Laser-driven electron beam acceleration and applications

L. Labate

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The ILIL (*Intense Laser Irradiation Laboratory*) group

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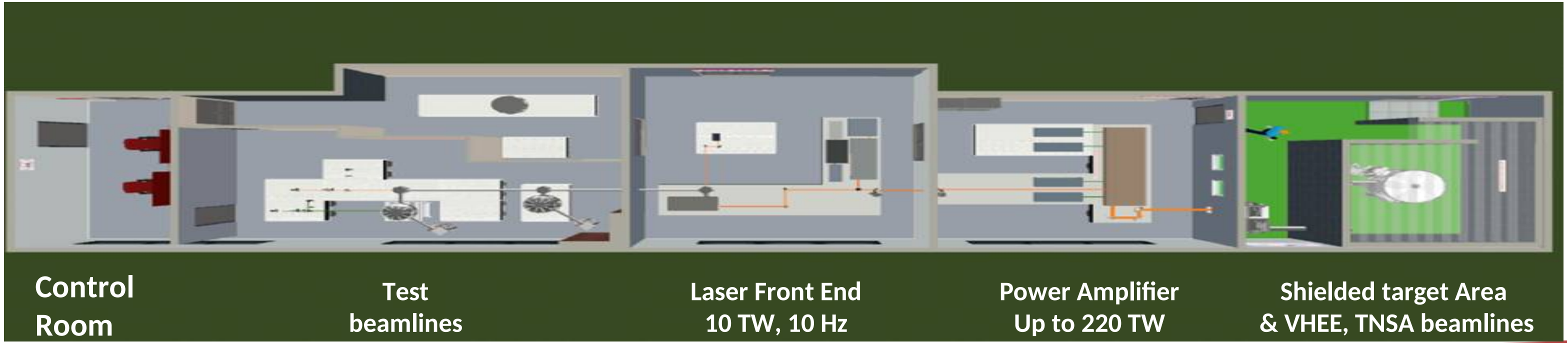
Gabriele **CRISTOFORETTI**
Petra **KOESTER**
Luca **LABATE***
Federica **BAFFIGI**
Lorenzo **FULGENTINI**
Alessandro **FREGOSI** term
Daniele **PALLA** term
Costanza **PANAINO** term
Simona **PICCININI** term
Martina **SALVADORI** term
Emma **HUME** postdoc
Federico **AVELLA** PhD student
David **GREGOCKI** PhD student
Simon **VLACHOS** PhD student
Gianluca **CELLAMARE** (associated)

Antonio **GIULIETTi** associated
**Also at Istituto Nazionale di Fisica Nucleare*

CNR Campus in Pisa

The Intense Laser Irradiation Laboratory (ILIL) at CNR-INO



Control Room

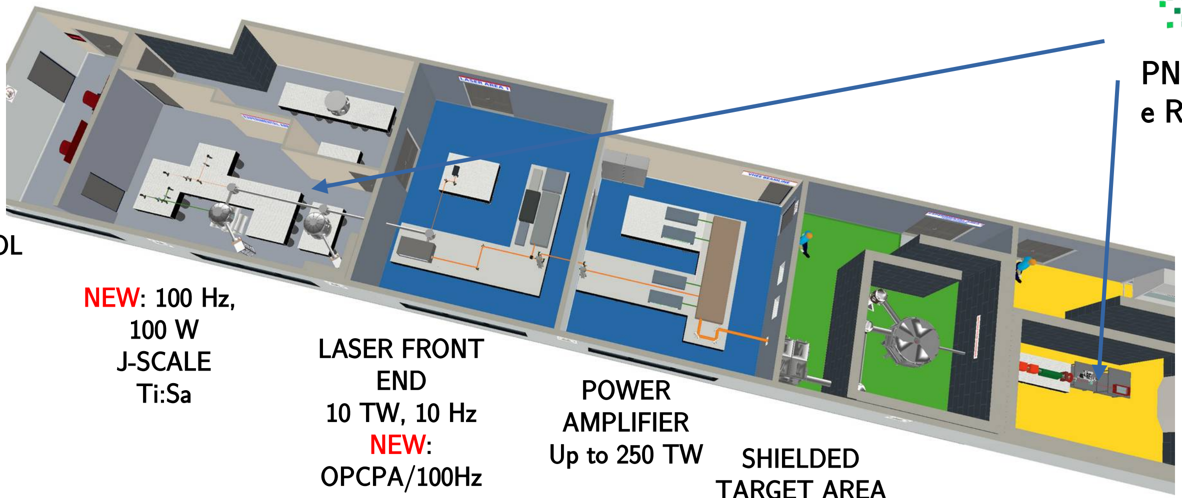
Test beamlines

Laser Front End
10 TW, 10 Hz

Power Amplifier
Up to 220 TW

Shielded target Area
& VHEE, TNSA beamlines

The Intense Laser Irradiation Laboratory (ILIL)



NEW: HAP kHz LASER DEV. LAB

USER CONTROL ROOM

NEW: 100 Hz, 100 W J-SCALE Ti:Sa

LASER FRONT END
10 TW, 10 Hz
NEW: OPCPA/100Hz UPGRADE

POWER AMPLIFIER
Up to 250 TW

SHIELDED TARGET AREA for PARTICLE ACCELERATION

NEW: BEAMLINE for *FLASH* PRE-CLINICAL STUDIES

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

PNRR ("Piano Nazionale di Ripresa e Resilienza")

NEW: UNDER- GROUND BUNKER

Main research fields

Laser-driven particle accelerators
- Electron acceleration and X-rays radiation sources
- Light Ion acceleration

Applications in medicine, material science, ...

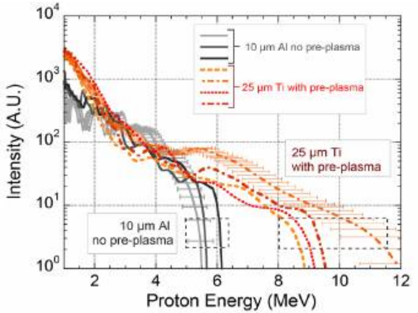
Laser-plasma interactions in ICF and Shock ignition*
Laser-driven instabilities and plasma characterization
Diagnostics of ICF-relevant plasmas

OPEN

Enhanced laser-driven proton acceleration via improved fast electron heating in a controlled pre-plasma

Leonida A. Gizzi[1,2]✉, Elisabetta Boella[3,4]✉, Luca Labate[1,2]✉, Federica Baffigi[1],
Pablo J. Bilbao[3], Fernando Brandi[1], Gabriele Cristoforetti[1], Alberto Fazzi[5,6]

Scientific Reports | (2021) 11:13728

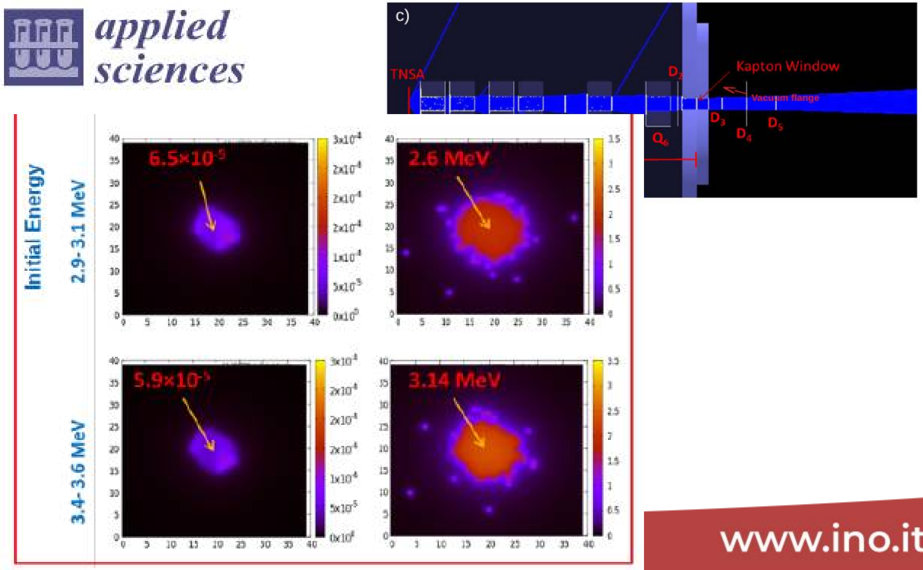


Article

A Few MeV Laser-Plasma Accelerated Proton Beam in Air Collimated Using Compact Permanent Quadrupole Magnets

Fernando Brandi [1,*], Luca Labate [1,2,*], Daniele Palla [1,†], Sanjeev Kumar [1,†,‡], Lorenzo Fulgentini [1],
Petra Koester [1], Federica Baffigi [1], Massimo Chiari [3], Daniele Panetta [4] and Leonida Antonio Gizzi [1,2]

applied sciences

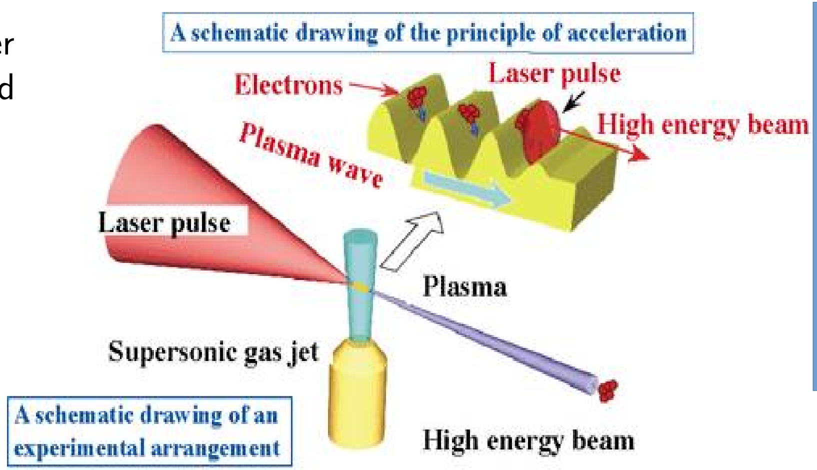


Outline

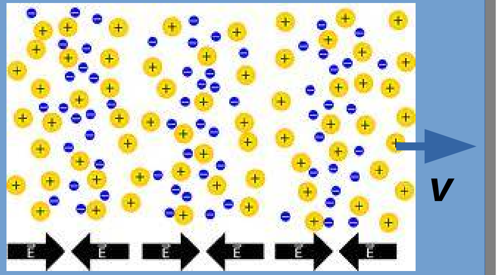
- A brief introduction to laser-driven electron acceleration
    - Laser Wake-Field Acceleration – LWFA
    - A glimpse at a typical LWFA experiment (diagnostics)
- A very brief introduction to laser-driven X/gamma-ray secondary sources
- Acceleration of Very-High Energy Electron (VHEE) beams for applications in medicine
- Summary and perspectives

A quick look at the basics of Laser WakeField Acceleration (LWFA) process

Ultrashort and ultraintense laser pulses can be fruitfully exploited to accelerate electrons up to relativistic energy



Electron plasma wave $v_{phase}^{(wake)} \simeq v_{group}^{(laser)} \simeq c$

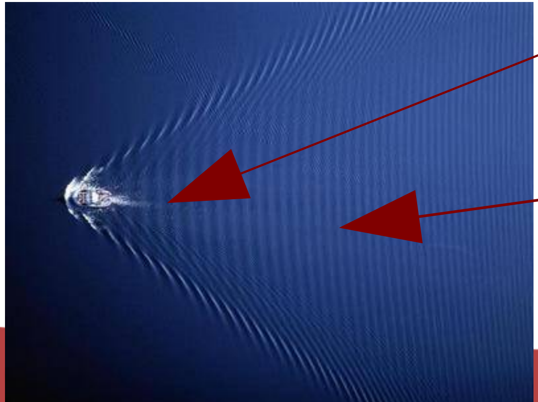


Longitudinal wave → longitudinal electric field

The basic ingredients:

1. Excite a plasma wave in the wake of the laser pulse

2. Let some electrons "surf" the wave (get injected into the right phase of the wake and gain energy)



Laser pulse

Plasma wave

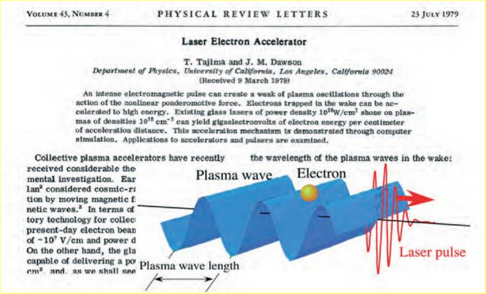
Electron bunch

A few “details” on LWFA

“Basic” requirements for a wave to accelerate electrons:
- intense longitudinal electric field
- phase velocity close to *c*

→ Fulfilled by wake (plasma) waves

***1979**: proposal by Tajima&Dawson*



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently
received considerable the
mental investigation. Ear
lan^2 considered cosmic-r
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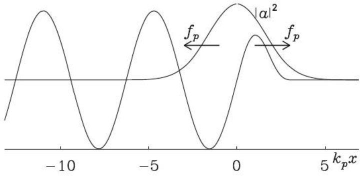
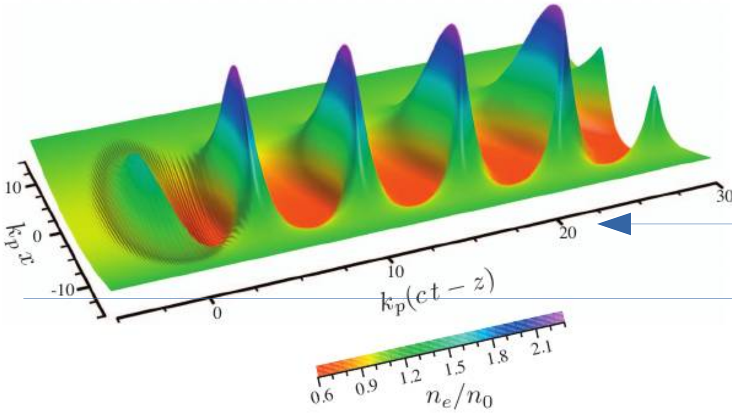
tory technology for collec
present-day electron bean
of ~10^7 V/cm and power d
On the other hand, the gla
capable of delivering a po
cm^2, and, as we shall see

the wavelength of the plasma waves in the wake:

The plasma wave can be excited in the wake of an intense laser pulse propagating in a plasma due to the ***ponderomotive force***

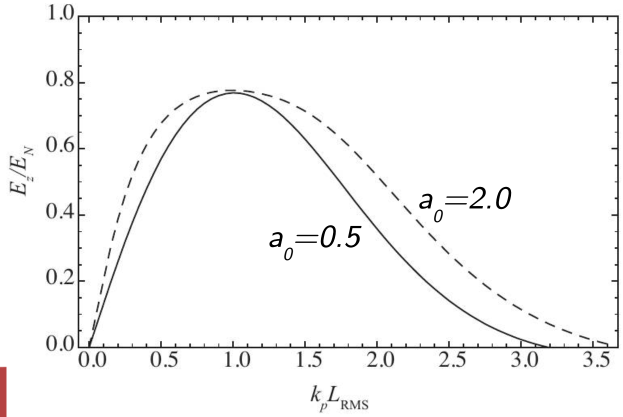




Linear wave

Highly nonlinear wave

The amplitude of the excited wave depends on the pulse length → need for ultrashort laser pulses



LWFA: maximum accelerating field

The maximum electric field amplitude is given by the wave-breaking limit, which in the relativistic case can exceed by several times the non-relativistic one

$$E_{\mathrm{WB}} = \sqrt{2}(\gamma_p - 1)^{1/2} E_0$$

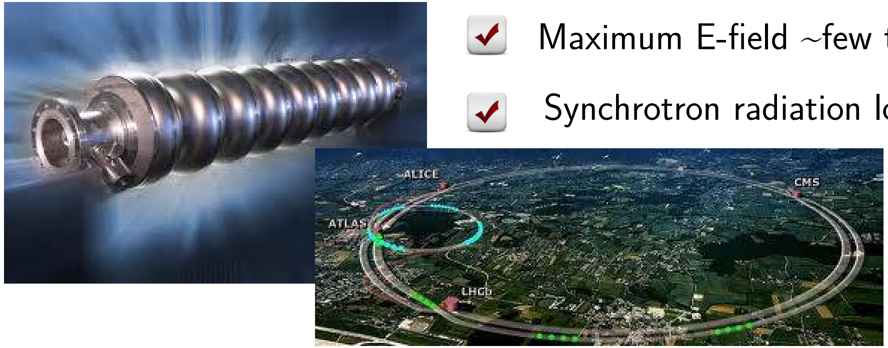
$\gamma_p \simeq \omega / \omega_p$ *(phase velocity ~ laser pulse group velocity)*

$E_0 = c m_e \omega_p / e$ *(cold, non-relativistic limit)*

Example: $n_e = 10^{17}\,\mathrm{cm}^{-3}$, $\lambda = 1\,\mu\mathrm{m}$, $E_{WB} = 14\, E_0$

$E \sim$ 300 GV/m (for 100% density perturbation at $n \sim 10^{19}\ \mathrm{cm}^{-3}$)

To be compared with **classical (RF-based) accelerators limits**

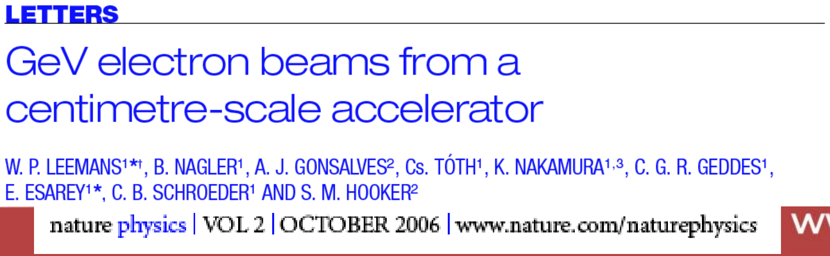


☑ Maximum E-field ~few tens of MV/m (due to breakdown)

☑ Synchrotron radiation losses → ***large radius***

The LWFA mechanism allows electron acceleration up to relativistic energy to be obtained over cm-scale acceleration lengths

→ ***table-top accelerators***



LETTERS

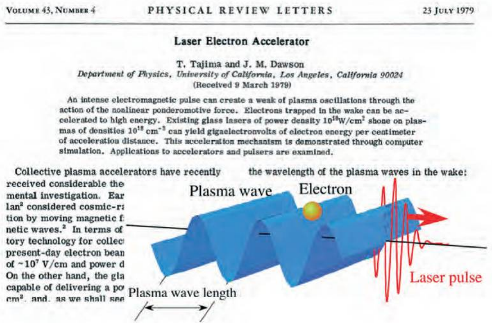
GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

nature physics | VOL 2 | OCTOBER 2006 | www.nature.com/naturephysics

A “historical” taste of the literature on LWFA

1979: *proposal by Tajima&Dawson*



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

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On the other hand, the gla
capable of delivering a po
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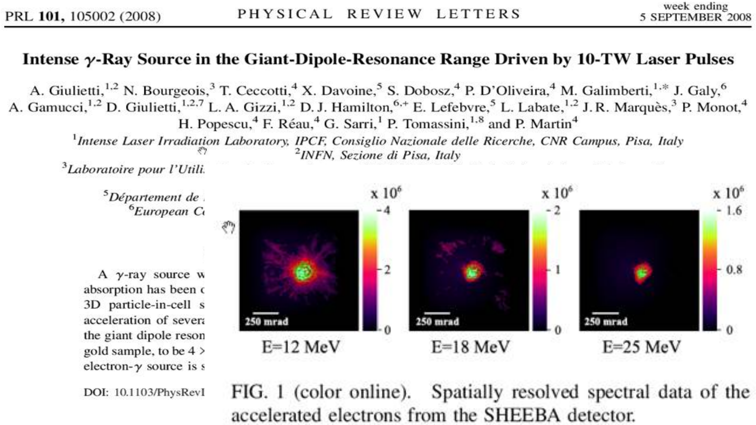
the wavelength of the plasma waves in the wake:

2004: *“Dream beam” front cover of Nature (3 papers reporting “high-quality” e⁻ bunch production)*

End of noughties: *routine production of stable e⁻ bunch*



PRL **101,** 105002 (2008) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2008

Intense γ-Ray Source in the Giant-Dipole-Resonance Range Driven by 10-TW Laser Pulses

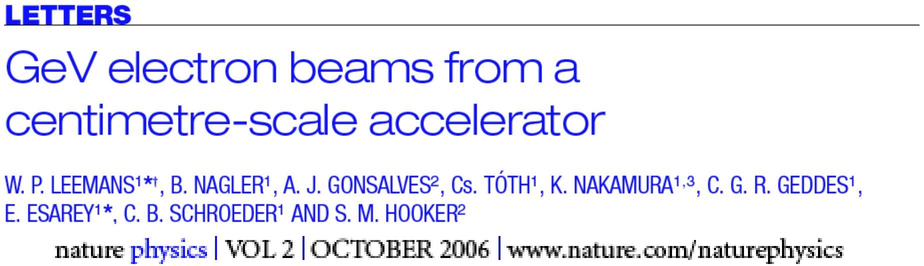
A. Giulietti,[1,2] N. Bourgeois,[3] T. Ceccotti,[4] X. Davoine,[5] S. Dobosz,[4] P. D'Oliveira,[4] M. Galimberti,[1,*] J. Galy,[6]
A. Gamucci,[1,2] D. Giulietti,[1,2,7] L. A. Gizzi,[1,2] D. J. Hamilton,[6,+] E. Lefebvre,[5] L. Labate,[1,2] J. R. Marquès,[3] P. Monot,[4]
H. Popescu,[4] F. Réau,[4] G. Sarri,[1] P. Tomassini,[1,8] and P. Martin[4]
[1]*Intense Laser Irradiation Laboratory, IPCF, Consiglio Nazionale delle Ricerche, CNR Campus, Pisa, Italy*
[2]*INFN, Sezione di Pisa, Italy*
[3]*Laboratoire pour l'Utili*
[5]*Département de*
[6]*European C*

A γ-ray source w
absorption has been
3D particle-in-cell s
acceleration of sever
the giant dipole reson
gold sample, to be 4 ×
electron-γ source is

DOI: 10.1103/PhysRevI

FIG. 1 (color online). Spatially resolved spectral data of the accelerated electrons from the SHEEBA detector.

2006: *GeV energy reported*



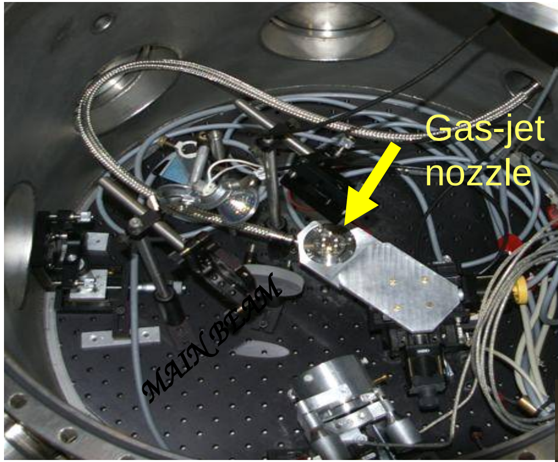
LETTERS

GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

nature physics | VOL 2 | OCTOBER 2006 | www.nature.com/naturephysics

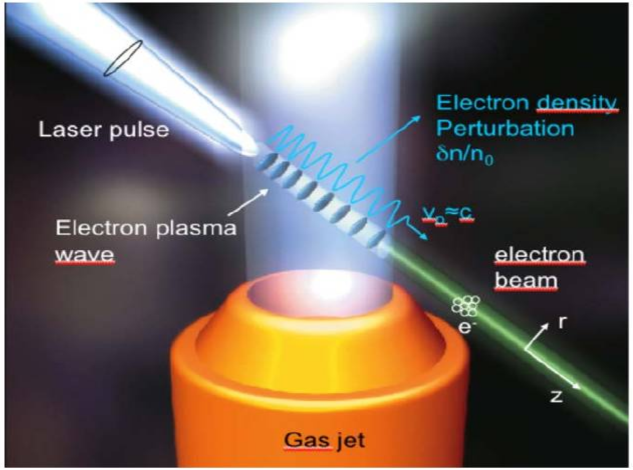
A glimpse of a typical “accelerator stage” setup and footprint

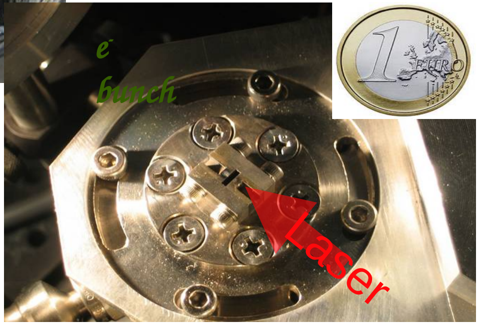


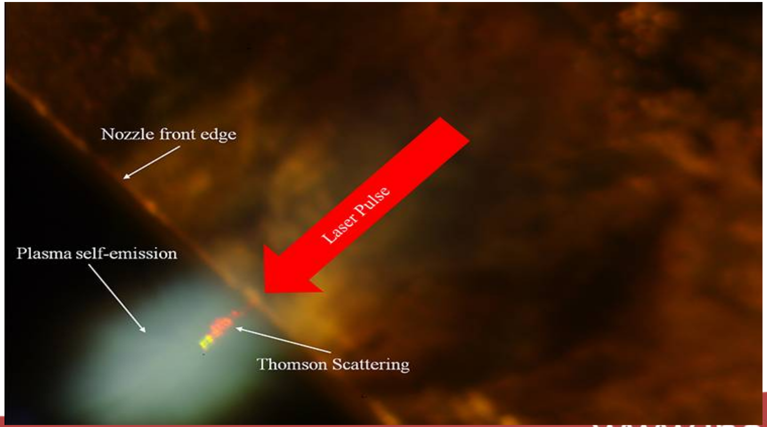
Basic arrangement

The laser pulse is focused in the proximity of the entrance edge of the gas-jet

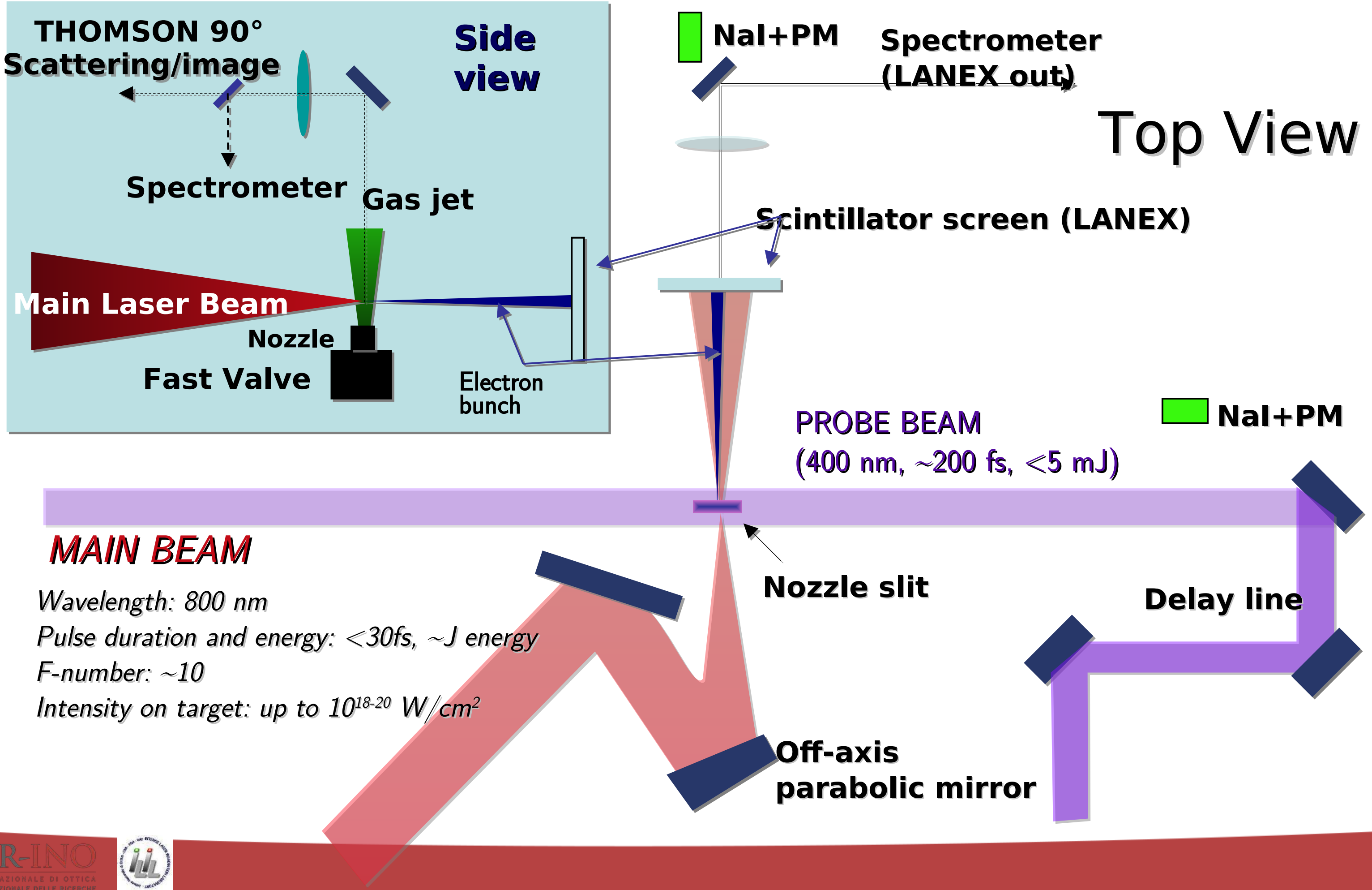
Electrons are accelerated in the forward direction







A typical LWFA experiment: Basic set of diagnostics



THOMSON 90°
Scattering/image

Side view

Spectrometer

Gas jet

Main Laser Beam

Nozzle

Fast Valve

Electron
bunch

NaI+PM

Spectrometer
(LANEX out)

Top View

Scintillator screen (LANEX)

PROBE BEAM
(400 nm, ~200 fs, <5 mJ)

NaI+PM

Nozzle slit

Delay line

Off-axis
parabolic mirror

MAIN BEAM

Wavelength: 800 nm

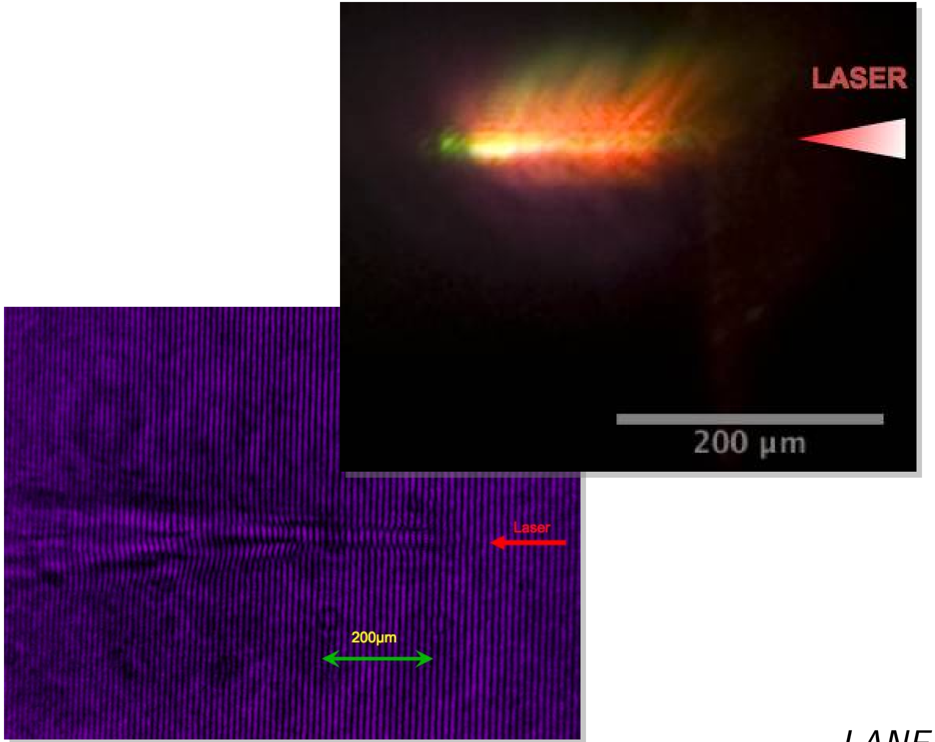
Pulse duration and energy: <30fs, ~J energy

F-number: ~10

Intensity on target: up to $10^{18\text{-}20}$ *W/cm*^{2}

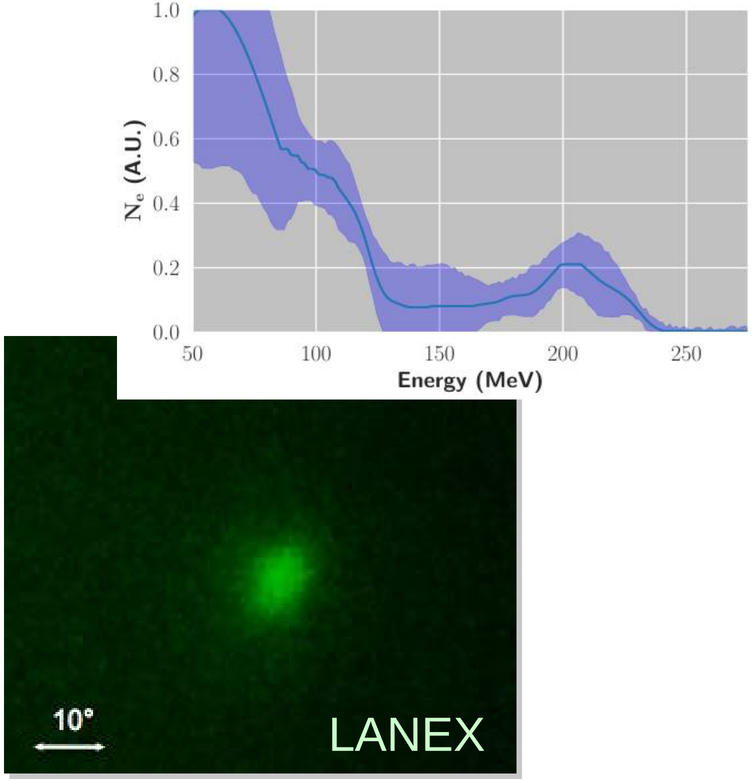
Examples of typical diagnostics output

Thomson imaging diagnostic allows the propagation to be "tracked"



Interferometry allows the plasma electron density to be retrieved

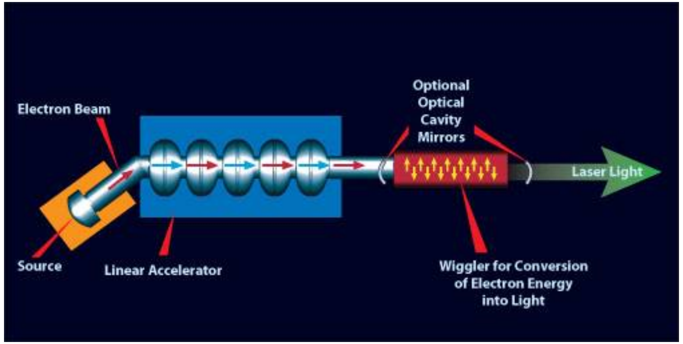
Magnetic spectrometer



LANEX (electron scintillator) imaging provides the bunch profile, also allowing the divergence to be retrieved

“All-optical” X/gamma-ray secondary sources of ionizing radiation

General scheme for the production of X/γ-rays driven by an electron beam



An all-optical X/γ-ray source basically takes advantage of the extreme compactness of a LWFA accelerator to enable “table-top” X/γ-ray sources to be developed, based on the following (almost) fundamental processes:

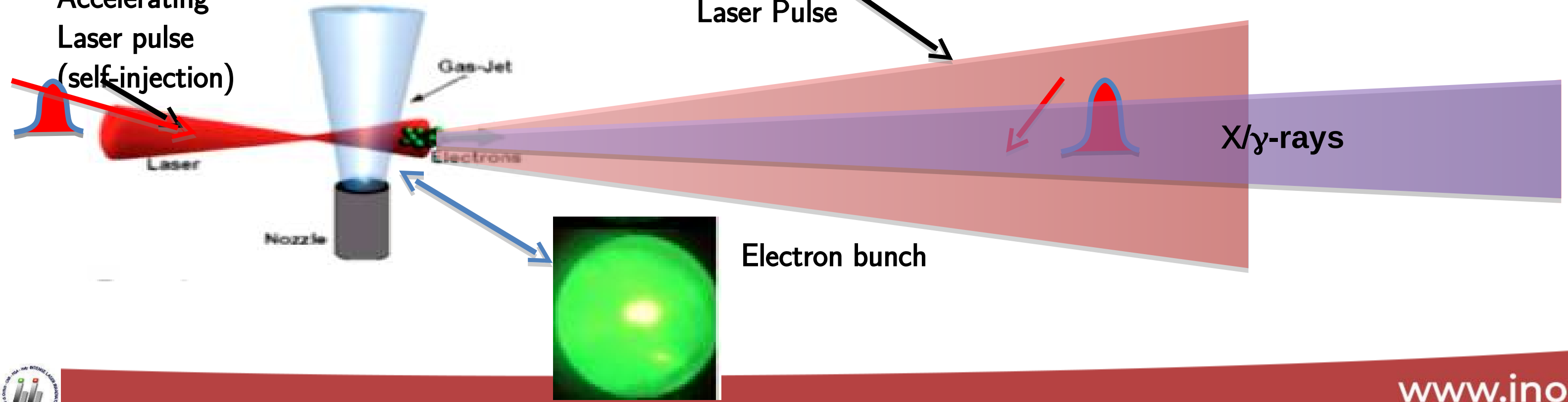
Thomson Scattering

“betatron” emission

Bremsstrahlung emission

These kind of source also feature:

- a tunable spectrum (with some caveat)
- an ultrashort duration
- typical photon energy ranging from a few keV up to the tens of MeV range



Counter-propagating, Scattering Laser Pulse

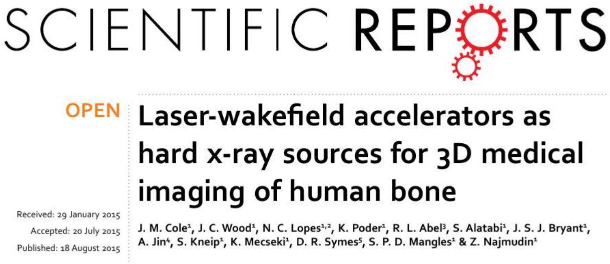
Accelerating Laser pulse (self-injection)

X/γ-rays

Electron bunch

All-optical X/gamma-ray sources applications: Examples

Foreseen applications include X/gamma-ray radiography, tomography, etc. in fields as diverse as medicine, material study, security, radioisotope production



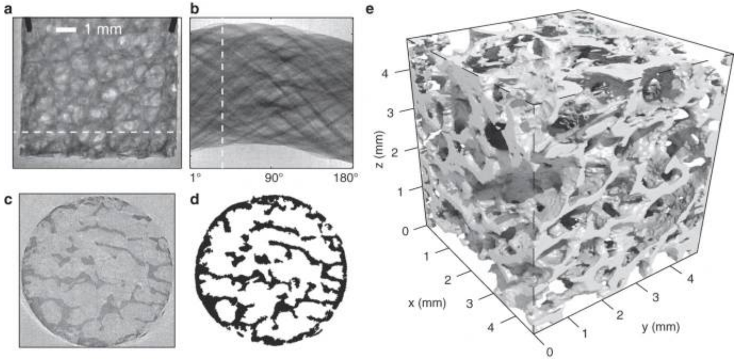
SCIENTIFIC REPORTS

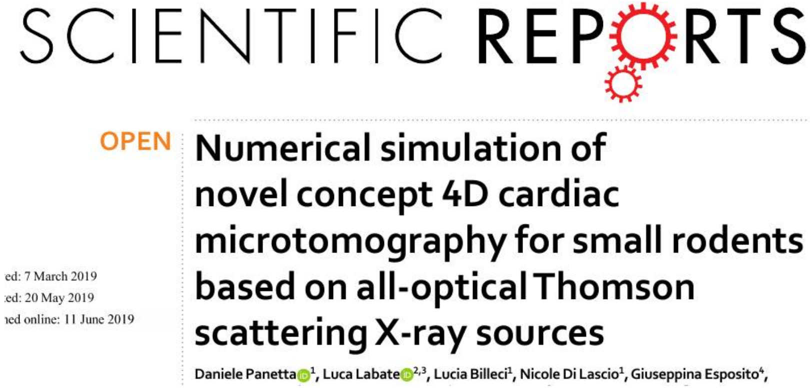
OPEN

Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone

Received: 29 January 2015
Accepted: 20 July 2015
Published: 18 August 2015

J. M. Cole[1], J. C. Wood[1], N. C. Lopes[1,2], K. Poder[1], R. L. Abel[3], S. Alatabi[1], J. S. J. Bryant[1], A. Jin[4], S. Kneip[1], K. Mecseki[1], D. R. Symes[5], S. P. D. Mangles[1] & Z. Najmudin[1]





SCIENTIFIC REPORTS

OPEN

Numerical simulation of novel concept 4D cardiac microtomography for small rodents based on all-optical Thomson scattering X-ray sources

ed: 7 March 2019
ed: 20 May 2019
ned online: 11 June 2019

Daniele Panetta[1], Luca Labate[2,3], Lucia Billeci[1], Nicole Di Lascio[1], Giuseppina Esposito[4],

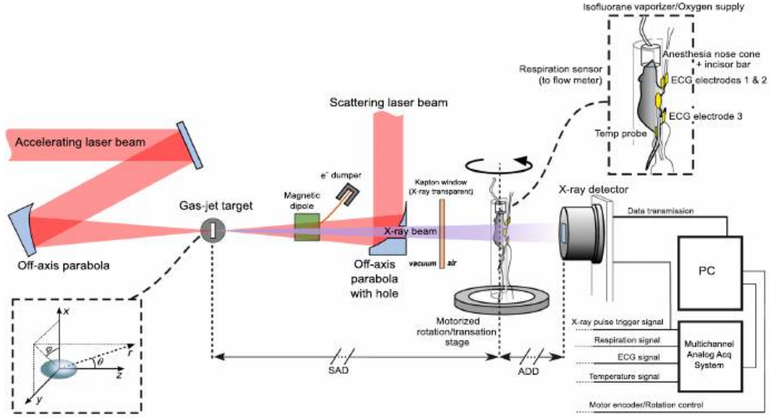
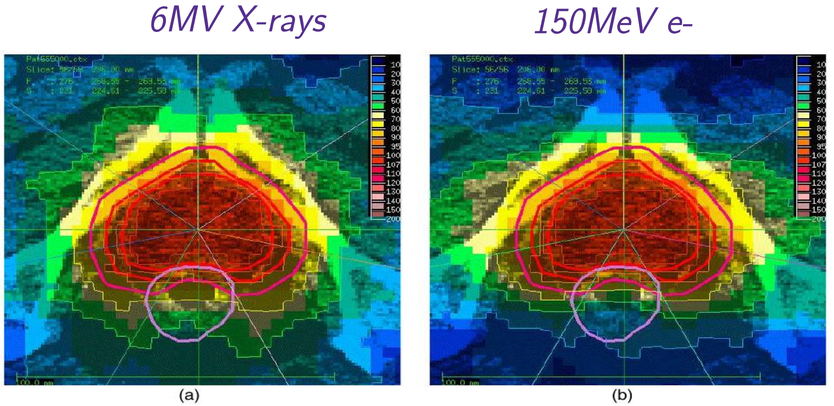


Figure 1. Conceptual scheme of the laser-based 4D μCT scanner prototype for cardiac imaging of small rodents.

Very High Energy Electrons (VHEE) beams: toward “real” applications in medicine

Very High Energy Electrons (VHEE): energy range 100-250 MeV

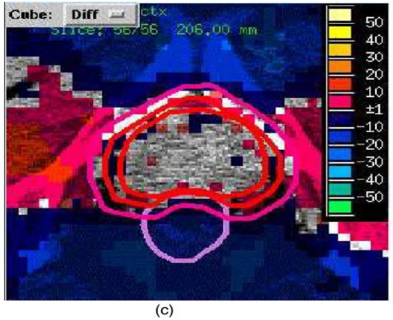
Investigated over the past 10 years by means of Monte Carlo simulations: potential for good dose conformation, comparable (or exceeding) that of current photon beam modalities [1,2]



Quality of a prostate treatment plan evaluated for a 6MV IMRT and a VHEE treatment

Better target coverage achieved
Extent of the sparing of organs at risk found to be dependent on depth (due to e- exhibiting larger scattering)

difference



More recently, the capability of dose deposition by VHEE of being relatively insensitive to tissue interfaces was assessed (using MC simulations) [3]

[1] T. Fuchs *et al.*, Phys. Med. Biol. **54**, 3315 (2009)
[2] Des Rosiers *et al.*, Int. J. Radiat. Oncol. Biol. Phys. **72**, S612 (2008)
[3] A. Lagzda *et al.*, Nucl. Instrum. Meth. Phys. Res. B **482**, 70 (2020)

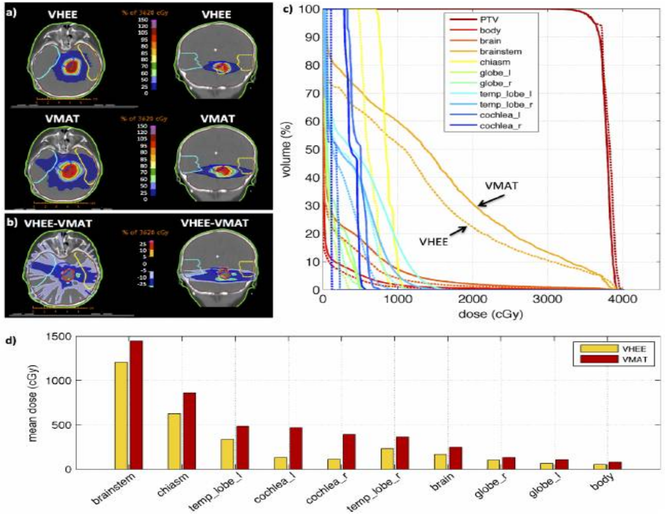
Very High Energy Electrons (VHEE) beams: toward "real" applications in medicine

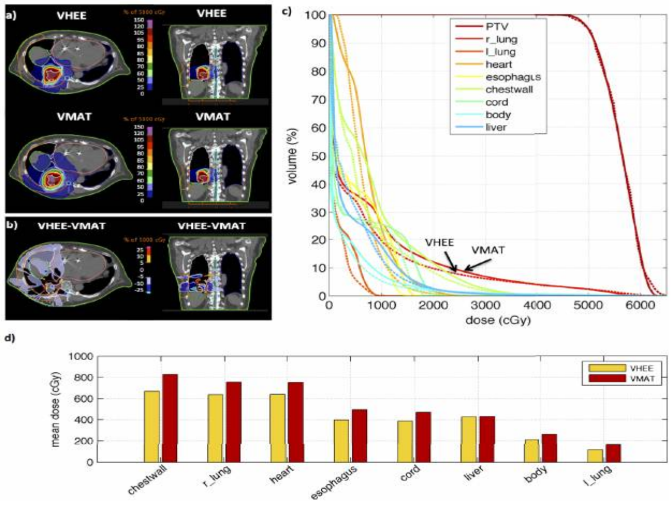
Recently, "state-of-the-art" Treatment Planning Systems have been (adapted to and) used to assess the quality of VHEE based RT as compared to conventional photon RT TP

Treatment planning for radiotherapy with very high-energy electron beams and comparison of VHEE and VMAT plans

Magdalena Bazalova-Carter, Bradley Qu, and Bianey Palma
Department of Radiation Oncology, Stanford University, Stanford, California 94305

Med. Phys. 42 (5), May 2015





Pencil beams with few mm transverse size

Toward “FLASH” radiotherapy with laser-driven VHEE beams?

So-called “FLASH effect” is sparking a lot of interest in the radiotherapy/medical physics community, due to its potential to change the current radiotherapy scenario

Clinical Oncology 31 (2019) 407–415

Contents lists available at ScienceDirect

Clinical Oncology

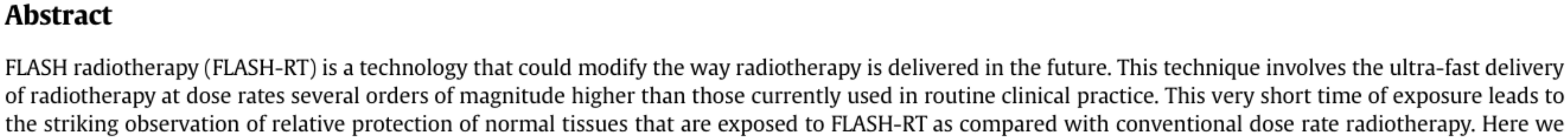
journal homepage: www.clinicaloncologyonline.net

ELSEVIER

Overview

Biological Benefits of Ultra-high Dose Rate FLASH Radiotherapy: Sleeping Beauty Awoken

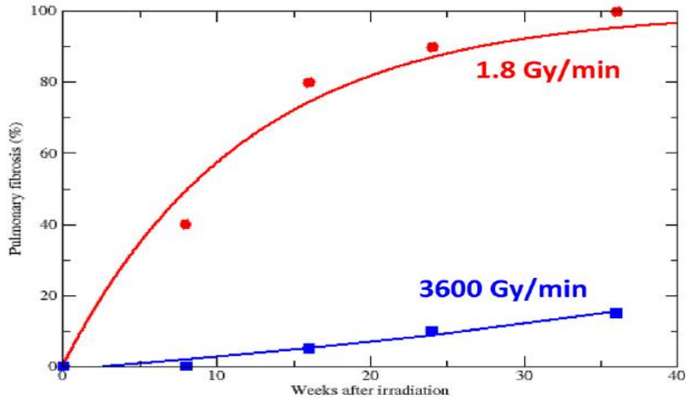
M.-C. Vozenin *†, J.H. Hendry ‡, C.L. Limoli §



Abstract

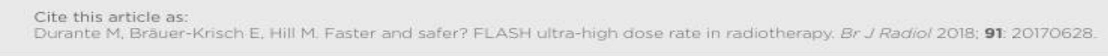
FLASH radiotherapy (FLASH-RT) is a technology that could modify the way radiotherapy is delivered in the future. This technique involves the ultra-fast delivery of radiotherapy at dose rates several orders of magnitude higher than those currently used in routine clinical practice. This very short time of exposure leads to the striking observation of relative protection of normal tissues that are exposed to FLASH-RT as compared with conventional dose rate radiotherapy. Here we

Figure 1. Time dependence of pulmonary fibrosis in C57BL/6J mice after thoracic irradiation at conventional (circles) or ultra-high dose rate (squares). Data points and all details in reference Favaudon et al[1] lines are guides for the eye.

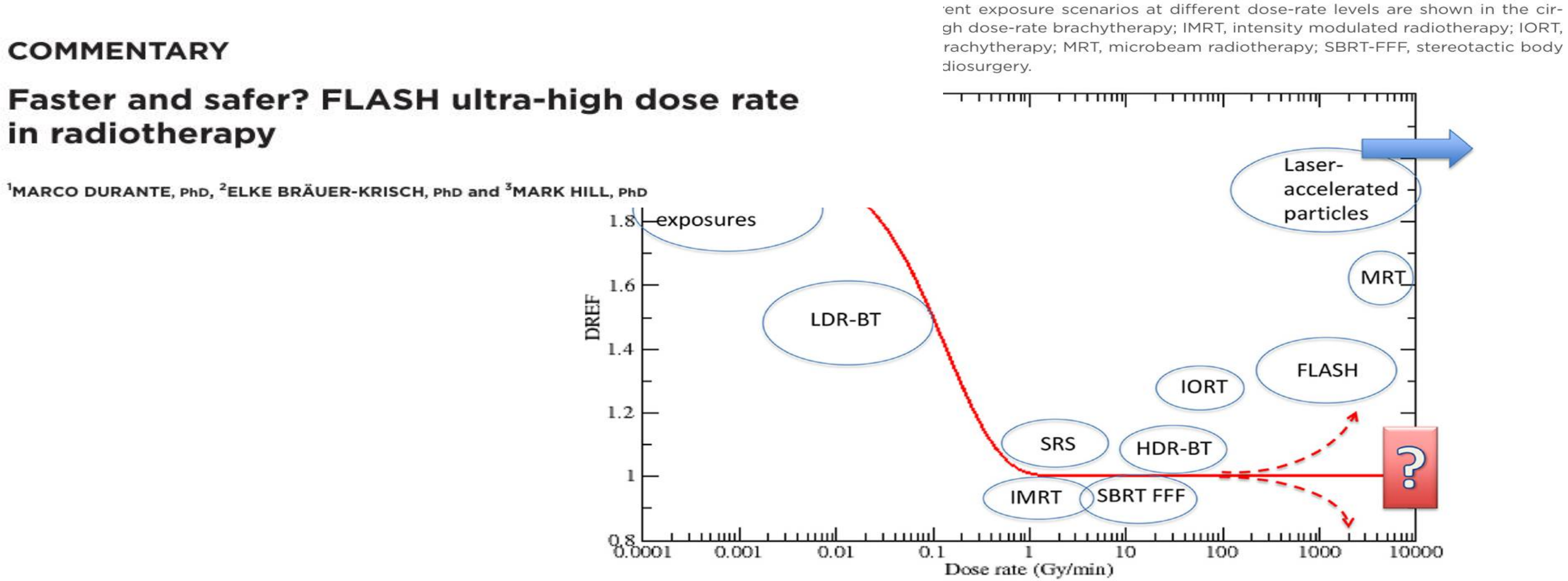


Toward “FLASH” radiotherapy with laser-driven VHEE beams? [2]

Due to the intrinsic low efficiency of *Bremsstrahlung* conversion, it is generally thought that *direct* usage of charged particle beams is in order to reach the ultra-high dose rates needed for FLASH. Laser-driven accelerators are among the most promising machine allowing at the same time *high current* and *high energy* (to penetrate human body)



Cite this article as:
Durante M, Bräuer-Krisch E, Hill M. Faster and safer? FLASH ultra-high dose rate in radiotherapy. *Br J Radiol* 2018; **91**: 20170628.



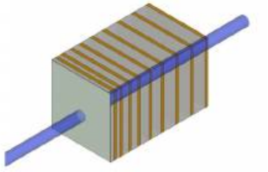
COMMENTARY

Faster and safer? FLASH ultra-high dose rate in radiotherapy

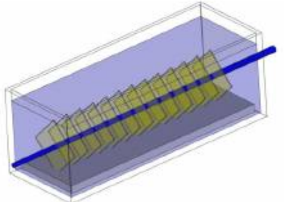
[1]MARCO DURANTE, PhD, [2]ELKE BRÄUER-KRISCH, PhD and [3]MARK HILL, PhD

ent exposure scenarios at different dose-rate levels are shown in the cir-
gh dose-rate brachytherapy; IMRT, intensity modulated radiotherapy; IORT,
rachytherapy; MRT, microbeam radiotherapy; SBRT-FFF, stereotactic body
diosurgery.

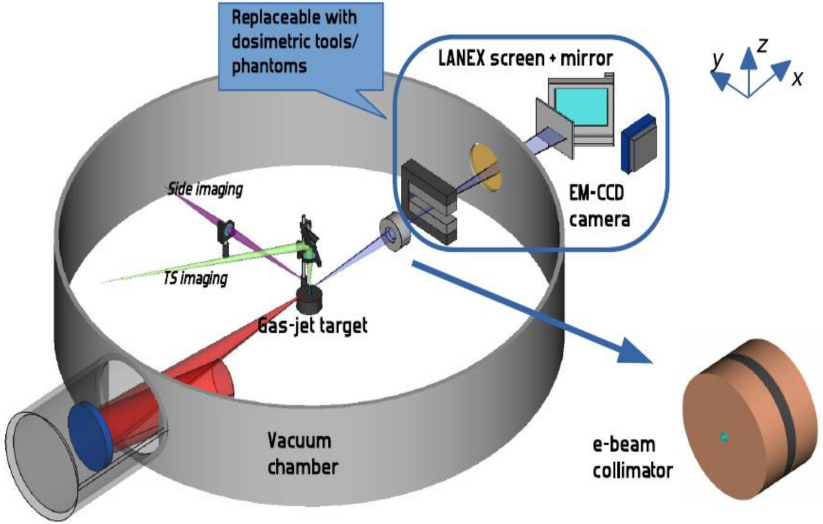
Toward “FLASH” radiotherapy: Demonstration of advanced irradiation schemes with laser-driven VHEE beams

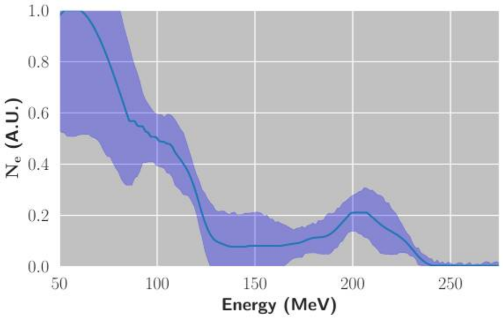


Solid water/GAF stack



Water/GAF stack





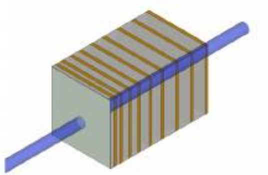
Average spectrum pretty stable when averaged over 20 shots

Divergence: ~14mrad FWHM

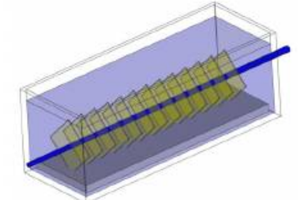
Bunch charge (within the collimator angle):
~120 pC/shot
(Shot-to-shot RMS ~15%)

L. Labate *et al.*, Sci. Rep. **10**, 17307 (2020)

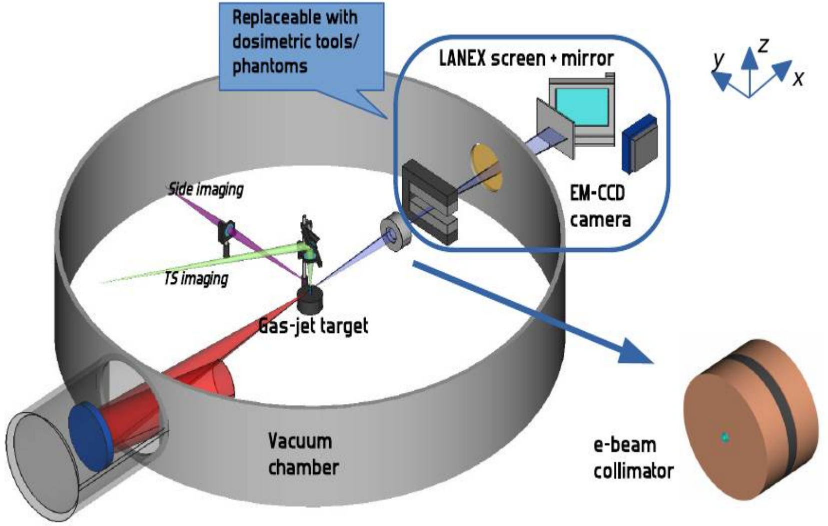
Toward “FLASH” radiotherapy: Demonstration of advanced irradiation schemes with laser-driven VHEE beams



Solid water/GAF stack

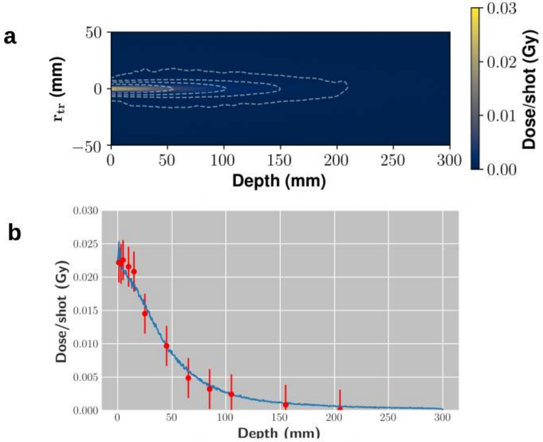


Water/GAF stack



L. Labate *et al.*, Sci. Rep. **10**, 17307 (2020)

Dose deposition pattern on the central (axis) plane



Dose/shot: ~3-5 cGy

Percentage Dose Depth:
$R_{50\%}$ ~40-50 mm

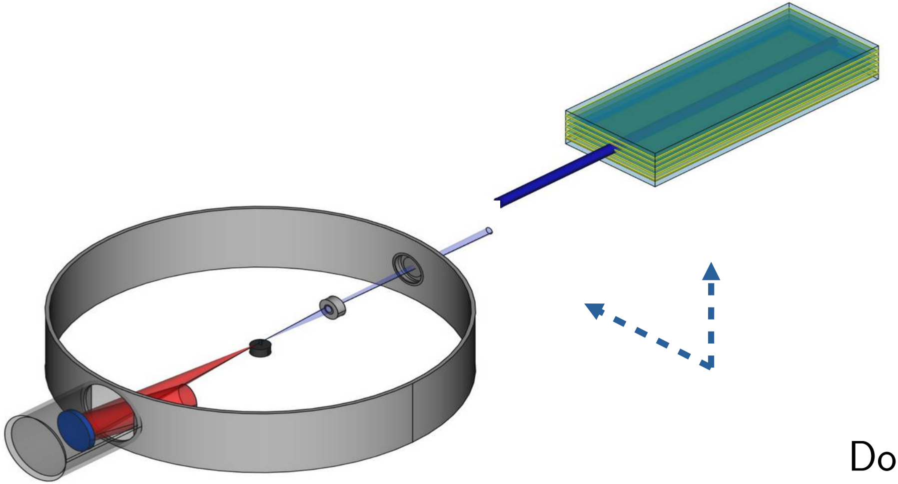
The dose deposition remains confined to few mm within ~150mm

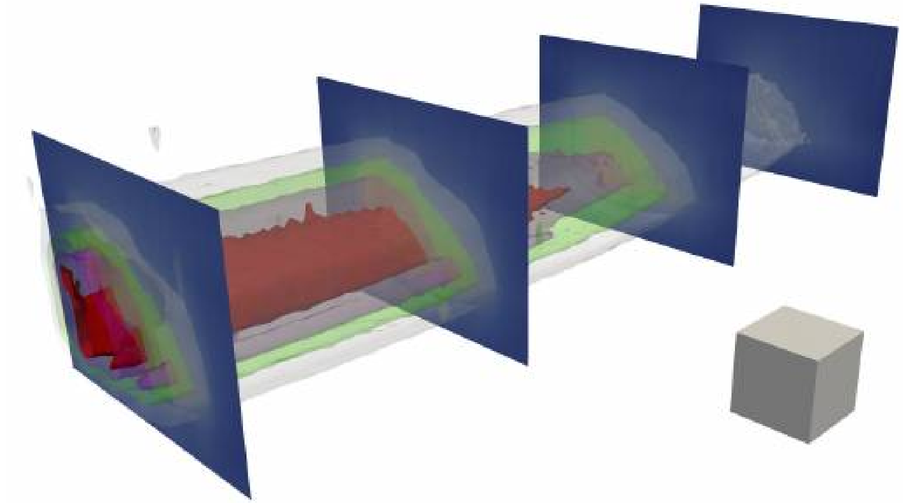
Mimicking intensity-modulated RT and multi-field irradiation with laser-driven e-

Our situation: “pencil (electron) beam”

IMRT can be obtained by changing the beam entrance point (2D pattern, at the moment) and varying the number of shots

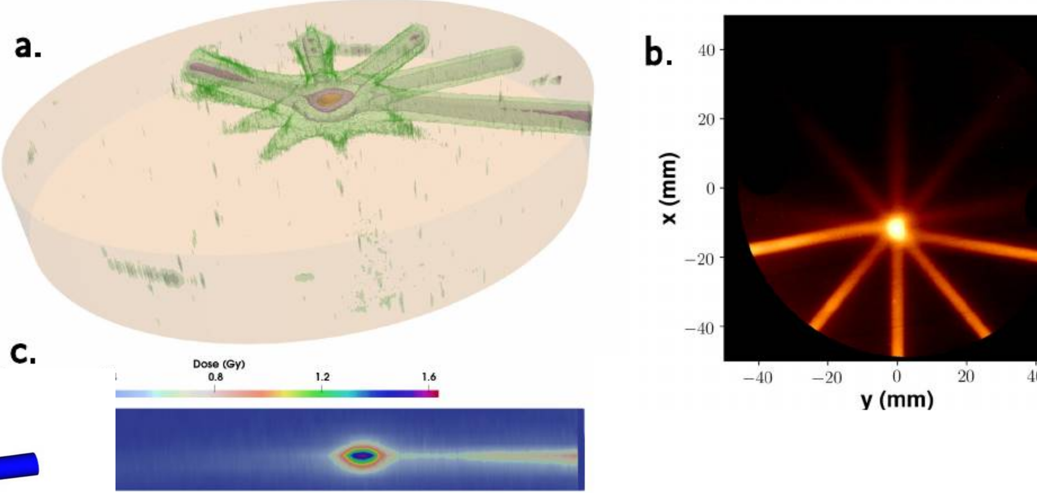
20	15	10	5
25	20	15	10
35	30	25	20



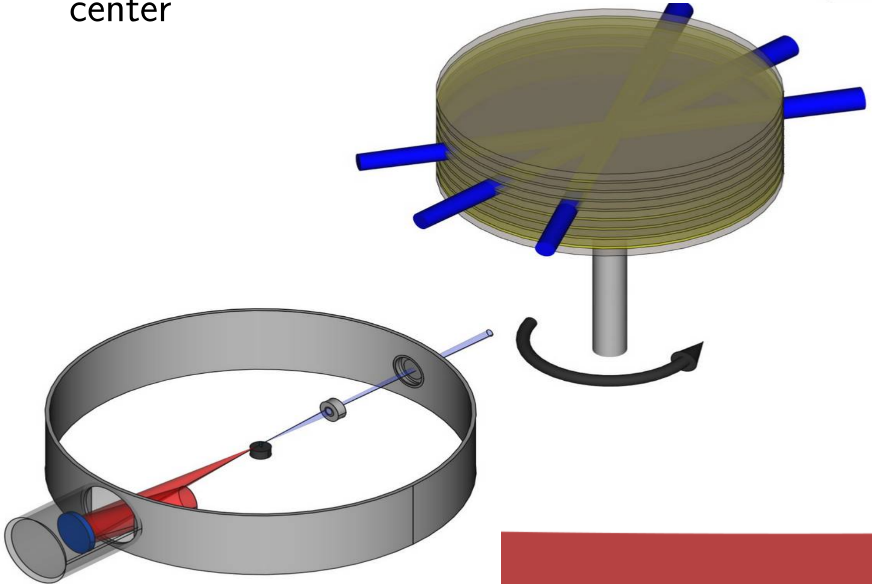


Dose transverse profile tailoring with mm resolution

Mimicking intensity-modulated RT and multi-field irradiation with laser-driven e-

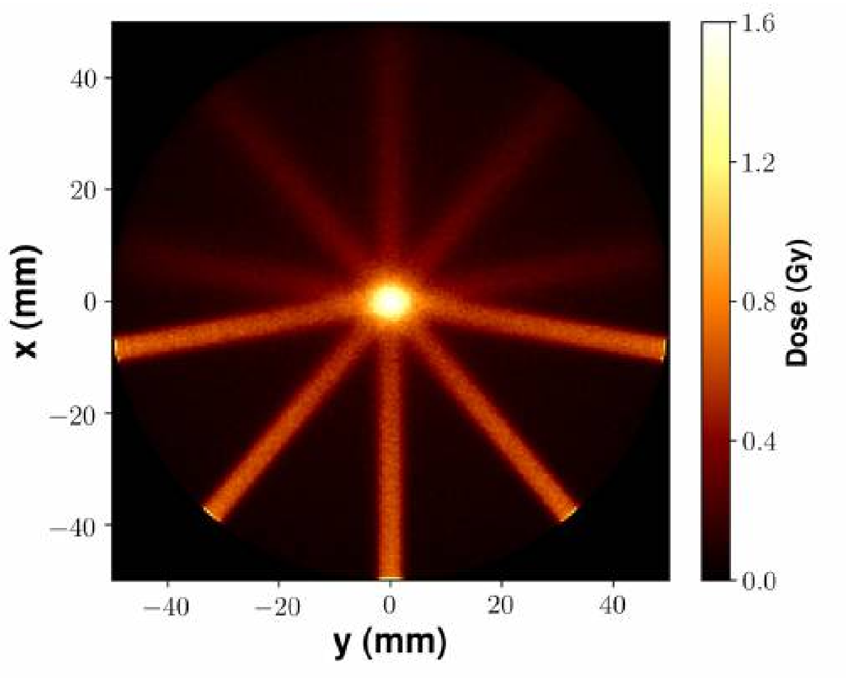


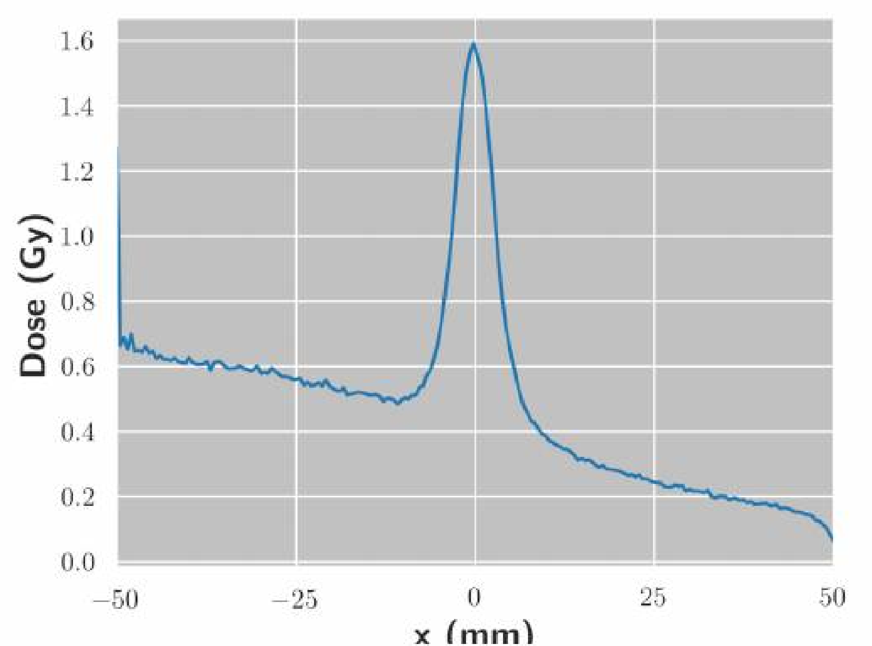
Up to ~1.6Gy reached on a small volume (~5mm size) at the (rotation) center



<20cGy distributed over a volume with ~15-20mm typical size surrounding this volume

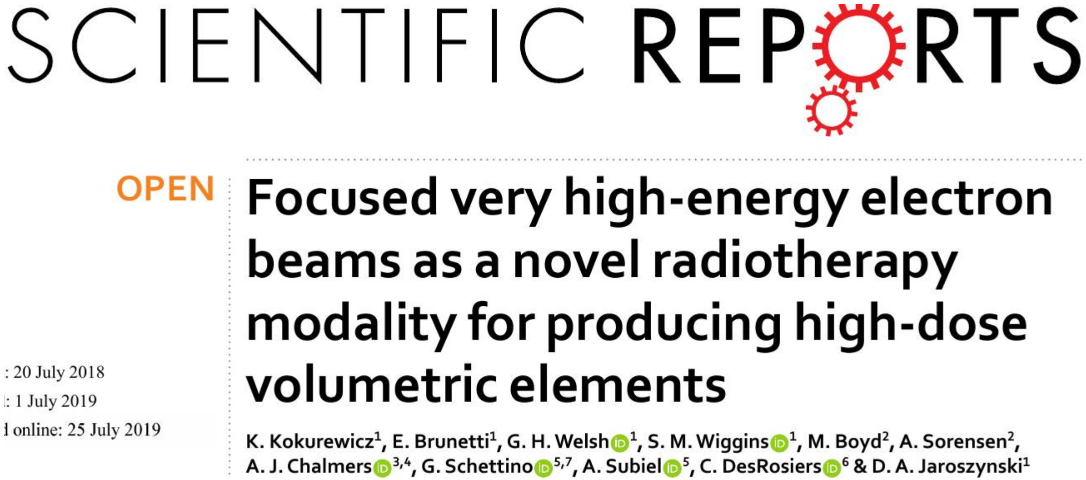
Multifield irradiation: Monte Carlo simulations





Maximum dose on the “target” volume ~2.5x dose at the entrance, ~3-4x dose a few mm apart

Other appealing issue of a VHEE RT



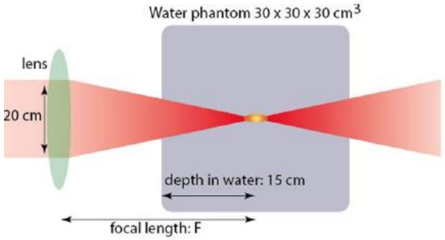
SCIENTIFIC REPORTS

OPEN

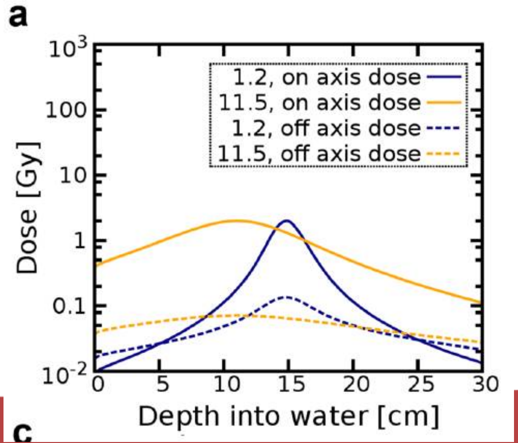
Focused very high-energy electron beams as a novel radiotherapy modality for producing high-dose volumetric elements

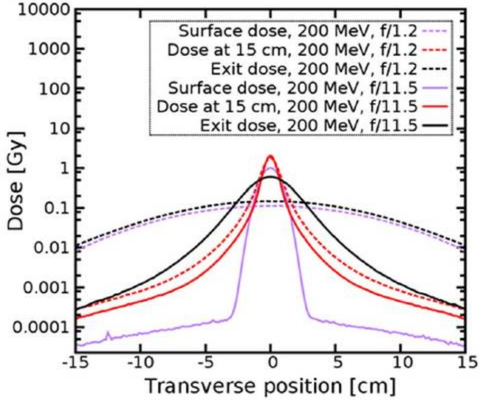
K. Kokurewicz[1], E. Brunetti[1], G. H. Welsh[1], S. M. Wiggins[1], M. Boyd[2], A. Sorensen[2], A. J. Chalmers[3,4], G. Schettino[5,7], A. Subiel[5], C. DesRosiers[6] & D. A. Jaroszynski[1]

: 20 July 2018
: 1 July 2019
online: 25 July 2019

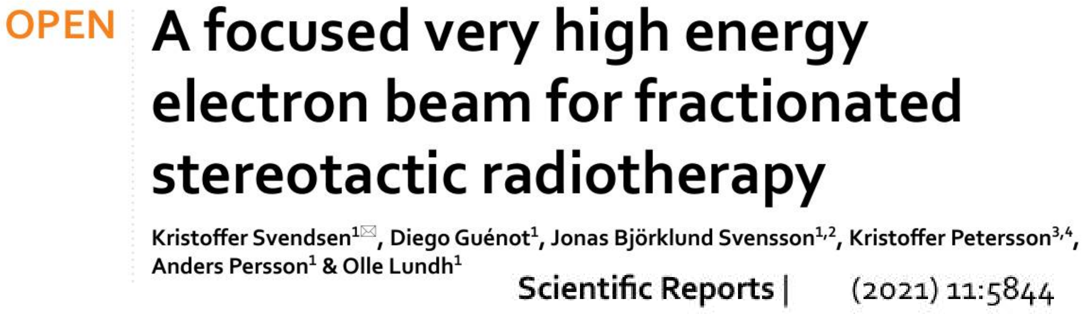


Steering and focusing VHEE:
- improved volumetric dose tailoring
- room for a better management of the physiological motion using fast magnetic scanning





Other appealing issue of a VHEE RT: focusing/stabilising the beam

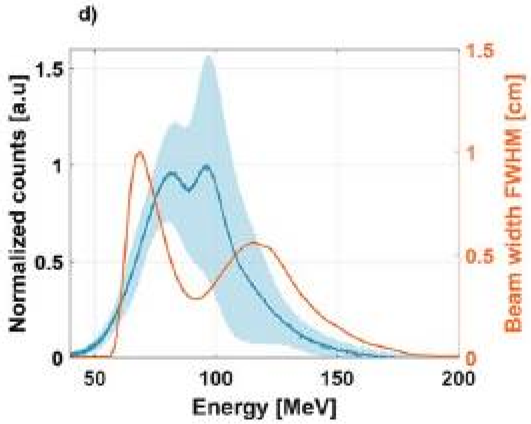


OPEN

A focused very high energy electron beam for fractionated stereotactic radiotherapy

Kristoffer Svendsen[1]✉, Diego Guénot[1], Jonas Björklund Svensson[1,2], Kristoffer Petersson[3,4], Anders Persson[1] & Olle Lundh[1]

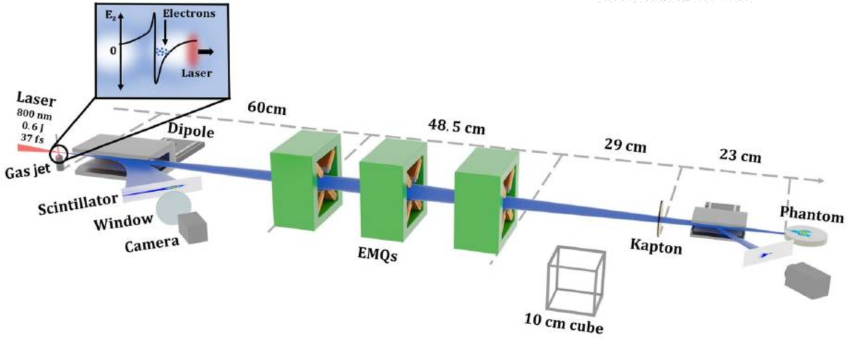
Scientific Reports | (2021) 11:5844



Transport of ~100-160 MeV VHEE to a phantom demonstrated

Dose/shot similar to our study (see later)

Improved charge shot-to-shot stability: SD~1%



Toward higher “average flux” beams: The 100Hz beamline upgrade ad ILIL

Funded by the European Union
NextGenerationEU

BEAMLINE for PRE-CLINICAL STUDIES

SHIELDED TARGET AREA for PARTICLE ACCELERATION

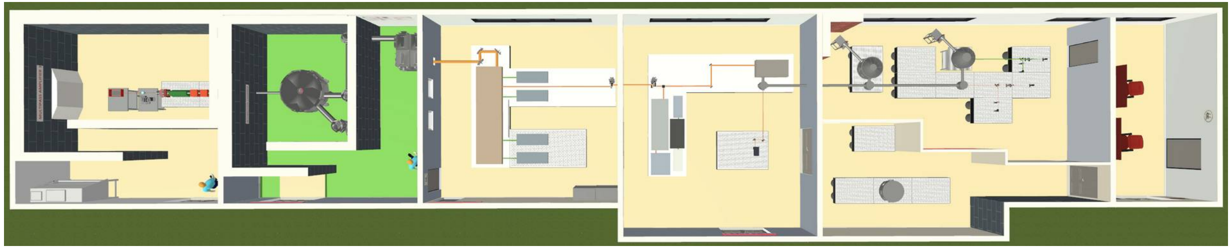
POWER AMPLIFIER Up to 250 TW

LASER FRONT END
10 TW, 10 Hz

RADIOBIOLOGY LASER-DRIVEN PARTICLE AND RADIATION

USER CONTROL ROOM

Underground bunker
100 Hz



Laser Dev. Lab
kHz

UPGRADE OF ILIL FACILITY FOR:

1. Upgrade of existing laser system (240 TW) for enhanced stability and control
2. **New laser systems for high repetition rate operation (100 Hz-1J, 1kHz-20 mJ)**
3. New Infrastructure development for user access to beamlines

Part of : PNRR I-PHOQS INTEGRATED INFRASTRUCTURE INITIATIVE IN PHOTONIC AND QUANTUM SCIENCES

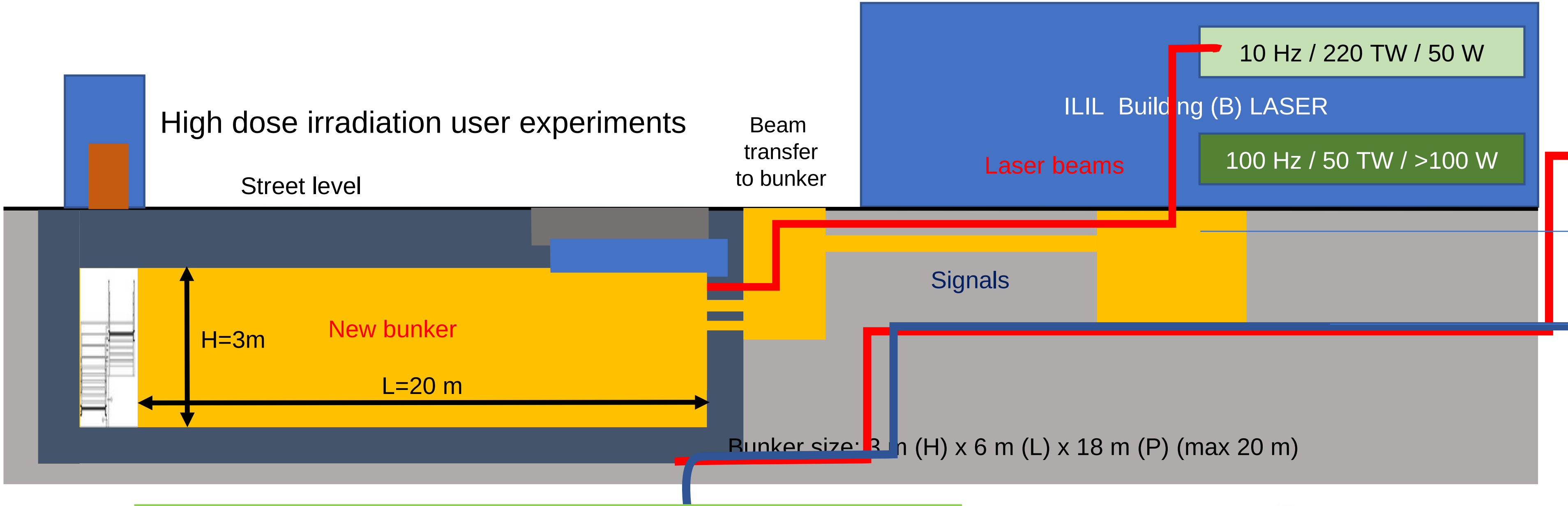
Strong link with eli ESFRI

Part of : PNRR EuPRAXIA Advanced Photon Source

User infrastructure upgrade

Funded by the European Union
NextGenerationEU

- **EuPRAXIA Advanced Photon Sources (EUAPS) project (NG-EU, INFN-CNR-UTV)**
- **Photonics and Quantum Science (IPHOQS) project (NG-EU, CNR, POLIMI, LENS)**



EUAPS WP2: High average power, high repetition rate laser beamline: 4.8 M€
IPHOQS A3.6 Ultrafast, high repetition rate radiation beamlines: 1.4 M€
IPHOQS A3.5:* High Intensity, extreme laser beamlines*: 1.5 M€

EUAPS
I-PHOQS
INTEGRATED INFRASTRUCTURE INITIATIVE IN PHOTONIC AND QUANTUM SCIENCES

New high-repetition rate Target Area

Funded by the European Union
NextGenerationEU

Summary (and takeaway messages on laser-driven particle acceleration)

- Ultrashort and ultraintense laser interaction with matter at relativistic intensity allows relativistic electron beams to be accelerated over cm-scale "acceleration stages"

  Current electron energy record: up to $\sim$10GeV

- "Table-top" sources, making them appealing for a widespread (hospitals, ...) usage, with applications in radiobiology, material studies, nuclear physics, ...

- "All-optical" secondary radiation sources can be obtained from primary electron beams (possibly using a second, "scattering" laser beam), with photon energy ranging from few keV up to the $\sim$10s MeV range

- VHEE beams (energy in the range 100-250MeV) can be "easily" accelerated with lasers and are expected to play a crucial role in order to deliver ionizing radiation at *Ultra-High Dose Rate (UHDR)*, thus allowing the so-called "FLASH regime" of radiation biology to be accessed

- Experiments aimed to demonstrate the possibility of precise dose delivery using laser-driven VHEE pencil beams are ongoing

- "Actual" applications will need high average flux particle beams, thus requiring the repetition rate of ultrashort/ultraintense lasers to reach the $>$100Hz figure