Treatment Planning With Very High Energy Electron Radiotherapy (VHEERT) for deep seated tumours

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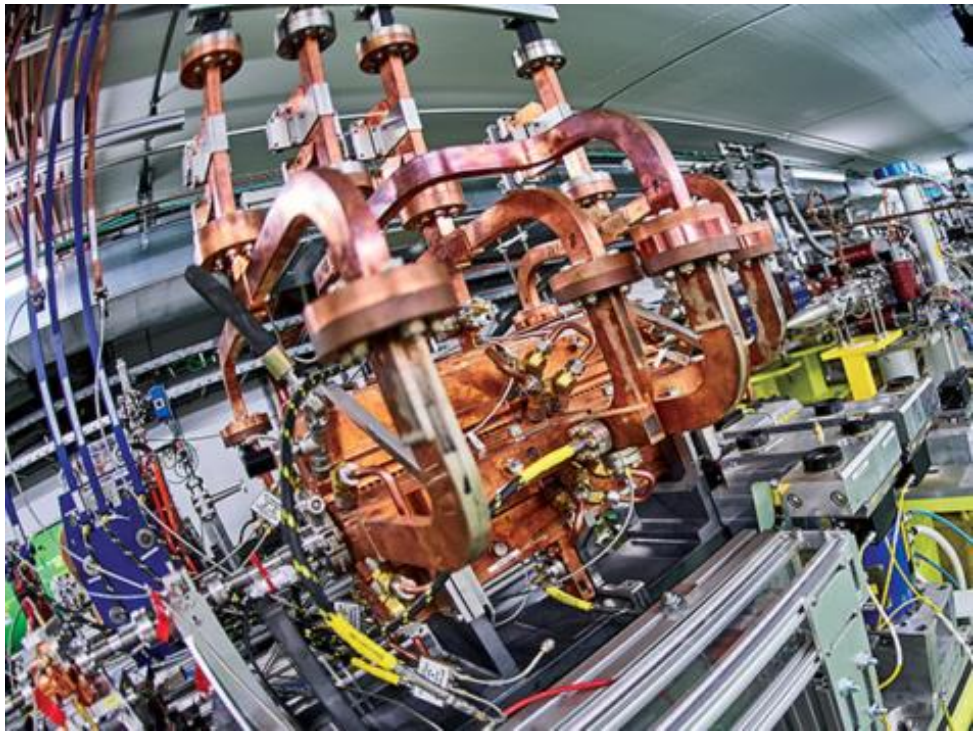
Overview

- Very High Energy Electrons (VHEEs) as a potential modality for radiotherapy
- Treatment Planning with VHEEs
- Comparing VHEE plans with VMAT plans
- Changes in patient anatomy
- The next steps forward & experiments
- Conclusions

Very High Energy Electrons

- Using new linac designs it's now possible to achieve roughly 200MeV electrons in 2/3m, not over 20m.
- Since the early 2000s this has spurred an interest in using Very High Energy Electrons (**VHEEs**) for treating deeper seated tumours. Typically energies over 40MeV are considered to be VHEEs.
- Currently no clinical machine available but there is interest
- Some interesting properties we can investigate without a machine



X-band technology at the CLEAR test facility at CERN. Image Credit: J Ordan / CERN

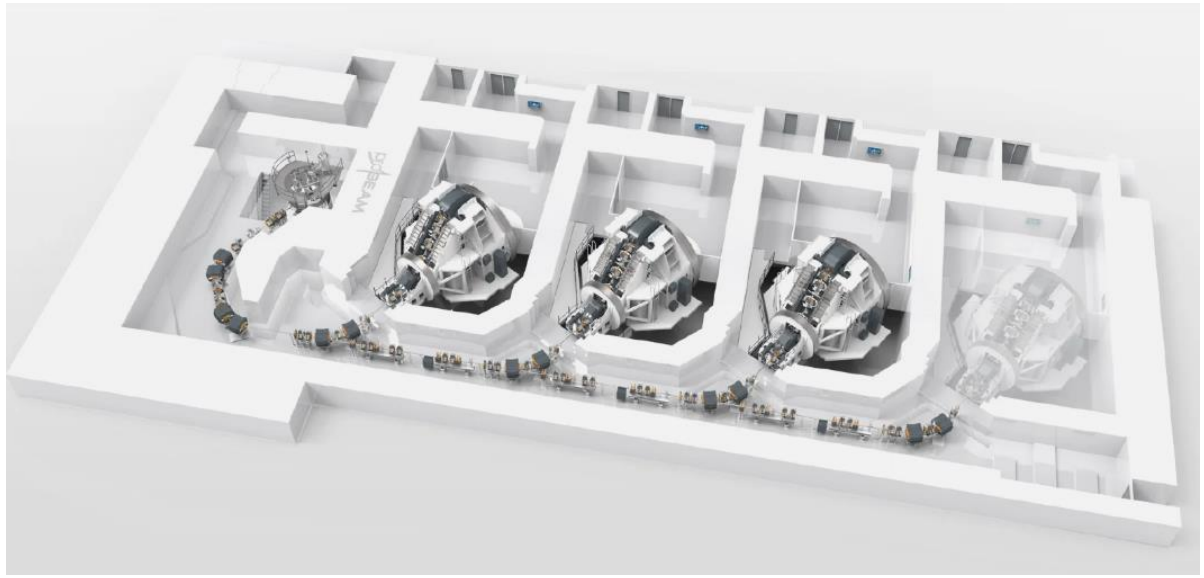
Very High Energy Electrons

Electrons & Photons

- Est. cost per course: **$15,000**
- Est. cost per facility**: $7,000,000**

Vs

Protons



- Est. cost per course: **$75,000**
- Est. cost per facility**: $200,000,000**

Figures from: https://www.medpagetoday.com/radiology/therapeuticradiology/65422

Very High Energy Electrons

Electrons & Photons **& VHEEs?**

- Est. cost per course: **$15,000**
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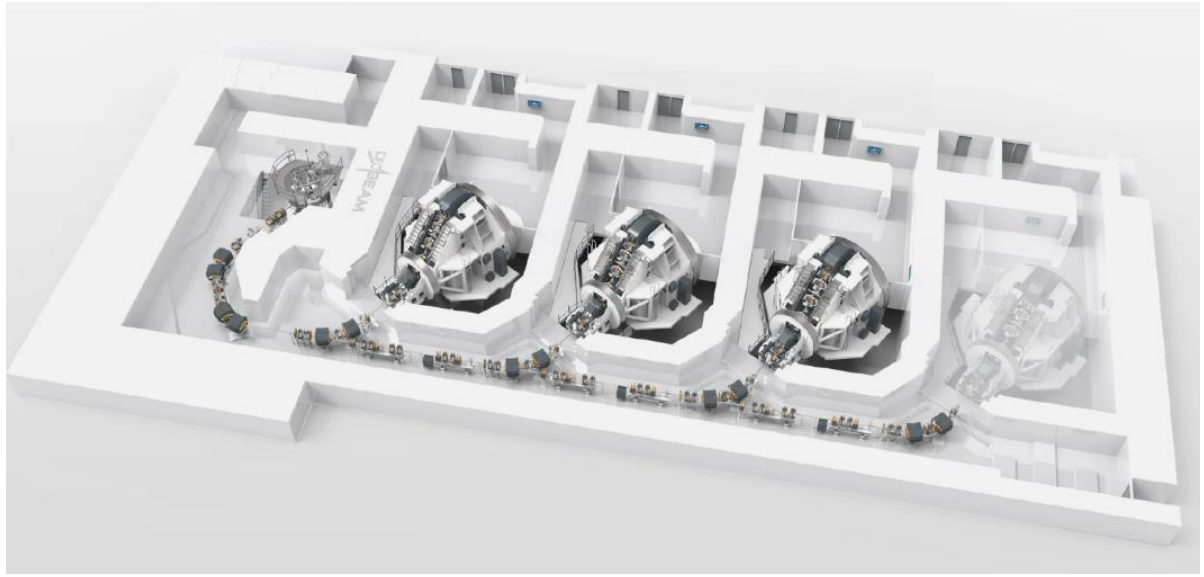
Protons



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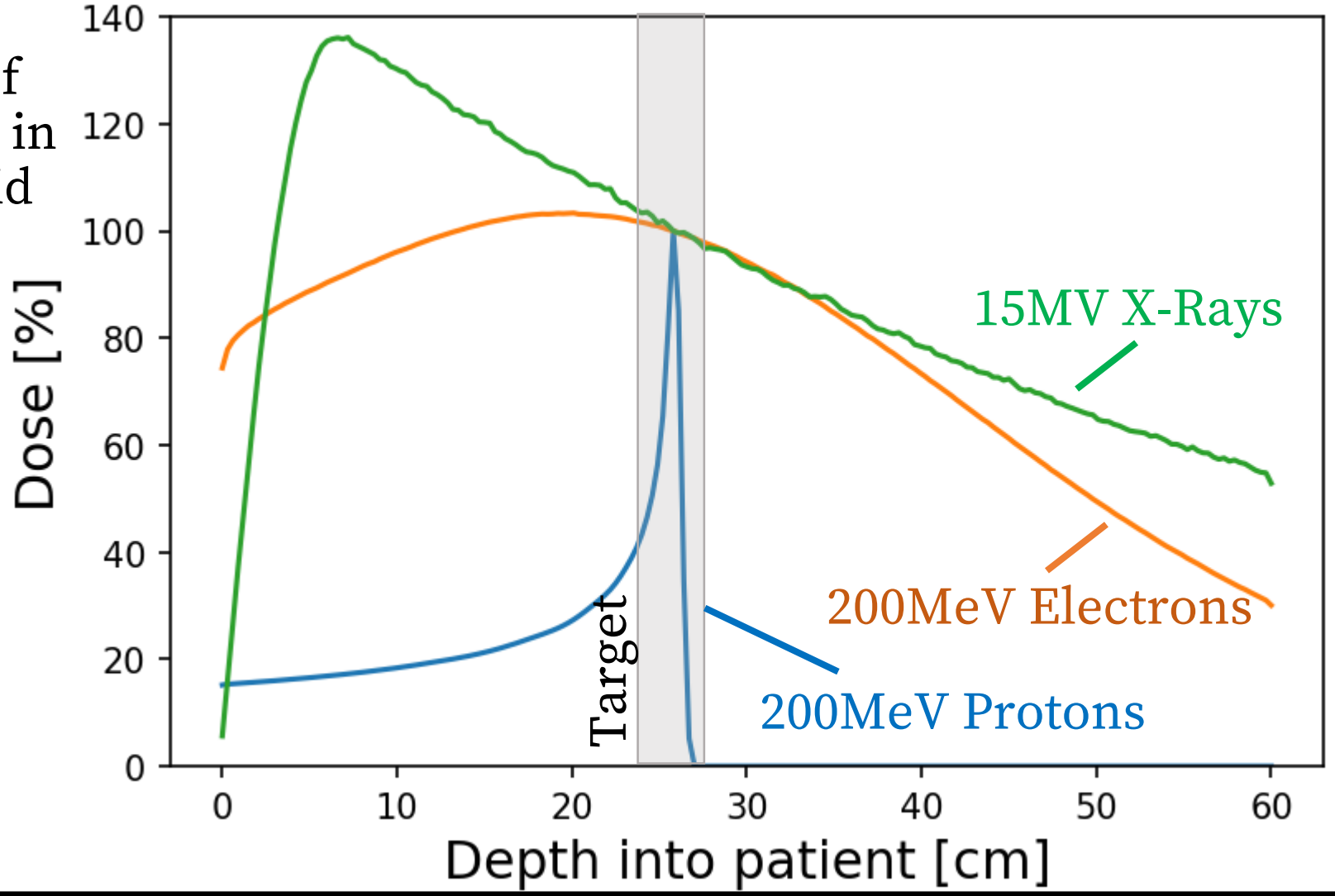
Why Use VHEEs?

- VHEEs are capable of delivering dose deep in to a patient, and avoid putting hot spots in healthy tissue, like photons do.



Why Use VHEEs?

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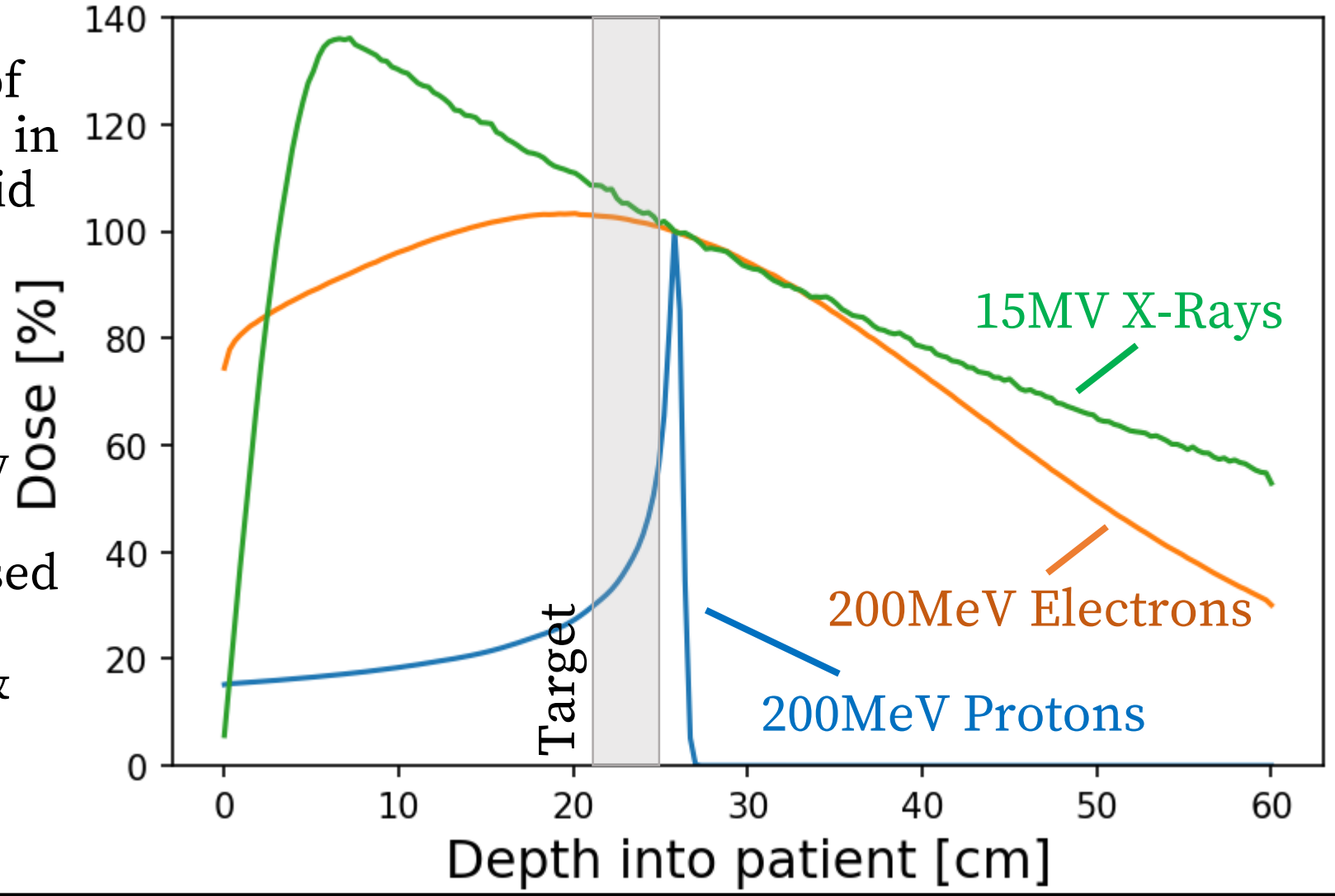
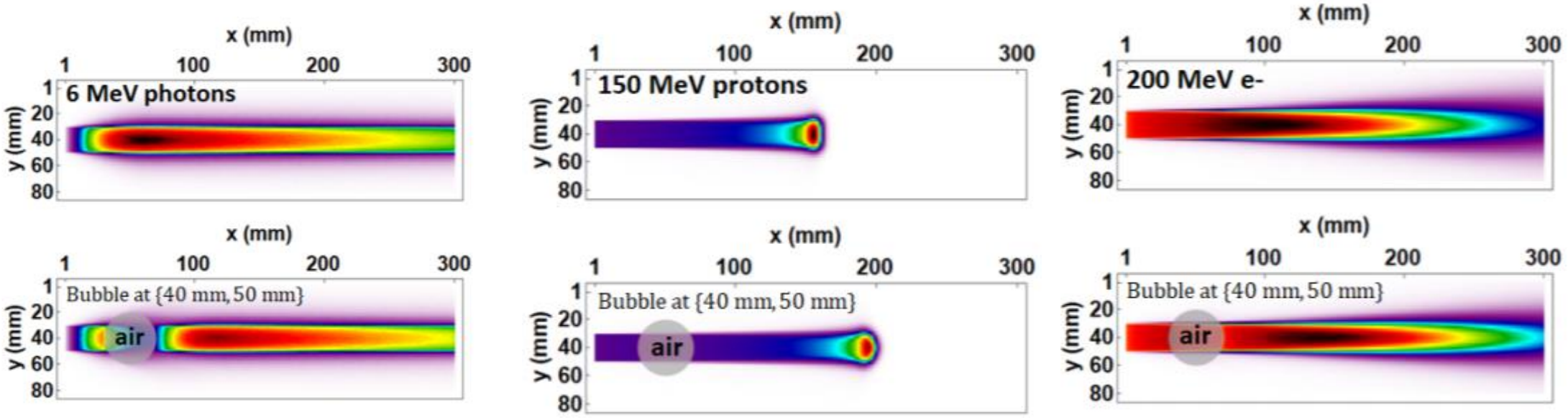
- And, they're not very susceptible to dose problems being caused by minor changes in patient positioning & geometry



Why Use VHEEs?

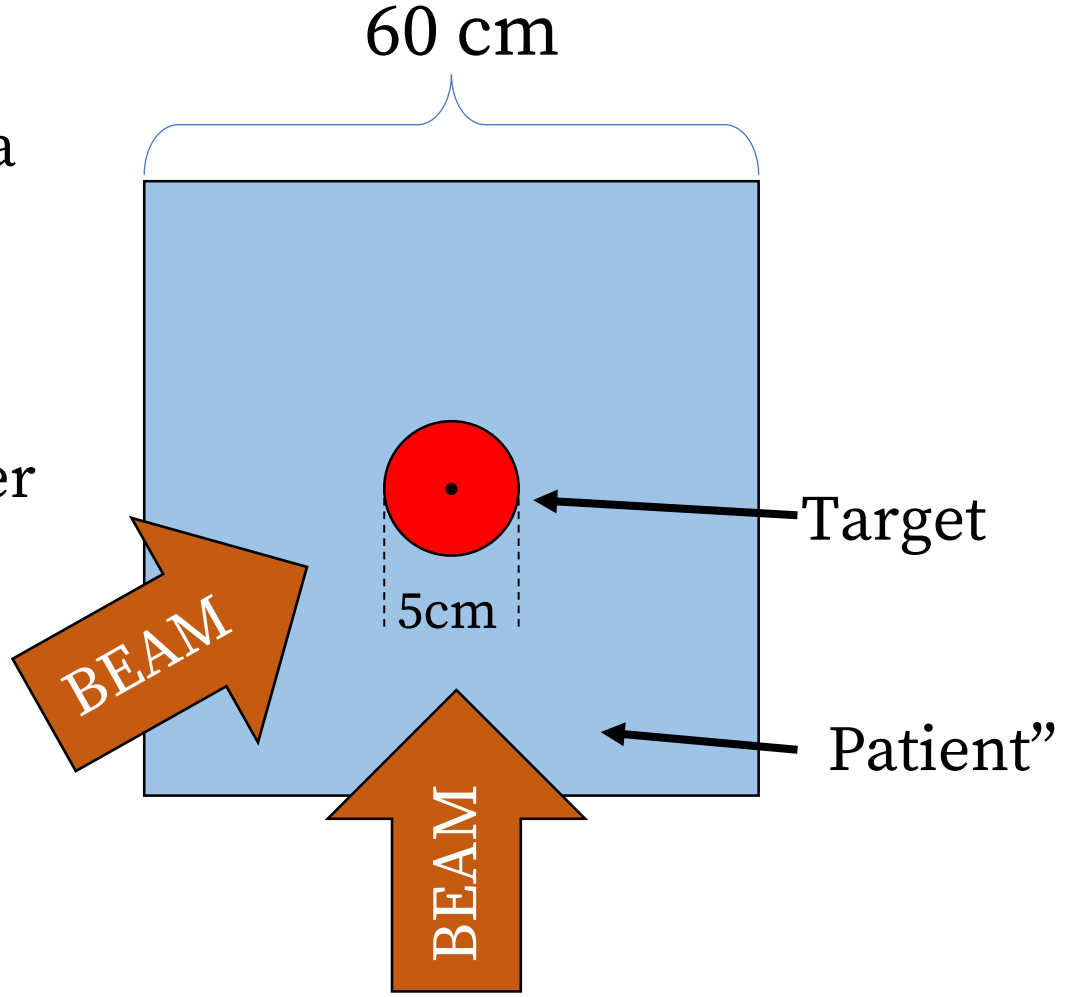
- One of the big advantages we would expect VHEERT plans to have is a strong insensitivity to unexpected changes in the path of the beam.
- Monte Carlo studies in blocks of water show that when a 2cm air bubble is inserted in the path of a VHEE beam dose shifts of only ~ ± 15% are seen. This is compared to photons where under and over doses of 70% and 80% respectively are seen. And protons where under / over doses of 70% and 96% are seen*.



*Applications of Very High Energy Electrons for Radiotherapy, A. Lagzda, CLIC Workshop 2017

A back of the envelope case: A Simple Water Phantom

- We can start by considering the simplest possible case, a cubic water phantom with a 5cm cylindrical tumour in the centre.
- We can treat" this by rotating a beam around the target. Each beam sees" only a flat square, so a flat field will suffice to cover the tumour



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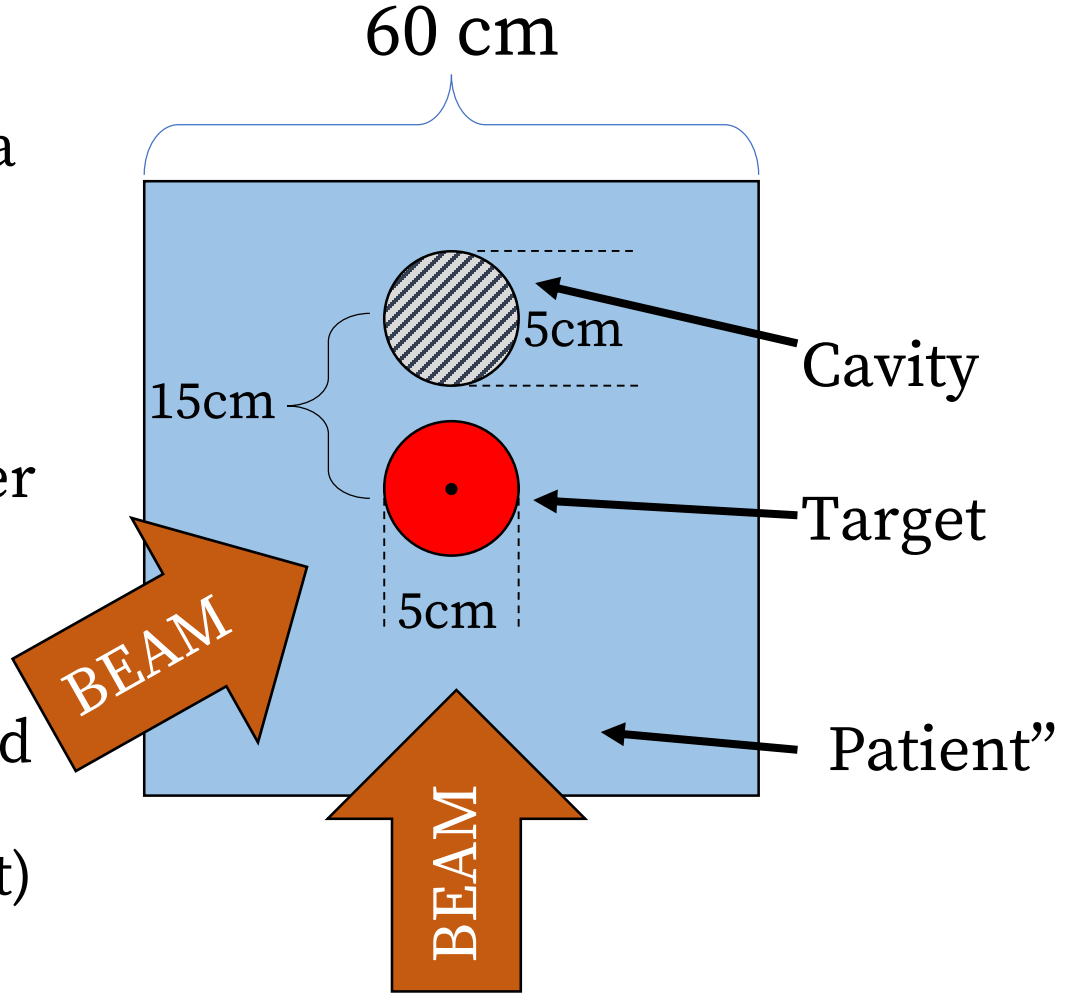
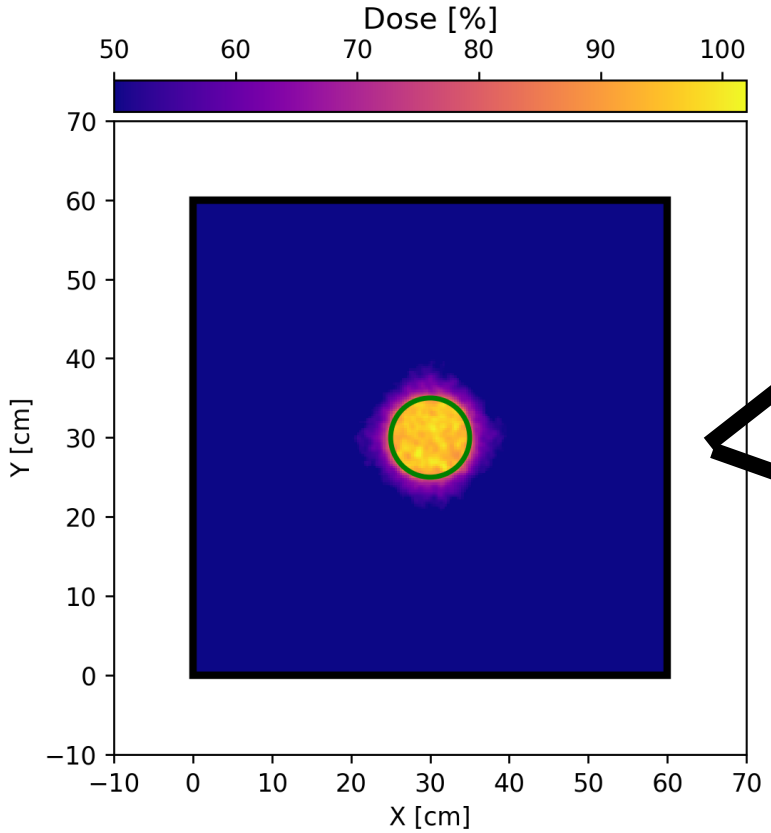
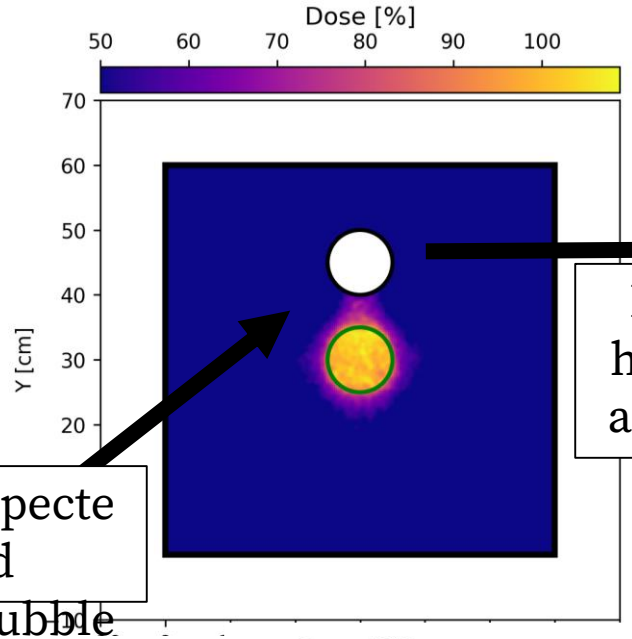
- We can treat" this by rotating a beam around the target. Each beam sees" only a flat square, so a flat field will suffice to cover the tumour
- Given that we're interested in the surprise appearance of changes we can also go ahead and include a cavity above the tumour: a 5cm diameter sphere that we can fill (or not) with whatever material we please.



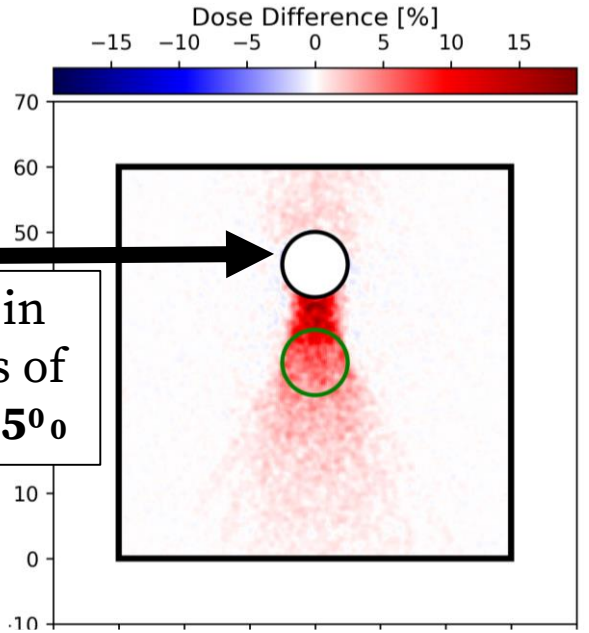
1.3MeV X-rays



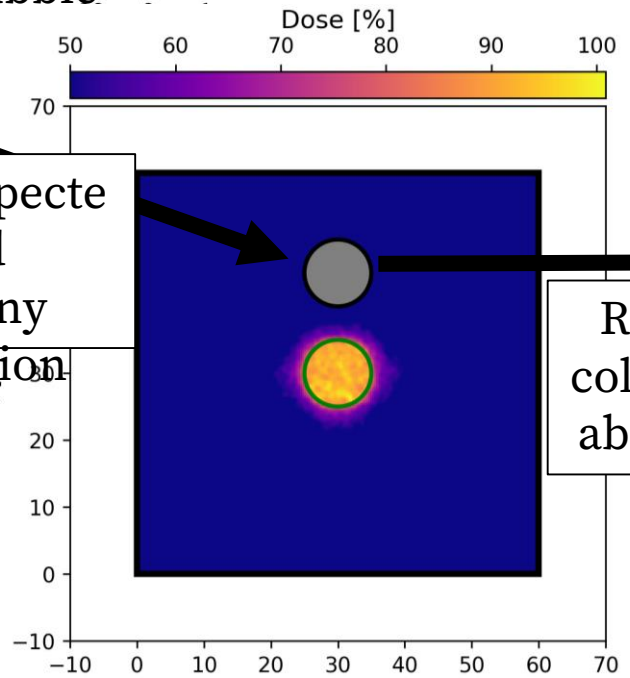
Unexpected Air Bubble



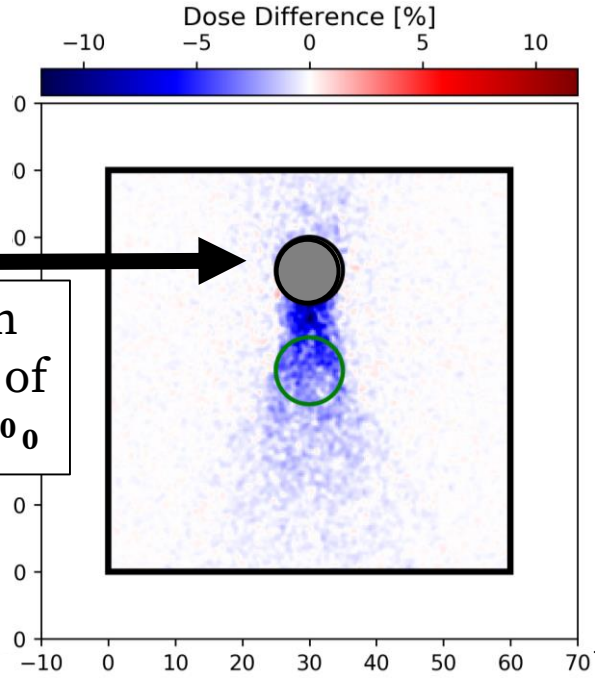
Results in hot spots of about ~15%



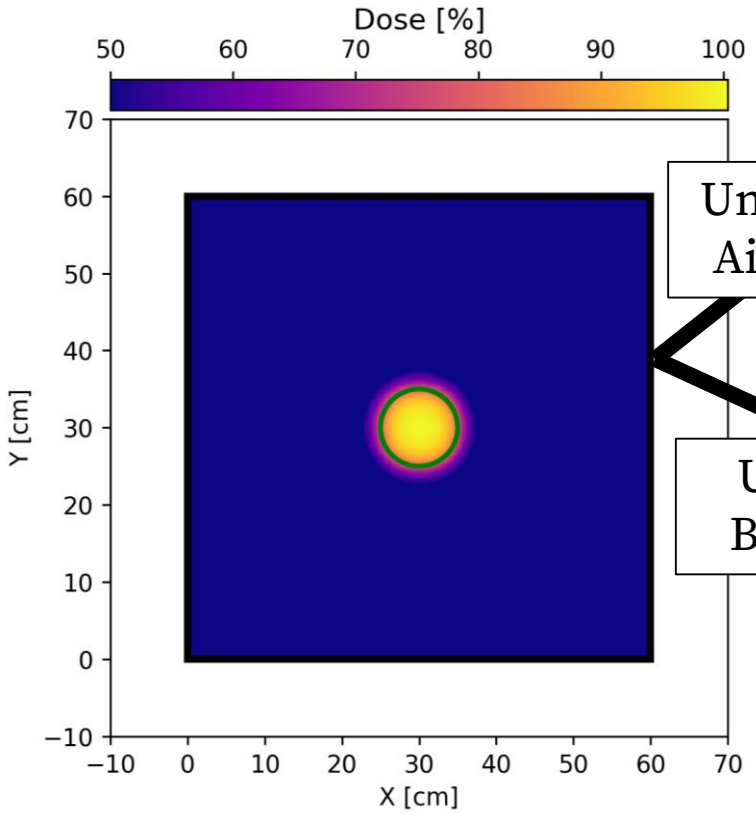
Unexpected Bony Region



Results in cold spots of about ~10%



250MeV VHEEs



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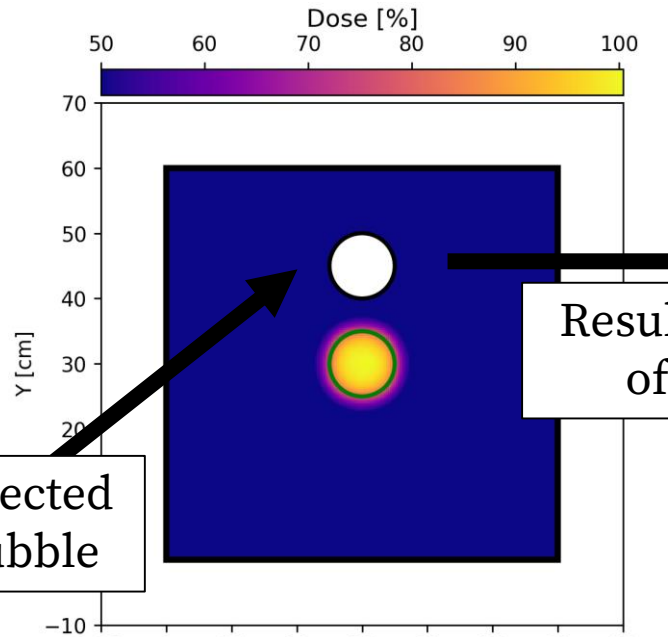
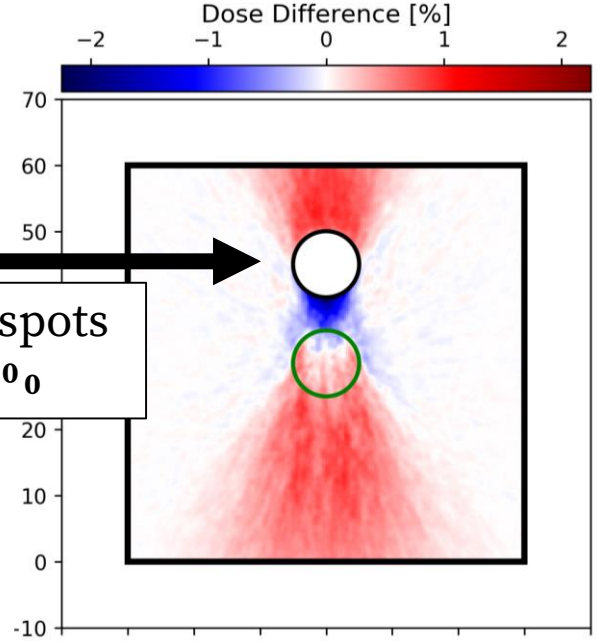


Results in hot spots of about ~2%



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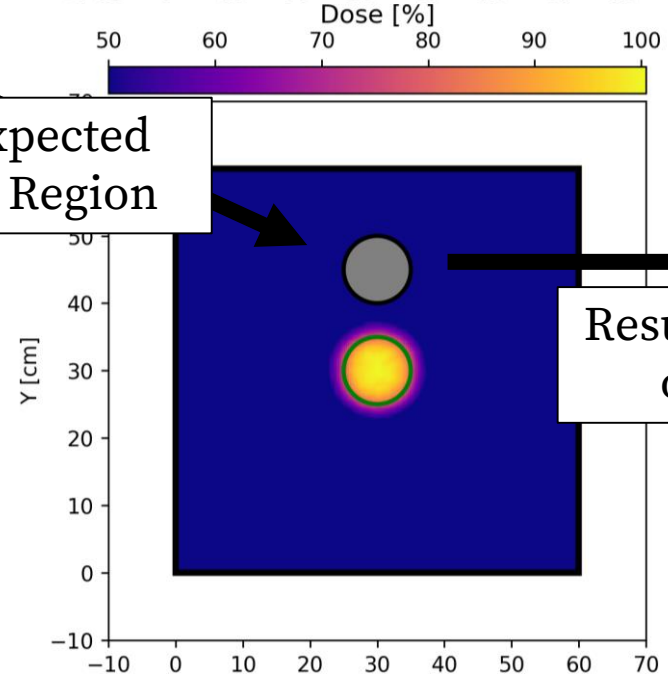

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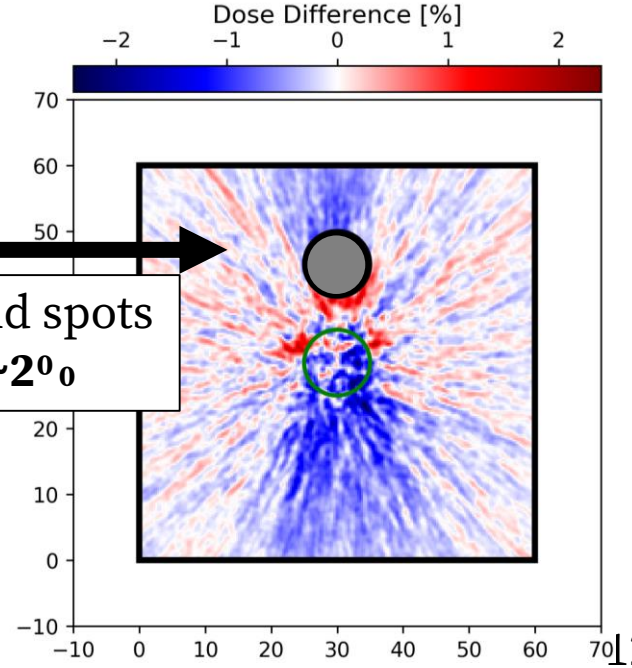

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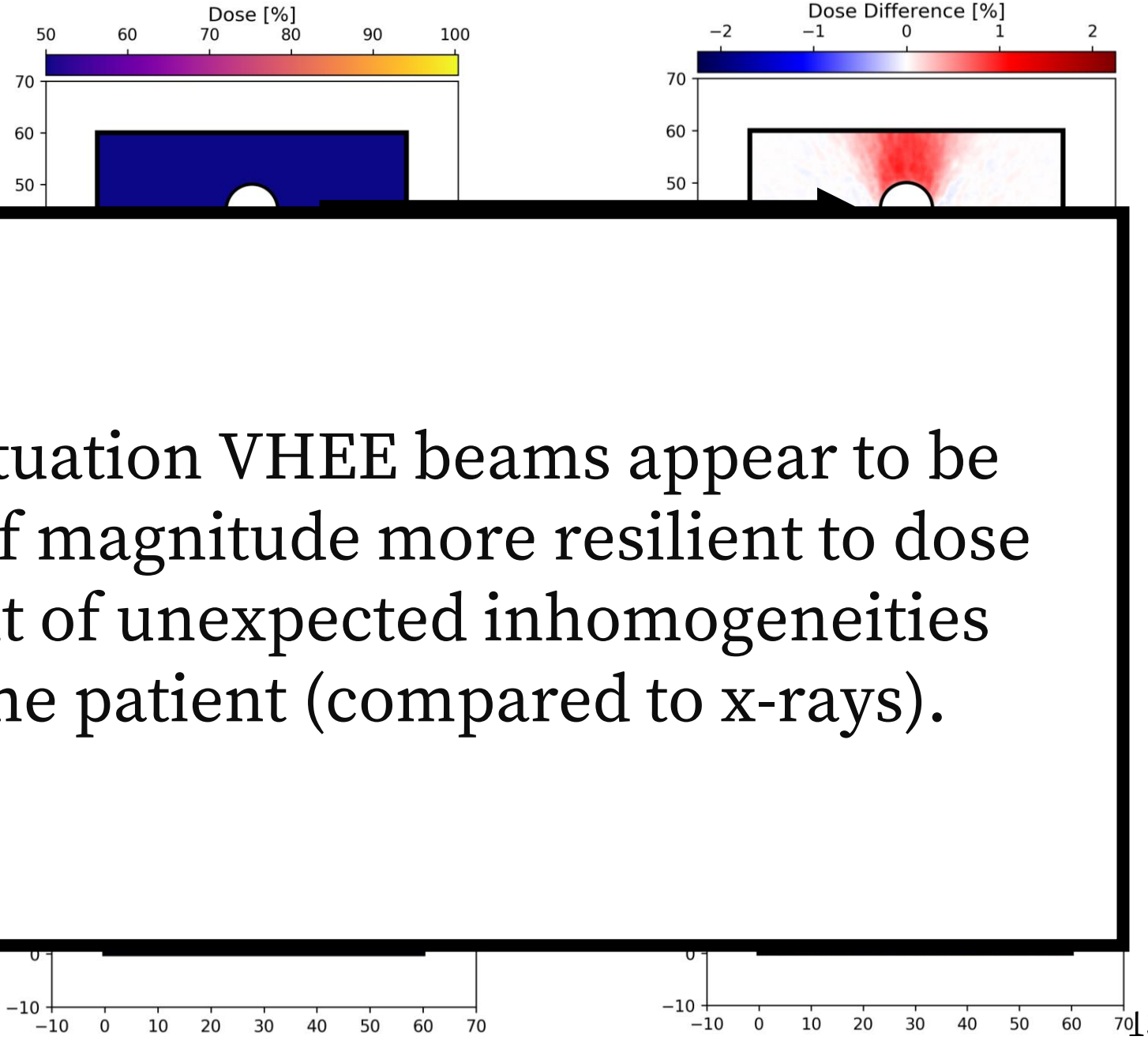
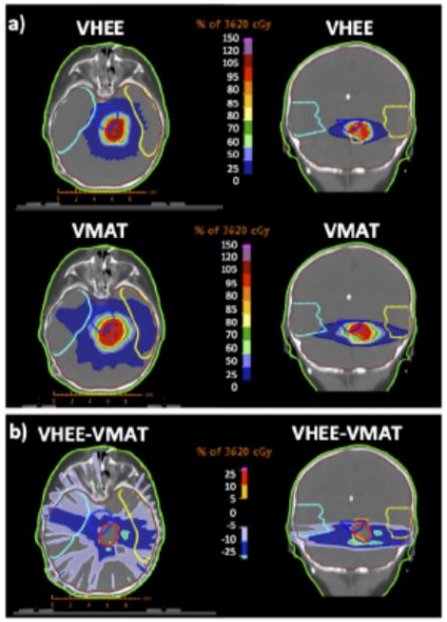
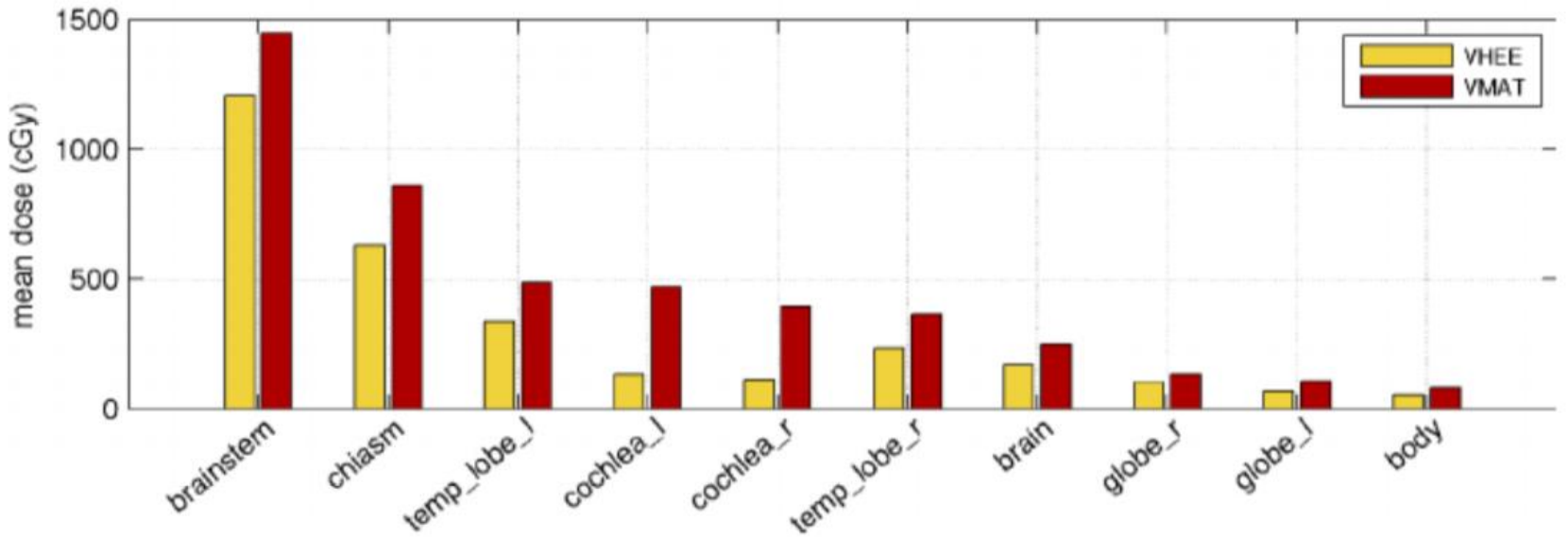


In this simple situation VHEE beams appear to be nearly an order of magnitude more resilient to dose errors as a result of unexpected inhomogeneities appearing in the patient (compared to x-rays).

Treatment Planning with VHEE beams

- When it comes to treatment planning with VHEEs in patient level complexity there have been relatively few so far.
- Looking at a paediatric brain case: using VHEE beams resulted in **nearly 70% dose decrease into nearby healthy tissue**, and improved conformity by nearly 20%





Treatment planning for radiotherapy with very high-energy electron beams and comparison of VHEE and VMAT plans." M. Bazalova-Carter et al

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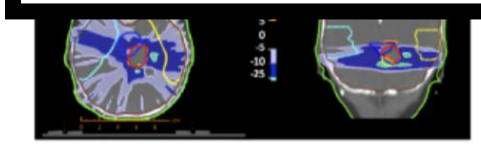
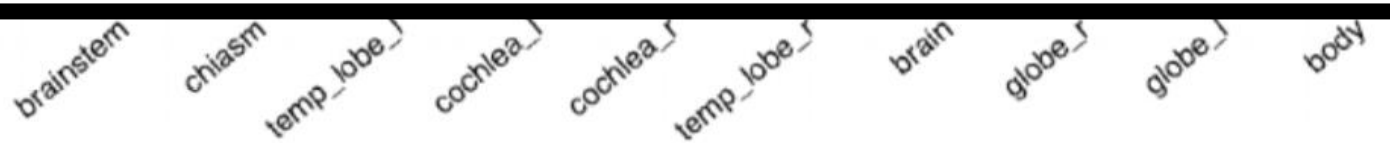
Is it possible to get most of the OAR sparing of protons with the cost and resilience of photons?

Potentially a best of both worlds….





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Treatment Planning with VHEE beams

- Which brings us to the work we have been doing on VHEE TP!

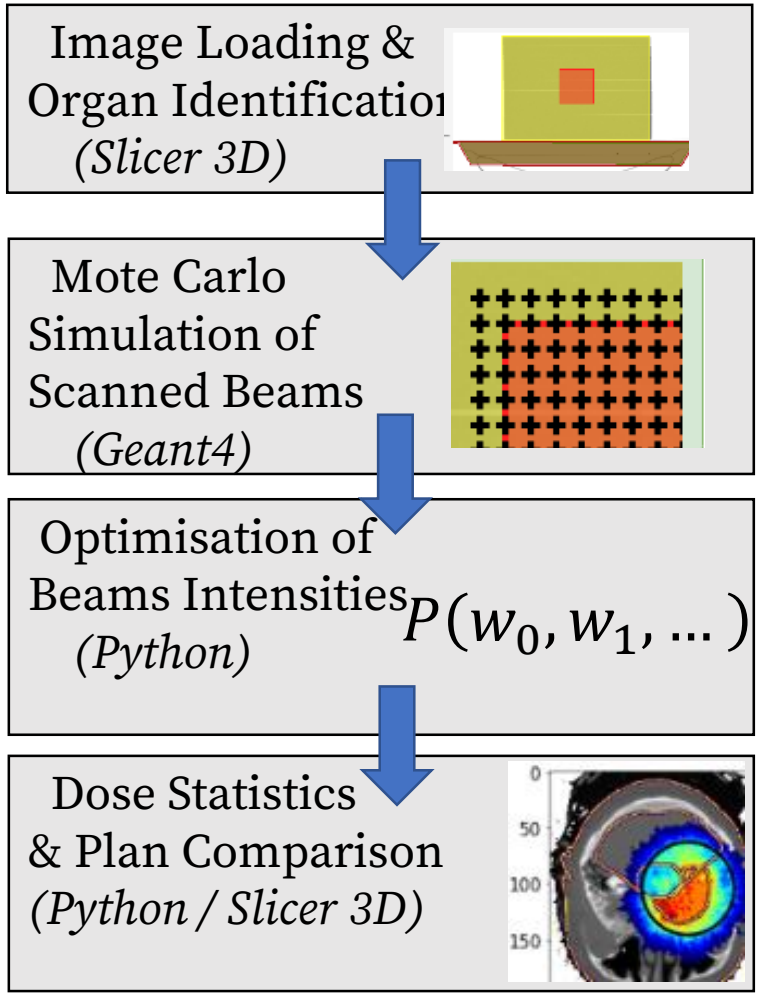
- We are developing a free open source treatment planning system for VHEEs, including:
  - **Medical Image Loading & Organ Identification:**

    Slicer 3D, free & open sourced, extremely flexible
  - **Monte Carlo Dose Calculation**:

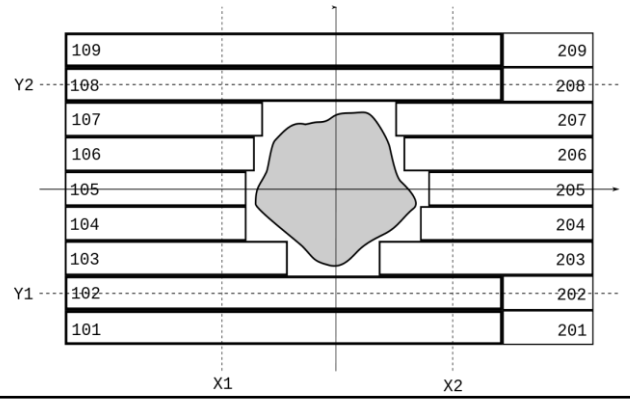
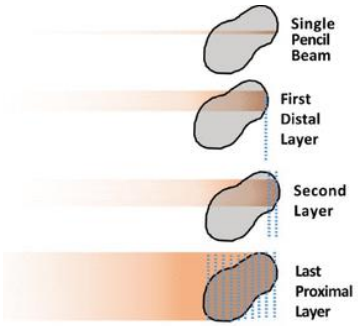
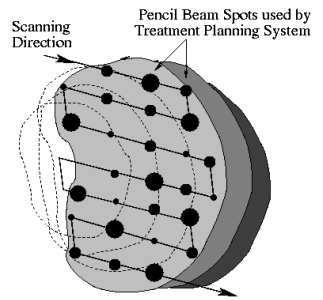
    Geant4, the high energy particle physics MC software
  - **Dose Optimisation:**

    Python implementation, KISS!
  - **Dose Statistics & Plan Comparison:**

    DICOM compliant plans exported for comparison



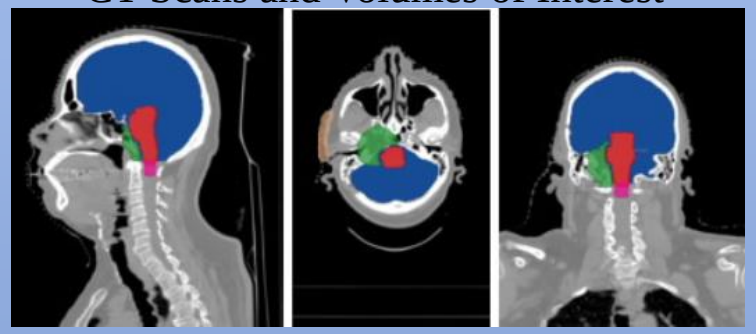
Plan Optimisation for VHEEs

X-Rays	Protons	VHEEs
		
• Beam is shaped by collimator leaves • We need only find the optimal position of each leaf. • This means there are relatively few variables in the optimisation (on the order of hundreds)	• Tumour is painted" in layers with different energies • Each energy only really impacts one layer of the tumour. • Therefore optimisations are loosely coupled & plans are fairly easy to calculate.	• Beam scans over the patient, so we have many variables to worry about • And electrons shoot all the way through the tumour • So each layer affects all the others. **HUGE OPTIMISATIONS**

Plan Optimisation for VHEEs

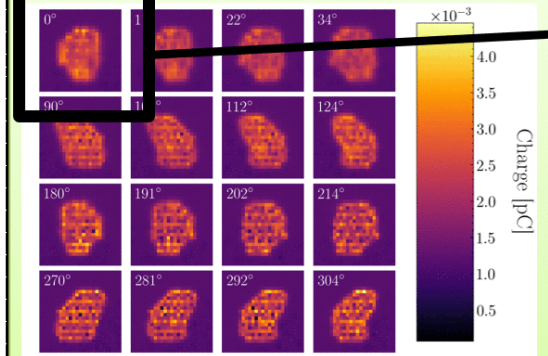
INPUTS

CT Scans and Volumes of Interest

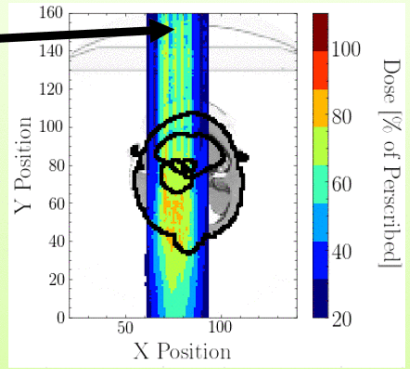


OUTPUTS

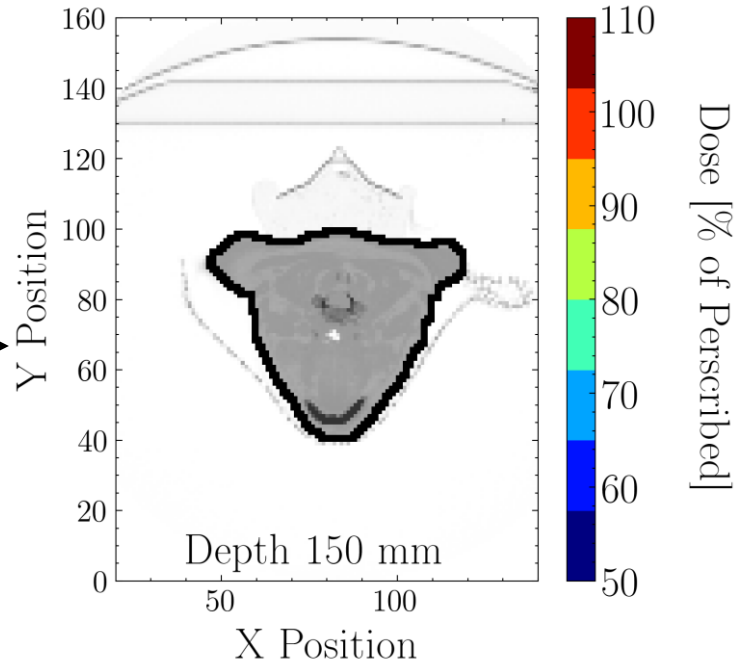
Set of Beam Profiles



And The Resulting Doses



ADD ALL OF THE BEAMS TOGETHER TO GET THE FINAL DELIVERED DOSE

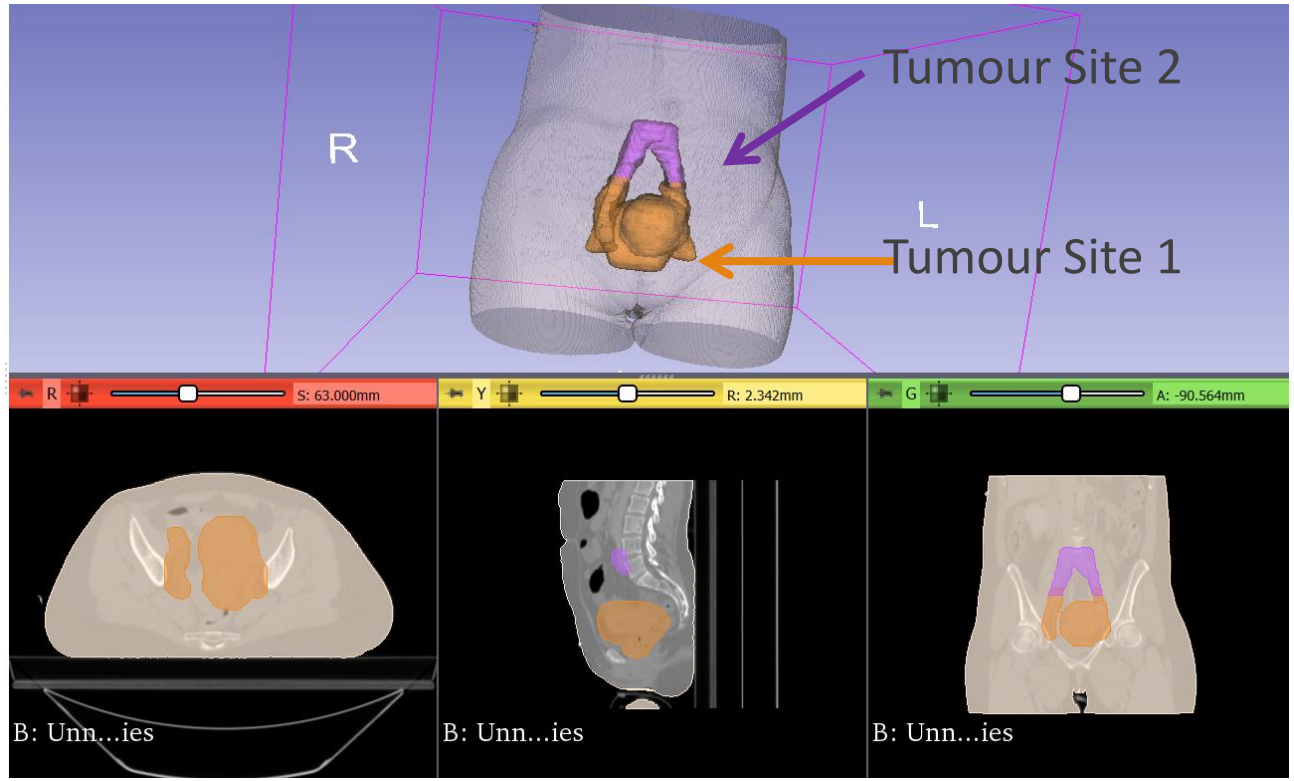


A Patient Case: Cervical Cancer

- So we can now look at a real case: a cervical cancer case with two large areas that need to be irradiated

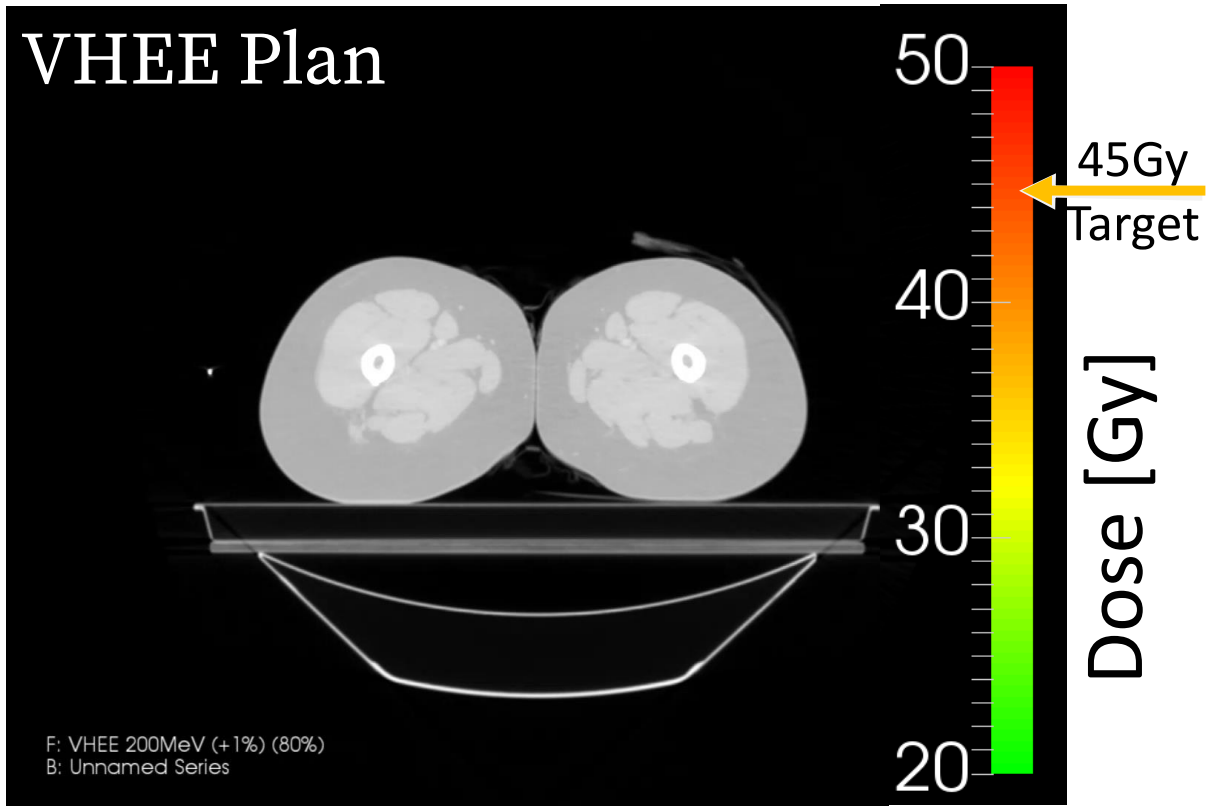
- Obviously, due to all of the radiosensitive tissues nearby (bowel, bladder etc) we need to shape this dose very carefully around the tumour

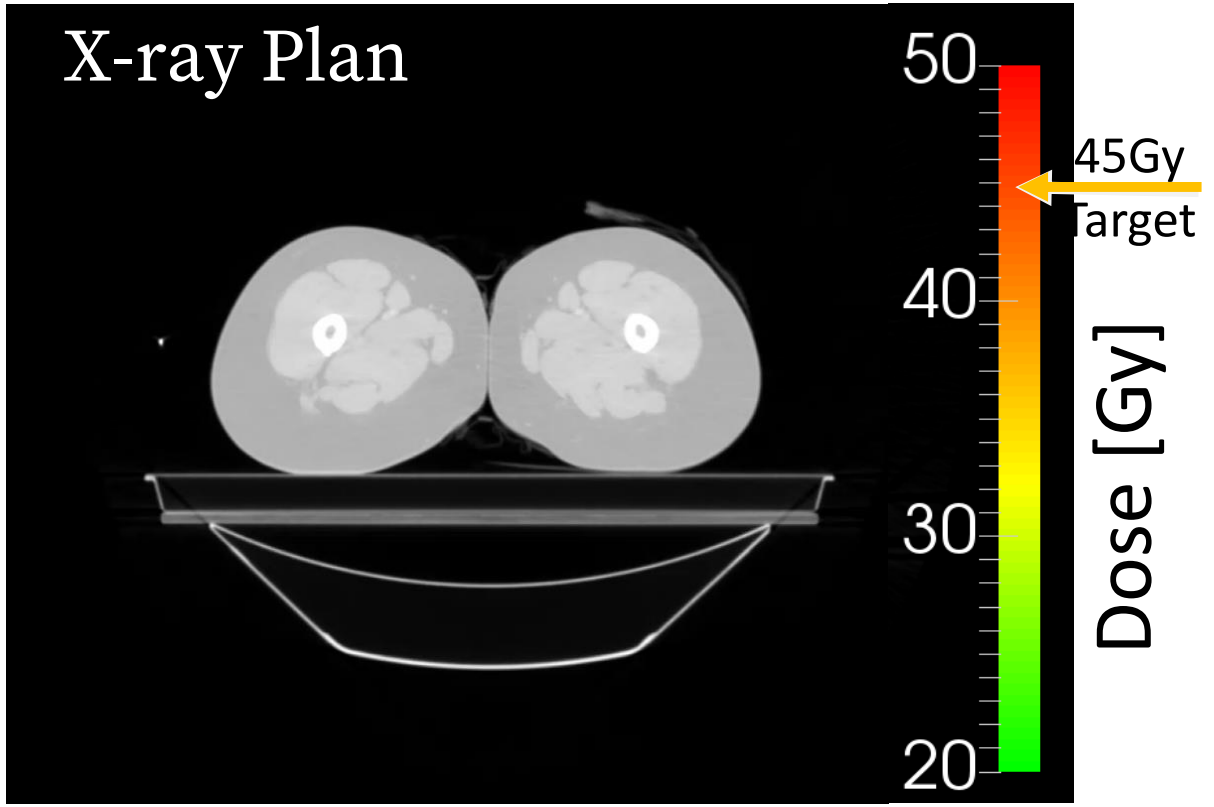
- A plan was calculated using our VHEE code and Monaco, the commercial x-ray treatment planning system to produce a VMAT plan.



Treatment Planning with VHEE beams

Comparing the VHEE and X-Ray plans





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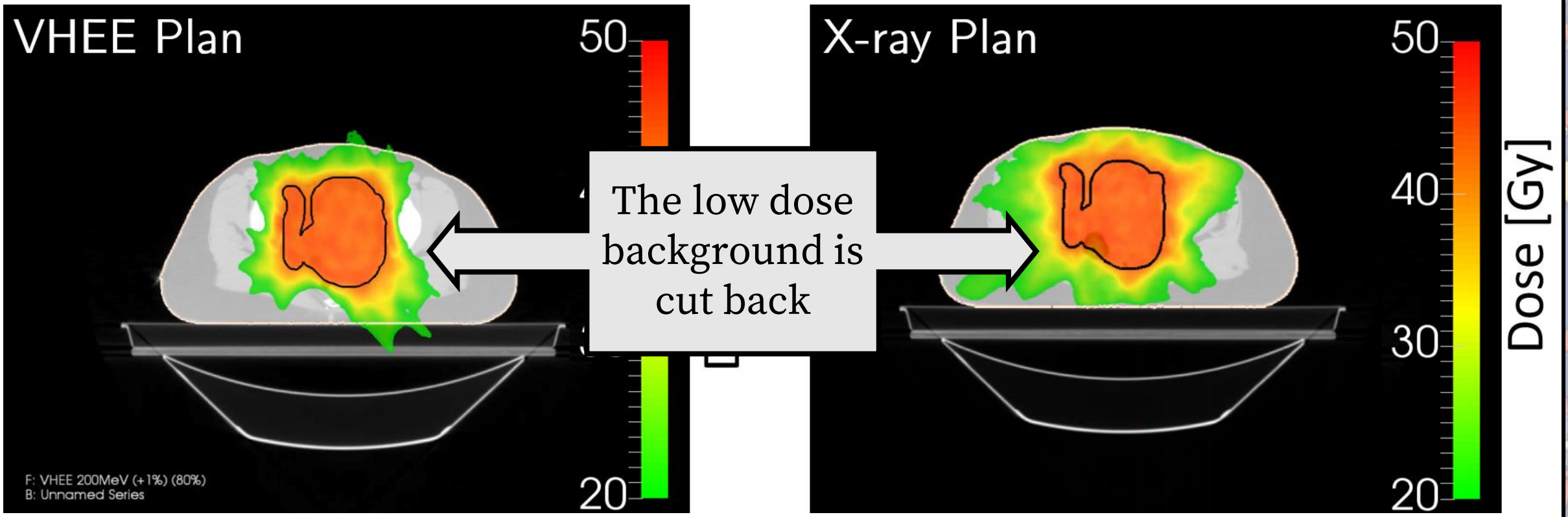


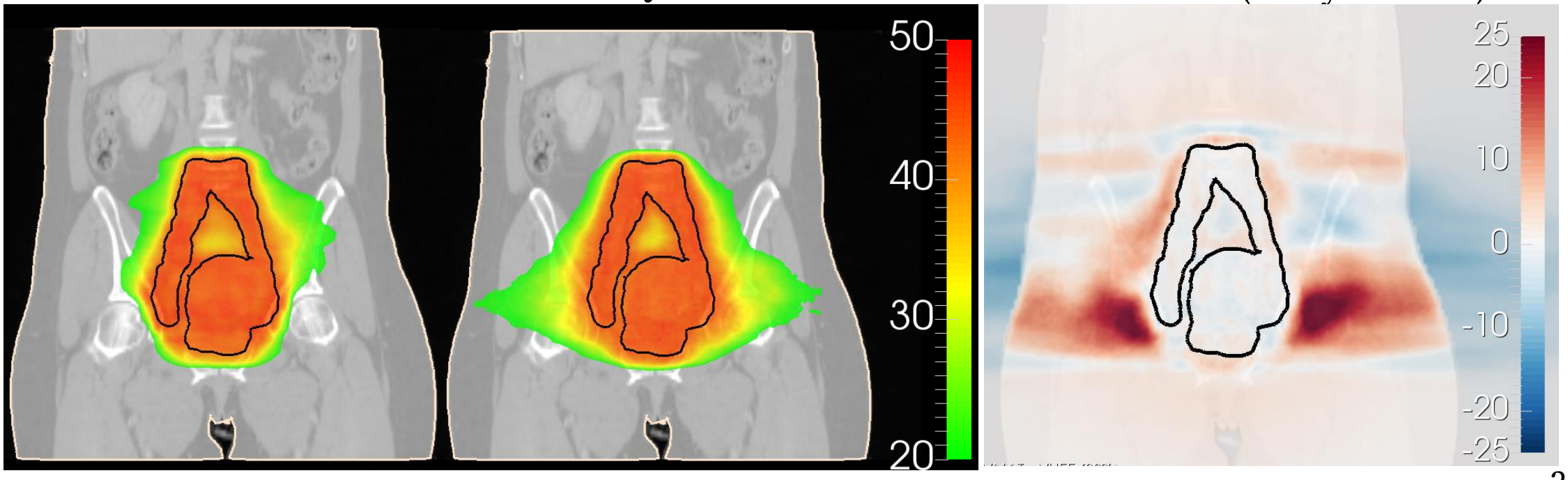
Treatment Plans: VHEE vs VMAT

- If we then also look at the difference between the two we can see there are barely any spots where the VHEE plan has a higher dose than x-ray plan (outside of the tumour)
- Inside the tumour we see more or less the same dose coverage.

VHEE Plan

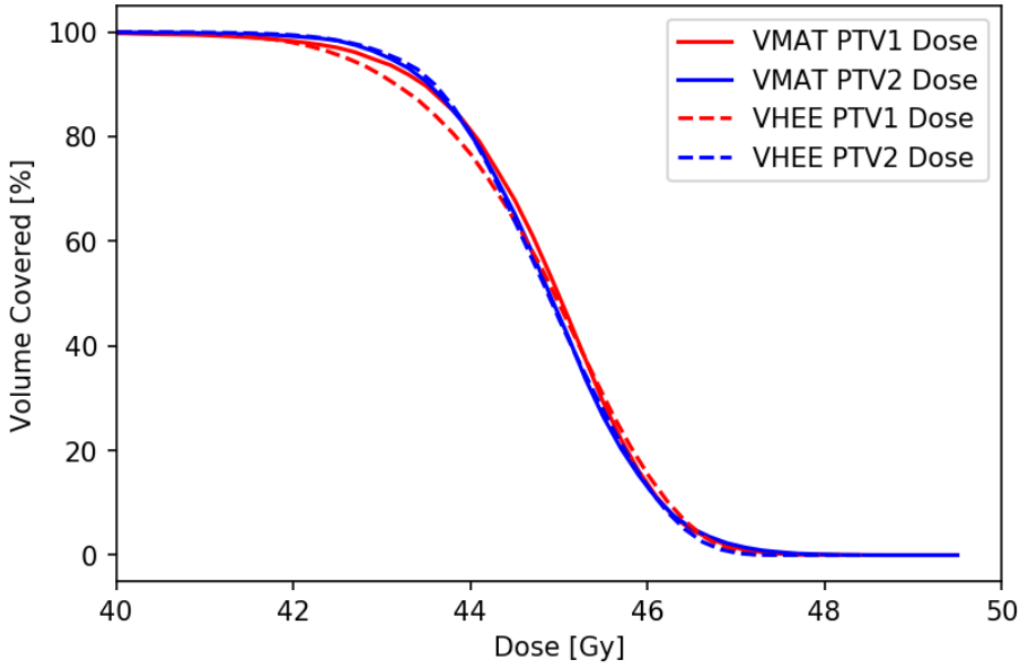
X-ray Plan

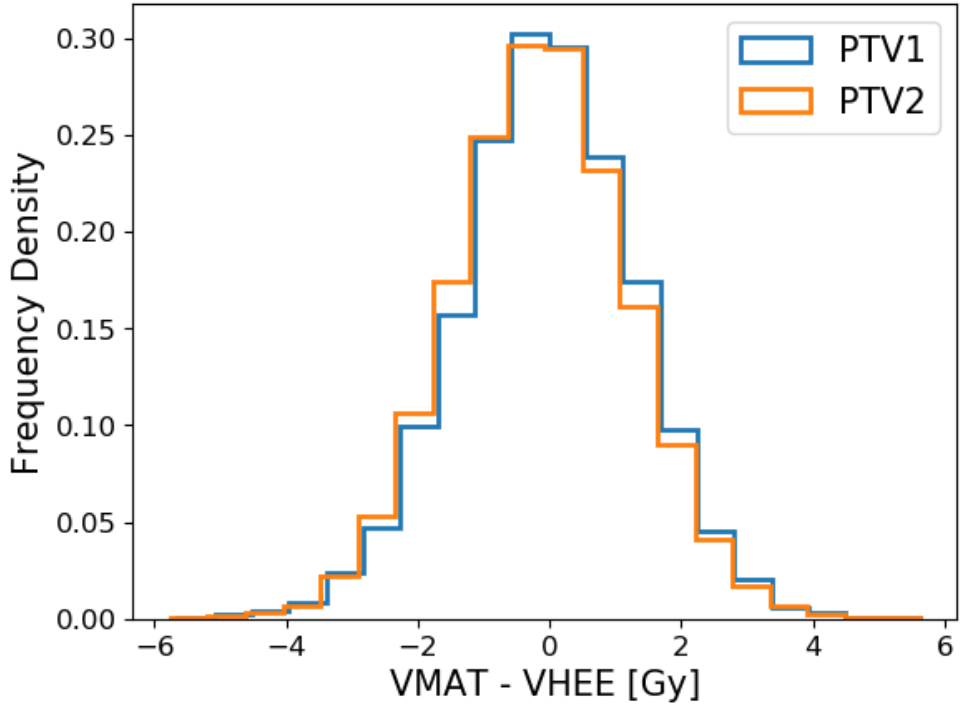
Difference (X-ray – VHEE)



Treatment Plans: VHEE vs VMAT

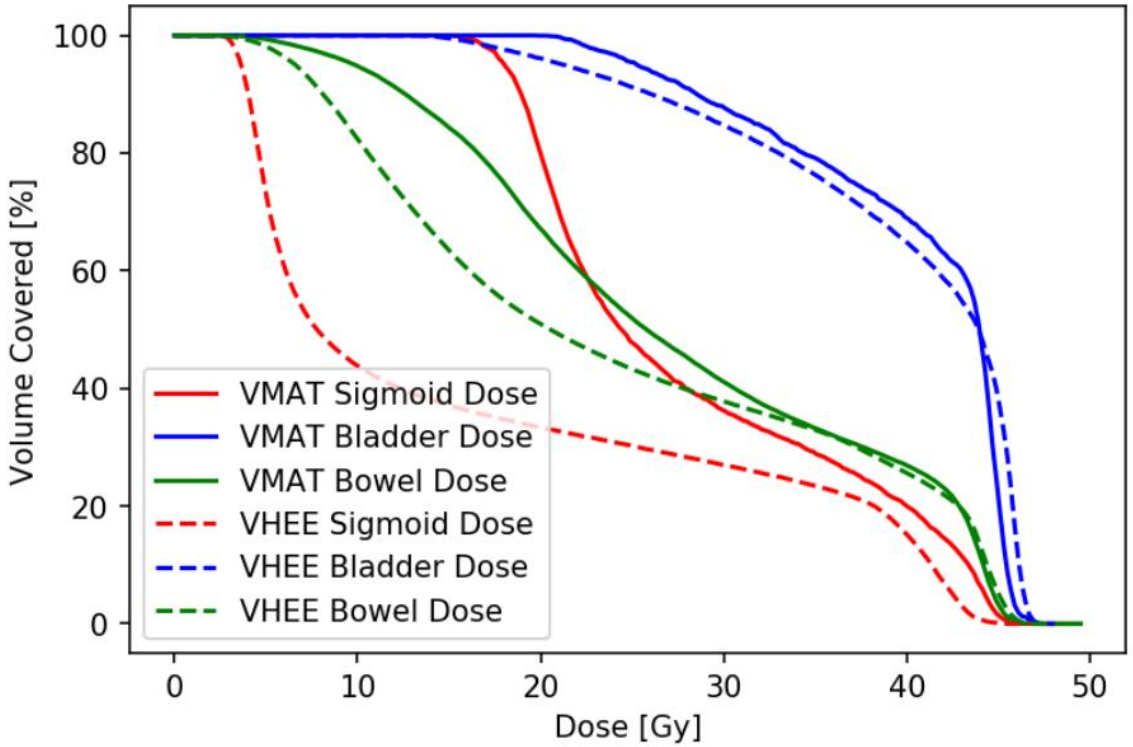
Two main Planning Treatment Volumes (**PTVs**) we care about:
- PTV1 is the main bulk of the tumour
- PTV2 includes the nodes near to the cervix, which are also irradiated to stop spread



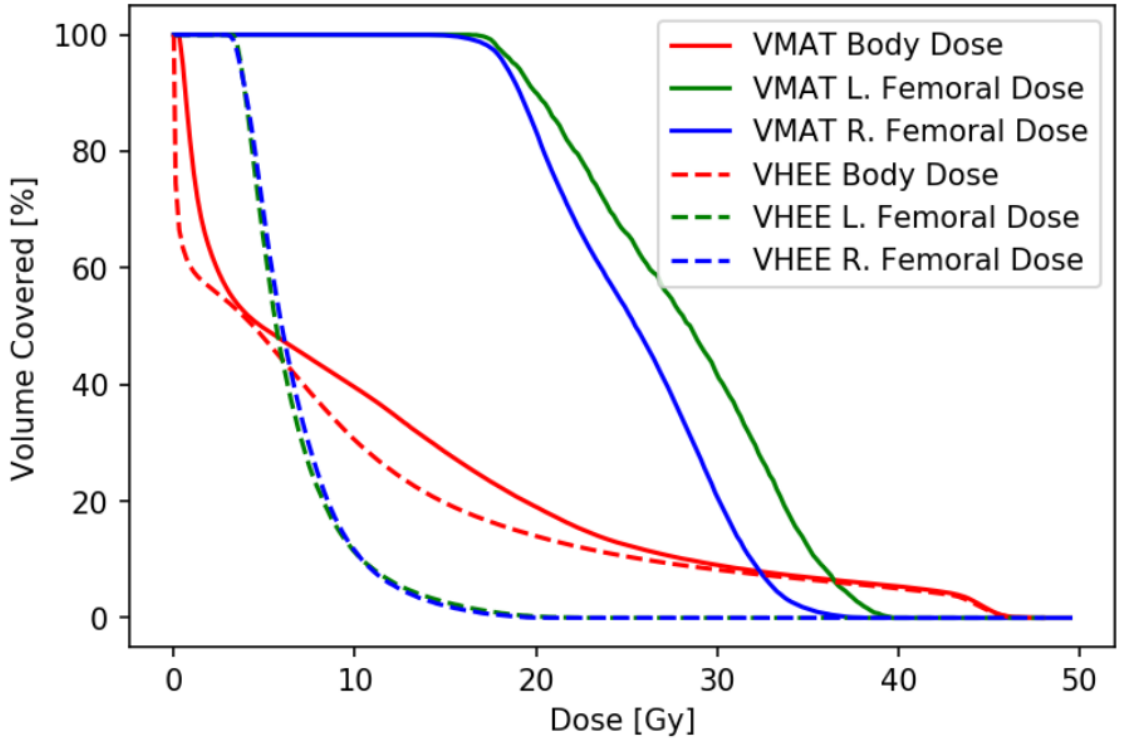


Treatment Plans: VHEE vs VMAT

- We see improvements in the DVHs for the organs near the PTVs



- For the organs further away from the tumour we see very significant decreases in dose.



Note: Solid lines = X-ray plans & Dashed lines = VHEE plans

Treatment Plans: VHEE vs VMAT

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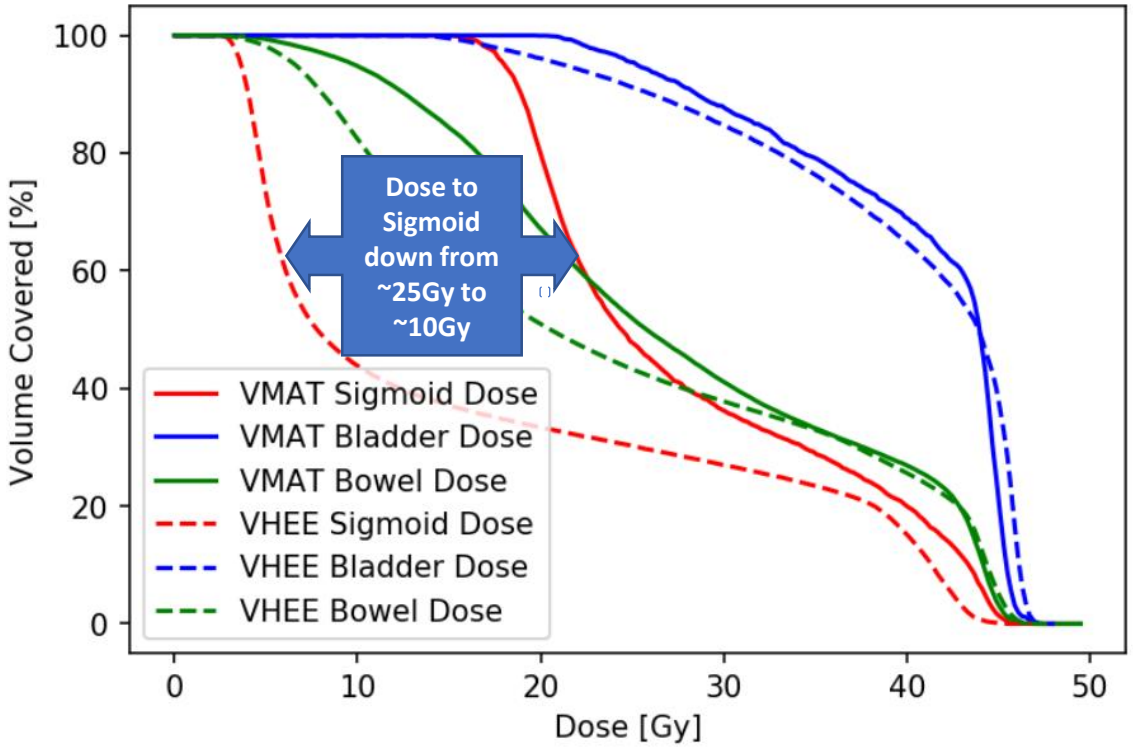

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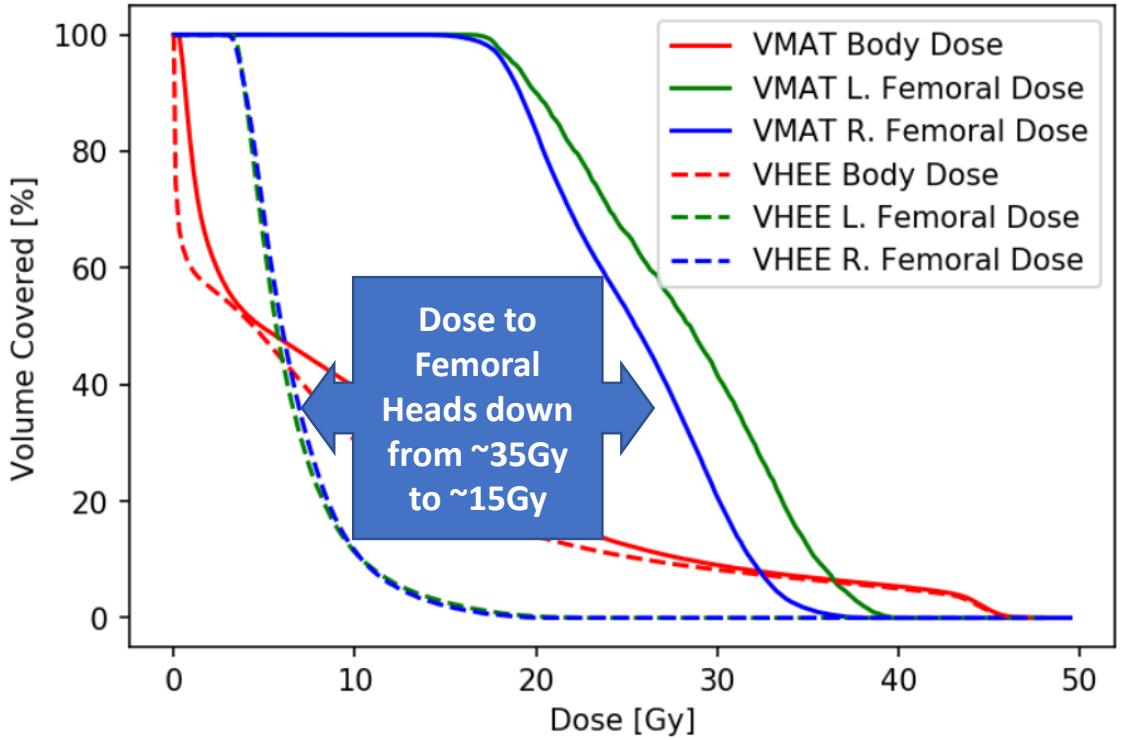

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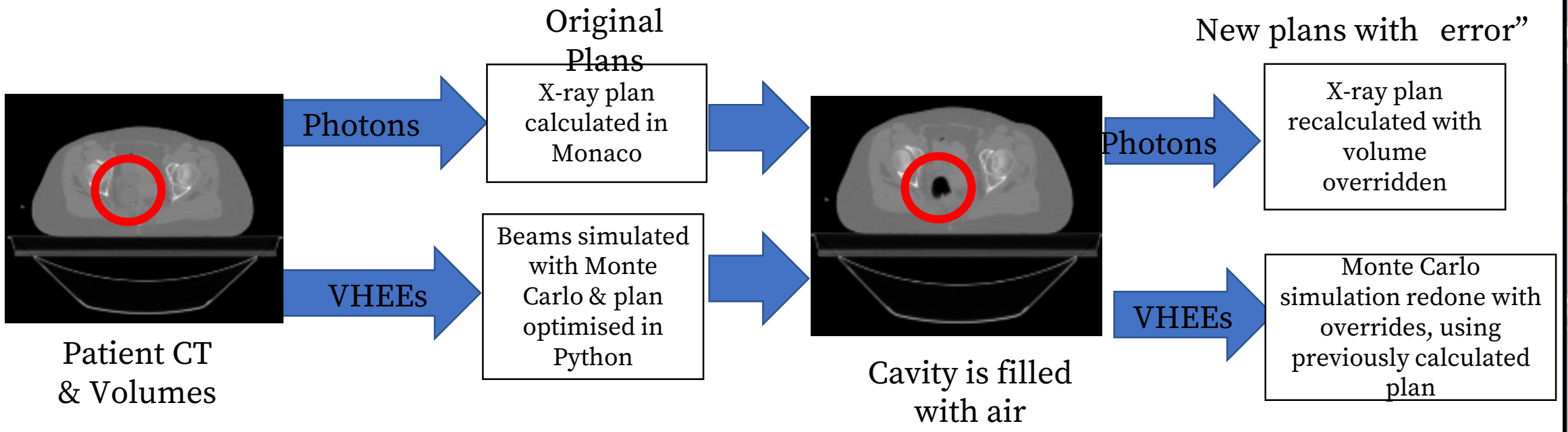
So, what about the patient changes then?

- For a cervical cancer patient we have **simulated the effect of the emptying of an cavity in the patient** between planning and delivery of the case.
- In the original plan the cavity is full of water.
- We then simulate the effect of a changing patient geometry by adding air into the cavity and resimulating the plans.

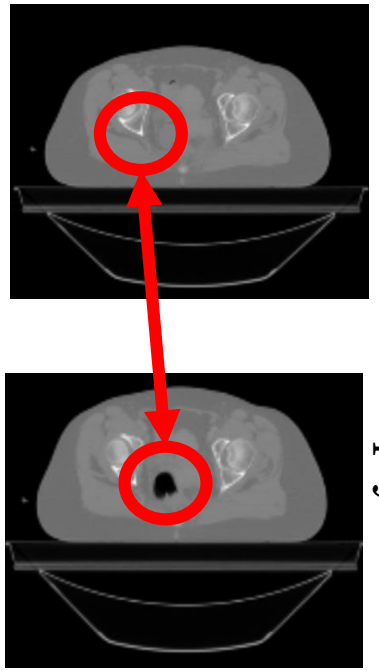


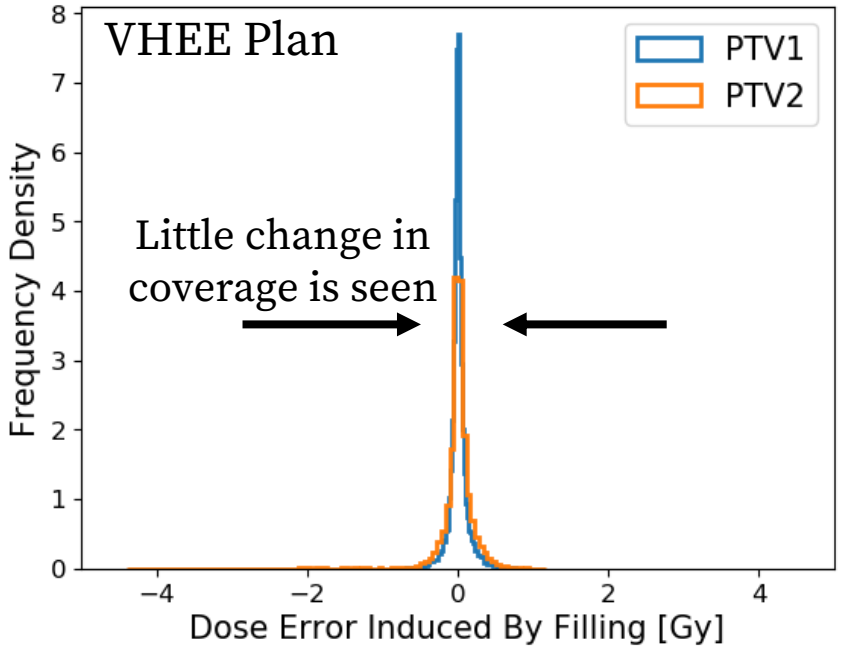
So, what about the patient changes then?

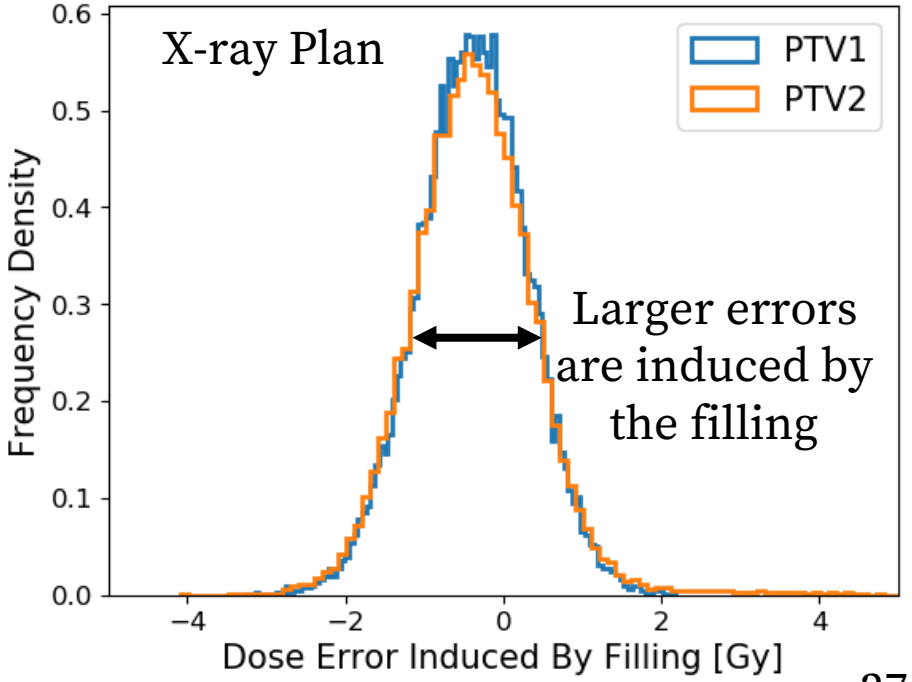
- We can now asses the impact that the unexpected volume filling makes. If we define the dose error as the difference in plan doses:

$$\text{Error} = \textit{Plan Dose}(\textit{ filled volume}) - \textit{Plan Dose}(\textit{ empty volume})$$

- For VHEEs this is ~0.15Gy, and for X-rays this is ~0.7Gy







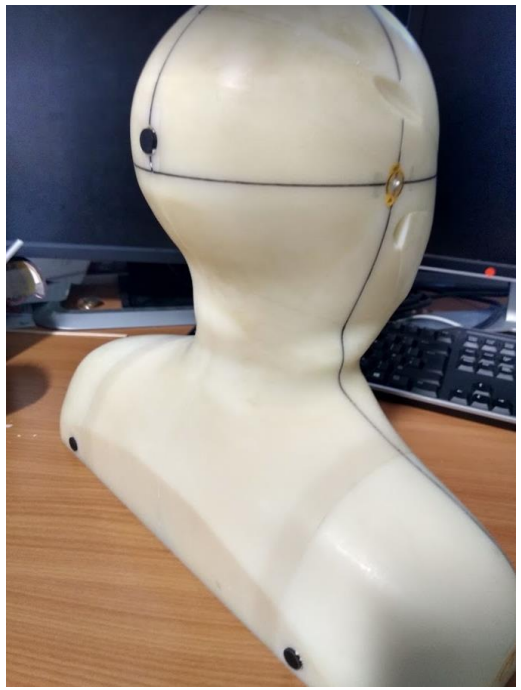
Next steps: Heading towards clinical use

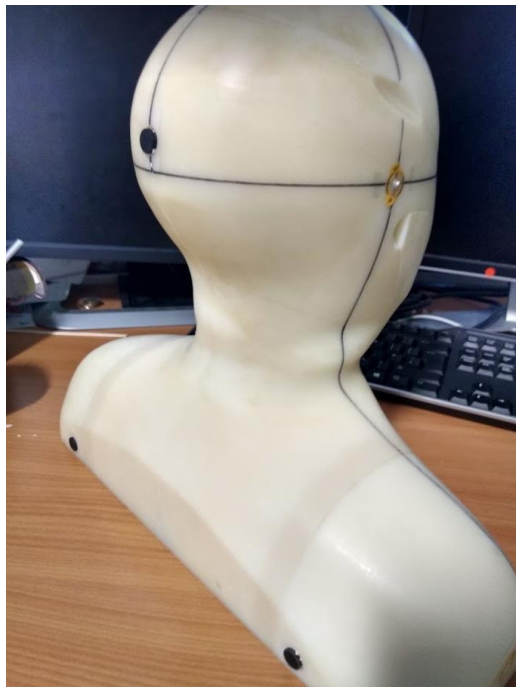
- The best of both worlds" promise does seem to be borne out so far!
- Obviously with such a new modality, there many different types of cases we want to consider. We're also now looking at preforming the same analysis with a lung case and brain case
- For now, the best next step is to start moving away from Monte Carlo set ups and towards putting real things in real beams.

Next steps: Heading towards clinical use

- **MARVIN:** The Model Anatomy for Radiotherapy Verification and audit In the head and Neck" is a plastic replica of a human head & neck used for audit by the Christie.

- So far, no such phantom has been used to assess dose deposition by high energy electron beams

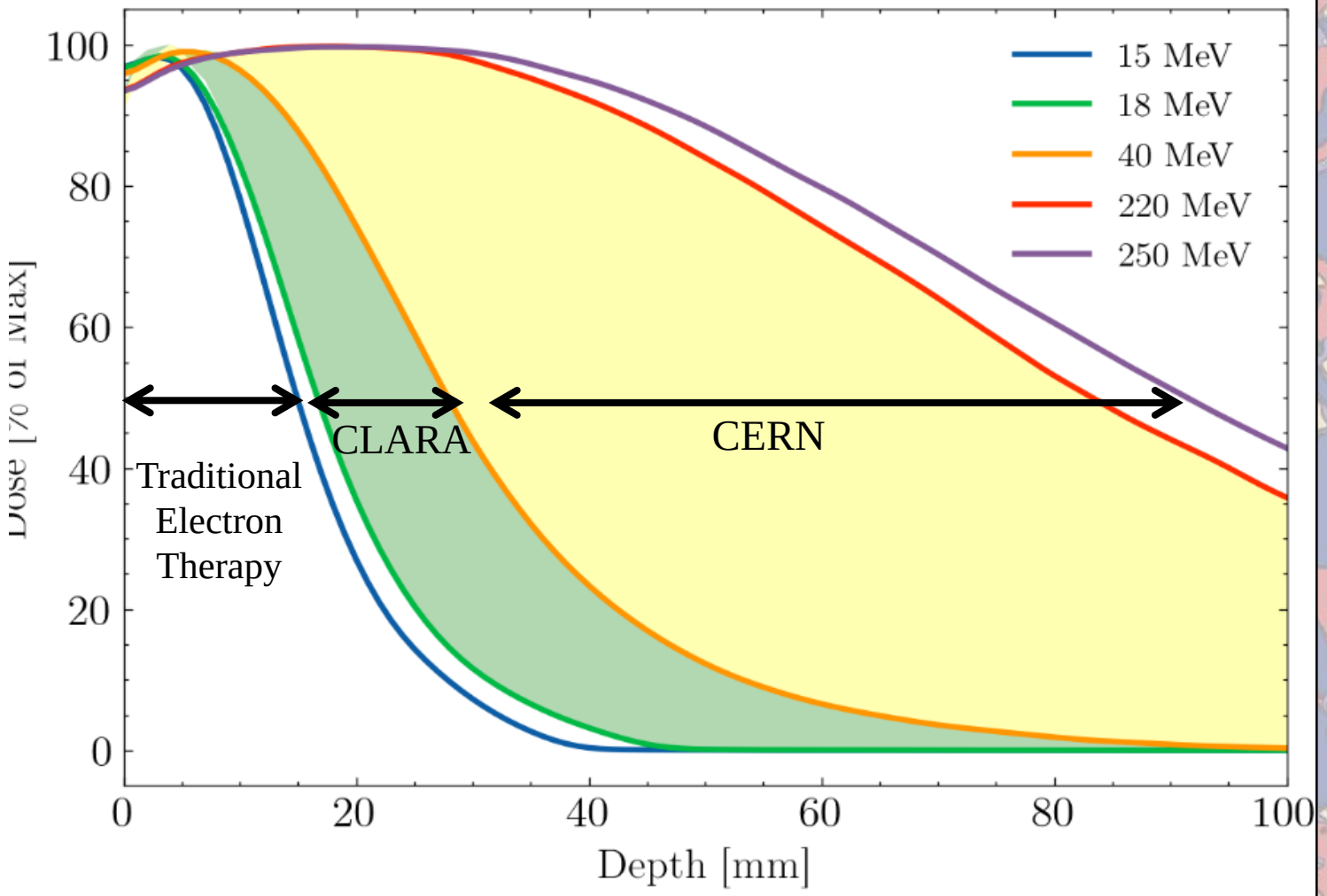




9kg total mass
ABS plastic
Height: 33cm
Width: 41cm
Depth: 21cm

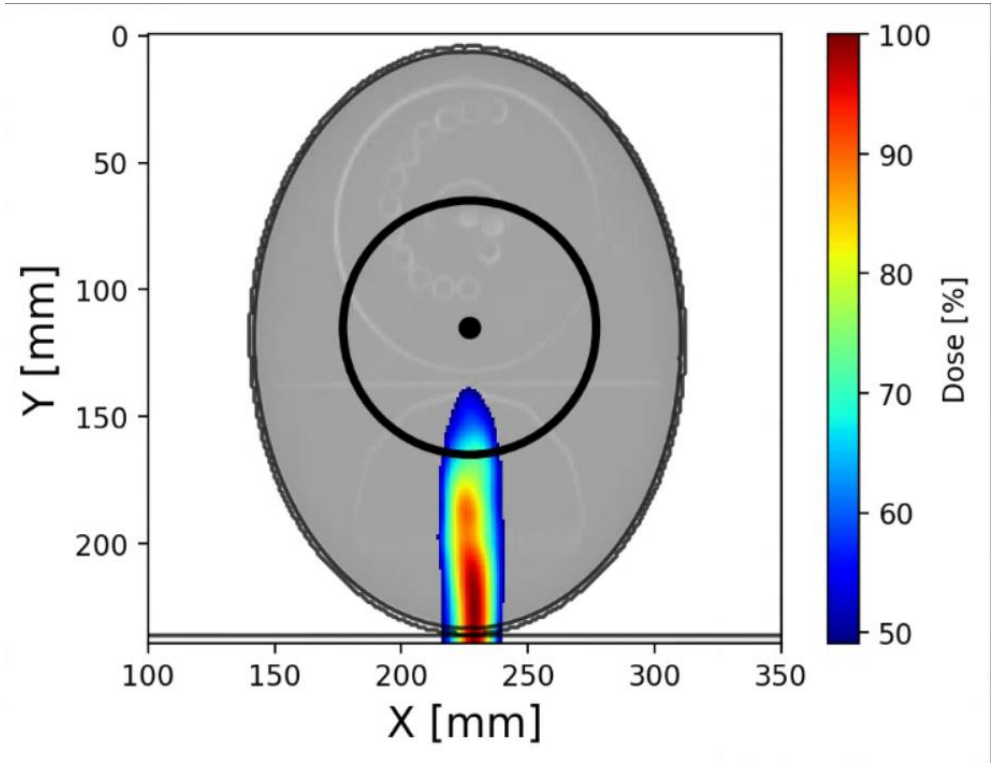
Next steps: Heading towards clinical use

- We're also looking to make experimental measurements of VHEE beams in a realistic environment
- CLARA is a 15-45MeV electron accelerator in the Daresbury Laboratory that we have been allocated time on
- We also have experience working with CLEAR at CERN. This gives us an energy span which will cover all therapeutic depths



Next steps: Heading towards clinical use

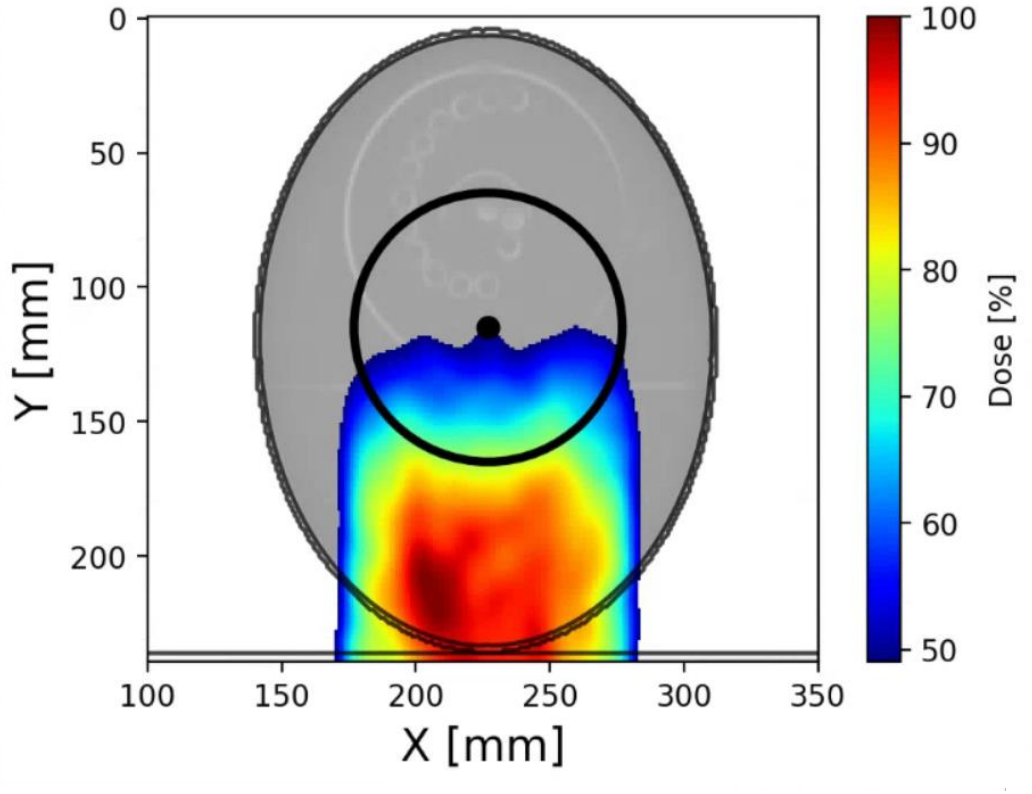
- Looking at a single CLARA style 45MeV electron beam into a patient, we don't see much penetration into the patient.



Next steps: Heading towards clinical use

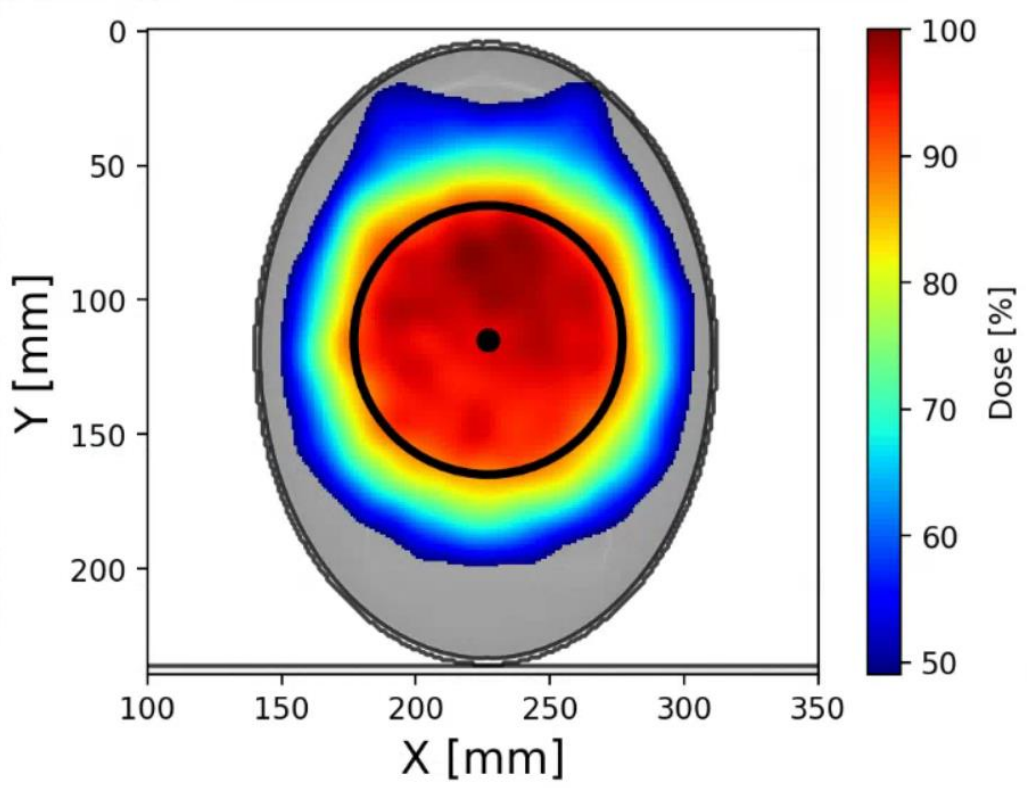
- Looking at a single CLARA style 45MeV electron beam into a patient, we don't see much penetration into the patient.

- However, by moving MARVIN in the horizontal plane we can simulate scanning the beam as would be done in a real treatment.



Next steps: Heading towards clinical use

- Looking at a single CLARA style 45MeV electron beam into a patient, we don't see much penetration into the patient.
- However, by moving MARVIN in the horizontal plane we can simulate scanning the beam as would be done in a real treatment.
- Finally, by rotating him (to simulate gantry motion) motion, we can attain a uniform dose distribution even relatively deep into tissue.



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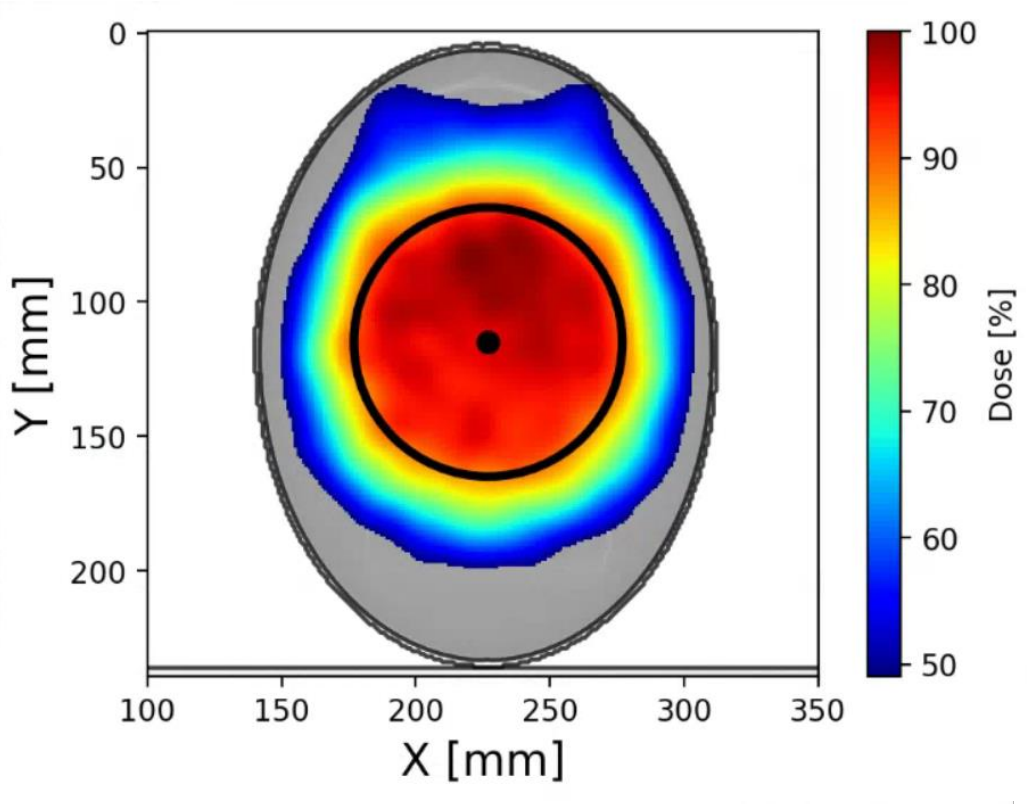
- Luckily, this is a great plan, and nothing can go wrong. The experiment is scheduled to finish on Wednesday the 25th of June.



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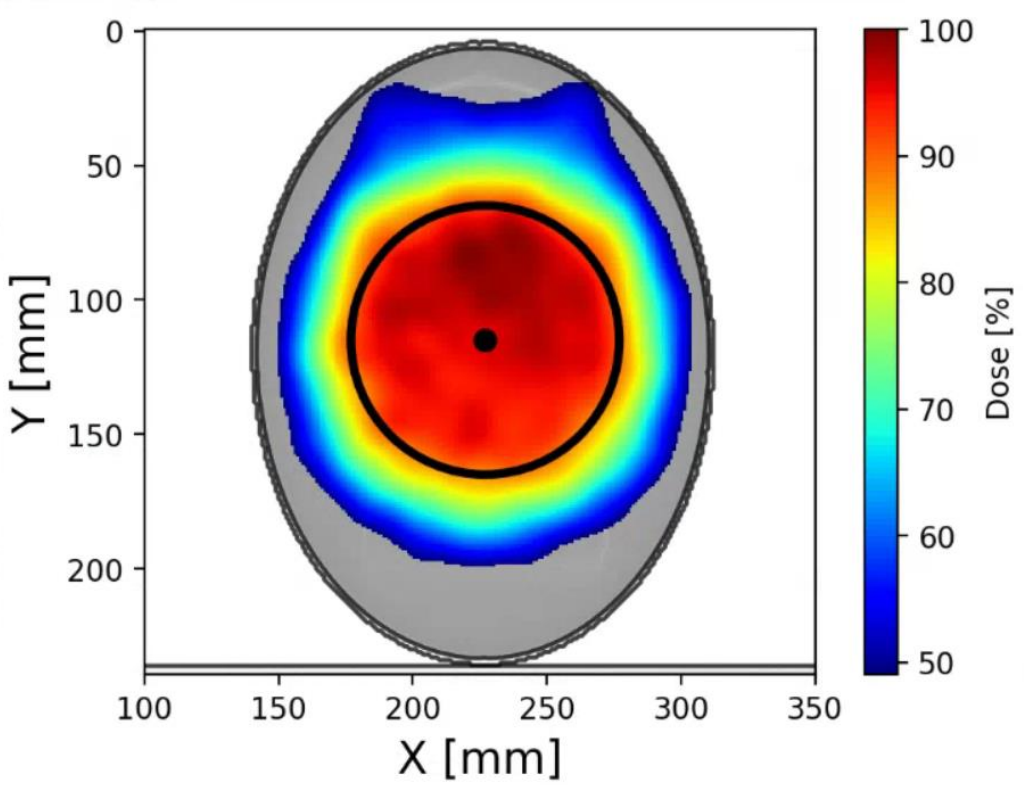
Experiment delayed due to global pandemic!



Conclusions

- The use of Very High Energy Electrons for radiotherapy has been assessed for a clinical test case, and it is found that they can provide equal treatment to tumours **and** improve sparing of healthy tissue.
- The choice of a Cervical case means that we can confirm (in silico) that VHEERT has the ability to treat tumours that are both deep and large in size.
- The insensitivity of VHEE beams has previously been shown in simple water tank simulations, and now in clinical cases where realistic inhomogeneities have been introduced.
- We should expect this to be of some clinical benefit.

Thanks for listening.

With thanks to Adam Aitkenhead, Neil Burnet and Peter Hoskin for their input and assessment of the plans.

The Christie
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