Intense Ion Beams for Fusion Research

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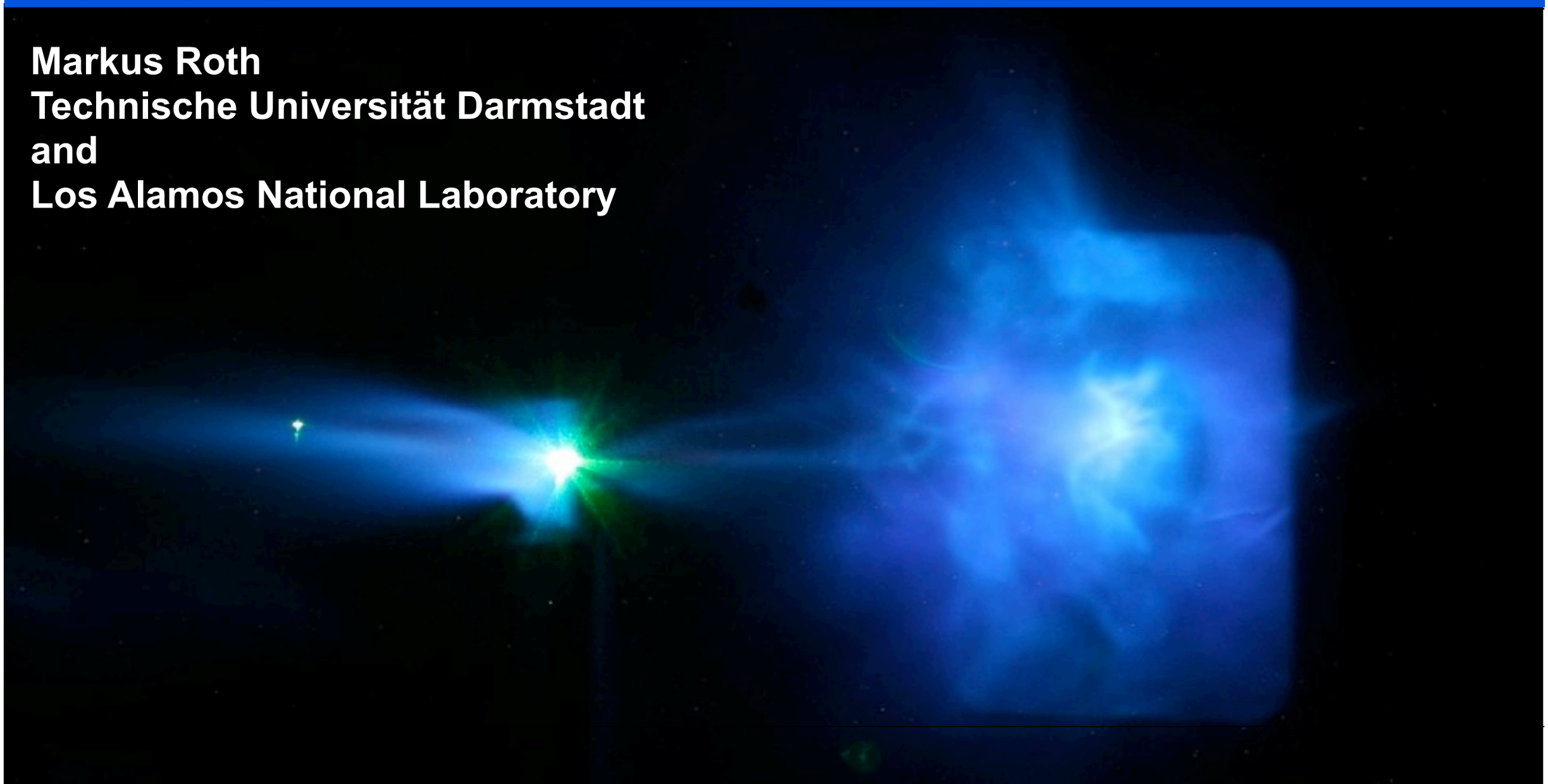
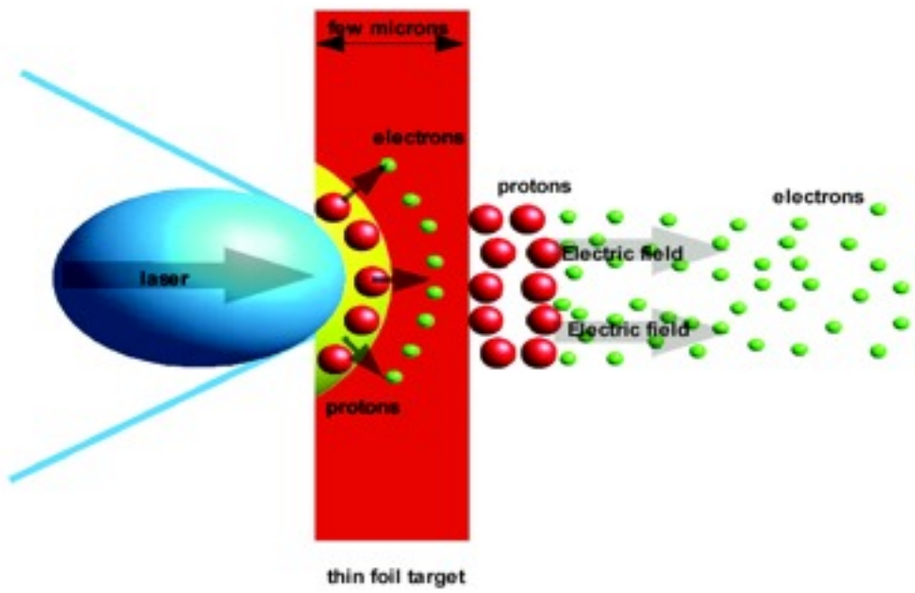
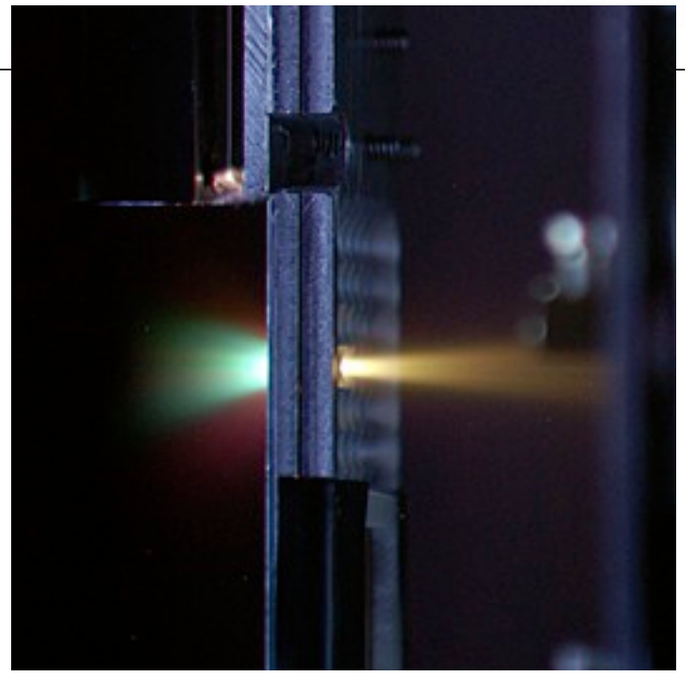
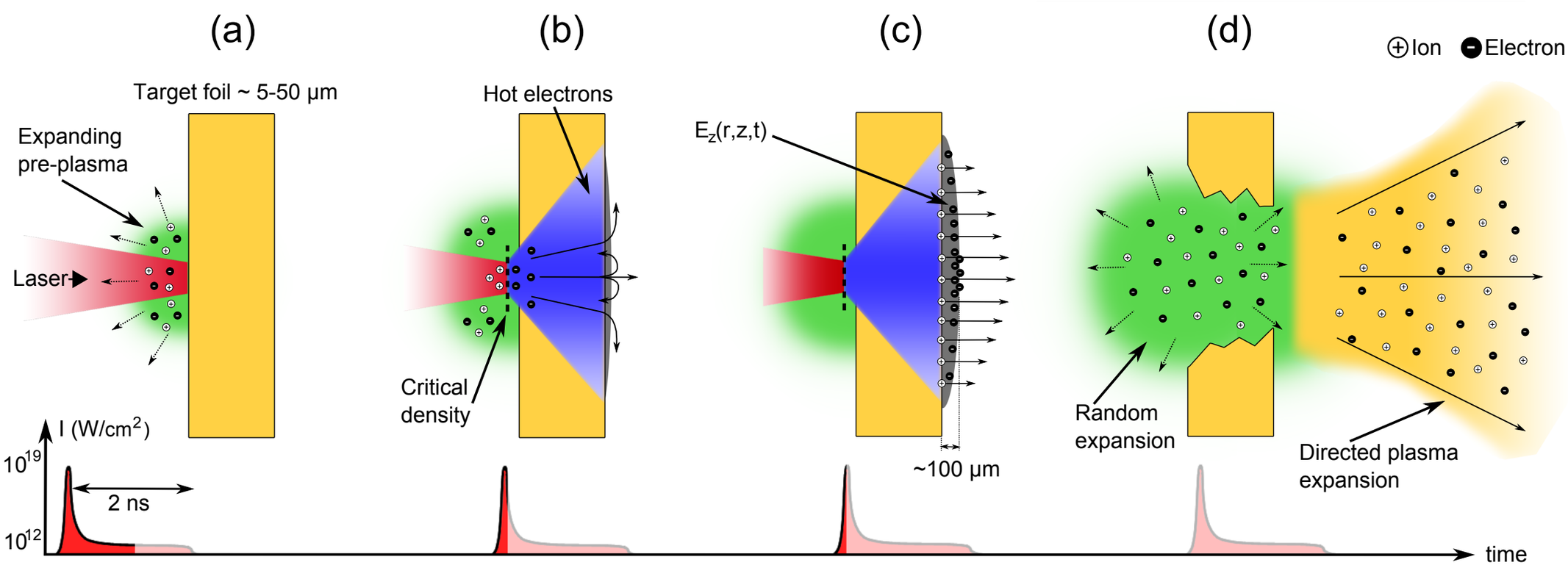
Technische Universität Darmstadt
and
Los Alamos National Laboratory



Proton acceleration with lasers : Static electric fields







Other proposed mechanisms

RPA for highest intensities

Light pressure drives the electrons forward and Ions have to follow

Radiation Pressure Acceleration:

Circular Polarization may enable RPA at „moderate“ intensities (>10^{20} W/cm²).

Radiation Pressure Acceleration with ultraintense lasers has been suggested as an effective ion acceleration mechanism at very high intensities (10^{23}-10^{24} W/cm²):

1. JAERI, Japan: Highly Efficient Relativistic-Ion Generation in the Laser-Piston Regime. T. Esirkepov, et al., PRL, 92 (2004)

Circular Polarization enables Radiation Pressure Acceleration (RPA) or Phase Stable Acceleration (PSA) at todays intensities (~10^{20}-10^{21} W/cm²):

2. SIOM, China: Efficient GeV ion generation by ultraintense circularly polarized laser pulse. Xiaomei Zhang, et al., **PoP 14**, 123108 (2007)
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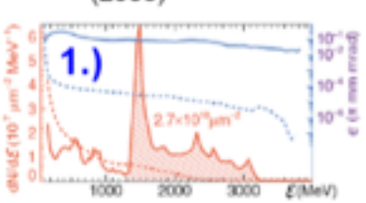
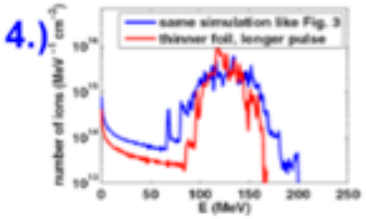
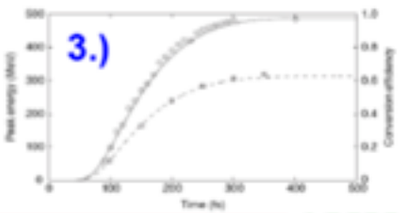
4. Czech Tech. Univ.: Monoenergetic ion beams from ultrathin foils irradiated by ultrahigh-contrast circularly polarized laser pulses, O. Klimo, et al., **PRST-AB 11**, 031301 (2008)
5. Peking Univ., China: Generating High-Current Monoenergetic Proton Beams by a Circularly Polarized Laser Pulse in the Phase-Stable Acceleration Regime, X.Q. Yan et al., **PRL 100**, 135003 (2008)







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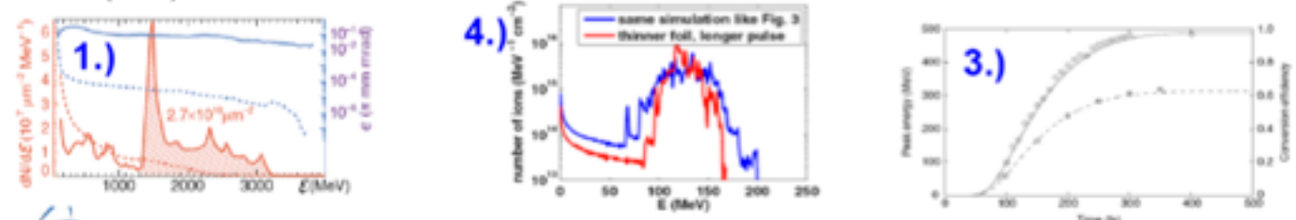

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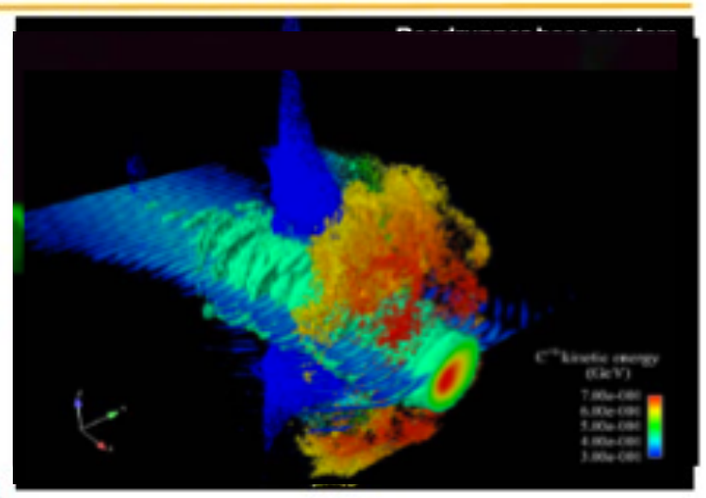
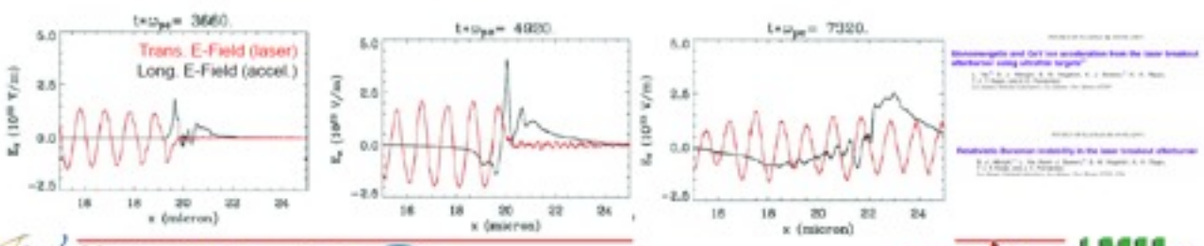
Break-Out Afterburner (BOA) acceleration

BOA proceeds in 3 stages: TNSA, Enhanced TNSA, Afterburner

1. Phase: Standard TNSA - a small fraction of electrons is promoted to 'hot' ⇒ modest acceleration
2. Phase: Enhanced TNSA - all electrons are promoted to 'hot': ⇒ Field increases, skindepth increases beyond target thickness (breakout).
3. Phase: Afterburner - laser penetrates the target, velocity difference in e- and ion distributions triggers kinetic instability ⇒ Electron transfer energy to ions, laser reheats electrons (afterburner).

- Largest ion energies emitted in an angle in plane orthogonal to polarization plane.
- Accelerating E-Field moves with the Ions





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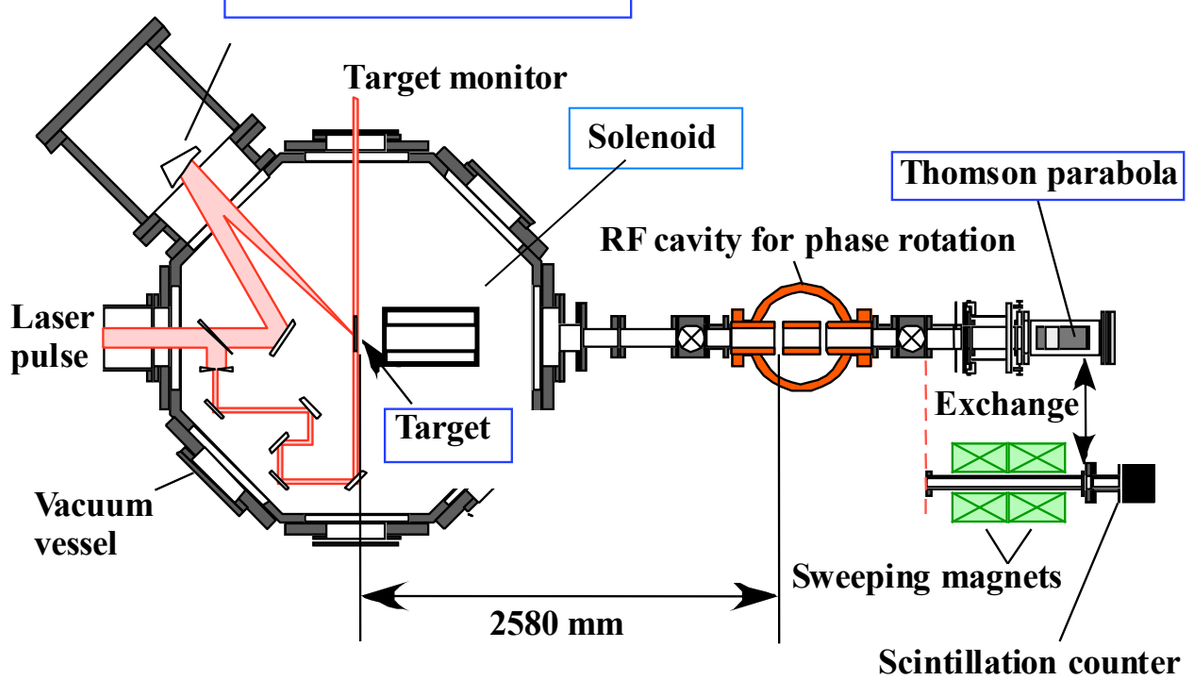
BOA mechanism
second boost of the hot electrons when target becomes transparent

Kinematic Buneman instability

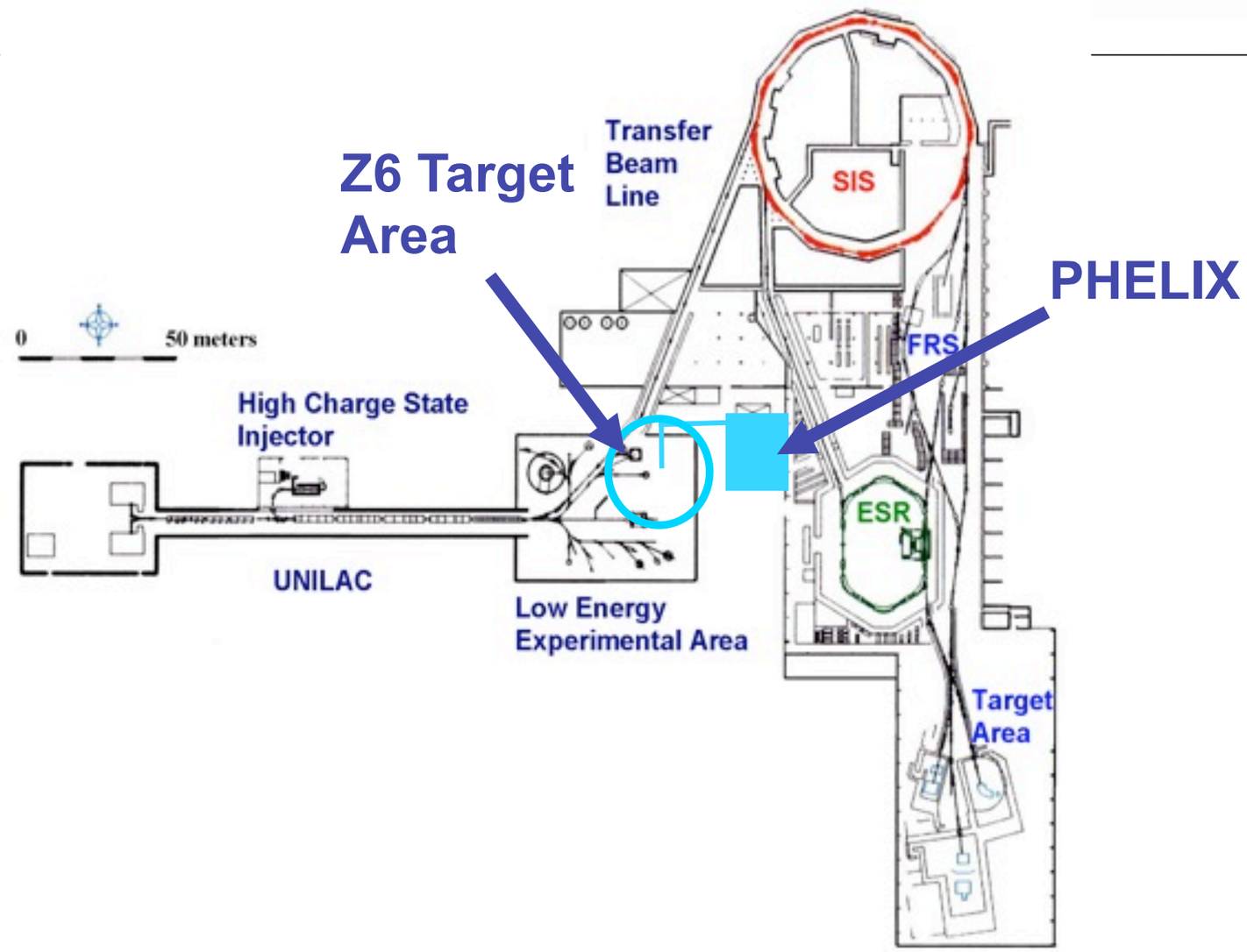
Slides from B.M. Hegelich (LANL)

Tailoring and transport of ion beams
- the LIGHT project -



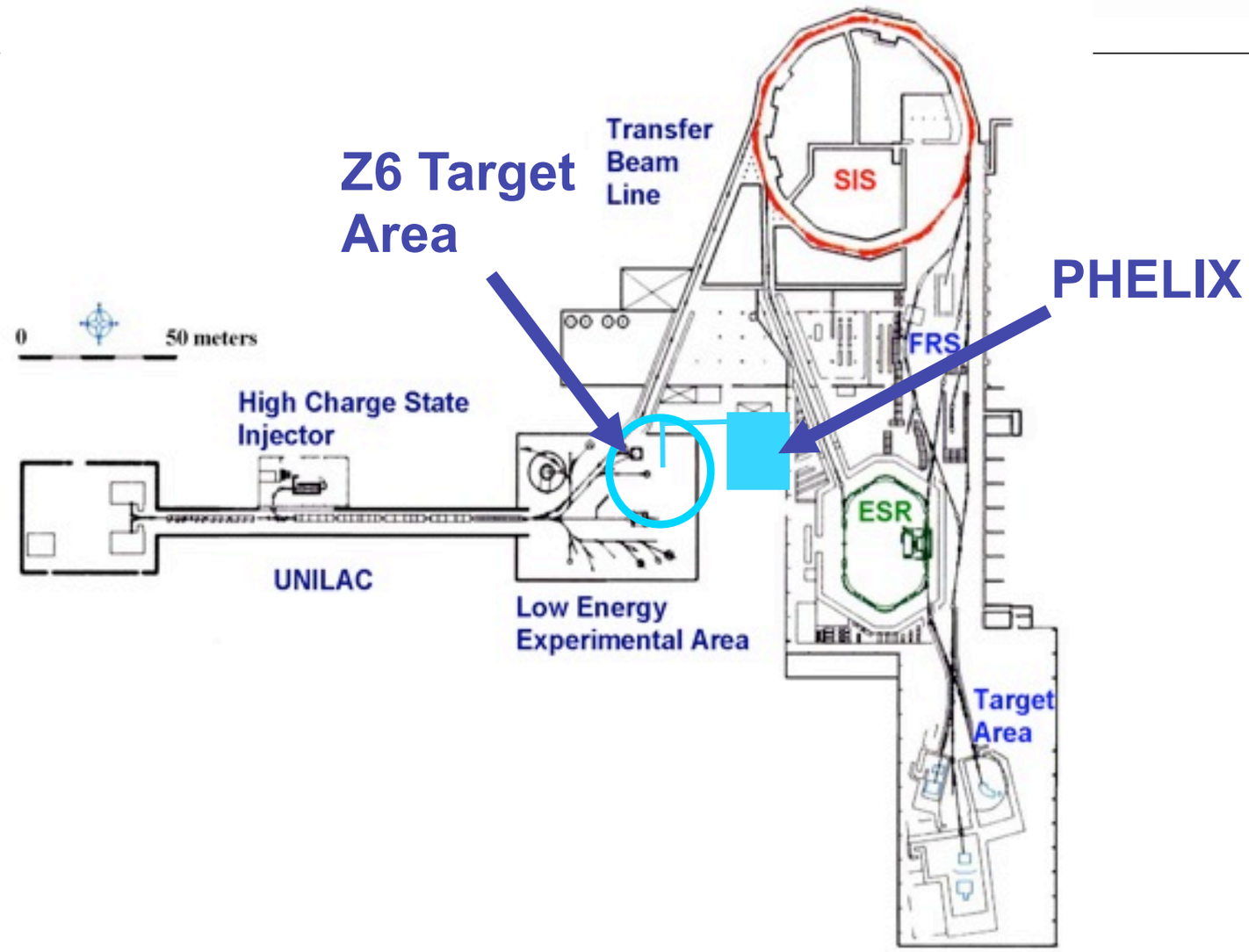
Picture: Courtesy of Paul Bolton (PMRC)

Motivation


Z6 Target Area
Transfer Beam Line
SIS
PHELIX
0
50 meters
FRS
High Charge State Injector
ESR
UNILAC
Low Energy Experimental Area
Target Area

Motivation

- **Leading expertise in both fields (laser acceleration, accelerator technology) available at GSI, surrounding universities, and HIJ**



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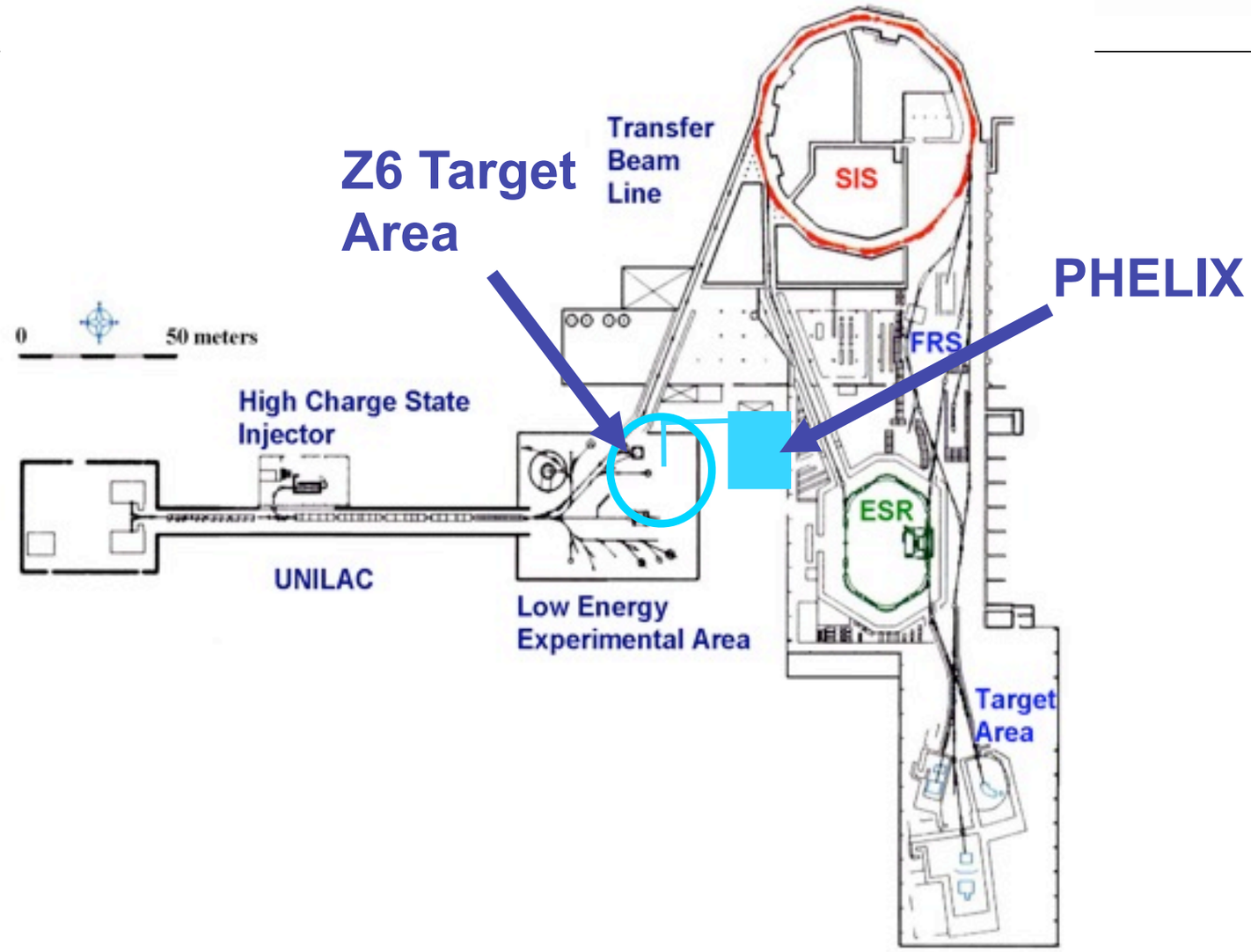

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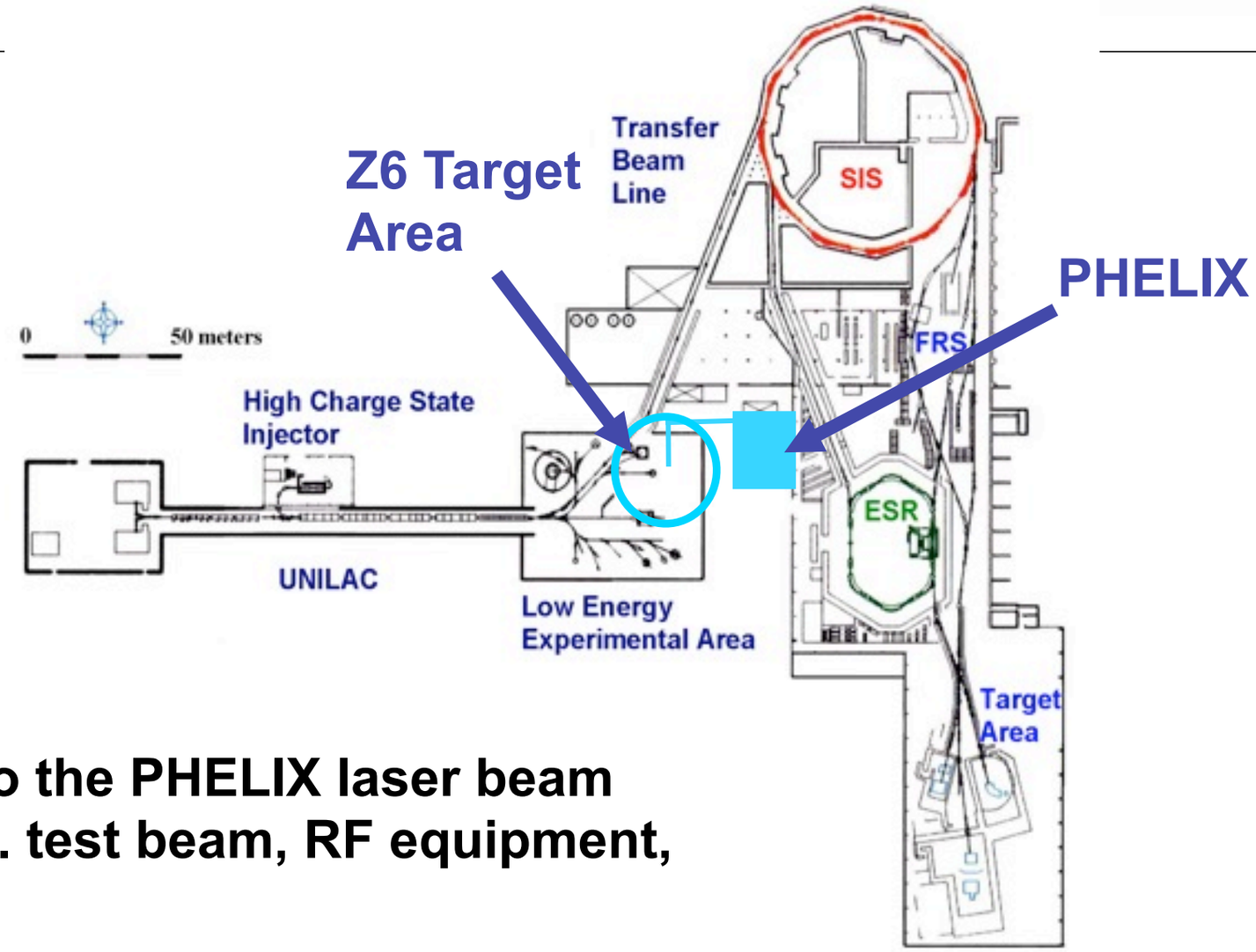

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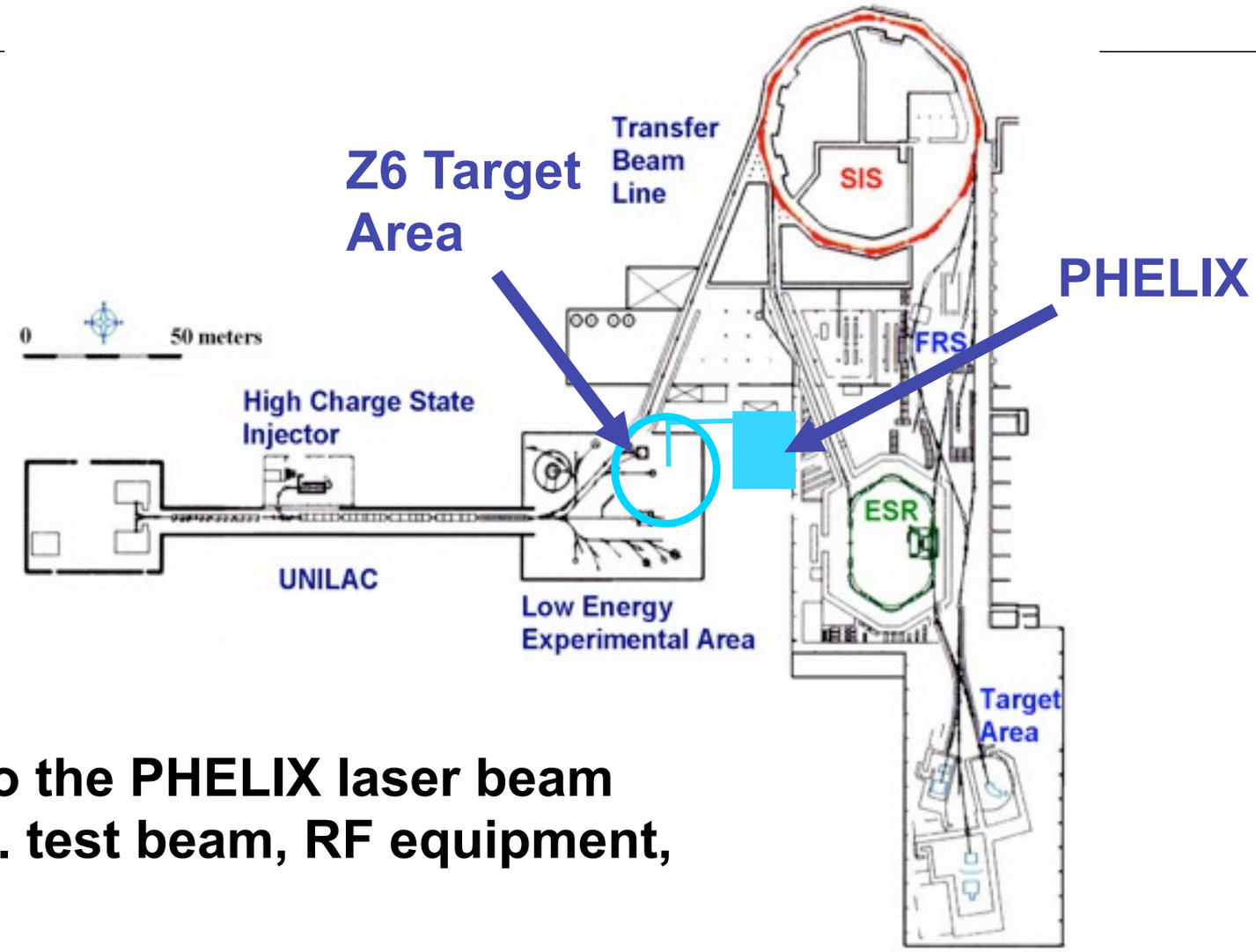

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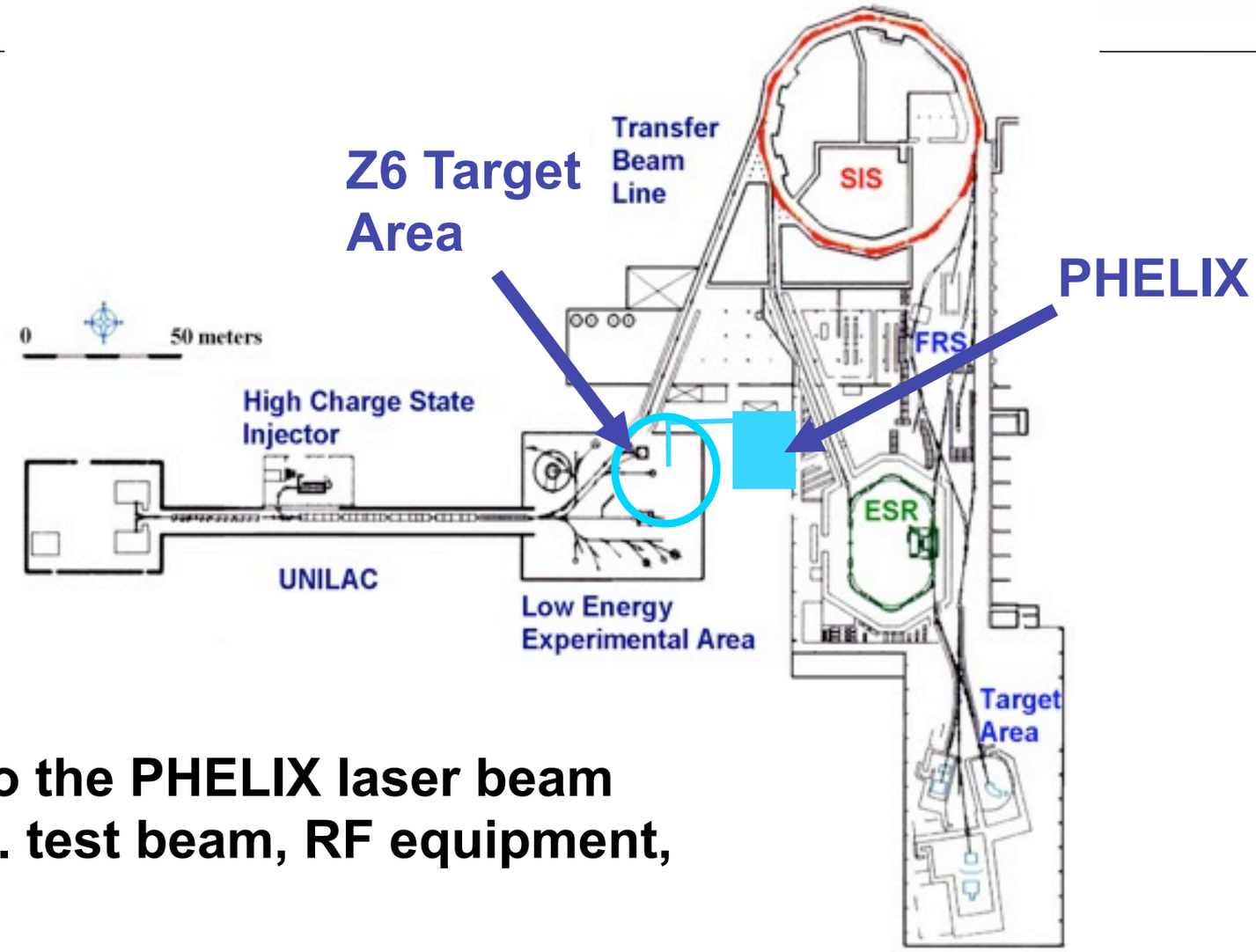

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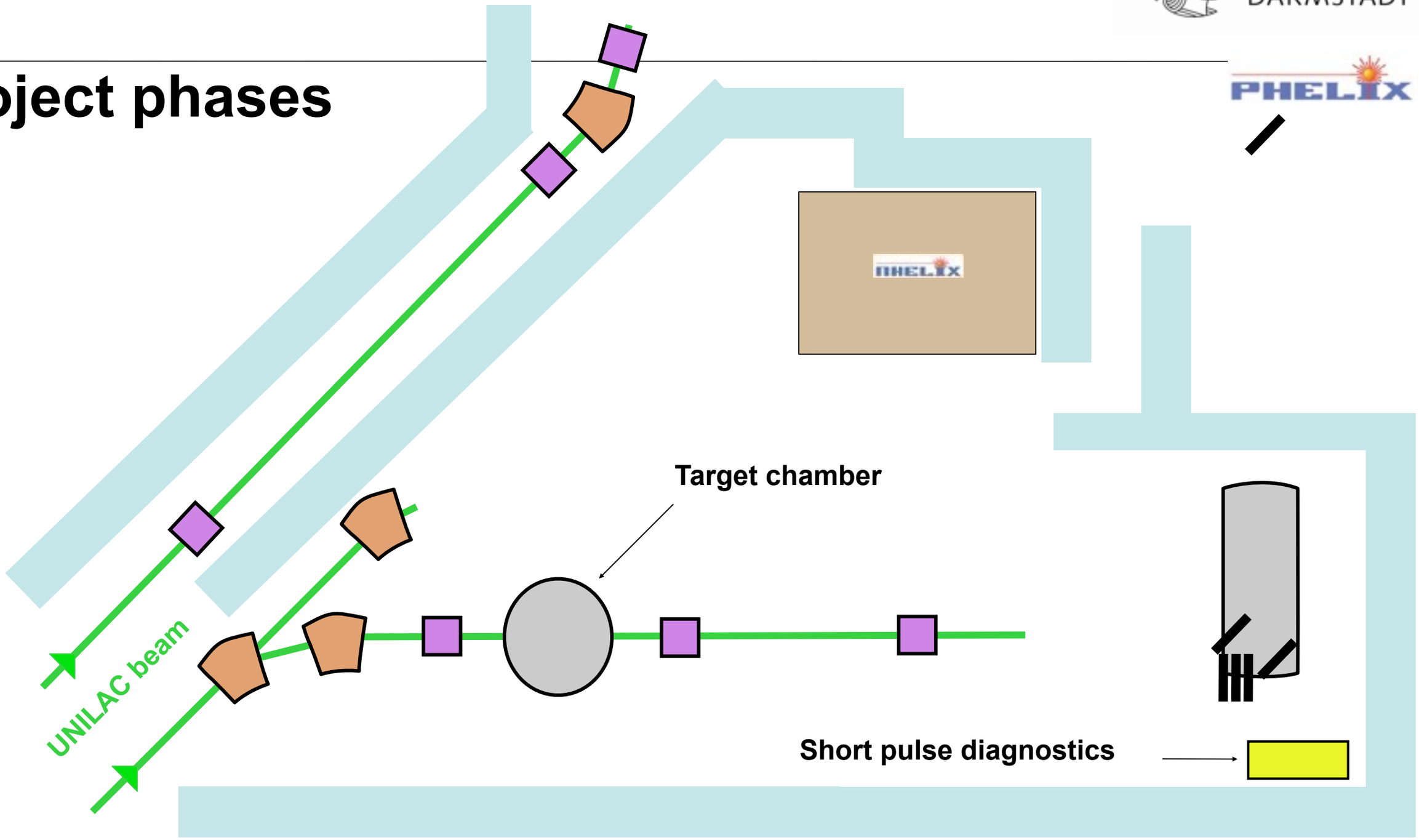
Idea to establish a test bed for laser ion - beam coupling and novel target and accelereation ideas

Project phases



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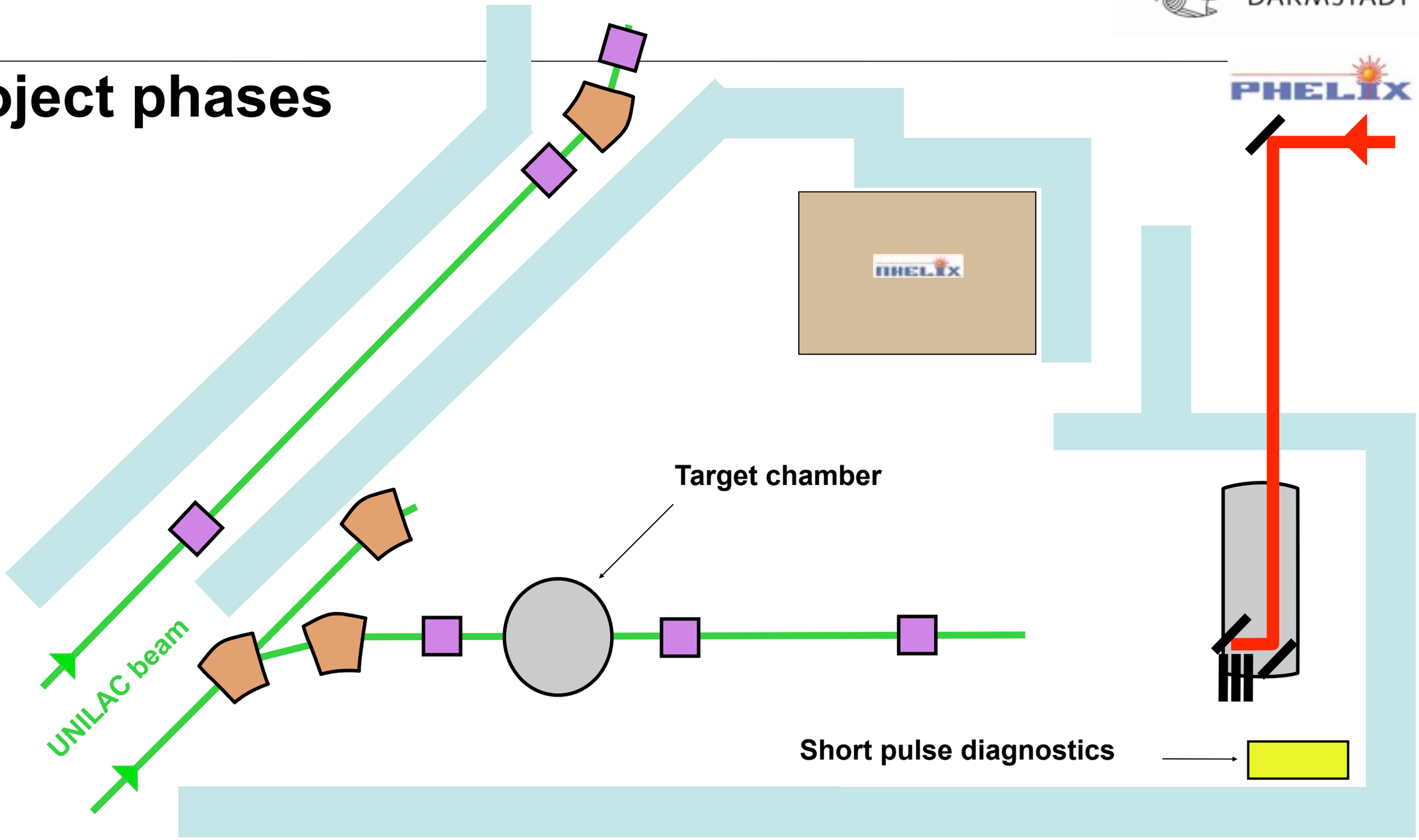

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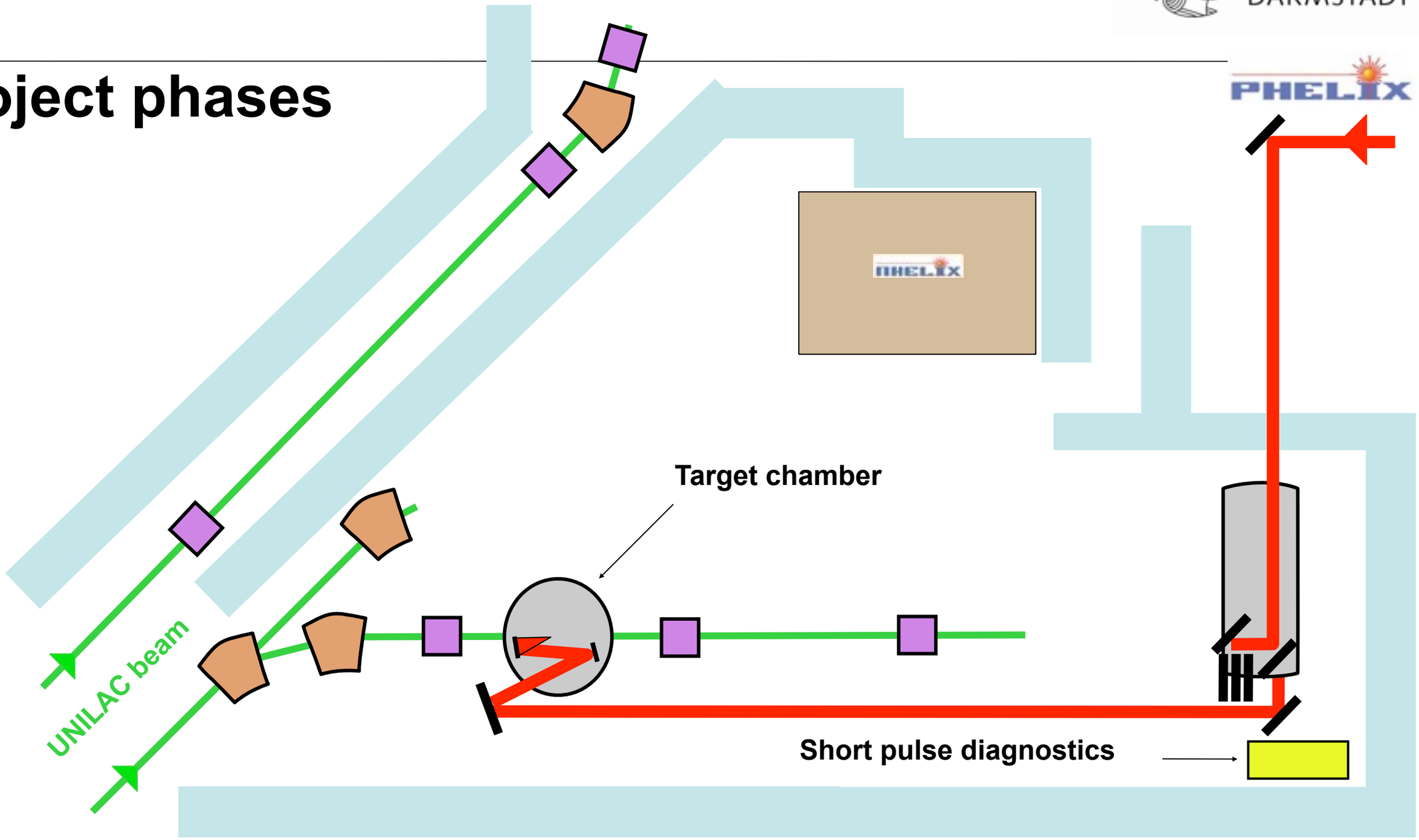

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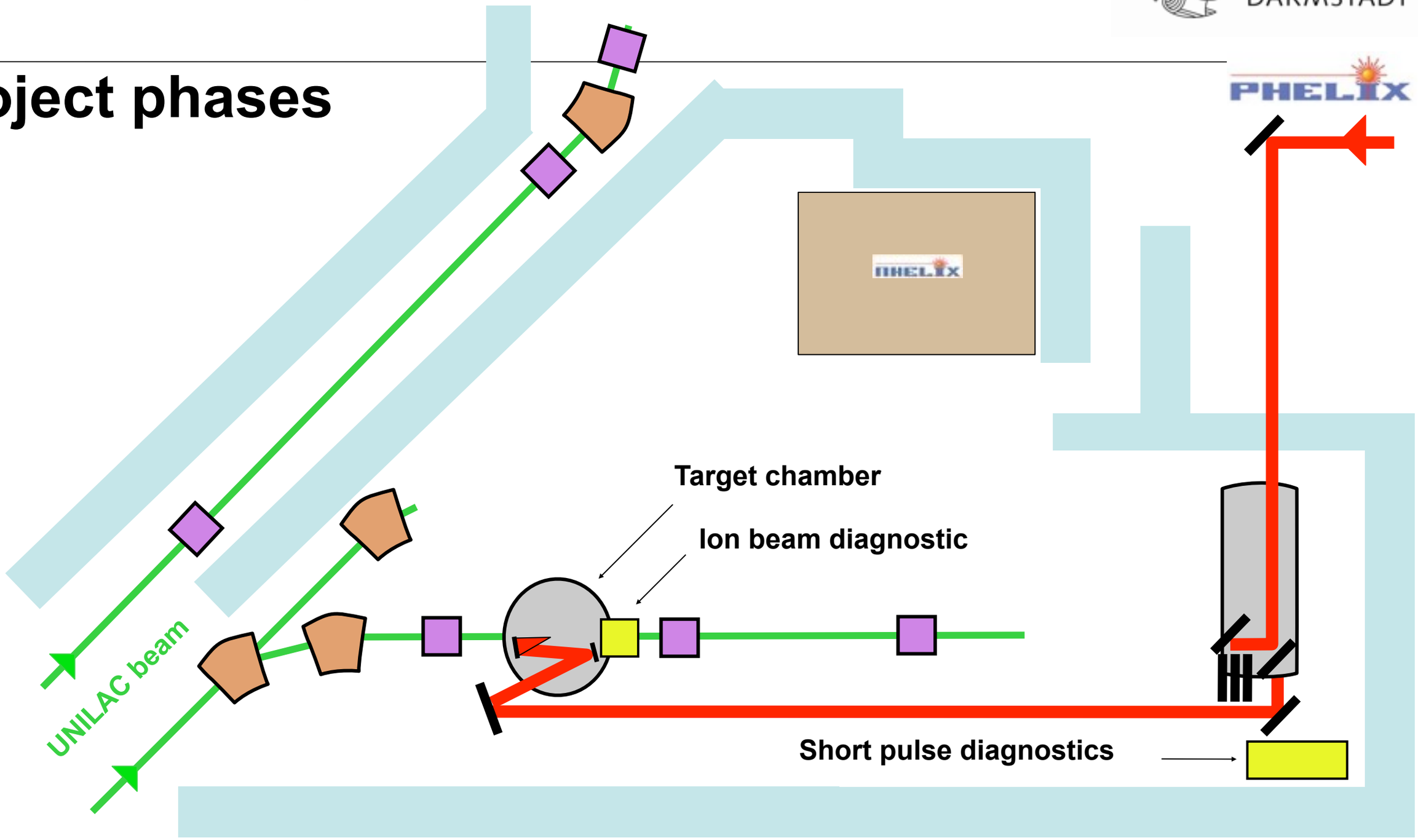

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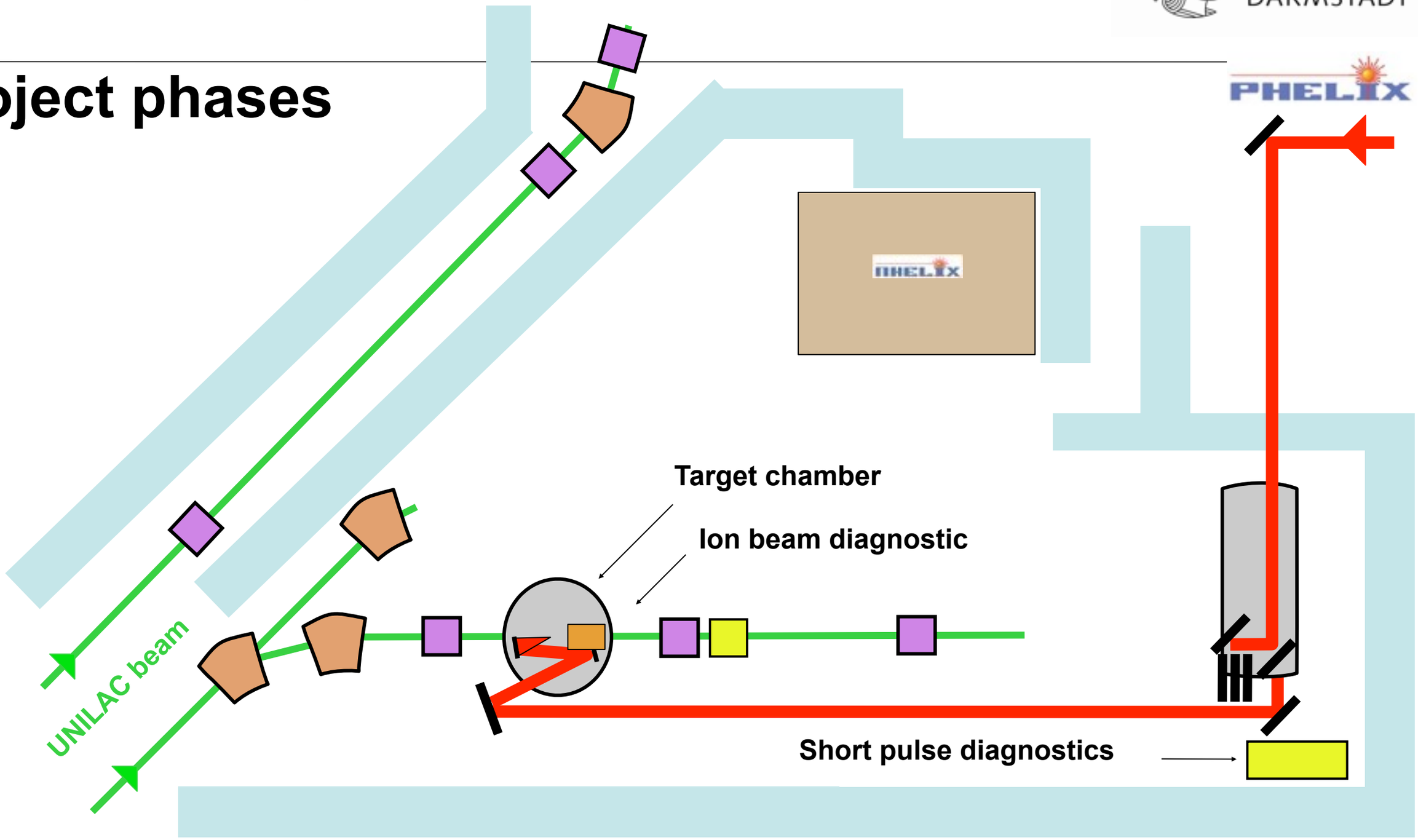

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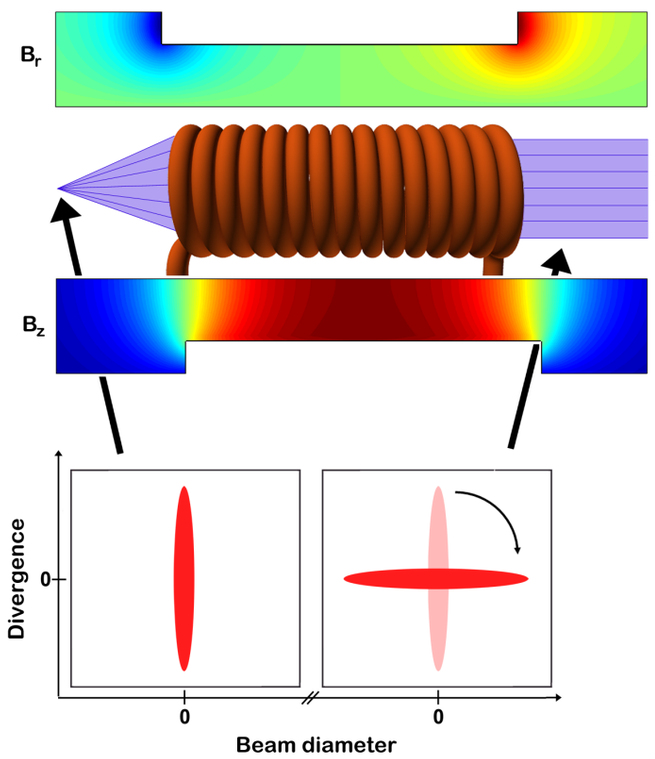

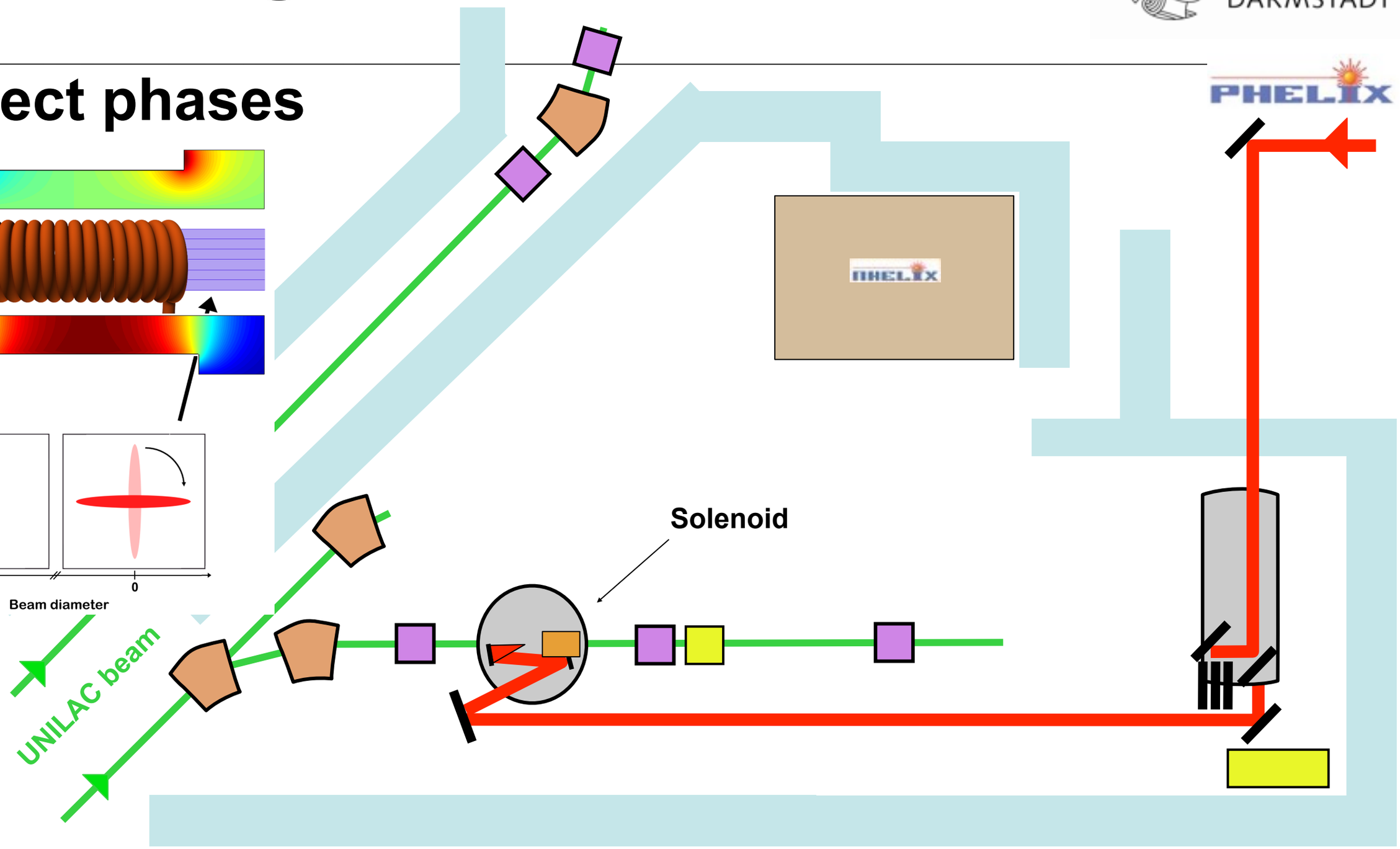

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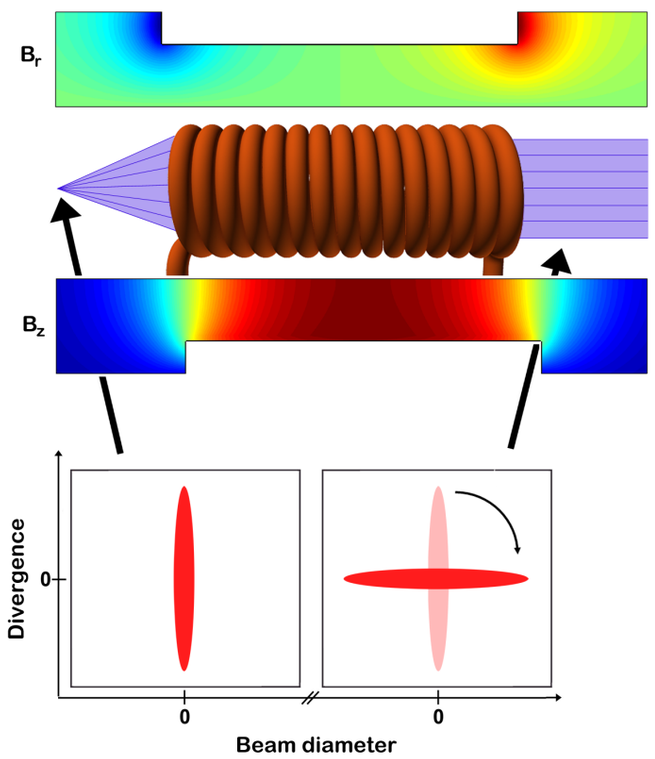

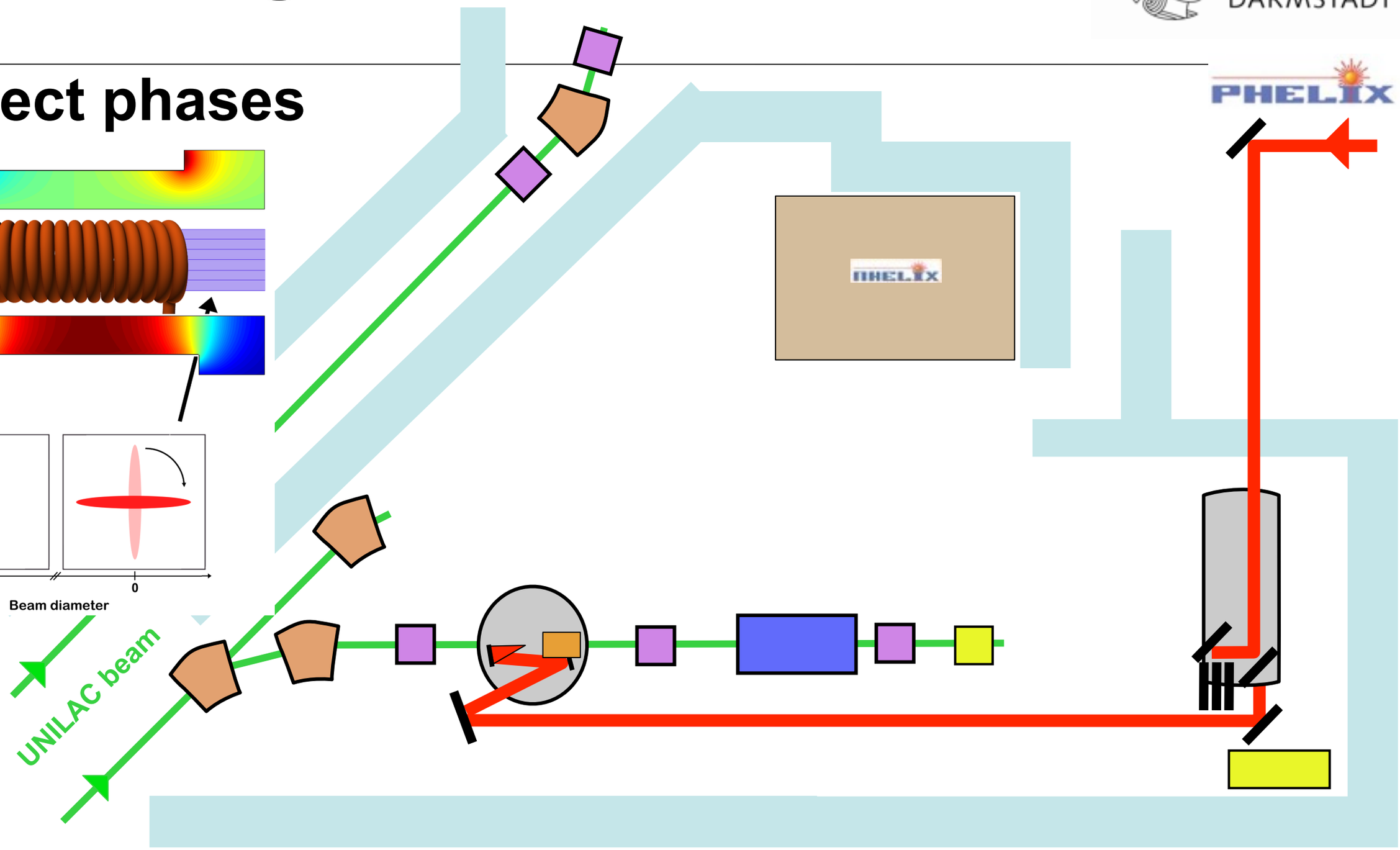

Laser Ion Generation Handling and Transport

LIGHT @ GSI

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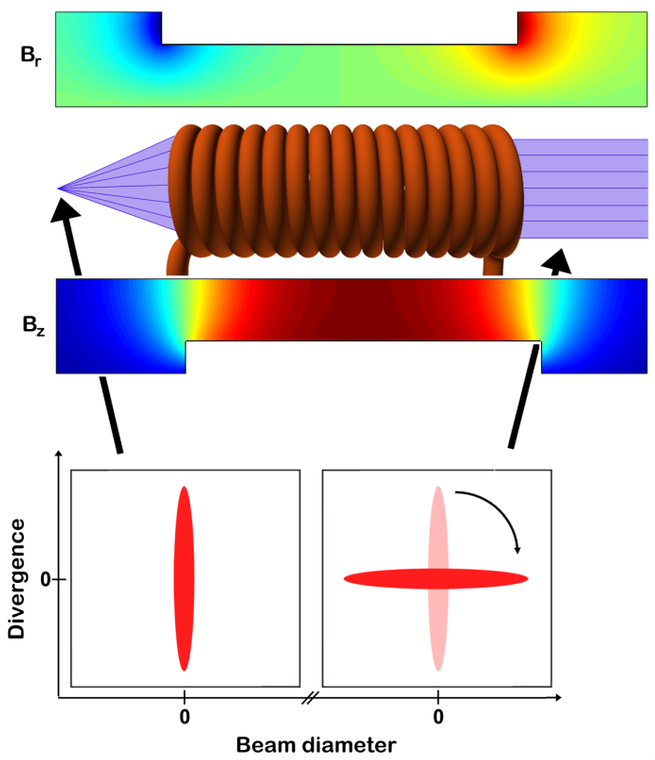

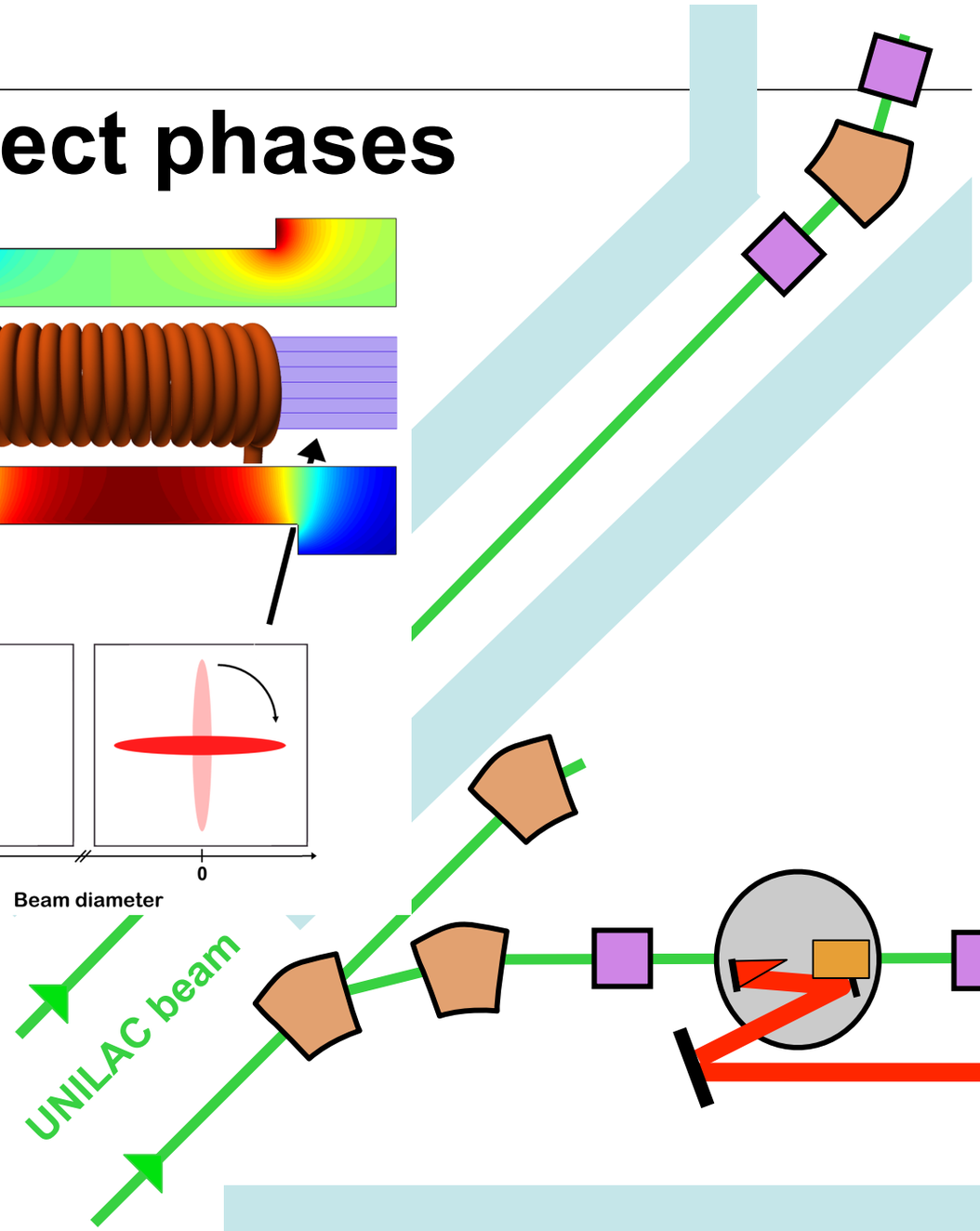

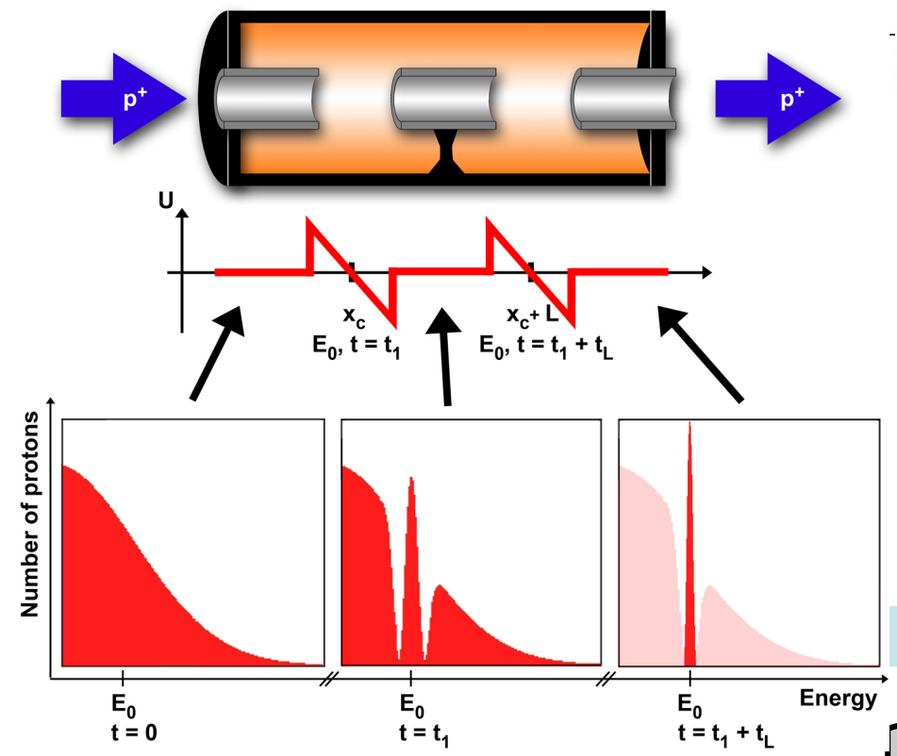

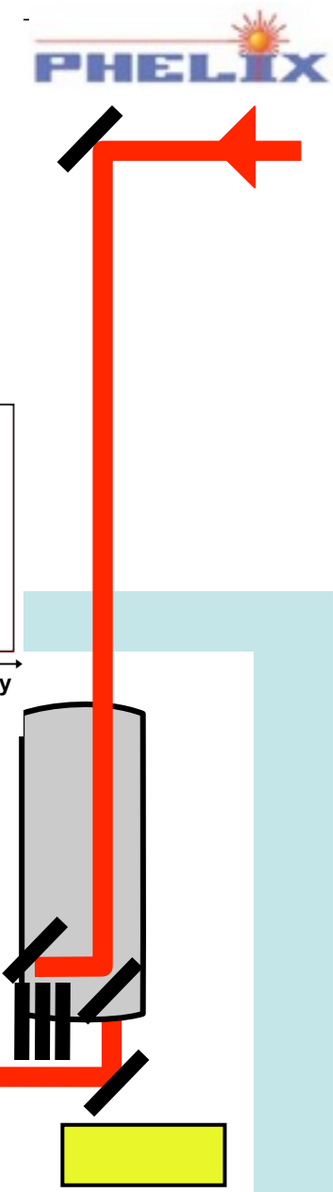

Debuncher cavity

Laser Ion Generation Handling and Transport

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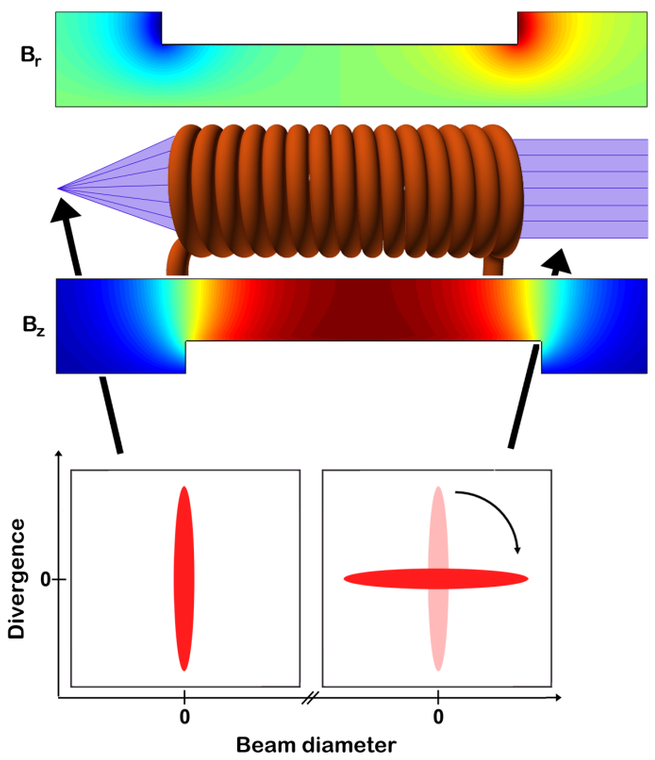

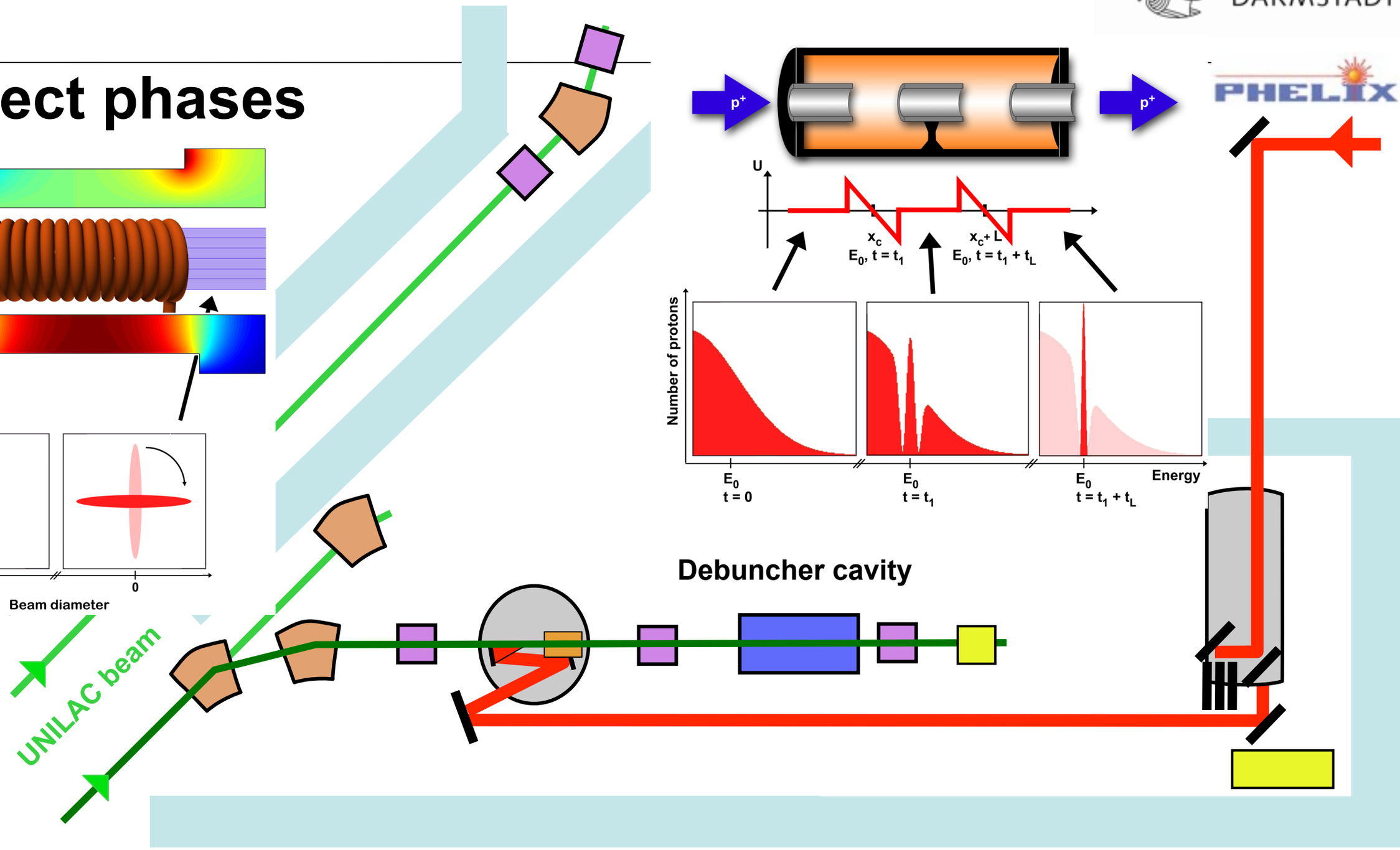

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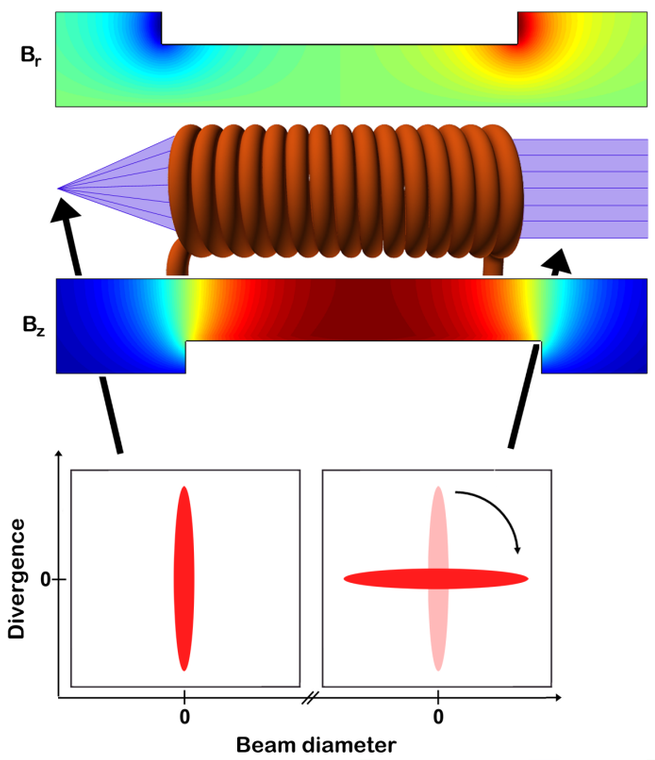

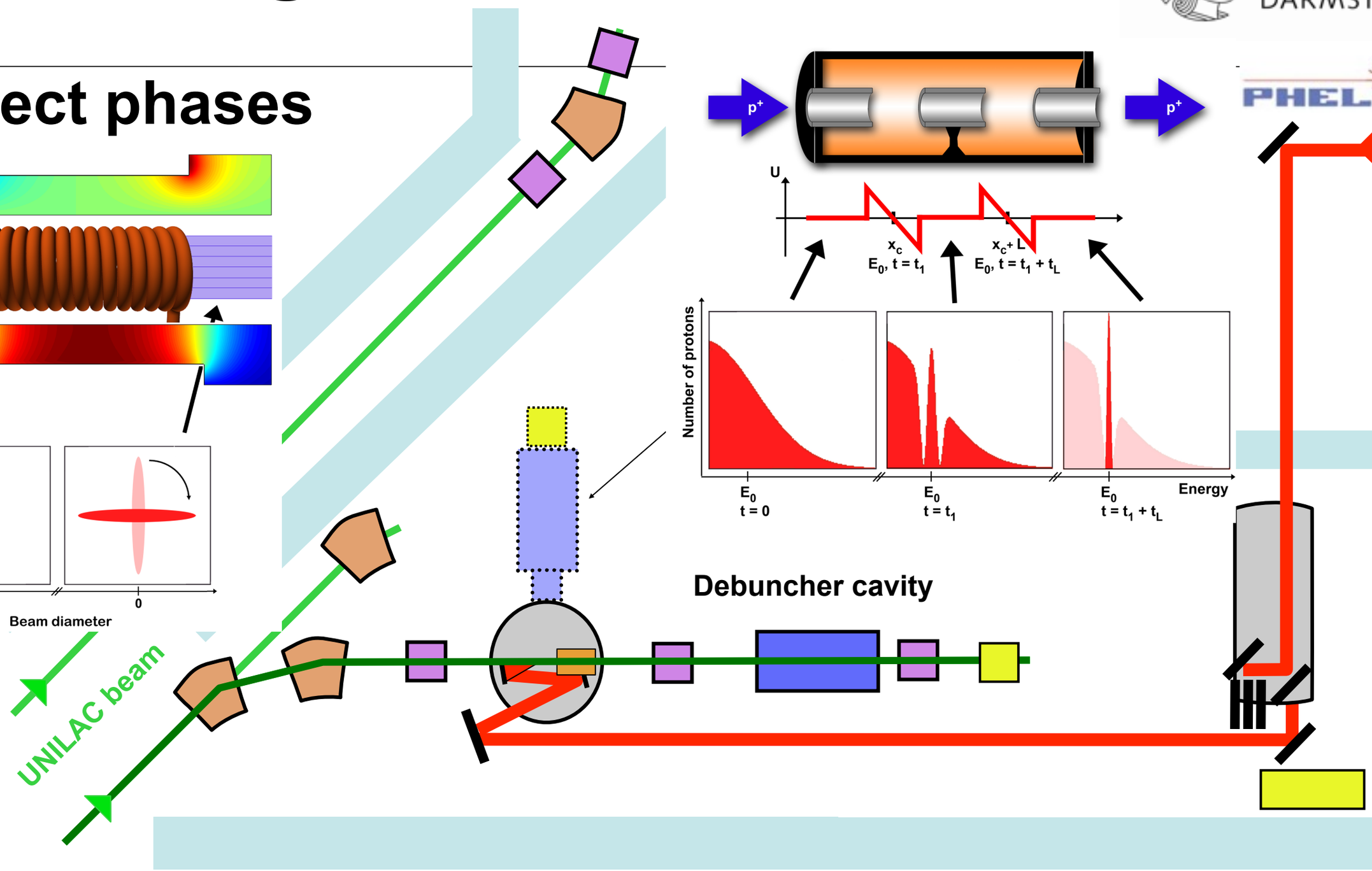

Recent results from preparation experiment

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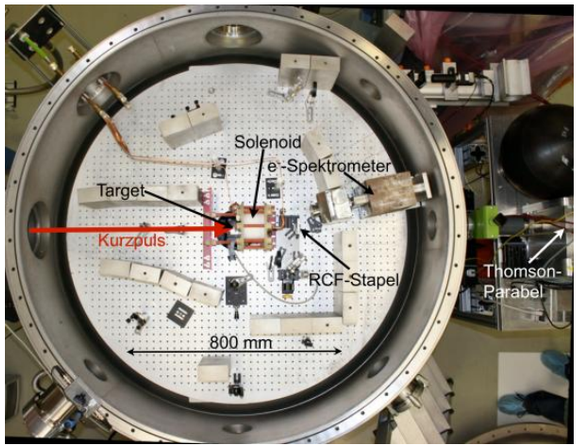
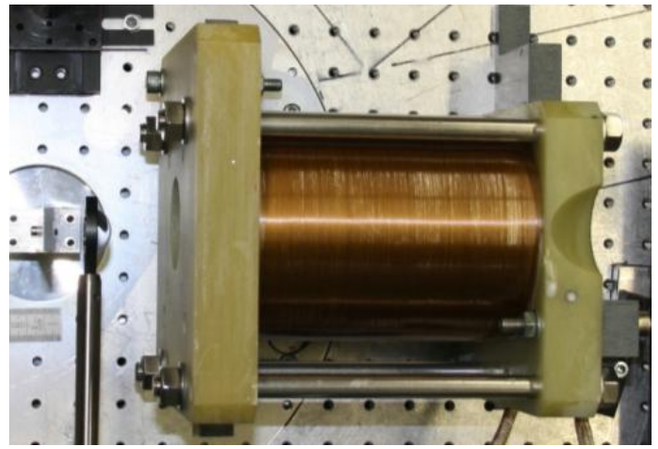
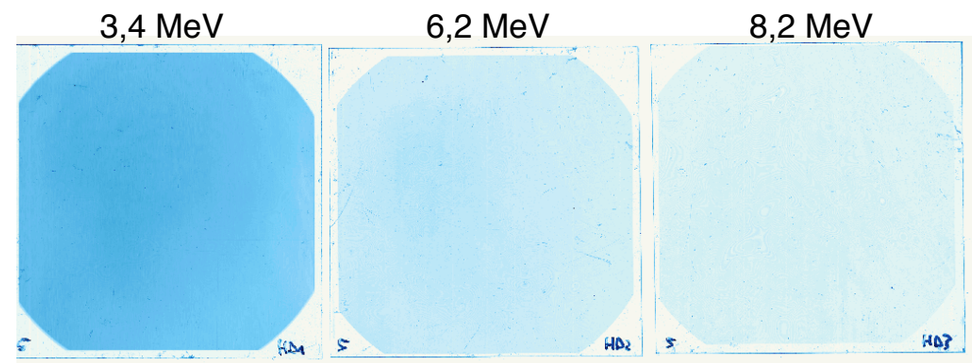
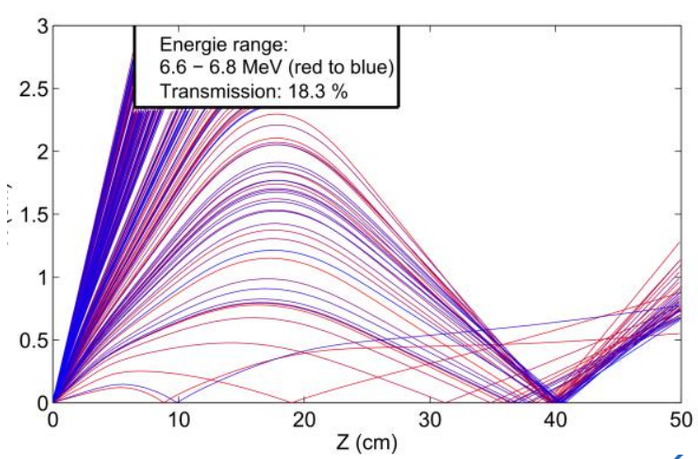


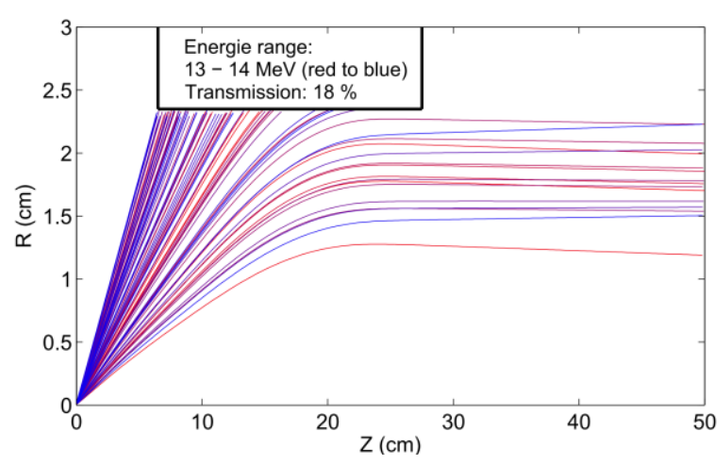




Experiment at Phelix/GSI (top):
- *(left)* setup target chamber
- *(middle)* solenoid version 2
- *(right)* proton signal in RCF detector stack (contrast optimized for the last 3 layers)

Warp PIC simulations (bottom):
- *(right)* simulated proton signal in virtual RCF detector stack,
- *(middle)* proton trajectories for collimation
- *(left)* proton trajectories for focussing





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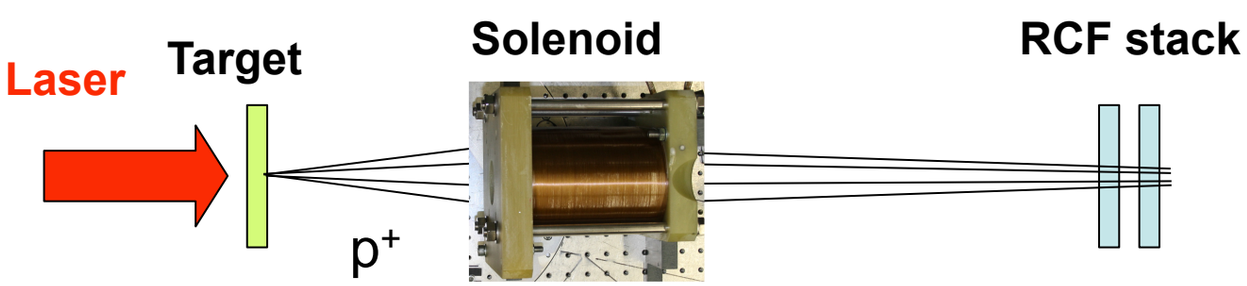

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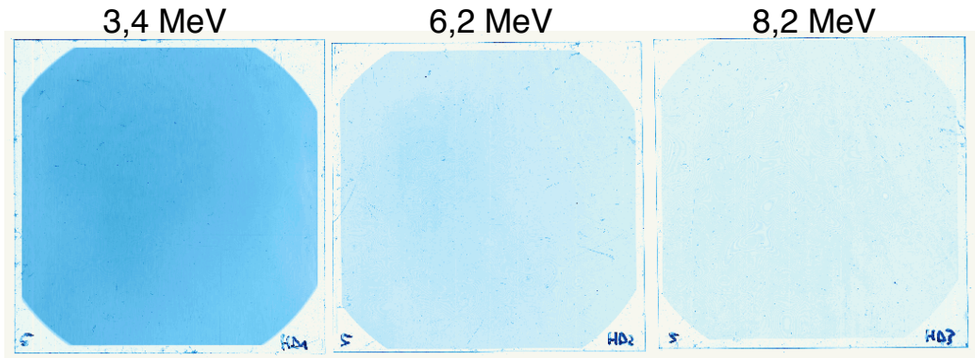

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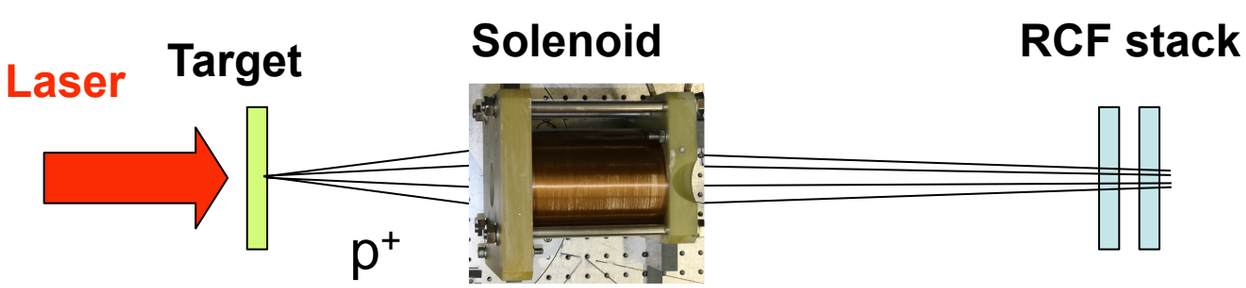

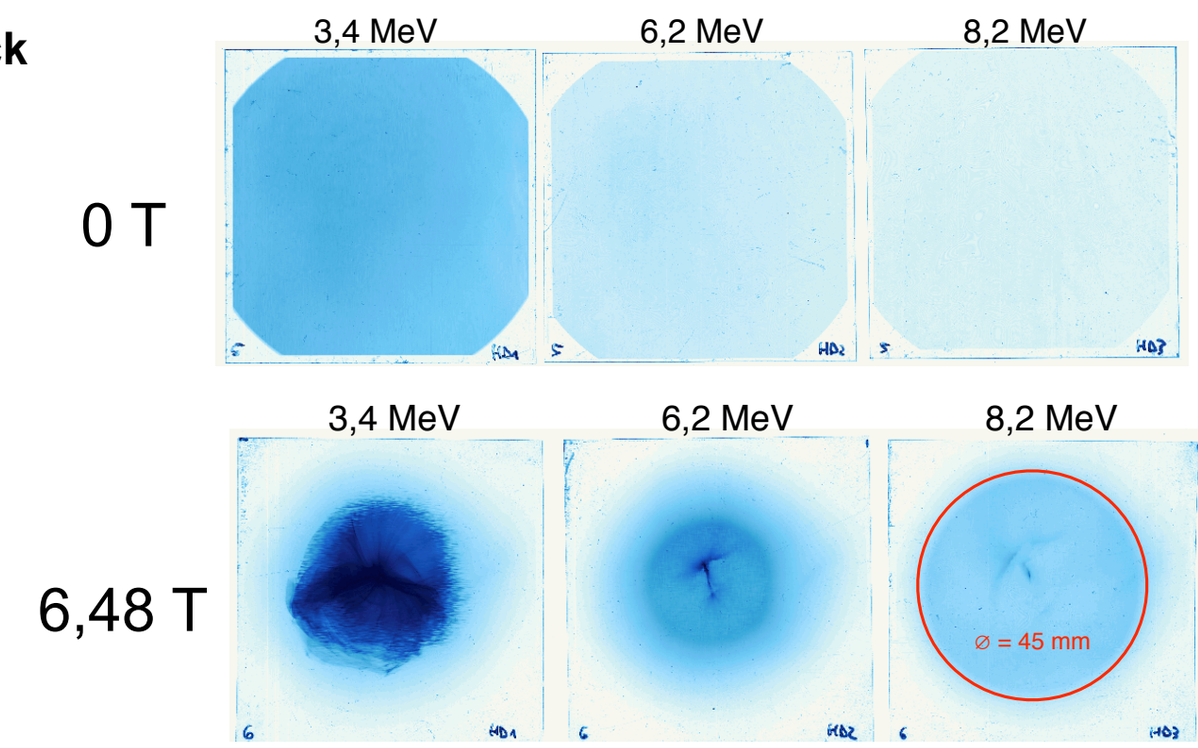

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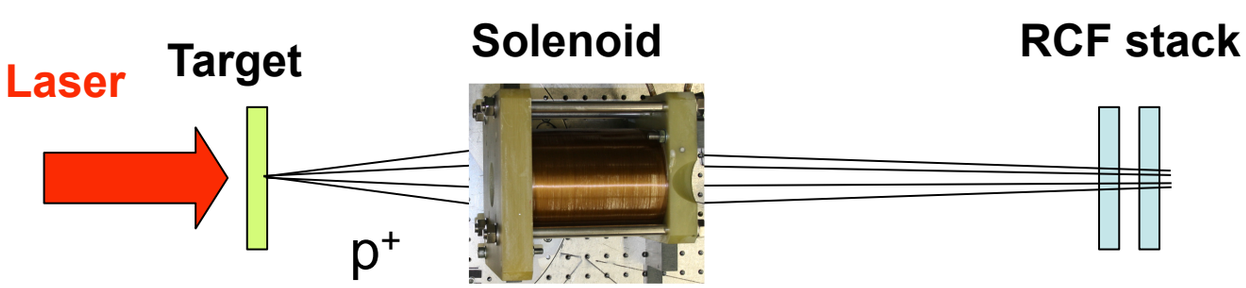

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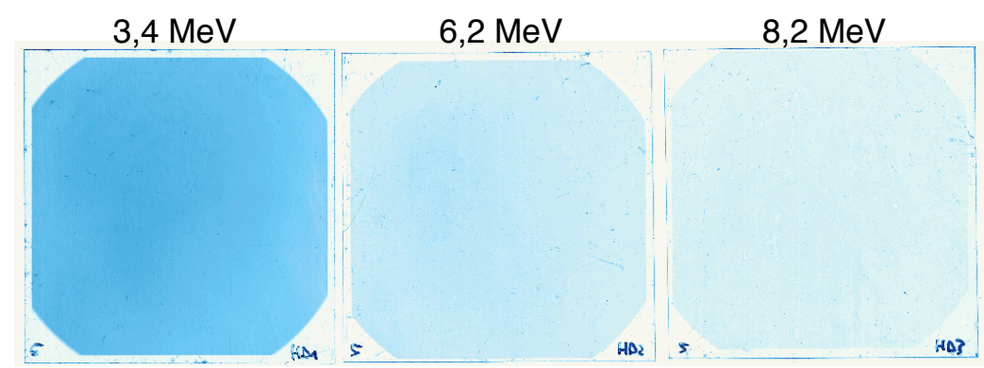

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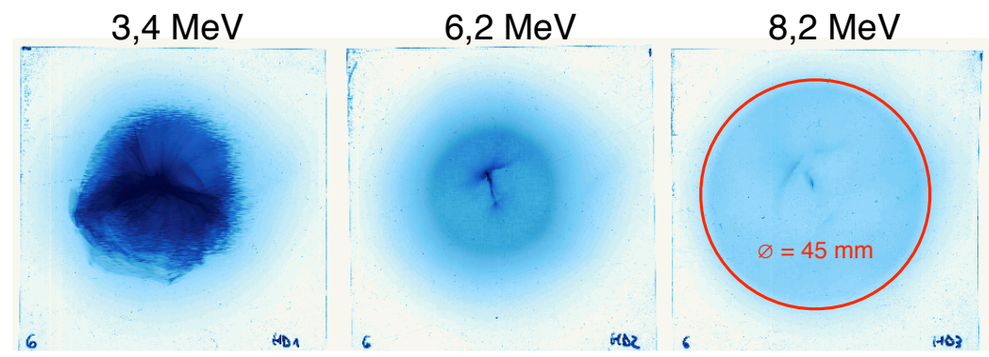

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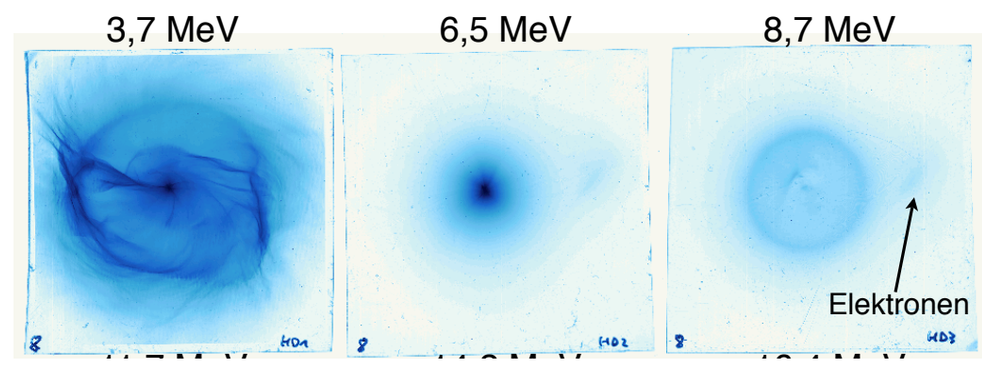

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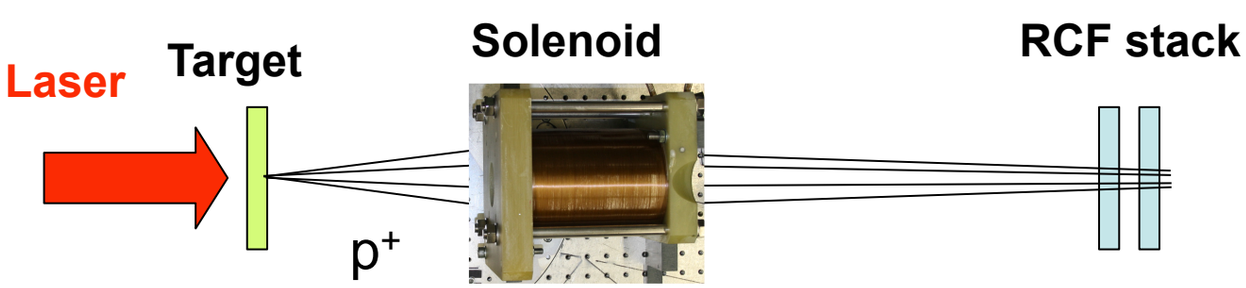
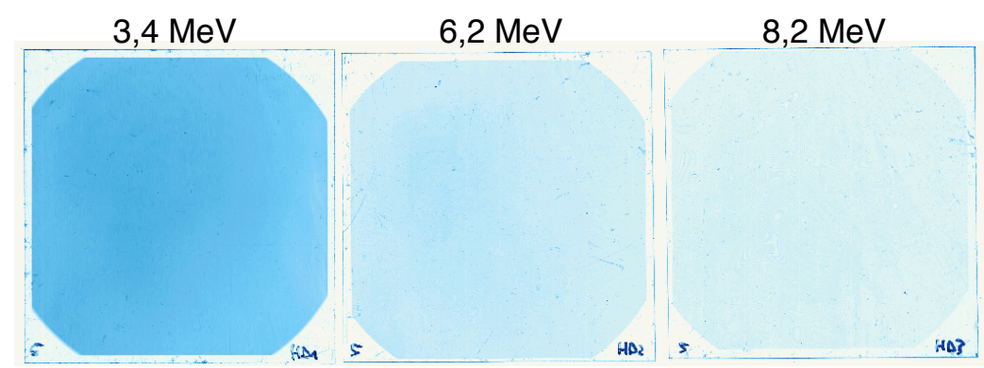
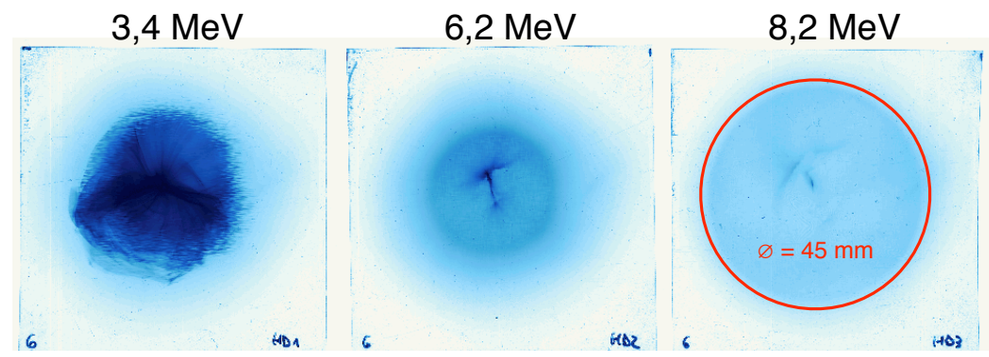


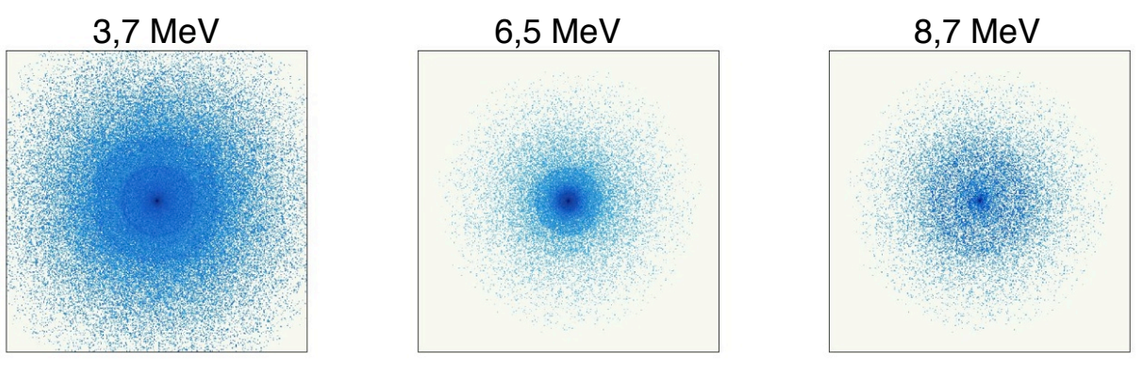
0 T



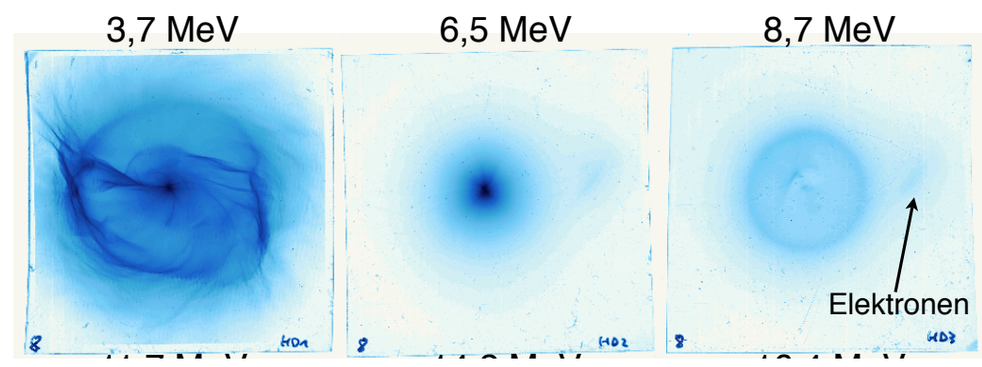
6,48 T



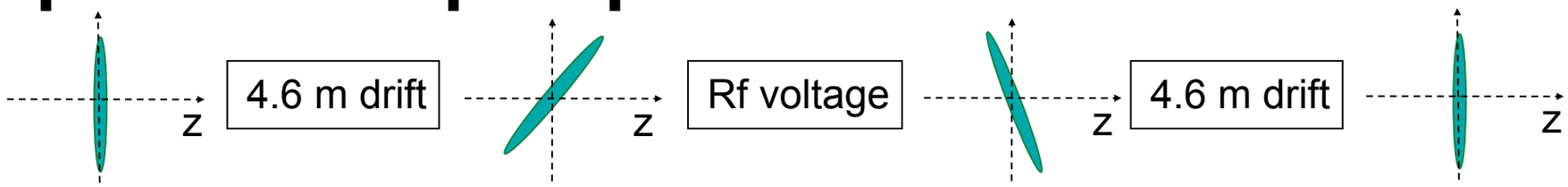
WARP - 8,2 T



8,2 T



Options and perspectives



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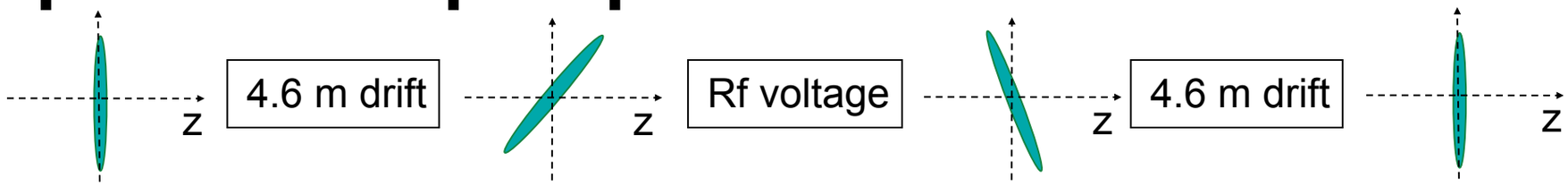
Options and perspectives



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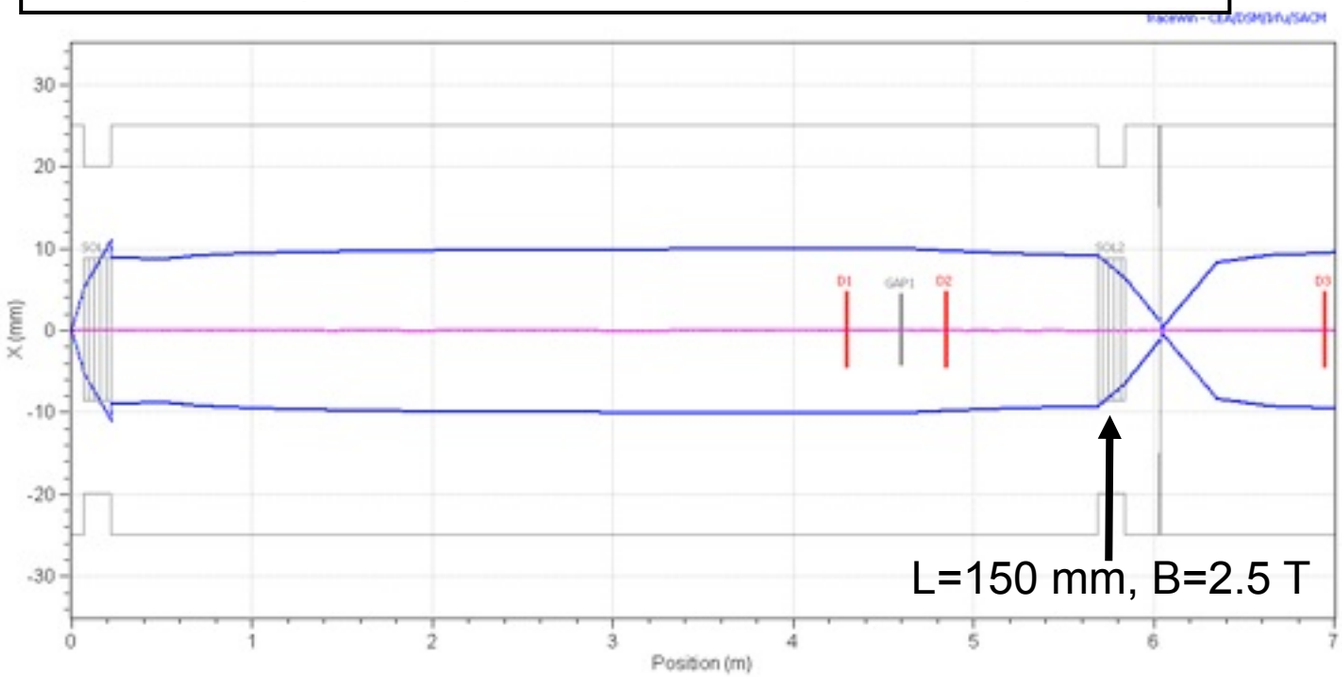
Second focus (2nd solenoid)

6 D focus - optimum performance without extra apertures -



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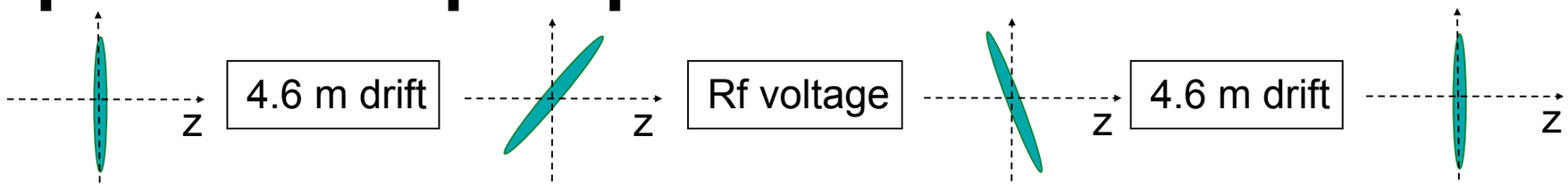
Options and perspectives



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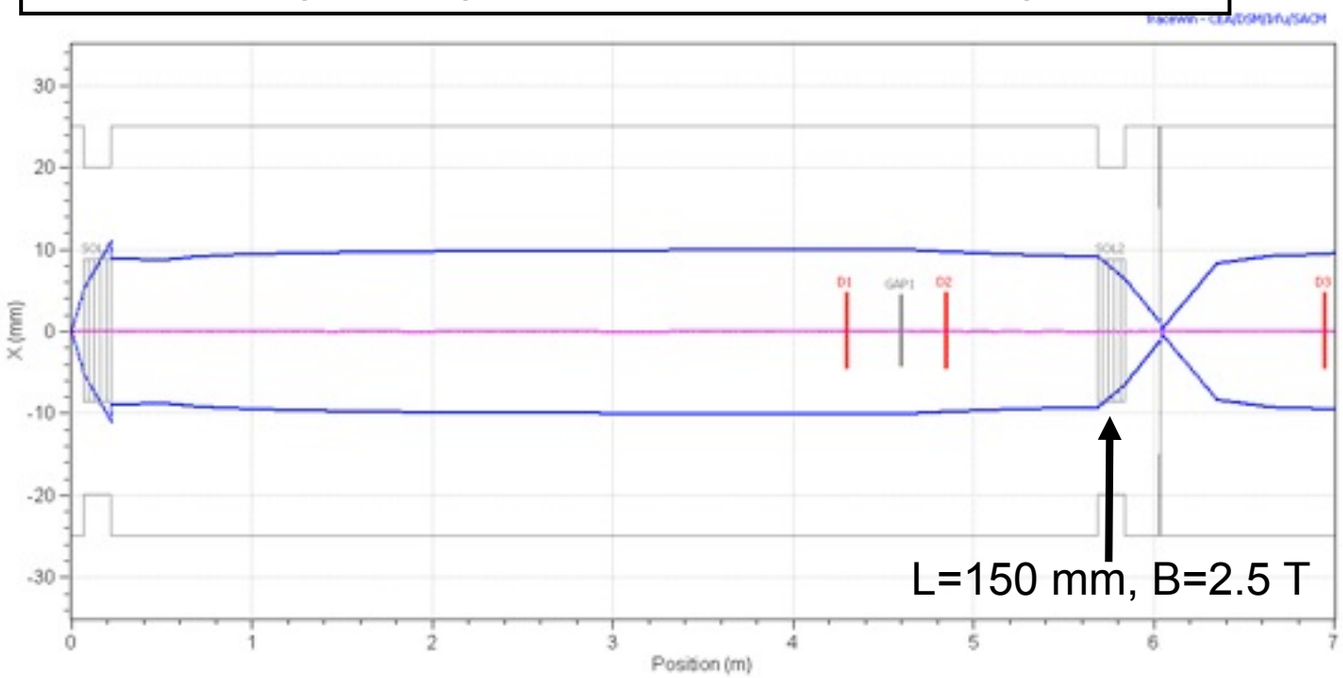

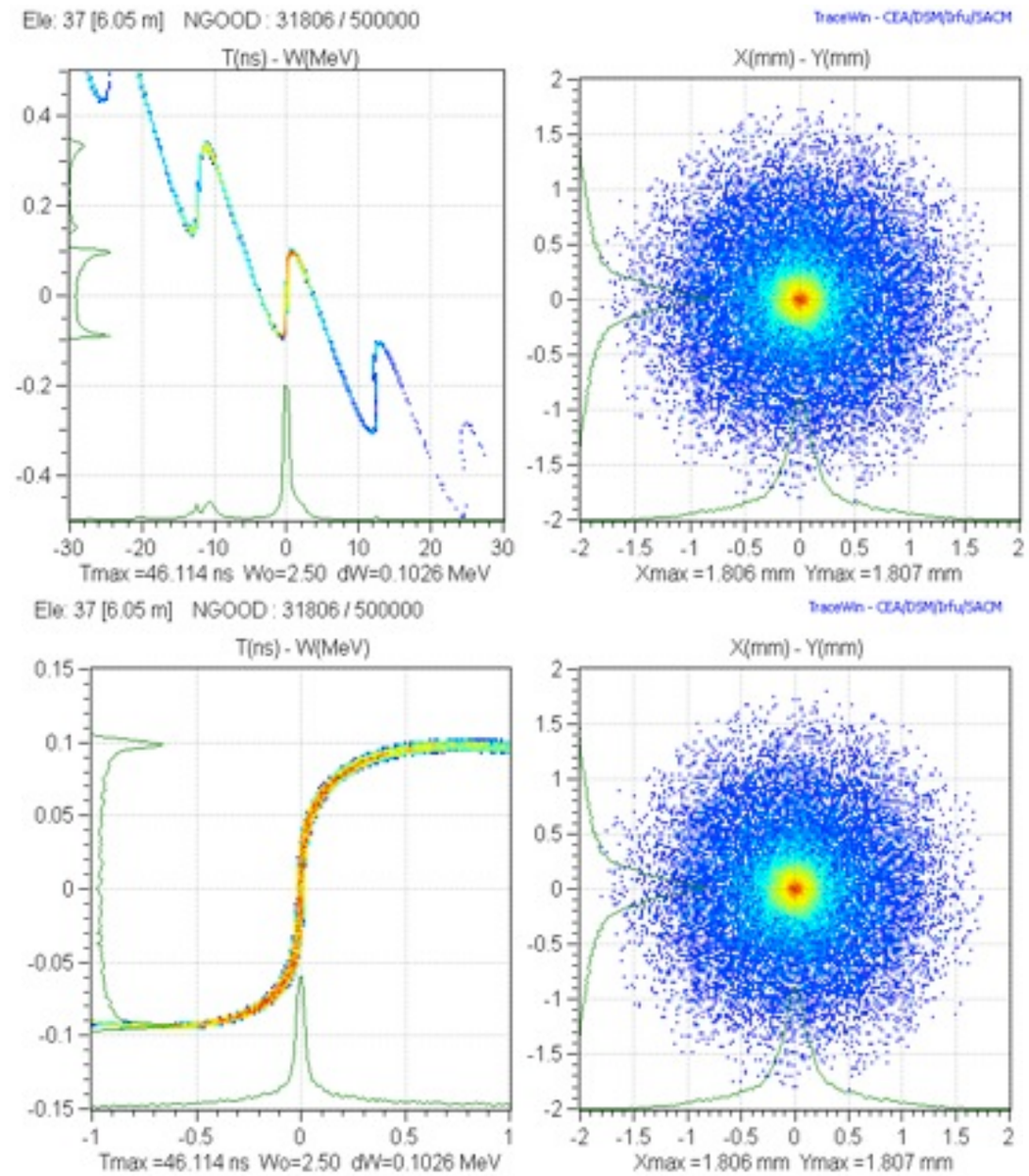

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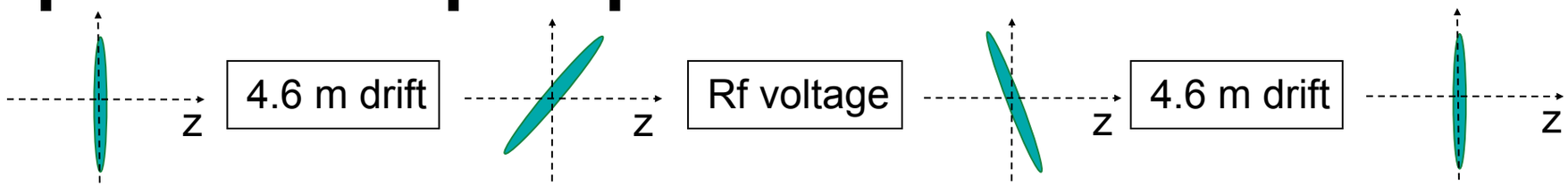
Options and perspectives



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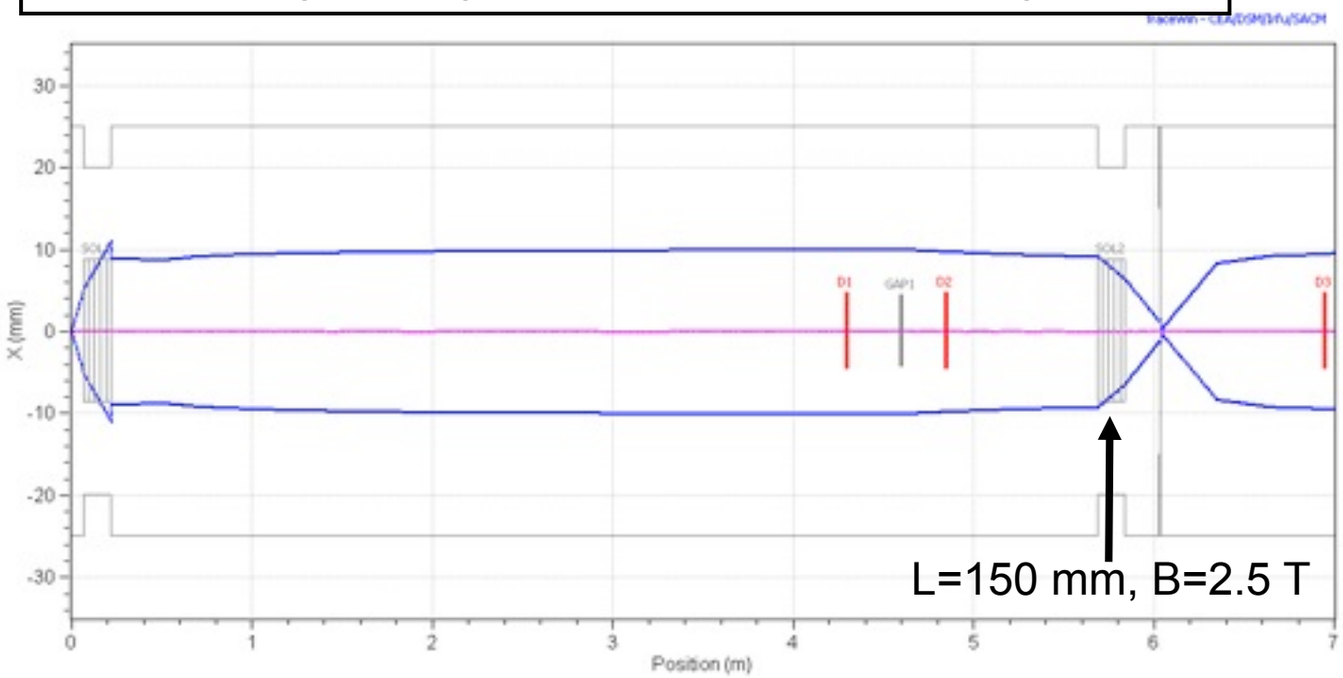

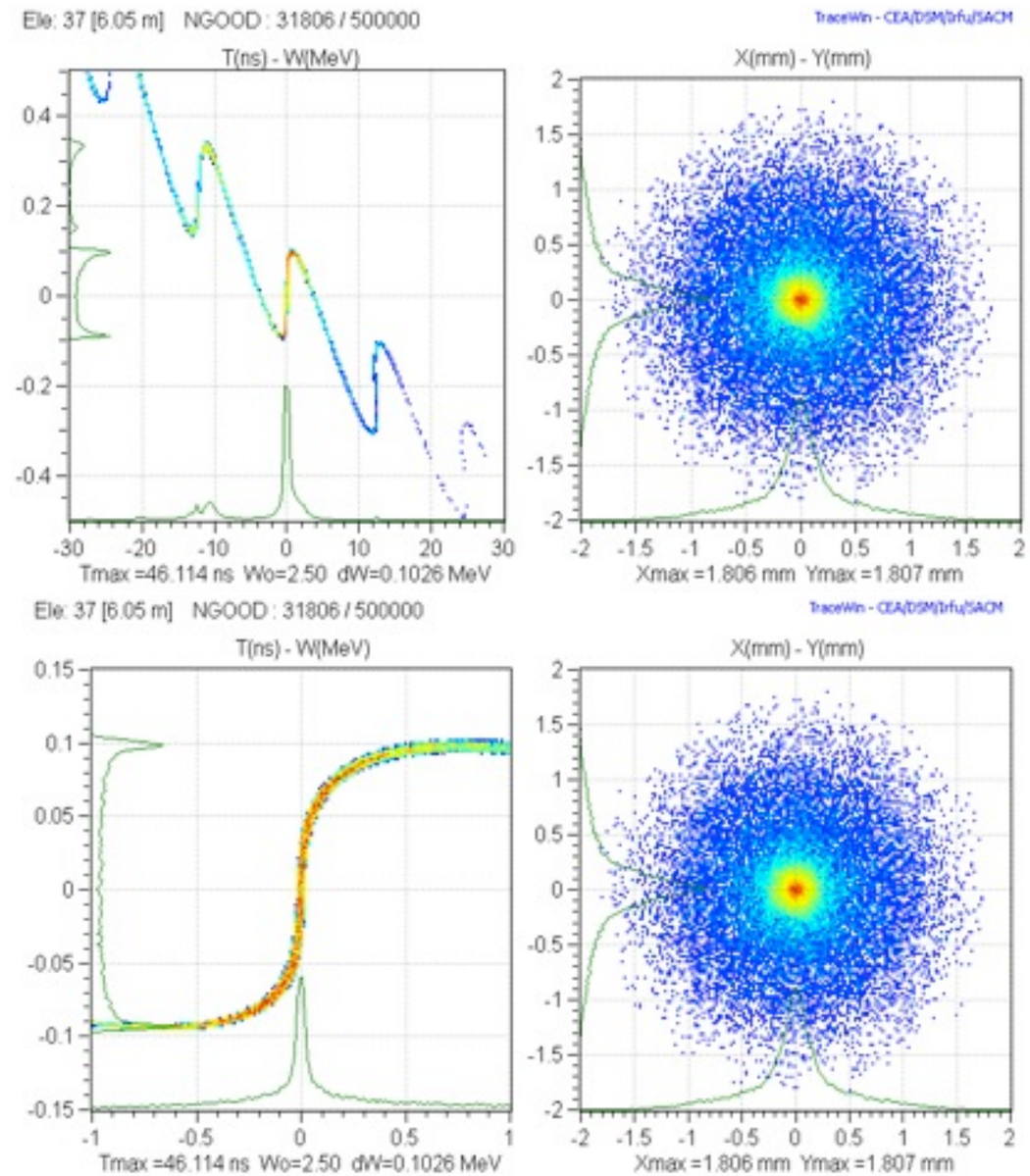

Time focus (< 100 ps) and spatial focus (< 200 μm)
coinciding (6.05 m) ~ 6% of input intensity

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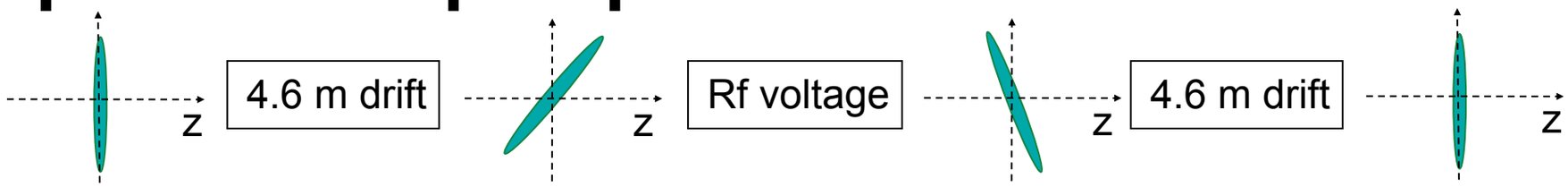
Options and perspectives



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Second focus (2nd solenoid)
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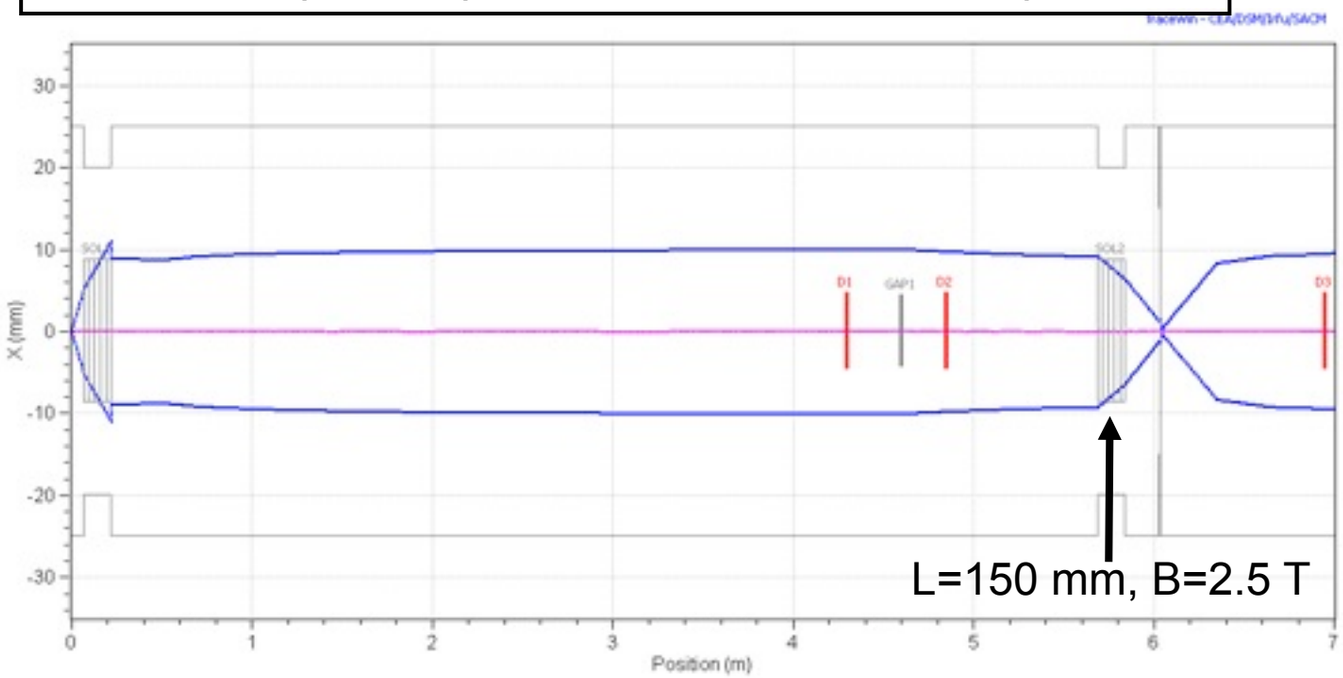

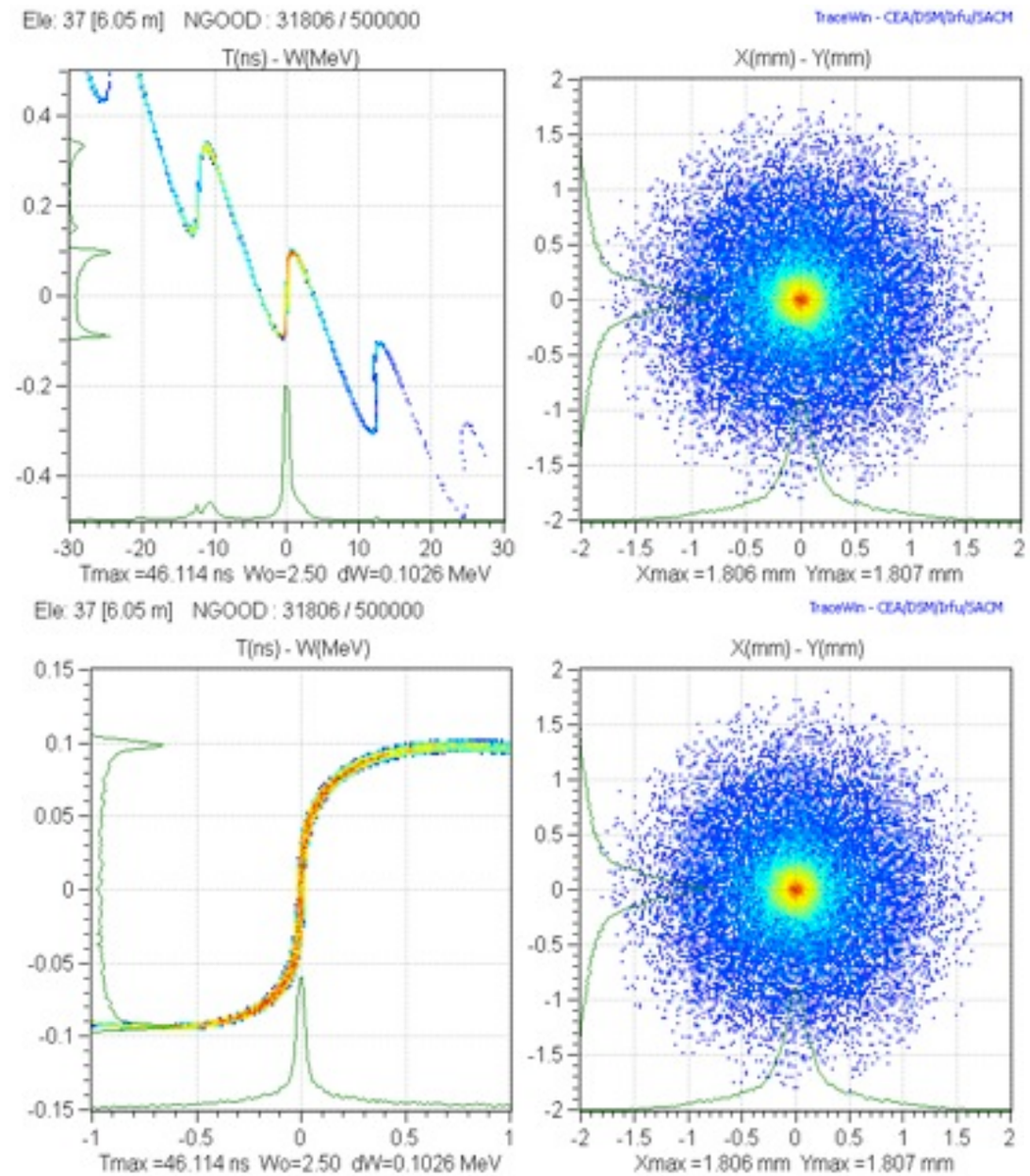

Time focus (< 100 ps) and spatial focus (< 200 μm)
coinciding (6.05 m) ~ 6% of input intensity

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

@ 10 MeV: 36 GW/cm^2

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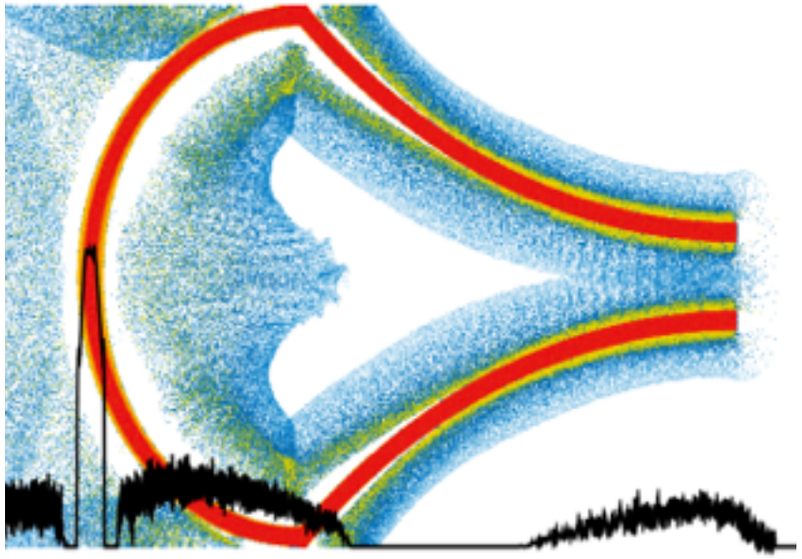
Cones...

A lot depends on the geometry, the difference in e-sheath, lateral and proton velocity



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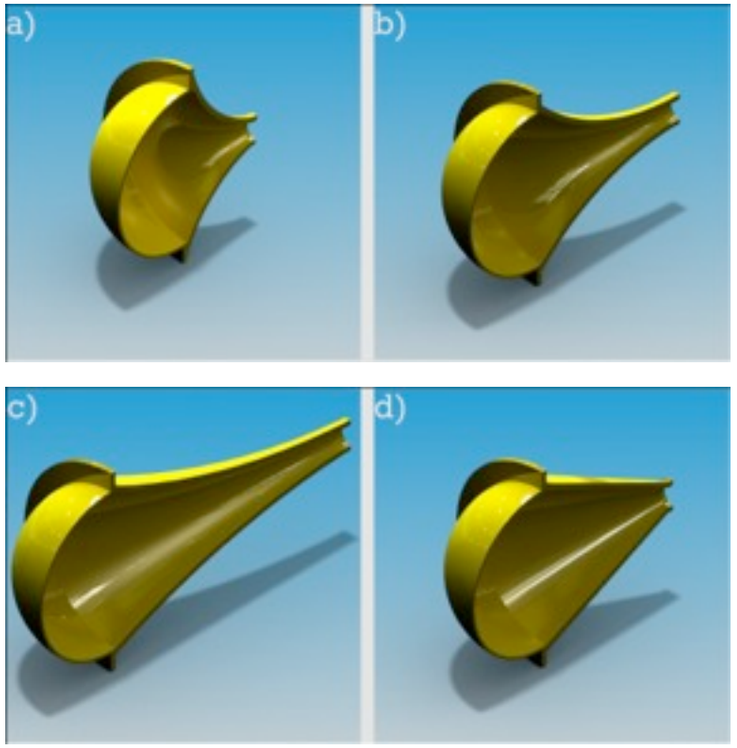

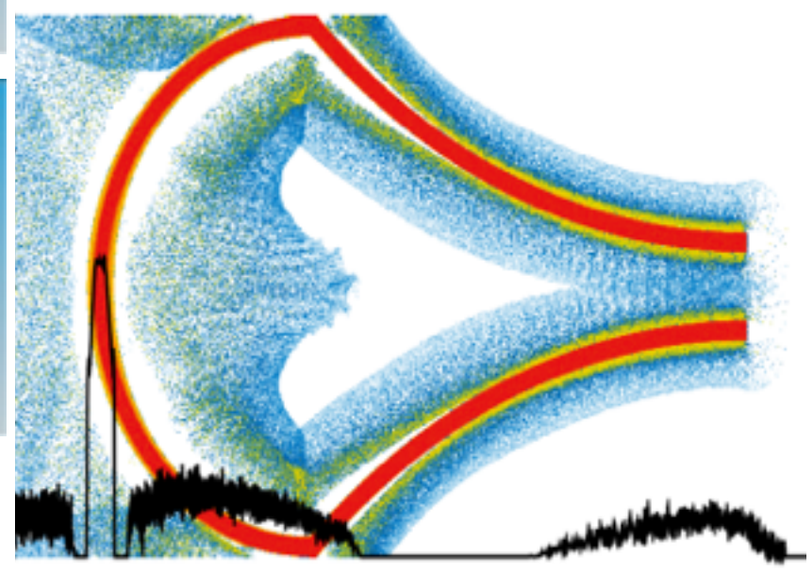

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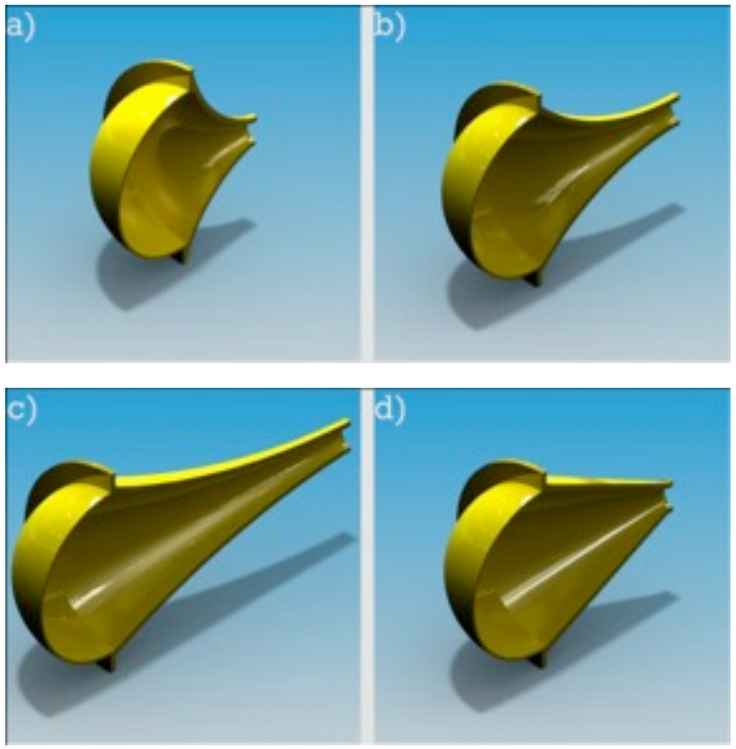

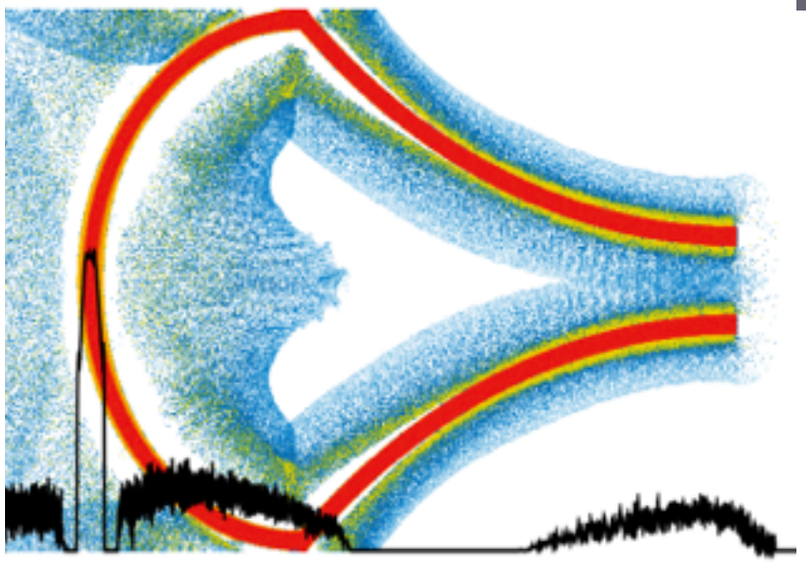

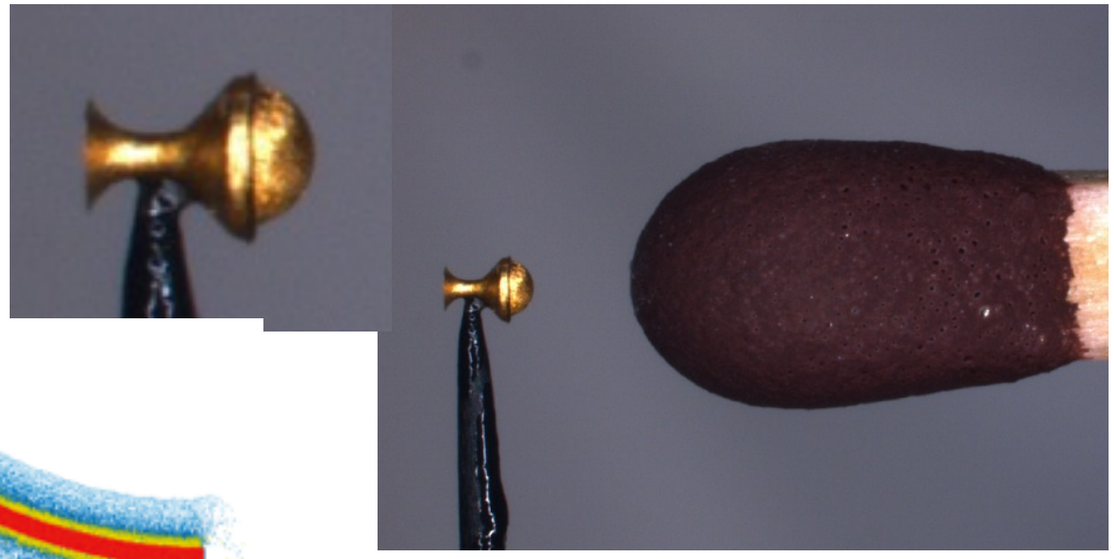

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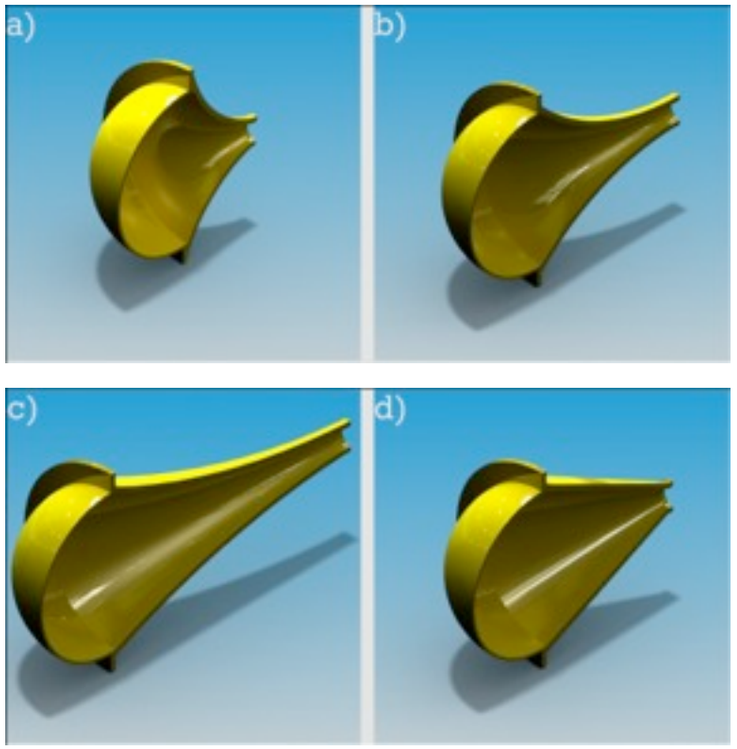

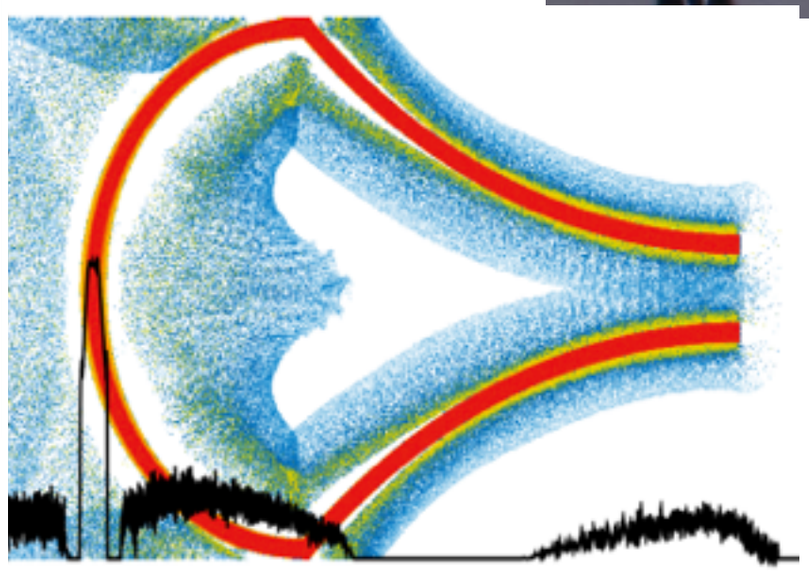

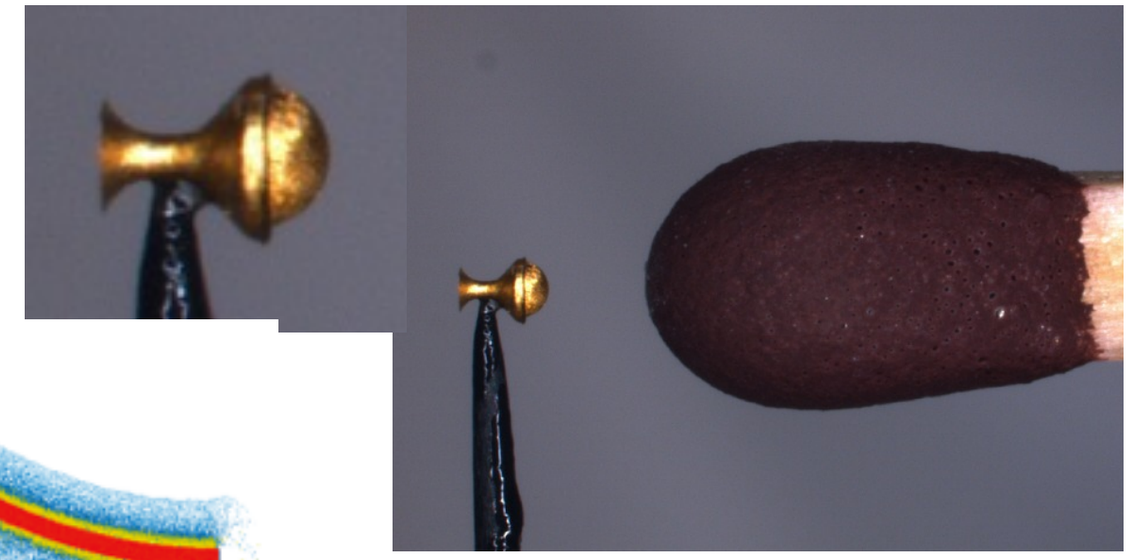

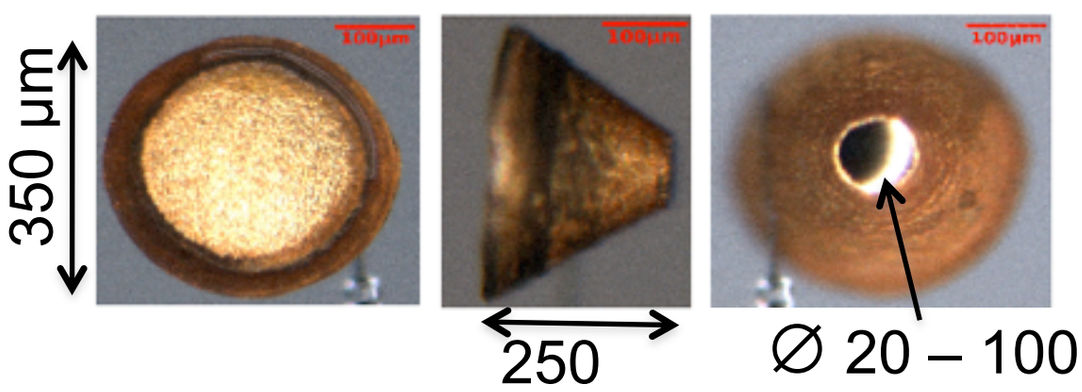

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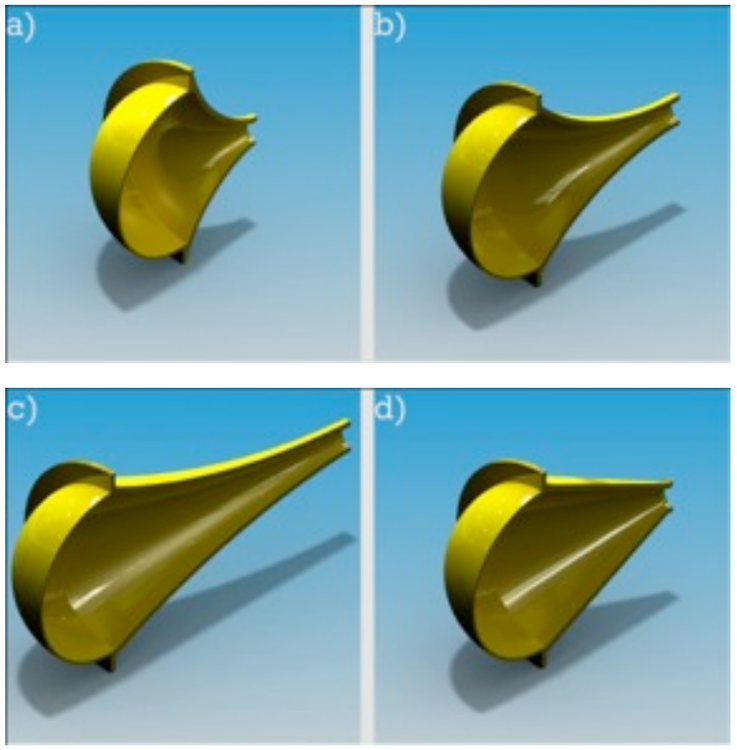

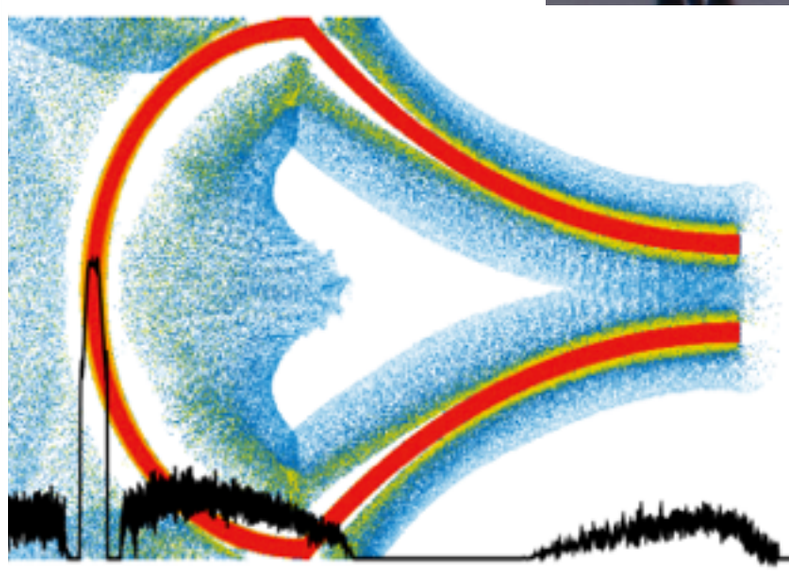

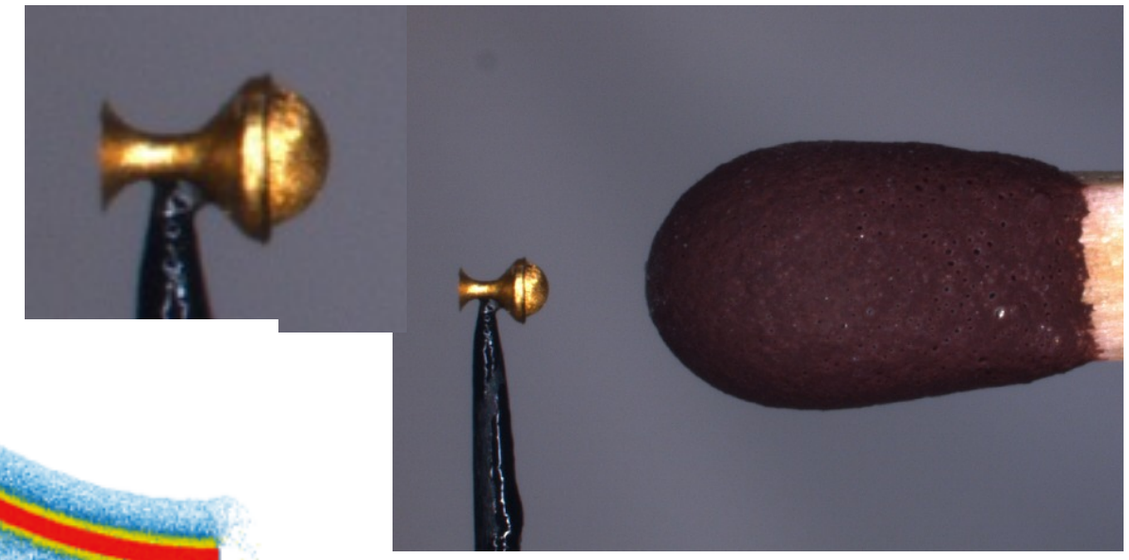

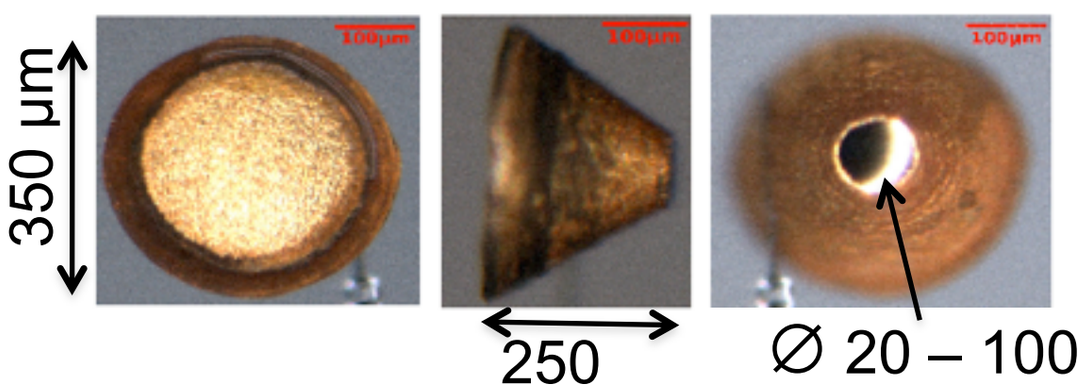

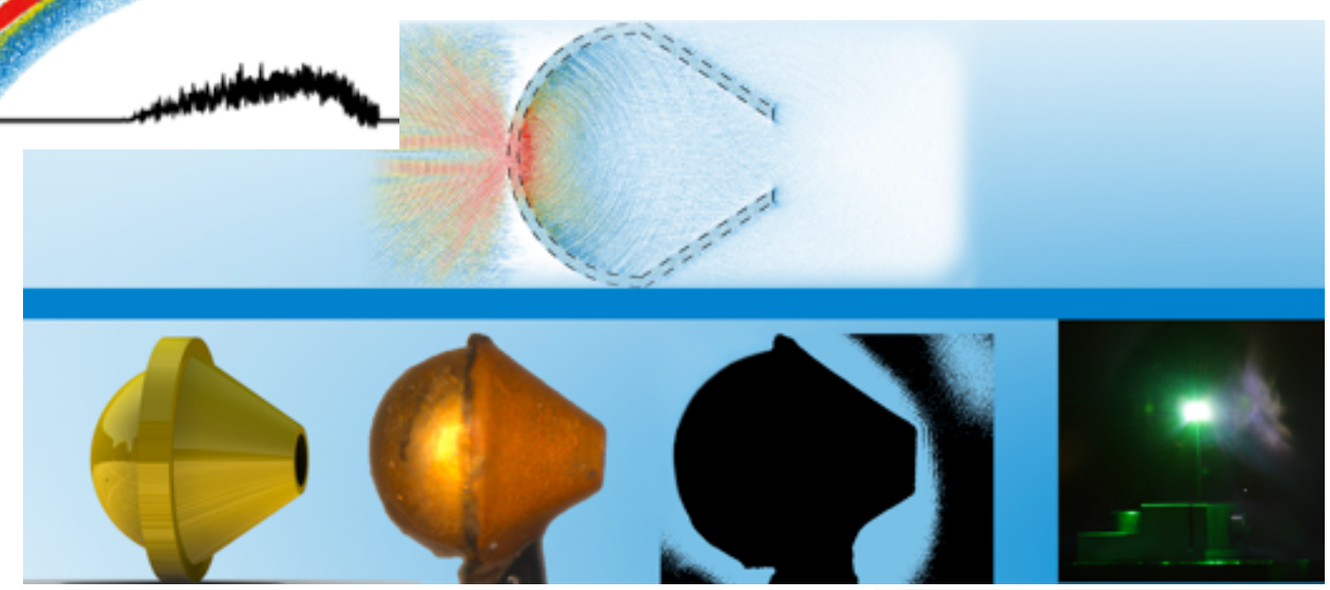

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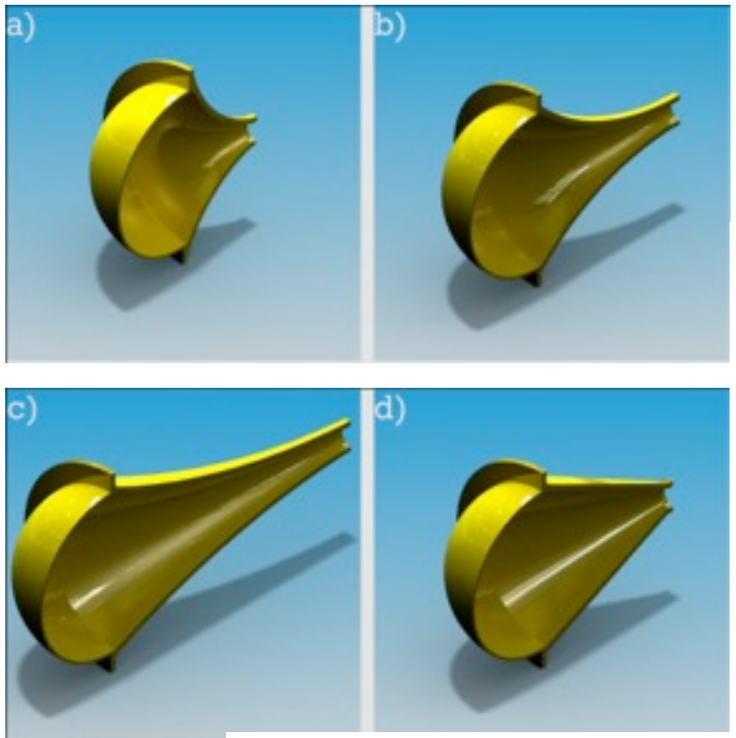
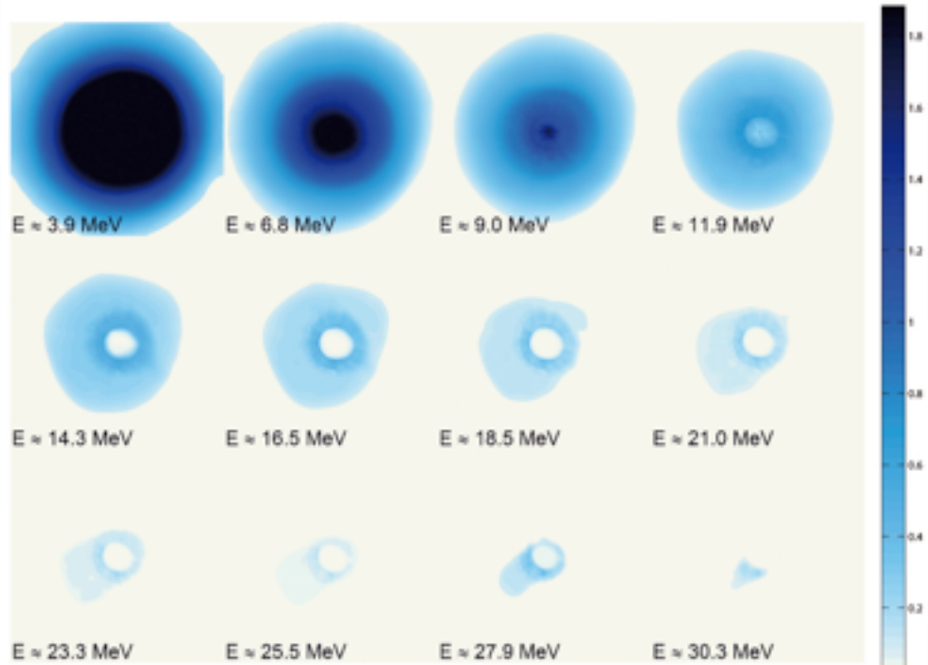
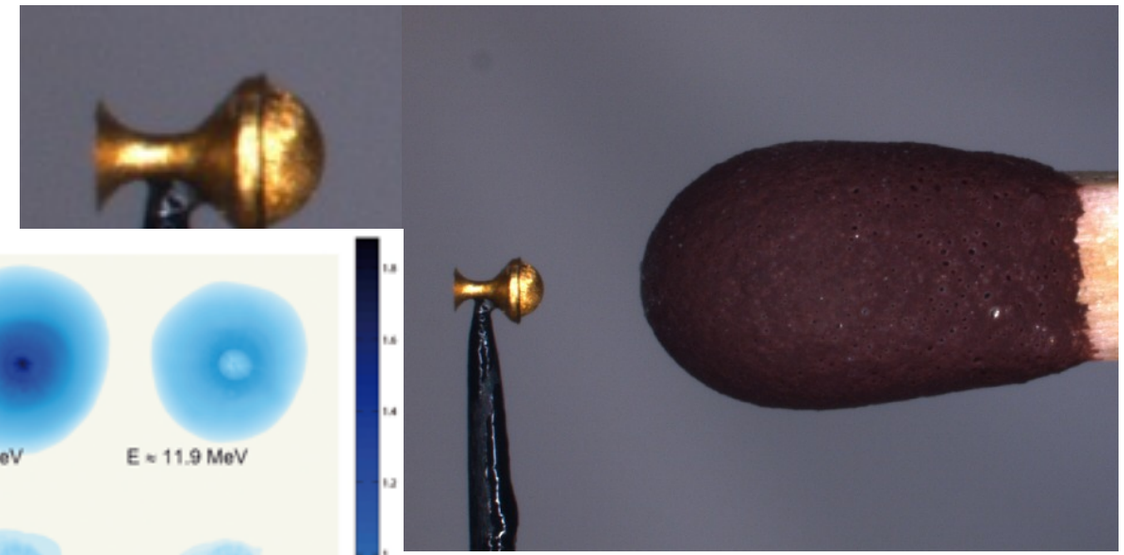
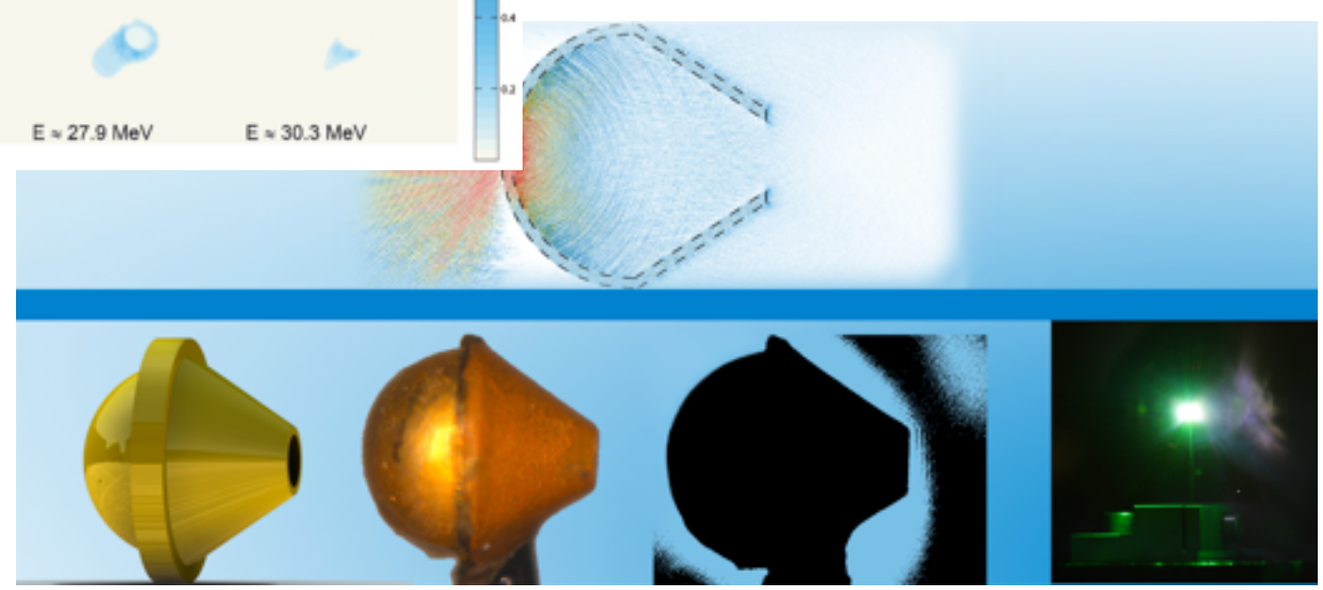


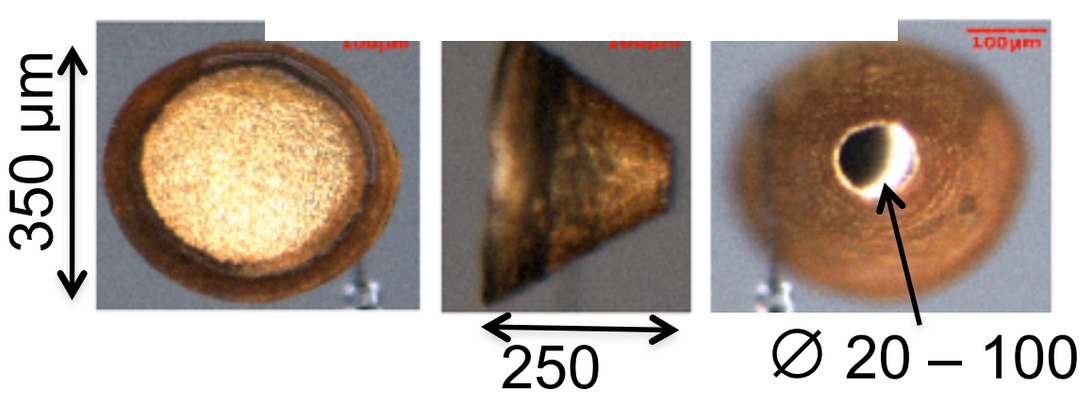
shot#22:

- T03-3 cone: l=316µm, d=163µm
- 115J@750fs@80µm
- Abstand Target-RCF: 51.5mm





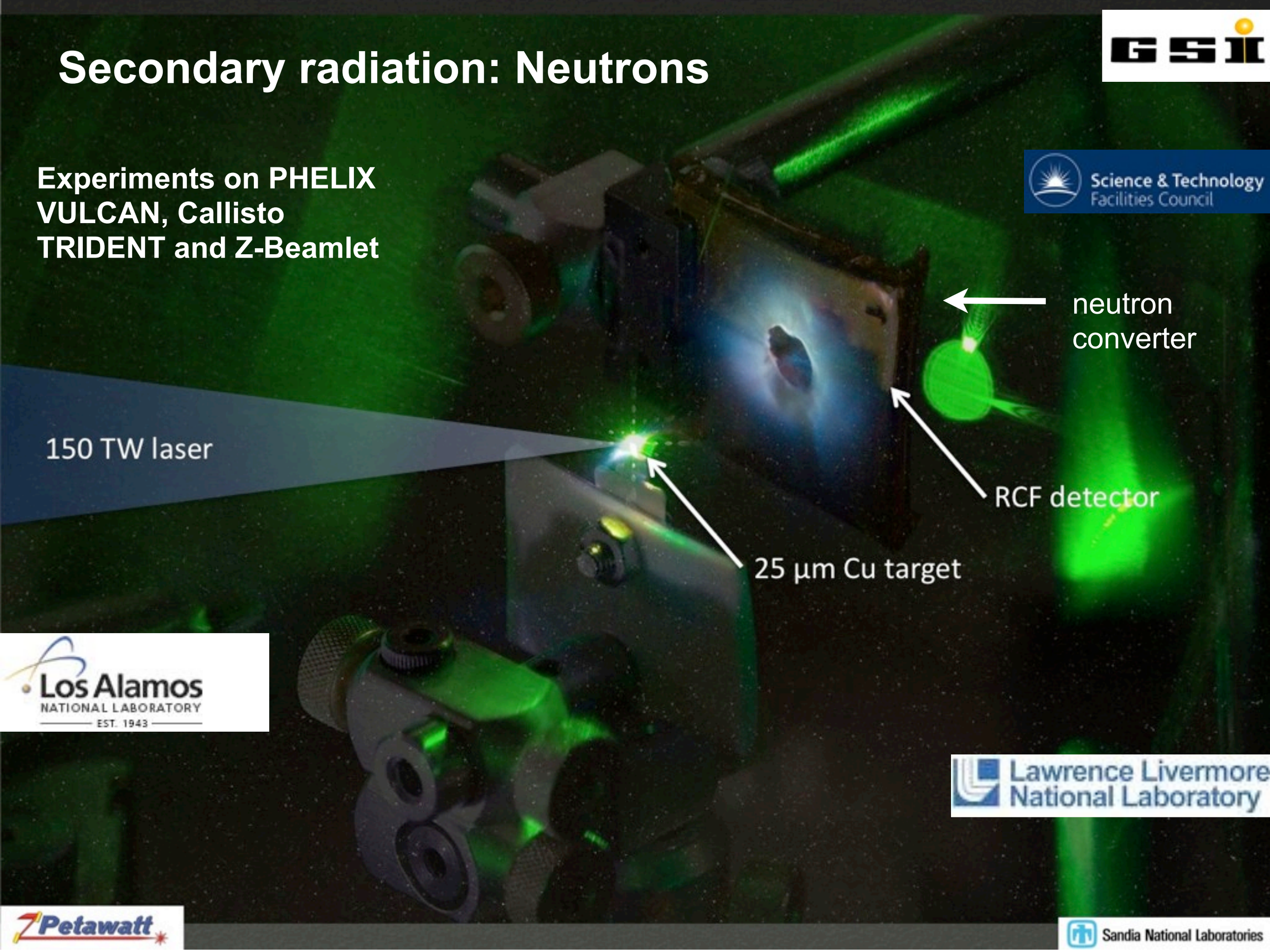




LLP Laser- und Plasmaphysik
Institut für Kernphysik
Technische Universität Darmstadt
Prof. Markus Roth

Secondary radiation: Neutrons

Experiments on PHELIX
VULCAN, Callisto
TRIDENT and Z-Beamlet



Neutrons are a unique tool to probe and alter material properties

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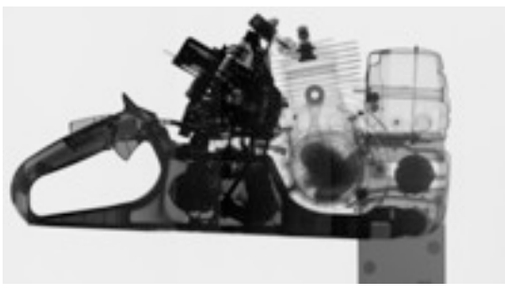
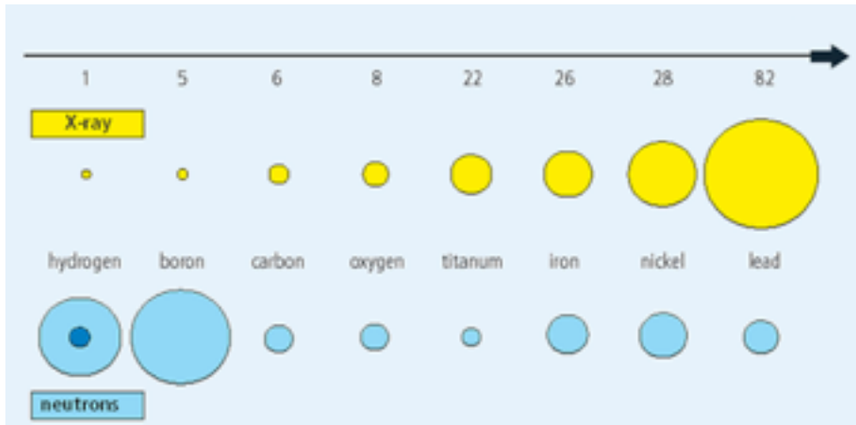
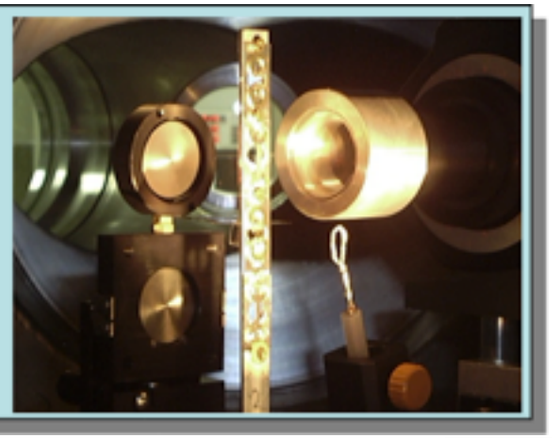
New Diagnostics: fast neutron radiography of transient phenomena

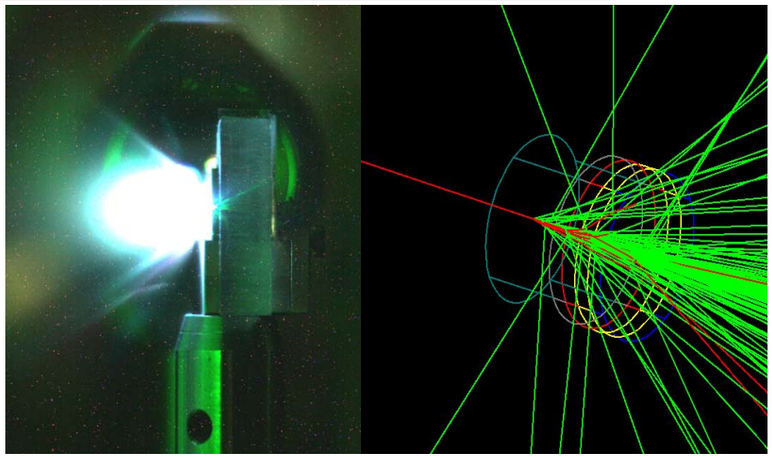


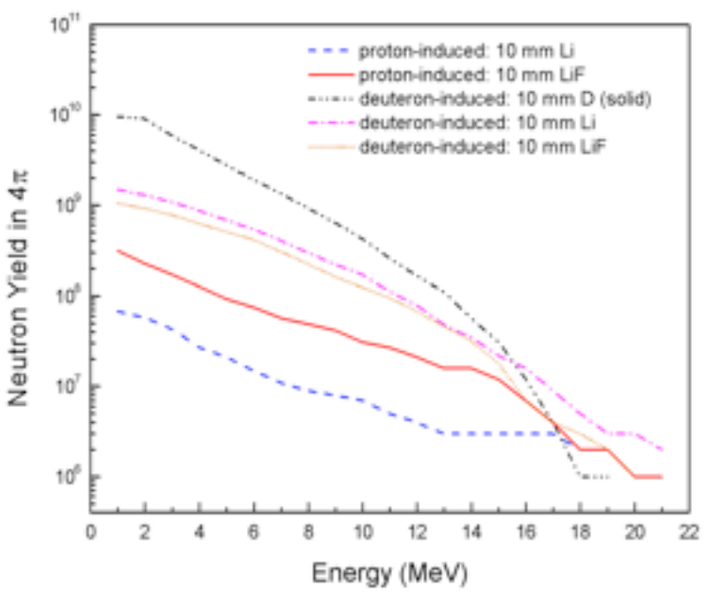


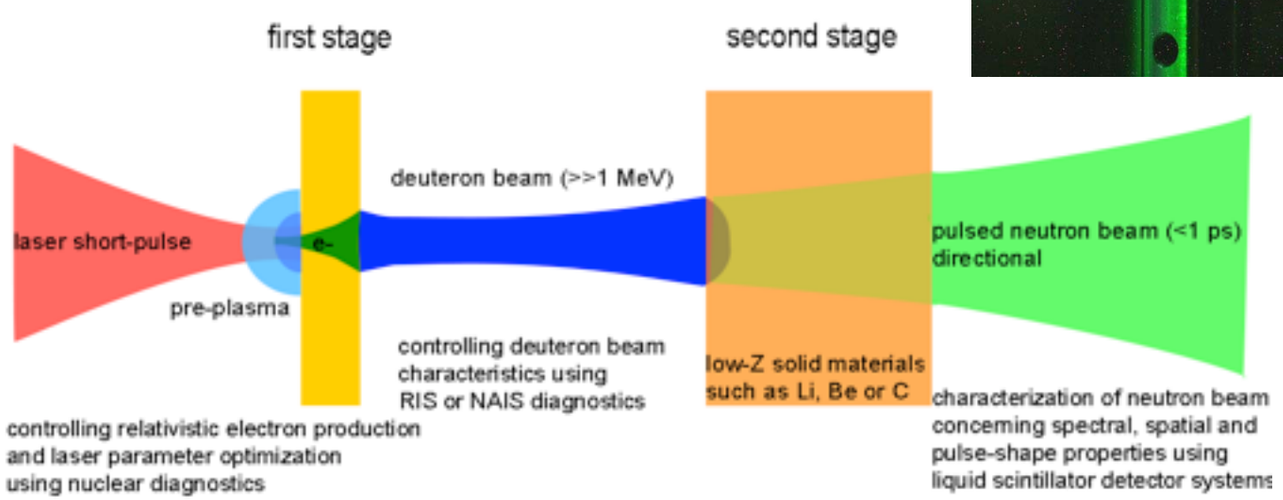
Pulsed neutron sources:

$4 \cdot 10^8$ /puls beamed d-d fusion

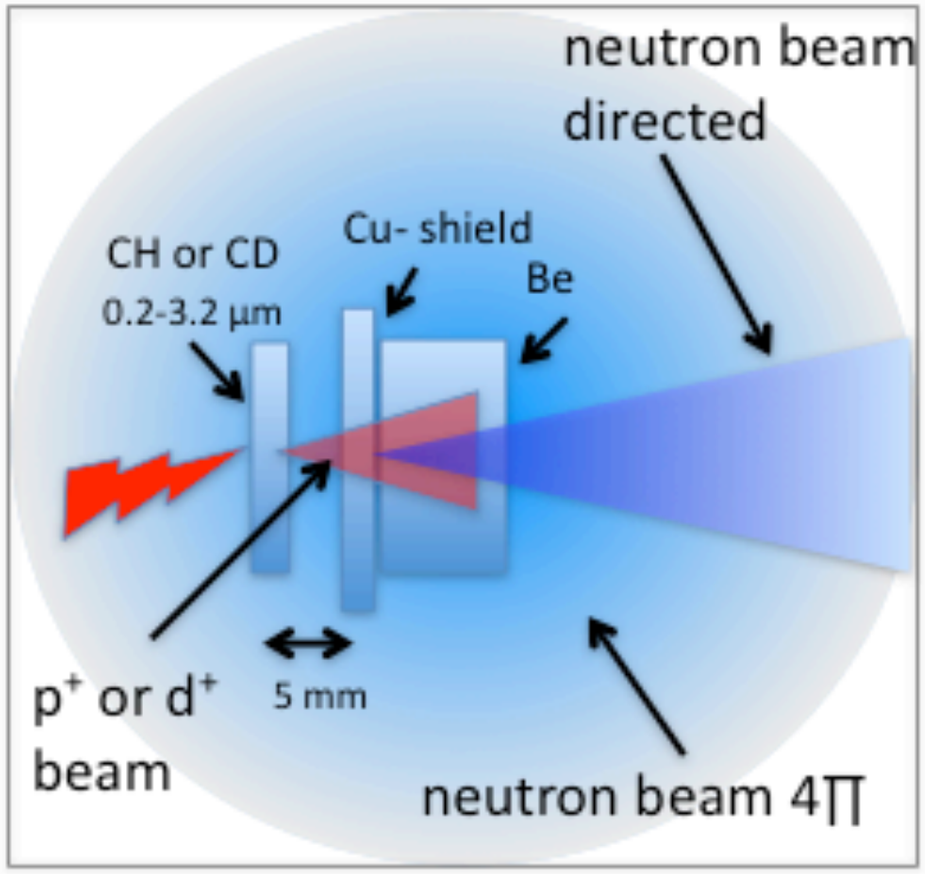


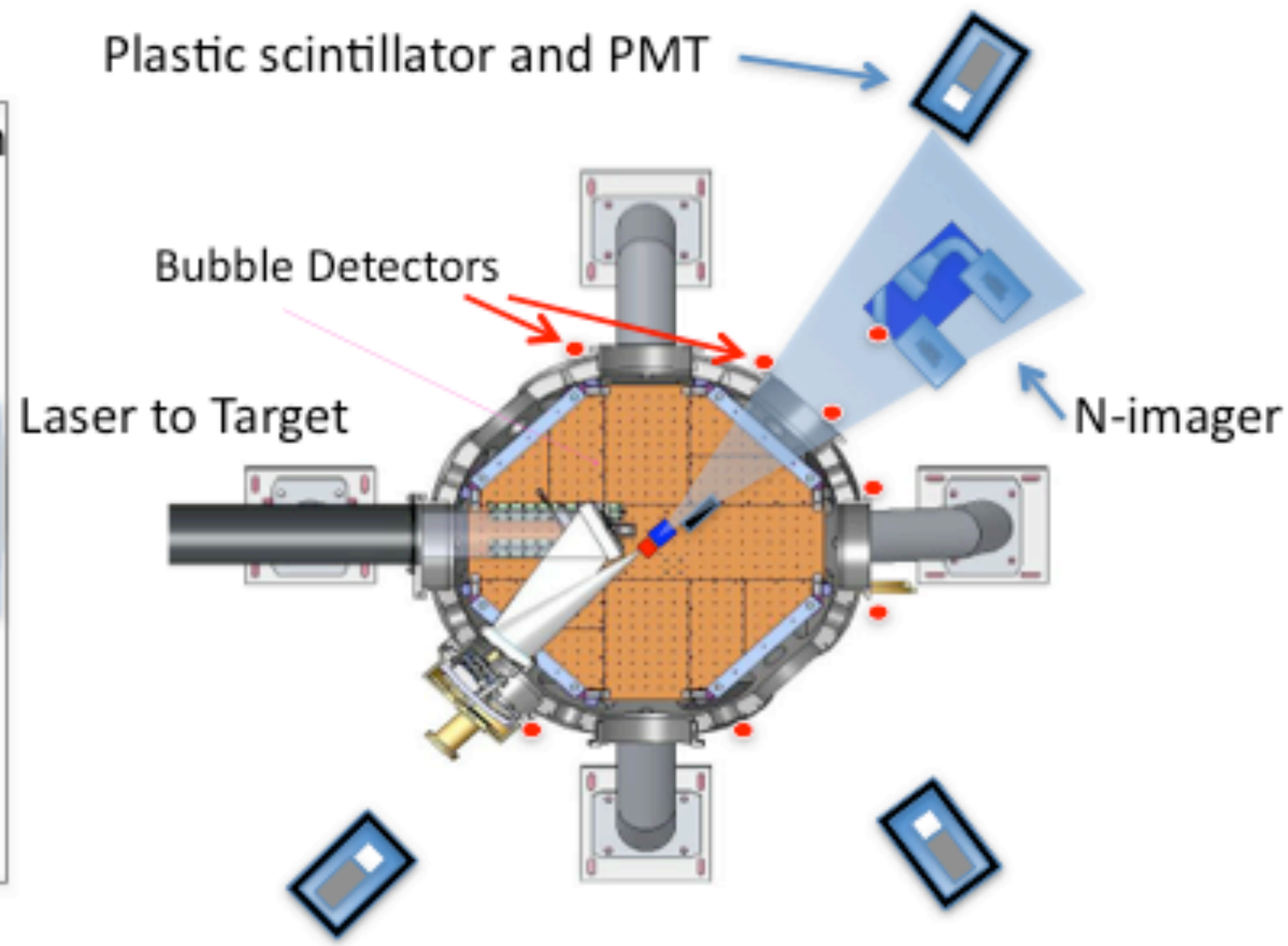




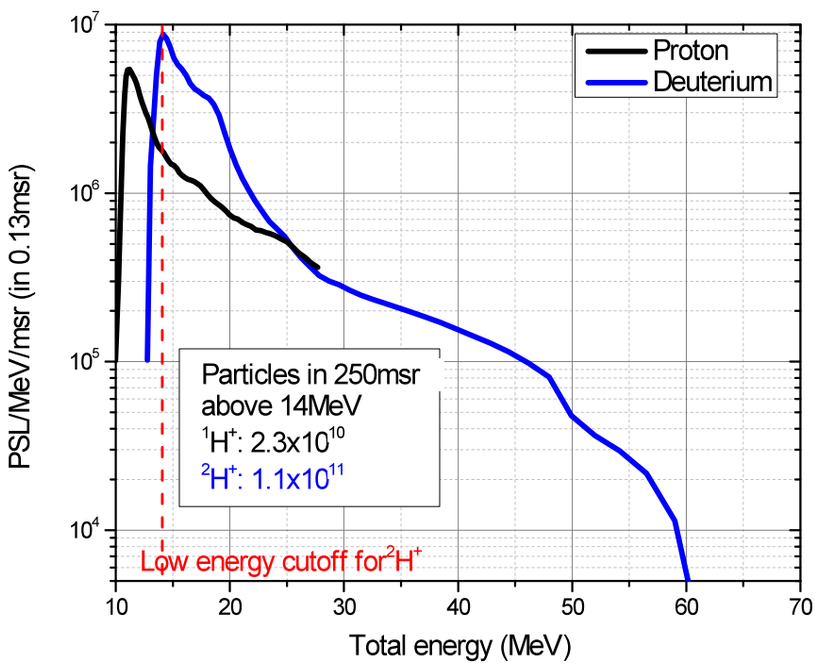


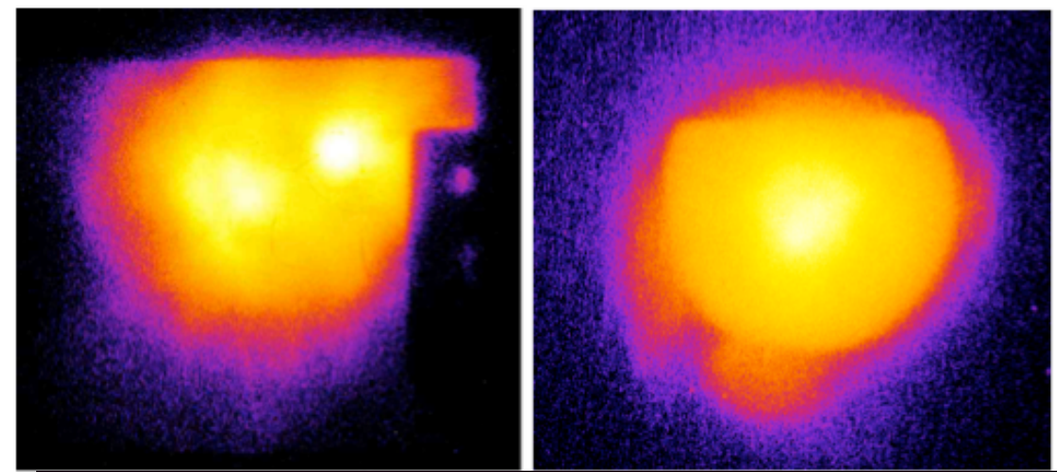
Experimental setup

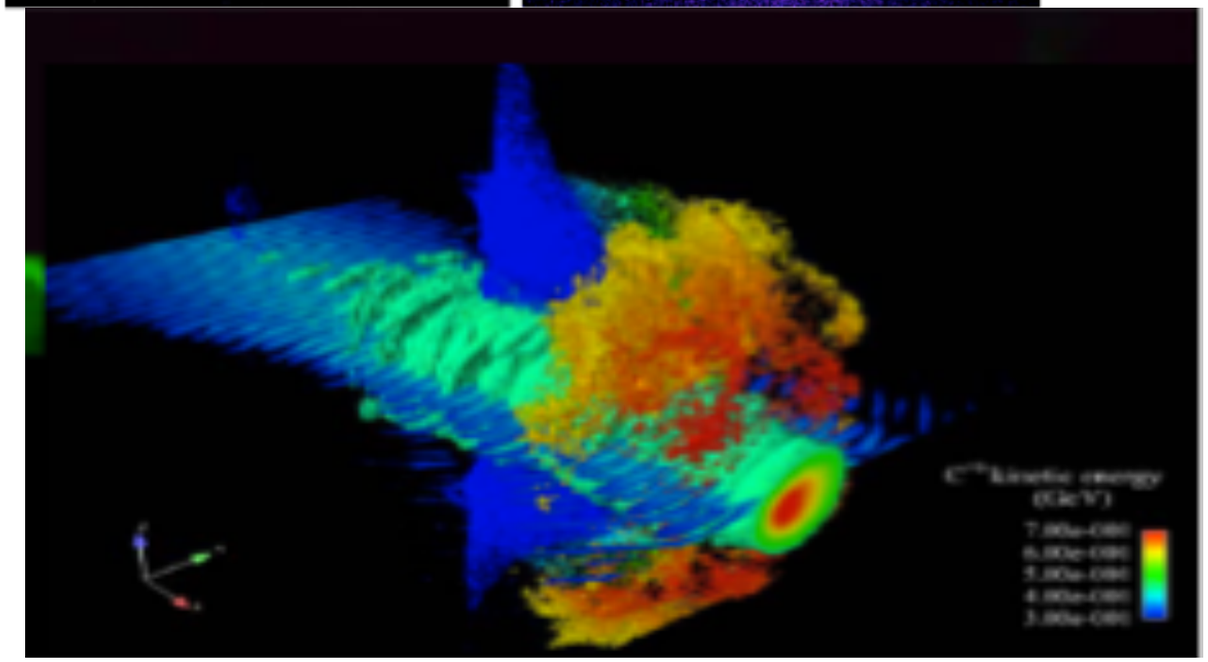




Volume instead of surface acceleration

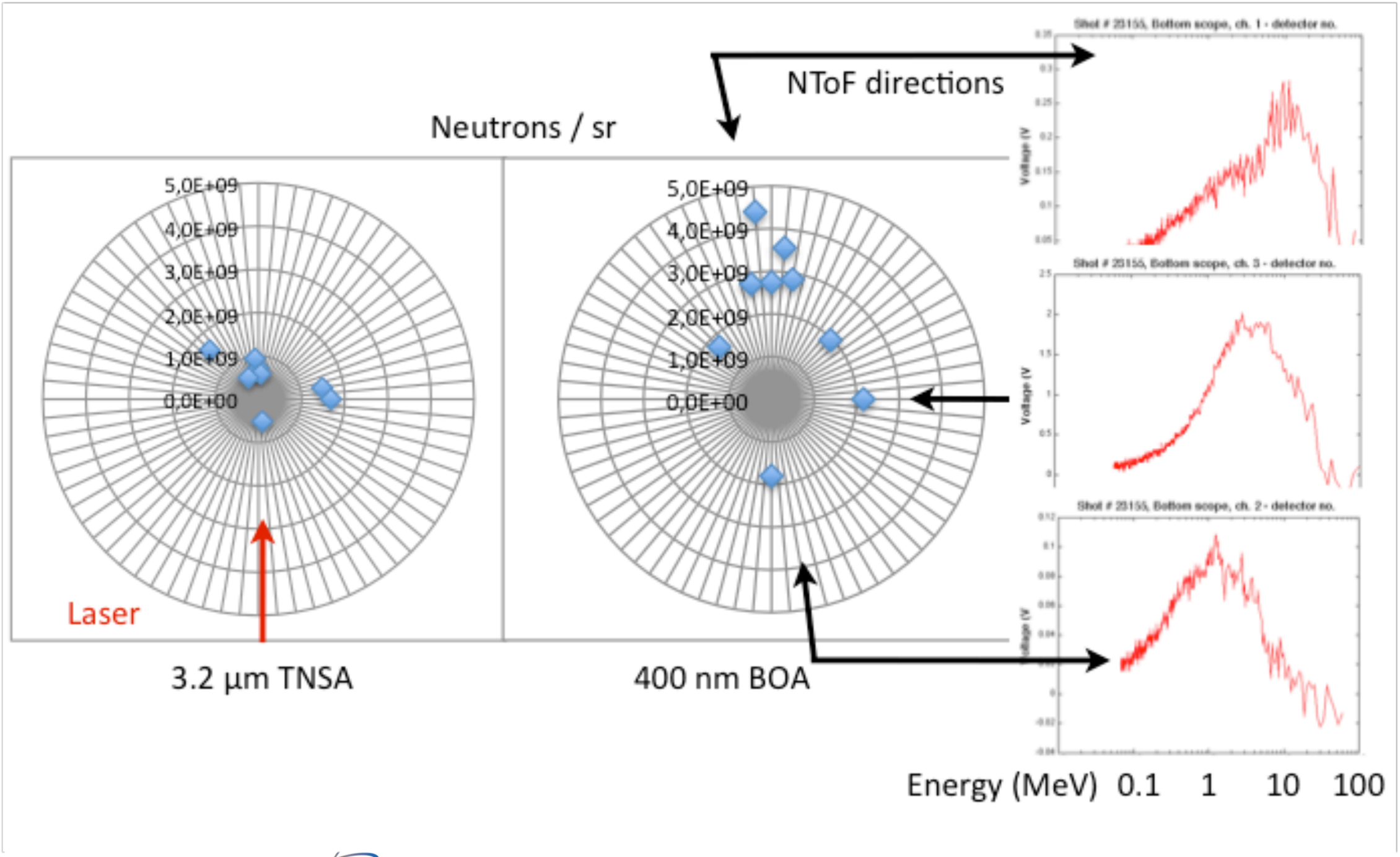




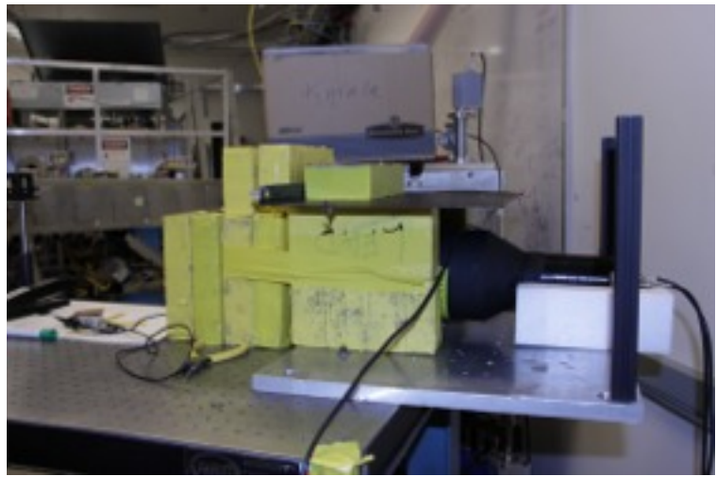


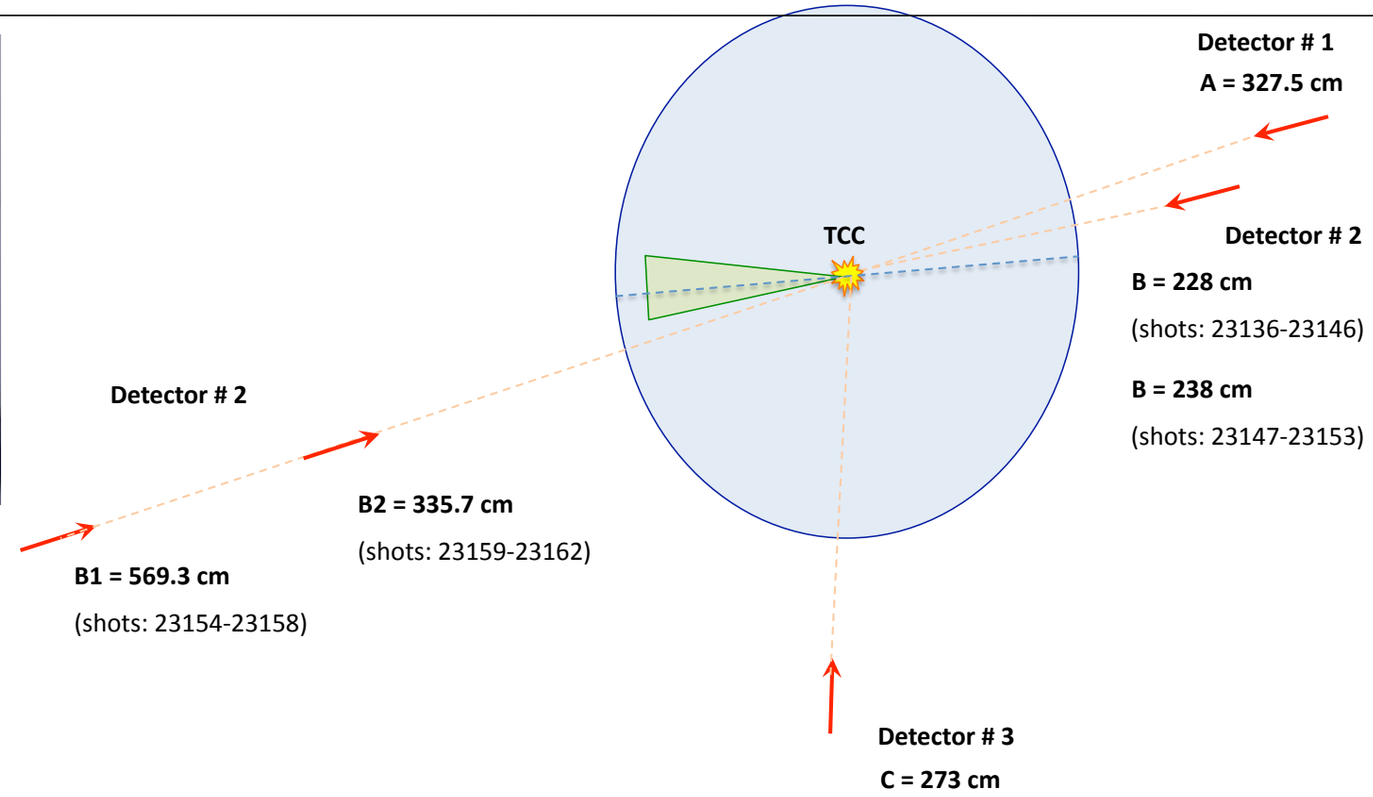
Using CD targets: No cleaning needed
one order of magnitude more deuterons than protons when using BOA

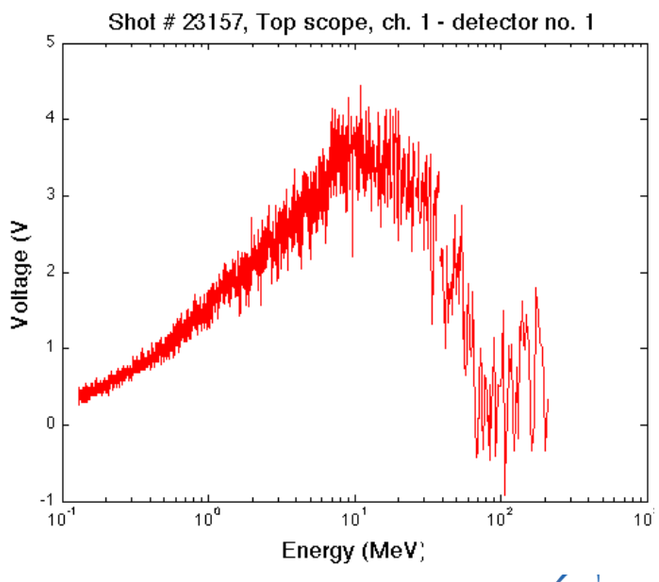
BOA vs. TNSA

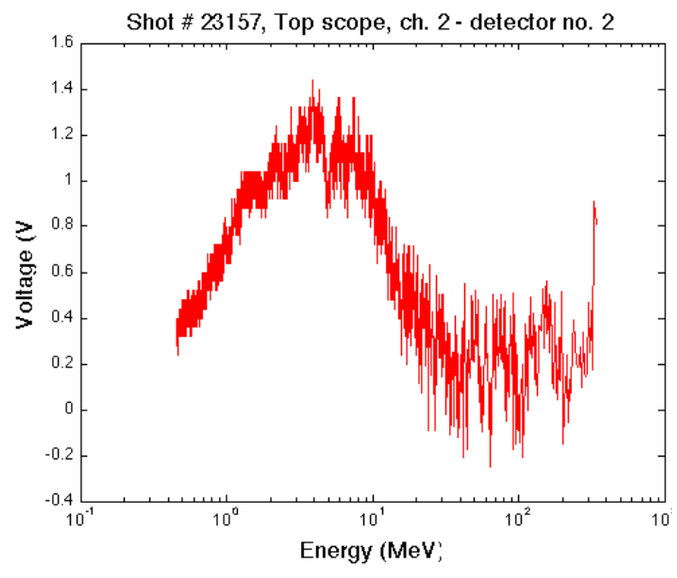

NToF directions
Neutrons / sr
5,0E+09
4,0E+09
3,0E+09
2,0E+09
1,0E+09
0,0E+00
Laser
3.2 µm TNSA
400 nm BOA
Shot # 23155, Bottom scope, ch. 1 - detector no.
Shot # 23155, Bottom scope, ch. 3 - detector no.
Shot # 23155, Bottom scope, ch. 2 - detector no.
Voltage (V
Energy (MeV) 0.1 1 10 100

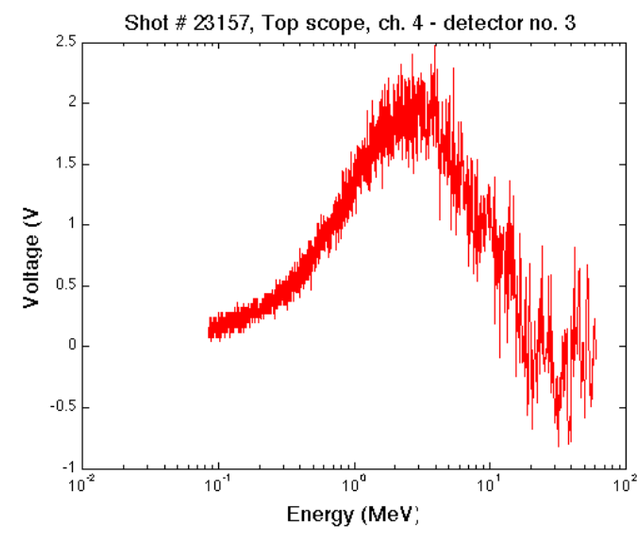
NToF Signals



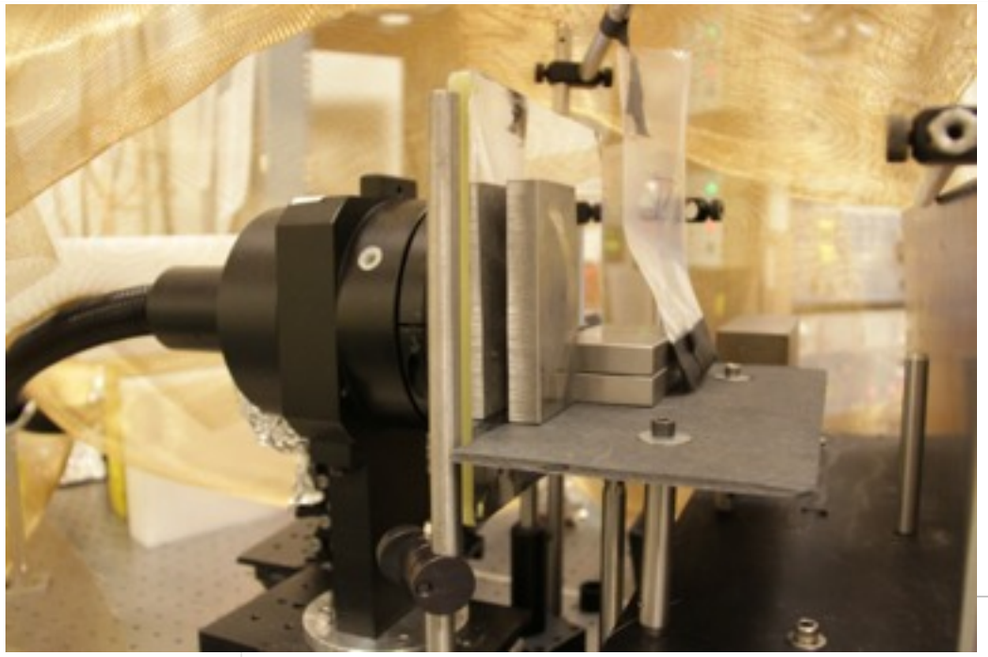


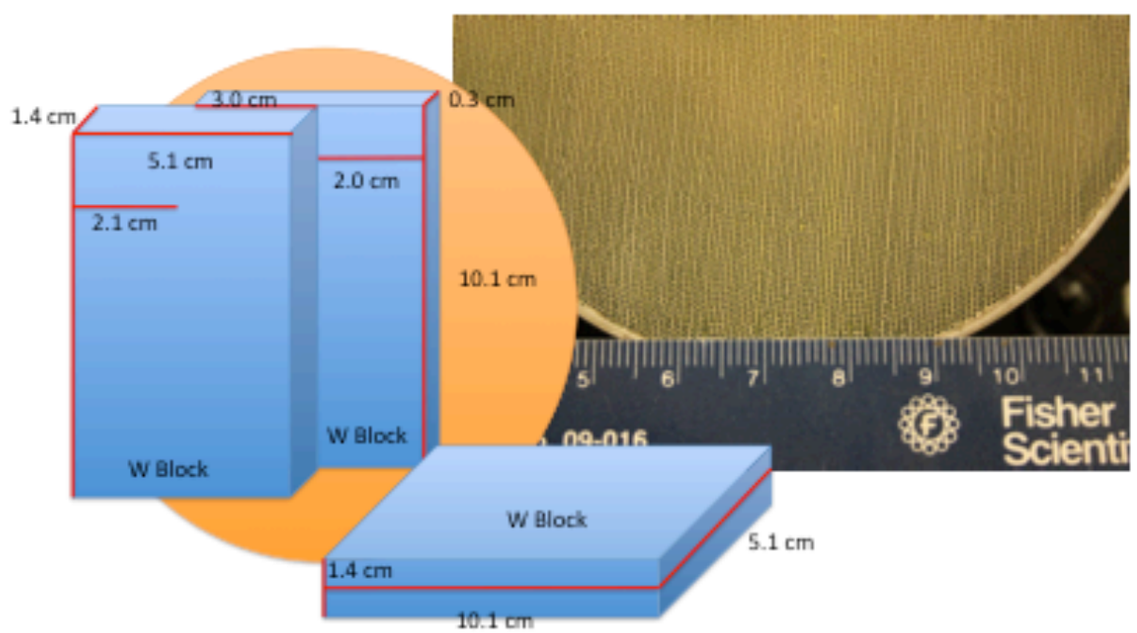


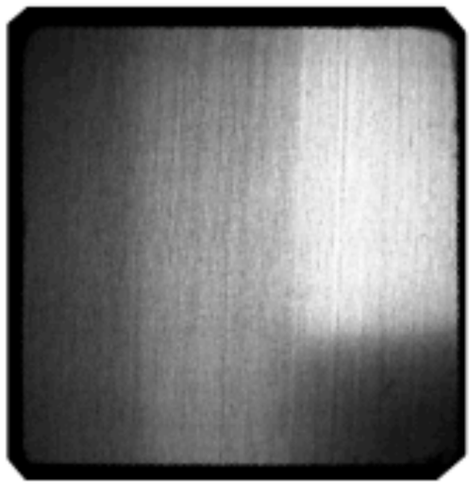




Gated Neutron Imager







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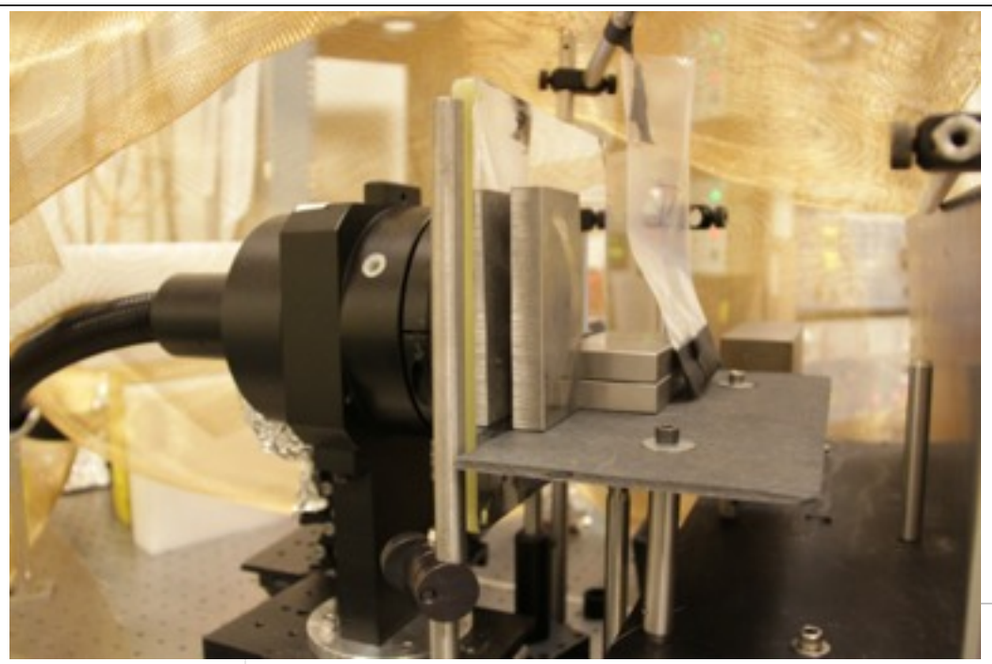

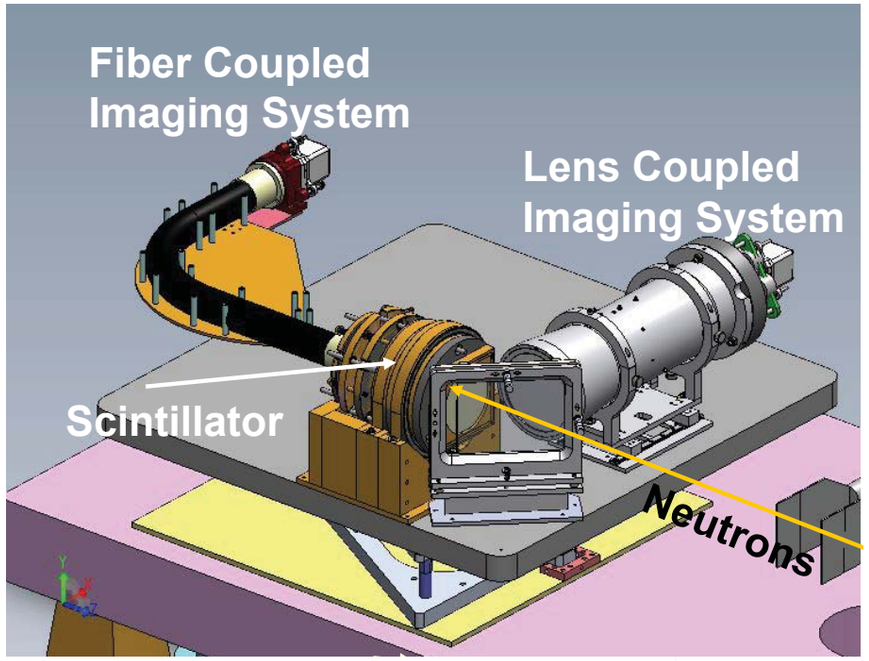

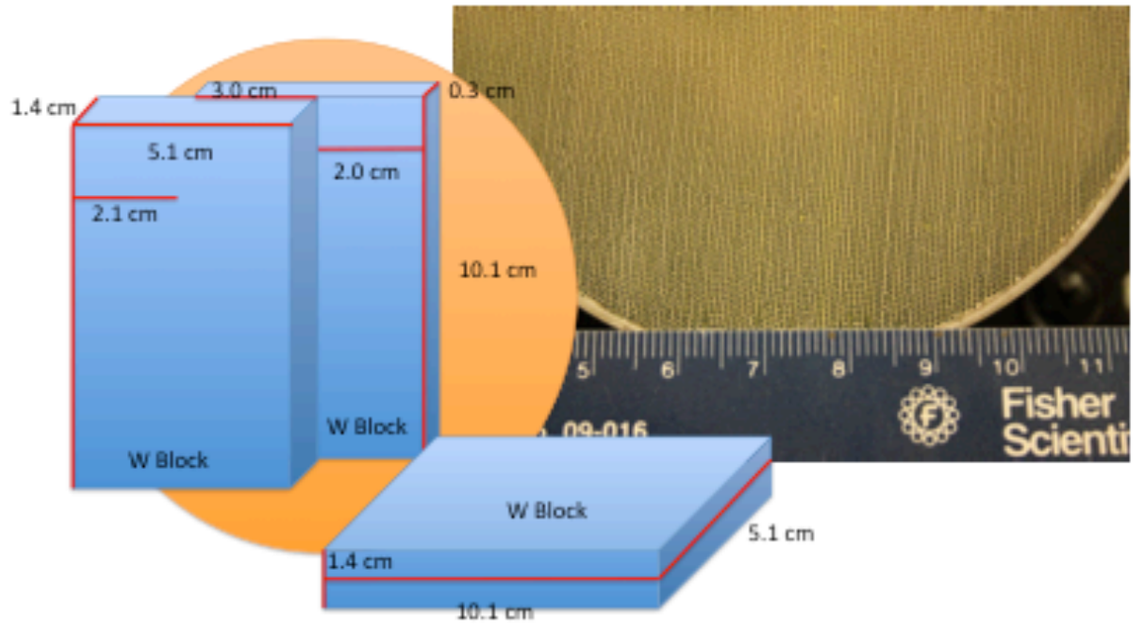

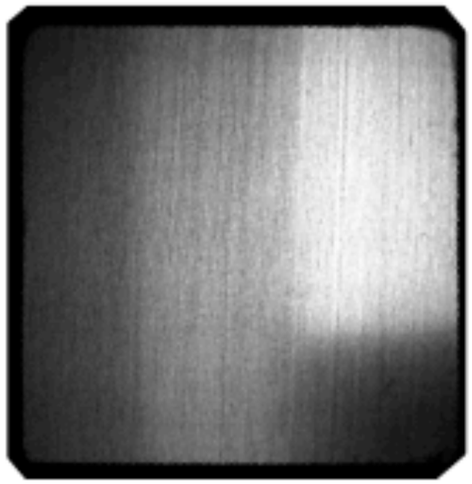

First short pulse laser driven fast neutron radiography

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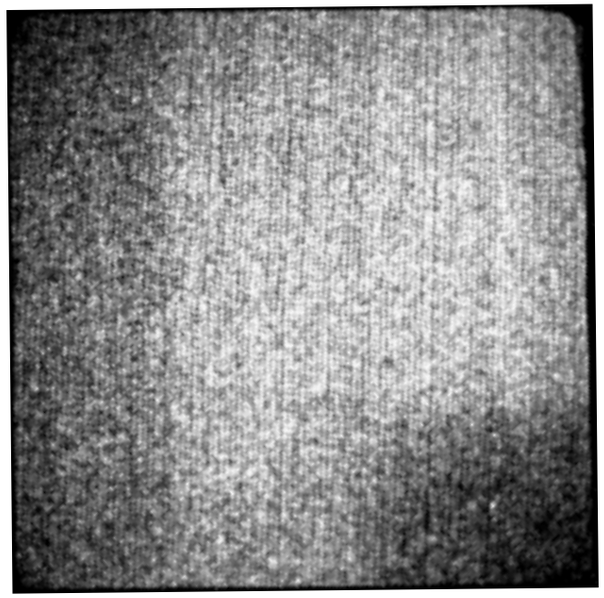
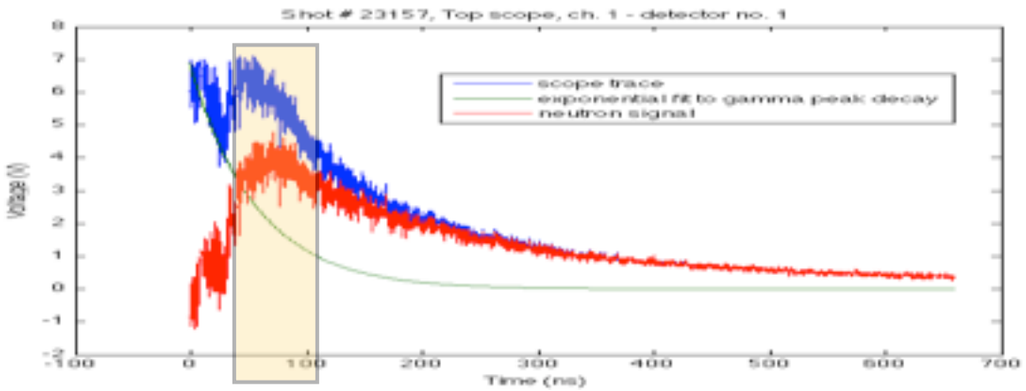
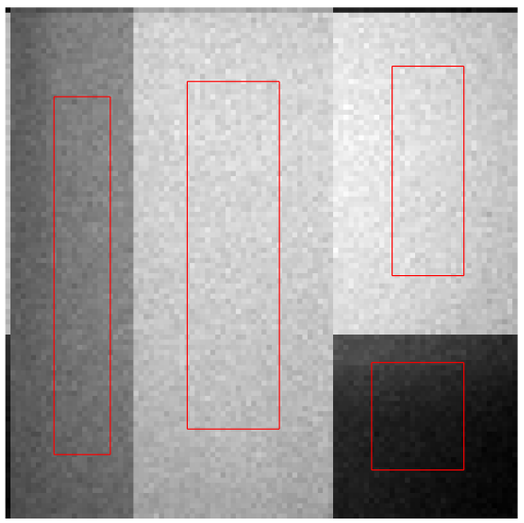
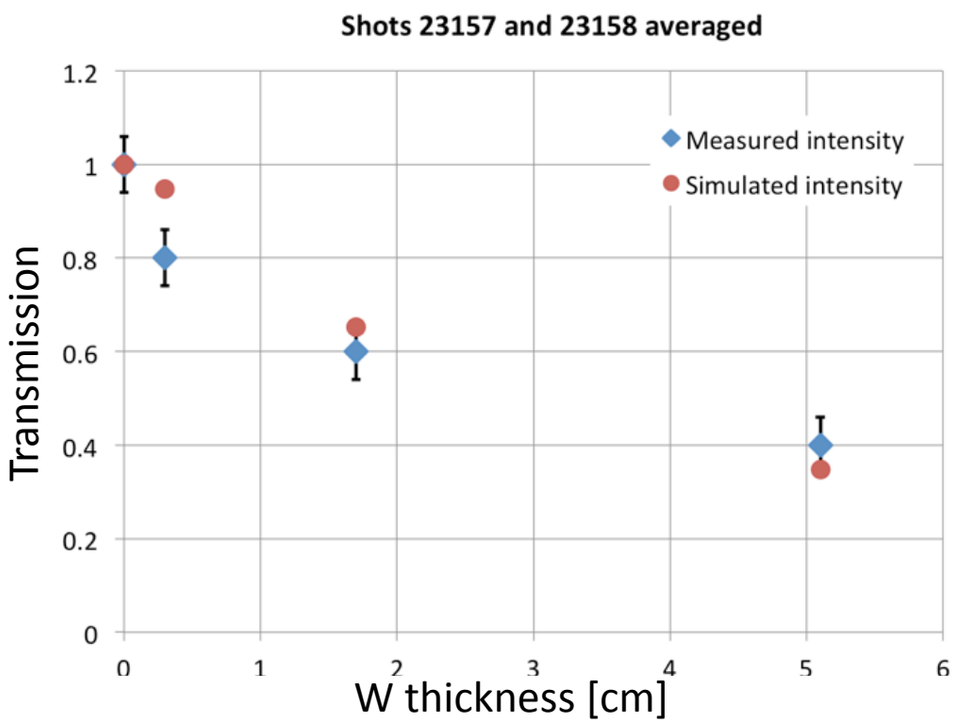






W thickness and simulated image



Summary

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- In a distance of 1 cm behind the converter: 40 n/μm^2 and 4 x 10^{18} n/cm^2s to alter material
- 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]

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TUD for the sabbatical