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Exploring beamline acceptance for fast energy regulation with an upstream degrader in pencil beam scanning (PBS) proton therapy

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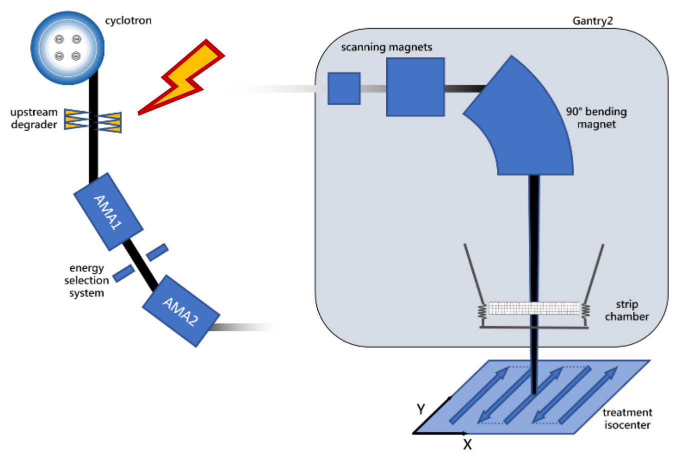
INTRODUCTION

At PSI, the beam energy is defined using a fast **upstream degrader** together with associated tuning of the beamline, ensuring accurate beam position and range at treatment isocenter.
Indeed, it is the beamline tuning that currently limits energy layer changes to **100 milliseconds.**



Beamlines have a finite **momentum acceptance**: within the acceptance the energy can be changed without retuning the entire beamline. For this study we considered energy variations within the Gantry 2 energy acceptance of ± **0.6% momentum acceptance dp/p**.

MATERIALS AND METHODS

We have evaluated whether the **upstream degrader** can be used to change the beam energy within the **gantry acceptance**, thereby obviating the need to re-tune the beamline, achieving **faster** modulation.
Beam properties have been characterised at four non-nominal energies within acceptance around **100**, **150** and **200** MeV, to obtain changes in beam range of ± 0.5 and ± 1 mm.
The goal of clinical level beam quality has been investigated analysing:

- Depth Dose Curves → Strip Chamber
- Beam position → Range Scanner
- Phase Space → CCD Camera

RESULTS

Depth-Dose Curves

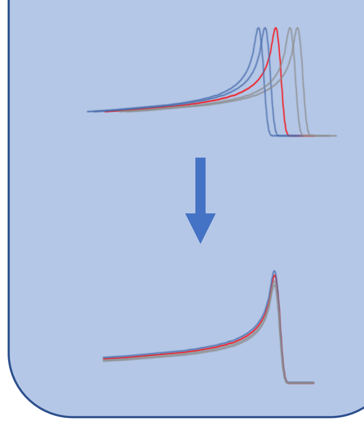
Integral depth-dose curves were measured with a large parallel-plate ionization chamber of 80 mm immersed in a water tank, the **range-scanner**.

1D Gamma pass-rate was calculated against respective nominal energies after Bragg peak alignment at R80.

Experimental data have shown negligible distortion in shape with overall gamma pass rate (1%/1mm) **above 94%**. The maximal variation in range were respectively 0.2 mm, 0.5 mm and 2 mm due to beam losses in the beamline.

Experimental set-up: Range Scanner

Depth alignment at R80



Degrader set-point [MeV]	R80 [cm]	Max variation	Gamma pass rate (1%/1mm)
200.459	26.04		98.24 %
200.226	26.02		100%
200	25.99	2 mm	
199.772	25.95		100%
199.545	25.84		95.29%
150.525	15.81		100%
150.264	15.8		100%
150	15.79	0.5 mm	
149.728	18.78		94.12%
149.450	15.76		96.9%
100.731	7.74		100%
100.366	7.73		100%
100	7.73	0.15 mm	
99.635	7.72		100%
99.270	7.72		98.78%

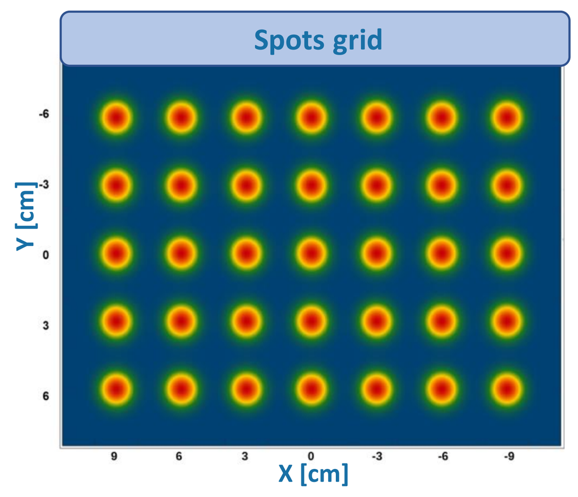
Beam position

Beam position error in the transversal plane has been verified using a **strip chamber** aligned at treatment isocentre.

The position of 35 dose spots evenly spaced on a grid to cover 20x12 cm scan range has been measured.

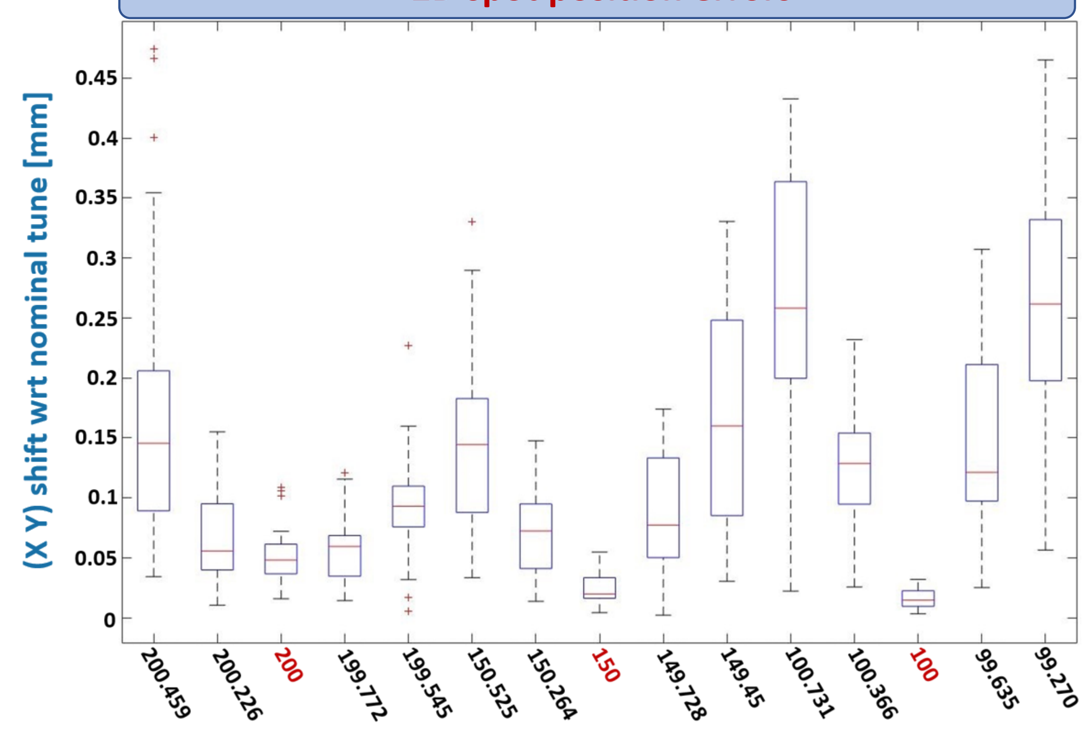
2D in-plane **position error** has been found to be as low as **0.09 mm** (IQR: 0.11 mm) on average.

Spots grid



Experimental set-up: Strip Chamber

2D spot position errors

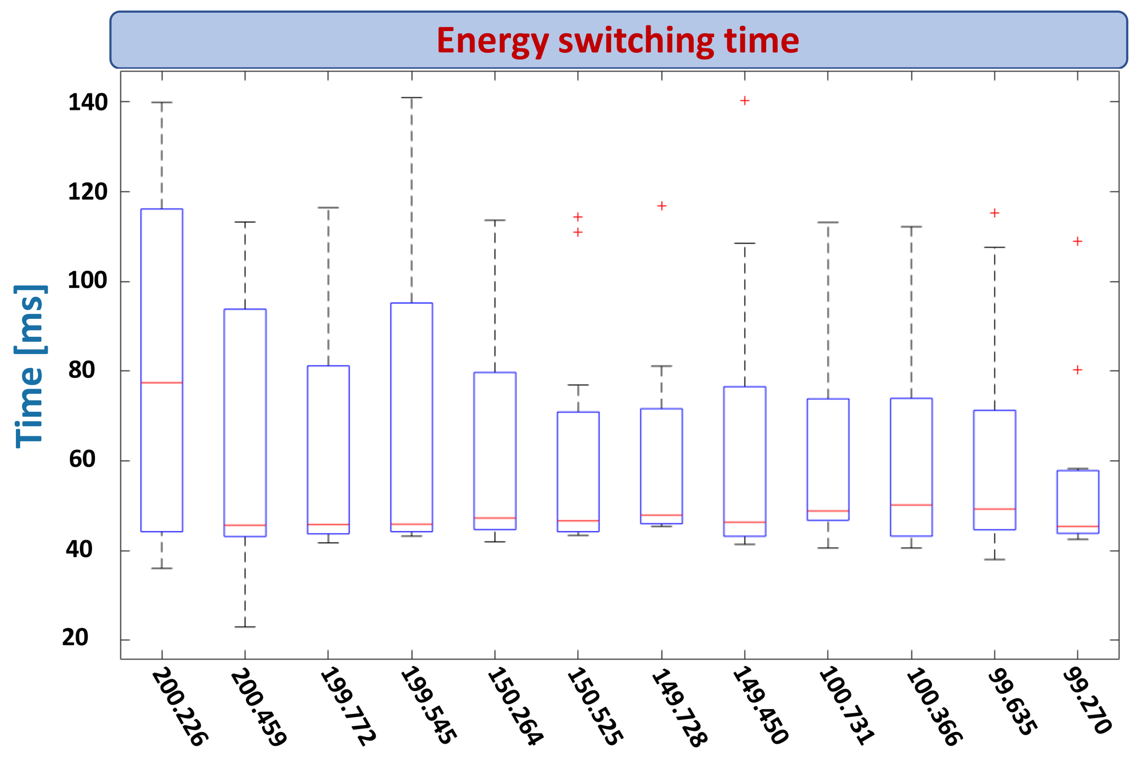


Time performance

The time performance of the upstream degrader has been investigated analysing the **machine logfiles** from multiple deliveries.

Even without ad-hoc changes of the clinical beamline, the upstream degrader could be controlled with a latency of **44.06 ms** (IQR: 15.46 ms) in repeated measurements.

Energy switching time



Phase Space

The **2D lateral profiles** were measured with a scintillating screen coupled with a **CCD camera** to evaluate the in-plane spatial variances: σx and σy.
Beam size was evaluated delivering a single spot at treatment isocentre in air. The difference in spot dimension with respect to clinical spot size has been considered:

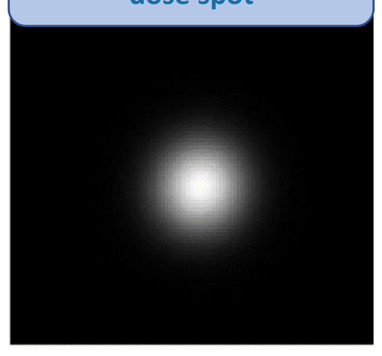
$$d\sigma = \sigma_{clinical} - \sigma_{measured}$$

Negligible distortion in **shape** and **size** of the beam spot has been found:

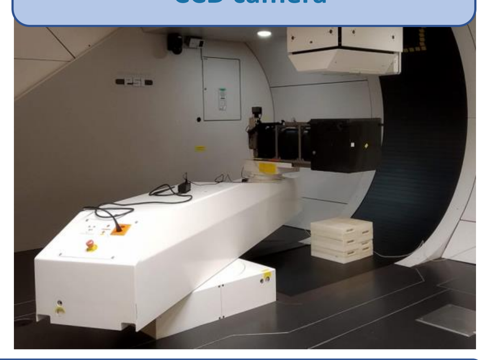
$d\sigma_x$ 0.05 mm (IQR: 0.05)

$d\sigma_y$ 0.06 mm (IQR: 0.09)

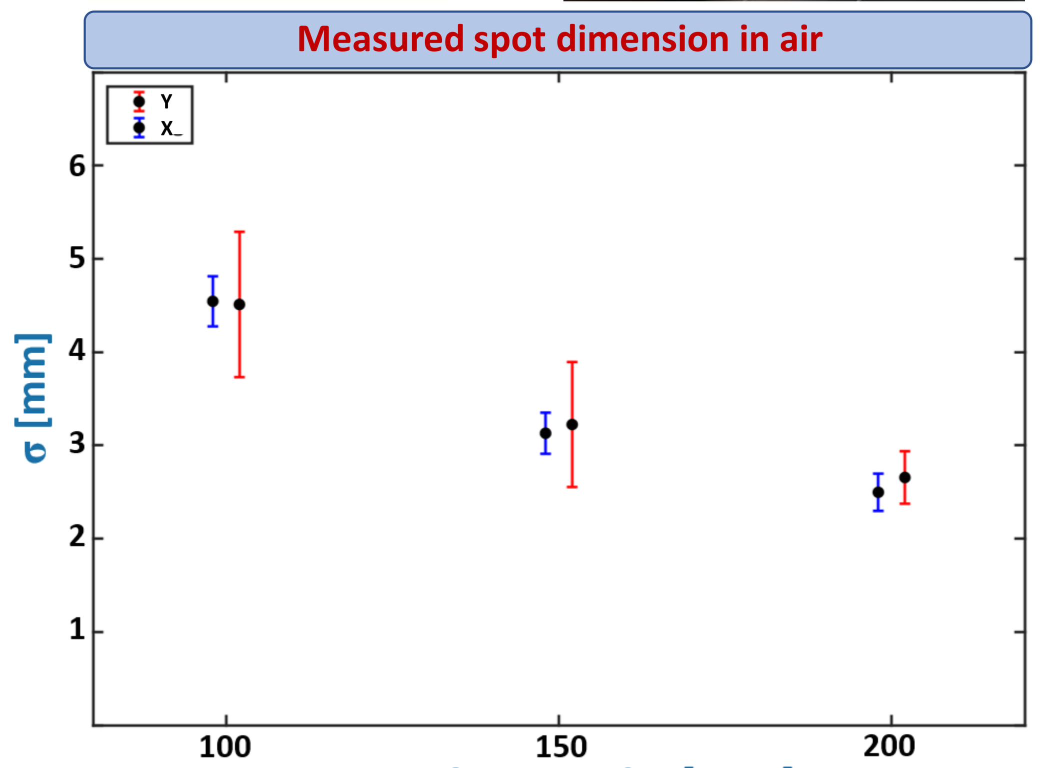
CCD image of the single dose spot



Experimental set-up: CCD camera



Measured spot dimension in air



CONCLUSIONS

Very **fast energy changes** can be realized within the momentum acceptance while **preserving clinical level beam quality**.
However, these preliminary results are for a nominal gantry acceptance, and potentially larger changes are possible, albeit with increased losses in beam current.
This solution does not require ad hoc changes in the beamline and it is therefore applicable in most clinical units.

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