Laser driven Particle Acceleration

Daniele Margarone

RP3 Leader at ELI-Beamlines
Institute of Physics of the ASCR
Prague, Czech Republic
daniele.margarone@eli-beams.eu

CERN Acc. School, "Introduction to Accelerator Physics", 31 August–12 September 2014, CTU, Prague

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  - ....
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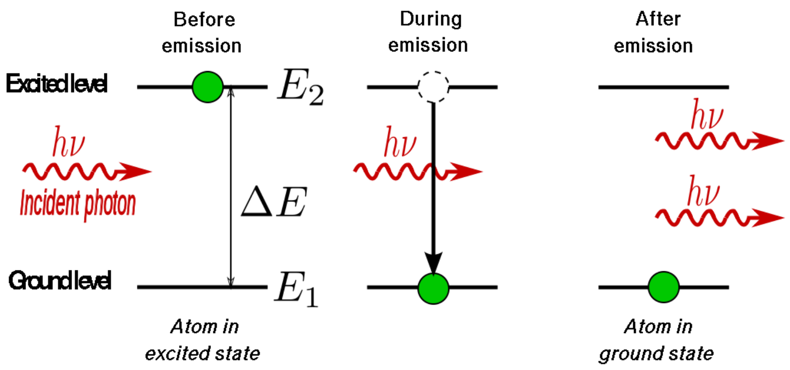
  - Ion Acceleration beamline
  - Electron Acceleration beamline

Laser?

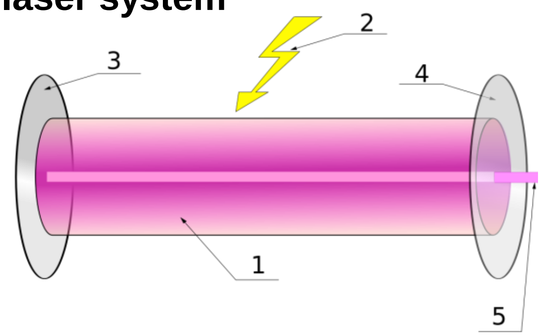
Light Amplification by Stimulated Emission of Radiation



$$E_2 - E_1 = \Delta E = h\nu$$

Components of a typical laser system

1. Gain medium
2. Laser pumping energy
3. High reflector
4. Output coupler
5. Laser beam



Types of lasers: Gas lasers; Chemical lasers; Excimer lasers; Solid-state lasers; Fiber lasers; Photonic crystals lasers; Semiconductor lasers; Dye lasers; FEL

- Laser **Energy: E_L**
- Laser pulse **duration**: τ_L
- Laser peak (or average) **Power**: $P_L=E_L/\tau_L$
- Laser **Focal Spot** (diffracion limit)
- Laser **Intensity**: $I_L=P_L/S=E_L/(S\tau_L)$

e.g. ELI-Beamlines L3 laser

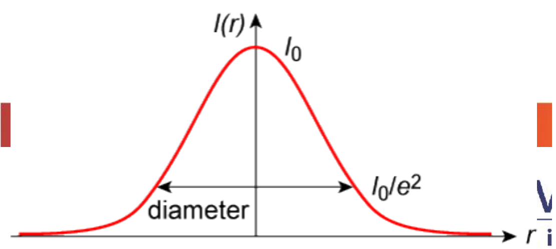
E_L~ 30 J

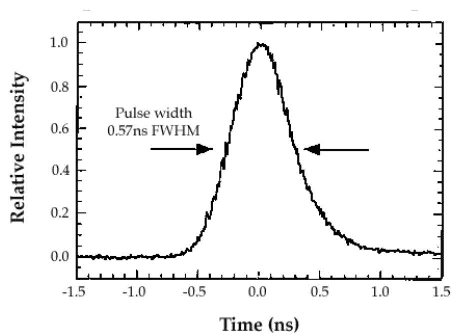
τ_L~ 30 fs = $3x10^{-14}$ s

P_L= **1 PW** = 10^{15} W (peak)

<P_L>= 300 W (average @ **10 Hz** rep. rate)

I_L ~ **10^{22} W/cm^2**





MINISTERSTVO ŠKOLSTVÍ MLÁDEŽE A TĚLOVÝCHOVY
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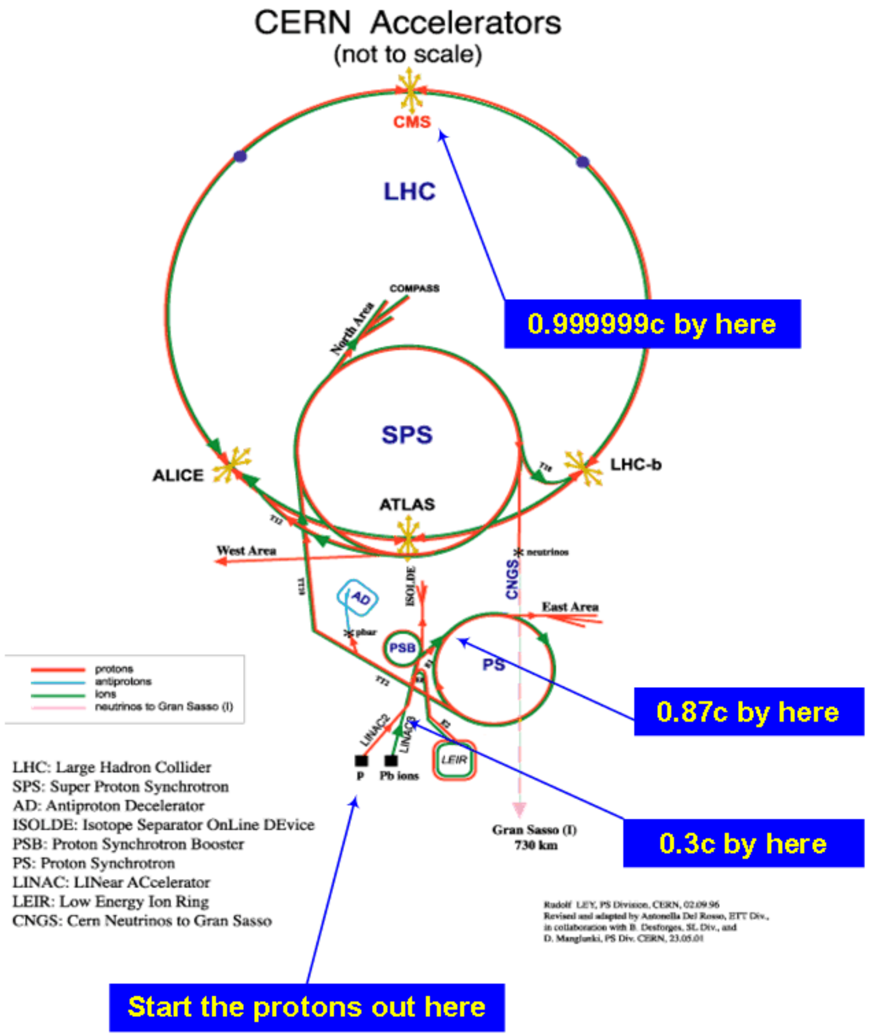
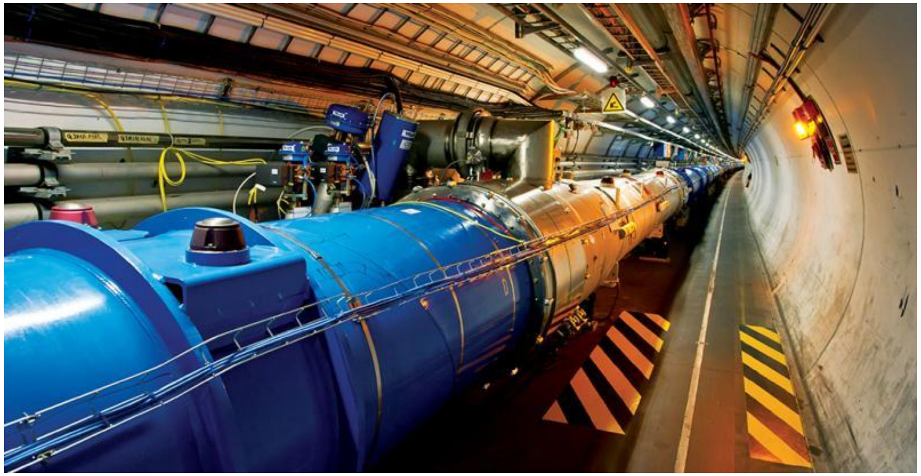
OP Výzkum a vývoj pro inovace

eli beamlines

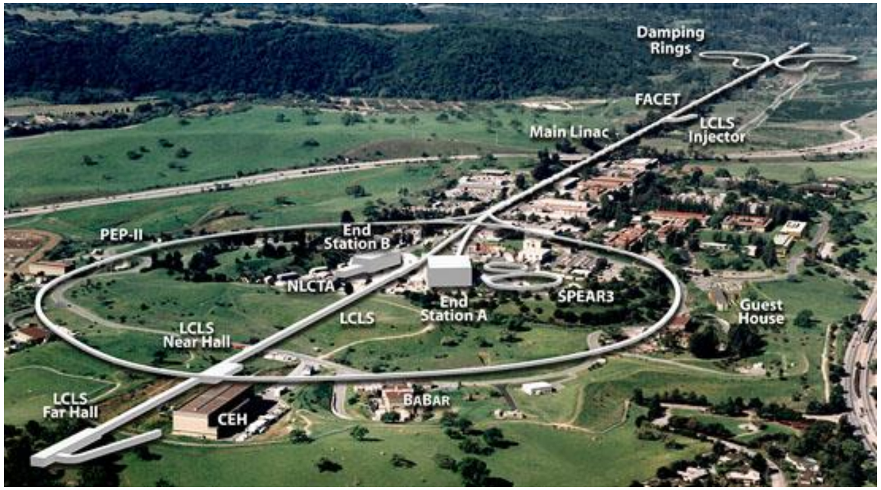
Conventional Acceleration

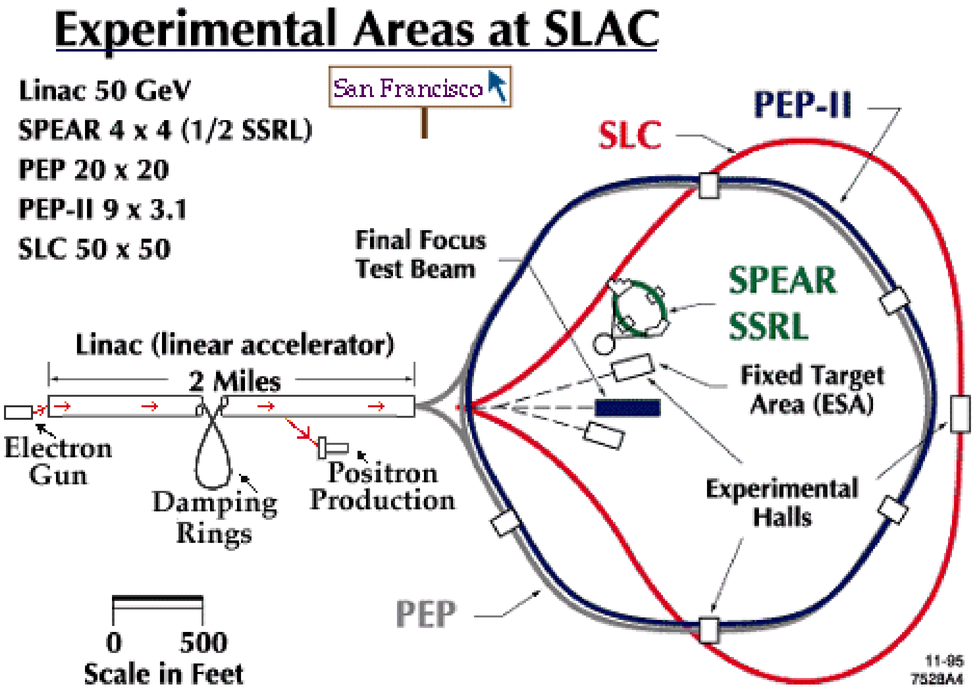


LHC @ CERN
- circular tunnel (<u>27 km long!!!</u>)
- superconductive electromagnets
- proton energy: 4 TeV



Standford University - SLAC





SLAC
- **linear accelerator (<u>3 km long!</u>)**
- **electron energy: 50 GeV**

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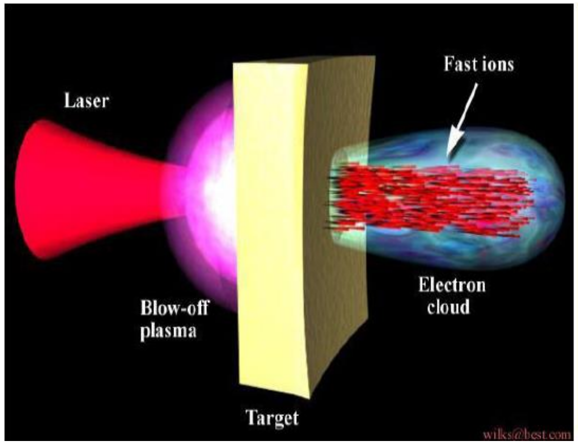
Laser Driven Acceleration

(associated e.m. fields)



I_L (laser intensity) = 10^{21} W/cm^2

Direct Laser interaction:

- **$E \sim I_L^{1/2}\lambda = 10^{14}$ V/m**
- **B = E/c = 3×10^5 T**
- **$P_{rad} = I_L/c = 3\times10^{10}$ J/cm^3 = 300 Gbar**

Laser-Matter interaction:

- **Debye Length:** ⟹ $$\lambda_D = 2.4\mu m \cdot \sqrt{\frac{T_{hot}}{1MeV}} \cdot \sqrt{\frac{10^{19} cm^{-3}}{N_{hot}}}$$ ⟹ **few μm!**
- **Acceleration time:** ⟹ $$\tau = \sqrt{\frac{\lambda_D^2 m_{ion}}{T_{hot}}} = 0.24 ps \sqrt{\frac{\lambda_D^2 n_{hot}}{10^{19}}}$$ ⟹ **few ps!**
- **Electric Field:** ⟹ $$\tau = \frac{T_{hot}}{e\lambda_D} \approx \frac{MV}{\mu m}$$ ⟹ **several TV/m!**

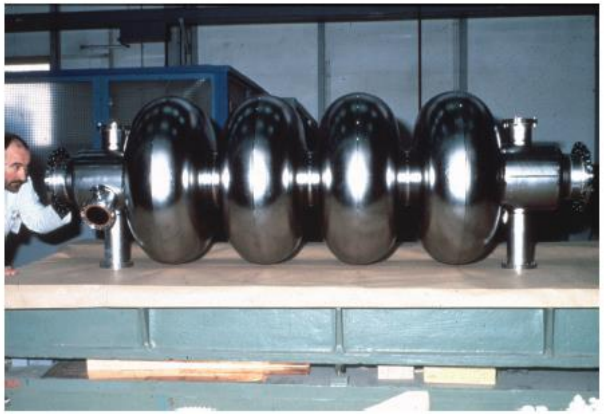
Energy gain for ions in laser-plasma accelerators:

tens of MeV in a few μm!!! (no break down limit in plasma!!!)

Laser Plasma Accelerators

E-field $_{max}$ ≈ few 10 M V /meter (Breakdown)

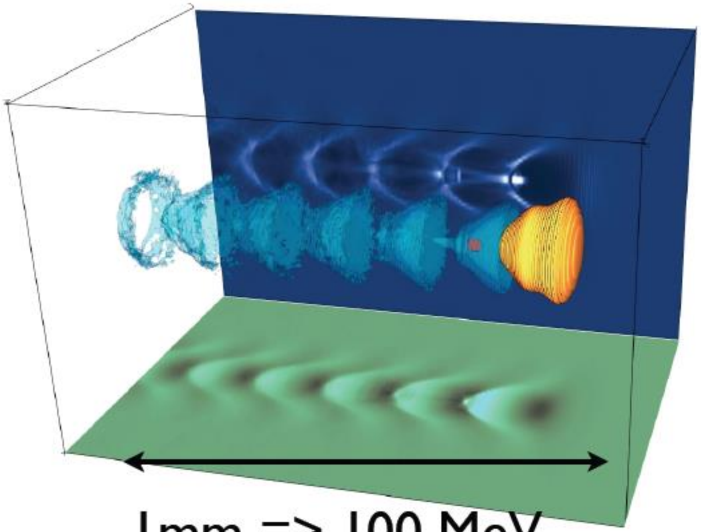
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

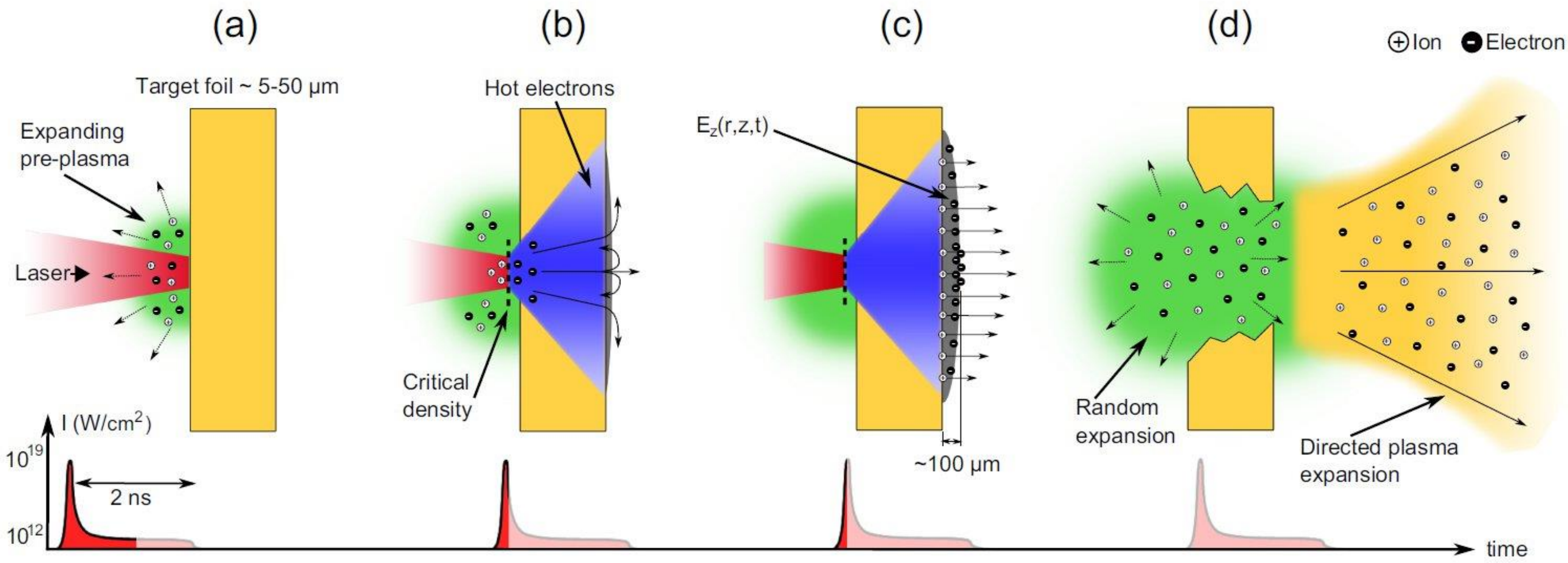
Plasma Cavity



1mm => 100 MeV

Electric field > 100 GV/m

Ion Acceleration Mechanisms: TNSA
(Target Normal Sheath Acceleration)



TNSA mechanism

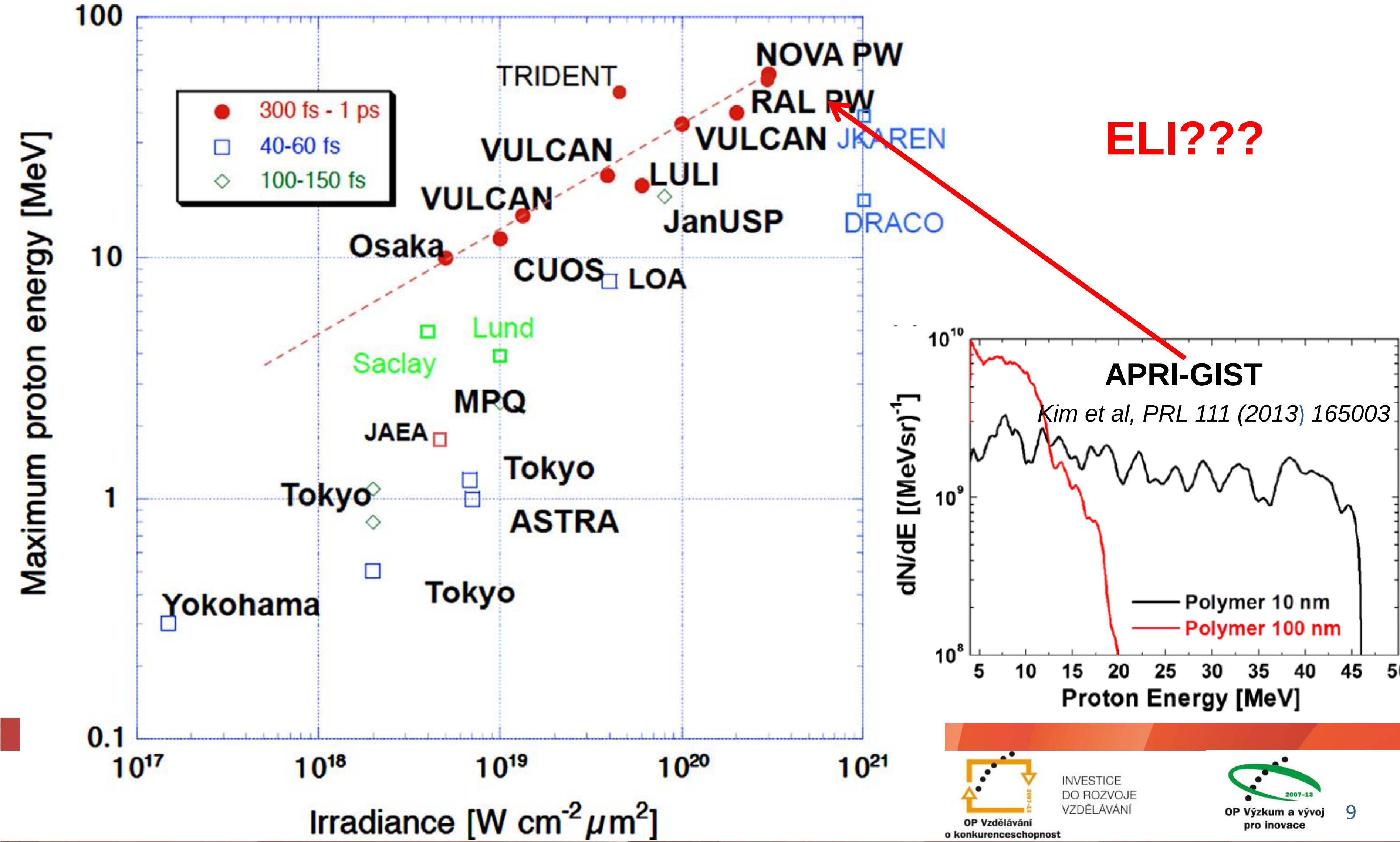
a. Typical Laser Intensity (**10^{18}-10^{20} W/cm^2**)
b. Accelerated **Relativistic Electrons** (multi MeV) traverse the thin target (0.1÷100 μm).
c. The H-ultrathin rear-side layer is ionized by the electron beam and **protons** are generated.
d. The fast electron cloud builds up a **quasi-electrostatic field** exceeding ~1 TV/m accelerating protons in the forward direction to multi-MeV energies.

TNSA features

- Ions are accelerated along the **target normal**
- Ions with the highest charge-to-mass ratio (**protons**) dominate the acceleration
- Large proton number: **10^{10}÷10^{13}**
- **Exponential ion energy distribution**
- Short bunch duration at the source: **few ps**
- High Beam Currents: **few kA**
- Low emittance: **$\varepsilon \sim 5 \cdot 10^{-3}\ \pi$ mm mrad**
- High Beam Divergence: **10-20°**
- Low shot-to-shot reproducibility

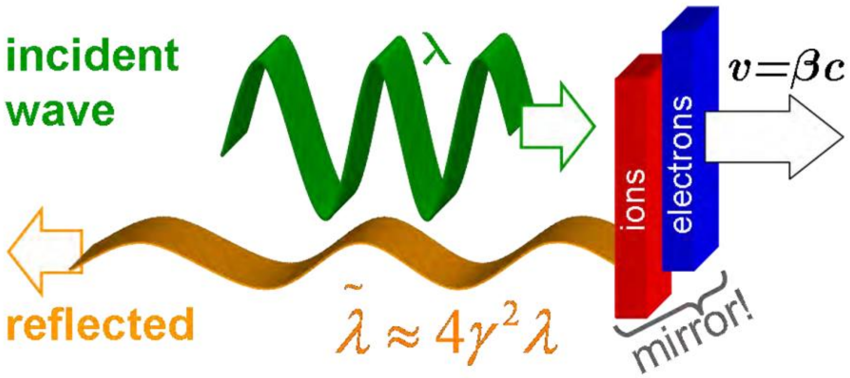
Experimental Scaling Laws

M. Borghesi, NIMA740 (2014) 6



Ion Acceleration Mechanisms: RPA
(Radiation Pressure Acceleration)

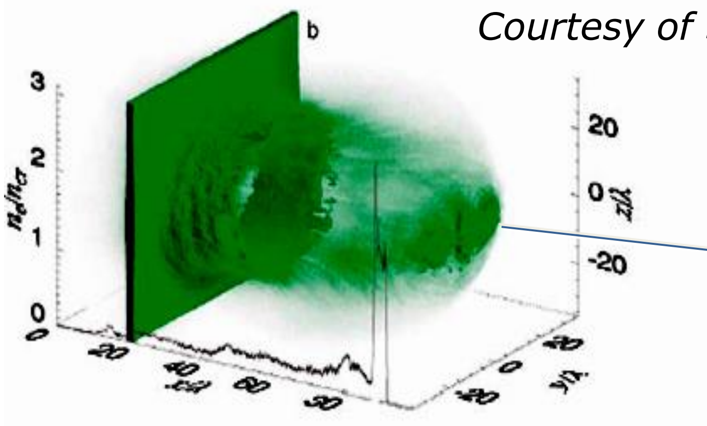
T. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, T. Tajima, Phys. Rev. Lett. 92,175003 (2004)

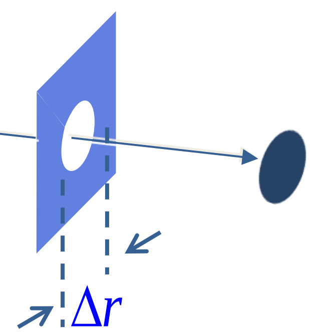


RPA features

- The e.m. wave is directly converted into ion energy via the space-charge force related to the displacement of all electrons in a **thin (nm scale) foil** (collective effect)
- All particles have the same velocity: **quasi-monochromatic energy spectrum**
- Production of **GeV-scale proton beams**
- **Ultrahigh intensities** (>10^{22} W/cm^2)
- **Ultrahigh laser contrast** is required

Courtesy of S.V. Bulanov



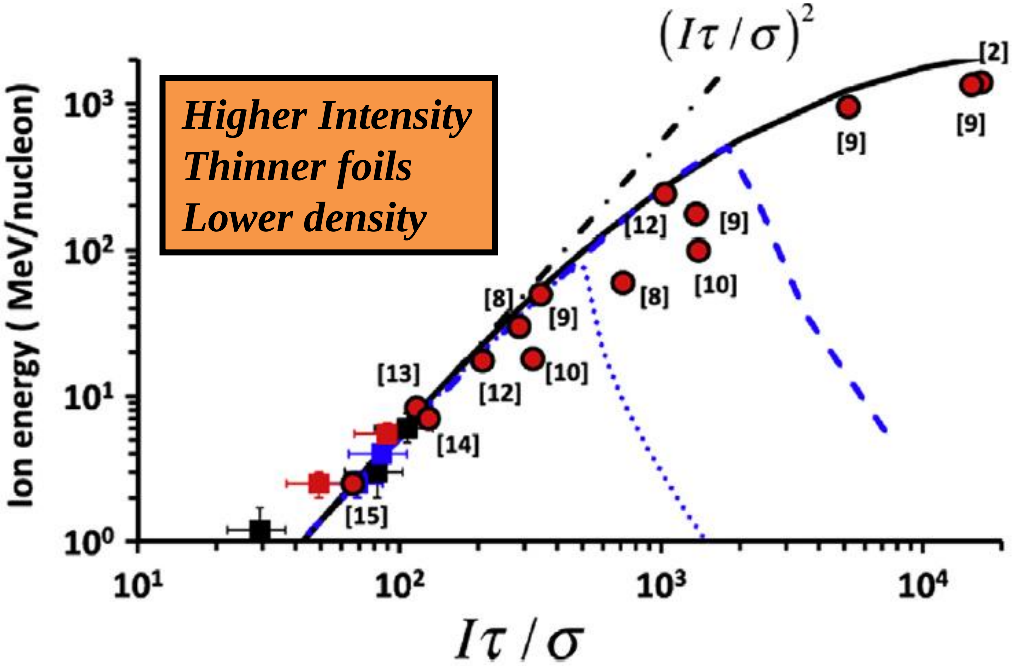


PIC simulations for multi PW-class laser

✓ Laser intensity: >10^{22}W/cm^2

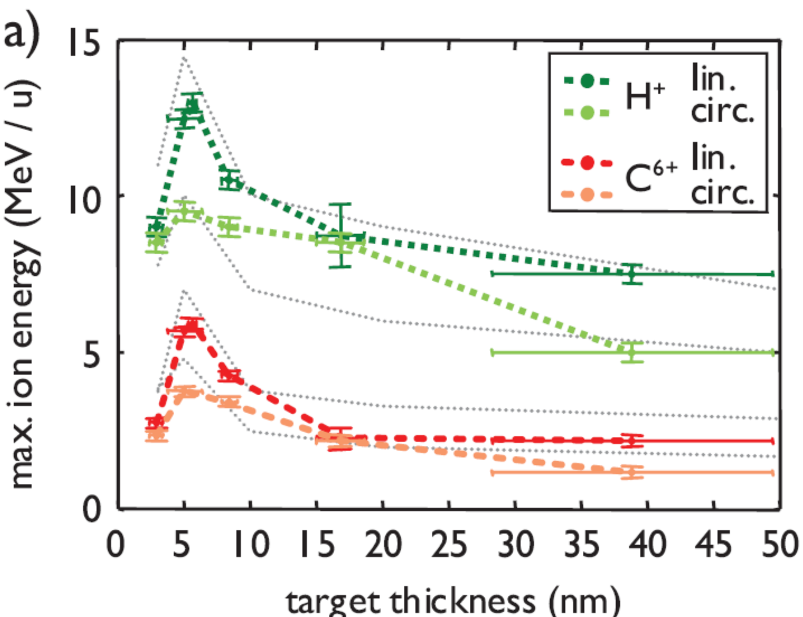
✓ Protons/ions: narrow energy spectrum (**spread <2%**), high energy (**>1GeV**), high efficiency (**η>0.7**)

Emerging Ion Acceleration mechanisms



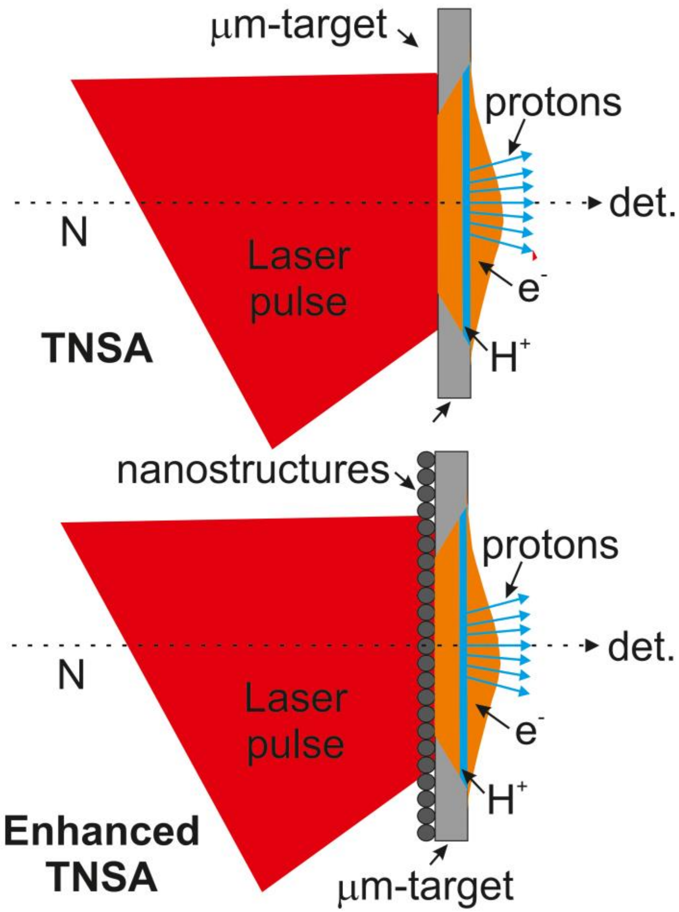
S. Kar et al., PRL 109, 185006 (2012)

H. Henig et al., PRL 103, 245003 (2009)



- Hole boring
- Light sail RPA
- Relativistic transparency
- Shock acceleration
- Directed Coulomb Explosion
- **Enhanced-TNSA**

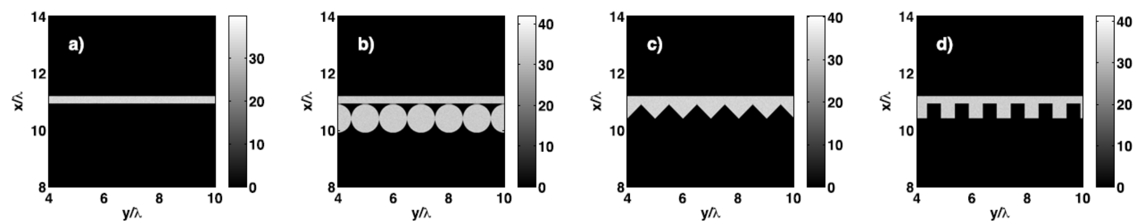
TNSA vs. enhanced-TNSA



Increase of **photoelectron** generation (low laser intensity):
M. Raynaud and J. Kupersztych, Phys. Rev. B 76 (2007) 241402

Increase of **X-ray** emission:
H.A. Sumeruk et al., Phys. Rev. Lett. 98 (2007) 045001

Increase of **proton acceleration** efficiency (*PIC simulations*):
Y. Nodera, S. Kawata et al, Phys. Rev. E 78 (2008) 046401
O. Klimo et al., New J. of Phys. 13 (2011) 053028

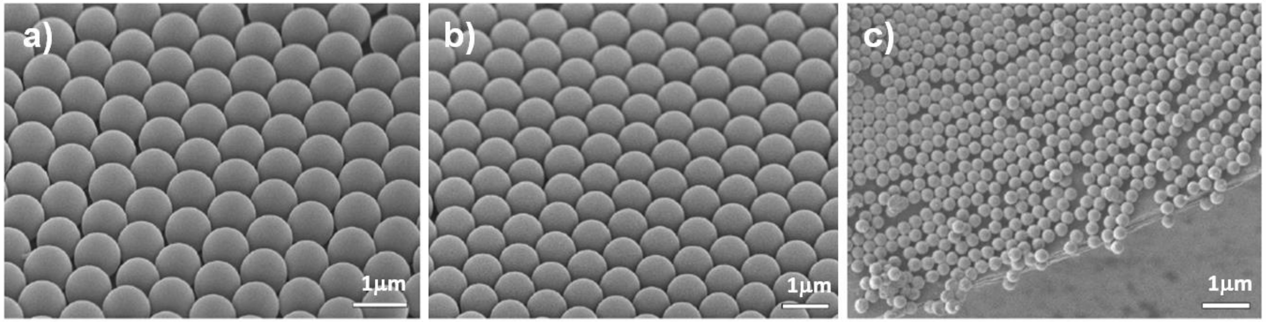


Increase of hot electron temperature (**stochastic heating**) in sub-micron clusters:
Boris N. Breizman Phys. Plasma 12 (2005) 056706

Target geometries

Target morphology

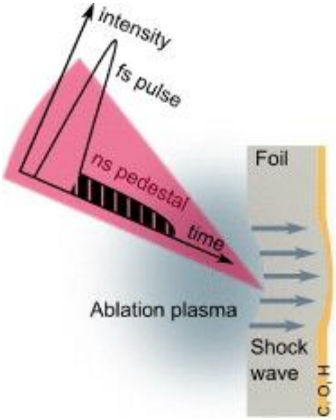
- monolayer of closely packed polystyrene spheres
- 1 μm mylar substrate
- self assembly in water *(@ CTU in Prague)*



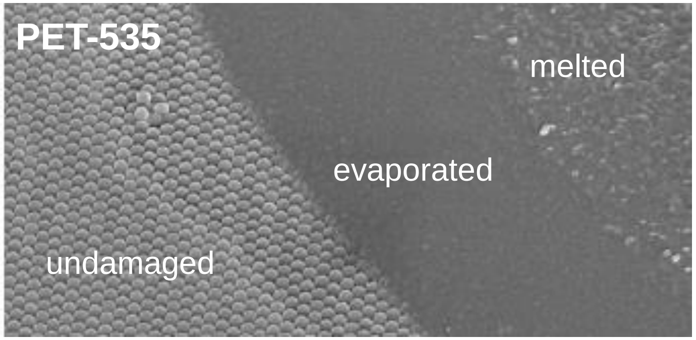
a) PET-266: 1 μm mylar + 266 nm polystyrene spheres
b) PET-535: 1 μm mylar + 535 nm polystyrene spheres
c) PET-920: 1 μm mylar + 920 nm polystyrene spheres
d) PET: 1 μm mylar (planar target)

Laser damaging threshold

✓ <u>ns-regime</u>
no damage for $I_L < 3x10^9$ W/cm^2
✓ <u>fs-regime</u>
no damage for $I_L < 10^{11}$ W/cm^2



D. Margarone et al., Appl. Surf. Sci. (2012)



Experimental setup @ CoReLS-APRI

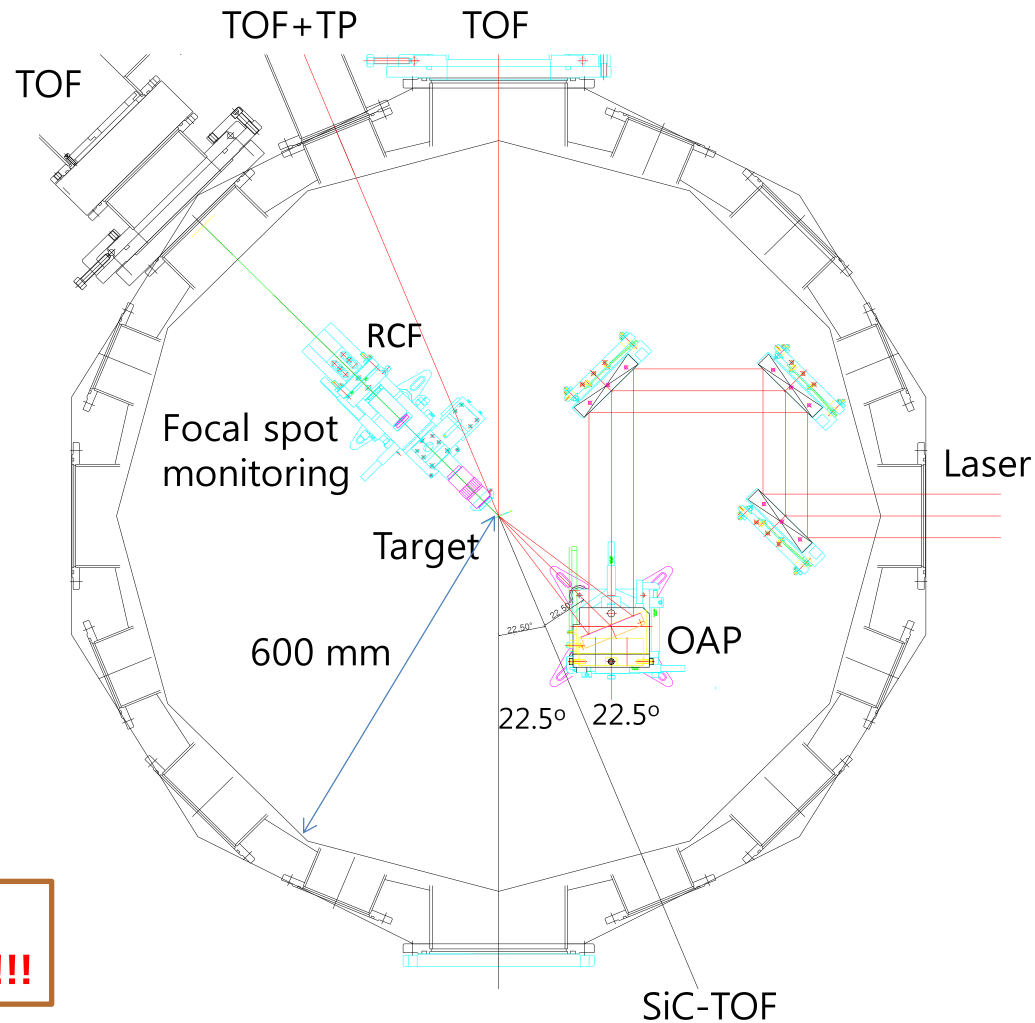
T. M. Jeong et al., J. Korean Phys. Soc. 50 (2007) 34

Laser parameters

- Max. laser energy/power/intensity:
  - without PM → 2J, **70 TW**, 10^{20} W/cm^2
  - with DPM → 1J, 35 TW, $\mathbf{5\times10^{19}}$ W/cm^2
- Pulse duration : **30 fs**
- Wavelength: 805 nm
- Polarization: p
- Standard spot diameter: 5 μm (FWHM)
- main/pedestal contrast:
  - without PM → ~10^7 @ 6 ps
  - with DPM → ~$\mathbf{5\times10^{11}}$ @ 6 ps

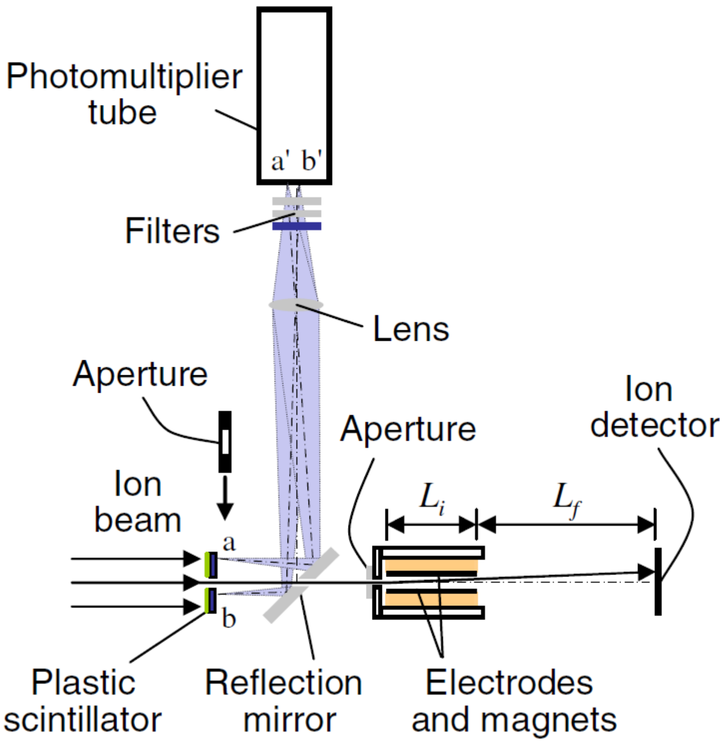
Pedestal intensity ~$\mathbf{10^8}$ **W/cm^2**

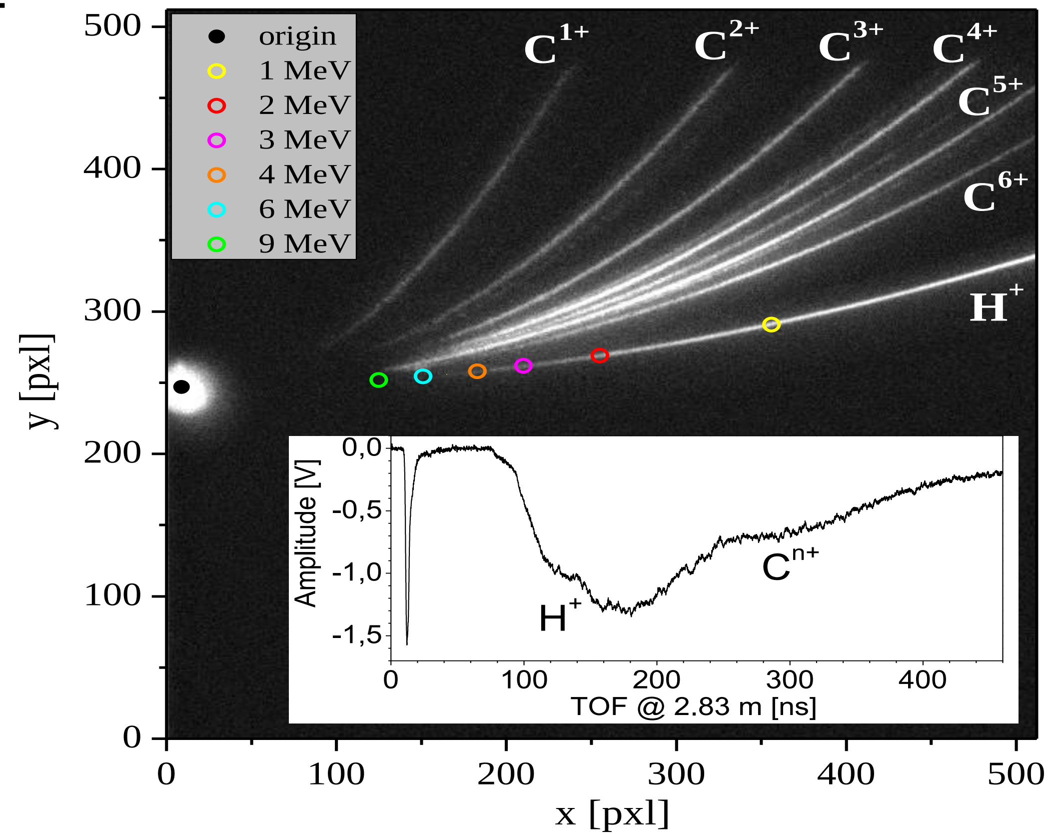
No laser damage for our nanostructures!!!



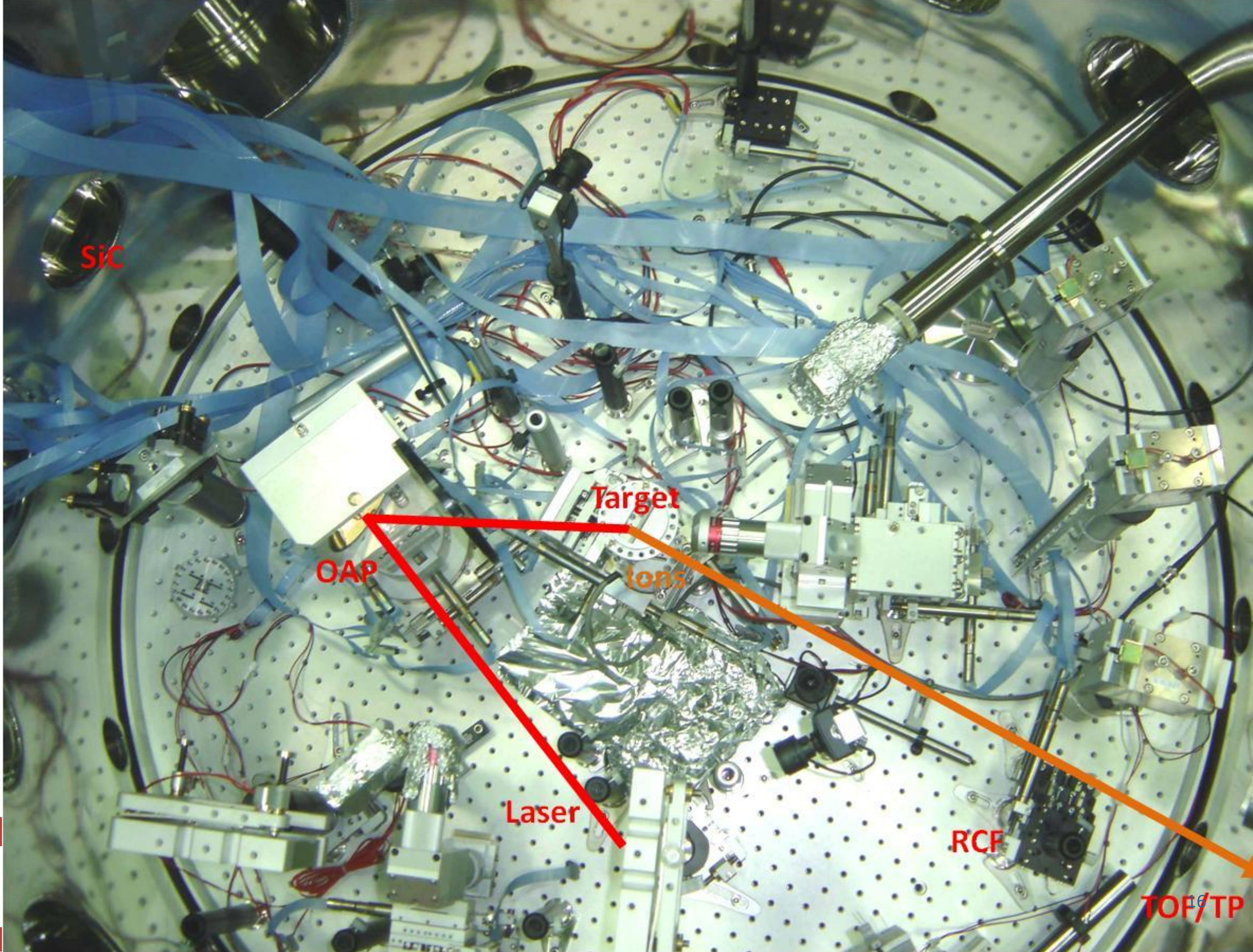
Proton/ion beam diagnostics

Thomson Parabola spectrometer & **TOF** measurements (simultaneous) + **RCF**

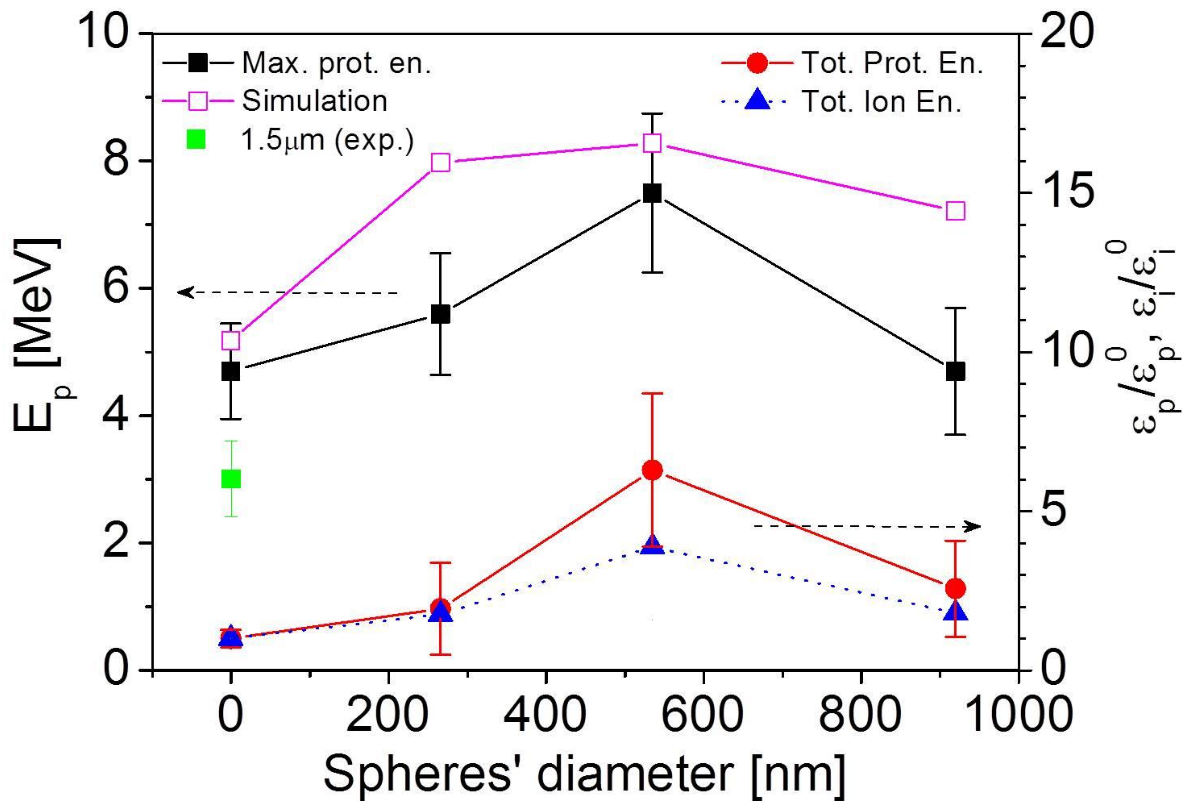




I.W. Choi et al., Rev. Sci. Instr. 80 (2009) 053302


SiC
Target
OAP
Ions
Laser
RCF
TOF/TP

Nanospheres size optimization



PRL **109,** 234801 (2012) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2012

Laser-Driven Proton Acceleration Enhancement by Nanostructured Foils

D. Margarone,[1] O. Klimo,[1,2] I. J. Kim,[3] J. Prokůpek,[1,2] J. Limpouch,[1,2] T. M. Jeong,[3] T. Mocek,[1] J. Pšikal,[1,2] H. T. Kim,[3] J. Proška,[2] K. H Nam,[3] L. Štolcová,[1,2] I. W. Choi,[3] S. K. Lee,[3] J. H. Sung,[3] T. J. Yu,[3] and G. Korn[1]

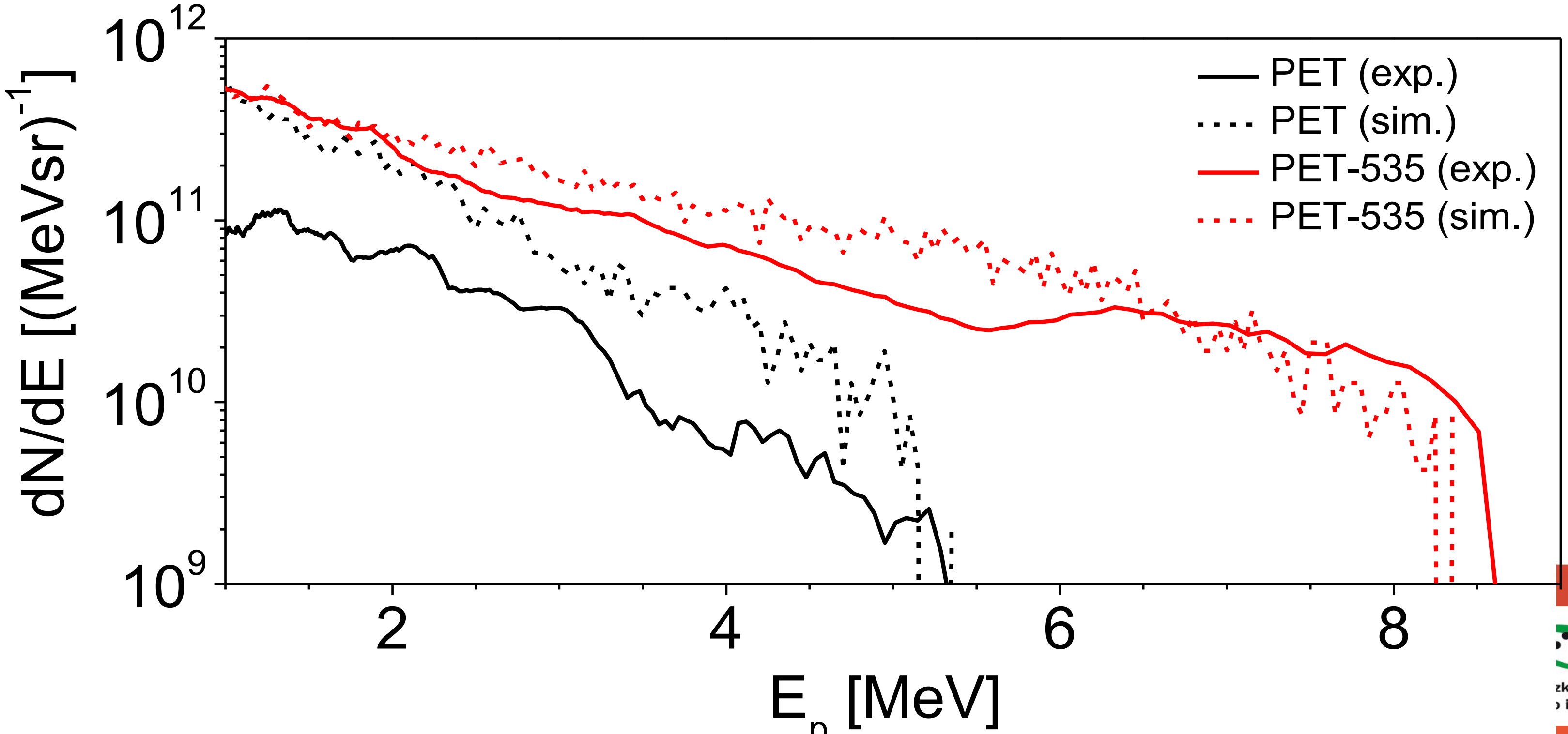
[1]*Institute of Physics of the ASCR, ELI-Beamlines/HiLASE project, Na Slovance 2, 18221 Prague, Czech Republic*
[2]*Czech Technical University in Prague, FNSPE, Brehova 7, 115 19 Prague, Czech Republic*
[3]*Advanced Photonics Research Institute, GIST, 1 Oryong-dong, Buk-gu, Gwangju 500-712, Republic of Korea*
(Received 3 June 2012; published 3 December 2012)

Main achievements

- Max. proton energy
  - PET: **5.3 MeV**
  - PET-535: **8.6 MeV**
  - energy increment: **62%**
- Relative proton accel. conv. efficiency
  - $\eta_{PET-535}/\eta_{PET}$: **6.9** (1-9 MeV)
  - $\eta_{PET-535}/\eta_{PET}$: **10.8** (4-5 MeV)

  efficiency estimation: 1.4% (PET), 9.4% (PET-535)

Stealth target for ion acceleration!



Numerical projections for a «PW-class» laser

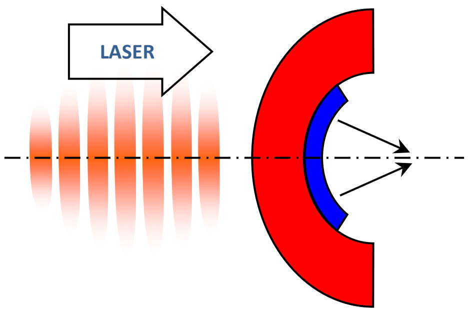
0.5 PW on target (DPM)	max. energy	proton number (28.5; 31.5) MeV	proton number (57; 63) MeV
linear, 1 μm	85 MeV	0.8×10^{9}	0.1×10^{10}
linear, 200 nm	130 MeV	1.5×10^{10}	0.5×10^{10}
linear, 1 μm, nanospheres	95 MeV	2.2×10^{10}	0.5×10^{10}
linear, 1 μm, gratings	140 MeV	1.1×10^{10}	0.9×10^{10}

2D PIC simulations by ***J. Psikal*** (CTU, Prague)
Laser inputs: 30 J, 30 fs, 3 μm (FWHM), 1.4×10^{22} W/cm^2 (a_0=81)
Target inputs: CH_2 (200 n_c electrons of density), normal incidence

Improving the ion beam divergence

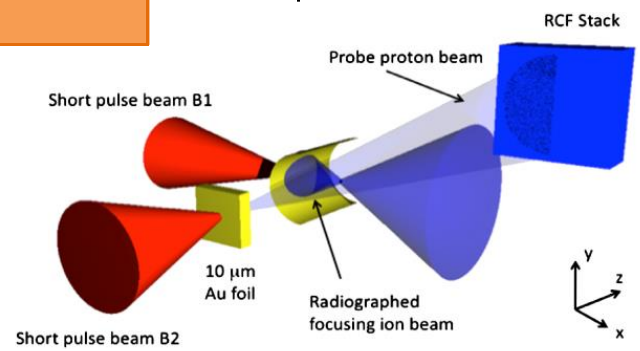
Pre-deformed/structured targets

PIC Simulations

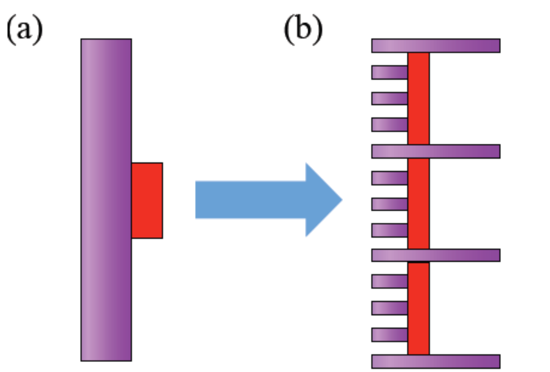


S. V. Bulanov, et al., JETP Lett. 71, 407 (2000)

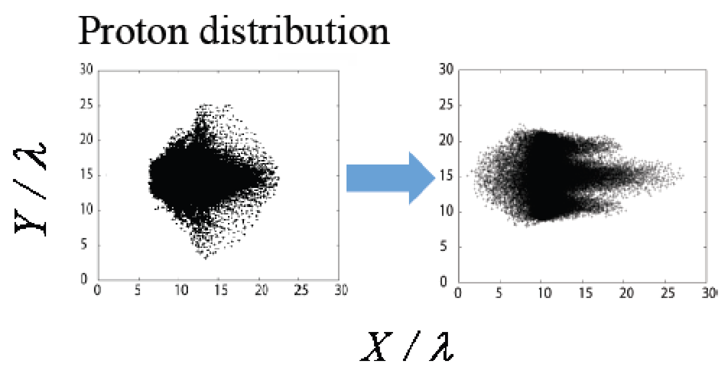
Experiment



S. N. Chen, et al., Phys. Rev. Lett. 108, 055001 (2012)

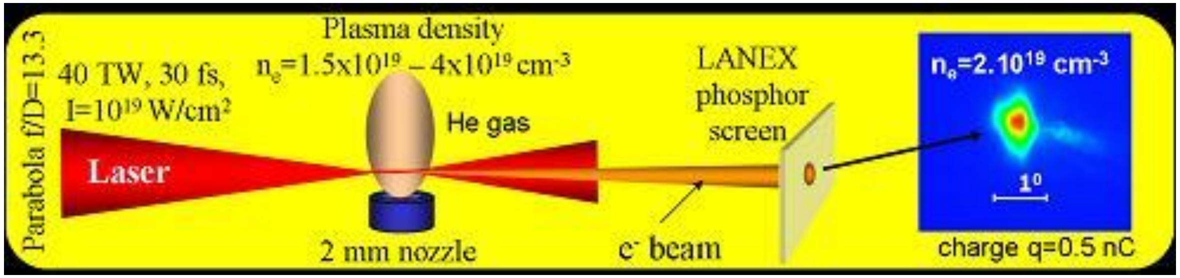


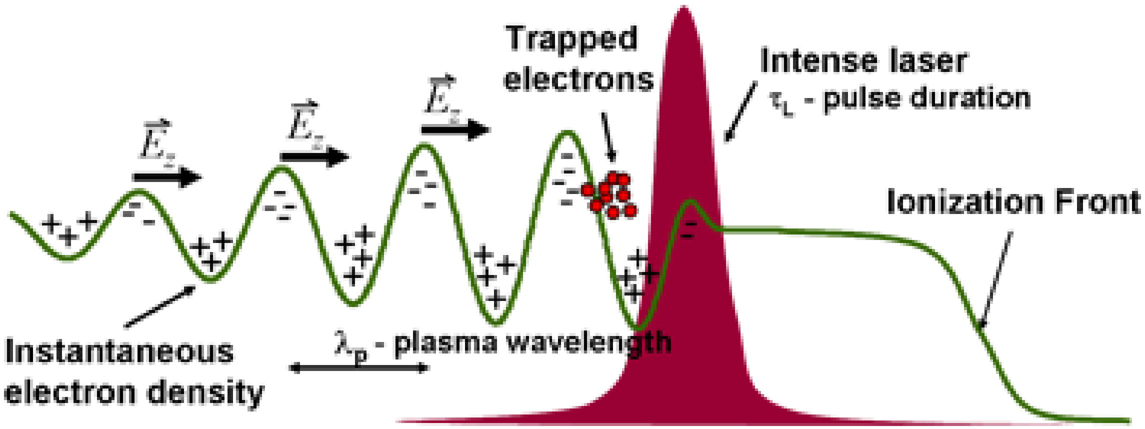
Plain target **Multihole target**



K. Takahashi, S. Kawata et al., Phys. Plasma 10 (2012) 0931102

Laser Driven Electron Acceleration
(Laser Wakefield Acceleration)





Review of laser driven electron accelerators

- *E. Esarey, C. B. Schroeder, and W. P. Leemans, Rev. Mod. Phys. 81 (2009) 1229*
- *W. Leemans & E. Esarey, Phys. Today 62 (2009) 44*

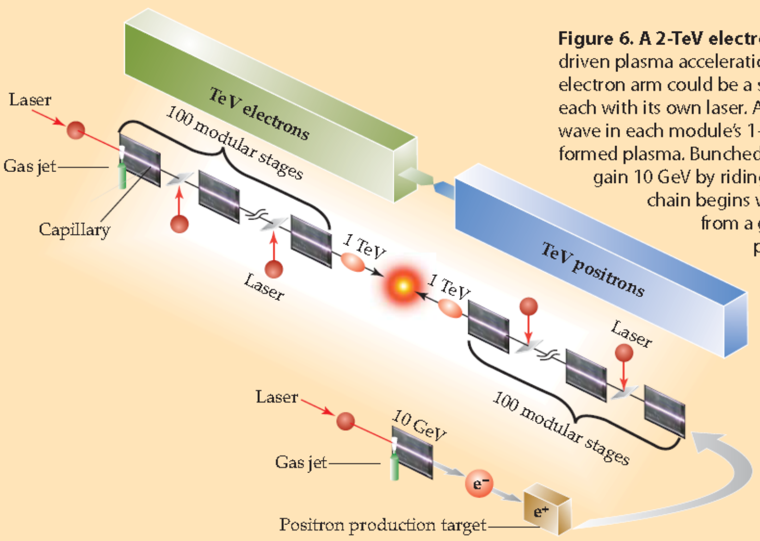
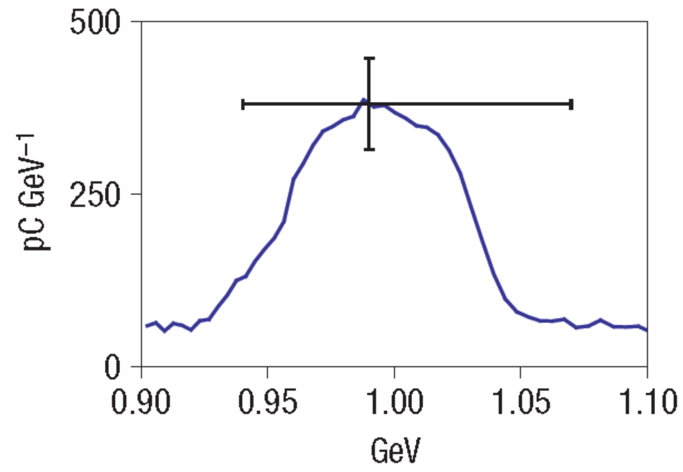


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

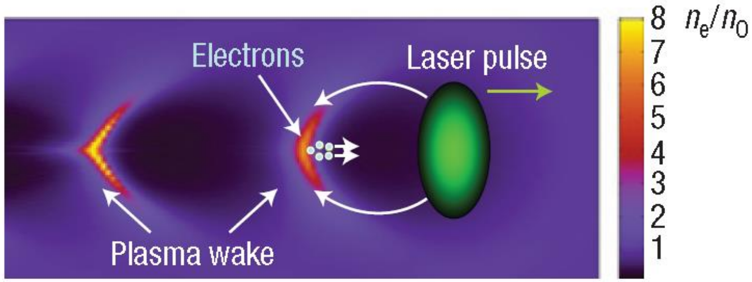
GeV, quasi-monoenergetic electron beam

W. Leemans et al., Nature Phys. 2 (2006) 696



Applications of laser driven electrons

V. Malka et al., Nature Phys. 4 (2008) 447



Contents

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- **Potential Applications**
  - Laser-induced Nuclear Reactions (fusion...)
  - Laser-based Cancer Therapy (hadrontherapy)
  - ....
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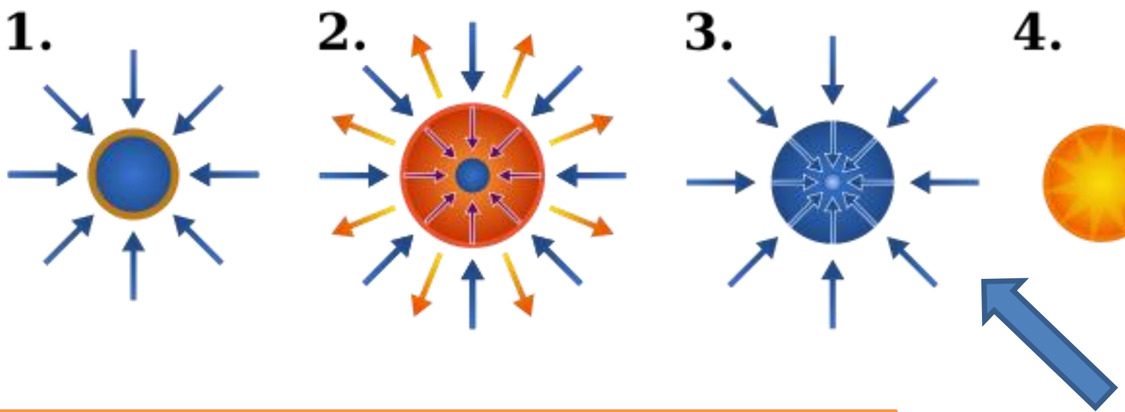
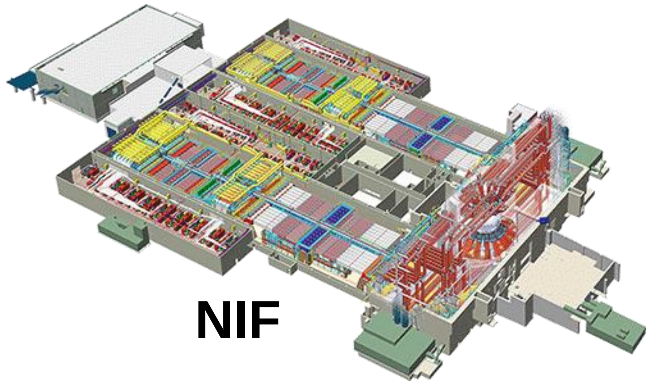
  - Ion Acceleration beamline
  - Electron Acceleration beamline

Laser Driven Ion Applications

- ✓ Diagnosis of intense interaction phenomena by **Proton Radiography**
- ✓ WDM (warm dense matter) by **Proton Heating**
- ✓ Laser fusion by proton **Fast Ignition**
- ✓ **Nuclear Reactions** Initiated by Laser-Driven Ions (PET, fast neutron radiography, proton-boron fusion, …)
- ✓ **Hadrontherapy**
- ✓ Technological Applications (ion implantation, ion lithography & micromachining, ion-induced material modification, …)

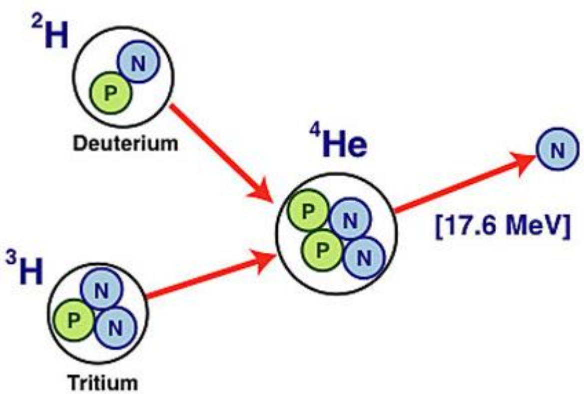
Inertial Confinement Fusion

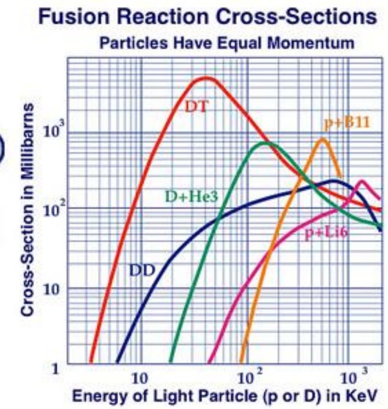




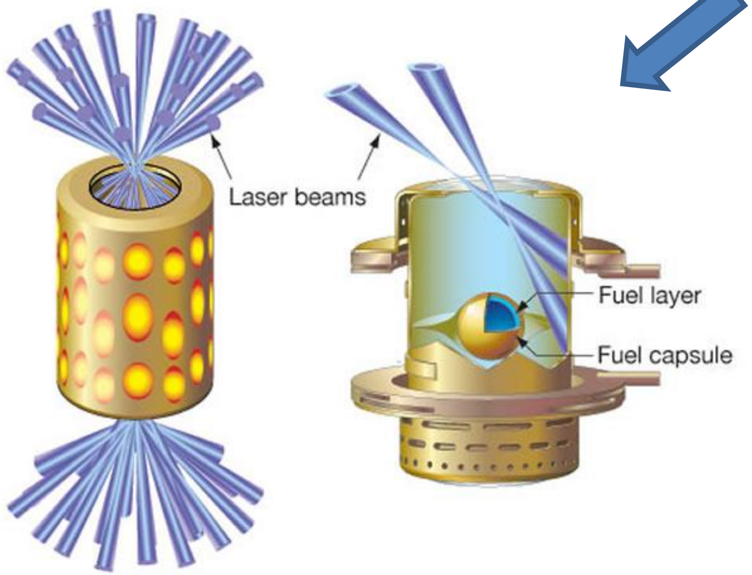
1. Laser beams rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.
2. Fuel is compressed by the rocket-like blowoff of the hot surface material.
3. During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 ˚C.
4. Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

Direct drive

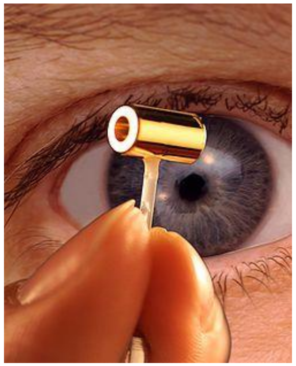




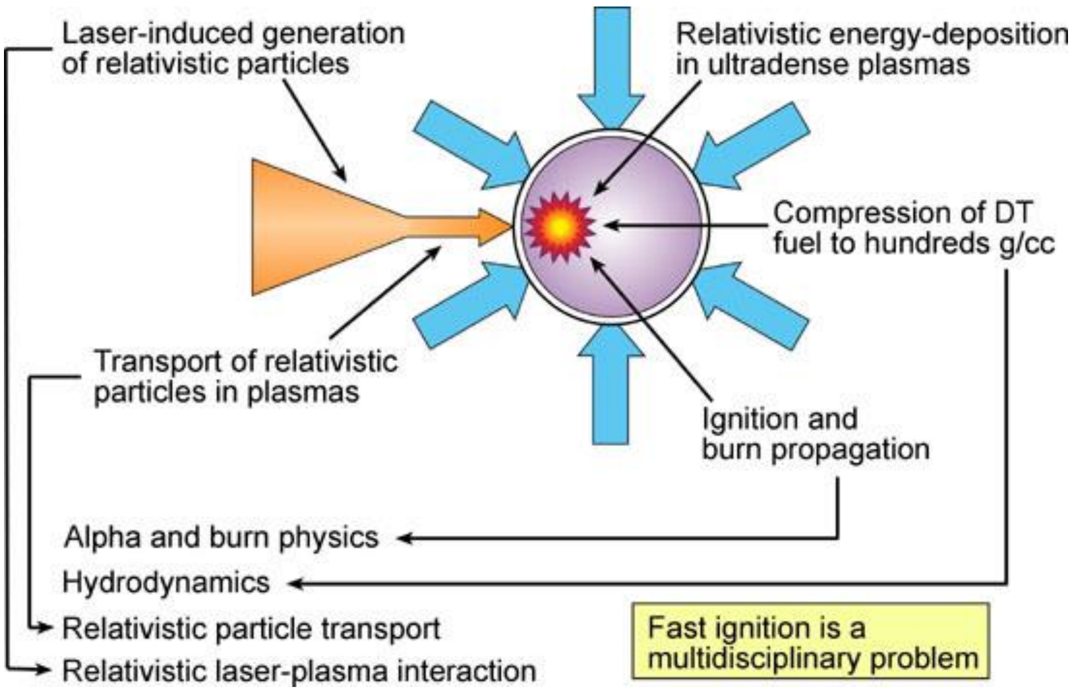
Indirect drive laser ICF uses a "hohlraum" which is irradiated with laser beams from either side on its inner surface to bathe a fusion microcapsule inside with smooth high intensity X-rays.



Indirect drive

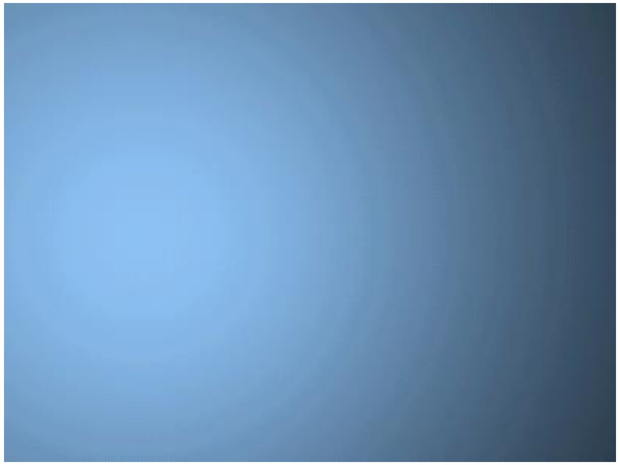


Fast ignition



Laser Induced Proton-Boron Fusion

$^{11}B + p \rightarrow 3\alpha + 8.7\ MeV$



First investigation in the 1930s:
Oliphant & Rutherford, L. Proc. R. Soc. London A 141 (1933) 259
Dee and Gilbert, L. Proc. R. Soc. London A 154 (1936) 279

Interest for future «ultraclean» nuclear fusion reactors:
Rostoker et al, Science 278 (1997) 1419
Kulcinski & Santarius, Nature 396 (1998) 725
Hora et al, Energy Environ. Sci. 3 (2010) 479

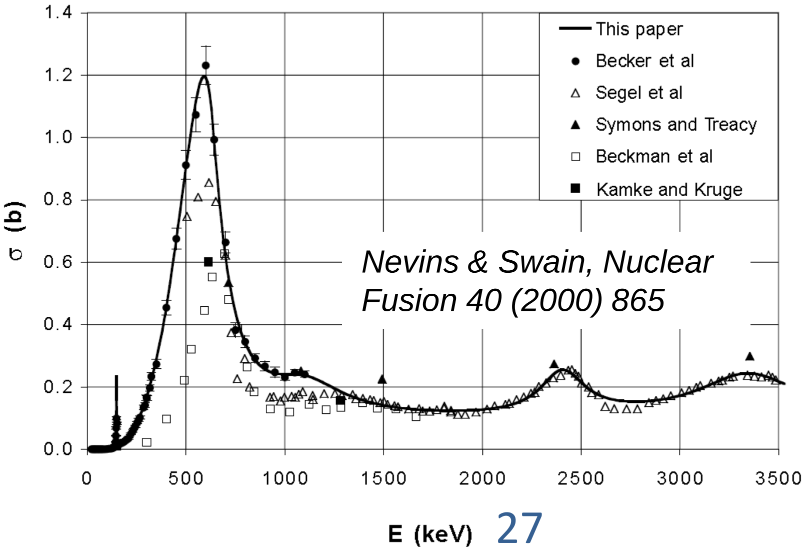
Numerical & Exp. (standard accelerators) studies:
Dmitriev, Physics of Atomic Nuclei 72, 1165 (2009)
Stave et al, Phys. Lett. B 696 (2011) 26

Experiments of Laser Driven p-B fusion
Belyaev et al, Phys. Rev. E 72 (2005) 026406
C. Labaune et al., Nat. Comm. 4 (2013) 2506

Maximum cross section: **675 keV (p)**

Main channel: α energy of **2-6 MeV** (maximum @ ~4 MeV)

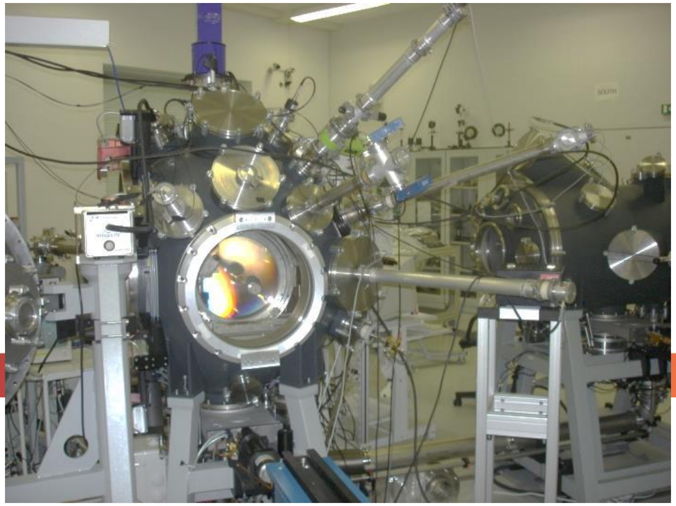
Secondary channel: α energy of **6–10 MeV**



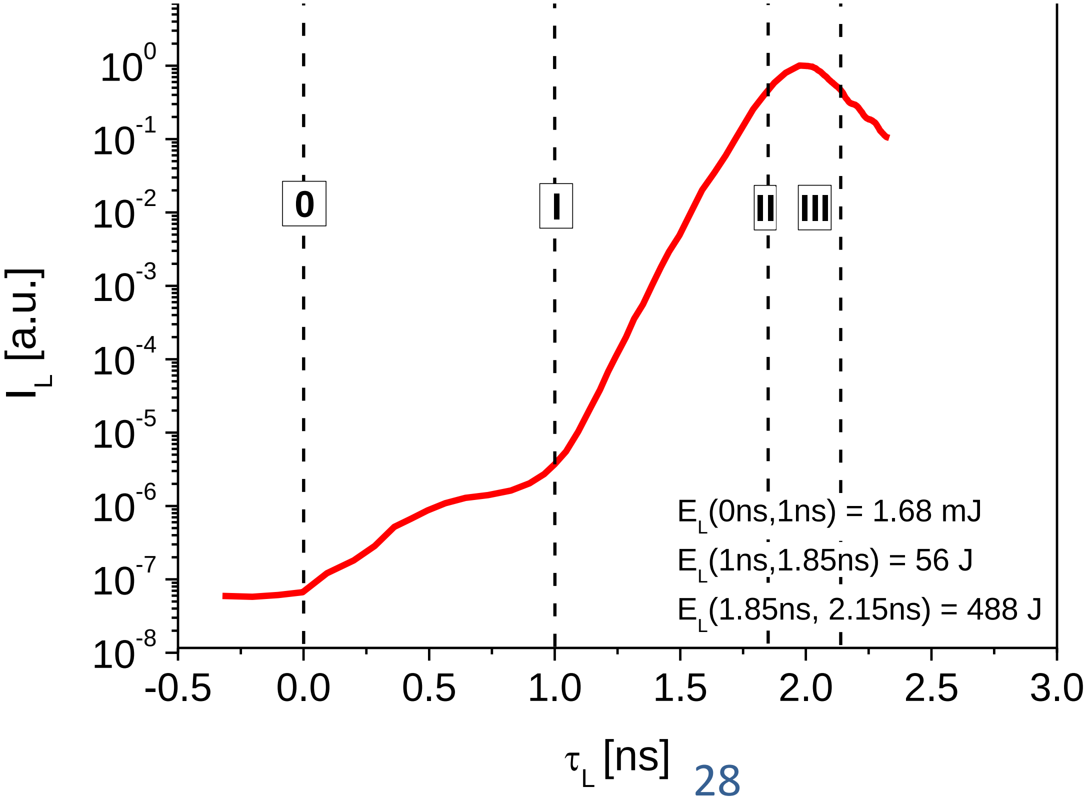
Nevins & Swain, Nuclear Fusion 40 (2000) 865

Our experiment @ PALS

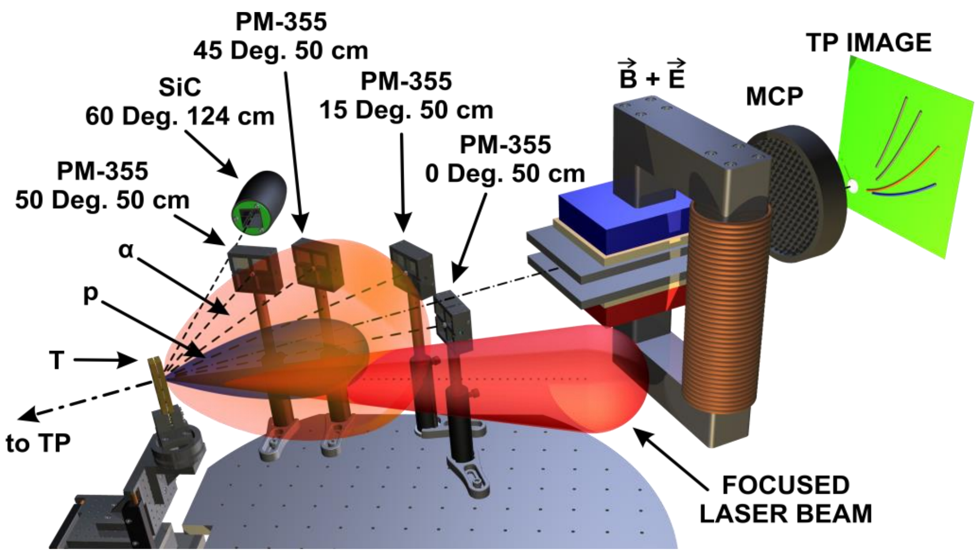
Laserlab Europe project:
PALS_001770 (January 2013)



Laser energy: 500 J
Laser pulse: **0.3 ns (FWHM)**
Laser wavelength: 1315 nm
Focal spot diameter: 80 μm
0-I (0-1 ns): 2 mJ → 3×10^{10} W cm^{-2}
I-II (**1-1.85 ns**): 55 J → **10^{15} W cm^{-2}**
II-III (1.85-2.15 ns): 500 J → **3×10^{16} W cm^{-2}**

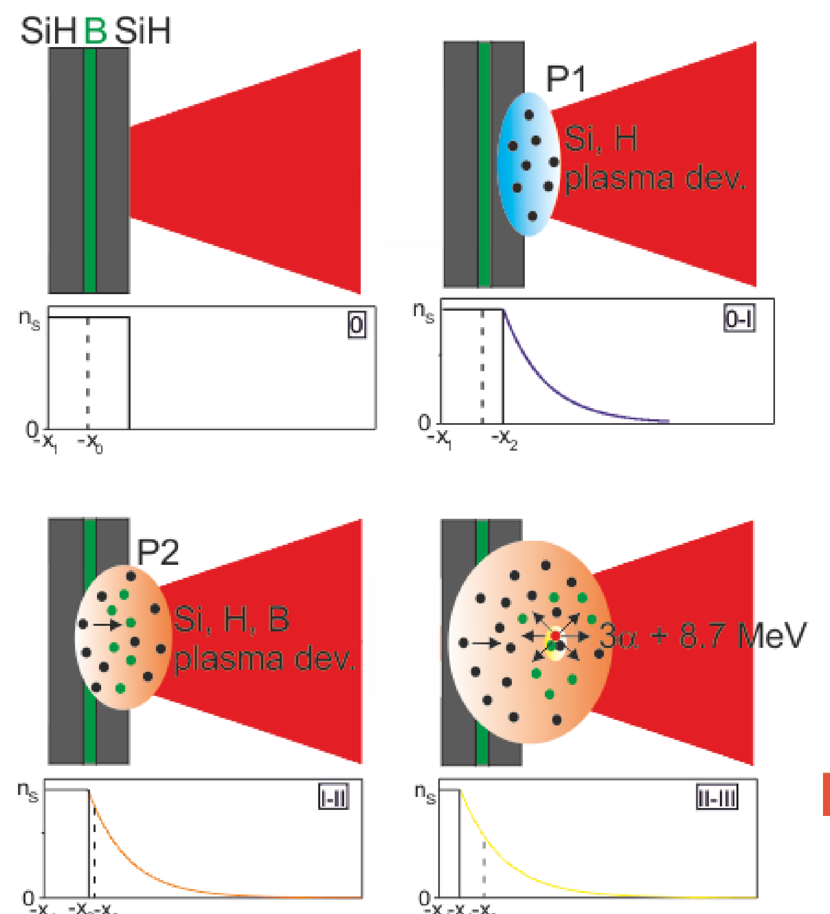


Exp. Setup and Target geometry



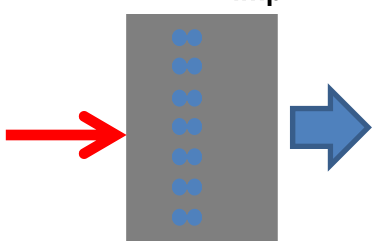
Simplified model ("artistic view")

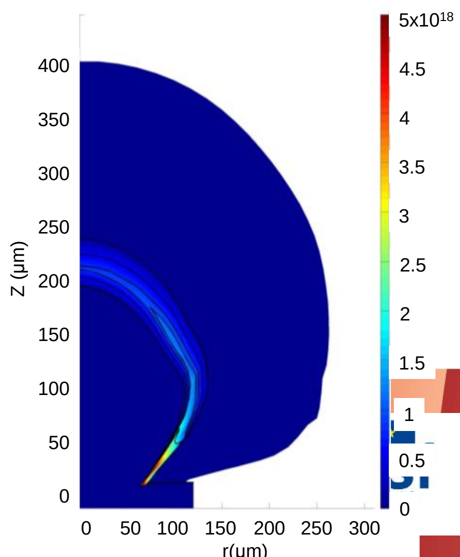
$p + B = 3\alpha + 8.7\,\mathrm{MeV}$



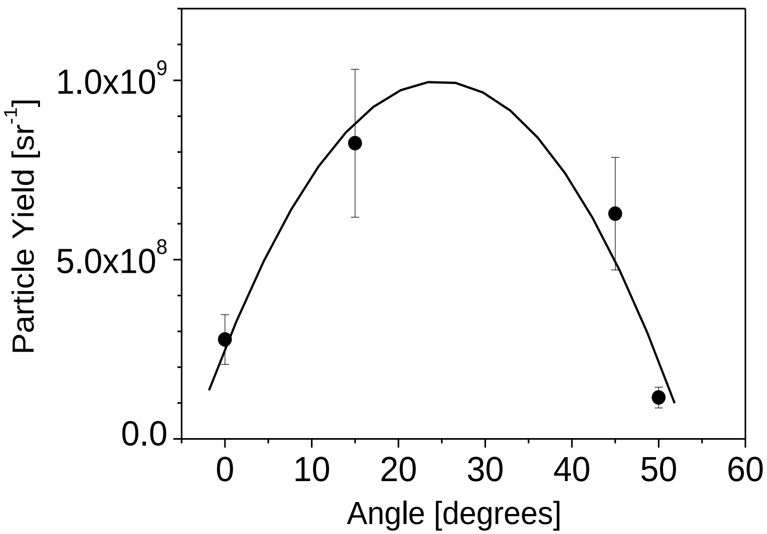
SiHB$_{impl}$: 0.5mm thick, 10^{22} cm^{-3} ^{11}B (@190 nm)

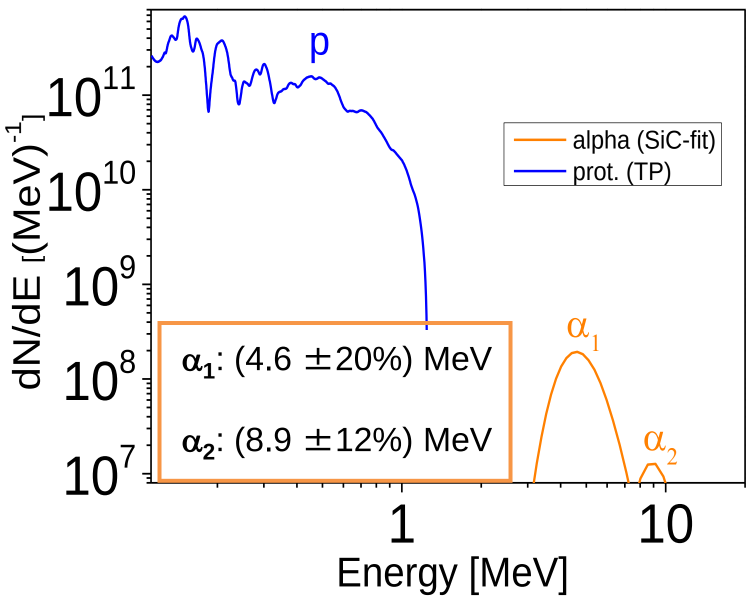
SiHB$_{impl}$





Alpha angular & energy distributions





PHYSICAL REVIEW X **4**, 031030 (2014)

Boron-Proton Nuclear-Fusion Enhancement Induced in Boron-Doped Silicon Targets by Low-Contrast Pulsed Laser

A. Picciotto,[1,*] D. Margarone,[2,†] A. Velyhan,[2] P. Bellutti,[1] J. Krasa,[2] A. Szydlowsky,[3,4] G. Bertuccio,[5] Y. Shi,[5] A. Mangione,[6] J. Prokupek,[2,7] A. Malinowska,[4] E. Krousky,[8] J. Ullschmied,[8] L. Laska,[2] M. Kucharik,[7] and G. Korn[2]

- Maximum alpha yield: **10^9/sr/pulse**
- Total alpha number: **4 × 10^8/pulse**
  - 2 x 10^3 times higher than *Belyaev et al.* (correction suggested in *Kimura et al, PRE 79 (2009)*) with 1.5-ps pulse width and 2 × 10^{18} W cm^{-2} intensity
  - 100-times higher than *Labaune et al.* (10^7/sr/pulse) with two laser beams (ns and ps) and two targets.
- Long laser pulse (**ns-class**), low contrast, maximum nominal laser intensity about 100-times lower (**3x10^{16} W cm^{-2}**)
- **High directionality, high current** ion beams with very compact systems compared to conventional accelerators
- To be used "in-situ" in laser plasma experiments: investigations on ion stopping power in plasma, on fusion cross section in plasma, or as diagnostic tool

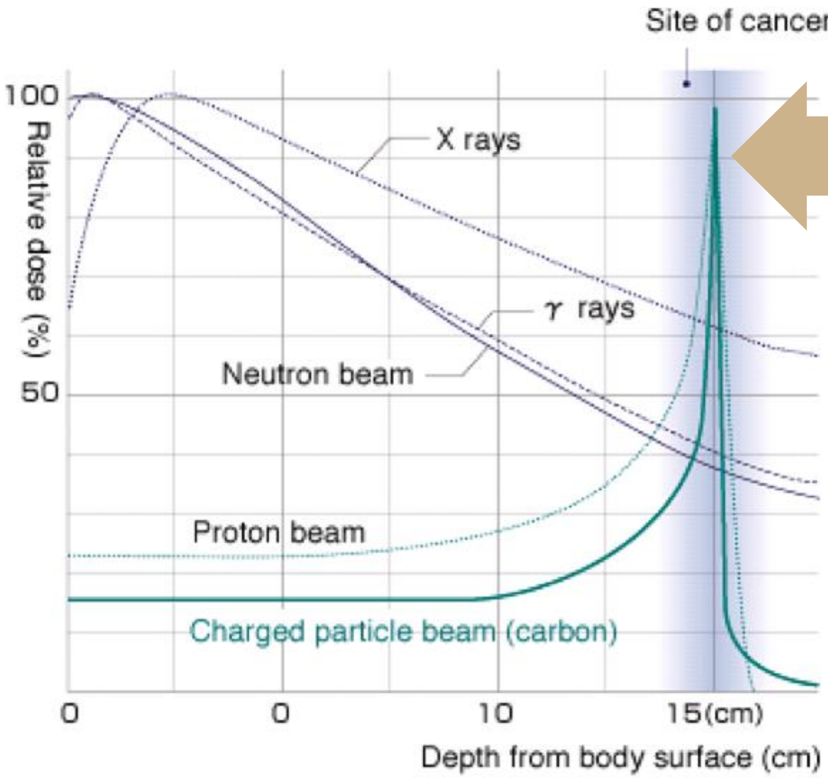
Medical research: Why?

Goal: use laser-driven ion beams for future applications

Good candidate as **demonstration-case** since medical applications are the most demanding in terms of beam characteristics and performances because they require the best effort in terms of:

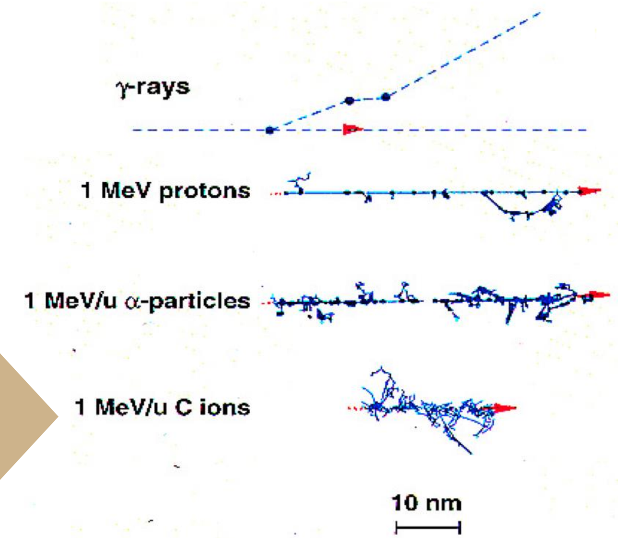
- beam delivering system
- development of advanced diagnostics
- absolute and relative dosimetry

Why Hadrontherapy?



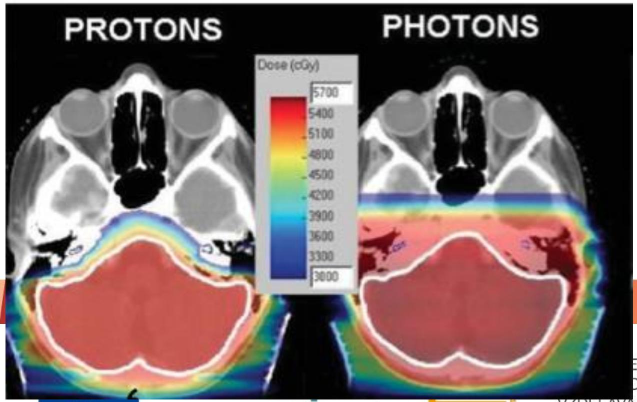
Physical advantages

Biological advantages

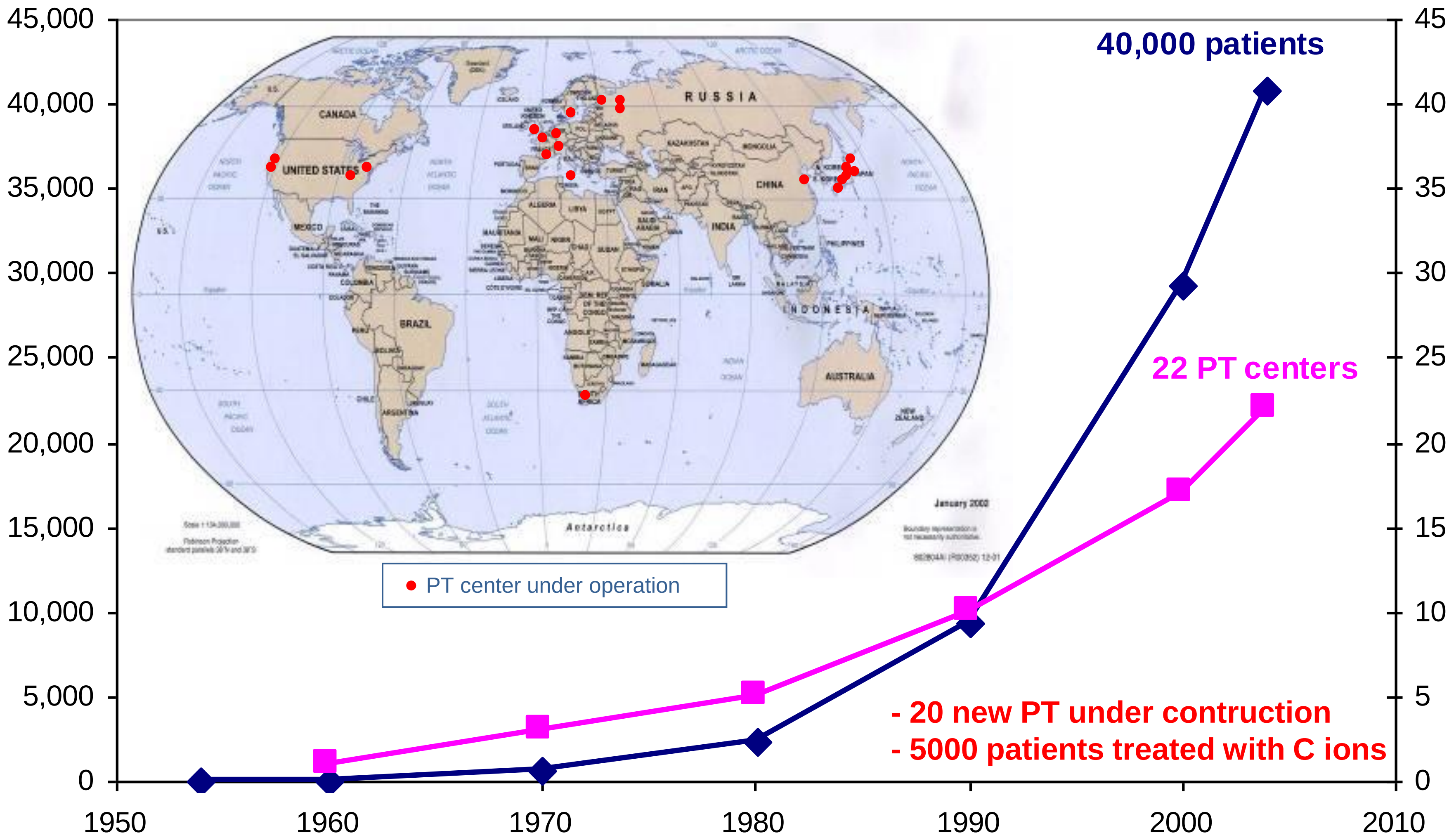


Density of secondary electrons is higher for charged radiation and it enhances DNA double strand break

Protons/ions allow precise tumor irradiation minimizing doses to healthy tissues



PT faces a fast growing demand!



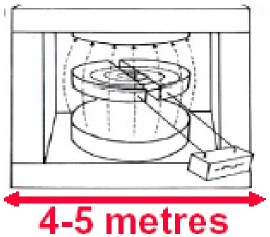
The spread of hadrontherapy centers is strongly limited by the <u>complexity</u> and <u>costs</u> of these facilities!

Hadrontherapy conventional accelerators

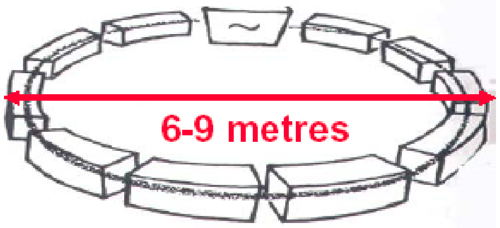
The accelerators used today in hadrontherapy are "circular"

Teletherapy with protons (200-250 MeV)

CYCLOTRONS (*) (Normal or SC)



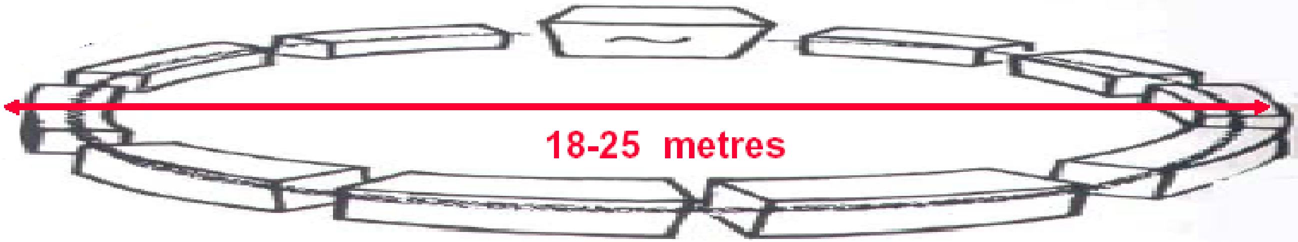
SYNCHROTRONS



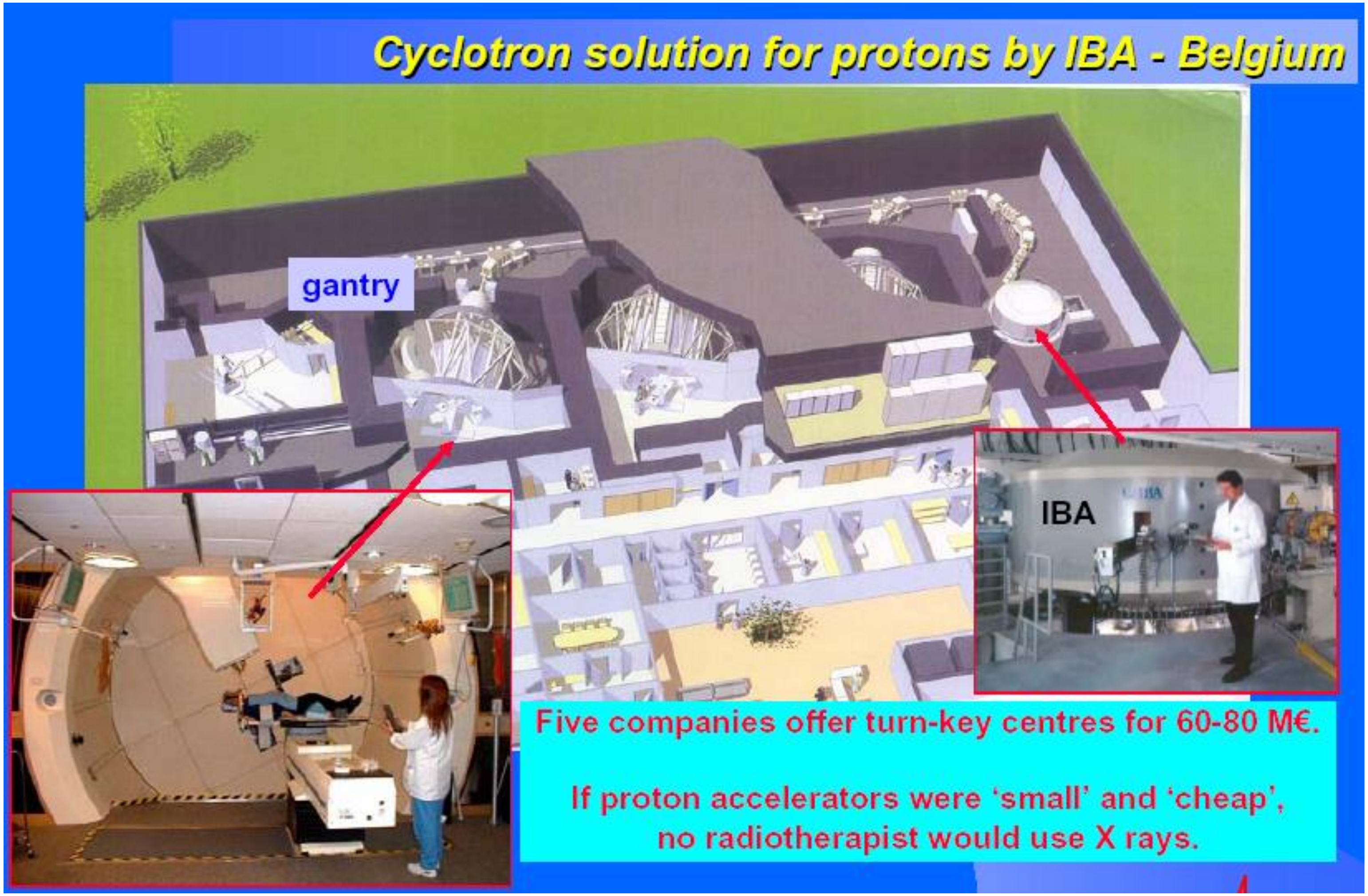
(*) also synchrocyclotrons

Teletherapy with carbon ions (4800 MeV = 400 MeV/u)

SYNCHROTRONS



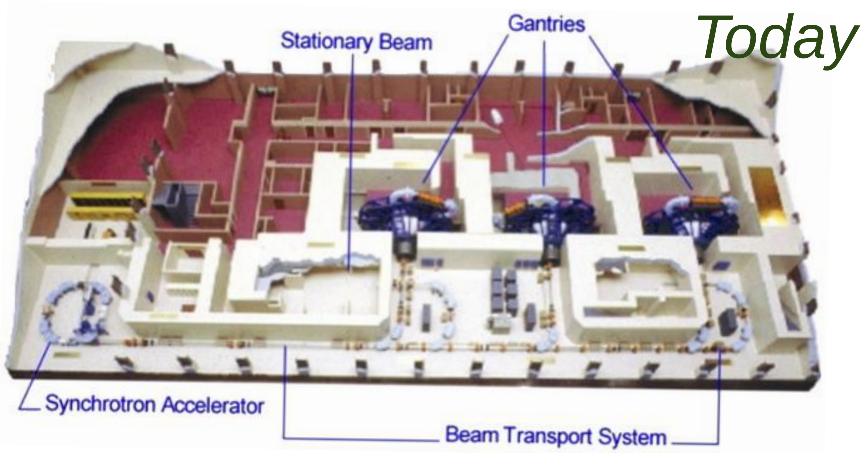
Hadrontherapy: a potential user case



…and a possible future for laser-based hadrontherapy facility?

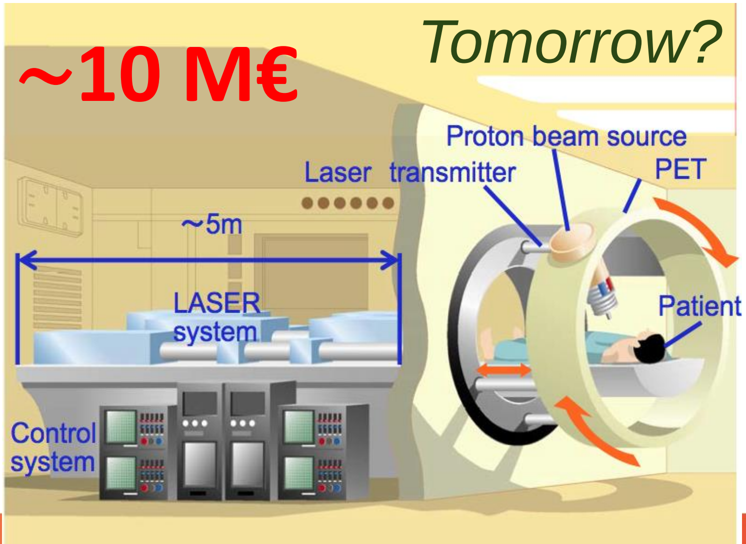
Conventional hadrontherapy facilities:

- High complexity for the beam production, acceleration and transport
- High cost: 100-200 M€

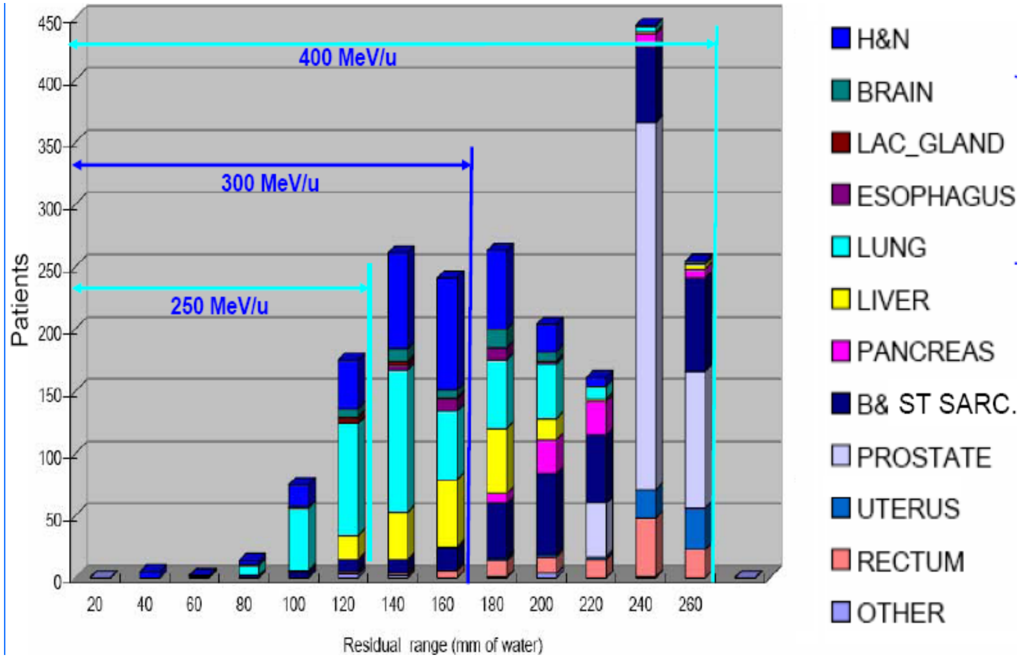


Laser-based hadrontherapy facilities:

- ***Compactness***
- ***Cost-reduction***
- ***Innovative treatment modalities:***
    - Variable energies in the accelerator (no degraders needed)
    - Hybrid treatment (protons, ions, electrons, gamma-rays, neutrons)
    - In-situ diagnostics (PET, X-rays)



but….

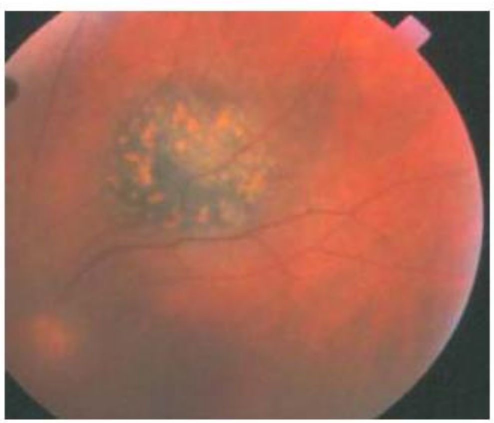


Drawbacks

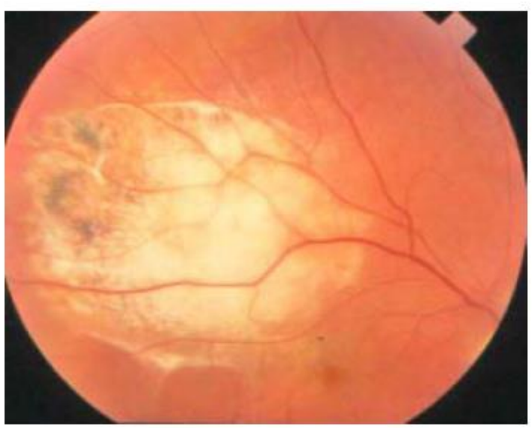
- **low reproducibility** (shot-to-shot)
- **large divergence**
- **large energy spread**
- **low energy** (<100 MeV for p)

Courtesy of P. Cirrone

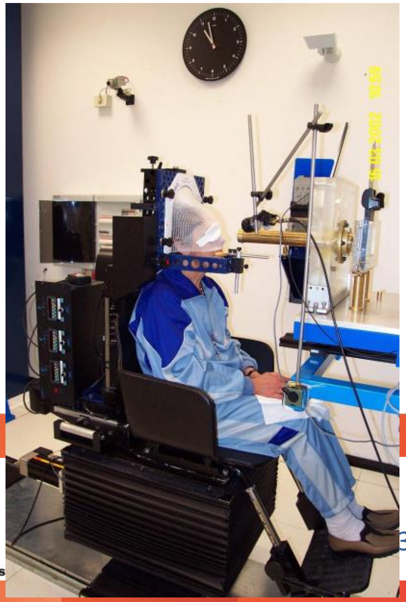
Eye tumor (62 MeV protons)



Melanoma (90%)



Hemangioma (10%)



Contents

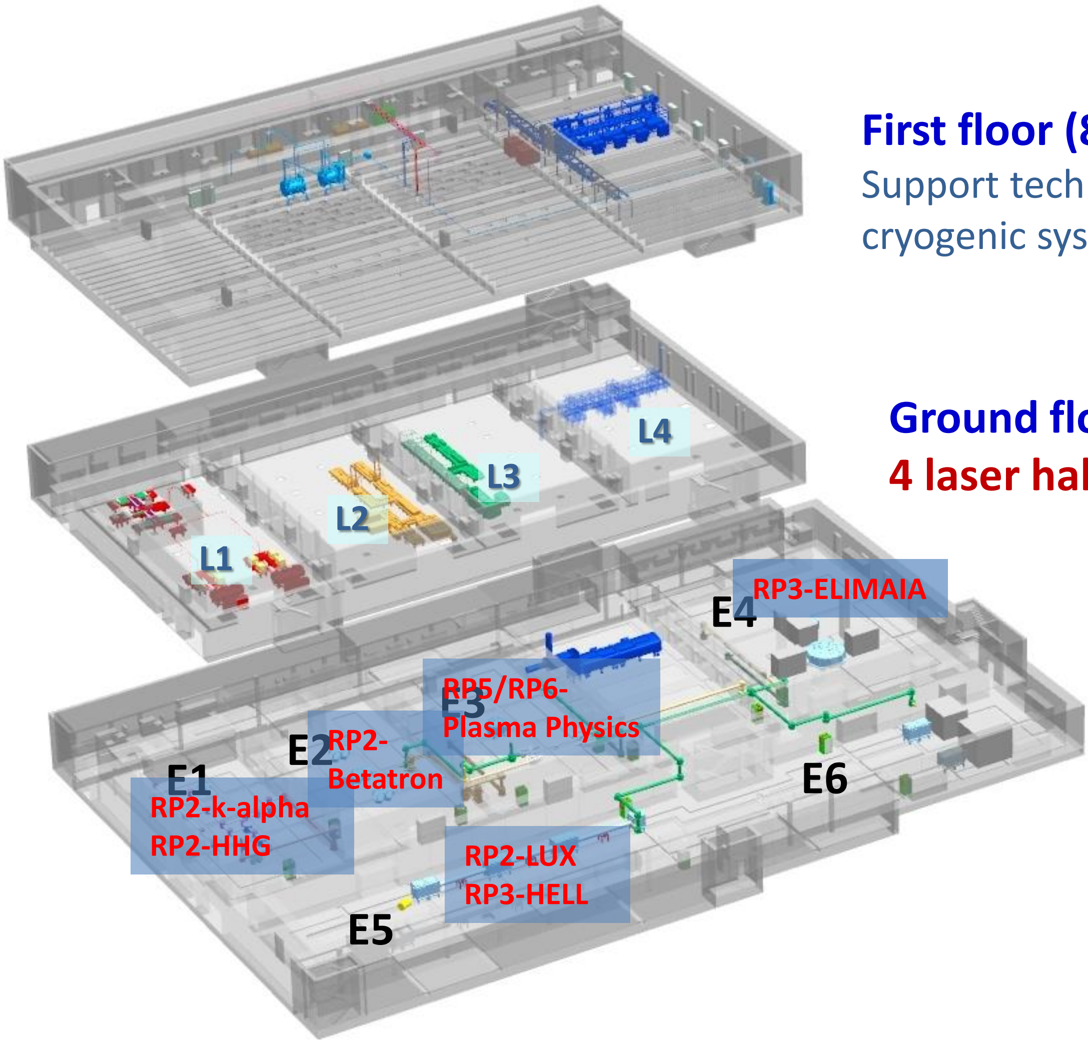
- Laser Driven Particle Acceleration

- Potential Applications
  - Laser-induced Nuclear Reactions (fusion...)
  - Laser-based Cancer Therapy (hadrontherapy)
  - ....

- **Particle Acceleration at ELI-Beamlines**
  - Ion Acceleration beamline
  - Electron Acceleration beamline

eli beamlines

ELI-Beamlines user facility



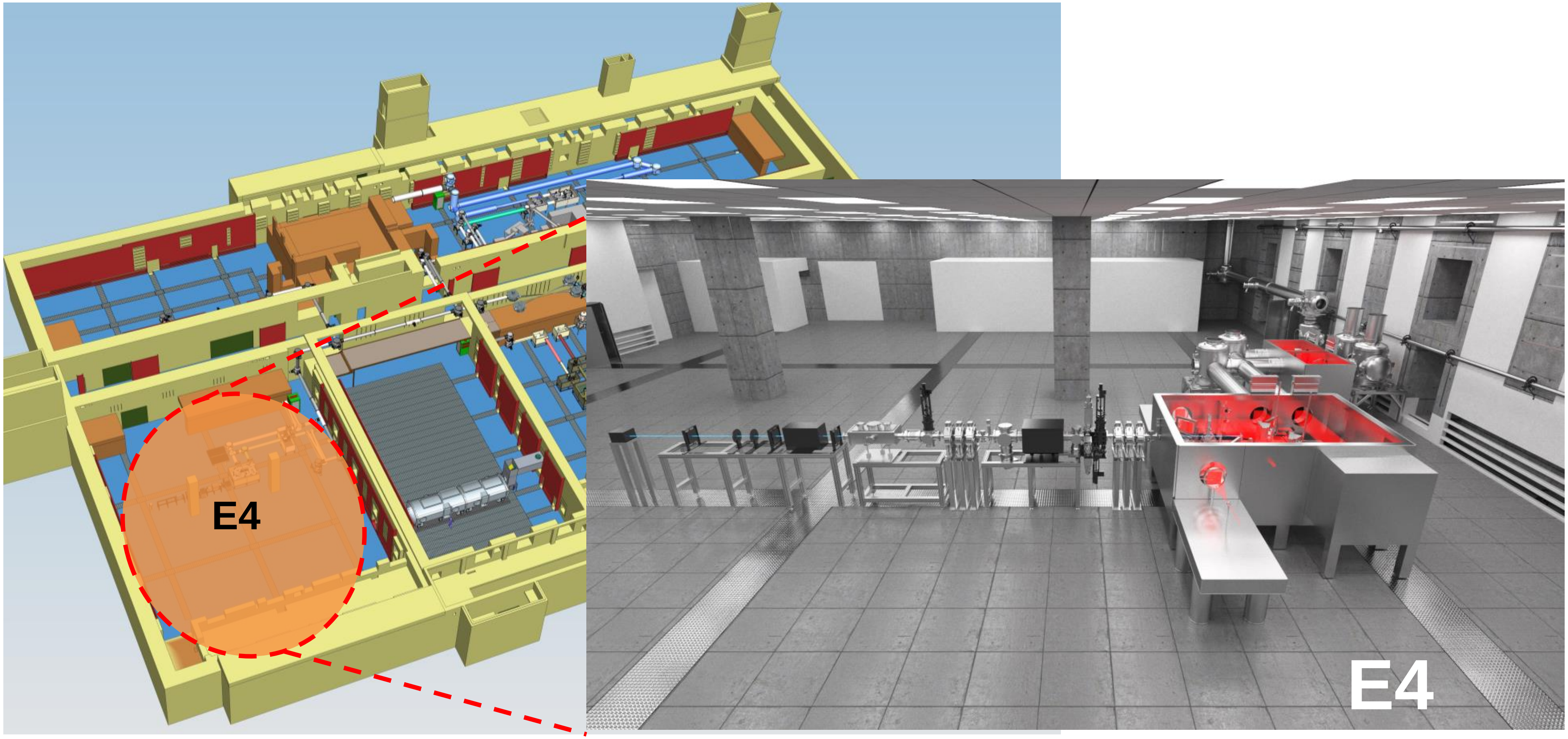
First floor (80 x 40 m)
Support technologies, cooling systems, cryogenic systems

Ground floor (80 x 40 m)
4 laser halls (L1 to L4)

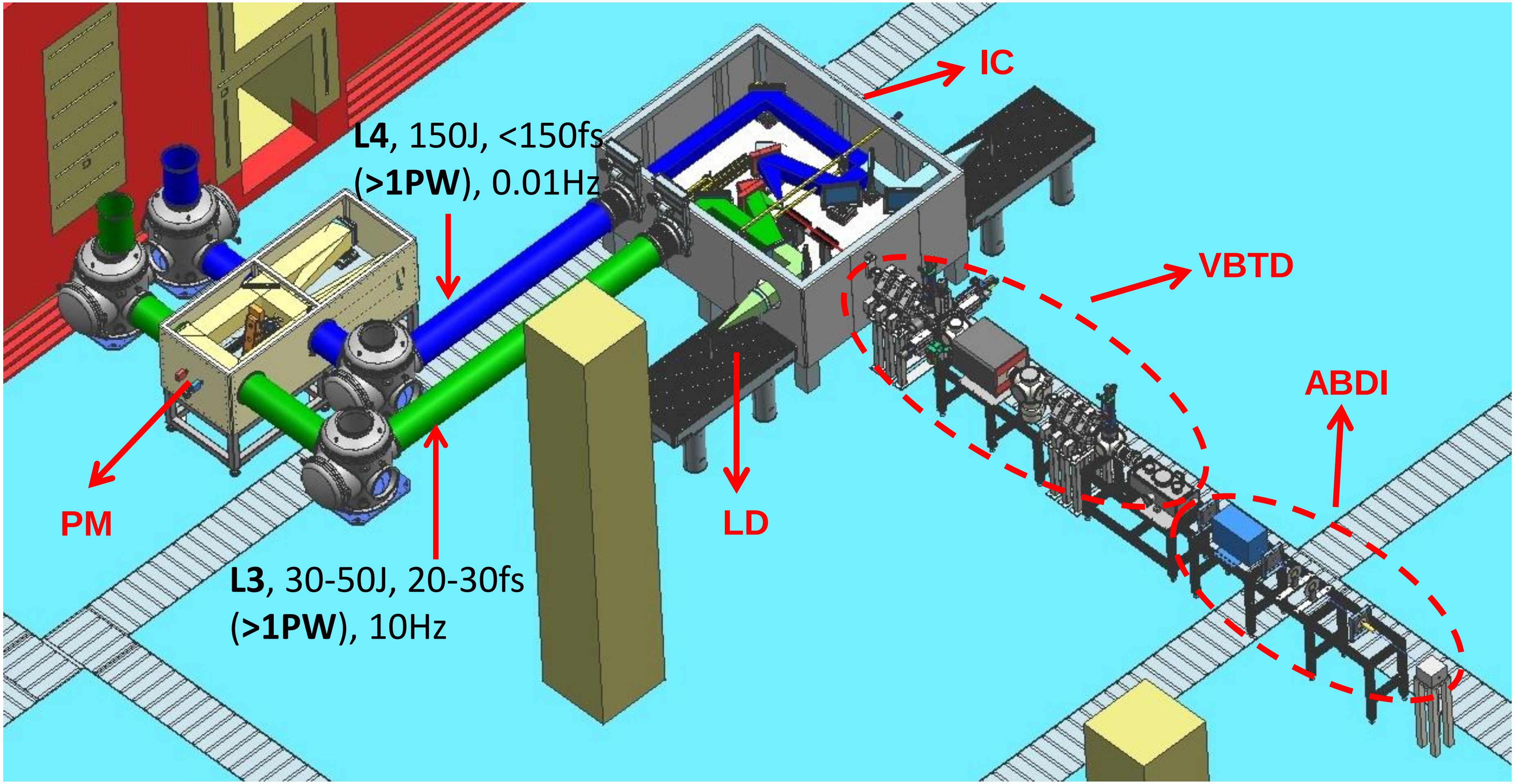
Basement (110 x 60 m)
6 dedicated experimental halls (E1 to E6)

ELIMAIA user beamline in E4

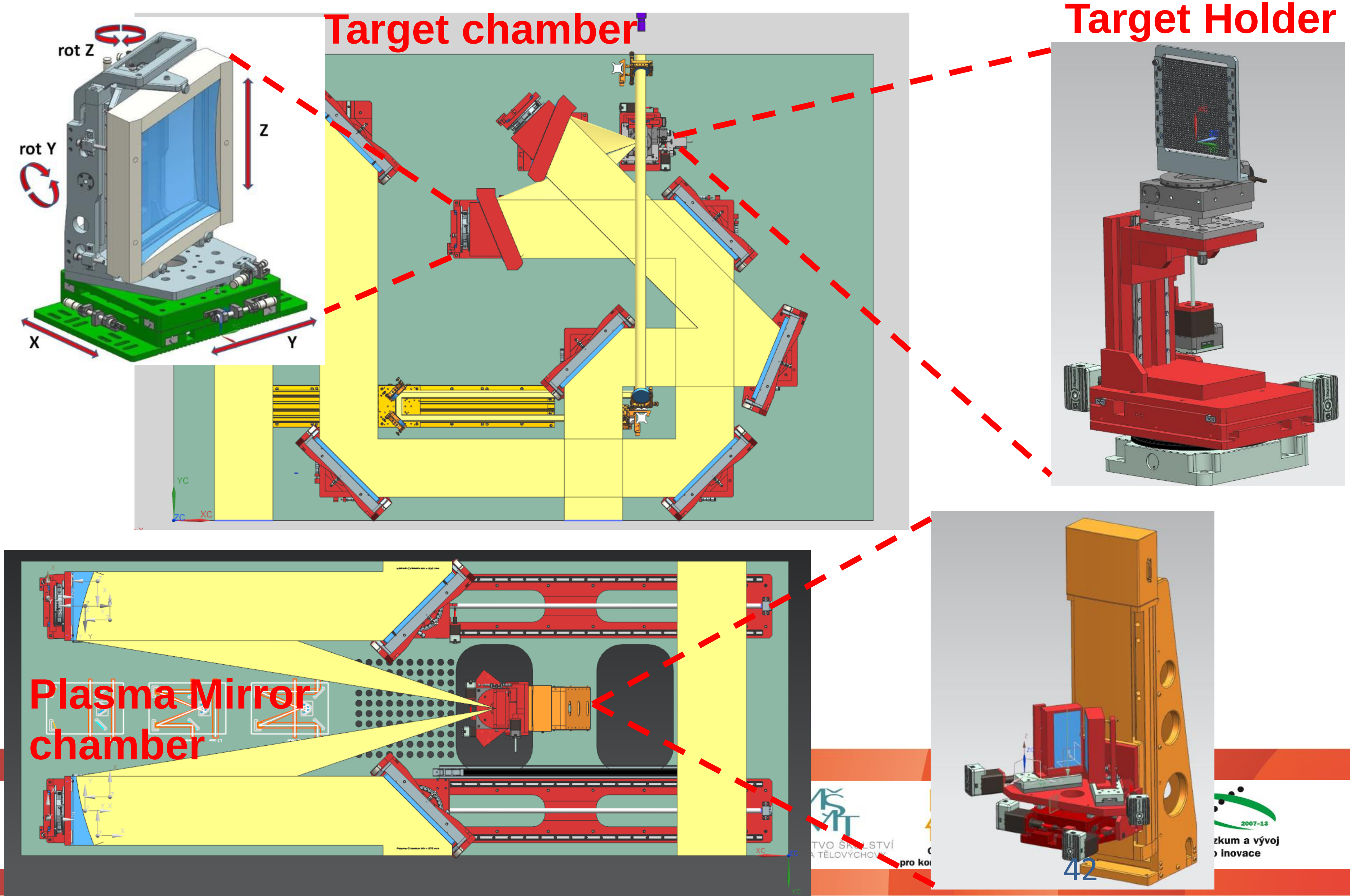
ELI Multidisciplinary Applications of laser-Ion Acceleration



ELIMAIA work packages

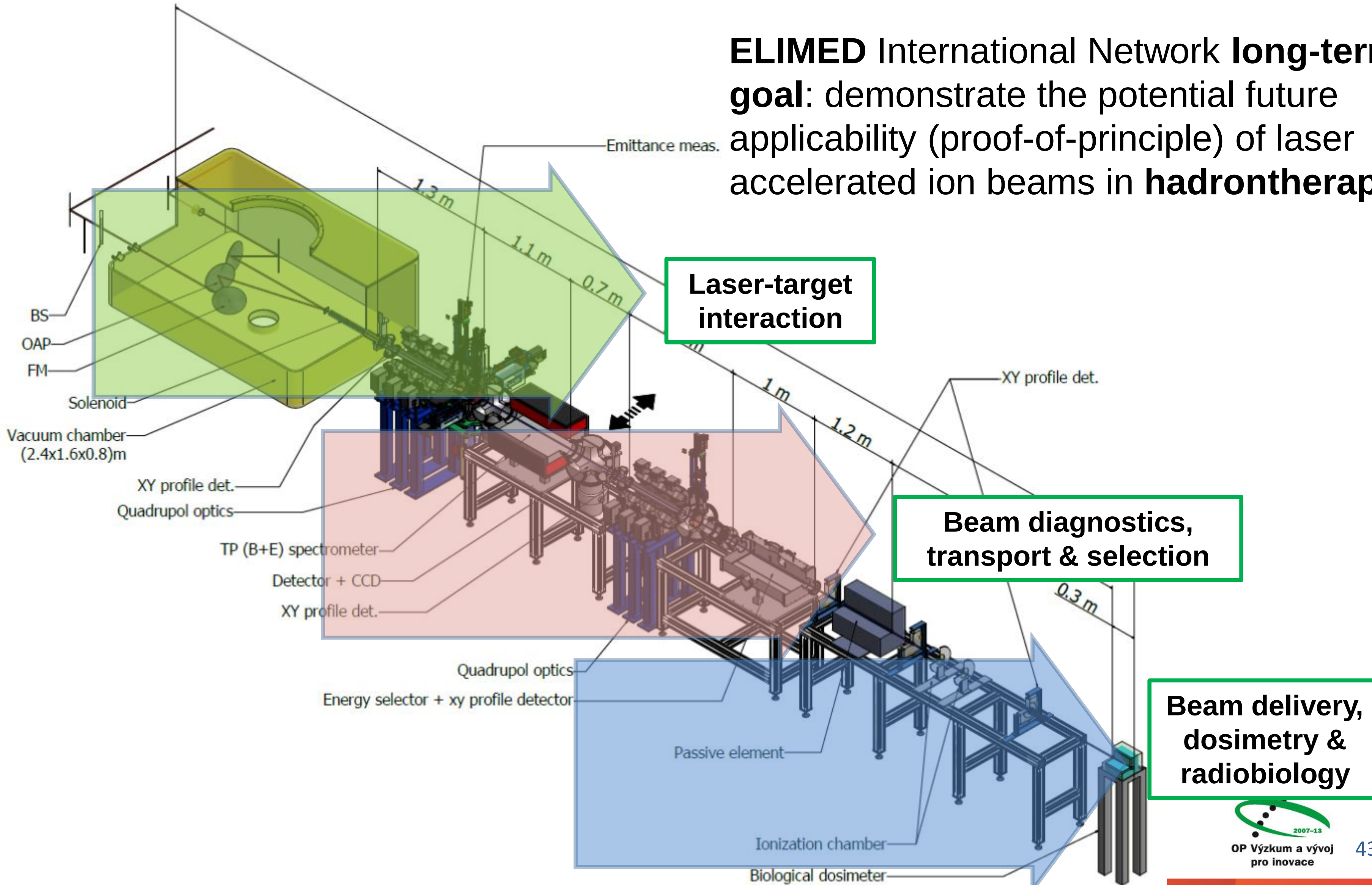


Towards a final design...



ELIMED network idea…

ELIMED International Network **long-term goal**: demonstrate the potential future applicability (proof-of-principle) of laser accelerated ion beams in **hadrontherapy**



OP Výzkum a vývoj pro inovace

eli beamlines

TÉCNICO LISBOA

FONDAZIONE BRUNO KESSLER

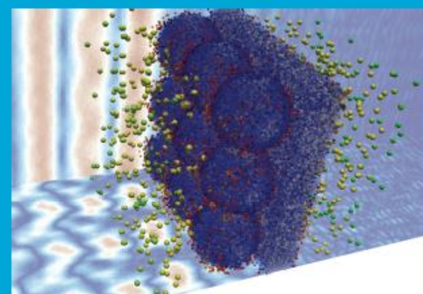
Queen's University Belfast

KPSI Kansai Photon Science Institute

Volume 1546

Conference collection

2nd ELIMED Workshop and Panel



Catania, Italy

18-19 October 2012

Editors

Daniele Margarone, Pablo Cirrone, Giacomo Cuttone and Georg Korn

AIP | Proceedings

proceedings.aip.org

2nd

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Azienda Ospedaliero Universitaria "Policlinico - Vittorio Emanuele" Catania Presidio "Gaspare Rodolico"

di Catania

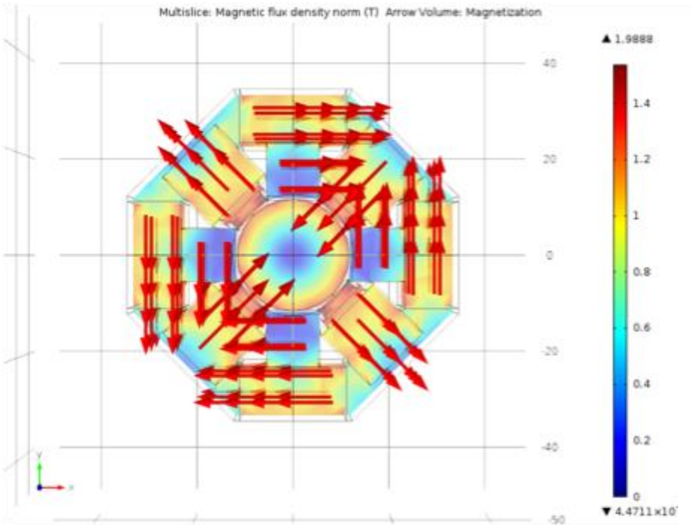
INFN

ITA Istituto Tecnologie Avanzate Laboratorio Nano Tecnologie

Consiglio Nazionale delle Ricerche Istituto di Bioimmagini e Fisiologia Molecolare

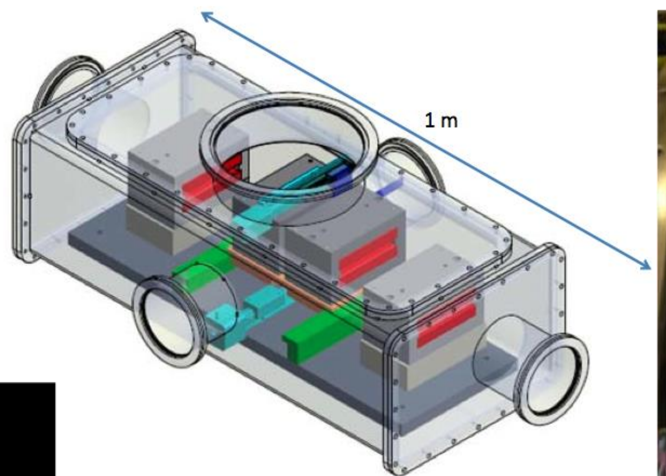
Beam Transport Prototypes

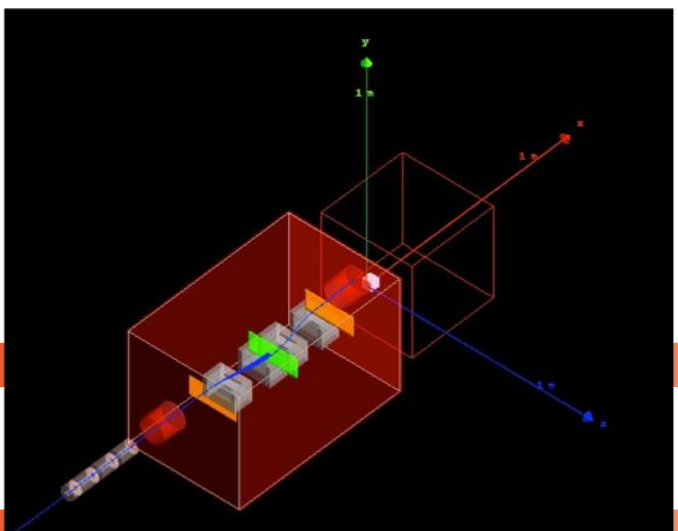
Quadrupole design for ion beam focusing



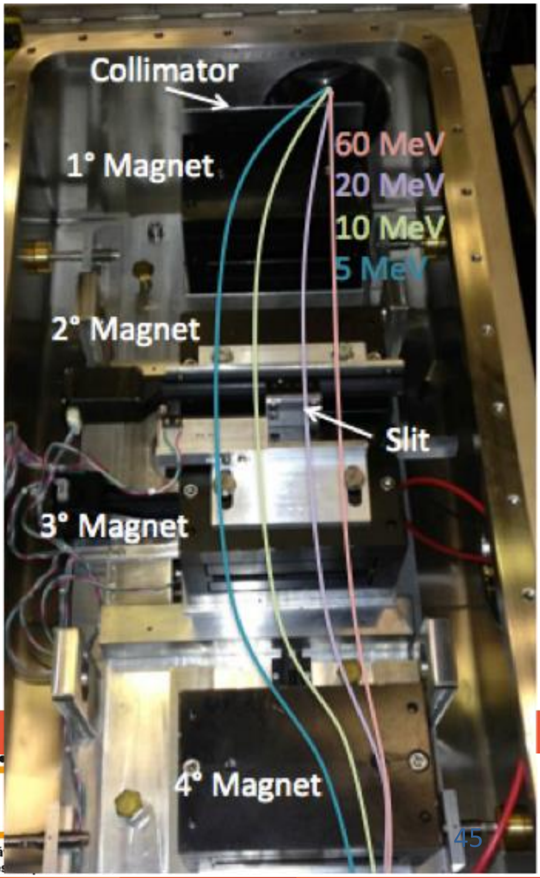
ESS (Energy Selection System):

- **Design and realization**
- **Calibration with 60 MeV proton beams (cyclotron)**
- **Numerical simulations (Geant4 toolkit)**



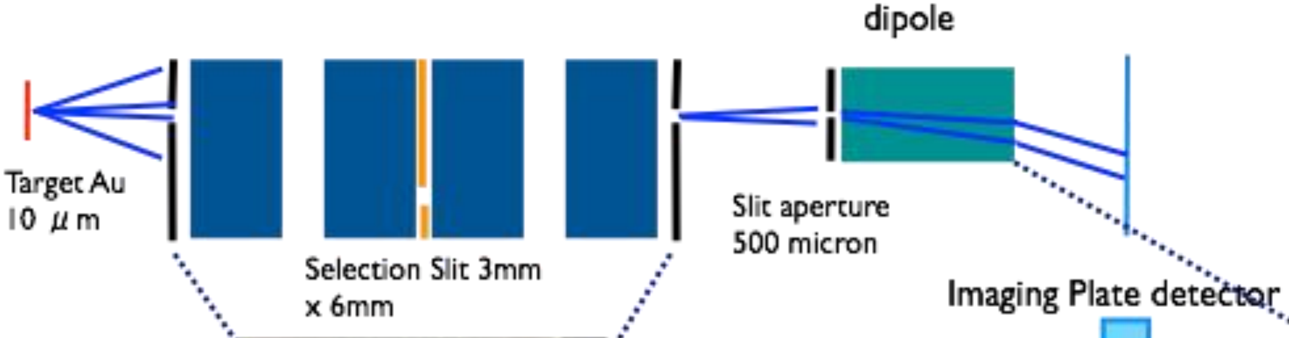


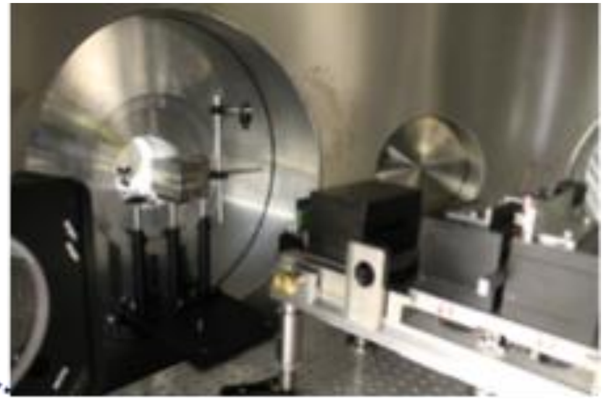
Courtesy of P. Cirrone

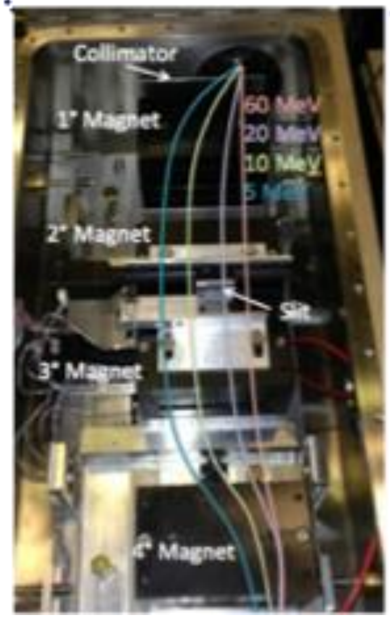


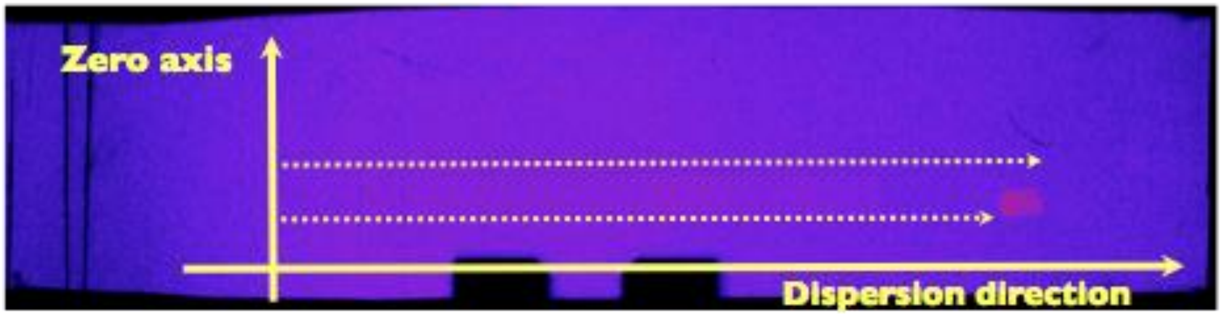
ESS tests with laser-driven protons @ TARANIS (Belfast)

Courtesy of P. Cirrone





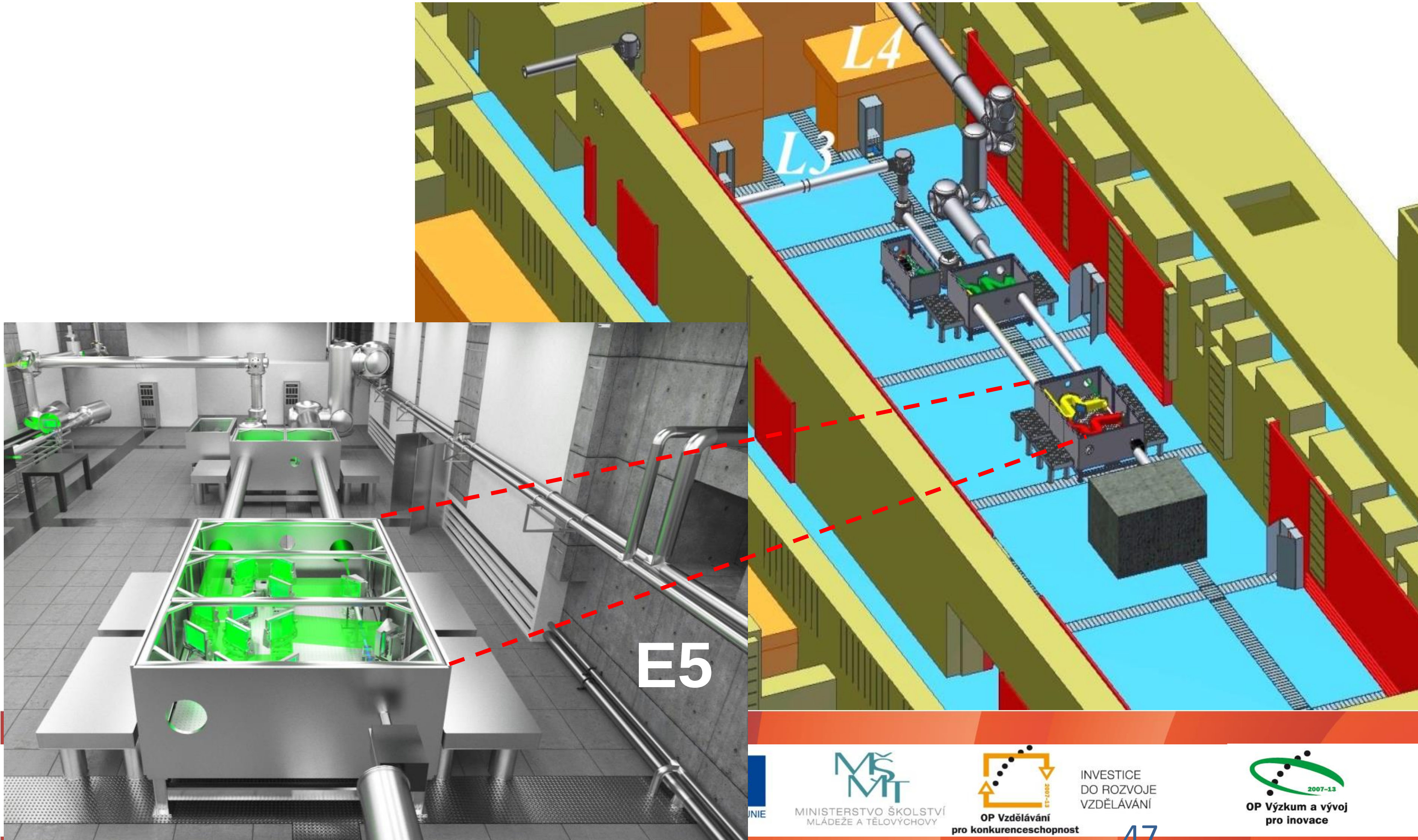




E_p(input): 1-10 MeV ($\Delta E/E$=100%)
E_p(output): 4.5±0.3 MeV ($\Delta E/E$=13%)
E_p(output): 7.4±0.6 MeV ($\Delta E/E$=16%)

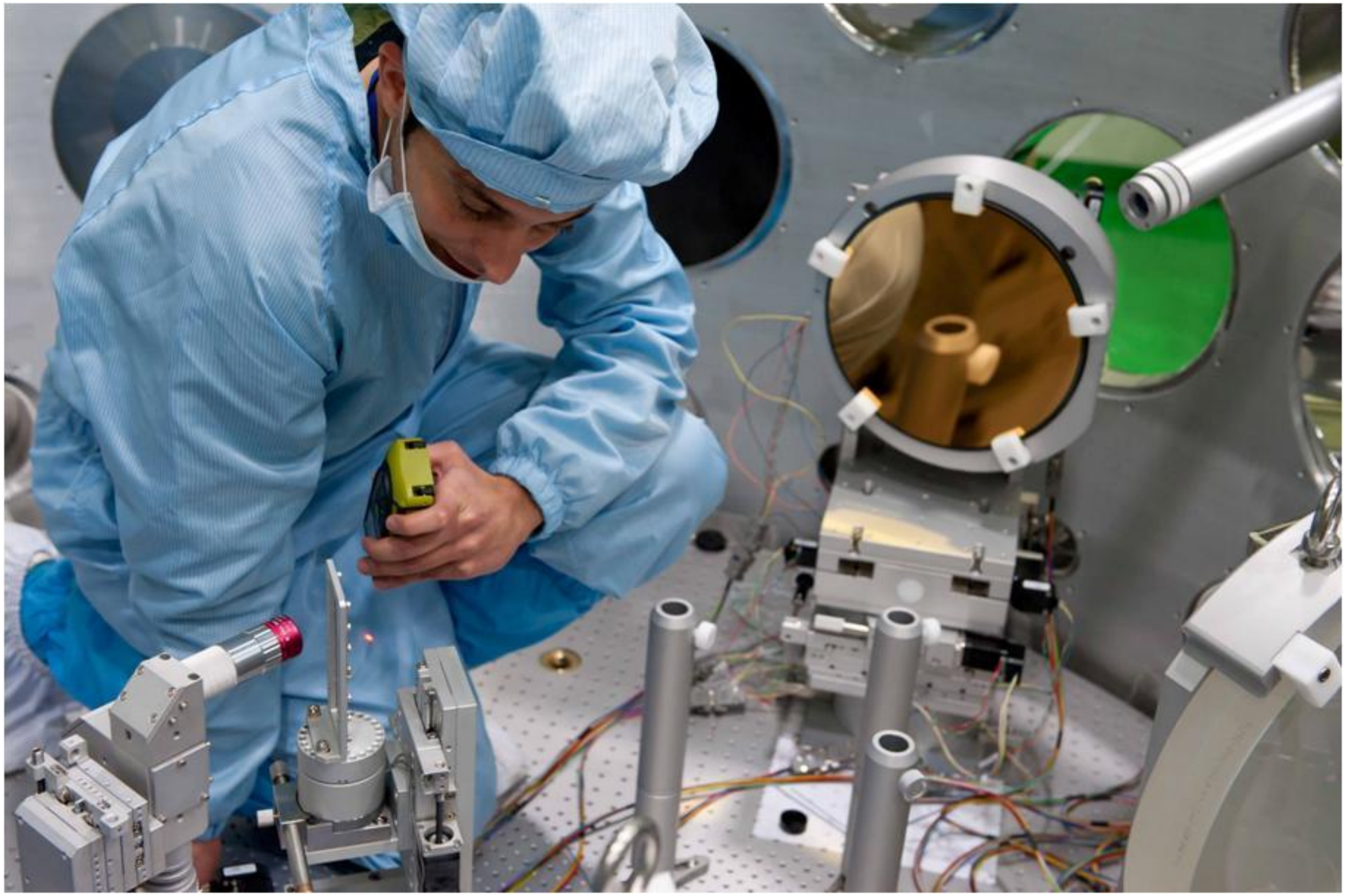
HELL user platform in E5

High-energy ELectron-acceleration by Lasers



eli beamlines

Thank you for your kind attention!



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esf evropský sociální fond v ČR

EVROPSKÁ UNIE

MINISTERSTVO ŠKOLSTVÍ MLÁDEŽE A TĚLOVÝCHOVY

OP Vzdělávání pro konkurenceschopnost

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

OP Výzkum a vývoj pro inovace

ELIMAIA goals and potential applications

Typical user requirements

- Wide **energy** and **fluenc**e range
- Small energy spread (**quasi-monoenergetic** beams)
- **Homogeneous** transverse beam distribution
- Shot-to-shot **stability** (energy and fluence)
- Variable beam spot size
- Full beam **control** (fluence and dose) with < 5% error
- Possibility of in-air irradiation (e.g. bio-samples)
- Use of different ion species (H, He, C, …)

Multidisciplinary Applied Research with laser driven ions

- Irradiation of **biological** and other samples (e.g. material science)
- Innovative approaches to **hadrontherapy**
- Time-resolved proton **radiography** of dense materials
- **Radiation damage** of various devices/materials (high dose rate)
- **Detector** characterization (high peak current)
- **Pump-probe** investigations (WDM, ion stopping power in plasma,…)
- Radio-isotopes for positron emission tomography (PET)
- **Beam-target** nuclear reactions for high brilliance secondary sources (alphas, neutrons)