R&D opportunities towards medical facilities and small facility options

K. N Sjobak, S. Stapnes, E. Lindberg, E. Adli

NorCC Workshop 2023, Sept. 27.–28.

Session on Norwegian Roadmap for Future Accelerators

Proton therapy in Norway

- Two centers under construction: Oslo (Radiumhospitalet) and Bergen (Haukland)
- First patient planned ~~2024~~ 2025
- Oslo: 3 gantries, 2 for patients and 1 for research
- Bergen: 2 gantries, 1 for patients and 1 for research

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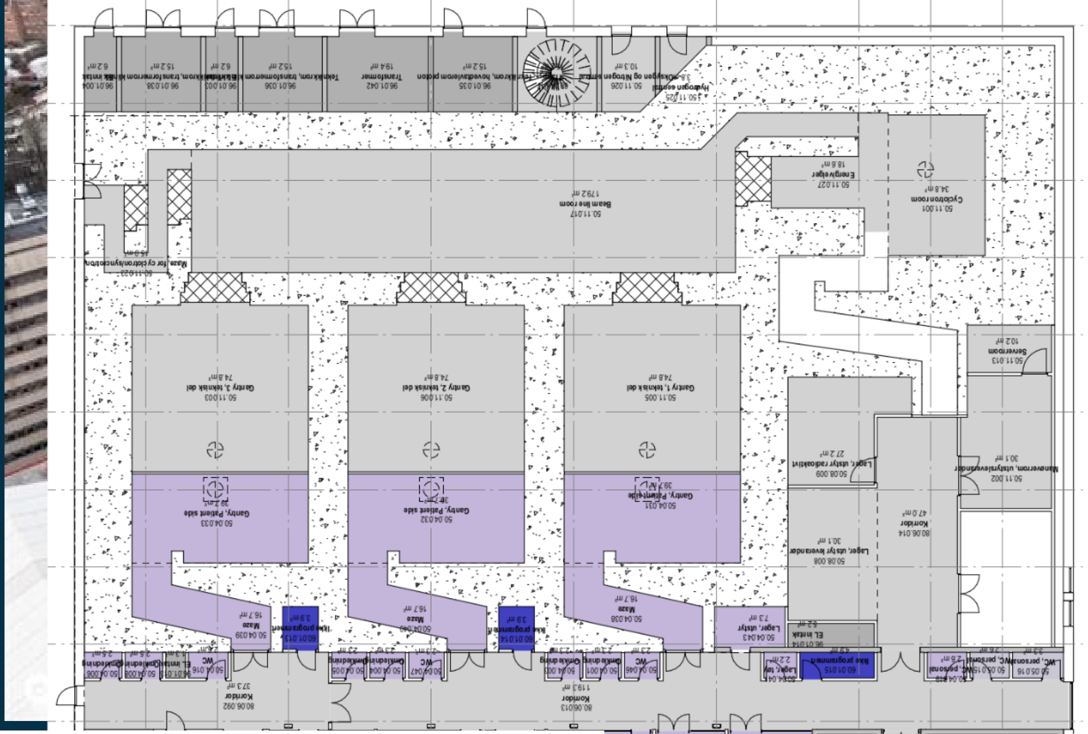
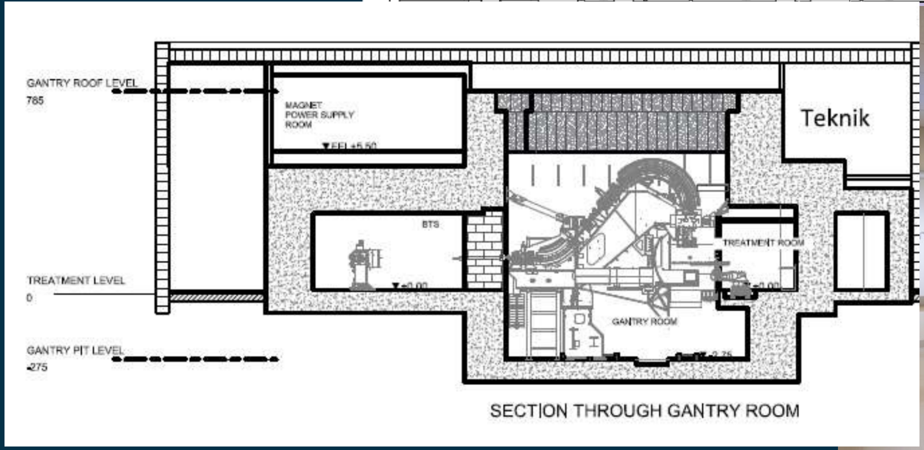




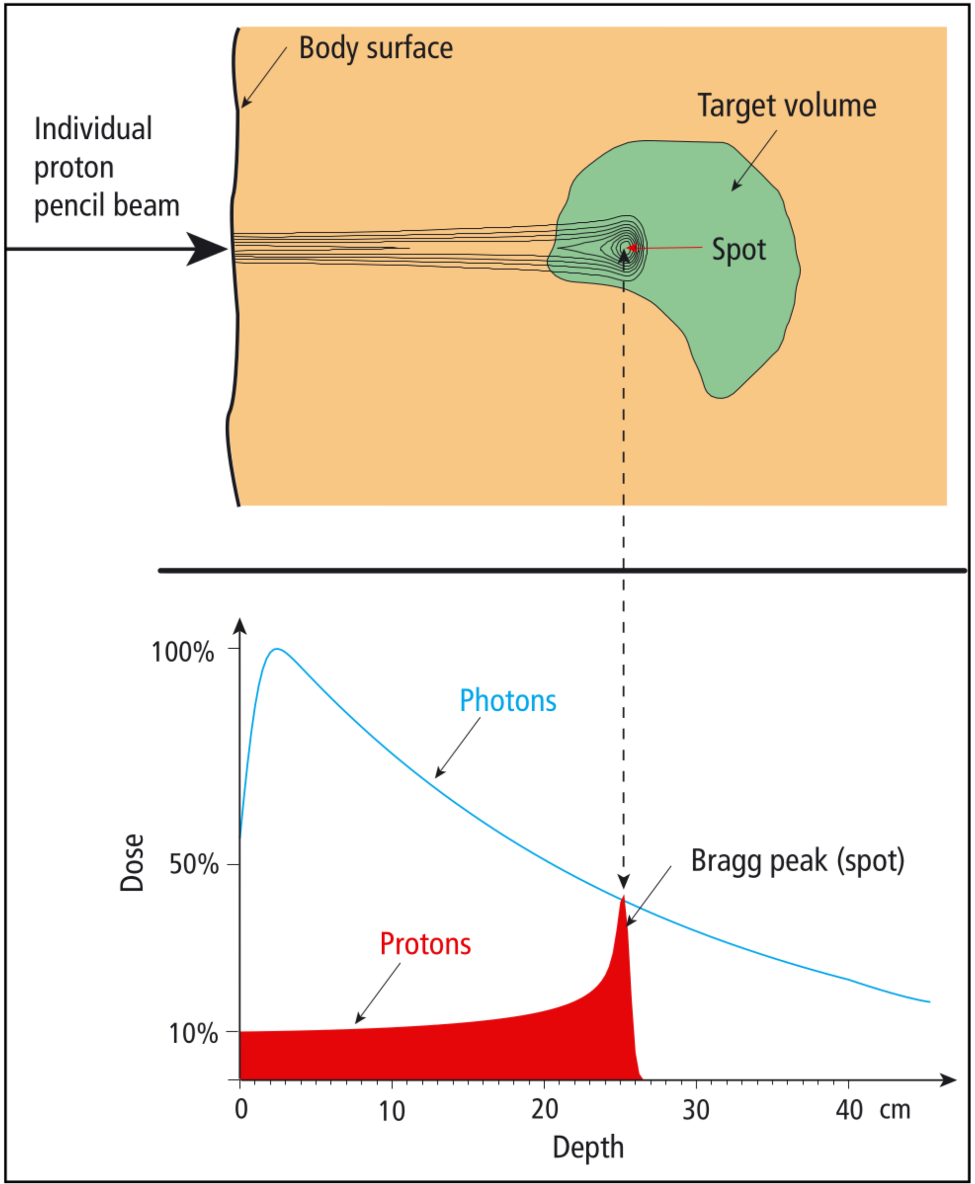
Particle radiation therapy

- Treatment of disease – mainly cancer – with particle beams
  - Proton and carbon ion therapy
  - Very High Energy Electron (VHEE) therapy
  - In addition to currently used photon and low-energy electron external beam ratiotherapy, and to brachytherapy (implanted source)
- Accelerator activity of NorCC is investigating how advanced accelerator technology can be used to improve particle therapy
- Close collaboration with local biophysicists
- Involvement in CERN and CLEAR medical program

Proton Therapy

- Method of external beam radiotherapy
  - Mostly used against cancer
  - EBRT today mostly with Photons
- Protons stop at a predictable range
- Deposit lots of energy near the end of their track
- Can be more precise than photons, which are commonly used today
  - Less damage to nearby tissues → Diminished side effects
  - **But:** Need to be careful to match beam energy and material density in order to stop at targeted depth

Figure from "Proton therapy at the Paul Scherrer Institute", 2011



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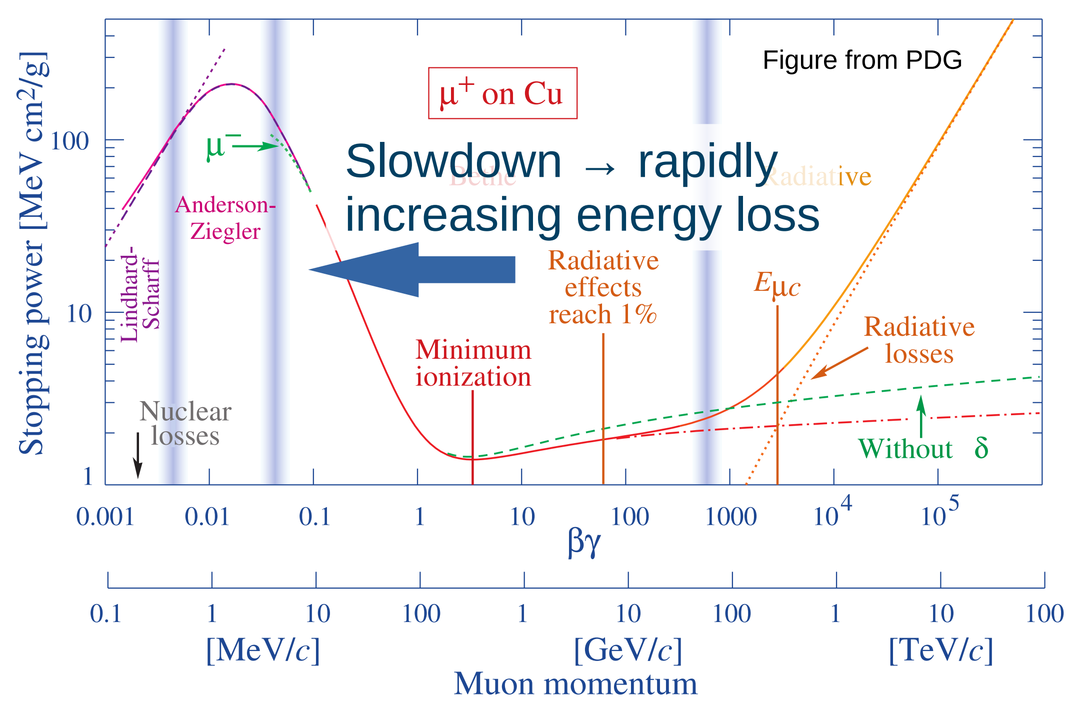

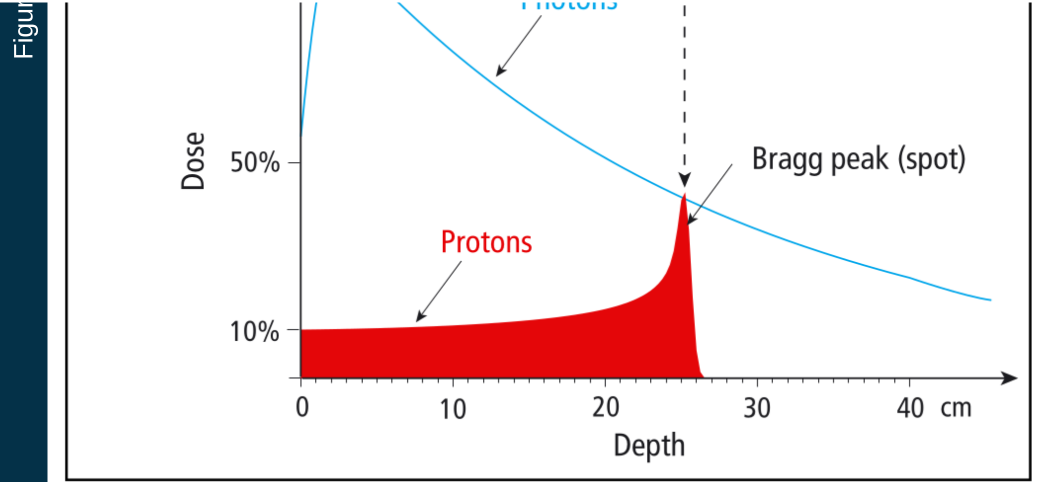

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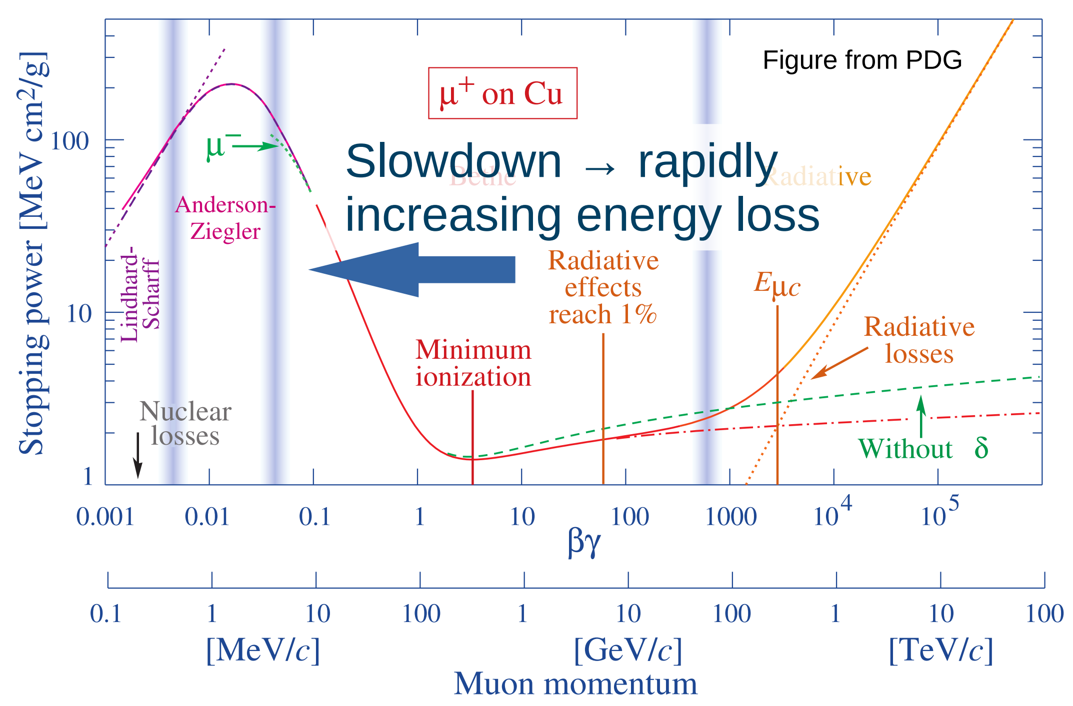
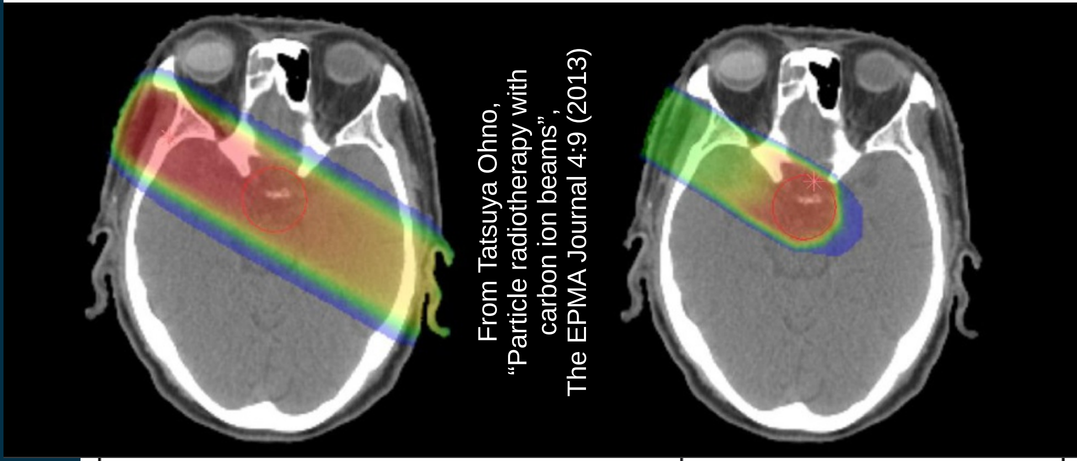




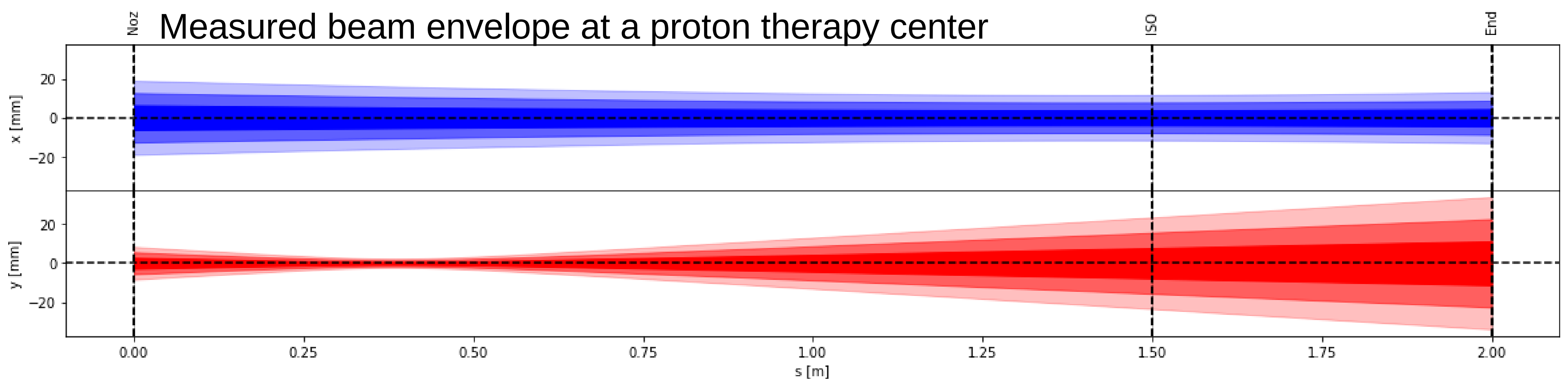
From Tatsuya Ohno, "Particle radiotherapy with carbon ion beams", The EPMA Journal 4:9 (2013)

Medical accelerator technology research opportunities for Norway

- Dose geometry – better beam optics for beam delivery:
  - Improve conformity – better dose ratio tumor vs organs at risk
  - Increase flexibility – enable patterning of dose for faster healing of skin and potentially triggering of abscopal effects
- Particle accelerator technology
  - Smaller and cheaper accelerators (CLIC or plasma tech.)
  - Higher performance accelerators for e.g. FLASH
- Diagnostics – on-line dose monitoring etc.
  - Needed for FLASH – see Erik's slides from Vilde yesterday

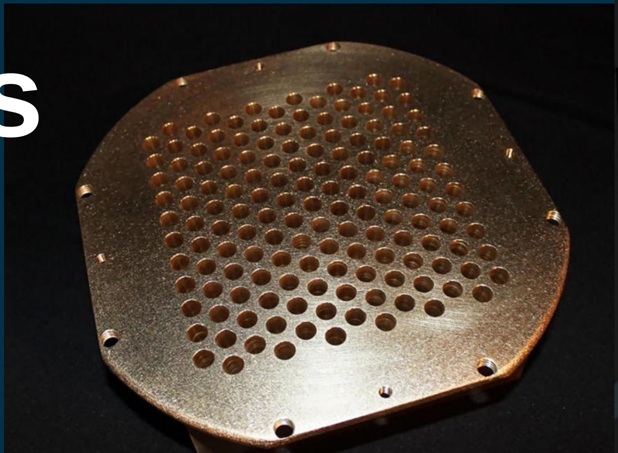
Sharp dose profiles

- Typical pencil beam radius for spot scanning is approx 5 mm, not always well converging

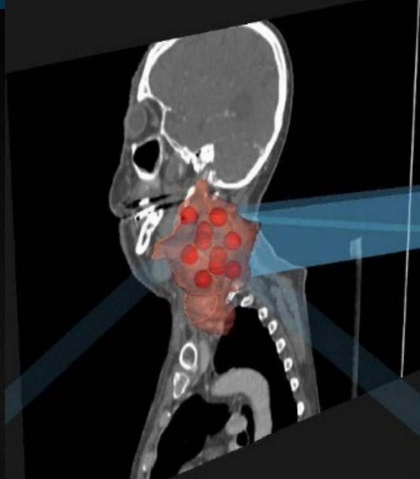


Sharp dose profiles

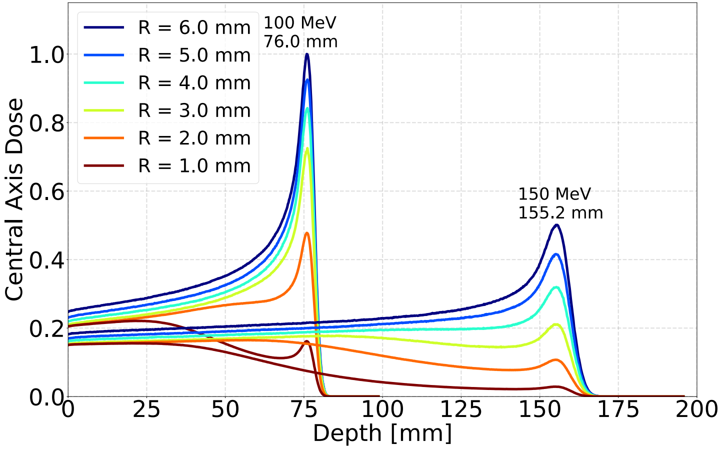
- Typical pencil beam radius for spot scanning is approx 5 mm, not always well converging
- Sometimes, we want a smaller beam...
  - To go close to sensitive organs
  - For GRID / spatially fractionated proton therapy
- Very narrow beams are difficult to control with collimation alone
  - Beam widens with depth due to multiple scattering
  - Dose at Bragg peak < dose at skin!

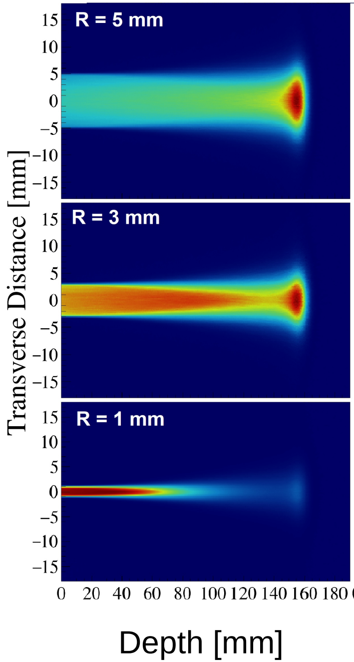


W. Yan et al., “Spatially fractionated radiation therapy: History, present and the future,” Clin Transl Radiat Oncol, vol. 20, pp. 30–38, Oct. 2019, doi: 10.1016/j.ctro.2019.10.004.



By E. Malinen and N. Edin

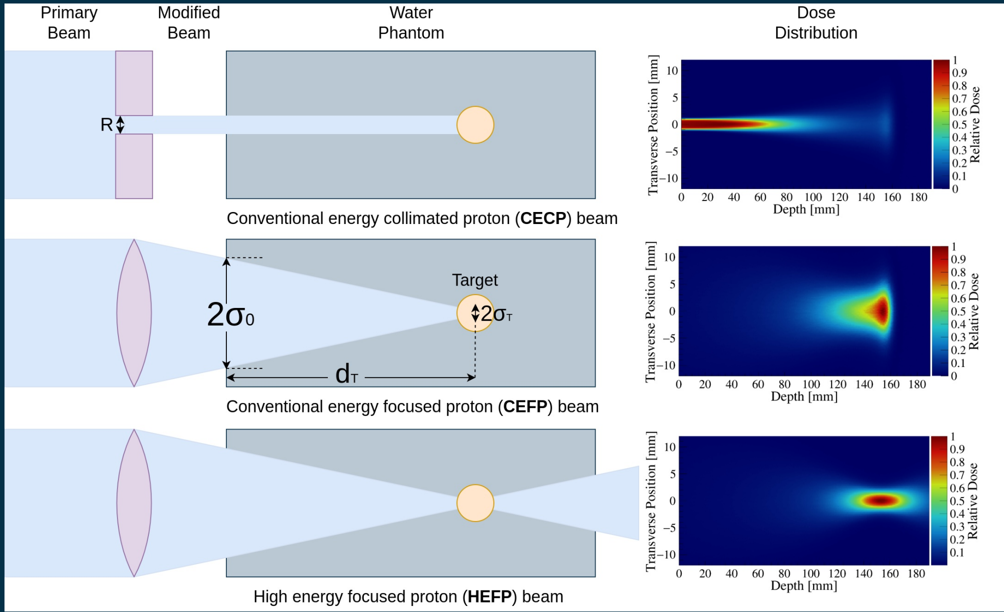




Reaz, F., Sjobak, K.N., Malinen, E., Jeppesen, N.F., and Adli, E. Sharp dose profiles for high precision proton therapy using strongly focused proton beams. Sci Rep 12, 18919 (2022). https://doi.org/10.1038/s41598-022-22677-0

Strongly focused proton beam for high precision

- We can also apply geometric focusing to proton beams
- Get Bragg peak + increased relative track density at target
- Much reduced dose on the surface due to lower track density
- Minimum achievable spot size still controlled by MCS
  - RMS beam size 3.2 mm at 155 mm, 1.8 mm at 73 mm
- Even smaller spot sizes are possible with high energy beams
  - Higher energy → Less MCS, submillimetric spots are possible
  - No Bragg peak
    - Insensitive to density
    - Reduced peak dose, nonzero dose behind target
  - Movable in 3D using only optics
  - Could be interesting for small spots requiring very high precision
- Next challenge is to design and hopefully test magnetic optics to achieve this
- Studied in collaboration with UiO biophysics group



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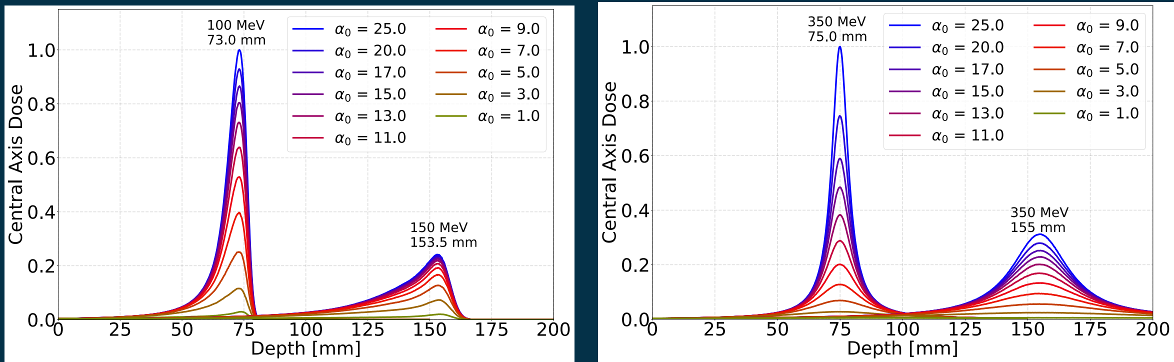


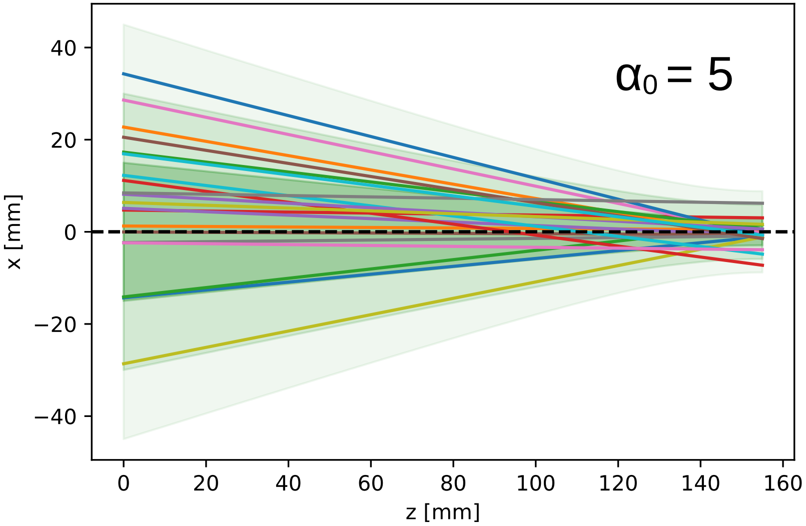
Challenge of symmetric sharp focusing

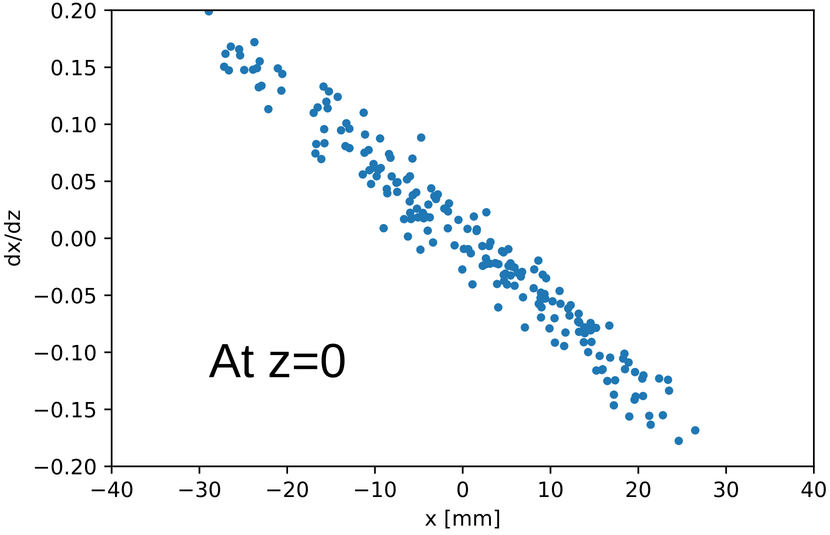
- Small final beam size requires large beam in final focusing magnets

- Difficult to create symmetric (round) large beams with quadrupole magnets
  - Always focusing in one plane and defocusing the other
  - Direct effect of groups tend to be net focusing

Sharp focusing

- More technically, the challenge is to achieve a large β function
  - Corresponds to a larger σ assuming same emittance ϵ_g
- We've found that for the focusing, the normalized posintion-angle covariance α is a useful parameter
  - The degree / quality of convergence denoted by α0, higher is better
  - Magnification: $\frac{\sigma_t}{\sigma_0} = \frac{1}{\sqrt{1+\alpha_0^2}}$





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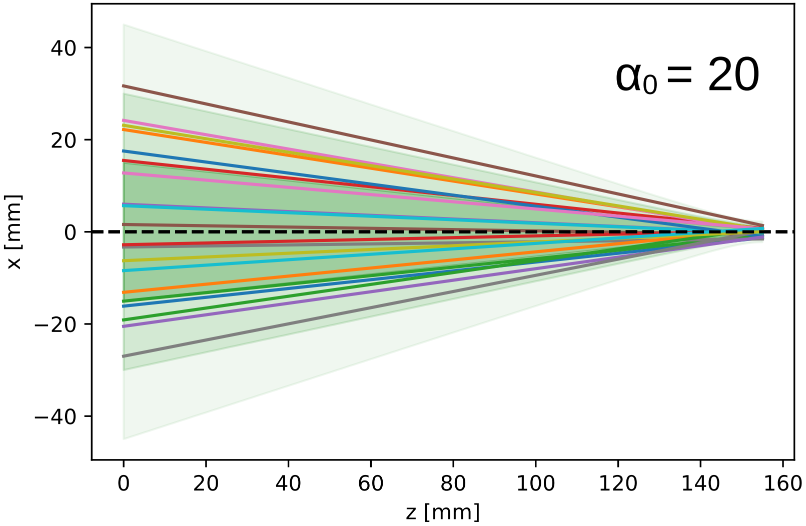
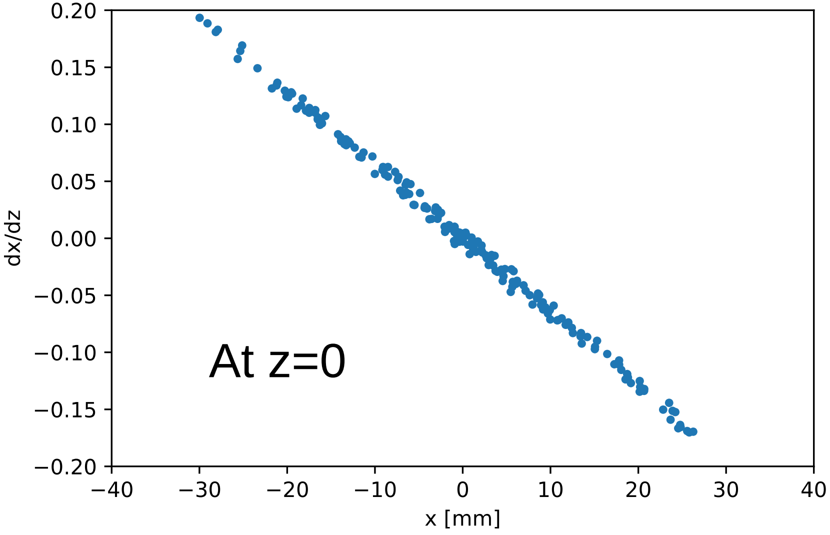
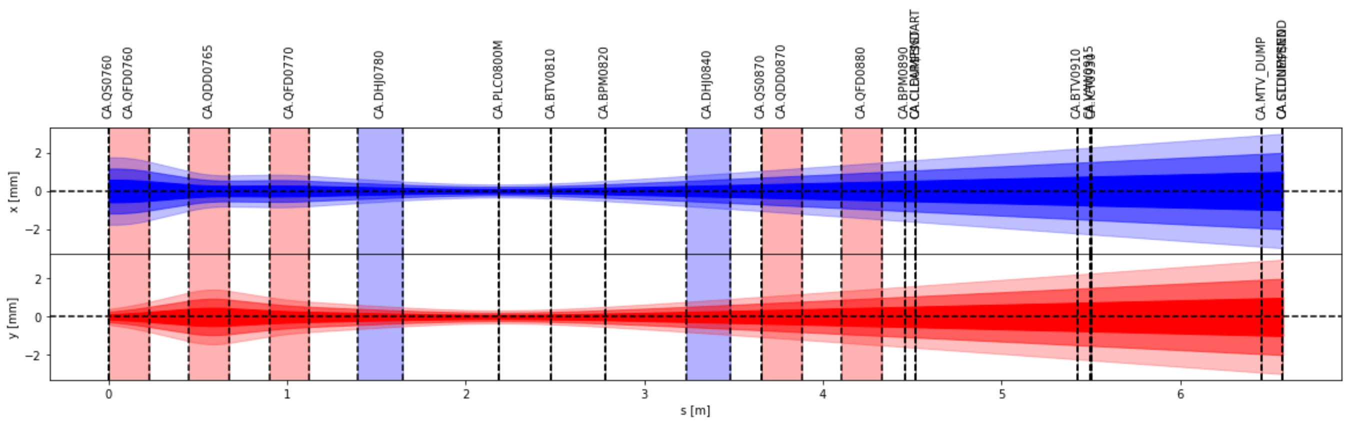


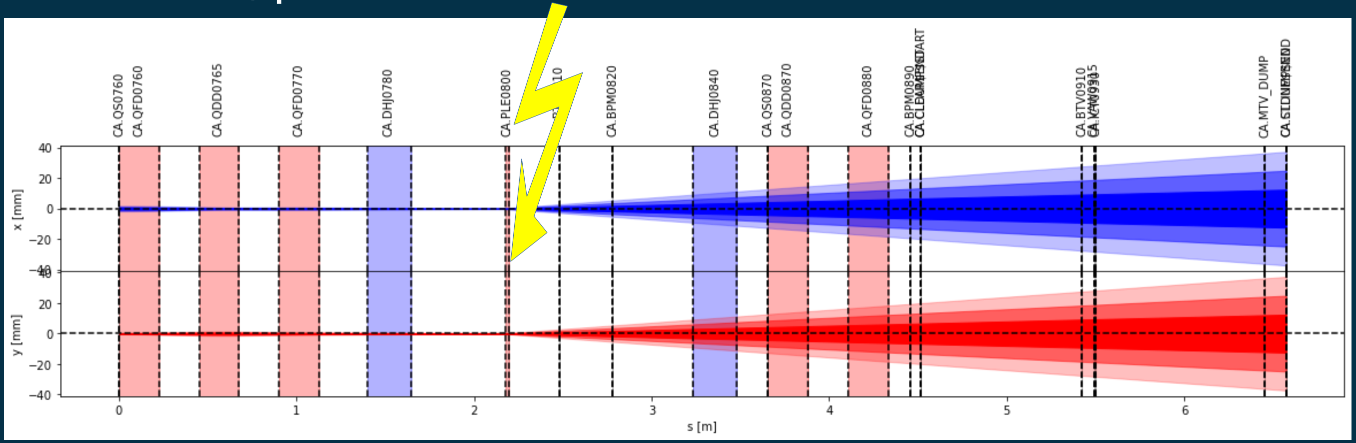


Diverging plasma lens optics – simulation

Beam size, plasma lens OFF:



Beam size, plasma lens ON:



- Sigma at end of beamline x12
  - Cover a larger area for irradiation
  - No extra radiation or energy spread (unlike scattering)
- Assuming a 15 mm long plasma lens with Ø = 1 mm, I = 1300 A
  - 1.12 kT/m, 0.56 T at R_{max}
- Also significantly larger beam size in final quadrupoles…

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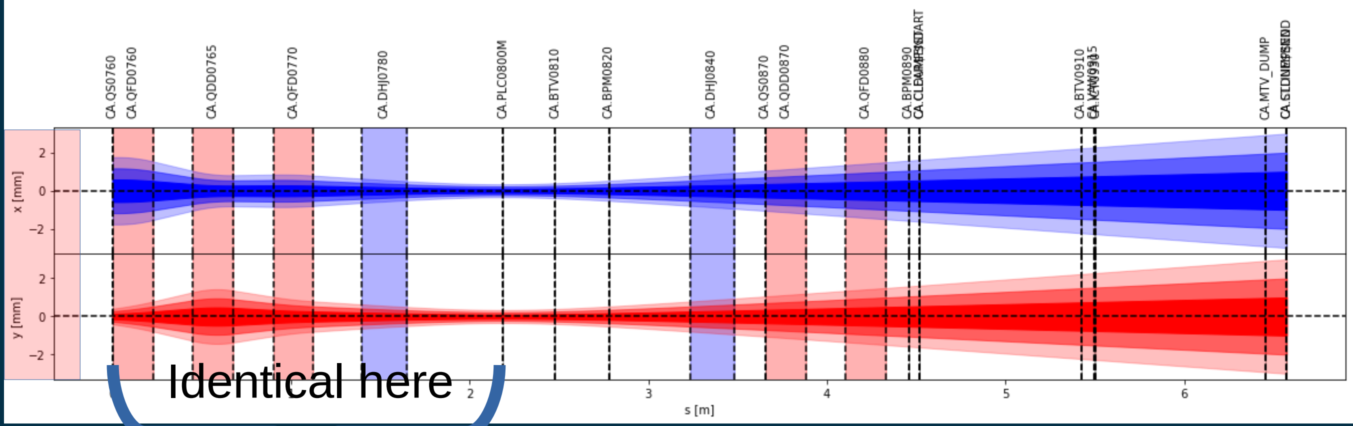

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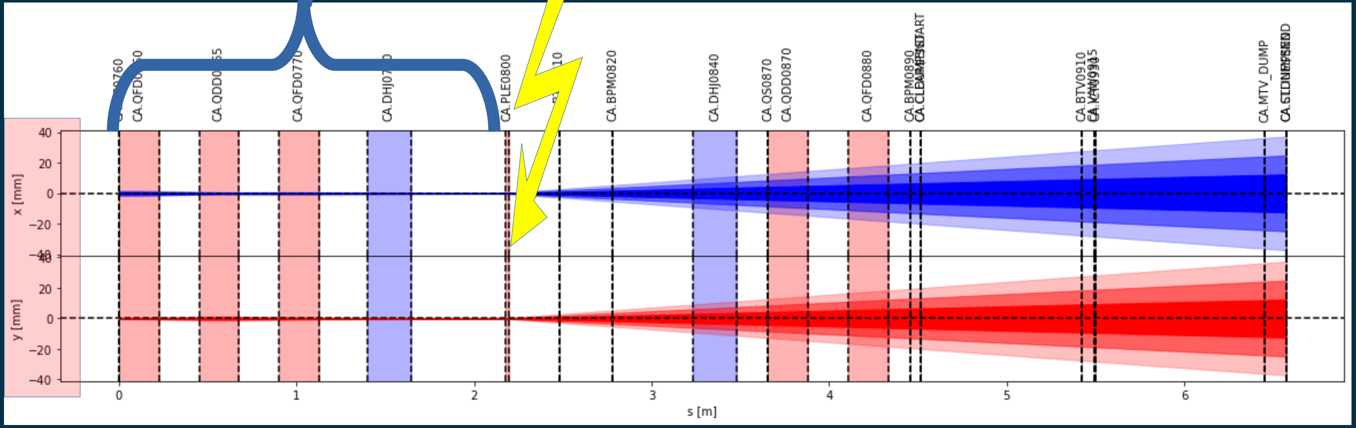

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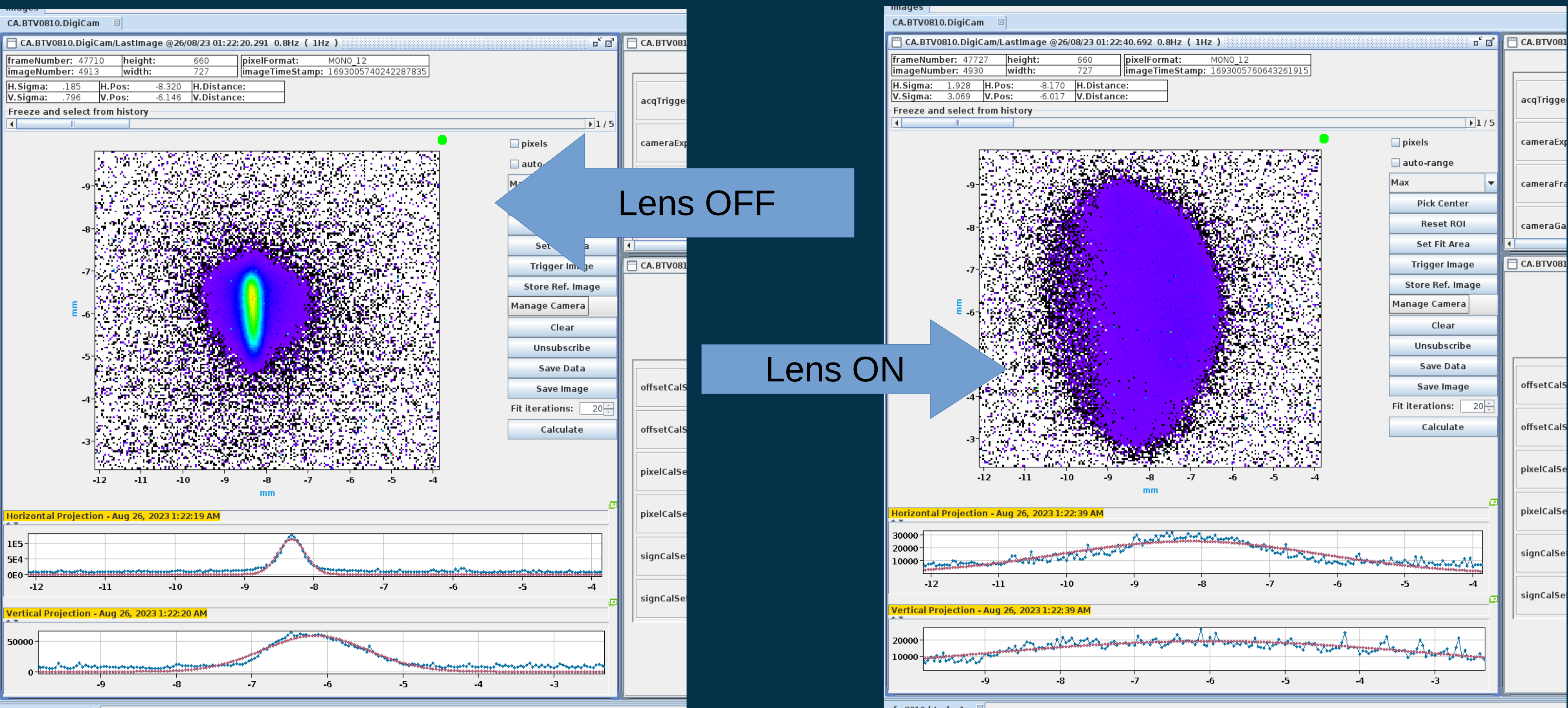
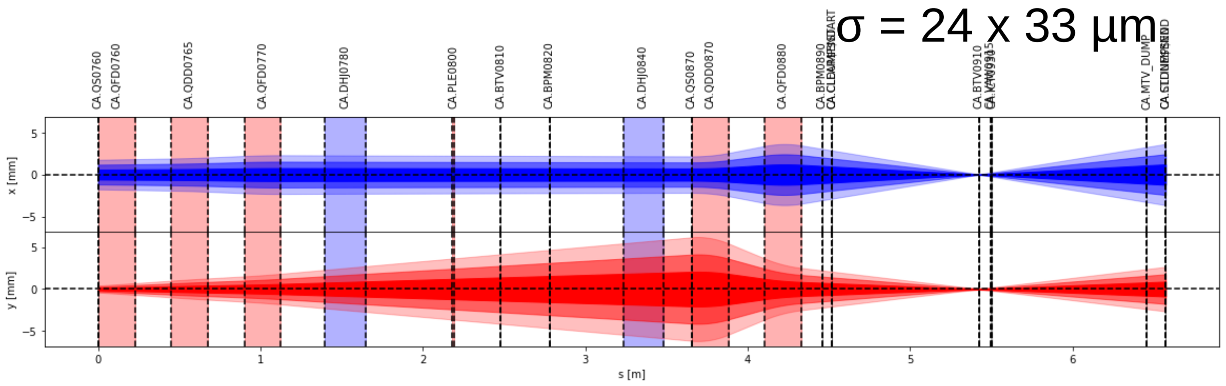
Initial test at CLEAR

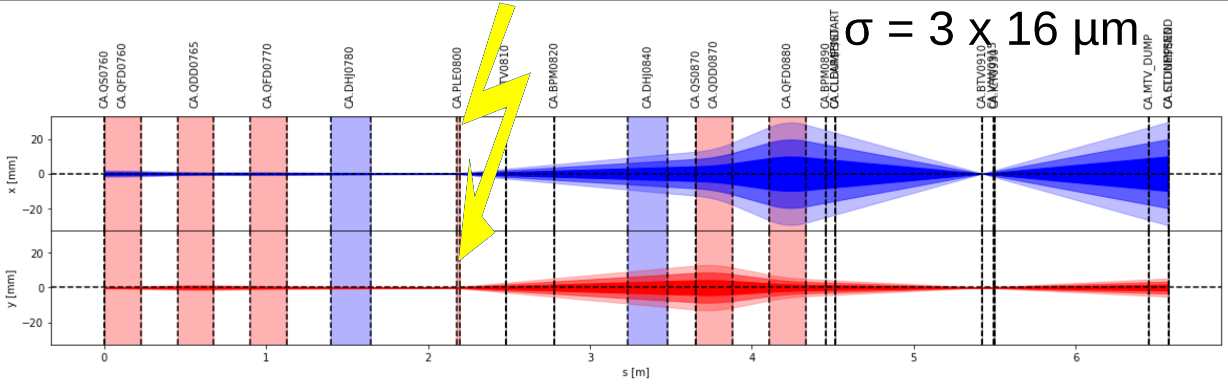


Strong focusing using diverging plasma lens optics

No plasma lens & 5 quads



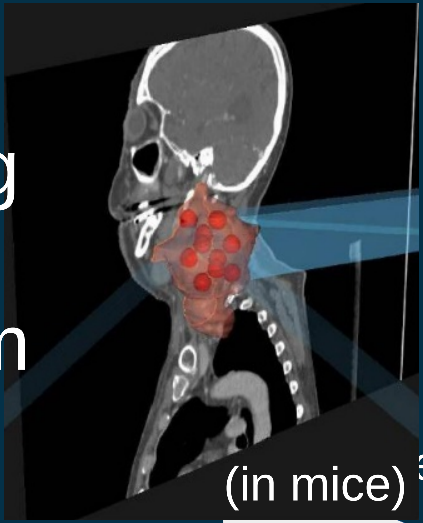
With plasma lens & 2 quads

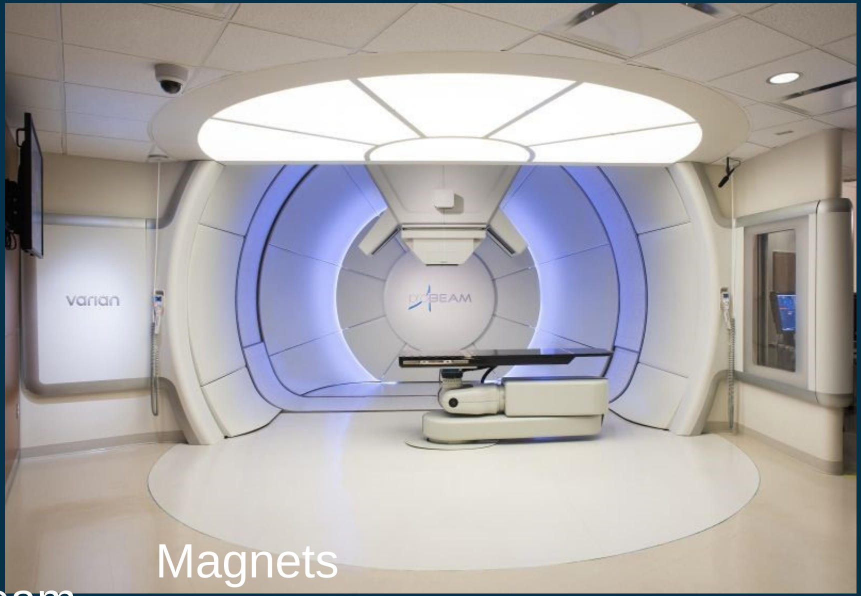


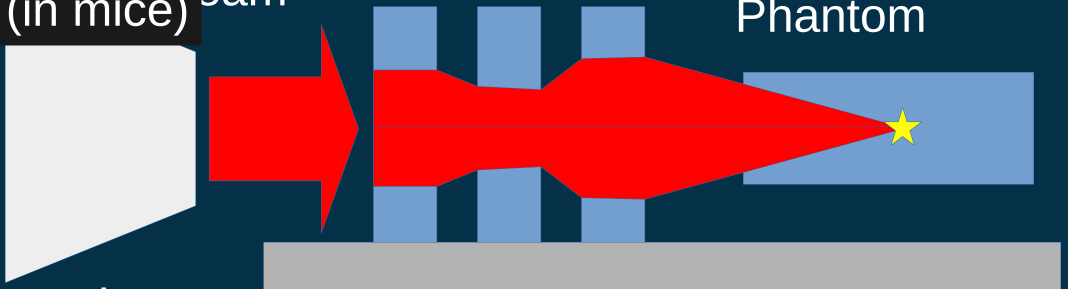
- Larger beamsize in final quad magnets =>
  - Sharper convergence
  - Smaller focal point
- Smaller irradiated point
- Possibility for higher dose rate
- Want to investigate this and more
  - Funding application from RCN/YRT pending

Proton therapy sharp focusing insert

- Need to test the biological effects of sharp proton minibeams
- Would be interesting to test with real proton therapy beam
  - Use research room
  - Needs to be compact!
- Close collaboration with biophysicists







UHDR and FLASH RT

- FLASH effect:
  - Reduced toxicity
    => healthy tissue sparing,
    less side effects
  - Maintained tumour control
  - Requires ultra-high dose rate (UHDR): > 40 Gy/s
    - conventional ~0.1 Gy/s
- Very hot topic in radiation oncology
  - One or very few fractions needed
- VHEE using CLIC technology well suited for this
- Dosimetry is challenging
- Accuracy is paramount

A. Schüller et al., The European Joint Research Project UHDpulse - Metrology for advanced radiotherapy using particle beams with ultra-high pulse dose rates, Physica Medica 80 (2020) 134-150.

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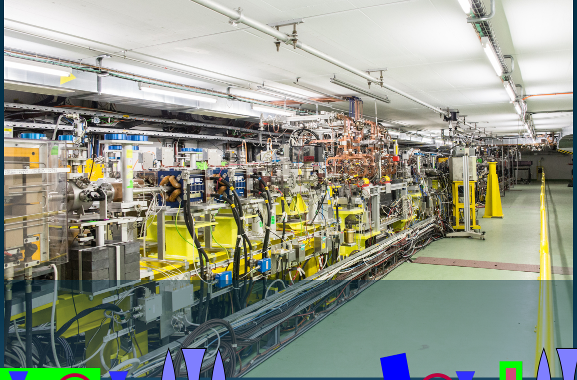
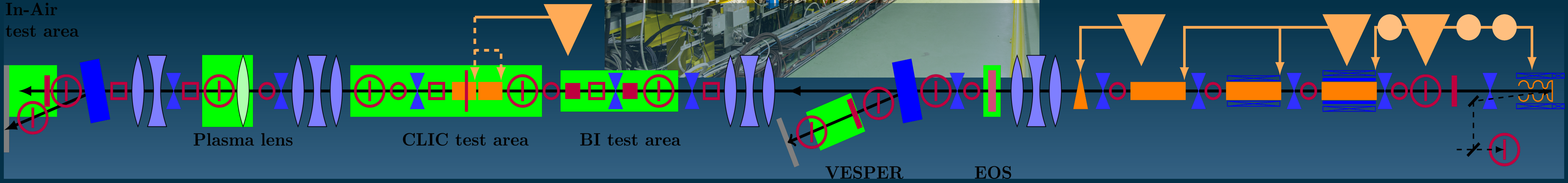
J. Bourhis et al,, "Treatment of first patient with FLASH-radiotherapy, Radiotherapy and Oncology, 2019

Fig. 1. Temporal evolution of the treated lesion: (a) before treatment; the limit
th PTV are delineated in black; (b) at 3 weeks, at the peak of skin reactions (grad
epithelitis NCI-CTCAE v 5.0); (c) at 5 months.



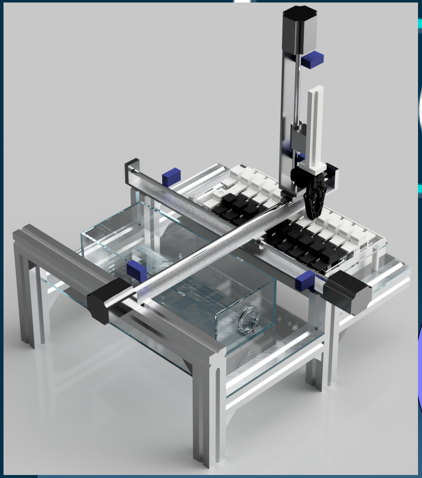


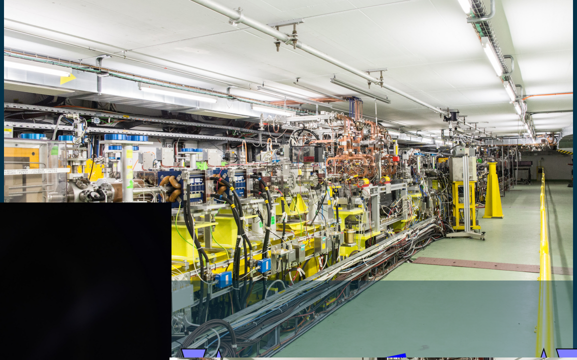
- CLEAR = CERN
  Linear Accelerator for Research
  - Based on the former
    CLIC test facility (CTF3)
- User facility:
  - Changing experiments on a
    ~weekly basis
  - Users from out- and inside CERN
- Diagnostics, data acquisition, and beam manipulation devices already installed
- Separated from rest of CERN accelerator complex → Ran through LS2

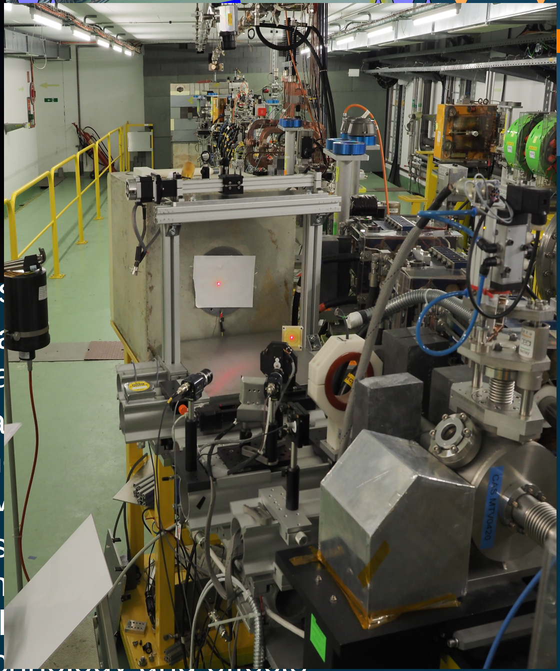
- Deep collaboration with accelerator group @UiO
- Examples of experiments:
  - Beam tests of plasma lens, beam position monitors
  - Irradiation of electronics, functional tests for radiation environments
  - Tests of novel radiotherapy schemes (e.g. FLASH in collaboration with CHUV): Technology and effects
- Electrons → Clean radiation environment, little activation

Beam parameters

- 60-200 MeV electrons
- 10 pC – 50 nC / pulse
- 1-10 pulses/second
- Pulse length 1 ps – 50 ns







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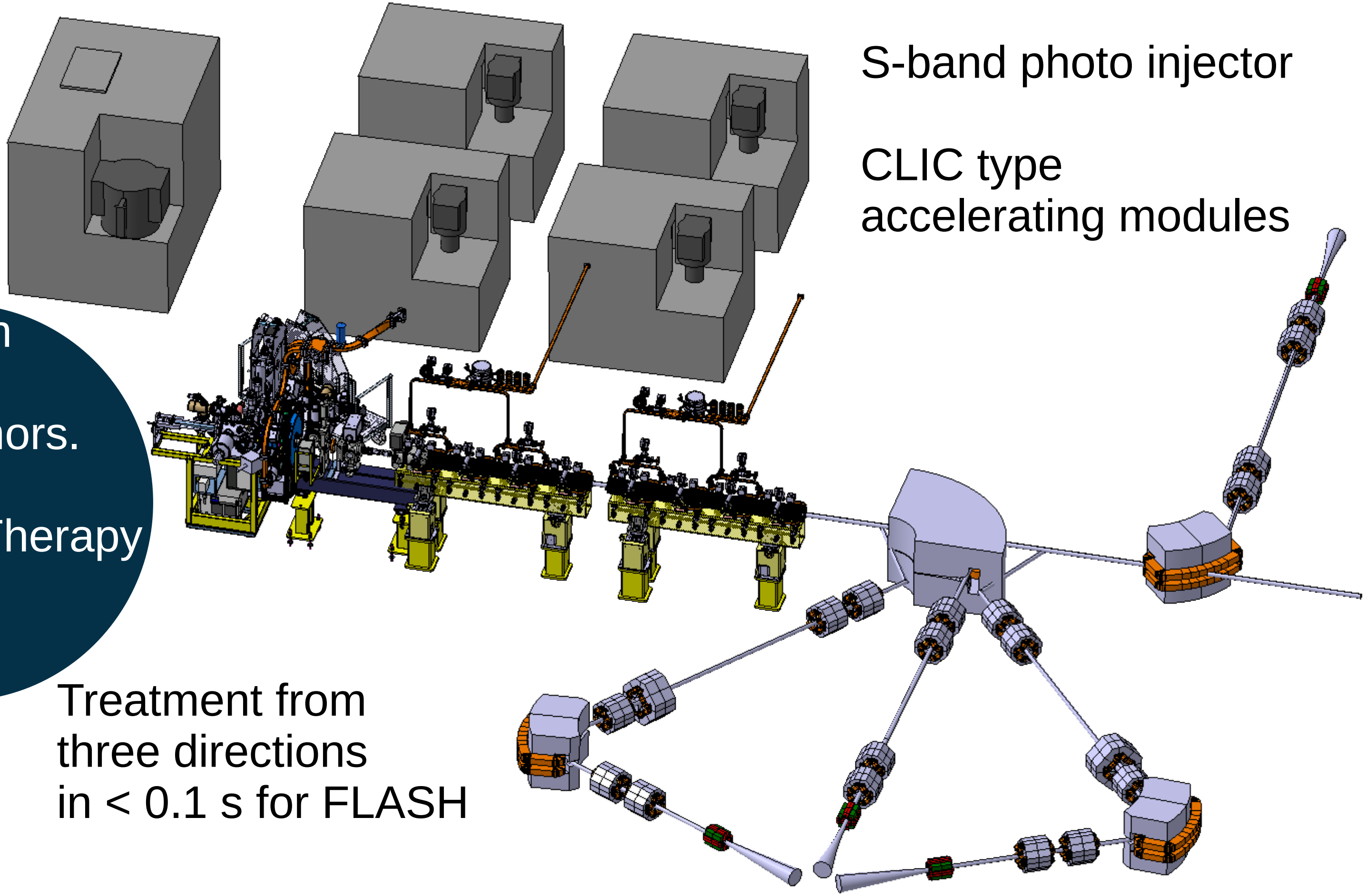
Slide from Steffen Doebert via Steinar Stapnes

The *DEFT* concept

CHUV and CERN collaboration
for a **VHEE FLASH facility**
to treat large, deep-seated tumors.

DEFT – Deep Electron Flash Therapy
Taking VHEE and FLASH
into the clinic.

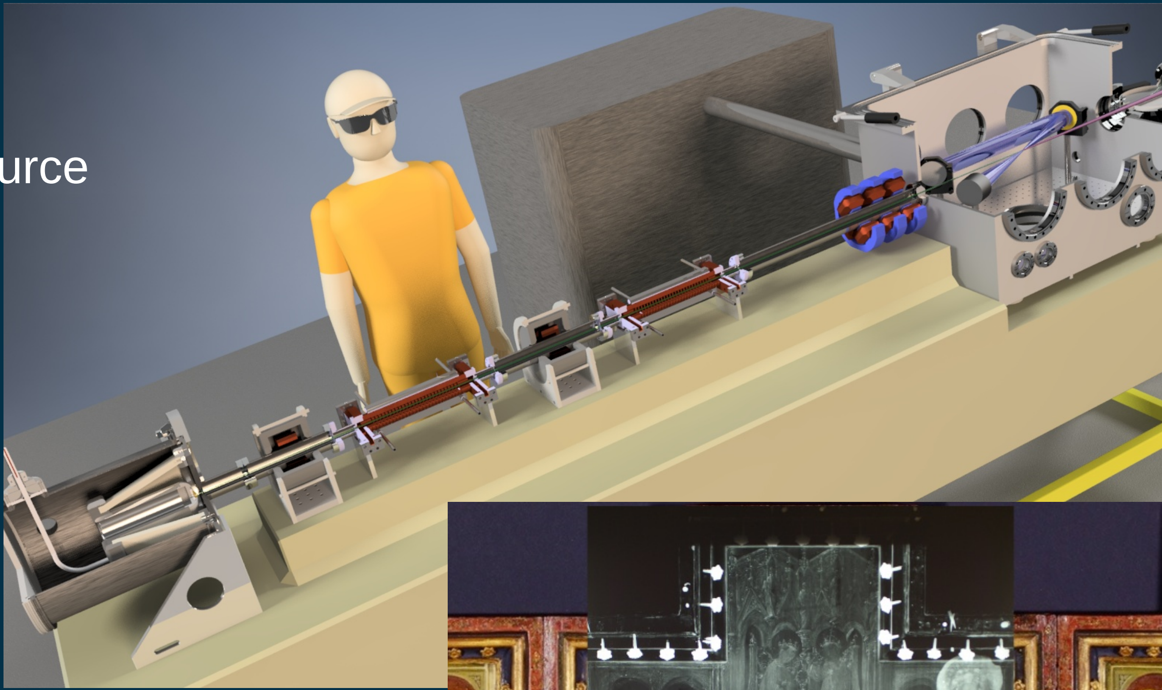
Technology transfer
to industry

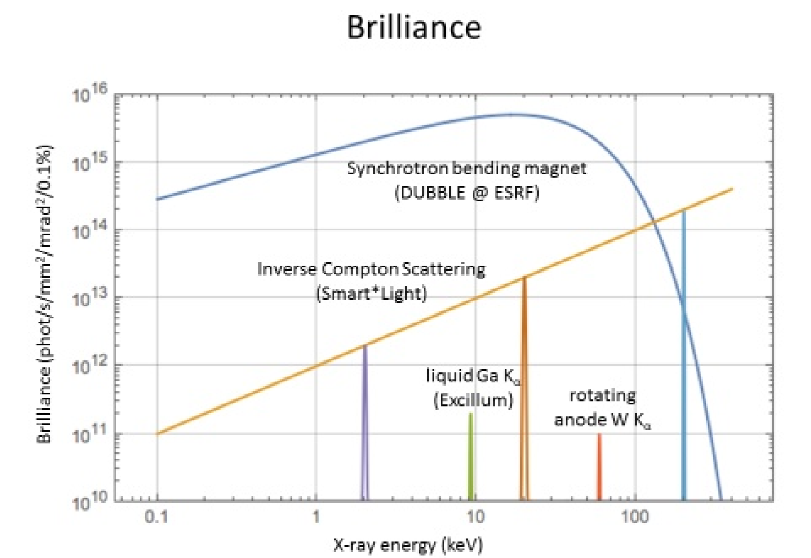


Slide adapted from Steffen Doebert via Steinar Stapnes

Inverse Compton Scattering Source: Smart*Light

- Compact, highly monochromatic X-ray source based on 50-100 MeV electron beam.
- Complementary to X-ray tube and synchrotron light source.
- Applications in cultural heritage, material science, medical, etc.





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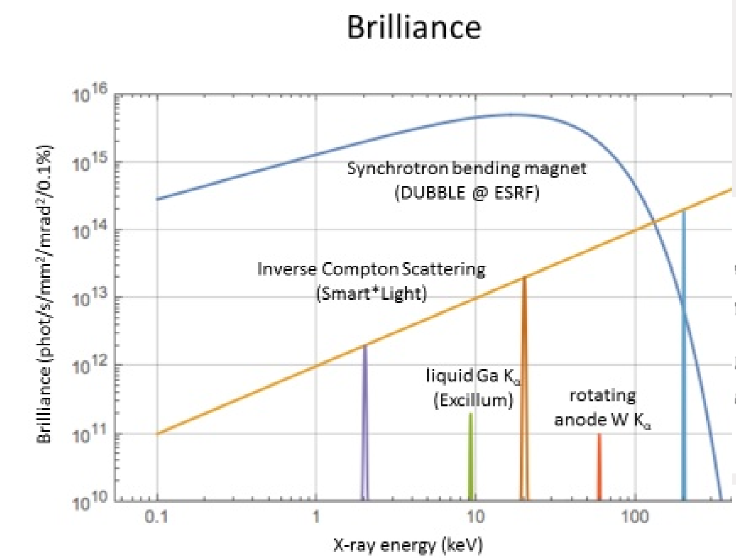

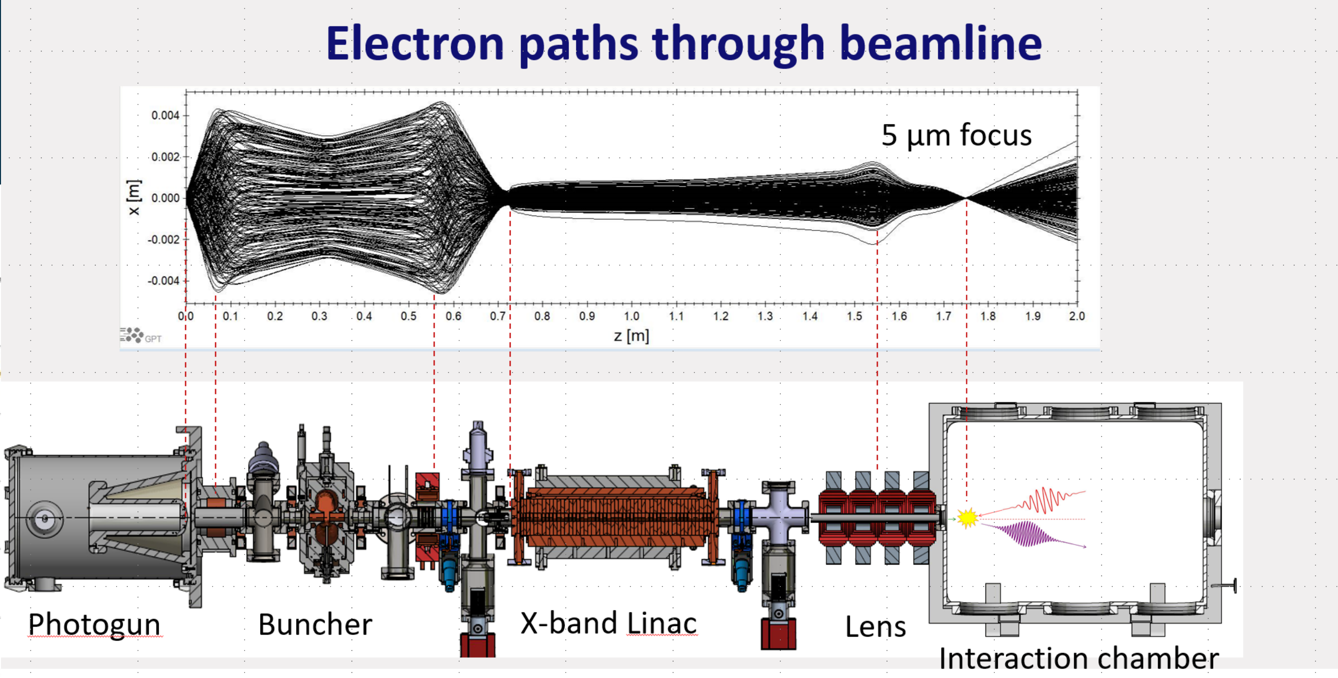

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Ultra compact Neutron Source for materials testing

Parameter	Value	Unit
Electron energy	30 to 40	MeV
Peak Current	≥ 0.2	mA
Pulse duration	1 to 5	µs
Repetition rates	≥ 100	Hz

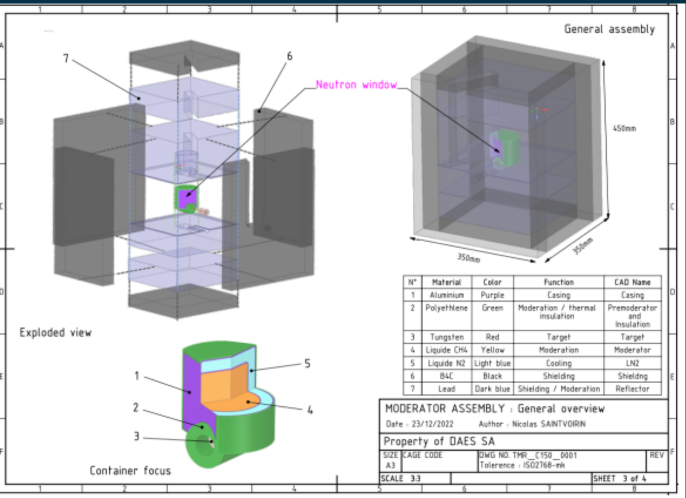
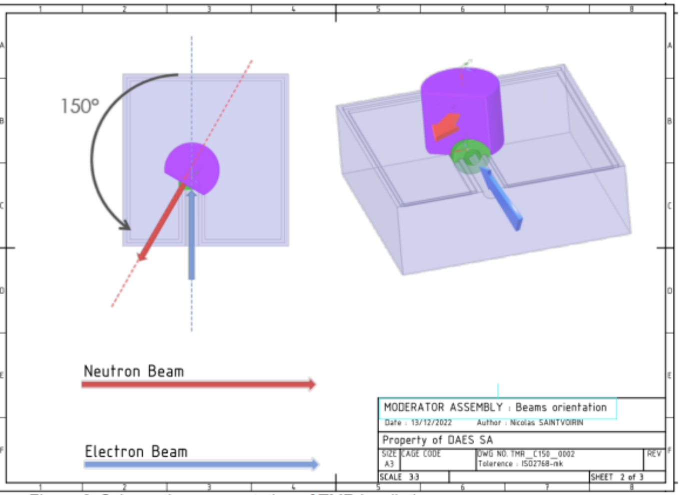


Figure 1. VULCAN TMR assembly.



- Development of a turn-key industrial compact neutron source for material testing.
- Initial tests will be performed with the CLEAR test accelerator at CERN.
- Supported by the CERN Innovation Programme on Environmental Applications.
- Important tool for future battery development

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CIPEA
CERN Innovation Programme on Environmental Applications

Conclusions & Outlook

- Technology for particle physics and particle accelerators have important medical applications
- Two proton therapy centers under construction in Norway with research rooms make this especially relevant now
- We are especially studying how to better control the dose deposition
  - Applied for funding through RCN/YRT (waiting), previously KD together with biophysics (failed)
  - Some activity through NorCC / Plasma Lens Experiment
  - New master student (E. Lindberg) in start-up phase
- Close collaboration with CLEAR keep us close to the center of activity
- Many very interesting applications of compact high performance accelerators