Consiglio Nazionale
delle Ricerche

INO-CNR
Istituto
Nazionale di
Ottica

Istituto Nazionale di
Fisica Nucleare

High Performance Computing at CNAF:
Accelerators and Plasma Physics
Bologna, Tuesday June 24, 2014

Laser acceleration of electrons and perspectives for Thomson X-rays at INO-CNR

Luca Labate

Istituto Nazionale di Ottica – UOS di Pisa
Consiglio Nazionale delle Ricerche

Also at Istituto Nazionale di Fisica Nucleare Sezione di Pisa and Laboratori Nazionali di Frascati

Outline

- Overview of the ILIL laboratory
- Recent LPA experiments @ ILIL: radiobiology toward radiotherapy

  - Motivation: radiotherapy with LPA electrons
  - First radiobiology experiments @ILIL
- PIC simulations of the LPA regime used for the radiobiology experiment
- Summary and overview of future plans

Outline

- Overview of the ILIL laboratory
- Recent LPA experiments @ ILIL: radiobiology toward radiotherapy

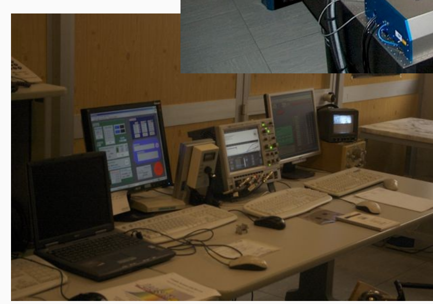
  - Motivation: radiotherapy with LPA electrons
  - First radiobiology experiments @ILIL
- PIC simulations of the LPA regime used for the radiobiology experiment
- Summary and overview of future plans

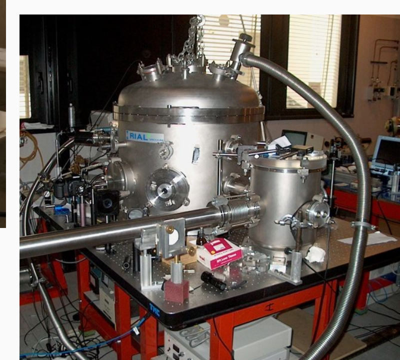
The Intense Laser Irradiation Laboratory group

PEOPLE

- Leonida A. GIZZI (CNR)* (Resp.)
- Giancarlo BUSSOLINO (CNR)
- Gabriele CRISTOFORETTI (CNR)
- Luca LABATE (CNR)*
- Fernando BRANDI (CNR), Ric. TD.
- Petra KOESTER (CNR), Ric. Contr.
- Tadzio LEVATO (CNR), Ric. Contr.
- Federica BAFFIGI (CNR), A.R.
- Paolo FERRARA (CNR), A. R.
- Lorenzo FULGENTINI (CNR), A.R.
- Antonio GIULIETTI(CNR), Assoc
- Danilo GIULIETTI (Univ. Pisa), Ass.*
- Daniele PALLA, PhD student *
- Antonella ROSSI (CNR) – Tech.

* Also at INFN

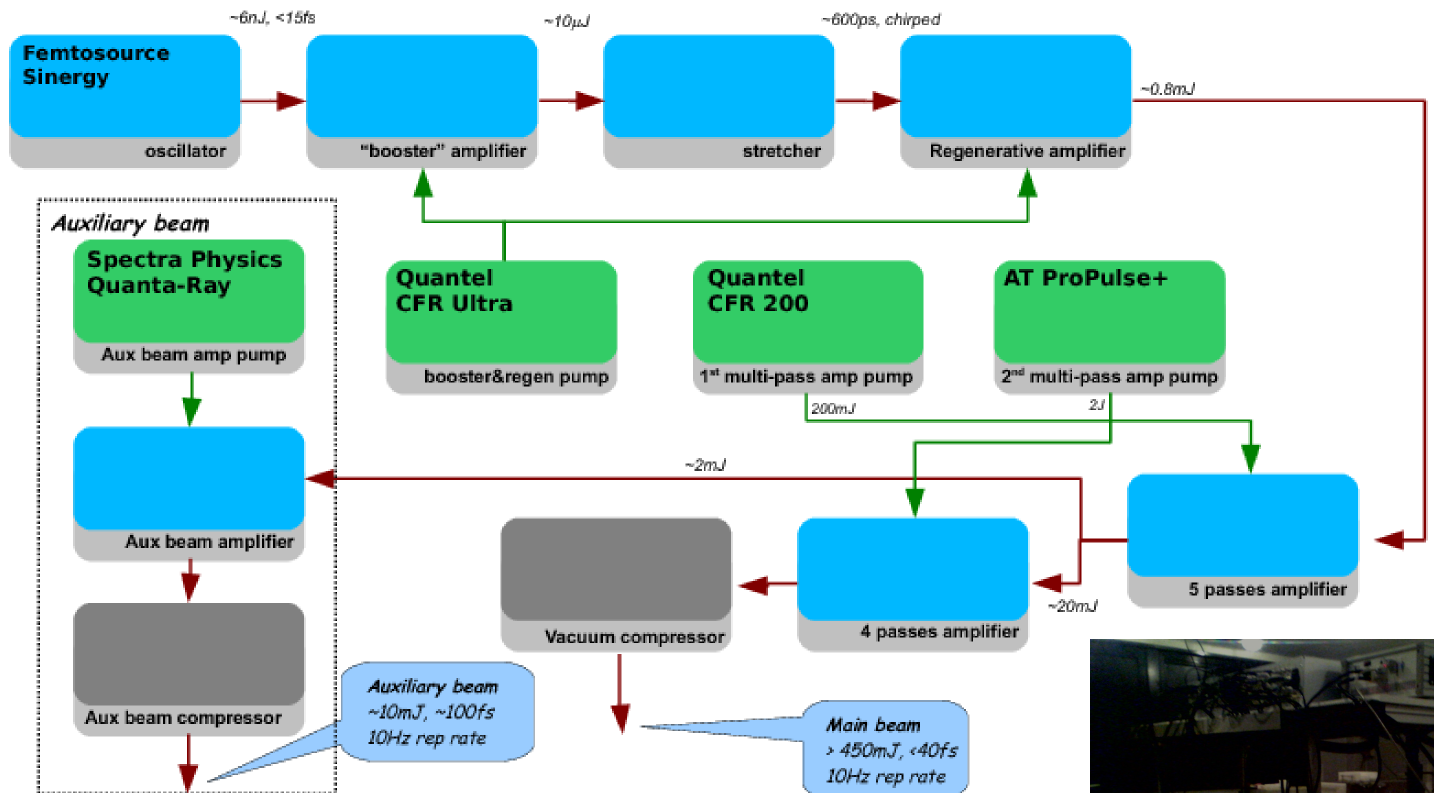




Main fields
- Laser-driven acceleration of electrons and related secondary sources
- Laser-plasma interaction studies relevant for ICF

http://ilil.ino.it

The 10TW laser system @ILIL: upgrade Q3-Q4/2013



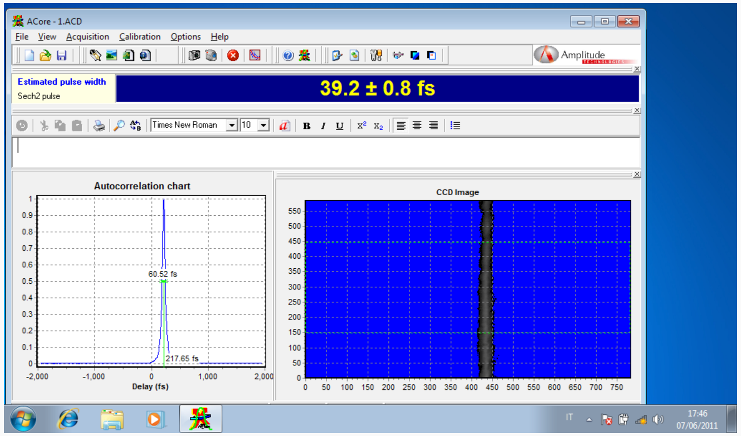
ILIL TiSa 10TW laser system
upgrade july/september 2013

INO-CNR Istituto Nazionale di Ottica

The ILIL laboratory

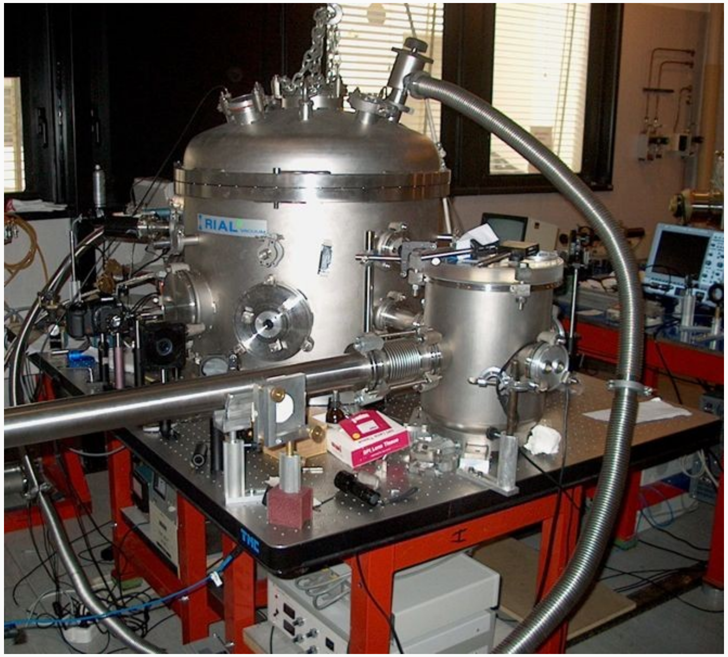
Laser main figures

- -energy: up to 450mJ on target
- -pulse duration <40fs
- -ASE contrast > 10^9
- -$M^2 < 1.5$
- -intensity: up to 2×10^{19} W/cm^2



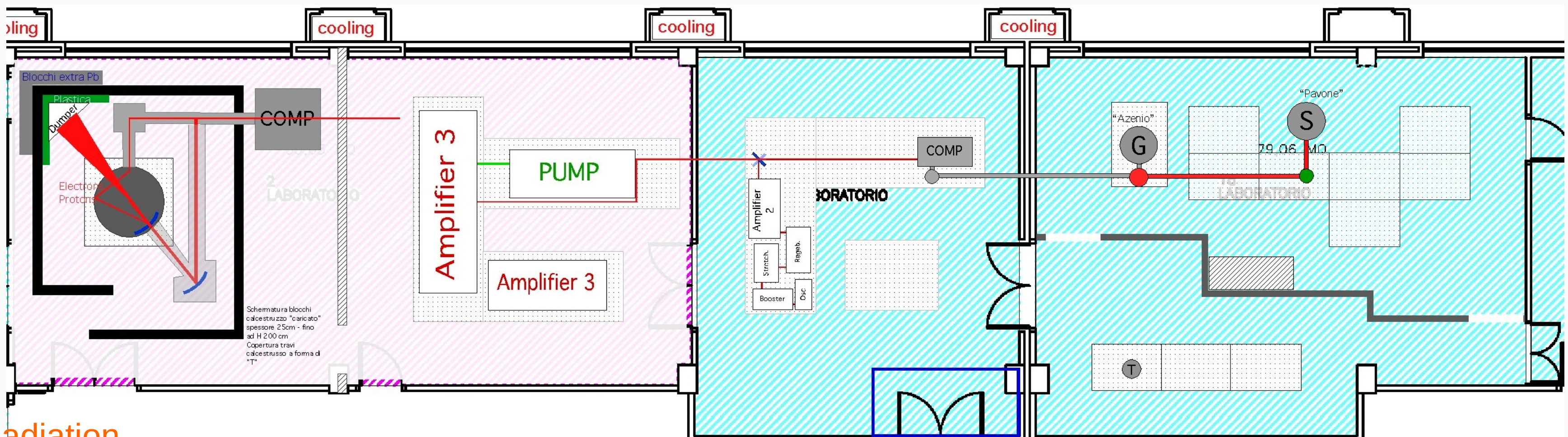
Target area equipment

- -2 “dedicated” vacuum chambers (“gas-jet” and “solid” targets)
- -optical and X-ray diagnostics
- -electron diagnostics
- -integrated environment for diagnostic data automatic collection



Upgrade in progress

Add an additional amplifier to the existing 10 TW laser and a new, radiation shielded target chamber for high energy radiation generation



Radiation Protected Interaction chamber

New

PW-scale Amplifier

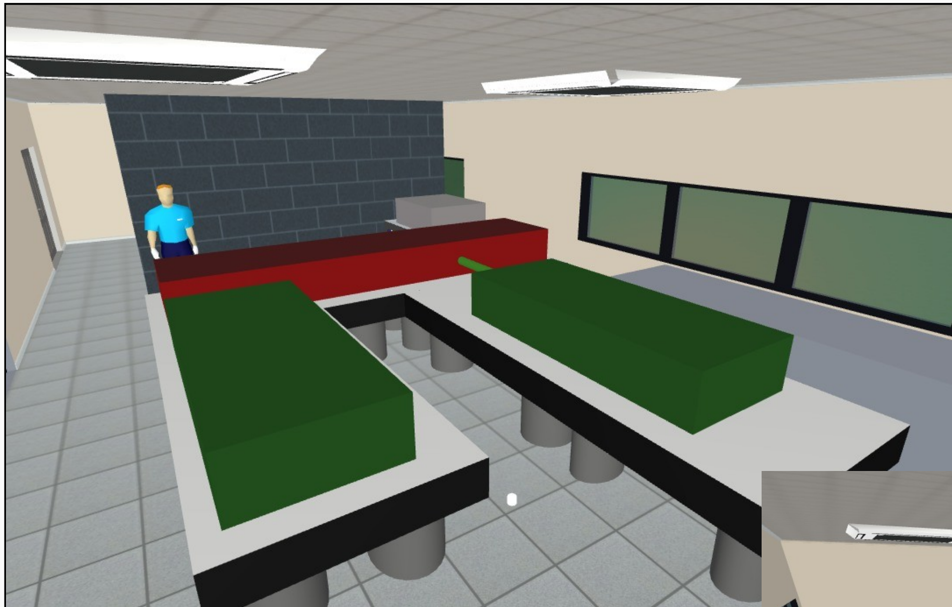
Existing

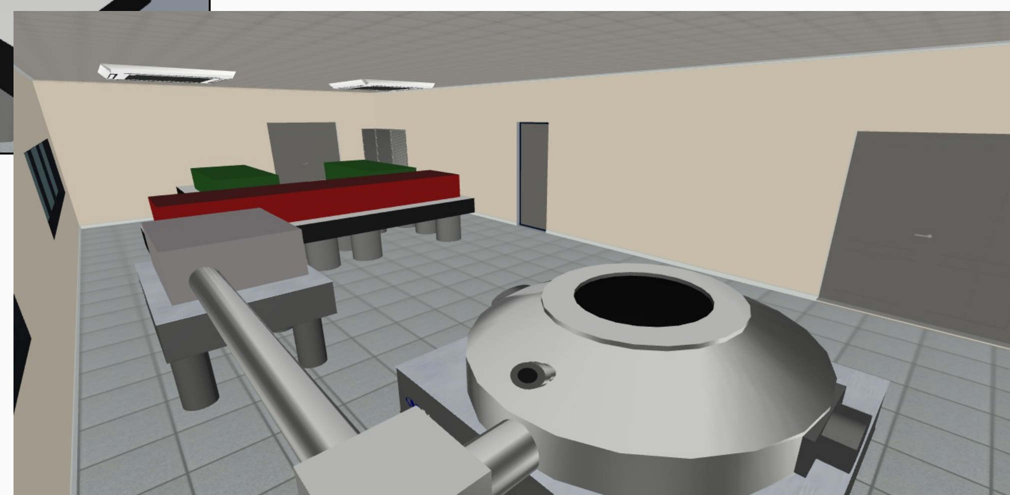
Laser room

Interaction

ELI-Italy, Italian funding from FOE (Ministry of Research, 2013-2015)

ILIL PW-scale Area 3D views





Expected to be completed at end 2015

Outline

- Overview of the ILIL laboratory
- Recent LPA experiments @ ILIL: radiobiology toward radiotherapy

  - Motivation: radiotherapy with LPA electrons
  - First radiobiology experiments @ILIL

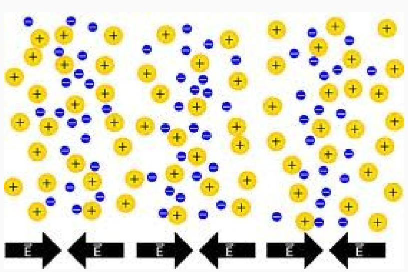
- PIC simulations of the LPA regime used for the radiobiology experiment
- Summary and overview of future plans

RF-based vs. laser-driven plasma accelerators

Classical (RF-based) accelerators limits

- Maximum E-field ~few tens of MV/m (due to breakdown)
- Synchrotron radiation losses → large radius

Laser-driven plasma accelerators



- Plasma is an ionized medium → no structural limits to the E-field

Electric field amplitude in a plasma wave: E~$\sqrt{n}$

E ~ 0.3 GV/m for 1% density perturbation at $n \sim 10^{17}$ cm^{-3}
E ~ 300 GV/m for 100% density perturbation at $n \sim 10^{19}$ cm^{-3}

A bit of literature

1979: proposal by Tajima&Dawson

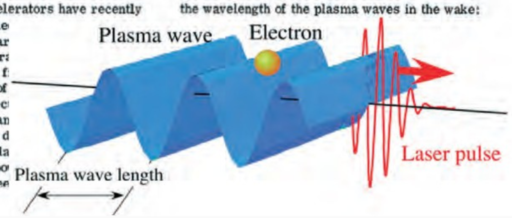
Volume 43, Number 4 PHYSICAL REVIEW LETTERS 23 July 1979

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-ra[...] tion by moving magnetic f[...] netic waves.[2] In terms of [...] 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:



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'Utilisation des Lasers Intenses, CNRS UMR 7605, Ecole Polytechnique, Palaiseau, France
[5]Départem[...]
[6]Europ[...]

A γ-ray so[...] absorption has [...] 3D particle-in[...] acceleration of [...] the giant dipol[...] gold sample, to[...] electron-γ sou[...]

DOI: 10.1103/Ph[...]

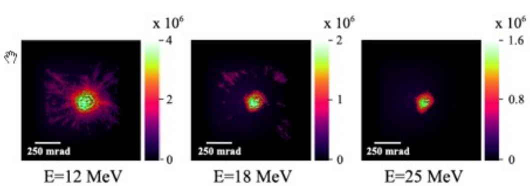


FIG. 1 (color online). Spatially resolved spectral data of the accelerated electrons from the SHEEBA detector.

2006: GeV energy reported

LETTERS

GeV electron beams from a centimetre-scale accelerator

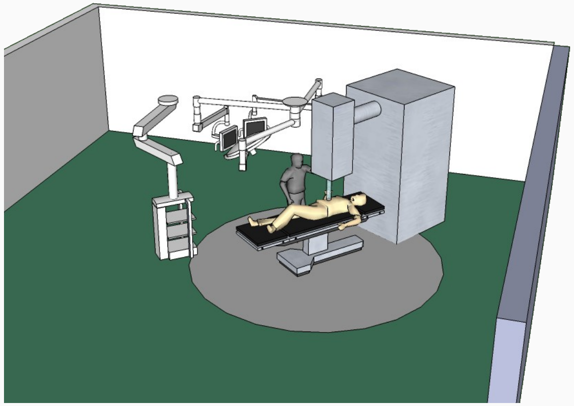
W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

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

Table-top e^- accelerators for medicine

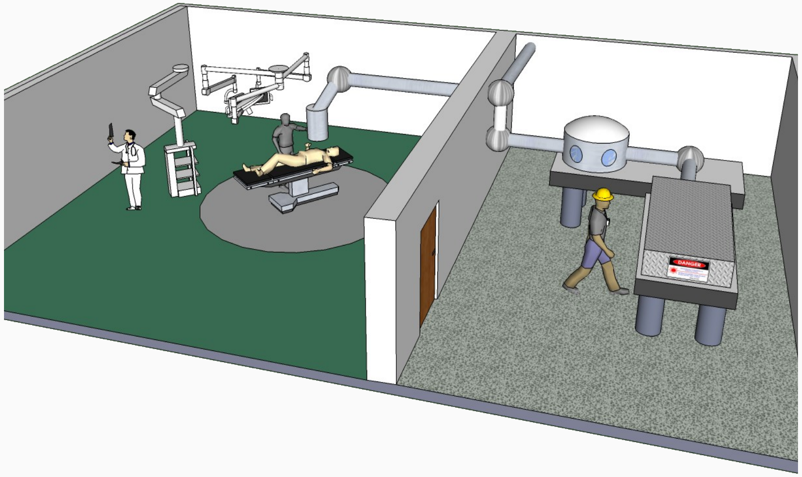
Using laser-driven (table-top) electron accelerators for radiotherapy is attracting increasing attention of the international scientific community

Limits of conventional accelerators:
- large footprint and reduced operational flexibility
- the available electron energy is limited by the LINAC size
- need for UHV (with possible failures)
- need for a large radioprotected area



Conventional (RF) accelerator

Laser-driven accelerator



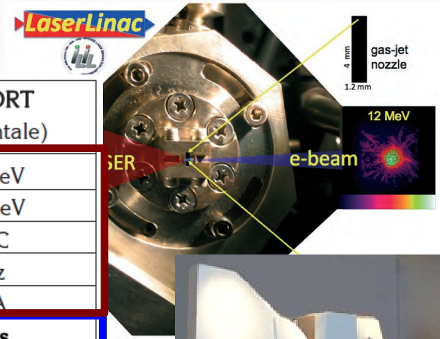
A laser-driven electron accelerator
- exhibits a reduced footprint, due to the fact that a single ultrashort laser system can be used for different treatment areas
- the “active” source (to be hosted in a radioprotected area) can be as small as a few tens of cm
- higher energy bunches could be available
- no need for UHV, high power supplies, ...

Conventional vs. laser-driven e^- bunches

Comparable figures as for electron energy, bunch charge, rep rate, average current

Bunch duration (→ peak current) of laser-driven accelerators much shorter

Prestazione	NOVAC7 (HITESIS SpA)	LIAC (SORDINA SpA)	Laser-IORT (sperimentale)
Energia cinet. max	≤ 9 MeV	≤ 12 MeV	≤ 50 MeV
Energie disponibili	3,5,7,9 MeV	4,6,9,12 MeV	2-50 MeV
Carica per pacchetto	6 nC	1.8 nC	1.6 nC
Frequenza di ripetiz.	5 Hz	5-20 Hz	10 Hz
Corrente media	30 nA	18 nA (a 10 Hz)	16 nA
Durata pacchetto	4 μs	1.2 μs	< 1 ps
Corrente di picco	1.5 mA	1.5 mA	> 1.6 KA



An assessment of the effects of such *high-current* e^- bunches on biological samples is needed at a pre-clinical stage
(and new applications in perspectives?)

BEE Med

Biological Effects of laser-accelerated Electrons for Medicine

DO GIOVANI RICERCATORI 2009

Ministero della Salute – Direzione Generale della Ricerca Scientifica e Tecnologica

Application resume

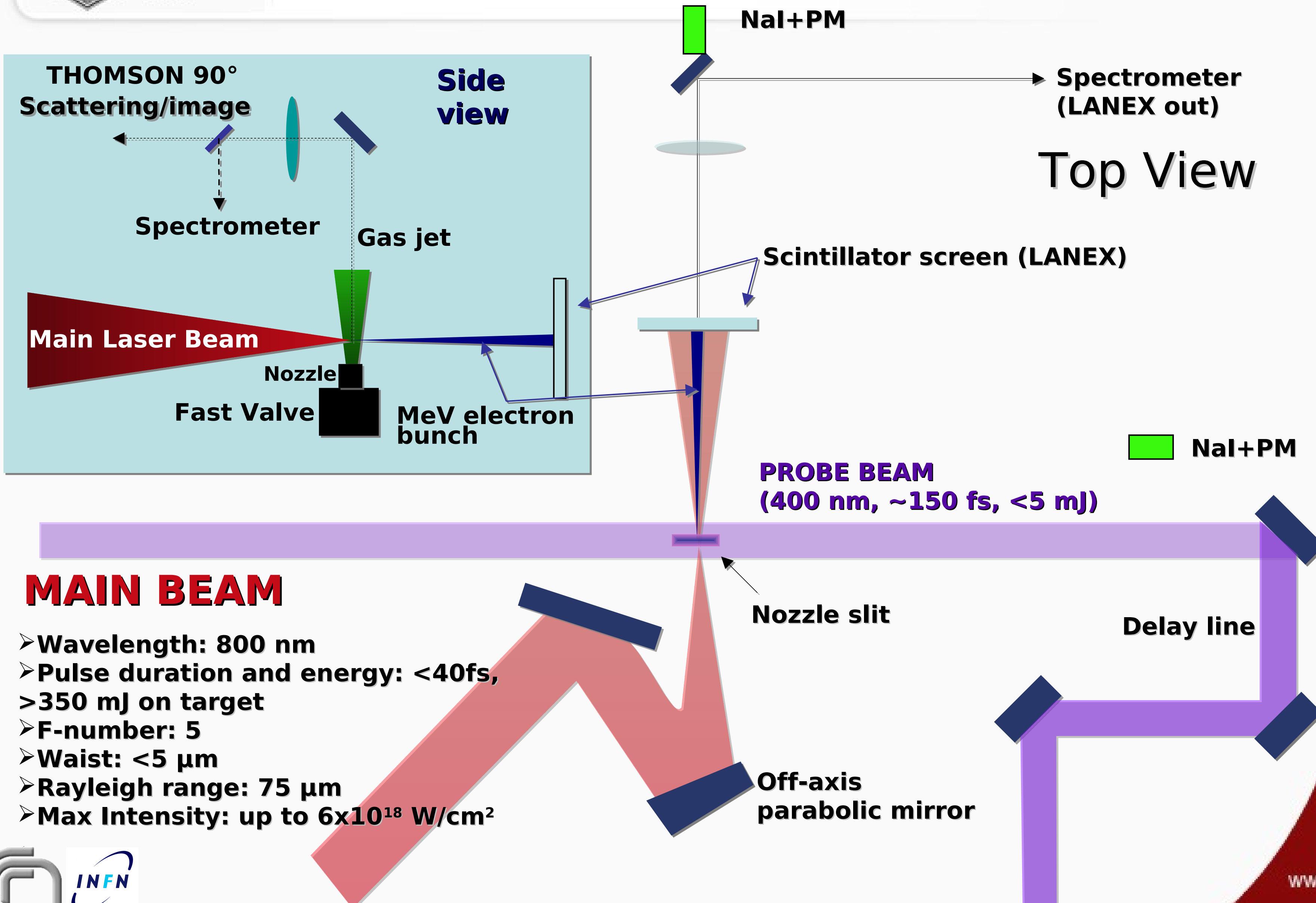
Title: Study of Radiobiological and Radiotherapic Effects of a Novel Laser Driven Electron Accelerator

The goal of this project is to assess the effectiveness of L-linacs and to study new potential applications, using established biomedical protocols. In particular, the project is aimed at: a) validating with non-clinical tests the effectiveness of the dose delivered with the laser-based experimenal device, also in comparison with the effect of dose delivered by current RF-based commercial device; b) investigate the possibility of a deeper dose release at higher kinetic energy; c) explore potential different effects due to the extremely different electron peak current available with the Laser and RF based techniques.

Outline

- Overview of the ILIL laboratory
- Recent LPA experiments @ ILIL: radiobiology toward radiotherapy
  - Motivation: radiotherapy with LPA electrons
  - First radiobiology experiments @ILIL
- PIC simulations of the LPA regime used for the radiobiology experiment
- Summary and overview of future plans

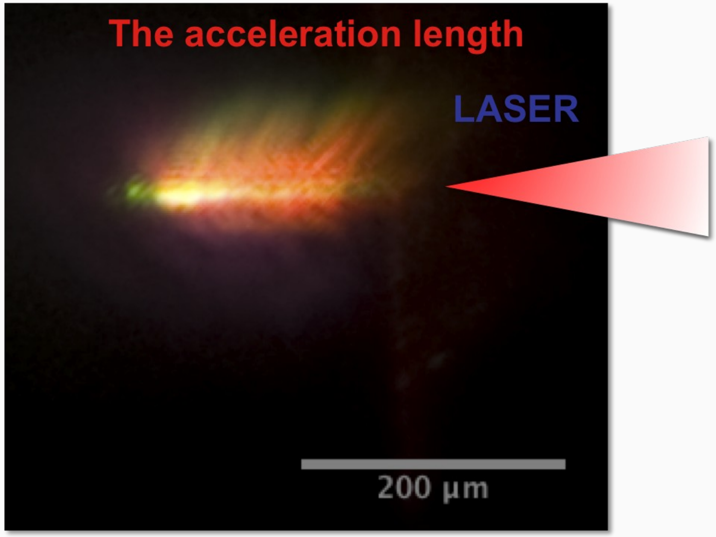
LPA exp @ ILIL: general layout



MAIN BEAM

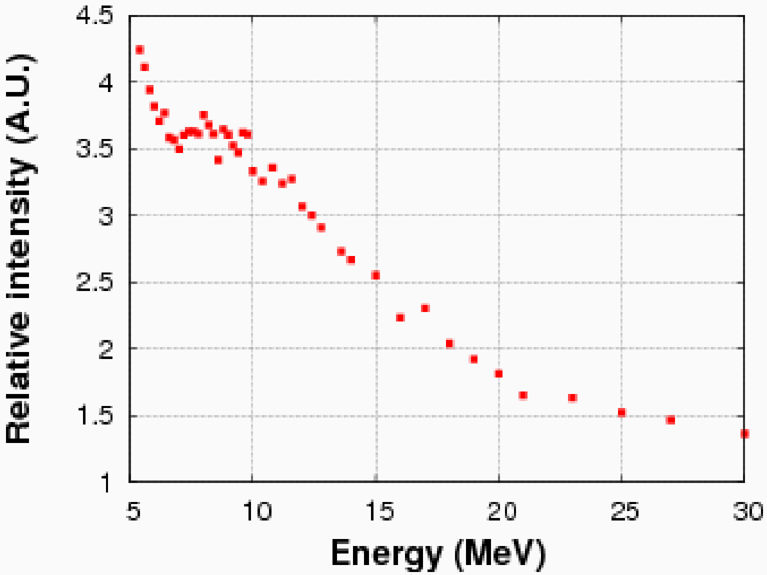
- Wavelength: 800 nm
- Pulse duration and energy: <40fs, >350 mJ on target
- F-number: 5
- Waist: <5 μm
- Rayleigh range: 75 μm
- Max Intensity: up to 6×10^{18} W/cm^2

LPA exp @ILIL 2014: general results

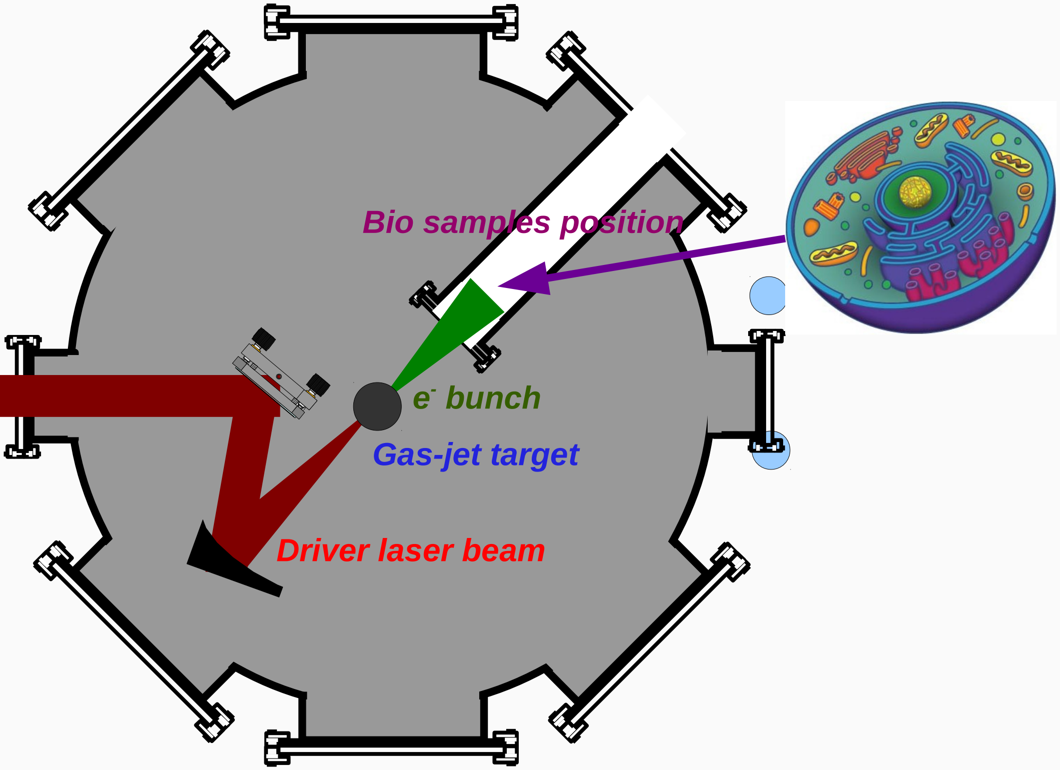


Thomson imaging clearly showed the region of propagation of the laser pulse, with evidence of self-guiding over a length approximately 2-3 times the depth of focus.

The acceleration regime best suitable to radiobiology applications was chosen with the following figures:
Electron energy up to ~10-15 MeV
Total bunch charge up to 1nC/shot
(both measured and simulated by PIC codes)



Radiobiology with LPA electrons: experiment @ILIL



Ad hoc vacuum-air feedthrough designed and simulated using Monte Carlo simulations

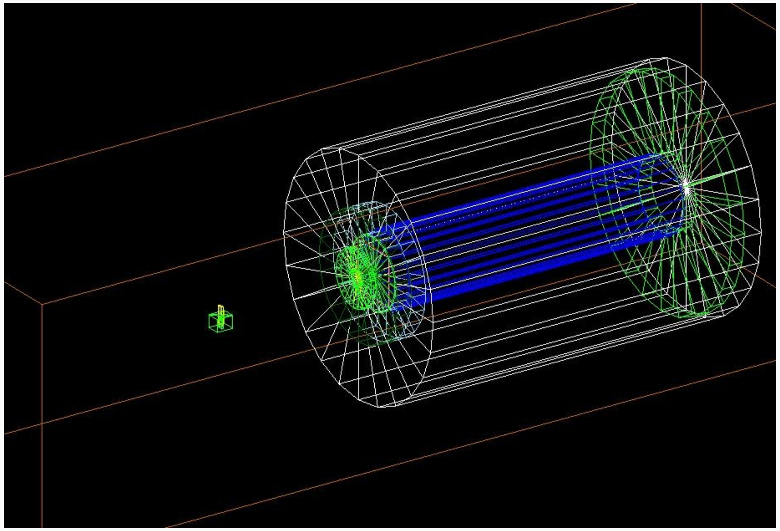
Total charge monitored on a single shot basis using an ICT device

Rep rate up to ~1Hz achieved → high radiation doses could be delivered on samples over time range similar to existing LINAC devices currently used for radiotherapy

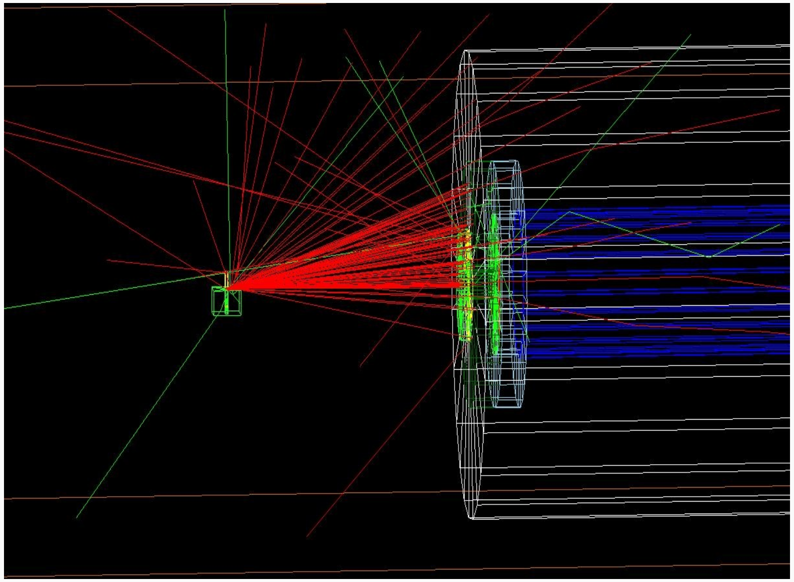
Dosimetric study and characterization of the electron beam carried out (collaboration with IBFM-CNR)

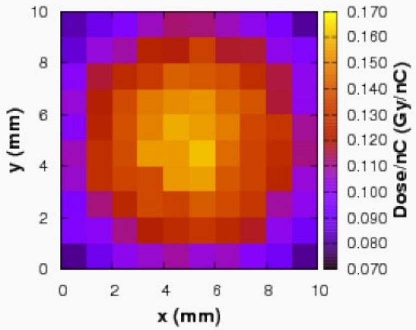
First measurements of cell damage carried out on human lymphocites and cancer (osteosarcoma) cells at high doses (collaboration with IFC-CNR and NANO-CNR)

MonteCarlo simulations of the delivered dose



The dose delivered to the samples was retrieved by using MonteCarlo simulations of the particles transport based on the CERN GEANT4 library



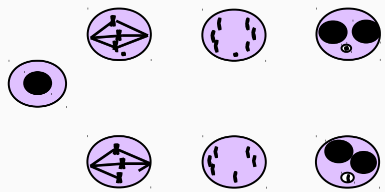


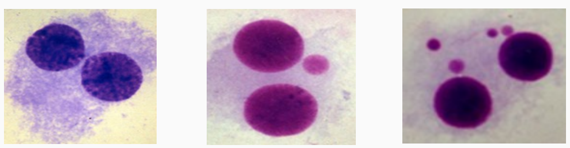
Transverse dose deposition profile uniform within ~10% over a field of ~6mm size (appropriate for radiobiology experiments with small samples)

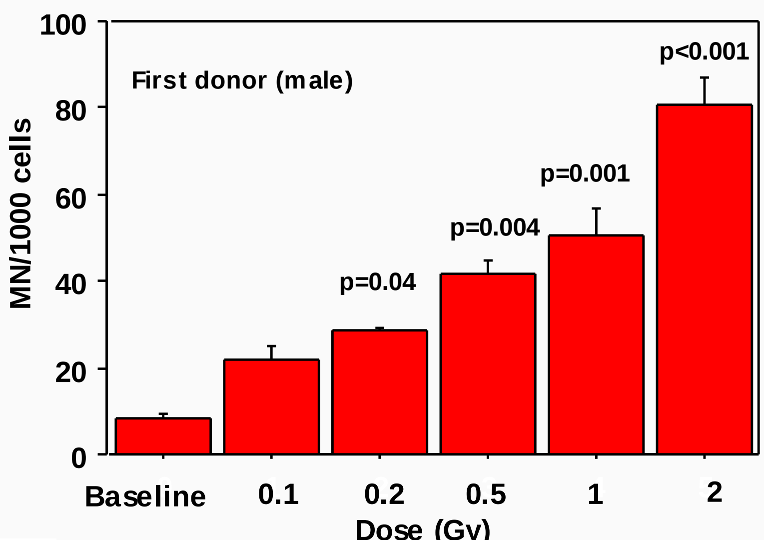
50-100 mGy/shot available on the samples → High doses (up to 10-20Gy) could be delivered in a few tens of seconds)

Example of DNA damage studies

Micronuclei induction in cytokinesis-blocked human blood lymphocytes







The nicronuclei assay was used to evaluate DNA damages in human blood lymphocites at different doses (the dose-response curve was obtained by scoring 1000 cells of two donors (each on two replicated experiments).

Rates of MNs were significantly higher than baseline from 0.20 Gy (p=0.04) and 0.5 Gy (p=0.009) for first and second donors, respectively.

A comparison with damage from X-rays at the same doses was carried out; a comparison with e- bunches from a LINAC is also ongoing

Outline

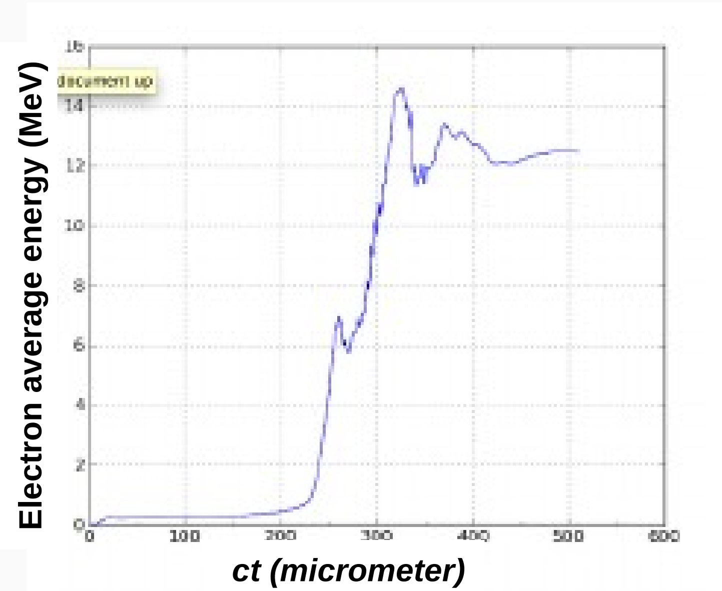
- Overview of the ILIL laboratory
- Recent LPA experiments @ ILIL: radiobiology toward radiotherapy

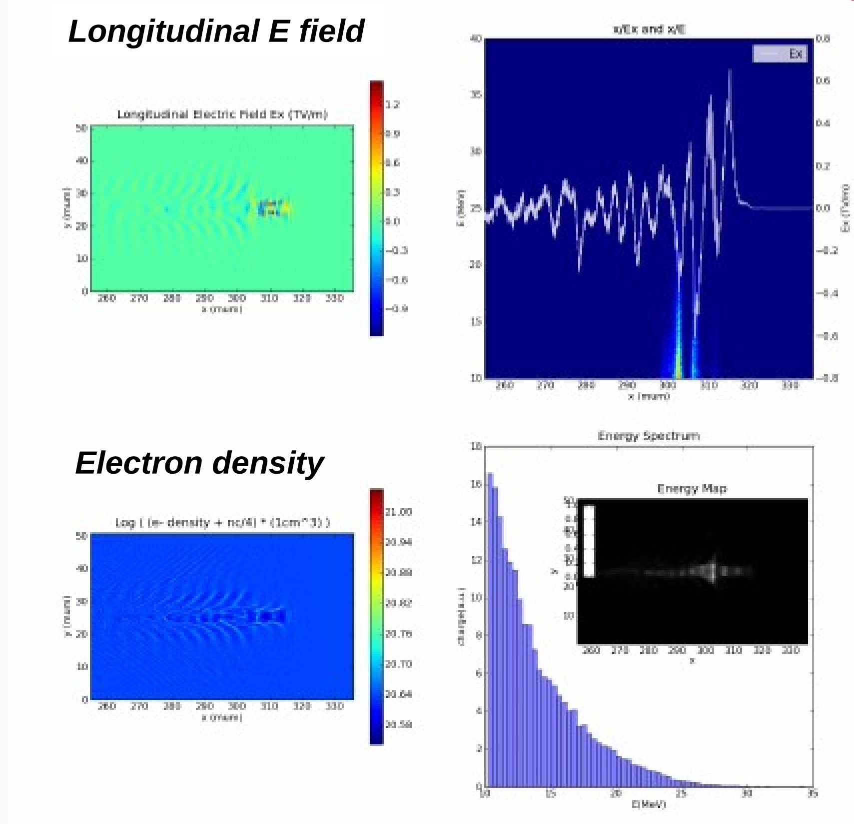
  - Motivation: radiotherapy with LPA electrons
  - First radiobiology experiments @ILIL
- PIC simulations of the LPA regime used for the radiobiology experiment
- Summary and overview of future plans

PIC simulations of the acceleration regime

PIC simulations carried out by F. Rossi, P. Londrillo, G. Turchetti

Plasma density: $3\times10^{20}cm^{-3}$ plateau with 800mm ramp-up (Nitrogen gas used)
Laser parameters as given above





Complete laser depletion is reached after 350µm propagation in the ramp
High divergence (~100mrad), high energy spread (~50%) electron bunches are accelerated
Total charge with energy >10MeV ~1nC

Summary and overview of future plans

- The group operating at the ILIL laboratory is carrying out a long term study of laser-driven electron accelerators and high energy photon sources
- In particular, a project is ongoing aimed at assessing, at a pre-clinical stage, the possibility of using small-scale, TW-class laser systems to produce electron bunches at a few tens of MeV energy, of interest for radiotherapy
- An acceleration regime has been identified particularly interesting for Intra-Operatory Radiation Therapy, providing electron bunches with energy up to 10-15 MeV and high charge/shot. Running the source at 1Hz allowed doses comparable to “real” treatments to be used for in vitro radiobiology experiments
- Radiobiology experiments have been being carried out, mainly aimed at assessing the biological effectiveness of LPA electrons in comparison to LINAC accelerated electrons

- An experiment is currently ongoing aimed at establishing a Thomson scattering source with the 10TW scale systems. Preliminary simulations and electron measurements show that e- bunches with energy up to a few 100s MeV can be produced.
- An upgrade of the ILIL TiSa laser system is ongoing, targeting the sub-PW scale. A new shielded target area is also under construction. The upgrade 1st phase is expected to be completed within 2015, with the laser system running at the 100TW level

Empty slide

Empty slide