BELLA-i a new tool for ion acceleration, rel. plasma physics and applications

Markus Roth
Technische Universität Darmstadt

Ultra - high intensity laser experiments

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- not just one of those laser systems: BELLA-i

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- Ion acceleration

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Ultra - high intensity laser experiments

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- Ion acceleration
- The concept of relativistic transparency
- Secondary radiation sources - neutrons
- Applications
- LIGHT
- Where do we go from here….

Not just any experimental facility

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Ion Acceleration

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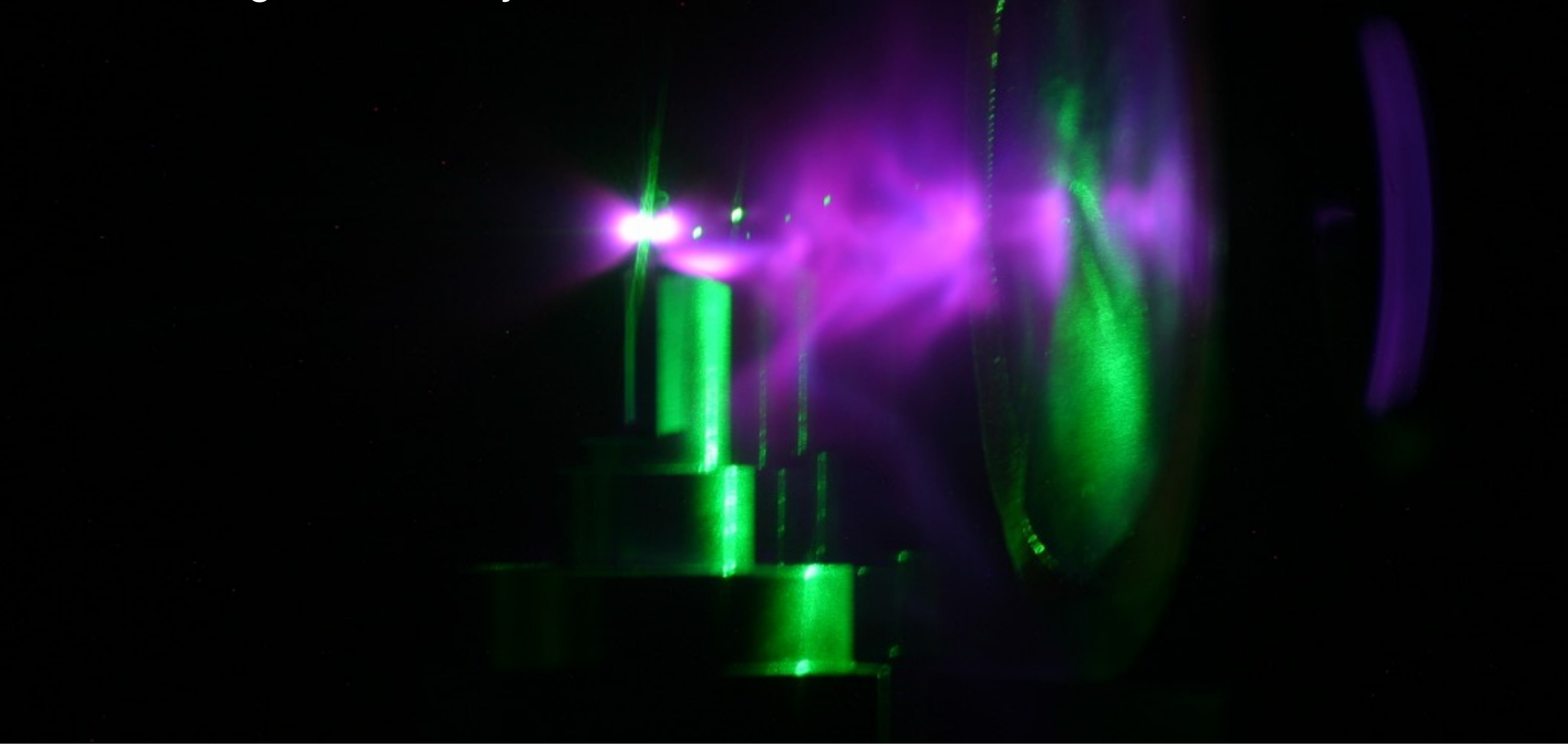
Answering some of the most fundamental questions in LIA, being around for years



Ion acceleration with lasers : Static electric fields

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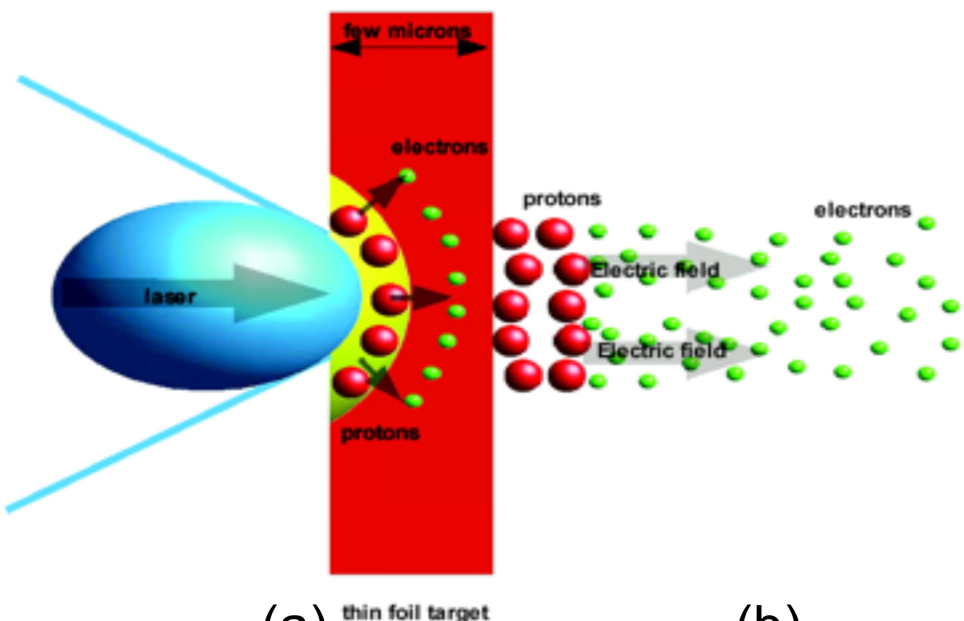
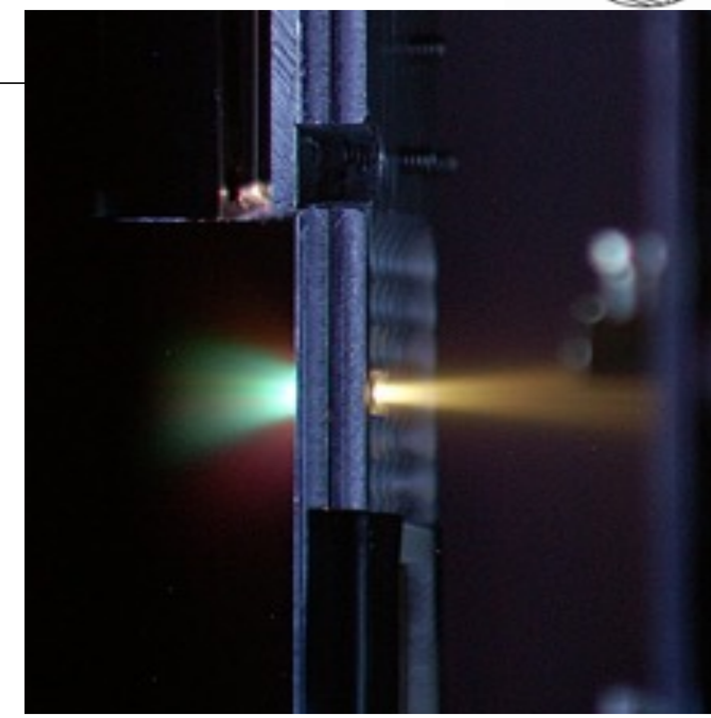
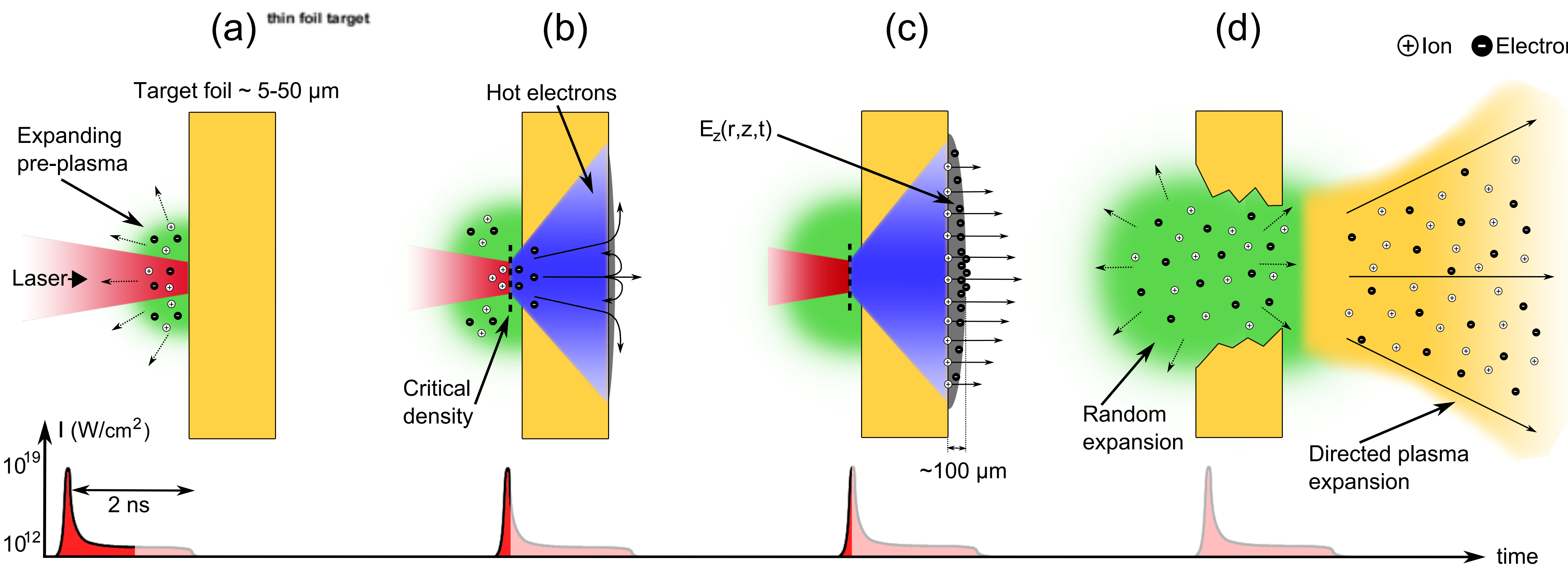
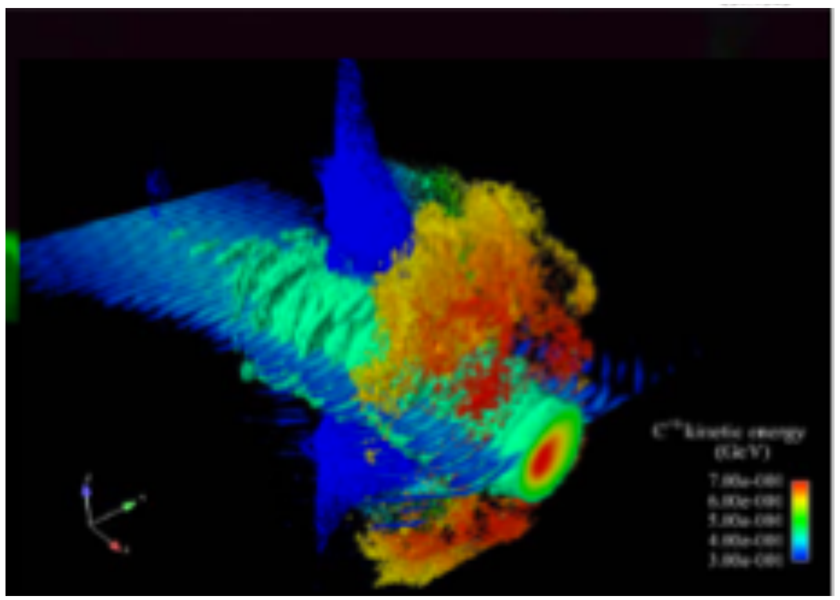
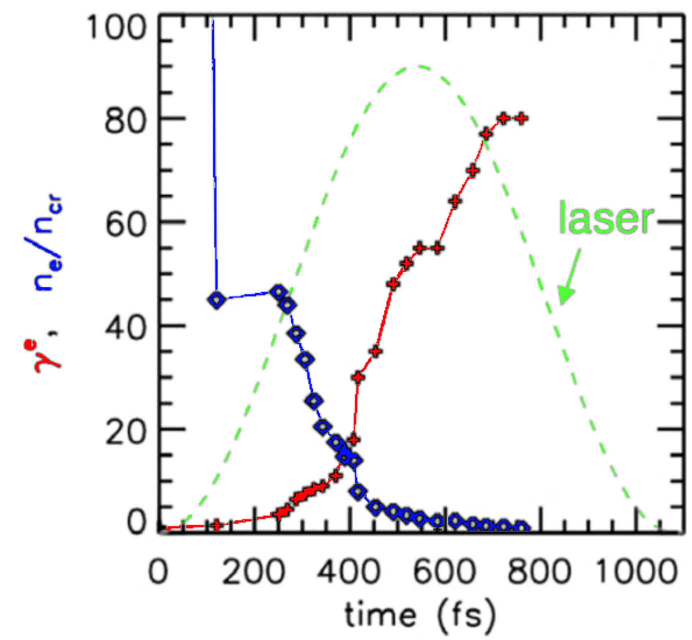






Break out Afterburner (BOA)





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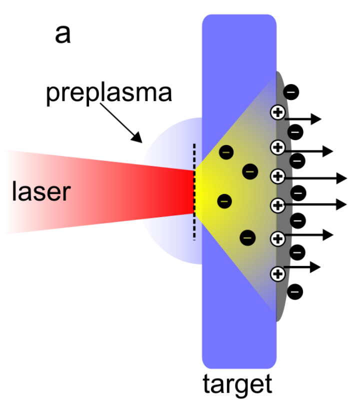

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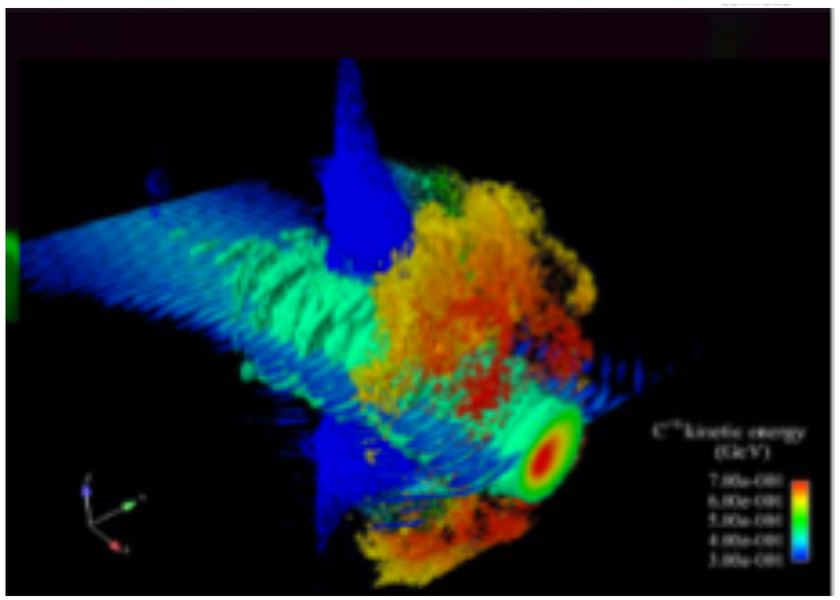

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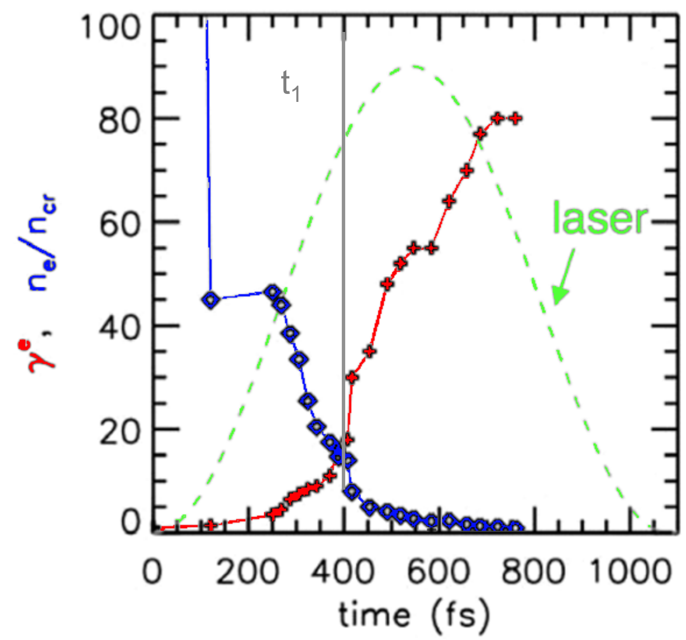
$$n' > 1 \geq n'/\gamma$$



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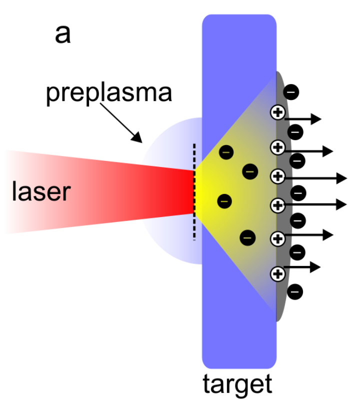

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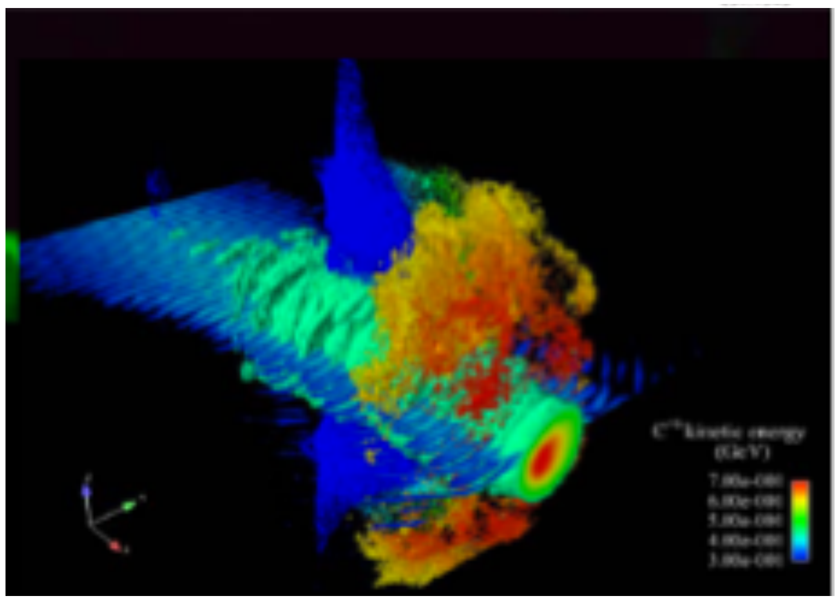

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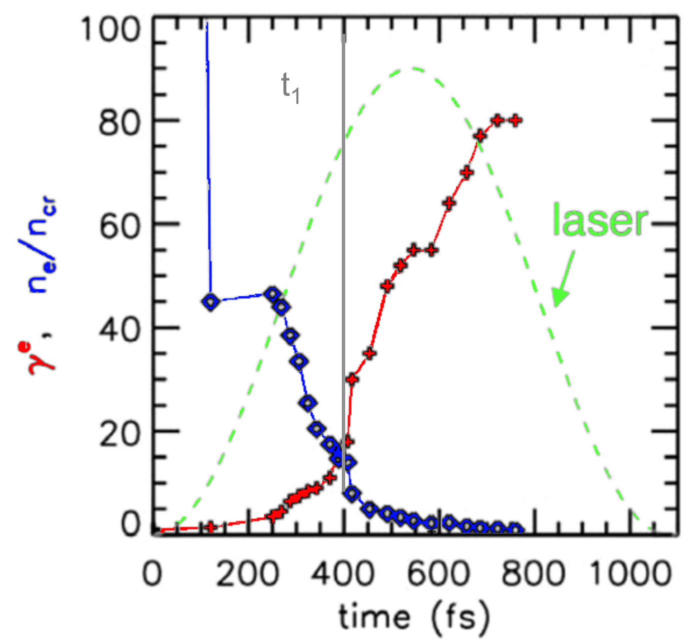

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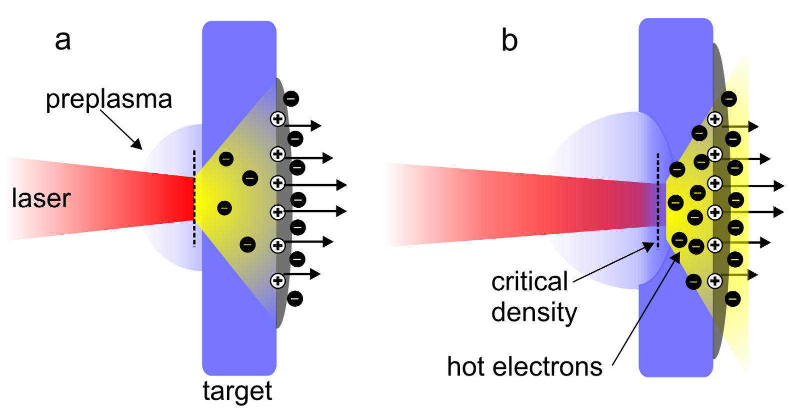

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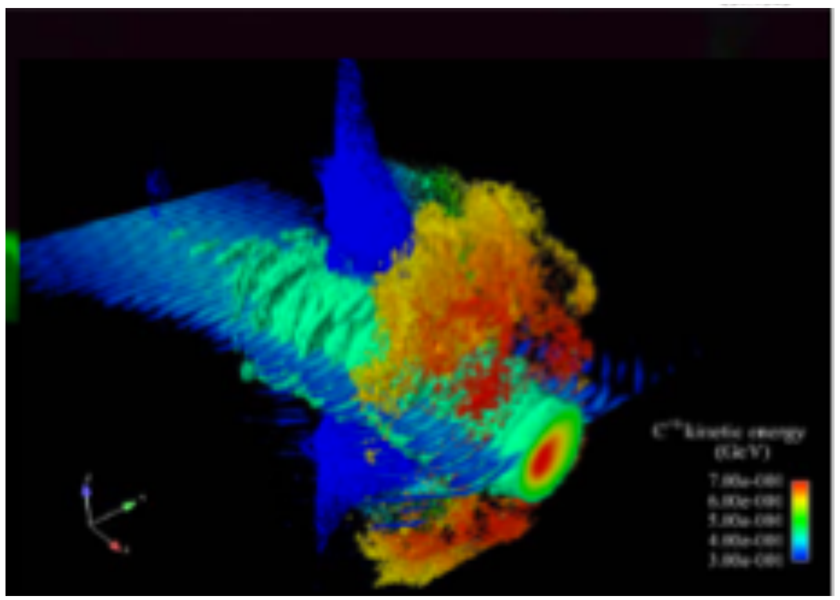

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t₂: classically underdense

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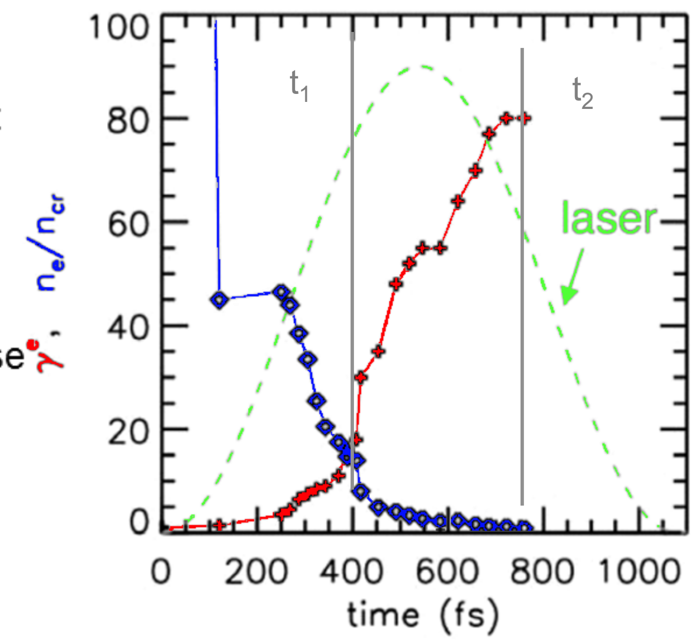

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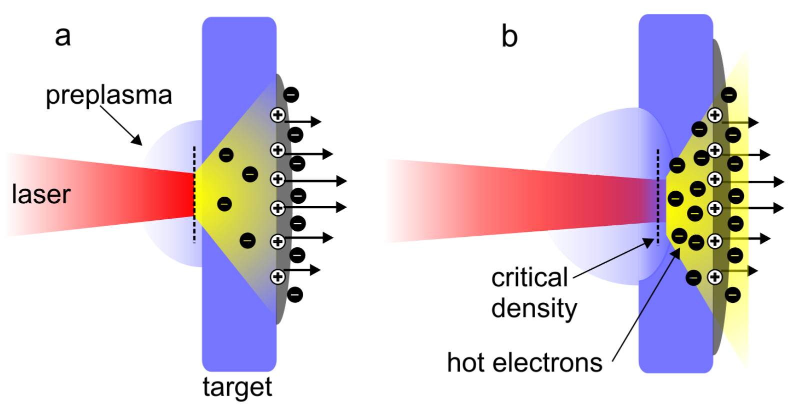

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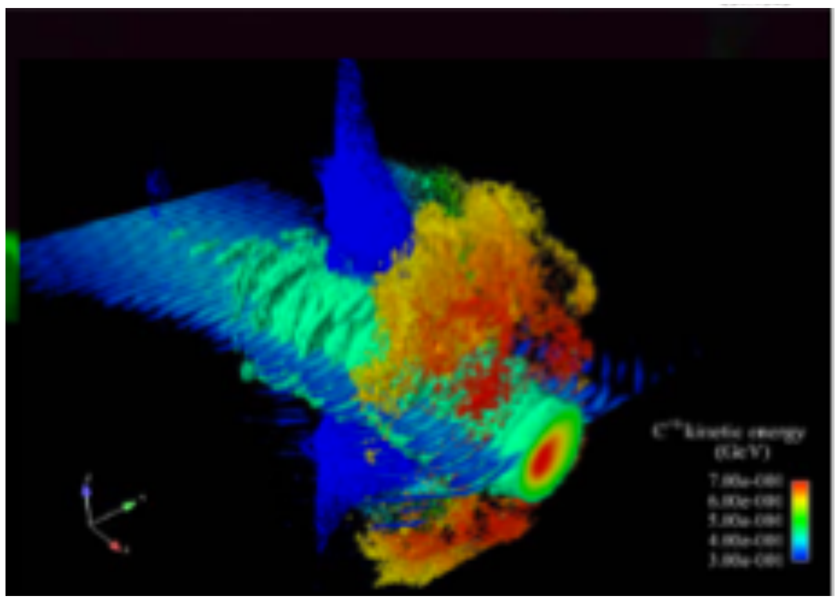

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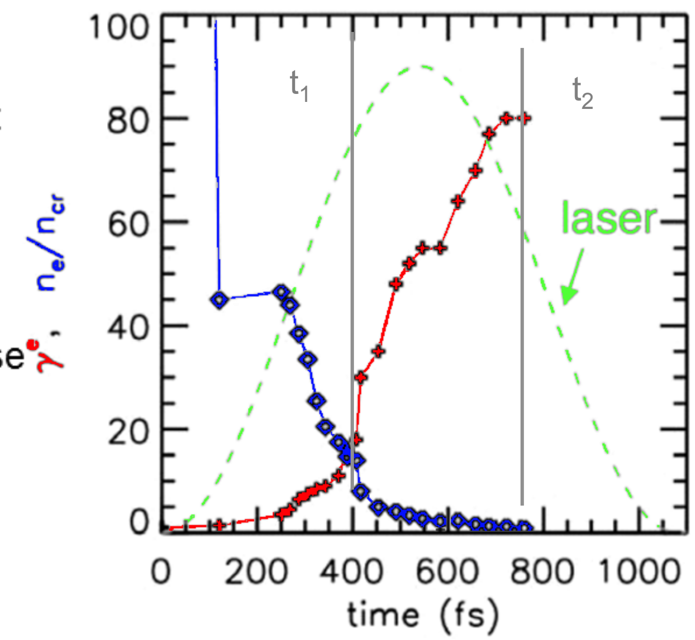

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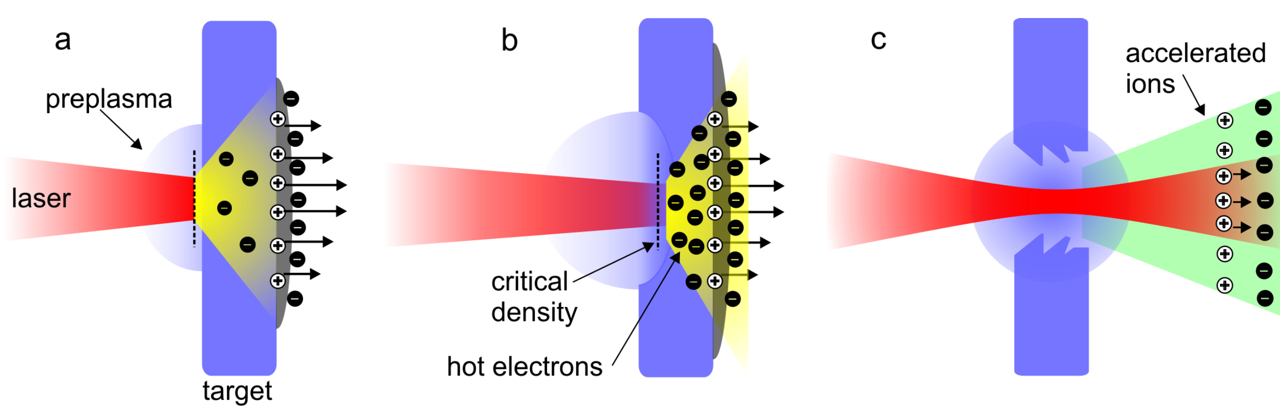

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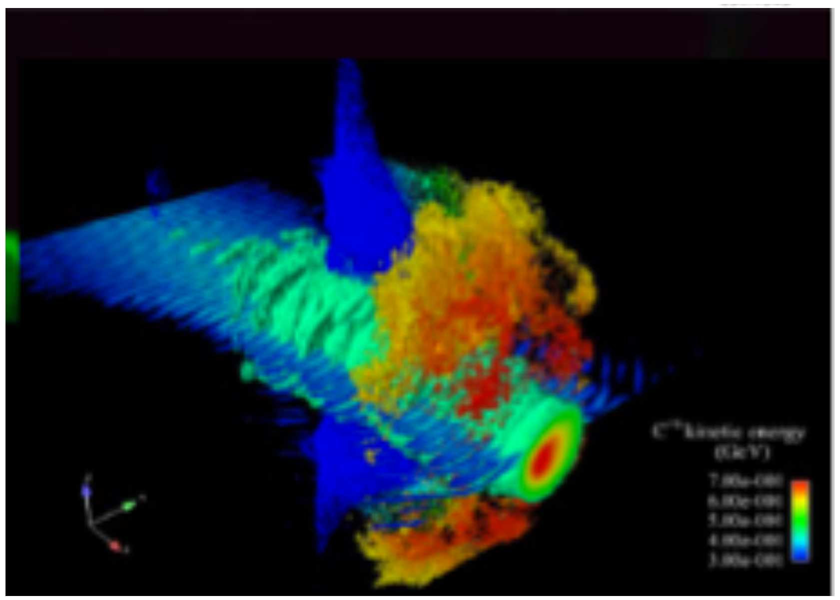

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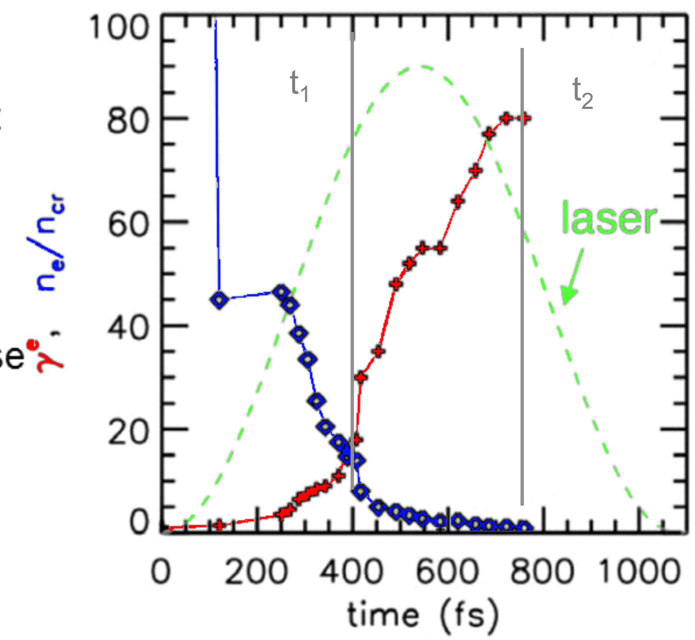

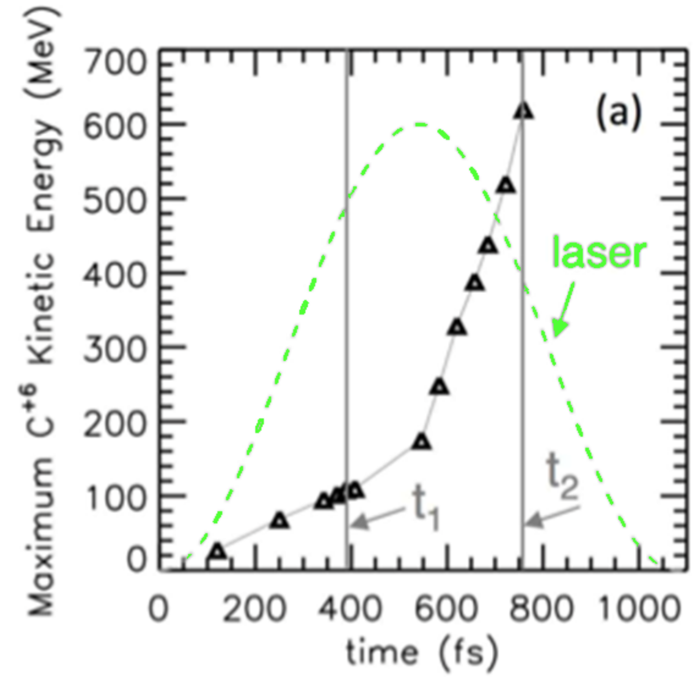

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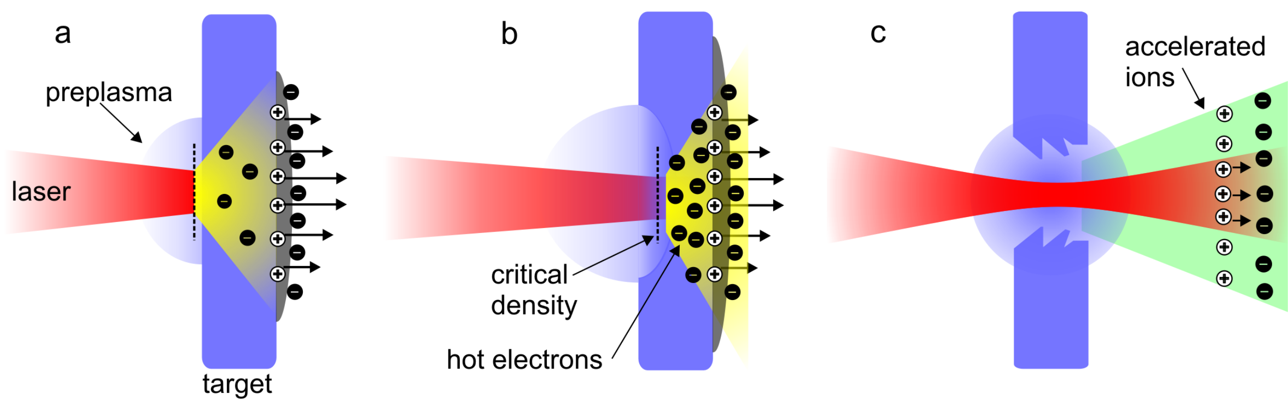

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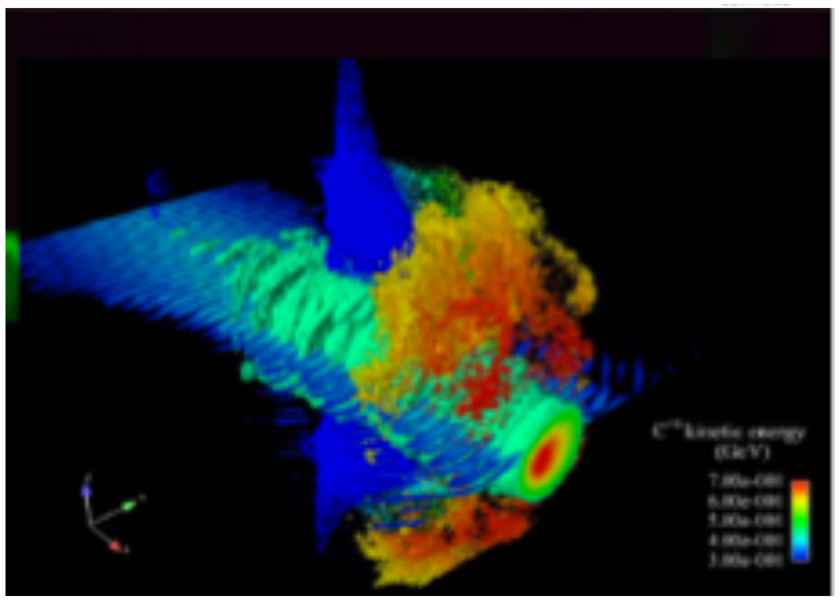

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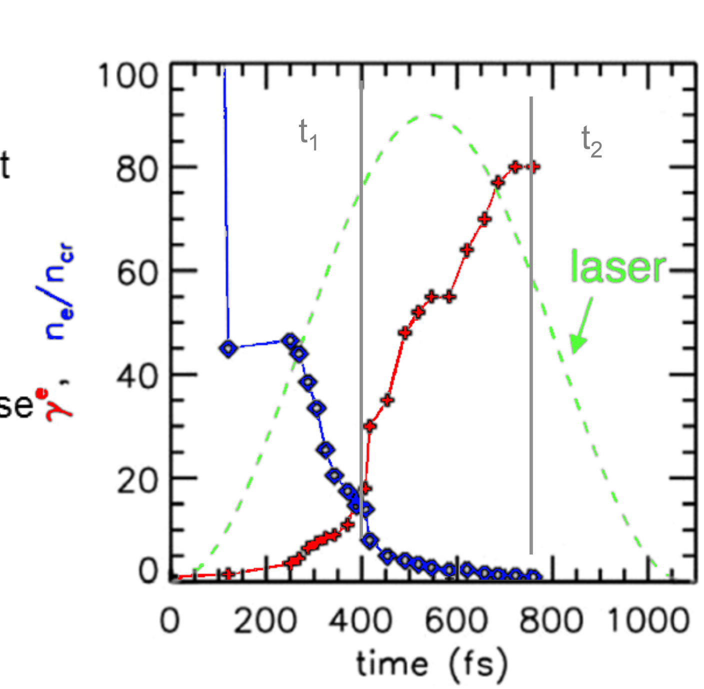

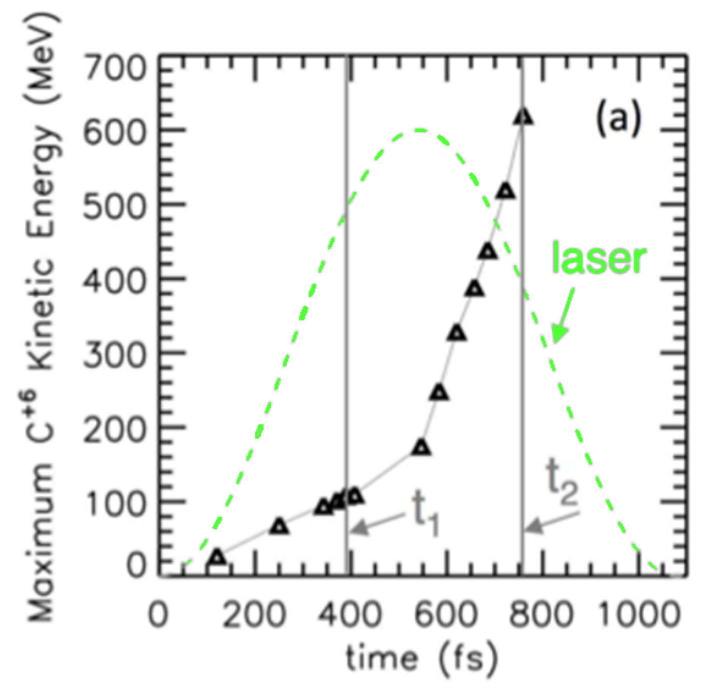

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Yin, et al., Laser and Particle Beams 24 (2006), 1–8
Yin, et al., Phys. Plasmas 14, 056706, (2007)
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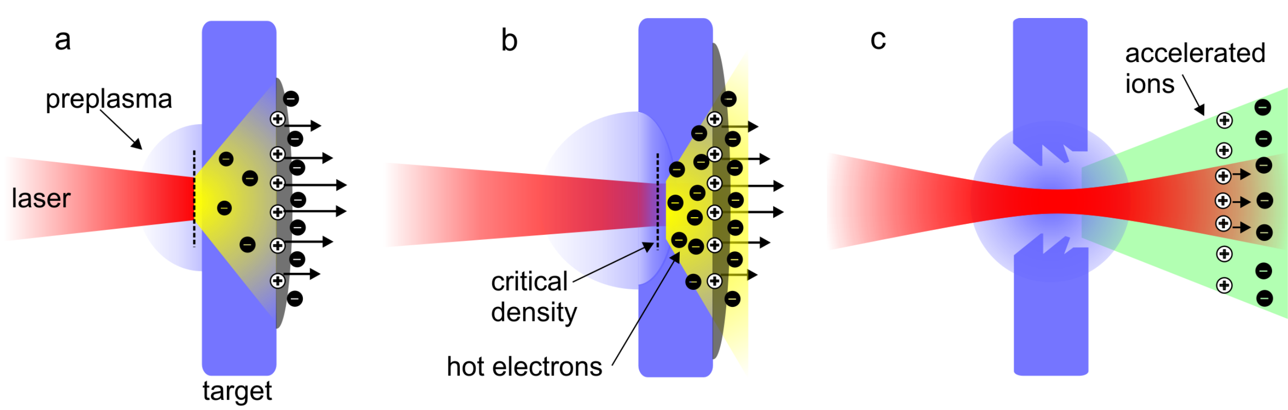

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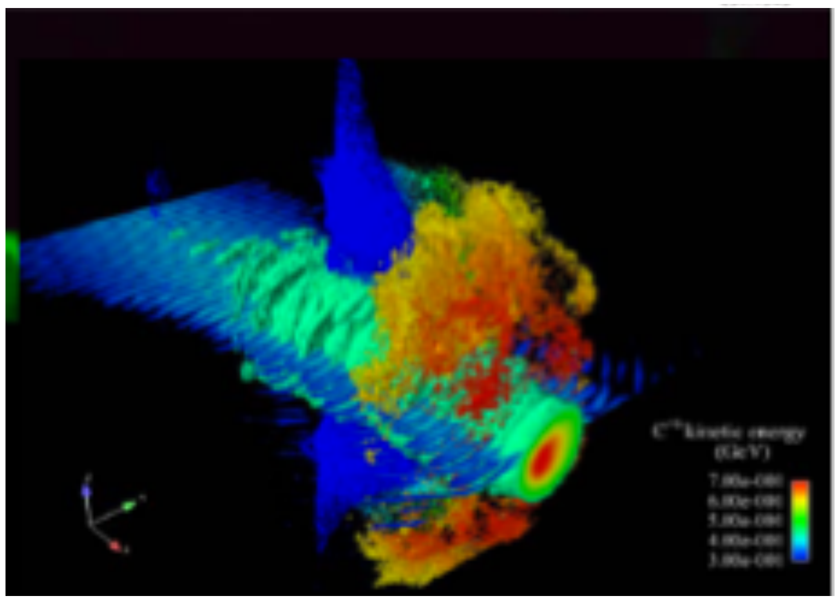

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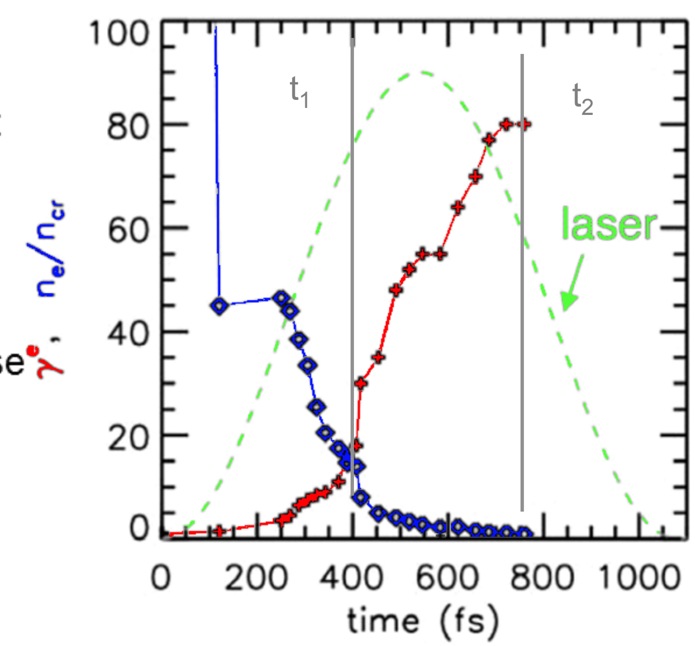

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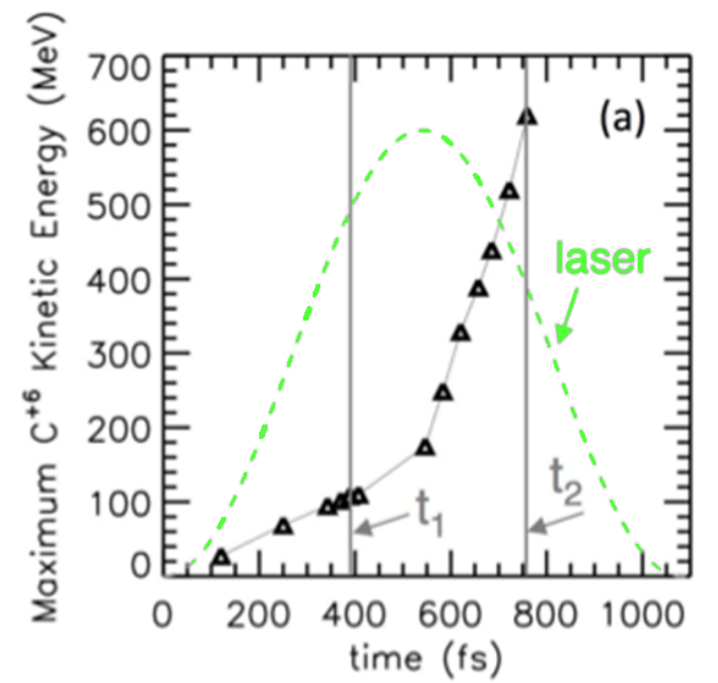

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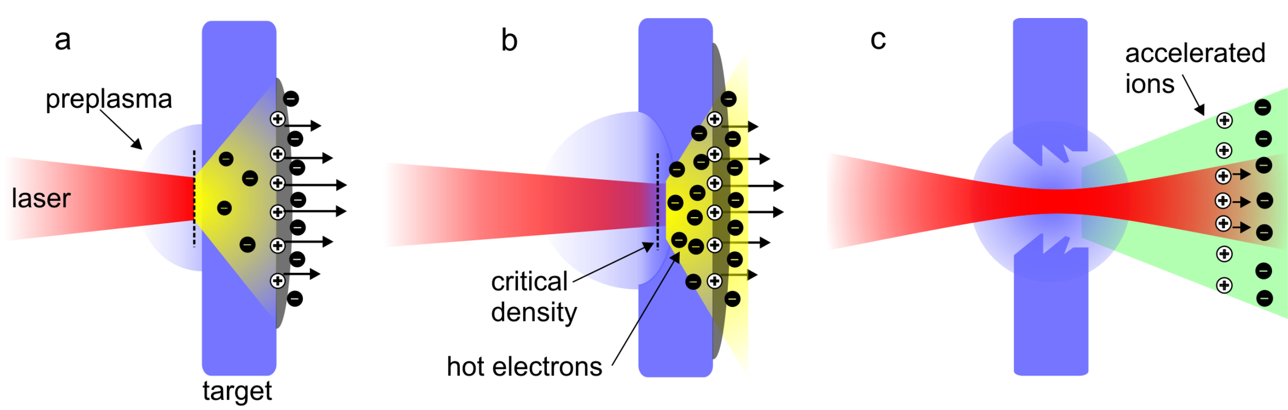

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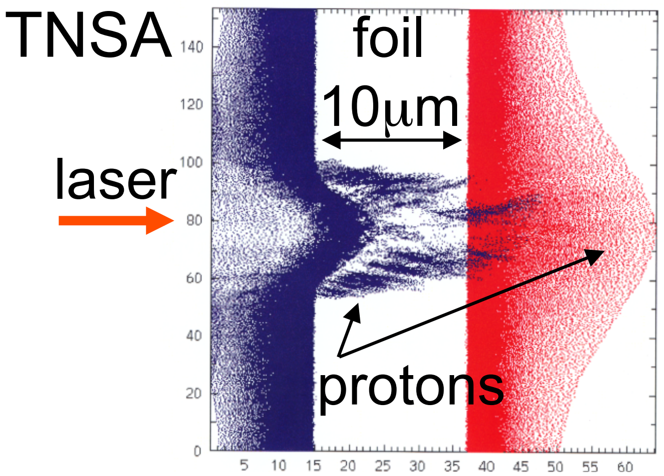
Max. energy	proton	carbon
Ideal laser	132 MeV	450 MeV
Real laser	121 MeV	447 MeV

VPIC: 100nm CH2 target & Trident laser with $2x10^{20}W/cm^2$

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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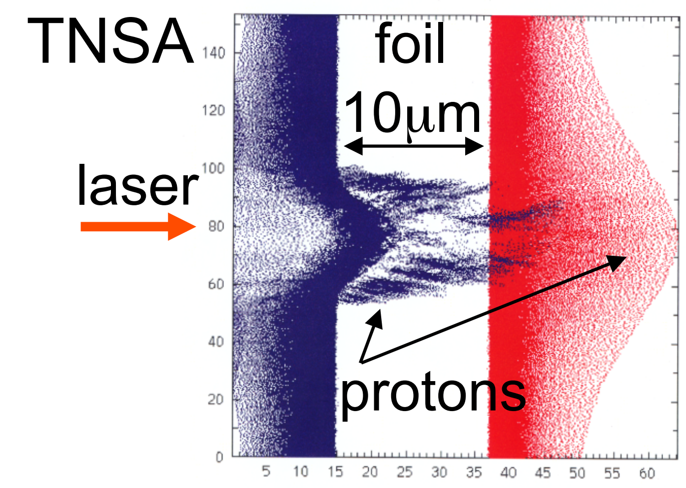

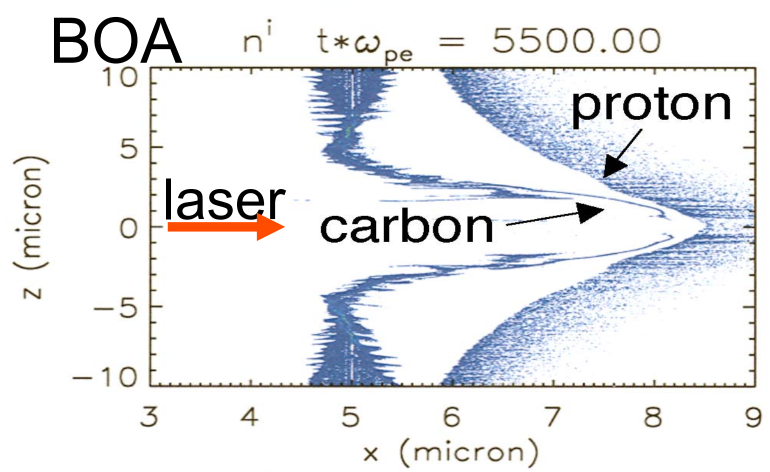

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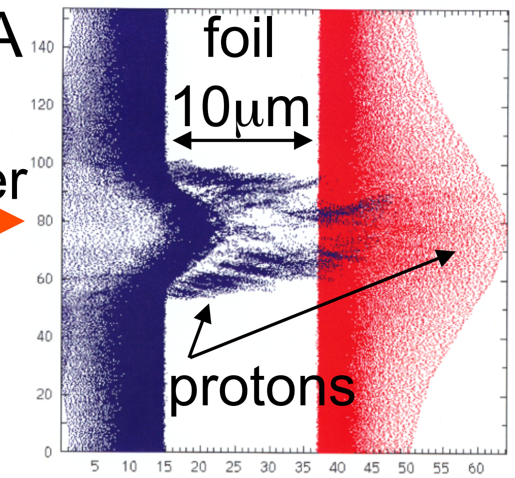
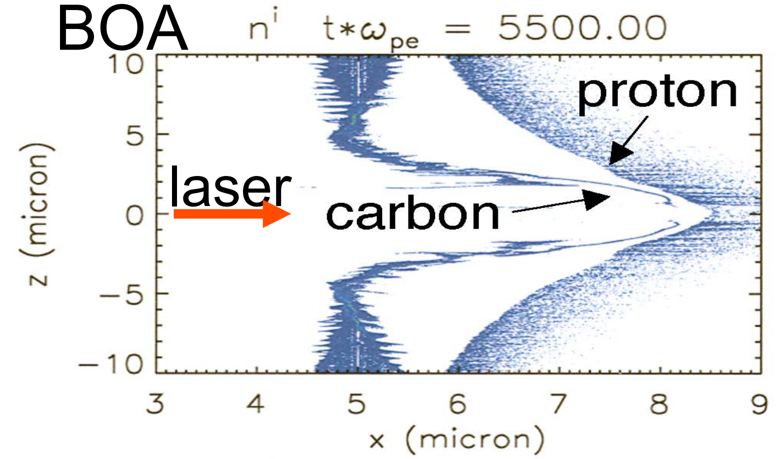
Radiation Pressure Acceleration, Aka Plasma Piston E.g., A.P.L. Robinson, *et al.,* New J. Phys. **10**, 013021 (2008)	RPA	Charge separation GeV protons? ✓ Circular Polar.

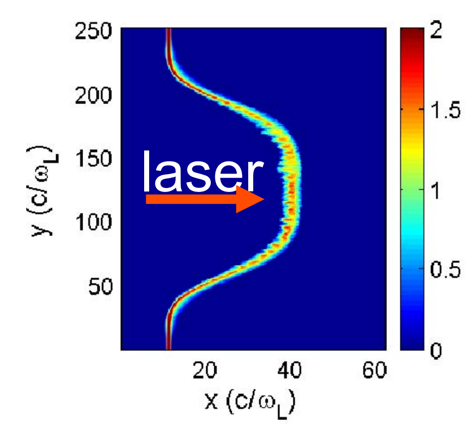
TNSA



BOA



RPA



Dependence on pulse duration

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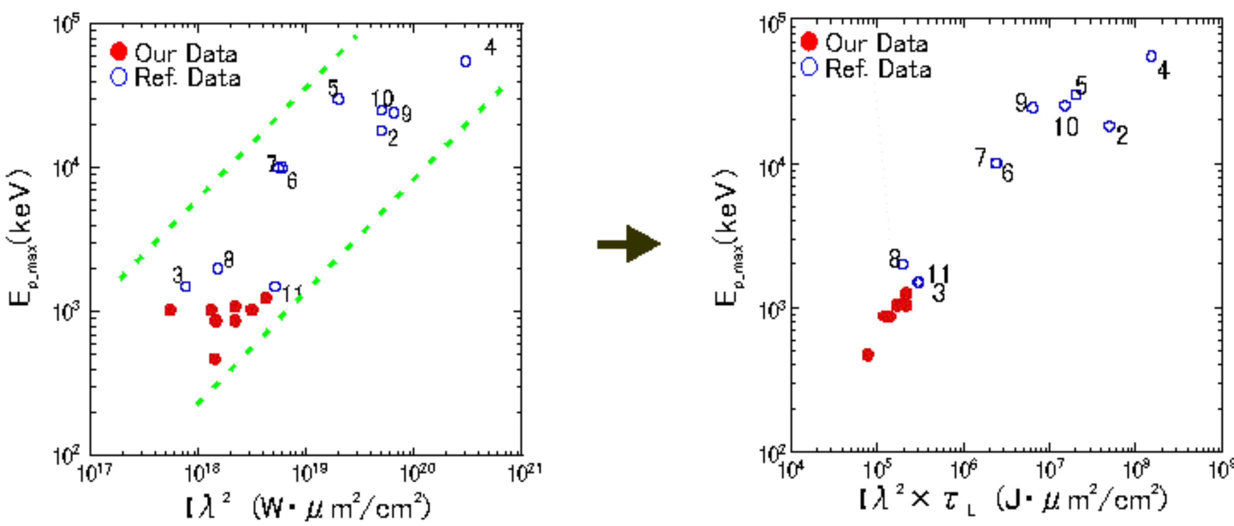
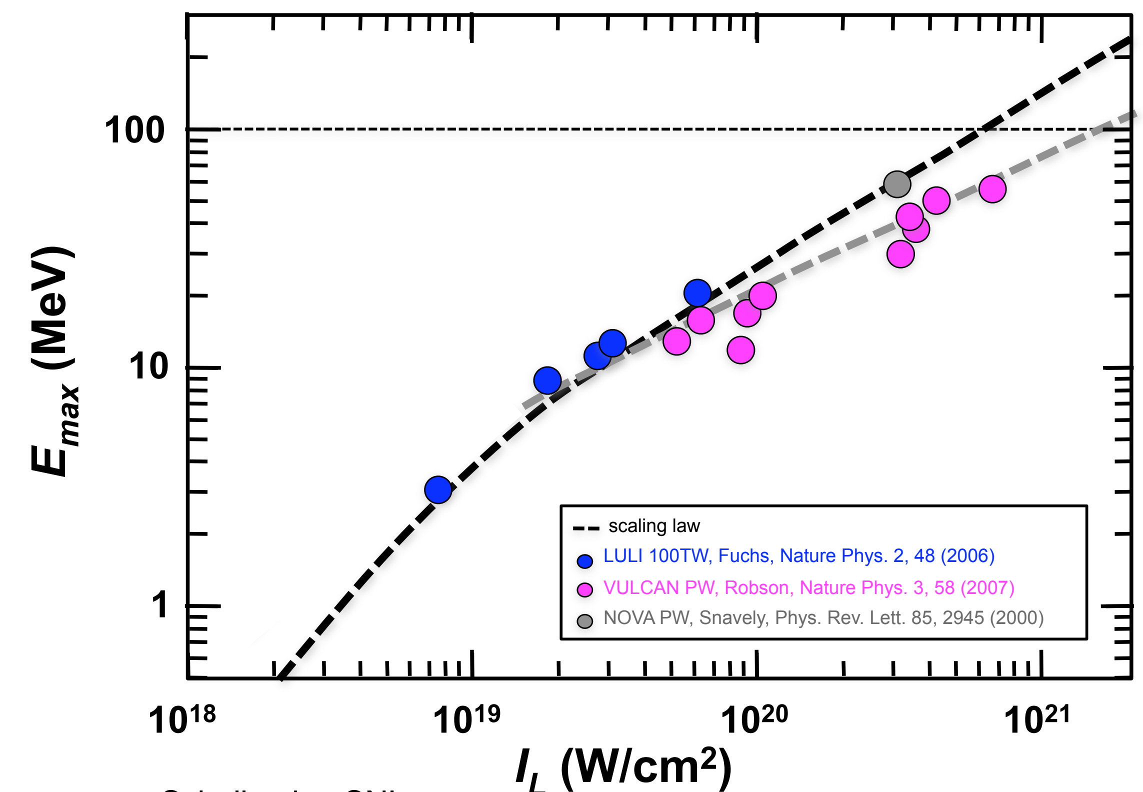
Comparison with other groups

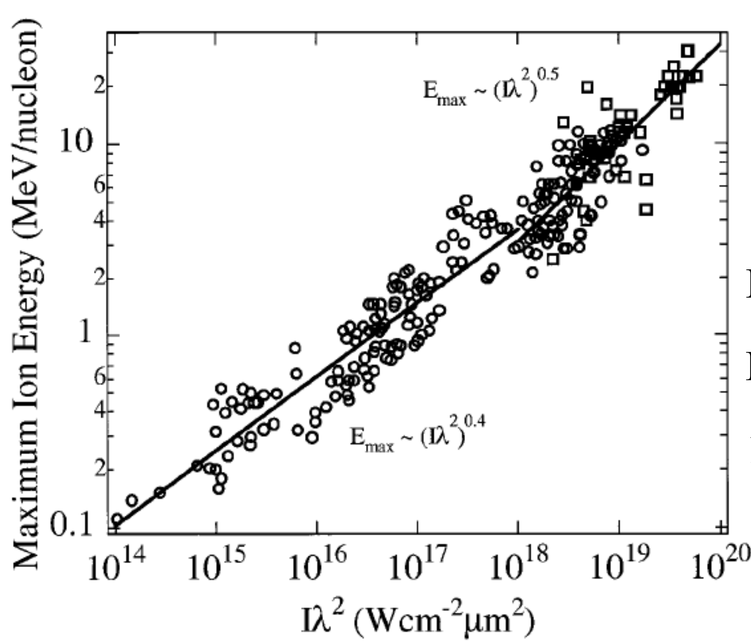


・Our results are mostly on the scaling line of $I\lambda^2$ vs E_{p_max}.
・However, a curve in $I\lambda^2 \times \tau_L - E_{p\_max}$ plane is more fit for our results. Other group's data are also on the curve.

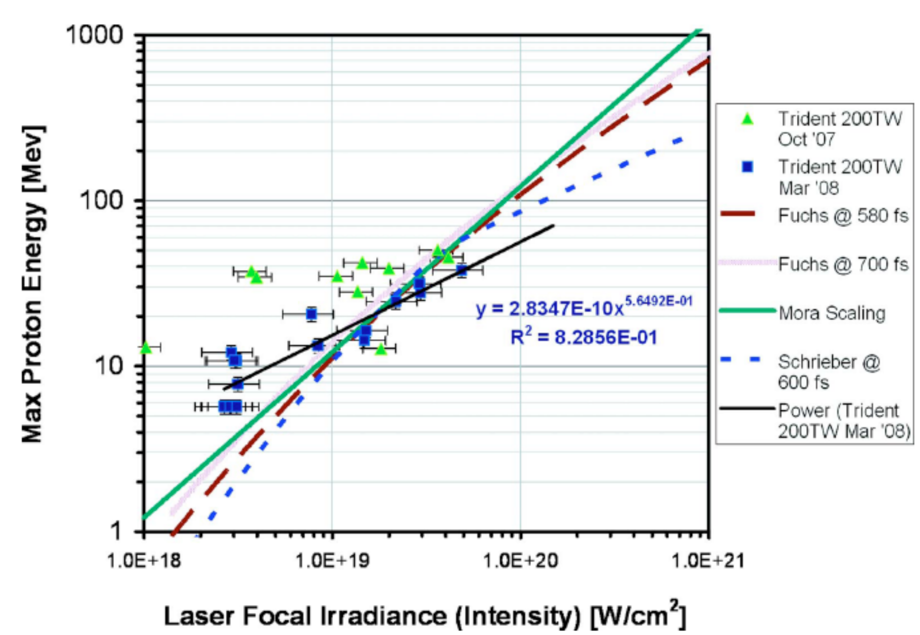
Oishi, Central Research Institute of Electrical Power Industry



Schollmeier, SNL



E. L. Clark *et al*., Phys. Rev. Lett. **85**, 1654 (2000)



K. A. Flippo *et al*. Rev. Sci. Instrum. **79**, 10E534 (2008);

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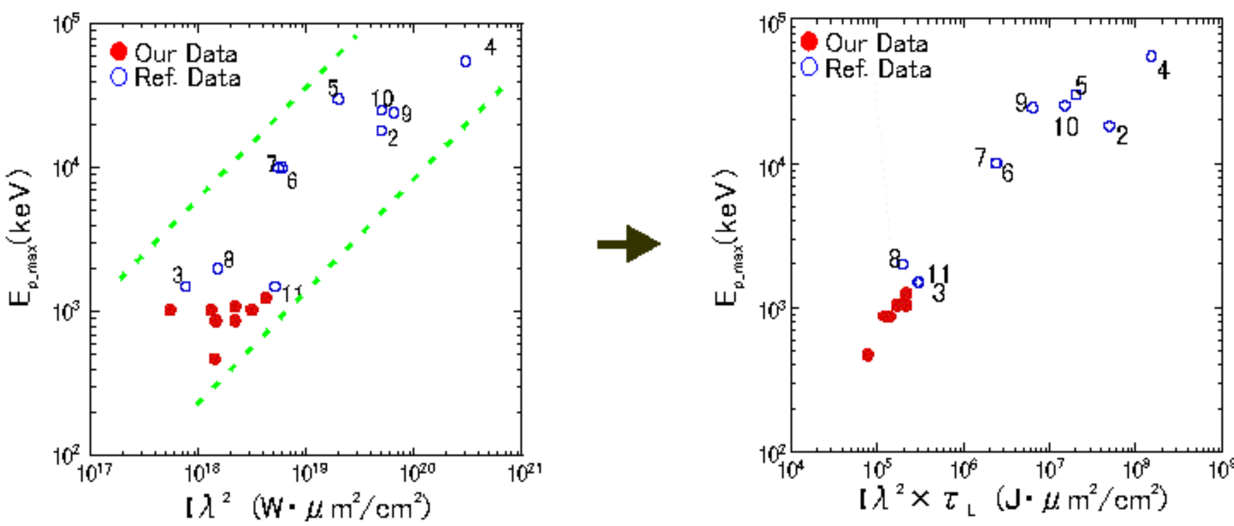
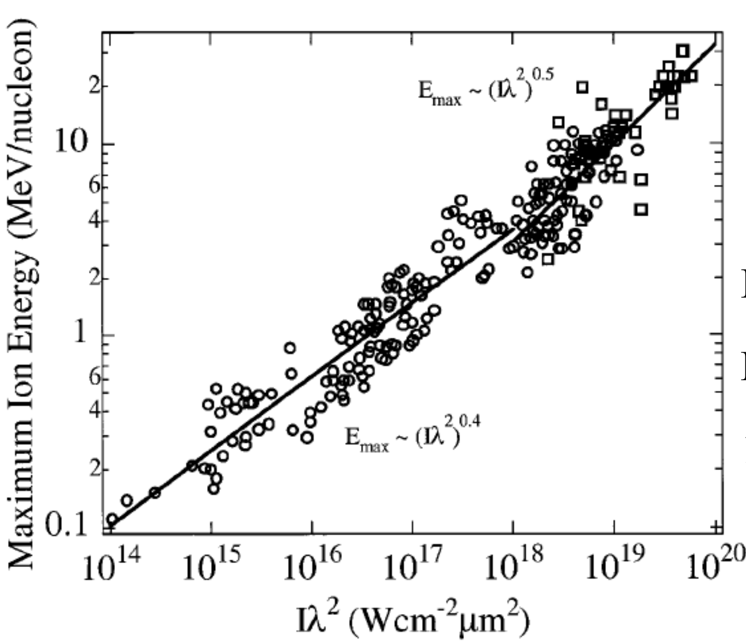
Comparison with other groups

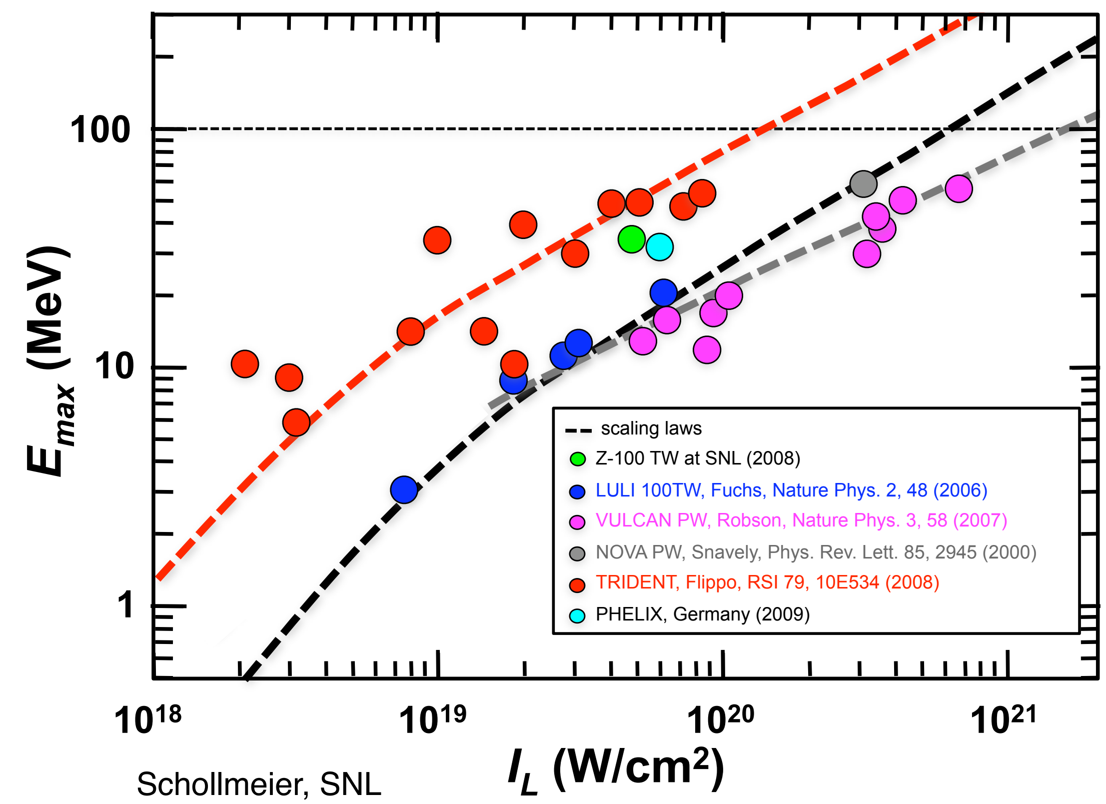


・Our results are mostly on the scaling line of $I\lambda^2$ vs E_{p_max}.
・However, a curve in $I\lambda^2 \times \tau_L - E_{p\_max}$ plane is more fit for our results. Other group's data are also on the curve.

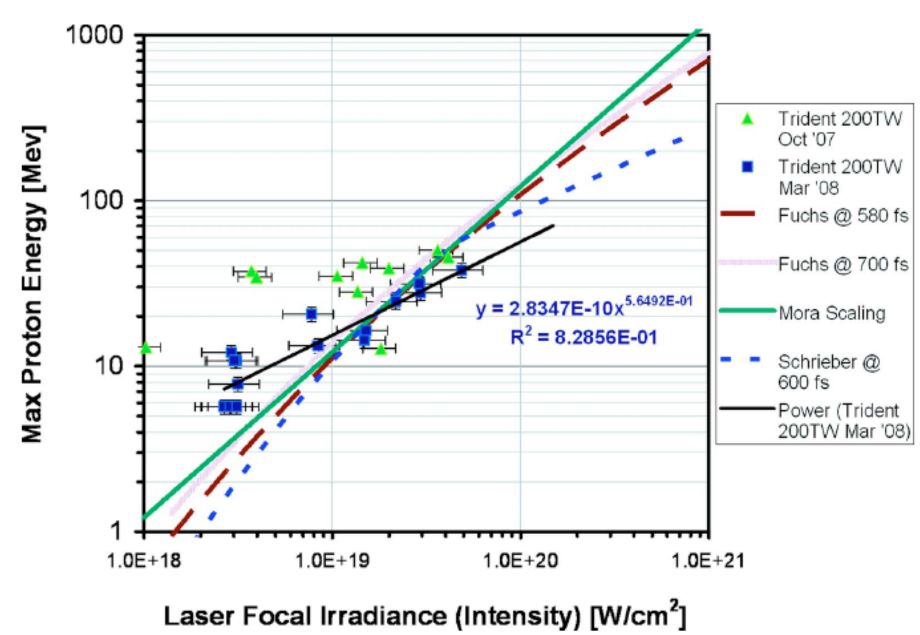
Oishi, Central Research Institute of Electrical Power Industry



E. L. Clark *et al*., Phys. Rev. Lett. **85**, 1654 (2000)

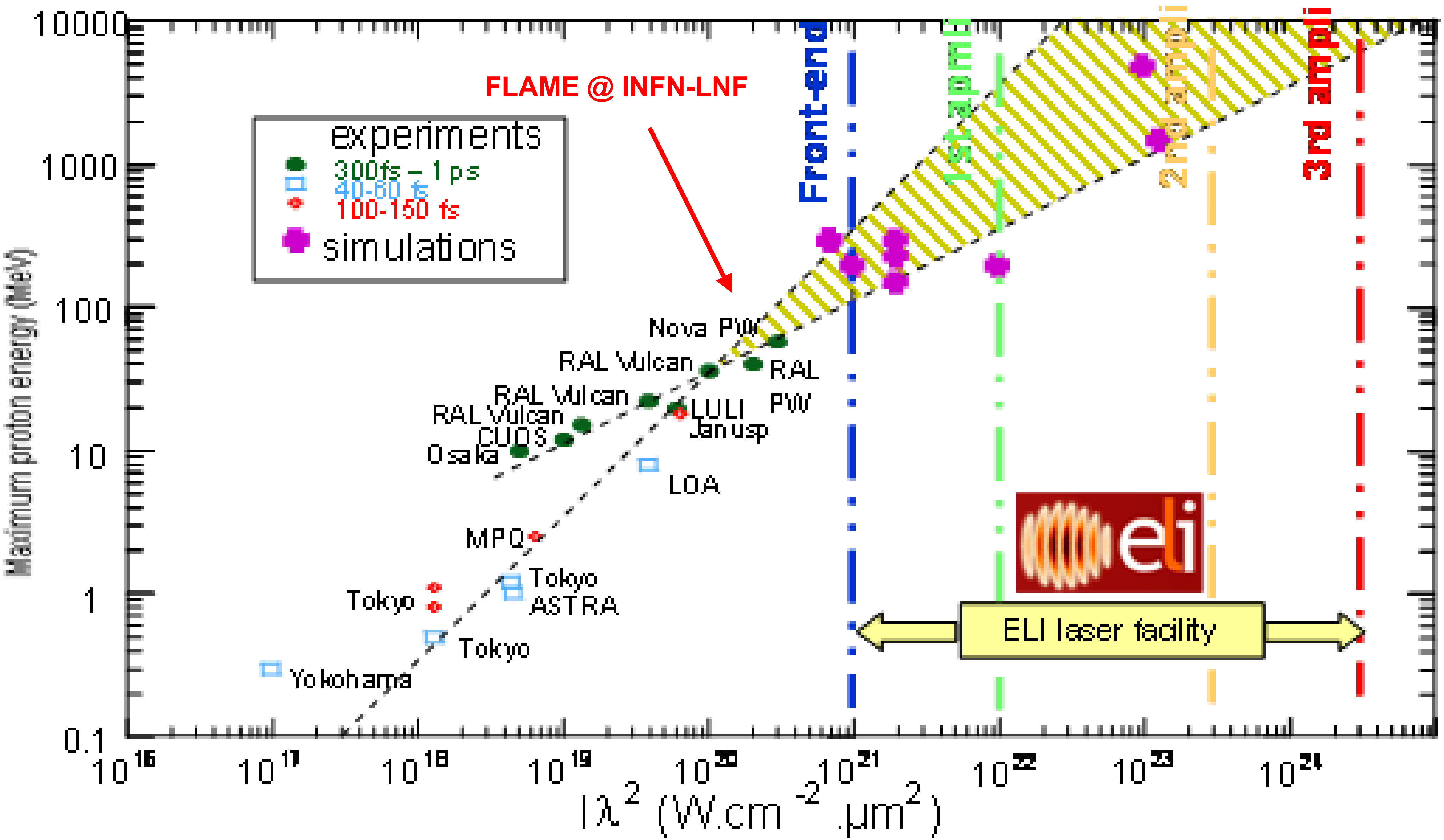


Schollmeier, SNL

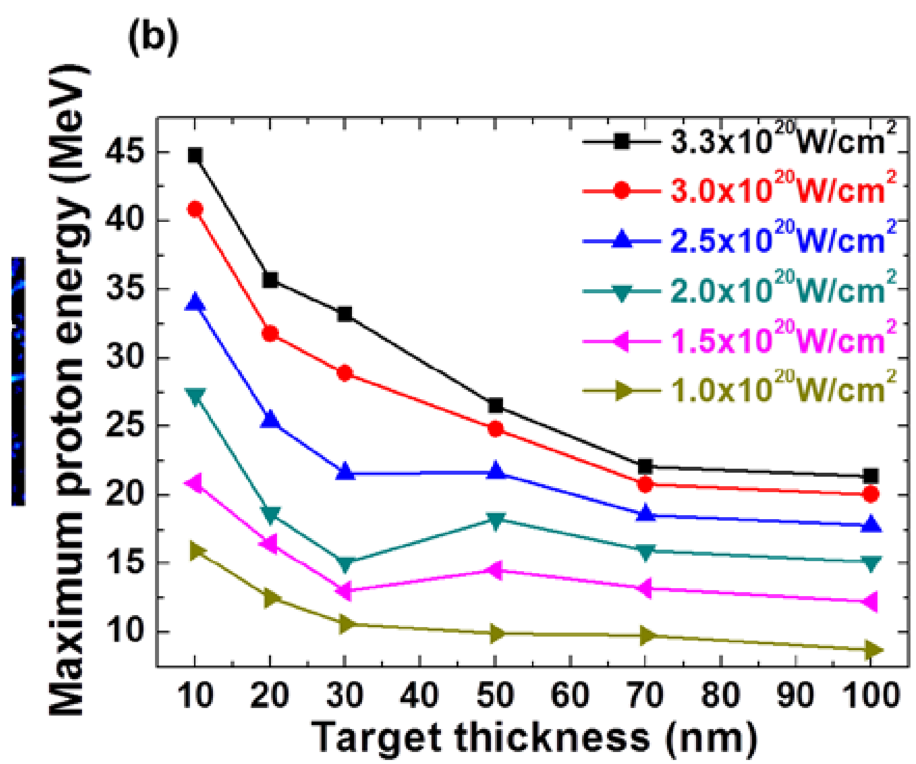


K. A. Flippo *et al*. Rev. Sci. Instrum. **79**, 10E534 (2008);

Dependence on pulse intensity



Dependence on target thickness



I Jong Kim, Advanced Photonics Research Institute, GIST, Gwangju 500-712, Korea

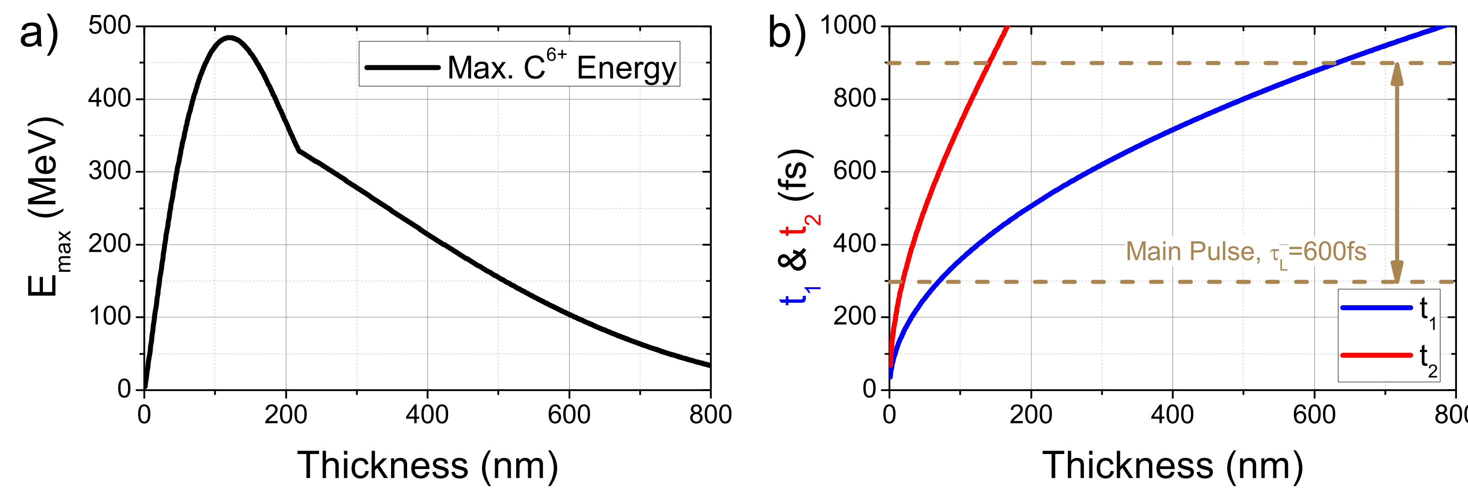
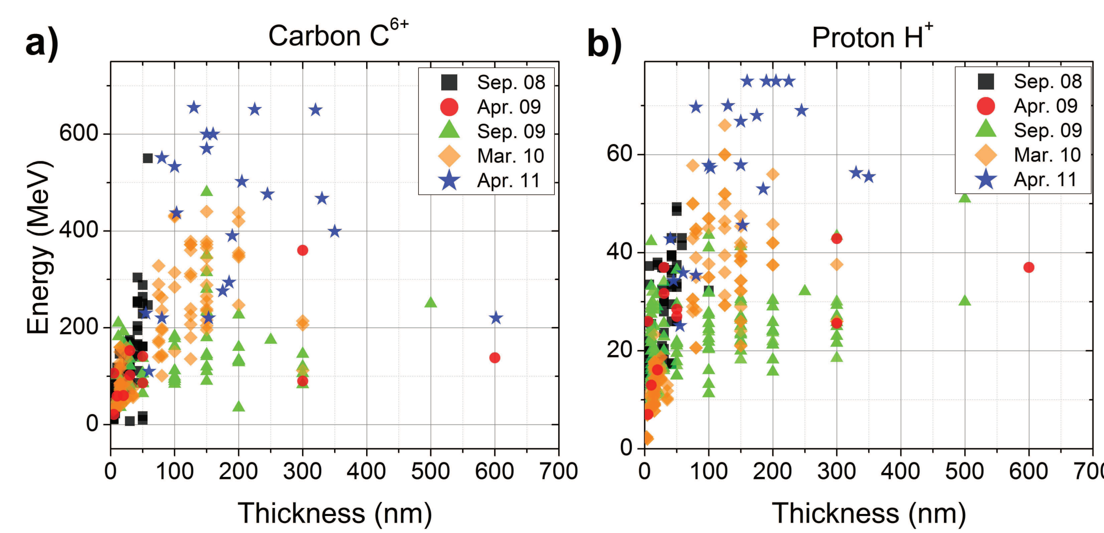


Figure 2.8: Model prediction a) of the maximum carbon C^{6+} energy vs. Thickness for Trident parameters with $\tau_\lambda = 600\,\text{fs}$, $E_L = 80\,\text{J}$, $n_0' = 660$, $q_i = 6$ for carbon C^{6+} and $a(t) = a_0 \sin^2(\pi t/2\tau_\lambda)$, with $a_0 = 16.8$; b) BOA acceleration times t_1 and t_2 for the same parameters



taken from D. Jung Dissertation
Munich 2012

Figure 4.3: Experimental data of 5 of the 6 campaigns showing the efforts in improving repeatability and accuracy of the measured maximum carbon C^{6+}ion a) and proton b) energies. The campaigns from Apr.08 through Mar.10 were done in the TP-setup, the last one in the iWASP-setup that covers a much larger solid angle of the ion beam. Campaigns from Mar.10 on also used the improved target and focusing system as described in Chap. 3.3.

Energy and pulse length scaling (BOA)

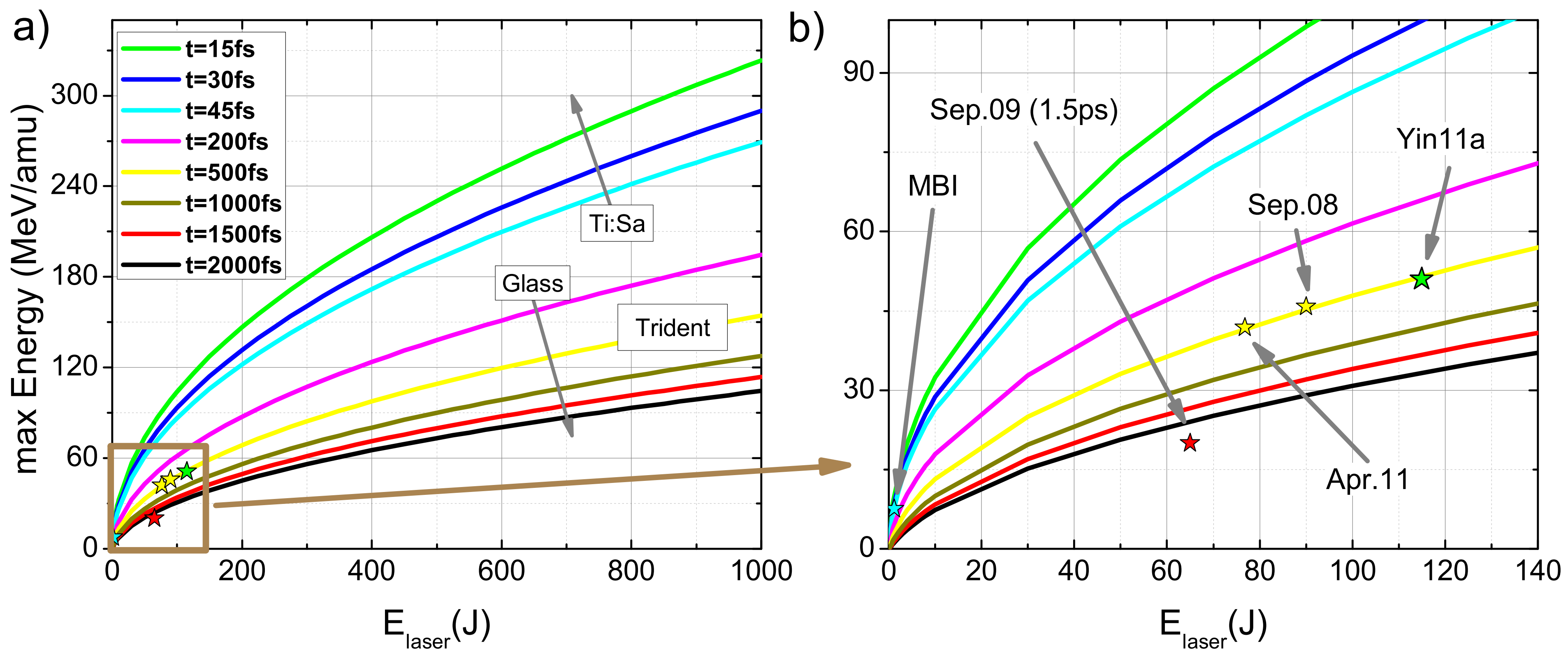
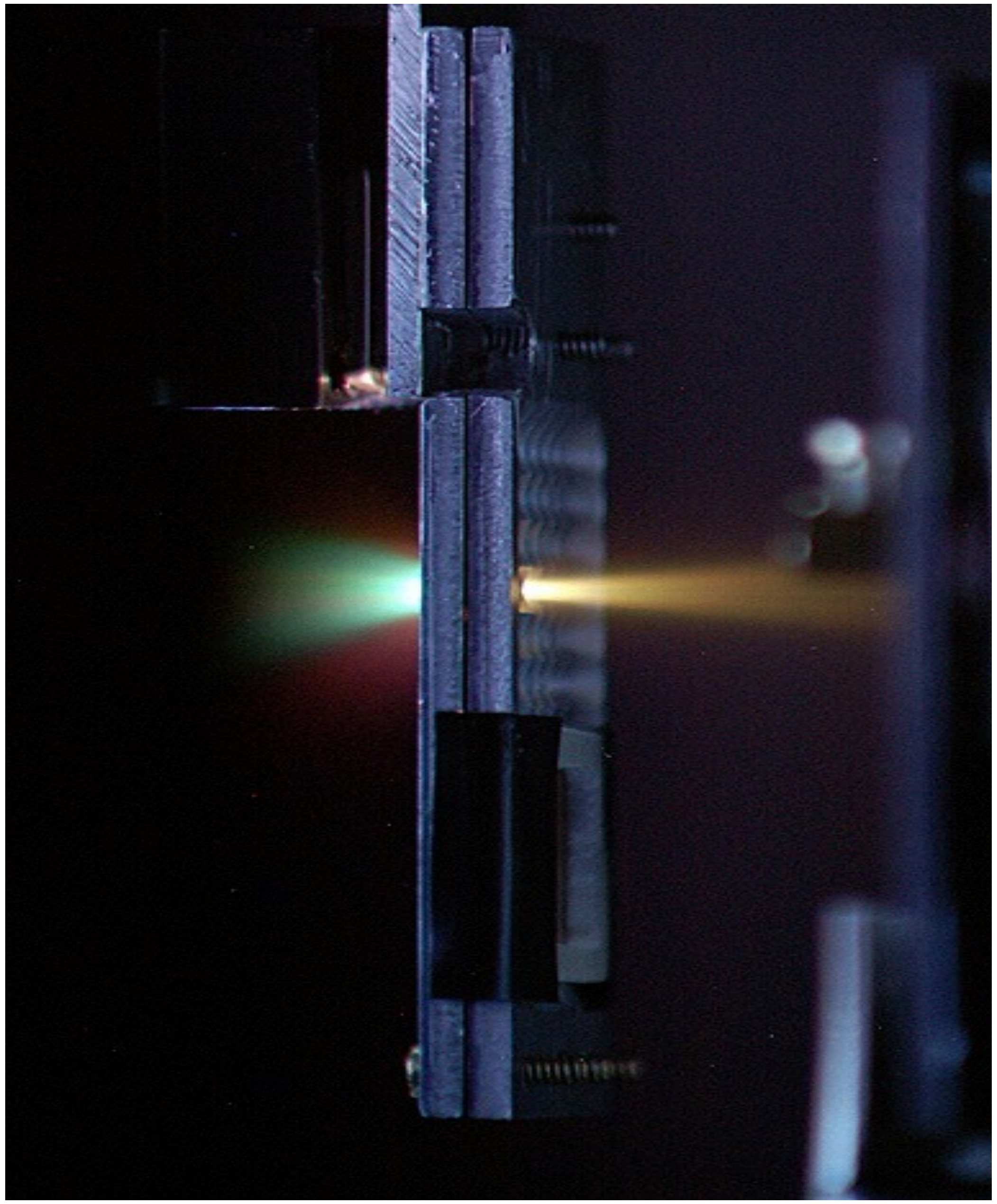


Figure 4.21: a) Pulse duration dependency of the BOA mechanism. Green, blue and light blue solid lines represent typical Ti:Sa pulse durations with 15 fs to 45 fs; the remaining lines correspond to Glass laser systems with pulse durations > 100 fs. The yellow stars are experimental results from Trident, the green star marked with "Yin11" is the result of a 2D VPIC simulation with Trident parameters [106]. The red star is obtained at Trident with a pulse duration of 1.5 ps. The blue star represents experimental results obtained at the MBI in Berlin [87]. b) zoomed in view of the brown rectangle in a) showing laser energies accessible with Trident

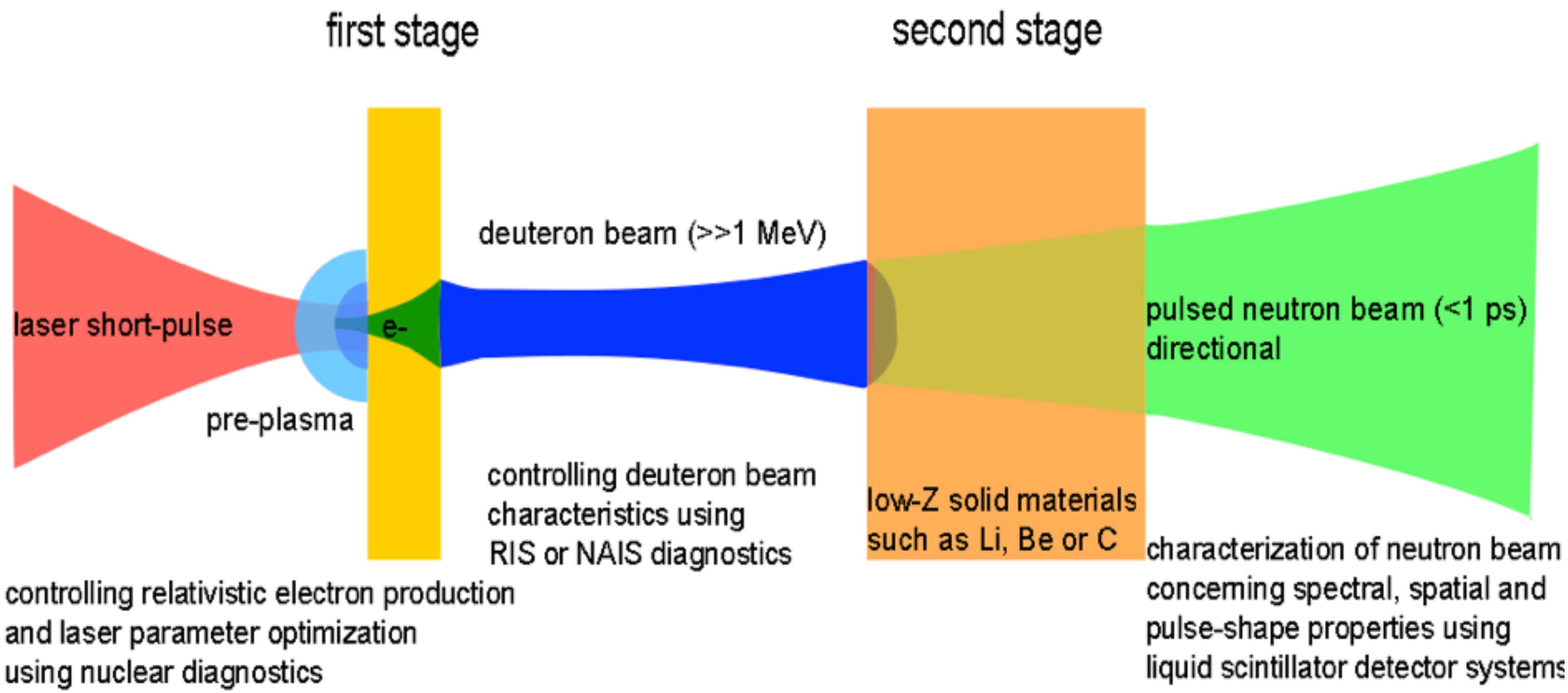
taken from D. Jung Dissertation
Munich 2012

What to do with LIA?

What to do with LIA?



What to do with LIA?



Why neutrons?

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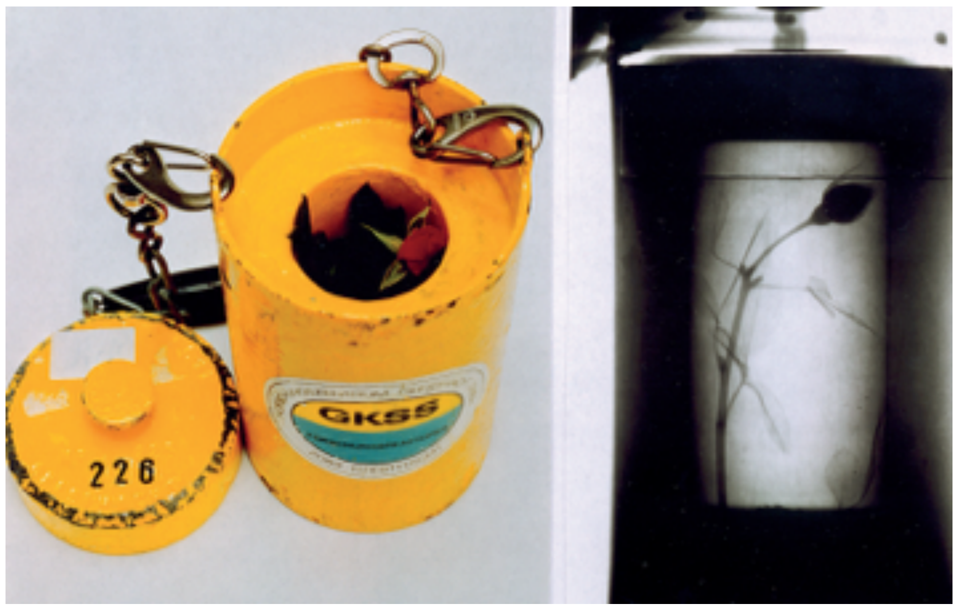
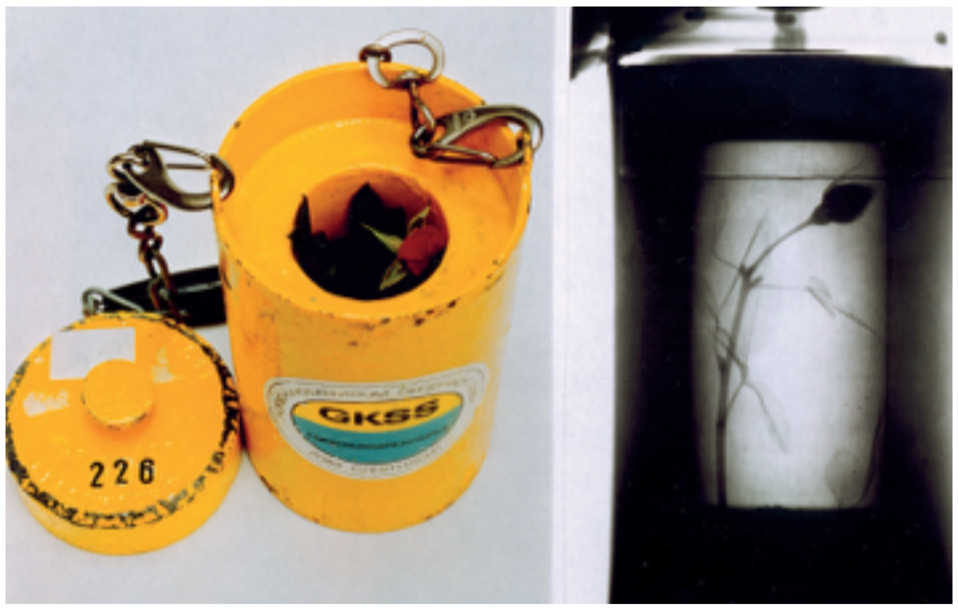
Highly penetrating



GKSS, Geesthacht

Why neutrons?

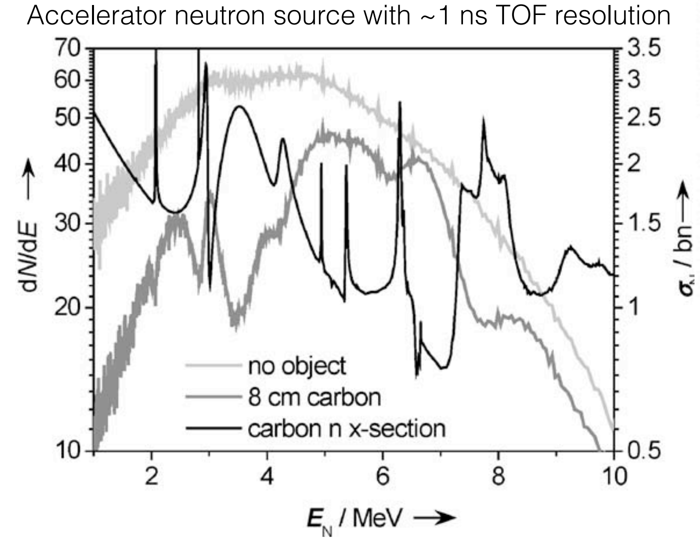
Highly penetrating



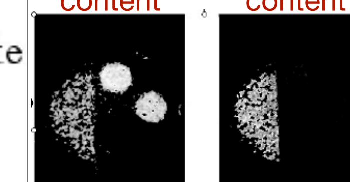
GKSS, Geesthacht

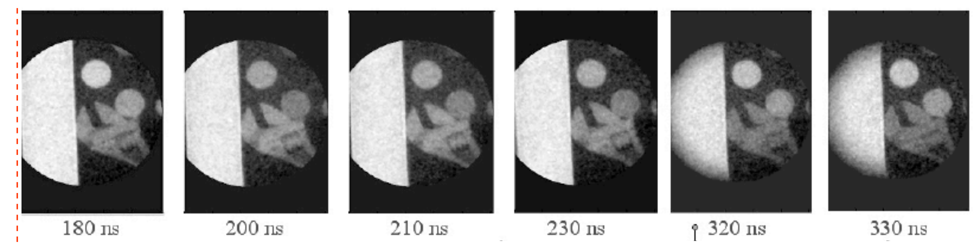
Material selective (fast neutron radiography)

Accelerator neutron source with ~1 ns TOF resolution



Ishay Pomerantz / U. Texas





Vartsky, D. et al. Nuclear Instruments and Methods A623, 603–605 (2010)

Why neutrons?

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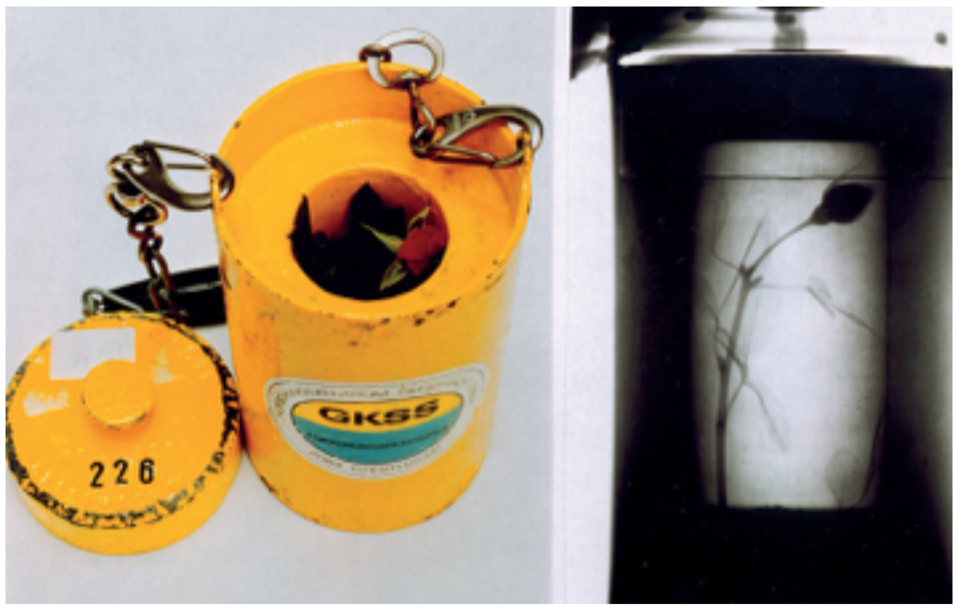
Highly penetrating



GKSS, Geesthacht

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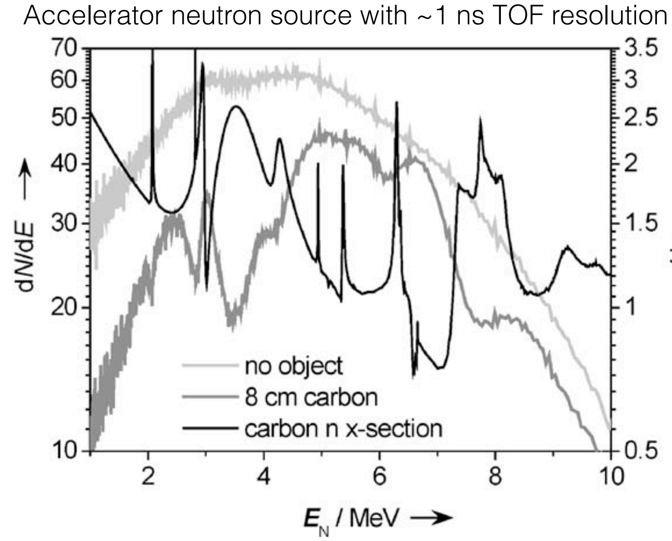
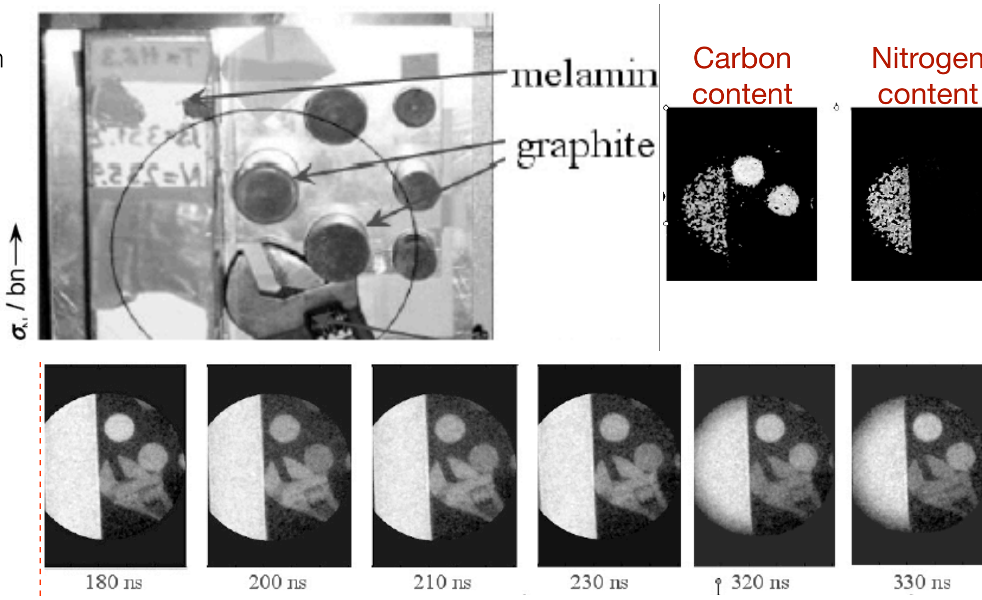
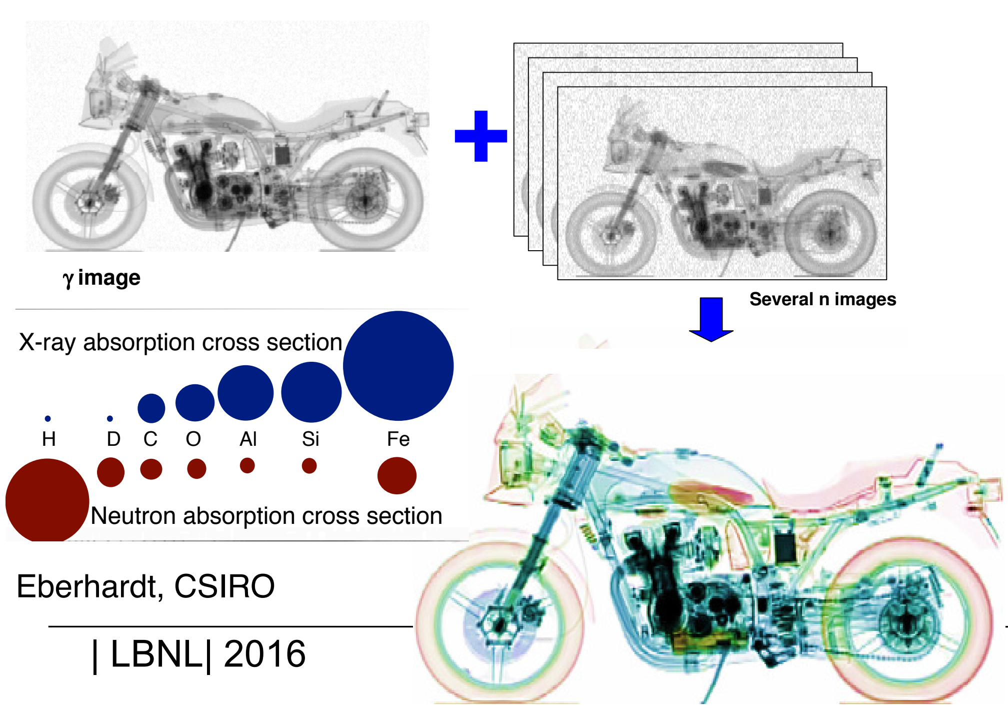


Ishay Pomerantz / U. Texas



Vartsky, D. et al. Nuclear Instruments and Methods A623, 603–605 (2010)

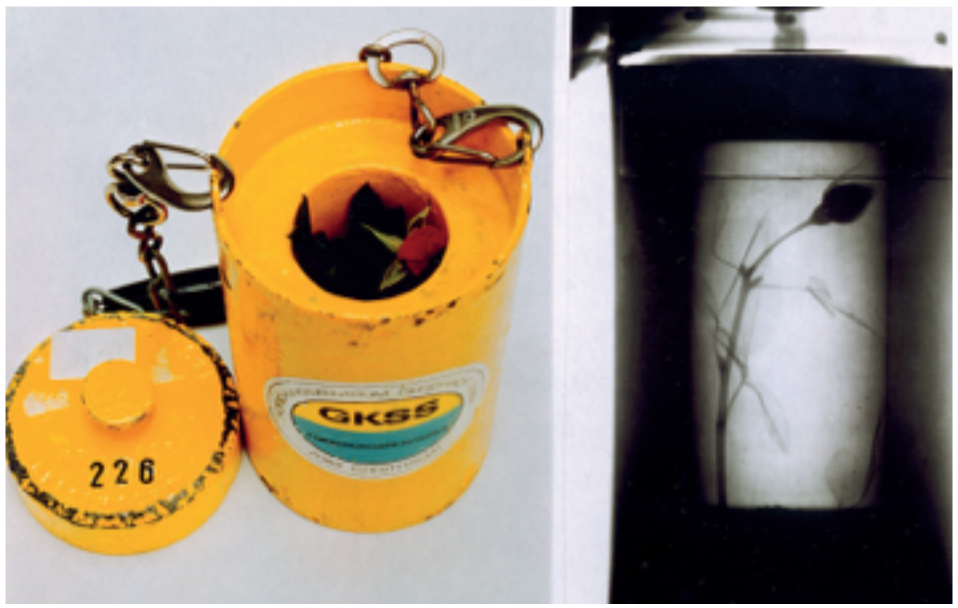
Complementary to X-rays



Eberhardt, CSIRO

Why neutrons?

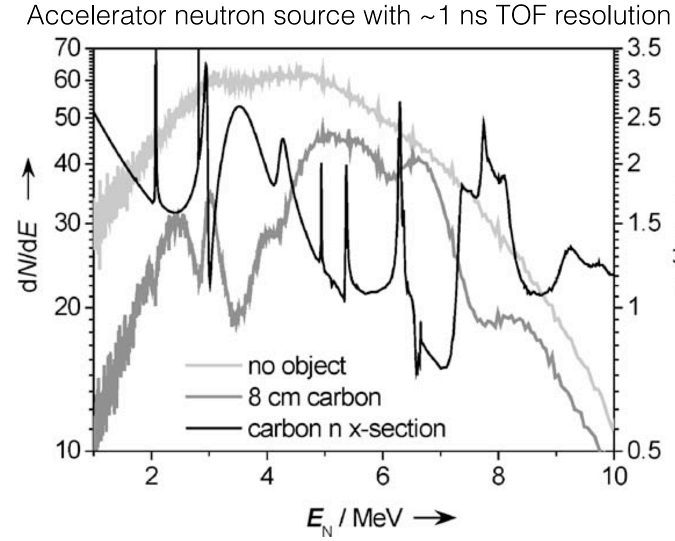
Highly penetrating



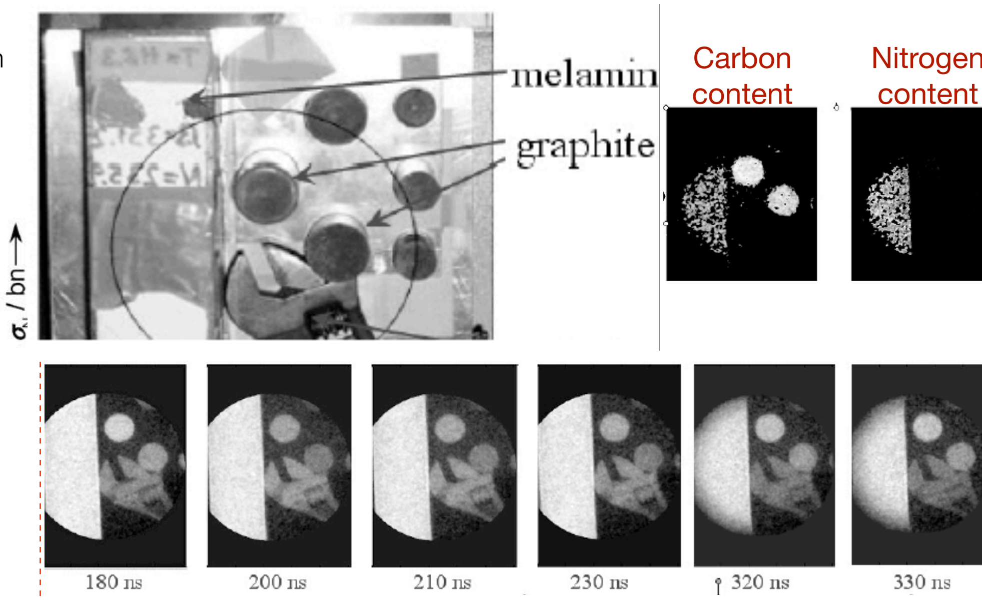
GKSS, Geesthacht

Material selective (fast neutron radiography)

Accelerator neutron source with ~1 ns TOF resolution

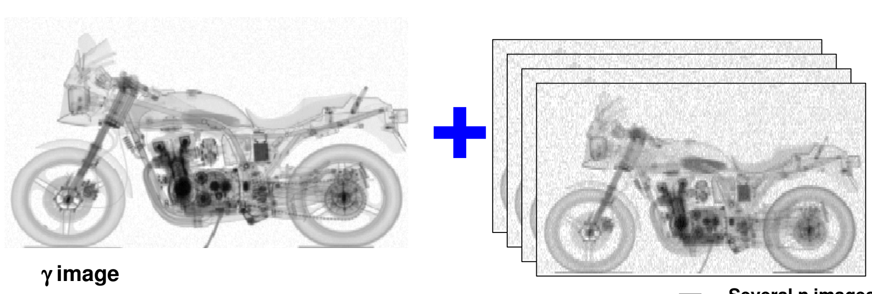


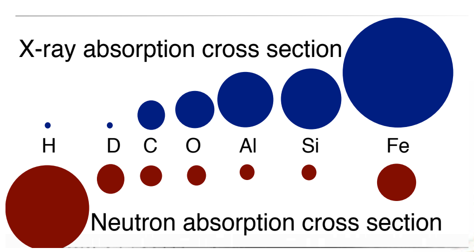
Ishay Pomerantz / U. Texas

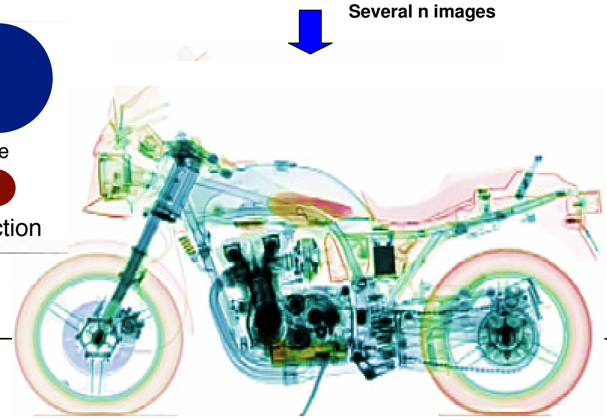


Vartsky, D. et al. Nuclear Instruments and Methods A623, 603–605 (2010)

Complementary to X-rays

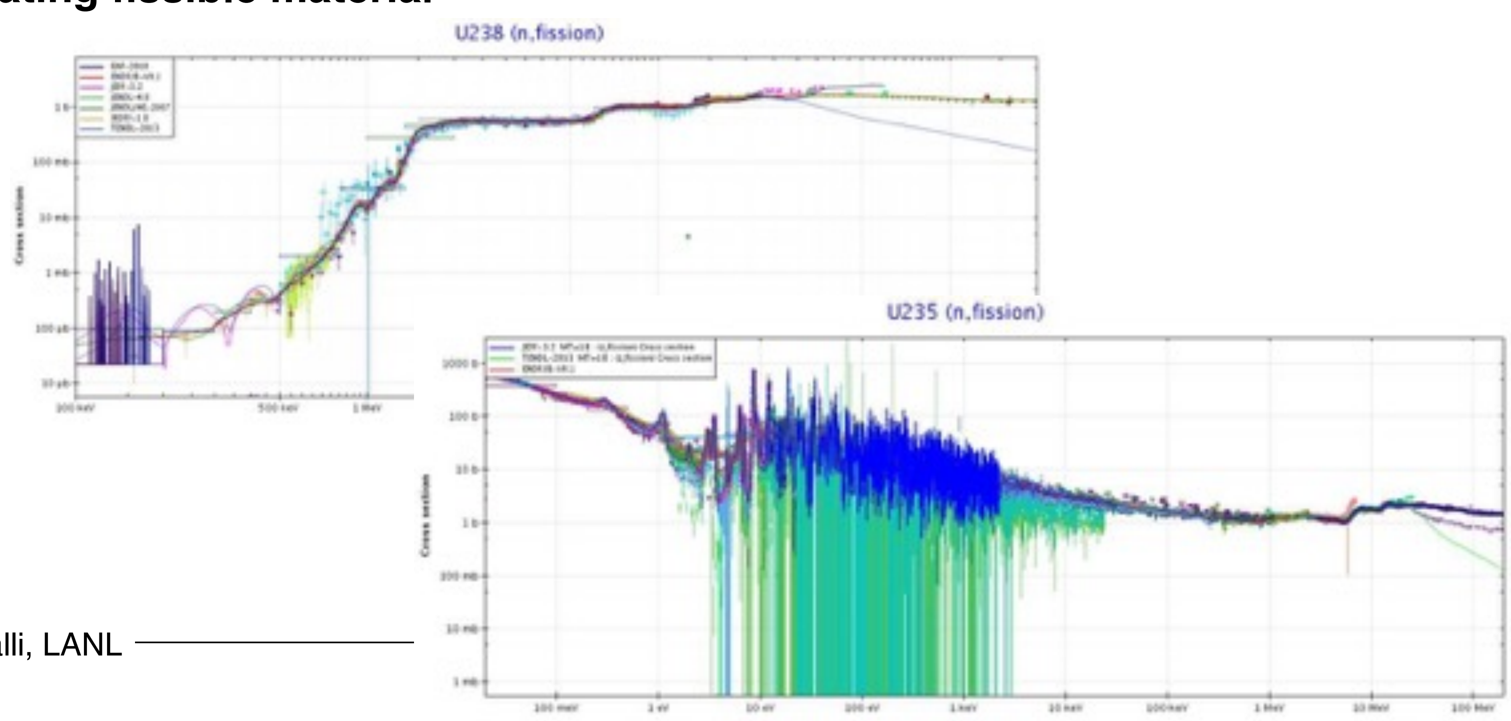






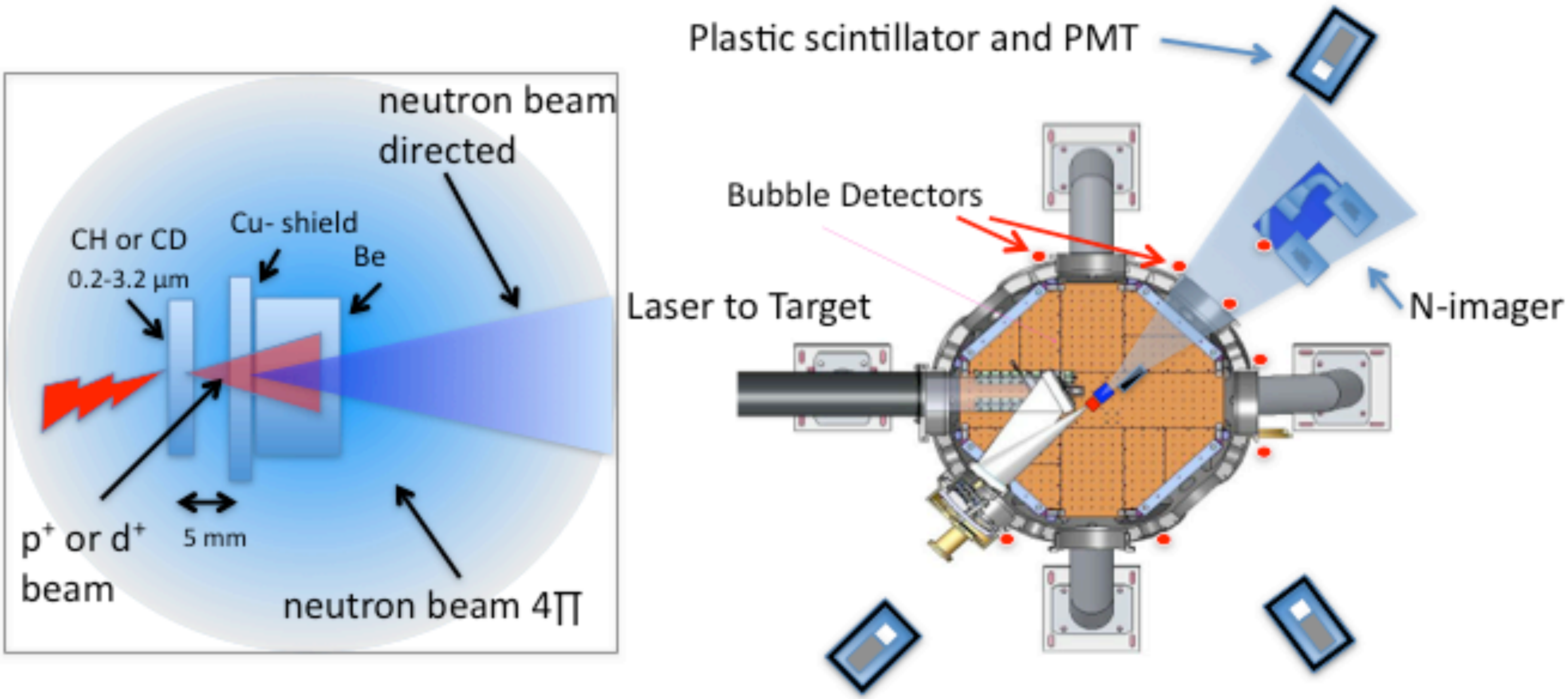
Eberhardt, CSIRO

Activating fissible material



A. Favalli, LANL

Experimental setup



For both campaigns there is a strong optimum in target thickness, as expected for BOA

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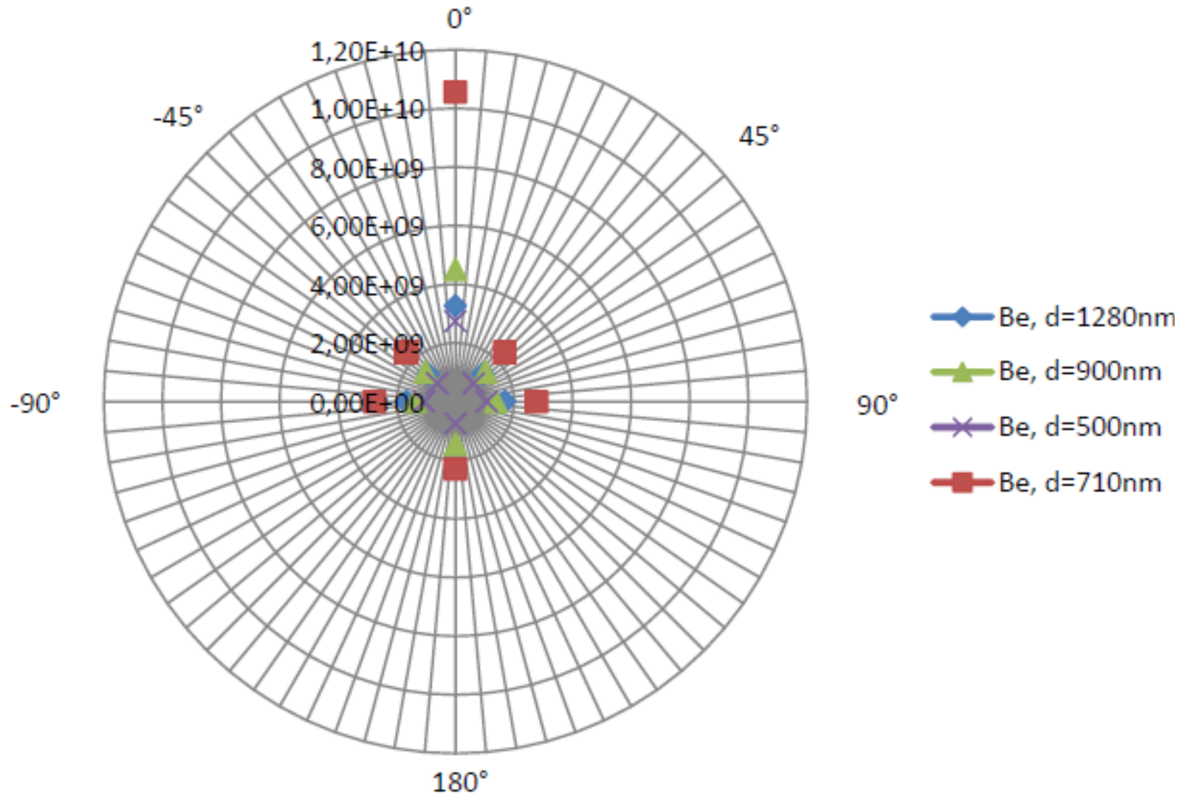
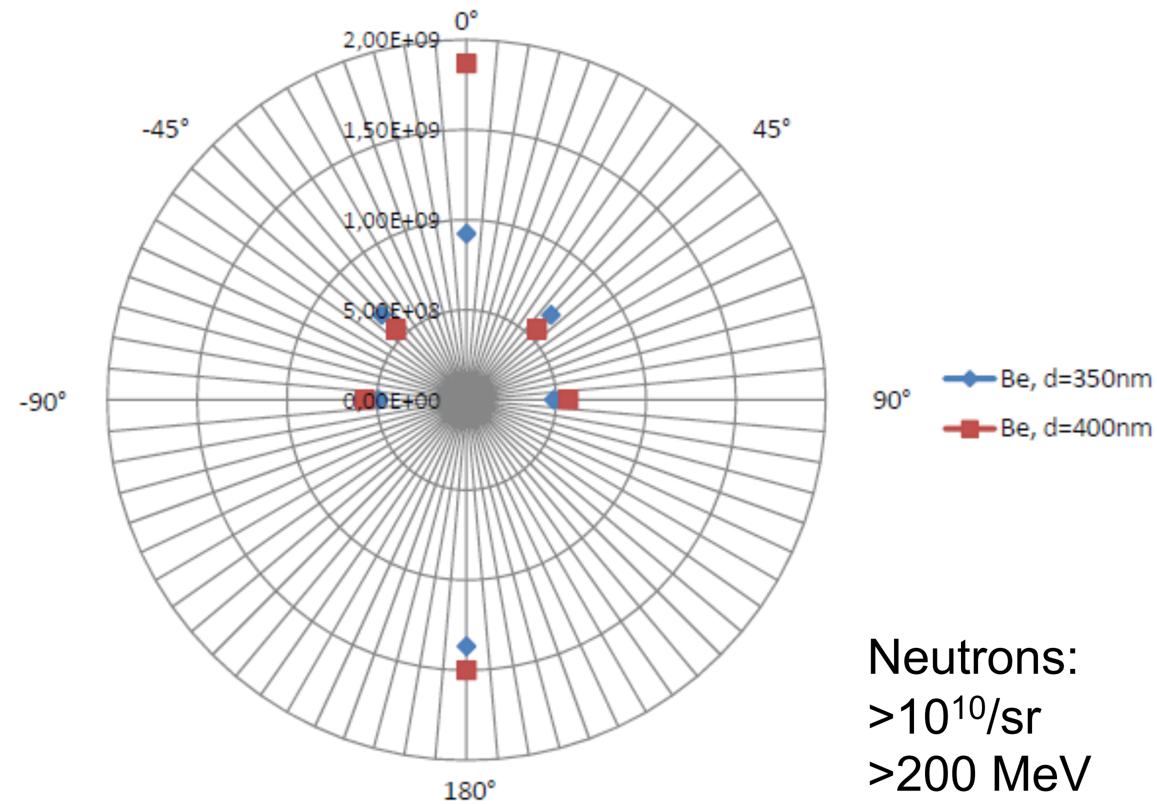
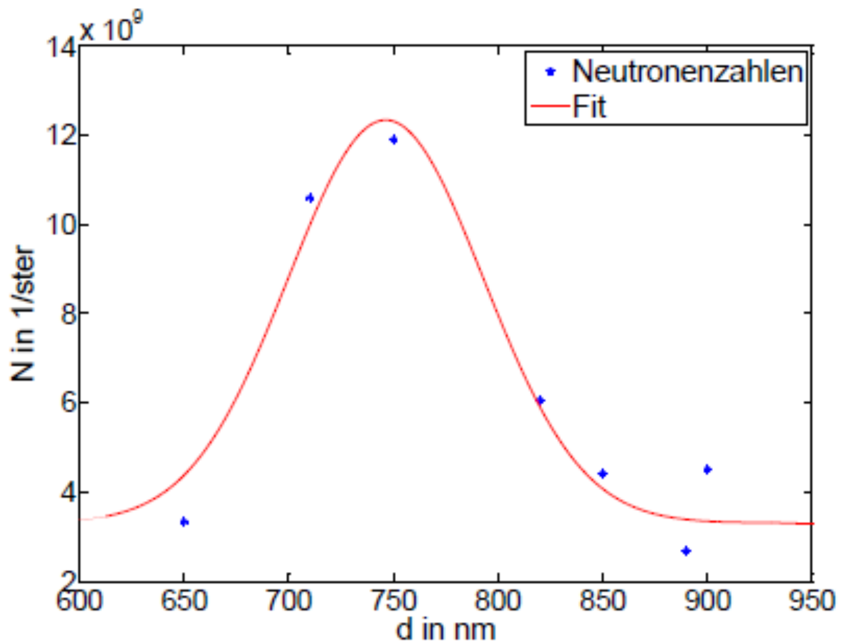
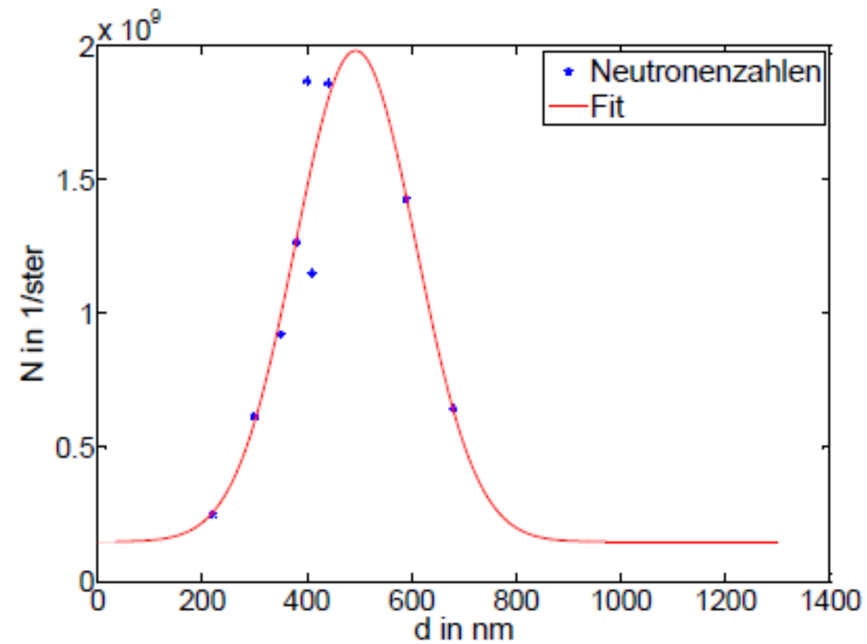




Neutrons:
$>10^{10}$/sr
>200 MeV
Peak @ 70 MeV

60 J of Laser energy
$1x10^{21}$ W/cm^2





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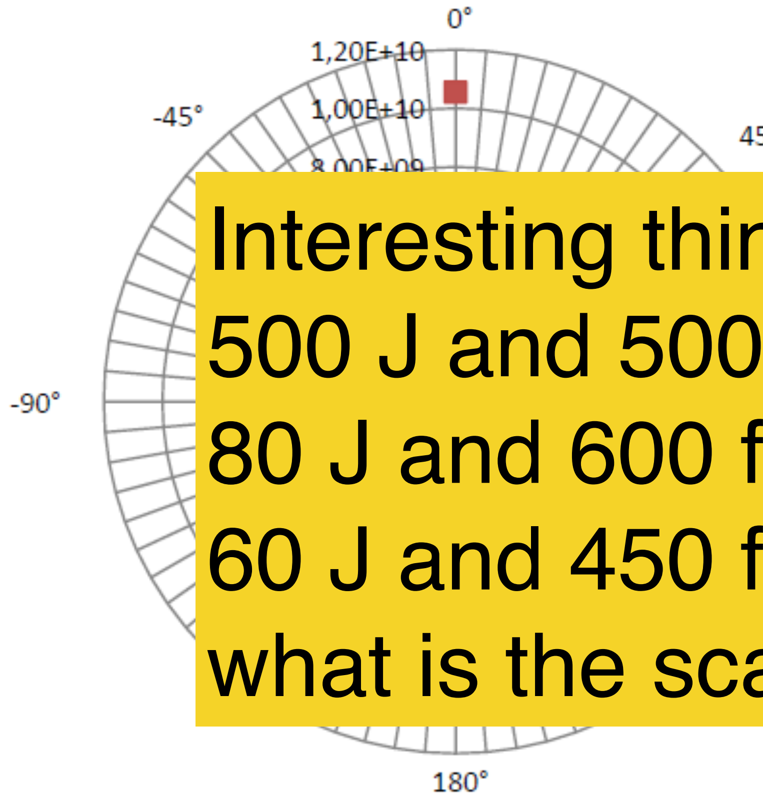
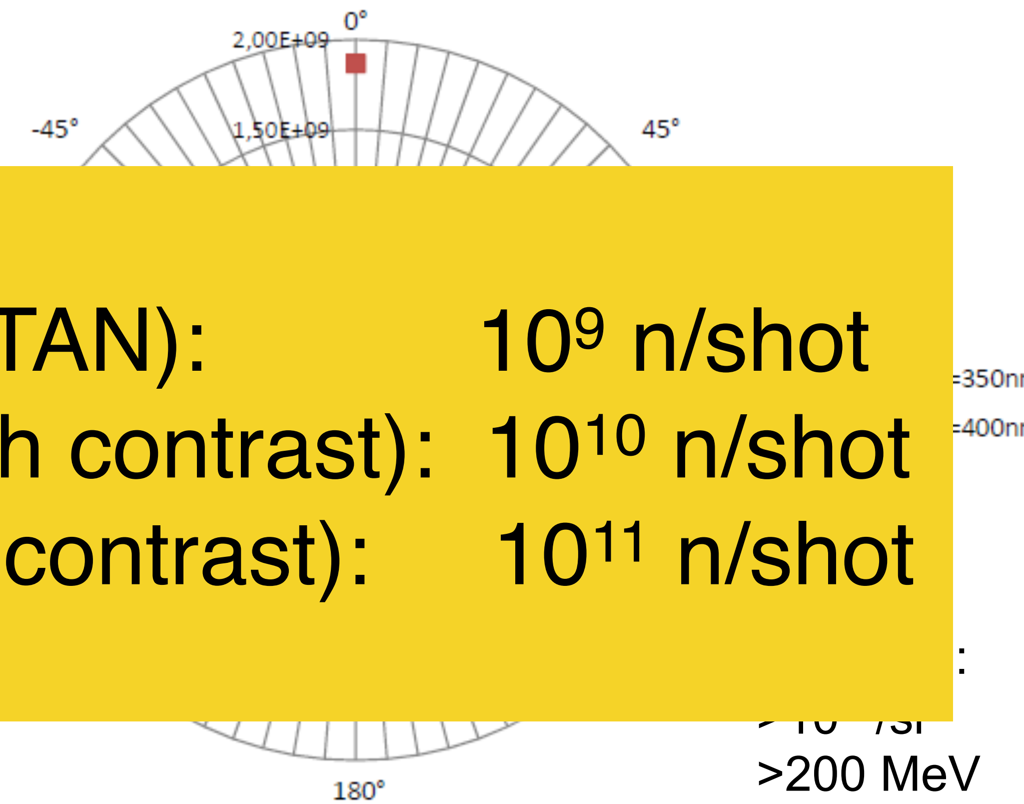
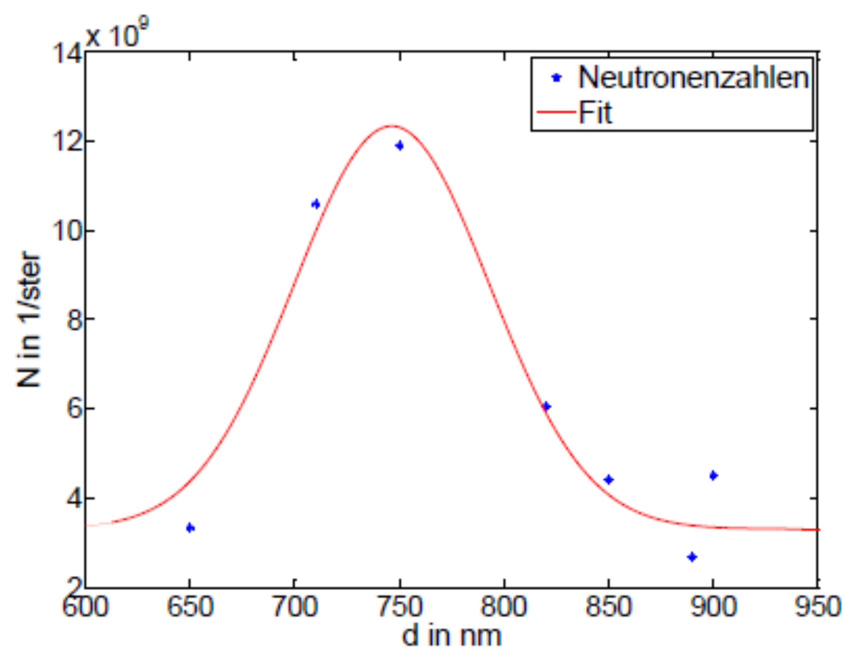


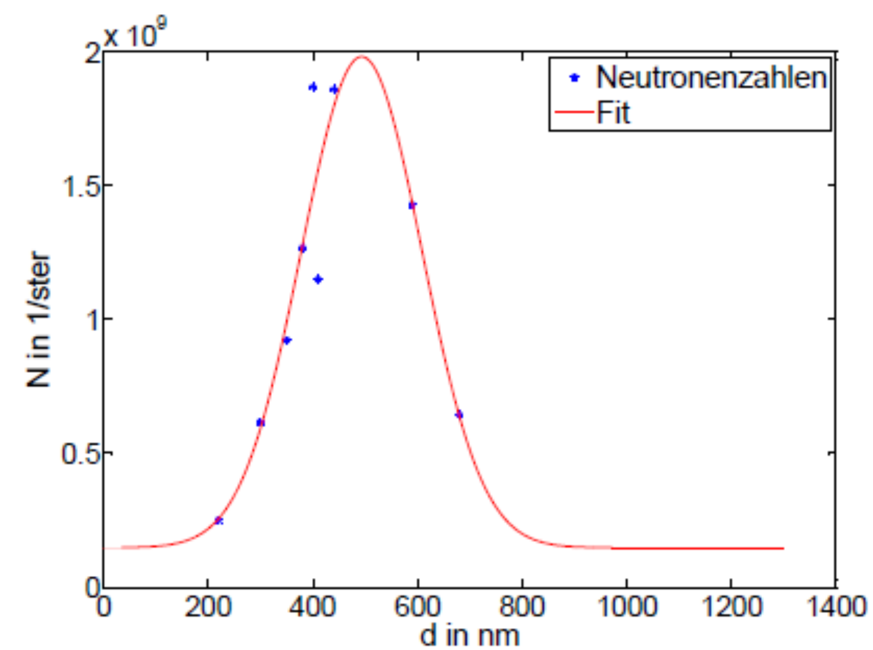


Interesting thing to check:
500 J and 500 fs VULCAN (TITAN): 10^{9} n/shot
80 J and 600 fs TRIDENT (high contrast): 10^{10} n/shot
60 J and 450 fs PHELIX (high contrast): 10^{11} n/shot
what is the scaling law here?

>200 MeV
Peak @ 70 MeV

60 J of Laser energy
1×10^{21} W/cm^2

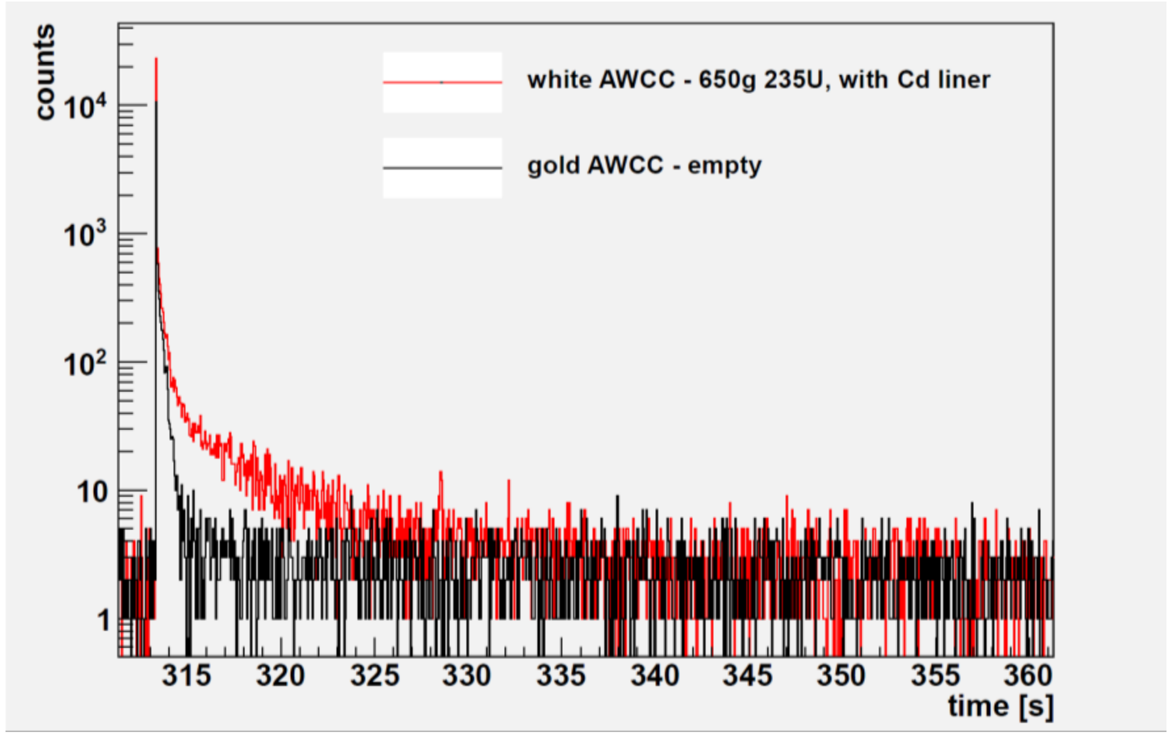


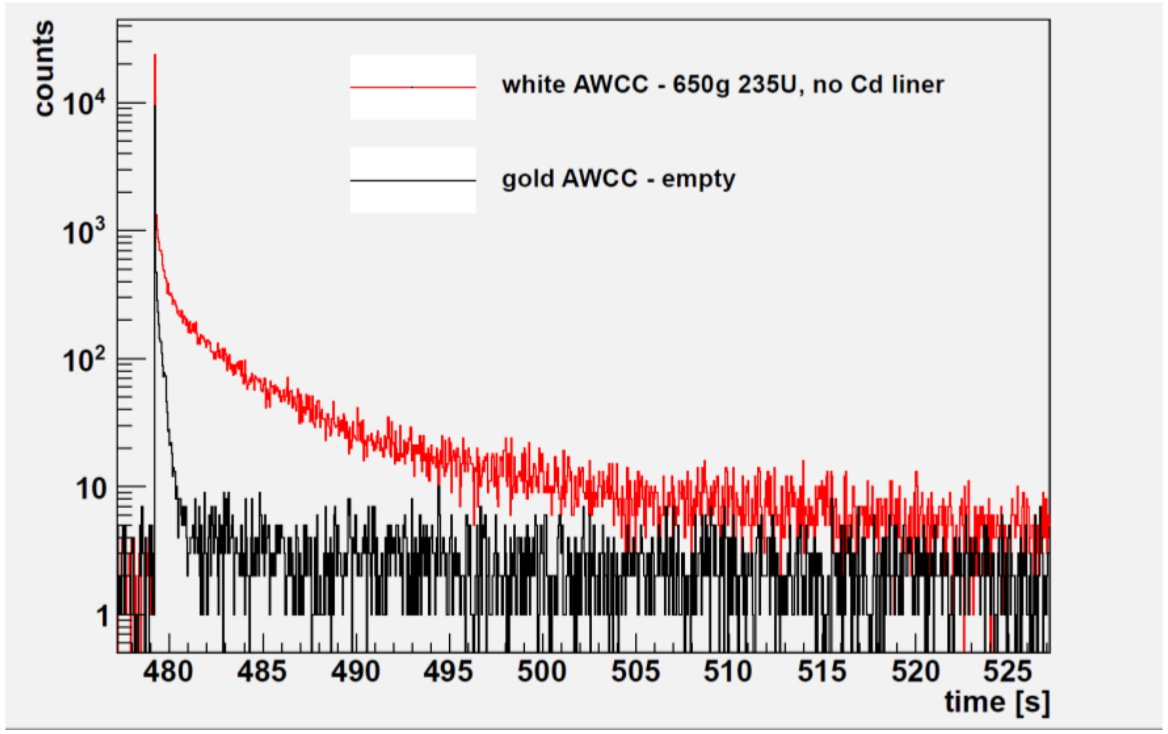


Application:
Interrogation of an enriched uranium sample

PI: Andrea Favalli, LANL

Sample: High Enriched Uranium (990 g U, of which 650g ^{235}U)



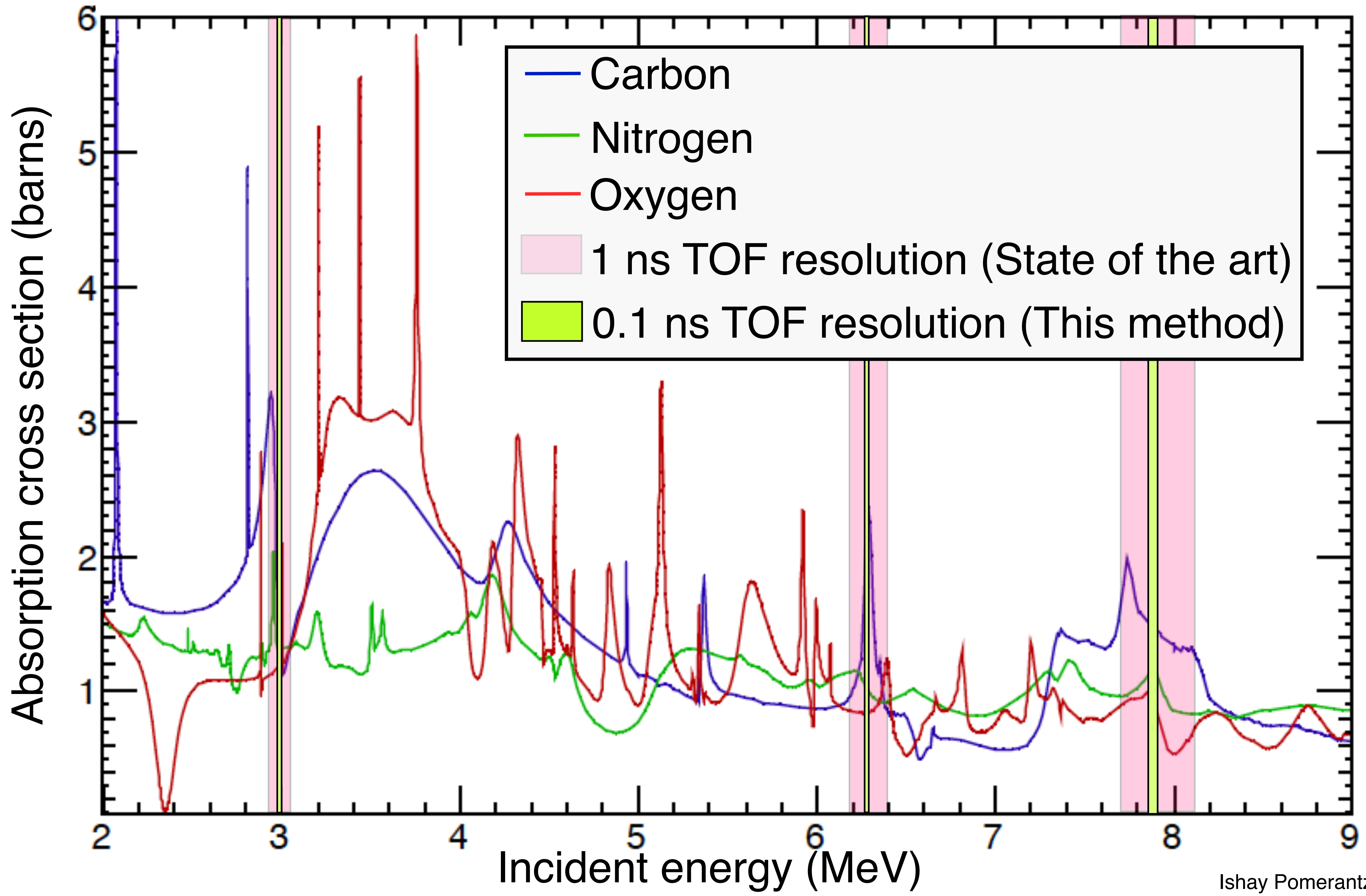


Fast Mode (*with* Cd sleeve)

Thermal Mode (*without* Cd sleeve)

Delayed Neutrons chosen as signature, these neutrons are characteristic signatures for nuclear fission (few other process yield delayed neutrons)

Prospects:
Fast Neutron Radiography
(from I. Pomerantz, PRL 113, 184801 (2014))



Ishay Pomerantz

Tailoring and transport of ion beams
- the LIGHT project -

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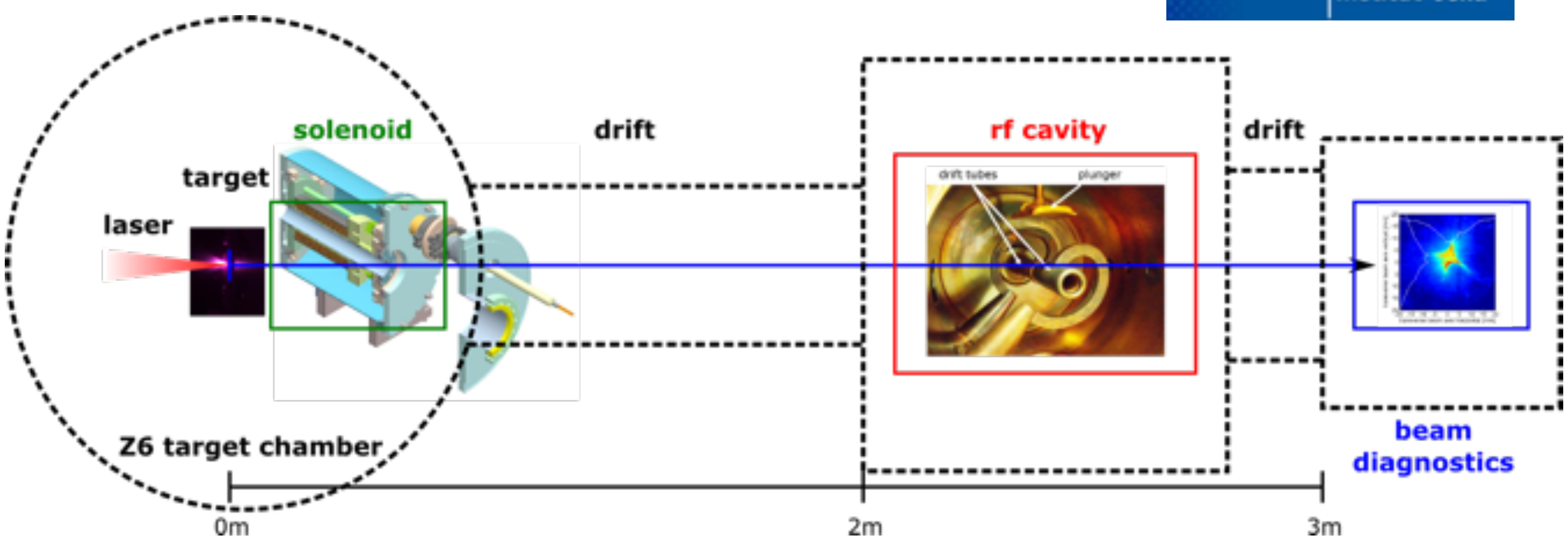
unique beam and hybrid technology testbed
N = 10^{10} protons
E = 10 MeV
t ≈ ns / sub-ns
DE ≈ 1%

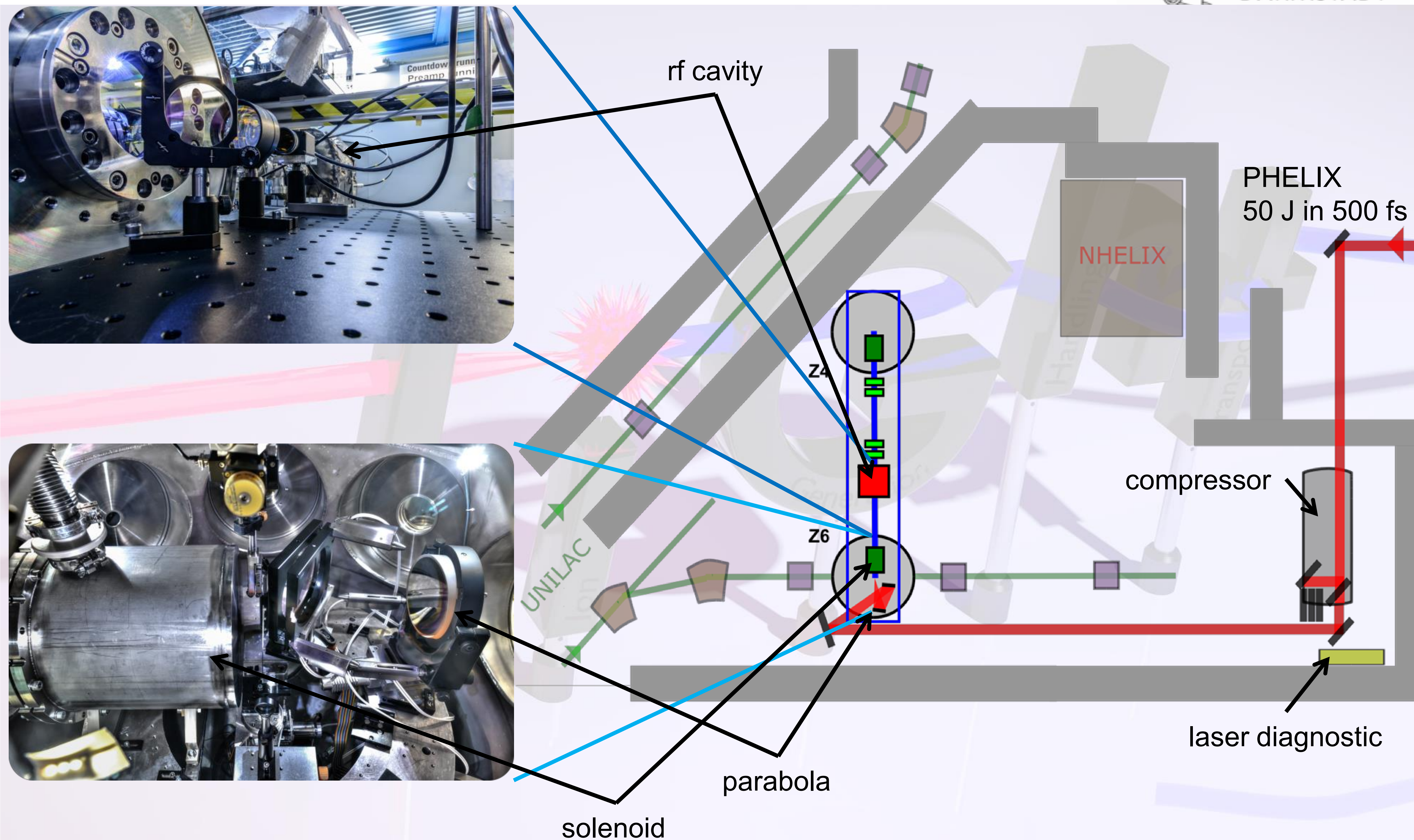
LIGHT

Laser Ion Generation, Handling and Transport

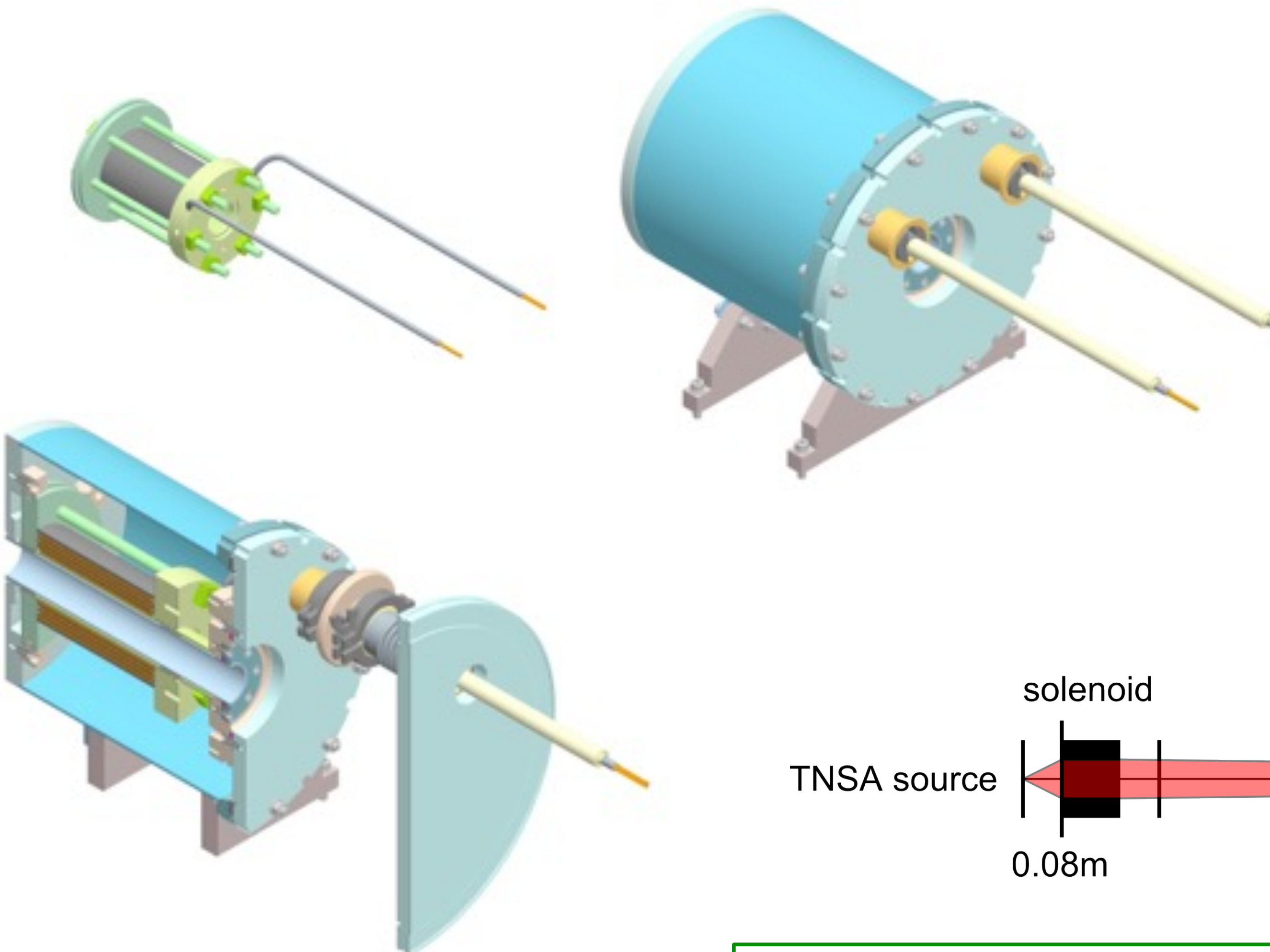


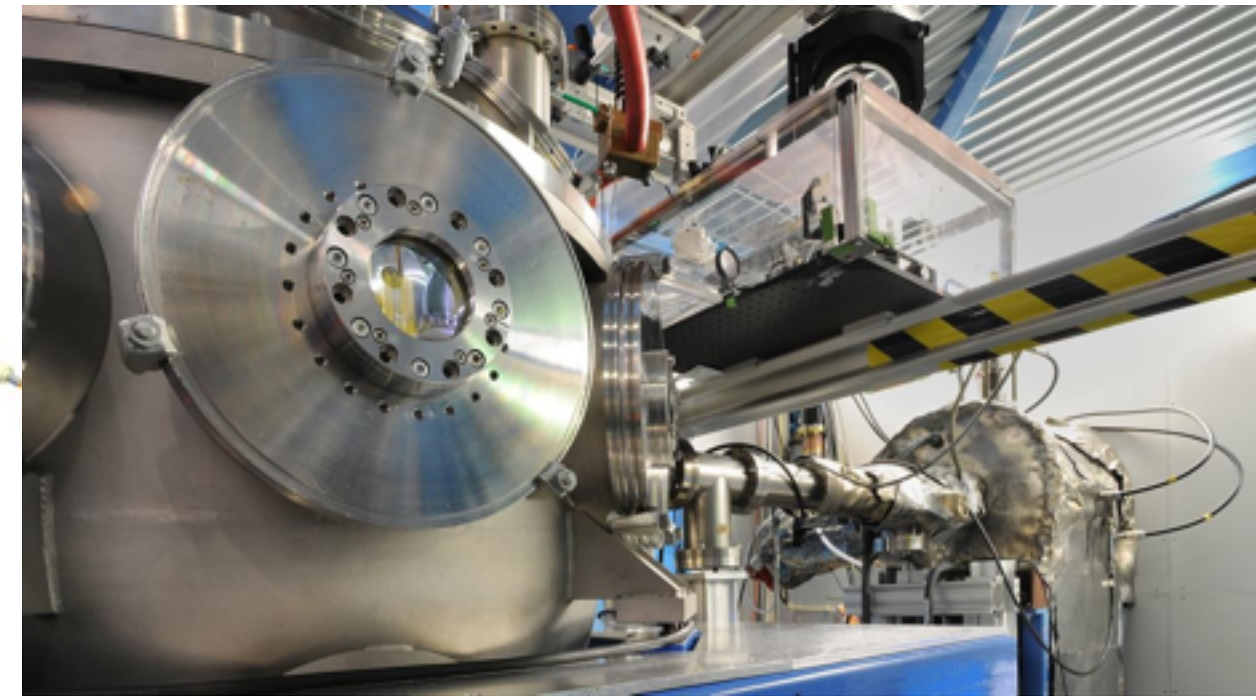
Picture: Courtesy of Simon Busold

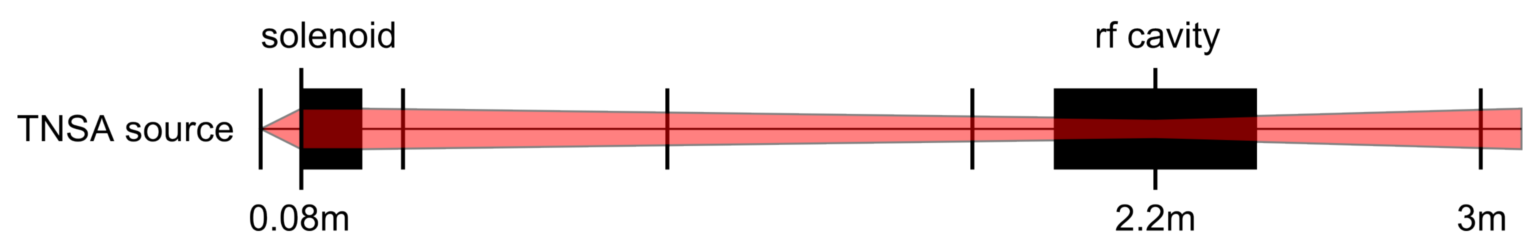
The LIGHT Beamline



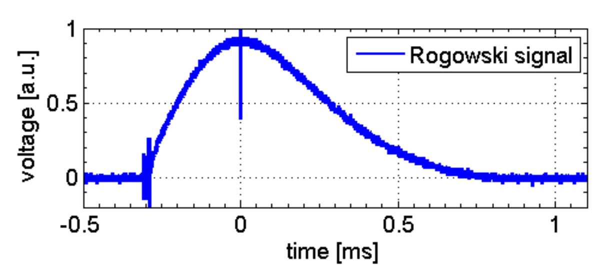
Coil design from HZDR



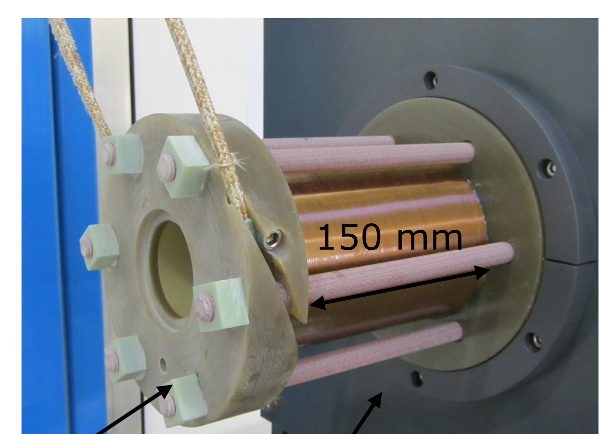




stand alone pulsed power system



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



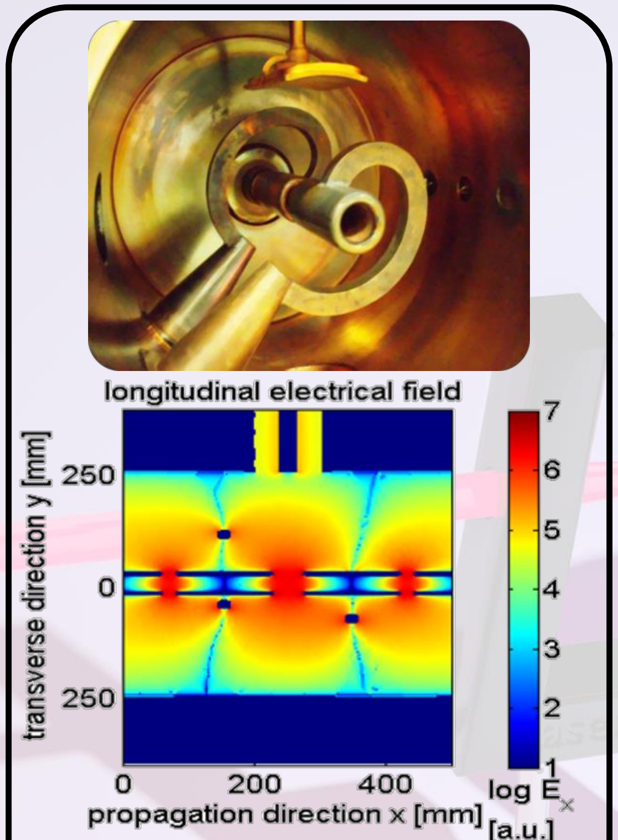
40.5 mm open aperture

4 layers copper windings

Courtesy: Thomas E. Cowan

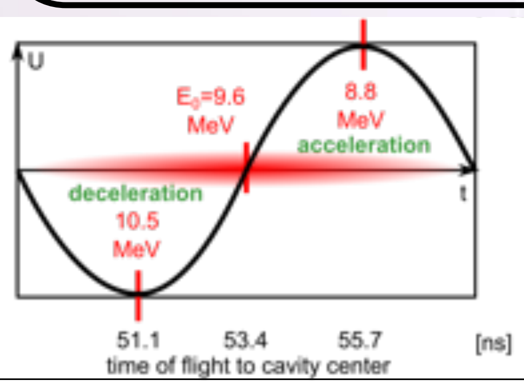
phase rotation

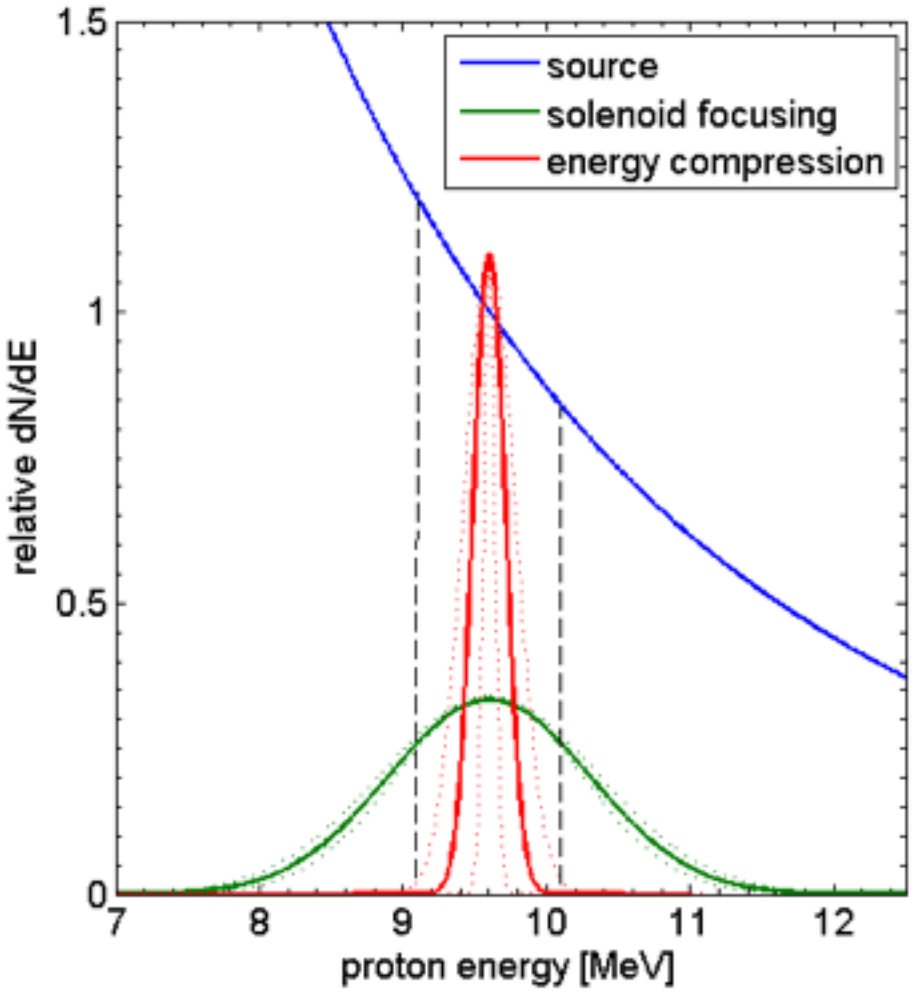
S. Busold et al., PR-STAB 17, 031302 (2014)



double spiral resonator

- > 100 kW rf power
- 3 gaps
- ±1 MV acc. voltage
- 108.4 MHz

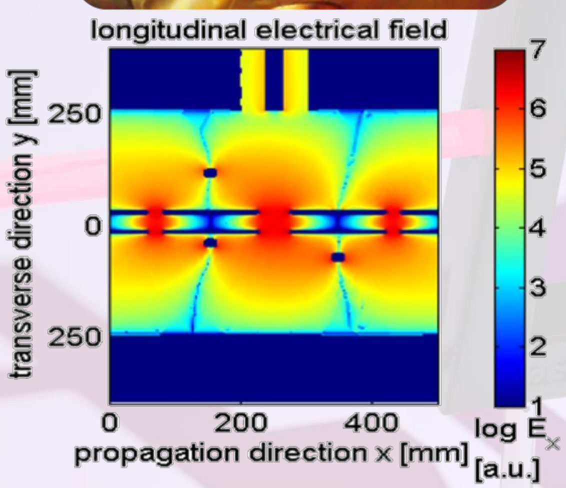




Energy selection and width for 9.6 MeV :
18.0 ± 3.0 % due to chromatic focusing of the solenoid
2.7 ± 1.7 % using the cavity

phase rotation

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



double spiral resonator

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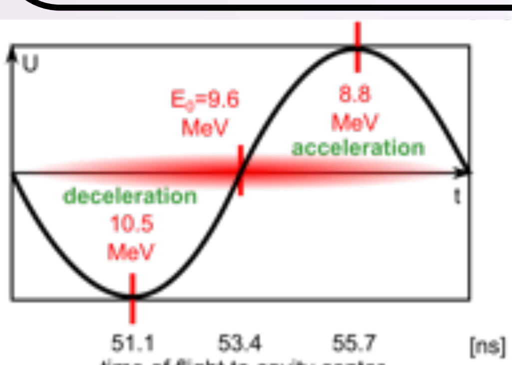
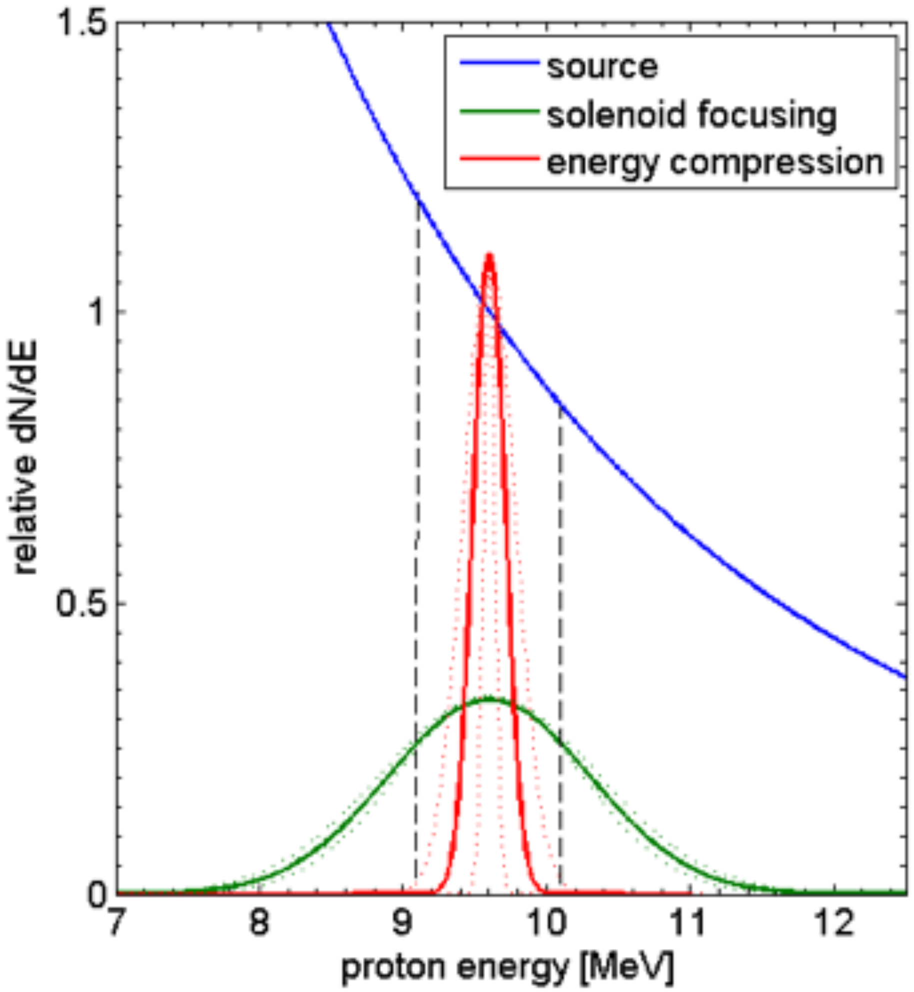
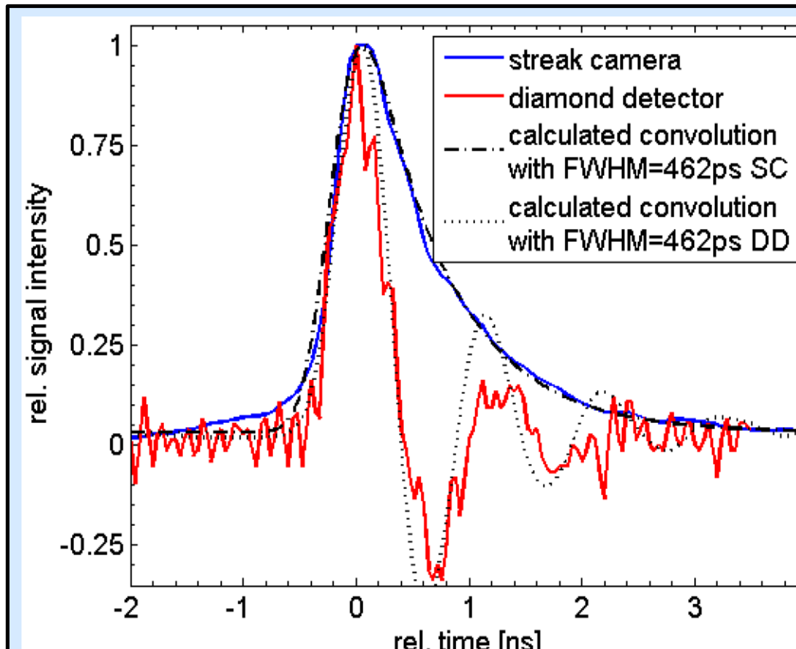




Energy selection and width for 9.6 MeV :
18.0 ± 3.0 % due to chromatic focusing of the solenoid
2.7 ± 1.7 % using the cavity

n_p= 5 x 10^8
t = (250 ± 15) ps
I = 100 mA

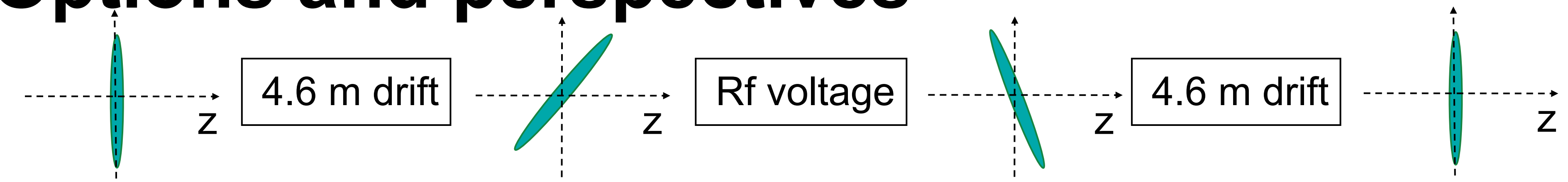


shortest measured pulse length:

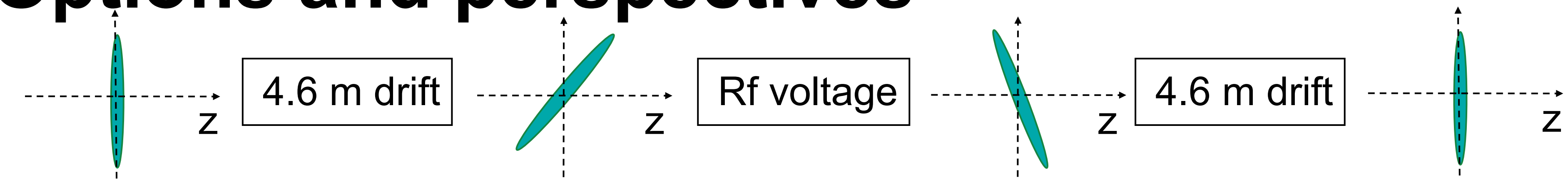
- FWHM: ~~462 ps~~ ± 40 ps

250 ± 15 ps

Options and perspectives



Options and perspectives



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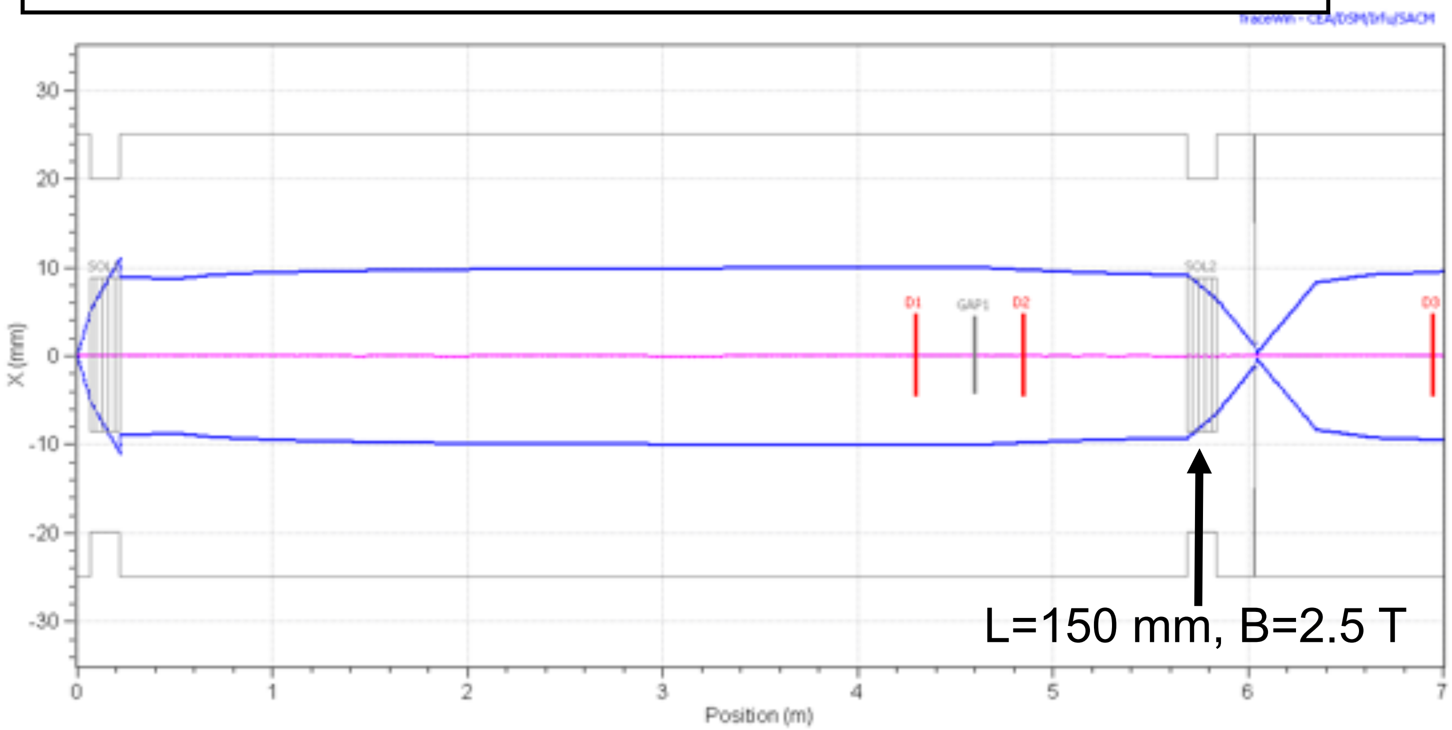
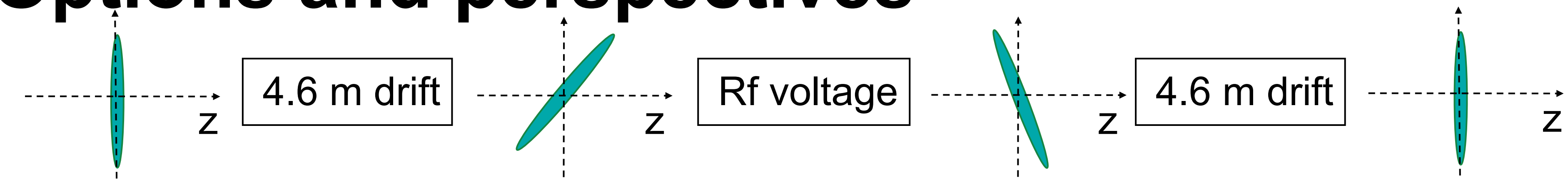
Second focus (2nd solenoid)

6 D focus - optimum performance without extra apertures -

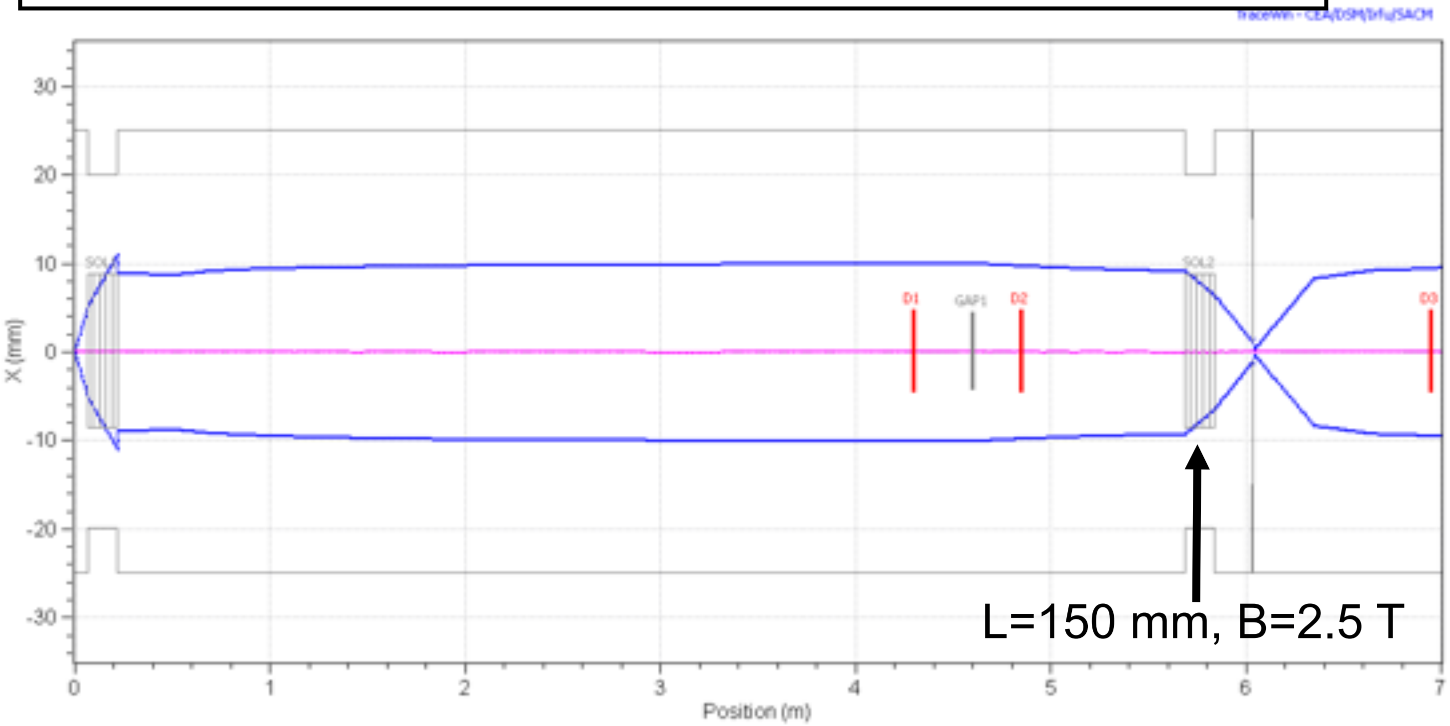


Options and perspectives



Second focus (2nd solenoid)

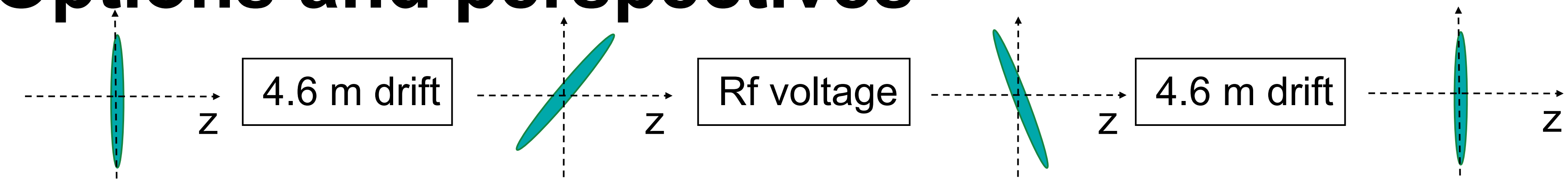
6 D focus - optimum performance without extra apertures -



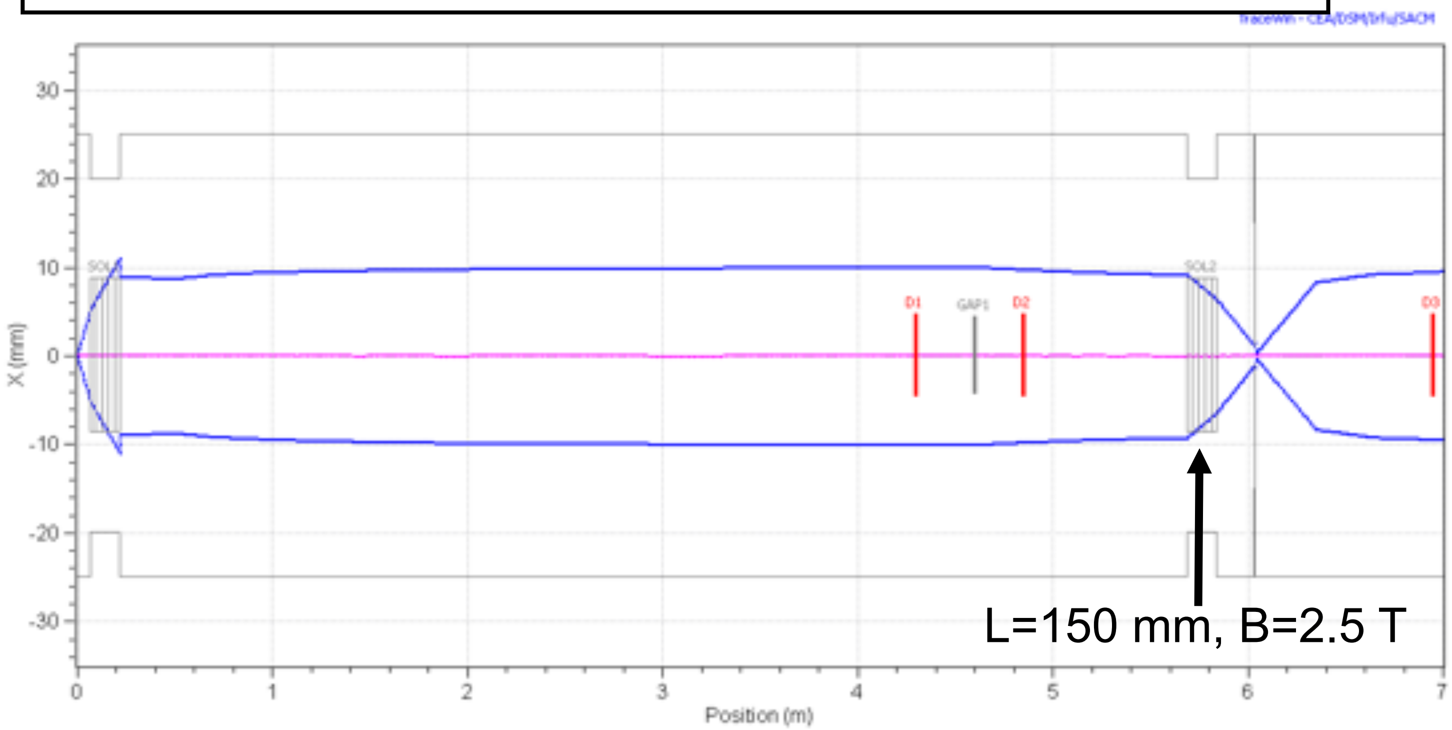
Time focus (< 100 ps) and spatial focus (< 200 μm)

coinciding (6.05 m) ~ 6% of input intensity

Options and perspectives



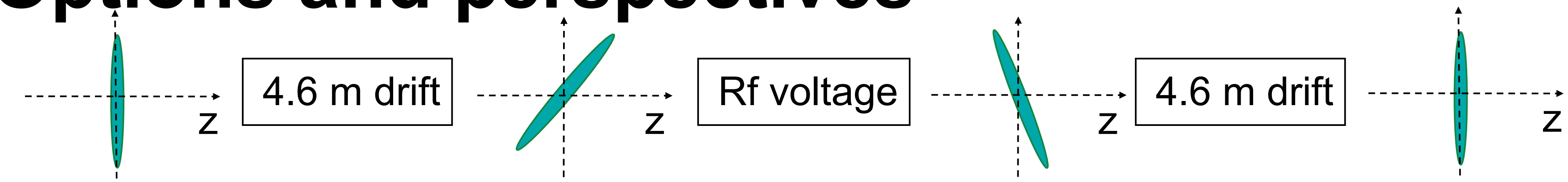
Second focus (2nd solenoid)
6 D focus - optimum performance without extra apertures -



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

10^{10} Protons: $6x10^{18}$ p/s; $2x10^{22}$ p/(s cm^2)
@ 10 MeV: 36 GW/cm^2

Options and perspectives



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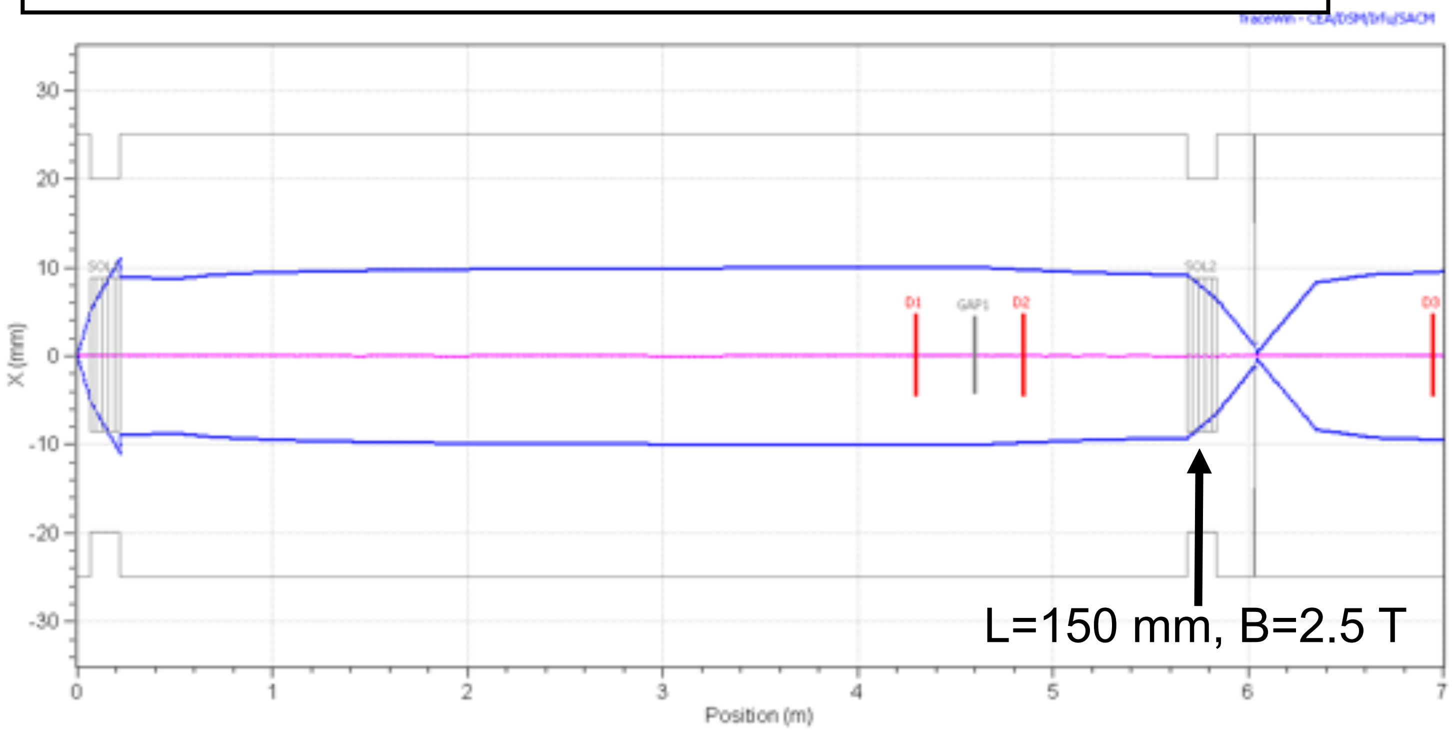

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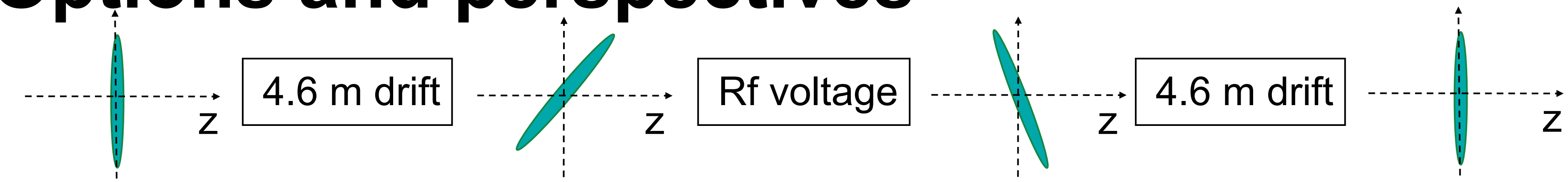

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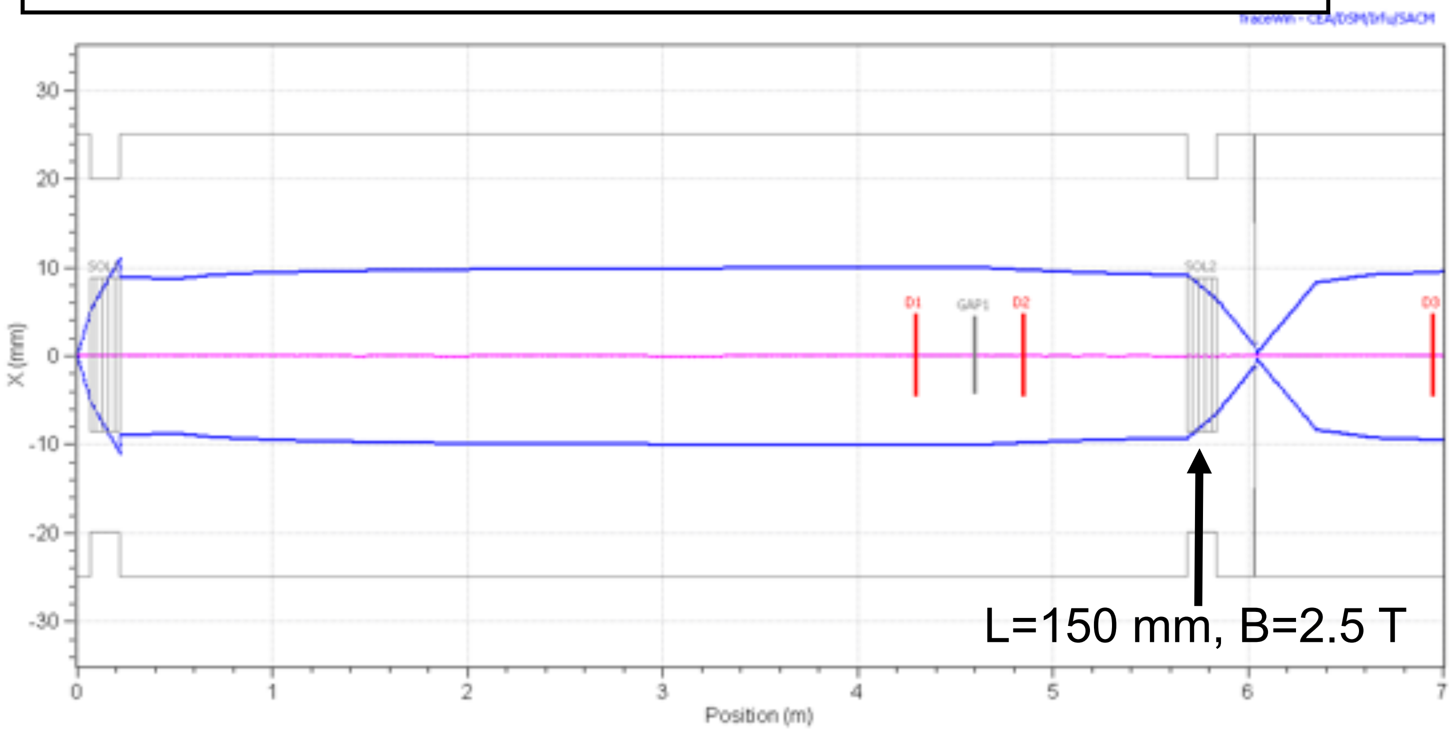

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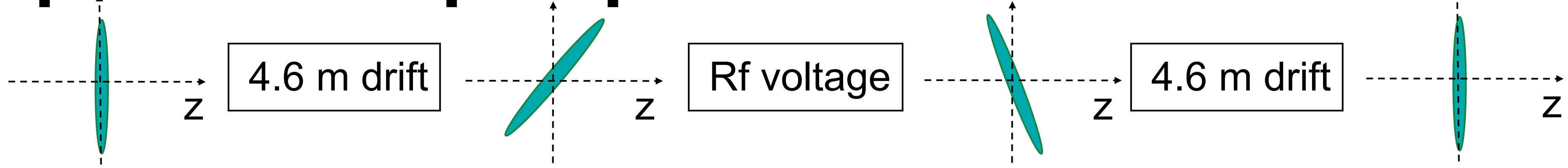

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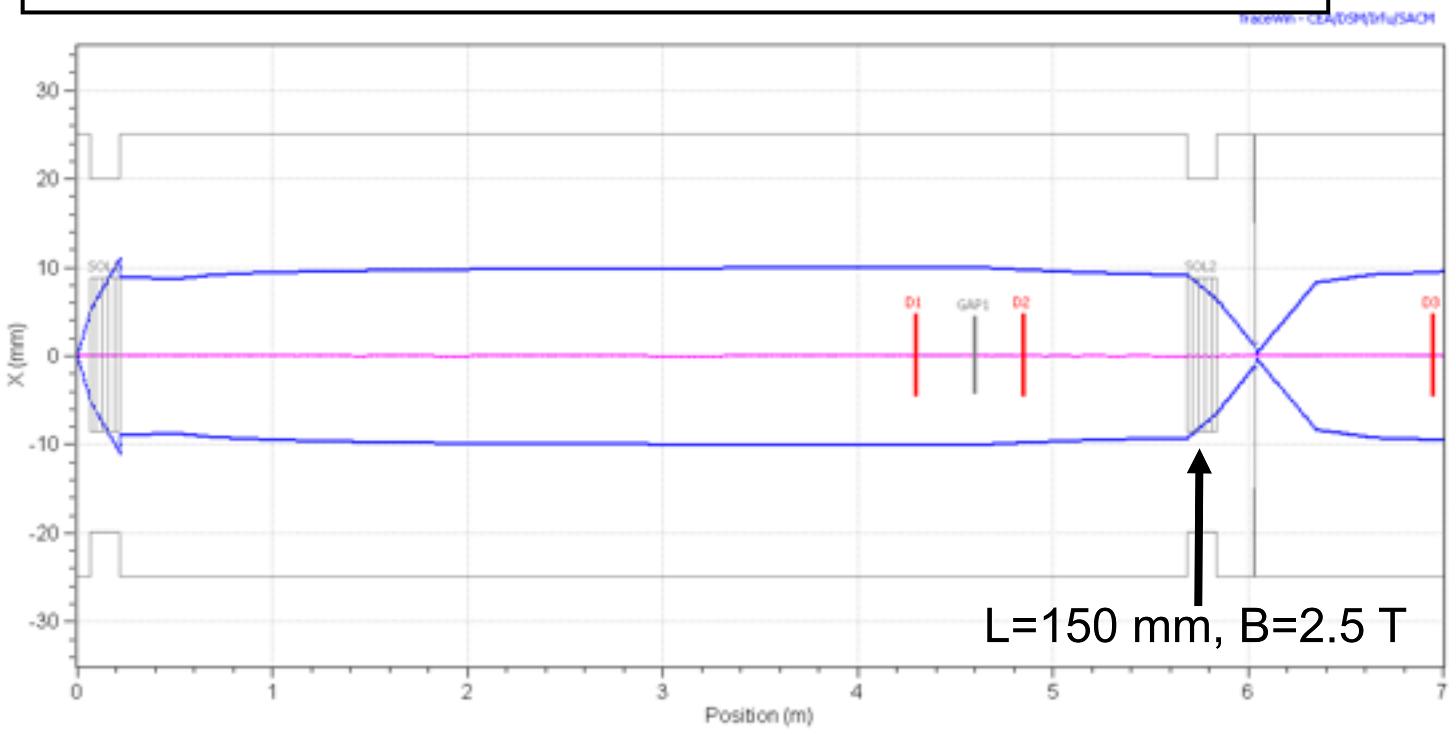

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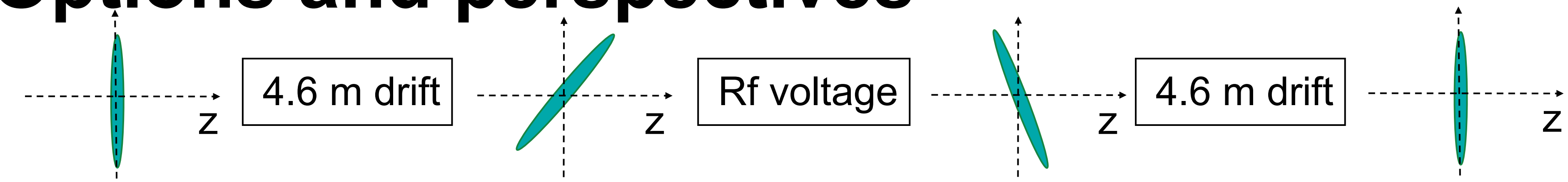

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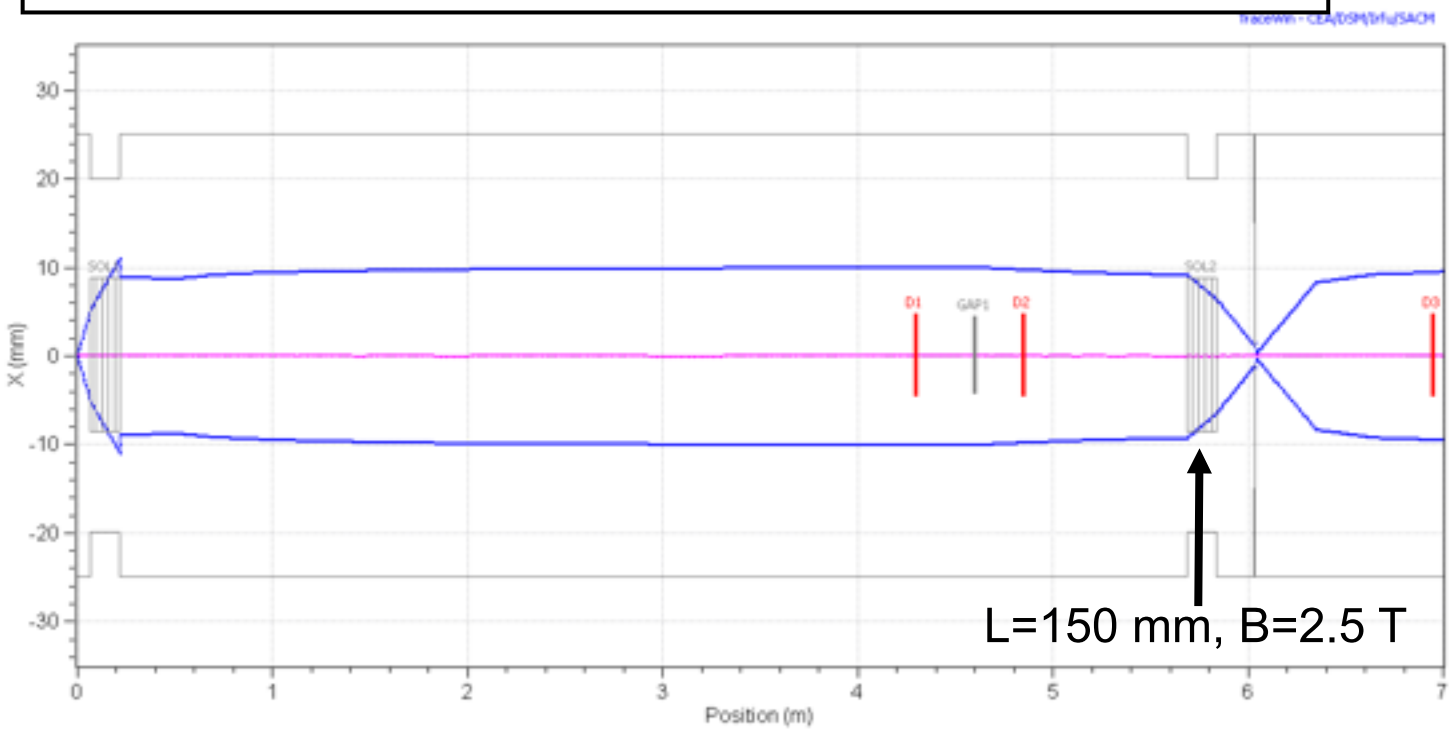

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@ 250 ps pulse duration, there is little time for hydro-motion

Stopping power in plasmas

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dense and uniform plasma state
very good agreement of experiment and simulation

energy loss

unexpected high
+ 70 %

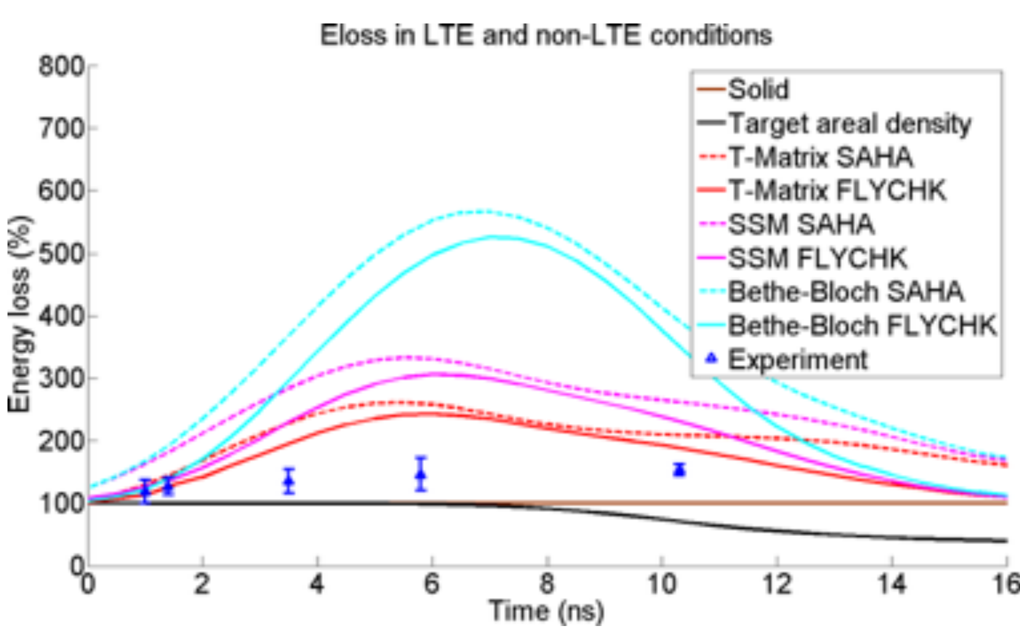
v/v_{th} = 10
non-ideal plasma

dense and uniform plasma state
very good agreement of experiment and simulation

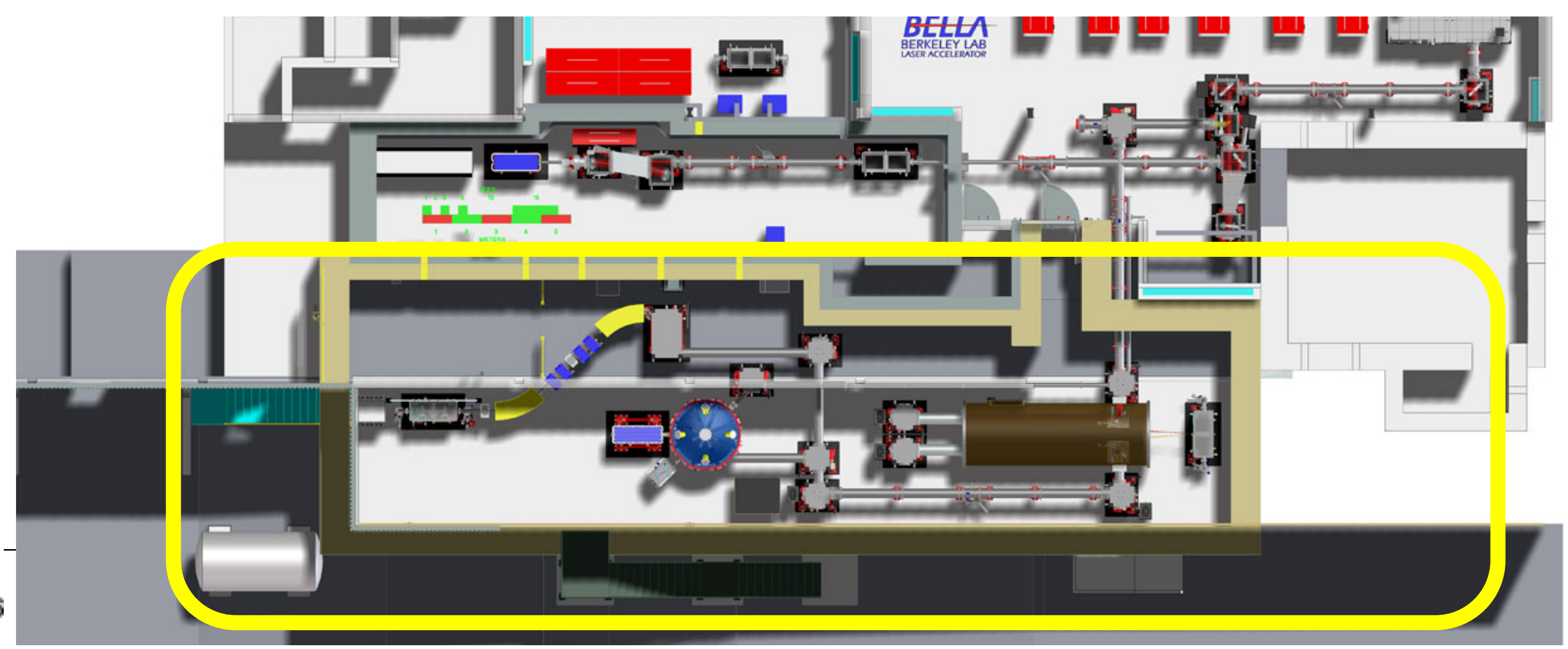
energy loss

unexpected low
- 50 %

v/v_{th} = 1
ideal plasma



Experiments limited by pulse duration



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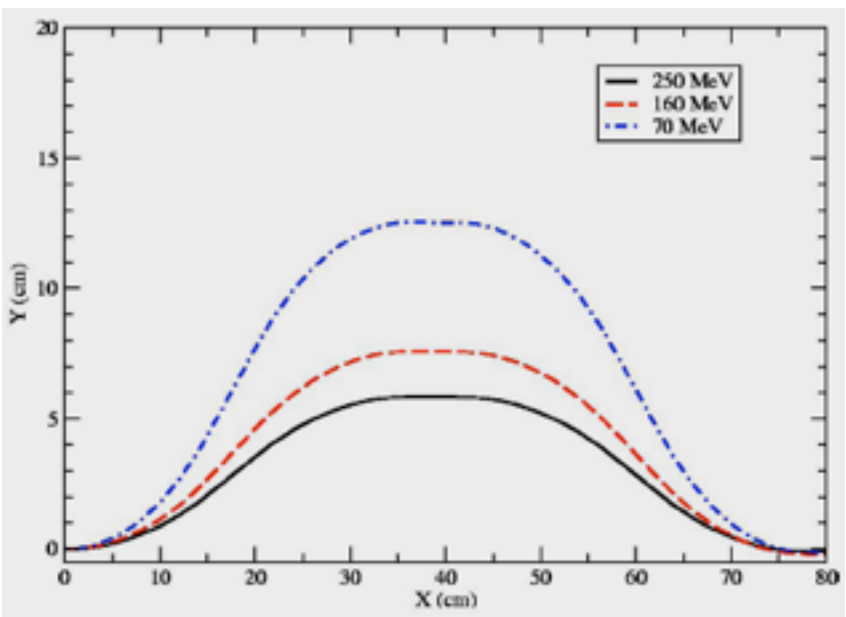

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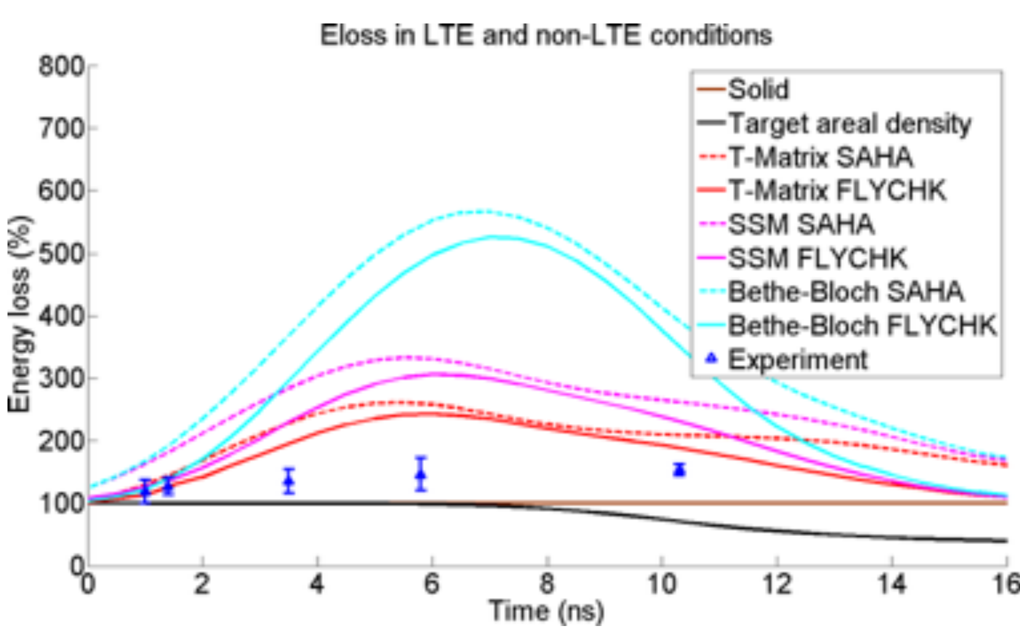

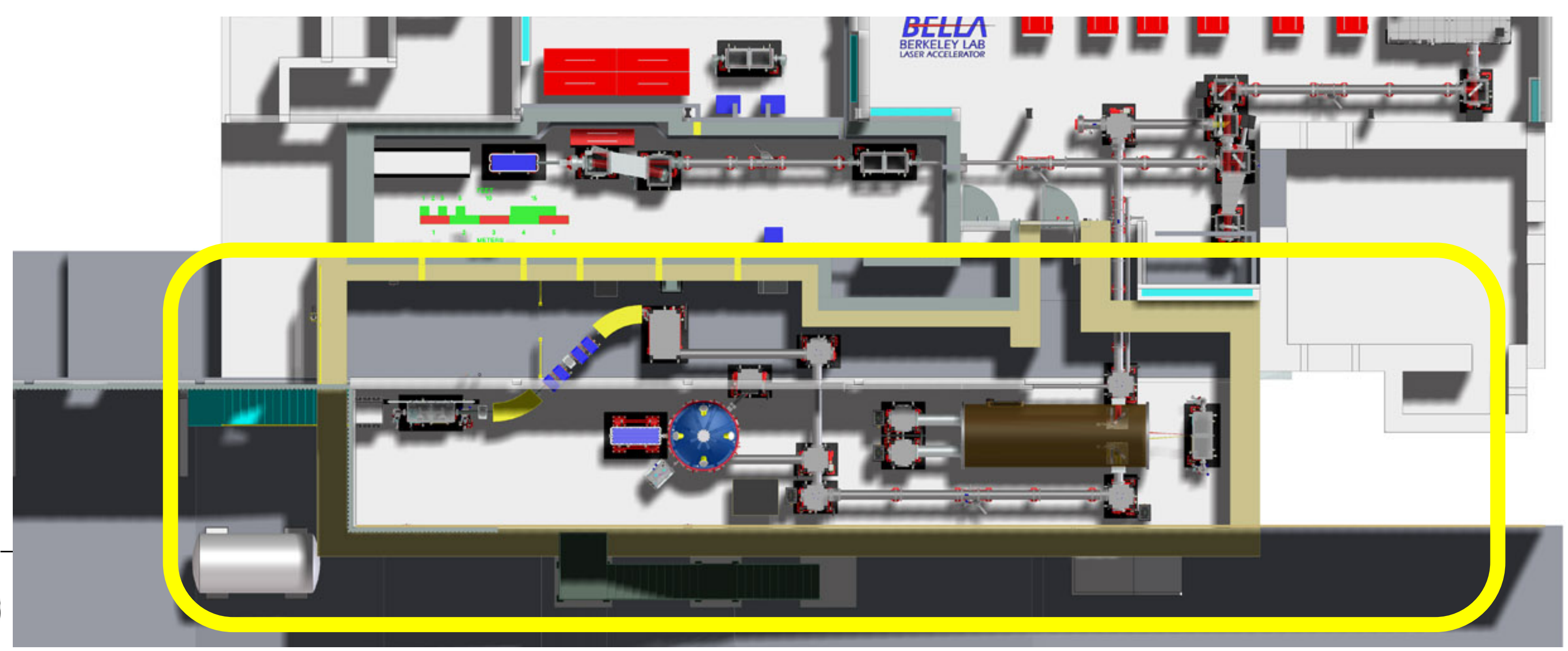

Nuclear Pyrometry and activation

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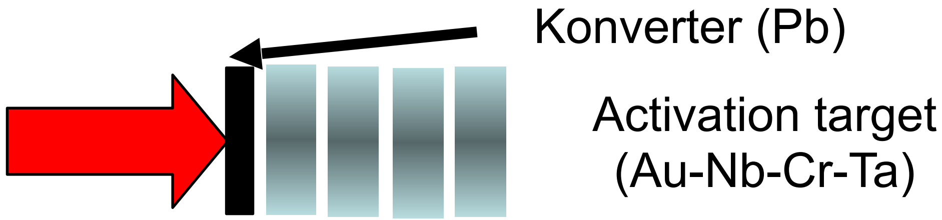

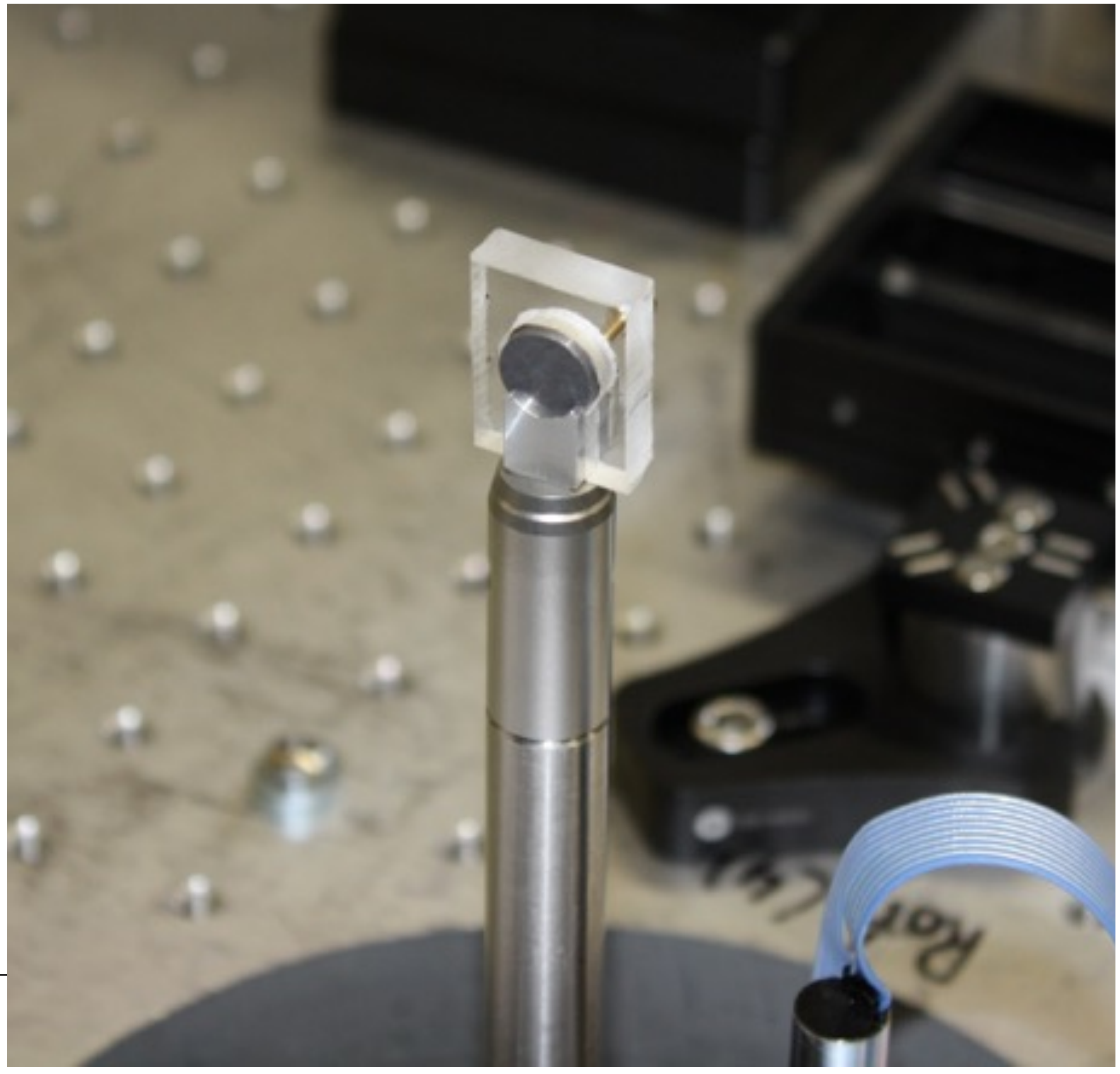

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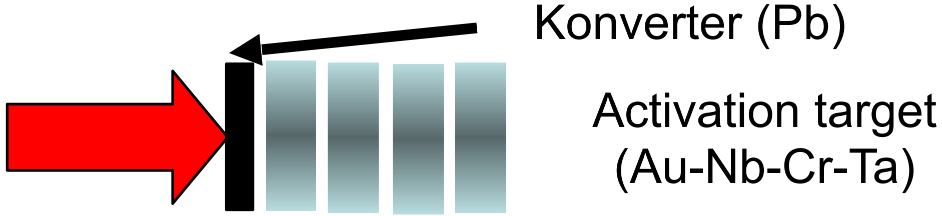
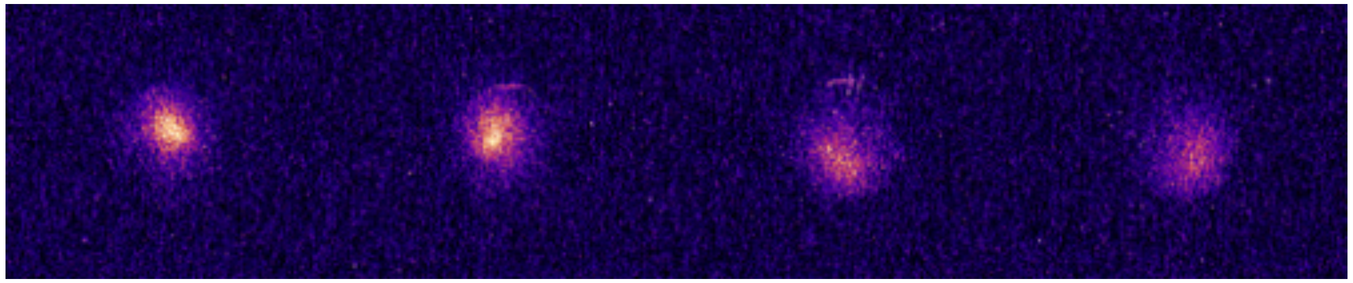
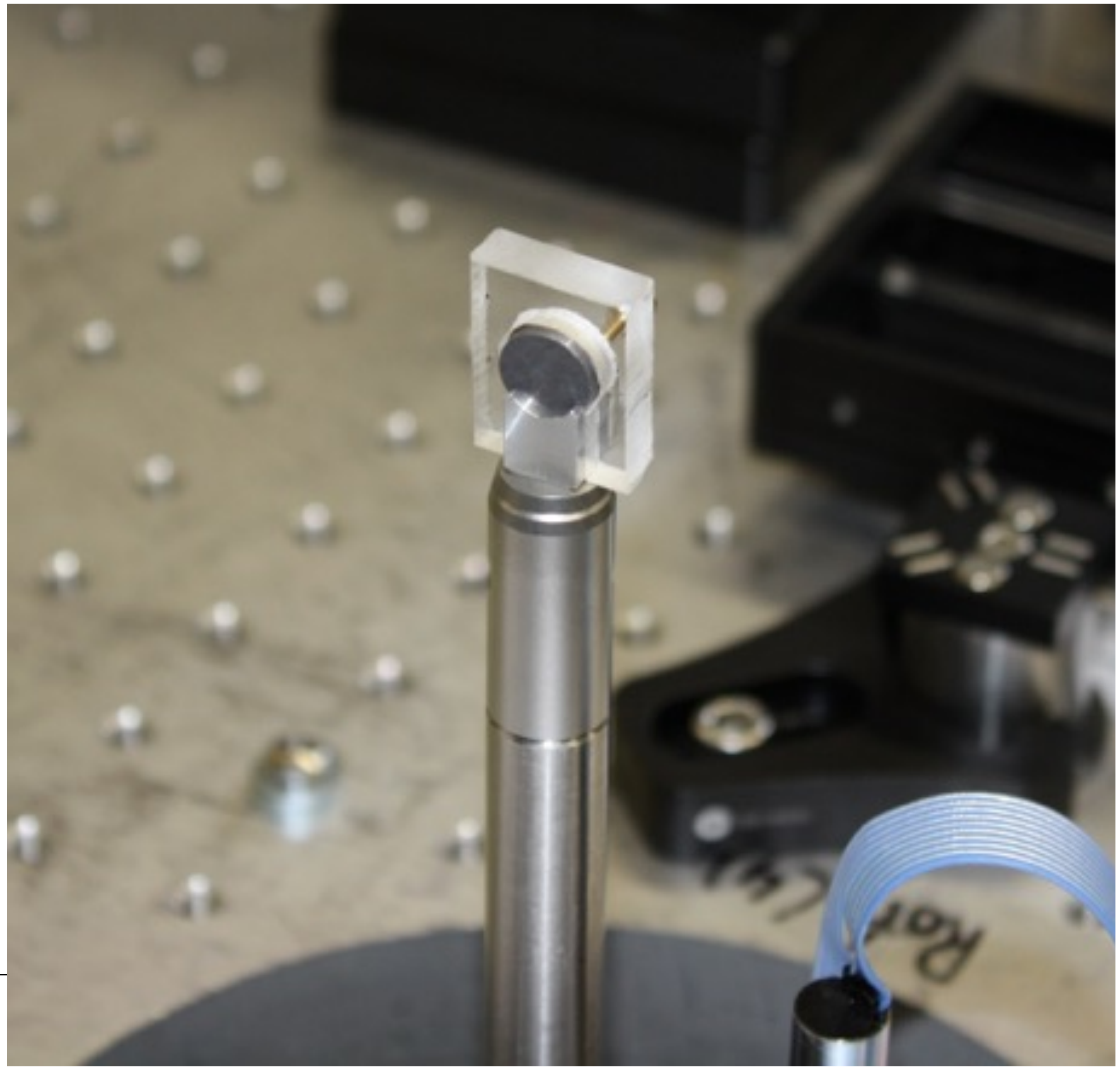




Autoradiography



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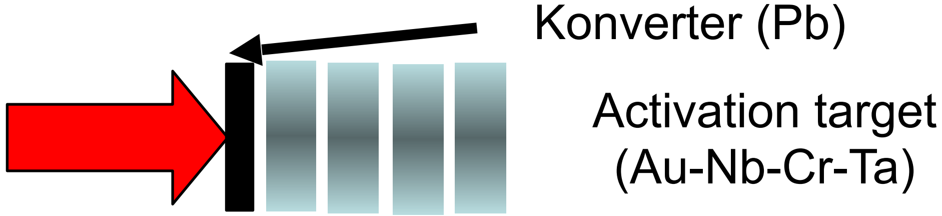

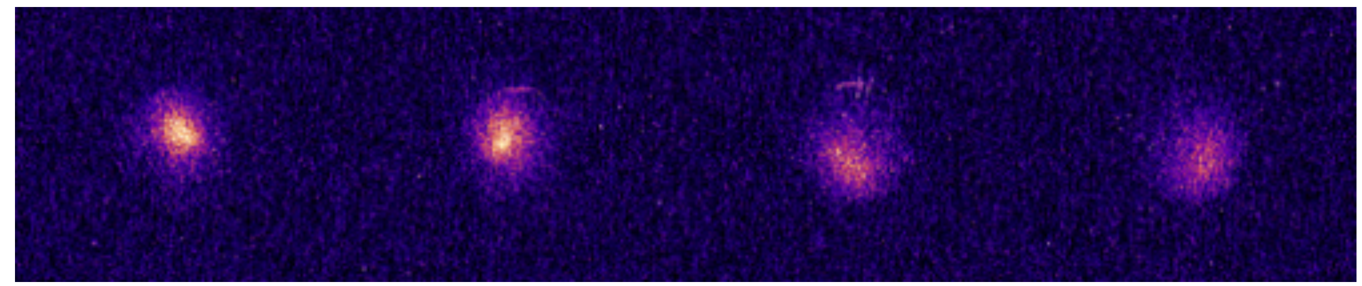

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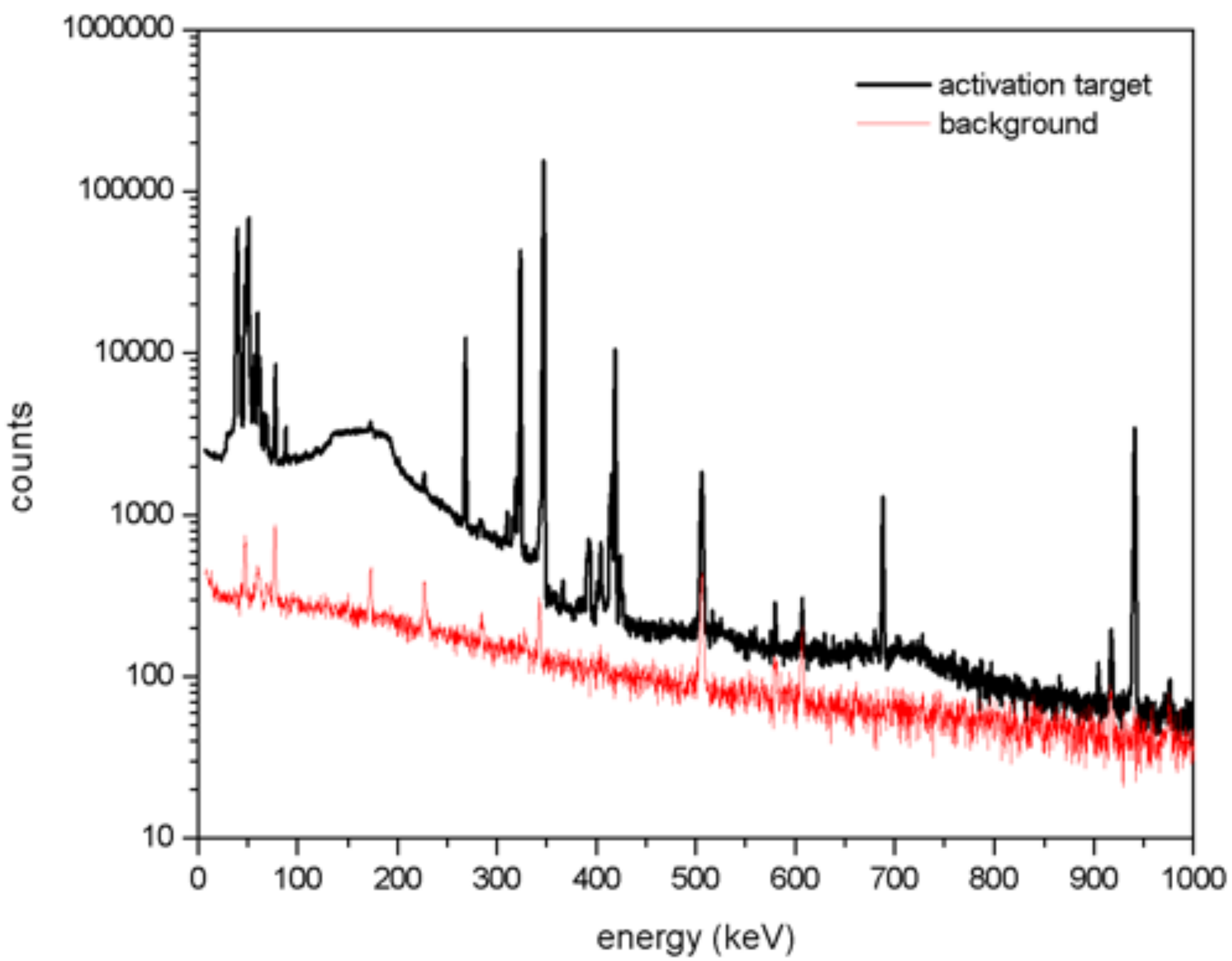
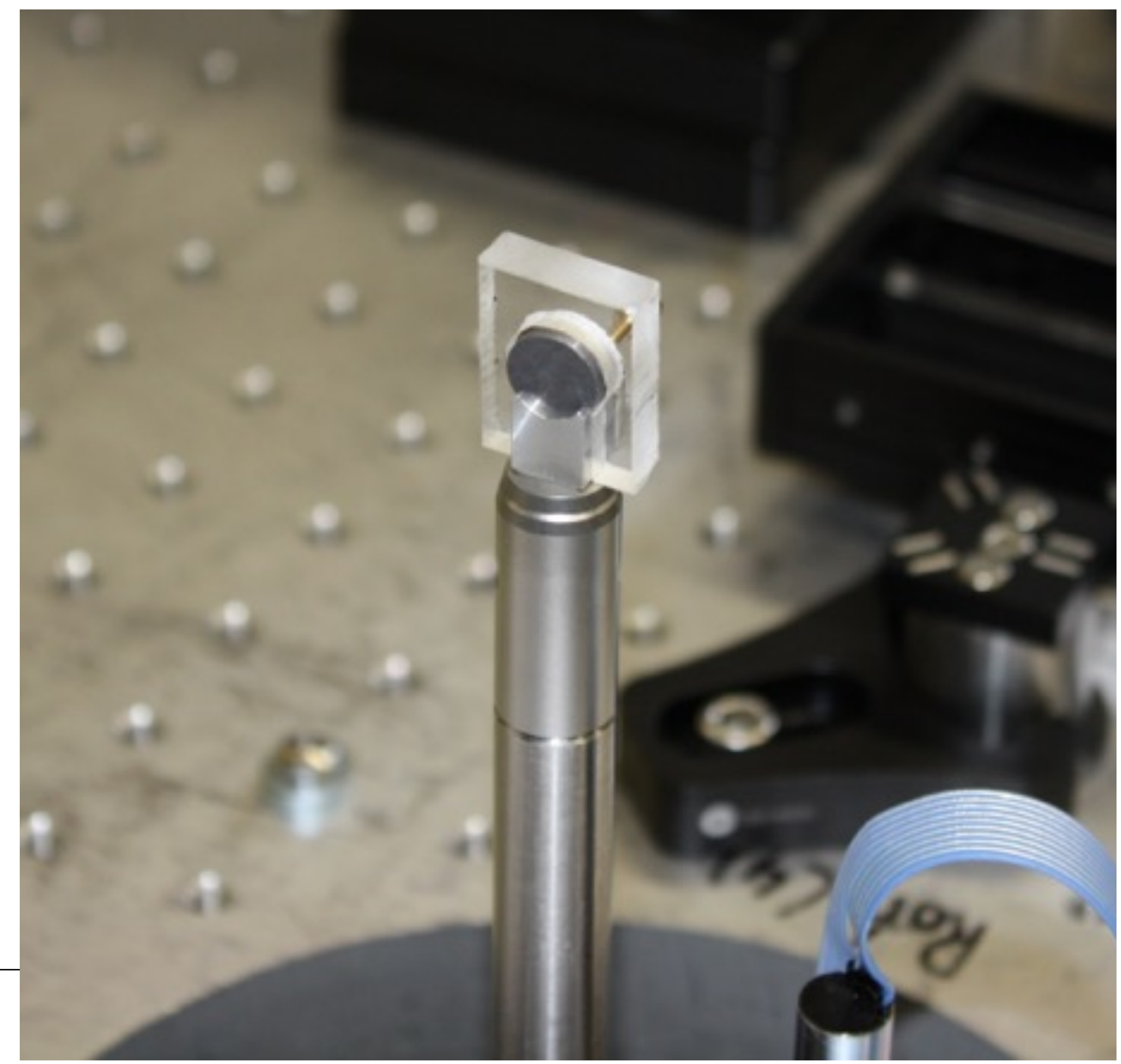
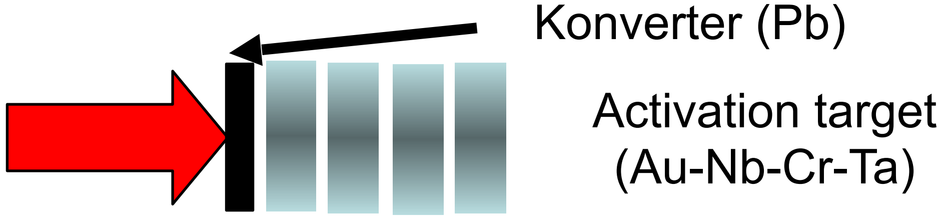


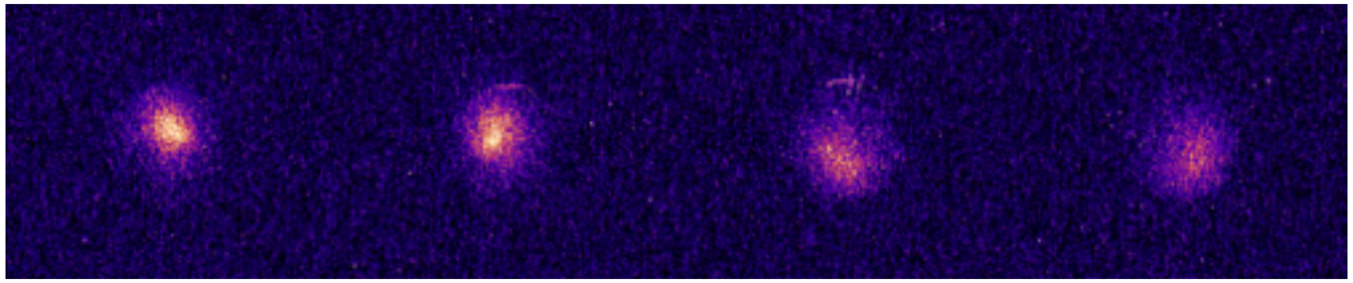


Observed up to Au(γ,4n): Photons up to 50 MeV

Nuclear Pyrometry and activation

for medium half life isotopes (e.g. C, F)
a minute of BELLA operation is similar to
a 2.5 kJ 40 fs laser





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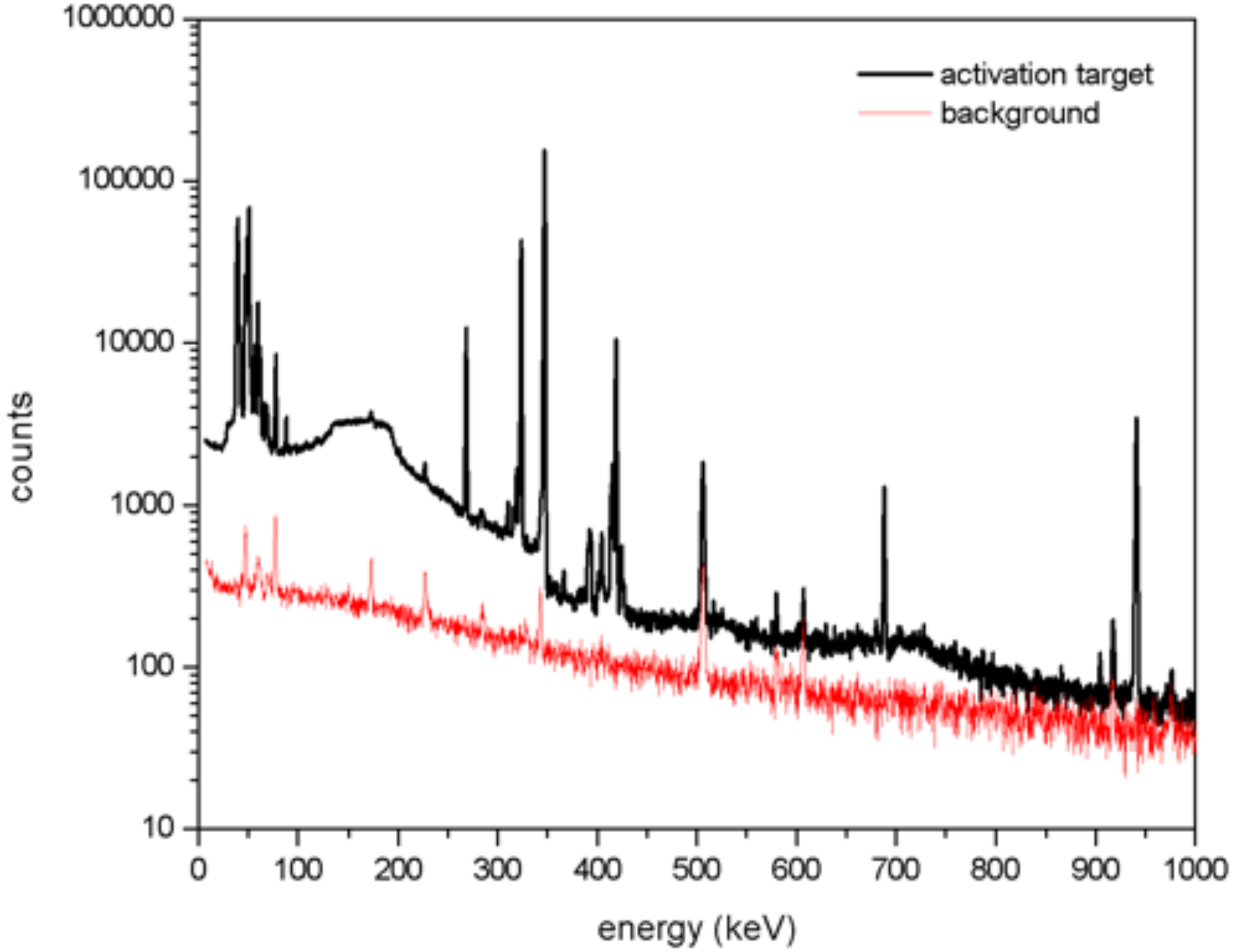

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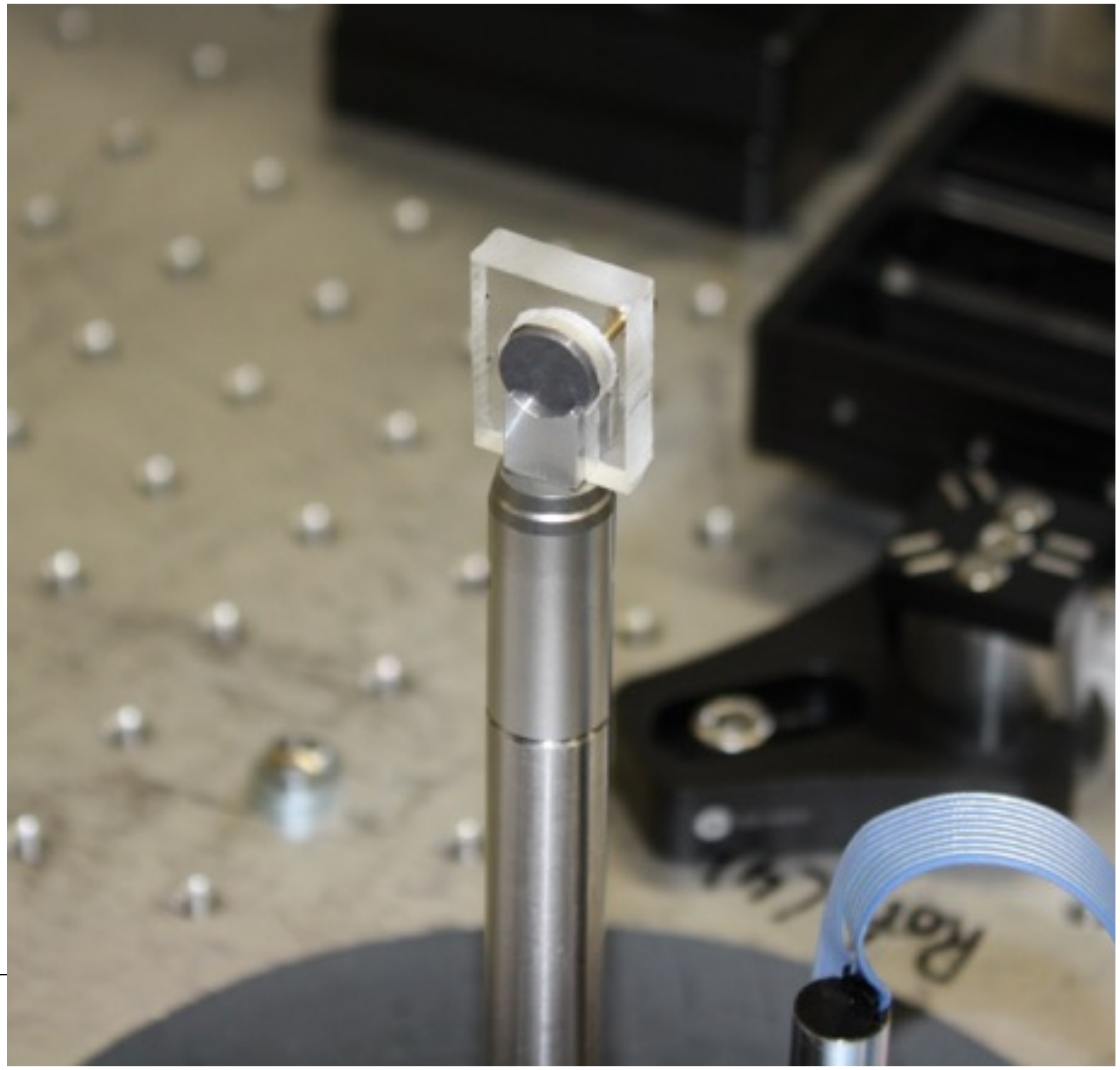
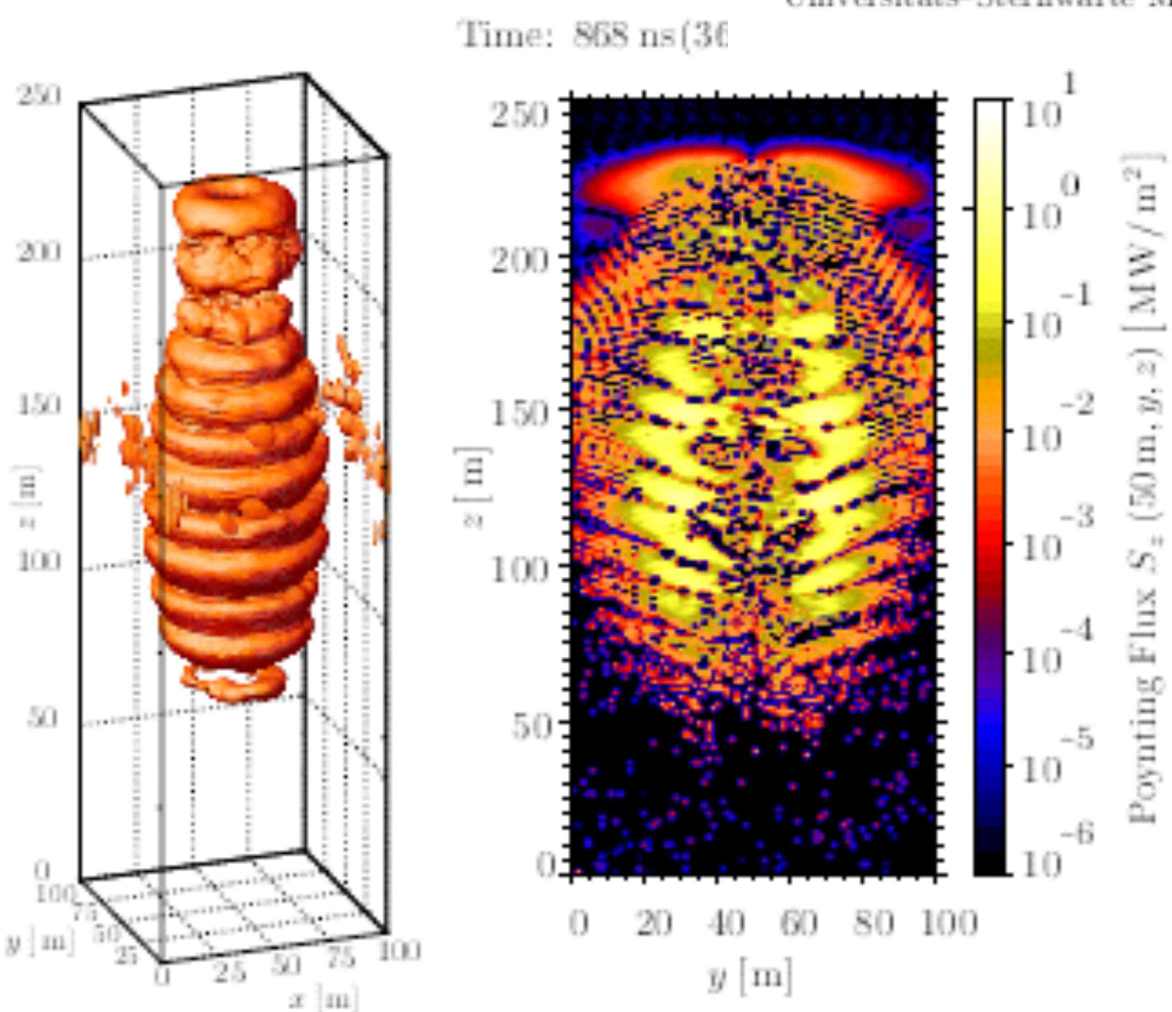


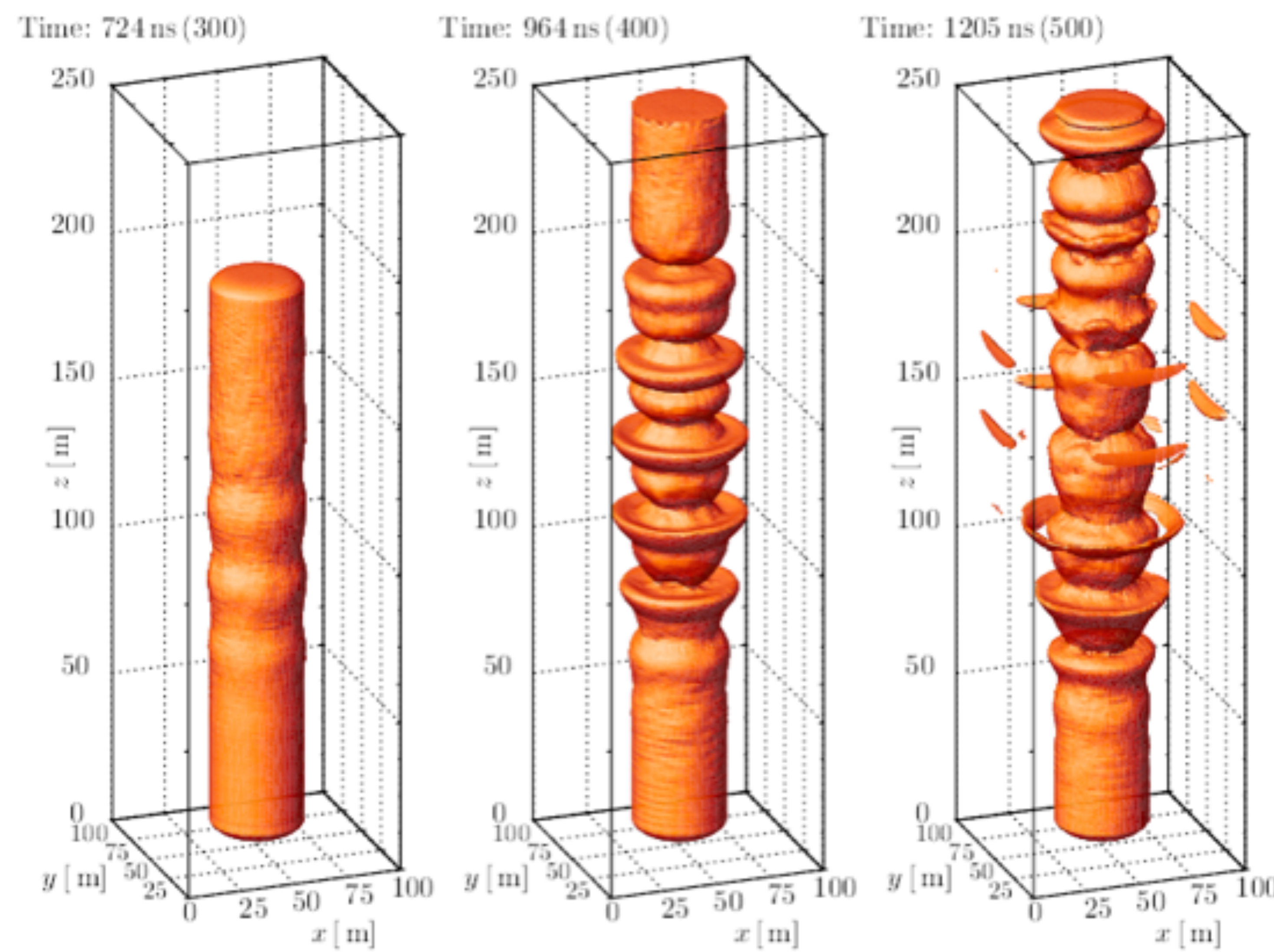
Coherent radio emission from Pulsar surfaces

The Free Electron Maser in Pulsar Magnetospheres

R. Schopper[1,4], H. Ruhl[2], T.A. Kunzl[3] and H. Lesch[4]

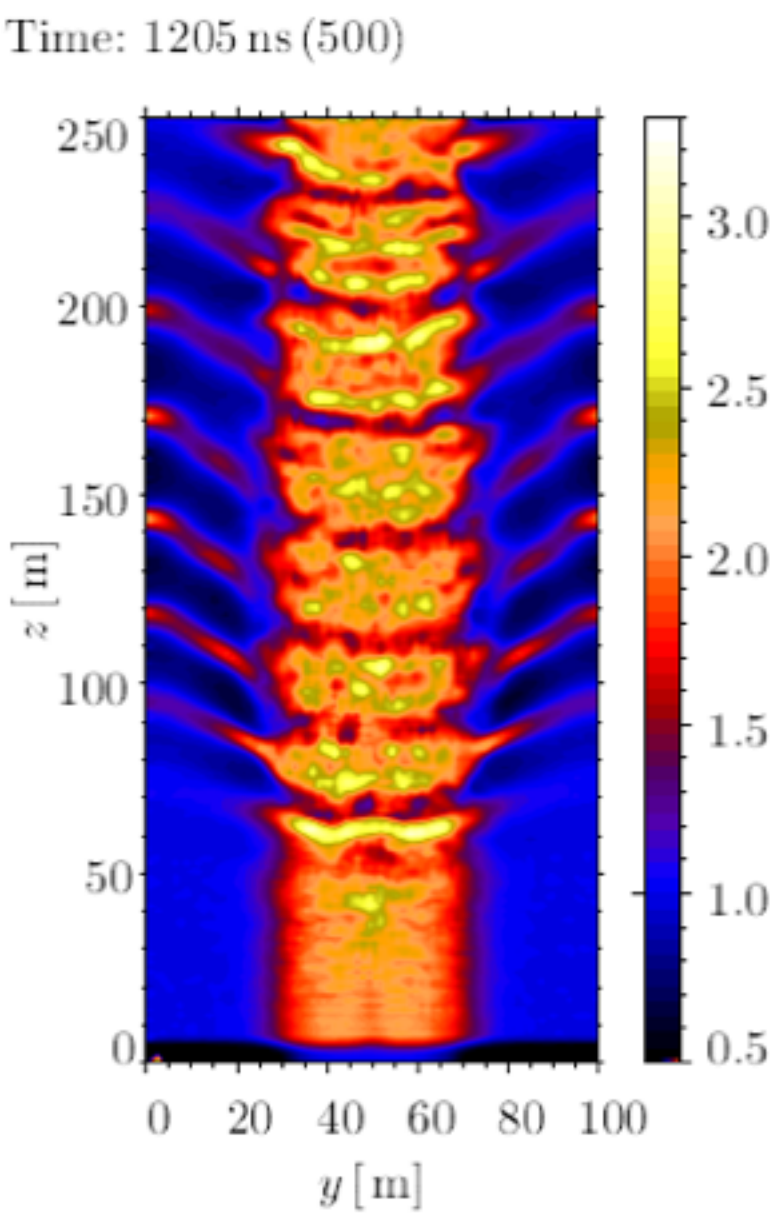
[1] Max–Planck–Institut für extraterrestrische Physik, Giessenbachstraße, 85740 Garching, Germany
[2] General Atomics, San Diego, CA, USA
[3] Max Planck Institut für Quantenoptik, Garching, Germany
[4] Universitäts–Sternwarte München, Scheinerstraße 1, 81679 München, Germany, Centre for Interdisciplinary Plasma Science

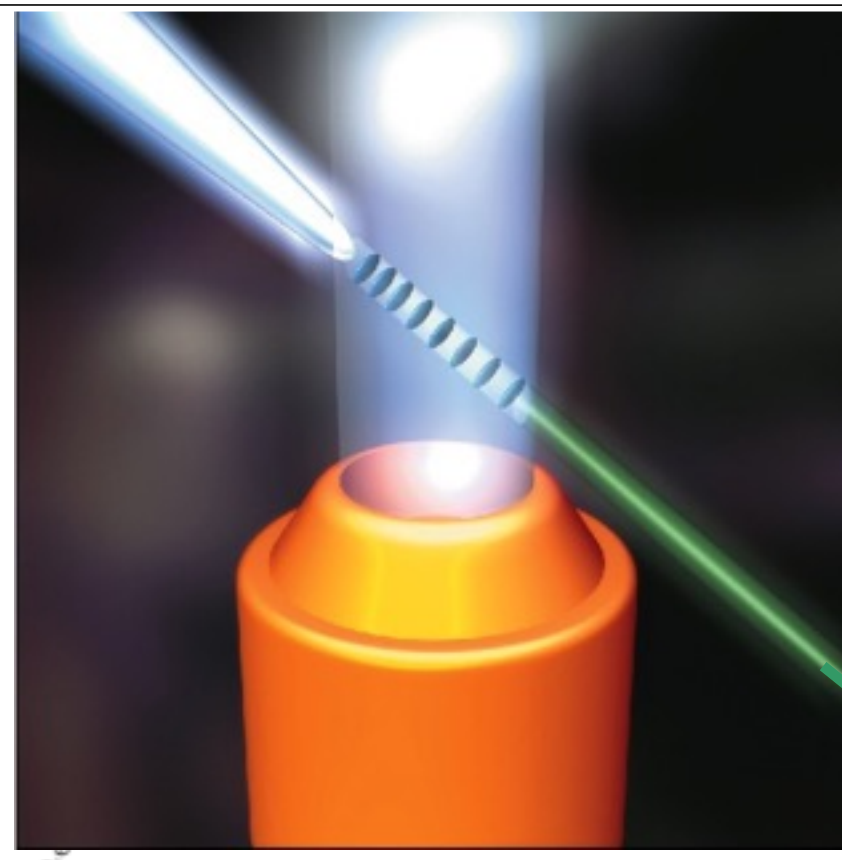


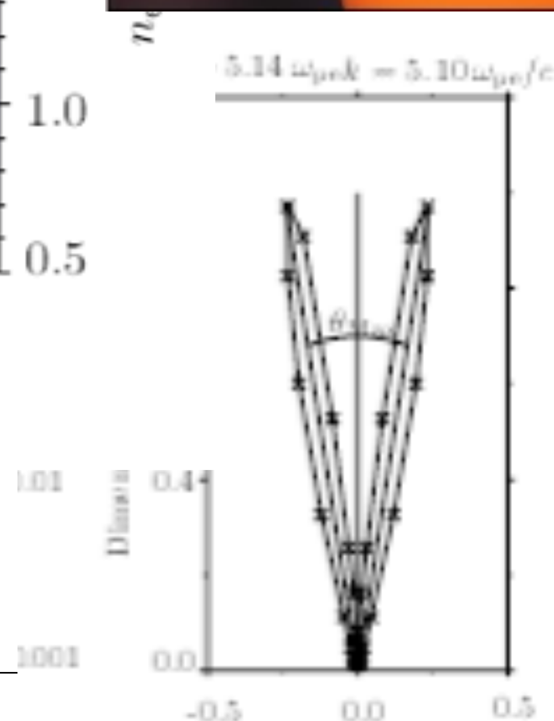


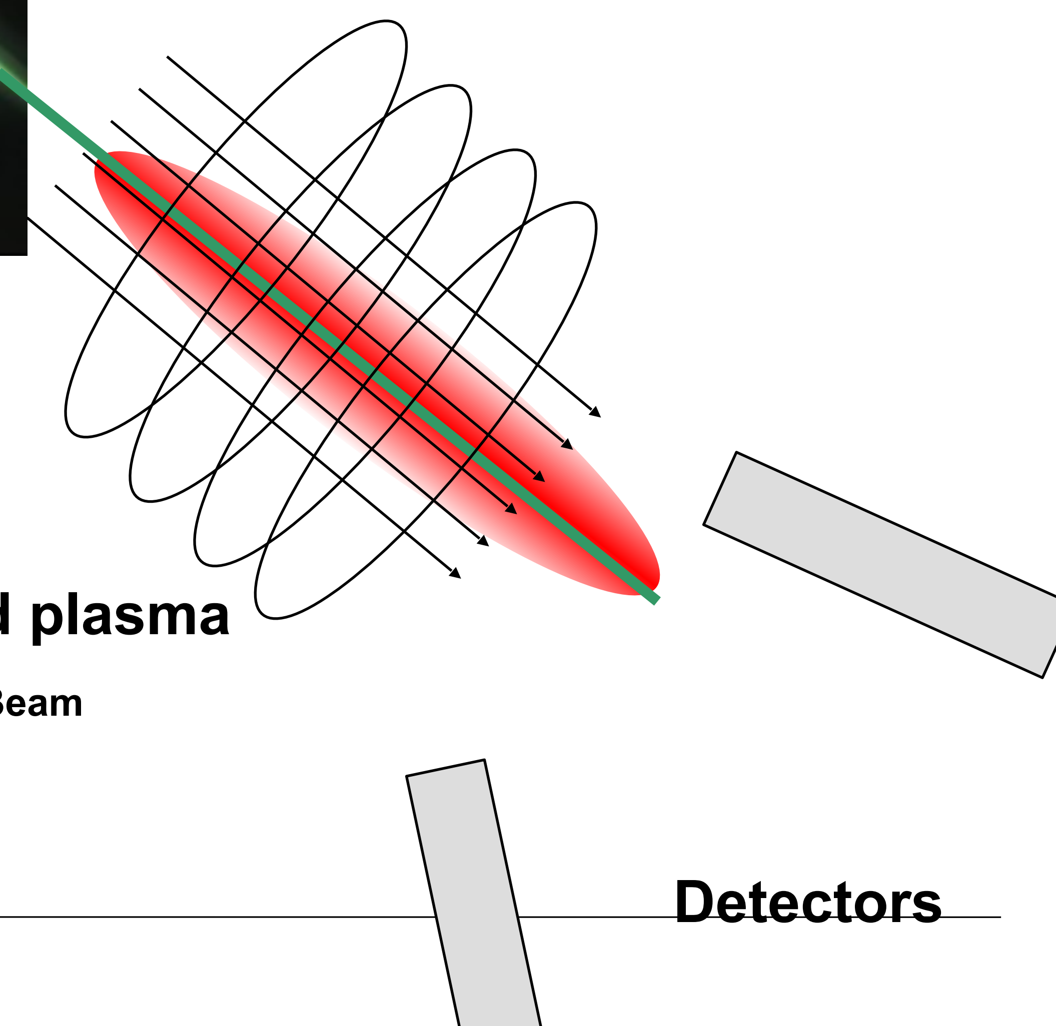
Experiment on longitudinal FEL

(Bild von Viktor Malka)

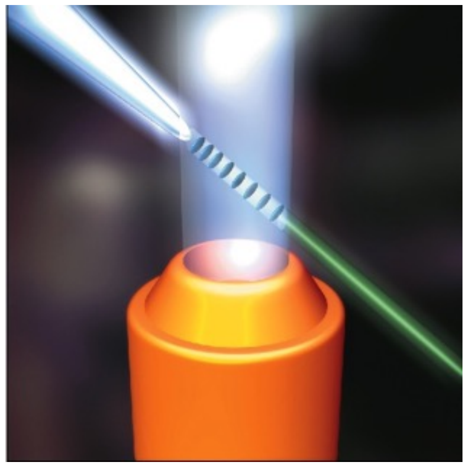








BELLA-i will drive an entire new effort of target fabrication and diagnostics



Gas and liquid jets
how long do they last?
70 shots?

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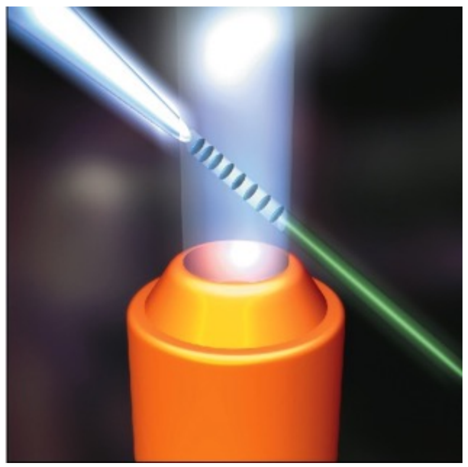

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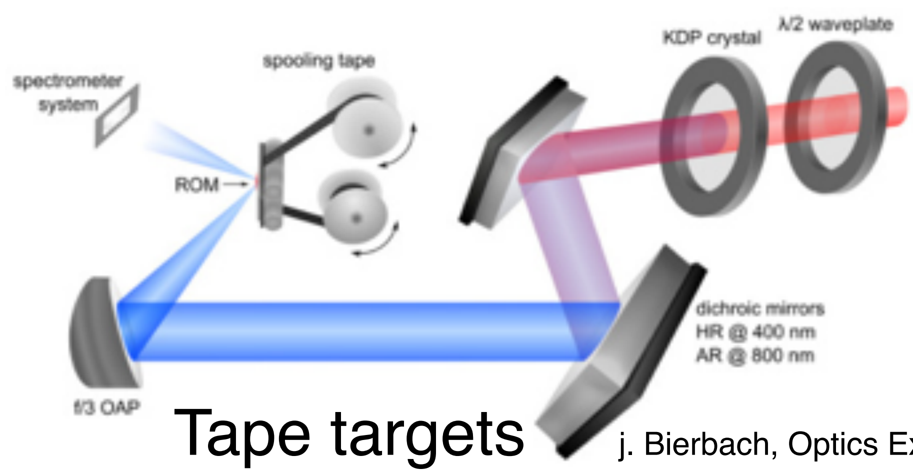
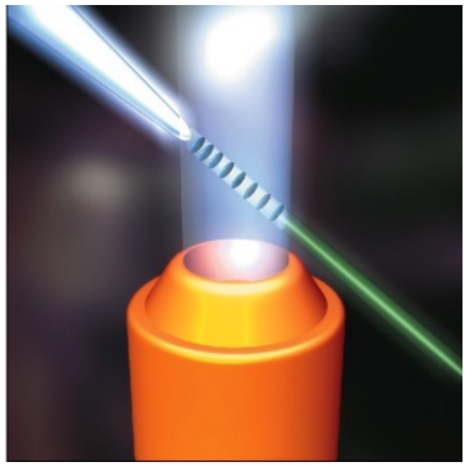


j. Bierbach, Optics Express

Tape targets
simple for TNSA, but for RPA?
Debris?

BELLA-i will drive an entire new effort of target fabrication and diagnostics



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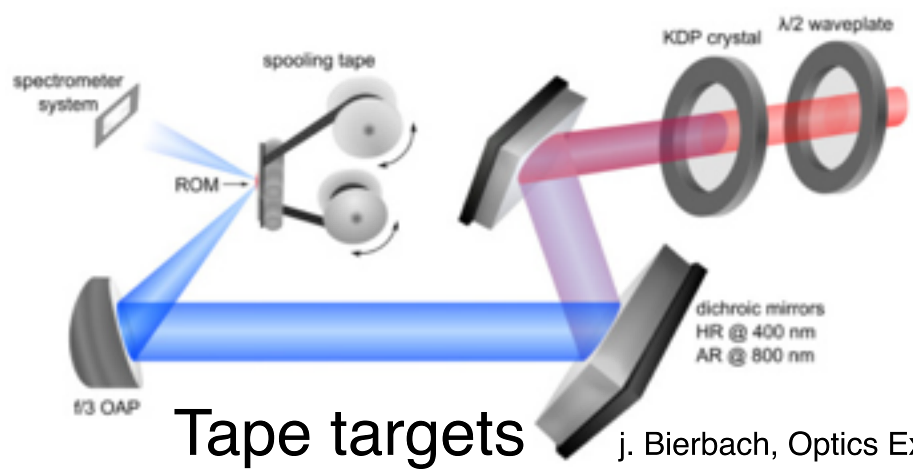

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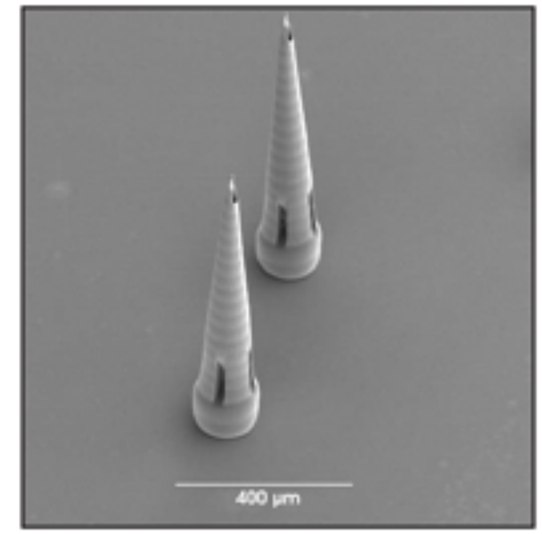

Figure 9. This SEM image shows microneedles for drug delivery fabricated by two-photon polymerization of Ormocers. The microneedles exhibit appropriate mechanical properties and can penetrate skin without fracturing.

Mass production of
shaped targets

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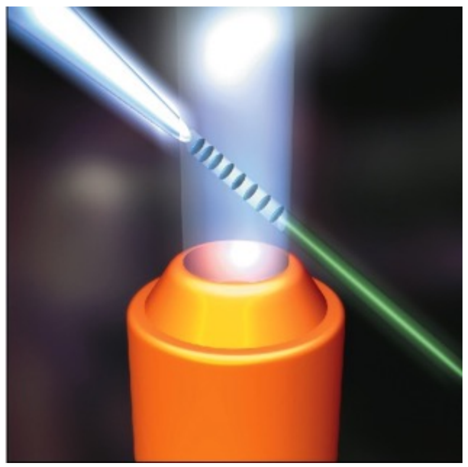

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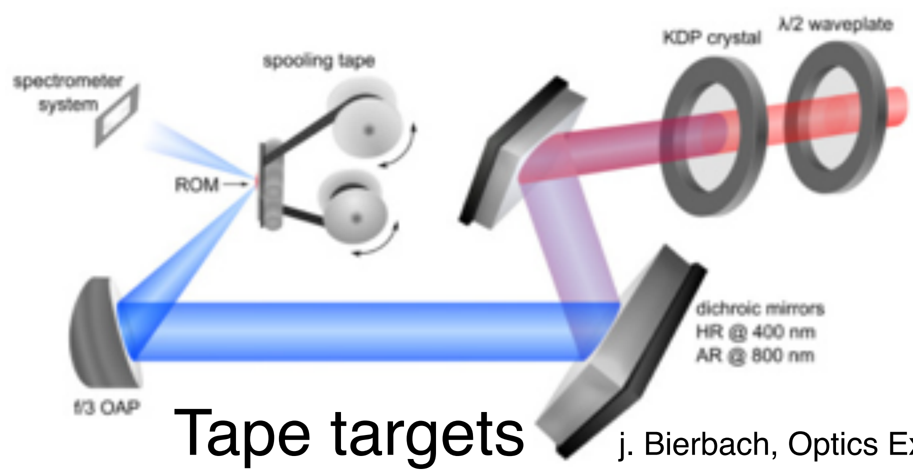

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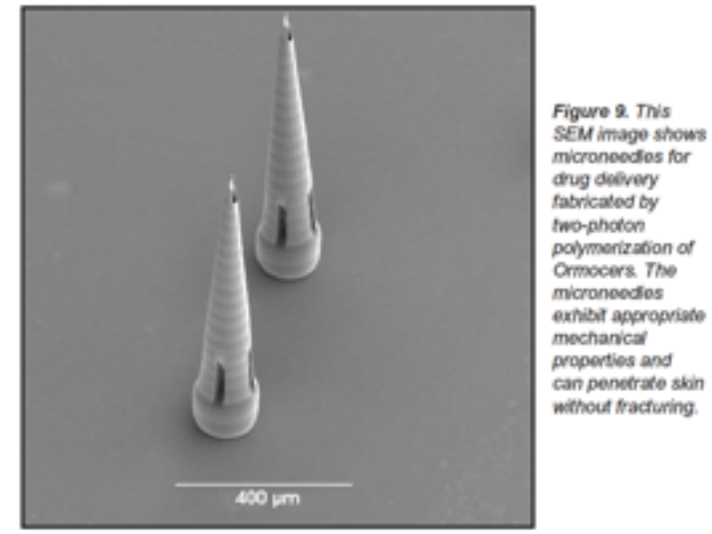

Mass production of
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Particle detectors with
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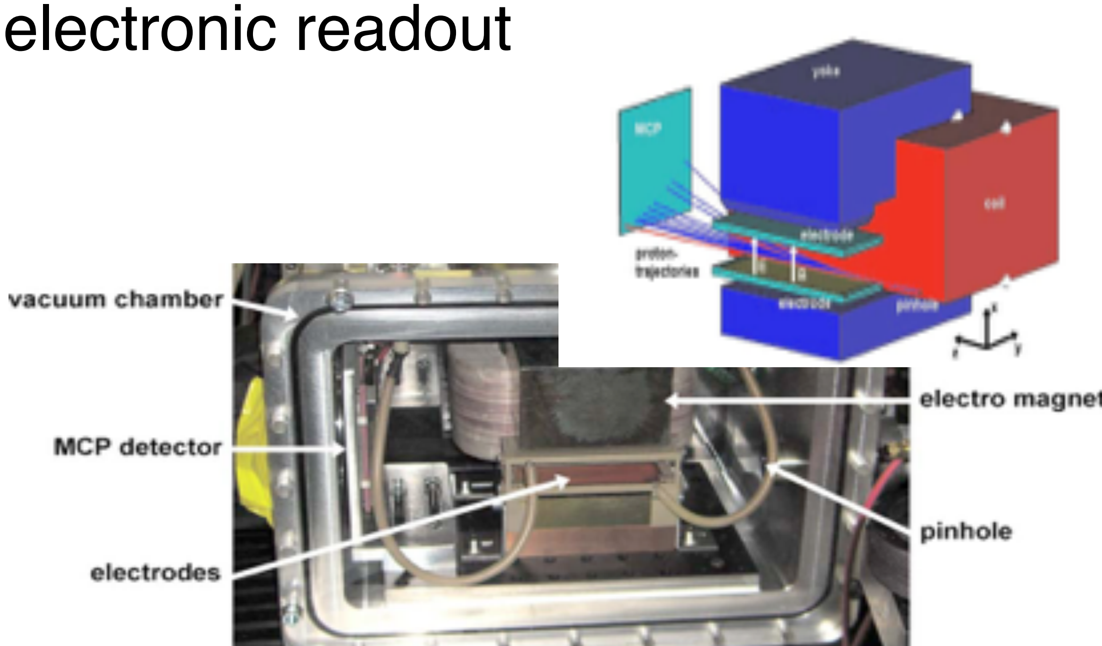

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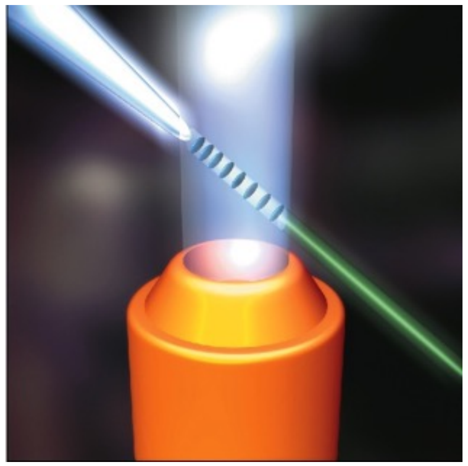

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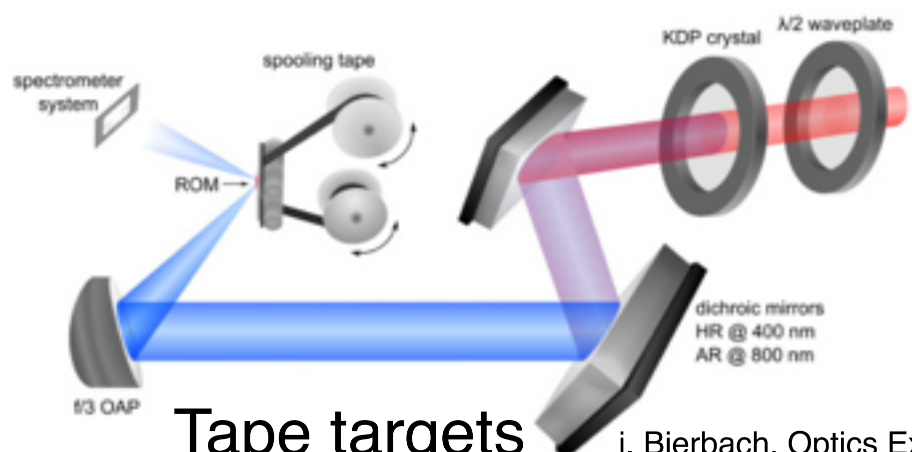

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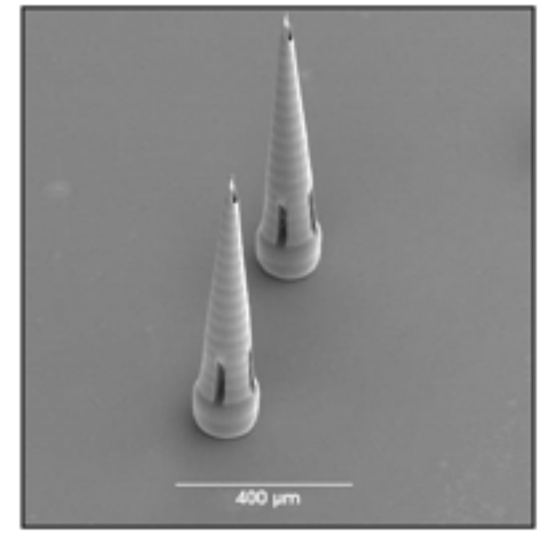

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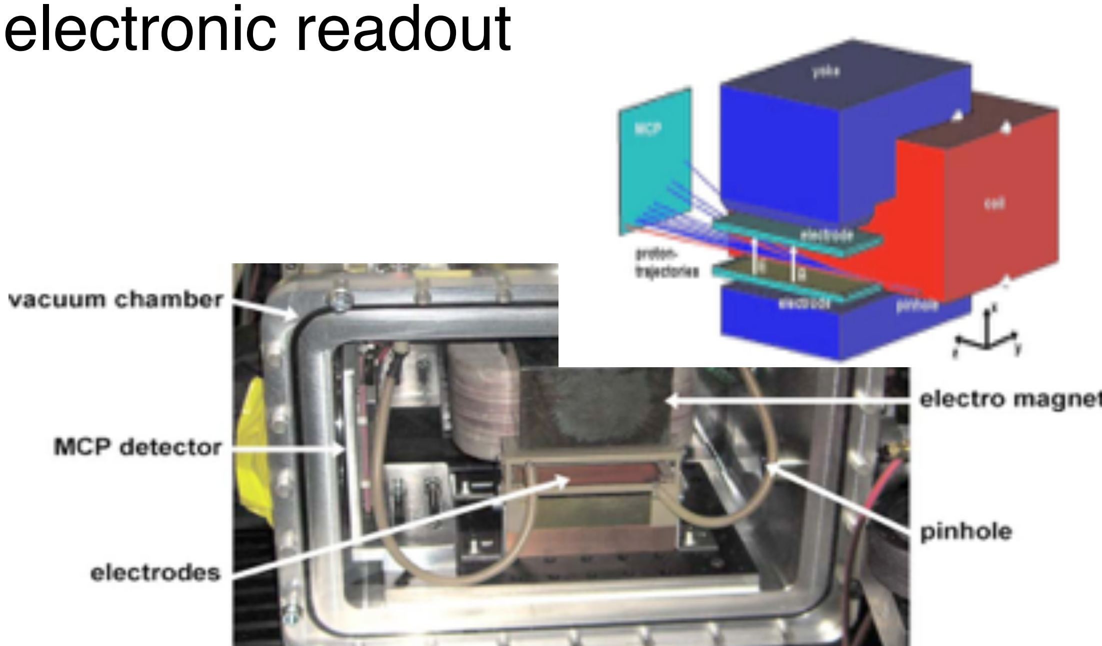

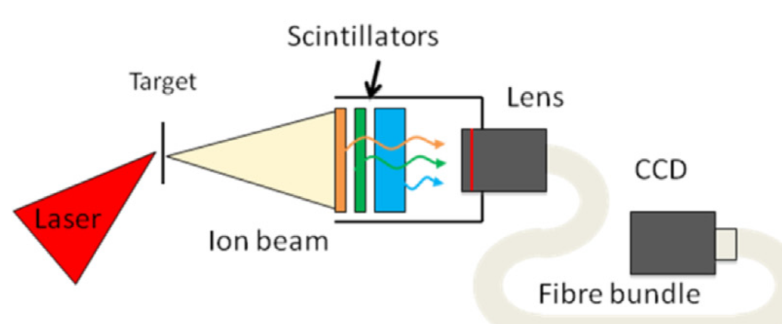

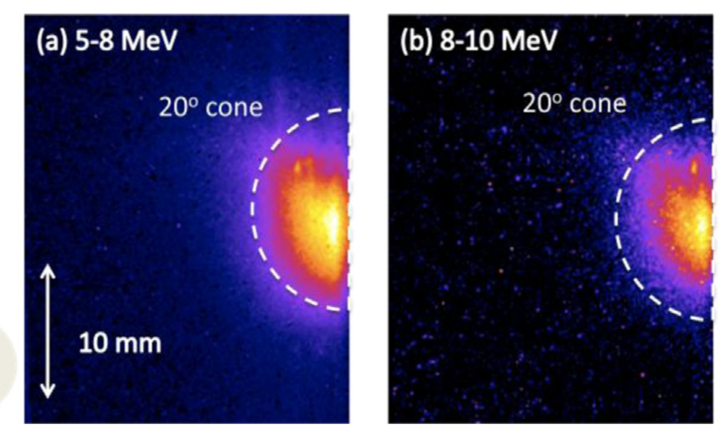

Beam monitoring with spectral optical separation

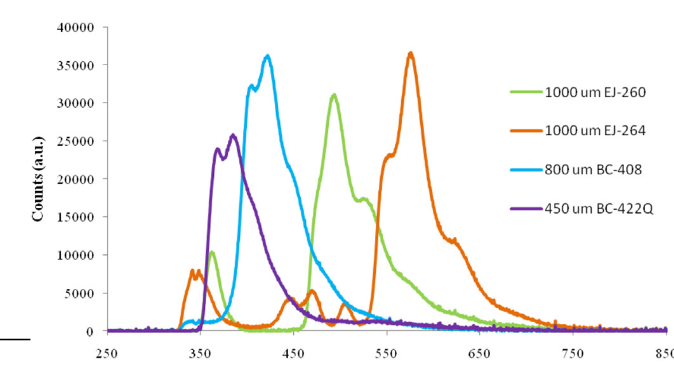

Figure 7. Emission spectra for EJ-260, EJ-264, BC-408 and BC-422Q organic scintillators.

Summary

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- BELLA -i could drive the development of next generation diagnostics and target fabrication


Thank you