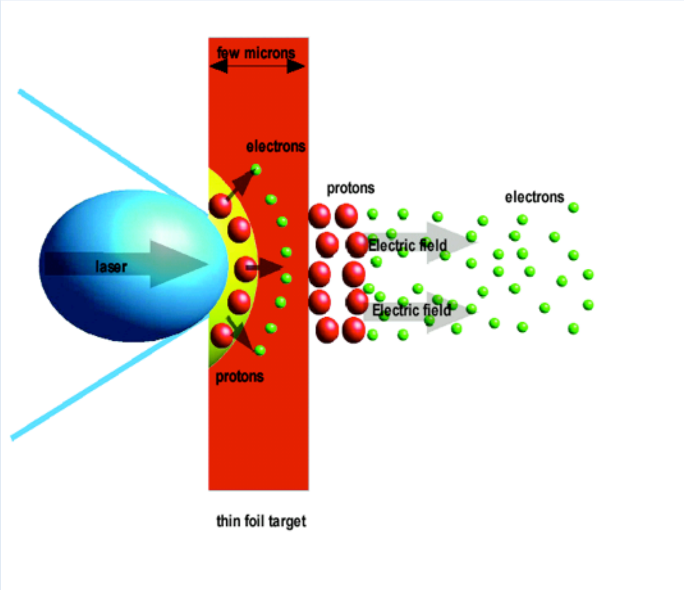
Proton Beams Produced by Laser Interaction in Italy: from the First Experiences at the INFN FLAME Facility toward the Development of a Multidisciplinary Proton Beam Line (ELIMED)

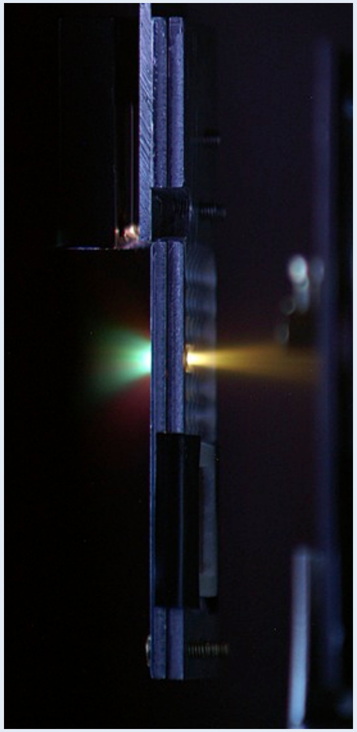
Dario Giove on behalf of the NTA_SL_LILIA and ELIMED groups

NTA-SL-LILIA (Laser Induced Light Ions Acceleration)

NTA-SL-LILIA LILIA is an experiment of light ions acceleration trough laser interaction with thin metal targets to be done at the SPARC-LAB facility under operation in Frascati.

The main goal is to obtain a beam suitable for injection in other accelerating structure.





Laser Parameters

Beam diameter 120mm
~flat top
M2≈1.5
Waist (I/e2)≈ 10µ
contrast≈10^{-10}
Raileigh length= 260µ
Pulse duration: 25-35 fs
Max Energy on target: 4J
Long focal length parabola
Max Intensity I=6.8 10^{19}W/cm^{2} (35 fs) or 9.6 10^{19} (25fs)
Short focal length OA Parabola: waist≈2.5µ, I≈1021W/cm2

Study and Simulation of the Proton Emission

Scaling in TNSA regime from AlaDyn simulation, theory and Dresda data

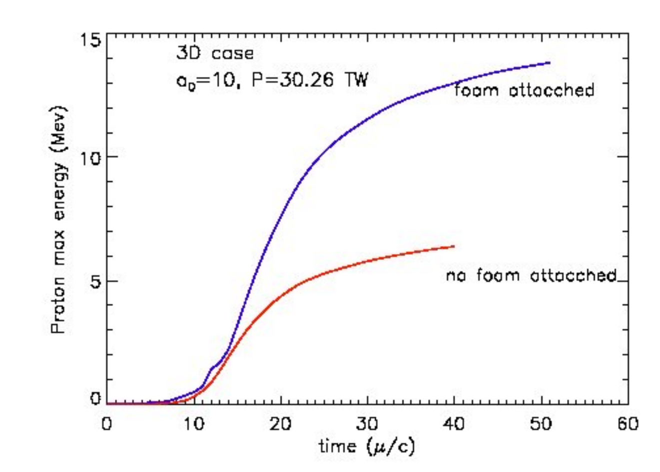
$E_{max} = k\ a^{1.6}$ with $a \sim I^{1/2}$.

For LILIA at the beginning we expect a < 8 e Emax ~ 4 MeV.

At the foreseen FLAME higher power we expect

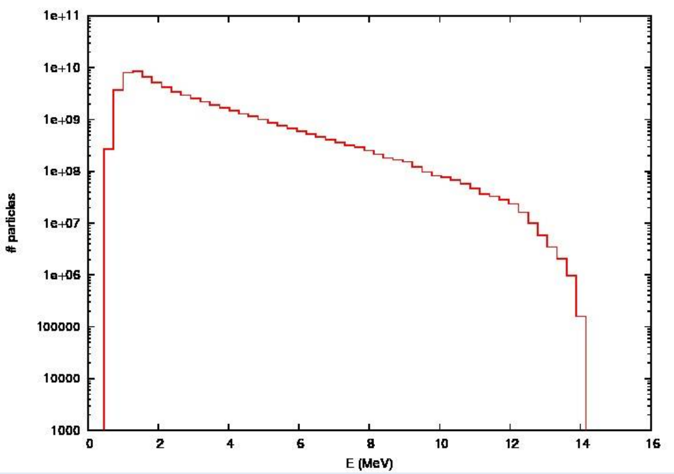
a> 30 e Emax > 30 MeV. With structured targets we can double the energy

Energy evolution for a bare and structured target



Energy distribution $r(E)= N/E_0\ e^{-E/E_0}$

$E_0 \approx E_{max}/8$ average energy



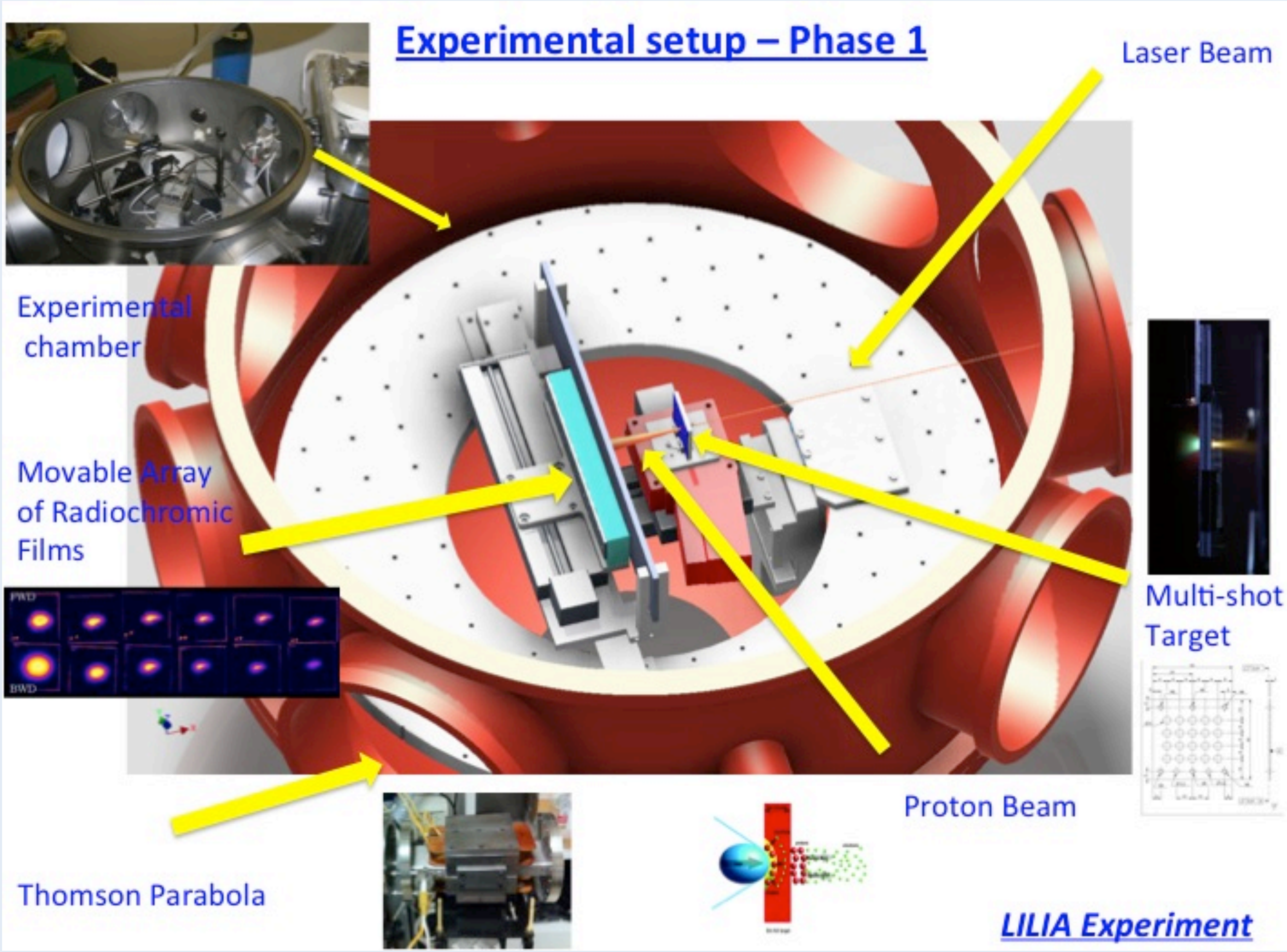
NTA_SL_LILIA (2012 and up to December 2013)

A parametric study of the correlation of the maximum TNSA accelerated proton energy, with respect to the following parameters:

Laser pulse energy (in the range 0.1-4 J)
Metallic target thickness (in the range 1-10 microns).

In such a frame we would deeply investigate the experimental scale rules within the possibilities offered by the FLAME facility.

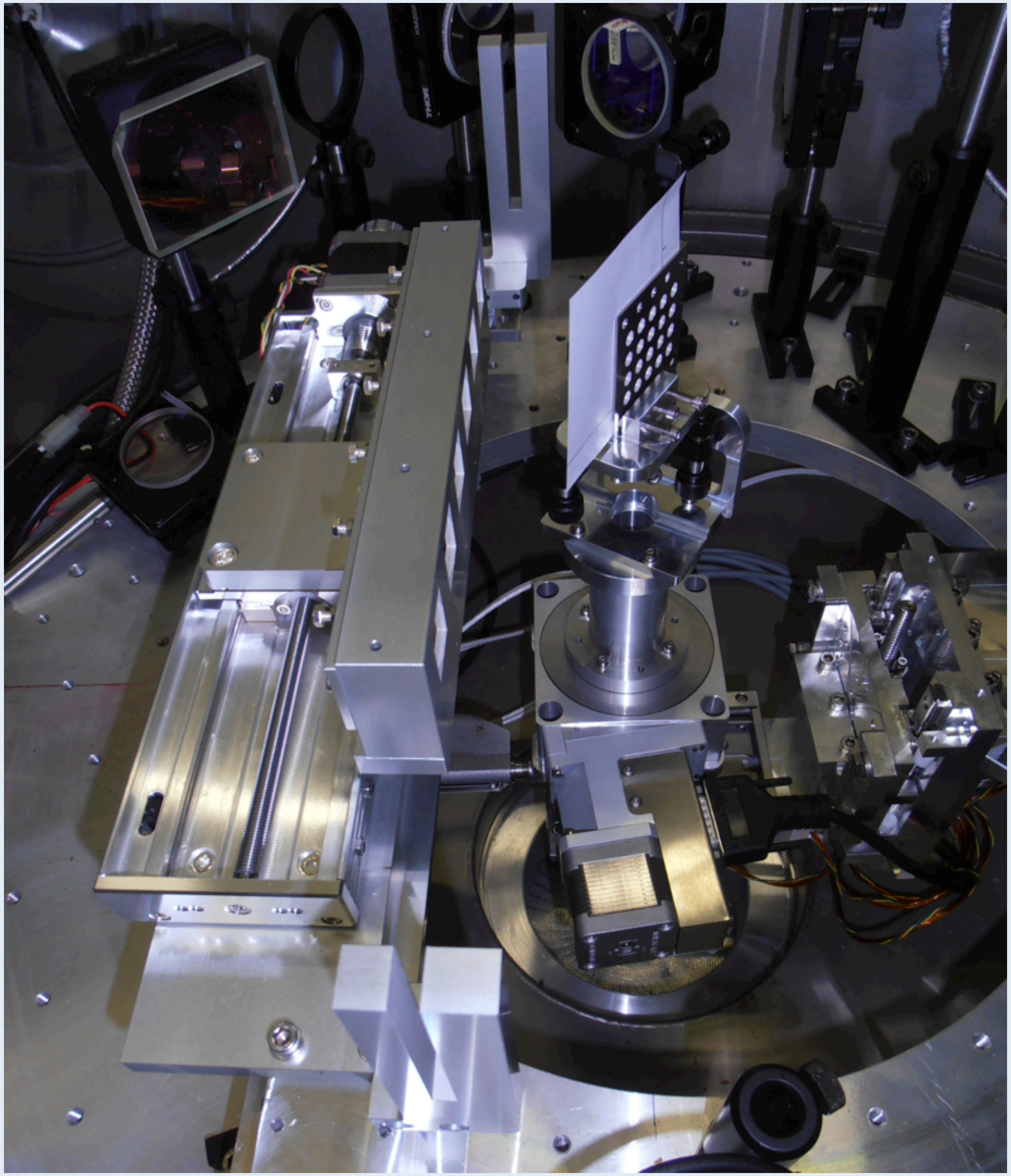
Moreover, this will provide the opportunity to get experience in the development of diagnostic techniques and in target optimization.


Experimental setup – Phase 1
Laser Beam
Experimental chamber
Movable Array of Radiochromic Films
Multi-shot Target
Proton Beam
Thomson Parabola
LILIA Experiment

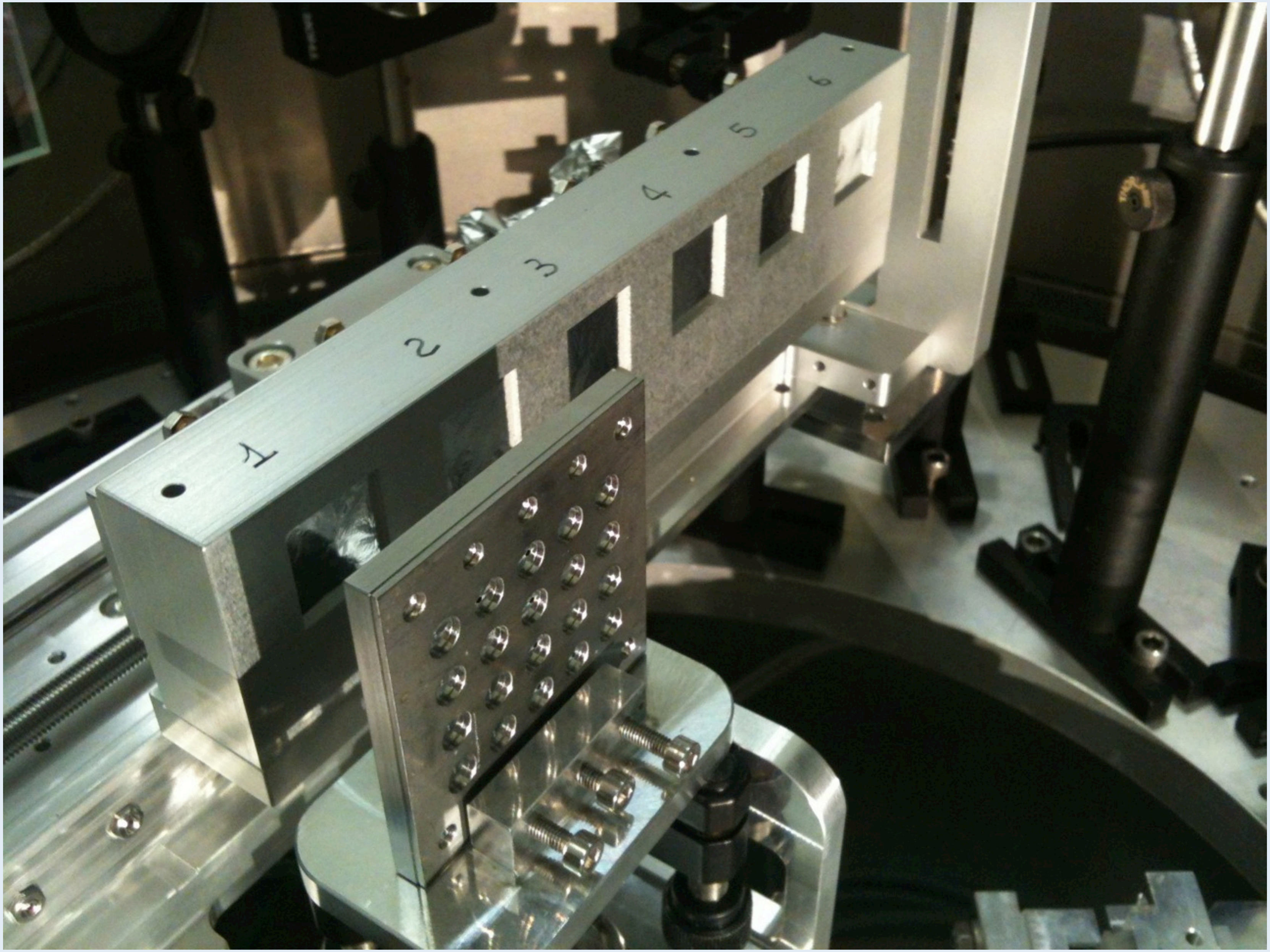
6

Status @ 7 November 2012

- Mechanical setup assembled and aligned in the experimental chamber
- 4 linear stages and 1 rotation stage (for target and detectors) fully integrated in the main control system
- Start of the tests with the FLAME laser from November 13 2012
- PIN diodes detectors assembled in the interaction chamber for tests on electronic noise



Beam tests from November 13 to December 22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2
3
4
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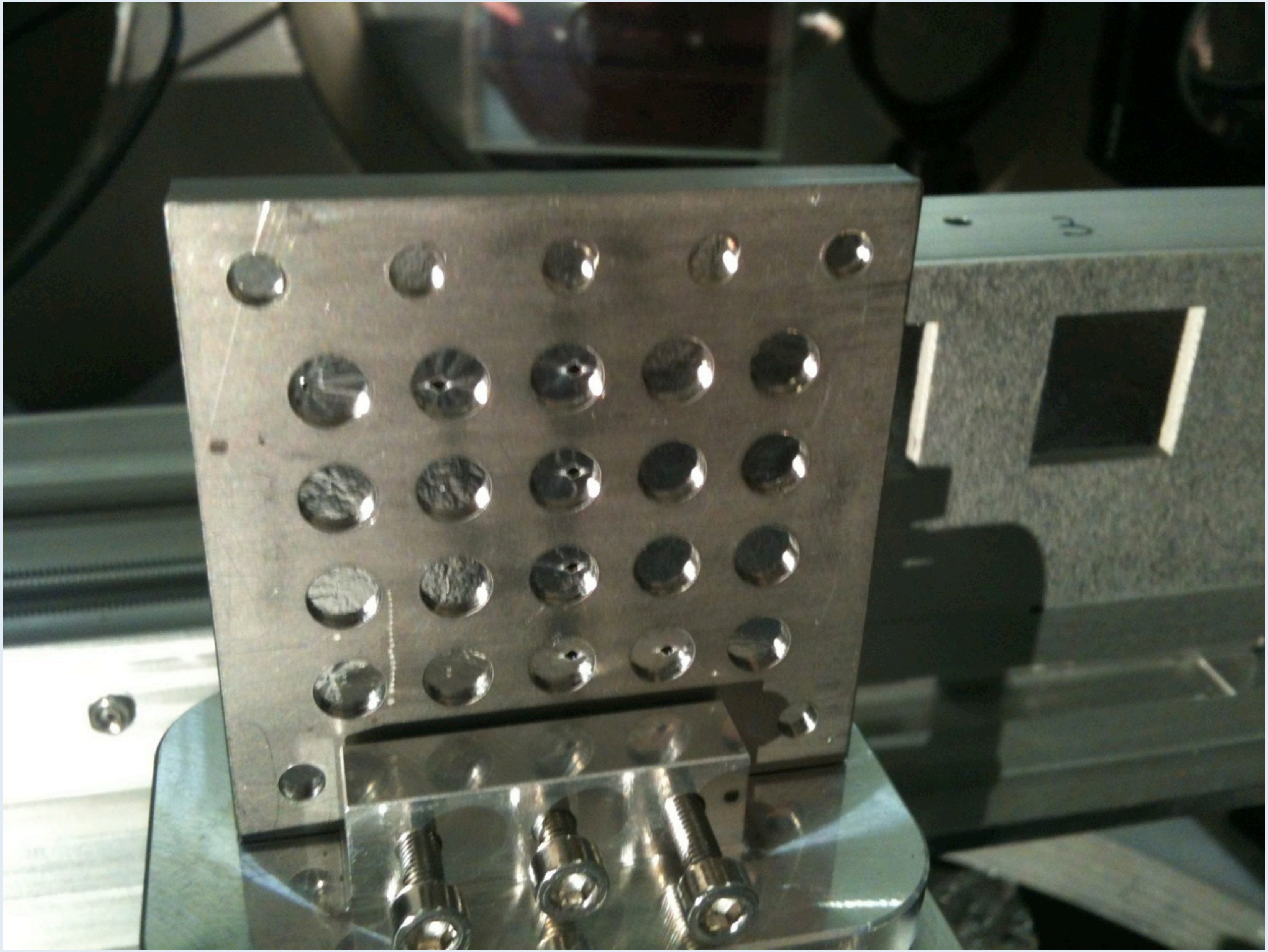
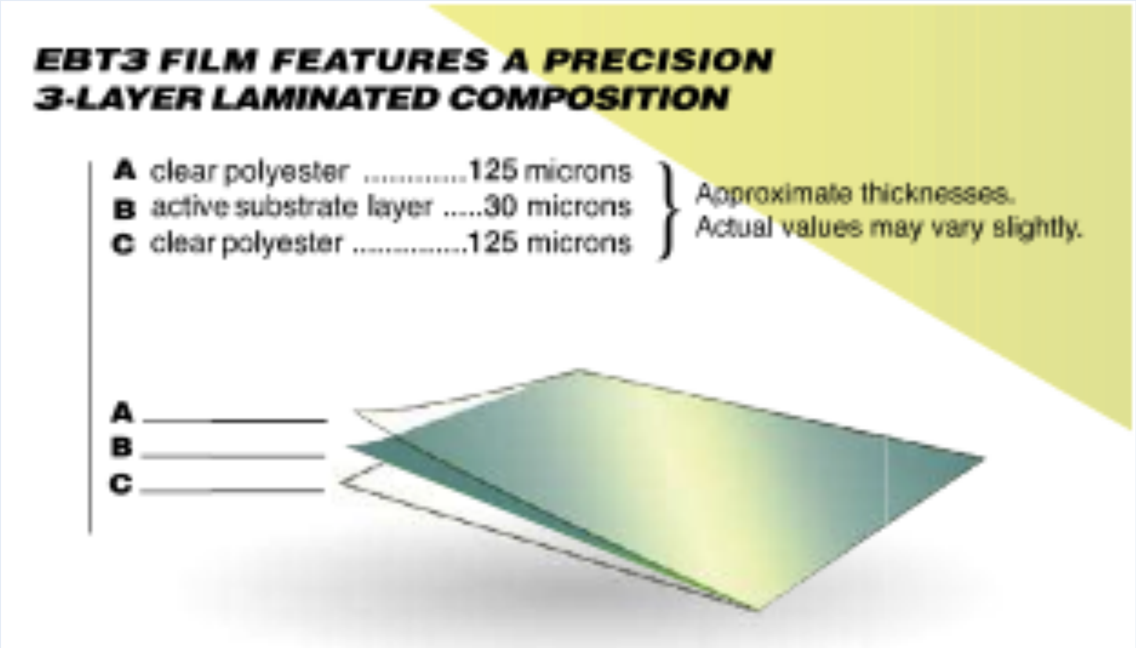
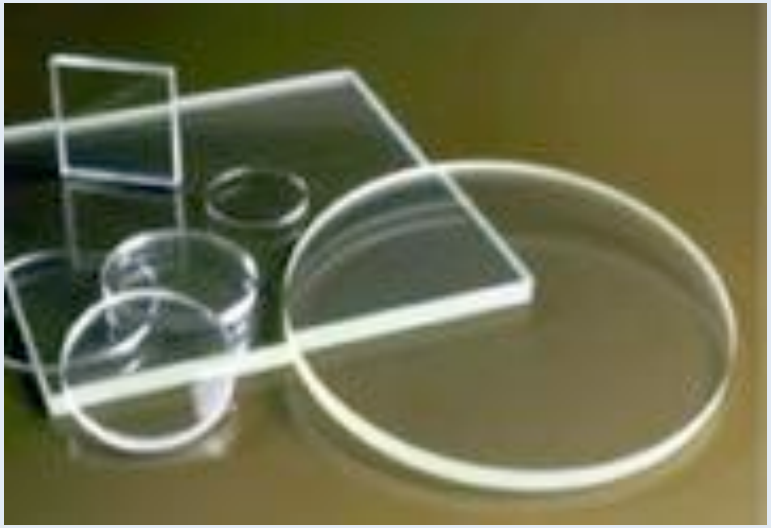
6





Range 0.01-40 Gray

CR-39 is an allyl glycol carbonate plastic that has been widely used as a passive, limited spectral resolution, solid state nuclear track detector (SSNTD)



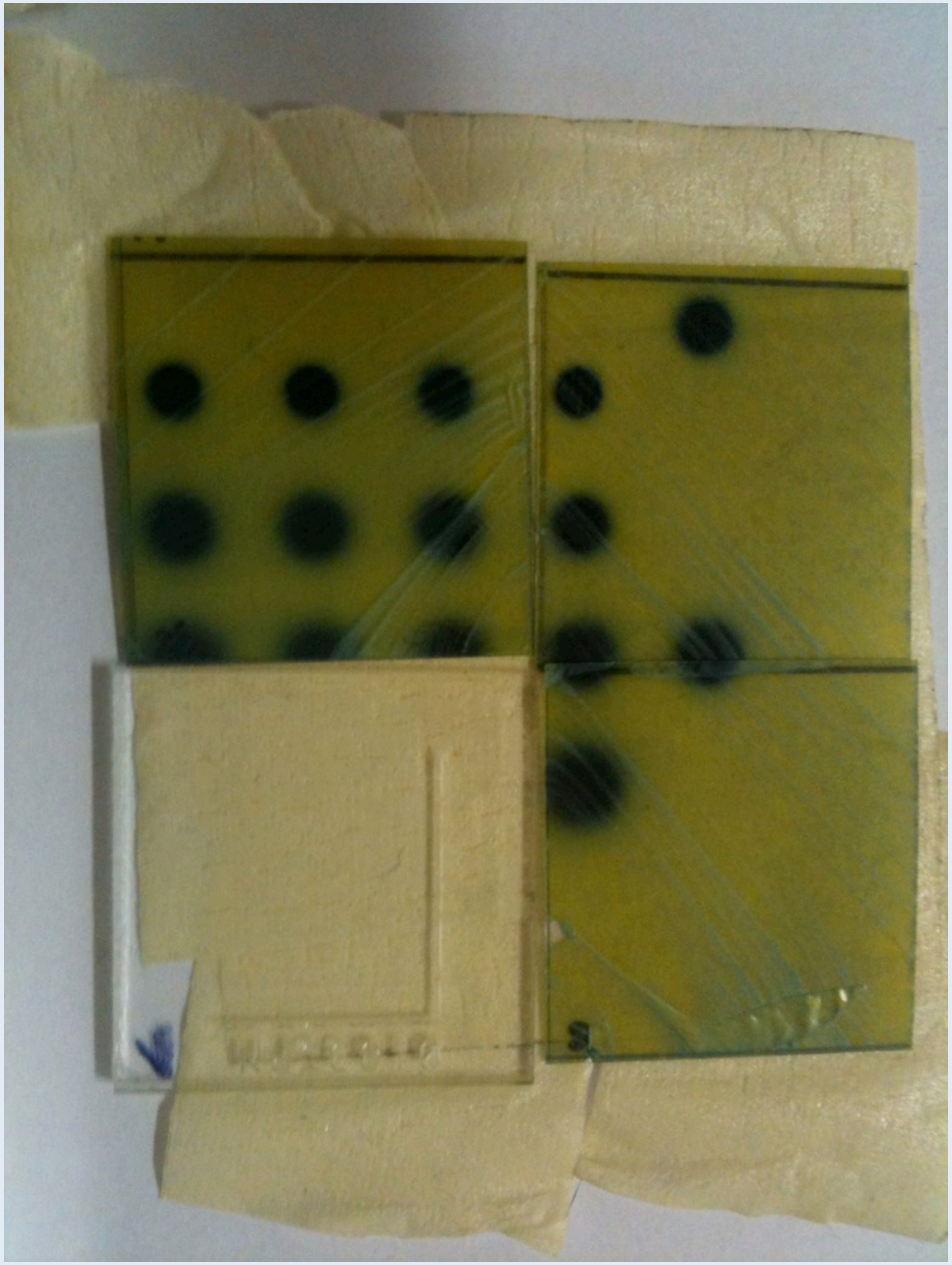
Target: Al foil. Depth from 12 to 3 μm

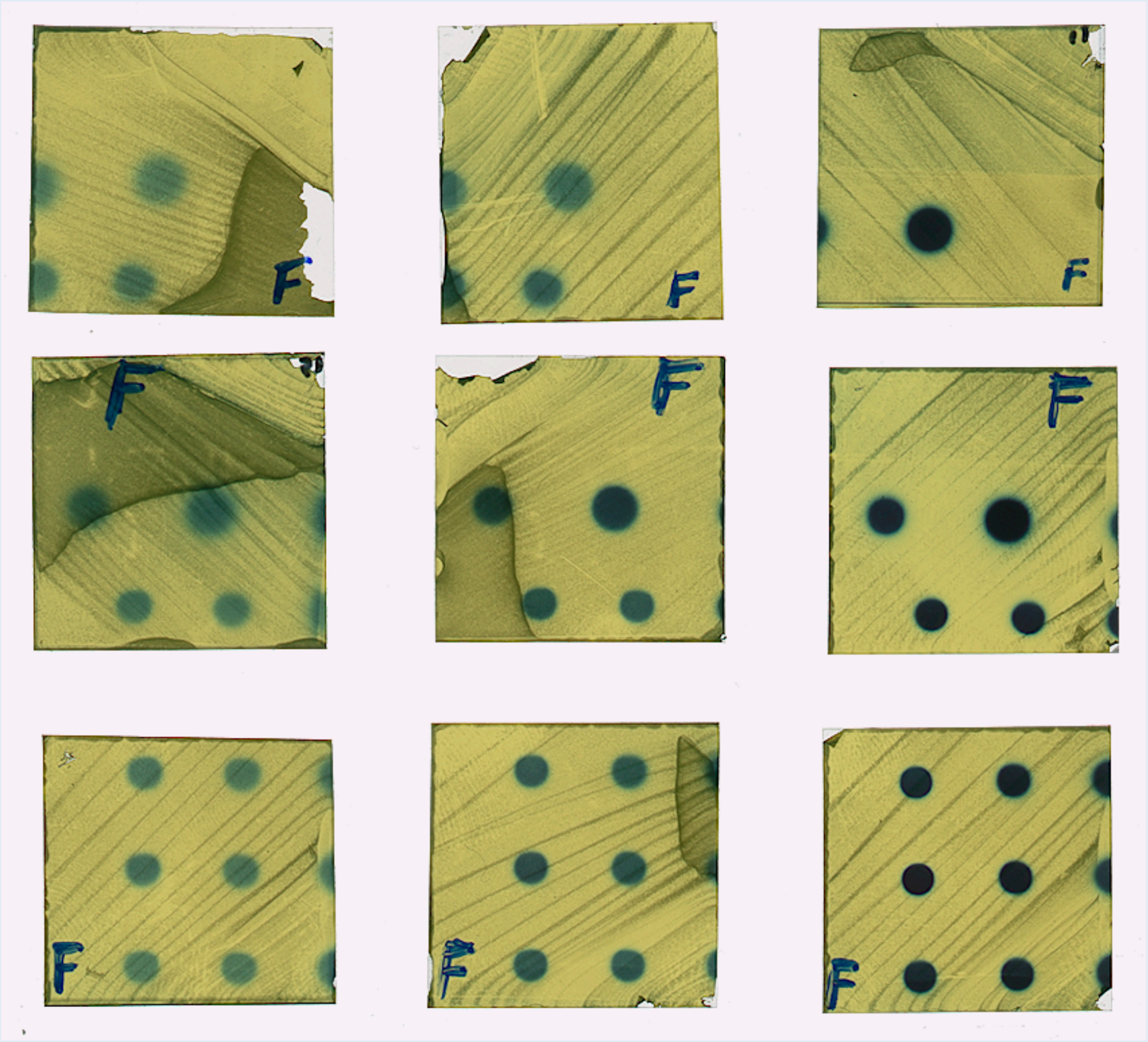
Thin Al foil in front of the gafchromic detectors (3 μm)

Al foil in front of the CR39 detector (16 to 6 μm)

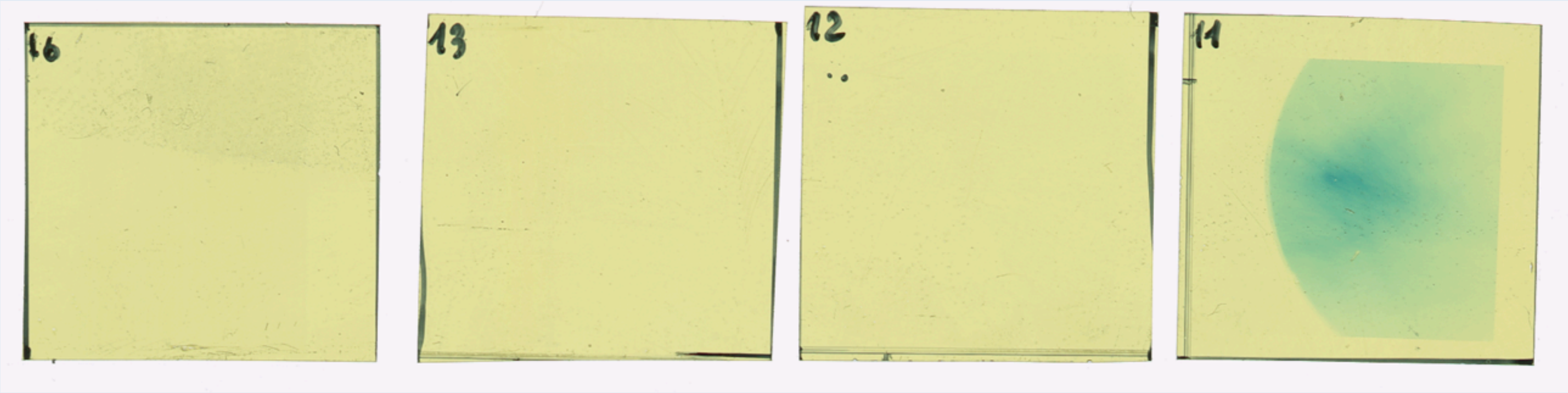
800 KeV protons have a range in Al equal to 10,42μm
1.1 MeV protons have a range in Al equal to 16,00 μm

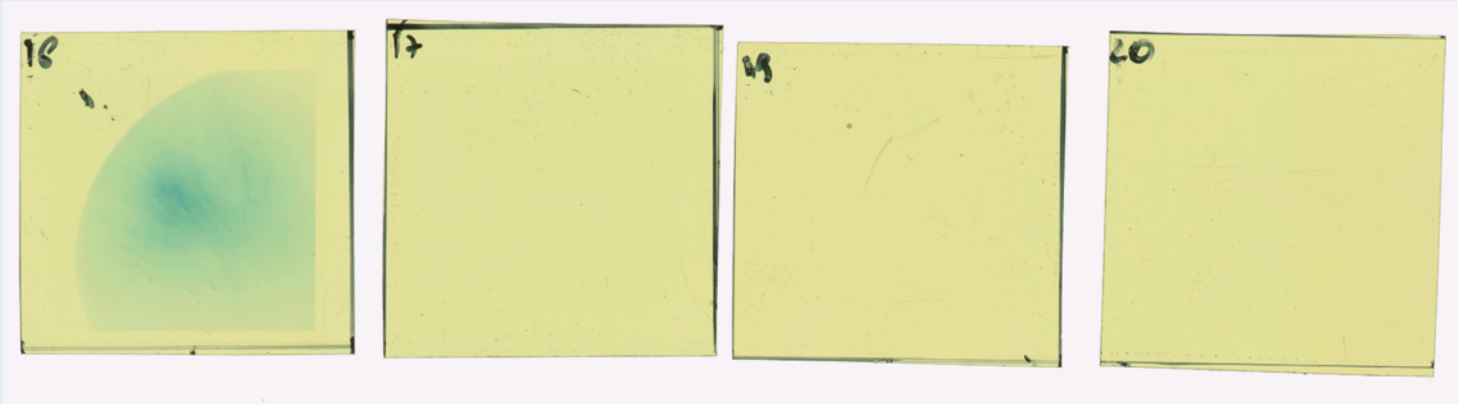
4 MeV protons have a range in poliethilene
(density ’ 0,93 g/cm$^{3)}$ equal to 210,64 μm.

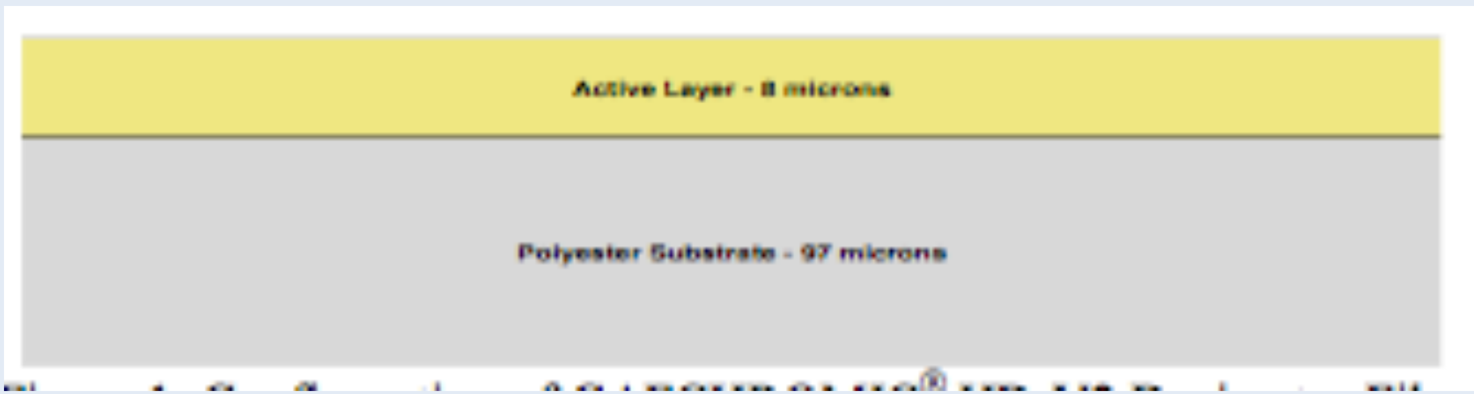




Detectors @ 45 mm from the target

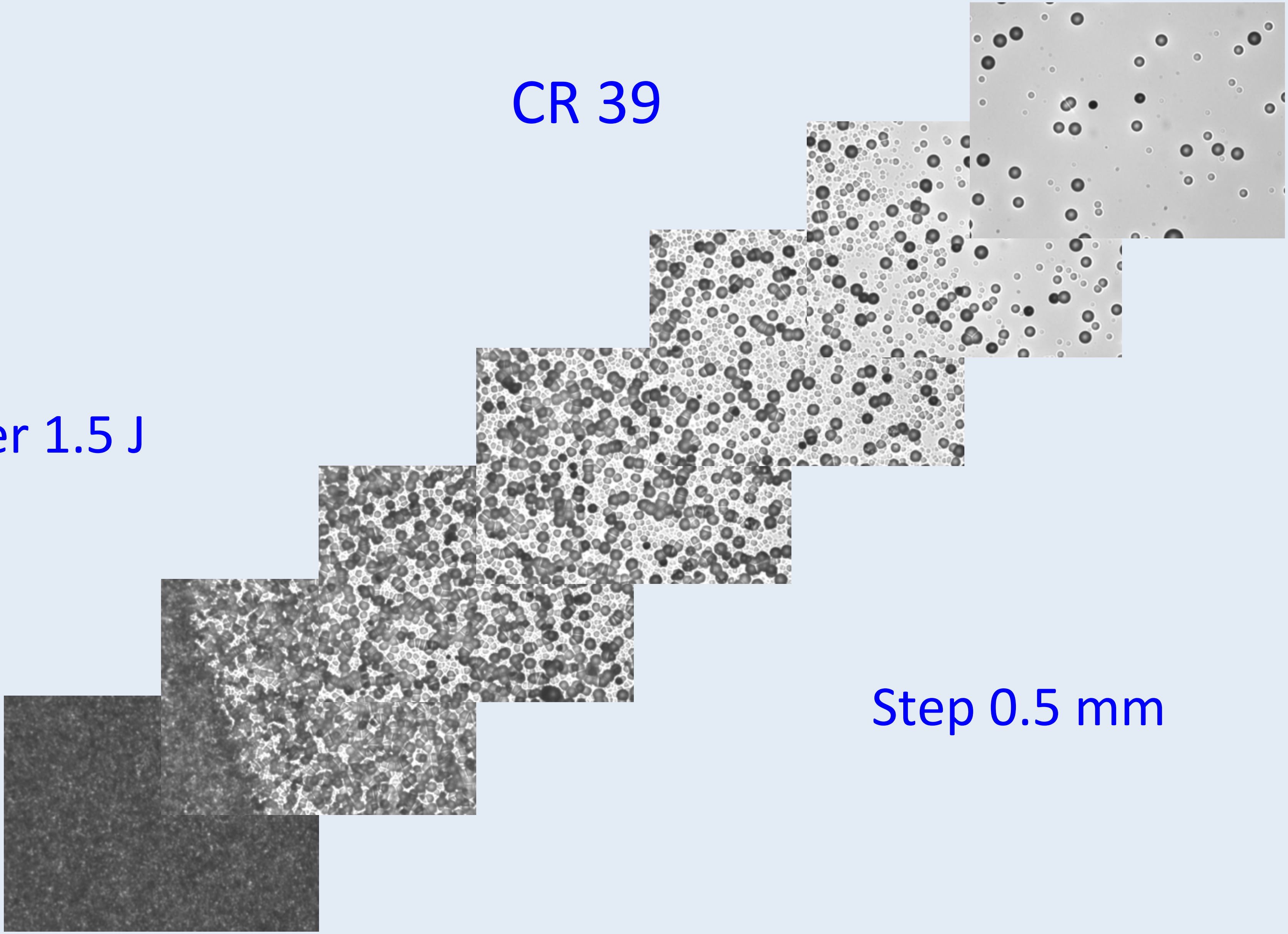




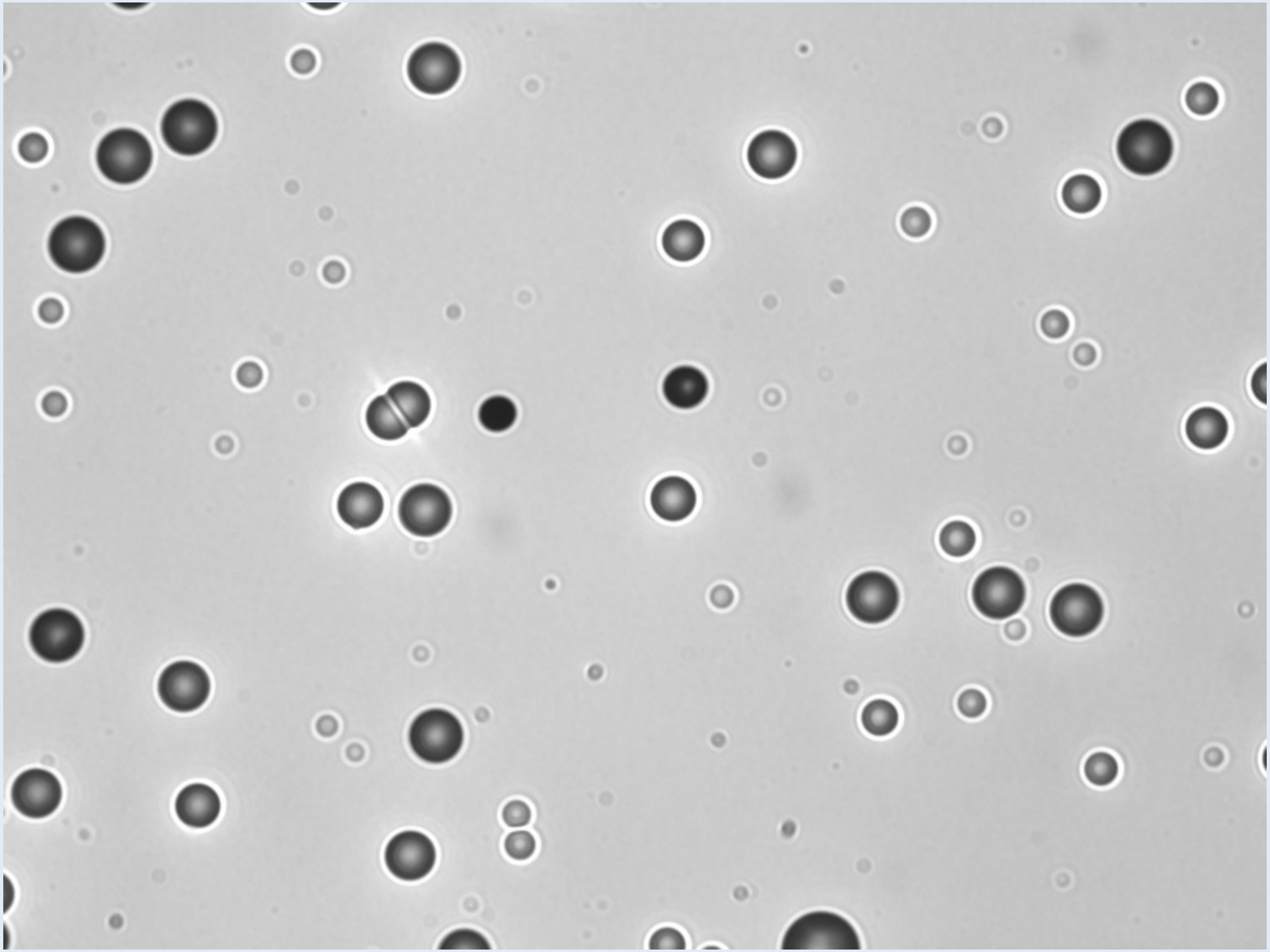

Active Layer - 8 microns
Polyester Substrate - 97 microns

CR 39

laser 1.5 J



Step 0.5 mm



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Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Determination of *LET* in PADC detectors through the measurement of track parameters

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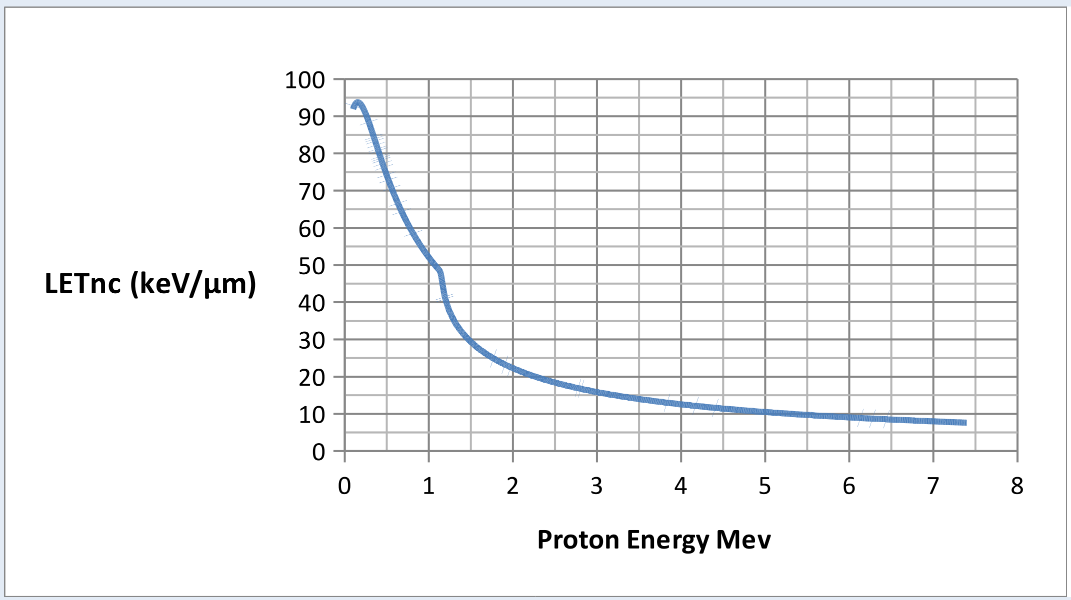
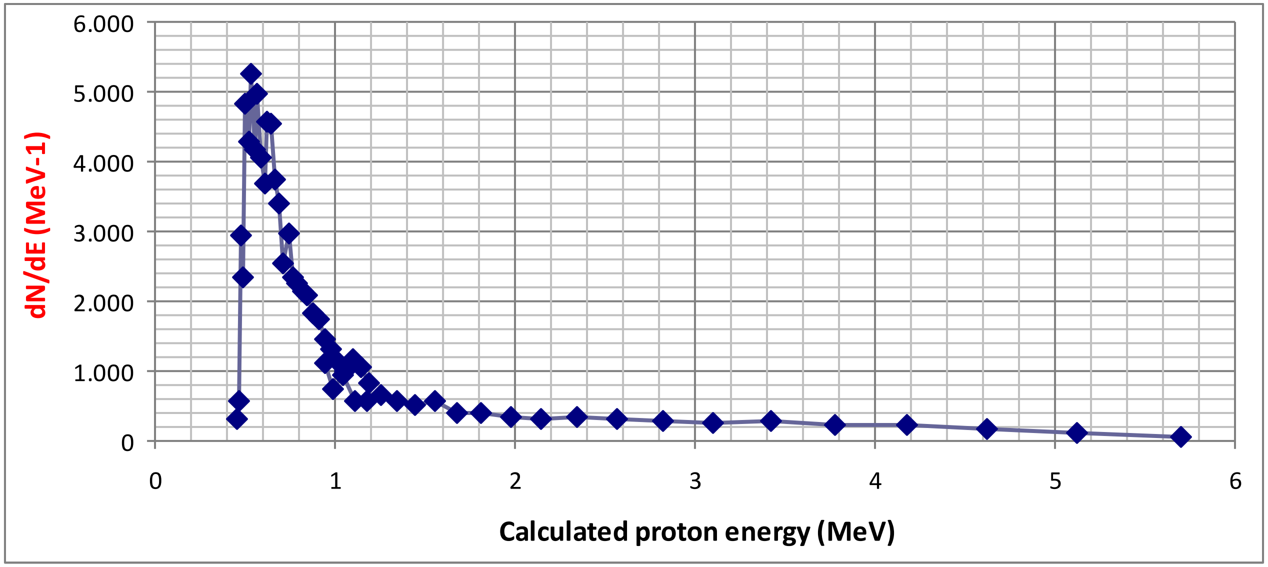
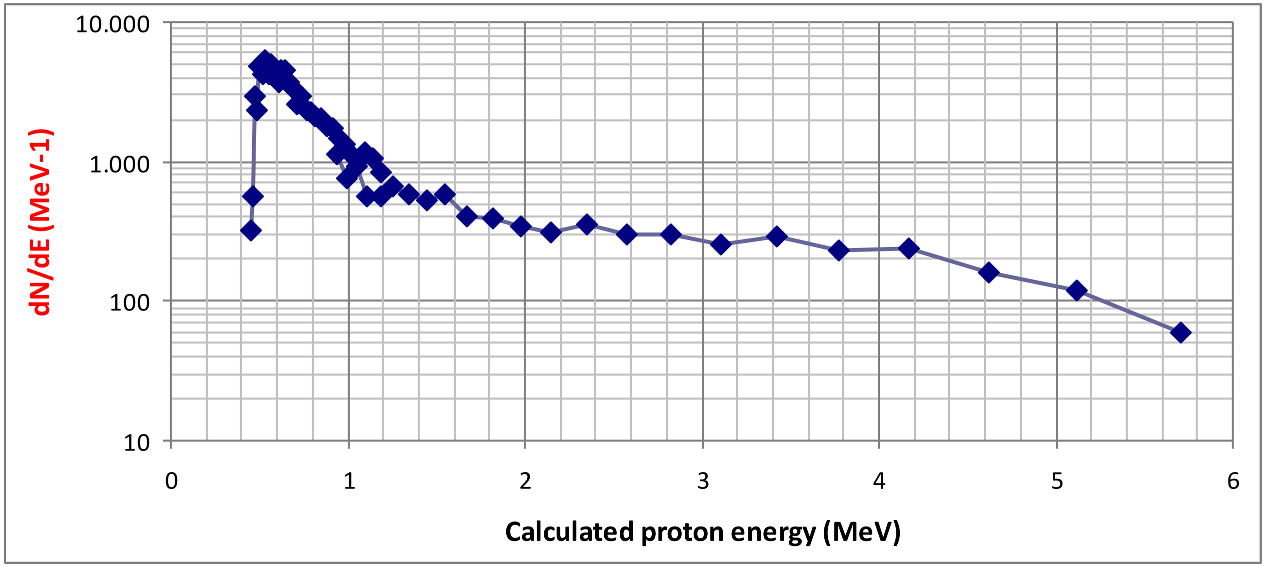
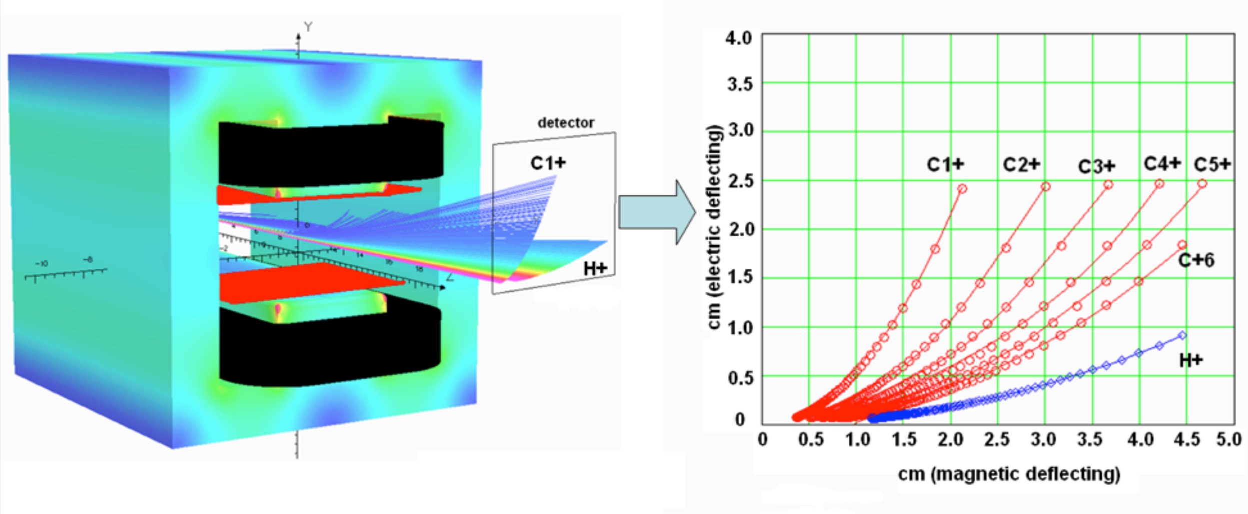
[b] Fondazione CNAO, via Caminadella 16, 20123 Milano, Italy
[c] Paul Scherrer Institut (PSI), Radiation Metrology Section, CH-5232 Villigen PSI, Switzerland



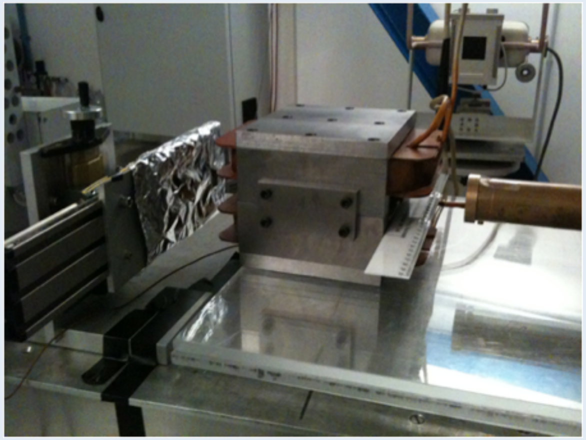

6.000
5.000
4.000
3.000
2.000
1.000
0
dN/dE (MeV-1)
0 1 2 3 4 5 6
Calculated proton energy (MeV)


10.000
1.000
100
10
dN/dE (MeV-1)
0 1 2 3 4 5 6
Calculated proton energy (MeV)

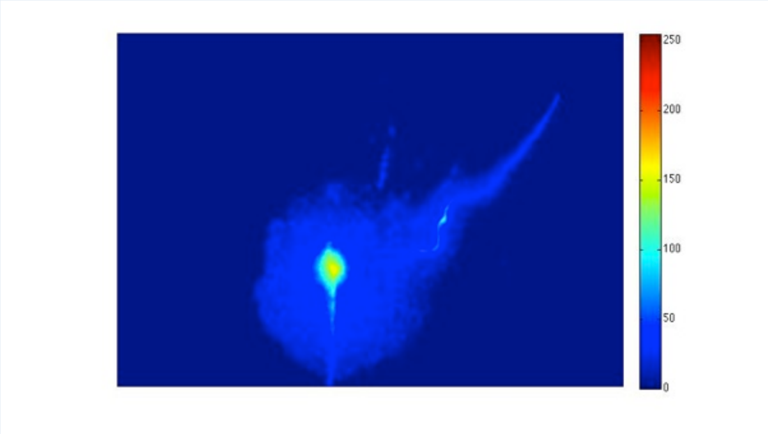
May 2013 run



Thomson Parabola during tests with a proton beam at LNS cyclotron



THOMSON SPECTROMETER: Analysis of proton and carbon beams (Q=+1 to + 6) from 0.1 MeV to 10 MeV

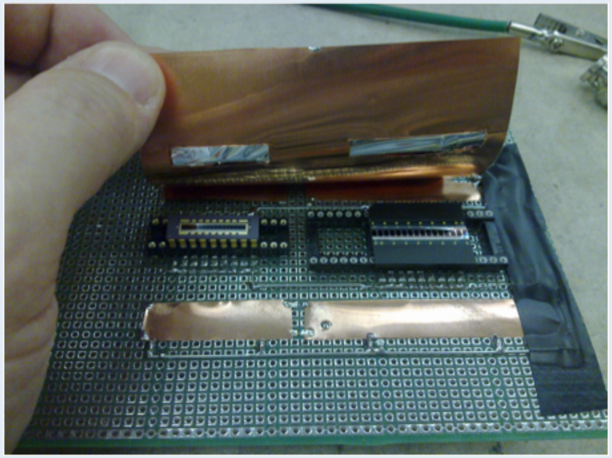


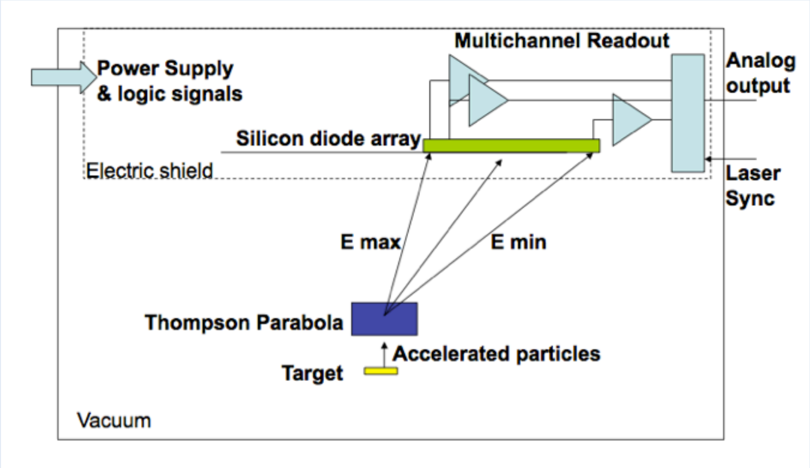
Laser Shot Induced Noise

Very Preliminary

- Background em noise along signal cables (length up to 50 m):
  +-50 mV, 5 MHz, 2 μs, 16 kHz

- Em noise induced by the laser shot on the target:
  +-1 V, 250 MHz, 200 ns





In progress

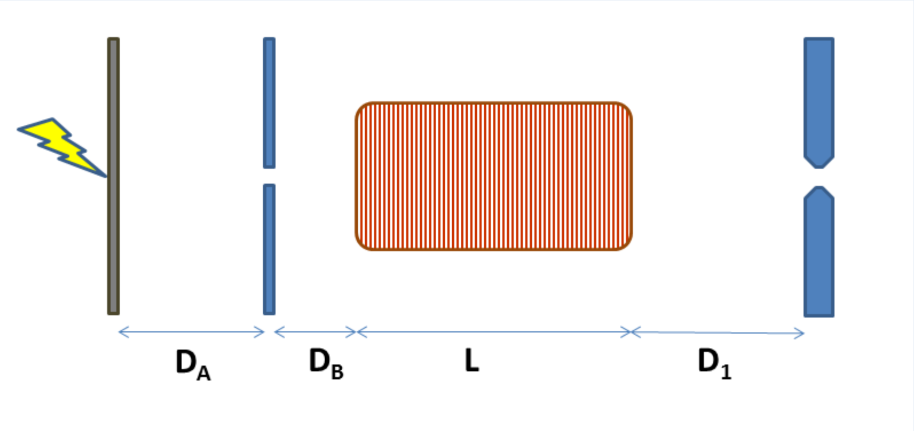


FIG. 4: Schematic draw of the transport line. $D_A = D_B = 10$ mm, $D_1 = 510$ mm, L = 300 mm, first iris radius = 0.5 mm, second iris radius = 0.6 mm, second iris minimum thickness = 5 mm.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 031301 (2013)

Transport and energy selection of laser generated protons for postacceleration with a compact linac

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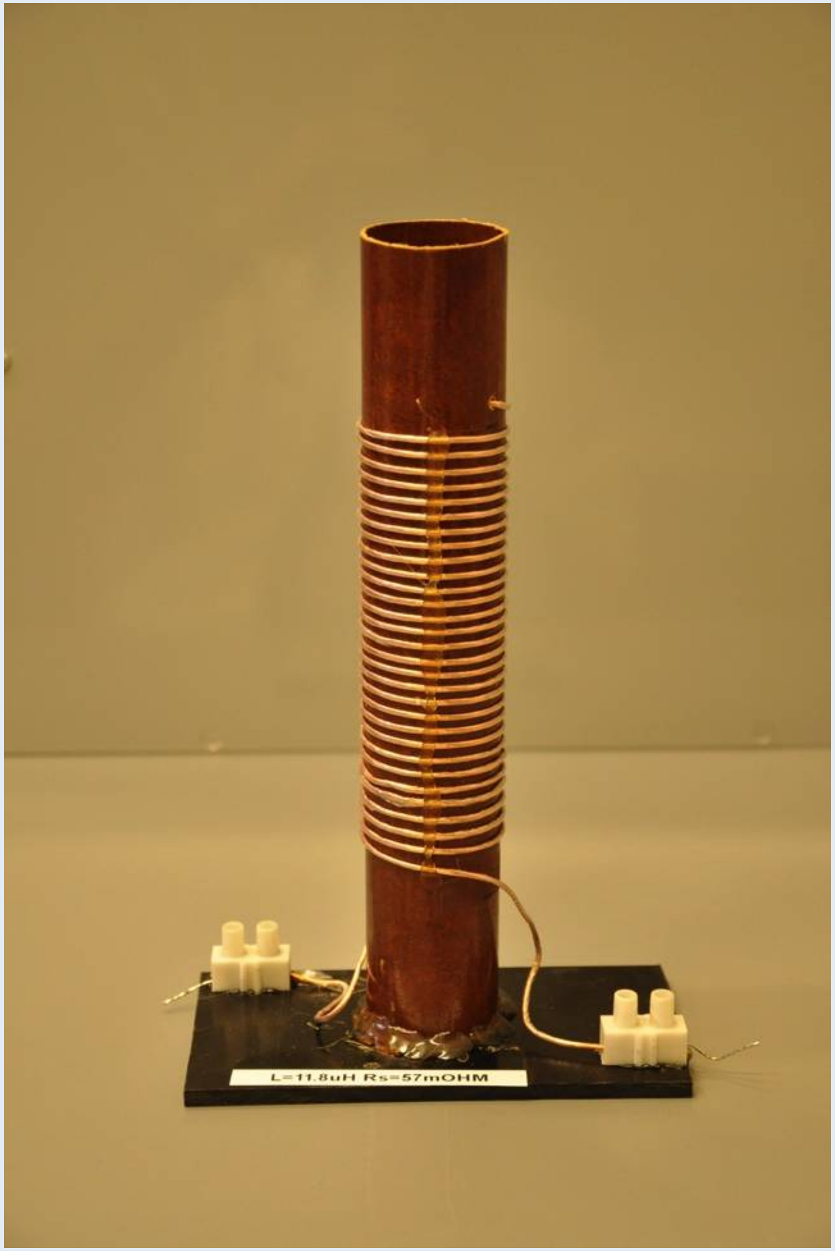
(Received 23 May 2012; published 1 March 2013)

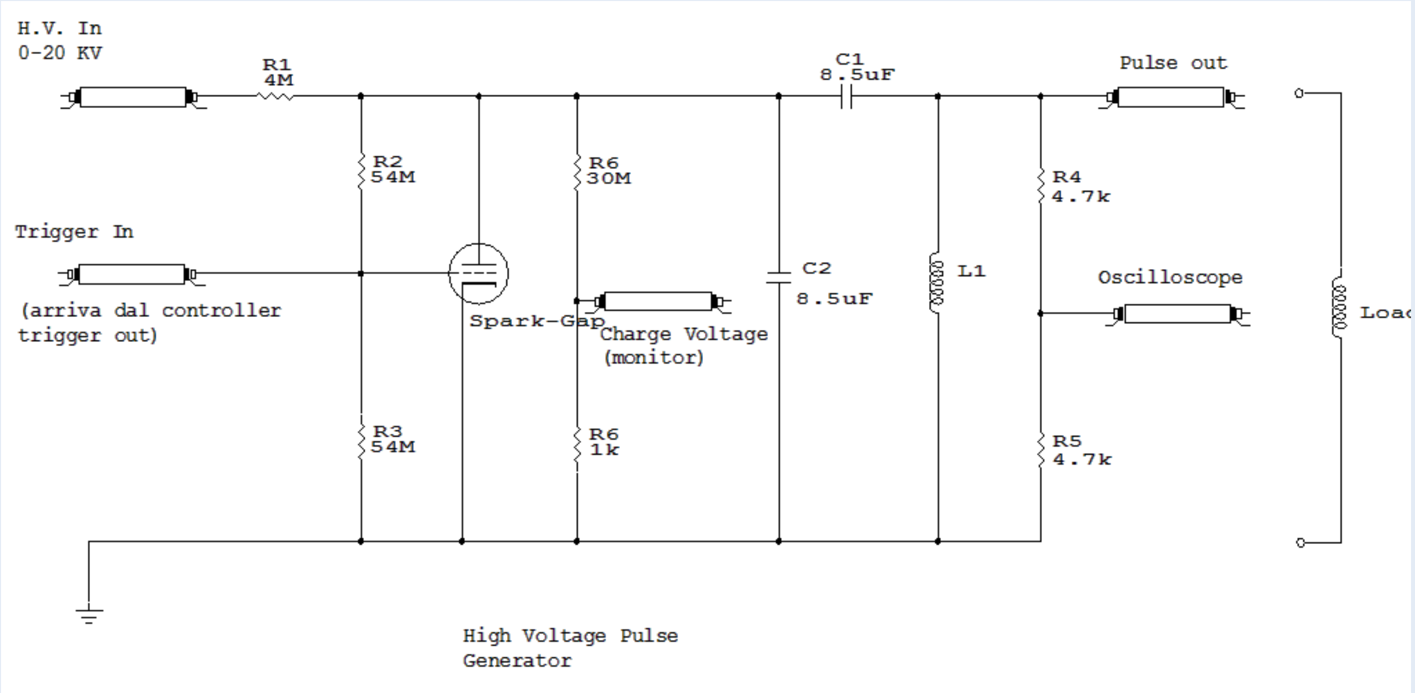
In progress

Prototype of a solenoid designed for pulsed operations and maximum field of 3 Tesla. The internal diameter is of 50 mm.

The excitation pulse will last nearly 10 microseconds and the related current is of the order of 20 kA.



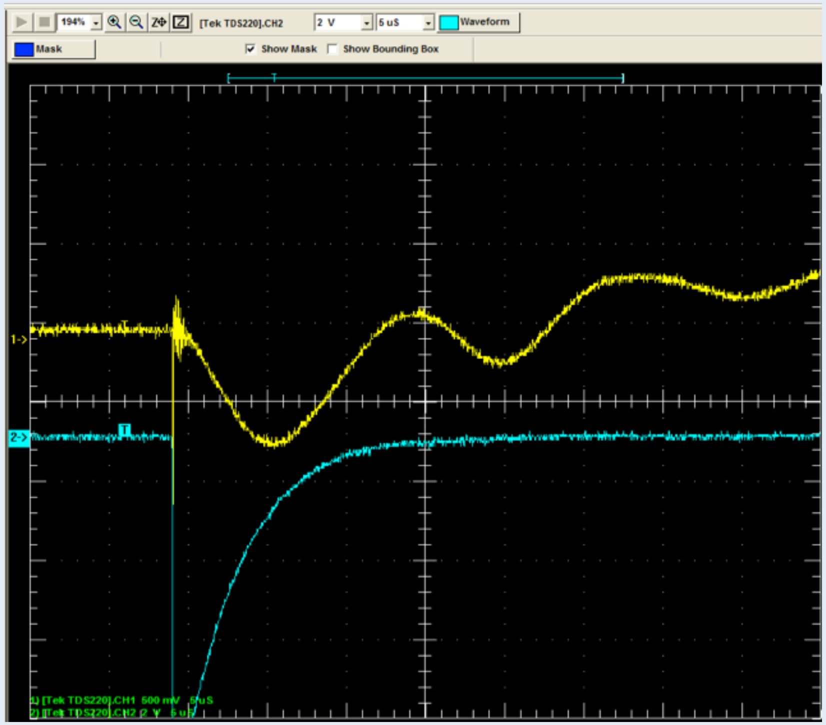
In progress



Basic scheme of the foreseen pulsed high voltage power supply.
The two capacitors named C1 and C2 will charge to a maximum voltage of 20 KV due to the connection to an external standard high voltage, few mA high voltage power supply. The spark gap in the scheme will discharge suddenly the stored energy toward an external solenoid (named load in the picture).

In progress

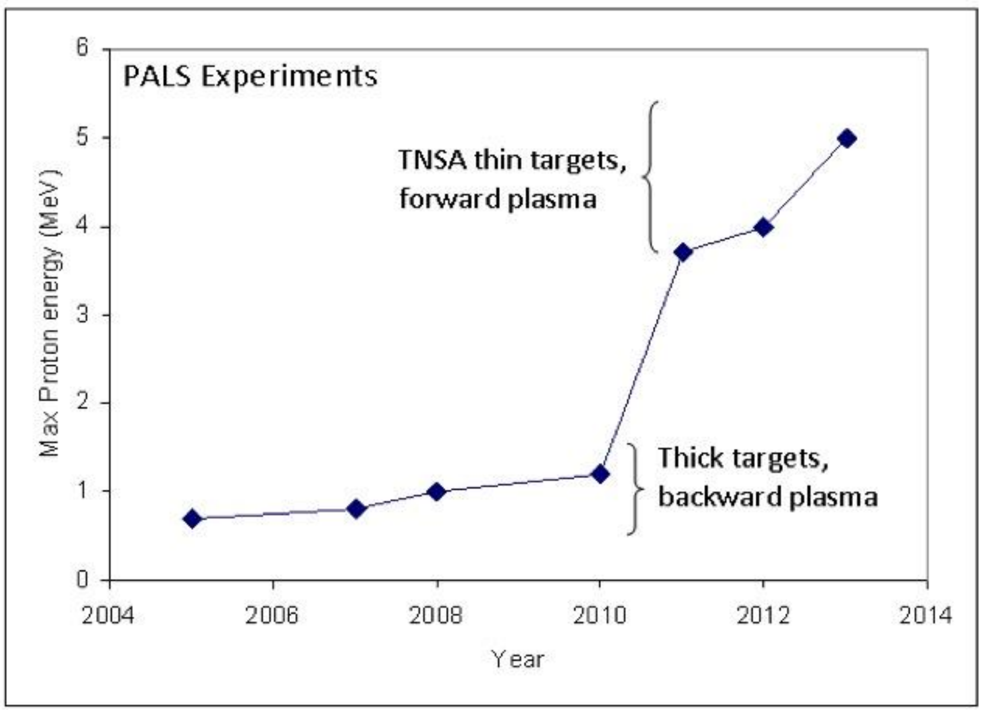

H.V.
0V
0÷25 KV 0÷5 mA
HEINZINGER
PNC 10000-6 pos
mA
kV

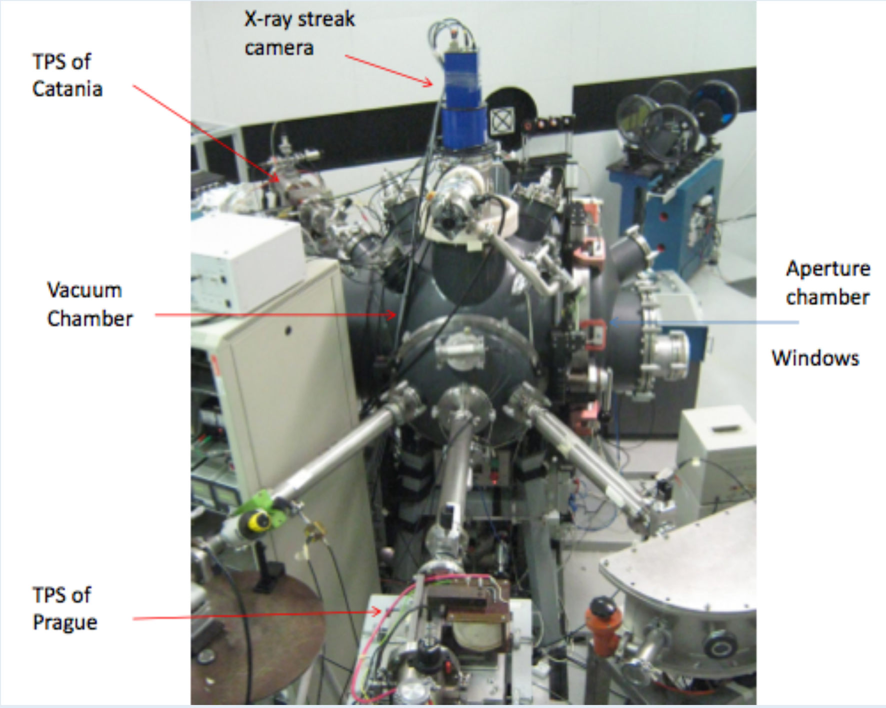

194%
[Tek TDS220].CH2
2 V
5 uS
Waveform
Mask
Show Mask
Show Bounding Box
1->
2->
1) [Tek TDS220].CH1 500 mV 5 uS
2) [Tek TDS220].CH2 2 V 5 uS

WP-1 Target and plasma diagnostic

M-1.1.a: Realization and test of nanostructured and porouses targets up to 1 micron thickness
M-1.2.a: Test and data analysis of IC, ICR, SiC and Diamonds using TOF approach at PALS laboratory (I=10^16 W/cm^2) ->80%

Name and description of the approved proposal @ PALS laboratory:
"High energy proton acceleration from thin advanced targets at PALS"



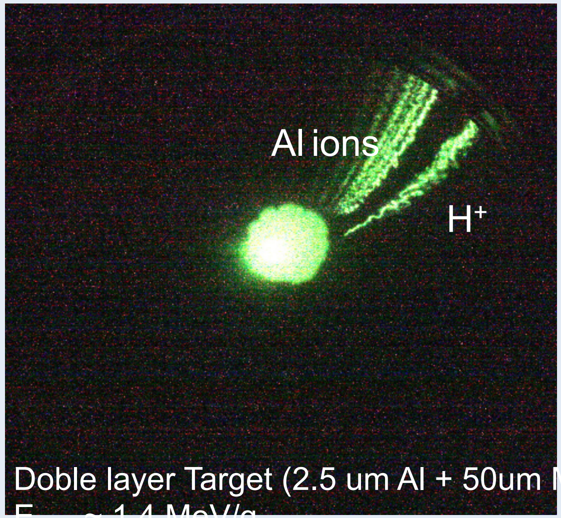


Experiment subdivision
- **1° week:** Pure target irradiations & detector preparation;
- **2° week:** Irradiation of Nanostructured thin targets in TNSA approach with resonant abs. effects;
- **3° week:** Investigtion of laser-plasma in Nuclear Physics

WP-1 Thomson Parabola Spectrometer

M-1.2.b: Upgrading of the Thomson spectrometer

2012 @PALS (Cz)

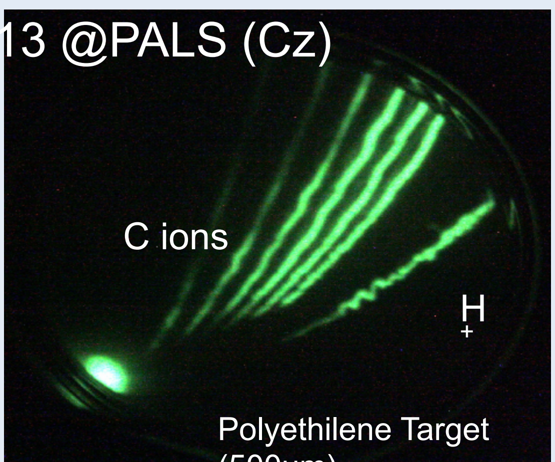


H^+

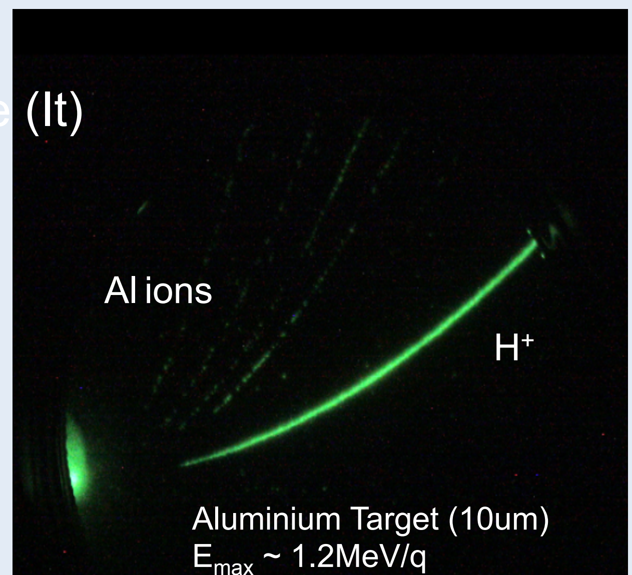
<u>Next step</u>-> Energy Calibration @ LNS (Tandem proton beam) <u>October 2013</u>

H^+

2013 @PALS (Cz)

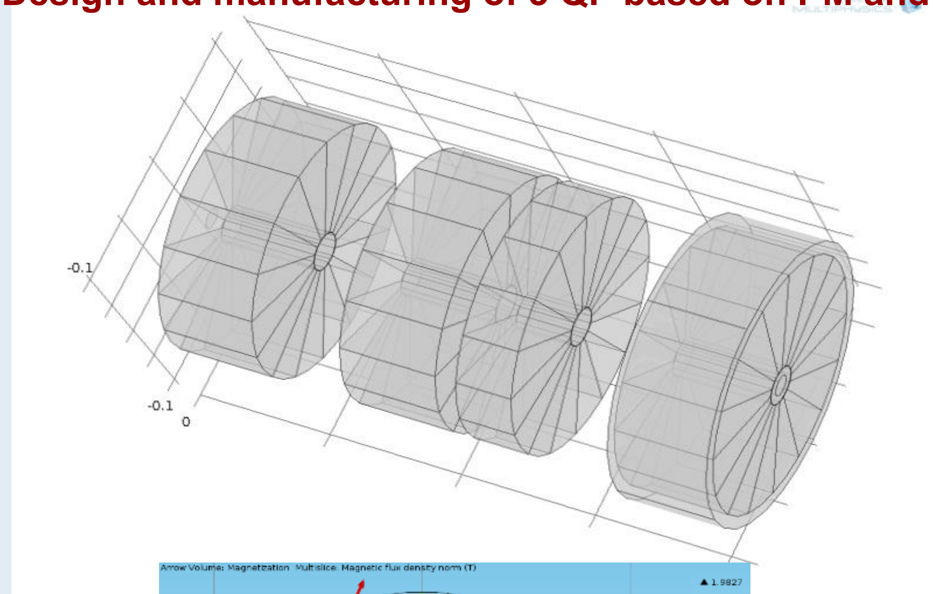


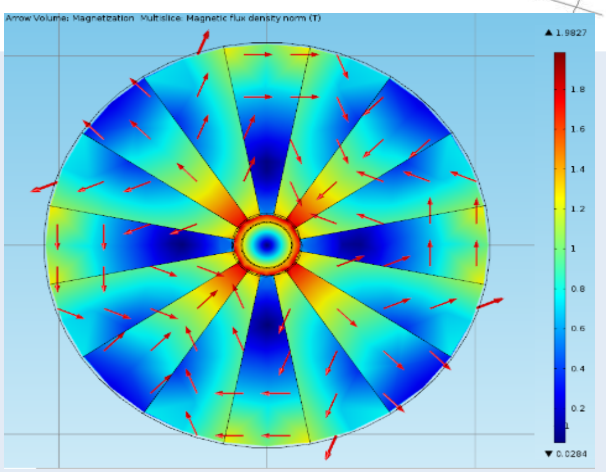
2013 @Flame (It)



WP-2: 16 Halbach domain quadrupoles triplet

M1.3b: Design and manufacturing of 3 QP based on PM and related movement system (2014)





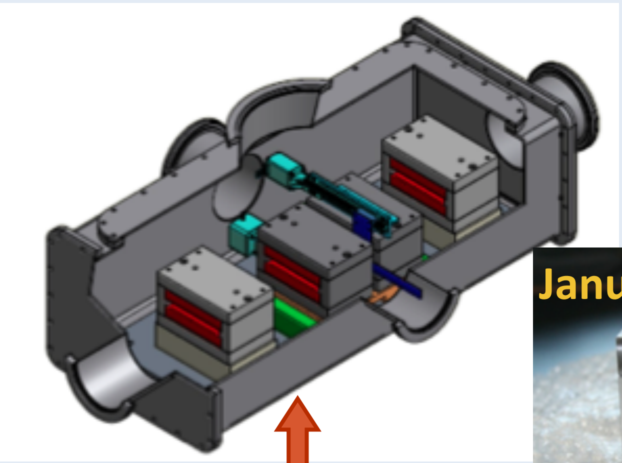
Halbach Domain - 16 Sectors
Magnetic flux intensity and magnetization direction (red arrows)

- ➔ 3 main elements
  - 70 mm length
  - 30 mm bore
  - 100 mm outer radius
  - ~110 T/m peak gradient
  - 1.6 T maximum field

- ➔ 1 smaller element for increasing the focusing of the central quadrupole (required for higher energy)
  - 40 mm length
  - 30 mm bore
  - 100 mm external radius
  - ~100 T/m peak gradient
  - 1.4 T maximum field

WP-2: ESS assembling @ LNS

M-2.3.a: Design, Construction and Assembly of the Energy Selector System (ESS)->100%



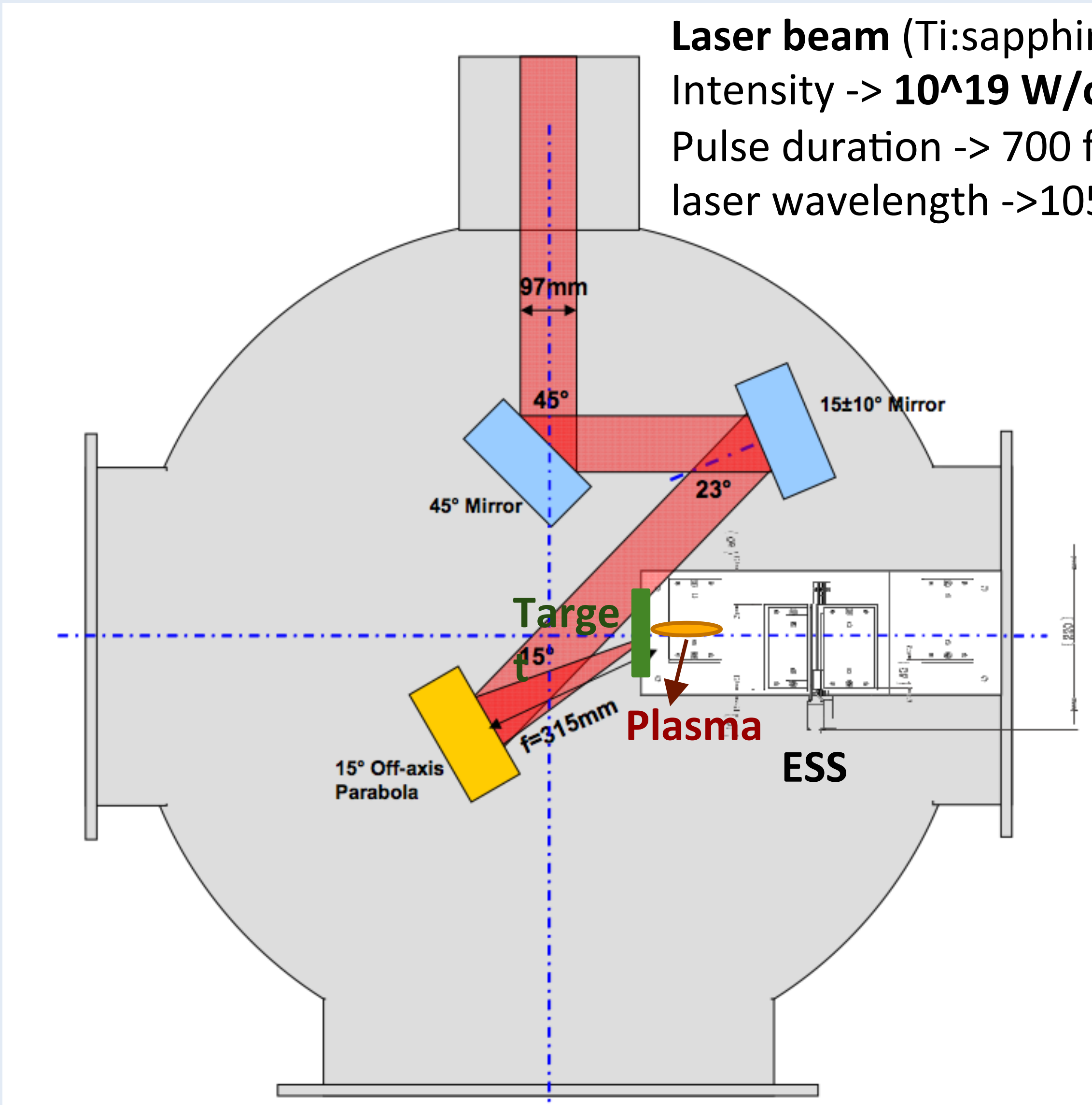
Technical design

The First dipole prototype

The ESS

The ESS inside its vacuum chamber

WP-2: The TARANIS experiment



Laser beam (Ti:sapphire-Nd:glass)
Intensity -> **10^19 W/cm^2**
Pulse duration -> 700 fs
laser wavelength ->1053 nm

Proton beam detectors:

- **CR-39**
- **RCF GafChromic**
- **Si** detector (surface barrier or strips)
- **SiC**
- **Diamond** detector
- Detectors for chemical dosimetry (as **Alanine detector)**

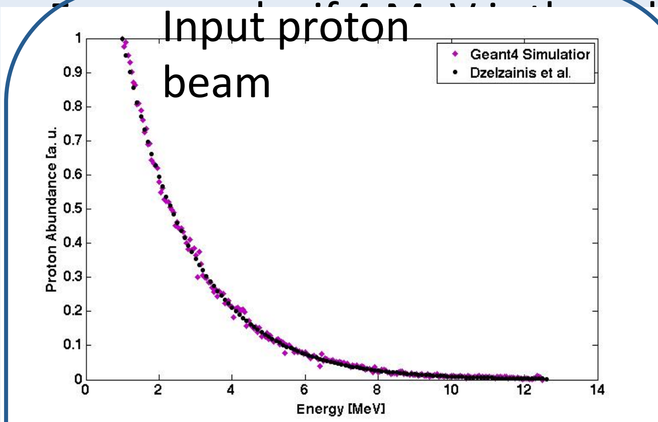
WP-3: Geant4 simulations and dose evaluation

M-3.1.a: Monte Carlo simulations for the evaluation of dose distribution in the TARANIS configuration

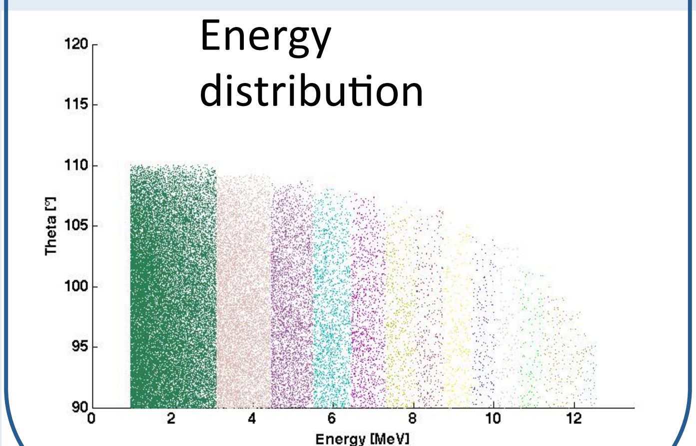
For the Taranis configuration, we have selected two energies: **4** and **6 MeV**. For each energy we have evaluated the energy distribution, the profile, the dose and the fluence of the output beam.

[illegible] lected energy:

Input proton beam

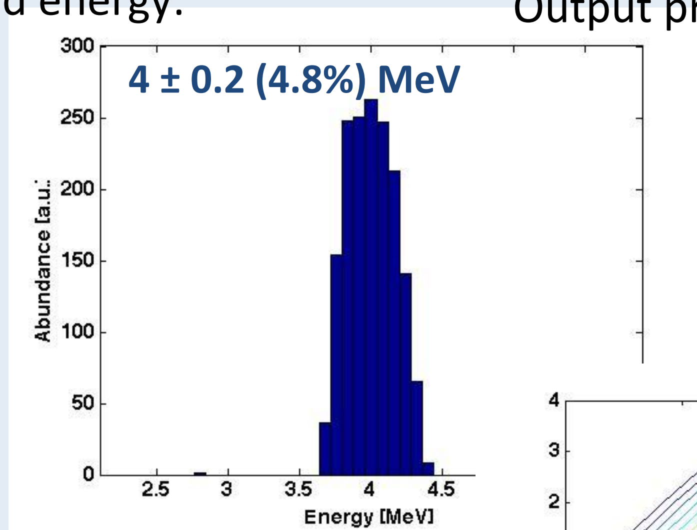


Energy distribution



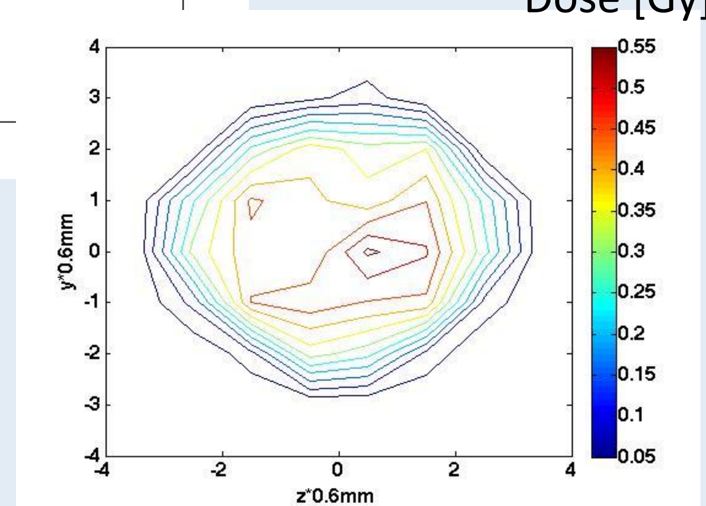
Angular distribution

Output proton beam



Energy distribution

Dose [Gy]



Isodose curves

WP-3: Dosimetric system

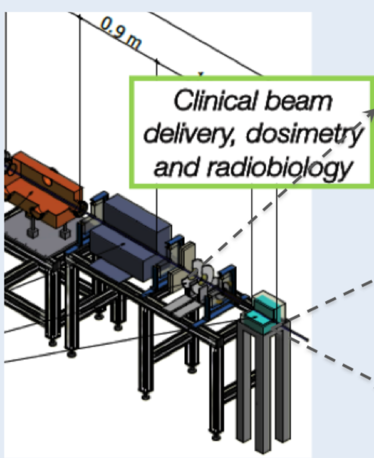
M-3.3.a: Study and design of a dosimetric system for dosimetry and irradiation of bio samples -

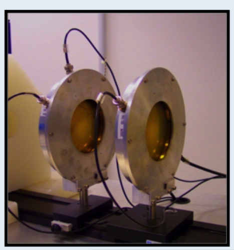
Solutions adopted for relative dosimetry:

- GafChromic films (passive)
- High-rates Transmission chamber (on-line)

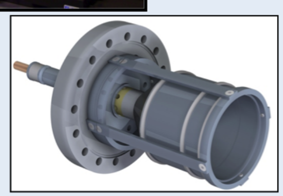
Solutions adopted for the absolute dosimetry:

- Faraday cups coupled with:
    - GafChromic/CR39 stacks for energy spectrum (Spectroscopic method) and beam spot measurements at the entrance (passive)
    - Scintillating fibers for energy spectrum measurements (on-line)

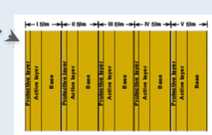




On-line relative dosimetry:
•Transmission IC
•ELIMON detector

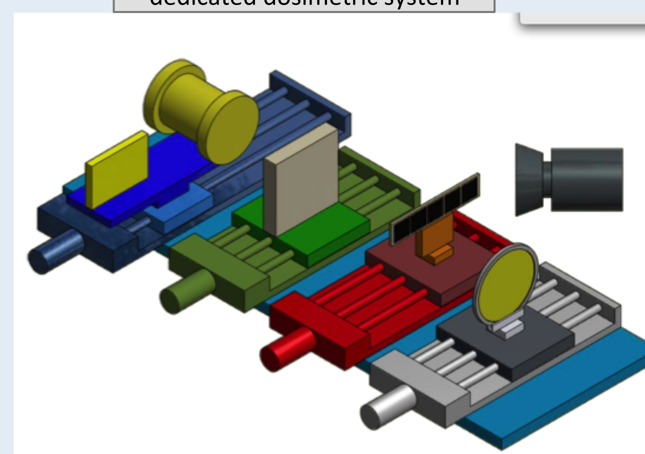


Absolute dosimetry:
• Faraday cup



Energy spectrum measurements:
• Radiochromic films (stack)
• CR39 detectors
• Scintillating fibers (real-time)

preliminary design of a dedicated dosimetric system



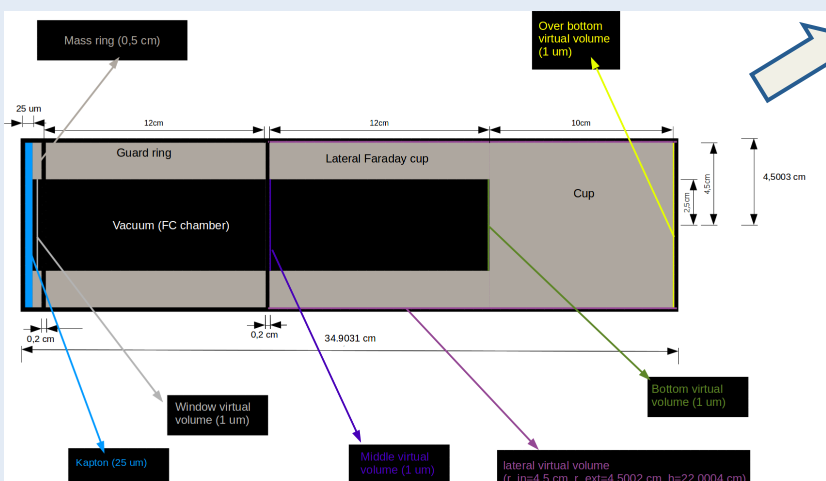
WP-3: Faraday Cup

M-3.3.a: Design and development of a dedicated Faraday cup for absolute dose measurements -

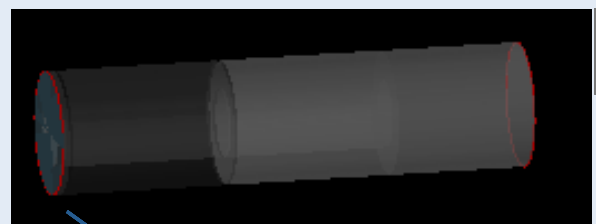
Optimization of shape, size, material of the cup in order to *minimize the uncertainties on absolute dose measurement:*

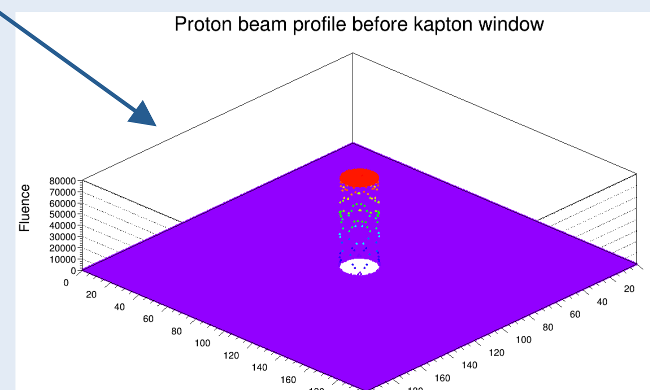
- GEANT4 simulations:
  - minimize the number of the secondary electrons emitted taking into account the effect of:
    - size (cup with respect to guard ring), shape of cup bottom, electric and magnetic fields applied
  - prediction of the beam spot area at different depth and at the bottom of the cup
  - investigation on the cup window to study innovative solution for on-line measurement of the beam spot area

preliminary design the Faraday Cup



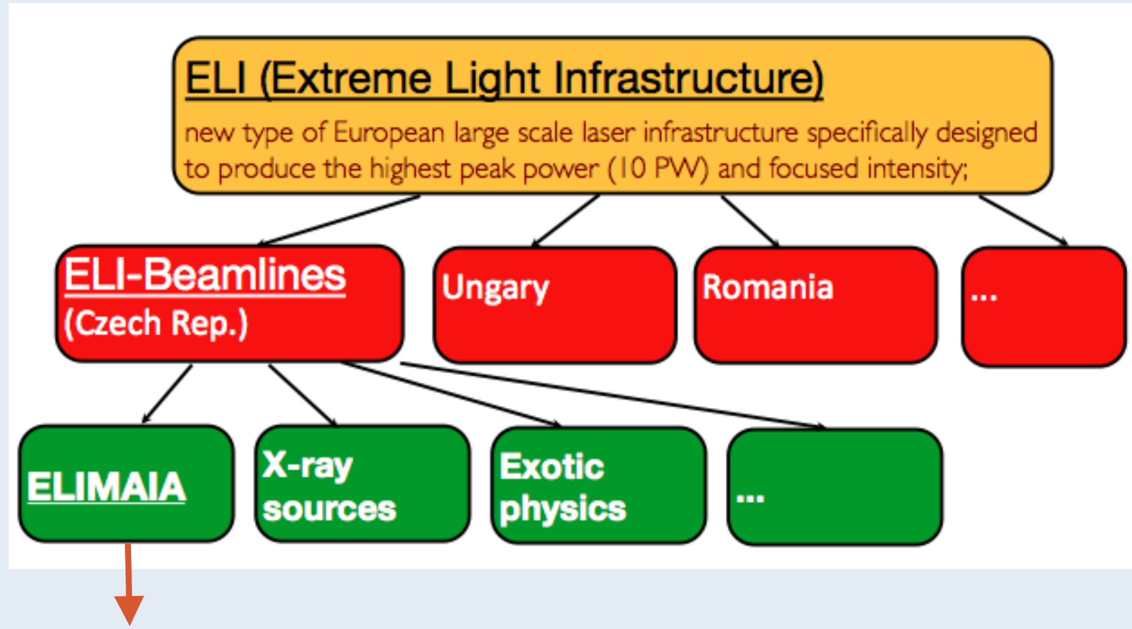
GEANT4 simulation





ELIMED in 2014

ELIMED in the ELI project



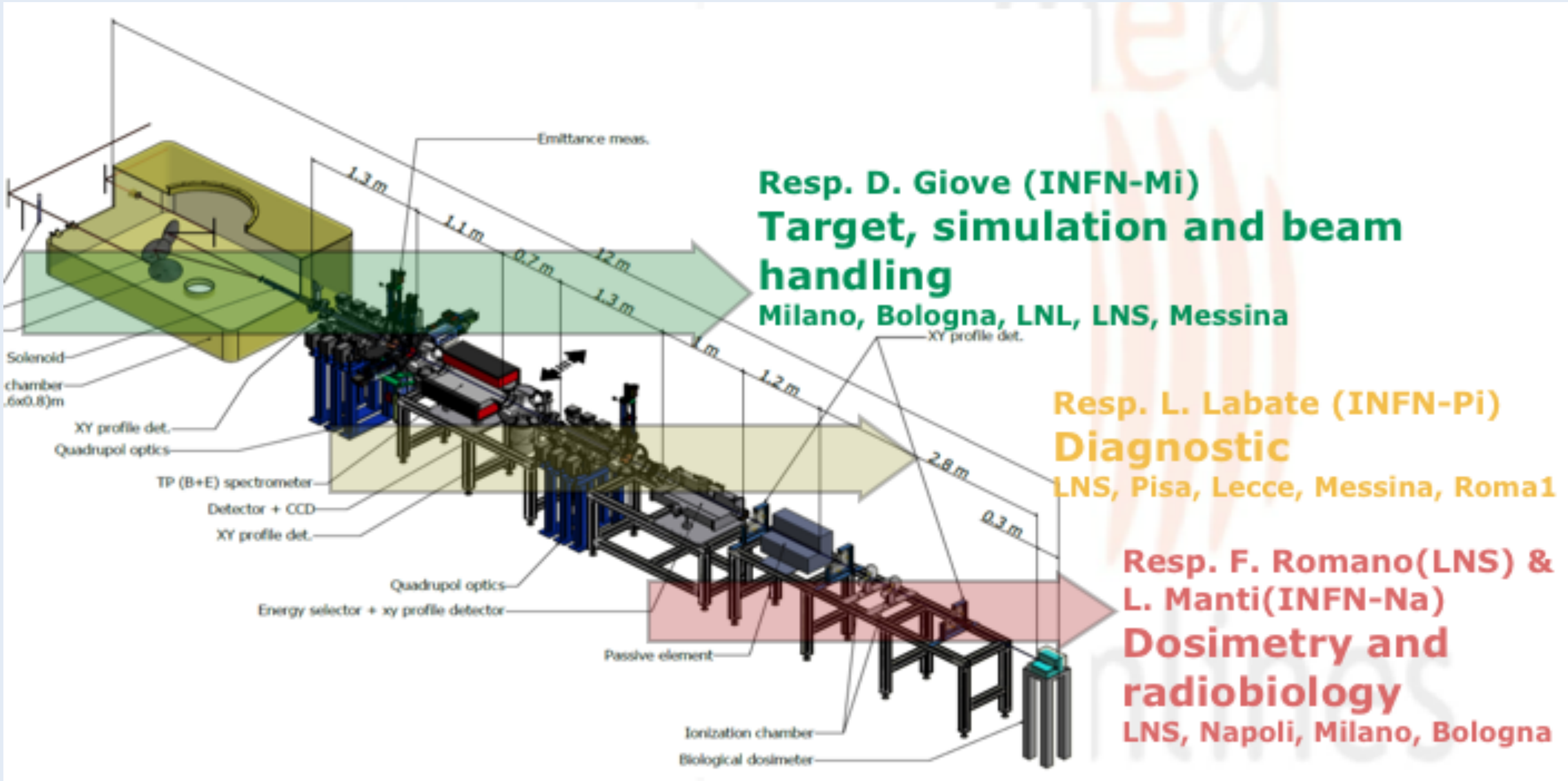
ELIMAIA beamline in Prague

ELI Multidisciplinary Applications of laser-Ion Acceleration

ELIMED-INFN -> Preliminary studies for target, beam handling, dosimetric deliering system and radiobiology for laser-driven particles

Main aims of the ELIMED project

- Preparation for the scientific work on the ELIMAIA beam line in Prague
- Development of innovative targets for the optimization of the proton emission
- Development of innovative beam transport solution and dosimetric system to be used in the new laser-driven beams
- Radiobiology studies for these peculiar radiation beams in light of their medical applications (proton therapy)


Resp. D. Giove (INFN-Mi)
Target, simulation and beam handling
Milano, Bologna, LNL, LNS, Messina
Resp. L. Labate (INFN-Pi)
Diagnostic
LNS, Pisa, Lecce, Messina, Roma1
Resp. F. Romano(LNS) & L. Manti(INFN-Na)
Dosimetry and radiobiology
LNS, Napoli, Milano, Bologna
Emittance meas.
1.3 m
1.1 m
0.7 m
12 m
1.3 m
1 m
1.2 m
2.8 m
0.3 m
XY profile det.
Solenoid
chamber
.6x0.8)m
XY profile det.
Quadrupol optics
TP (B+E) spectrometer
Detector + CCD
XY profile det.
Quadrupol optics
Energy selector + xy profile detector
Passive element
Ionization chamber
Biological dosimeter

Main issues of ELIMED: WP-1, WP-2 ,WP3

Working Groups aims

- Thin target development (structured target and with special microstructures) to obtain proton beams up to 50-60 MeV
- Definition of a strategy bringing to the design and realization of a beam line prototype able to work with laser with specific characteristics:
  E ≈ 5-7 J; λ =0.8 μm; τ ≈ 50 fs; spot size ≈ 10 μm (FWHM);
  intensity ≈ 10exp20-10exp21 W/cm2;
- To handle the produced beam in order to obtain a controlled beam with E≈30 MeV, AE/E=1%; Intensity 10exp7-10exp8 ppb
- Monte Carlo evaluations of the clinical applicabilities of the transported beam
- To realize a complete dosimetric system for absolute and relative dosimetry and to perform the first radiobiology characterizations
- International collaboration network: experimental sessions, share of expertise and instrumentation, etc.

WP-1: Target and holder development

- Study, preparation and characterization, with available laser system, of thin *targets* (pure material or hydrogen reached or with superficial foam) in single layer or continuous foil configuration for the test with higher power laser systems. Determination of a procedure for the target realization. **[06/2014]**
- Characterization of studied targets at low power with higher power lasers. Preliminary studies of targets with particular geometric configuration **[12/2014]**

- Study and realization of a single thin (also about 10 nm thick) targets *holder*, compatible with the low energy diagnostic detectors **[6/2014]**
- System adjustment for the integration of standard and advanced (solid state detectors) diagnostics **[6/2014]** and of magnetic optics for an early focalization **[12/2014]**

Involved units: MI, LNS, ME, LE, RM1

WP-1: PIC simulations

- Simulation of the transport beam line to study also potential coupling with post acceleration systems **[2/2014]**
- PIC simulations of the studied thin targets **[6/2014]**
- PIC simulation of the planned experimental session at JKAREN, Nara (J)
  Power=1.5 PW (30 fs, 45 J)
  Rep Rate=0.1 Hz
  Intensity=10^22 - 10^23 W/cm2 **[10/2014]**

Involved units: BO, MI, LNS

W.P-1: Beam transport line

- Experimental test of the realized energy selection system (TARANIS facility)
- Realization of the designed quadrupole system **[3/2014]**
- Study, realization and laboratory tests of a model of the focusing system based on a pulsed solenoid **[6/2014]**
- Study and simulation of the complete transport beam line: solenoid, quadrupoles and ESS

Involved units: BO, MI, LNS

W.P-2: Laser-plasma diagnostic (I)

- Characterization of the laser-plasma interaction in the TNSA regime using *K*-shell and *Ka* X-ray imaging&spectroscopy (either using Bragg crystals or single-photon detection)
- Visible and UV optical spectroscopy for pre-plasma characterization
- Test of new concept detectors as plasma protons diagnostics:
  - IC and ICR detectors with new geometries and possible array assembling
  - SiC with new metal and depletion layer structures and array assembling
  - monocrystal CVD diamond detectors

X-ray K-shell spectrocopy provides informations on the plasma electron density and temperature; Ka spectroscopy provides informations on the fast electrons beam transport through the target up to the sheath layer

Visible and UV spectroscopy allows the regime of laser-plasma interaction to be identified (possible pre-plasma generation, parametric instabilities leading to lower energy coupling to the target, ...)

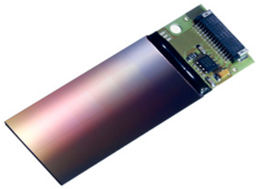
W.P-2: Laser-plasma diagnostic (II)

Proton beam diagnostics

- Development of a detector based on pixel solid state CMOS module for destructive diagnostics (Milano)

Large area detector: CMOS photodiodes array

- *Detector size 25 x 50 mm*
- *Pixel size 48 micron*
- *512 by 1024 matrix of silicon photodiodes*
- *Dinamic range 85 dB*
- *Max. frame rate 4.5 fps*



- Study and design of an ICT (Integrated Current Transformer) for ultrashort duration (~ps) proton beams (Milano, with LNS-Pisa support)
- Conceptual design/study of a proton beam length measurement diagnostics (possibly based on OTR (Optical Transition Radiation) + streak-camera) (Milano and LNS-Pisa)

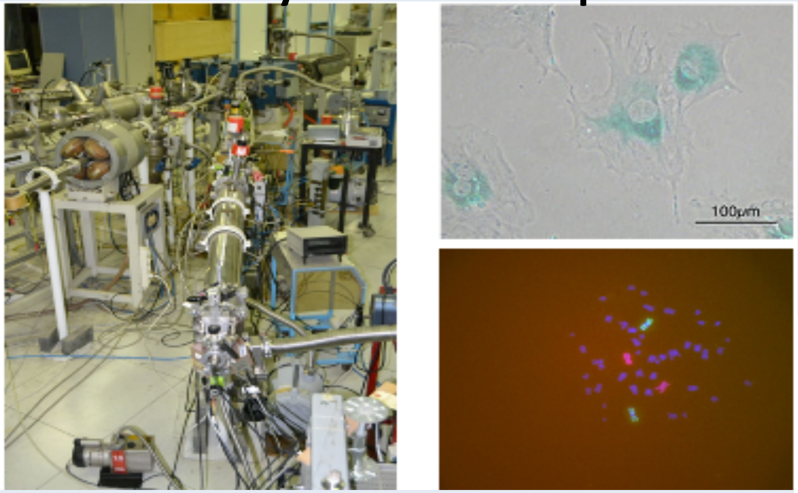
Involved units: Milano and Pisa

W.P. – 3 Radiobiological studies and measurements

Within ELIMED, radiobiological studies will be **exclusively** dedicated to validate the biological feasibility of laser-driven beams for cancer treatment

It is necessary to **compare the biological effects of laser-driven proton beams** (highly pulsed and very high dose rates) **with those from "conventionally" accelerated particle beams**.

The goal will be to determined by the end of 2014 preliminary values for the efficiency (RBE) of these beams on causing **tumour inactivation** (prostate cancer cells) and **sublethal damage in normal cells** (chromosome aberrations and premature cellular senescence in fibroblasts and endothelial cells), **of importance for risk of secondary cancers and adverse reactions in healthy tissues**



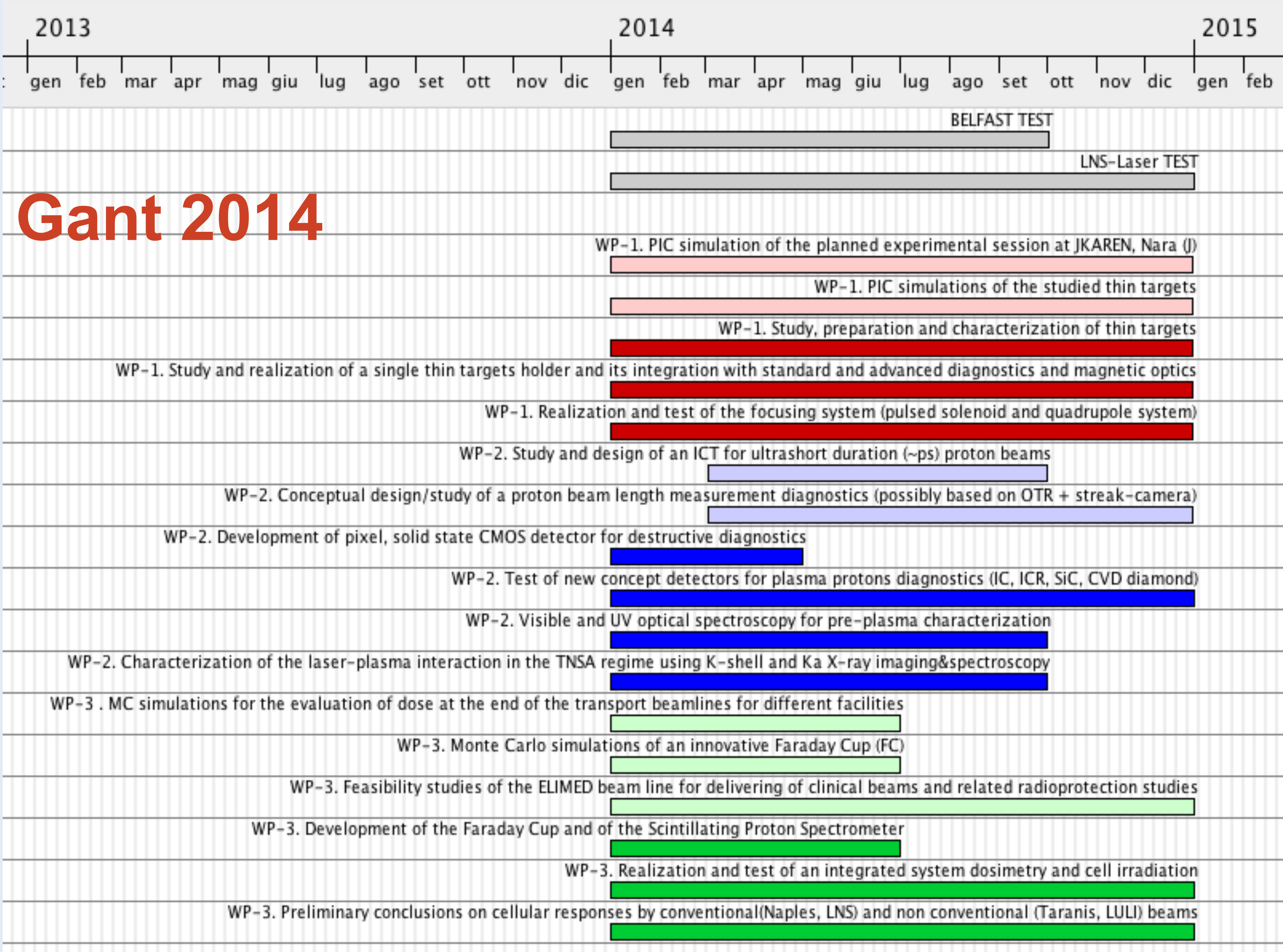
Left: view of the radiobiological set-up at Naples Tandem accelerator; right: senescing cells (top) and FISH-painted chromosomes (bottom)

❑ Planned activity for 2014:

- ❑ Proof-of-principle irradiations at the *TTT-3 Naples* tandem accelerator with pulsed proton beams up to 6 MeV (pulse duration: tens of ns, dose rates: tens of Gy min^{-1}) to optimize protocols and assays and at *INFN-LNS cyclotron* with energies in the therapeutic range with both conventional proton beams and pulsed and very-high dose rate (hundreds of Gy min^{-1}) beams
- ❑ Irradiations with laser-driven proton beams of up to tens of MeV (peak energy) at *TARANIS* (UK) and/or *LULI* (France) facilities

The obtained data will be essential to determine the potential clinical relevance of laser-driven beams

Gant 2014



2013
2014
2015
gen feb mar apr mag giu lug ago set ott nov dic gen feb mar apr mag giu lug ago set ott nov dic gen feb
BELFAST TEST
LNS-Laser TEST
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WP-1. PIC simulations of the studied thin targets
WP-1. Study, preparation and characterization of thin targets
WP-1. Study and realization of a single thin targets holder and its integration with standard and advanced diagnostics and magnetic optics
WP-1. Realization and test of the focusing system (pulsed solenoid and quadrupole system)
WP-2. Study and design of an ICT for ultrashort duration (~ps) proton beams
WP-2. Conceptual design/study of a proton beam length measurement diagnostics (possibly based on OTR + streak-camera)
WP-2. Development of pixel, solid state CMOS detector for destructive diagnostics
WP-2. Test of new concept detectors for plasma protons diagnostics (IC, ICR, SiC, CVD diamond)
WP-2. Visible and UV optical spectroscopy for pre-plasma characterization
WP-2. Characterization of the laser-plasma interaction in the TNSA regime using K-shell and Ka X-ray imaging&spectroscopy
WP-3 . MC simulations for the evaluation of dose at the end of the transport beamlines for different facilities
WP-3. Monte Carlo simulations of an innovative Faraday Cup (FC)
WP-3. Feasibility studies of the ELIMED beam line for delivering of clinical beams and related radioprotection studies
WP-3. Development of the Faraday Cup and of the Scintillating Proton Spectrometer
WP-3. Realization and test of an integrated system dosimetry and cell irradiation
WP-3. Preliminary conclusions on cellular responses by conventional(Naples, LNS) and non conventional (Taranis, LULI) beams