Breaking the 70 MeV Proton Energy Threshold in Laser Proton Acceleration and Guiding Beams to Applications

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Markus Roth
Technische Universität Darmstadt

Requirements for ion acceleration

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  - Rep rate matched to conventional accelerator structures (e.g. 50 Hz)
  - Ion energy a few tens of MeV
  - Radial beam shaping for divergence optimization
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- Medical Application:
  - Ion energy >250 MeV for protons and >400 MeV/u for e.g. Carbon (prob. no TNSA)
  - High contrast
  - Rep rate 10 to 30 Hz
  - Energy stability better 3%
  - Relatively low particle numbers required (10^{11} or 10^{9} per patient)
  - Uniform ion beam --> Laser beam shaping

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  - Tailored energy spectrum up to a few tens of MeV (TNSA might be ok)
  - High conversion efficiency
  - High particle numbers (high laser energy)
  - Pulse length can be up to ps
  - Beam overlay, beam synchronization
  - 10 Hz rep rate

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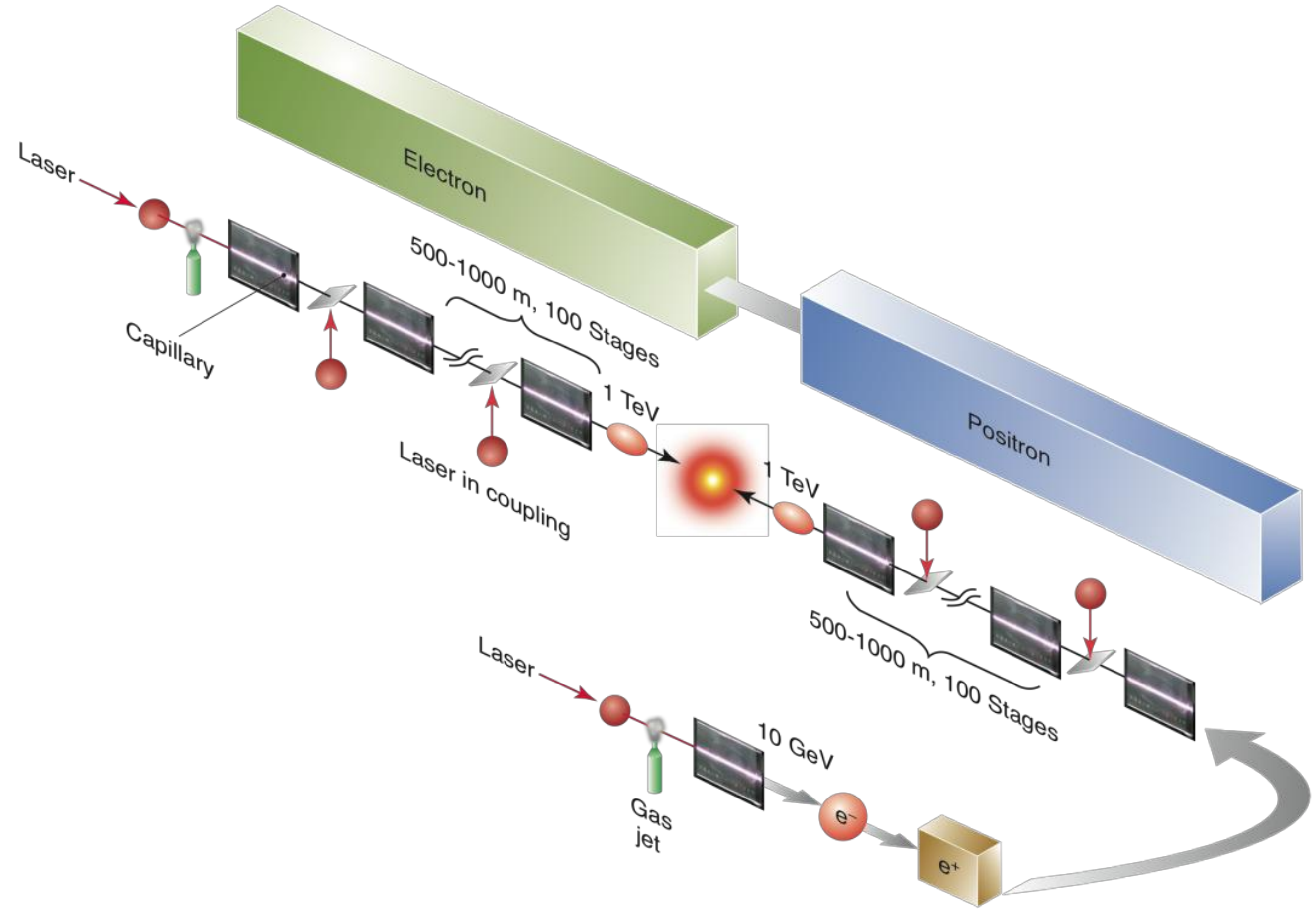
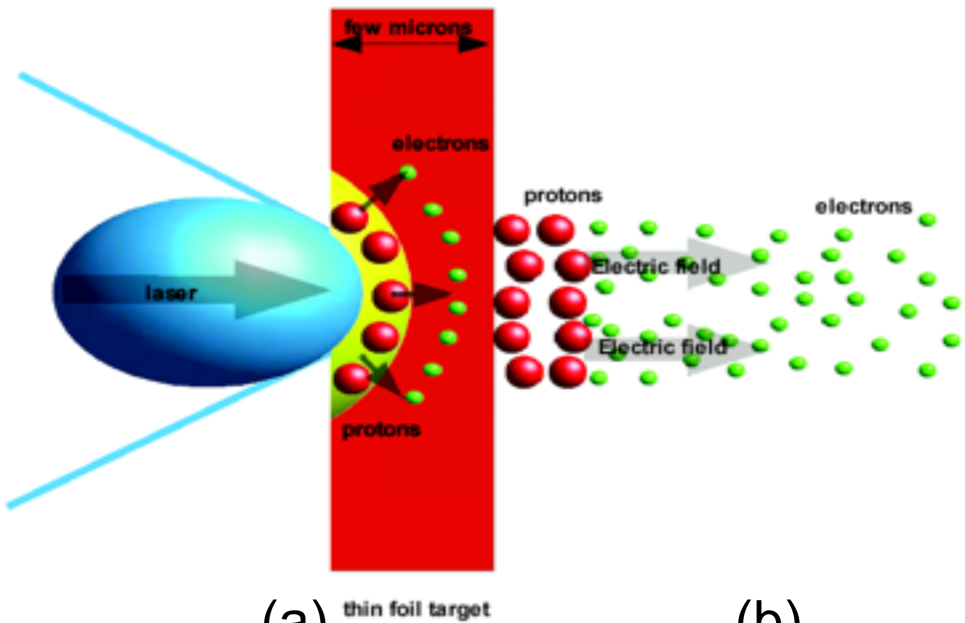
  - Beam overlay, beam synchronization
  - 10 Hz rep rate
- Security applications
  - relaxed rep rate
  - Ion energy up to GeV
  - High contrast
  - Mobile / compact

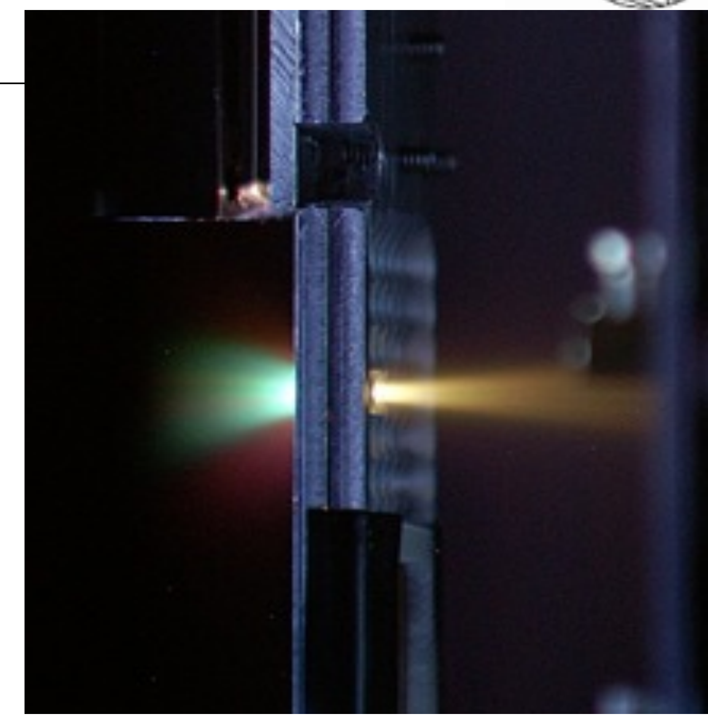
Requirements for ion acceleration (cont.)

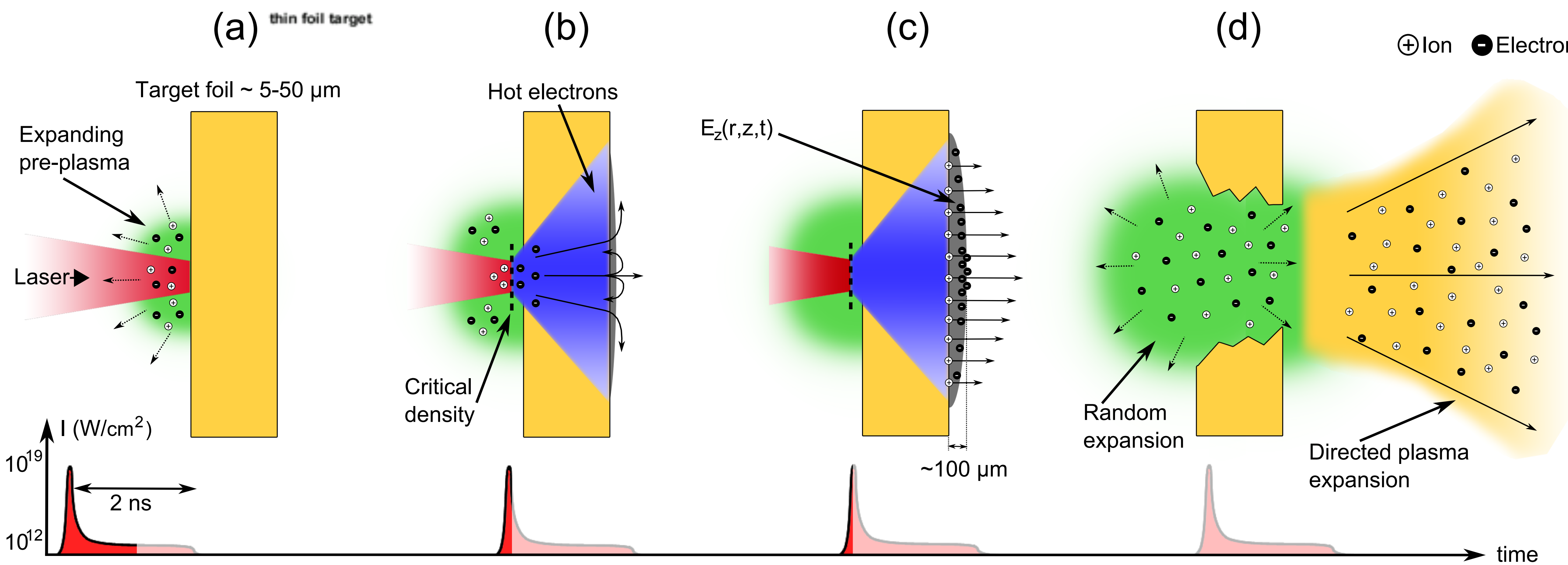
- Accelerators (all optical)
  - High gradients
  - High Particle numbers
  - High Rep Rate
  - Staging
  - High Average Power
  - Many Beamlines (...100)



Proton acceleration with lasers : Static electric fields

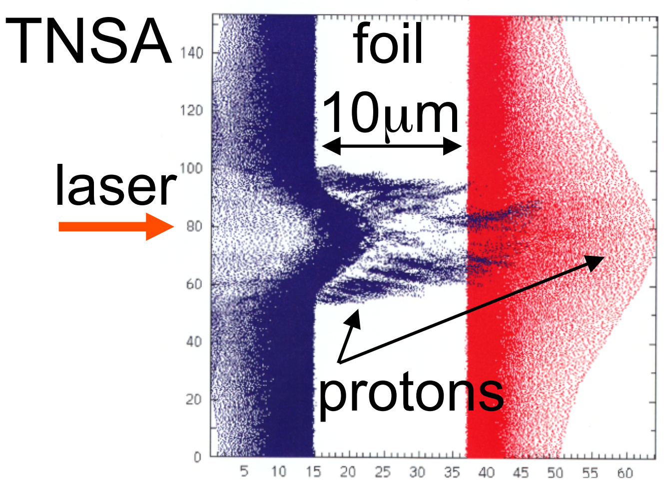






Ion Acceleration Mechanisms

Ion acceleration mechanism	Acronym	Ion Accel. process
Target-Normal Sheath Acceleration S. Hatchett *et al.*, Phys. Plas. **7**, 2076 (2000)	TNSA	Charge separation GeV protons? X



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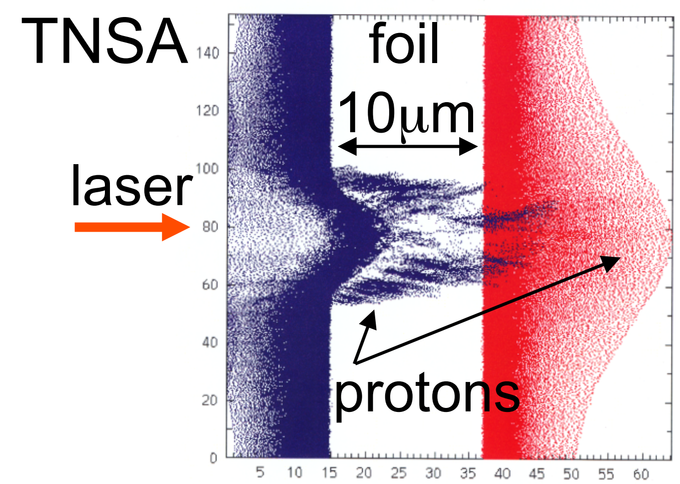

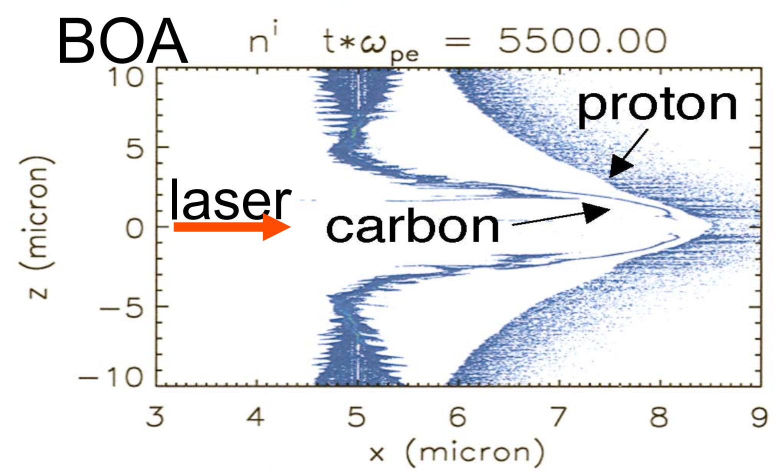

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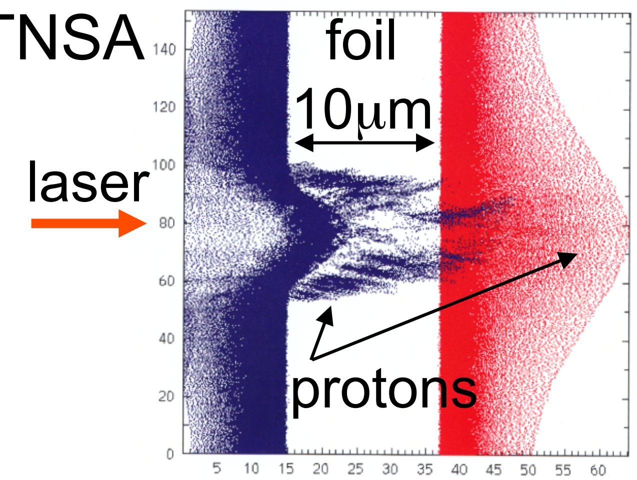
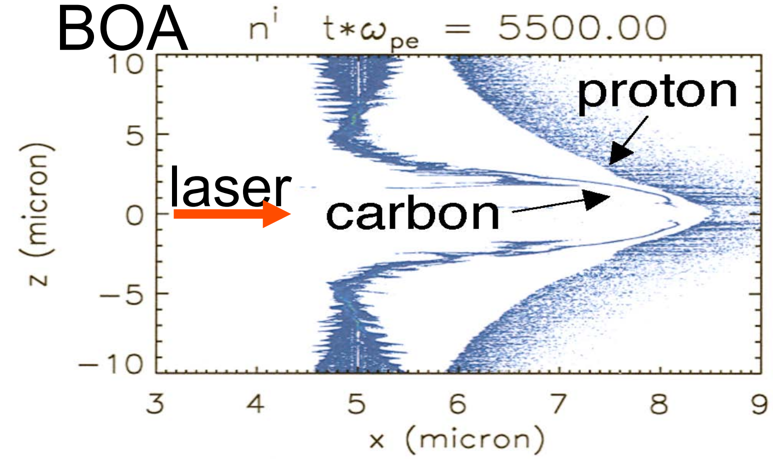
Radiation Pressure Acceleration, Aka Plasma Piston E.g., A.P.L. Robinson, *et al.,* New J. Phys. **10,** 013021 (2008)	RPA	Charge separation GeV protons? ✓ Circular Polar.

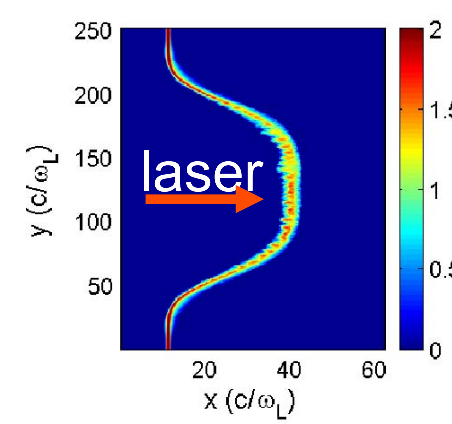
TNSA



BOA



RPA

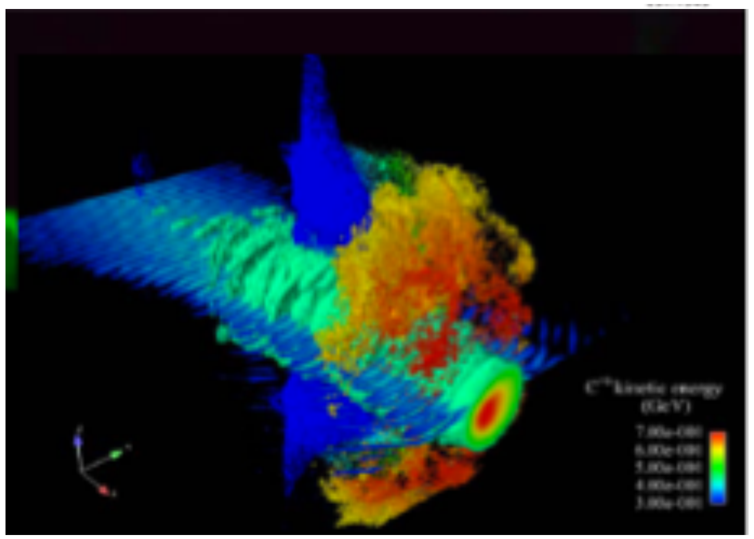


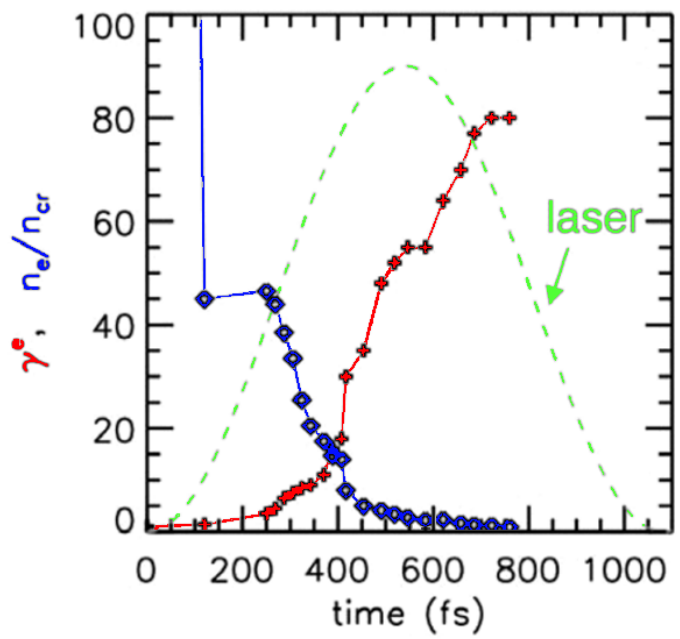
TNSA vs. BOA

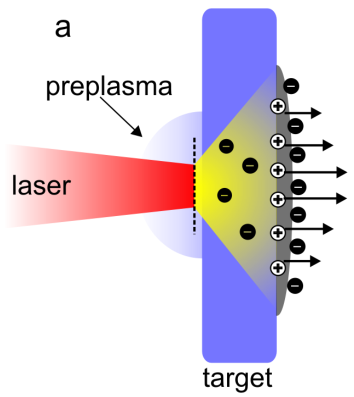
Accessible with moderate contrast lasers
Micrometer sized targets
Spectrum limited to 70 MeV
Surface acceleration

High contrast lasers needed
Sub-Micrometer sized targets
Ion energies exceeding 120 MeV/u
Volume acceleration
Heavy ions (deuterons) at same speed as protons
Lower EMP and less debris

Break out Afterburner (BOA)







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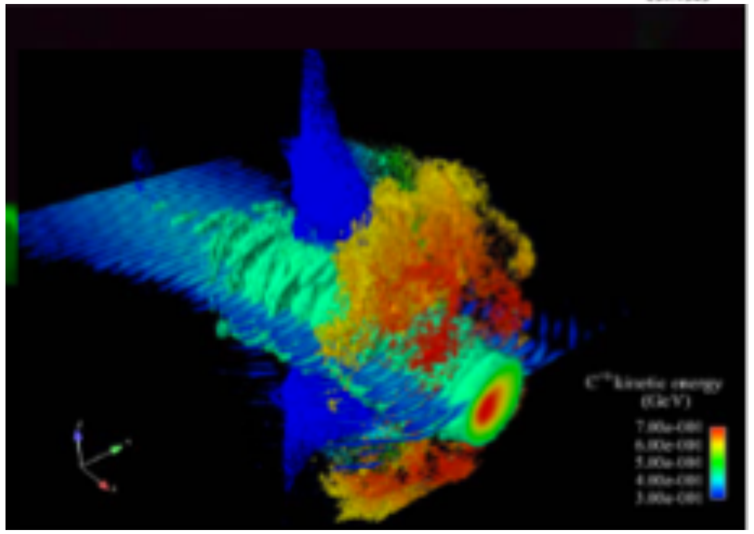
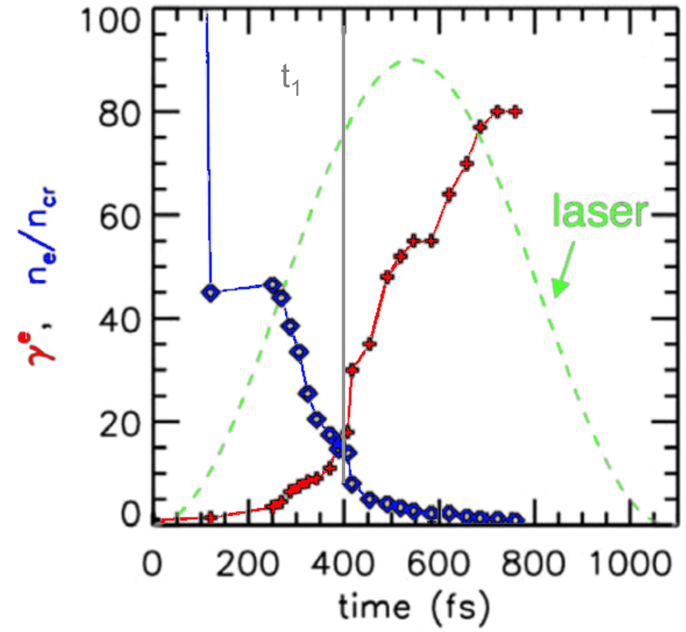
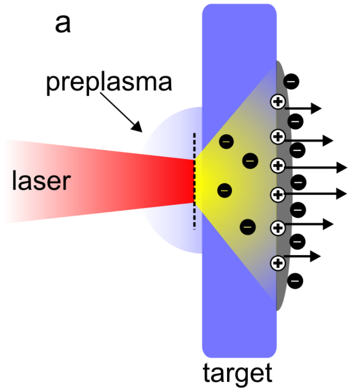


t_1: relativistic transparent

$$n' > 1 \geq n'/\gamma$$





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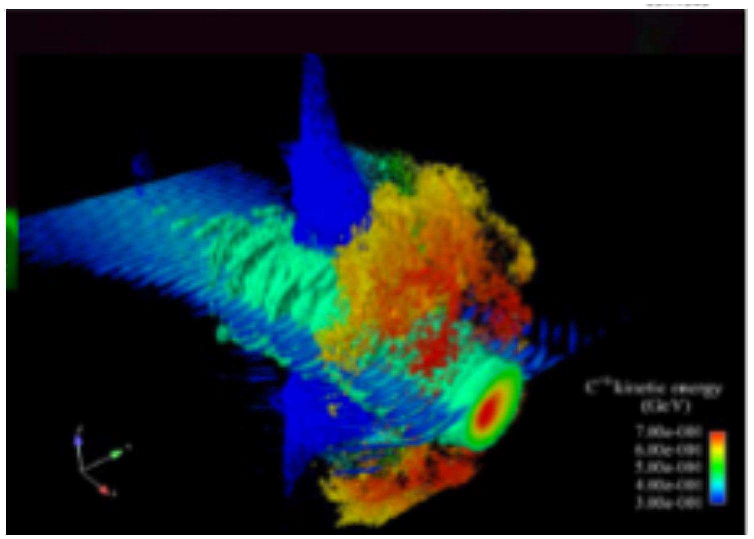

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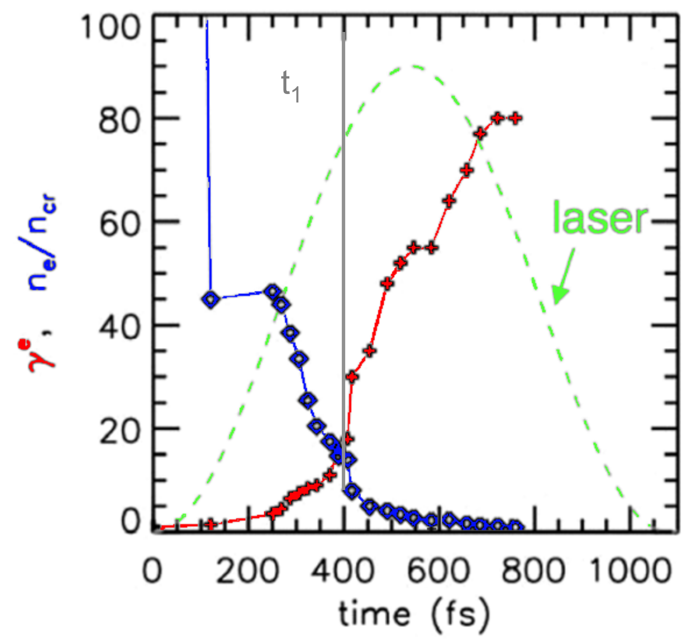

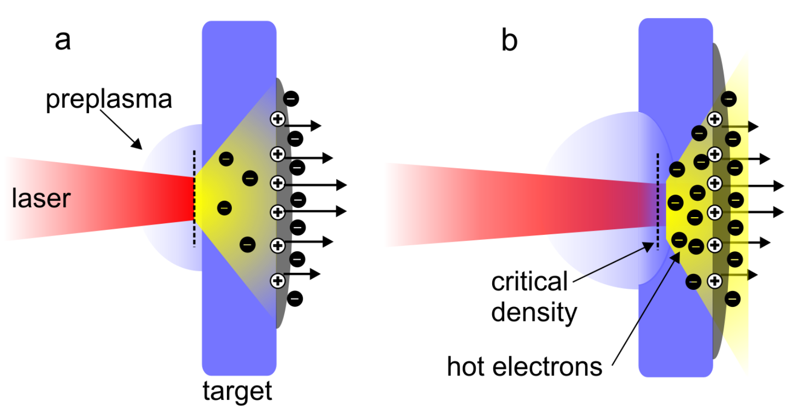

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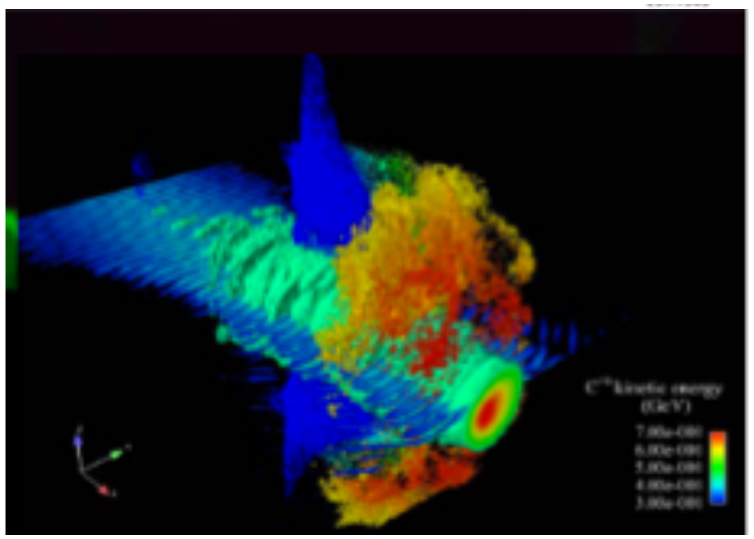

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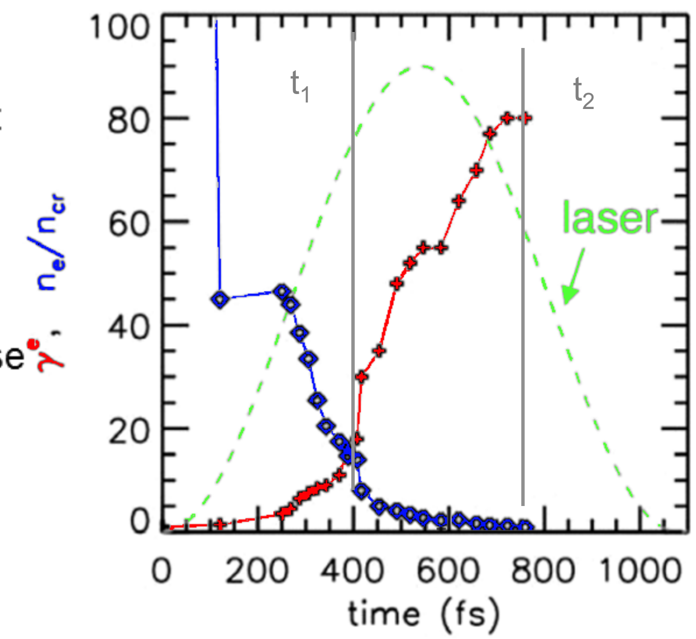

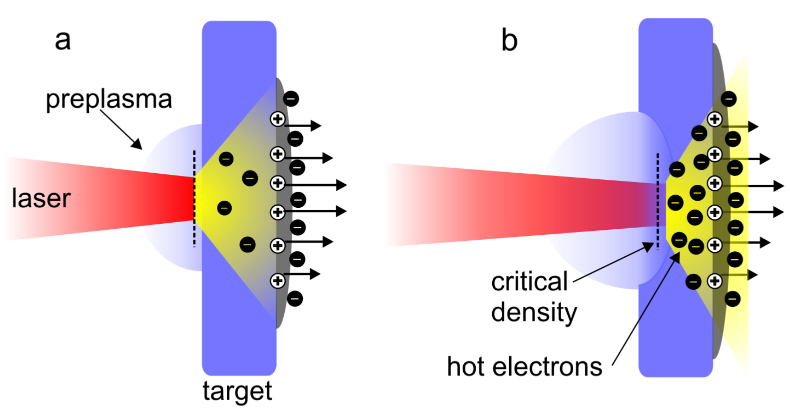

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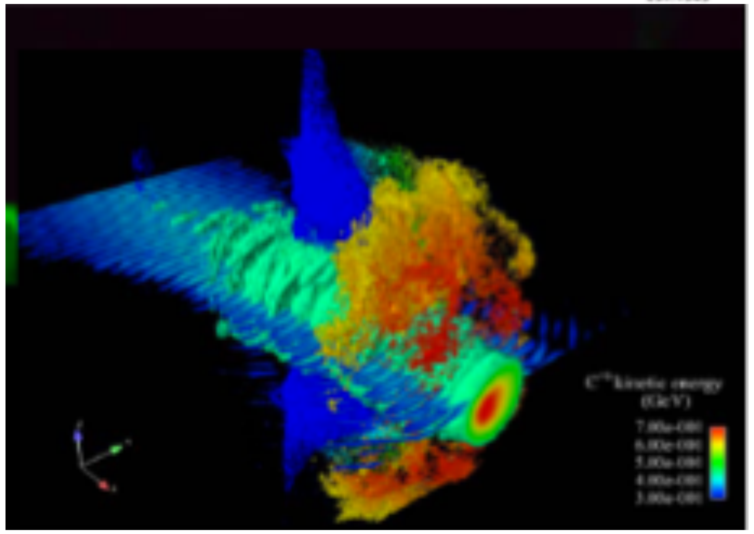

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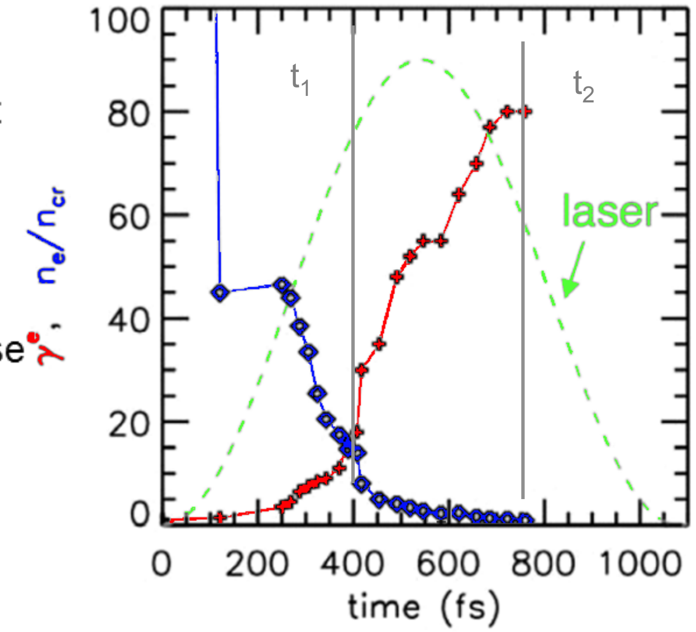

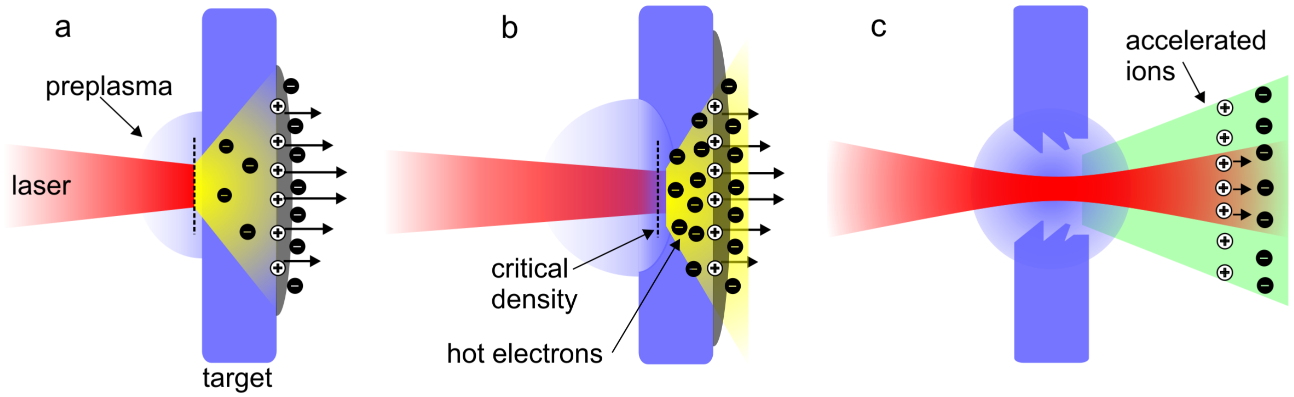

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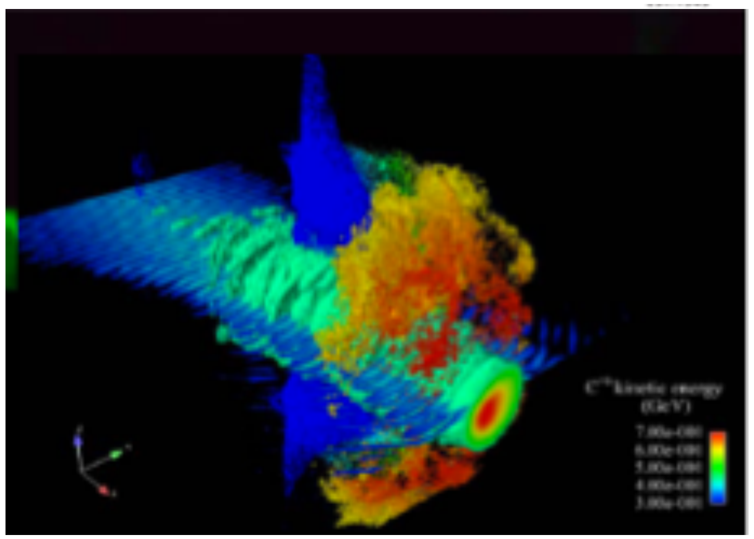

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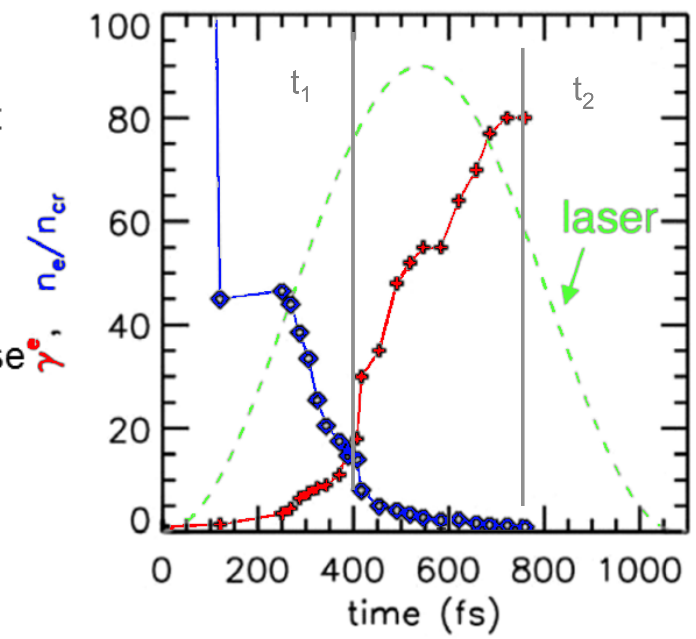

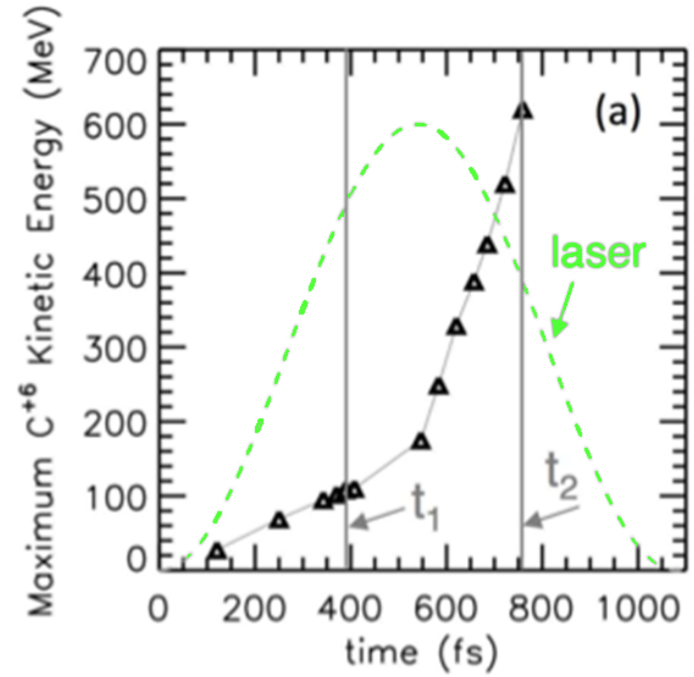

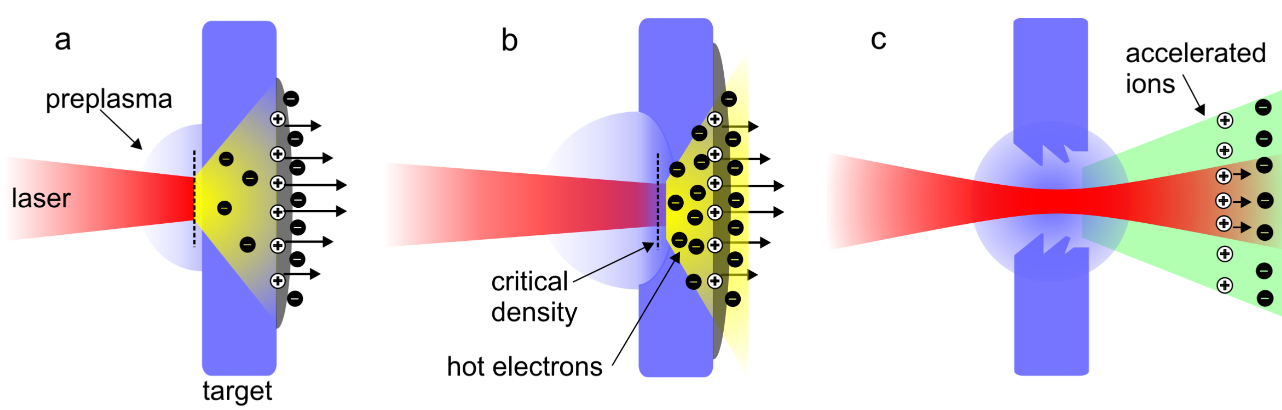

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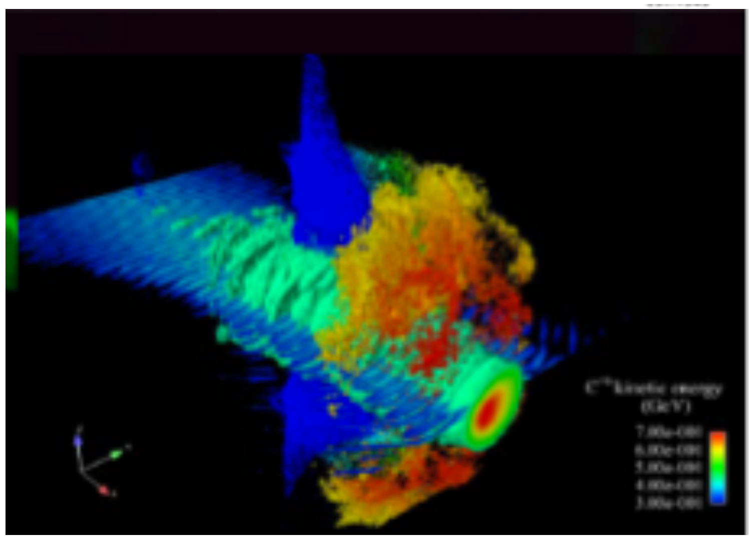

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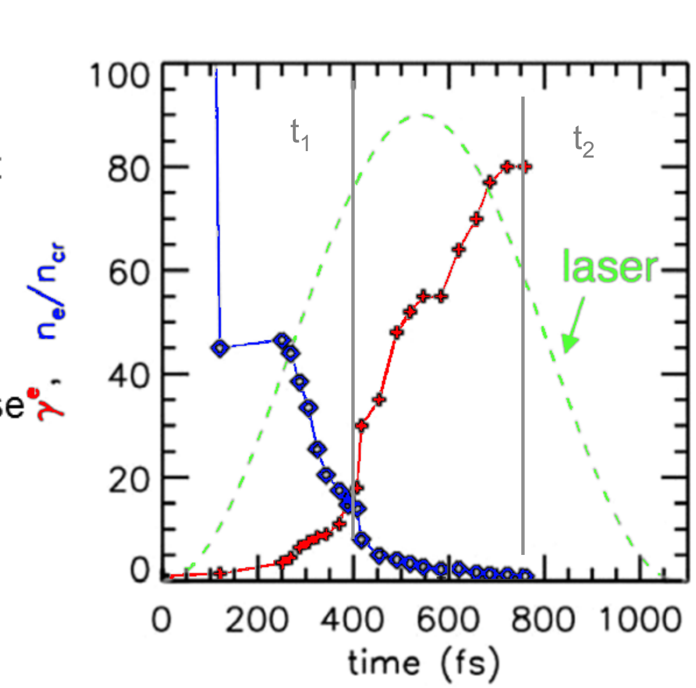
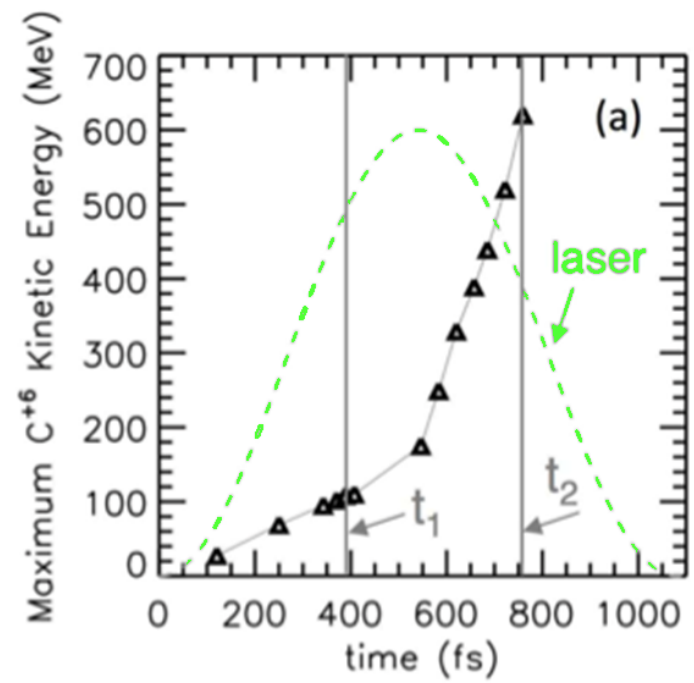


Yin, et al., Laser and Particle Beams 24 (2006), 1–8
Yin, et al., Phys. Plasmas 14, 056706, (2007)
Yin, et al., Phys. Plasmas 18, 063103 (2011)



Albright, et al., Phys. Plasmas 14, 094502 (2007)
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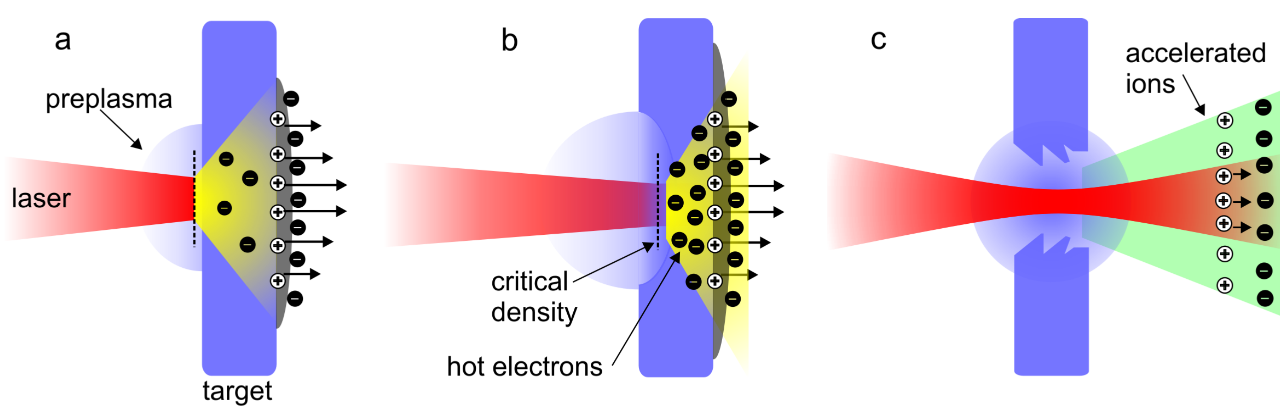

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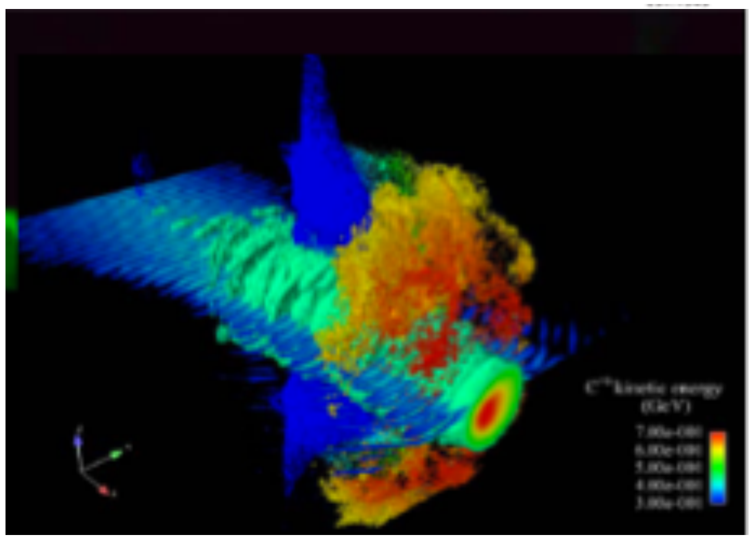

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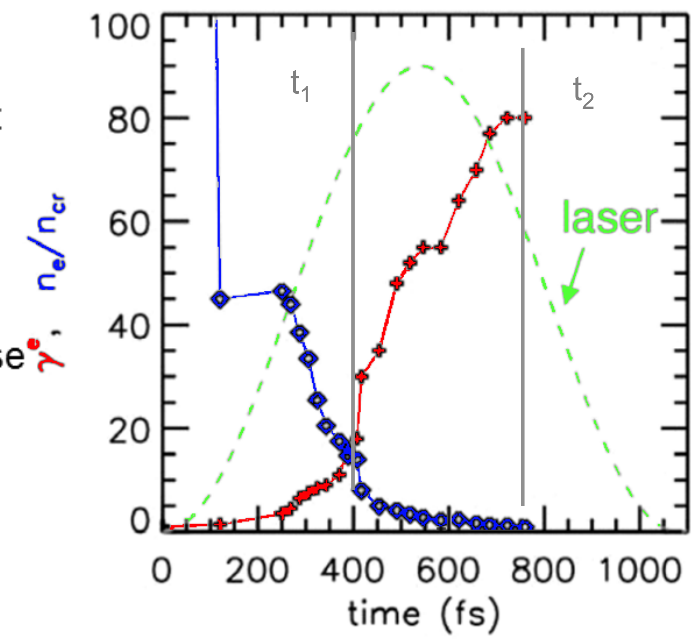

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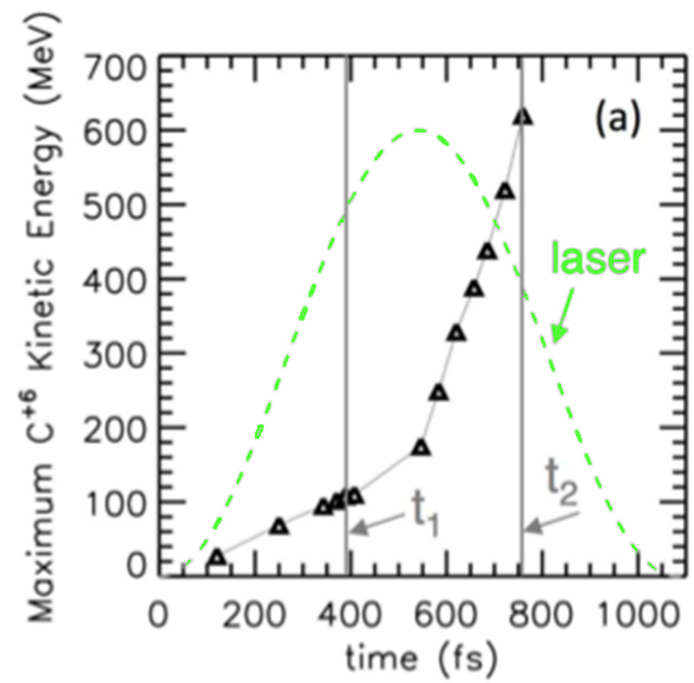

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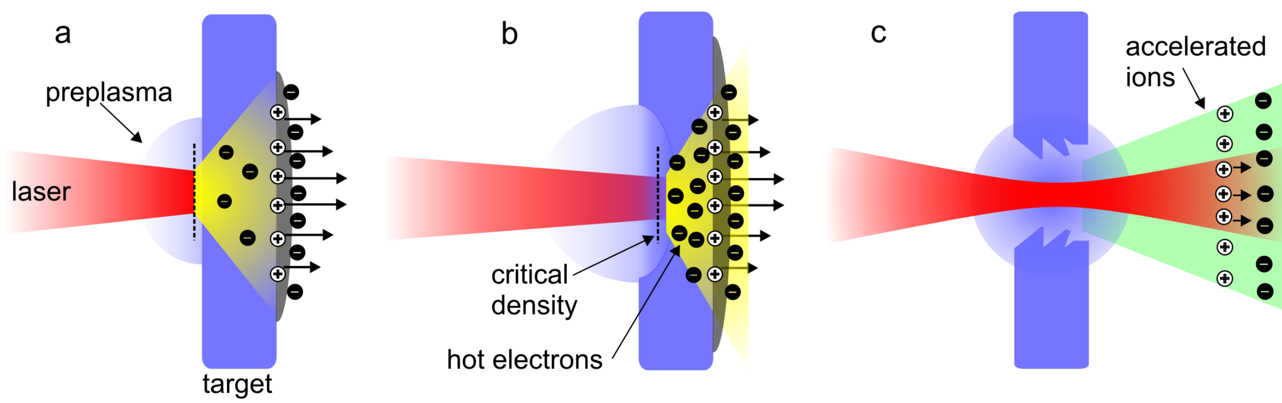

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VPIC: 100nm CH2 target & Trident laser with 2×10^{20}W/cm^2

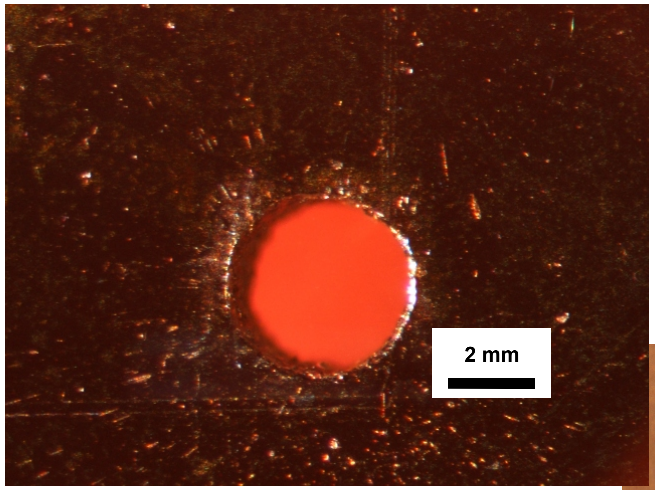
Max. energy	proton	carbon
Ideal laser	132 MeV	450 MeV
Real laser	121 MeV	447 MeV

Targets for BOA

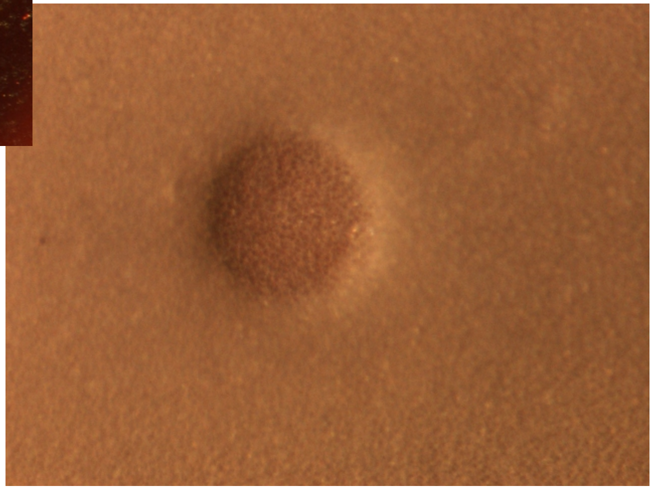
CH_2 Targets

- Poly(4-methyl-1-pentene), trade name TPX (Mitsui, Inc.)
- Soluble in cyclohexane
- Full density films (800 mg/mL) dip- or spin-cast (<200 nm – 1 um)
- Low density foams (5 – 50 mg/mL) produced by freeze-dip-casting, freeze drying (~50 um)

Full-density film

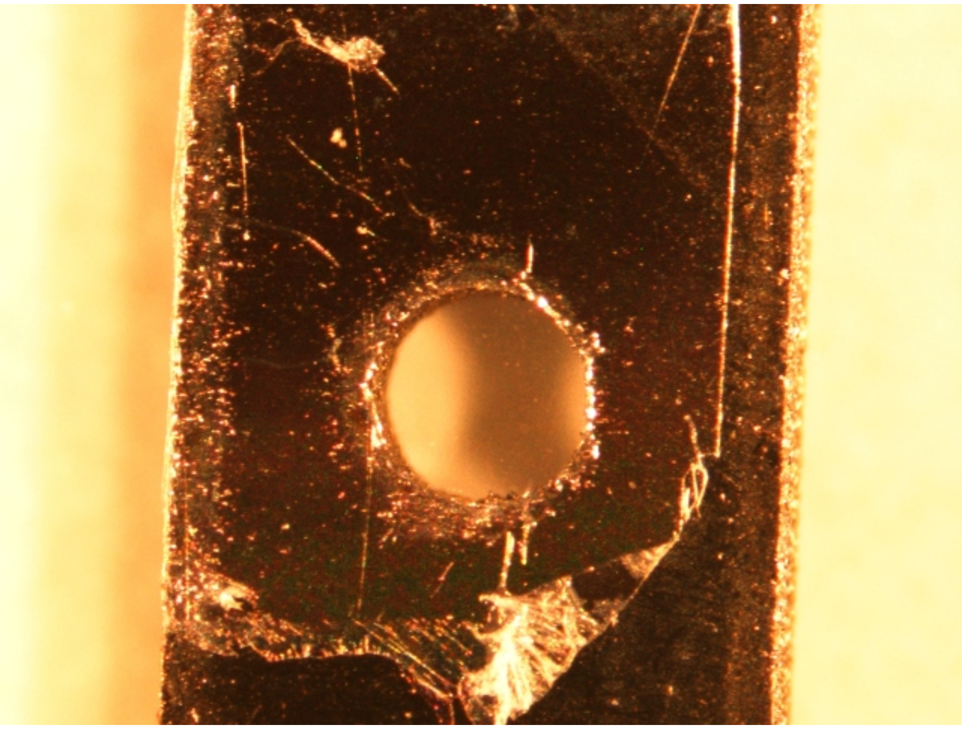


Low-density film



CD_2 Targets

- Deuteropolyethylene(85% D content)
- Soluble in hot toluene/ xylenes
- Full density films (940 mg/mL) drop-cast onto warm Si wafers (300 nm- 1um)



High contrast Lasers (PHELIX)

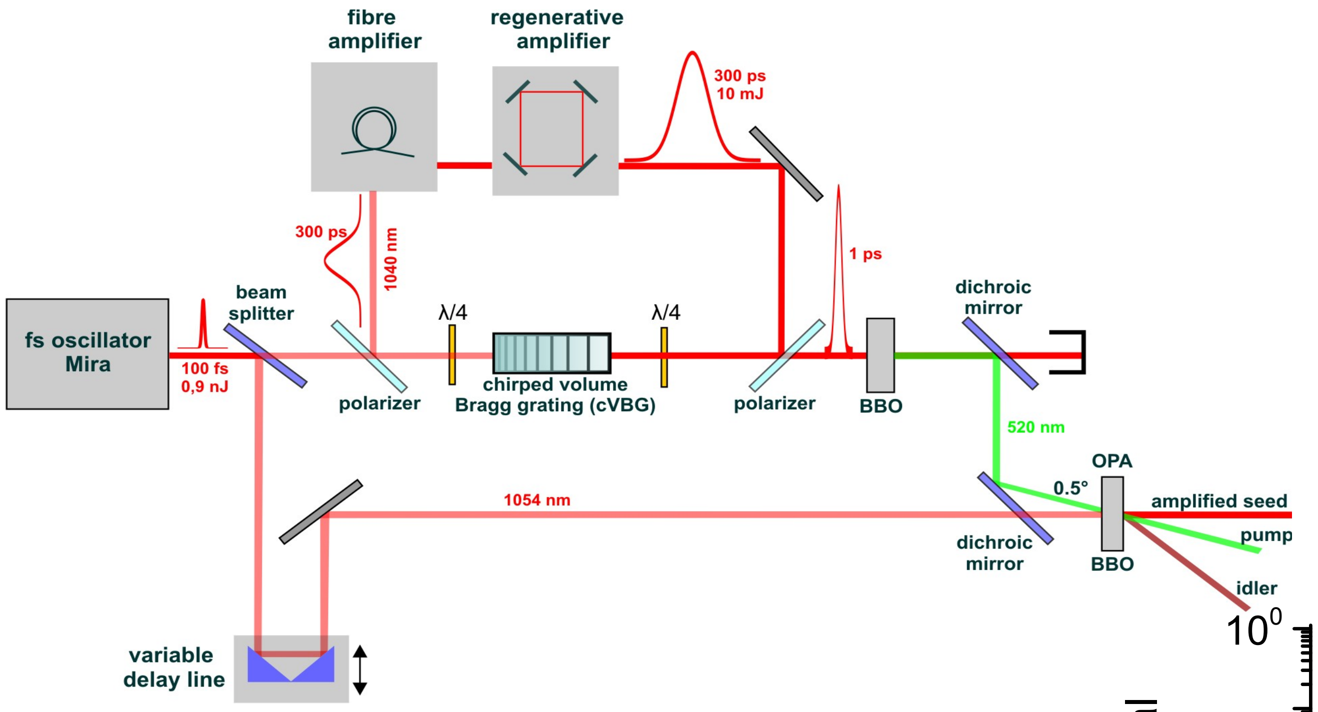
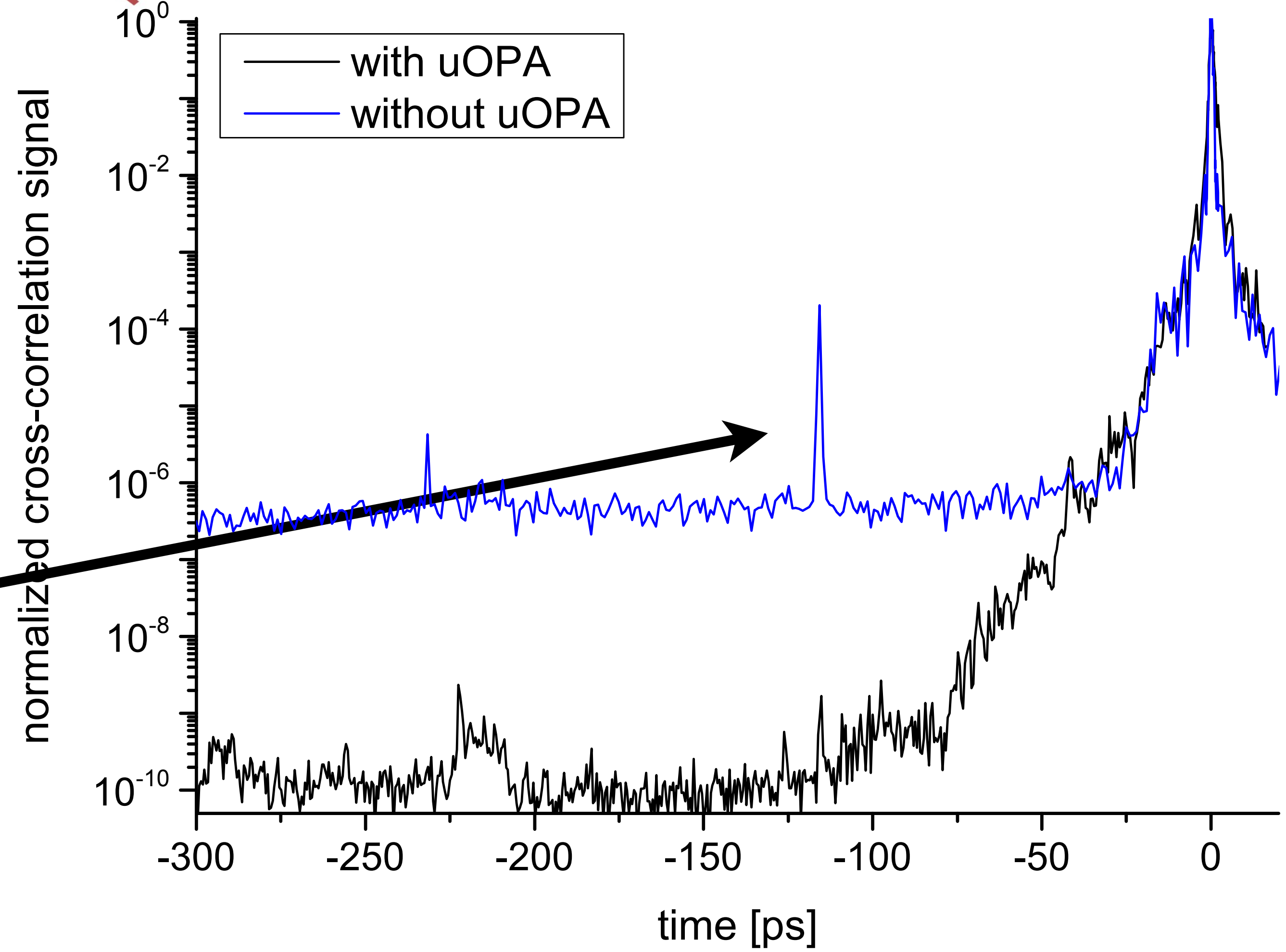


Fig. 2: Setup of the contrast-boosting module



Prepulse from the oscillator

F. Wagner et al., Applied Physics B (2013)

Nuclear activation imaging spectroscopy (NAIS)

M. Günther et al., Rev. Sci. Instr. 84, 073305 (2013)

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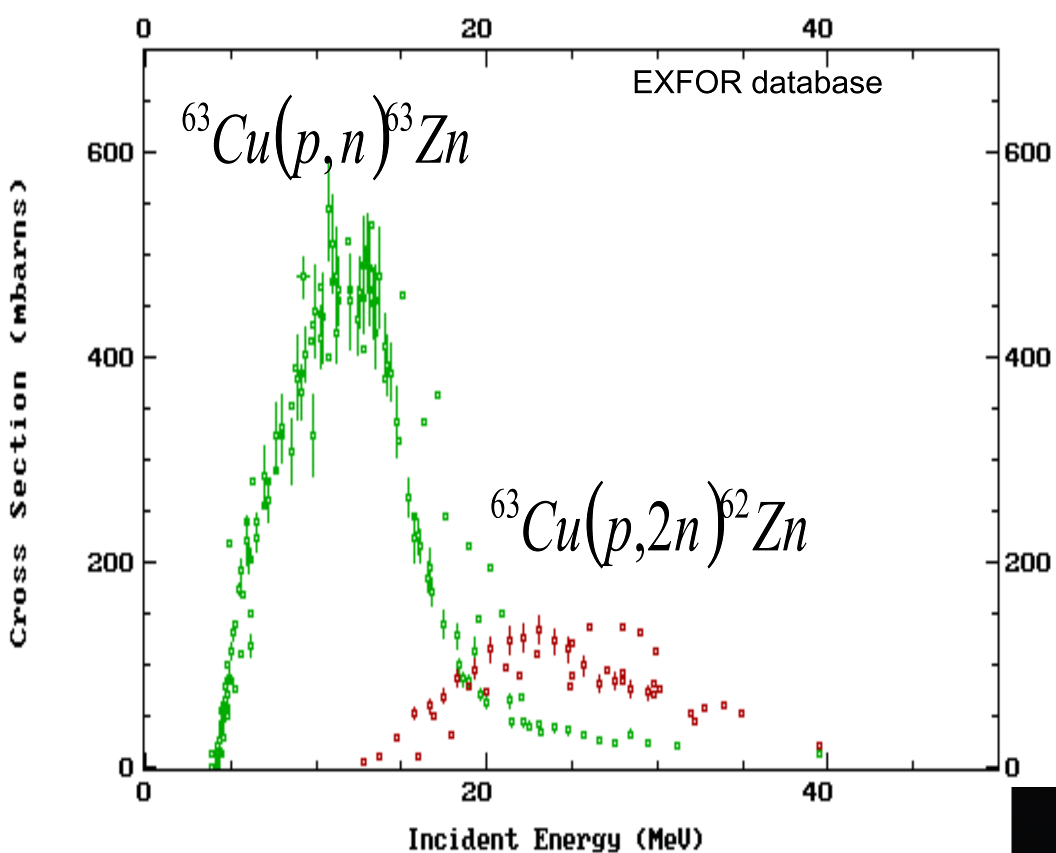
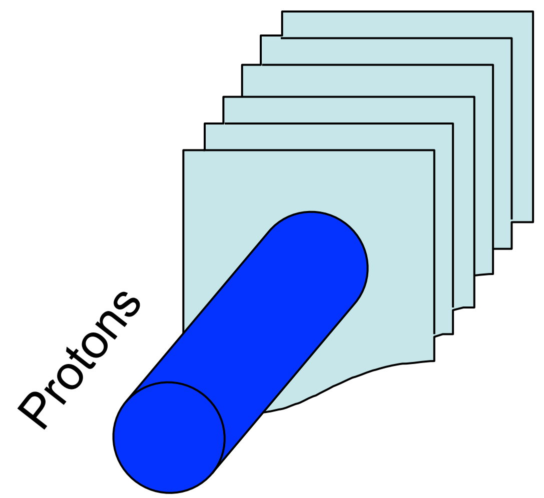
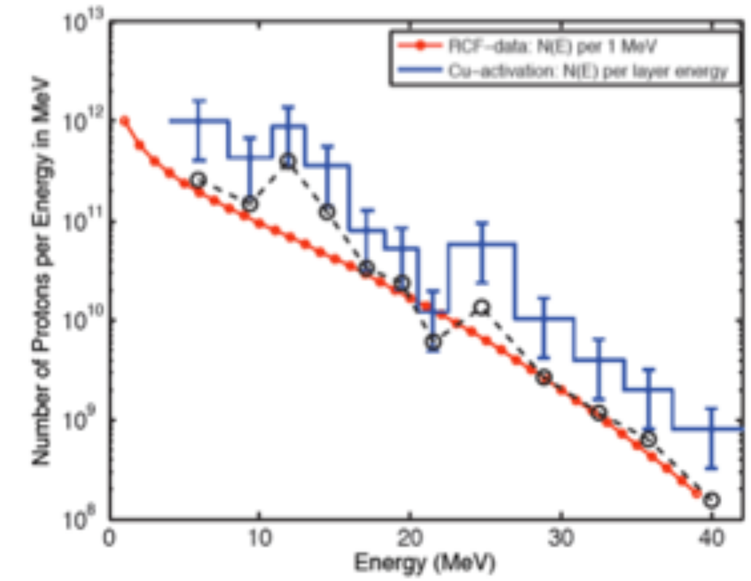
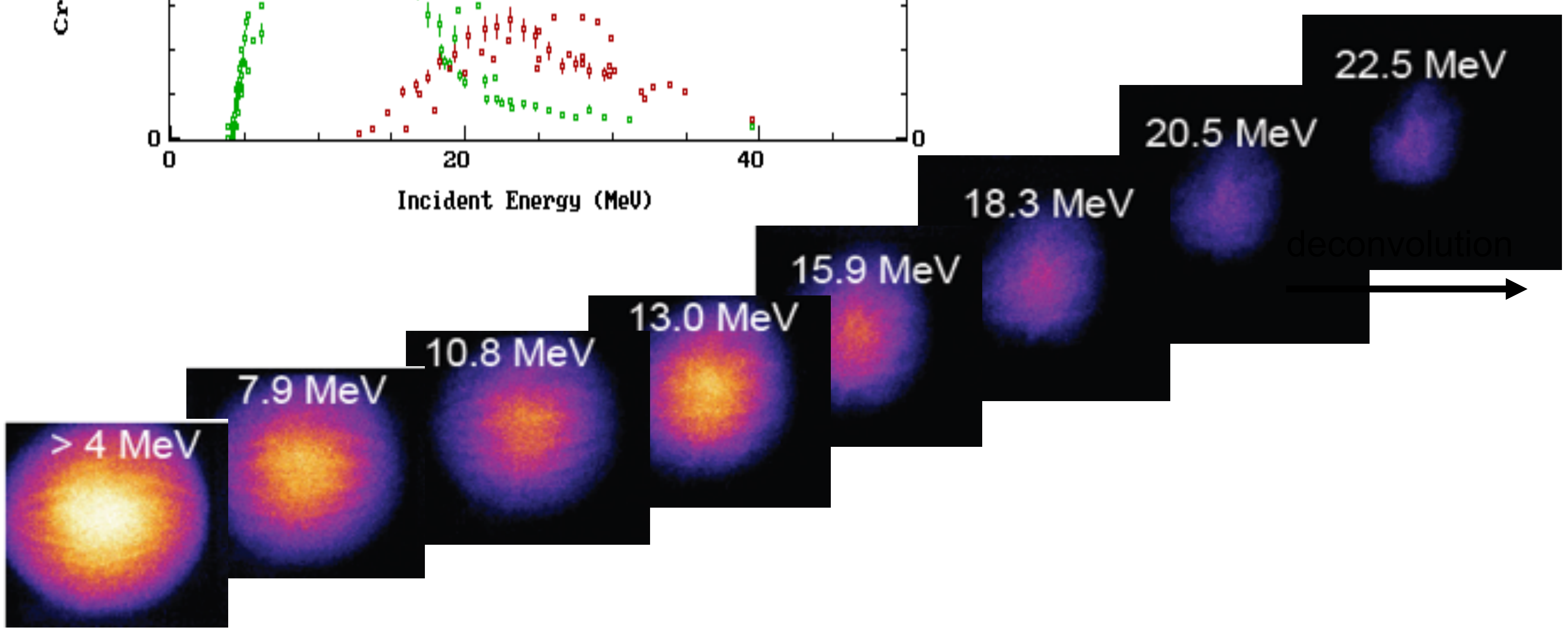
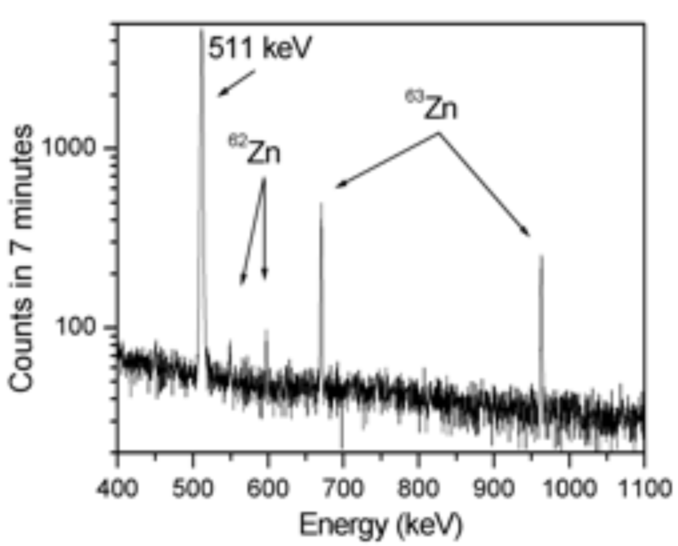




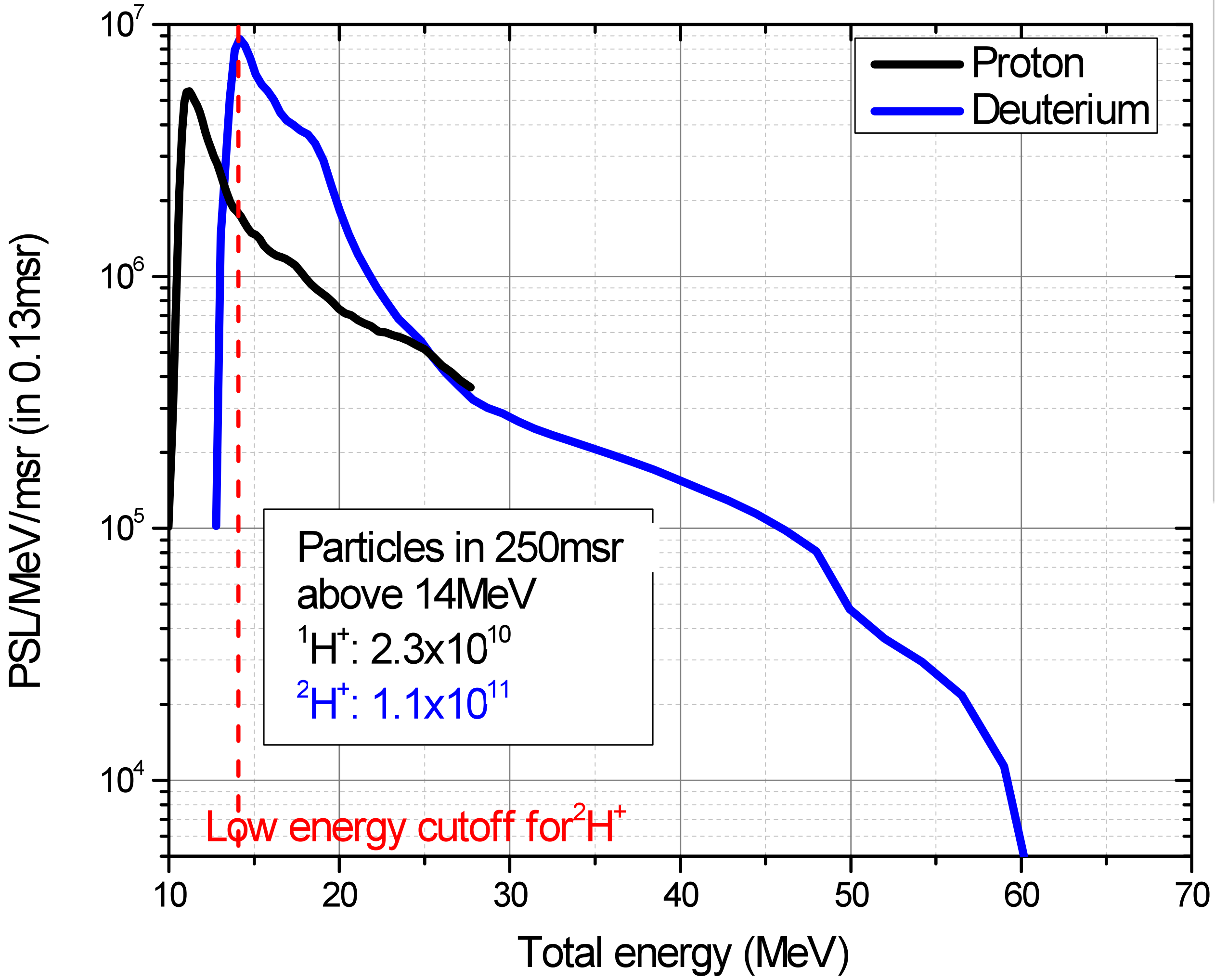


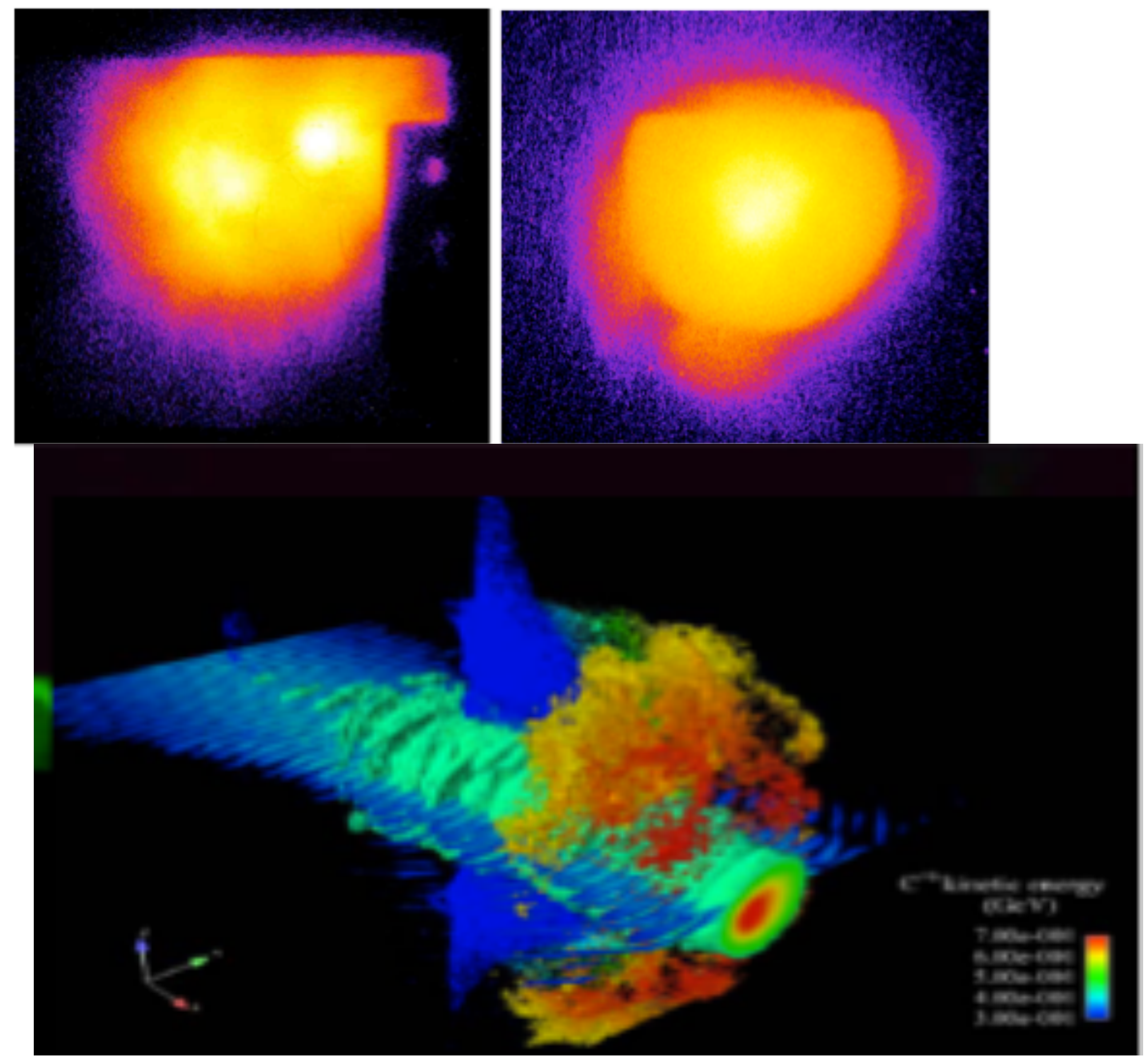
$$Y = N_T \int_{S_n}^{\infty} \sigma(E_p) N_p(E_p) dE_p$$





Volume instead of surface acceleration

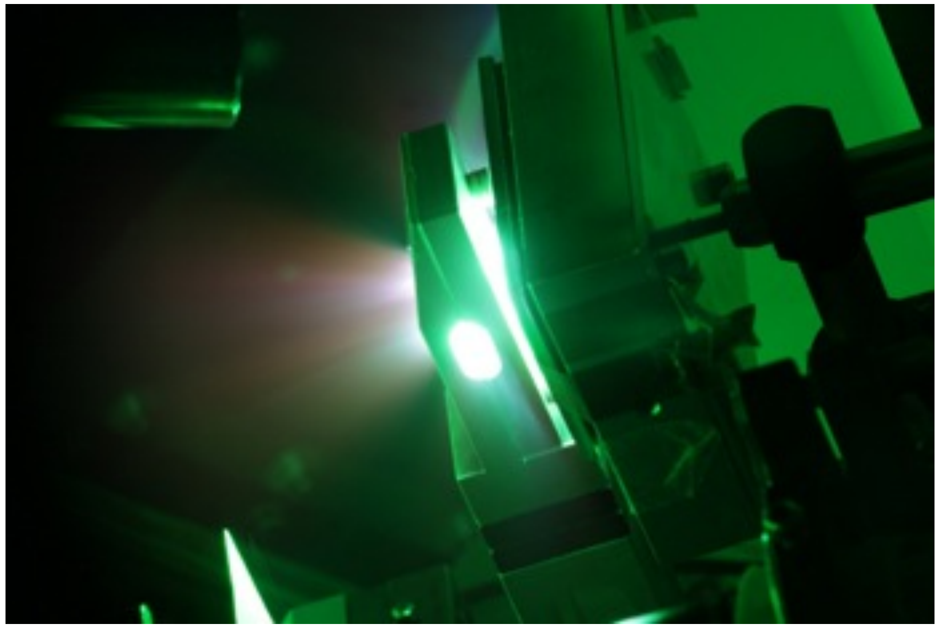




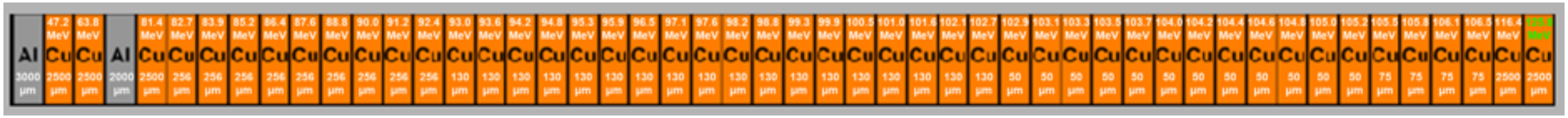
Using CD targets: No cleaning needed
one order of magnitude more deuterons than protons when using BOA

BOA does really work

Ultimate test of ion energies using NAIS



PROTONS



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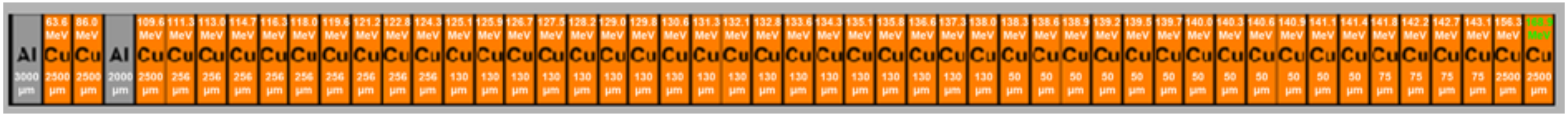

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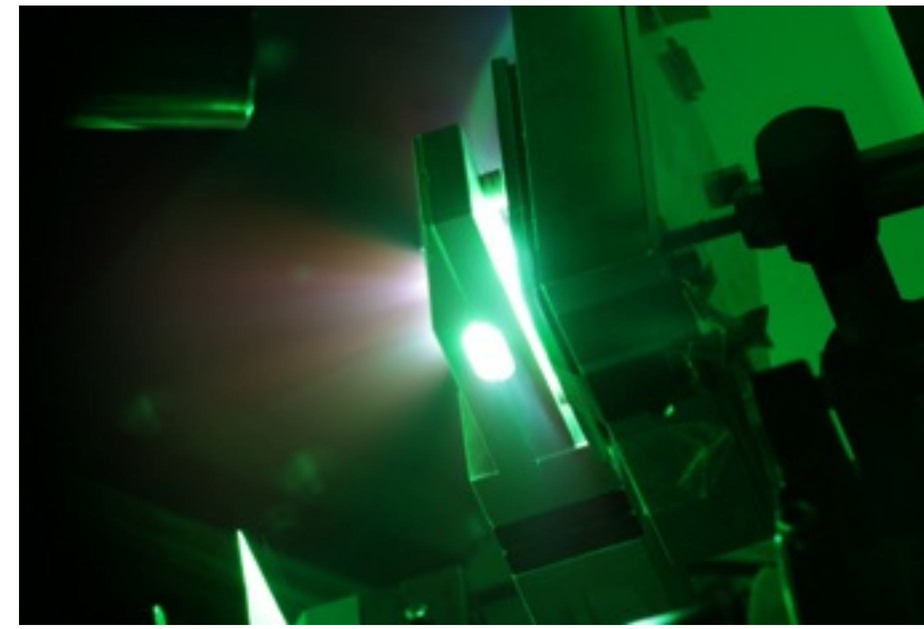

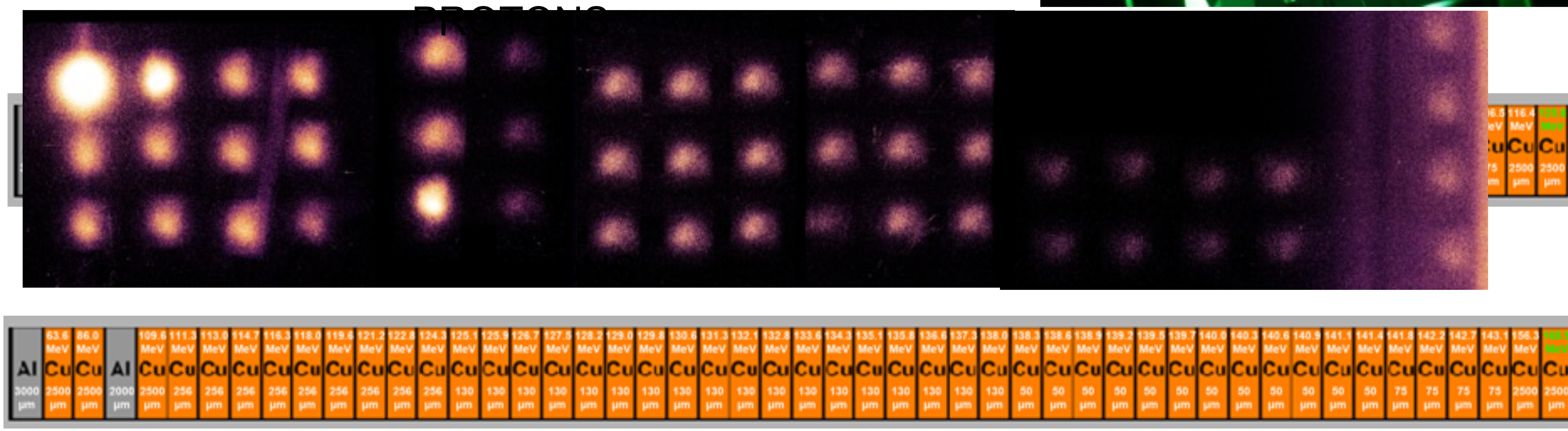

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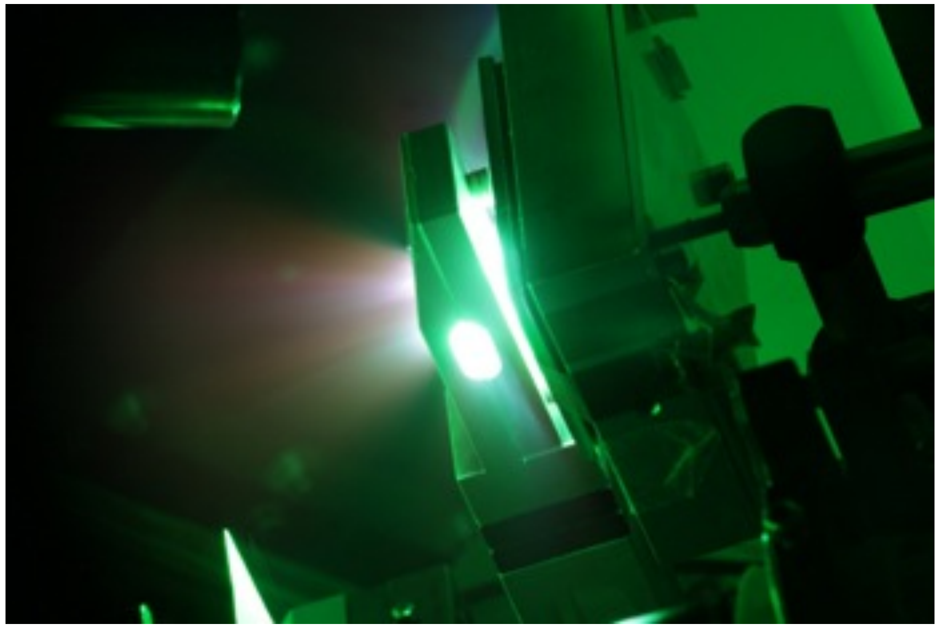
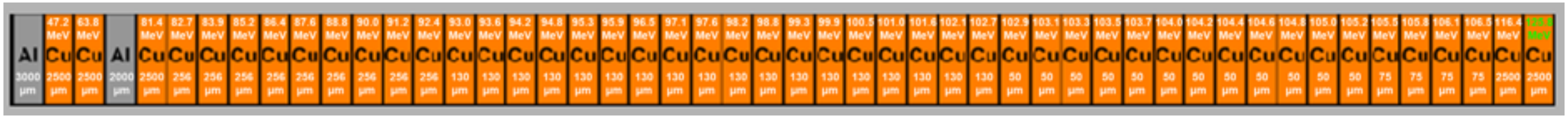
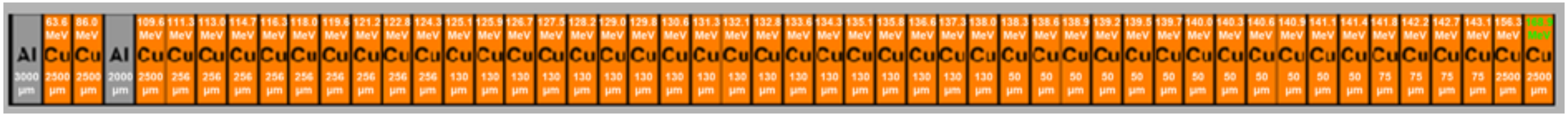


Ultimate test of ion energies using NAIS

PROTONS



DEUTERONS



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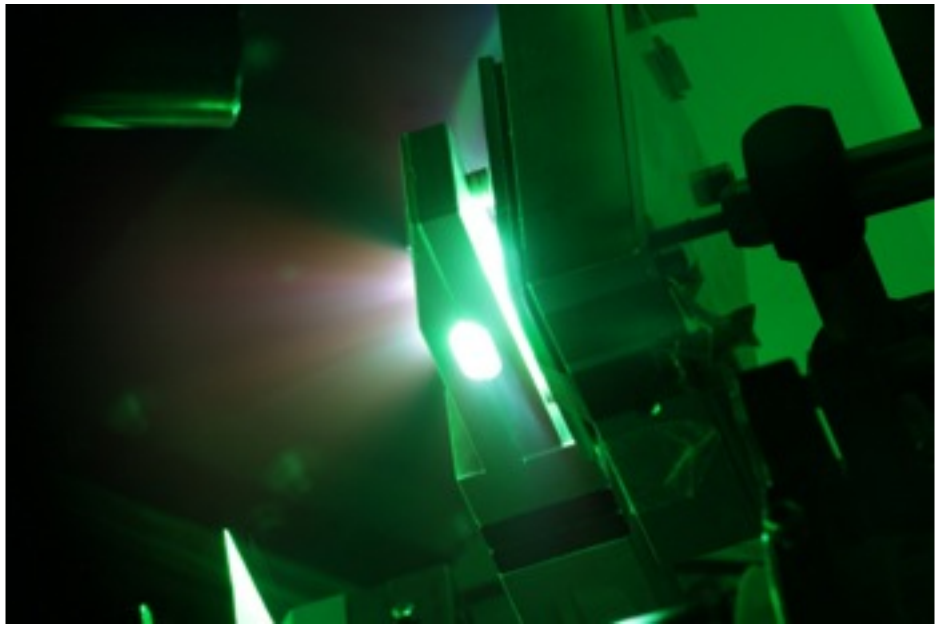
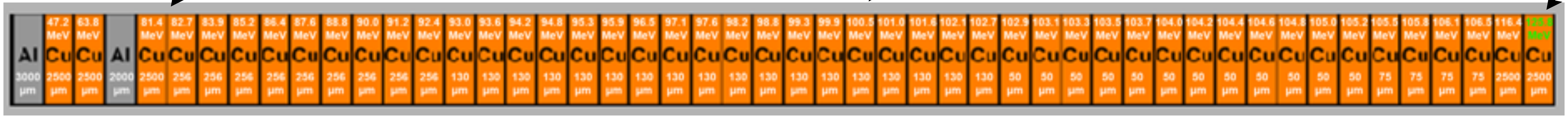


85 MeV PROTONS 105 MeV 130 MeV



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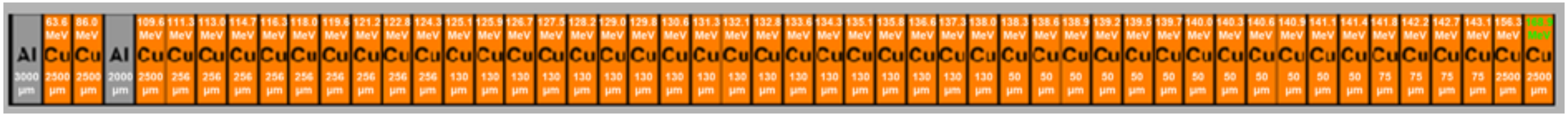
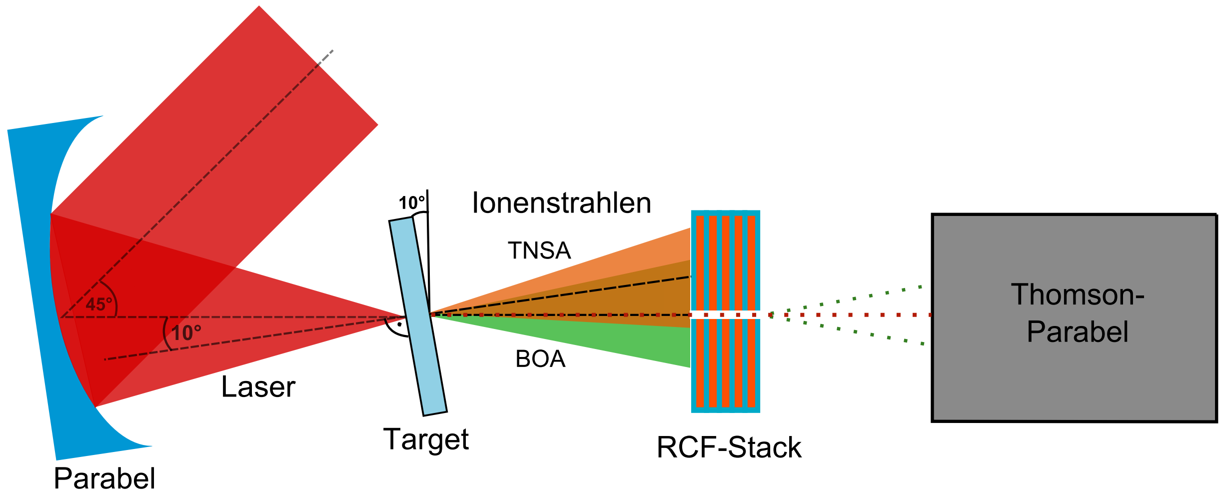
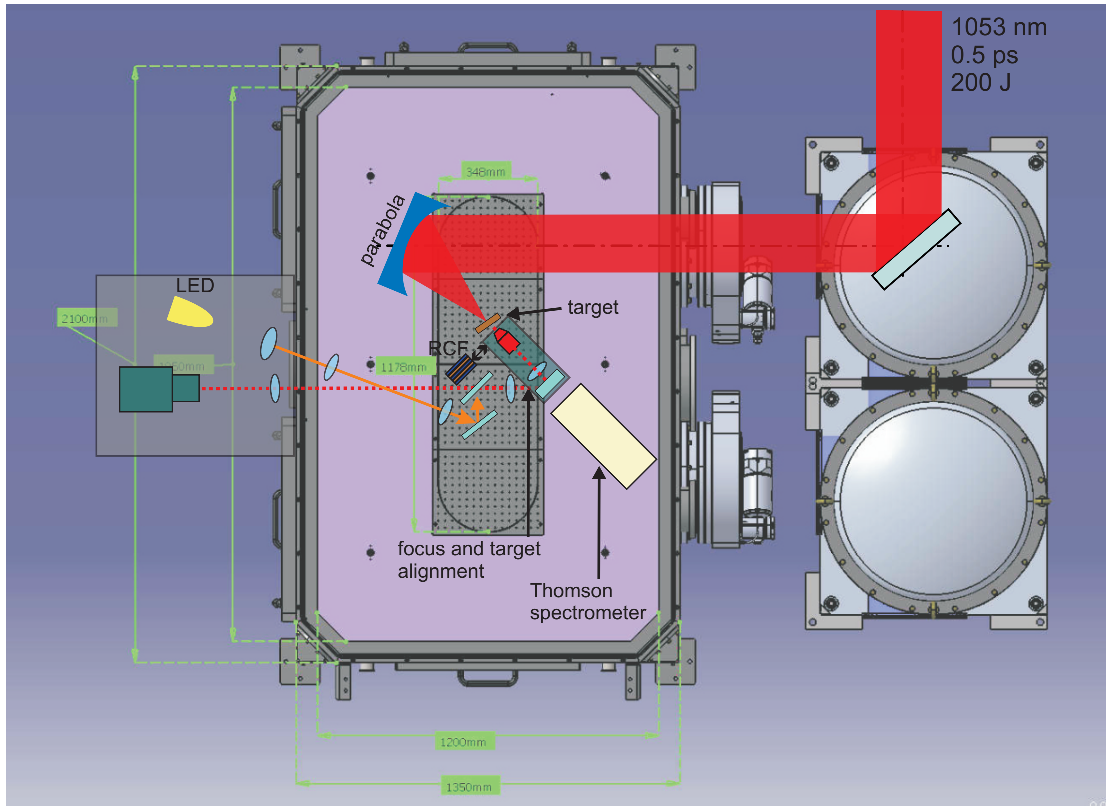


Demonstration of BOA at the PHELIX laser





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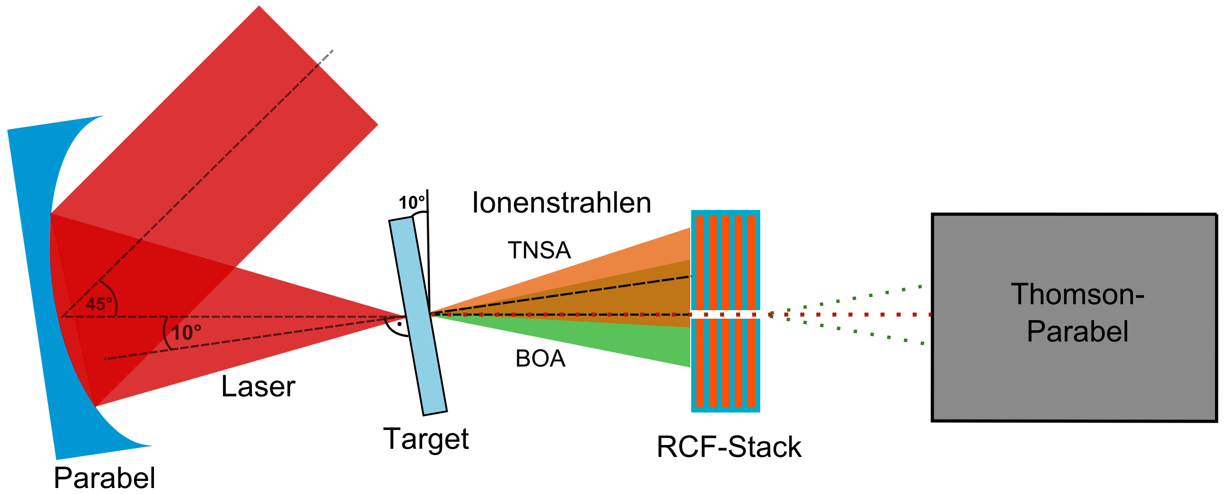
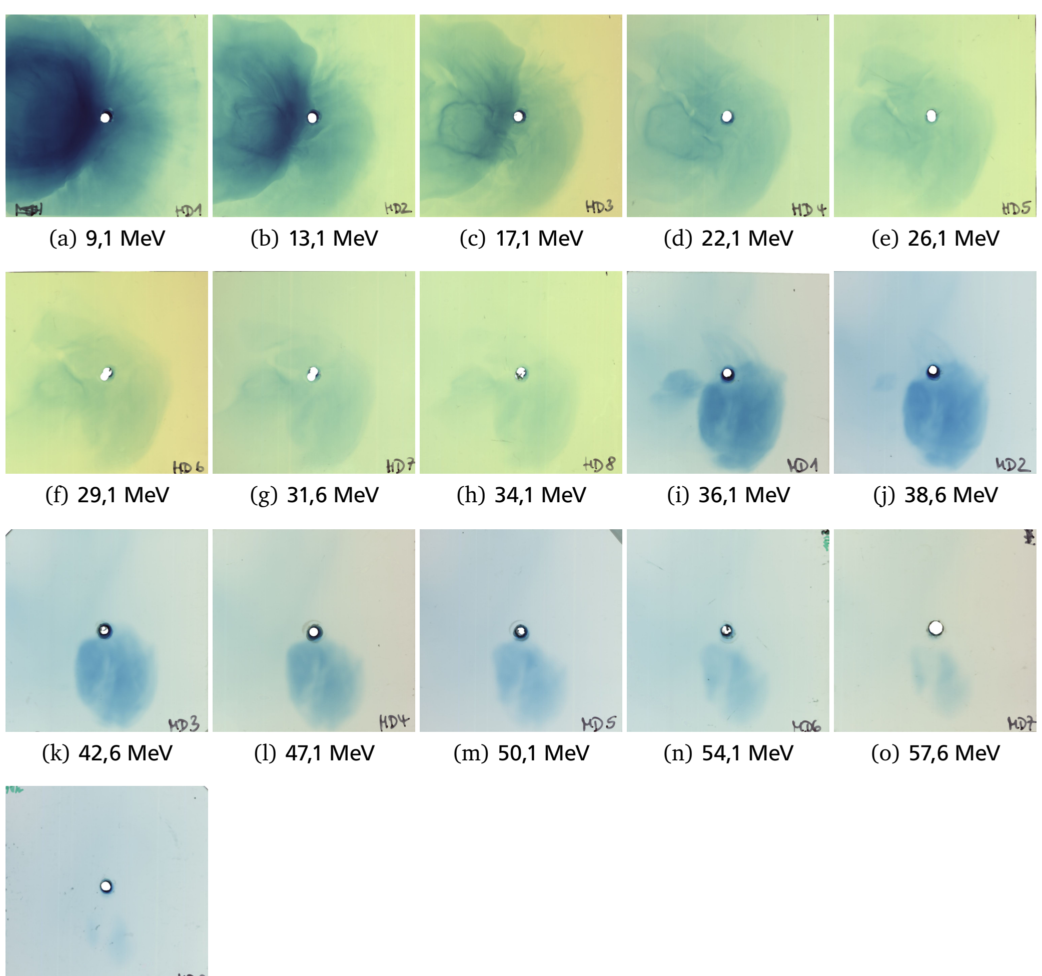
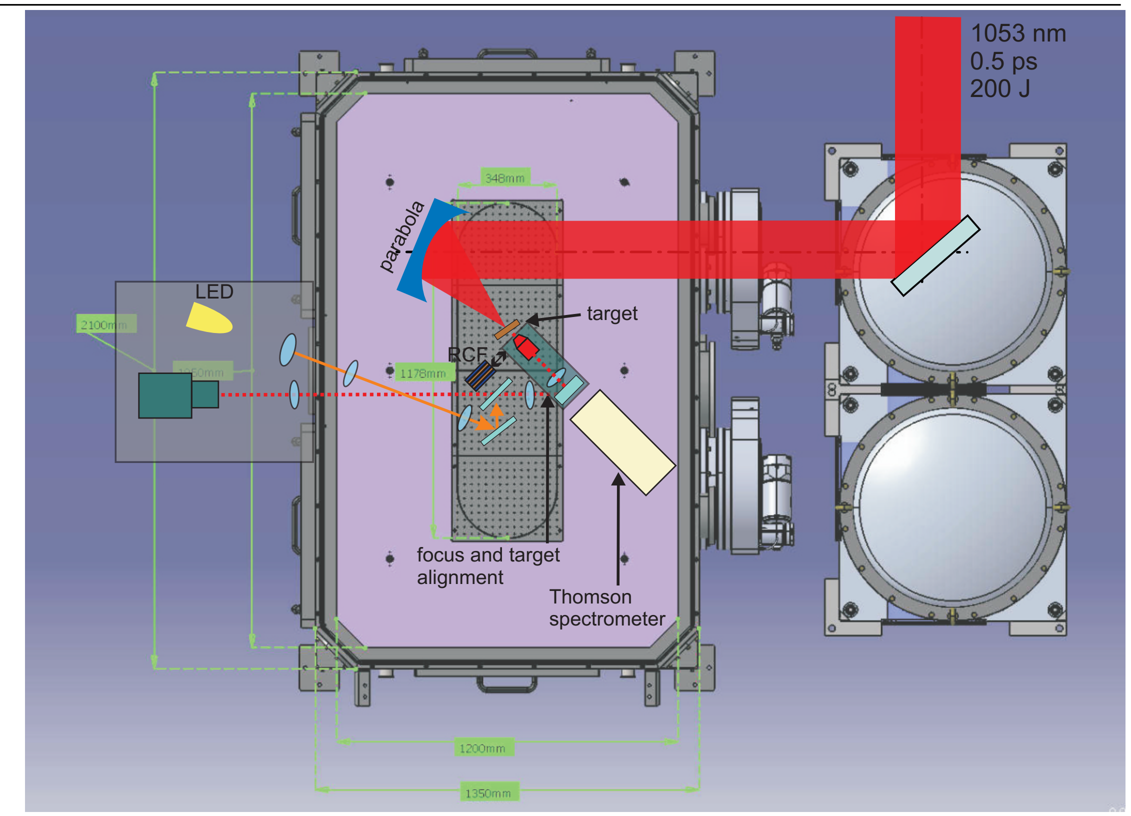




(a) 9,1 MeV (b) 13,1 MeV (c) 17,1 MeV (d) 22,1 MeV (e) 26,1 MeV
(f) 29,1 MeV (g) 31,6 MeV (h) 34,1 MeV (i) 36,1 MeV (j) 38,6 MeV
(k) 42,6 MeV (l) 47,1 MeV (m) 50,1 MeV (n) 54,1 MeV (o) 57,6 MeV
(p) 61,1 MeV



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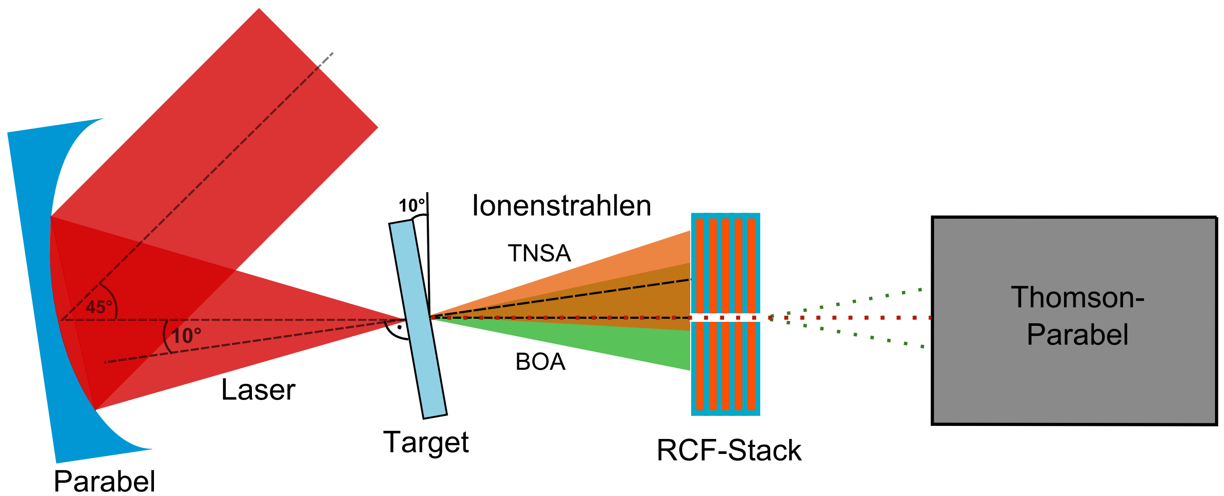

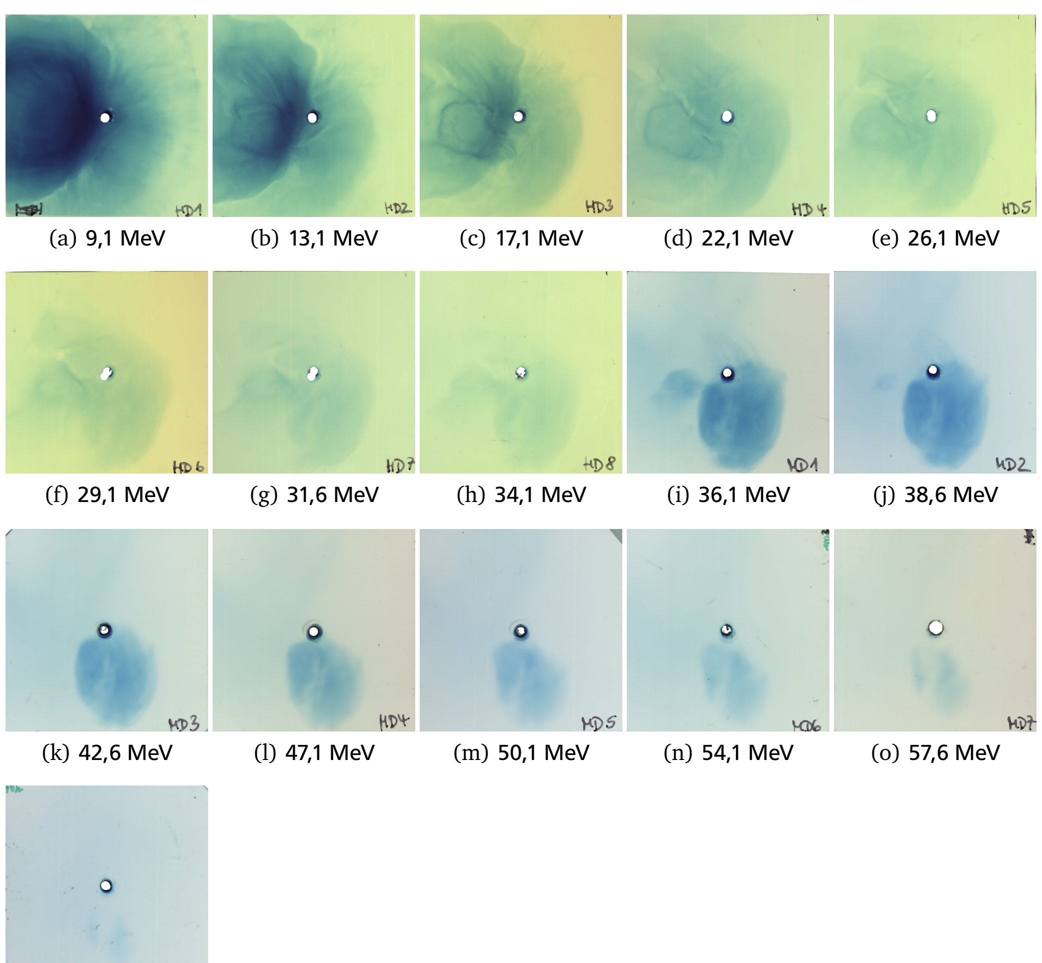

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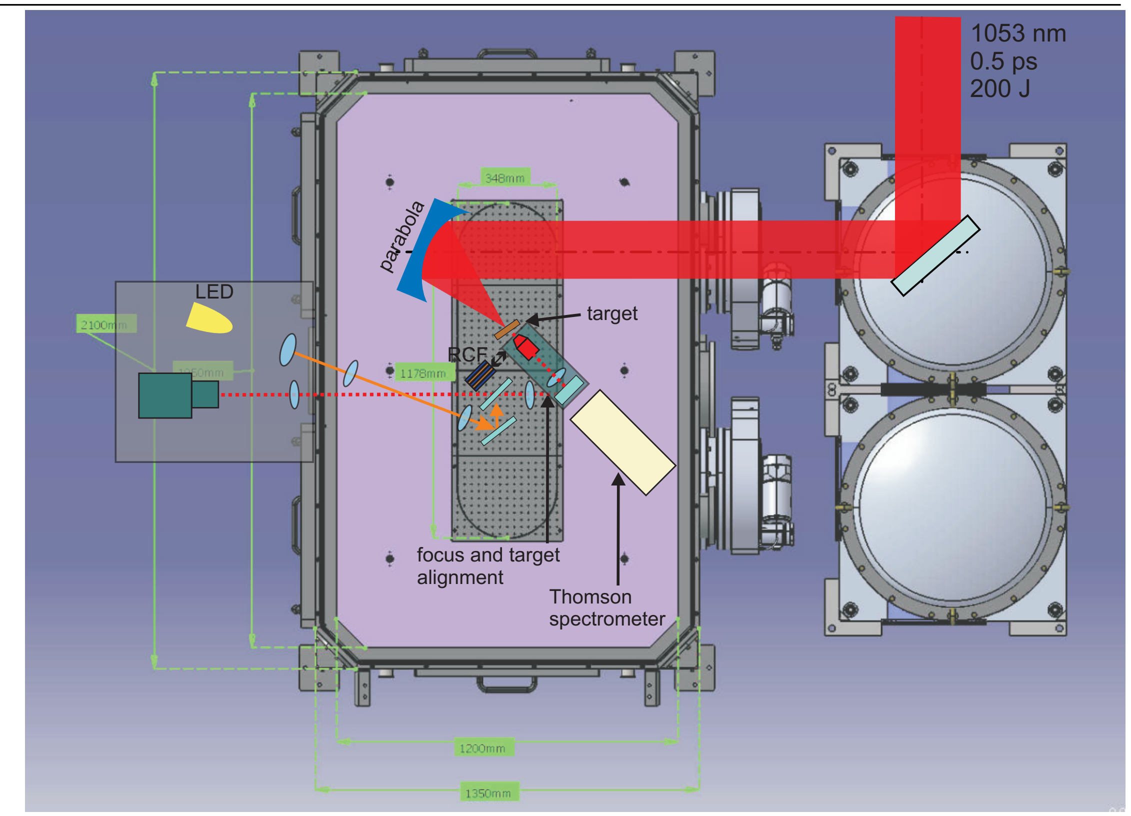
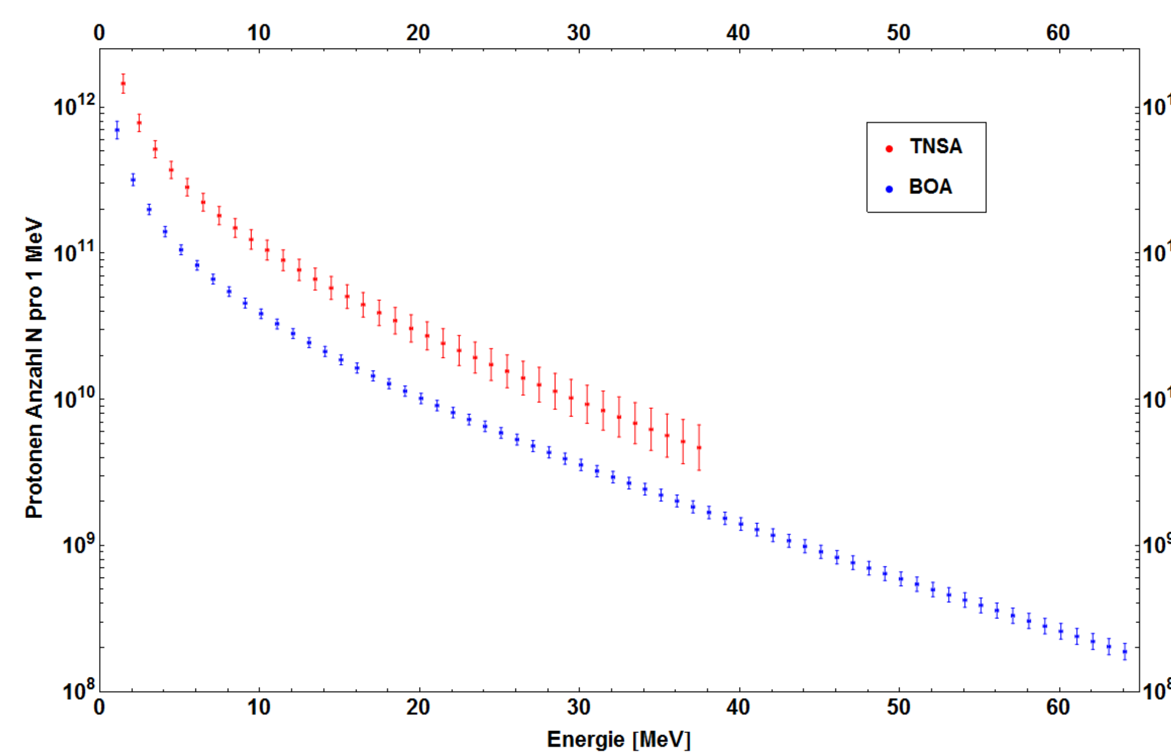
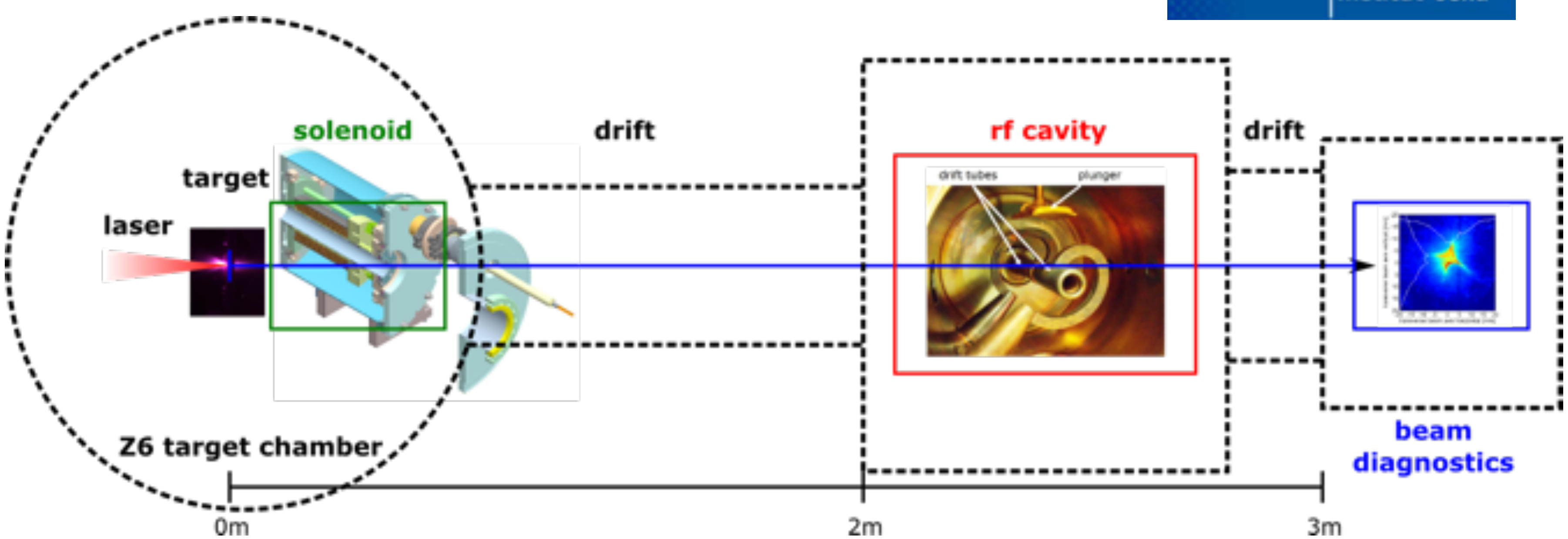




LIGHT

Laser Ion Generation, Handling and Transport

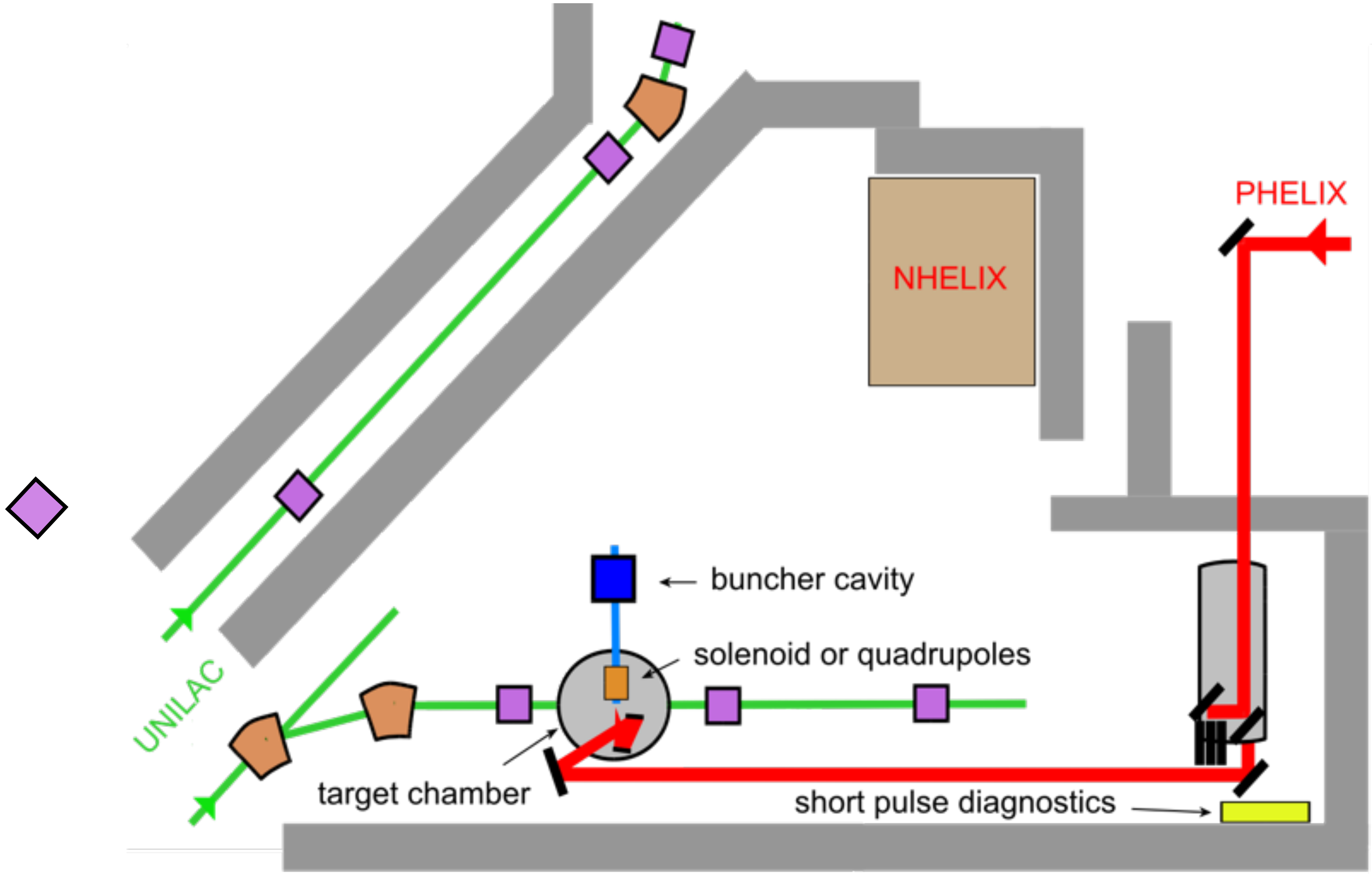
unique beam and hybrid technology testbed
N = 10^{10} protons
E = 10 MeV
t ≈ ns / sub-ns
DE ≈ 1%



Picture: Courtesy of Simon Busold

Laser Ion Generation Handling and Transport

LIGHT @ GSI



Laser Ion Generation Handling and Transport

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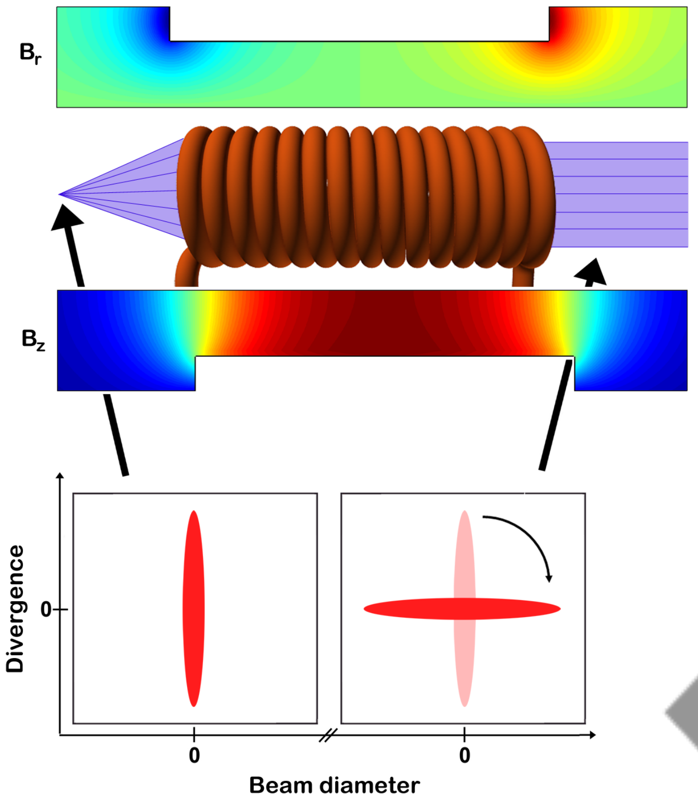

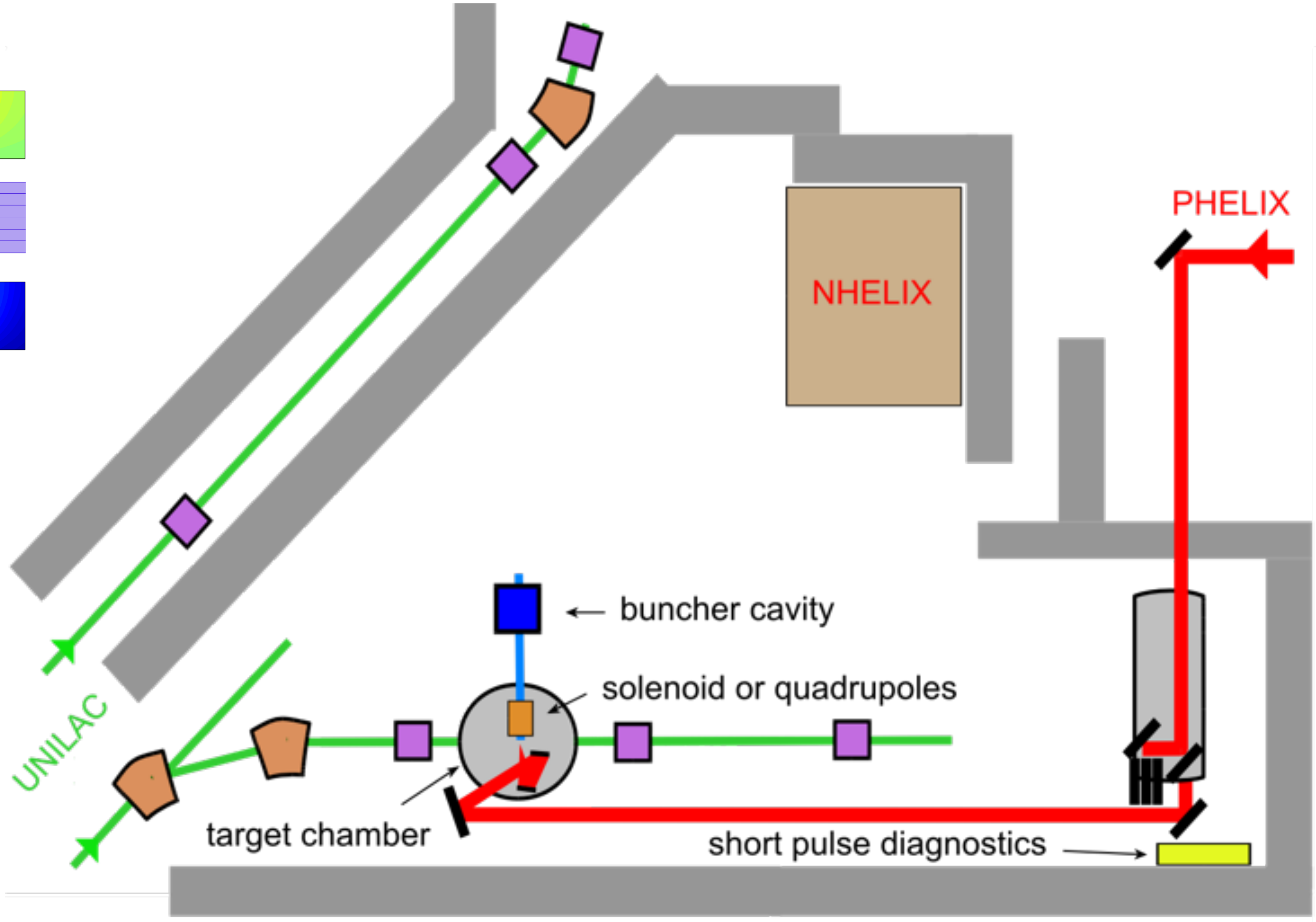

Coil design from HZDR

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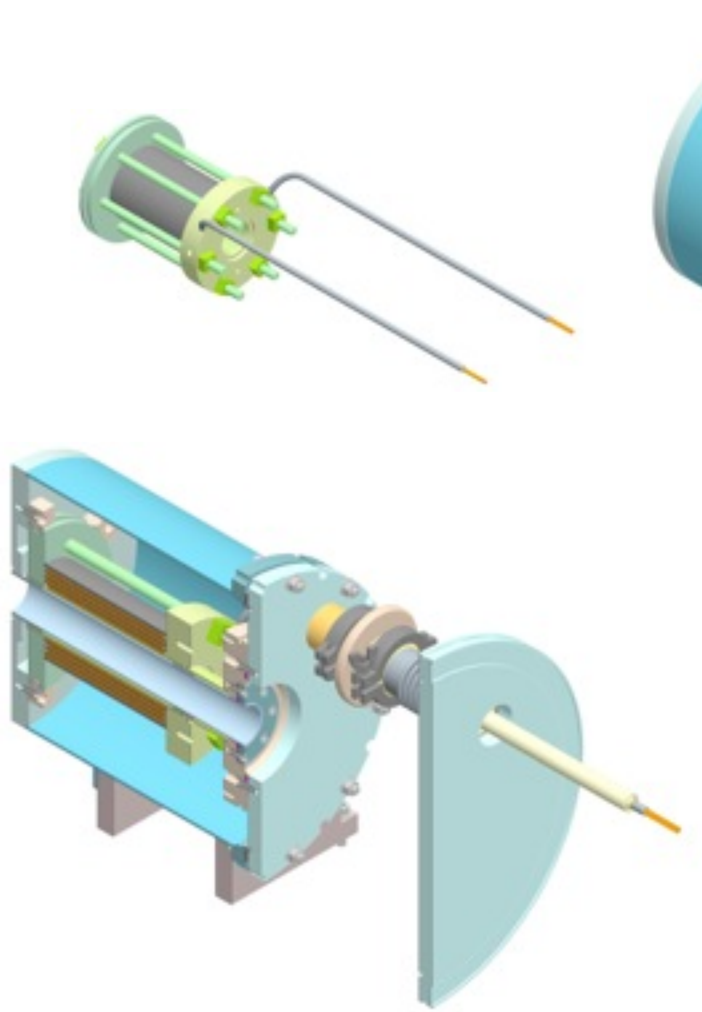
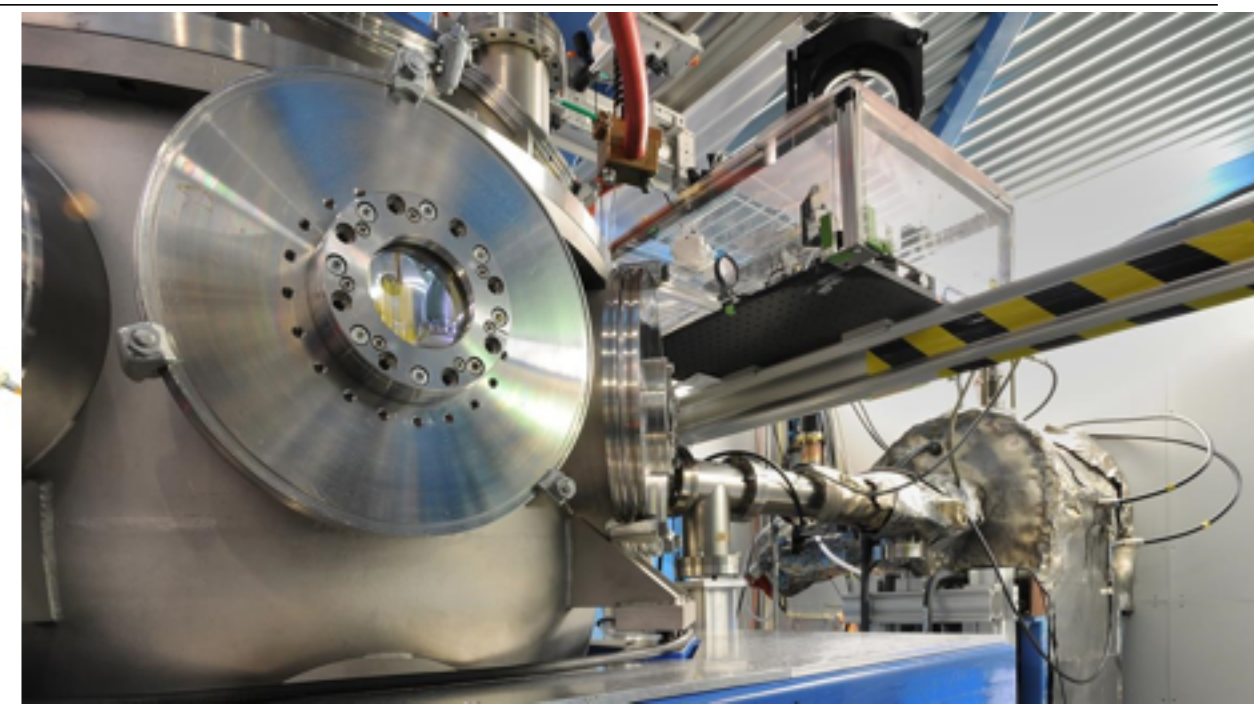
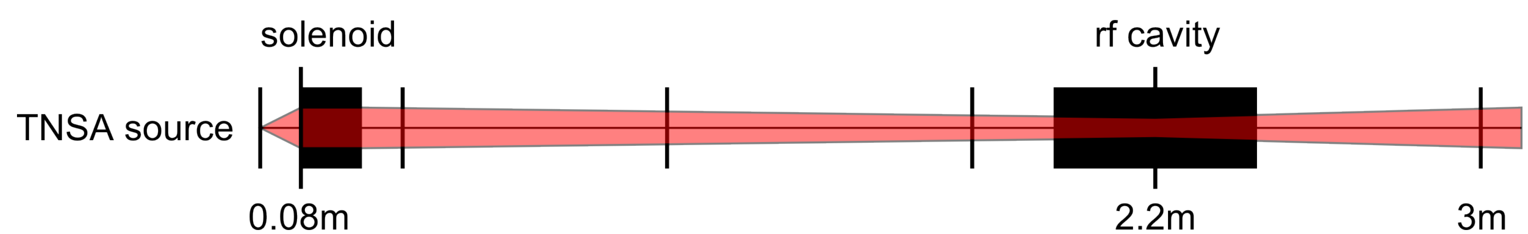
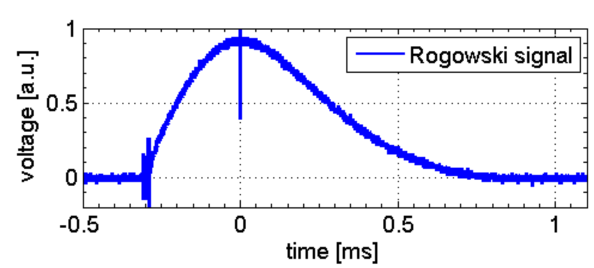


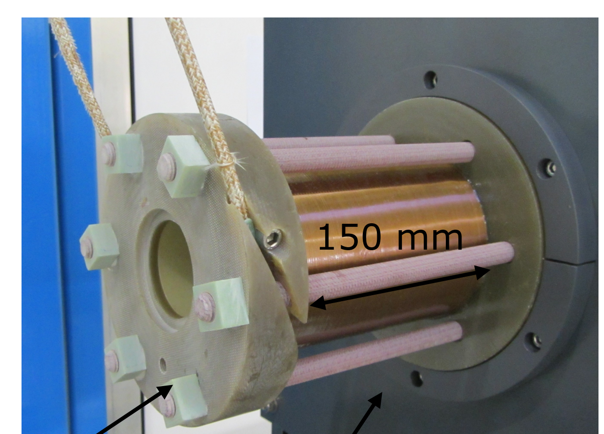




stand alone pulsed power system



- $B_{z,max}$ = 8.7 T in solenoid
- large open aperture for high capture efficiency



40.5 mm open aperture

4 layers copper windings

Courtesy: Thomas E. Cowan

DRESDEN concept

HZDR

bunch characterization for cavity

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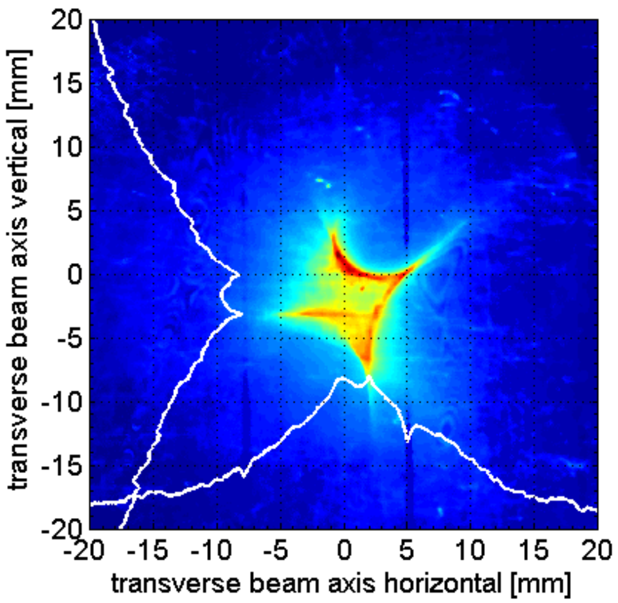
S. Busold et al., PR-STAB 16, 101302 (2013)

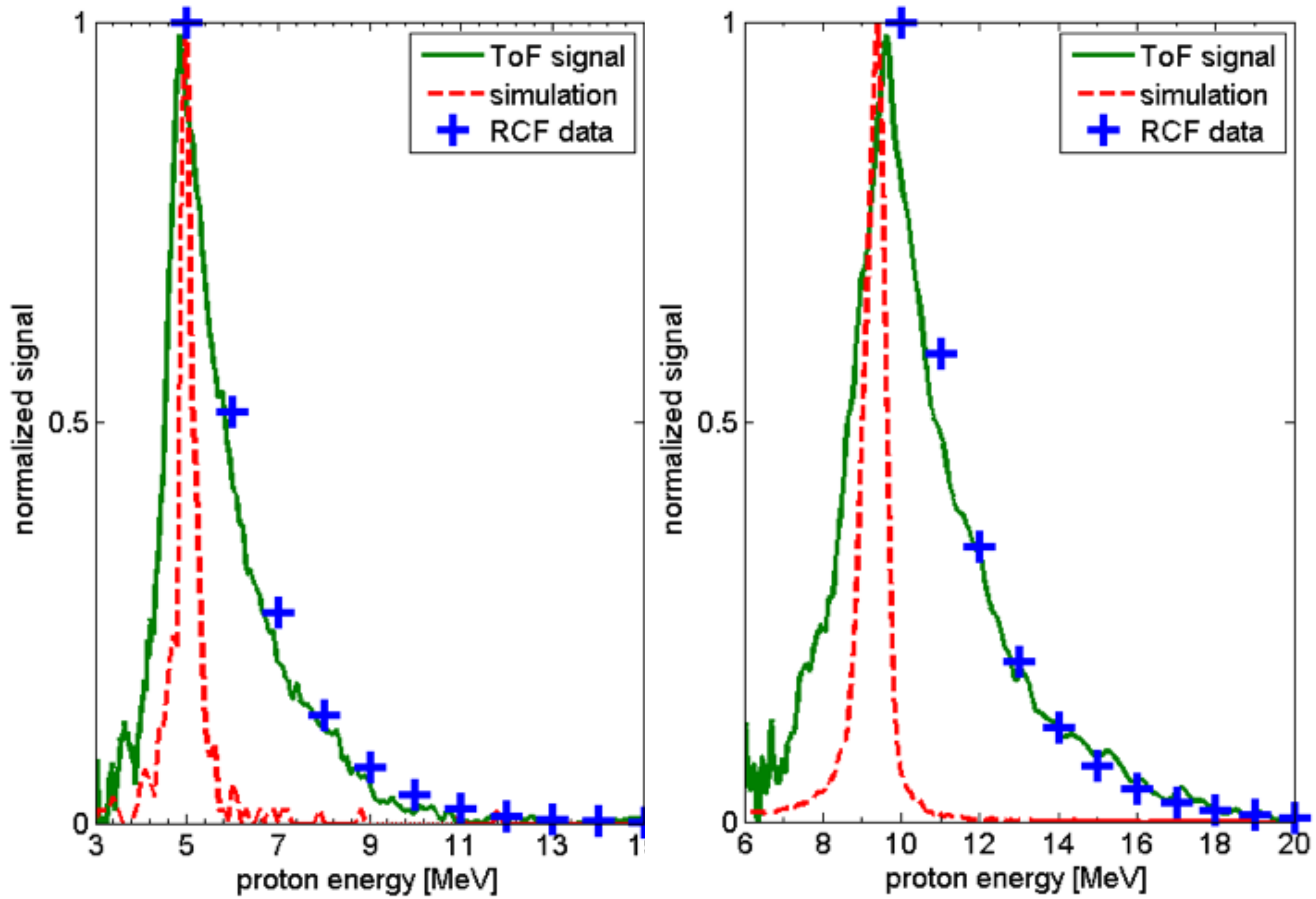
focussing at 2.2m distance to source



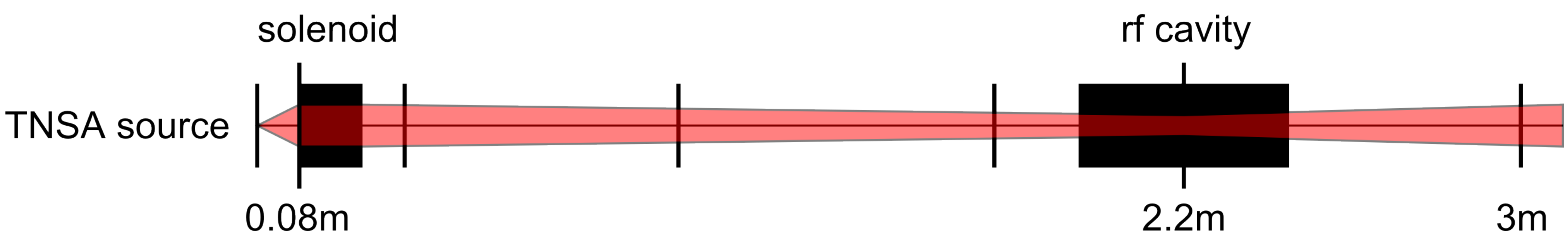
→ 6.5e8 protons of 9.5MeV in spectral bin of 1MeV

→ real bunch much broader

→ additional focusing inside solenoid through electrons on center axis?

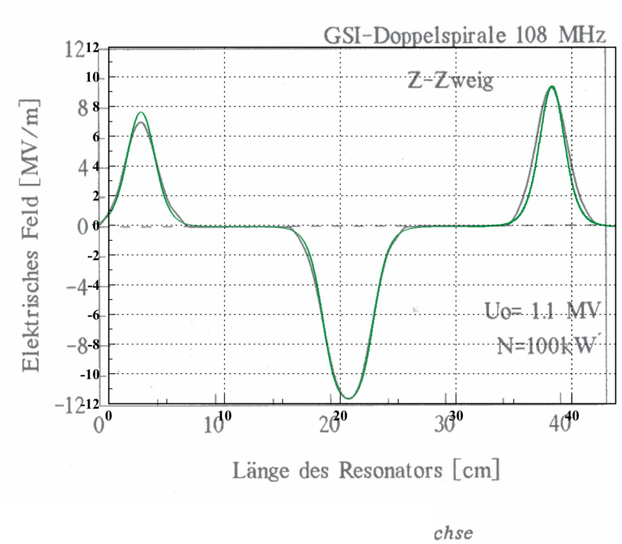


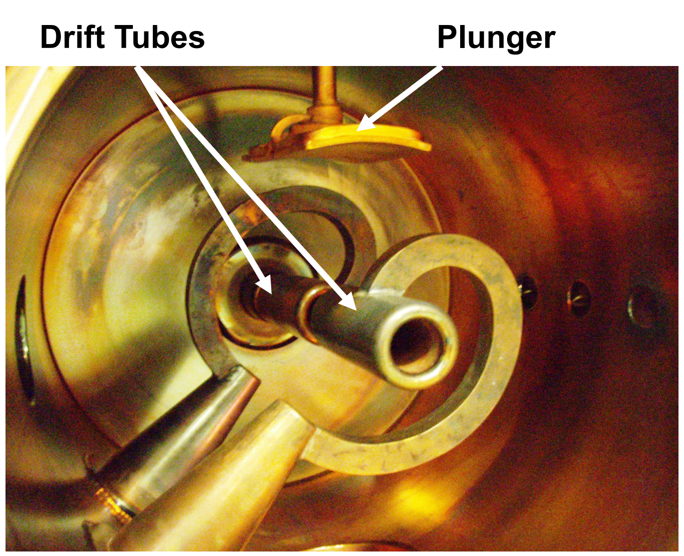
cavity



connection to UNILAC HF

- 3 gap spiral resonator
- 108.4 MHz
- power >100 kW, >1 MV
- 35 mm open aperture

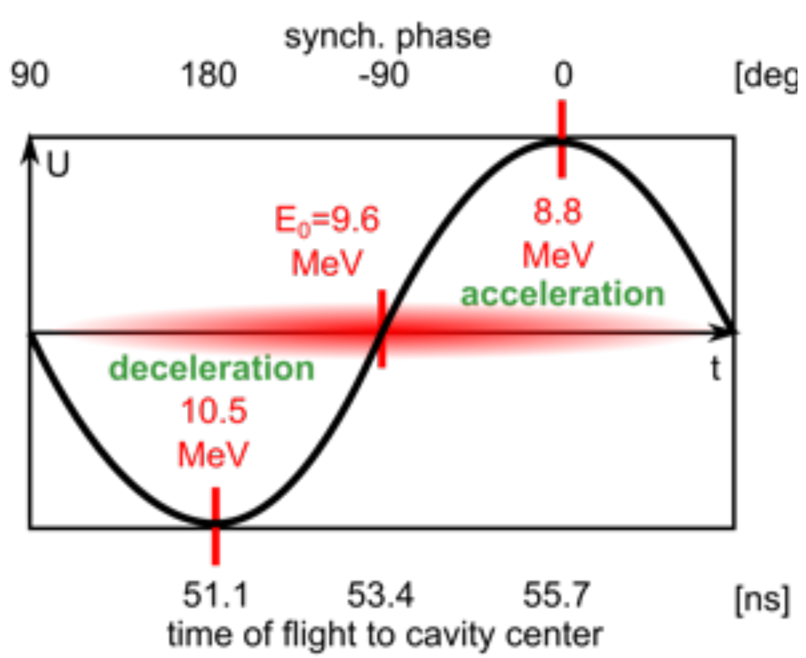


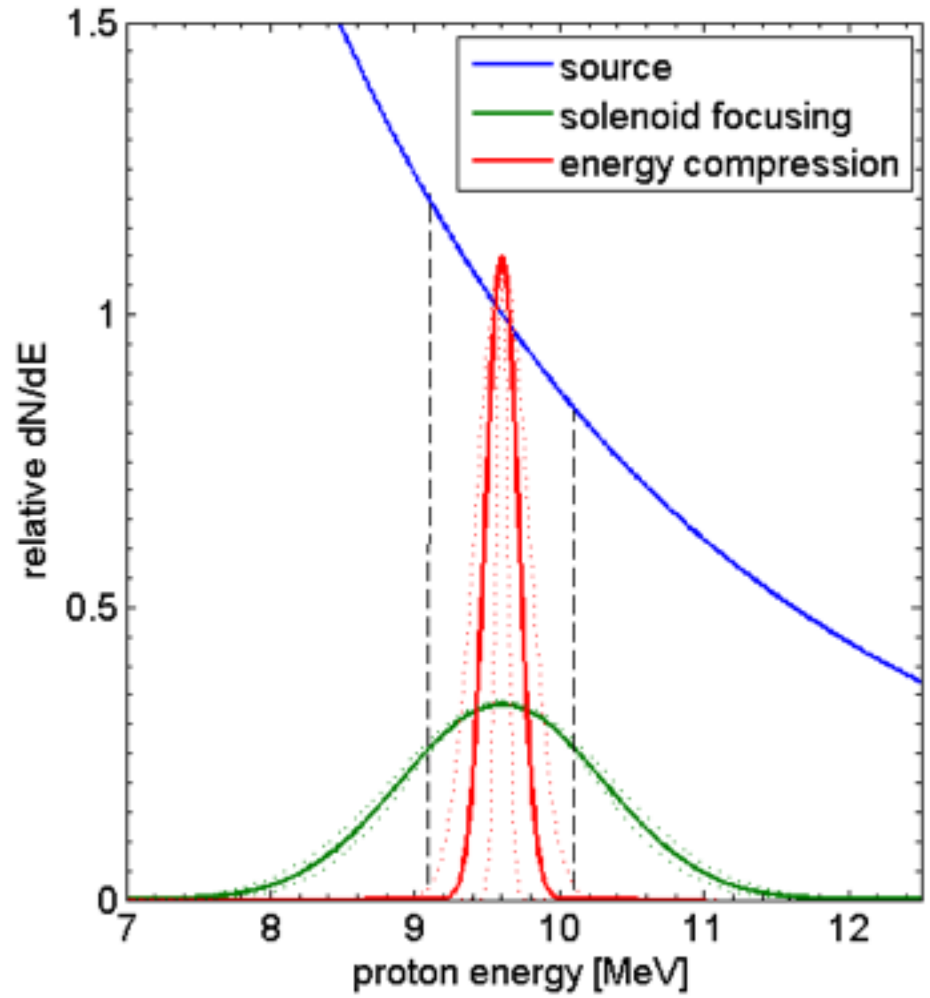


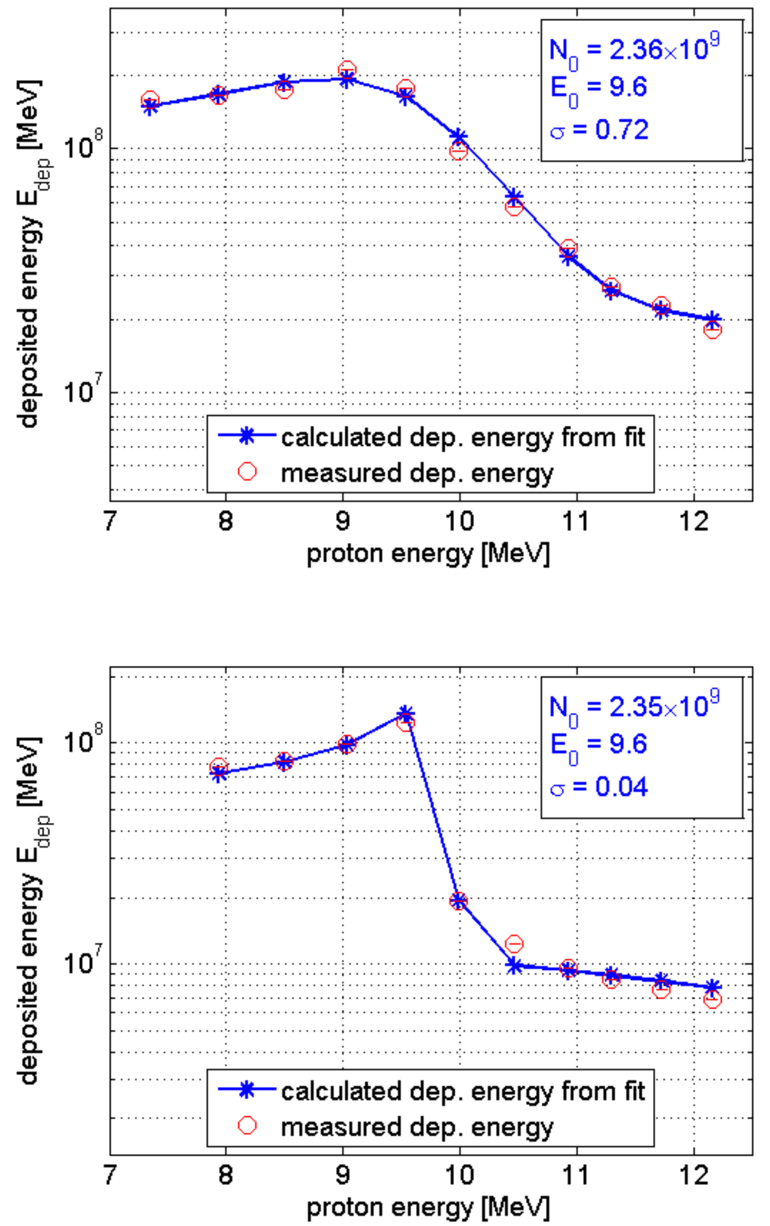
phase rotation

S. Busold et al., PR-STAB 17, 031302 (2014)

Energy selection and width for 9.6 MeV :
18.0 ± 3.0 % due to chromatic focusing of the solenoid
2.7 ± 1.7 % using the cavity

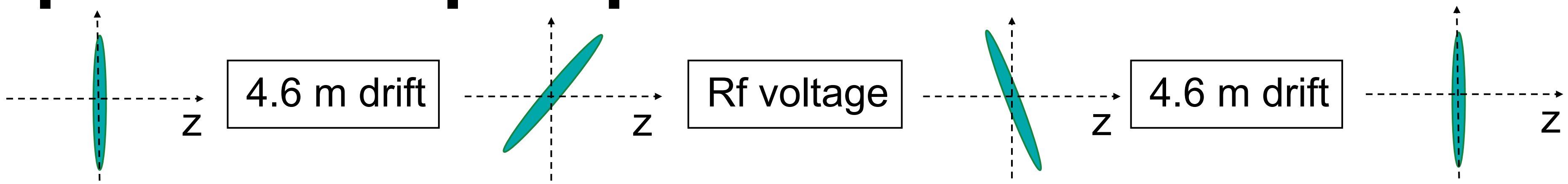






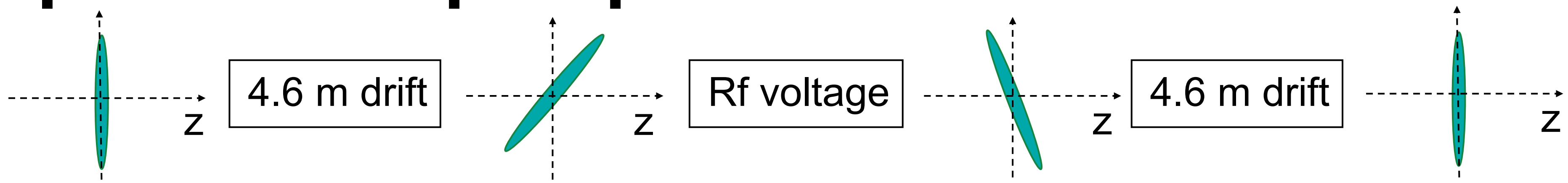
F. Nürnberg et al., RSI 80, 033301 (2009)

Options and perspectives



Ingo Hofmann
Helmholtz Institut Jena / GSI

Options and perspectives



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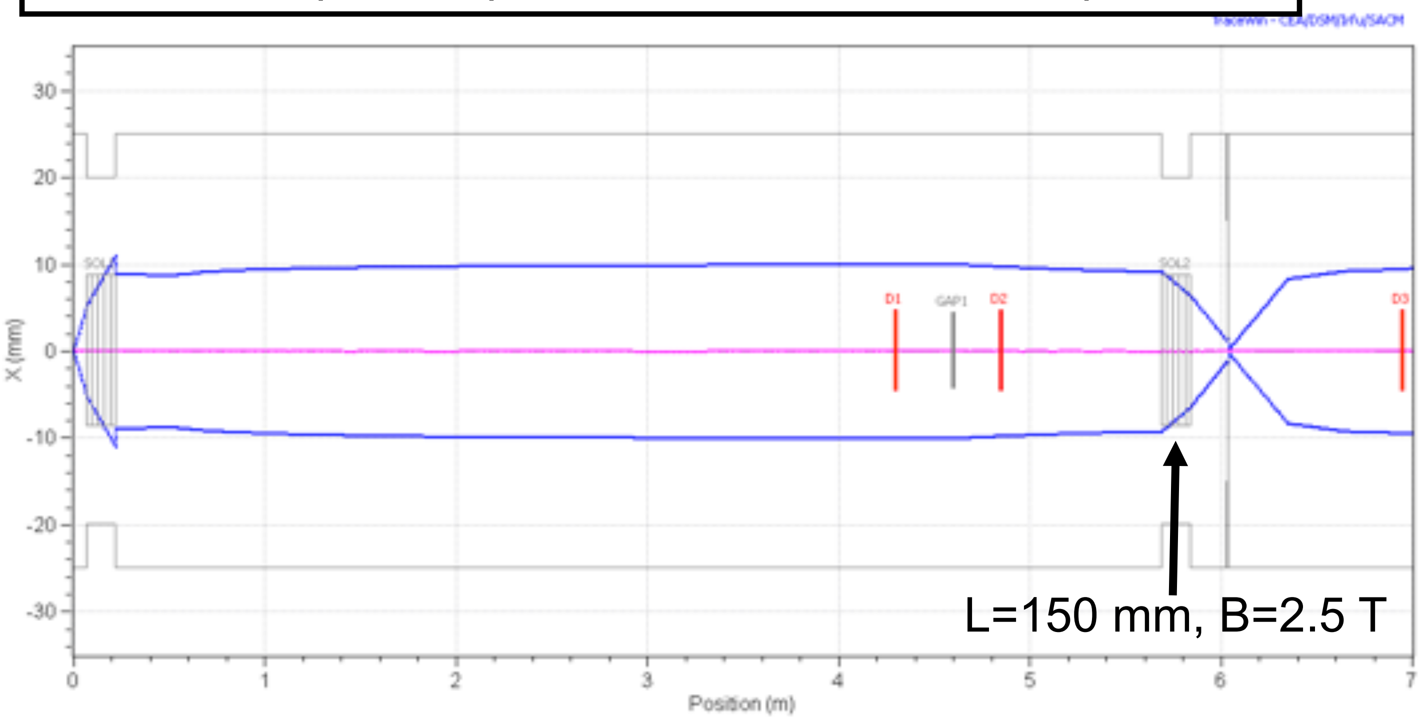
Second focus (2nd solenoid)

6 D focus - optimum performance without extra apertures -



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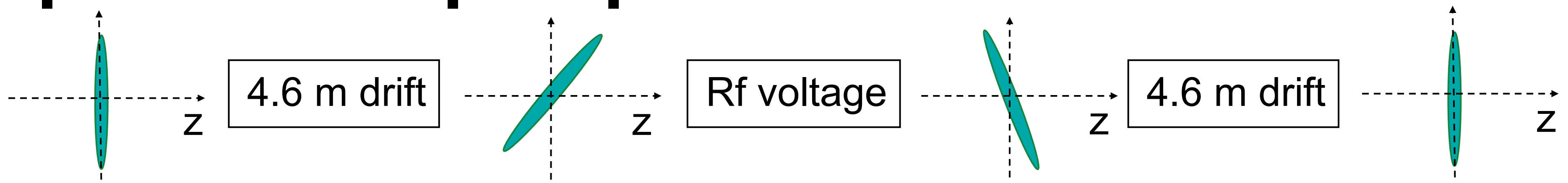

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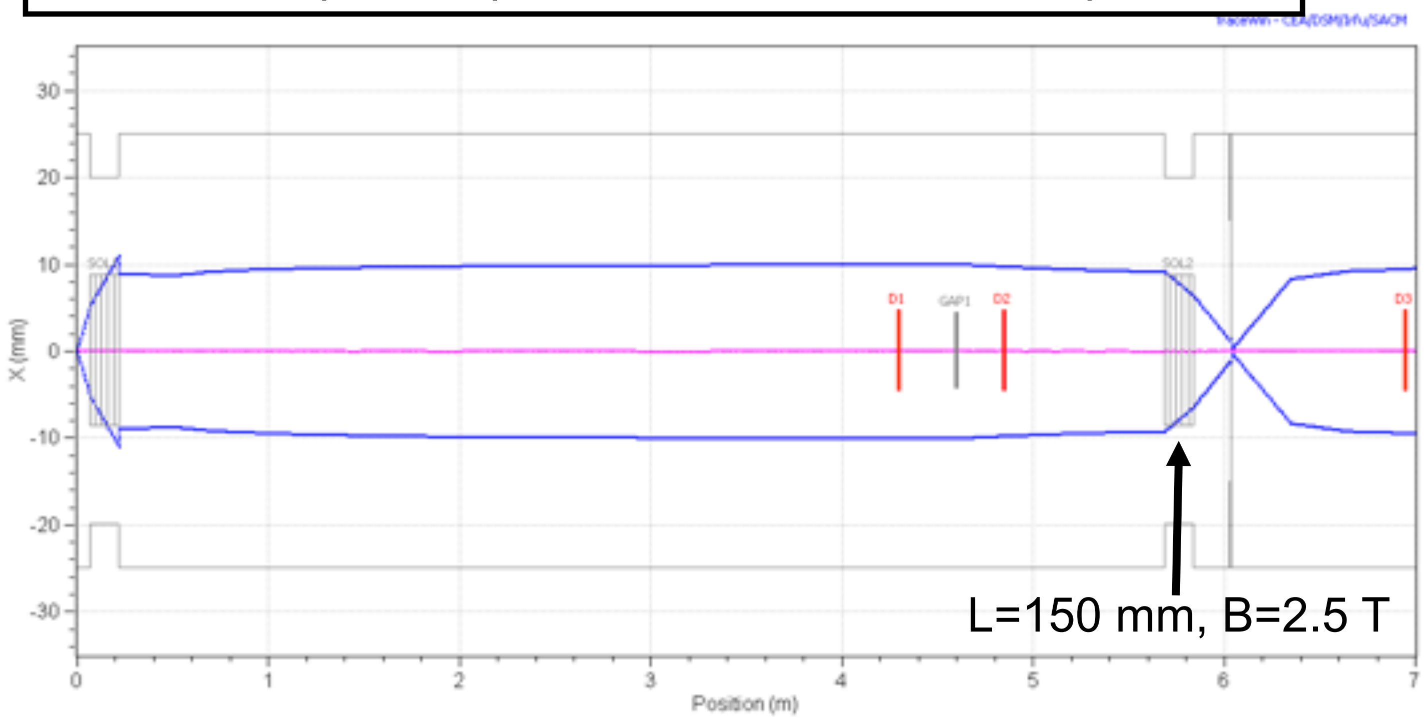

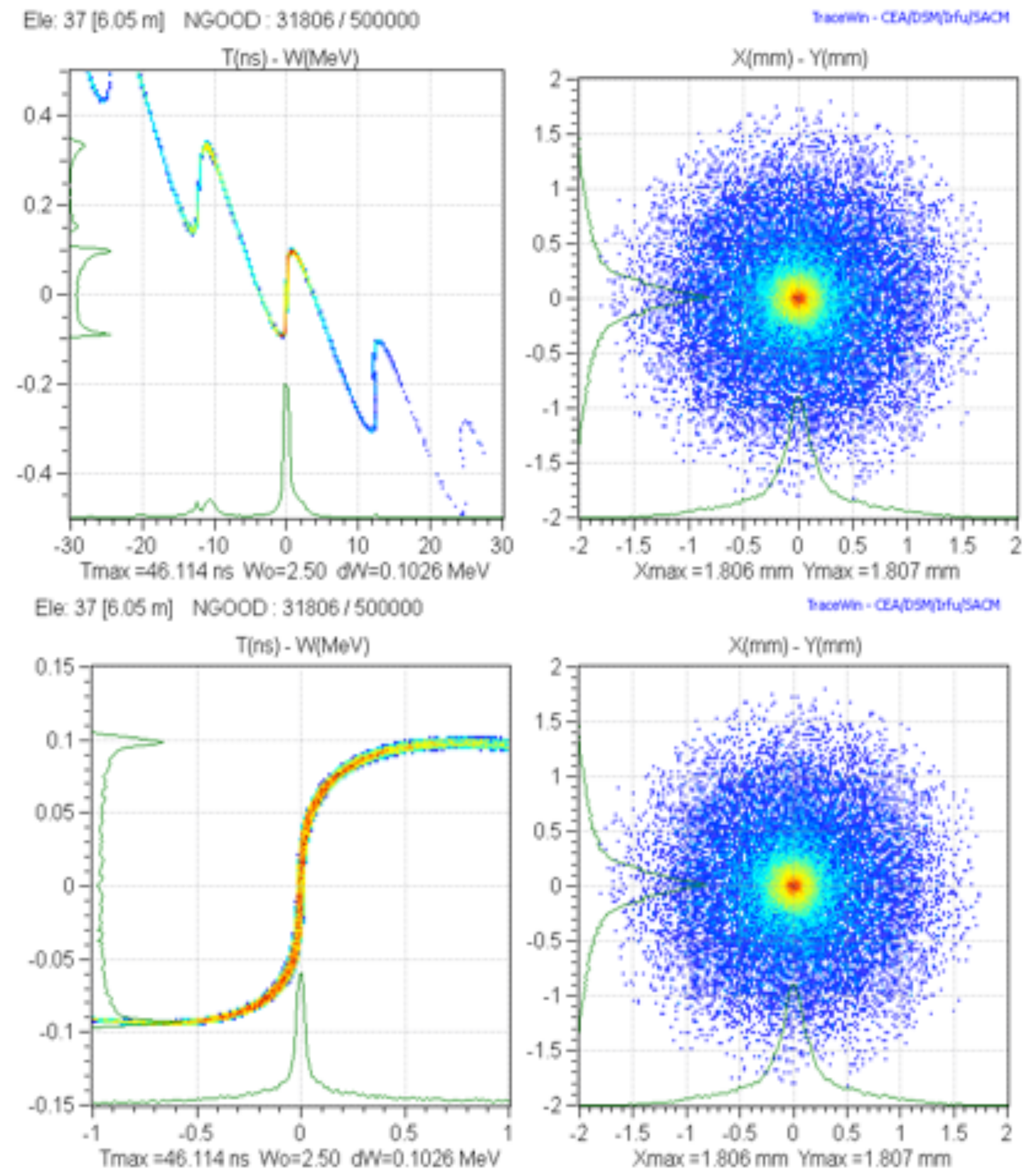

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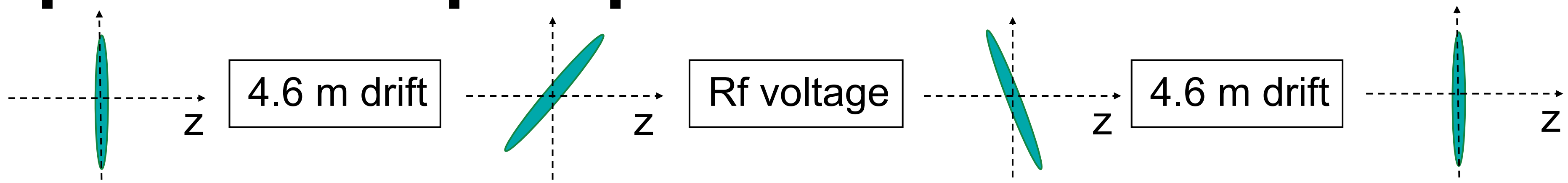

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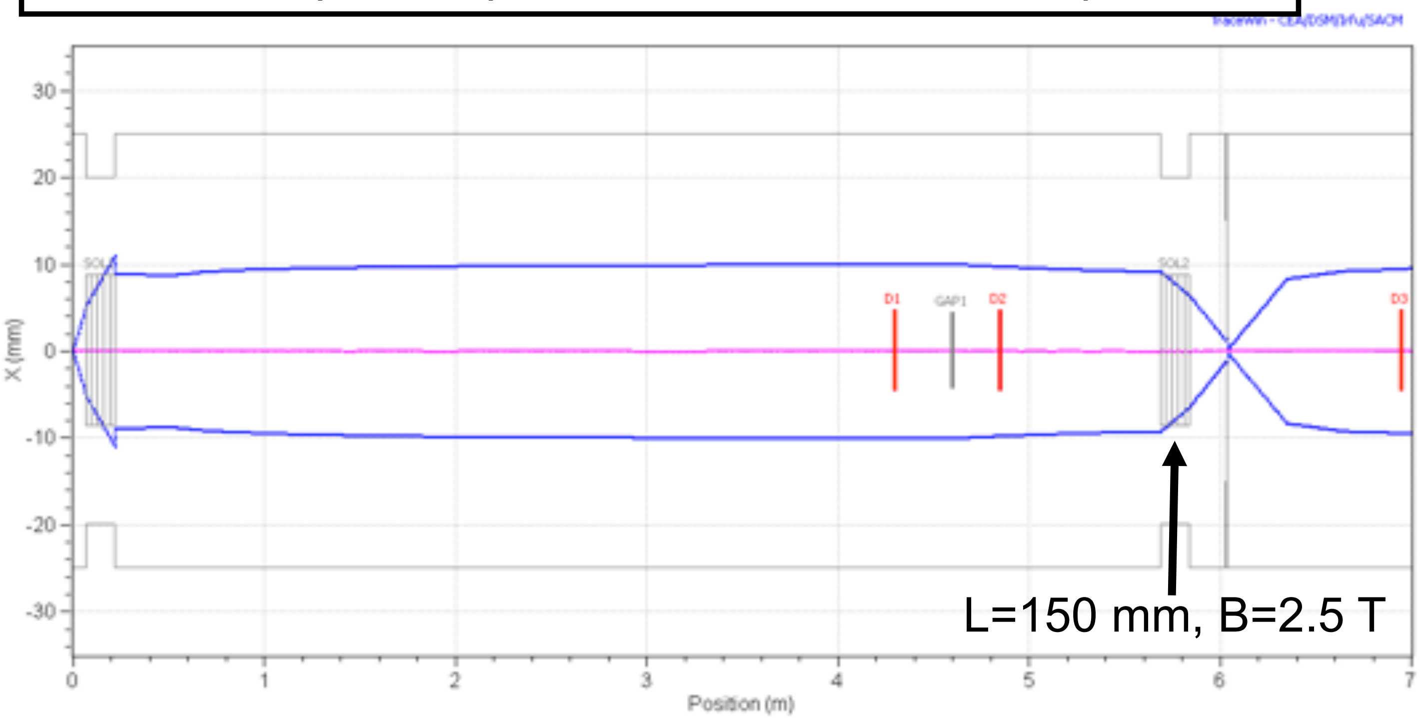

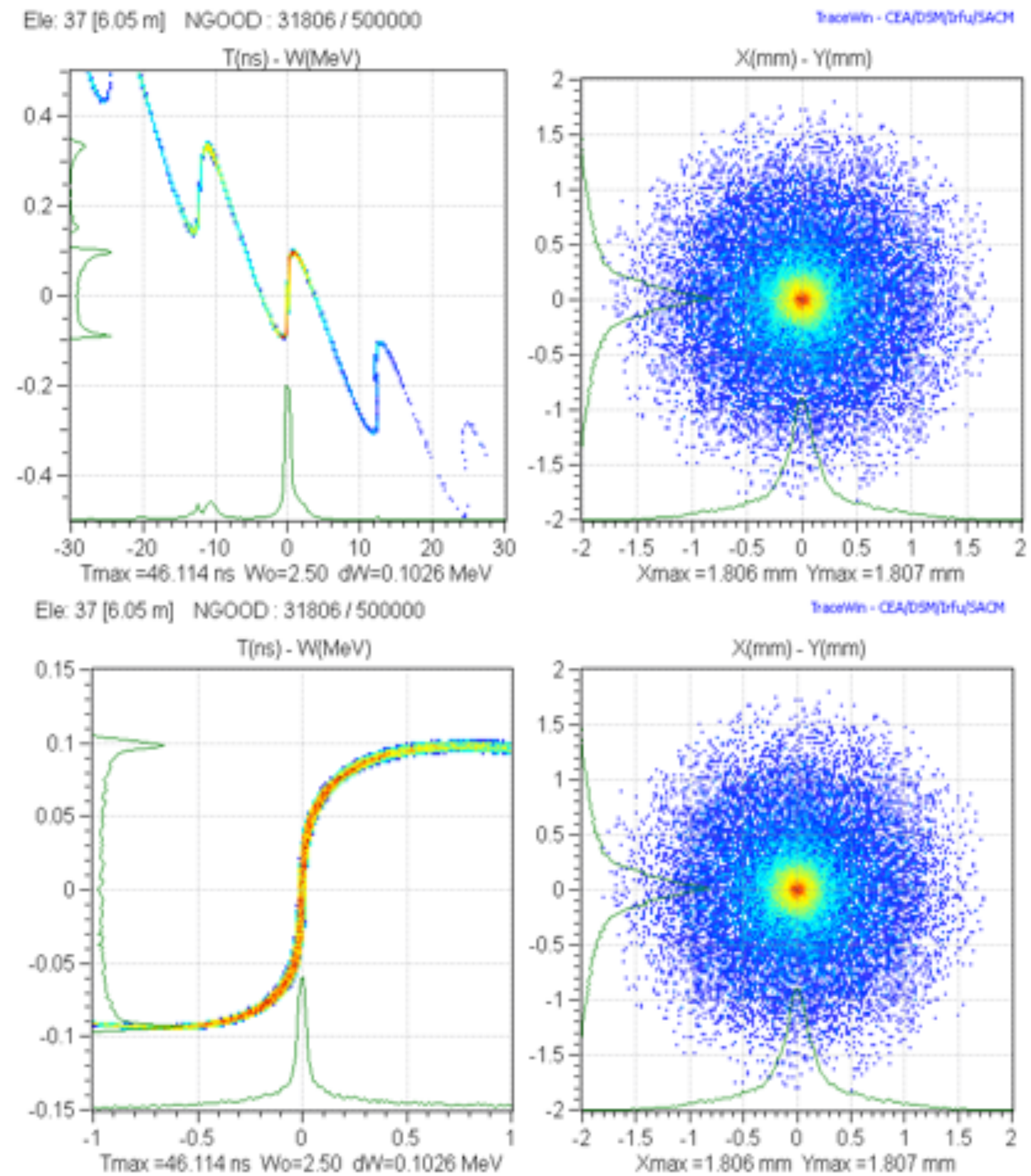

Time focus (< 100 ps) and spatial focus (< 200 μm)
coinciding (6.05 m) ~ 6% of input intensity

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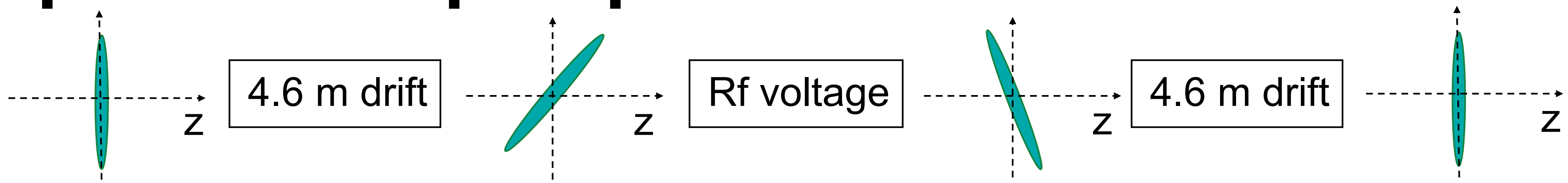
Options and perspectives



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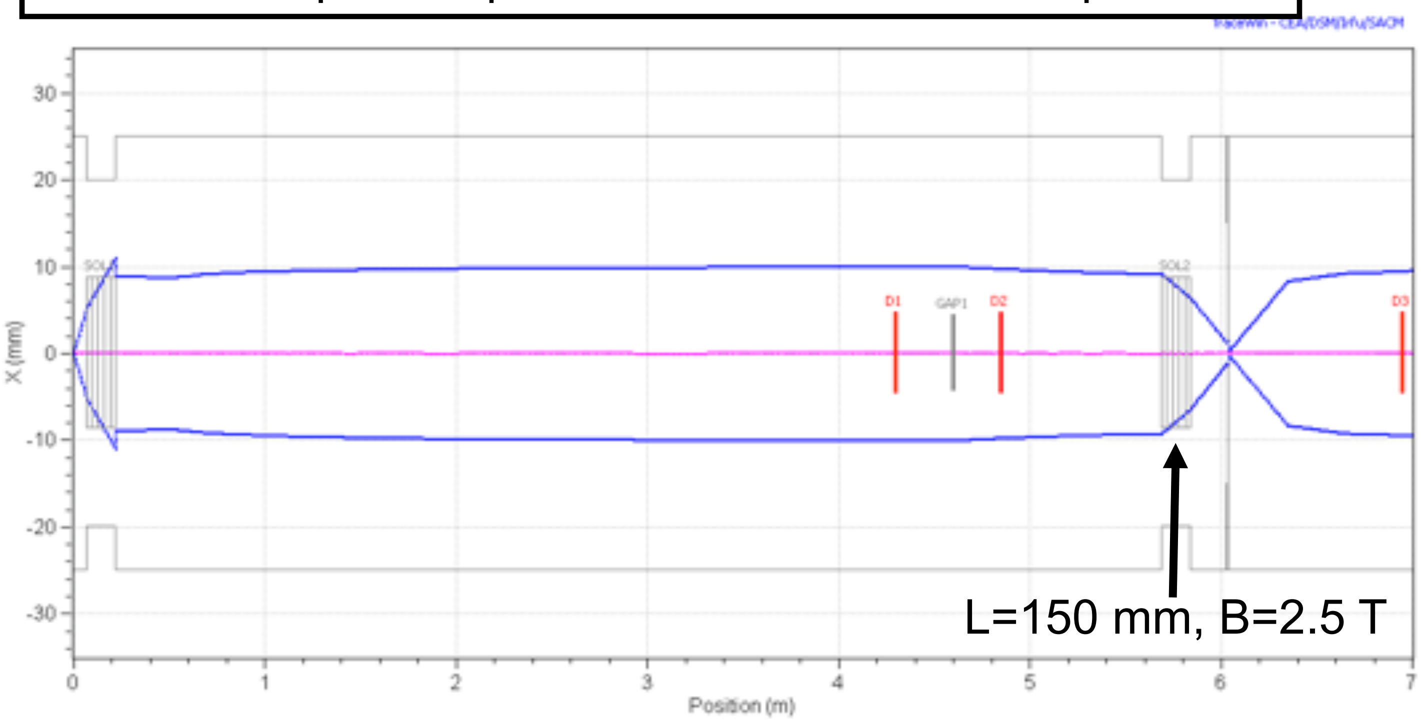

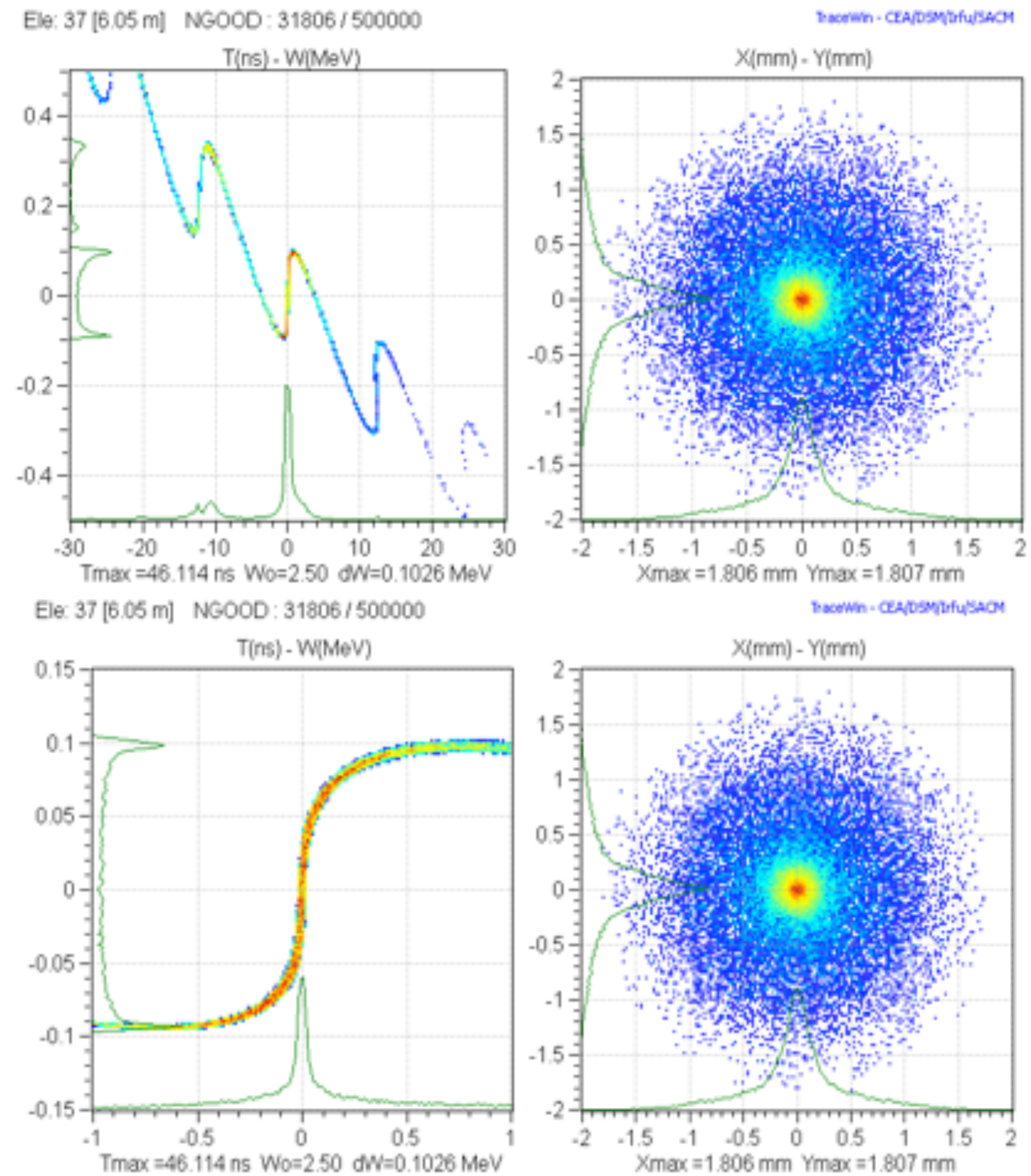

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10^{10} Protonen: 6×10^{18} p/s; 2×10^{22} p/(s cm^2)

@ 10 MeV: 36 GW/cm^2

Ingo Hofmann
Helmholtz Institut Jena / GSI

Summary

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TECHNISCHE UNIVERSITÄT DARMSTADT

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- Ion beams physics and neutron science becomes available to universities using short pulse lasers

Thanks to

Oliver Deppert[1], Matthew Devlin[2], Katerina Falk[2], Andrea Favalli[2], Juan Fernandez[2], Cort Gautier[2], Mattthias Geissel[3], Nevzat Guler[2], Robert Haight[2], Chris Hamilton[2], Manuel Hegelich[2], Randall P Johnson[2], Daniel Jung[2], Frank Merrill[2], Gabriel Schaumann[1], Kurt Schoenberg[2], Marius Schollmeier[3], Tsutomu Shimada[2], Joshua L. Tybo[2], Stephen A Wender[2], Carl, H Wilde[2], Glen Wurden[2]

[1]Technische Universität Darmstadt, 64289 Darmstadt, Germany

[2]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

[3]Sandia National Laboratory, Albuquerque, New Mexico 87185, USA

The LANL for the Rosen Scholar award

TUD for the sabbatical

Thanks to: LIGHT

Laser Ion Generation, Handling and Transport

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Kick Off meeting 2010 @ GSI - Helmholtzzentrum für Schwerionenforschung