Optical injector for protons and biomecal applications

The PROMETHEUS project

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Origin and present state
Virtual experiments by Aladyn
Protons transport and injection

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The Bologna context

Activity of theoretical beam dynamics at Physics Deparment

Activity of plasma dynamics simulation at Astronomy Department

Activity on plasma devices at Energetics Department

Research institutes for subnuclear phyics INFN and energy ENEA

Laboratory at Montecuccolino which hosted a nuclear reactor RB3

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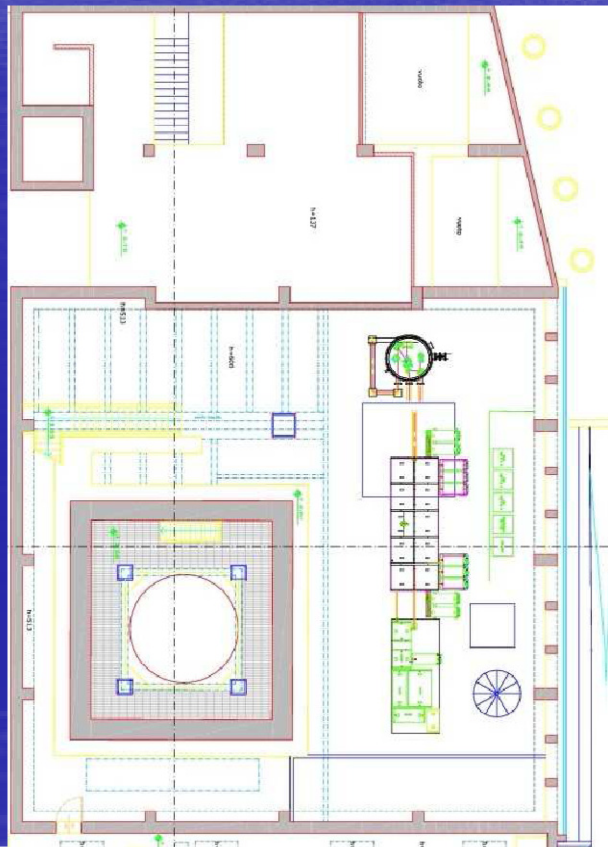
Montecuccolino laboratories

On the Bologna hills, 10 minutes from downdown centre (4 Km) hosted 3 small nuclear rreactors. The largest one is RB3 decomminissioning complete winter 010-spring 011. Cube 17 m size with moving crane and composable biological screen. Side buidings 220 mq. Underground area 300 mq. Power supply 1 MW.



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Short history

Presentation to the MIUR survey on large infrastructures in 2008

Approval by the Academic Senate in 2008

Priority of the RB3 hall at Montecuccolino in 2009

Participation to LILIA and start-up of design study in 2010

Reasearch agreement ENEA-UNIBO and RB3 decomissioning 2010

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Work plan

Aug. 2009 COULOMB09 Workshop on Optical acceleration of protons

June 2010 Meeting ABO-UNIBO for project funding

Dic. 2010 Public presentation and workshop. Consortium formation

June 2011 Completion of design study

Bologna the world oldest University

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Main objective

Develop a compact hybrid accelerator for proton therapy

Main requirement reliability and shot to shot stability

Secondary objective

Fully optical high brilliance coherent X ray source

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Workplan

Phase 0 ’10-’11 Feasibility study aimed to define the TiSa laser specifications

Phase I ’12-’15 Optical p injector & postacceleration

Phase II ’16-’19 Upgrade p injection energy.

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WHY AN OPTICAL INJECTOR ?

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The single room facility is considered the best option for the proton therapy development. Various solution have been proposed and are under investigation

A) Superconducting synchrocyclotron
B) Slow cycling proton synchron
C) Dielectric wall accelerator DWA
D) High frequency proton linac

Solution D) is very advanced and developed in Italy, but requires a 30 MeV cyclotron for injection.

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The energy of a proton beam accelerated in TNSA regime has an exponential energy spectrum with cutoff.

As a consequence even though high energies may be reached the intensity becomes a major problem.

A tipical figure required for therapy is $N=10^9$ protons per bunch at 10 Hz frequency but $N=10^8$ may be acceptable at first.

In an initial stage one might reduce the number to $N=10^7$ still having the same dose on a sample of a few grams.
Preclinical studies with mice rather than humans.

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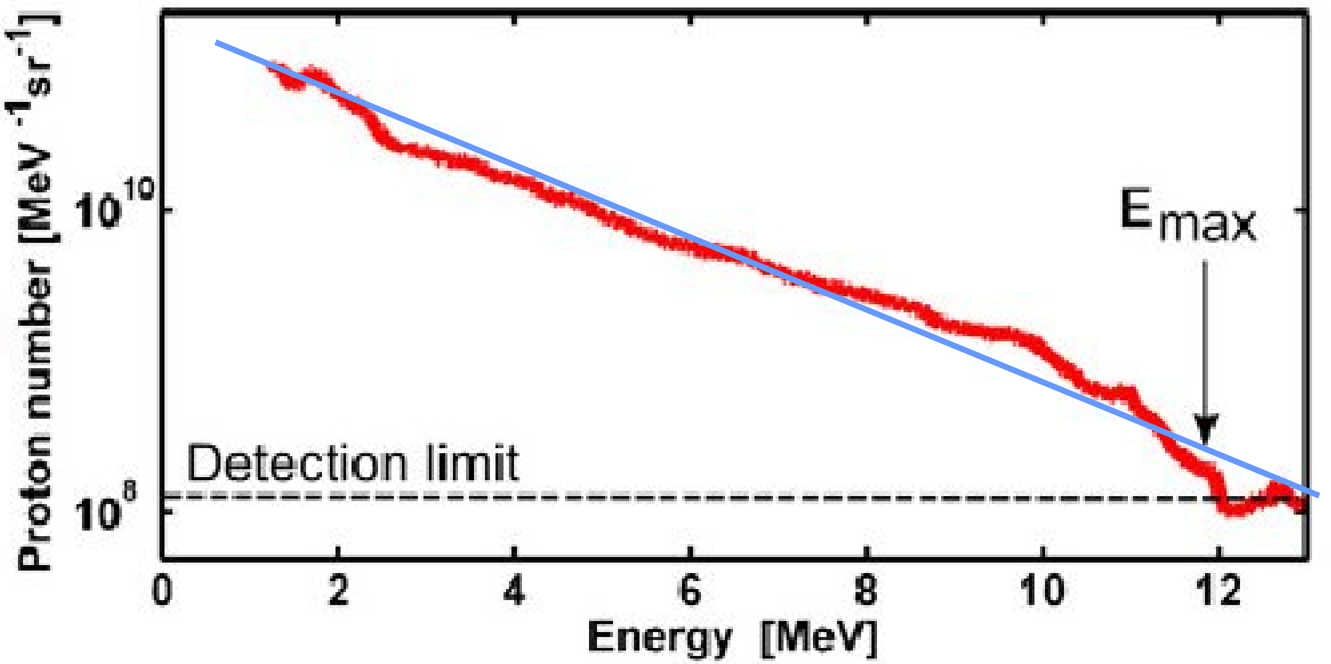
The spectrum below referring of an experiment at Dresden with $P=100$ TW and $I=10^{21}$ is fitted by $dN/(dEd\Omega) = 3\ 10^{11}\ e^{-E/E_0}$ where $E_0=1.7$ MeV. From 10 to 10.1 MeV there are $10^7 \sim 10^8$ protons. Notice that if $N_0=10^{12}$ then $E_0 N_0=0.3$ J or 10% of E_{laser}



K. Zeil et al. New Journal of Physics 2010

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Let us consider the distribution

$$dN/dE = N_0/E_0 \; e^{-E/E_0}$$

$N_{tot} = \int dN/dE \, dE = N_0$ $\qquad$ $E_{tot} = \int E \; dN/dE \, dE = N_0 \, E_0$

The average energy is $\langle E \rangle = E_{tot} / N_{tot} = E_0$

The number of protons in a given small interval $[E, E+\Delta E]$ is

$$N[E, E+\Delta E] = N_0 \frac{\Delta E}{E_0} e^{-E/E0}$$

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It seems possibile to select from an accelerated proton beam an injectable bunch at 10 MeV with $\Delta E/E = 1\%$ with a sufficient number of protons.

If the average energy can reach 4 MeV o more a bunch owith E> 25 MeV with $\Delta E/E \sim 1,2\ \%$ suitable for injection into ligh field linacs like ACLIP or TULIP may be selected.

To start we would like to demonstrate that we can produce an injectable beam of 10^7 protons at 10 MeV.

In a second stage we would like to upgrade the energy at 30 MeV and increase the intensity

Liquid H jets might allow to reach 30 MeV for injection

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In tipical experiments N_0 ranges between 10^{11} to 10^{13} whereas E_0 ranges from 2 to 4 ($\sim 10^{11}$ and 1.7 for Desden 1.5 $\sim 10^{13}$ and 4 for GSI experiments)

Selecting E=10 and 20 MeV respectively with $\Delta E/E$= 1% the number of protons ranges between 10^8 and 10^9. After angular selection the beam should be injectable.

The number of protons involved in the acceleration appears to be larger than the illuminated volume. Indeed asuming n= 100 n_c namely n~ 2 10^{11} μ^{-3} all the protons in a layer 1 μ thick would be accelerated.

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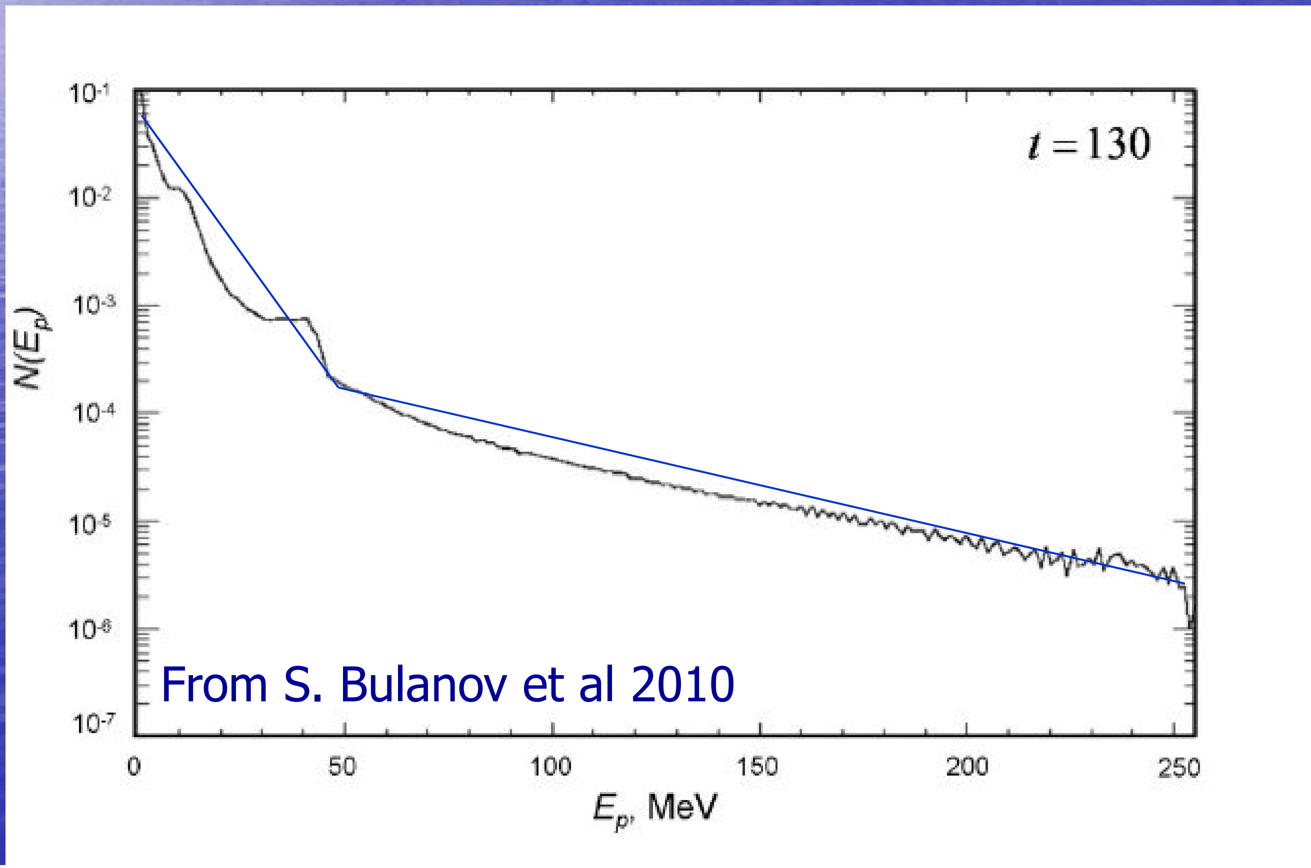
Simulations in the near critical regime show a different behaviour due to a different acceleration mechanism. Two different slopes if exponential. Intensity at 30 MeV 1% of total. Liquid H targets might be suitable for an injector



From S. Bulanov et al 2010

P=100 TW

d= 50 μ

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VIRTUAL EXPERIMENTS

with

AlaDyn

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Developed since January 07 C. Benedetti et al IEEE TPS 36 (08)

- Fully self-consistent, relativistic EM-PIC code
- Laser pulse(s) + injected bunch(es)
- In C and F95 , parallelized MPI, organized as LIBRARY
- Cartesian 1D, 2D & 3D, cylindrical 3D

- High order space-time schemes+moving window+stretched grid
- Boosted Lorentz frame + hierarchical/adaptive particle sampling

Devel. & maintain. @ Dep. of Phys. – UniBo

Phylosophy: reduce computational load to be run on small clusters

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Simulations of protons TNSA acceleration

Intensity I= 8 10^{20} W/cm^2 (P= 200 TW spot 25 μ^2)

A) Single layer H density n= 20 n_c thickness 0.5 μ

Exponential spectrum with energy increasing spread. Not realistic

B) Double layer target Al thickness 1 μ n=100 n_c
plastic 0.05 - 0.1 μ n=10 n_c (1.8 10^{22} cm^{-3})

Sharp peak which broadens as the beam accelerates.

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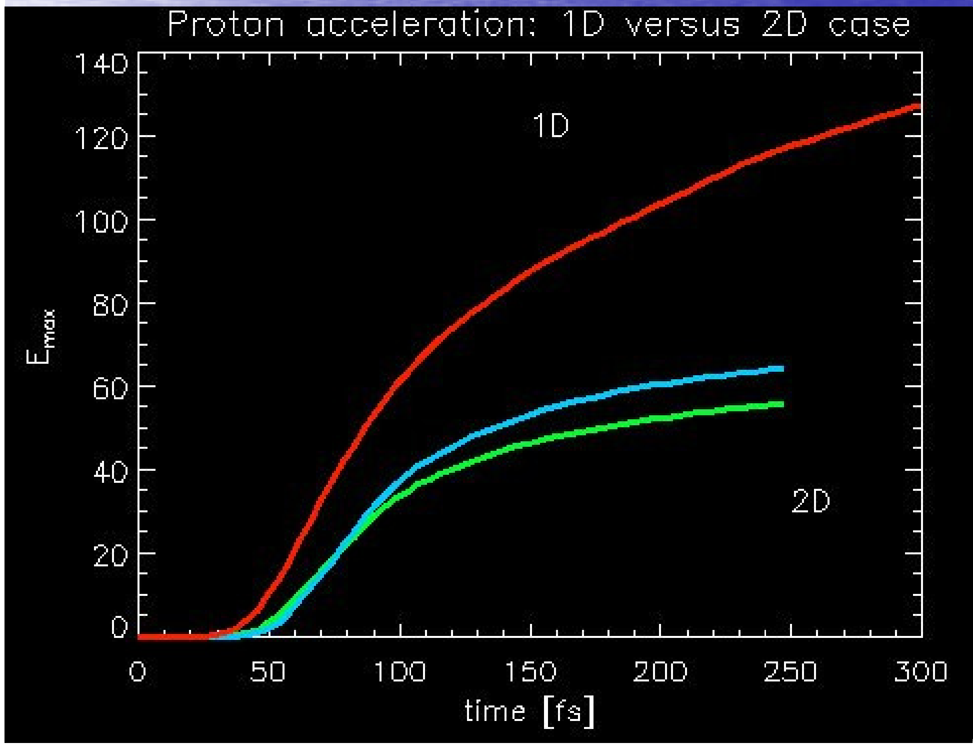
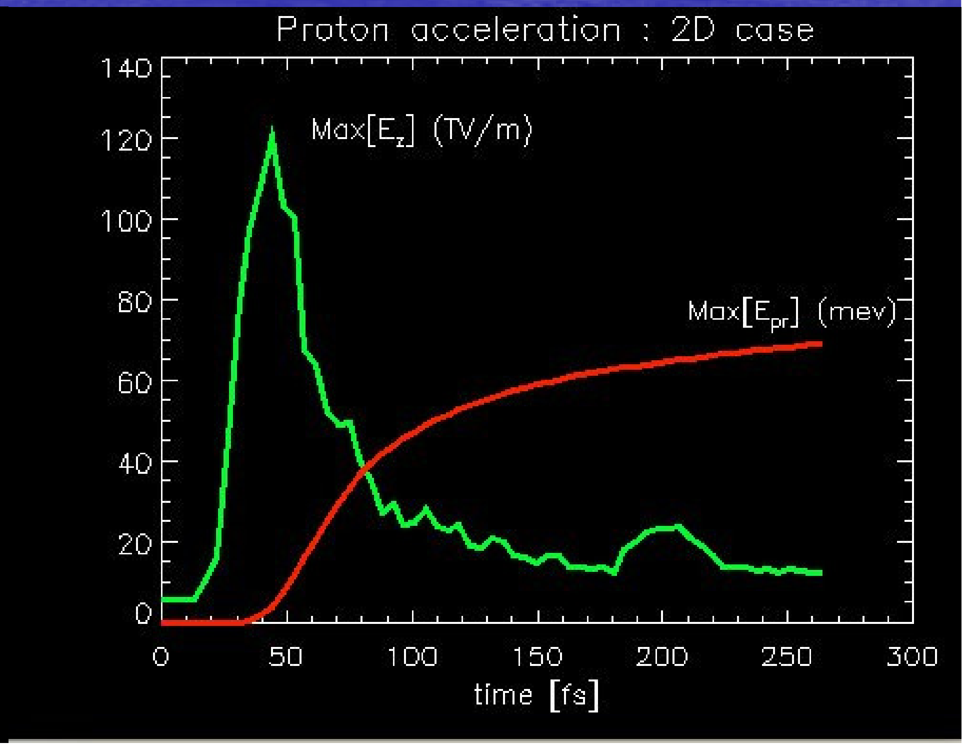
A) Single layer. Energy E_{max}= 50 MeV <E> ~ 4MeV

The energy drops as 1/D where D=1,2,3 in PIC simul.





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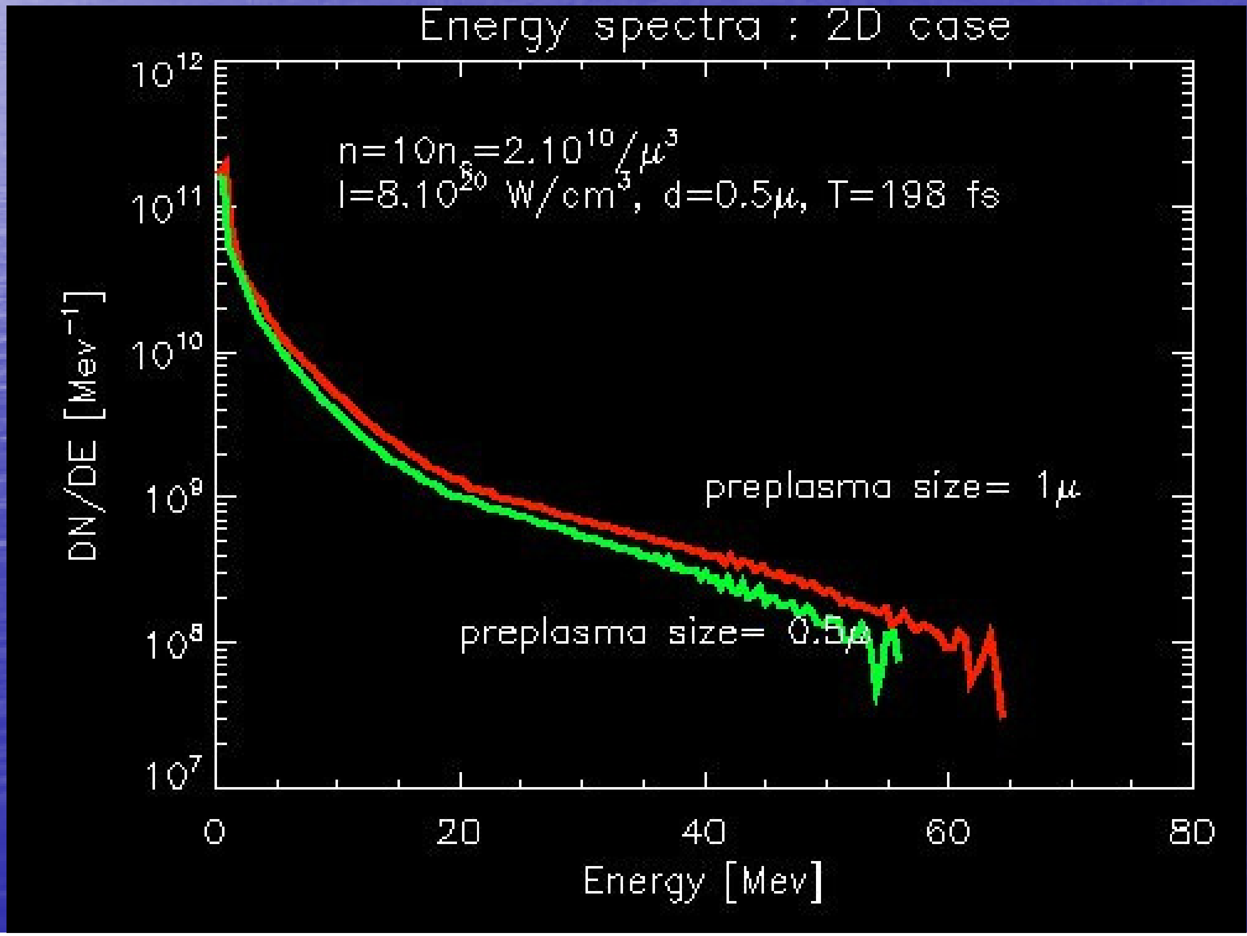
Simulation 2D

Power 160 TW , focal spot 20 μm^2 , I = 8 10^{20} W/cm^2.
Thick 0.5 μm con n=20 n_c. preplasma ramp 0.5, 1 mm
Total number N=6 10^{11}



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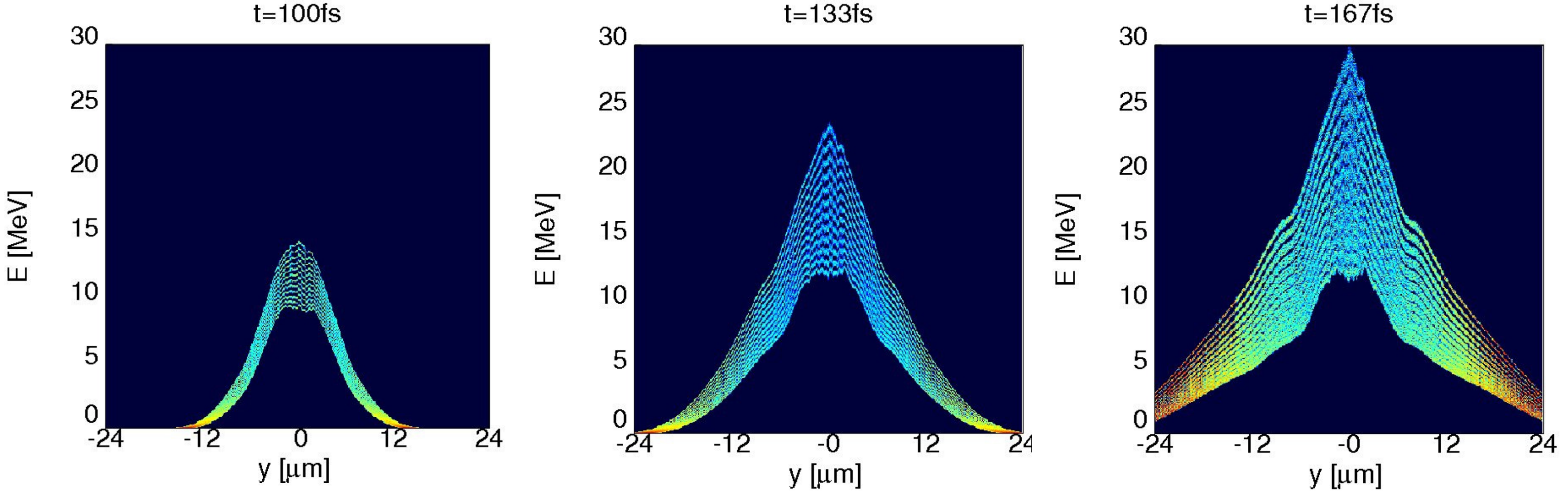
B) Double layer target

The beam propagates and spreads



Beam widening whille moving forward

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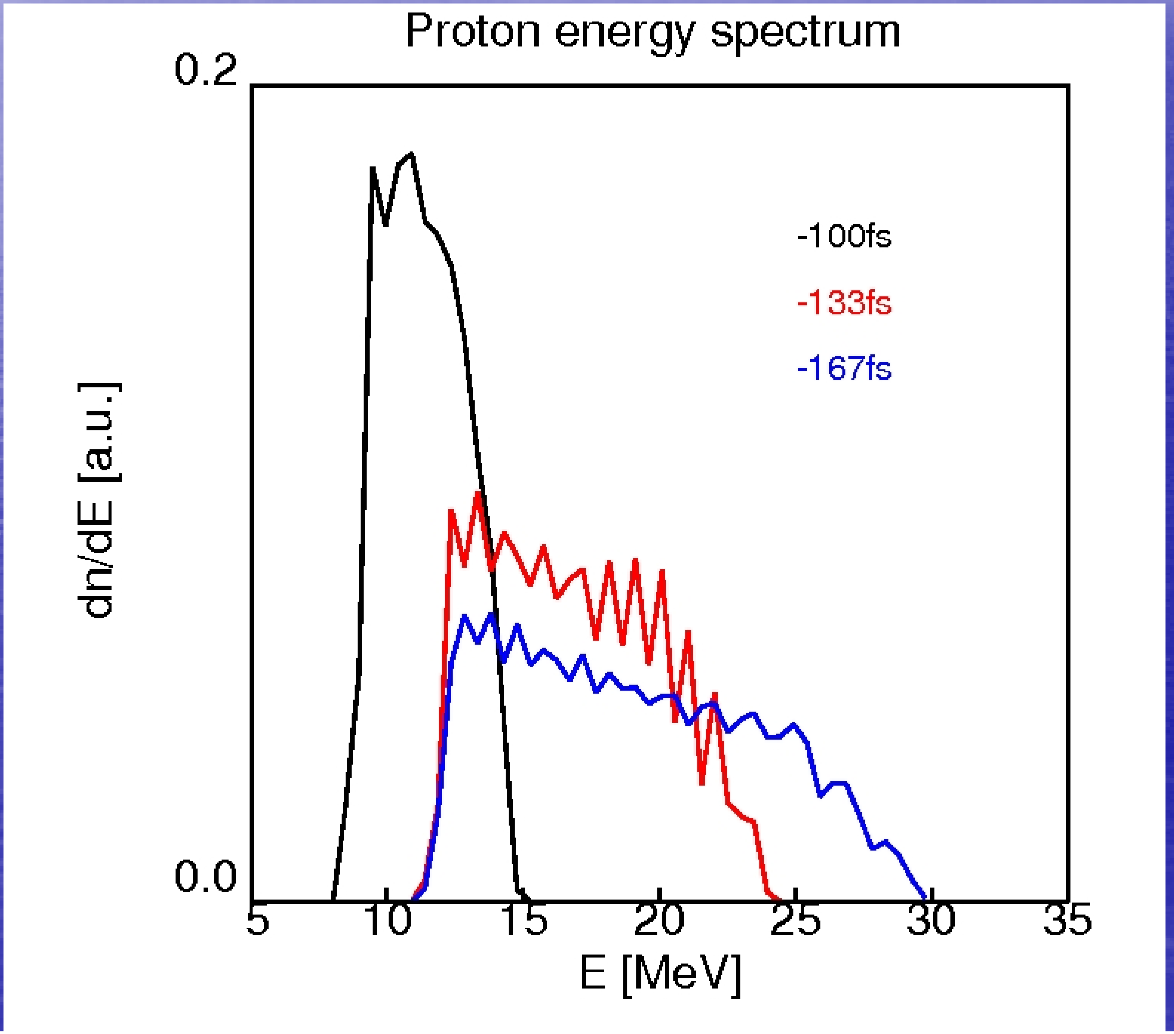
Energy spectrum at different times



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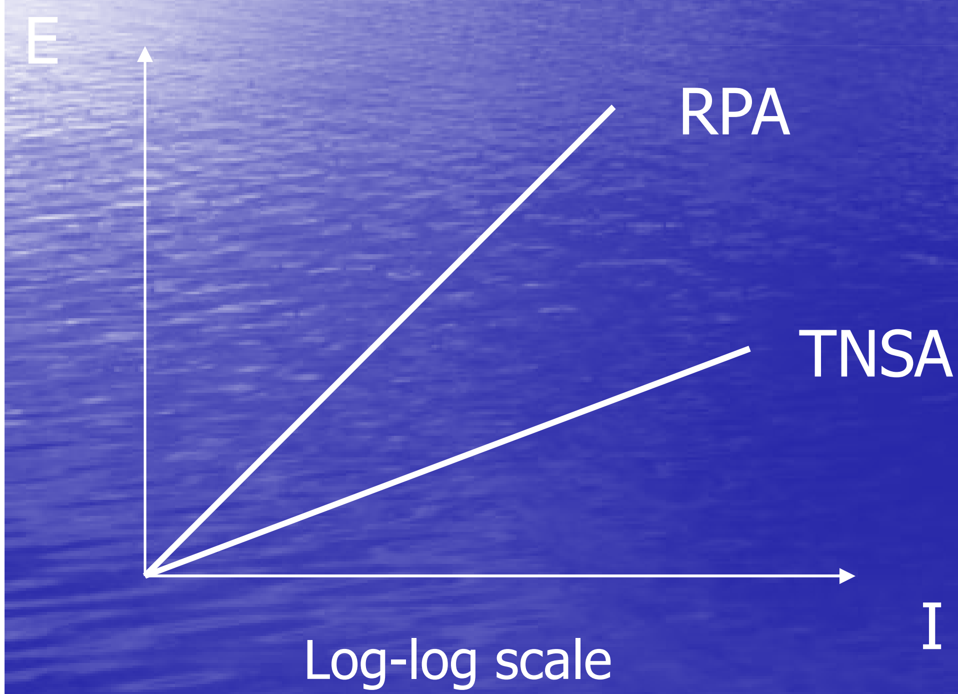
New perspectives are opened by RPA acceleration ultrathin targets the relativistic mirror regime. The CO_2 laser might be considered because of circular polarization and efficiency.

Breakdown at transparency. Simulations 3D needed



Hole boring

depressed by $\frac{n_c}{n}$

Relativistic mirror
Ideal

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TRASPORT for INJECTION

Experimento a SNL Schollmeier et al PRL 2008

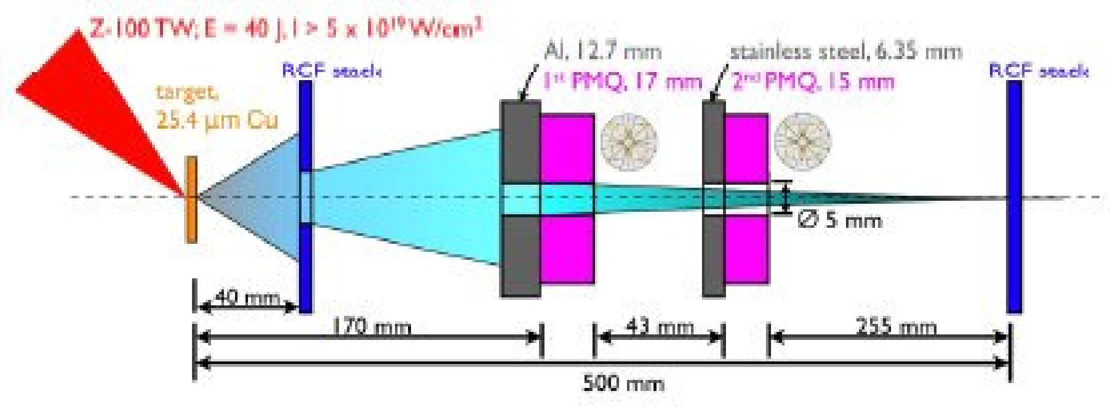
Energy 40 J focal spot 80 μm^2 with τ=1 ps hence I= 5 10^{19}

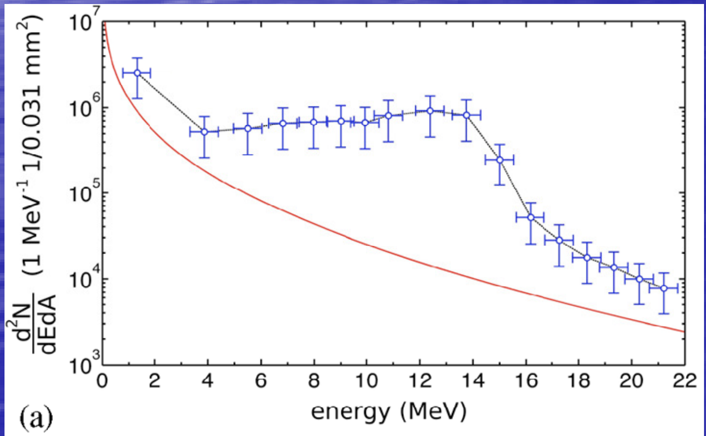
Protons up to 22 MeV

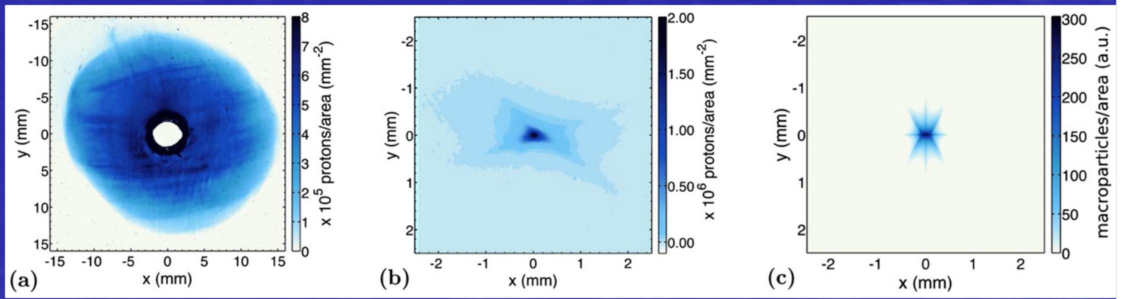
Spot 0.3x0.2 mm at

50 cm from source

About 10^6 protons







Images from Schollmeier et al.

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Esperiment at GSI

Collimazione and trasport: main problem angle-energy spread

dispe

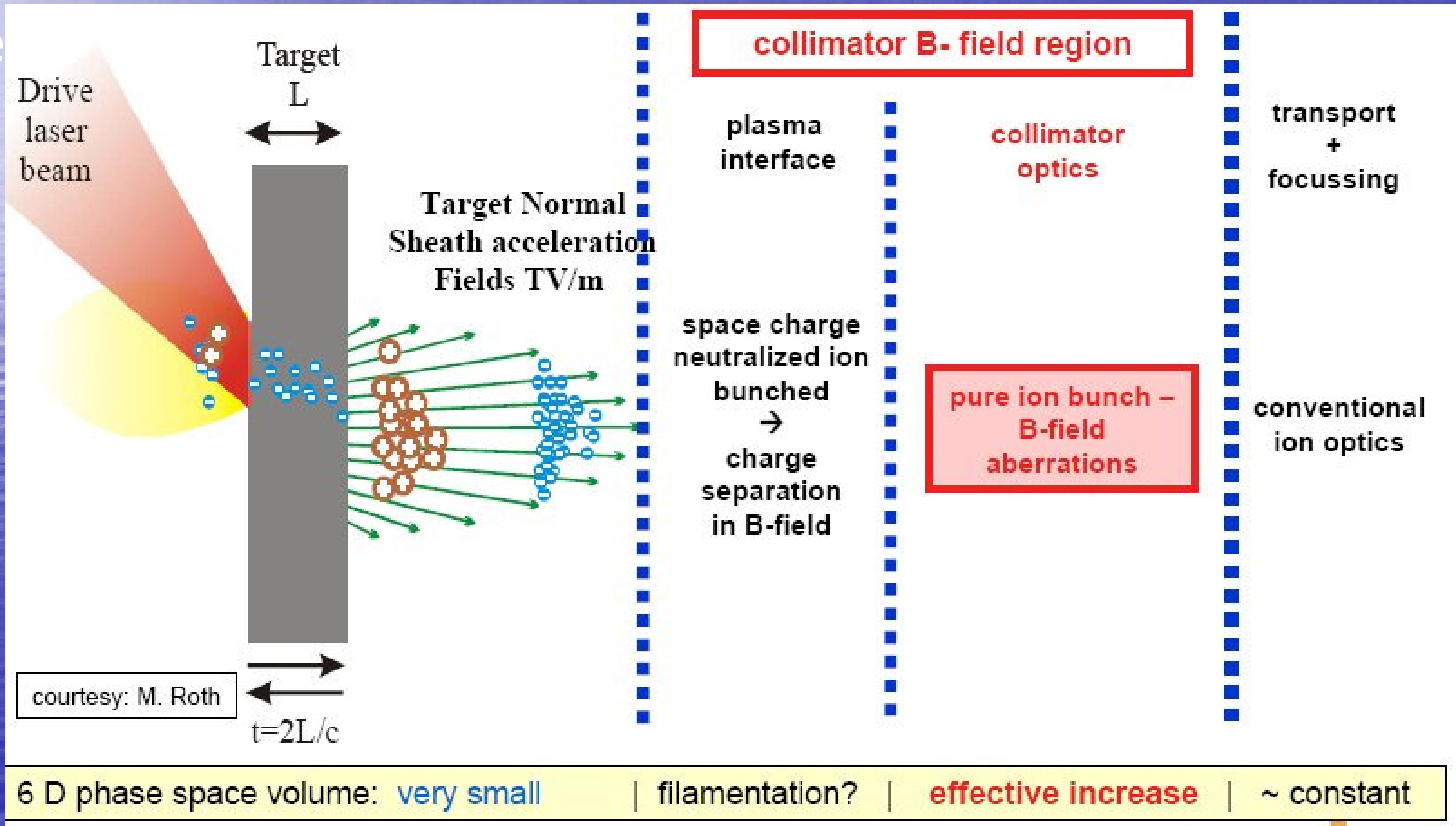

Image from Ingo Hofmann presentation http://www.mpq.mpg.de/APS/Frontiers/index.html

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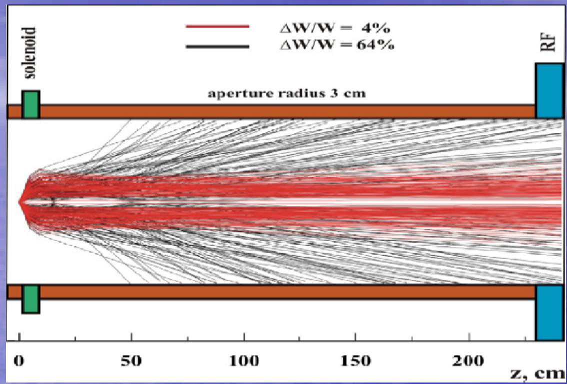
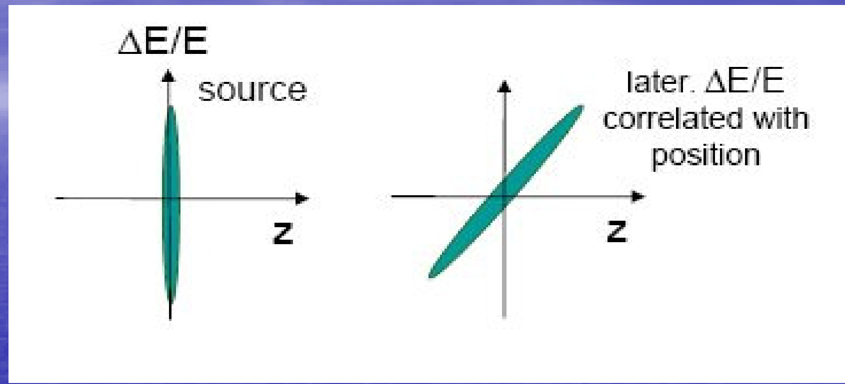
Angle
energy
selection
collimation





Experimet with laser FELIX
At GSI

Yaramishev simulations with
Dynamion. Scaling law

$$\varepsilon = \alpha\ \Delta E/E\ x'^2$$

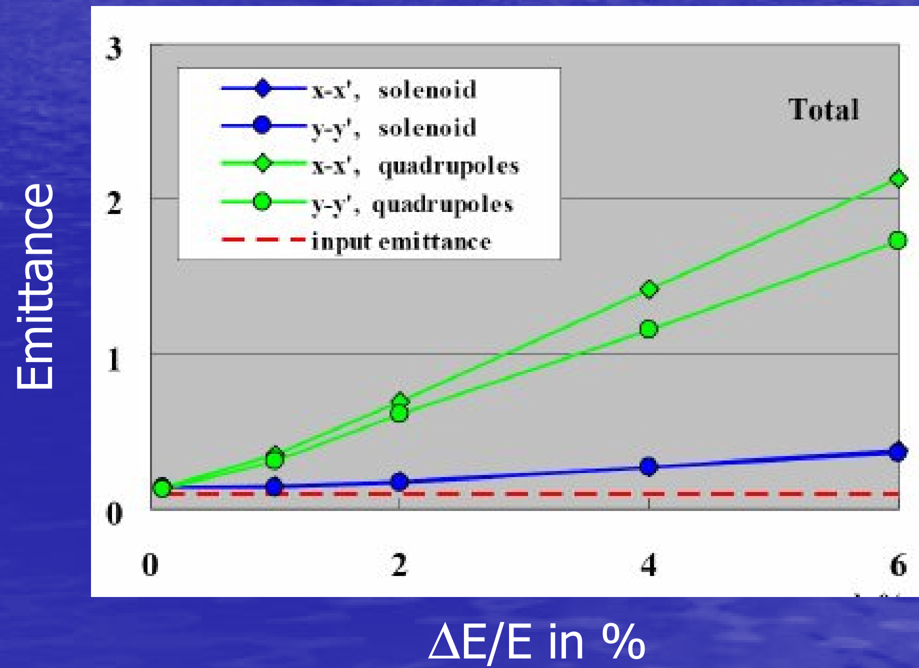


Image from Ingo Hofmann presentation

Post accelerazione di protoni

FELIX spectrum

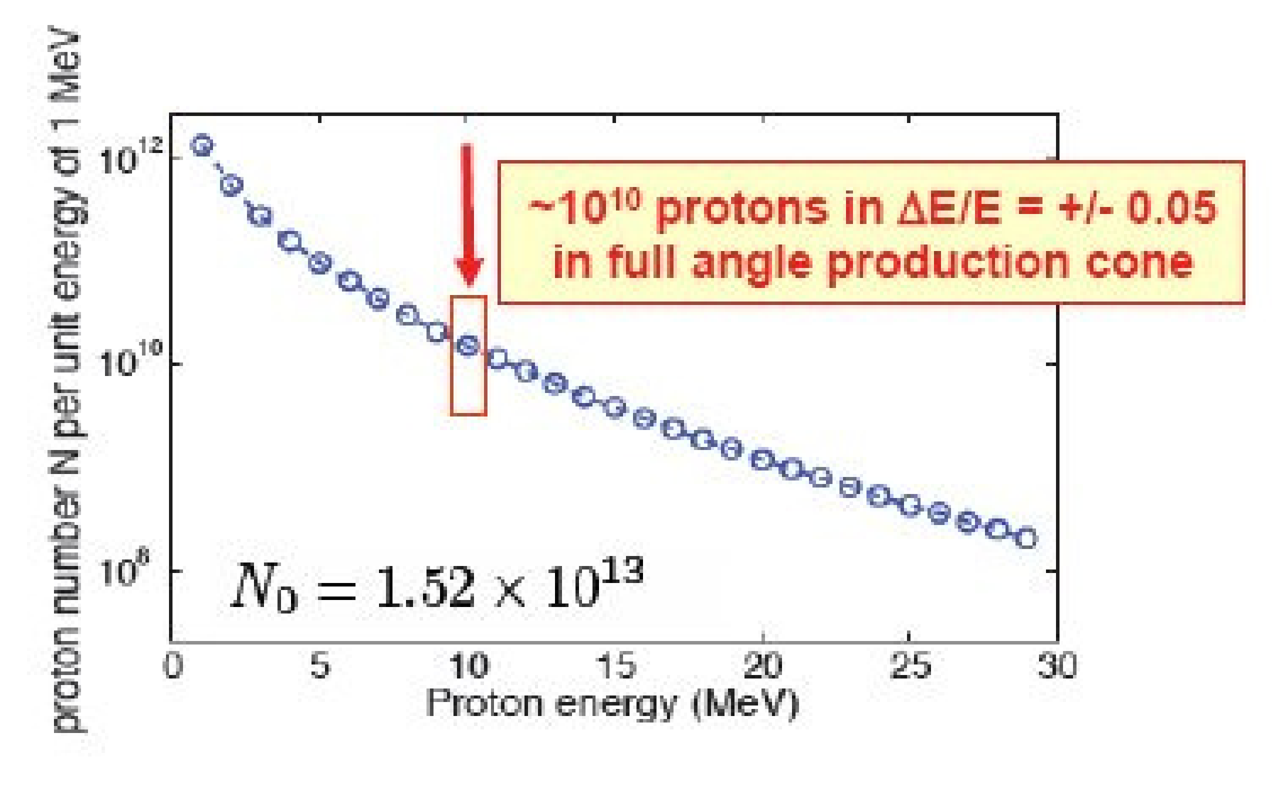
Window at 10 MeV

$\Delta E/E = 5\%$

$x' = {}_{170}$ mrad = 10°

$N = 10^{10}$ (0.1% tot)

$\varepsilon =$ 100 mm-mrad



fit $dN/dE = 4\ 10^{12}\ e^{-E/4}$

PHELIX Laser Ne-Yag E = 1 kJ impulse 0.5-20 ps

Image from Ingo Hofmann presentation

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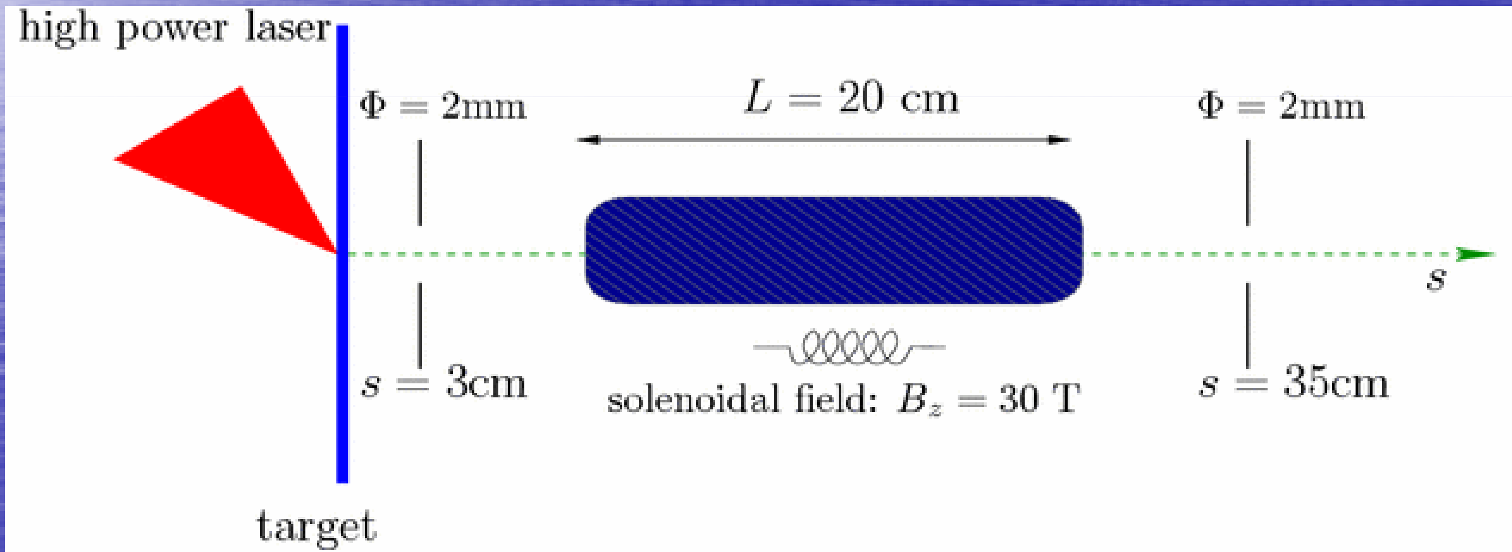
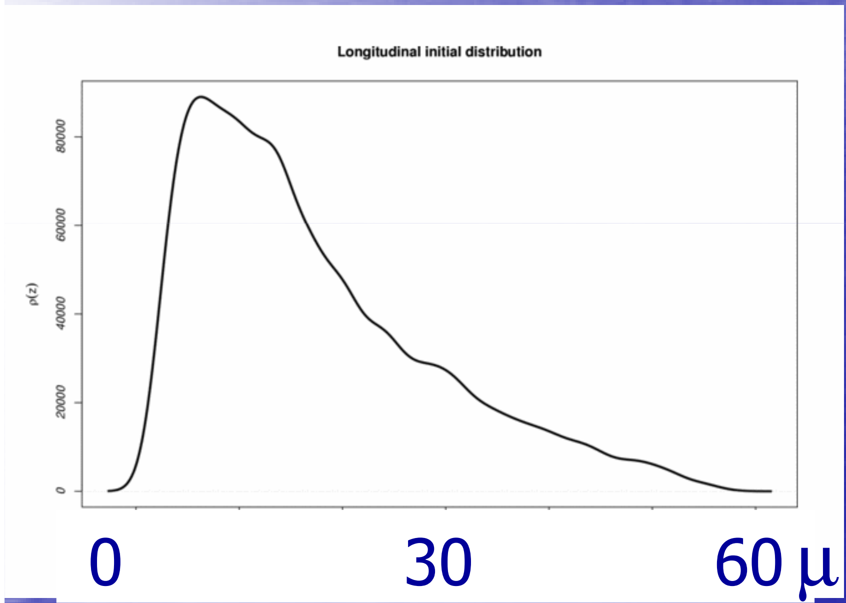
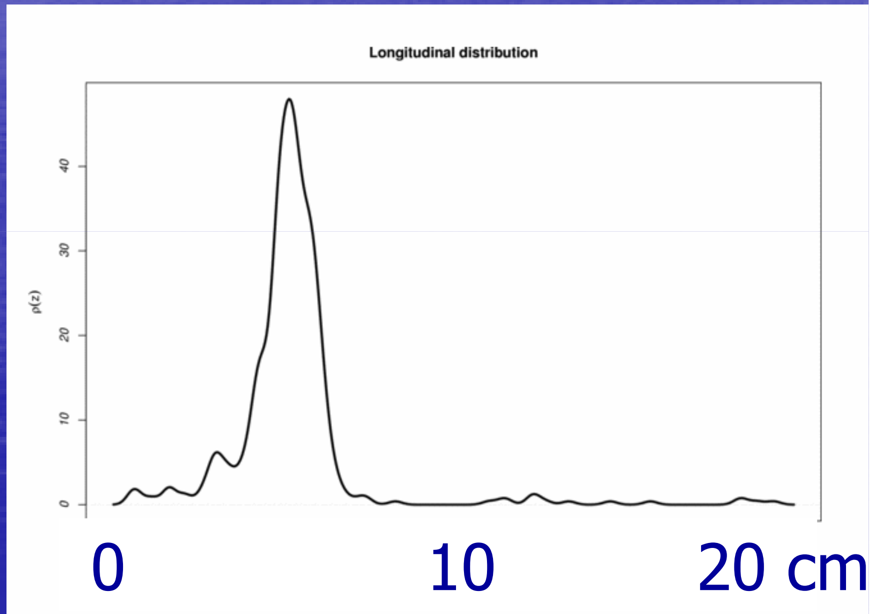
Scheme for transport collimation and focusing before injection into first RF and p LINAC



PROMETHEUS PROJECT

Initial and final density $\rho(z)$





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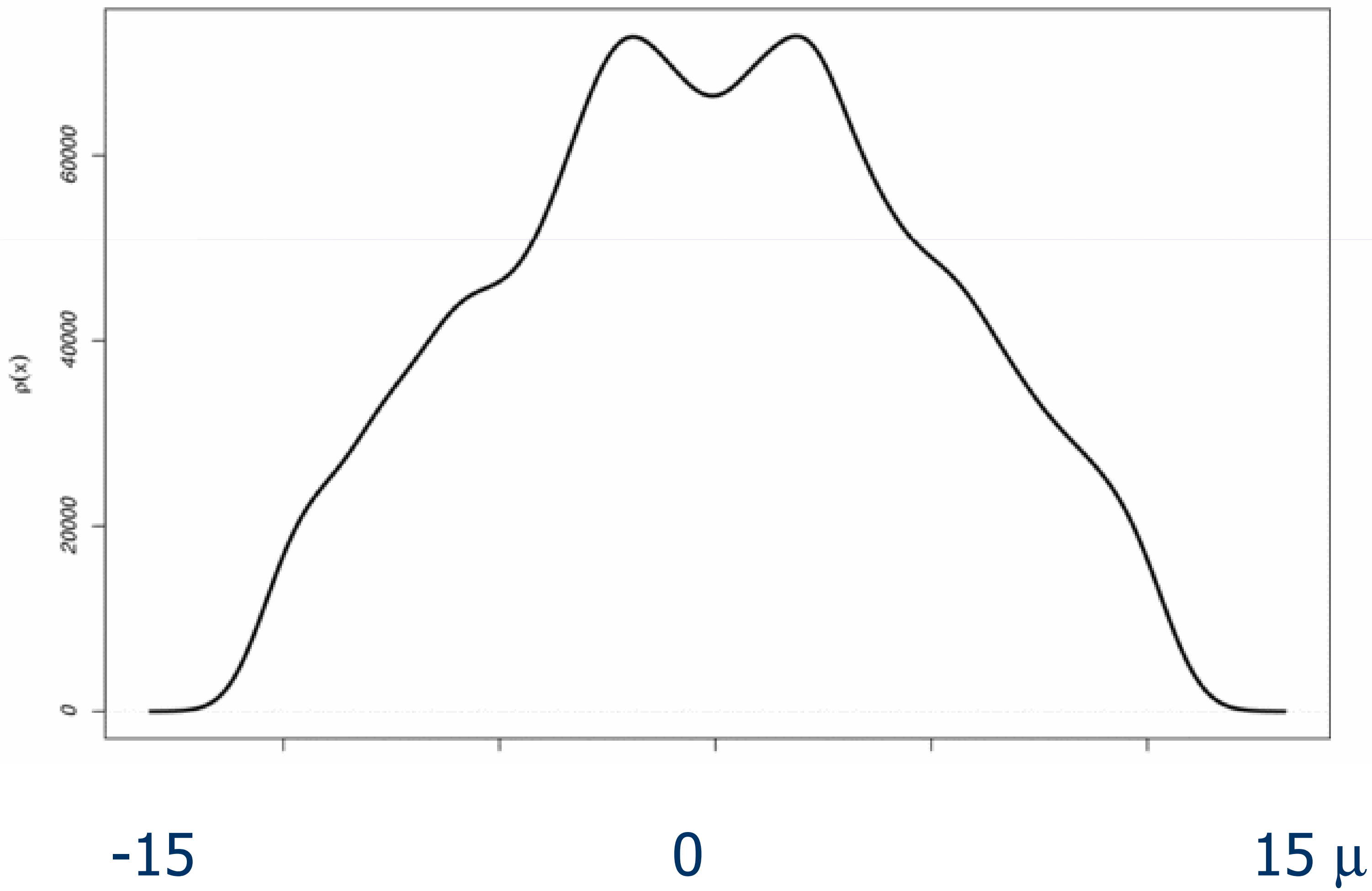
Initial density $\rho(x)$

Horizontal distribution $\rho(x)$



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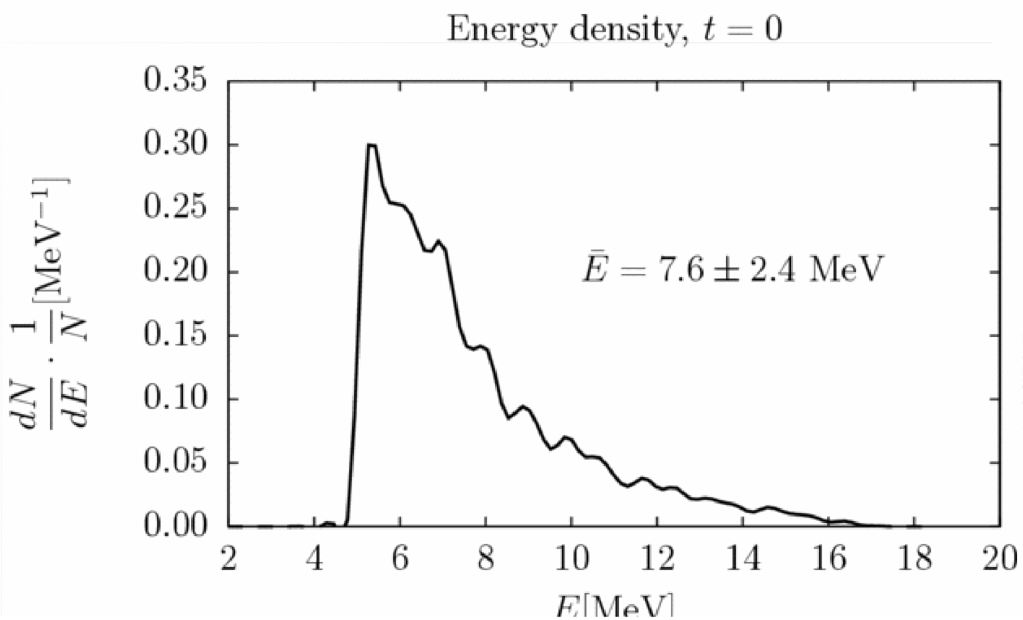
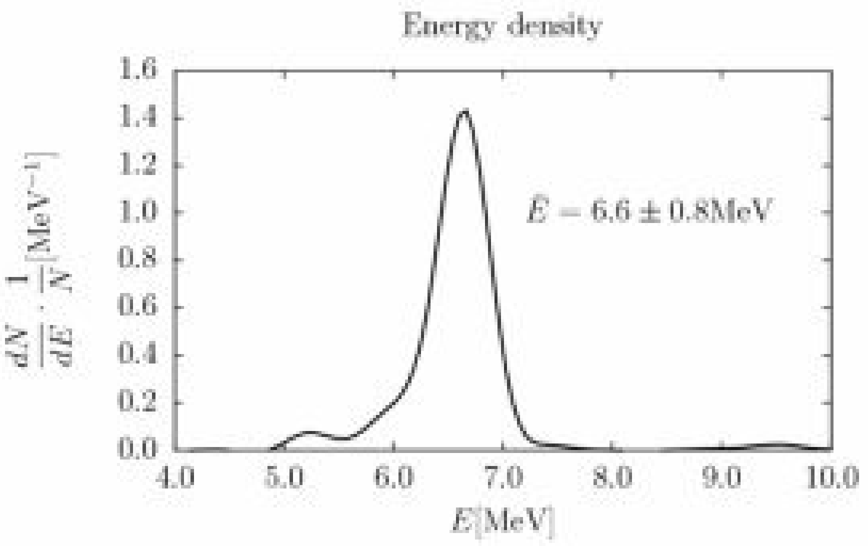
Initial and final density ρ(E)

Transported beam 4%





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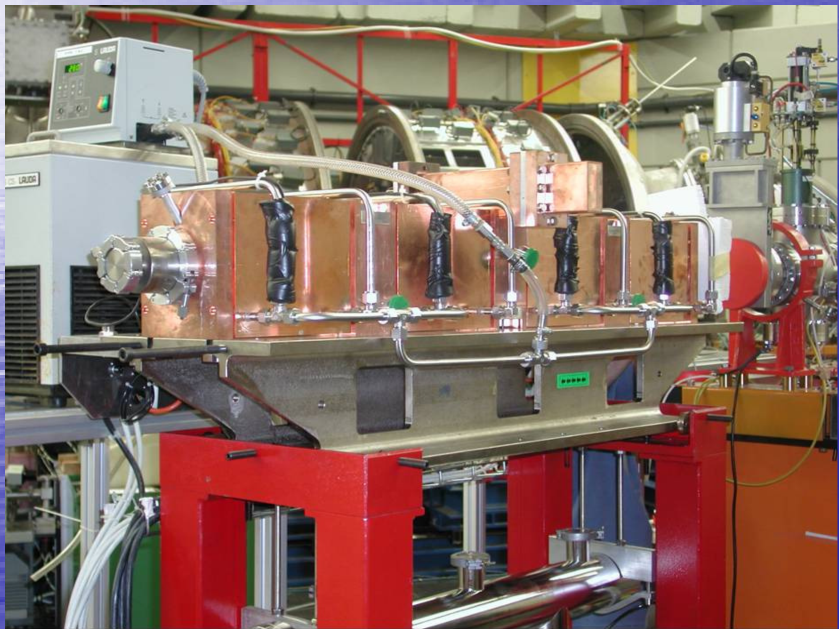
Emittances at the beginning and the end of transmission line from laser target to RF

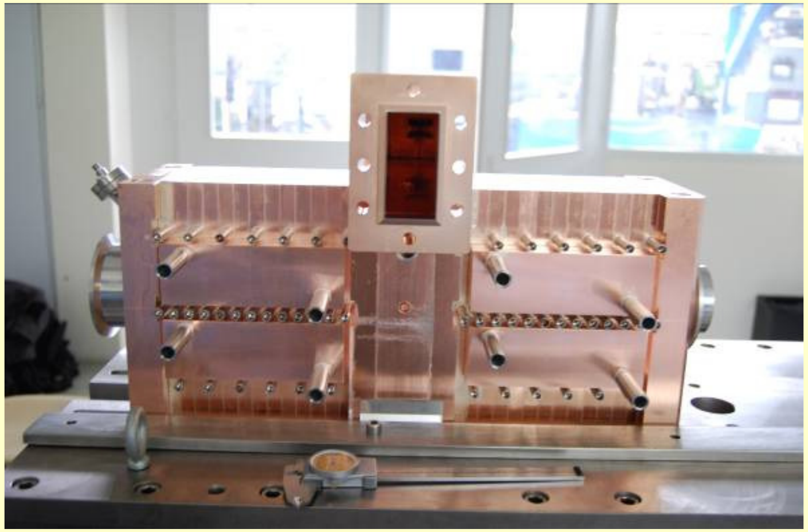
	σ_x	σ_y	σ_z	ε_x	ε_y	ε_z
Start	5 μ	5 μ	6 μ	0.07 mm-mrad	0.07 mm-mrad	0.04mm-mrad
End	1.7 mm	1.7 mm	23 mm	4 mm mrad	4 mm-mrad	0.06 mm-mrad

Developed hardware . INFN has developed high fiels for compact linacs at 3 GHz

LIBO: 60 MeV proton linac booster) at LNS during installation in the beam line

ACLIP: a 30 MeV linac booster, assembly of the first module





$\mathscr{E}$ = 20 MV/m

-RF High Power Tests on the First Module of the ACLIP Linac , **V. Vaccaro** et al. Proceedings PAC09 (Particle Accelerator Conference . Vancouver, Maggio 2009

LIBO - A LINAC-Booster for Protontherapy: Construction and Tests of a Prototype - *Nuclear Instruments* and Methods A, Volume 521, 2-3, aprile 2004 **U. Amaldi et al**

-BEAM TESTS ON A PROTON LINAC BOOSTER FOR HADRONTHERAPY **C. De Martinis** et al- Proceedings EPAC 2002 (European Particle Accelerator Conference . Parigi, Giugno 2002

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DIAGNOSTICS

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Basic steps of PROMETHEUS the feasibility study

1) Characterization of the proton bunch

Energy and angle ditribution. Intensity

2) Design of transport line and chacacteriaztion of transported bunch

Rms space values, emittances, energy spread

3) Electron distribution and temperature

diagnostics proposed by Fuchs

RADIOBIOLOGY

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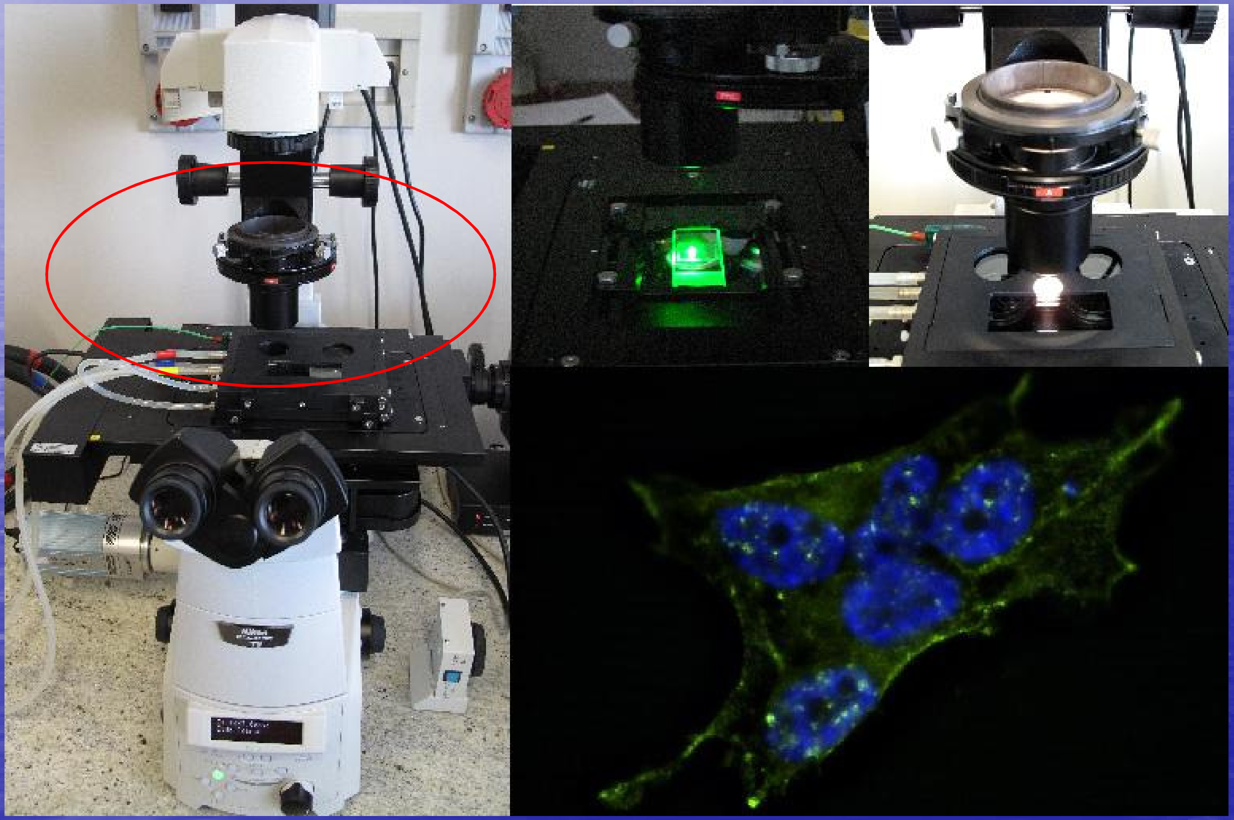
Dynamical fluorescent microscopy



Biophysics laboratory , UniBO

http://www.df.unibo.it/star/lab_biofisica.html

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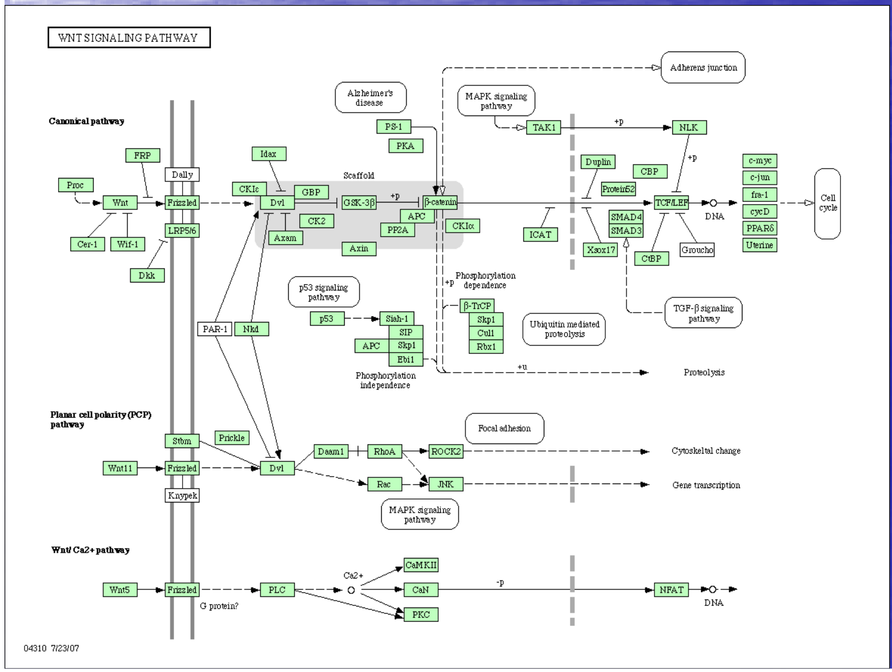
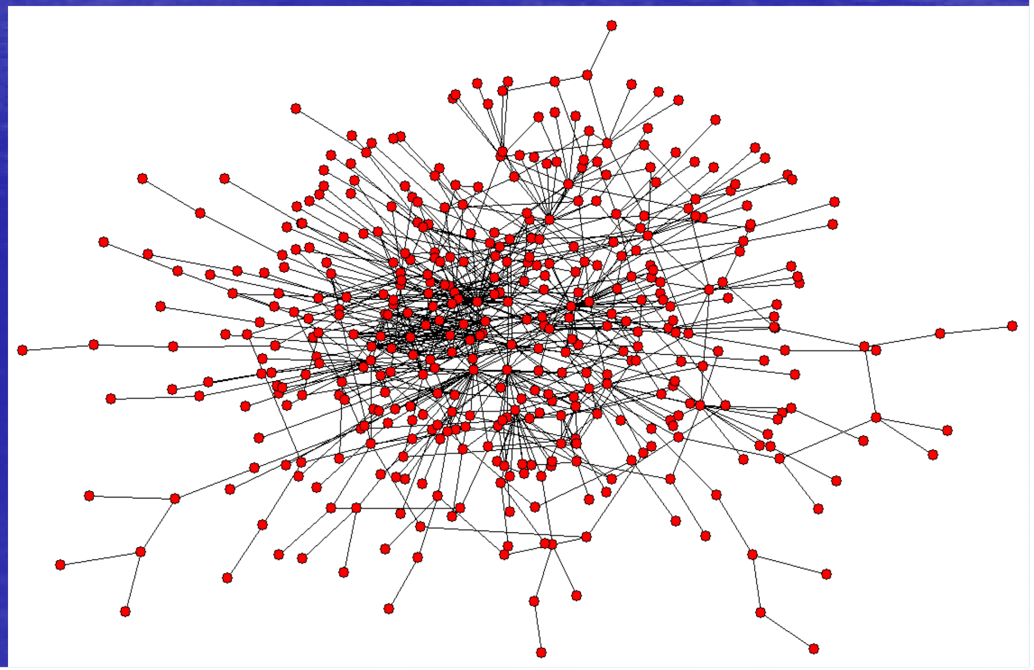
Gene expression

Genic expression via microarrays allows to observe the mRNA of single genes (up to 30.000 on a chip) and to investigate the biochemical pathways.

www.genome.jp/kegg/





CONCLUSIONS

Design study complete june 11

Simulations & experiments PMRC & GSI

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PROMEHEUS italian facility for high intensity laser applications to biomedicine (IF)

A) First goal: p injector of medical quality

Ibrid acceleration of E> 60 mJ in 3 minutes

Next step: upgrade injection energy and intensity

B) Second goal: build a TW class CO_2 laser.

Develop the AOFEL and explore RPA acceleration for p and ions

Time schedule: 10 years Budget: 30 M€

THE END

Thanks for your attention