Dose controlled irradiation experiments with laser-accelerated protons at Draco Petawatt

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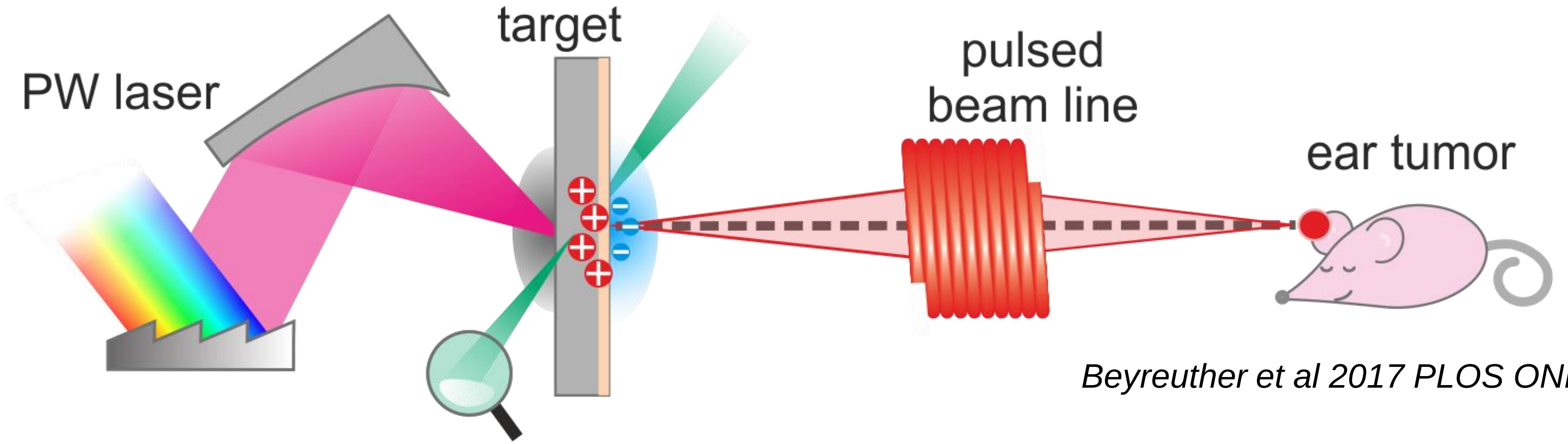
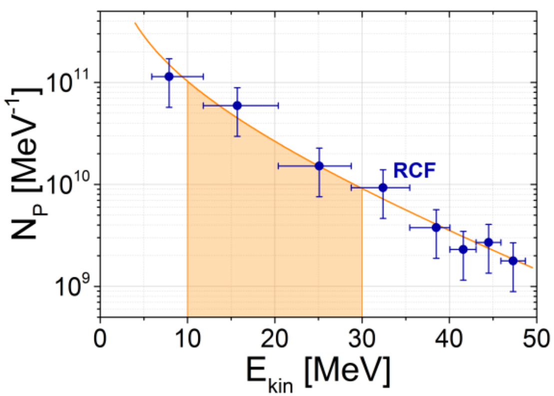
Laser-driven dose delivery for 3D *in vivo* irradiation



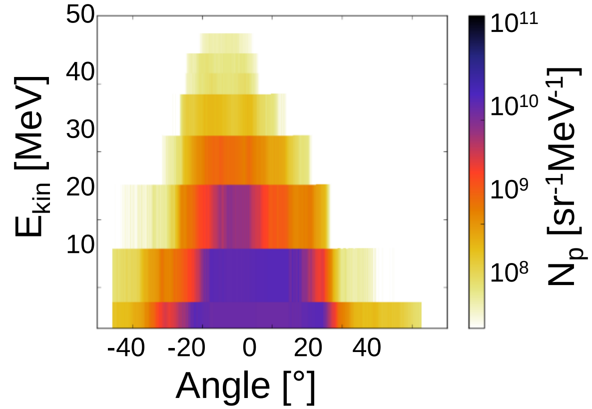
Beyreuther et al 2017 PLOS ONE 12

- exponentially decaying, broad energy spectrum



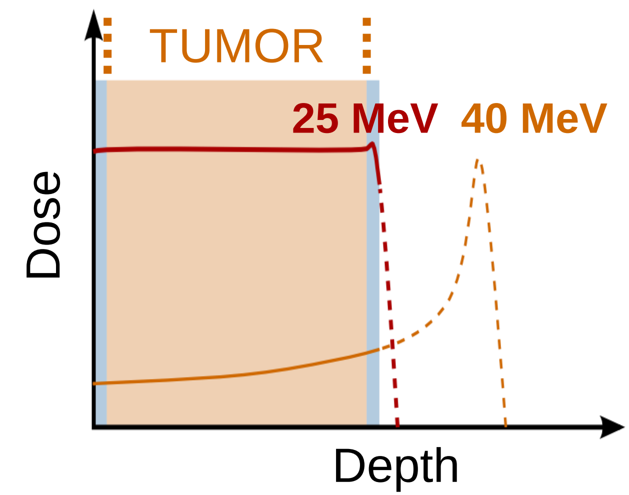
$N_p > 10^{11}$ in ~ps bunch

- angular spectrum



Half-angle divergence ~ 20°

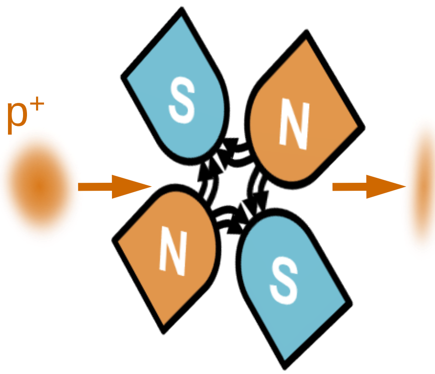
- Requested dose distribution



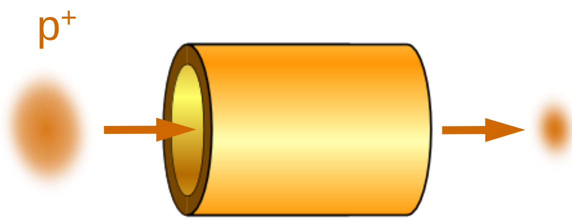
Dose homogeneous within $5\times5\times5$ mm³

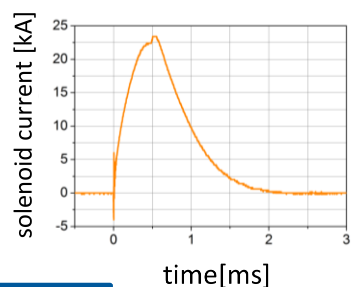
Pulsed high field magnets for medical beam line

Quadrupole



Solenoid





B-field: 1 T → 10 T

focal length

$$f_Q = \frac{pr}{qlB}$$

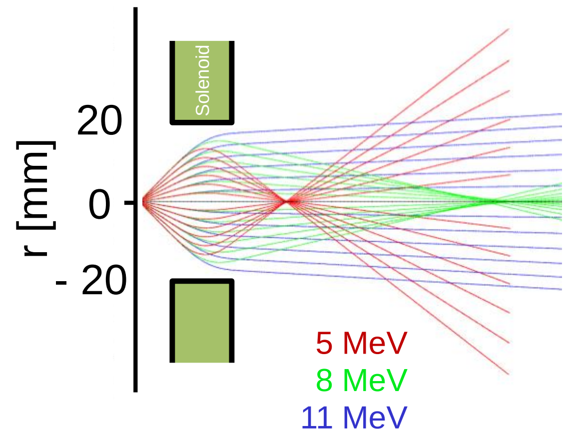
10

focal length

$$f_S = \frac{4p^2}{q^2 B^2 l}$$

100

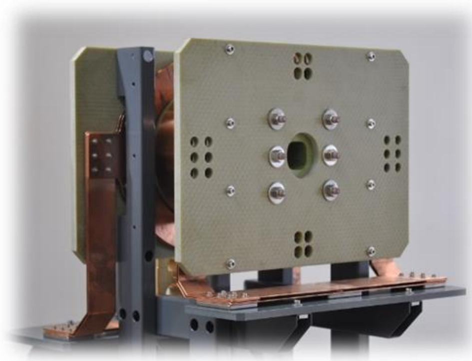
- Chromatic focusing
  - Energy selection via input current
  - Beam guiding



- larger open aperture
  - high transmission efficiency due to high angular acceptance

Pulsed high field magnets for medical beam line

Quadrupole

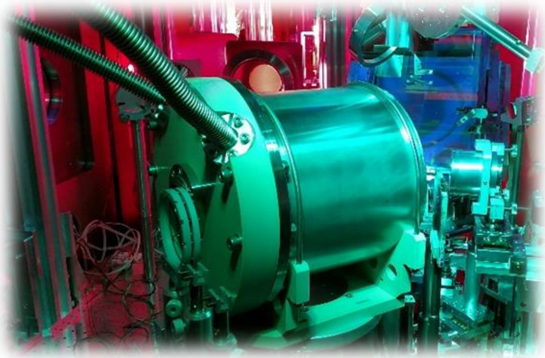


250 T/m

focal length

$$f_Q = \frac{pr}{qlB}$$

Solenoid



20 T

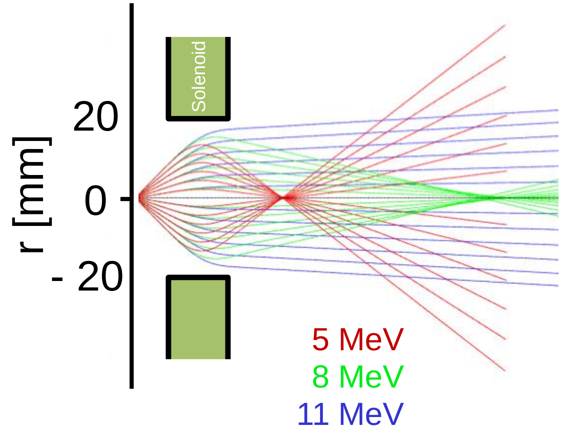
focal length

$$f_S = \frac{4p^2}{q^2B^2l}$$

- Solenoids suitable for broad energy range & large angular distribution of TNSA protons
- Pulsed power portfolio @HZDR for beam-line optics (Solenoid, Quadrupoles, Dipole)
  - pulsed power Gantry

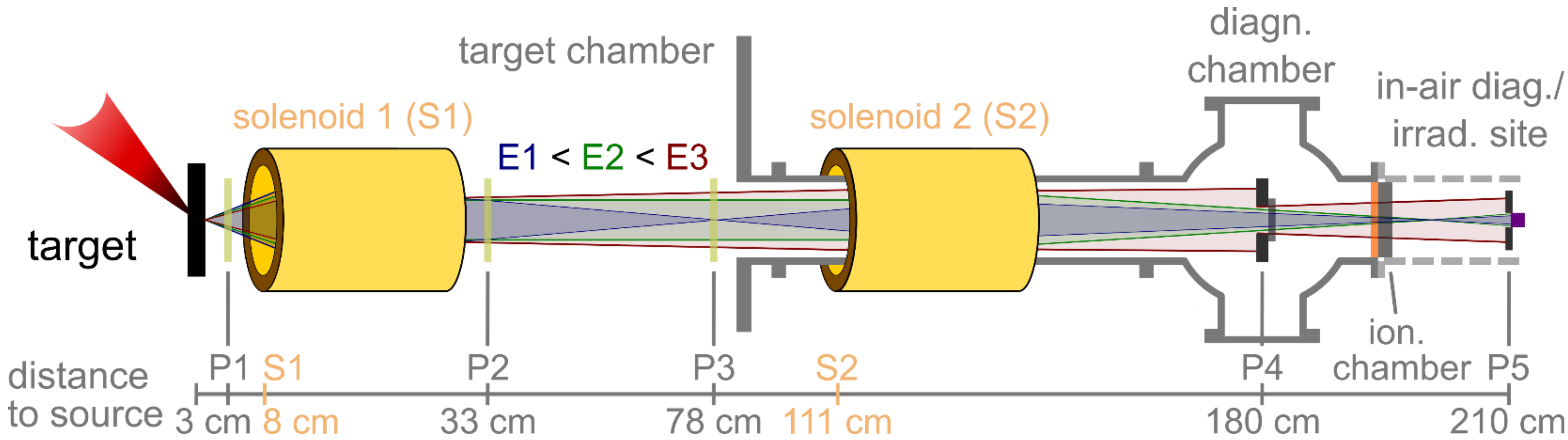
U Masood et al 2017 Phys. Med. Biol.

- Chromatic focusing
  - Energy selection via input current
  - Beam guiding
  - collimation of 70 MeV

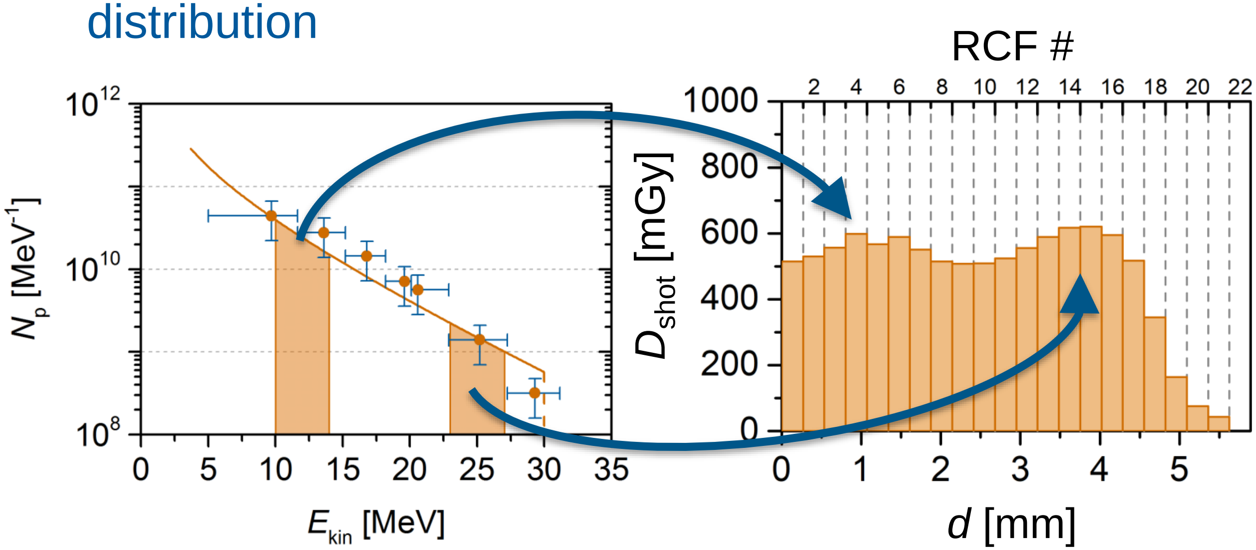


- 40 mm open aperture
  - high transmission efficiency due to high angular acceptance
- B_{max} = 21 T (I_{max} = 24 kA)
- few years operation (1000+ pulses)

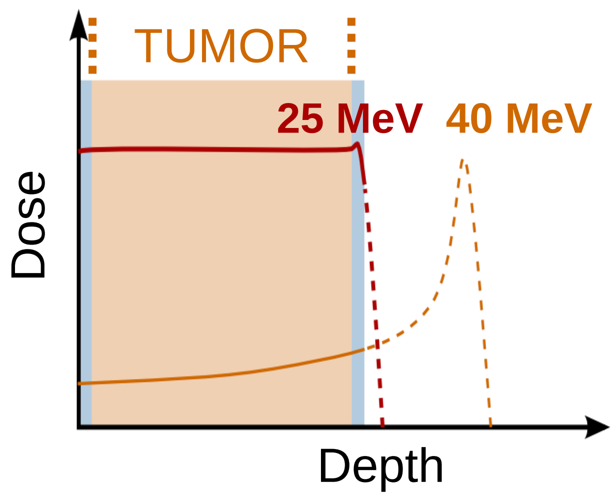
Laser-driven dose delivery for 3D *in vivo* irradiation



- Dual solenoid setup focuses protons of two independent energies
- Spectral shaping to a homogeneous depth dose distribution



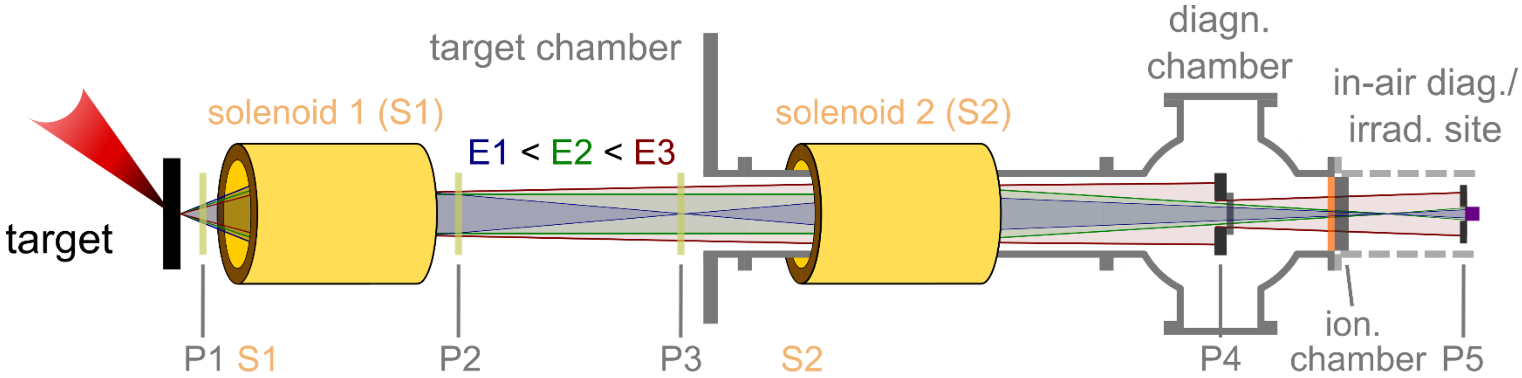
- Requested output



Dose homogeneous within 5×5×5 mm³

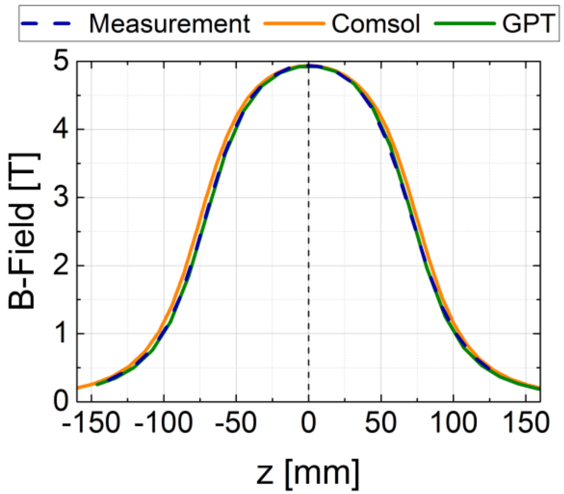
Beamline modelling and experimental verification

Parameter prediction based on particle tracing simulations with GPT



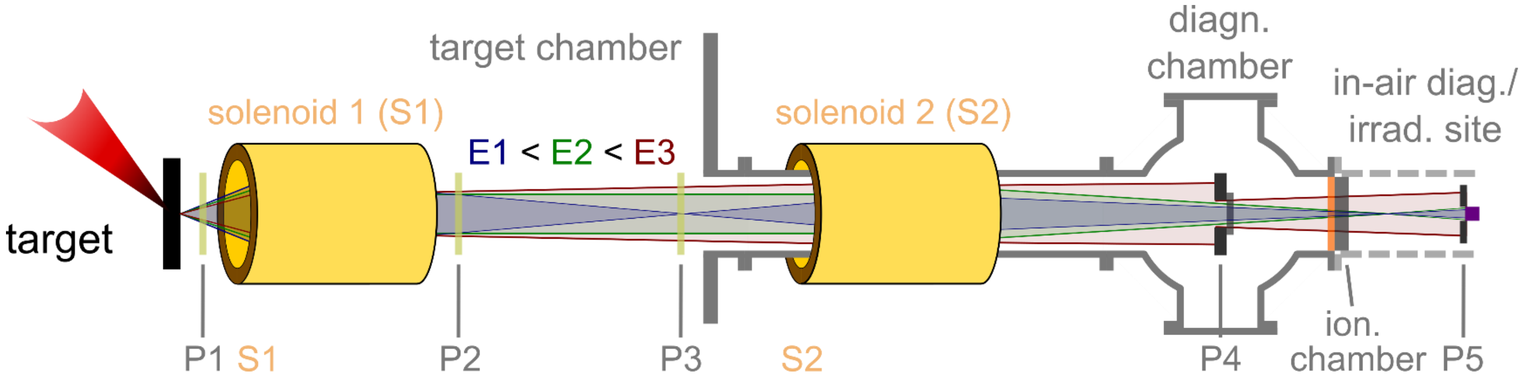
- Tunable beamline allows fast adaptation to a requested output, with GPT model we can predict:
  - distances, solenoid currents ($I_{S1/2}$), transmission efficiency
  - Generate output for Monte Carlo dose simulations (e.g. TOPAS)

- Pulsed beamline/magnets modelling complicated, no detailed 3D B-field measurement
- Measurement along main axis legitimates further simulations with GPT



Beamline modelling and experimental verification

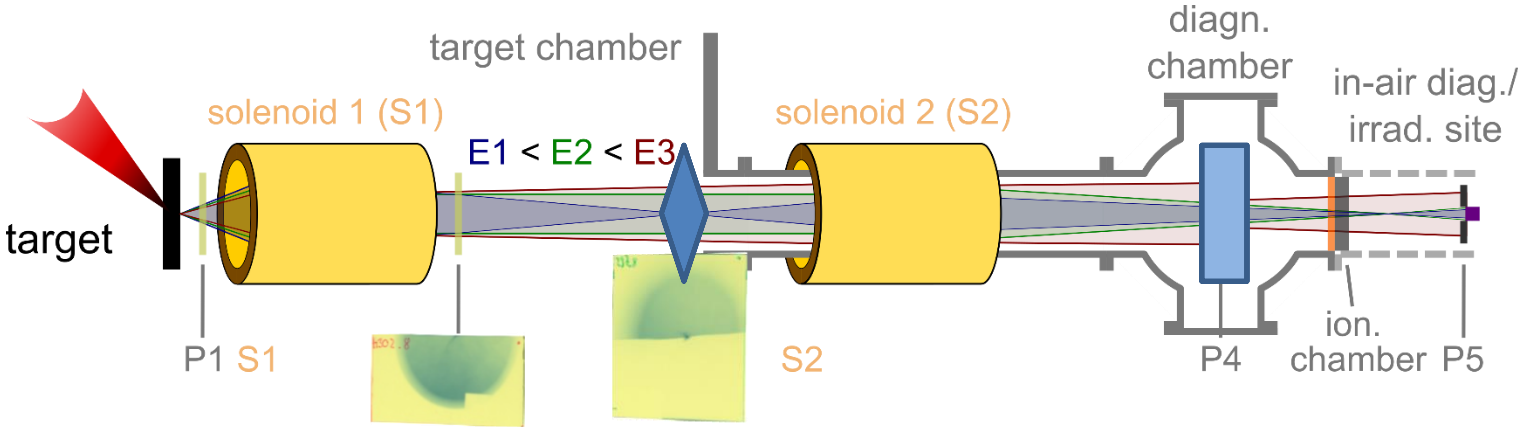
Finding translation factors from simulation model to experiment



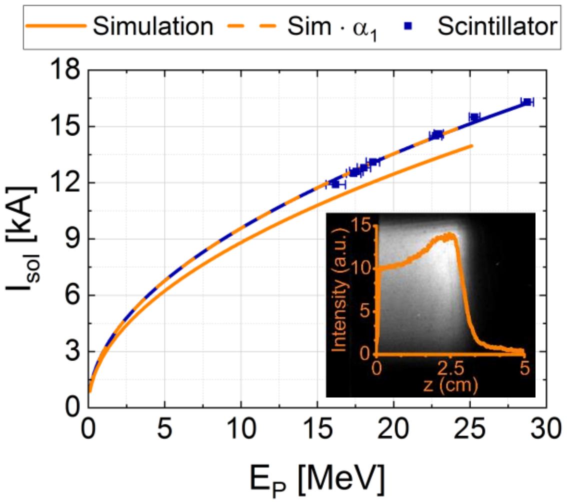
- Three independent methods, all single-shot, in sight of the pulsed source and solenoids and are based on particle transport

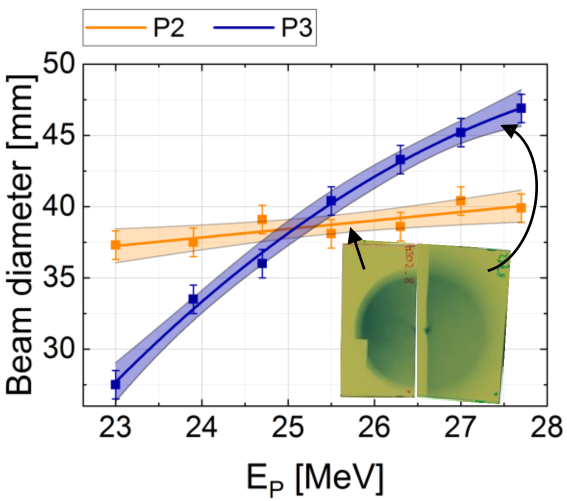
Beamline modelling and experimental verification

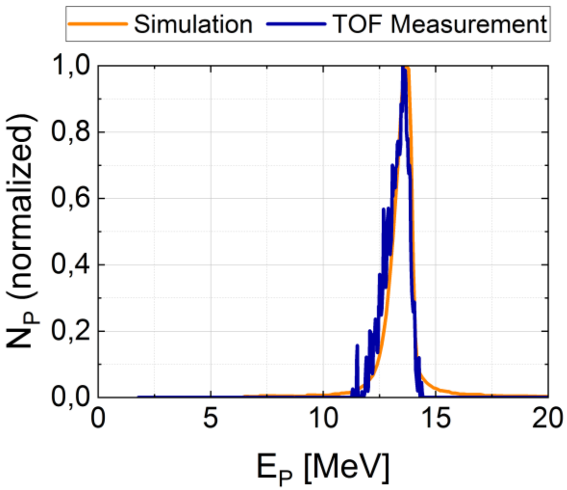
Finding translation factors from simulation model to experiment



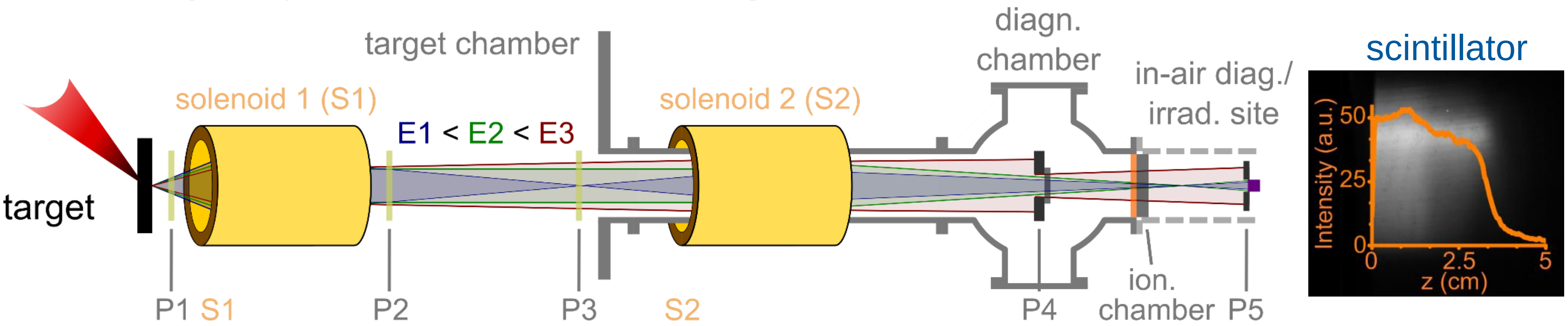
- Focused proton energy (detection via scintillator at P4) to solenoid current
- Collimated beams at P2 & P3, beam size evaluation for surrounding energies
- Simulated proton spectrum to measured time-of-flight (diamond detector at P3)



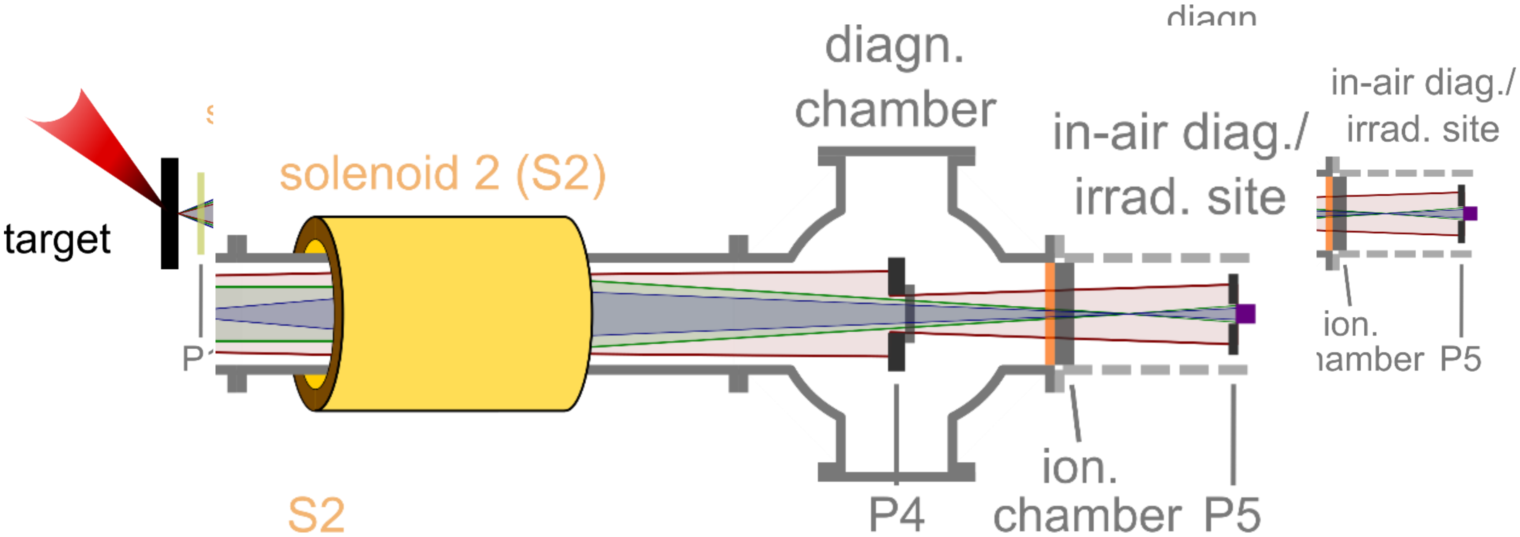


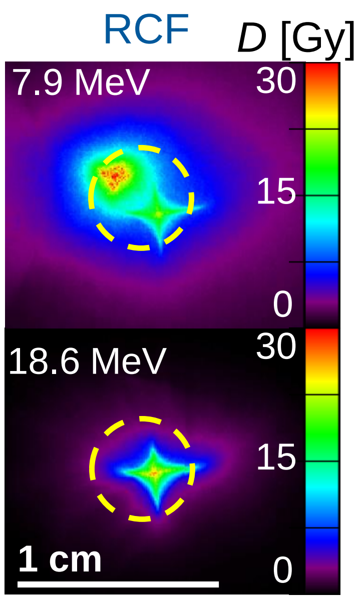


Shaping of laser-driven proton beams

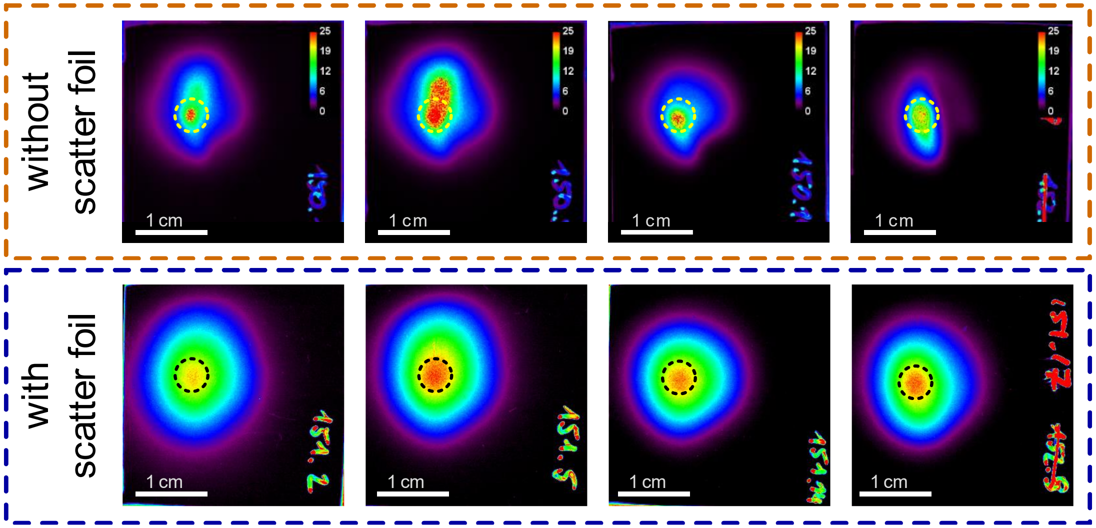


Shaping of laser-driven proton beams





- After **spectral** homogenization → **lateral** homogenization
- focus in front of irradiation site & energy selecting aperture at P4
- Introduce scatter foil at P4



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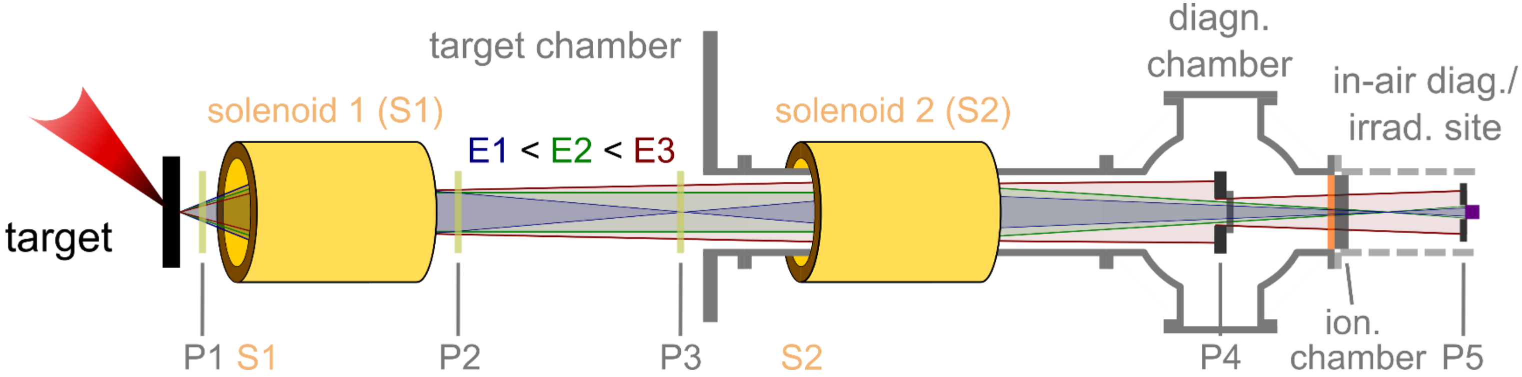
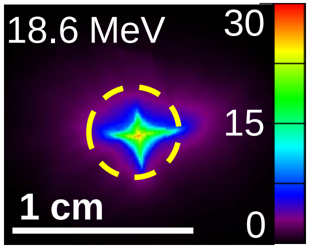
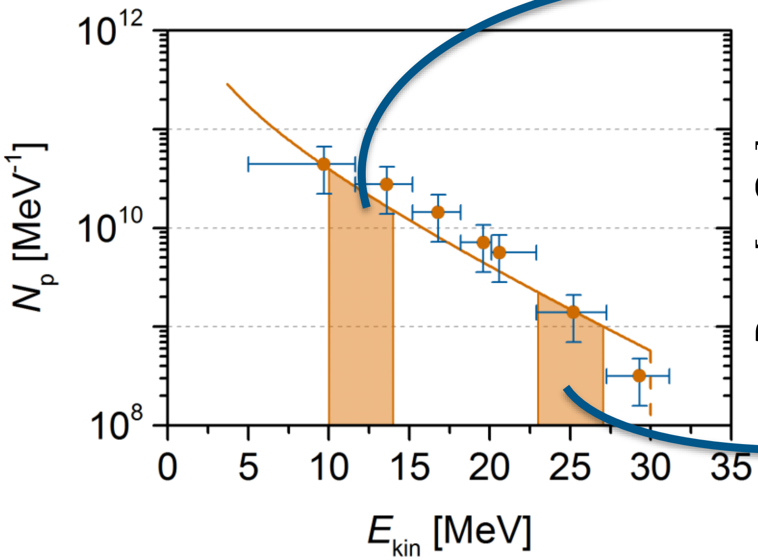
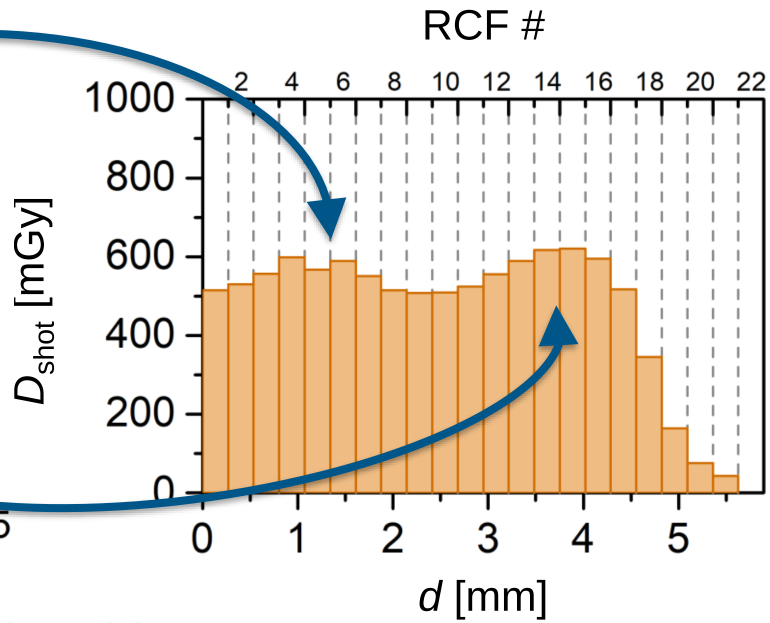
Shaping of laser-driven proton beams

- Combining **spectral** (2 solenoids) and **lateral** (scatter foil, focal distance, energy selecting aperture) **homogenization** and final aperture of irradiation sample

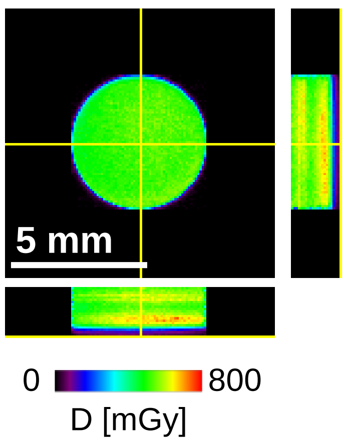






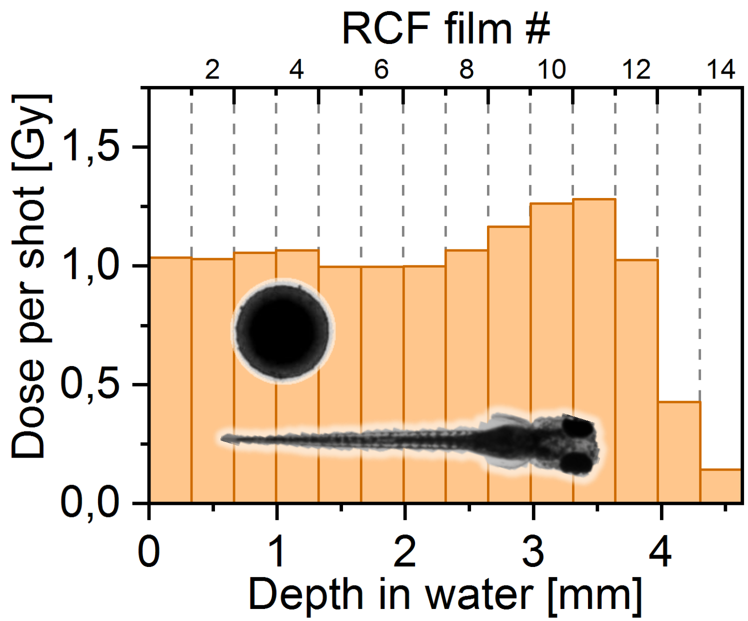


Transmission efficiency 50.6 %



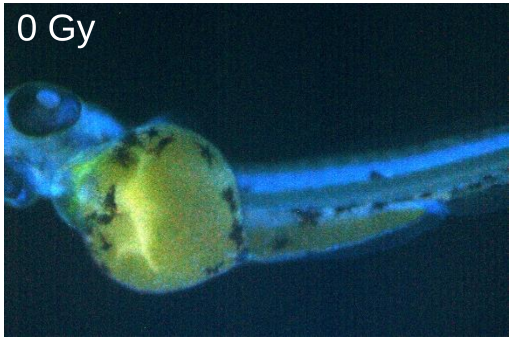
Both modulations below ±8,5%

Pulsed high-field dose delivery experiments at Draco

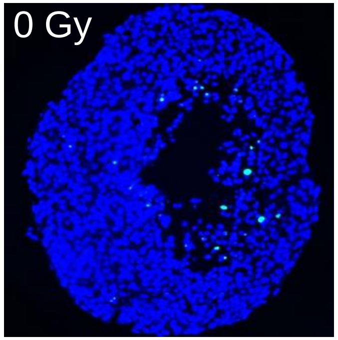


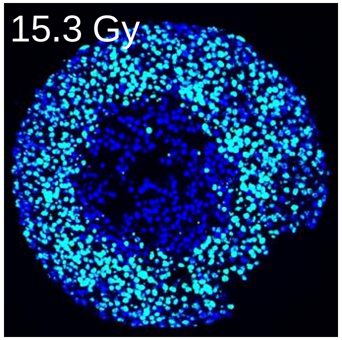
- Pulsed high-field beamline enables **3D dose delivery** for sophisticated radiobiological experiments
- First **irradition studies** with **tumor spheroids** and **zebrafish embryos** have been performed
- too low dose for irradiation damage to the ZF embryos, spheroids show a **DNA-DSB rich ring** induced by **laser-driven protons**

Zebrafish embryo (*in-vivo*)



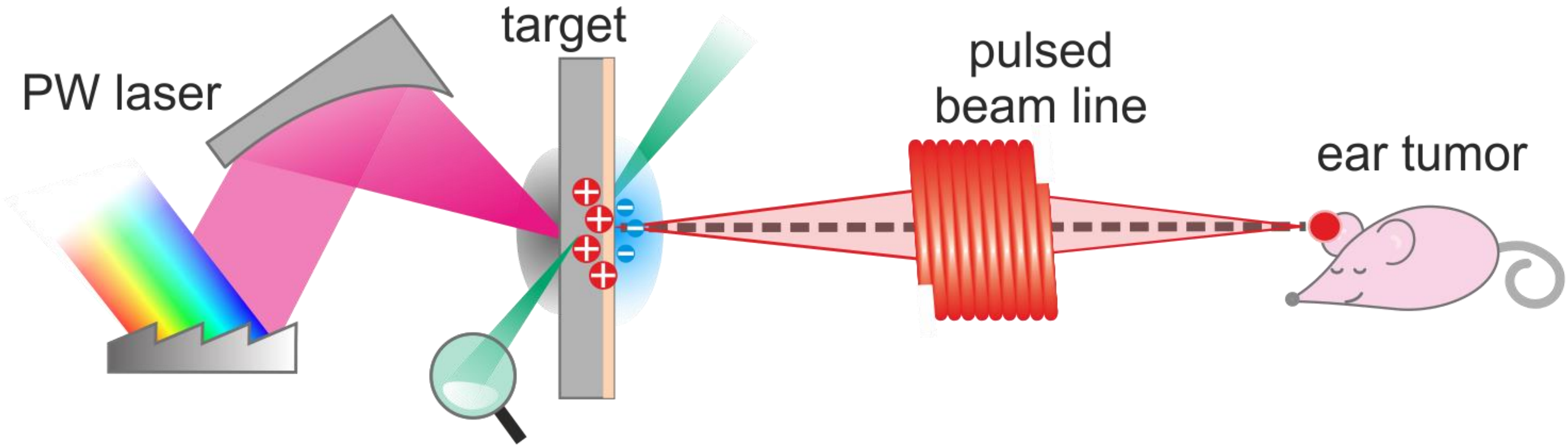
Tumorspheroids (*in-vitro*)





Publication to be submitted

Laser-driven dose delivery for 3D *in vivo* irradiation



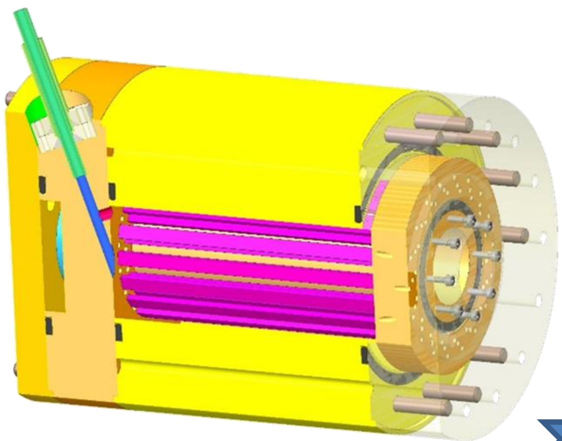
- *Currently*: Radiobiological requirements close to limits of the beamline
  - required dose rate of 1 Gy/min within 5x5x5 mm³ sample volume and integrated dose (minimum 10 Gy)
  - low repetition rate pulser combined with strong ohmic heating/long cooling time for solenoids are major bottlenecks
- *Development*: Higher dose rates (and integrated dose) via
  - higher proton number/energy from laser driven proton source
  - high repetition rate pulse generators and solenoids

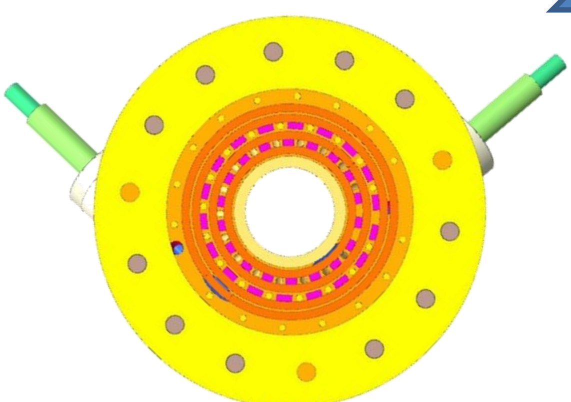
Talk by K. Zeil on Thu 16:20

High rep-rate magnet development

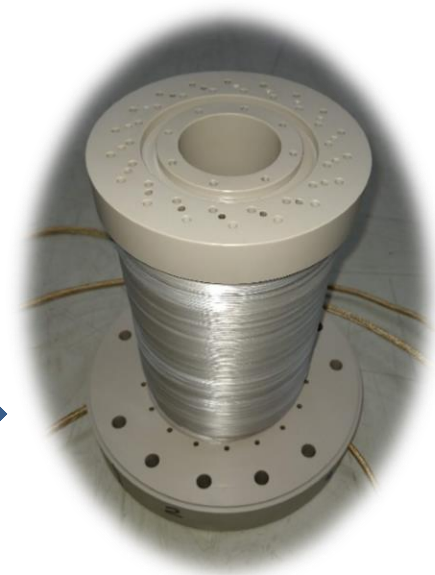
- *Development*:
  - cooled solenoids (with channels for cold air/liquid between winding layers)
  - Thyristor-based pulse generator with energy recuperation at 1 Hz

Cooling Concept





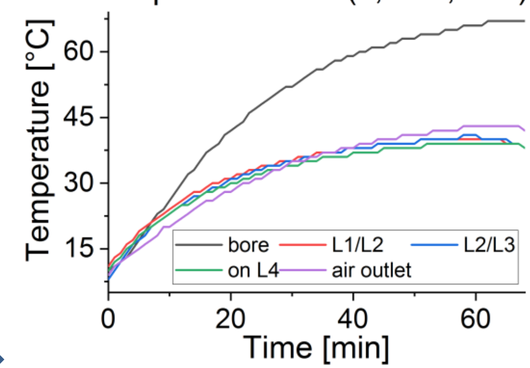
Prototype



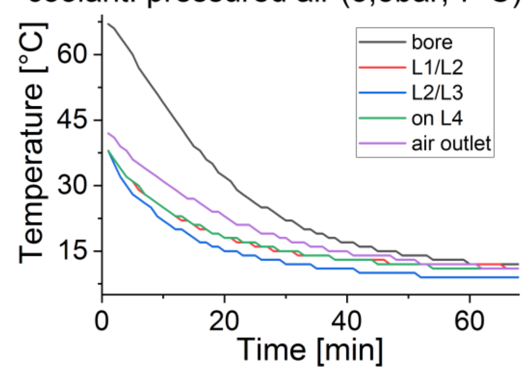
Cool down times reduced from hours to minutes

Testing

Ohmic heating (50A, DC)
coolant: pressured air (3,5bar, 7°C)



Cooling after heating (50A, DC)
coolant: pressured air (3,5bar, 7°C)



Thank you for your attention!