Optical Acceleration of Ions and Perspective for Biomedicine

Bologna (IT) | November 4 – 5, 2011

Sala Refettorio, Istituto Storico Parri Emilia Romagna

Via Sant'Isaia 18

Coulomb '11

A Compact Post-acceleration Scheme for Laser Generated Protons

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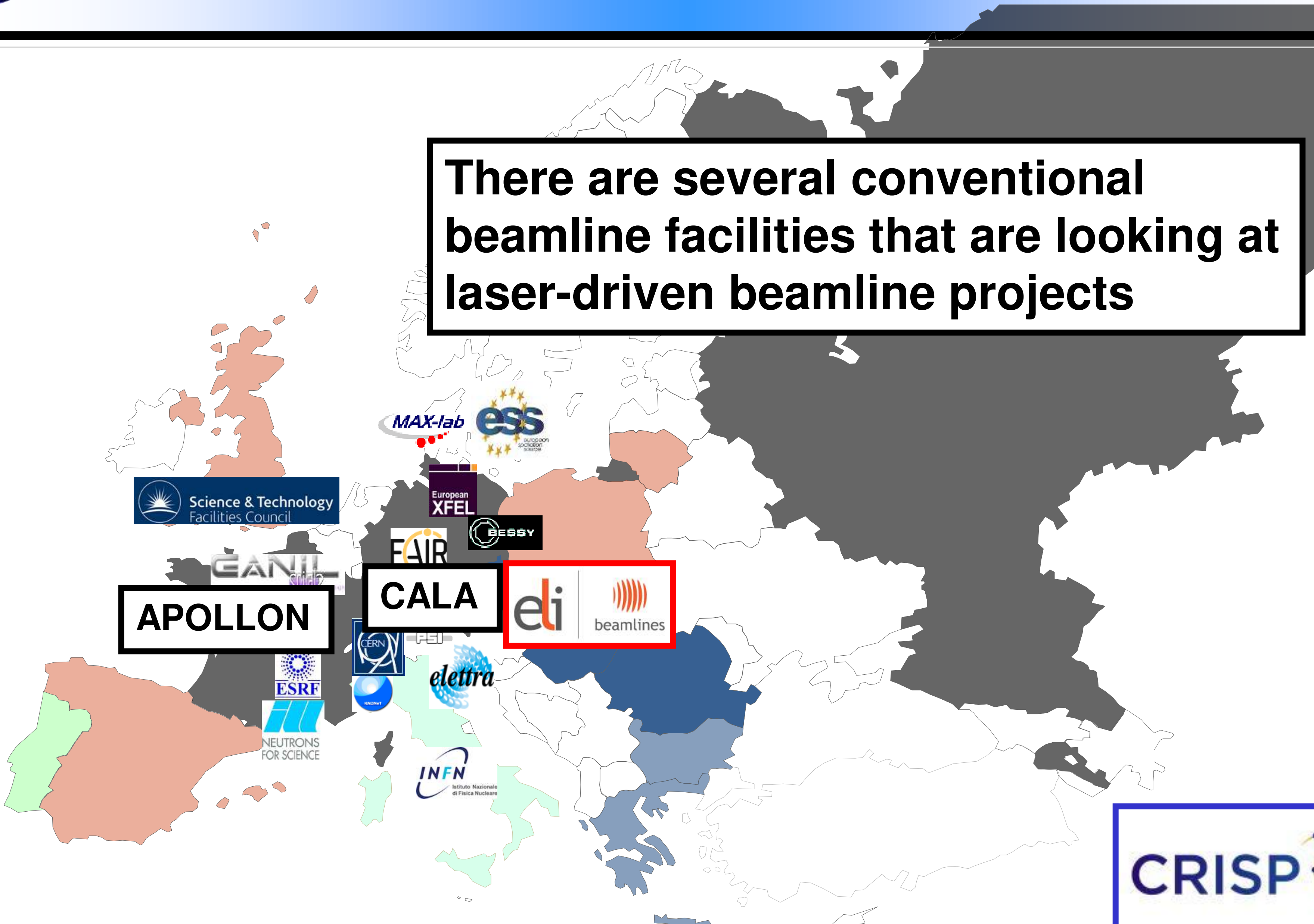
ENEA C.R. Frascati

CRISP

Motivation and context

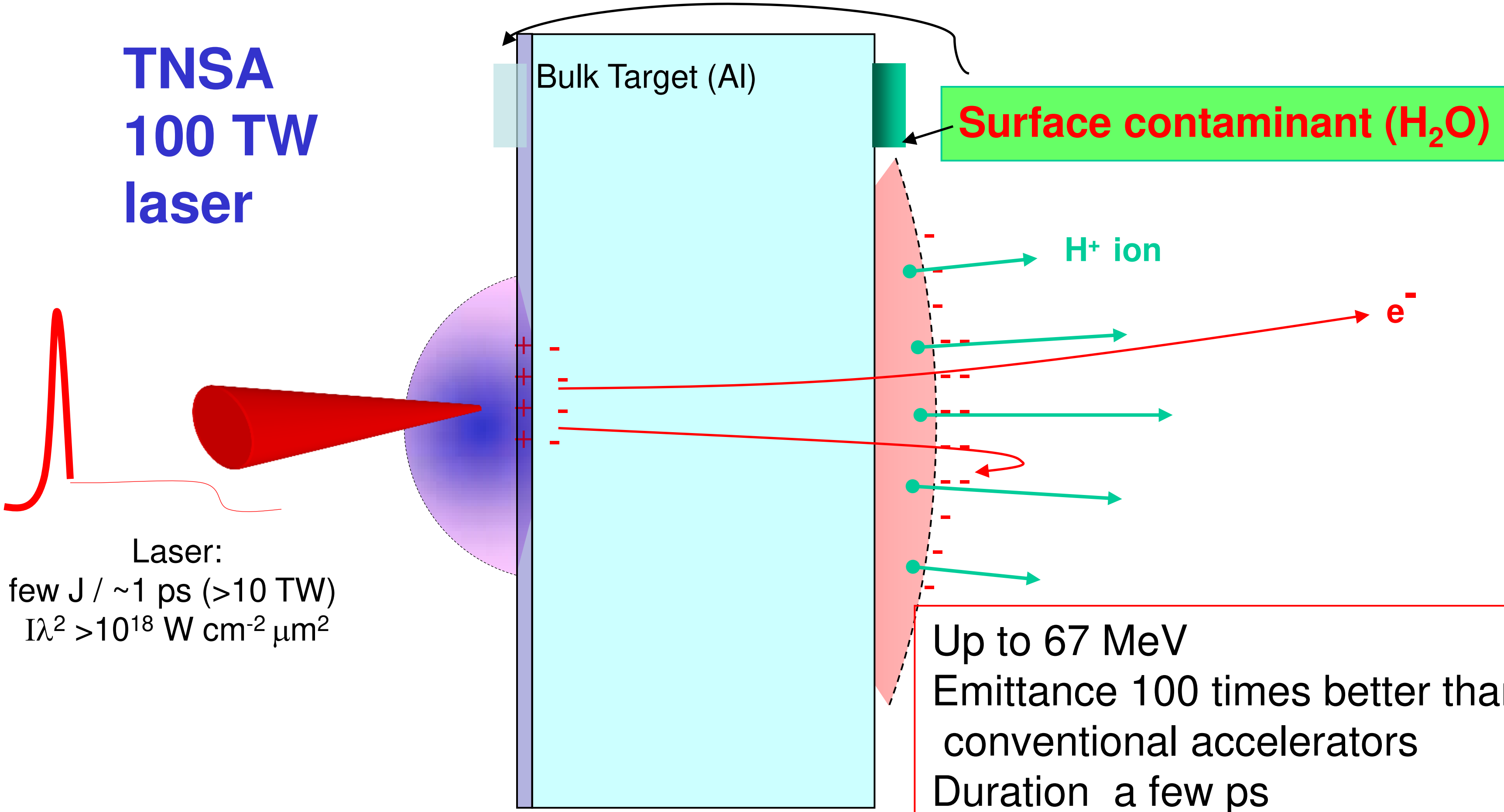
There are several conventional beamline facilities that are looking at laser-driven beamline projects



CRISP

Starting point: we consider „today“ measured parameters and try to make beamlines out of it

TNSA
100 TW
laser

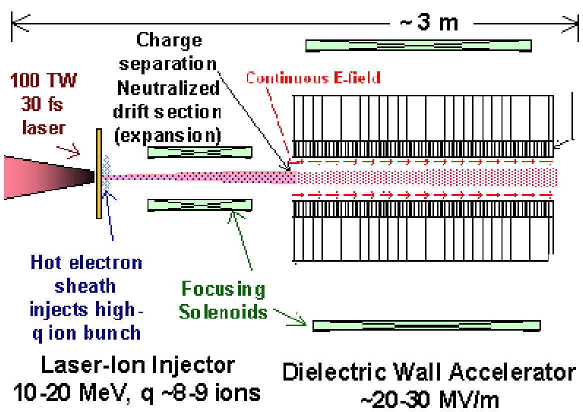


Up to 67 MeV
Emittance 100 times better than conventional accelerators
Duration a few ps

Issue: Large energy spread
Large beam divergence
(Low energy)

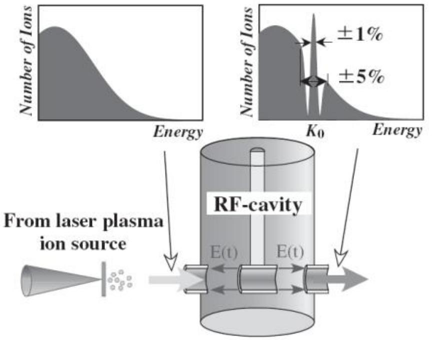
Improvements using beam shaping with conventional accelerator devices

Combined accelerator



Logan, Caparasso, Roth, Cowan, Ruhl et al. (LBNL-LLNL-GSI-GA) (2000)

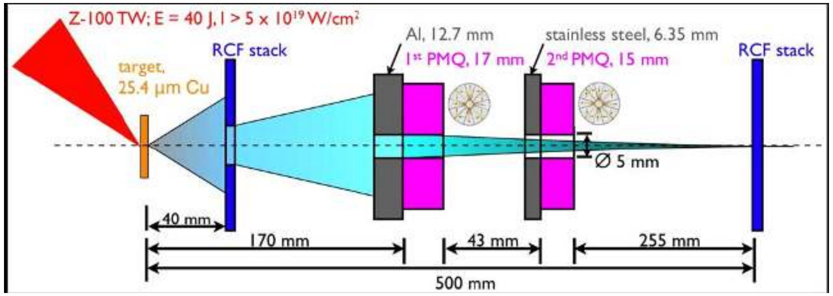
Injection studied using RF-cavity



5 % spread

S. Nakamura et al. Jap Jour. Appl. Phys. 46 L717 (2007)

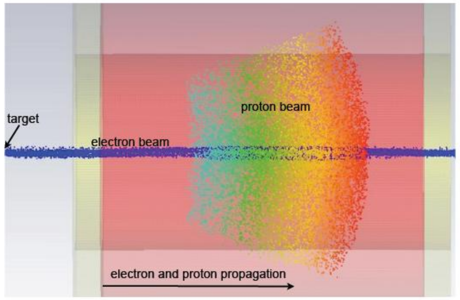
Focalisation using Quadrupoles



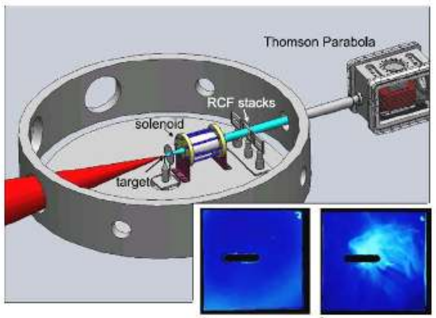
M. Schollmeier et al., PRL 101, 055004 (2008)

Beam shaping with conventional accelerators becomes more fashionable

Focusing with Solenoids



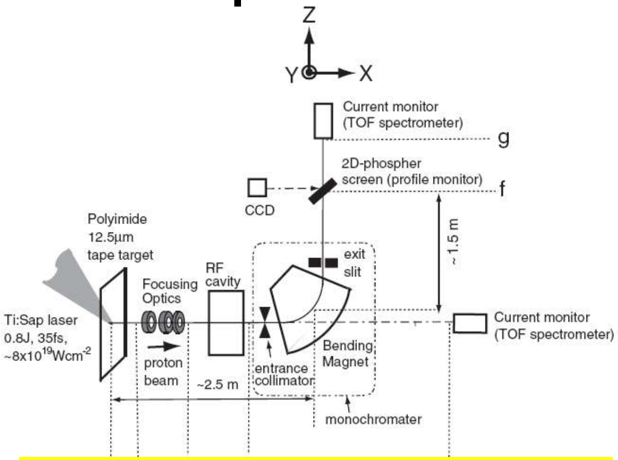
K. Harres et al J. Phys Conf. Series 244 022036 (2010)
F. Nürnberg et al.,
PAC 2009



V. Bagnoud et al., APB (2009)

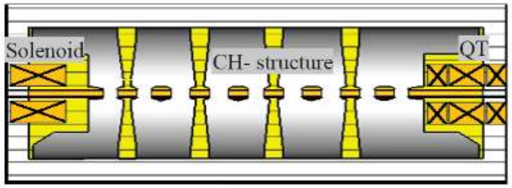
8 T solenoid

Transport with 1 Hz



M. Nishiuchi et al Phys Rev STAB 13 071304 (2010), 5% spread, 10% efficiency

Post-acc with modified DTL



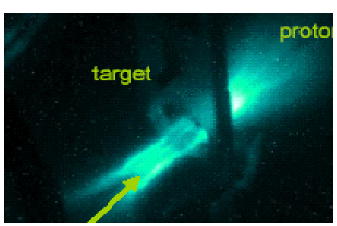
A. Almomani et al., Proceeding IPAC (2010)

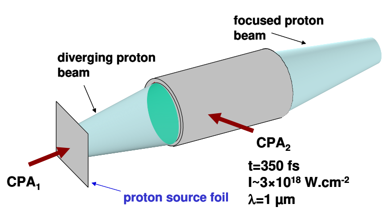
General scheme for beam capture and post-acceleration

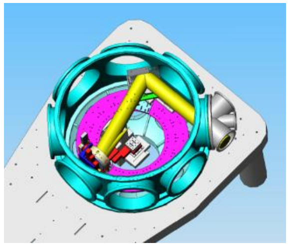
Looking for the best compromise in terms of

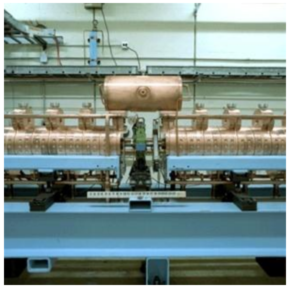
1) Highest (stable) energy
2) Highest dose
3) Lowest energy spread
4) Smallest beam divergence
5) Fully characterized source
6) Feasible

Laser-generated proton source → Device to focus and energy-select protons → Drift space (to exit target chamber) → Conventional capturing section (4 or 5 Quadrupoles) → Accelerating section (48 DTL cells)

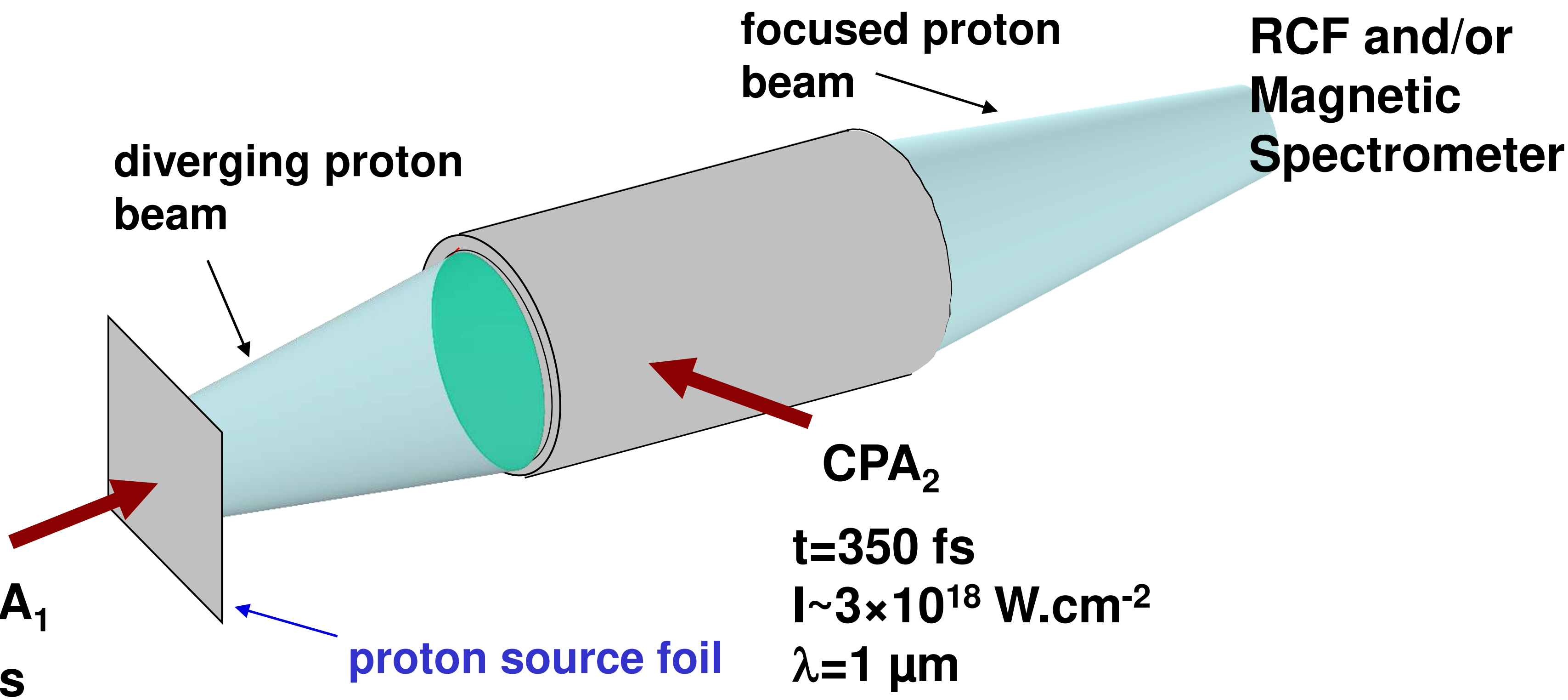








Focusing & energy selection: ultra-fast laser-triggered ion micro-lens



CPA$_1$

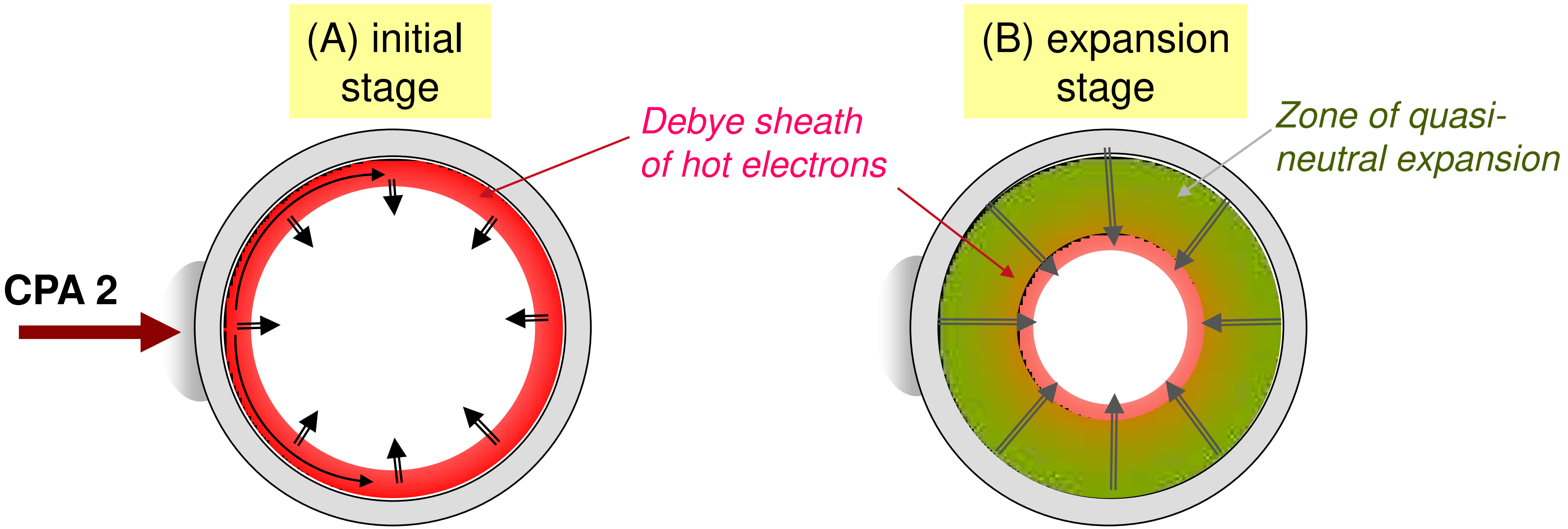
t=350 fs
I~3×10^{19} W.cm^{-2}
λ=1 μm

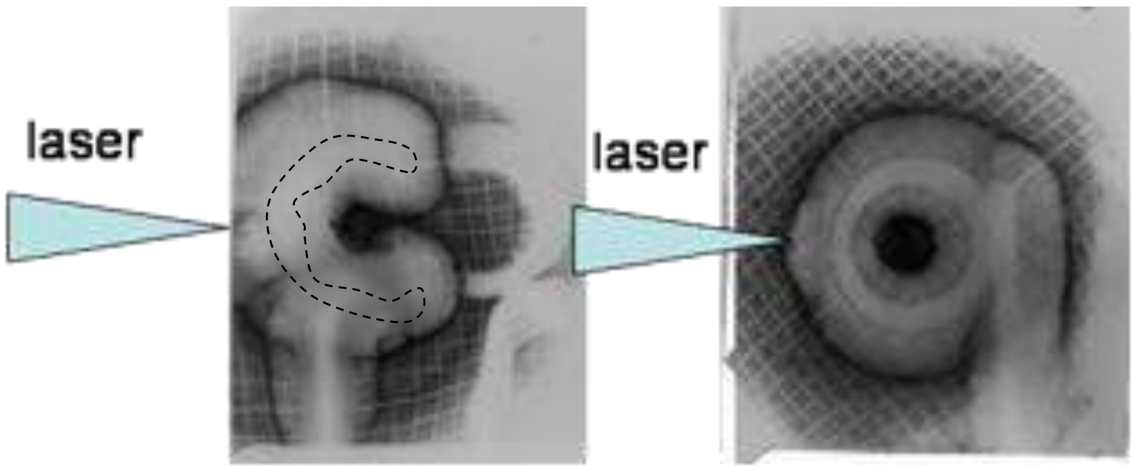
CPA$_2$

t=350 fs
I~3×10^{18} W.cm^{-2}
λ=1 μm

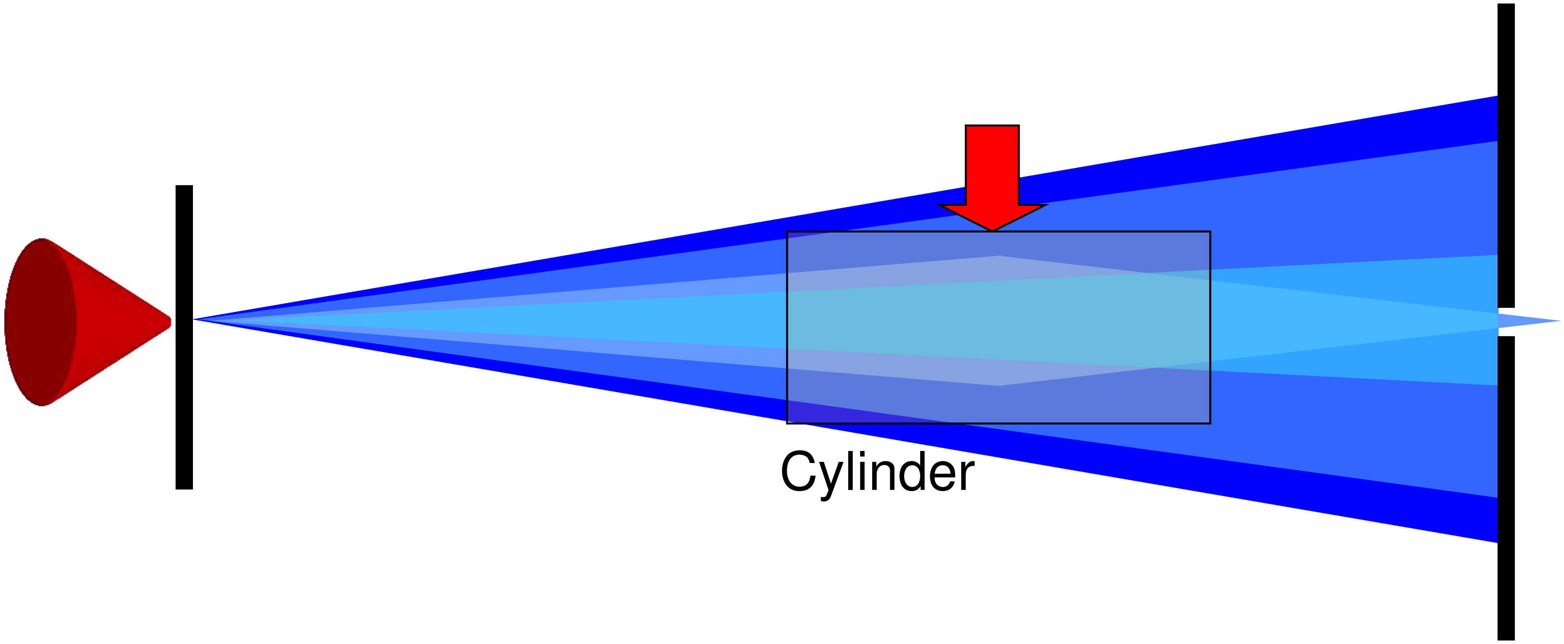
T.Toncian et al; Science 16 Feb. (2006)
Patent: 10 2005 012 059.8 PILZ (2005)

Focusing fields are Debye sheath fields driven by the hot electrons

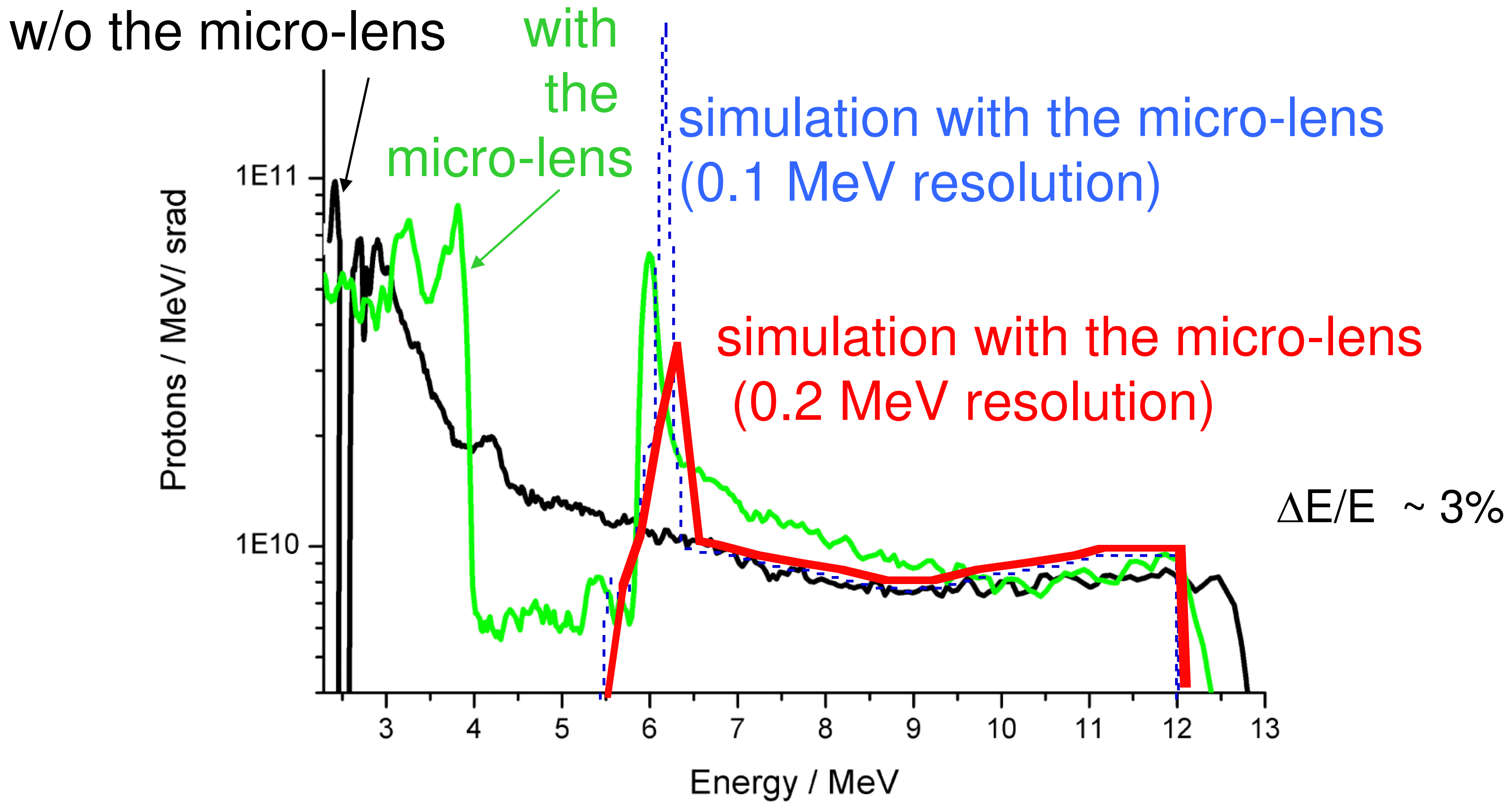




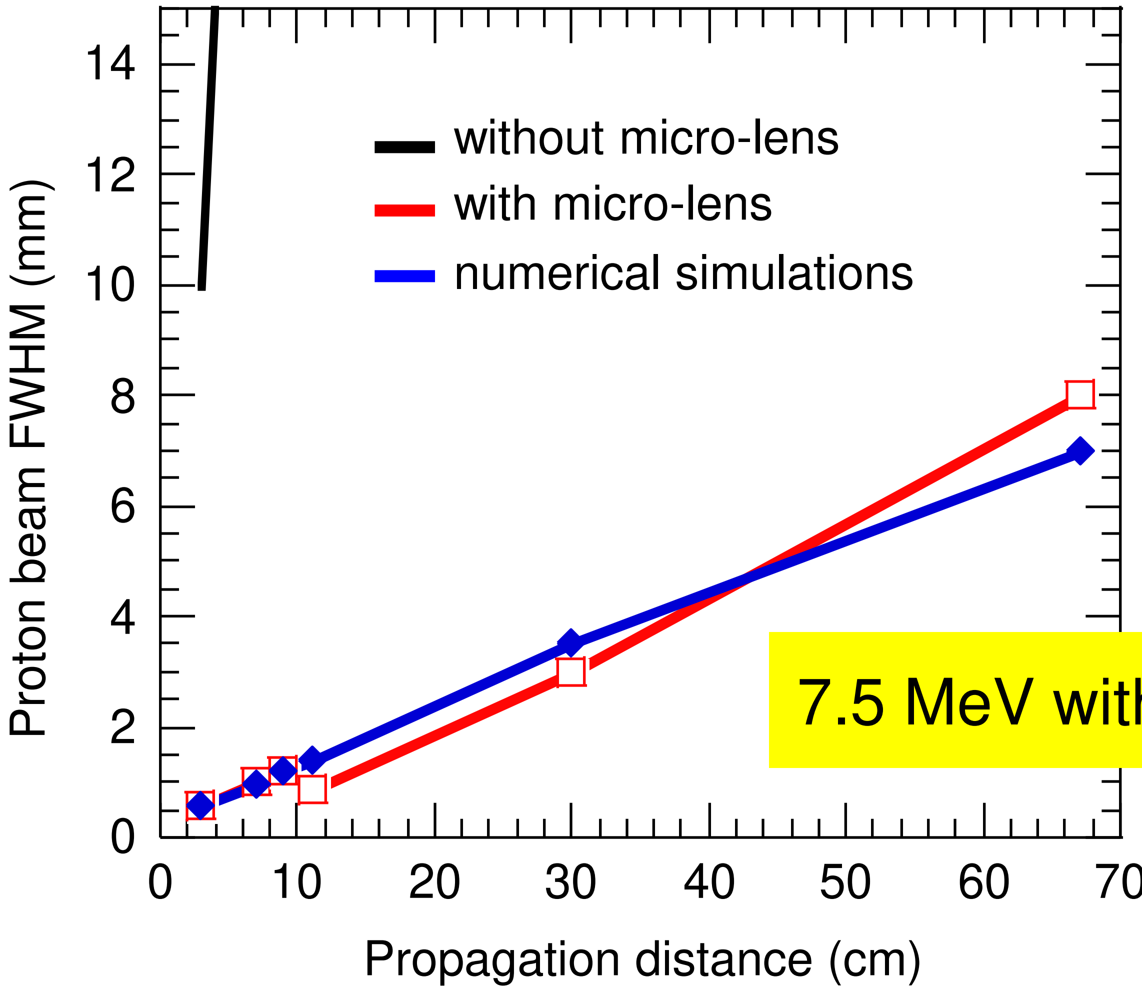
The micro-lens offers (tunable) energy selection



Best results in terms of energy spread, number of protons and beam divergence



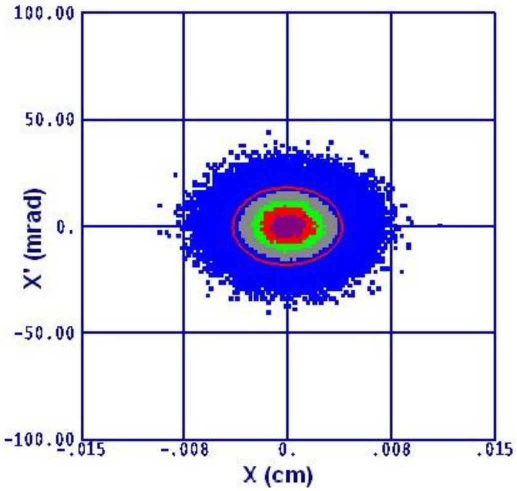
Efficient reduction of the beam divergence (tunable)



7.5 MeV with > 5 A collimated

We use parameters measured in the micro-lens output for injection in the conventional section

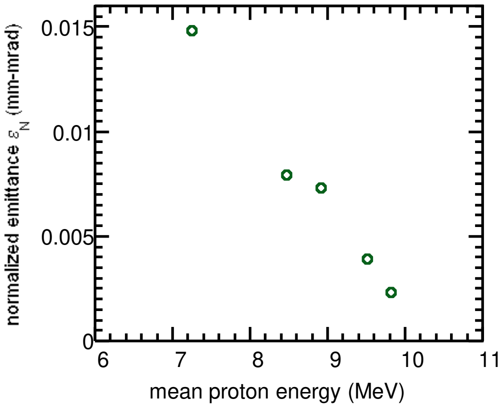
- 6.9 to 7.1 MeV after the cylinder → 2 10^9 protons (320 pC)



- transverse source sizes (FWHM): x=y=80 μm with σx=σy=20 μm

- residual divergence: x'=y'=40 mrad with σx'= σy'=9 mrad

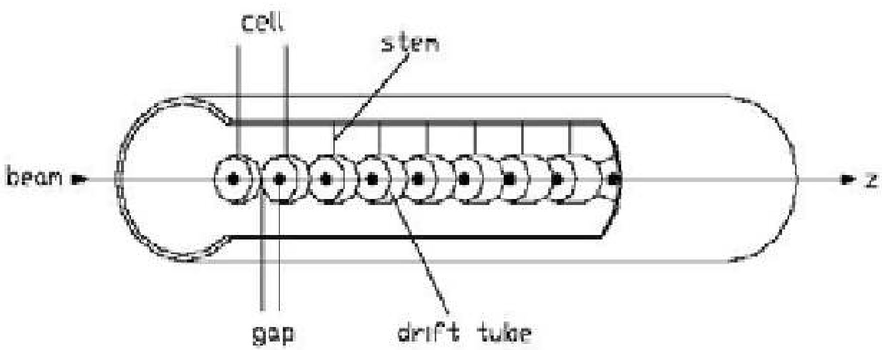
- un-normalized emittance 0.180 mm.mrad

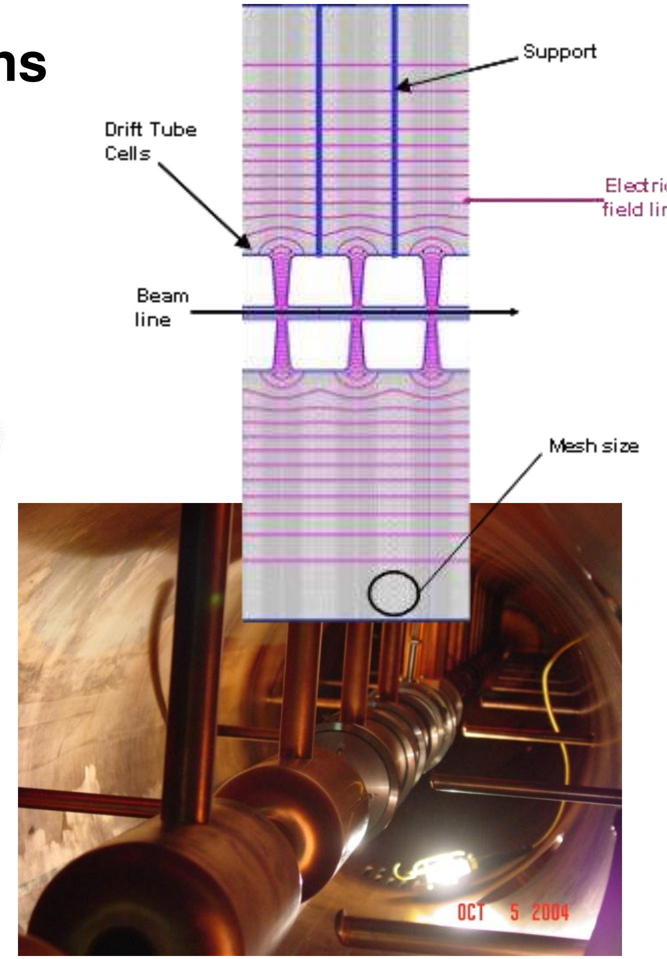


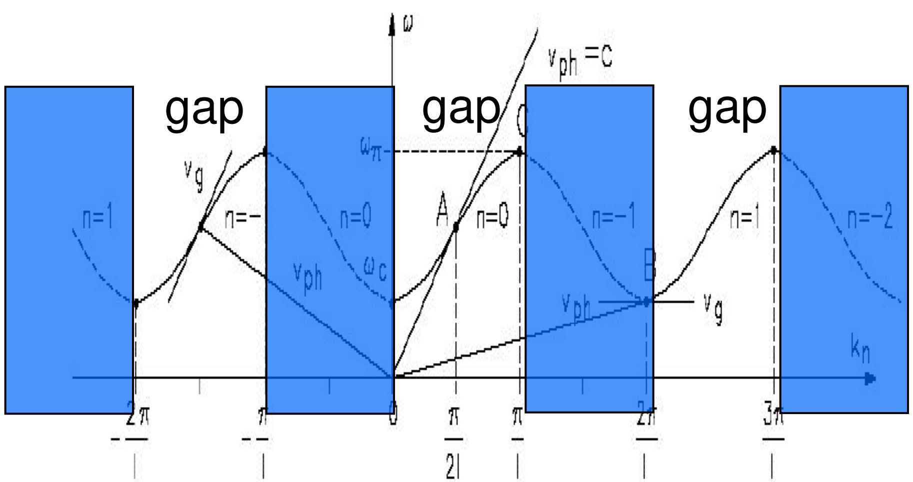
Simulations: Parmela / TStep

Drift Tube Lin(ear)ac(celerator) designed with EM Field solver for particle accelerators

We used typical state of the art capturing sections and accelerating structures DTLs (SNS)
48 cells, 0.17 MeV/cell, f=350 MHz

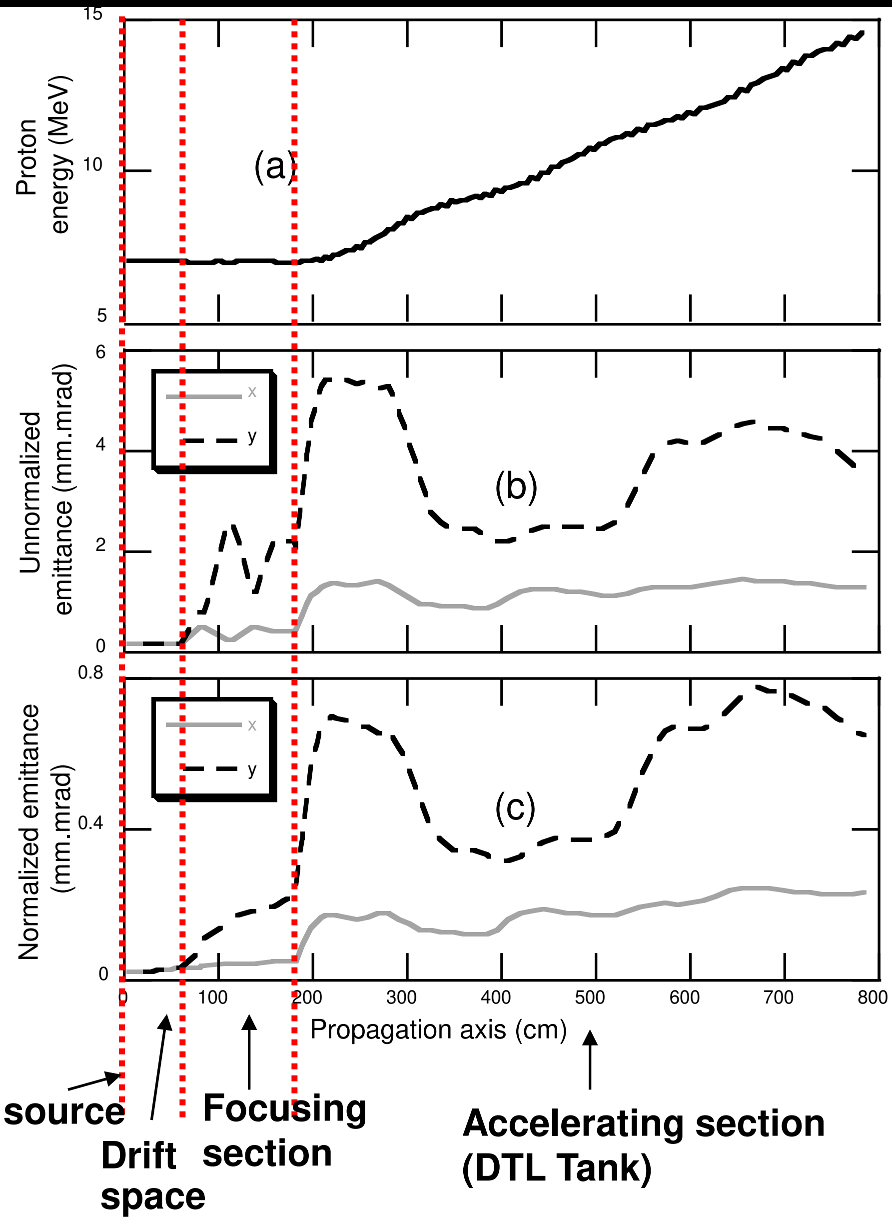


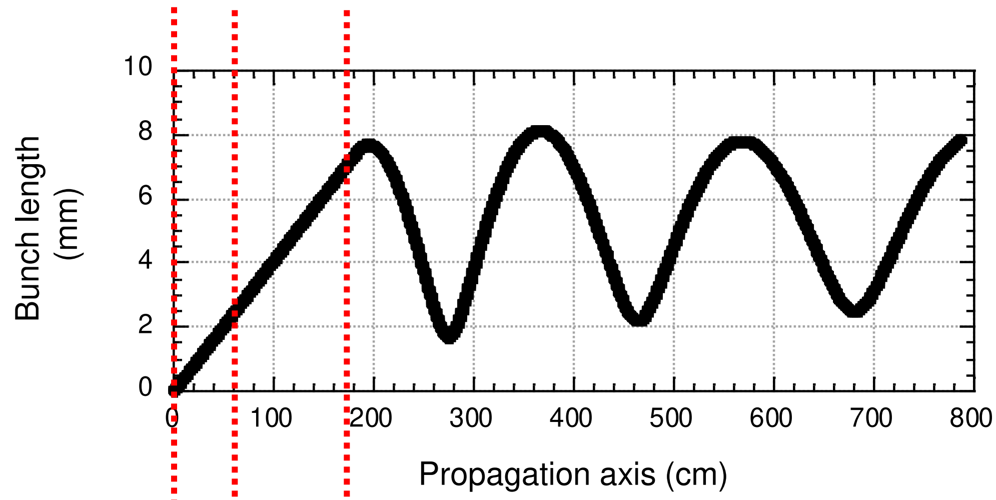


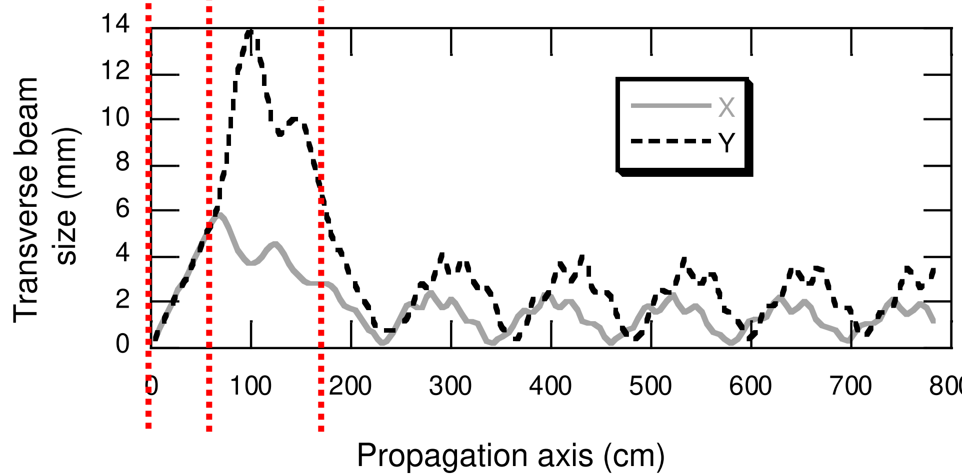


We use the drift-kick method (electric fields are designed with SUPERFISH, average = 3 MV/m)

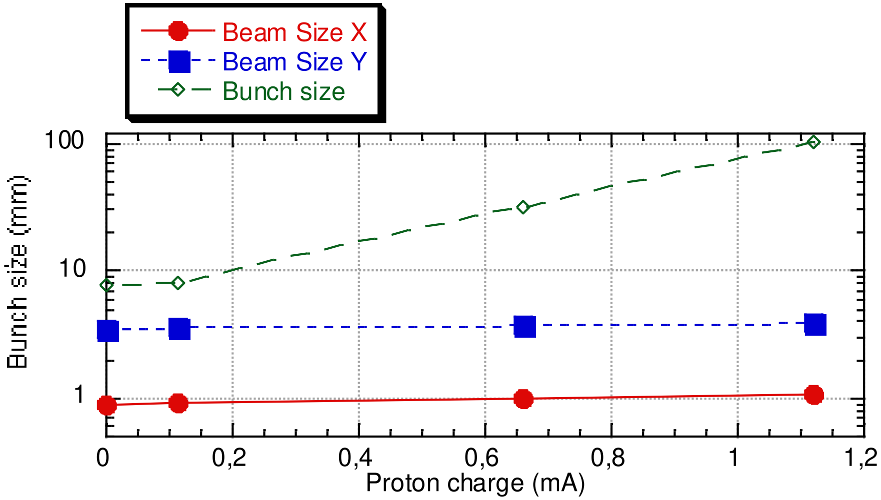
Parmela results without space-charge

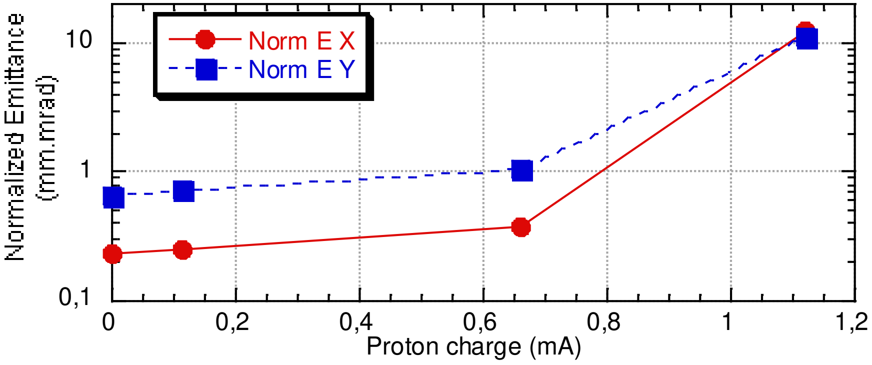


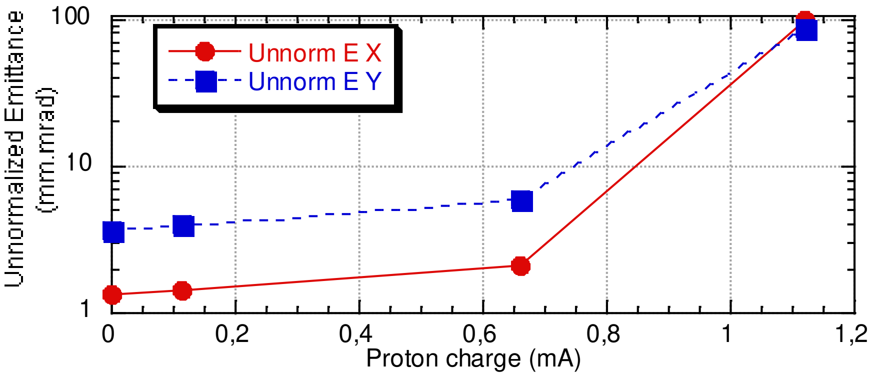




Space charge effects







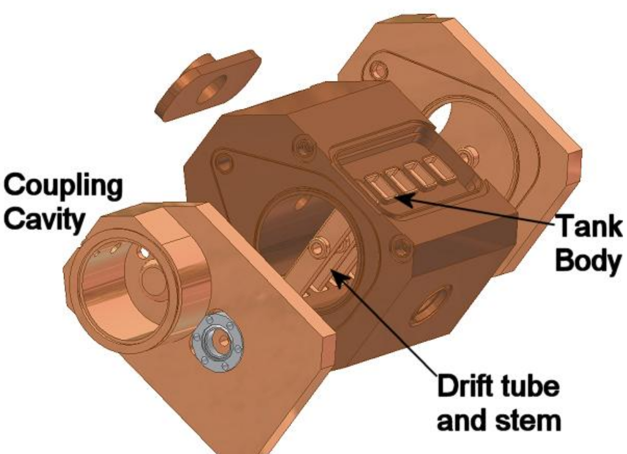
Average current for 350 MHz (all particules = 112 mA), SNS is 0.11 mA

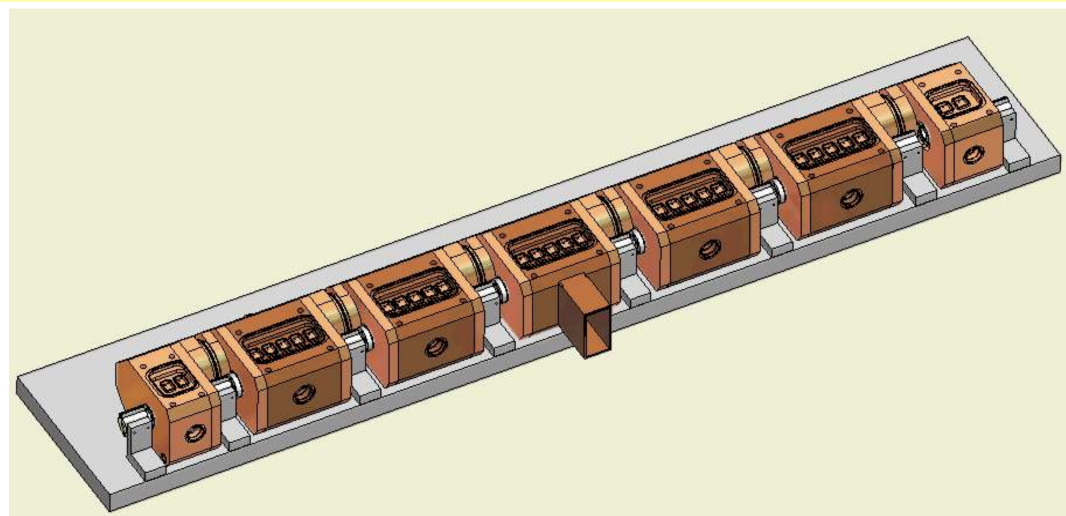
P. Antici et al., J. of Applied Physics, 104, 124901 (2008)

SCDTL improves capturing and post-acceleration

SCDTL:

- **Short DTL tanks + side coupling cavities**
- **Side coupling cavities on axis with very small Permanent Magnet Quadrupole (PMQ) (3 cm long, 2 cm o.Ø, 6 mm i. Ø) for transverse focusing.**
- **Designed for medical applications**
- **S-band (3 GHz) very versatile to develop**



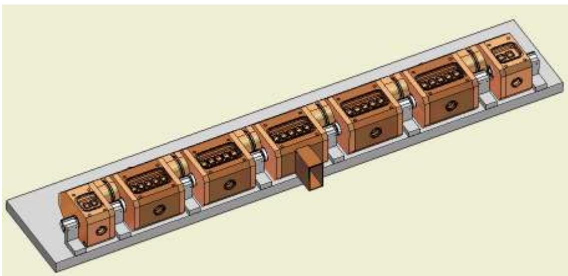


L. Picardi et al., "Struttura SCDTL", Patent n. RM95-A000564

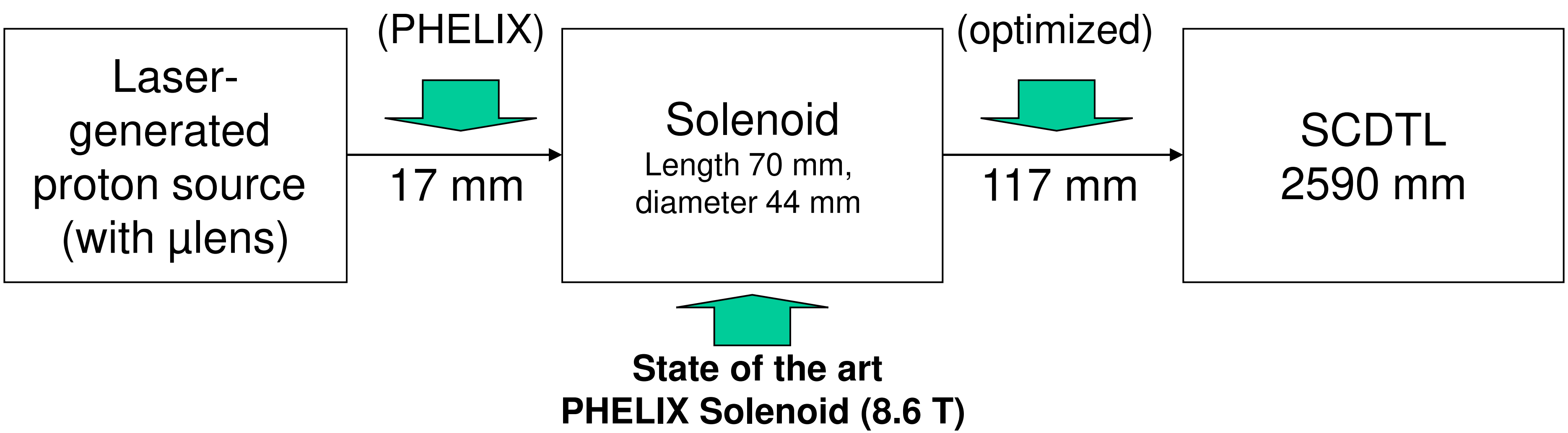
SCDTL specification

Frequency	3 GHz
Number of modules	2
Number of tanks/module	11
Number of cells/tank	4
Inter-tank distance	4.5 $\beta\lambda$ in module #1, 4.5 $\beta\lambda$-3.5 $\beta\lambda$ in module #2
Bore radius	2 mm in module #1, 2.5 mm in the module #2
Total length	2.59 m
Average electric field, E_0	11.3 MV/m
Acc. electric field, E_0T	between 7 and 7.75 MV/m
Synchronous phase,φ_s	-30°
Maximum PMQ gradient	220 T/m
RF power for the structure	<1.5 MW

Lattice structure using Side Coupled DTLs



Total length	**2.59 m**
Average electric field	**11.3 MV/m**
Acc. electric field, E_0T	**7 - 7.75 MV/m**
Max PMQ gradient	**220 T/m**

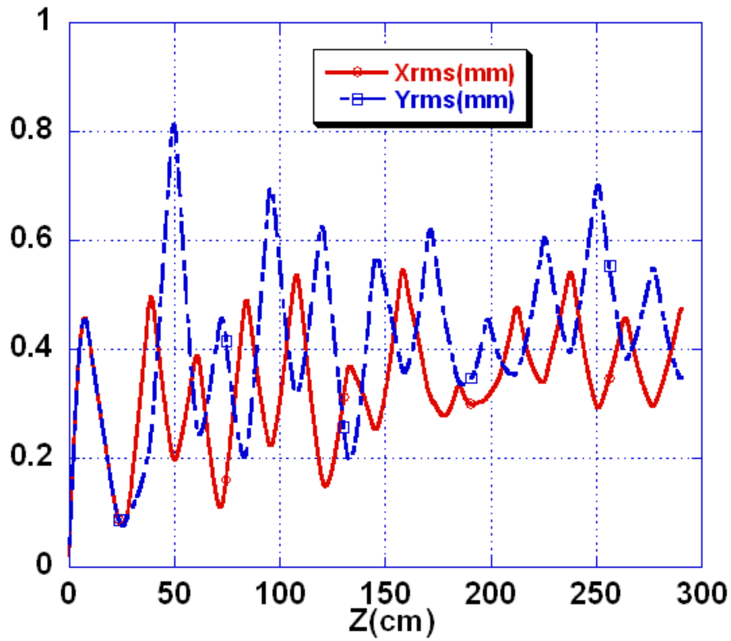


K. Harres et al., Phys. Plasmas 17, 23107 (2010)

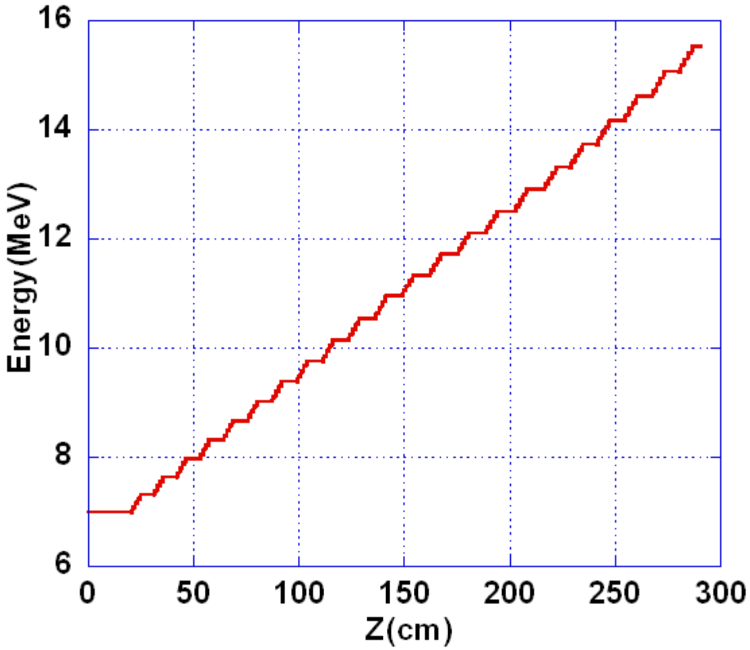
C. Ronsivalle et al., Proceedings of IPAC'10, Kyoto, Japan

Output of SCDTL

Beam Envelope

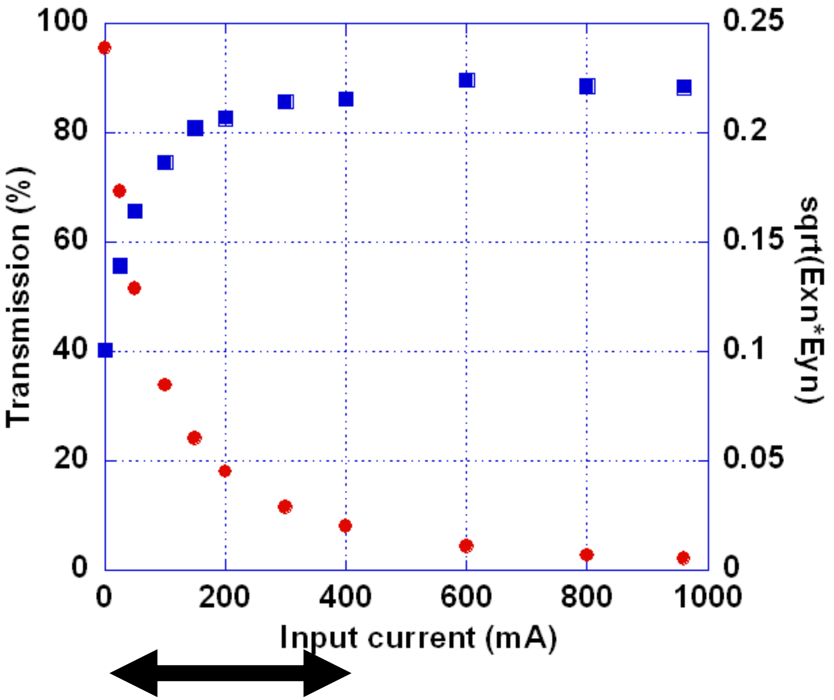


Beam Energy

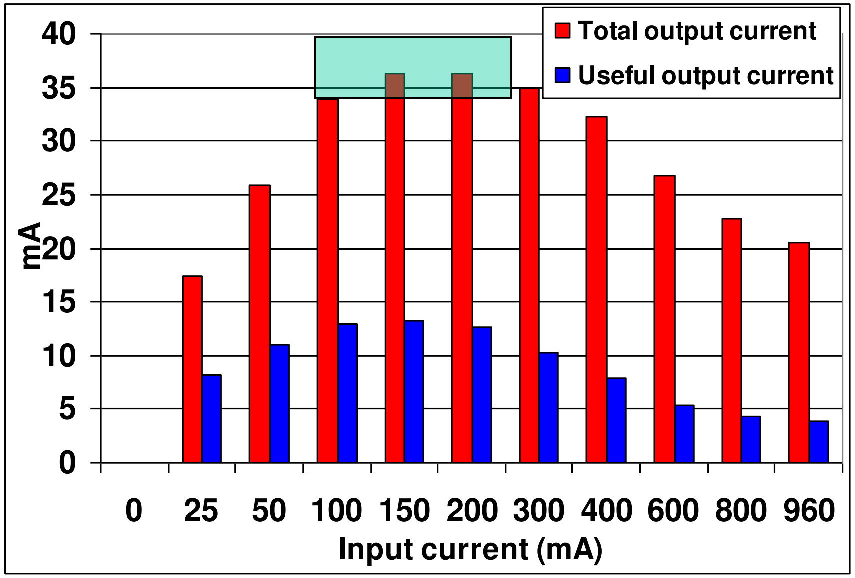


Shorter DTL

Beam dynamics with space charge yield high output current



Transmission (red points), output norm. emittance (blue points) versus the input current

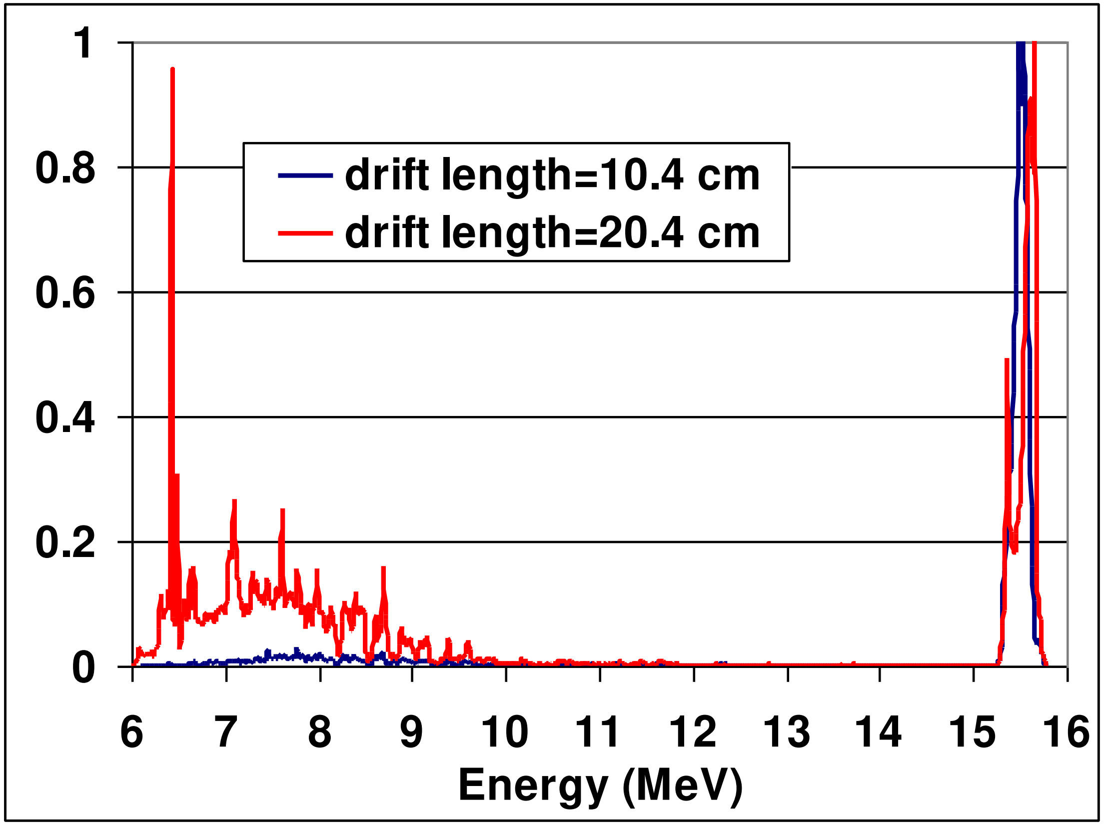


Total output current (red) and useful output current (i.e. 0.6 MeV around maximum)(blue) versus the input current

Useful output current=13 mA, ~36 % of total

TSTEP, 3 10^5 macroparticles

Spectrum becomes even more monoenergetic using the SCDTL



Normalized energy spectrum for 100 mA input current and two different lengths of the leading drift.

We have a laser-driven proton beamline !

P. Antici et al., PoP 18, 073103 (2011)

Sensitivity study (typical for a beamline)

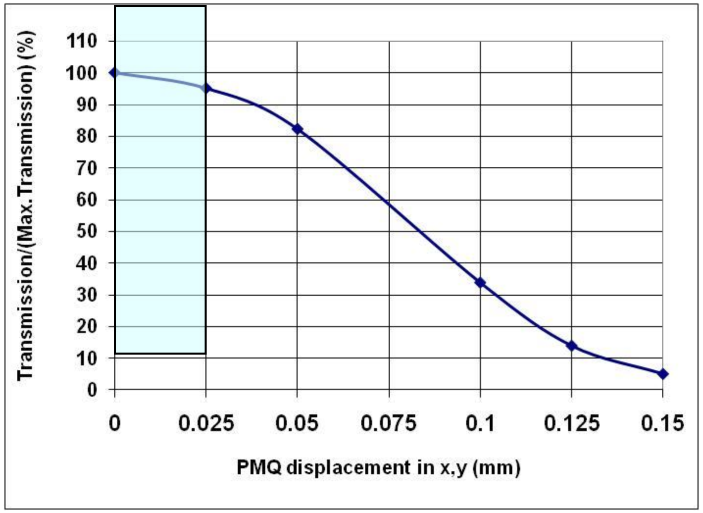
Study at the proton source

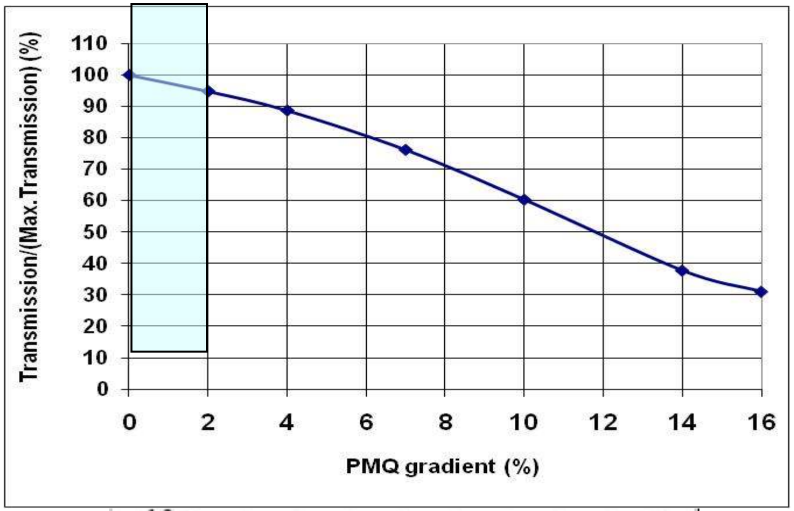
Case	Input σx (µm)	Input σx' (mrad)	Input rms unnormalized emittance (mm-mrad)	Total output current (mA)	Useful output current (mA)	Output rms normalized emittance (Exn*Eyn)0.5 (mm-mrad)
1	20	9	0.18	37	13	0.264
2	40	9	0.36	64	26	0.197
3	20	18	0.36	30	10	0.210
4	40	18	0.72	47	20	0.209

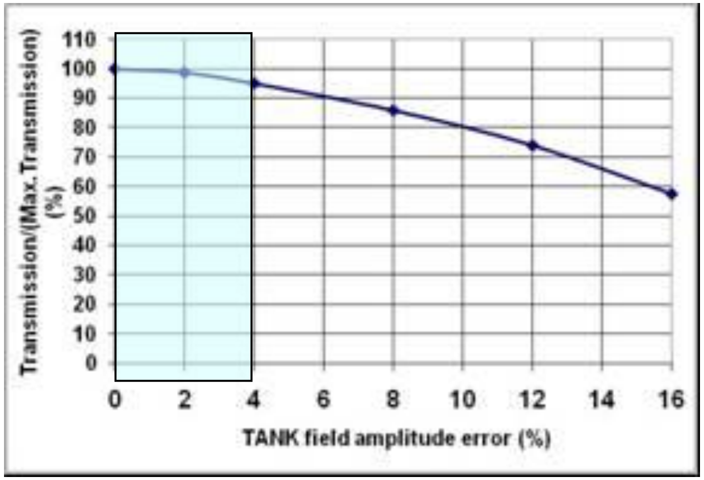
Sensitivity study (typical for a beamline)

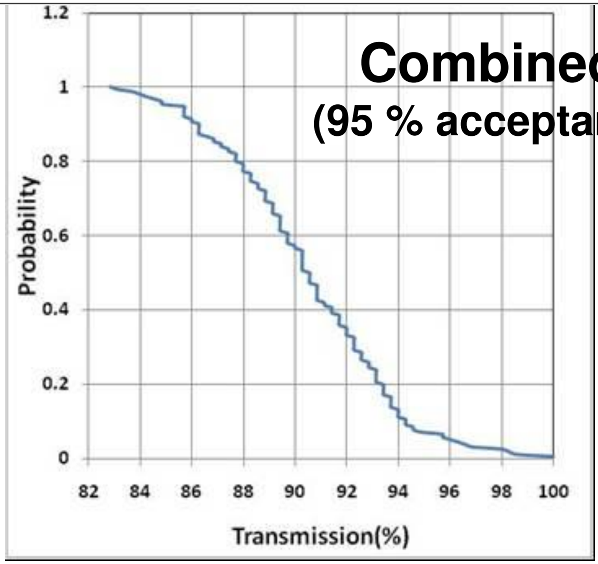
Study with the lattice structure

50 runs, values uniformly distributed ±|Error amplitude|









P. Antici et al., Submitted to J. Plasma Phys

Conclusions

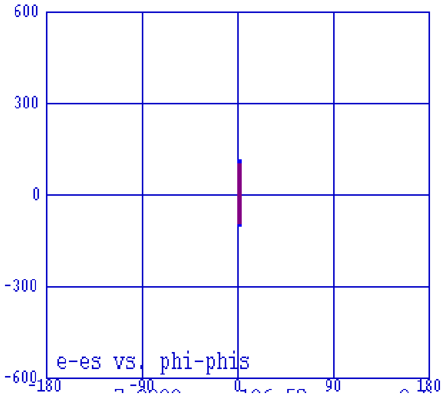
- **It is possible to couple laser-generated protons to a high frequency LINAC in a compact acceleration hybrid scheme.**
- **A current between 13 and 26 mA can be captured and accelerated up to 15.5 MeV in ~3 m.**
- **A 10 Hz laser repetition rate corresponds to an average proton current of 43-86 pA that could be used to perform radiobiology experiments.**
- **Conventional accelerator community could provide necessary know-how and techniques to reach laser-driven beamlines**

Thank you for your attention

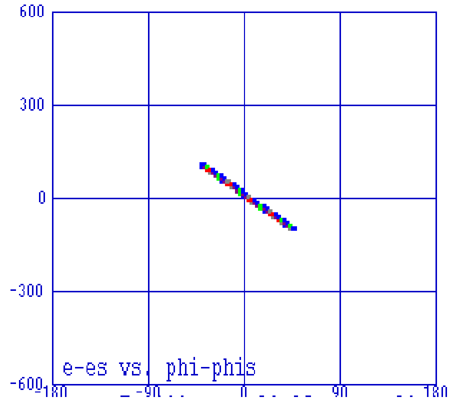
Phase space in the structure

Δ Energy

Laser source



SCDTL Input



SCDTL Output