PoPLaR - SCAPA Phase 1

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29th - 1st August 2025

1 Setup 1

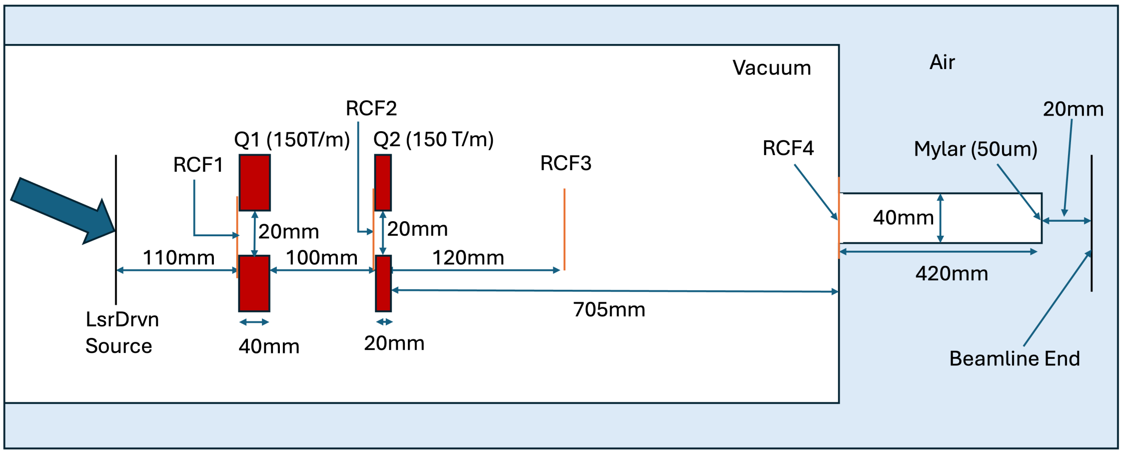


Figure 1: Setup 1: Q1 should be an FQ (focusses in x) and Q2 should be DQ (focusses in y). This is only true after Shot 3. Note the RCF are positions where RCF can be placed. It is not always there.

1.1 Shot 1

First, a Thomson parabola spectrometer (TPS) placed ∼X mm after the beam line end shown in figure 1 was used to establish the maximum energy of protons exiting the vacuum chamber. After improving the laser focal spot, the median maximum proton energy increased from ϵ_{pmax}=(11 ± 1) MeV to ϵ_{pmax}=(12 ± 2) MeV as shown in figure 2.

As the TPS measures only a small fraction of the proton beam, a stack of 2x HDV2 and 8x EBT3 RCF films, each (5 x 5)cm was placed ∼3.9 cm behind the solid target for a shot under the initial 'poorer' focal spot quality conditions. Figure 3 shows that protons deposited dose up to the 4th EBT3 layer. SRIM modelling confirms this corresponds to a maximum energy of ϵ_{pmax}=11.2 MeV, in good agreement with the TPS measurement for these laser focal spot condition.

Under the expectation that the laser-target interaction conditions don't change significantly from this point onwards, the quads were placed in the setup shown in Figure 1. An RCF stack of only EBT3 was placed at the beamline end. However, no dose was recorded.

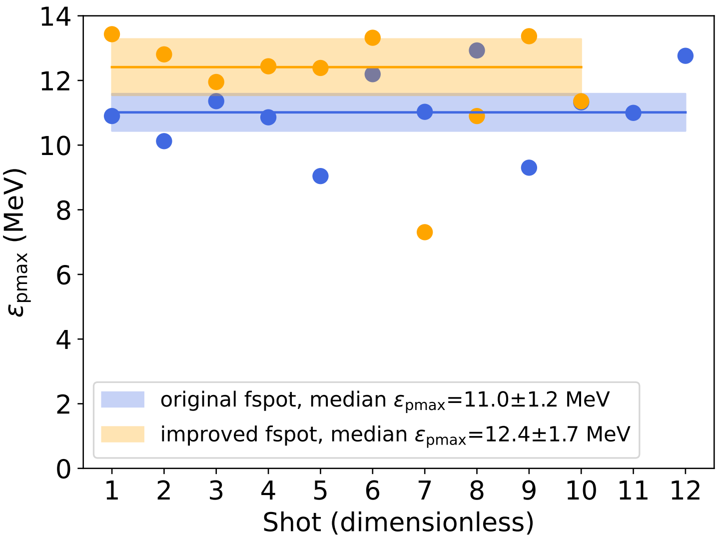


Figure 2: Maximum proton energies detected using a Thomson parabola spectrometer over a series of shots are shown as scatter points before (blue) and after (orange) the laser focal spot quality was improved. Lines and shaded regions indicate the median and ±1 standard deviation for each data-set.

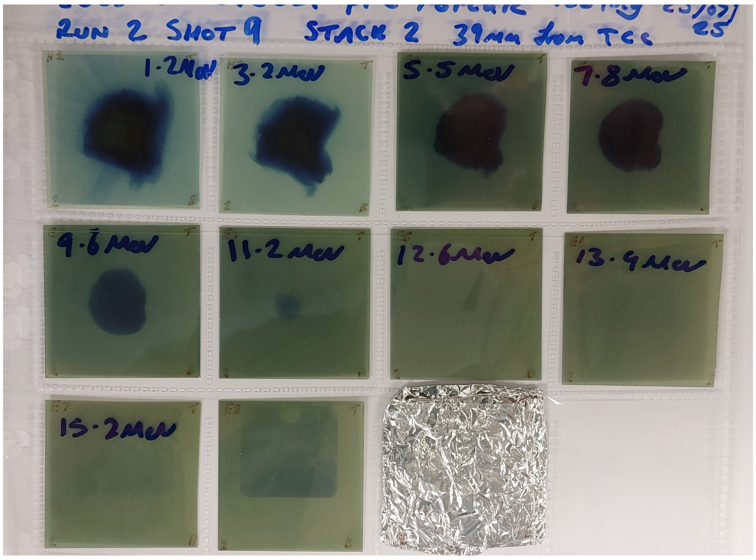
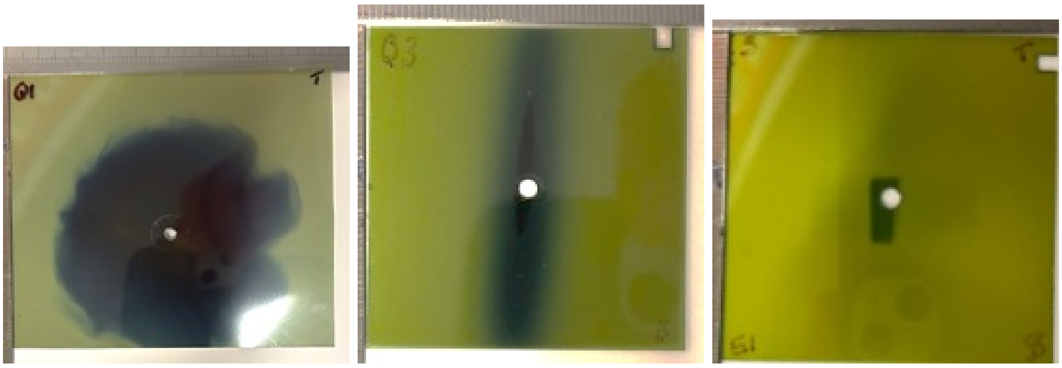


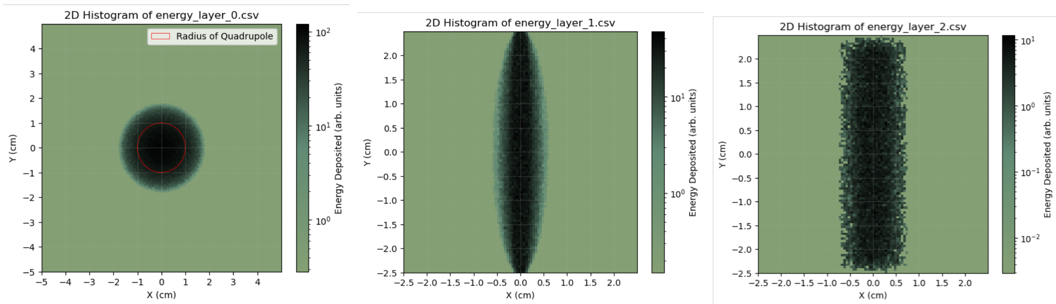
Figure 3: Stack of RCF film with optical density changed due to dose deposited by protons at various energies calculated using SRIM and indicated on the individual layers. Protons deposit dose up to a maximum of 11.2 MeV.

1.2 Shot 2

To test the setup was correct, and determine what was happening to the beam, single sheets of 5cmx5cm EBT3 covered in 13μm thick Aluminium were placed at the face of Q1 and Q2. There was a third sheet placed at 12cm after the rear of Q2. These are indicated in Figure 1 as RCF1, RCF2 and RCF3 respectively. The sheet at RCF1 saw the expected circular blob, and the sheet at RCF2 saw the expected vertical beam. This indicated that the beam was being produced and the first quad was in the correct rotation. The sheet at RCF3 however, only saw a small dose profile. The sheets had small apertures cut into them for alignment with a laser, we believe this small profile came from particles that had passes through this aperture on the previous two sheets. The results are shown in Figure 4



(a) Pre Q1 (b) Pre Q2 (c) 12cm after the rear of Q2

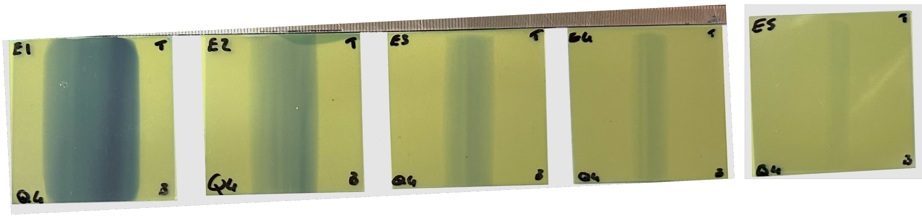


(d) Pre Q1 Sim (e) Pre Q2 Sim (f) 12cm after the rear of Q2 Sim

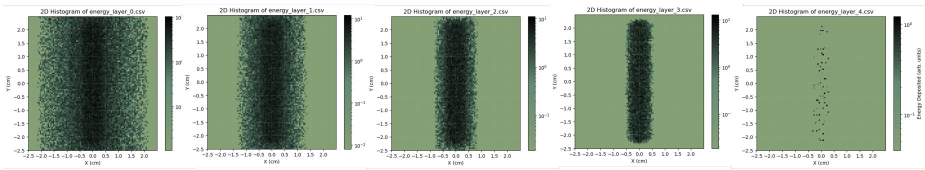
Figure 4: Comparison of Experimental and Simulated RCF, all from Shot 2 (The scales on thes simulated axes match the size of the actual RCF)

1.3 Shot 3

To investigate what happened to the beam after Q2 further, a stack of EBT3 wrapped in the Aluminium, was placed at RCF3. This time a wider vertical line was seen and energy deposition up to the fifth layer of the stack. This places the maximum energy of the beam between 11.4MeV and 12.7MeV. The dose profile indicates Q2 was acting as an FQ rather than a DQ,. This was supported in simulation, as shown in Figure 6, and in 5

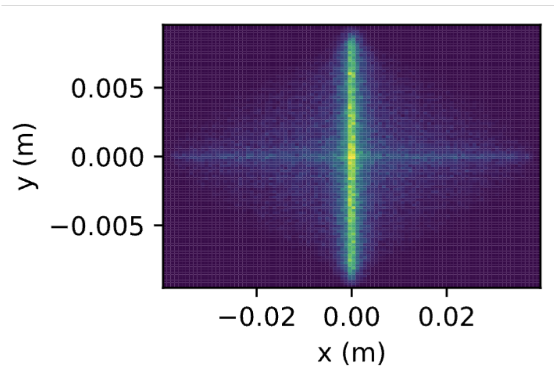


(a) Stack 12cm after the rear of Q2, where Q2 is an FQ

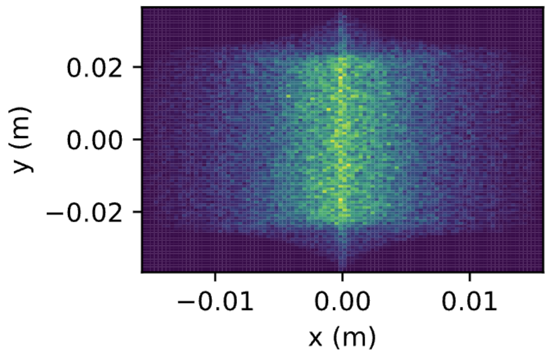


(b) Stack 12cm after the rear of Q2, where Q2 is an FQ sim

Figure 5: Shot 3



(a) Q2 correctly placed as a defocussing Quad



(b) Q2 incorrectly placed as a focussing Quad

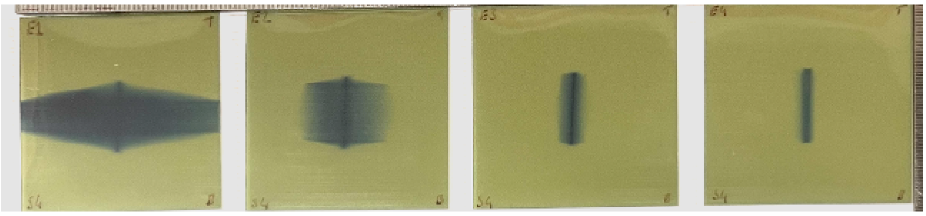
Figure 6: Beam Profiles at 12cm after Q2

1.4 Shot 4

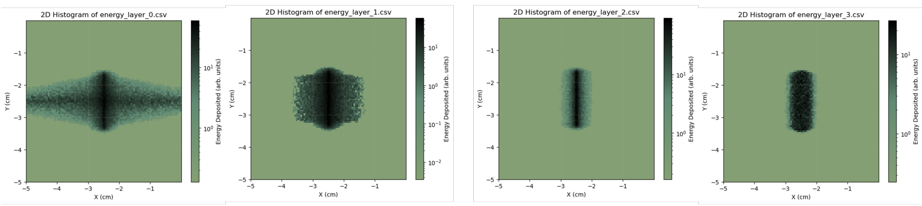
After rotating Q2 by 90 degrees, a 10cmx10cm sheet of EBT3, covered in Al, was placed at RCF3, and a full stack of 5cmx5cm EBT3 was placed at the beamline end. The first sheet saw a profile that matched the profile seen in simulation, but the stack saw no beam [Again, worth adding a photo and comparing to sim?]. It is possible that there are not enough high energy particles to pass through the Al, EBT3, Al and mylar to make a signal on the stack at the end.

1.5 Shot 5

To understand the higher energies, a full stack of EBT3, covered in Al, was placed at RCF3. Particles once again produced a dose profile up to layer 5 indicating the maximum energy of the beam is between 11.4MeV and 12.7MeV. Shown in Figure 7



(a) Stack 12cm after the rear of Q2, where Q2 is an DQ



(b) Stack 12cm after the rear of Q2, where Q2 is an DQ sim

Figure 7: Shot 5

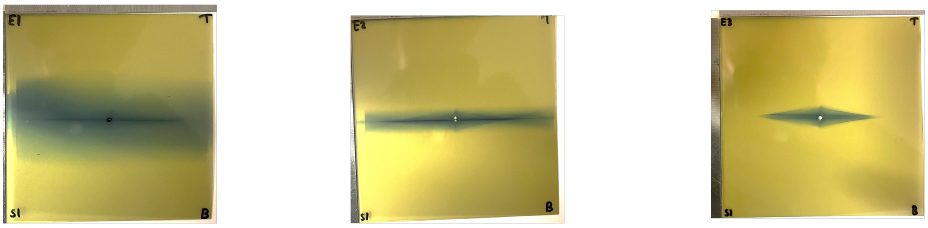
1.6 Shot 6

There also was a concern that the quads may be transversely offset. Therefore, a full stack of 10cmx10cm EBT3, covered in Al, was placed at the hole, indicated in Figure 1 as RCF4. This showed a wide horizontal beam with no clear offset, indicating the quads were aligned and shown in Figure 8. It did however show that the beam focussed too soon, shown in Figure 9. To remedy this the quads could be moved closer to the target. This is supported by the optimisation runs on the best positioning of the quads, as shown in Figure 10.

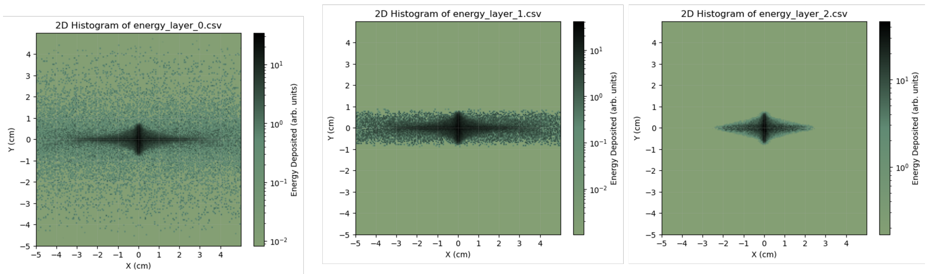
1.7 Summary of RCF placements in shots

2 Setup 2

Due to the drives under the quads and their bases as well as the base of the tape target, it was difficult to move the quads closer to the source. However, Robbie managed to shift the quads closer



(a) Stack at hole



(b) Stack at hole sim

Figure 8: Shot 6

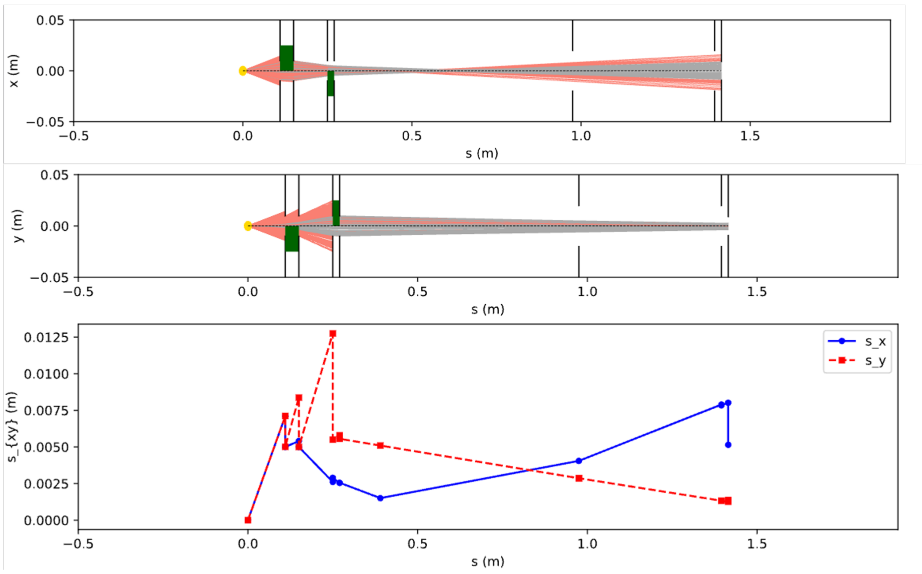


Figure 9: Beam Plots for D1: 110mm

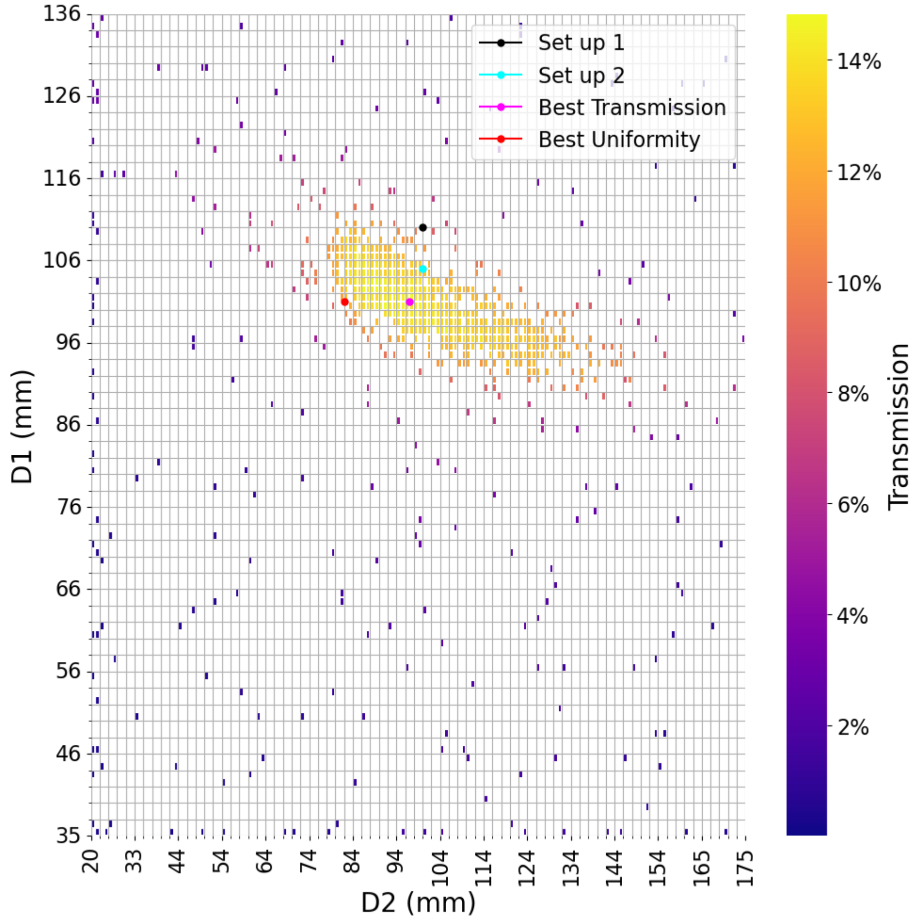


Figure 10: Results of best transmission of a Gaussian spectrum beam centred on 10MeV.

Shot Number	RCF 1	RCF 2	RCF 3	RCF 4	End
1	-	-	-	-	Stack
2	EBT3 (Al wrap)	EBT3 (Al wrap)	EBT3 (Al wrap)	-	-
3	-	-	Stack (Al wrap)	-	-
4	-	-	EBT3 (Al wrap)	-	Stack
5	-	-	Stack (Al wrap)	-	-
5	-	-	-	Stack (Al wrap)	-

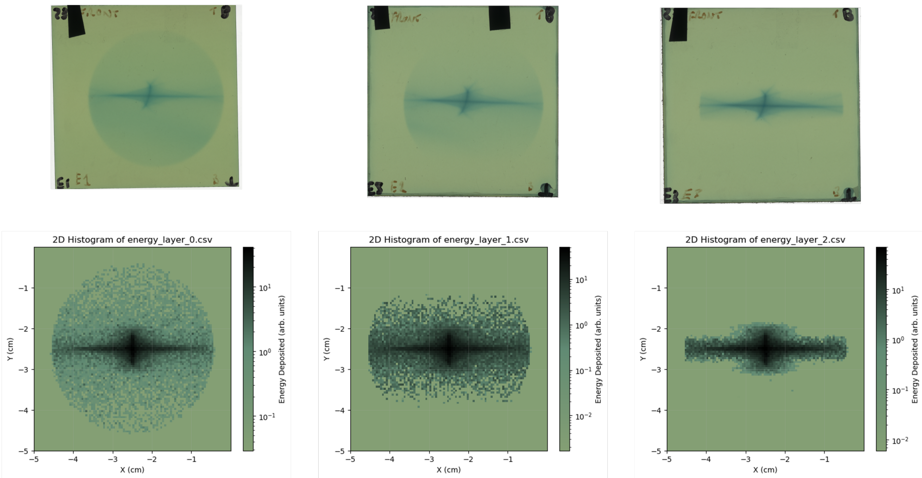


Figure 11: RCF stack at beamline end for Setup 2.

by 5mm so that the setup now becomes:

2.1 Shots on Lanex Imager

Next, a piece of Lanex was placed at the beamline end position indicated in figure 12 and a camera was setup to image scintillation from this Lanex caused by protons of energy >9MeV, determined by adding 7 layers of 100 μm mylar before the Lanex, and the 50 μ mylar window (we should check this cut-on value again with SRIM, especially based on thin window + maybe ND?). A bandpass filter and small sheet of neutral density (ND) film with optical density = 1 were used to preferentially transmit light of wavelength 532 nm and attenuate it by one order of magnitude.

After the steps of section 1 - rotating the second quad, moving both quads closer, and verifying a focused beam was centred on the chamber exit hole - the Lanex imager now saw a beam. Figure 13 shows the beam was predominantly a horizontal line with a slightly tilted smaller vertical line. 20 shots with unchanged laser and target conditions were undertaken at this position to understand the variability of the beam, and variations were seen in count and dose profile. For example, the vertical line occasionally disappeared, as shown in figure 13. These both are believed to be explained by variation in the maximum proton beam energy.

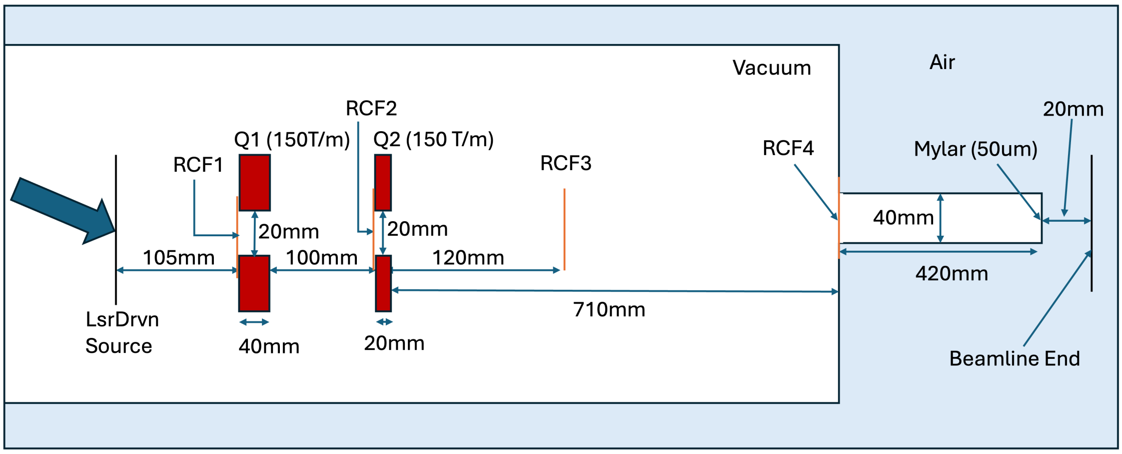


Figure 12: Setup 2. Both quads have shifted closer by 5mm.

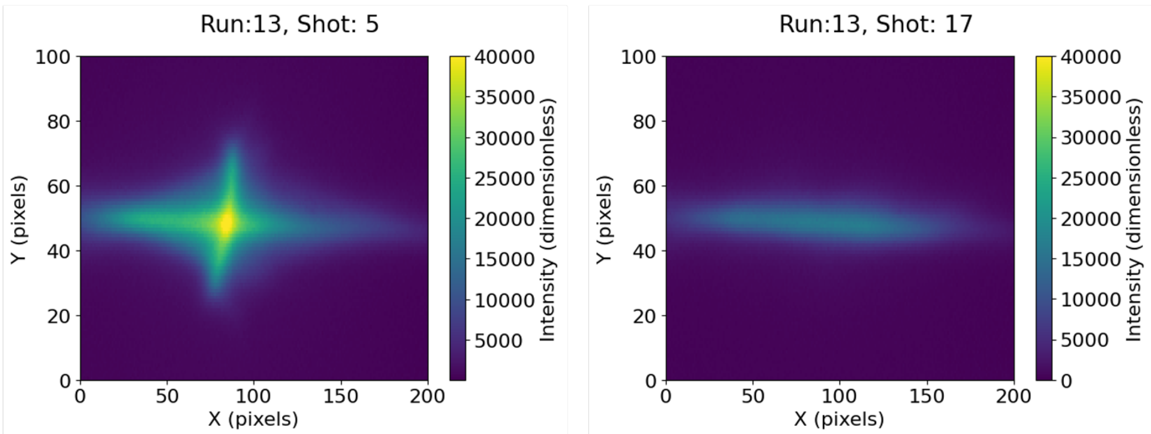
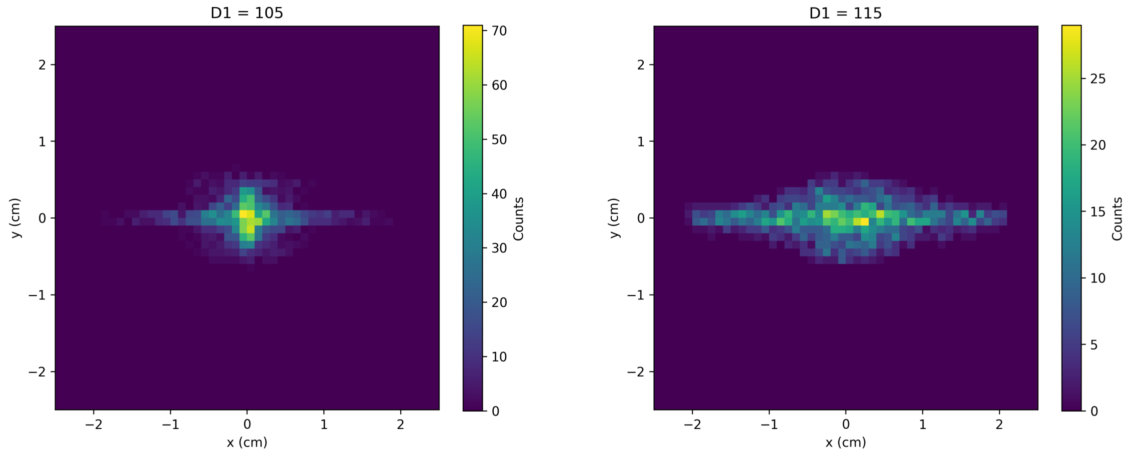


Figure 13: Images of light captured from a Lanex scintillator irradiated by >9 MeV protons. The spatial-intensity profile of the light varies between two shots with nominally identical laser-target interaction conditions.

2.2 Z Scan

After this both quads were shifted back in 1mm increments. At each increment, 3 shots were taken and imaged on the Lanex imager. After a shift of around 5mm the vertical line disappears. The trend towards a horizontal line is supported by simulation, as shown in Figure 14. However, when using the drives to return the quads back to the original position, the vertical line did not reappear. After checking the setup, there is clear evidence that the drives did not return the quads to the same position. This explains this discrepancy. It should be noted that the new pellicle installed in front of the off-axis parabola (OAP) to protect it from debris may have picked up considerable debris by this point, which can reduce the laser energy resulting in lower maximum proton energies.



(a) Profile at default D1=105   (b) Profile at default D1=115

Figure 14: Beam Profile progression with increasing D1

2.3 Establishing proton beam control using quads

The quads were then set back to the closest Z position and a new pellicle was installed in front of the OAP to maximise the laser energy and remove concerns over using a burnt pellicle. The first quad's X, Y, and rotation drives were then moved in various increments, and the proton beam was observed to move around on the Lanex imager diagnostic. Three shots were taken at each new position to also observe beam variation. The first quad was then set back to conditions where the beam was centred on the diagnostic and the same movements were made on the second quad. In both cases the proton beam clearly moved in X and Y, and rotated, when the appropriate drives were moved, establishing that the proton beam spatial profile at the cell irradiation position can be controlled.

2.4 Final tests and statistic gathering

Next, a test was done to establish whether the proton beam signal on the Lanex imager was reducing over time either because the pellicle before the OAP, or the Lanex itself, was burning. A new pellicle was installed in the data-set discussed in the last secion so data should be available for this comparison using the same piece of Lanex.

To test whether the Lanex was burning, ten shots were taken where the laser and target conditions weren't changed, and where both quads were in the current 'optimal' condition, as close as possible to the target, and such that the beam is centred on the Lanex imager.

The Lanex was replaced with a fresh piece, and another ten shots at these conditions were performed.

We then replaced the Lanex with a stack of 7x EBT3 covered in 13 μm aluminium foil, to measure the number of protons at various energies, at the cell irradiation position. Three shots onto three stacks were performed, to give some limited statistics for us to work with.

[Insert 3x scanned RCF stacks to show data and variation in data?]

Next, we put the Lanex back in place and changed the filtering, from 7 layers of 100 μm mylar, to 4 layers of 100 μm mylar, then to 10 layers of 100 μm mylar, then to 11 layers of 100 μm mylar. Ten shots were taken under each condition to observe the spatial-intensity profile of proton beams with four distinct cut-on energies, with some limited statistics.

[Insert figure showing representative Lanex imager images at each condition plus beam detection turning 'on/off' at highest energy condition indicating variable maximum proton energy - as shown in LhARA meeting slides?]

We then changed the pellicle again to install a new pellicle as another test of whether the pellicle was burning, affecting the proton beam spatial-intensity profile. Shots were taken first with the Lanex imager in place, then a single shot was taken with a stack of 7x EBT3 covered in 13 μm aluminium foil in place, to characterise the number of protons at various energies under the fresh pellicle condition.

More shots were taken with the Lanex imager in place, the quad Z position was adjusted slightly, then another single shot was taken with another RCF stack in place.

[Include images of scanned RCF data?]

Finally, twenty shots were taken with the Lanex imager in place.

As a final note, the laser focal spot quality may have been diminishing throughout the experiment because no wavefront optimisation was performed after the initial optimisation which increased the maximum proton energies, as shown in figure 2. Focal spot data was saved throughout the experiment, and can be analysed if the proton diagnostics indicate decreasing maximum proton energies/numbers throughout the experiment, to determine whether this is occurring due to diminishing focal spot quality, towards the first condition shown in figure 2.

3 Conclusions and Further Work

The main takeaway is that a beam of protons was successfully delivered to the beamline end where the cells would be. Also that >10 MeV protons were delivered to this position, as desired for PoPLaR. The simulations were shown to be a useful tool and usually managed to accurately recreate the beam.

Moving forward, the main things to consider are:

- To improve the quality of the proton beam both the distance the quads are from the source and from each other could be reduced. However, this requires rearrangement of the drives and possibly the tape target.
- Stabilising the beam at a higher maximum energy should produce more reliable 10MeV results. The team at SCAPA indicated that this was doable.
- Pellicle burn - Robbie is writing a paper on this so hopefully will be able to predict roughly when it could occur.

- PMQ hysteresis - Robbie has mentioned a magnet strip to make the drives more precise in their positioning