ELI: EXTREME LIGHT INFRASTRUCTURE

New frontiers of particle acceleration, radiation sources and applications

Luigi Palumbo

University of Rome "La Sapienza" and INFN, Italy

Channeling, Capri 6 October, 2014

ESFRI, the European Strategy Forum on Research Infrastructures,
is a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach.

The **mission of ESFRI is to support a coherent and strategy-led approach to policy-making on research infrastructures in Europe**, and to facilitate multilateral initiatives leading to the better use and development of research infrastructures, at EU and international level.

ESFRI covers:
Social sciences and humanities,
Materials and physical sciences **(ESS, XFEL, FAIR, ELI, ….. € 7.5 billion)**
Energy and engineering
Environmental, Earth
Life sciences.

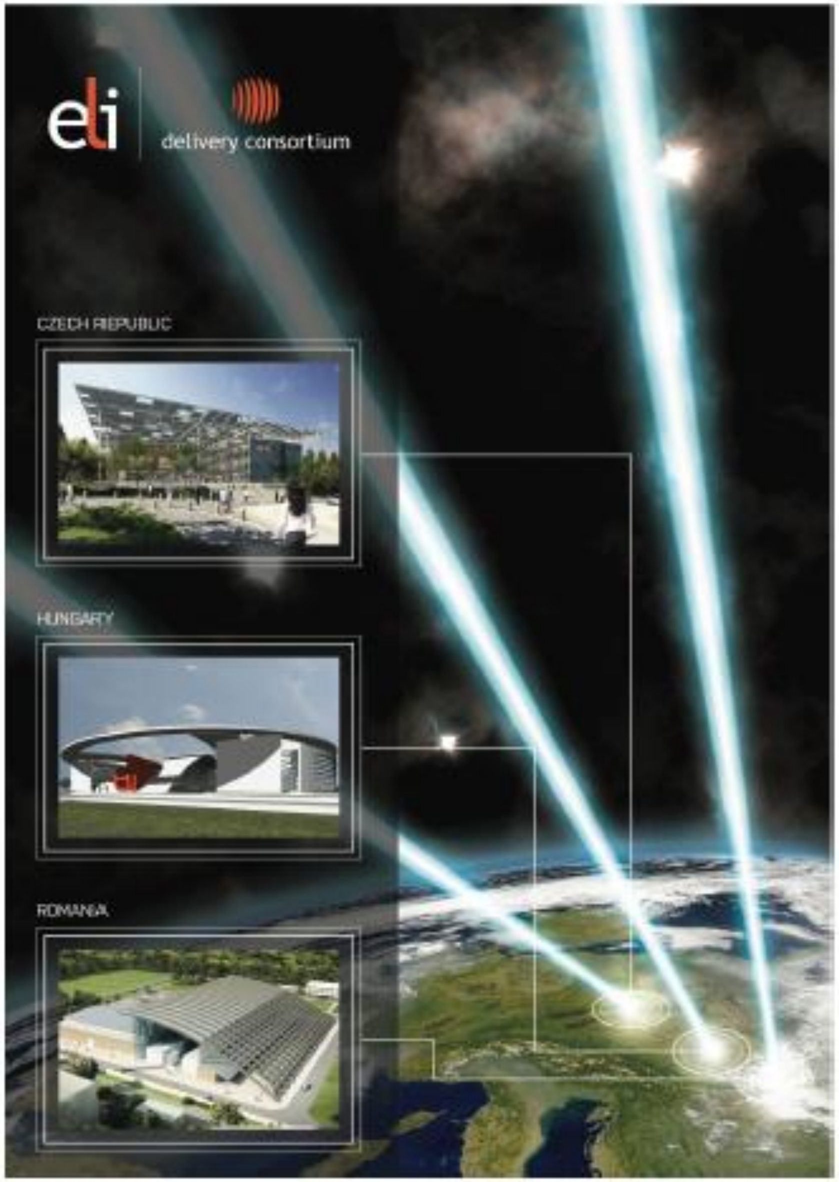
ELI: Implementation Phase

Three Pillars

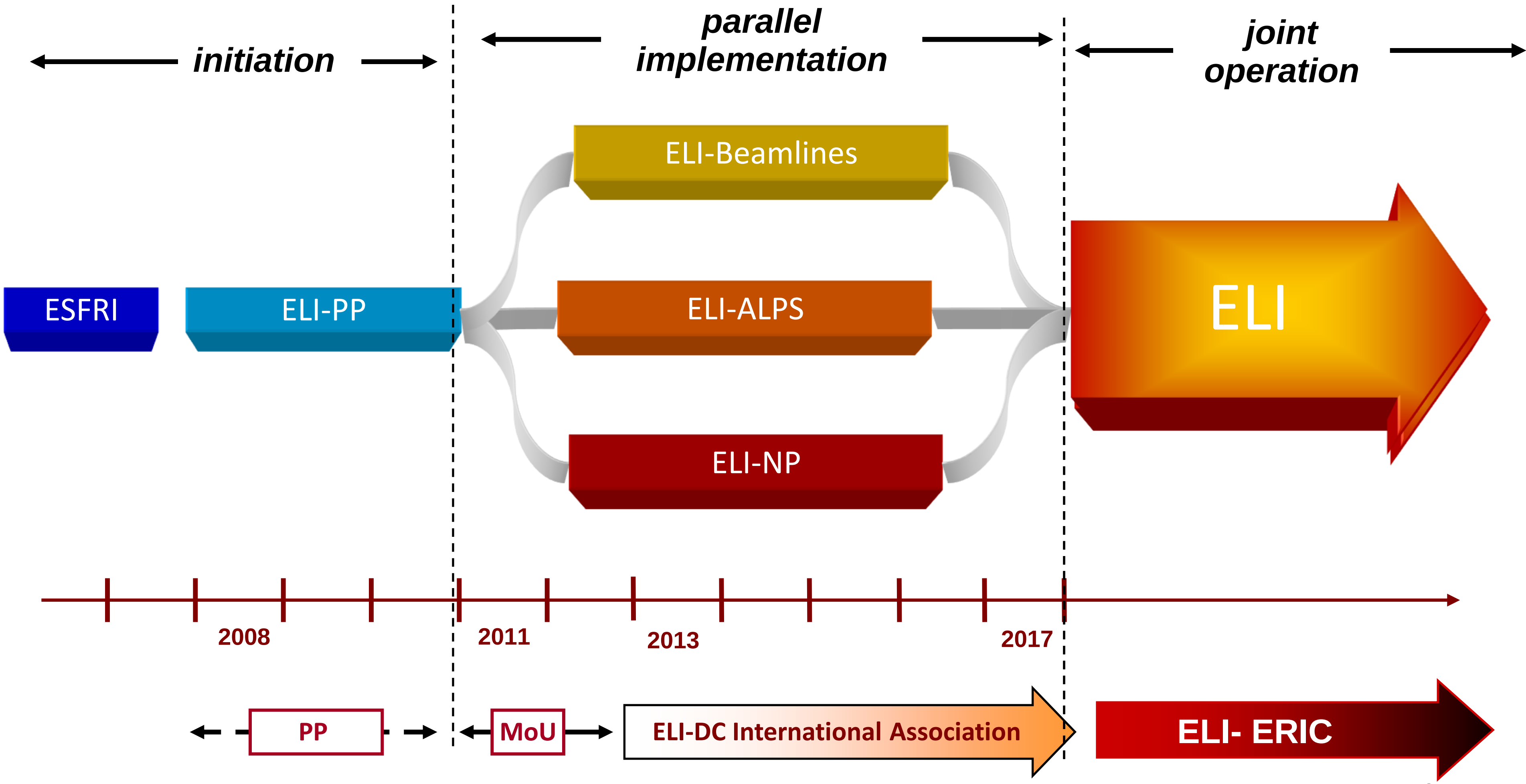
- **ELI High Energy Beam-Line Facility (ELI-Beamlines) (Czech Republic):** highly competitive source of extremely short pulse X-rays, accelerated electrons, or protons for applications (also biomedical).

- **ELI Attosecond Light Pulse Source (ELI-ALPS) (Szeged, Hungary):** ultrafast light sources (coherent XUV and X-ray radiation) including single attosecond pulses, to investigate electron dynamics in atoms, molecules, plasmas and solids.

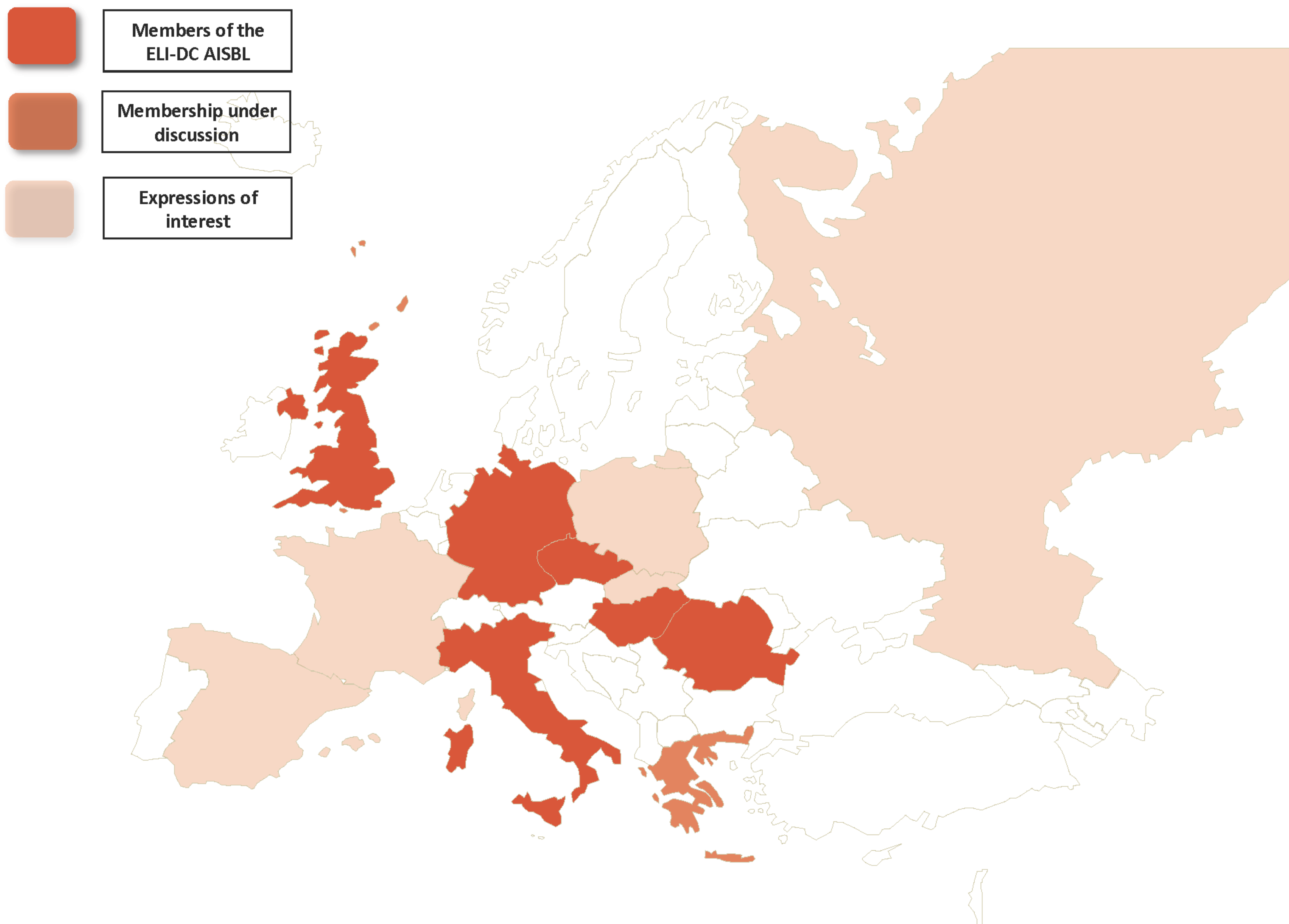
- **ELI Nuclear Physics Facility (ELI-NP) (Magurele, Romania):** laser and gamma beams (low bandwidth, energies in the 20 MeV range) with unique characteristics perform frontier laser, nuclear and fundamental research.



Timeline and milestones



ELI Consortium members and expression of interest



ELI Beamlines (Czech Republic)

High Energy Beam Science

development and usage of dedicated **laser-driven beam lines** with ultra short pulses of high energy radiation and particle acceleration

- The laser systems in the Czech Republic will consist of high repetition and high-intensity lasers **(nominally 10-PW**)

- The laser front end will deliver **5-fs pulses** with high contrast, at **a repetition rate 1 kHz**, and will feed pulses into amplifiers and Beamlines of the laser chain.

- The designed ELI facility will involve two blocks providing the peak power of 10-PW. These blocks will provide energy of 200-300 J in 20-30 fs pulses at the repetition rate of up **to 0.1 Hz**. These blocks will serve to test and prototype technologies for the ELI high-intensity facility that is intended to deliver **200 PW** peak power.

- The pulse length at the output of these systems will be adjustable for the needs of research of the **electron and proton acceleration.**

ELI-Attosecond -
particle acceleration program

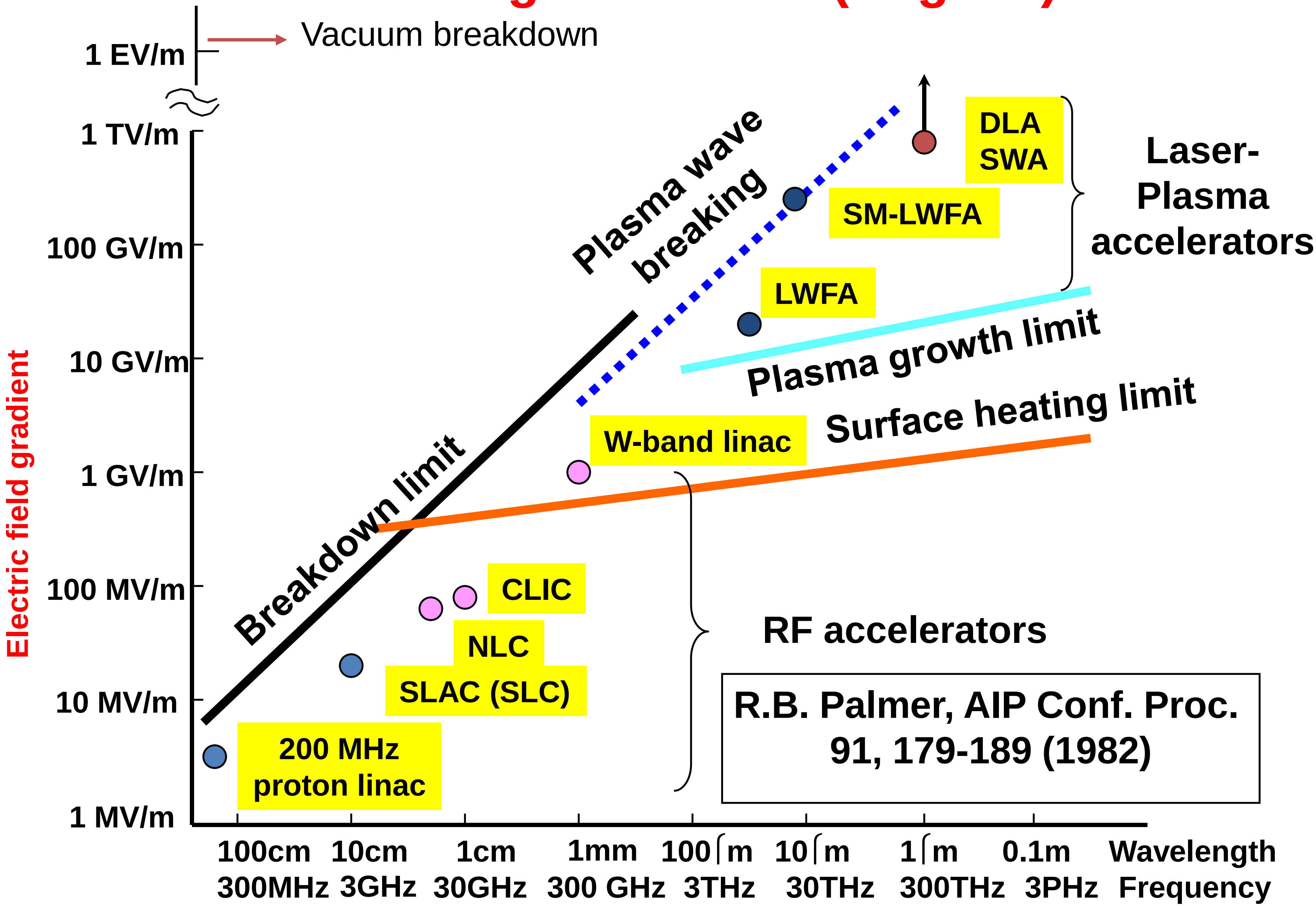
attosecond

What can be innovative applications for ELI-ALPS

We can profit of some unique parameters

1. Short bunch time (5-20fs laser)
2. Versatile source
3. High proton flux (10^{11} protons/shot - 5 Hz)
4. High energy (e.g. protons 10-100 MeV)

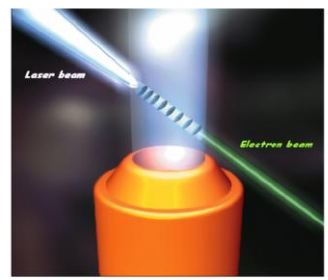
Accelerating field limits (original)



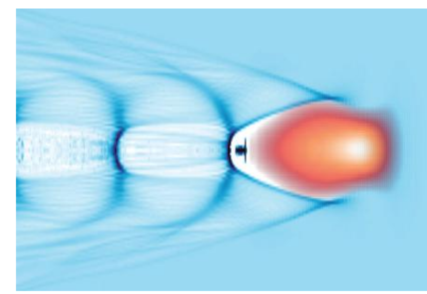
Laser-driven electron acceleration

- Laser-driven electron acceleration has made its breakthrough on tens of TW laser systems in 2004 and reaching 1 GeV in 2006

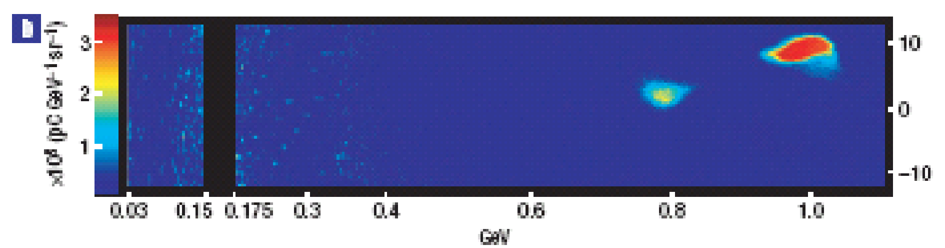
2004



V. Malka, LOA

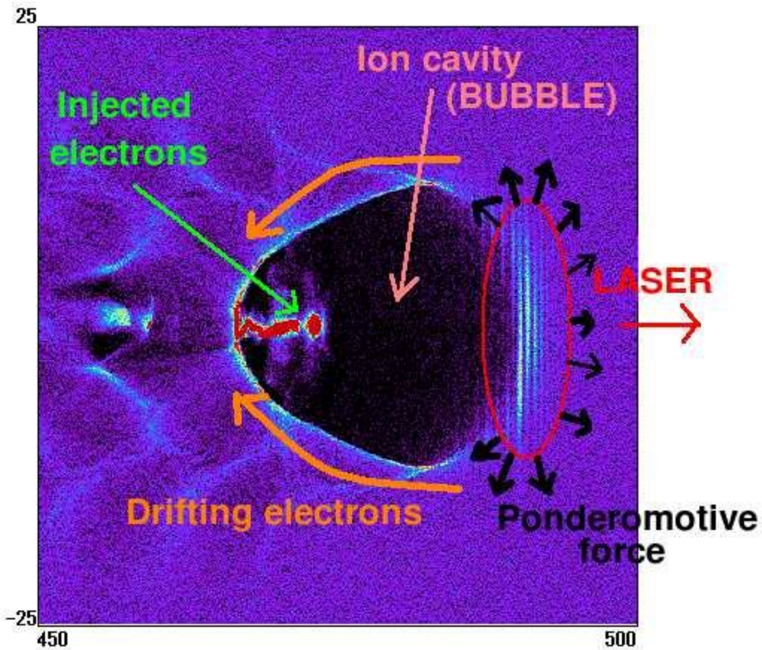


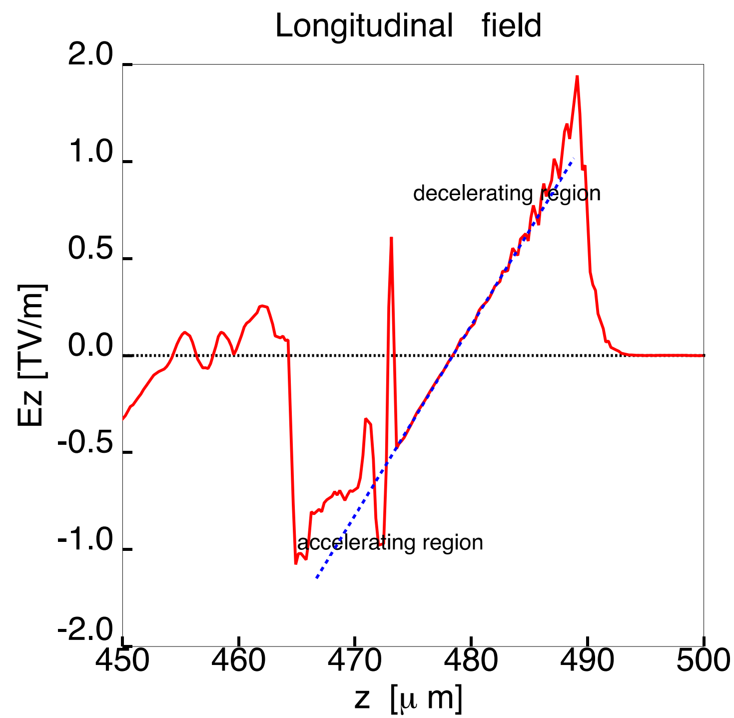
L. Silva, IST



Leemans et al., Nature Physics 2006

- **Nonlinear 3D regime (bubble)** [a]





- $R_{bub} \simeq O(\lambda_p)$ $\qquad E_z^{(max)} \simeq 100\sqrt{n_0[\text{cm}^{-3}] \times a_0}$ [V/m]
- $\begin{cases} v_{elect} \simeq c \\ v_{bub} \simeq c(1 - 3\omega_p^2/(2\omega_0^2)) < v_{elect} \end{cases}$ $\Rightarrow$ acc. length is finite + monochromatici

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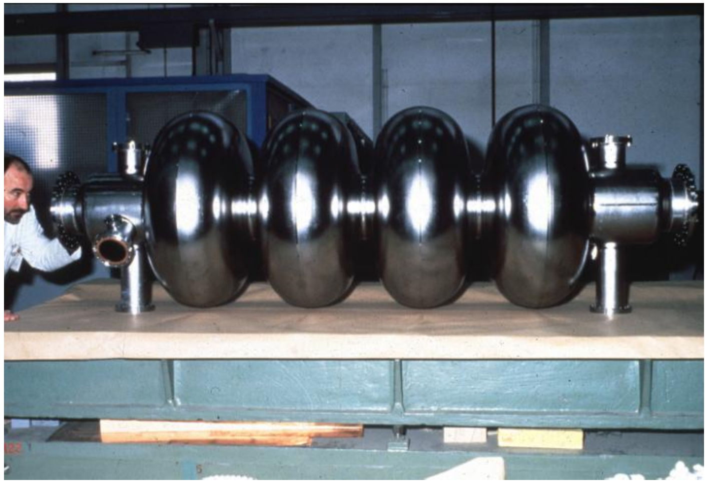
[a] S. Gordienko and A. Pukhov, Phys. Plas. 12 (2005) / W. Lu *et al.* PRSTAB 10 (20

S.P.D. Mangles et al., Nature, 431, 535 (2004); C.G.R. Geddes et al., Nature, 431, 538 (2004);
J. Faure et al., Nature, 431, 541 (2004);

GeV scale acceleration

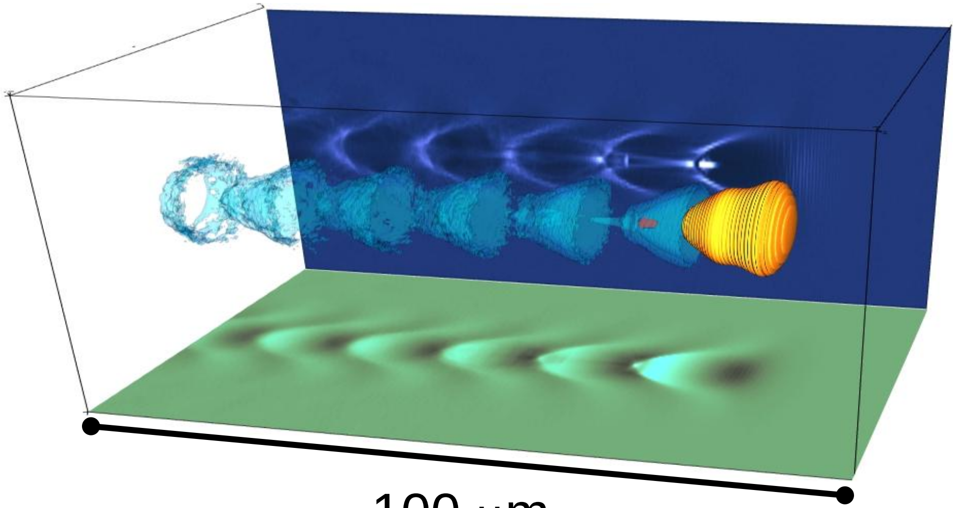
Laser-plasma acceleration

A plasma allows generating Electric fields much higher than conventional accelerator cavities



1 meter long RF cavity
Gain = 50 MeV

E. Lefebvre, CEA/DAM



100 microns Plasma cavity
Gain = 30 MeV

Tajima and Dawson, PRL (1979)

Laser-driven proton sources

- Ultra-intense short pulse laser proton beams are generated on hundreds of TW systems and make their breakthrough in 2000 achieving up to 60 MeV from μm targets

Year 2000

VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids

R. A. Snavely,[1,2] M. H. Key,[1] S. P. Hatchett,[1] T. E. Cowan,[1] M. Roth,[3,*] T. W. Phillips,[1] M. A. Stoyer,[1] E. A. Henry,[1] T. C. Sangster,[1] M. S. Singh,[1] S. C. Wilks,[1] A. MacKinnon,[1] A. Offenberger,[4,*] D. M. Pennington,[1] K. Yasuike,[5,*] A. B. Langdon,[1] B. F. Lasinski,[1] J. Johnson,[6] M. D. Perry,[1] and E. M. Campbell[1]

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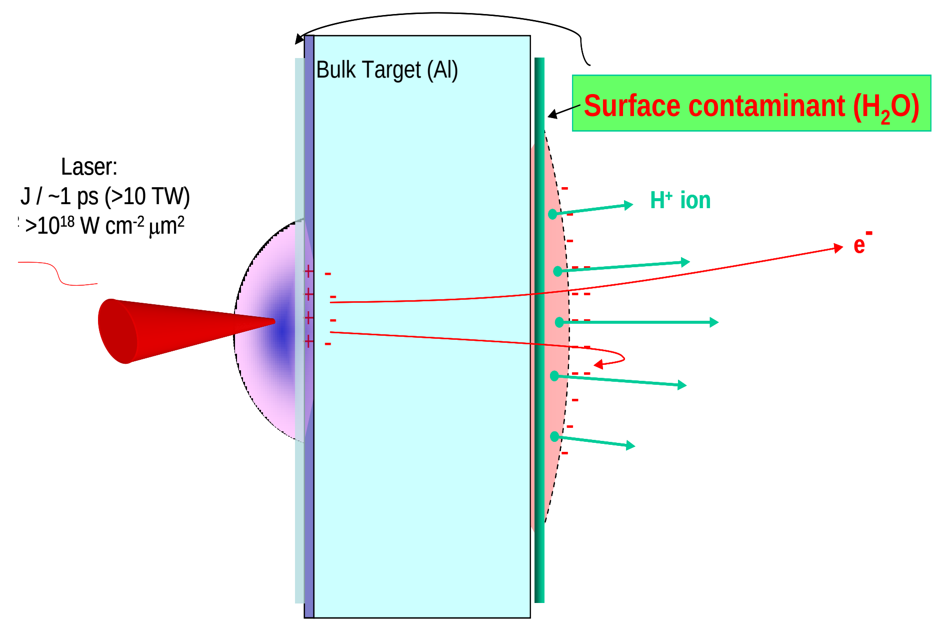
[5]*ILE, Osaka University, Suita, Osaka 565, Japan*
[6]*George C. Marshall Space Flight Center, Huntsville, Alabama 35812*



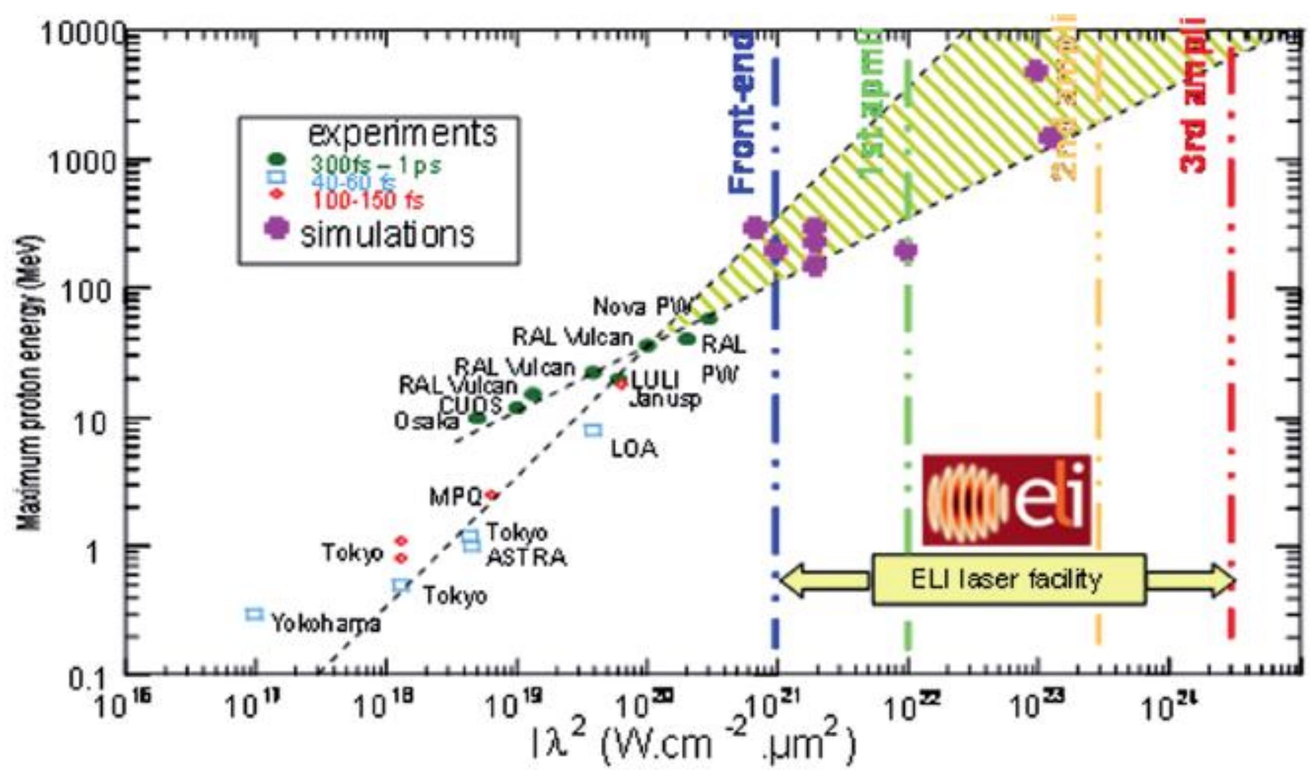
Target Normal Sheath Acceleration

Properties:

- **High number (~10^{13})**
- **High energy (~60 MeV)**
- **Produced in short time (~ ps)**
- **Laminar (100 times better than conventional accelerator)**

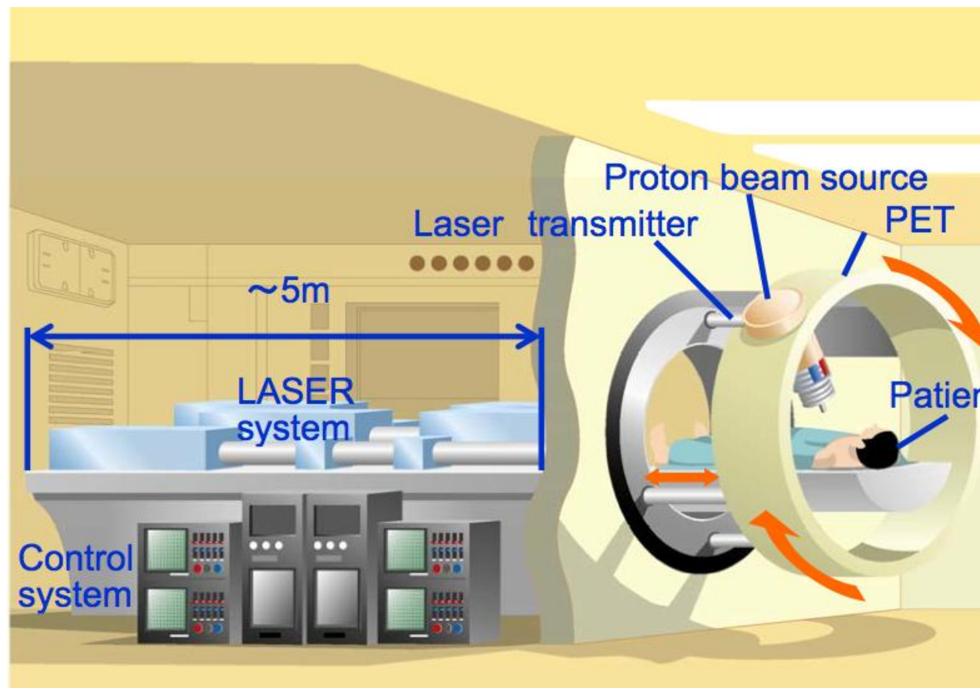
Laser-driven proton acceleration

- Scaling laws indicate that higher-power systems should generate ions suitable for many applications



ELI Whitebook

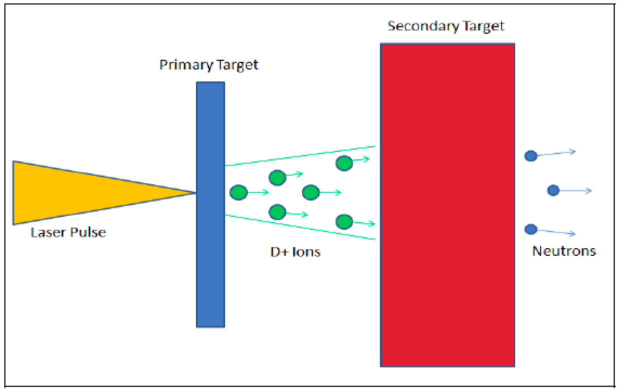
Today



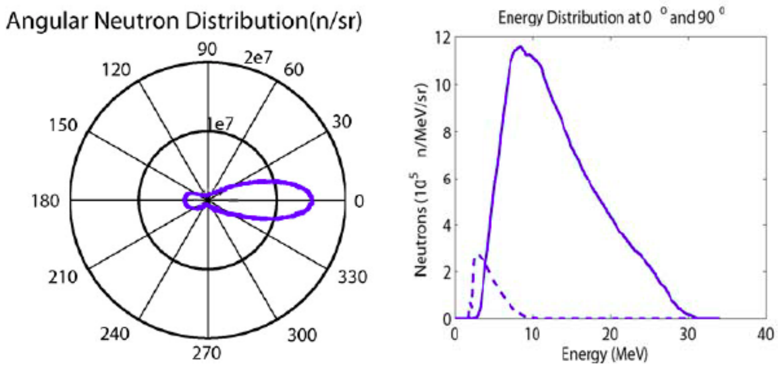
Tomorrow ?

Laser-driven neutron sources

Laser driven neutrons can be generated over a secondary reaction of laser-generated protons interacting with a « catcher » element such as LiF (Lithium Fluoride).



Laser-generated neutrons have innovative properties (short (ps) bunch, high intensity) and can be used for pump-probe experiments or homeland security

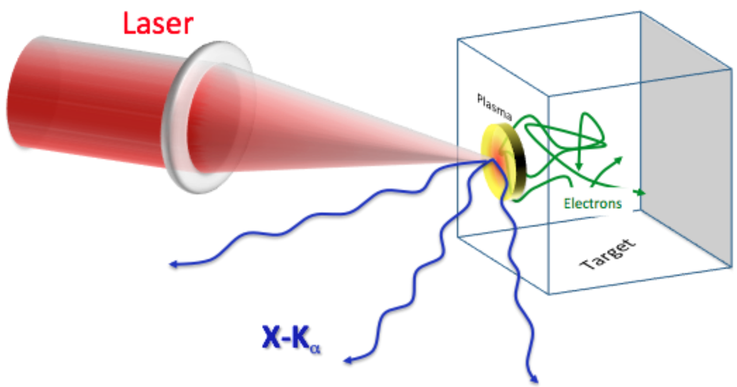


M. Roth et al., Bright Laser-Driven Neutron Source Based on the Relativistic Transparency of Solids, Phys. Rev. Lett. 110, 044802 (2013)

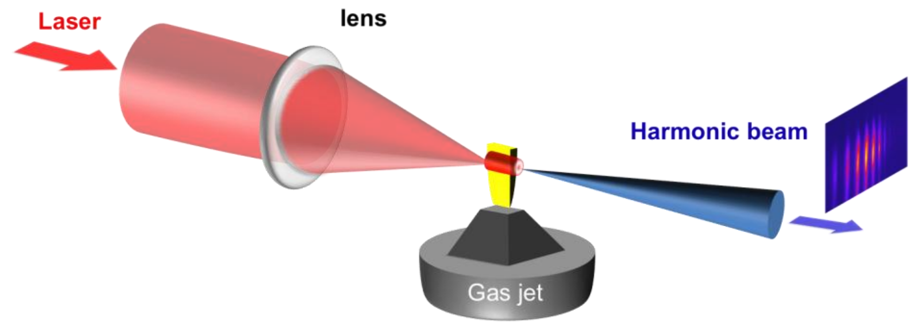
http://www.lanl.gov/newsroom/news-releases/2013/June/06.04-laser-driven-neutrons.php

Laser-driven X-ray sources @ ELI Beamlines

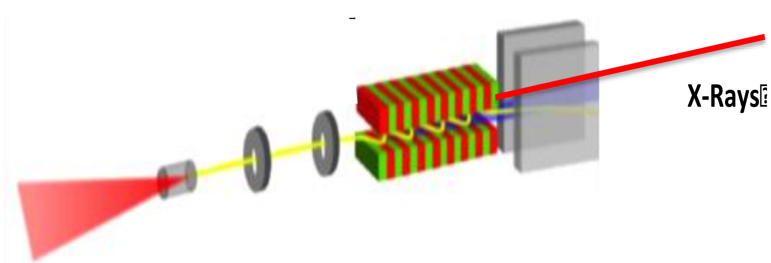
Plasma sources



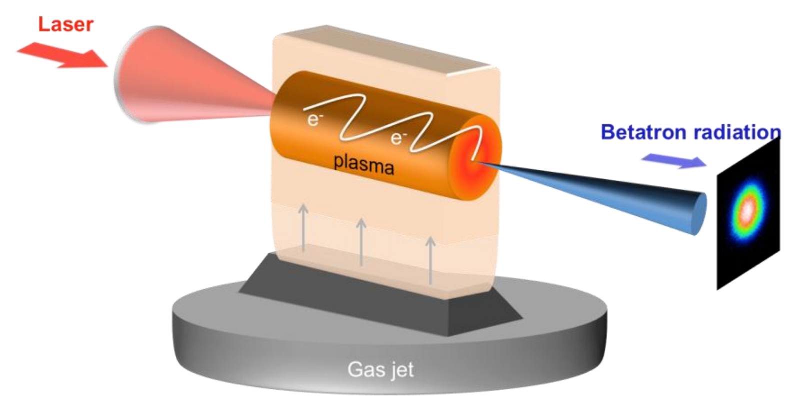
Harmonics (gas)



LUX/XFEL



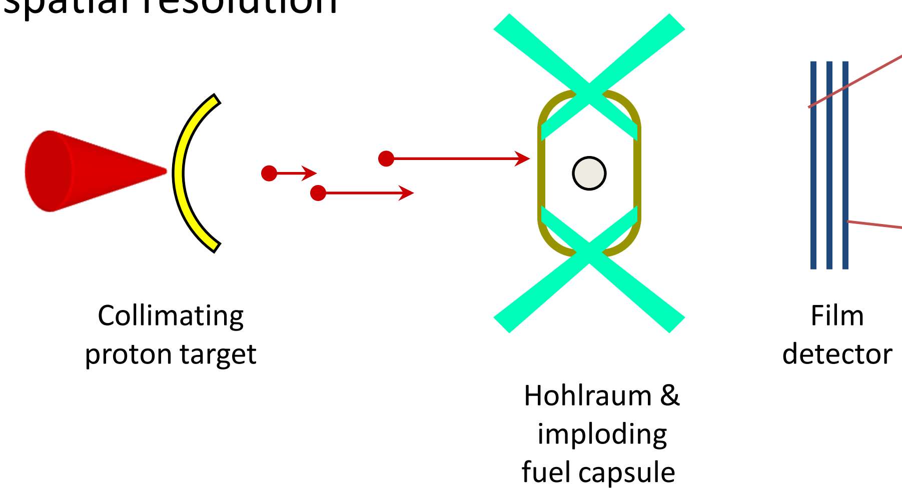
X-rays from relativistic e-beams

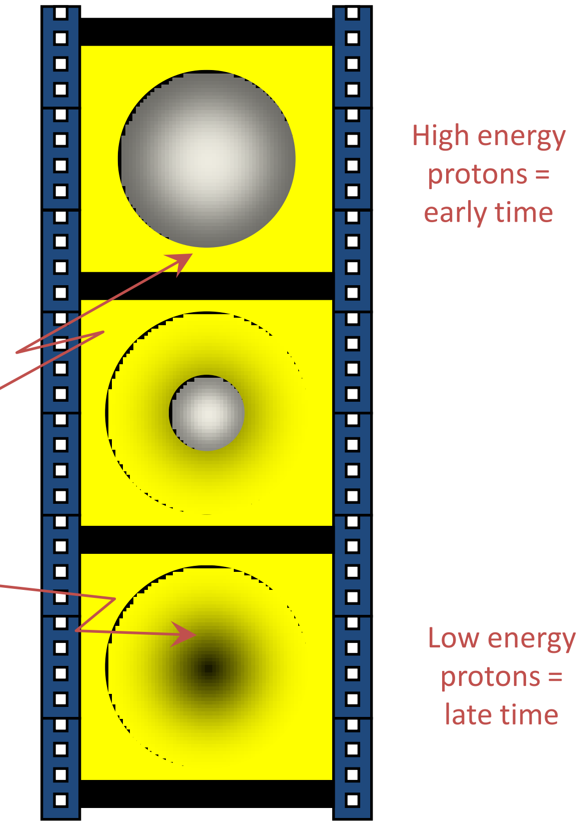


APPLICATIONS

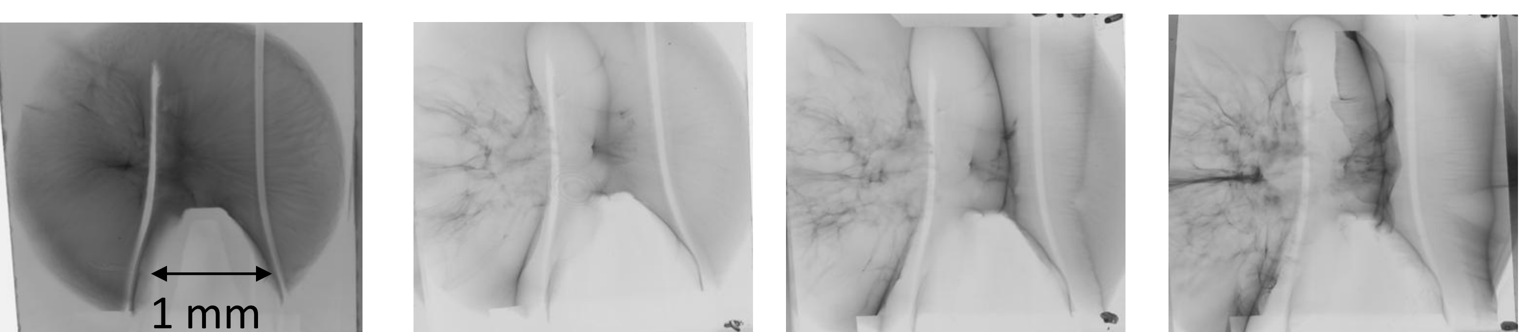
Radiography of dense material

Temporal evolution of phenomena on a single-shot (TOF) can be obtained by energy dependent time-of-flight
with
- ps temporal resolution
- µm spatial resolution





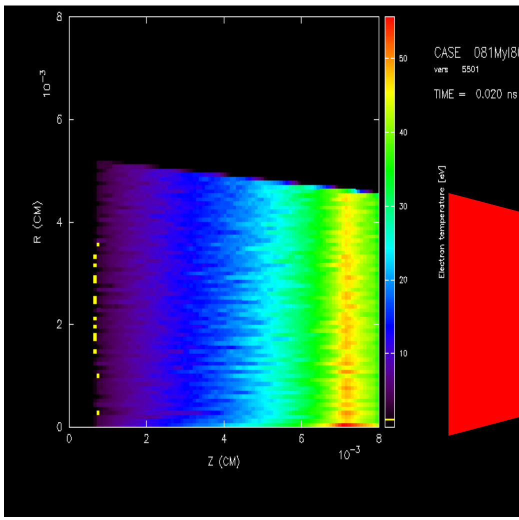
t=0 +1 ps +3 ps + 6 ps

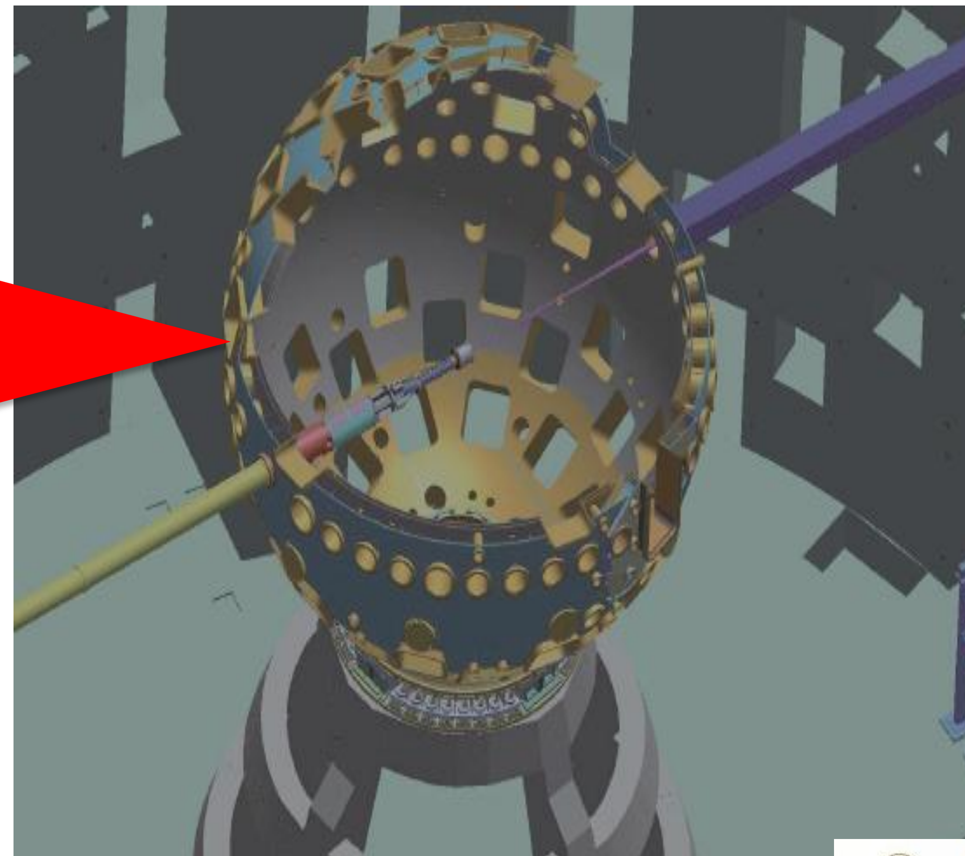


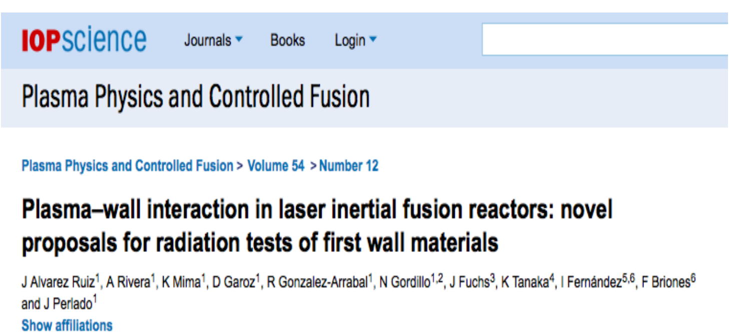
M. Borghesi

Material Science – stress test

Use laser-generated protons as source of high-energy flux in a short time, reproducing extreme conditions as found in nuclear reactors



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Plasma Physics and Controlled Fusion

Plasma Physics and Controlled Fusion > Volume 54 > Number 12

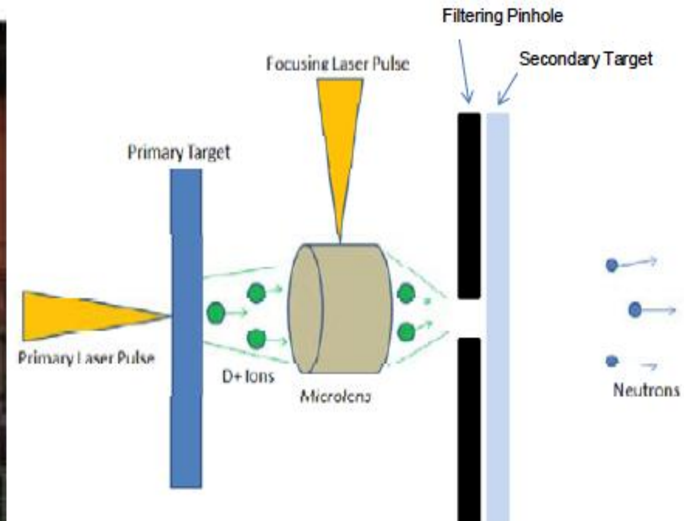
Plasma–wall interaction in laser inertial fusion reactors: novel proposals for radiation tests of first wall materials

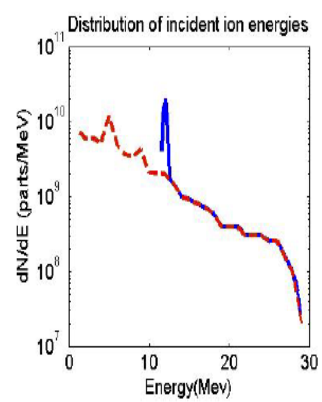
J Alvarez Ruiz[1], A Rivera[1], K Mima[1], D Garoz[1], R Gonzalez-Arrabal[1], N Gordillo[1,2], J Fuchs[3], K Tanaka[4], I Fernández[5,6], F Briones[6] and J Perlado[1]

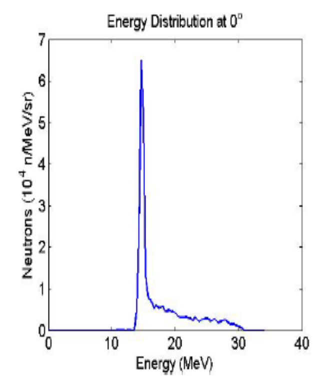
Show affiliations

Neutron spectroscopy of biological molecules

Secondary reaction of protons generate very high-neutron fluxes with very short duration which enhances the temporal resolution of neutron spectroscopy by many orders of magnitude





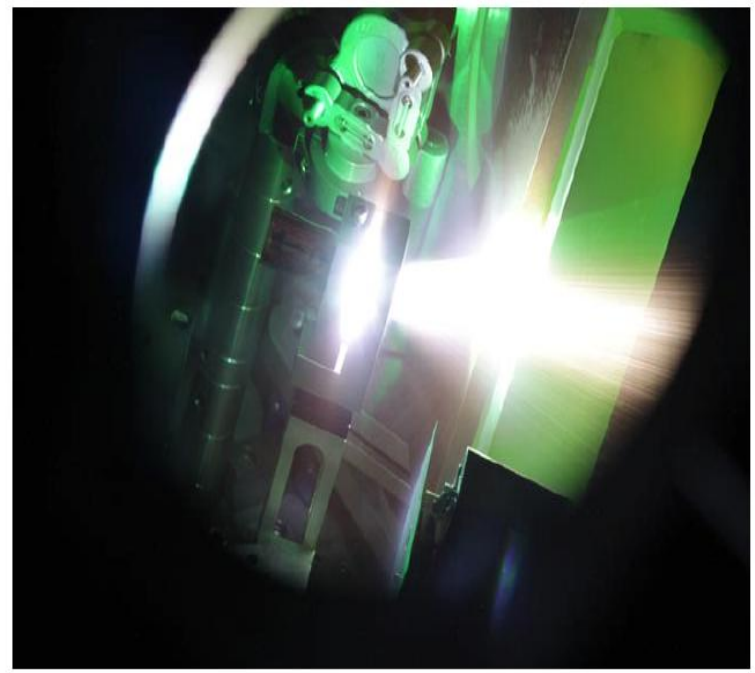


Homeland security

Short neutron bunches can be used to probe nuclear elements, since they will generate fission. The nuetrons generated in this process can be distinguished from the neutrons revealing nuclear material

Using laser-driven neutrons to stop nuclear smugglers

June 4, 2013

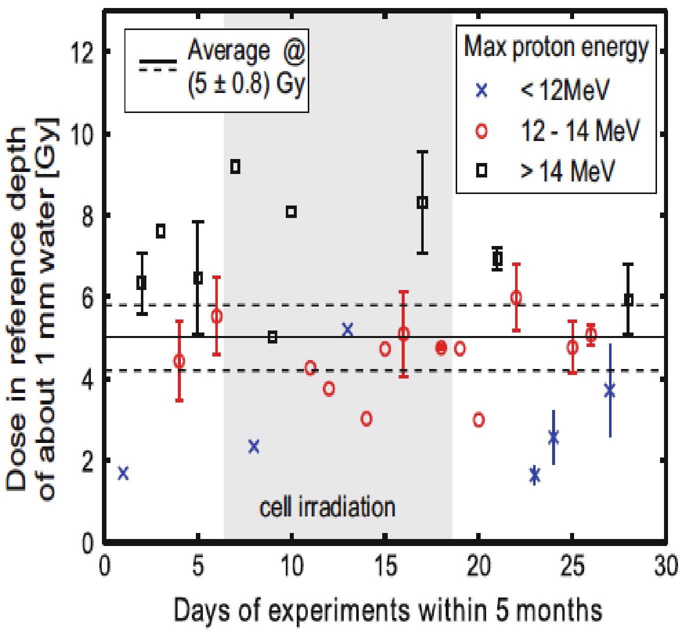


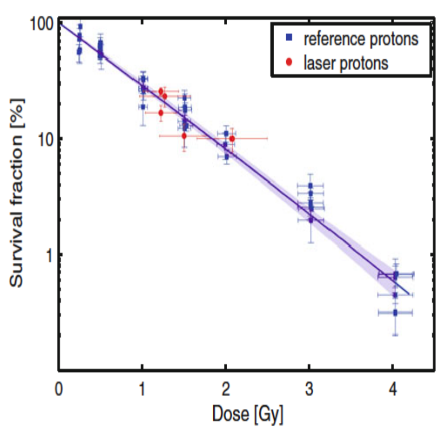
Los Alamos shows first nuclear material detection by single short-pulse-laser-driven neutron source

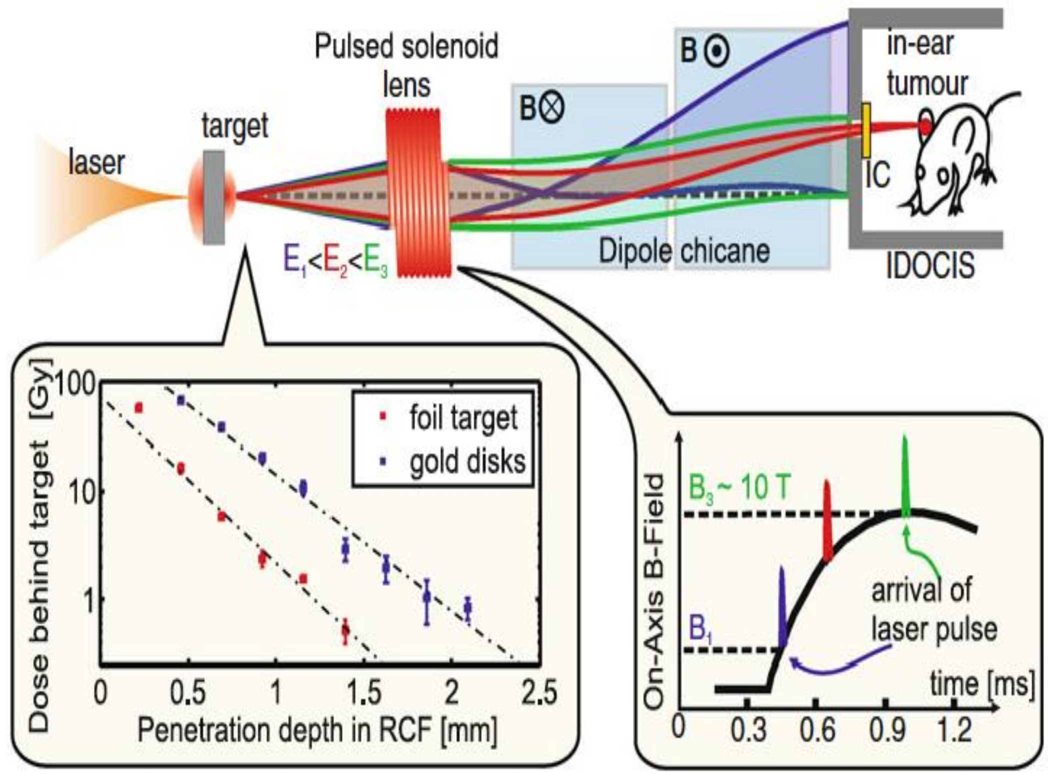
LOS ALAMOS, N.M., June 4, 2013—Los Alamos National Laboratory researchers have successfully demonstrated for the first time that laser-generated neutrons can be

Radiobiological

Laser-generated protons can be used for Radiobiological studies, testing the option of using laser-generated protons for medical purposes

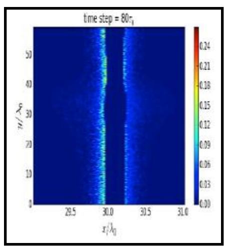


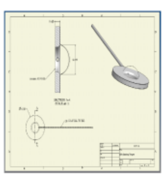


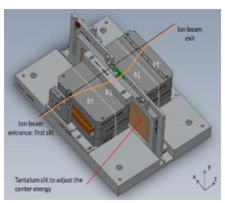


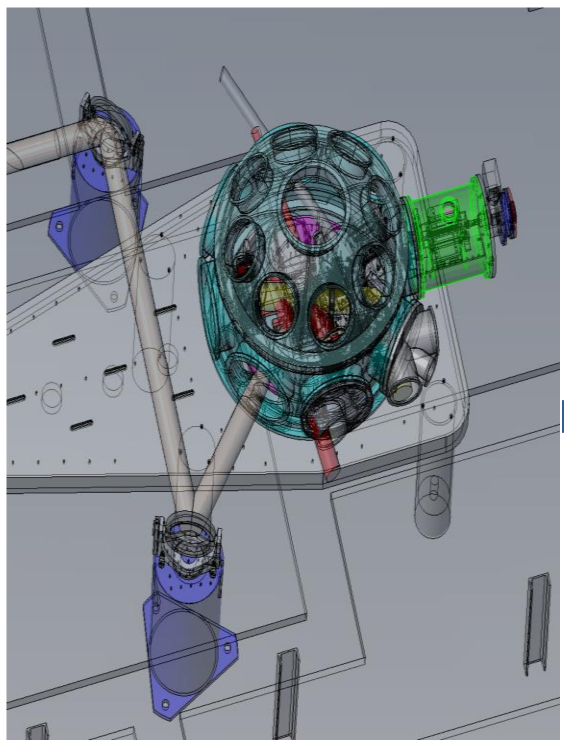
Laser-generated protons for cultural heritage

Laser-generated protons can be used for an improved non-destructive analysis of archeological artifacts using PIXE (Particle Induced X-ray Emission) and PIGE (Particle Induced Gamma-ray Emission). Their tunability allows probing ranges of micrometer up to several tens of µm with high resolution.









Ultra-controlled growth of nanocrystals

Nanocrystals can be grown using proton irradiation. The short proton bunch duration of laser-generated protons allows a much more precise growth of nanomaterials than currently available.

Available online at www.sciencedirect.com
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Nuclear Instruments and Methods in Physics Research B 246 (2006) 351–354
NIM B
Beam Interactions with Materials & Atoms
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Synthesis of size and shape-selective Au nanocrystals via proton beam irradiation

Yeong-Joon Kim [a], Gyoujin Cho [b], Jae Hee Song [c,*]

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[b] Department of Chemical Engineering, Sunchon National University, Suncheon 540-742, Republic of Korea
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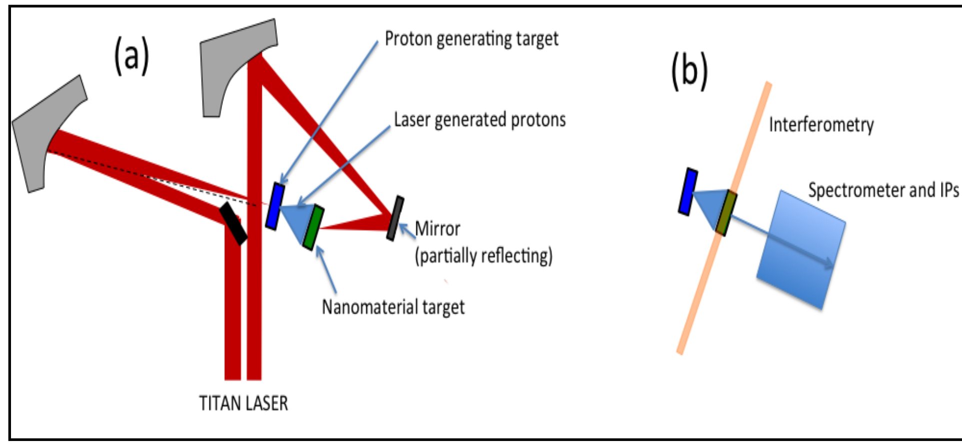
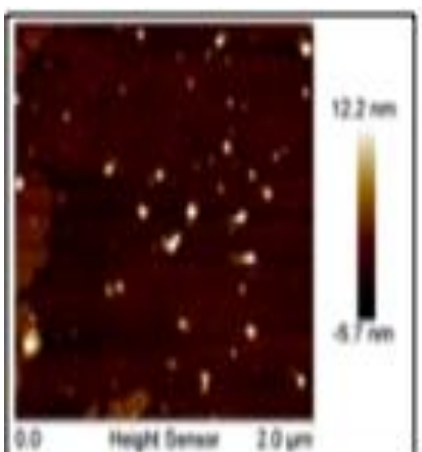
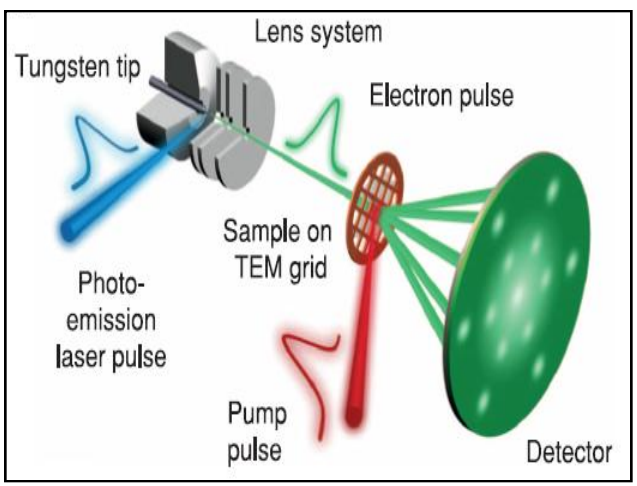
Received 5 December 2005; received in revised form 23 December 2005
Available online 14 February 2006

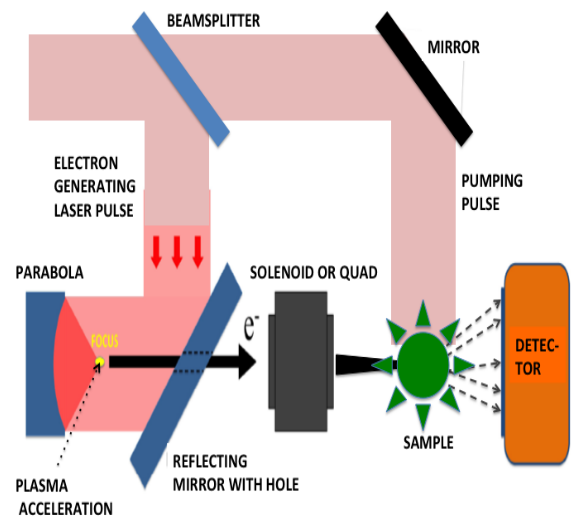




Laser driven Ultra-short Electron diffraction

Ultra Fast laser-driven Electron Diffraction has a great potential for studying 4D structural dynamics, the combination of high spatial resolution (on a sub-atomic scale, i.e. 8-10 pm) and high temporal resolution (scale of chemical reactions i.e. sub 50 fs) makes it possible to perform online analysis of structural changes and energy redistribution in many chemical and biological systems.



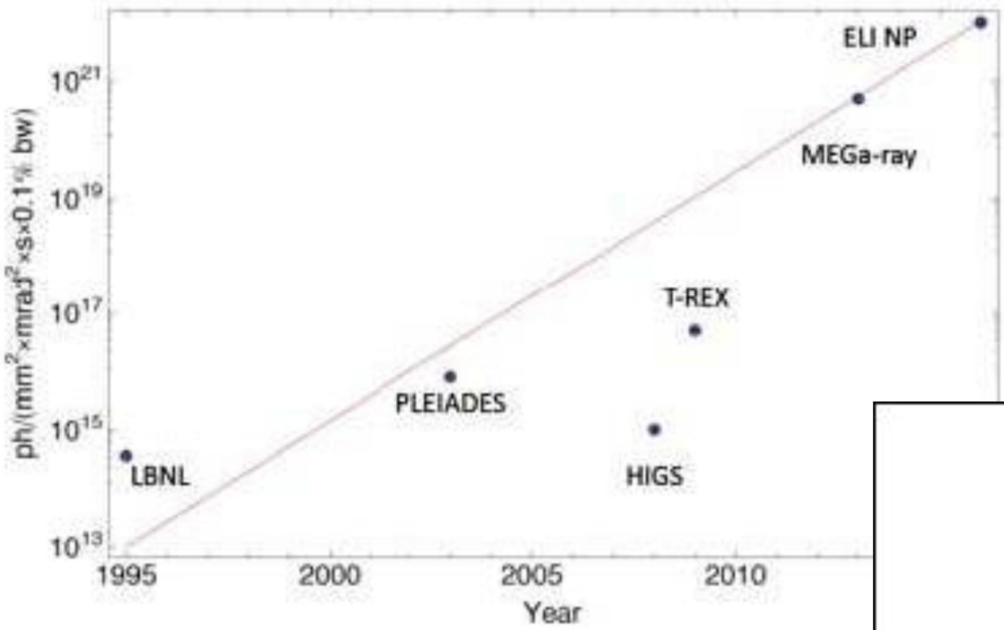


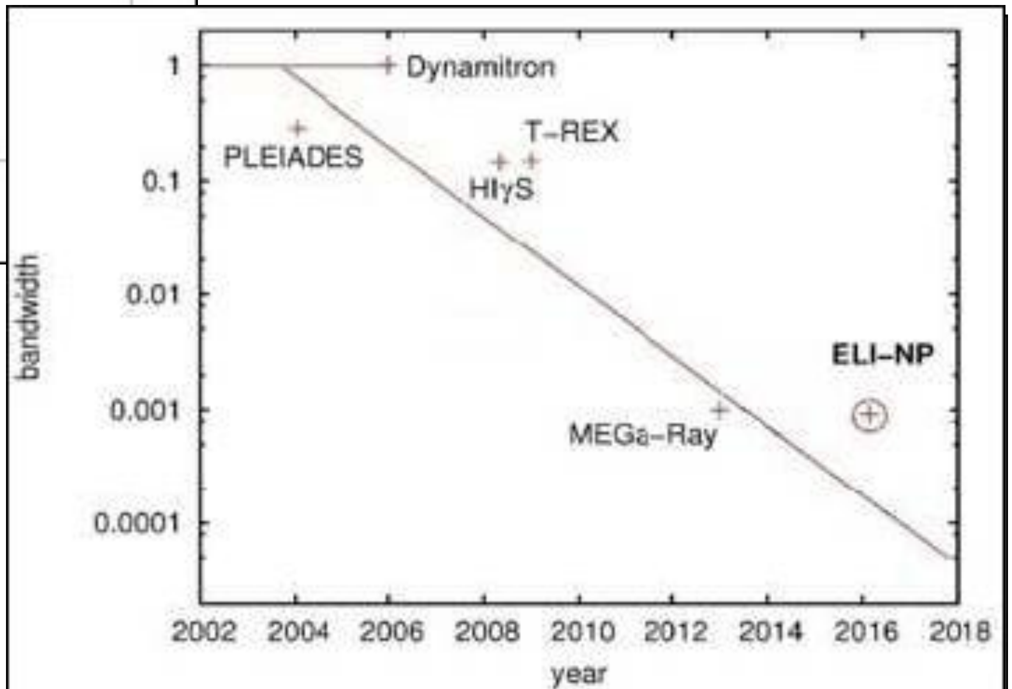
ELI Nuclear Physics (Romania)

Laser-Induced Photonuclear Physics

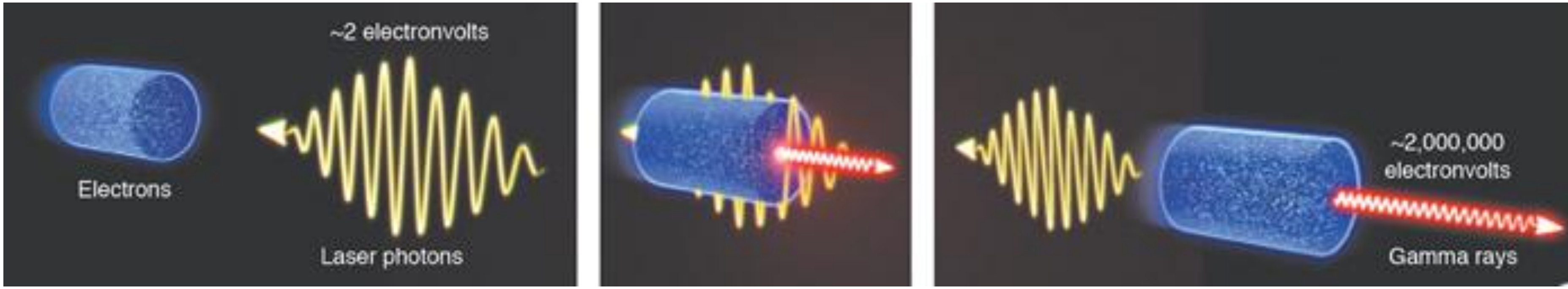
nuclear physics methods to study laser-target interactions, new nuclear spectroscopy, new photonuclear physics

ELI-NP γ beam: the quest for higher flux and narrow bandwidths





Courtesy V. Zamfir – ELI-NP



$\textit{Gamma-ray Energy}: 1\text{-}20\ MeV$

$\textit{rms Bandwidth}: \ 0.3\%$

$\textit{Spectral Density}: \ 10^4 \ \ photons/s\times eV$

Outstanding electron beam @ 720 MeV with high phase space density (all values are projected, not slice!)

$$Q = 250\,pC \ ; \ \varepsilon_n = 0.4 \ \ mm\cdot mrad \ ; \ \frac{\Delta\gamma}{\gamma} = 8\cdot 10^{-4}$$

Scattering off a high quality J-class psec laser pulse

$$U_L = 400 \ \ mJ \ ; \ M^2 = 1.2 \ ; \ \frac{\Delta\nu}{\nu} = 5\cdot 10^{-4}$$

Technical Design Report

E-Gammas proposal for the ELI-NP Gamma beam System

With 79 tables and 252 figures

O. Adriani, S. Albergo, D. Alesini, M. Anania, D. Angal-Kalinin, P. Antici, A. Bacci, R. Bedogni, M. Bellaveglia, C. Biscari, N. Bliss, R. Boni, M. Boscolo, F. Broggi, P. Cardarelli, K. Cassou, M. Castellano, L. Catani, I. Chaikovska, E. Chiadroni, R. Chiche, A. Cianchi, J. Clarke, A. Clozza, M. Coppola, A. Courjaud, C. Curatolo, O. Dadoun, N. Delerue, C. De Martinis, G. Di Domenico, E. Di Pasquale, G. Di Pirro, A. Drago, F. Druon, K. Dupraz, F. Egal, A. Esposito, F. Falcoz, B. Fell, M. Ferrario, L. Ficcadenti, P. Fichot, A. Gallo, M. Gambaccini, G. Gatti, P. Georges, A. Ghigo, A. Goulden, G. Graziani, D. Guibout, O. Guilbaud, M. Hanna, J. Herbert, T. Hovsepian, E. Iarocci, P. Iorio, S. Jamison, S. Kazamias, F. Labaye, L. Lancia, F. Marcellini, A. Martens, C. Maroli, B. Martlew, M. Marziani, G. Mazzitelli, P. McIntosh, M. Migliorati, A. Mostacci, A. Mueller, V. Nardone, E. Pace, L. Palumbo, A. Pelorosso, F.X. Perin, G. Passaleva, L. Pellegrino, V. Petrillo, M. Pittman, G. Riboulet, R. Ricci, C. Ronsivalle, D. Ros, A. Rossi, L. Serafini, M. Serio, F. Sgamma, R. Smith, S. Smith, V. Soskov, B. Spataro, M. Statera, A. Stecchi, A. Stella, A. Stocchi, S. Tocci, P. Tomassini, S. Tomassini, A. Tricomi, C. Vaccarezza, A. Variola, M. Veltri, S. Vescovi, F. Villa, F. Wang, E. Yildiz, F. Zomer

108 Authors, 327 pages

Luca Serafini Editor

http://arxiv.org/abs/1407.3669

How can we make 100 times better than the state of the Art?

DEVELOP a SOUND and FEASIBLE PROPOSAL for the PROJECT

- **Based mainly on "state of the Art" Technology.**
- **Relying on a short term R&D compatible with the schedule of construction**
- **Able to garantee the generation of a "gamma radiation beam" with unique features of interest to the experimental nuclear physics community.**
- **A system thought to further improvement of performances**

MOTIVATION OF THE TECHNOLOGY CHALLENGES IN THE ELI-NP GBS ACCELERATOR PROJECT

To increase the gamma flux we need to **increase the number of collision per second**

100 Hz repetition rate

Multi bunch in the RF pulse

-Damping of HOM in RF structures to avoid BBU instabilities

-Compensation of **beam loading effects**

-accurate thermal design

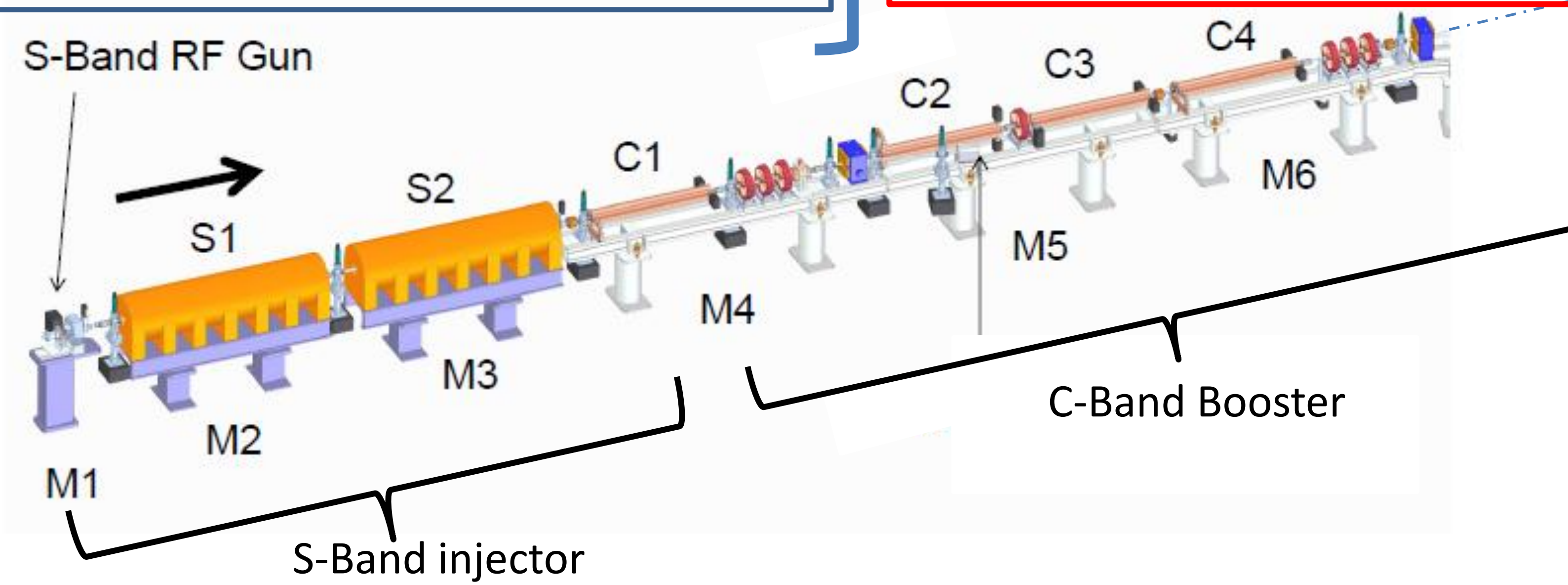
To reduce the accelerator overall dimensions: **compact system**

High gradient

High frequency

-C-band LINAC combined with an S-band Injector: the "state of the art" in last generation accelerators technology and RF power sources

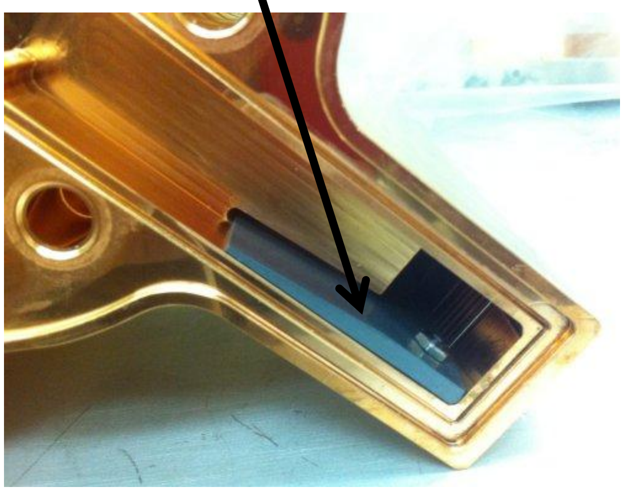
-accurate **RF design and mechanical realization**

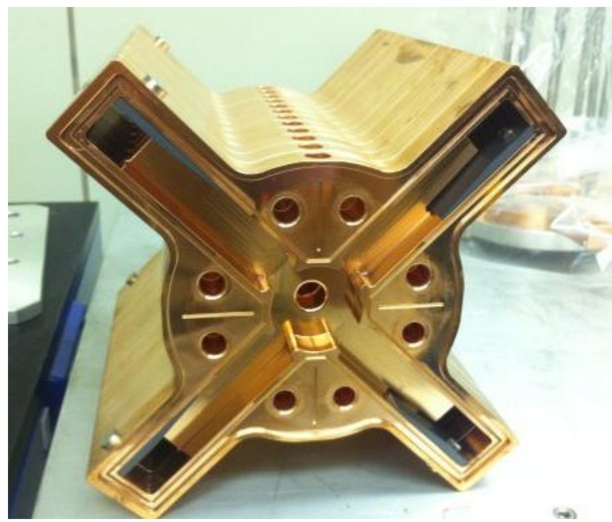


C-BAND STRUCTURES: PROTOTYPES REALIZATION

An intense activity of prototyping has been started to setup and optimize the realization process of the structures. First prototypes have been fabricated to verify both feasibility of copper cells machining and effectiveness of brazing process. We are now focalizing in the realization of two prototypes previous the realization of the first complete structure. The first prototype (“**mechanical prototype**”) is a full scale device, under construction, without precise internal dimensions conceived to test the full brazing process, verifying structure deformations and vacuum leaks. This prototype does include SiC absorbers to test also the vacuum performances of the structure. The second prototype (“**RF prototype**”) is a device with a reduced number of cells that we would like to fabricate to test the RF properties of the structure at low and high power. Also this second device includes the SiC absorbers and has precise internal dimensions with tuners.

SiC Absorber



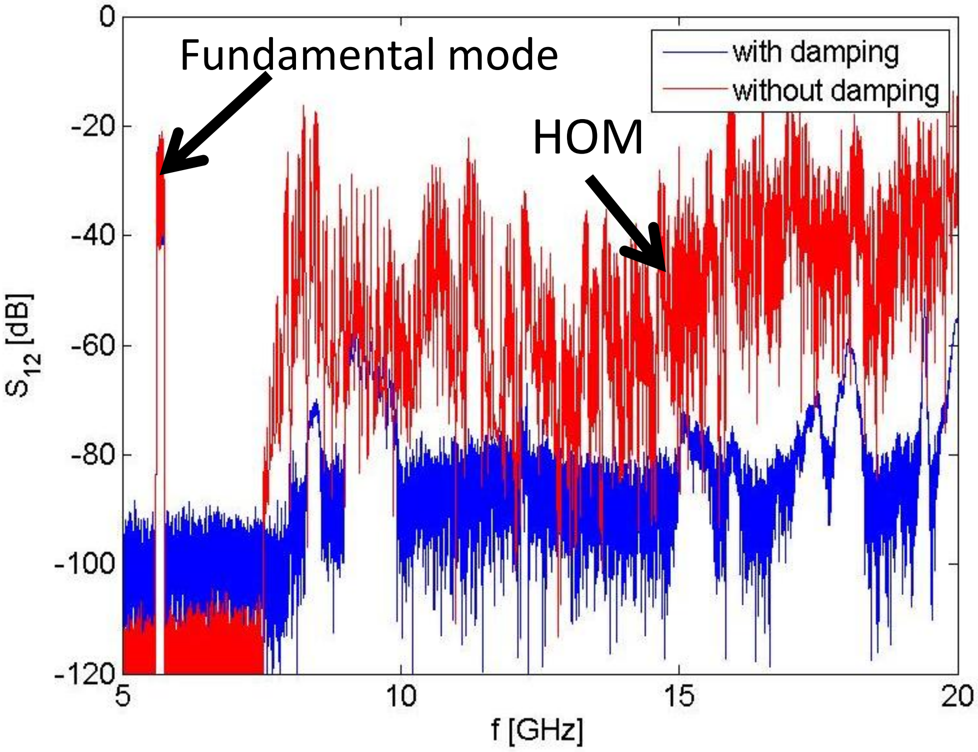


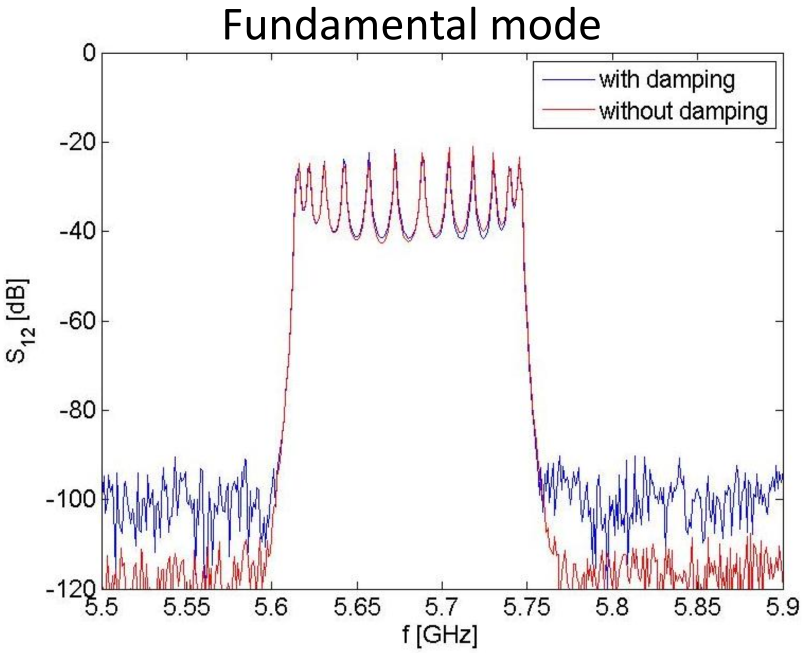
It has been necessary a strong R&D program in close collaboration with Italian Companies (COMEB, CERINCO, ANDALOGIANNI, TSC)

12 cells module

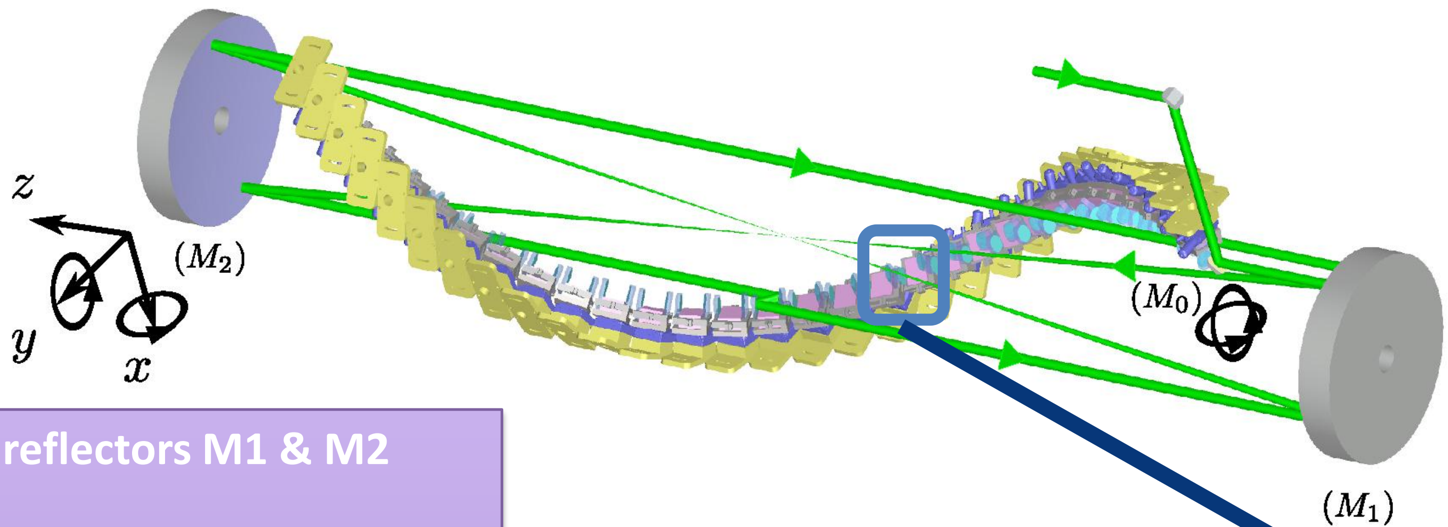
C-BAND STRUCTURES: RF MEASUREMENTS ON PROTOTYPES

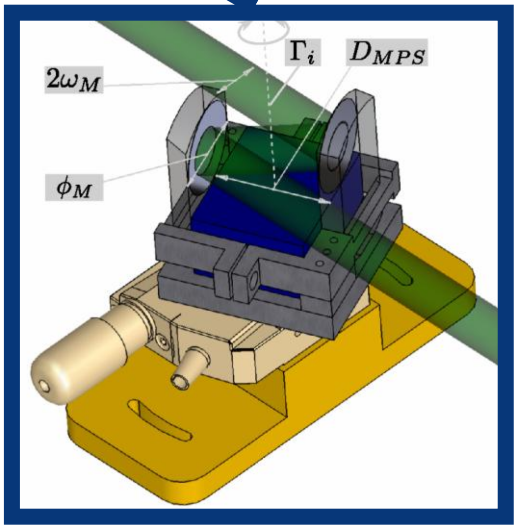
RF test at low power have been performed in the single 12 cell module with and without the SiC absorbers. The results are given in the figures where the transmission coefficient between two antennas coupled with the structure modes are reported. The measurements show the effectiveness of the SiC absorbers since the HOM disappear after the insertion of the absorber themselves. The remaining modes are TE-like modes that have a negligible transverse and longitudinal impedance.





Technical solution: the *dragon shape* circulator





2 parabolic reflectors M1 & M2

- M1 fixed
- M2: 5 degrees of freedom
- M0: 2 tilts for injection

Mirror-pair system

- For interaction plane switch
- Rotation for synchronization

→Alignment issues

Summary of Applications

- Compact GeV electron accelerating systems
- Compact Proton and Neutron Sources
- Table-top, fs X-ray FELs
- Radiotherapy with tunable, high-energy electrons, including <u>IORT</u>
- γ-ray radiography for bio-medical and materials science
- Efficient on-site production of radio-isotopes;
- All-optical, tunable, monochromatic (Thomson-scattering) X-ray source for medical applications;
- …….

CONCLUSIONS

- ELI reserach infrastructure will be based on high power Lasers (10 PW) with a significative research program on particle accelerators and innovative sources.

- New techniques and new technologies are being developped in the realization of accelerating system and particle/radiation sources.

- ELI is an extraordinary opportunity for training a new generation of scientists about the the most advanced techniques of particle acceleration and radiation/particle sources.

- A wide interdisciplinary field of applications is foreseen from material science to medical applications