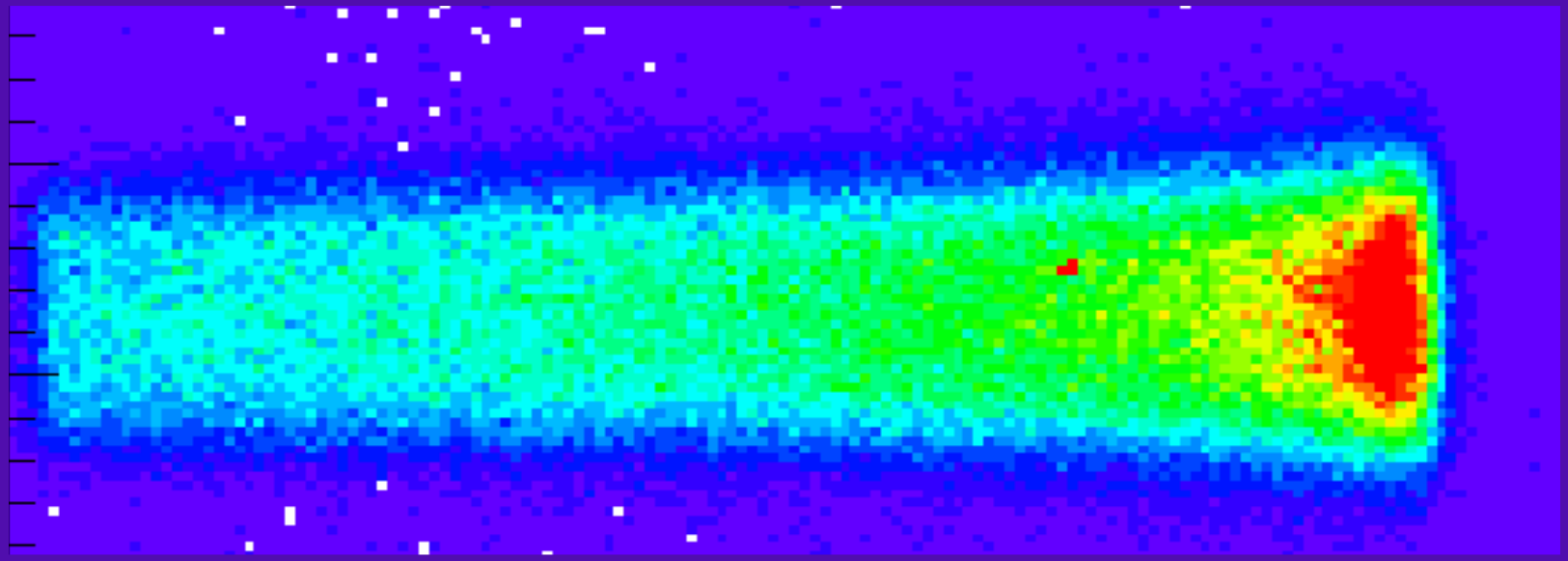
Water based 3D optical dose imaging for particle therapy



***Oksana Kavatsyuk*[1], *Marc-Jan van Goethem*[1,2], *Aart van 't Veld*[2], *Sytze Brandenburg*[1]**

[1] KVI-CART, University of Groningen, Groningen, Netherlands
[2] Department of Radiation Oncology, University Medical Center Groningen, Netherlands

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Demonstrator

PARTREC
High precision, innovation & patient comfort

umcg

Proton therapy technique

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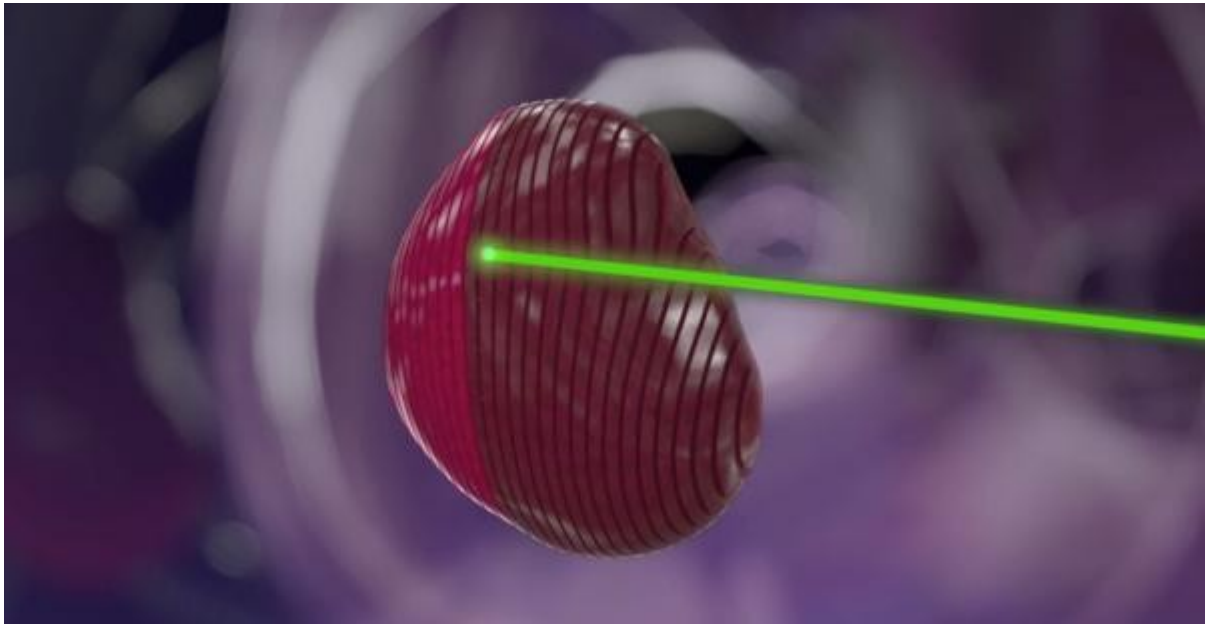
- state-of-the-art: pencil-beam scanning
- complex process
  - 3D-delivery: X, Y and energy (penetration depth)
  - typically **~10 000** beams for 1 litre volume

✔ verify treatment plan (**plan QA**) prior to treatment

↳ **check delivered dose distribution**



http://www.iba-protontherapy.com/iba-today/pencil-beam-scanning-pbs-progress-date

Proton therapy plan QA

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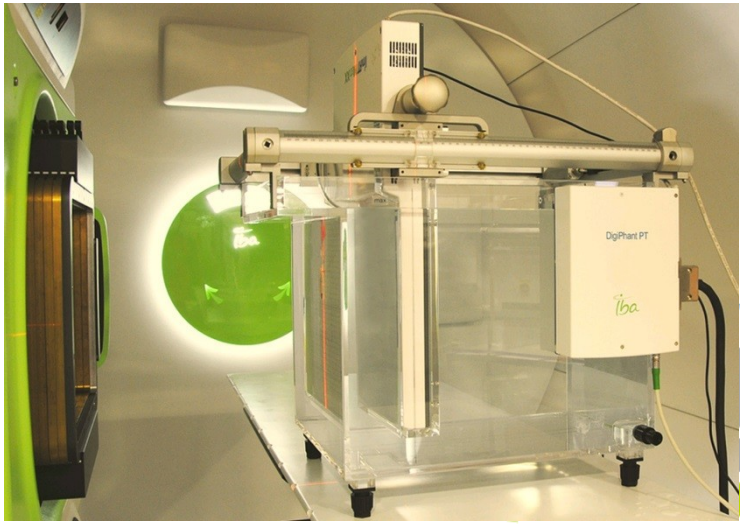
current clinical standard
for verification of dose distributions in proton therapy:

2D array of ionization chambers
measuring at various depths in water
prior to the treatment course

coarse grid (typically 1 cm)
slow (measurements at ~20 depths = 40 min)
not suitable for scanned ion-beams
(response of ionization chambers
depends on beam size and beam position)



needed:
method for **rapid** verification of
dose distributions for scanned ion-beams

Proton therapy plan QA

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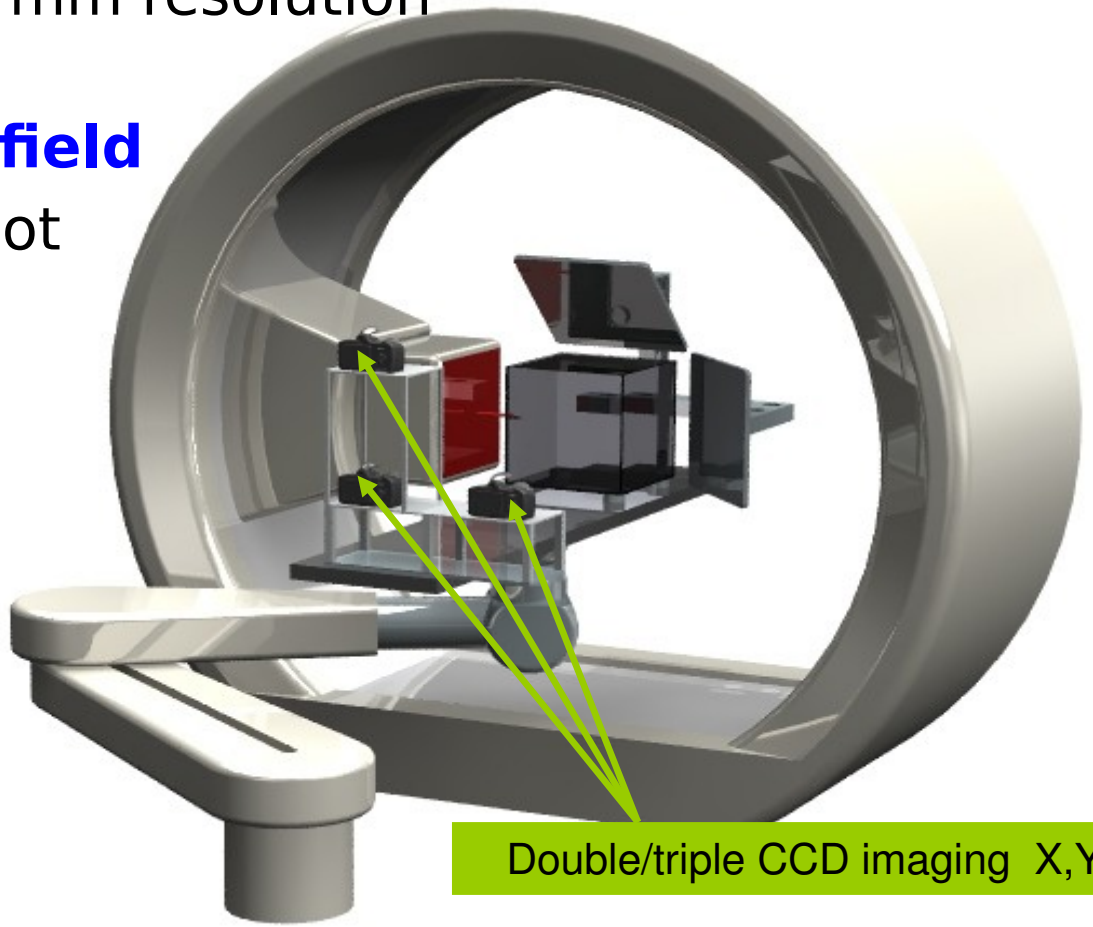
Our method:

- imaging of proton-induced light
  (dose delivery verification in water tank)
- 3D reconstruction with ~1 mm resolution
- fast: single plan delivery
  40 min => **3 min per field**
- set-up with positioning robot



Proton therapy plan QA

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OUR WISHES

water
standard medium
for plan verification in radiotherapy

real time measurement of 3D dose distribution

↓

scintillator

Proton therapy plan QA

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OUR WISHES

water standard medium
for plan verification in radiotherapy

↓

Is water a scintillator?

real time measurement of 3D dose distribution

↓

scintillator

Proton therapy plan QA

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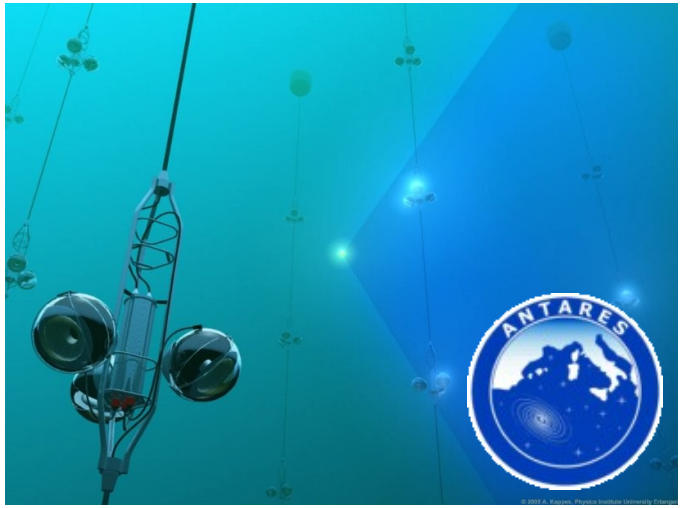

used as Cherenkov detector in HEP

→ **Would it work below the Cherenkov threshold?**

real time measurement of 3D dose distribution

↓

scintillator

Proton therapy plan QA

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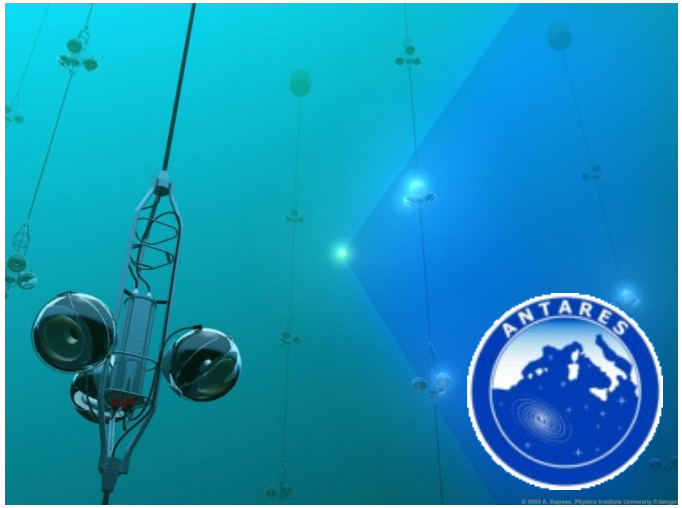
OUR WISHES

water
standard medium
for plan verification in radiotherapy

real time measurement of 3D dose distribution

Is water a scintillator?

scintillator



used as Cherenkov detector in HEP

YES!
We DO see light below the Cherenkov threshold!

Cherenkov radiation

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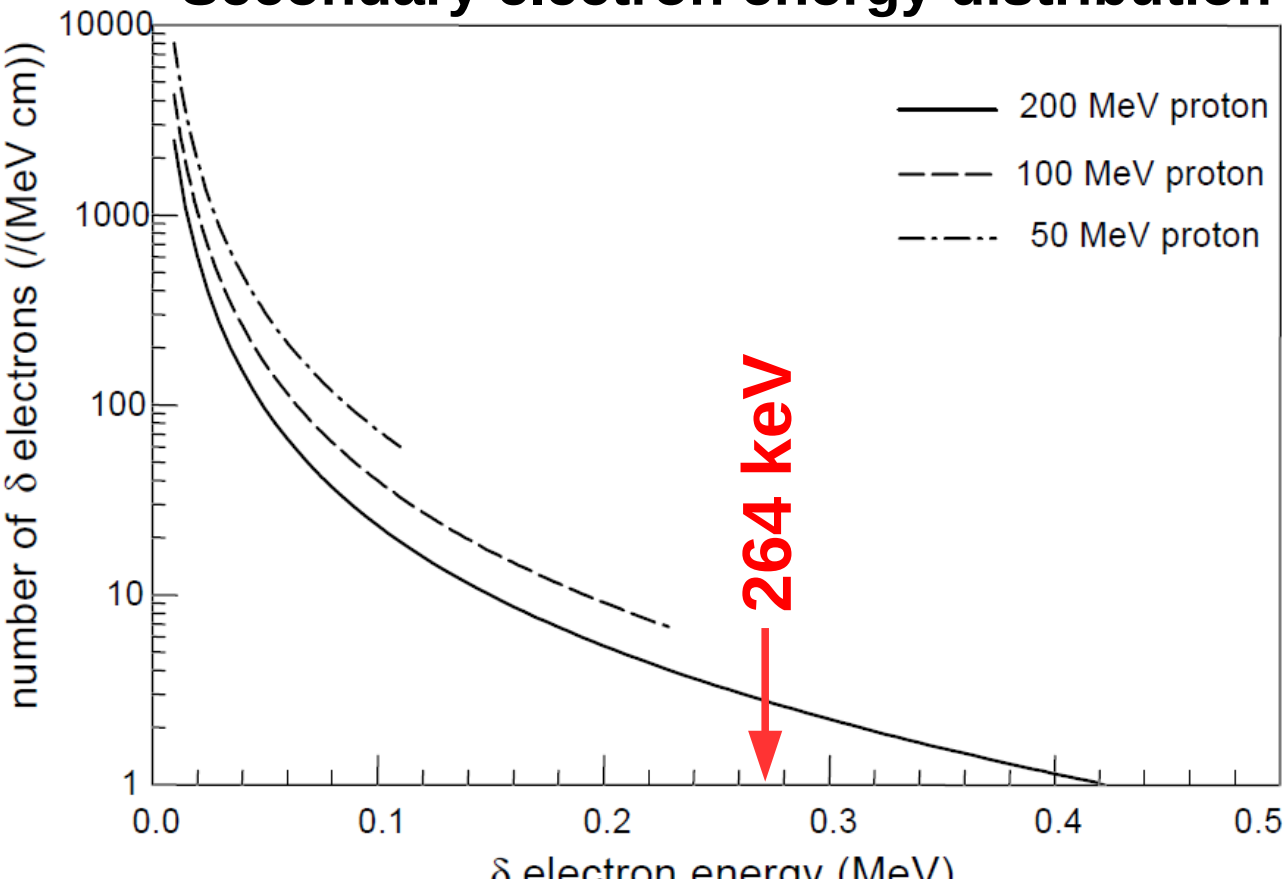
Limits for Cherenkov radiation:
protons: **486** MeV
electrons: **264** keV (produced by ~114 MeV protons)

Secondary electron energy distribution



PhD thesis S. Boon (1998) , University of Groningen

Cherenkov radiation

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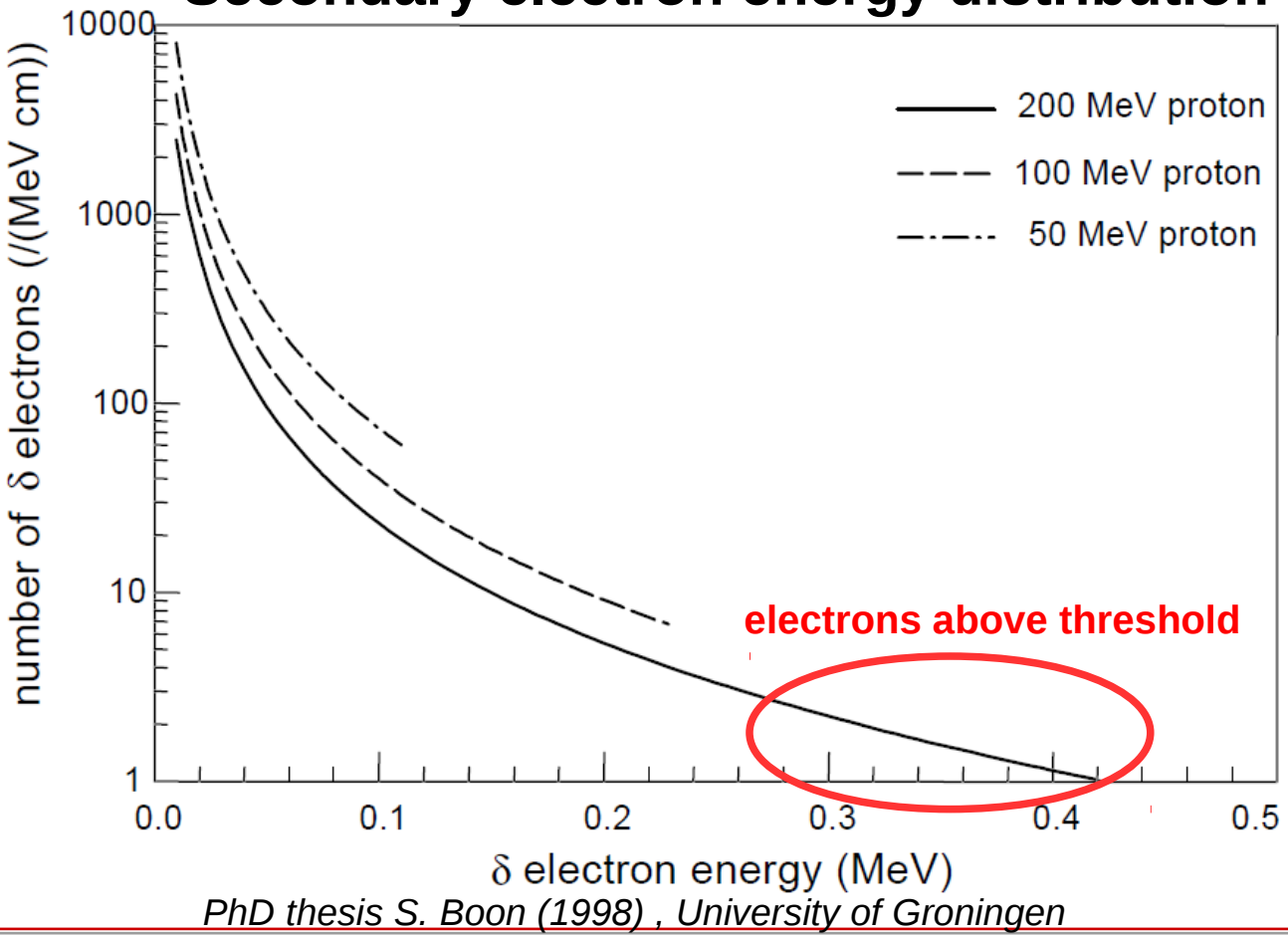

PhD thesis S. Boon (1998) , University of Groningen

In our experiments with 90 MeV protons NO Cherenkov

To be considered

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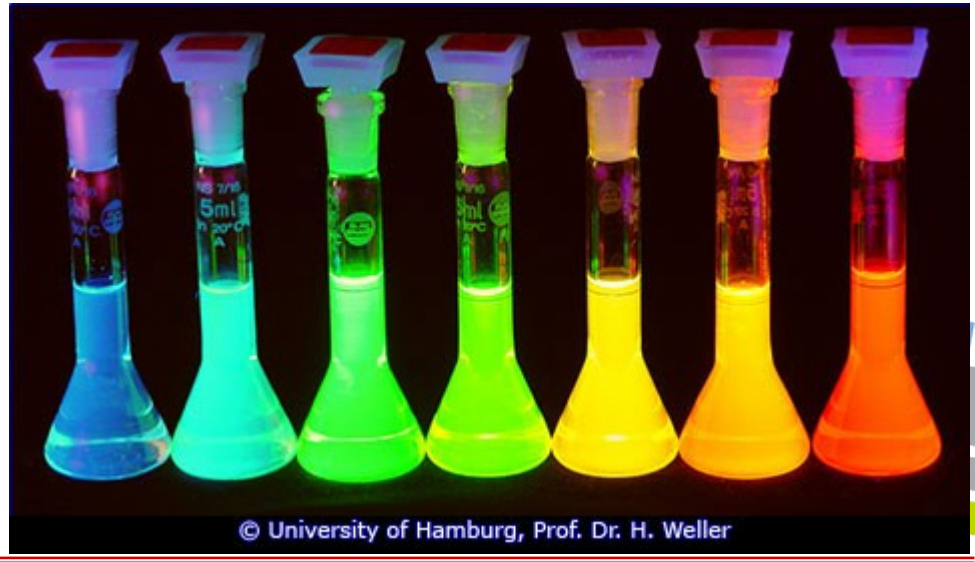
- suitable fluorescent compounds
  water soluble

- **quantum yield=** $\frac{\text{photons emitted as fluorescence}}{\text{photons absorbed}}$

- **quenching:** reduction in fluorescence intensity
  or light response at high LET
  ↳ not a problem for spatial distribution

- dose ⟺ light yield relation
- dose rate/flux effects
- water quality, Oxygen influence, aging
- dose reconstruction from image



Dose vs. light yield

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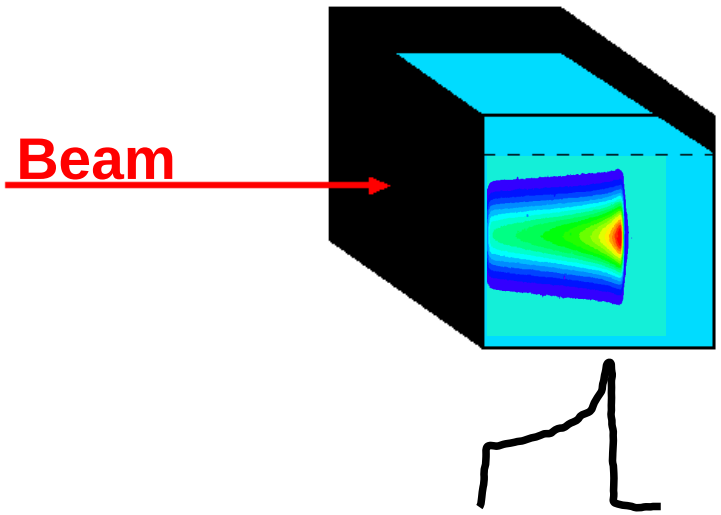
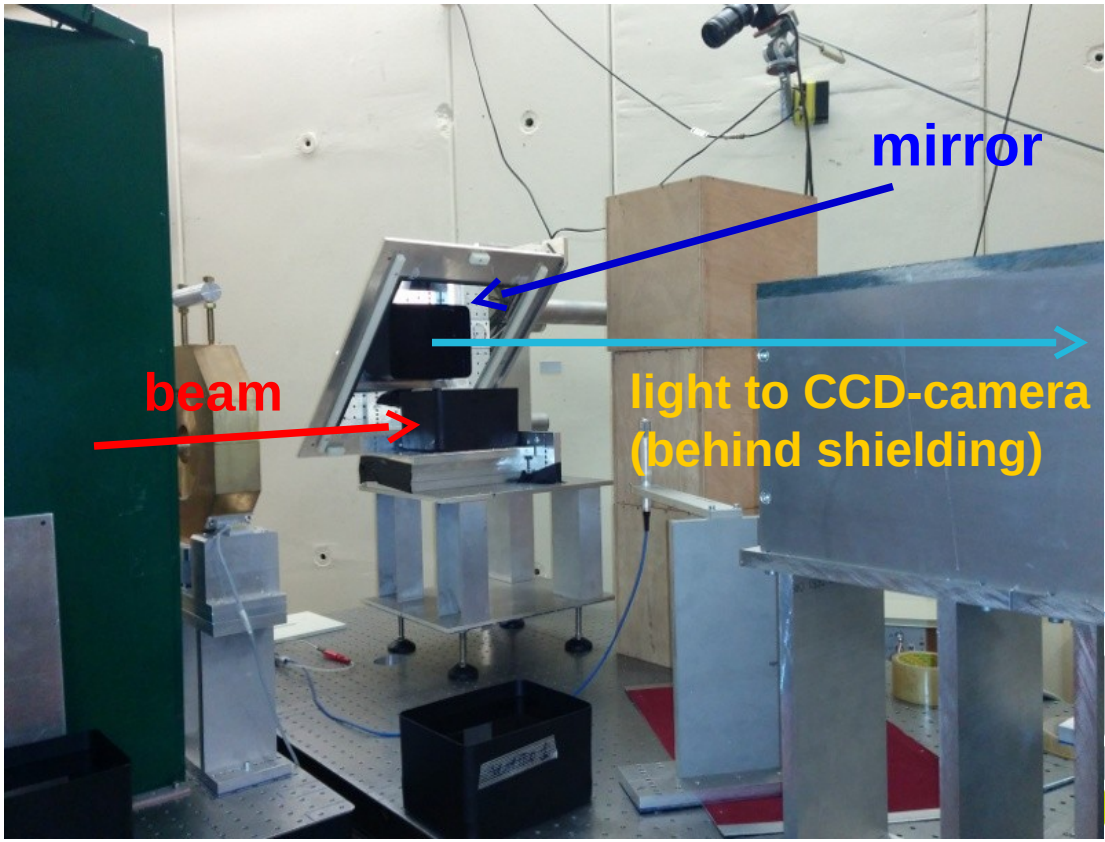
- measurements for protons, ^{4}He and ^{12}C
- pure water and water + fluorescent/scintillator various solutions and concentrations
- fast UV sensitive CCD camera
- **visible** light and **UV**





Dose vs. light yield

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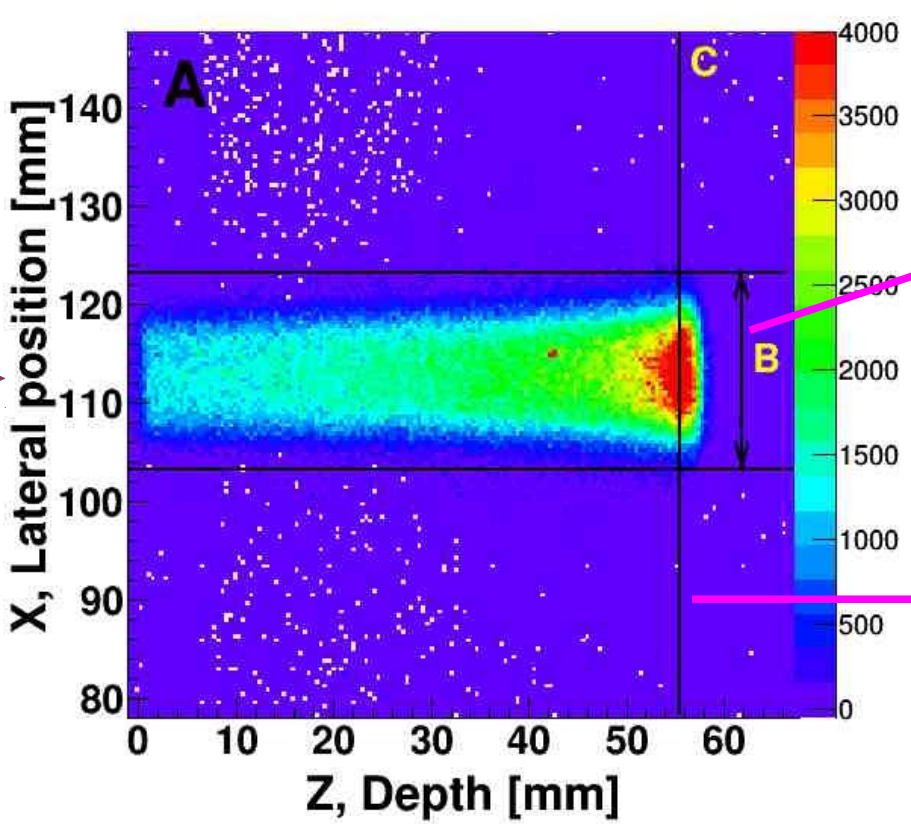
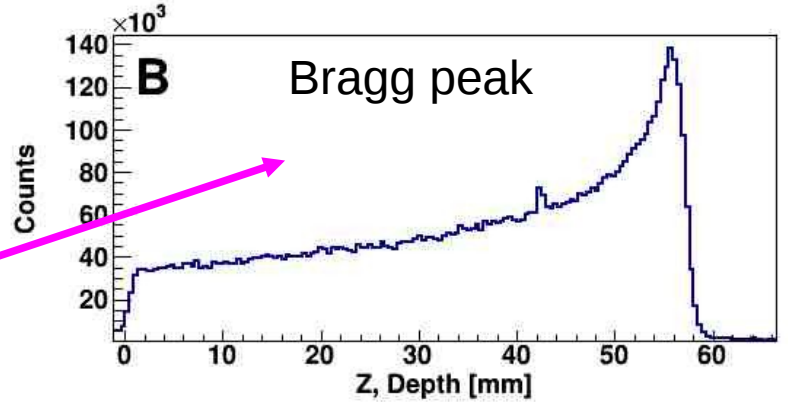
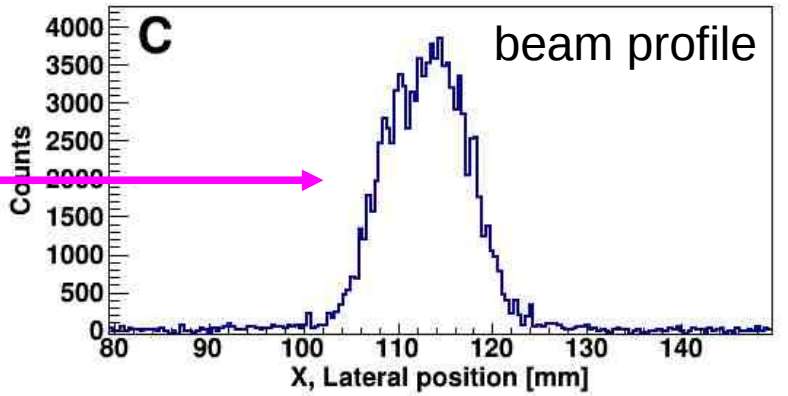
90 MeV protons, 0.5 Gy, Solution Type1

beam







Quenching effects

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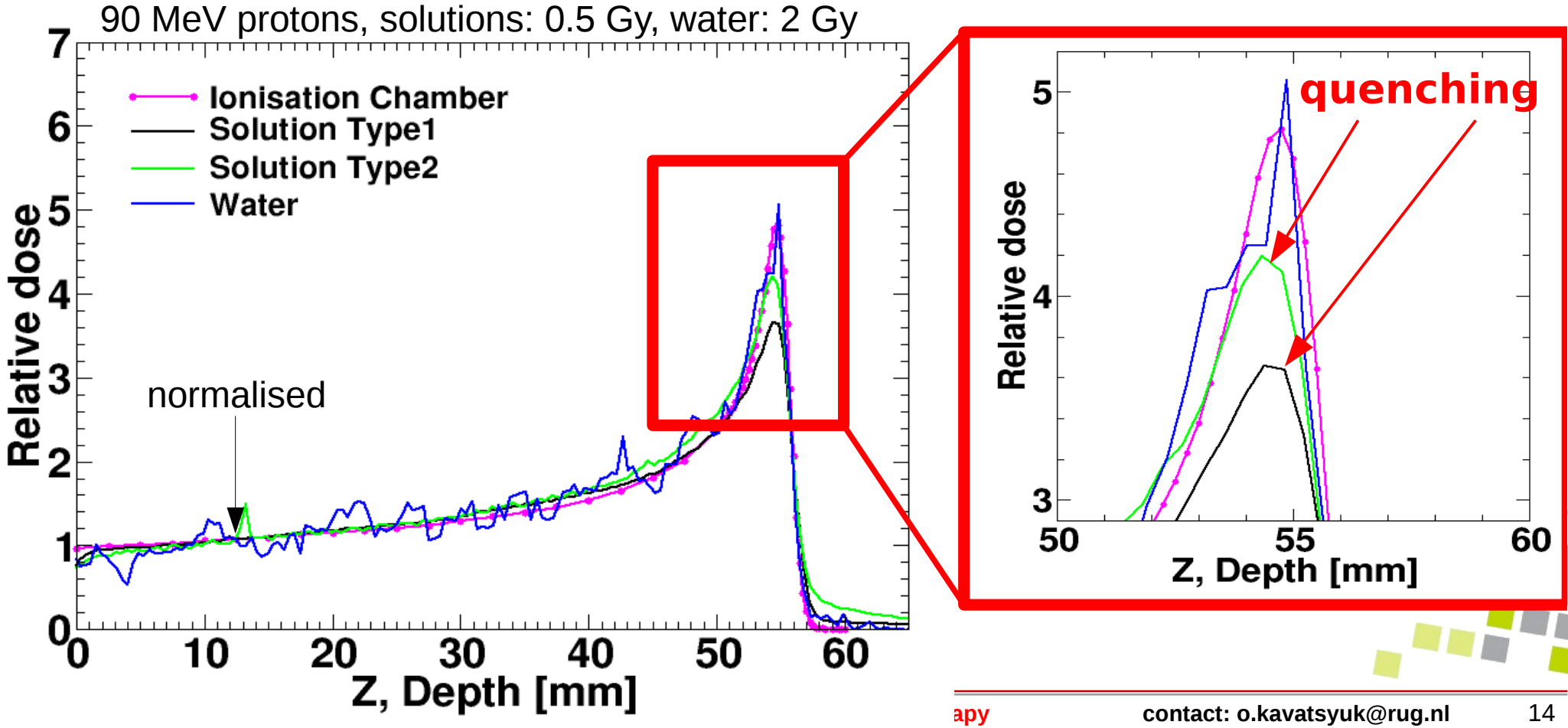
- fluorescent solutions: lower ratio peak – entrance
- LET-dependent quenching due to direct scintillation
- water (blue) shows good agreement with ionisation chamber measurements



Why quenching?

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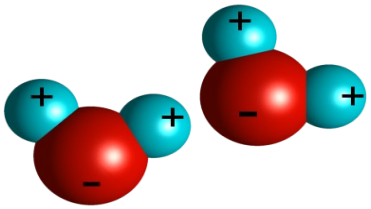
Proton beam

excites

Water molecules



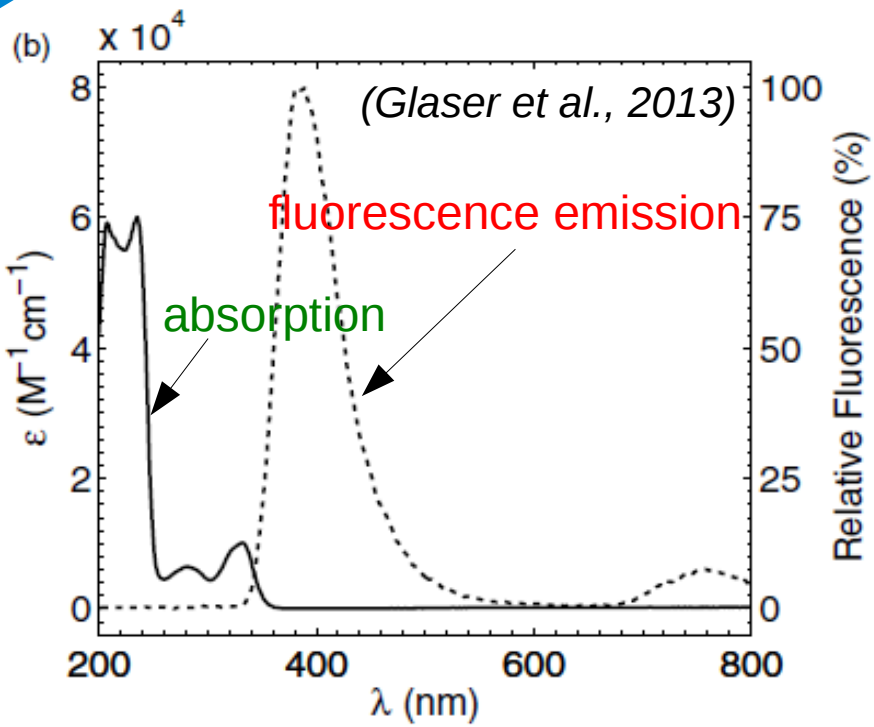
emit

UV light

absorbed by

excites

fluorescent



Why quenching?

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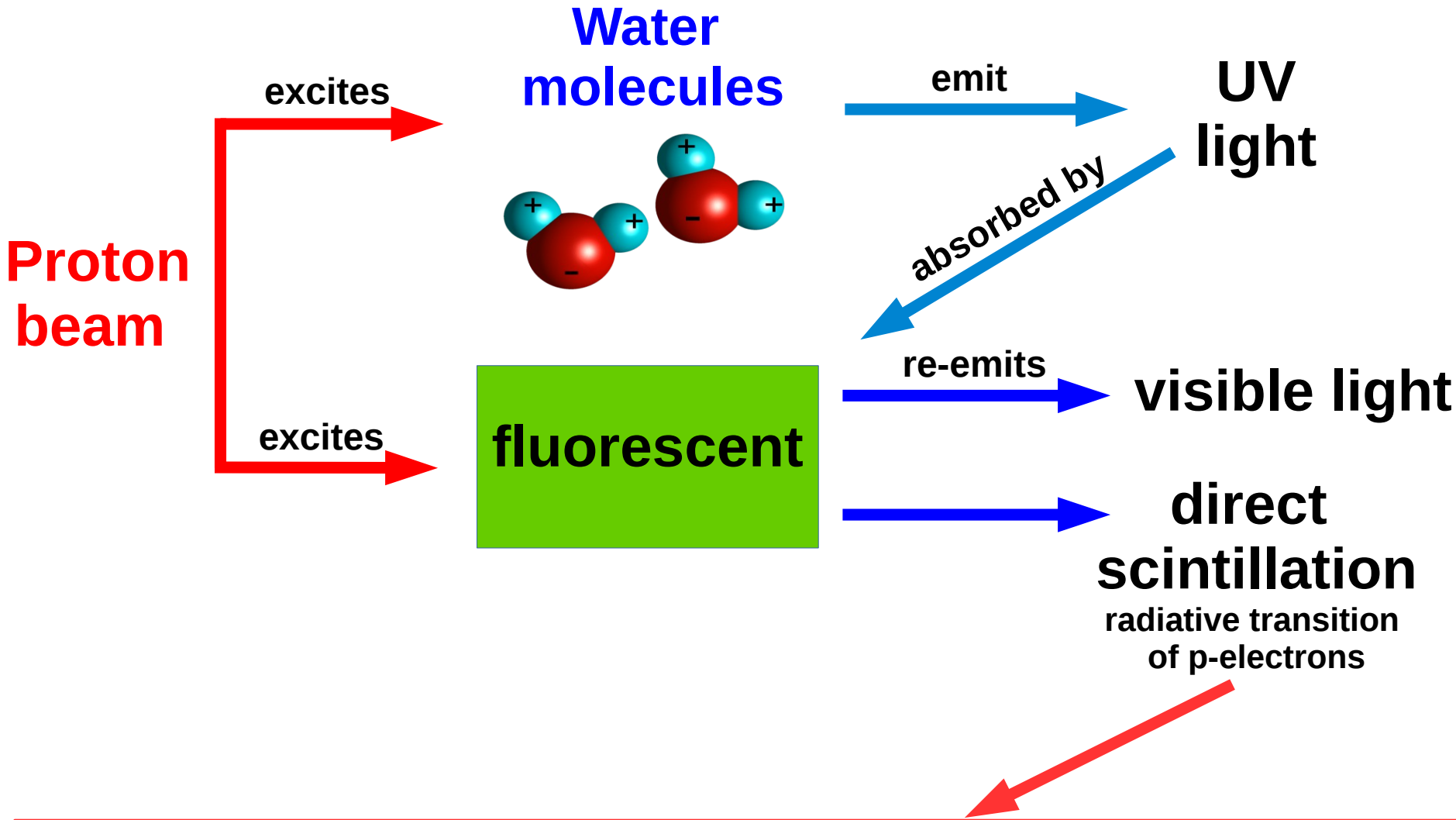

at large dE/dx the dense ionized ions quench the excited p-electrons

Light production mechanisms

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- **We observe**
  light yield increasing for concentrations:
  from 0.001 g/L up to 10 g/L (max. used)

- **for fluorescence UV**:
  attenuation length: **1 g/liter = 0.5 mm**

  ↳ so higher output at higher concentrations due to **other mechanism**

at least two mechanisms:
fluorescence UV -> visible (as wavelength shifter)
dominant at low concentration, little quenching

direct scintillation
dominant at high concentration, more quenching

Results

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Investigated:

- Depth profiles of the light output
  as a function of the fluorescent concentration
- most promising fluorescent compounds
- light output vs. delivered dose
- dose rate/flux effect ➡ **No**
- influence of water properties
  - purity ➡ **No**
  - influence of Oxygen on light output of the solutions ➡ **No**
- aging effect (> 1kGy, 3 months) ➡ **No**

light output linearly correlates with delivered dose

Results

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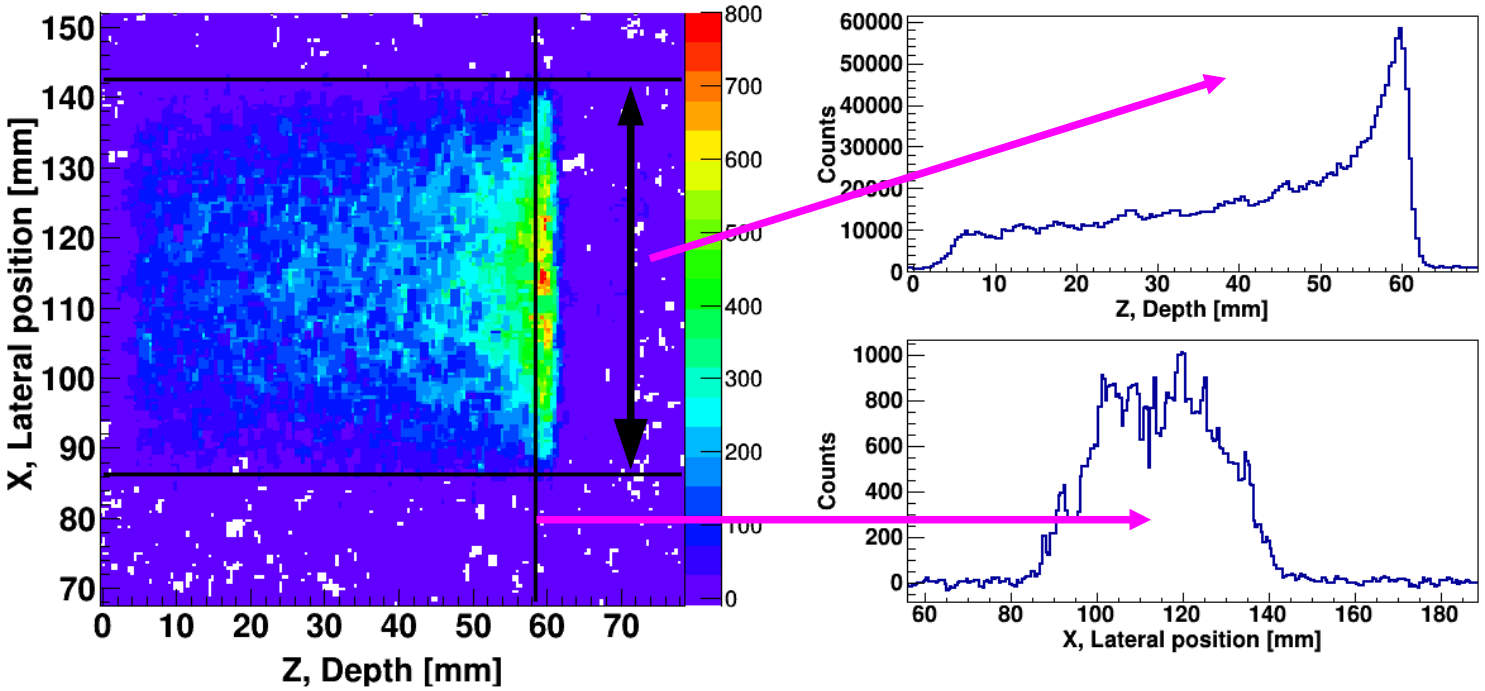
- **water is a scintillator, no quenching observed**
- Water + fluorescent = more light ➡ for precise measurements

beam

90 MeV protons, 2 Gy, water



STW-Demonstrator setup

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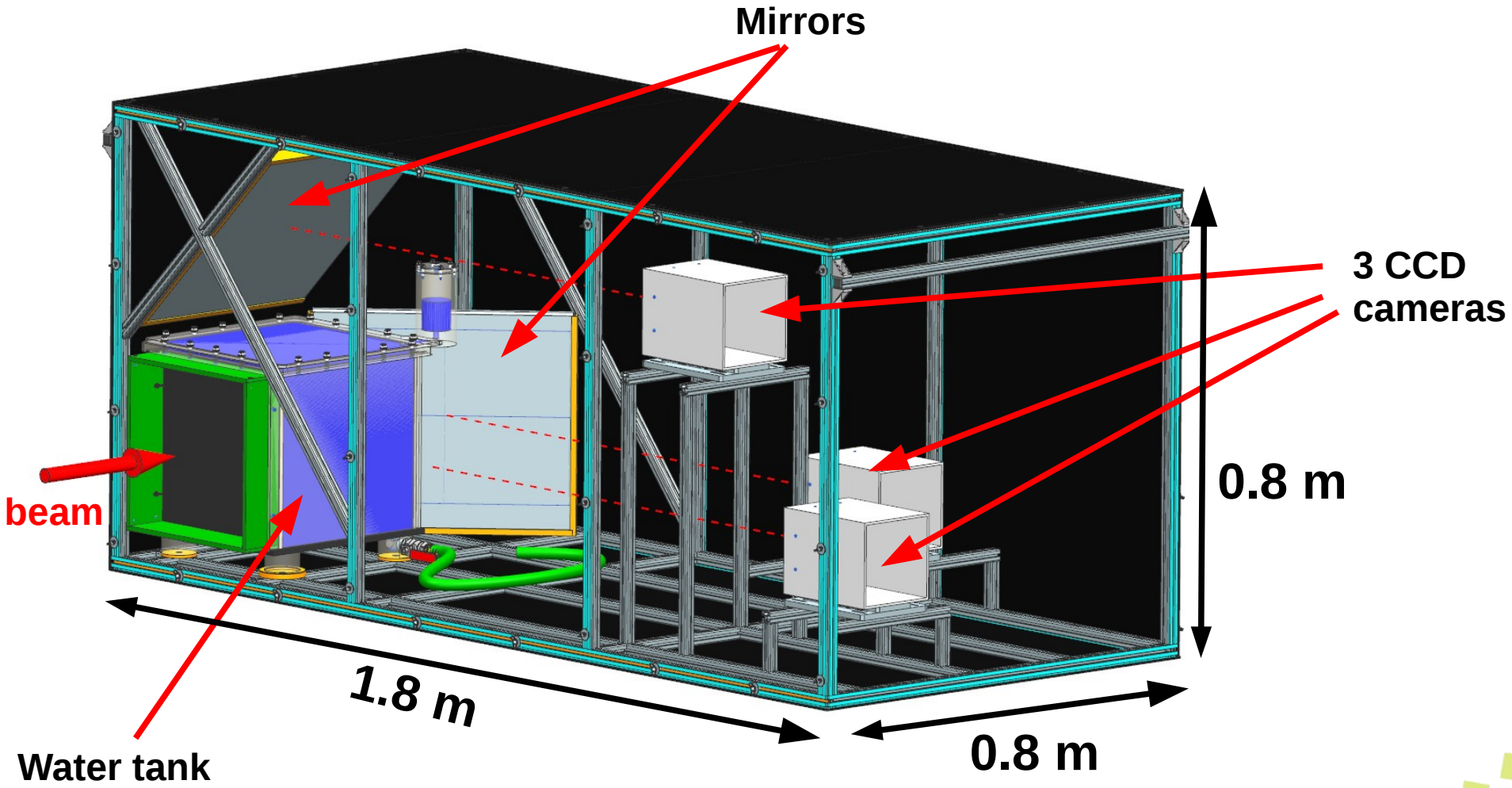
Optical Dosimetry Instrument (ODIN)

for use in proton therapy centers



Next: Tests in clinical conditions

This project is partially funded by the Dutch funding agencies **FOM** and **STW**

Demonstrator
Demonstratie van nieuwe technologie mogelijk maken

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umcg

FOM

Backup slides

- treatment room: ~300 patients/year
  - ~25 daily fractions per patient
  - total ~7500 fractions per year (~25 min room time /fraction)
- treatment plan QA for each patient
  - current: plan QA > 0.7 h room time per plan
- our method: plan QA < 0.2 h room time per plan

➨ productivity gain ~15 patients per year

➨ additional income ≥ 375 k€

- expected retail price ~200 k€
  - annual maintenance cost ~30 k€

near future: adaptive radiotherapy

 more plans per patient

 larger productivity gain

proton therapy: application perspective

- radiotherapy treatments
  - NL 56 000 per year
  - OECD 3 $\times 10^6$ per year
- current status proton therapy
  - ~100 treatment rooms
  - ~14500 patients per year
  - growth ~15 % per year
- Dutch Health Council report (2009):
  - benefit for 10 – 15 % of radiotherapy patients
  - ➡ up to 7000 patients/year
- licenses MinVWS (2013): 2200 patients/year
- extrapolation OECD: 120000 – 400000 patients/year
  - ➡ 400 – 1300 treatment rooms

Quenching effects

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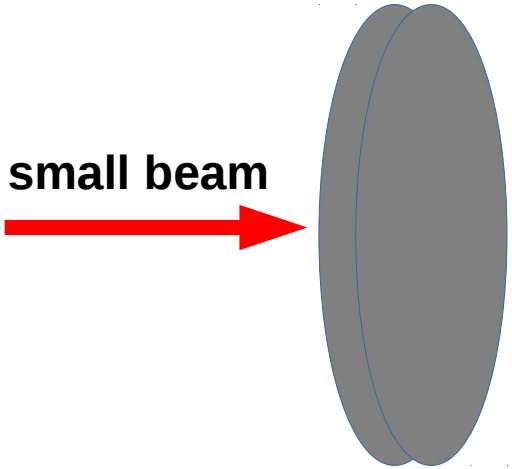
measurements with ionisation chamber

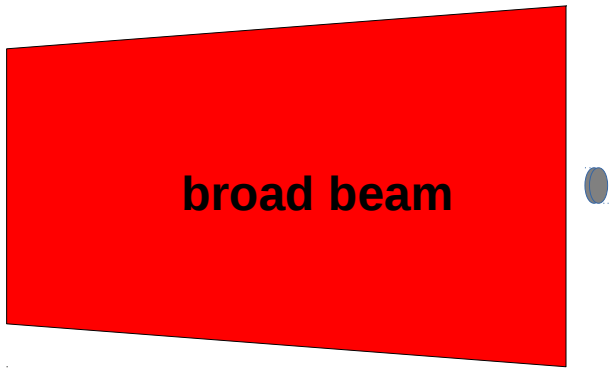
ionisation chamber D=0.5 mm
beam field = 50 mm

A

small beam



B



Beam induced UV light

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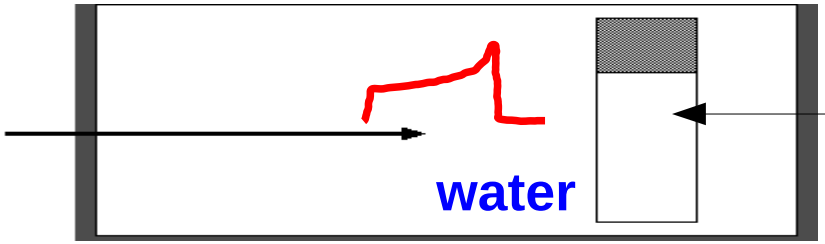
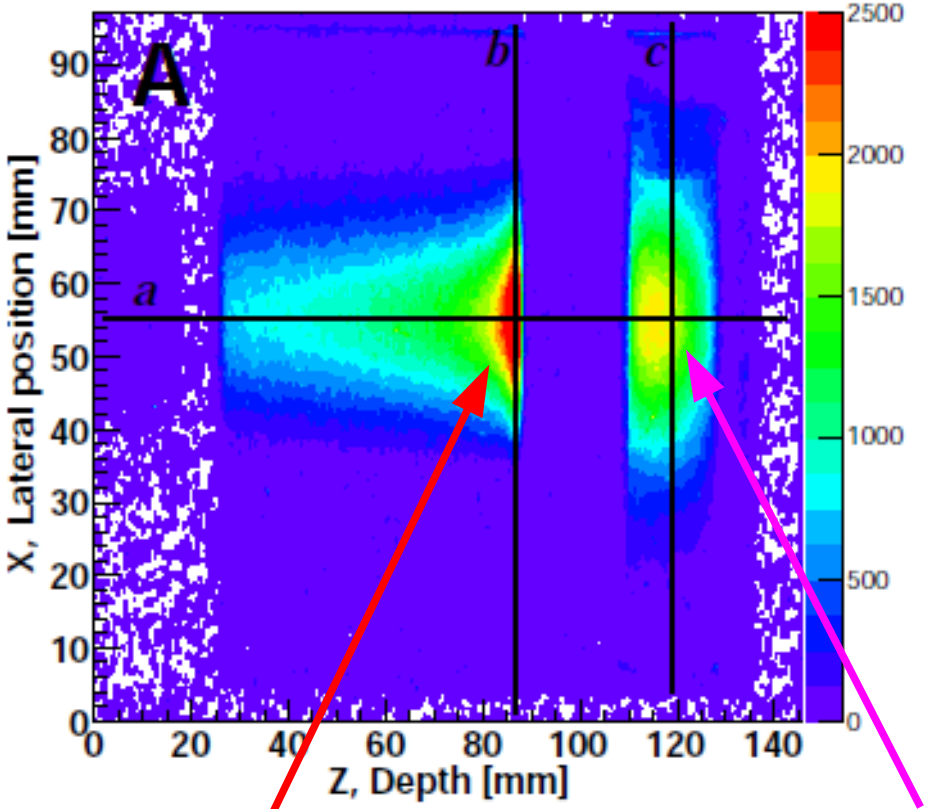
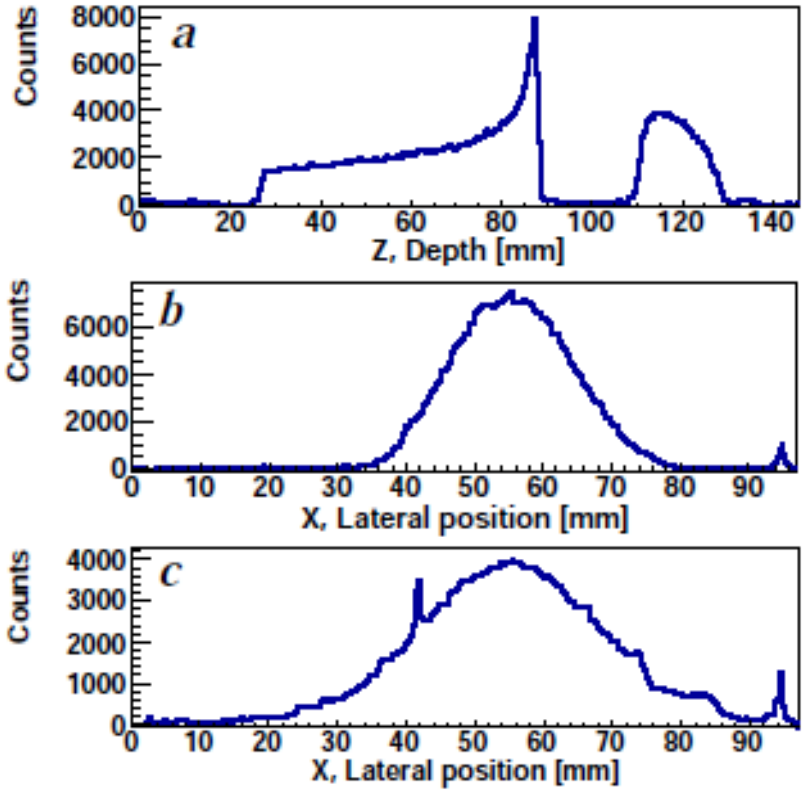


Measurements with quartz cuvette (filled with fluorescent solution)





due to UV part of the proton induced emission in pure water

visible part of the proton induced emission in pure water

Protons and photons

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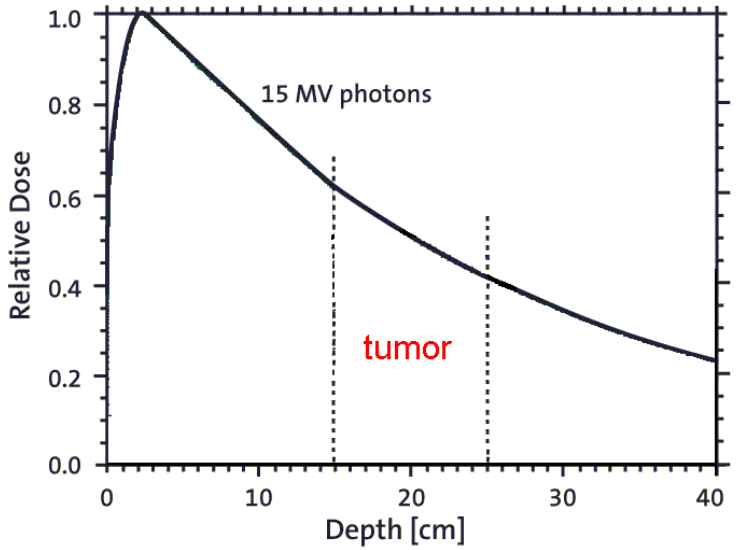
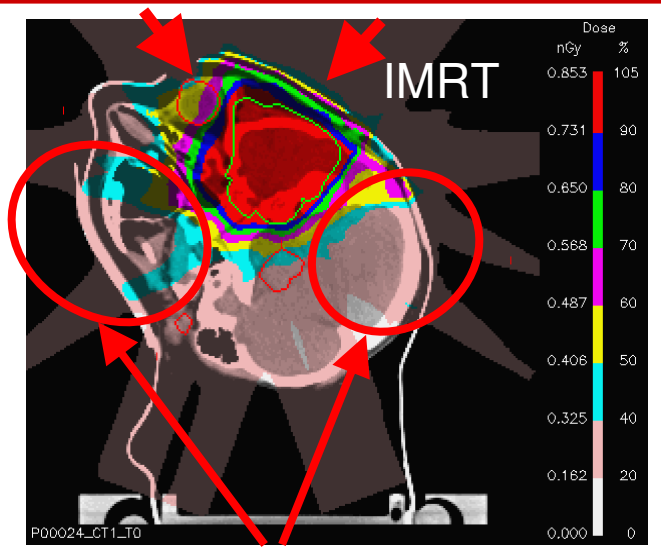
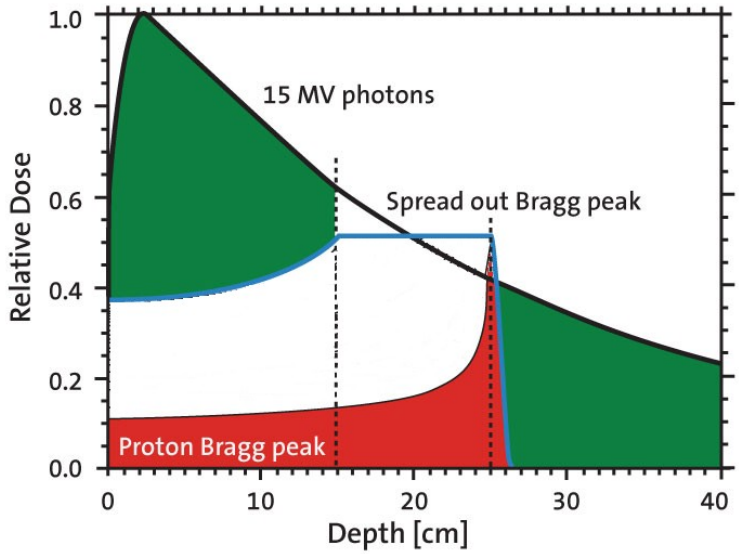
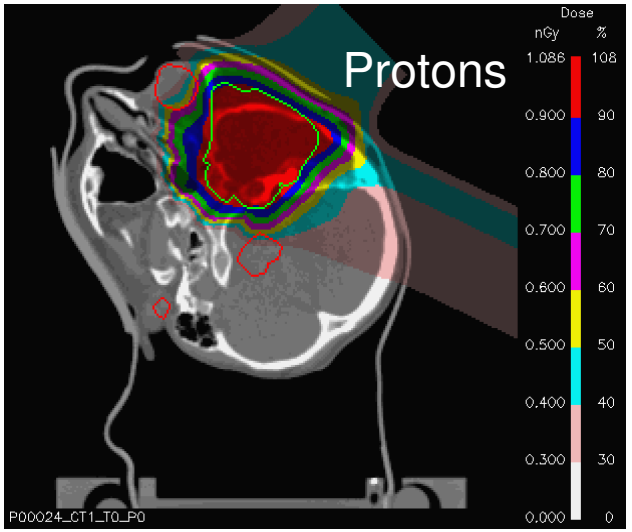




T. Lomax, PSI

a lot of dose "behind" tumor





T. Lomax, PSI

protons → reduction normal tissue complications expected

Cancer in Netherlands

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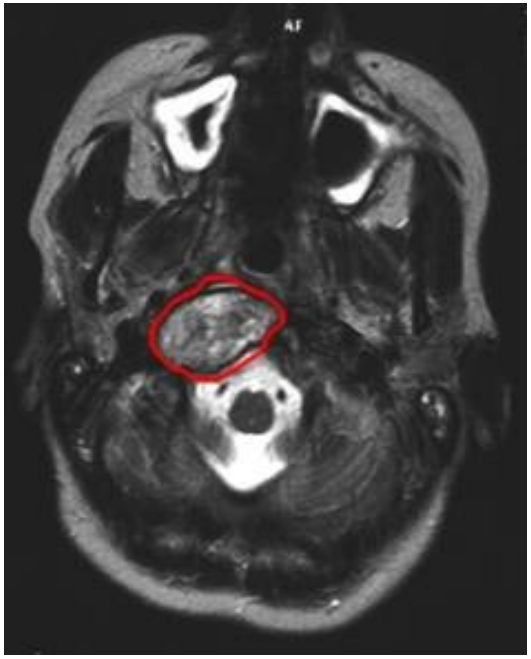

40 % **confront with cancer during their life**

Netherlands 2014:
32% death primarily caused by cancer

Radiotherapy:

60 % patients gets Radiotherapy in course of their treatment
(often combined with surgery or chemotherapy)

Number of Patients:

Netherlands ~50.000 / year
EU >1.5 million / year

Proton therapy technique

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- verify dose delivery in water phantom
- our proposal: imaging of proton-induced light
  - 3D reconstruction with ~1 mm resolution
  - fast: single plan delivery sufficient
- optimal solution
  - UV light: directly proportional to dose
  - image per individual pencil beam
- currently feasible
  - visible light + image per pencil beam
  - UV light + image per energy plane
- CCD technology rapidly developing
  - UV sensitivity
  - frame rate
  - ➡ upgrading feasible within few years