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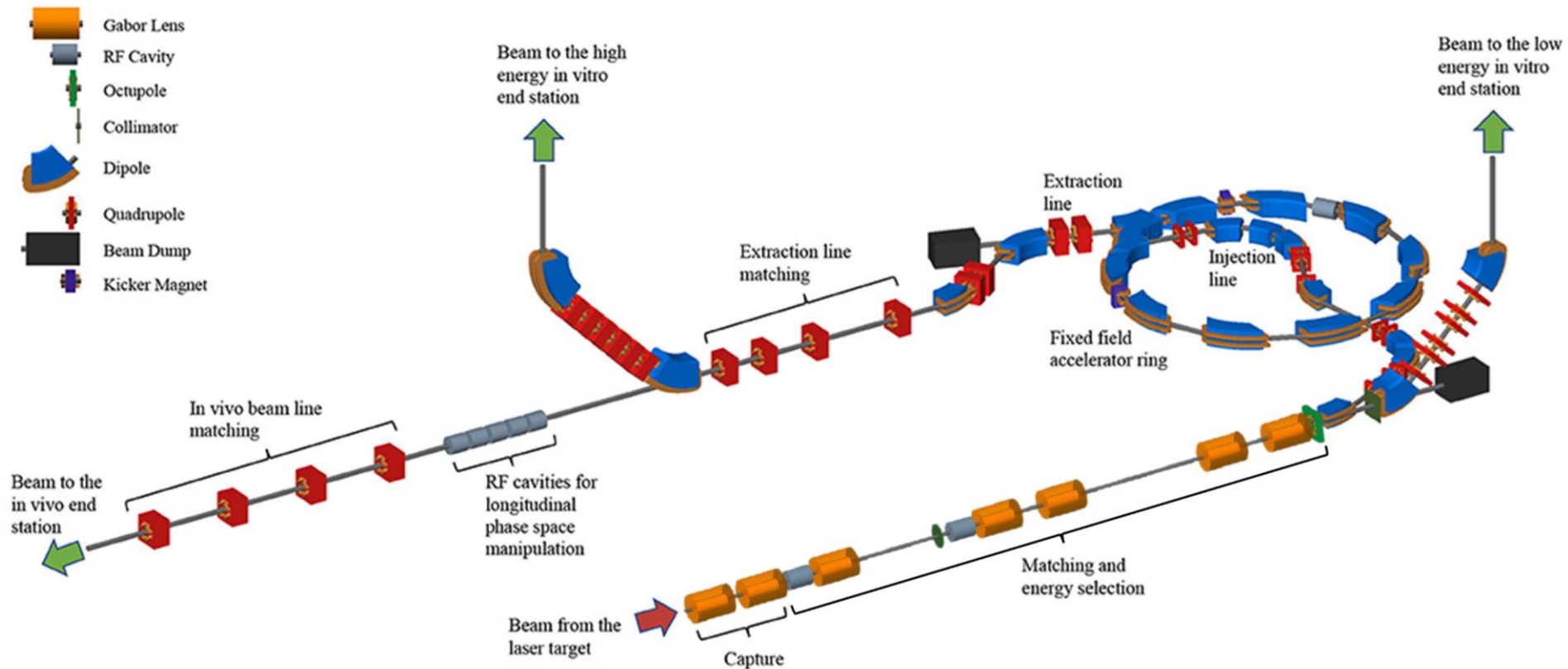
Development of Novel Beam Instrumentation for In Vivo and In Vitro End Stations for LhARA

Rehanah Razak
08/04/2025



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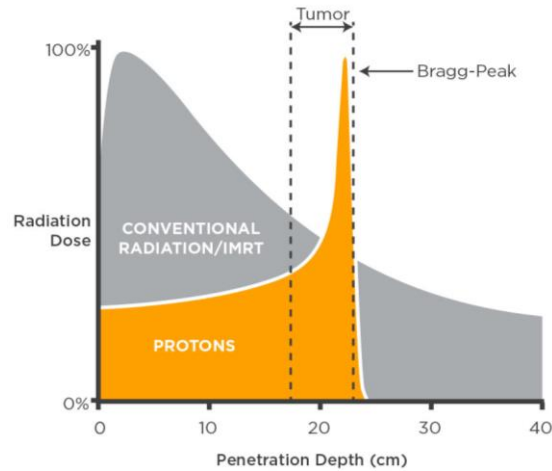




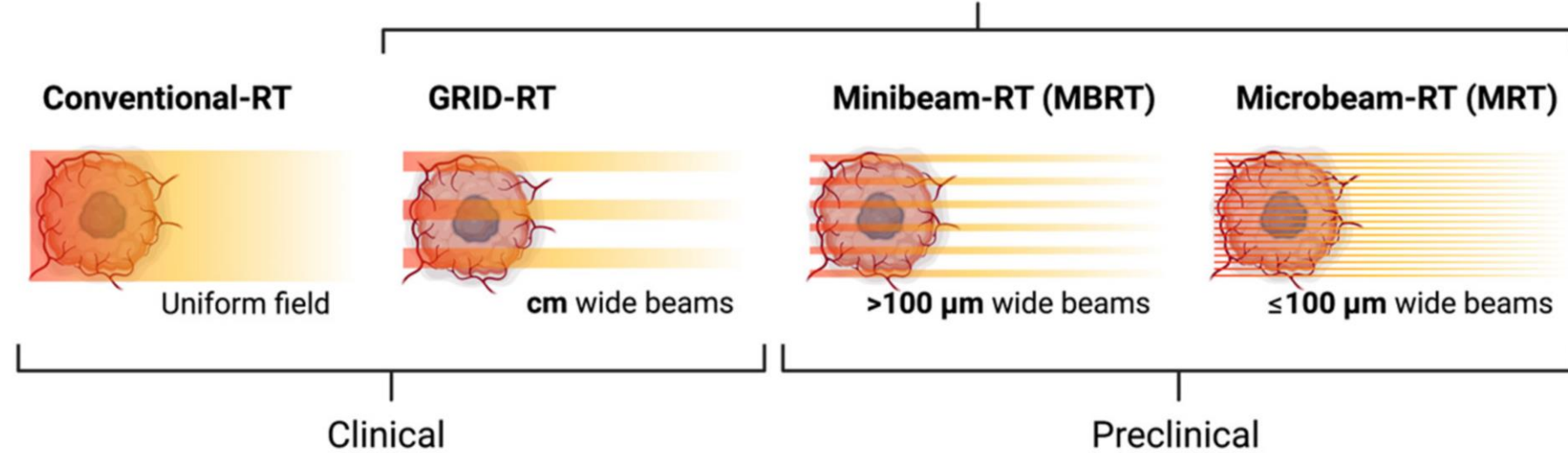
- **Flexible research facility** for the study of multi-ion Particle Beam Therapy and their radiobiological effects on tissue
- **Novel radiotherapy modalities:** ultra-high dose rates, Minibeam Radiation Therapy and Spatially Fractionated Radiation Therapy

Radiotherapy Modalities

Minibeam Radiation Therapy (MBRT)



Spatially Fractionated Radiation Therapy (SFRT)

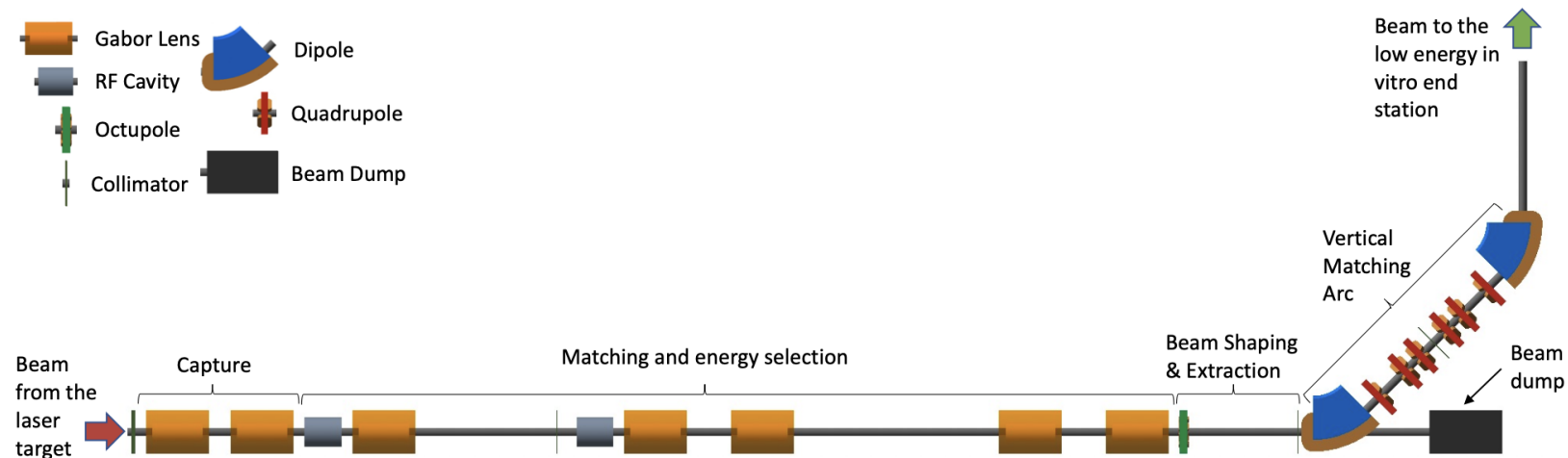


- **Minibeam Radiation Therapy (MBRT)** are beams with diameters of between 100 μm - 1 mm

- **Spatially Fractionated Radiation Therapy (SFRT)** delivers beam in fractions to minimise ionising radiation exposure to healthy tissue, promoting normal-tissue sparing effects

Magnetic Beam Focusing Requirements

- Current LhARA Stage 1 baseline design can deliver ultra-high dose rates of ~ 120 Gy/s with a 15 MeV proton beam
- This baseline can only deliver **spot sizes of 1-3 cm** to the end station with current 7 Gabor Lens setup
- So, a magnetic focusing system is needed to generate a **parallel** beam that satisfies the minibeam regime requirements and maintains beam intensity



Magnetic Beam Focusing

Beam Delivery System

Simulations



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Simulations of the beam delivery system have been developed in:

1. **BDSIM** (Beam Delivery Simulation; Geant4-based)
2. A **linear optics tracking code** (python-based)

Linear optics tracking code aims to:

- Implement beam dynamics structure that simulates the LhARA's linear optics
- Understand the beam emittance effects when generating proton minibeam

Magnetic Beam Focusing

Bayesian Optimisation



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JAI
John Adams Institute for Accelerator Science

Bayesian optimisation was chosen to minimise the beam size to < 1 mm, from a 1 cm spot size distribution by exploring the parameter space, iteratively, to finding optimal drift lengths

Optimisation parameters:

- **Drift lengths** between quadrupole magnets in the focusing system

Constrained cost function:

- Sum of drift lengths < 2 m

Cost function:

- Cost = σ_x (where σ_x is the rms beam radius – beam size)

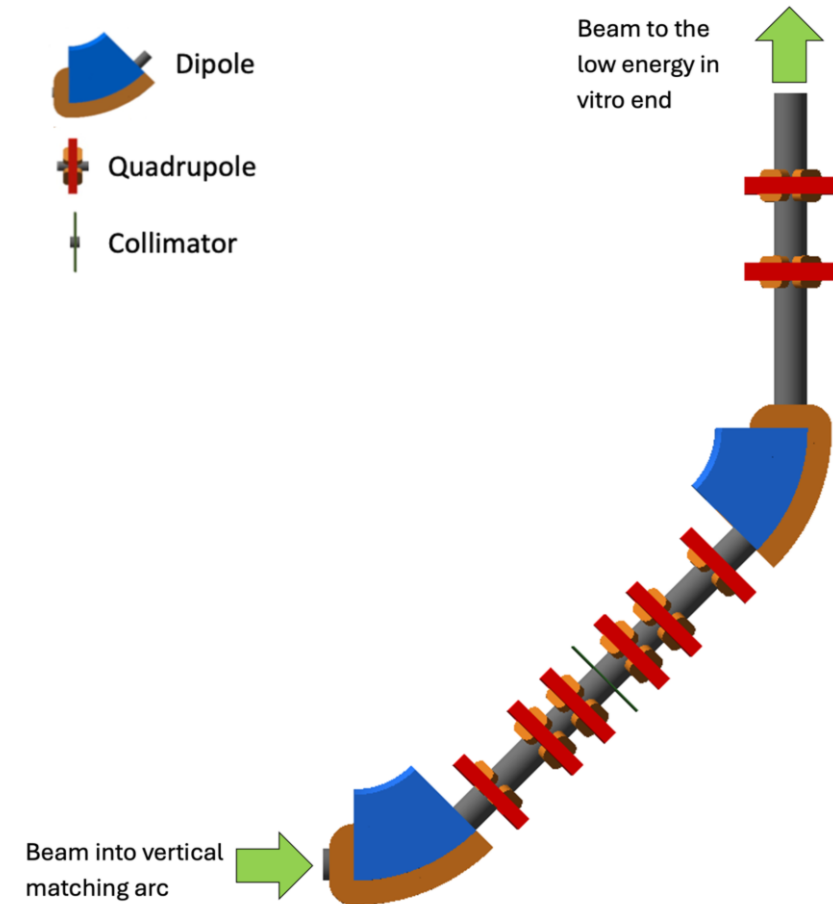
To achieve a minibeam, we want $\sigma_x = \sigma_y \leq \mathbf{0.5\ mm}$

Magnetic Beam Focusing

Quadrupole Doublet Configuration

Doublet (DOF):

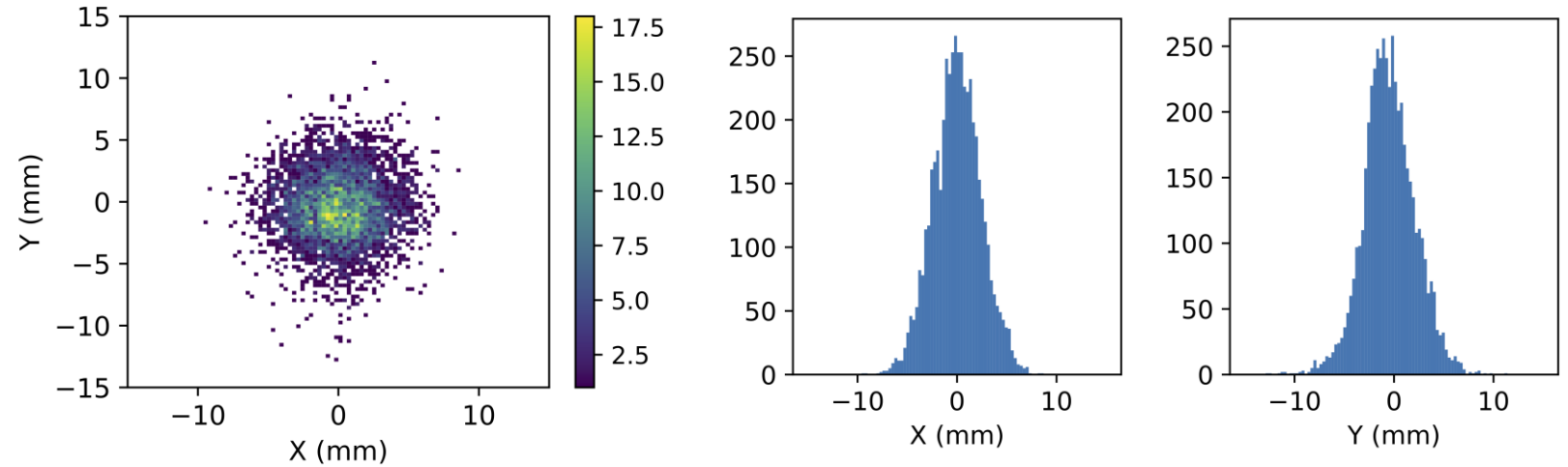
- Defocusing quadrupole magnet:
 - $L = 11.4 \text{ cm}$; $K = 11.695 \text{ T/m}$;
- Focusing quadrupole magnet:
 - $L = 11.4 \text{ cm}$; $K = -22.712 \text{ T/m}$;



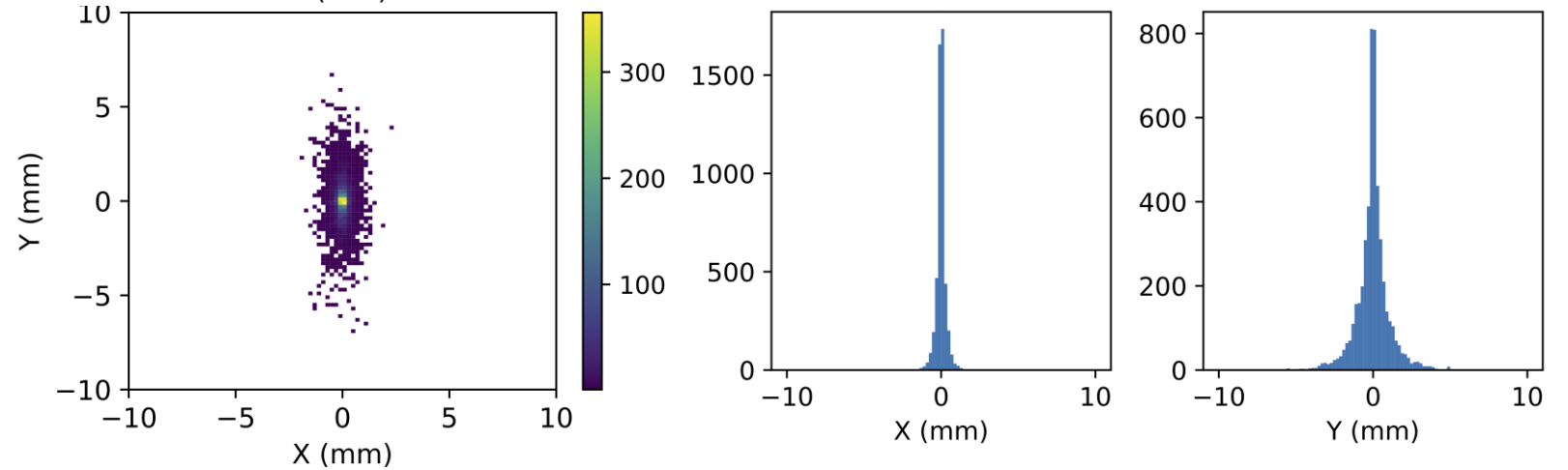
Magnetic Beam Focusing

Doublet Phase Space

- Before Quadrupole Doublet:



- After Quadrupole Doublet:



Magnetic Beam Focusing

Doublet Twiss Parameters

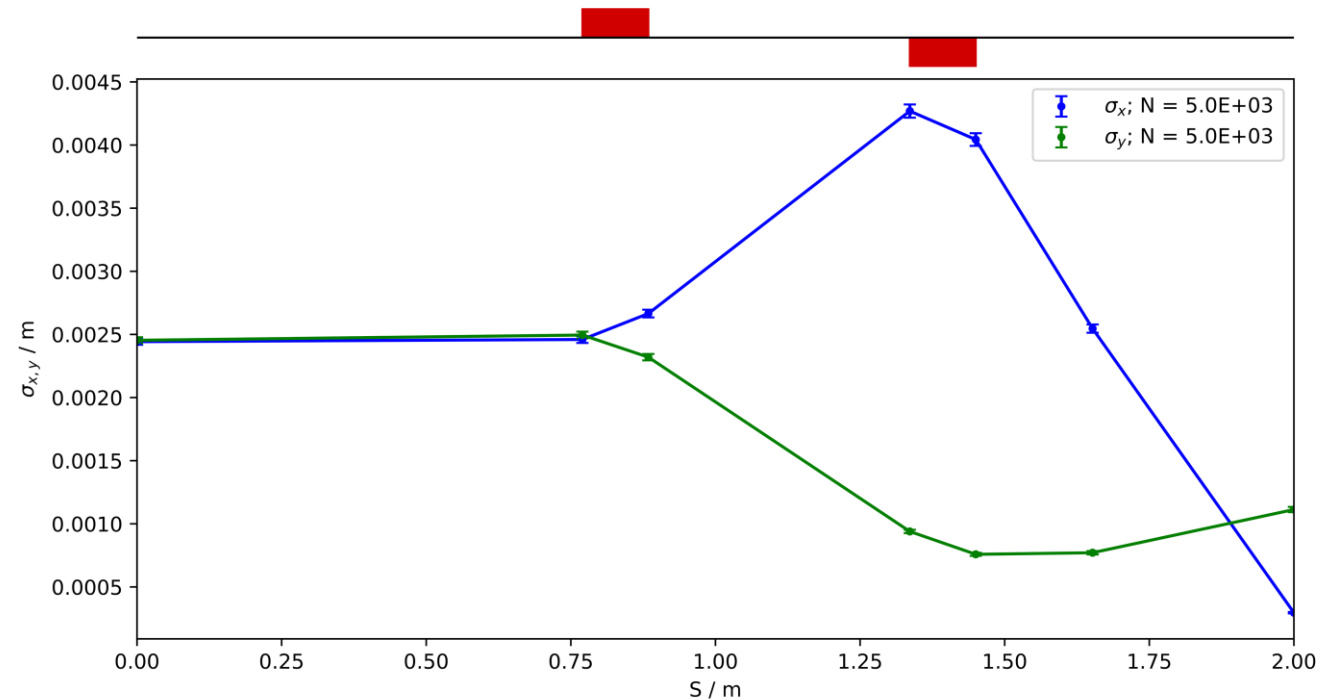
At the end station, this quadrupole doublet focusing configuration gives:

- $\sigma_x \approx 0.2$ mm
- $\sigma_y \approx 1.2$ mm

Beam focusing in the x-z plane satisfies the condition to be classed as a minibeam

Dispersion in the y-z plane is not fully compensated, so it does not satisfy the minibeam condition

However, we can use this configuration as a line focus beam



Magnetic Beam Focusing

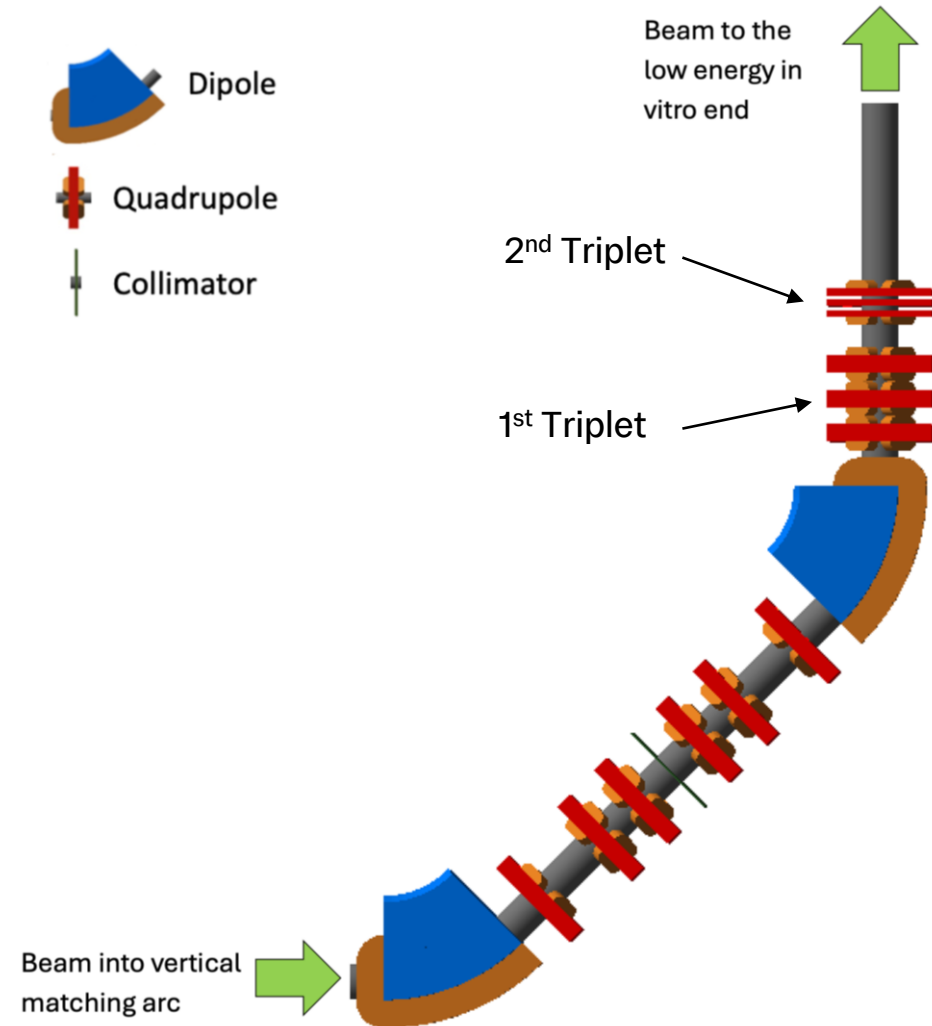
Quadrupole Triplet Configuration

1st Triplet (DOFOD):

- Defocusing quadrupole magnet:
 - $L = 0.1 \text{ m}$; $K = 30.256 \text{ T/m}$;
- Focusing quadrupole magnet:
 - $L = 0.1 \text{ m}$; $K = -53.393 \text{ T/m}$;

2nd Triplet (DOFOD):

- **Defocusing quadrupole magnet:
 - $L = 0.04 \text{ m}$; $K = 302.563 \text{ T/m}$;
- **Focusing quadrupole magnet:
 - $L = 0.04 \text{ m}$; $K = -551.7324 \text{ T/m}$;

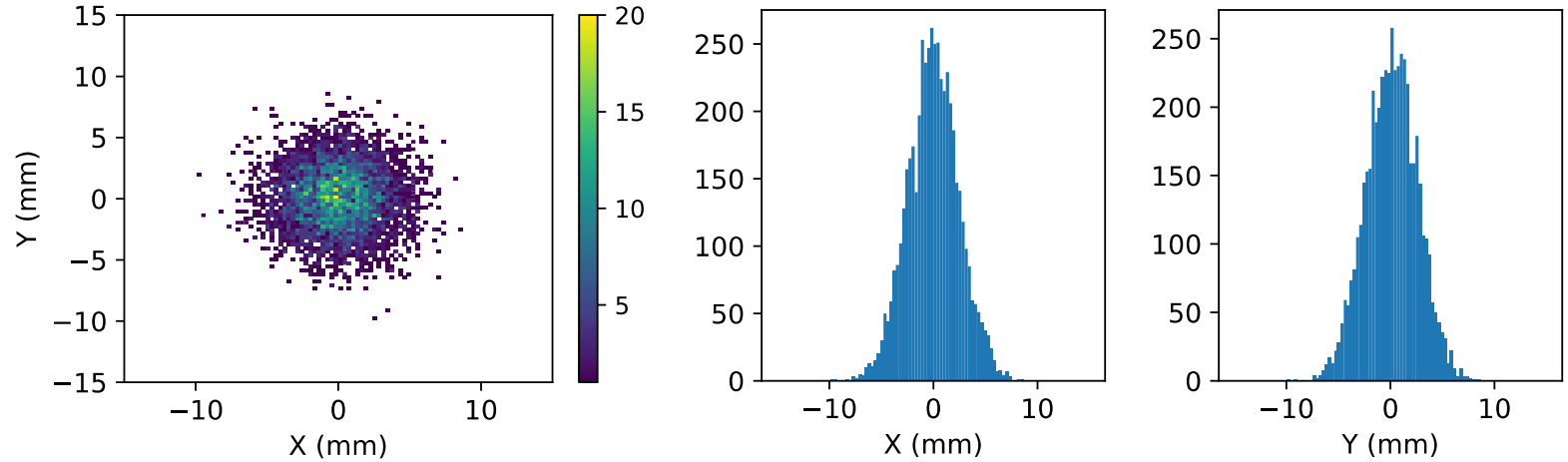


** Due to their high magnetic field strengths, these magnets are designed to be permanent quadrupole magnets

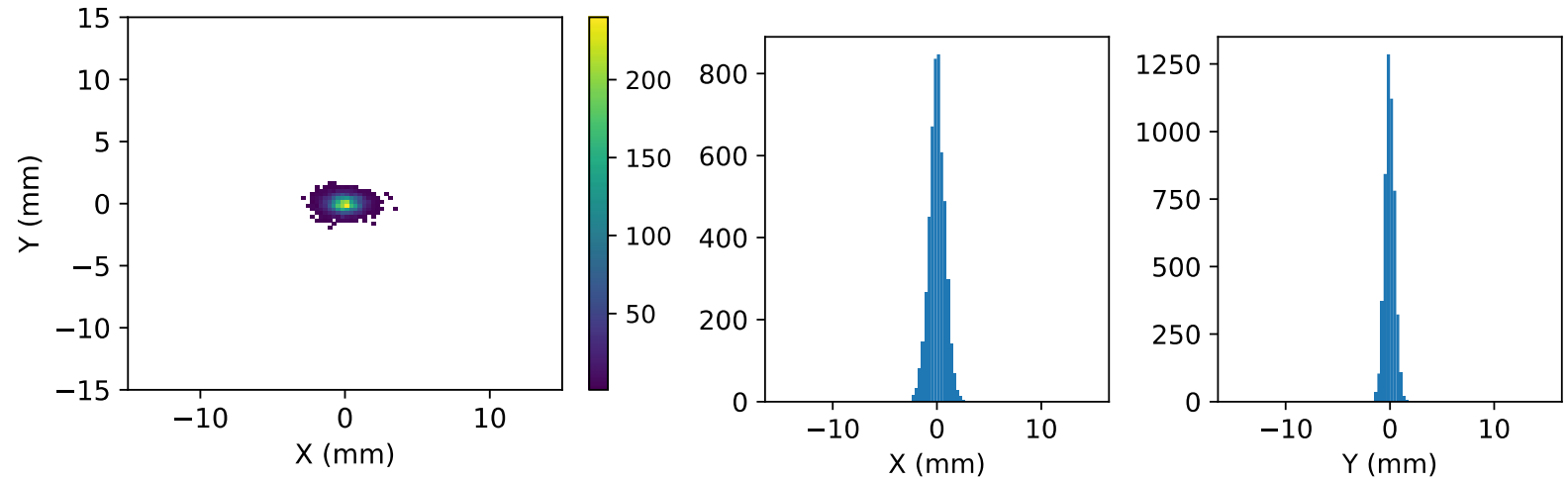
Magnetic Beam Focusing

Triplet Phase Space

- Before Quadrupole Triplets:



- After Quadrupole Triplets:

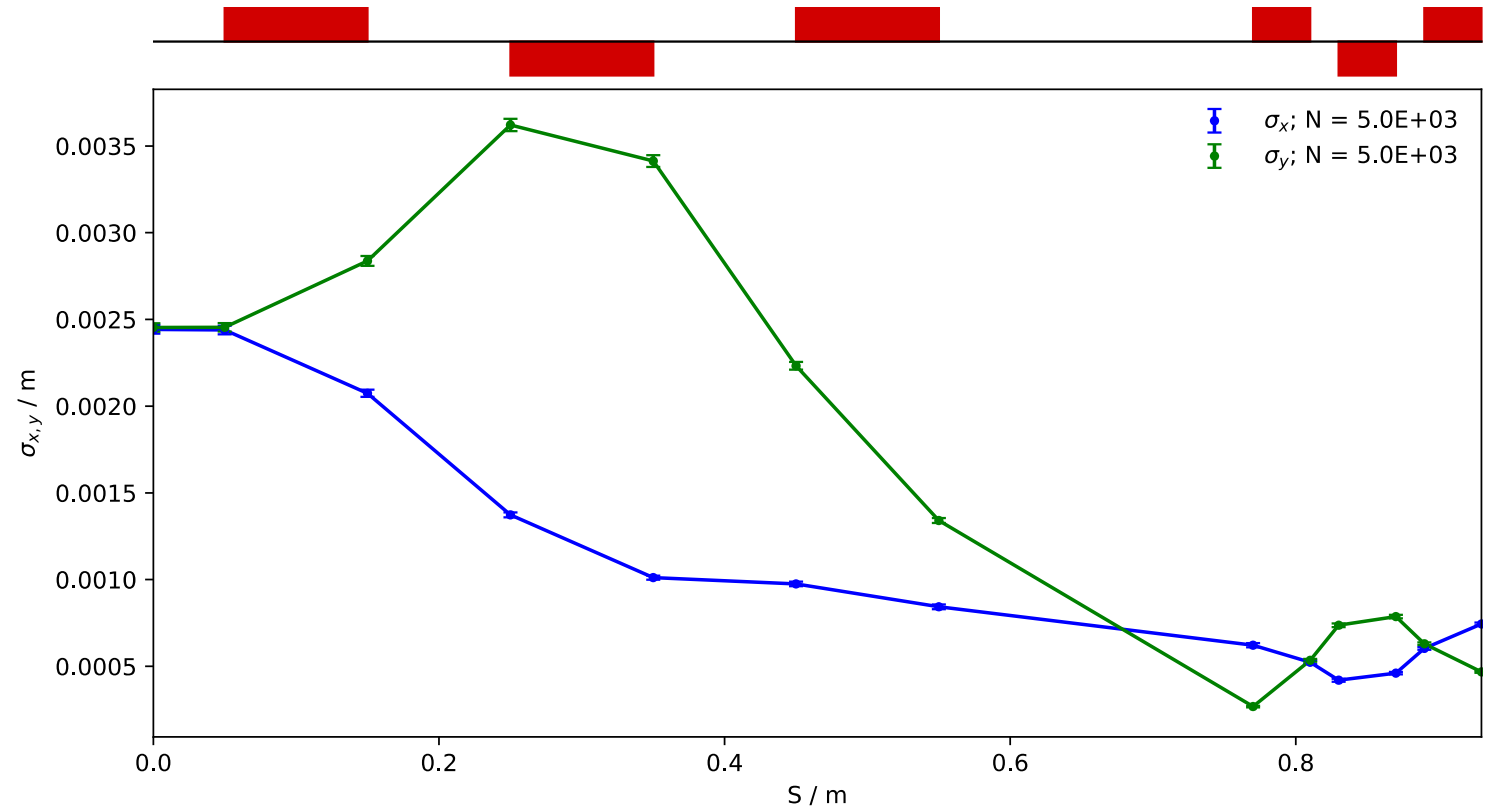


Magnetic Beam Focusing

Triplet Twiss Parameters

At the end of the focusing system,
this quadrupole triplet focusing
configuration gives:

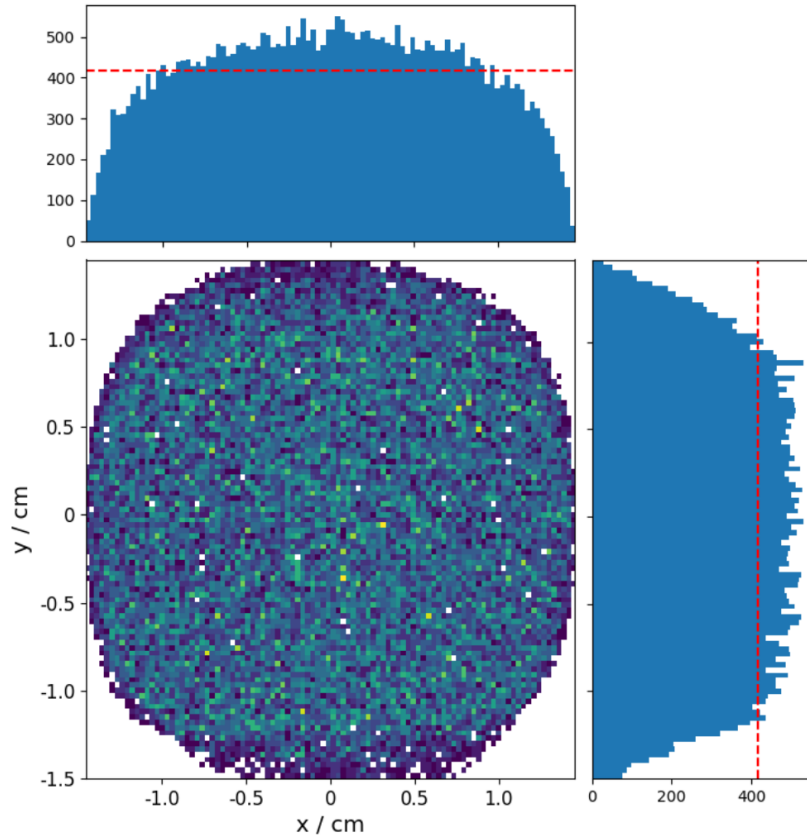
- $\sigma_x = 0.74$ mm
- $\sigma_y = 0.46$ mm



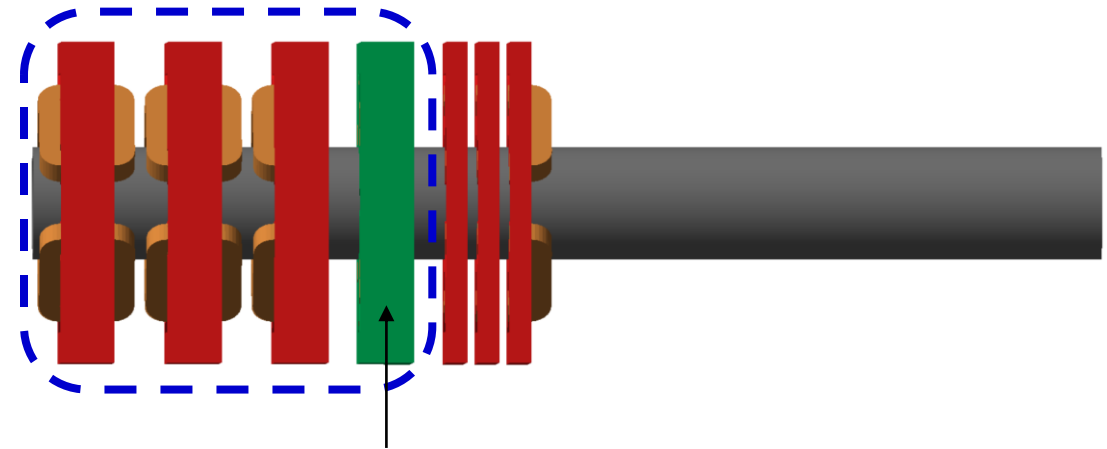
Magnetic Beam Focusing

Octupole – Nonlinear Focusing

- 3.0 cm Spot Size entering focusing system (primaries):



X Uniformity = $74 \pm 1.9 \%$
 Y Uniformity = $68.2 \pm 2.3 \%$
 Beam Capture = 99.7%



Single Octupole acting on x plane

$$K_{2n} = \frac{(n-2)!}{(n/2-1)!} \frac{(-1)^{n/2}}{(2\varepsilon\beta_0)^{n/2-1}} \frac{1}{\beta_0 \tan\phi}$$

$$2r_t = \sqrt{2\pi} \sqrt{\varepsilon\beta_t} |\cos\phi|,$$

Aiming for **95% uniformity** in both axes

Courtesy of Matt Pereira, RHUL

Magnetic Beam Focusing

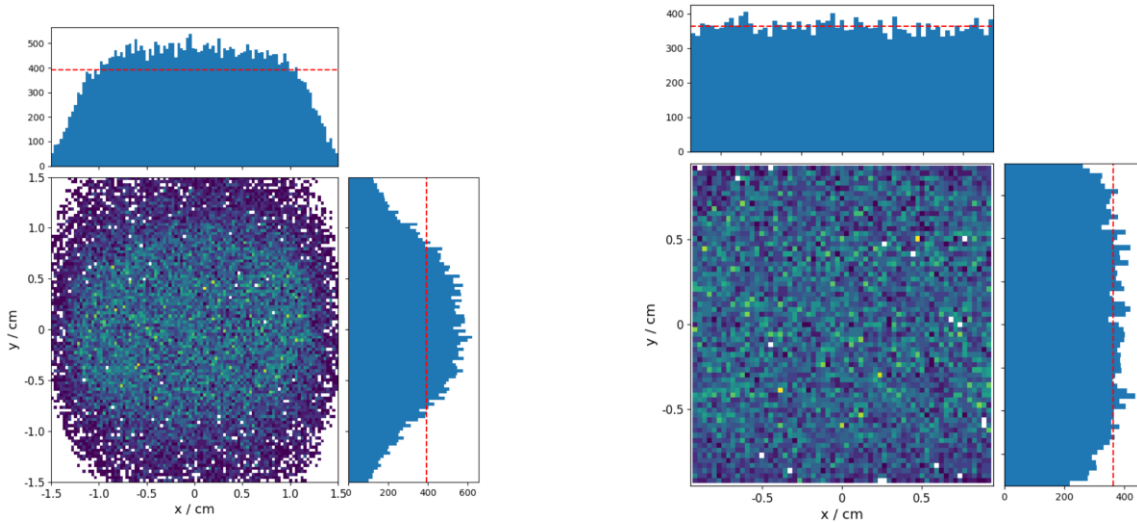
Octupole – Nonlinear Focusing



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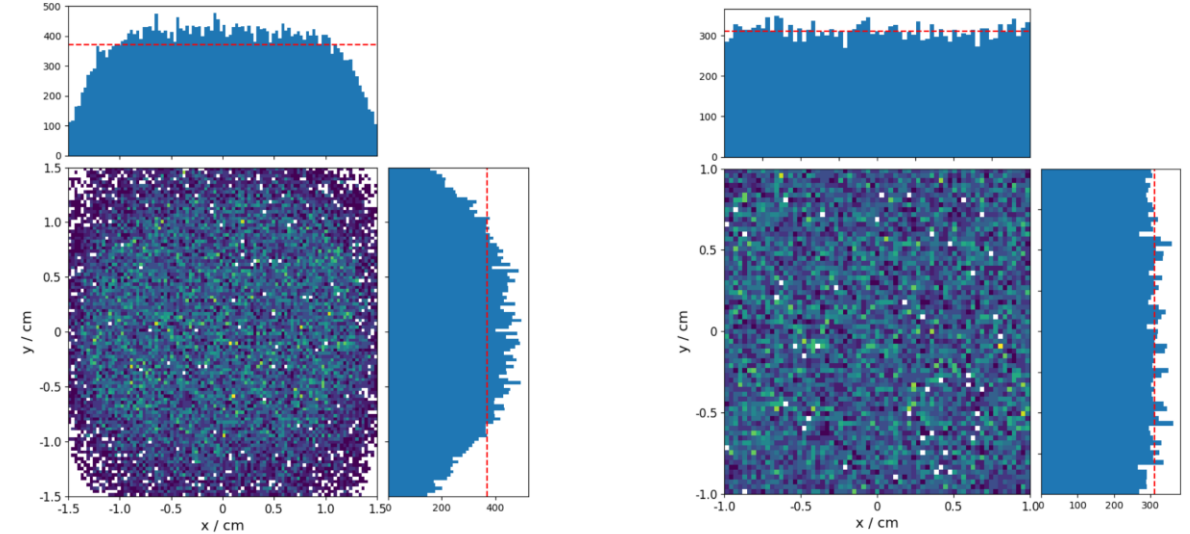
3.0 cm Spot Size (LHS) with 1.88 cm Uniform Width (RHS)



X Uniformity = 67.4 ± 2.3 %
Y Uniformity = 59.2 ± 2.0 %
Beam Capture = 95.6%

X Uniformity = 95.0 ± 0.5 %
Y Uniformity = 88.5 ± 1.0 %
Beam Capture = 55.7%

3.19 cm Spot Size (LHS) with 2.0 cm Uniform Width (RHS)



X Uniformity = 76.9 ± 1.6 %
Y Uniformity = 74.1 ± 1.8 %
Beam Capture = 90.3%

X Uniformity = 94.3 ± 0.5 %
Y Uniformity = 93.5 ± 0.6 %
Beam Capture = 50.8%

Max uniform width from current spot sizes

Spot Size, 2σ (cm)	Full Uniform Width, $2r_f$ (cm)
3.0	1.88
2.0	1.25
1.0	0.627

Required spot sizes for desired uniform widths

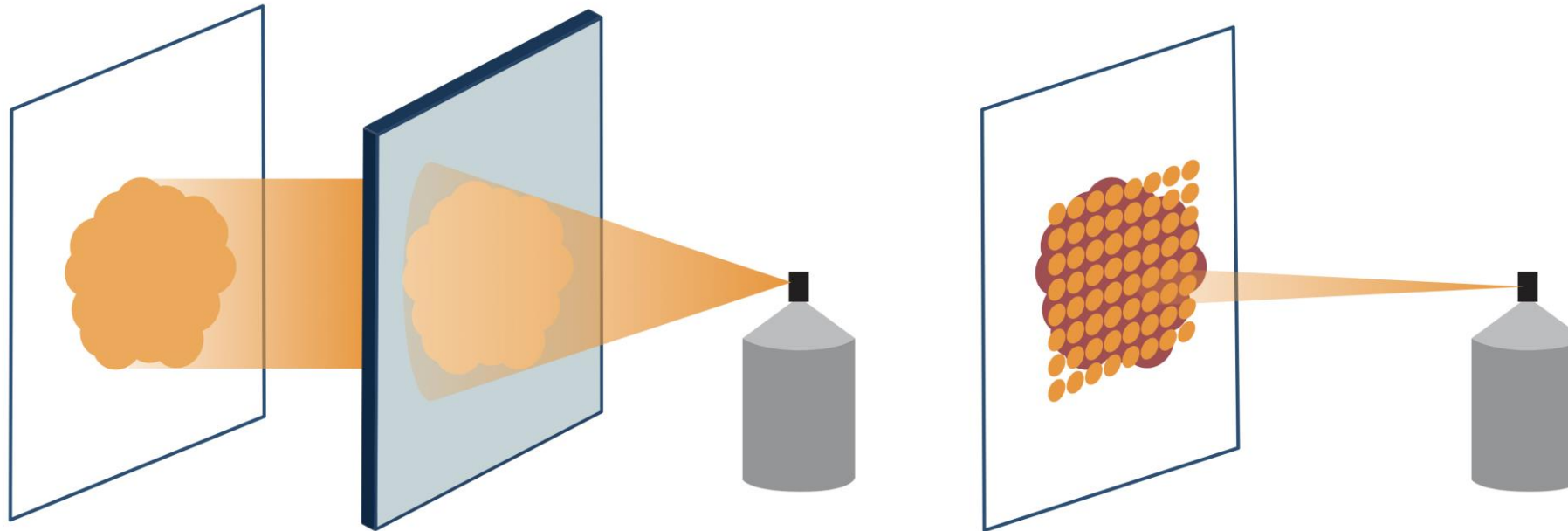
Uniform Width, $2r_f$ (cm)	Spot Size, 2σ (cm)
3.0	4.79
2.0	3.19
1.0	1.60

Courtesy of Matt Pereira, RHUL

Beam Delivery Modality

Spot Scanning (Future Work)

Solution: Kicker Magnet Pair – kicks beam in x and y planes



- **Passive Scattering** delivers a uniform radiation field to the target volume, in conventional radiotherapy

- **Spot Scanning** is a Spatially Fractionated Radiation Therapy (SFRT) beam delivery modality which delivers the radiation dose in “spots” across the target volume

Conclusions



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- The magnetic quadrupole triplet focusing system focusses the beam and decreases its overall dispersion
- With further optimisations, the requirement of delivering minibeam to the radiobiological end stations seems possible
- The introduction of one octupole provides a uniformity of at least $> 93.5\%$, in the both axes, for a spot size of 3.19 cm (2 cm uniform width)
- LhARA will be able to conduct radiobiological experiments to observe the ionisation effects of minibeam on tissue

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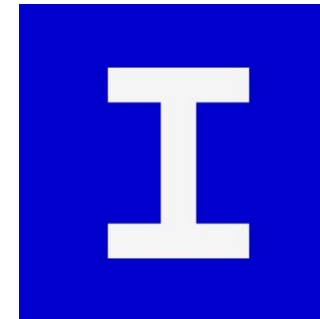


Thank you

Contributions:



- Matt Pereira
- Will Shields



- Kenneth Long

For further information, email rtr22@ic.ac.uk

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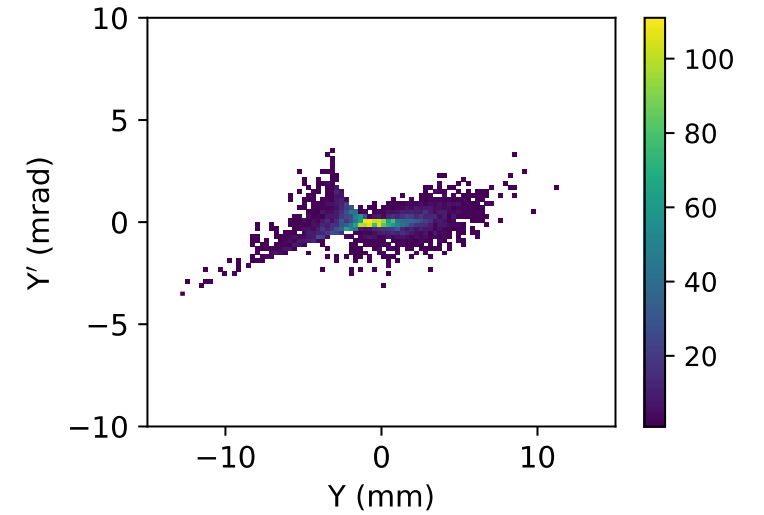
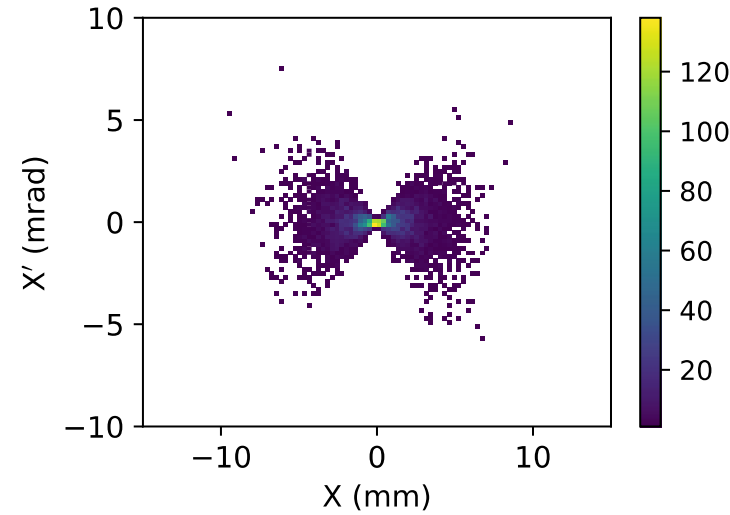
Back-up

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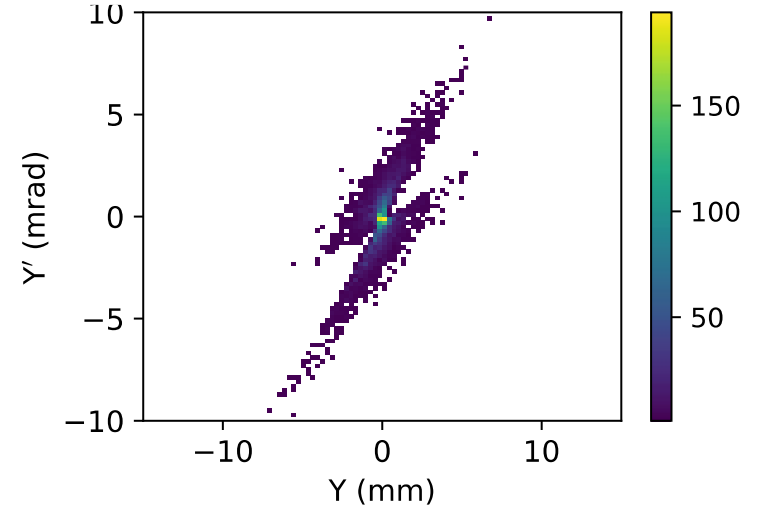
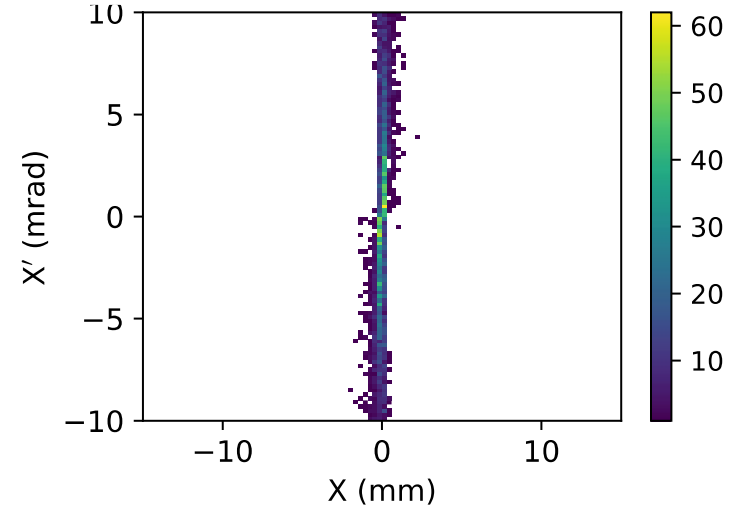
Magnetic Beam Focusing

Additional Doublet Phase Space

- Before Quadrupole Doublet:



- After Quadrupole Doublet:



Magnetic Beam Focusing

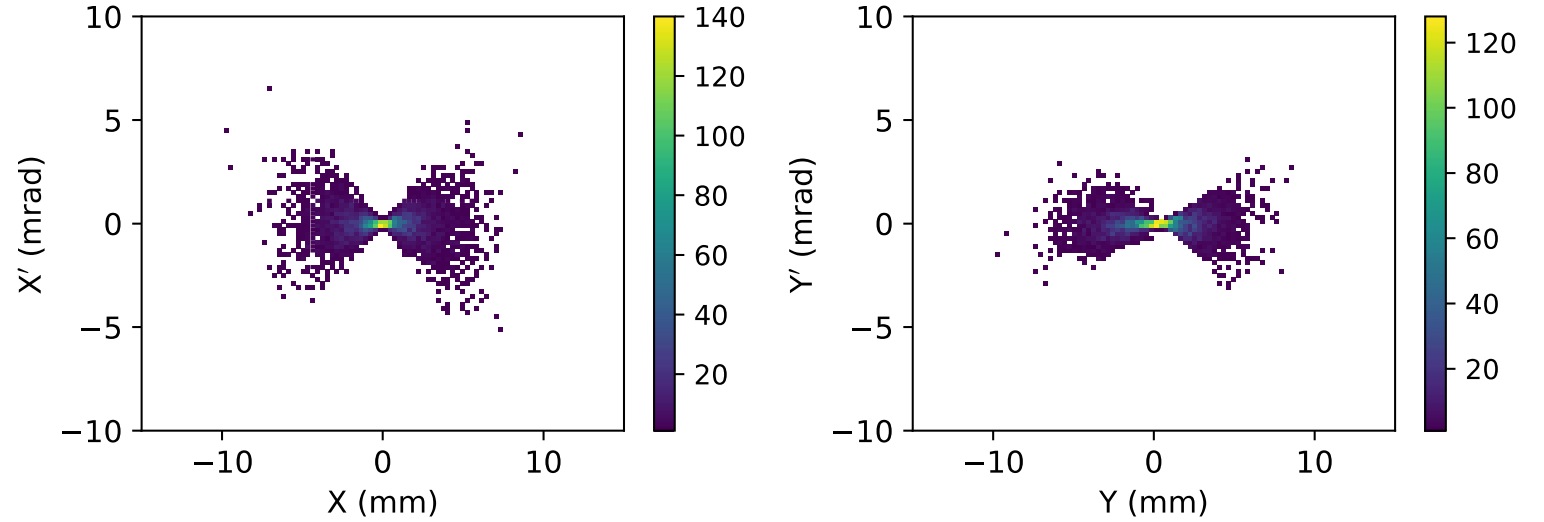
Additional Triplet Phase Space



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- Before Quadrupole Triplets:



- After Quadrupole Triplets:

