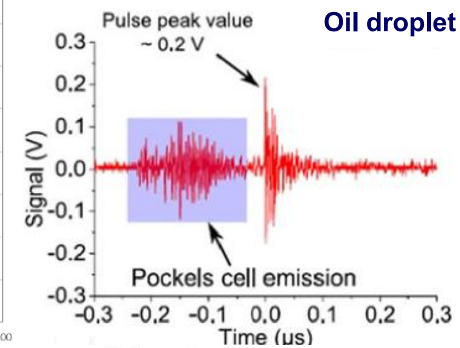
Methods of EMP mitigation: <u>holder</u>

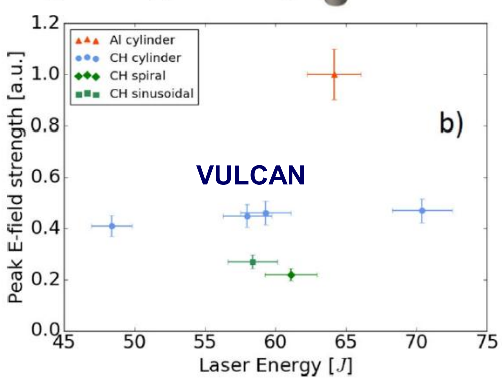
- **Shape and material of the holder may reduce the EMP emission up to a large extent**
- **High resistivity and specific impedance of the stalk can have notable results**
- **Spiral plastic stalks got a reduction of a <u>factor of 5</u> on the EMP intensity**
- **Conductive spiral holders may also reduce EMPs of about a <u>factor of 2</u>**
- **Levitating targets reduced EMPs of ~ <u>a factor of 25</u>, experiments on ps laser pulses**

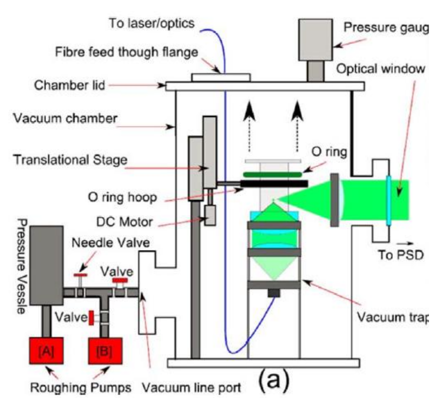


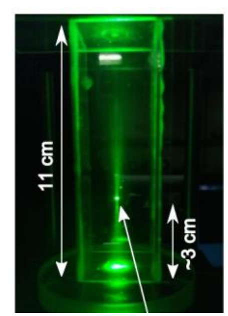




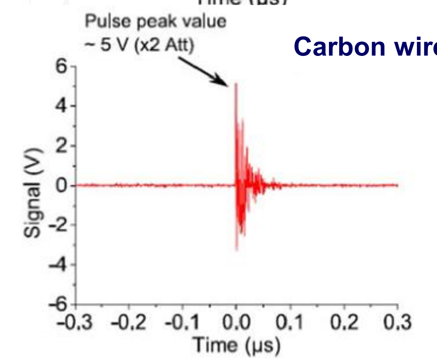








Imperial College

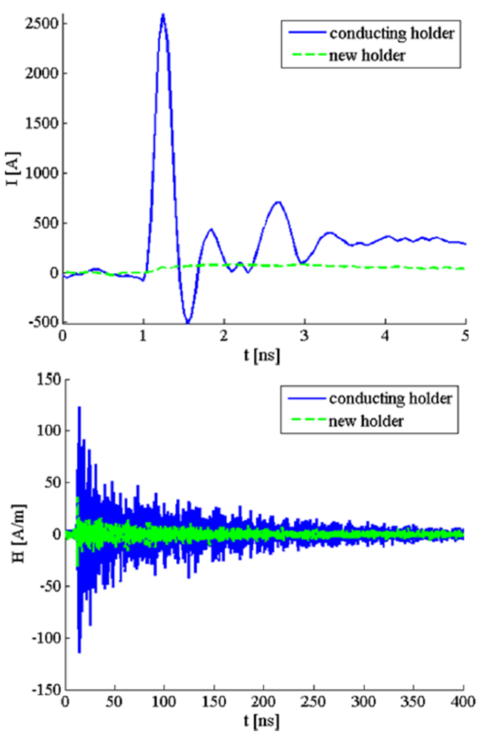


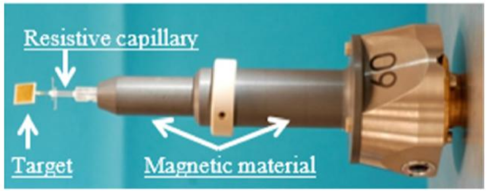
P. Bradford et al, High Power Laser Science & Engin. 2018; F. Consoli et al, High Power Laser Science & Engin. 2020; D.F.G. Minnenna, Phys. Plasmas 27, 063102 (2020); C. J. Price, Rev. Sci. Instrum. 86, 033502 (2015).

Methods of EMP mitigation: holder

- **Advanced holder: resistive capillary and magnetic material**
- **Reduce the discharge current intensity and EMP amplitude**
- **Guide the target charge to the ground through the holder**
- **Experiments at LULI (80 J/1.3 ps) about a factor of 3 reduction with respect to conductive holder**
- **Experiments at PETAL confirmed the LULI results**

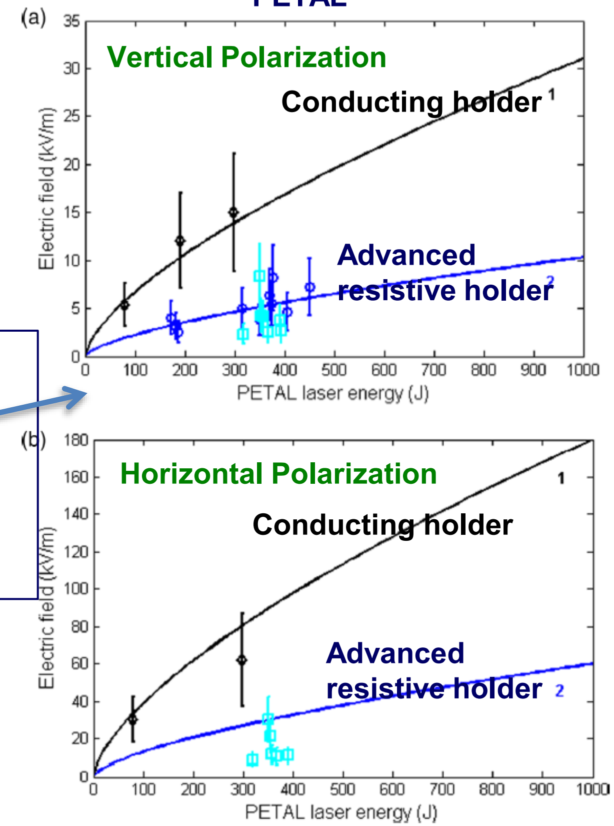
LULI





- **Target potential 10 MV**
- **Ejected charge 1 µC**
- **Discharge current 10 kA**
- **EMP amplitude 100 kV/m at a distance of 4 m**
- **Horizontal polarization parallel to the holder**

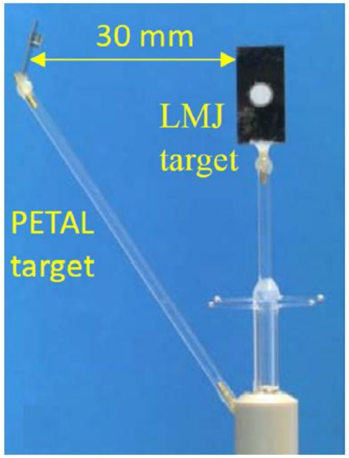
PETAL



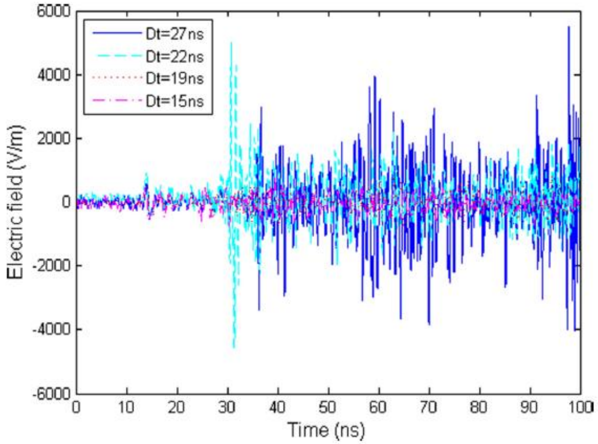
M. Bardon et al, Phy. Rev. Reses. 2, 033502 (2020)

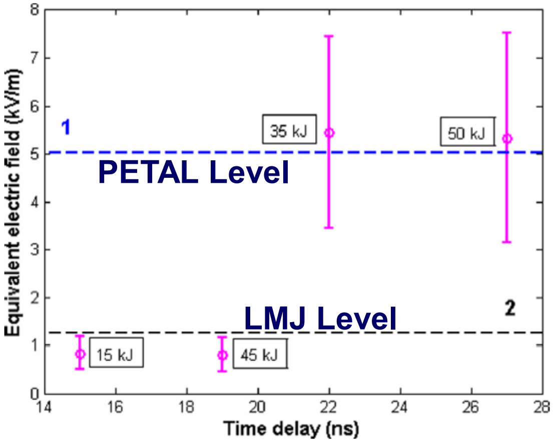
Methods of EMP mitigation: joint nano+pico

- Recent experiments with both LMJ and PETAL showed very high EMP reduction (~5)
- Explained by PETAL target screening in the low density plasma created by the X-ray emission from the LMJ target in the residual gas around the PETAL target
- Effect depending on delays between LMJ and PETAL: observed for <20ns delays



X-ray energy 3 kJ
Energy of photons 100 eV
Residual gas density 5×10-6 mbar
Plasma density 7×10^{11} cm^{-3}
Plasma frequency 7.5 GHz

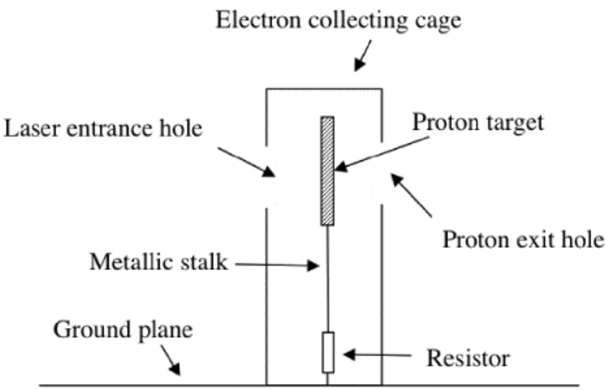


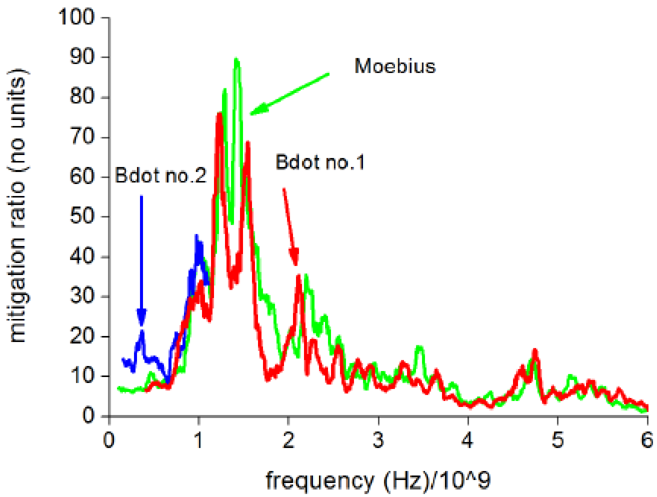


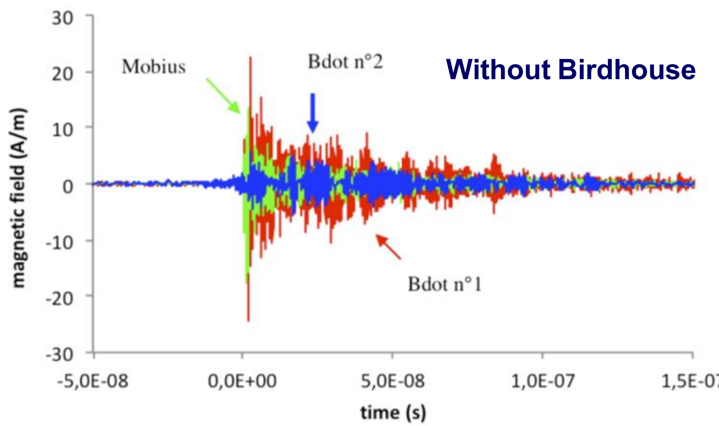
M. Bardon et al, Phy. Rev. Reses. 2, 033502 (2020)

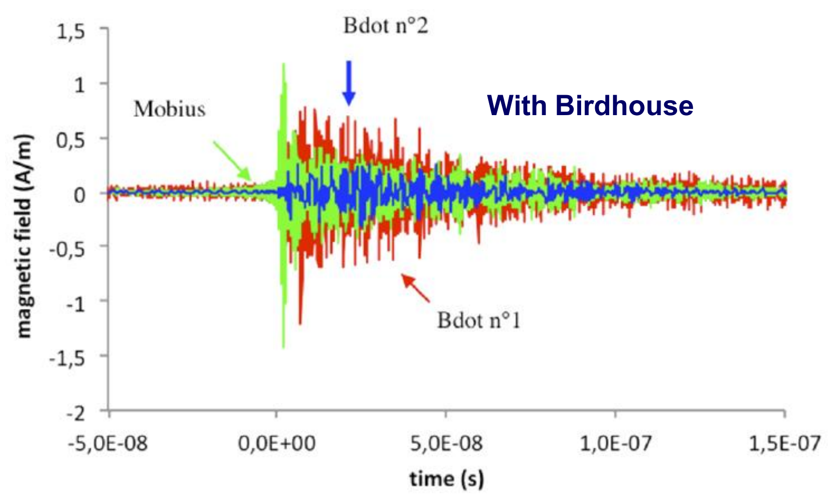
Methods of EMP mitigation: <u>target caging</u>

- **EMP fields confined within a Faraday cage built around the target: «birdhouse».**
- **The intense current must be dissipated by the target holder**
- **Experiments at IPPLM (330 mJ, 50 fs)**





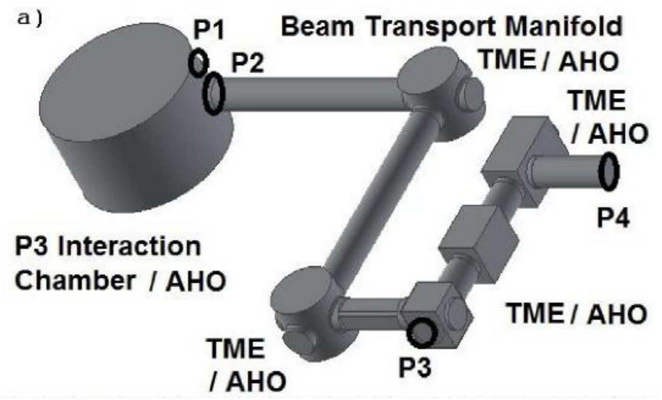




J.-L. Dubois et al. RSI 2018

Methods of EMP mitigation: EMP absorption

- The use of suitable RF-microwave absorbers can reduce the field propagation of more than a factor of 1000



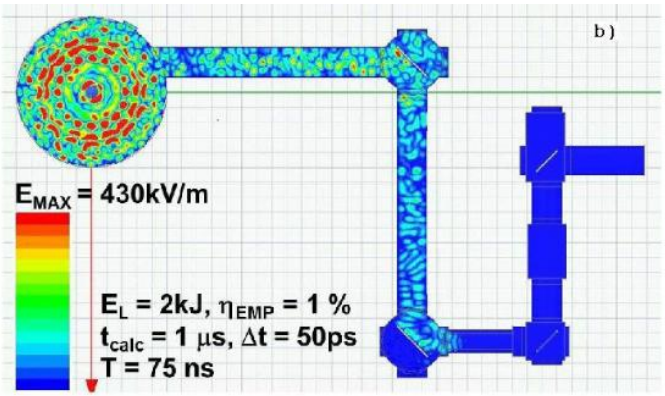


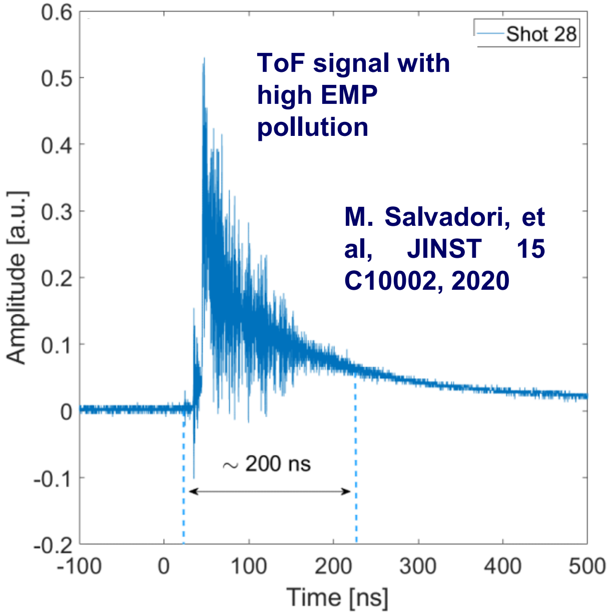
Table 4. EMP energy flow at the selected ports during 1 µs calculation in percentage of initial EMP energy for different absorbers. See text for explanation of abbreviations.

Port	P1	P2	P3	P4	P2-BR
	IChAux	IChL4	LDiag	L4 compr	BackRef
No Abs	16.8	48.1	6.6	2.06	20.3
TME	15.6	50.9	0.16	0.034	2.7
P3ICh	0.45	0.42	0.071	0.025	0.28
Both	0.47	0.45	0.002	0.001	0.066

F. Consoli et al, High Pow. Laser Sci.& Engin. 8, e22, 2020

Methods of EMP mitigation: EMC optimization

- **Source comprehension may allow for optimized EMC techniques for device and diagnostics survival and correct operation and for personnel security.**



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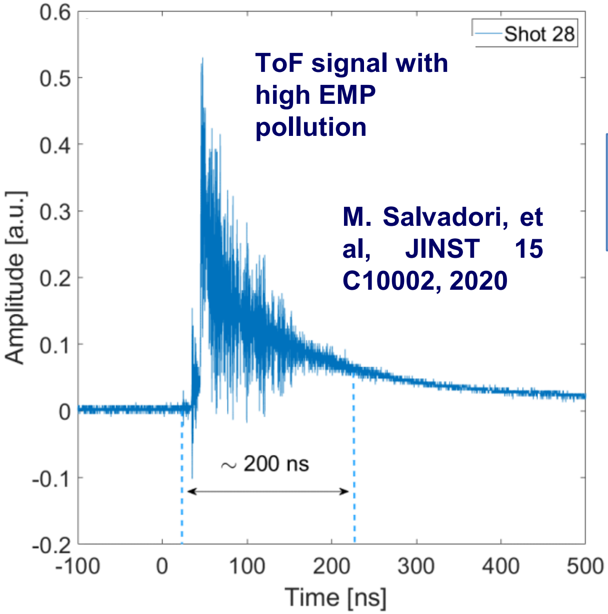

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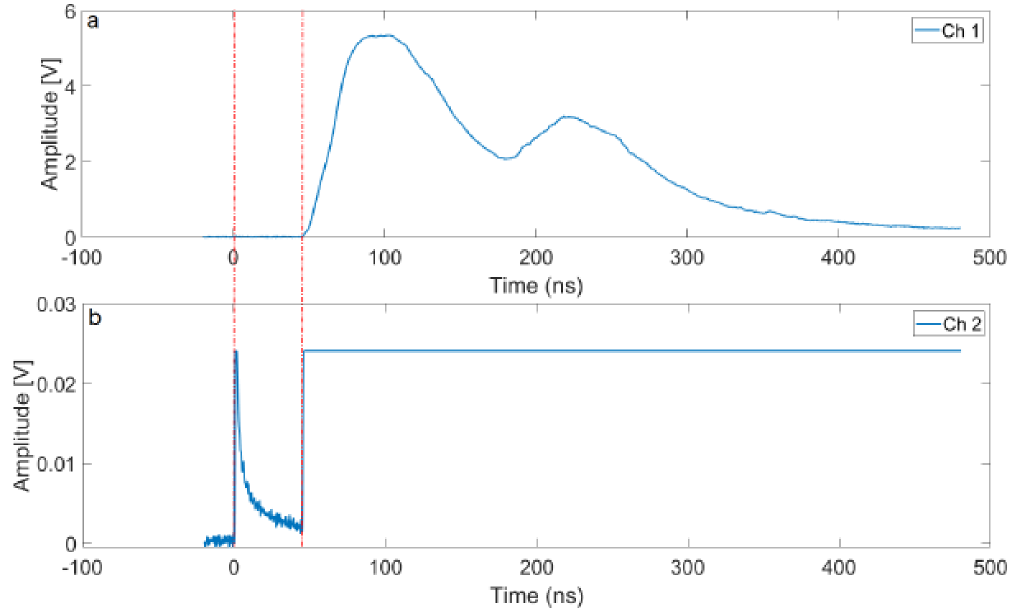

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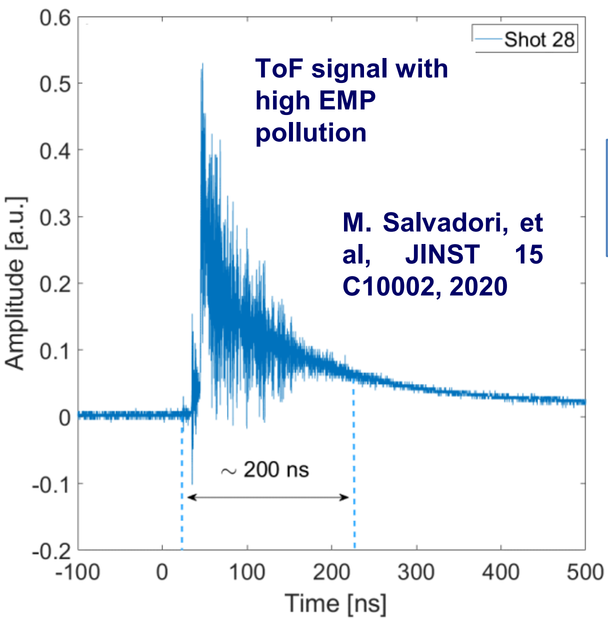

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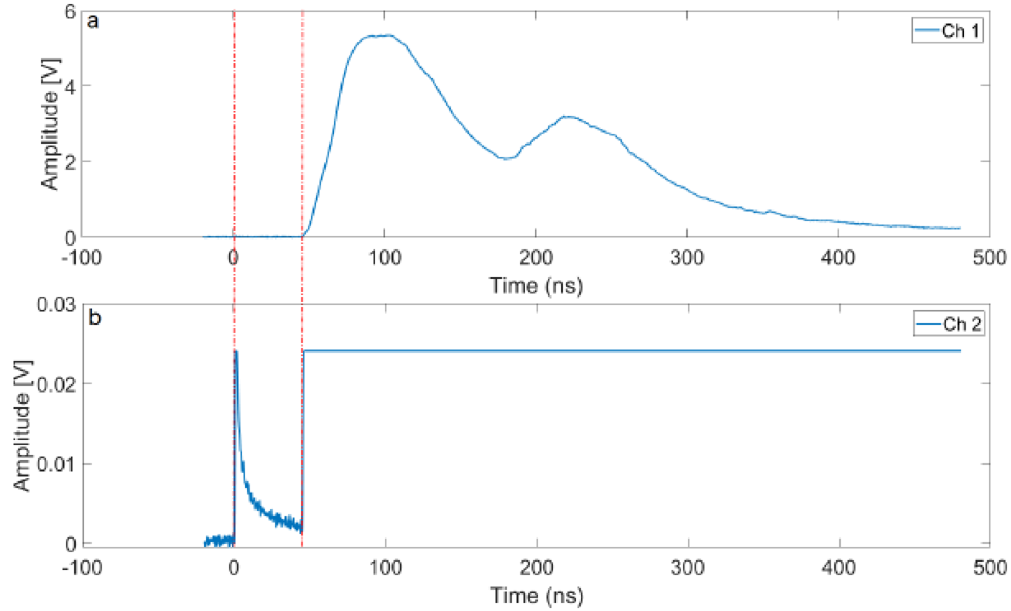

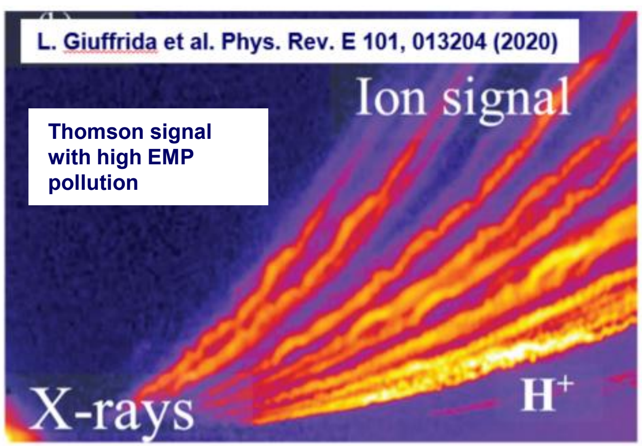

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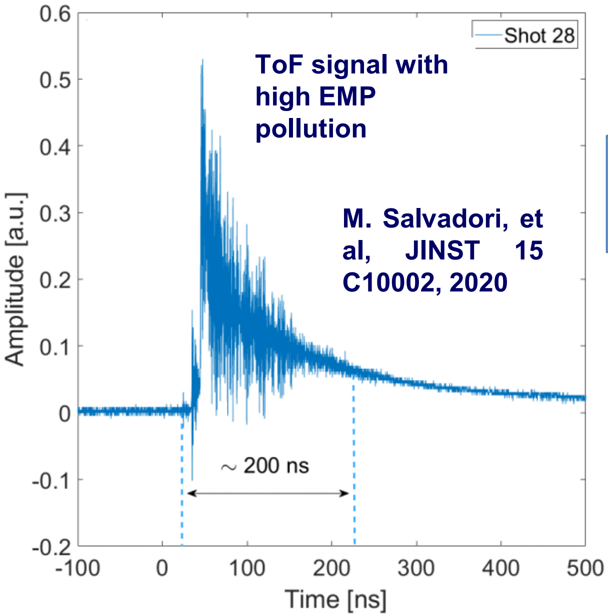

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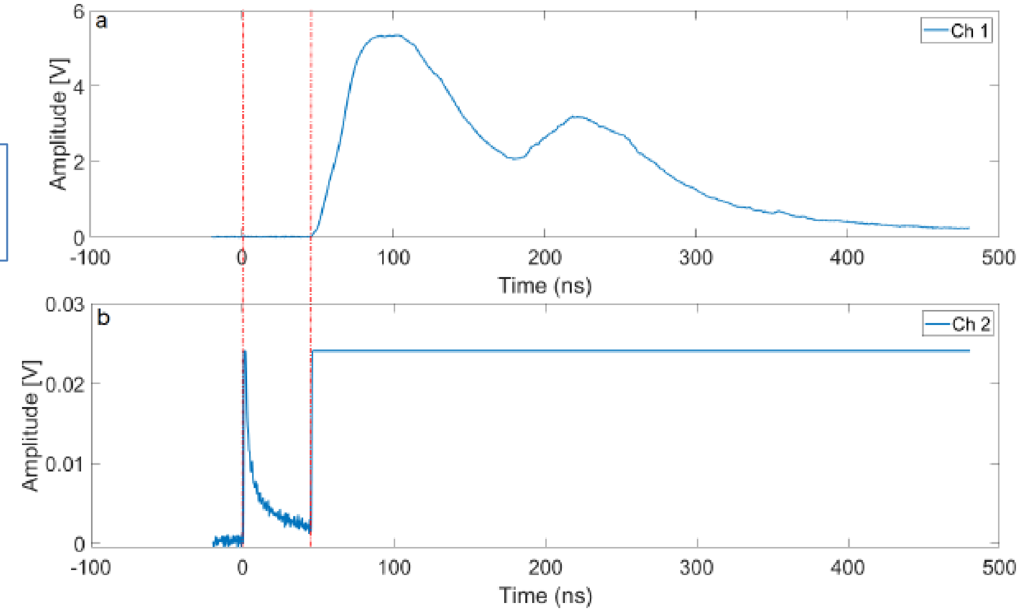

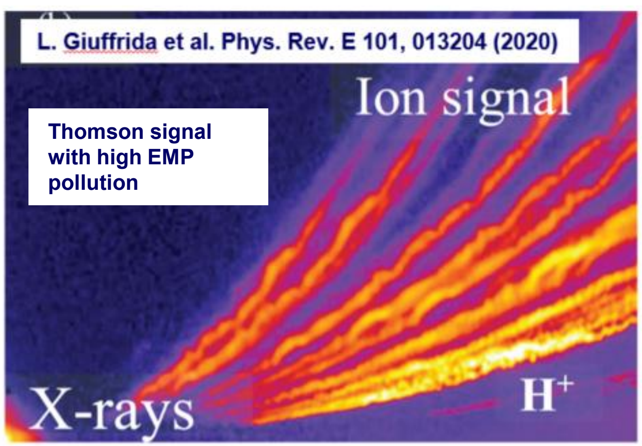

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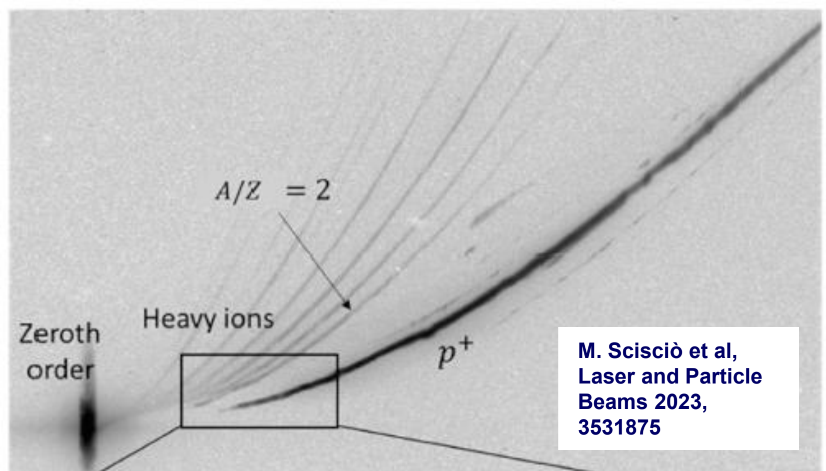
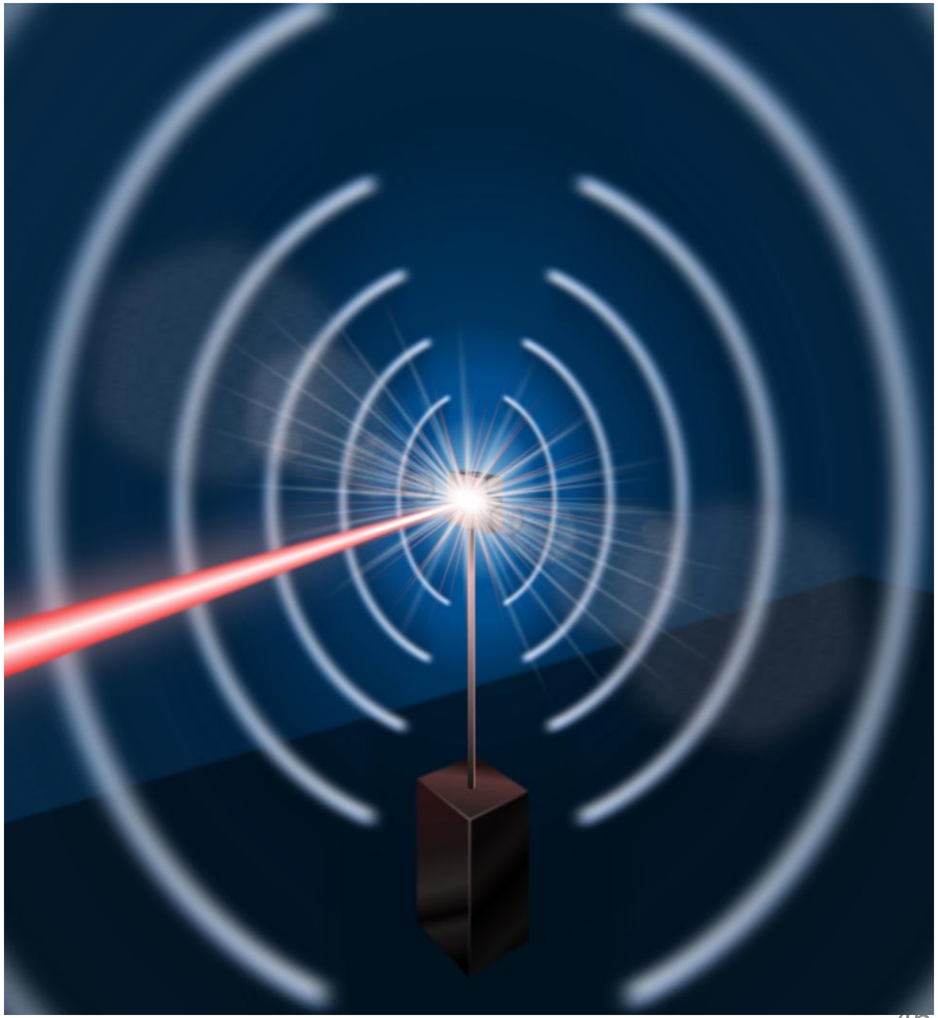


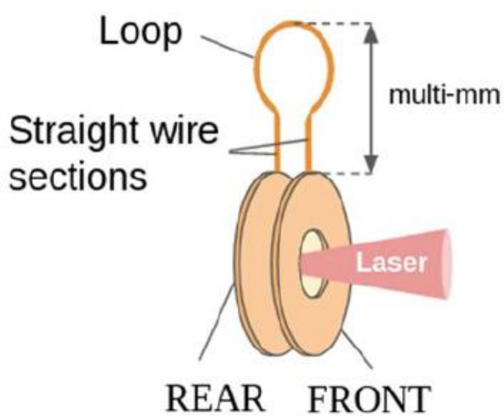
Outline

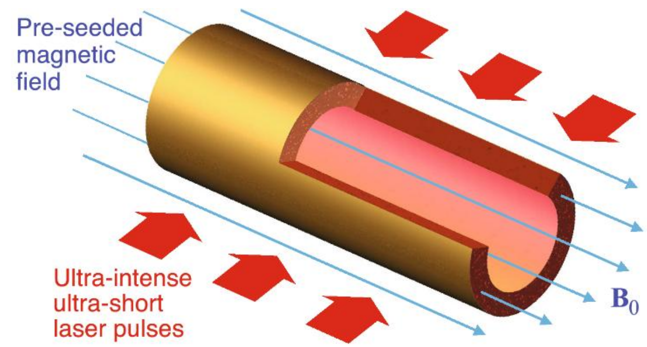
- Introduction to laser-generated electromagnetic pulses (EMPs)
- EMP generation
- Methods of EMP diagnostics
- Methods of EMP mitigation
- **EMP applications**

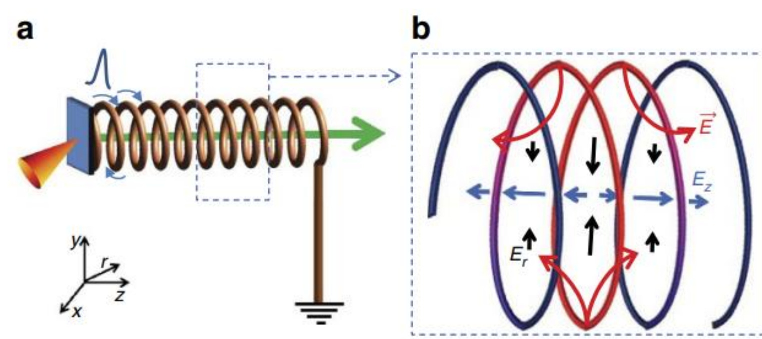


Laser-generated electromagnetic fields

- **Potential applications**
  - **Strong transient magnetic fields (kT order and beyond)**
  - **Proton acceleration by tailored traveling waves**
  - **Source of THz radiation of unmatched features and intensity**
  - **ENEA has proposed schemes for laser-generation of EM fields. ENEA Patent «A method of generating high-intensity electromagnetic fields» PCT/IB2020/057464, WO2021/024226**







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S. Fujioka et al. Sci. Rep. 3, 1170 (2013)
P Bradford et al PPCF 63 084008 (2021);
M. Murakami et al Sci Rep 10, 16653 (2020).
S. Kar et al. Nat. Commun. 7, 10792 (2016).

EMP Applications

- **Fields of application: material science, avionics, aerospace, electronics, medical and biological studies, electromagnetic compatibility (EMC), sensing.**

- **The technology can be also easily integrated in advanced schemes for particle acceleration, for particle-beam manipulation of unmatched quality, by laser and not.**

Conclusions

- Laser-matter interaction of high energy and intensity produce remarkable transient electromagnetic pulses, which presents a threat for electronics and personnel and have to be mitigated.

- Picosecond and fs laser pulses charge the targets to a few μC and excite strong broadband electromagnetic emissions with amplitude up to the MV/m order.

- Recognized major source of emission in the GHz domain is the neutralization current flowing through the target holder generating.

- Other sources of EMP are identified, but further investigation is needed.

- Minimization is possible, and it considers both source suppression and EMC optimized techniques.

- A large number of further 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.

EMP growing community

- **A growing international community has been set up on the topic of radiofrequency-microwave field generation**
- **Laserlab-Europe AISBL, an Interest/Expert group has been created on «Laser-generated electromagnetic pulses», coordinated by ENEA (F. Consoli), with more than 20 Institutions.**

F. Consoli et al, High Power Laser Science & Engin. 2020
F. Consoli et al, Phil. Trans. R. Soc. A 2020

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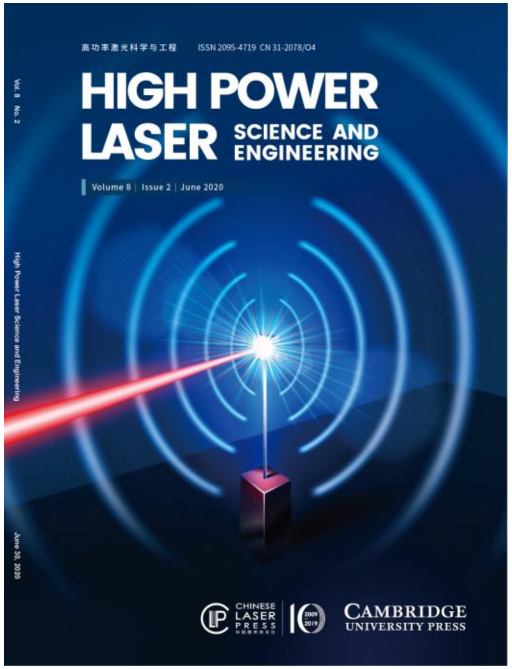
- **Review paper with contributions of the main laboratories on High Power Laser Science and Engineering, selected for the volume cover, got the Editor-in-Chief Choice Award 2020, and the Excellent Article for the 10th Anniversary of HPLSE Journal**



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

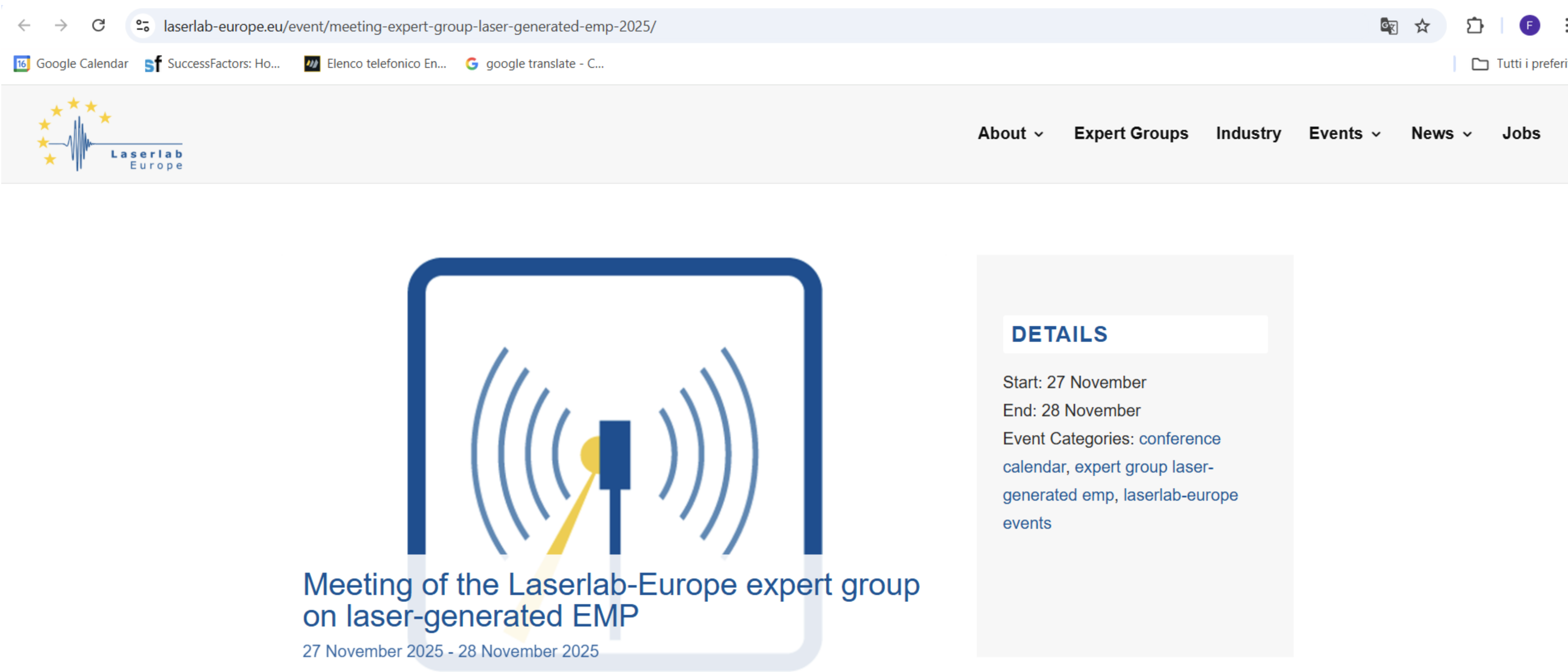
Laser produced electromagnetic pulses: generation, detection and mitigation

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]

F. Consoli et al, High Power Laser Science & Engin. 2020
F. Consoli et al, Phil. Trans. R. Soc. A 2020

EMP Expert group meeting

Meeting of the Laserlab-Europe expert group on laser-generated EMP
Central Laser Facility, Didcot
27-28 November 2025



Acknowledgments

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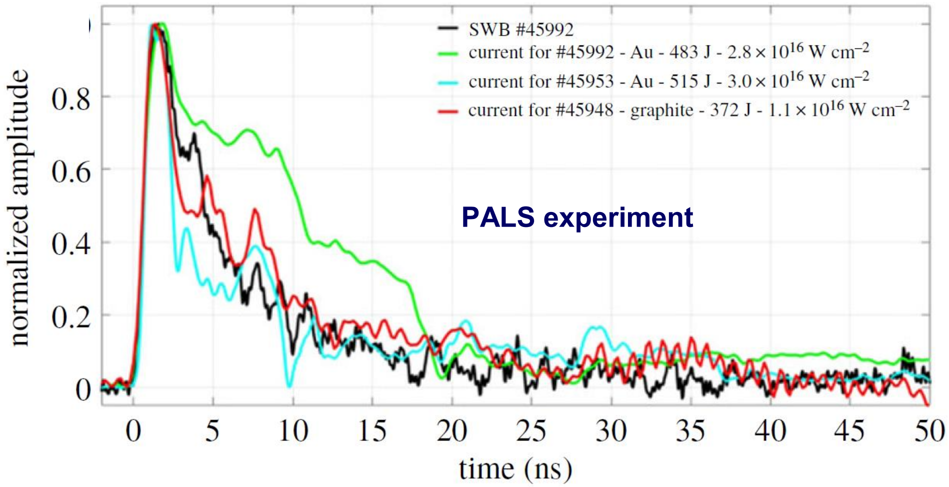
Gigahertz emission

- **Why the ps laser pulses are much stronger emitters in the GHz domain, compared to the ns pulses? → fs-ps pulses accumulate a big charge for a short period of time and discharge it in a short and intense current pulse**

- **ns pulses**
  - **potential is established by a balance between the rate of electron ejection and the amplitude of the return current through the stalk to the ground.**
  - **relatively weak continuous current induced → much weaker emission.**
  - **nevertheless, remarkable and very dangerous values of EMPs are observed for nanosecond high-energy and high intensity facilities.**



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

- **The EMP signal can be significantly enhanced if a long and a short laser pulses interact with the same target.**

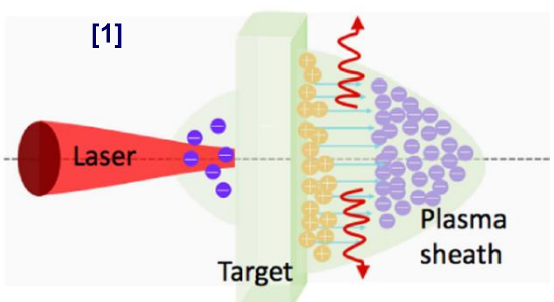
F. Consoli et al, High Power Laser Science and Engineering 8, e22 (2020)

Terahertz emission

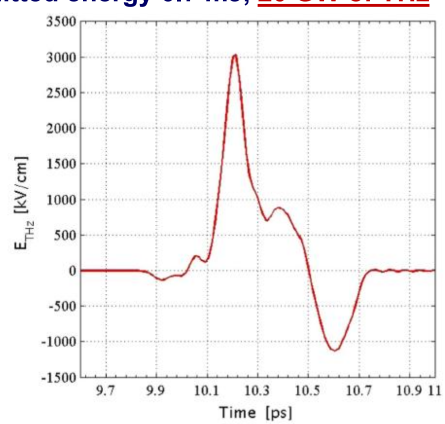
- ps or sub-ps laser pulses → the ejected electron bunch has millimetrical length
- THz in experiments observed with maximum in the plane perpendicular to the direction of electron emission → <u>sheath dipolar emission</u>
- Dipole emission produced during the electron ejection time, proportional to the second derivative of the dipolar moment *D*, significative only during the electron ejection time

Larmor Formula $$P_E = \frac{\mu_0}{6\pi c}|\ddot{D}|^2 \qquad \mathcal{E}_{\mathrm{THz}} \simeq \frac{Z_0}{6\pi t_{\mathrm{ej}}} Q_e^2$$

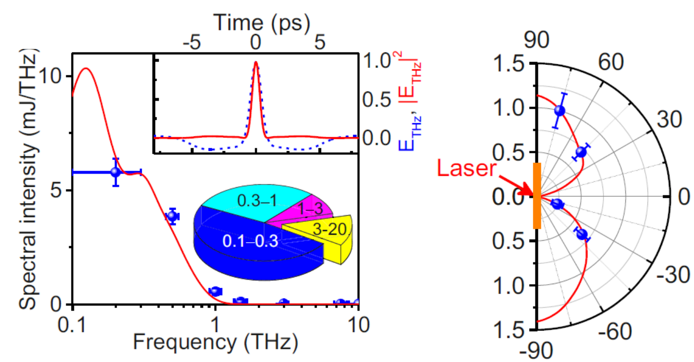
- Coherent process: total energy proportional to the square of electron charge, inversely proportional to the electron ejection time. Most important for the sub-ps lasers.
- <u>Not of primary concern for electronic damage</u>. Many possible applications.



[1] JETI: 30 fs/1 J, intensity 5×10^{19} W/cm^2
emitted energy 0.7 mJ, <u>20 GW of THz</u>



[3] Vulcan: 1.5 ps/60 J, intensity 5×10^{19} W/cm^2
emitted energy 10 mJ, <u>7 GW of THz</u>



[1] S. Herzer et al. NJP 2018; [2] A. Poyé et al. Phys. Rev. E 2018; [3] G. Liao et al. PNAS 2019; [4] J. Déchard et al Phys Plasmas 2020
[5] V.T. Tikhonchuk et al, Electromagnetic pulse generation in experiments on high power laser facilities, IVth UltraFastLight, Moscow, September 28 - October 2, 2020