Stage 1 Beam Delivery

Minibeam Focusing and Beam Uniformity Studies

Matt Pereira

(matthew.pereira.2023@live.rhul.ac.uk)

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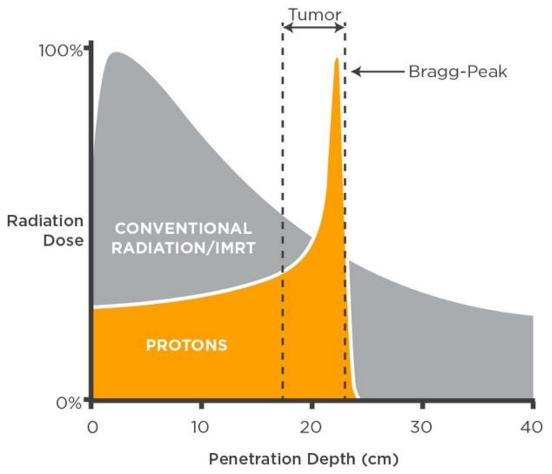
ROYAL HOLLOWAY UNIVERSITY OF LONDON

LhARA Laser-hybrid Accelerator for Radiobiological Applications

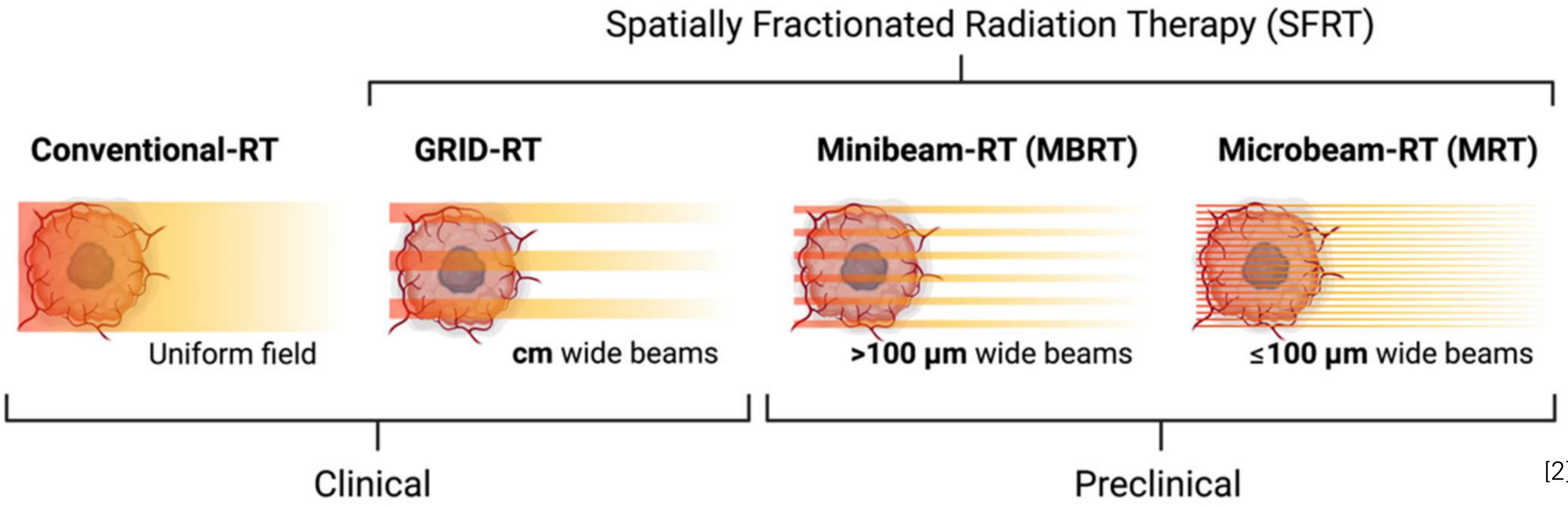
JAI John Adams Institute for Accelerator Science

Minibeams

Radiobiological Motivation



[1]



[2]

- **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

Presented on behalf of Rehanah Razak, ICL

Minibeams

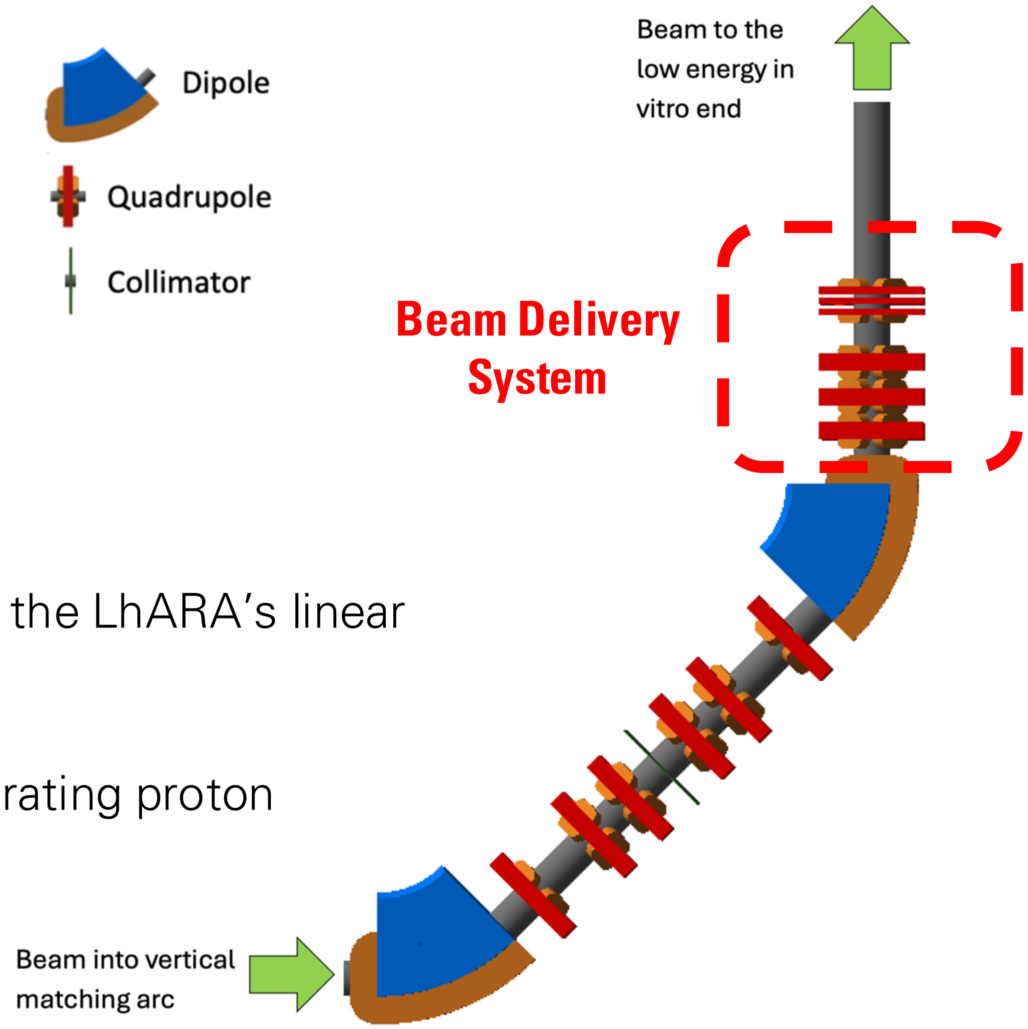
Simulations of LhARA Stage 1

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 minibeams



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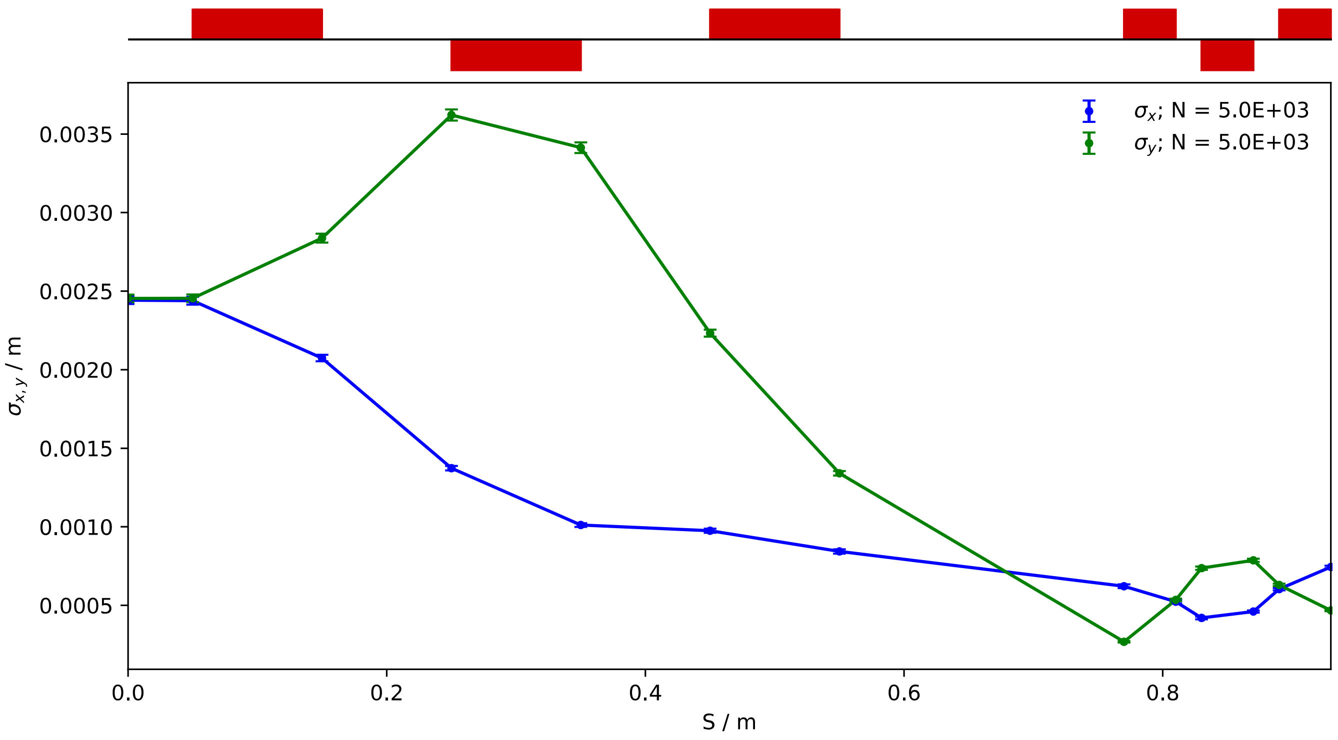
Minibeams
Quadrupole Optimisation

Optimisation:
- Targeting $\sigma_x = \sigma_y \leq 0.5$ mm
- Varying drift lengths between quadrupoles
- Constrained to a maximum length of 2m

1st Triplet (DOFOD):
- Defocusing quadrupole magnet:
  - L = 0.1 m; K = 30.256 m^{-2};
- Focusing quadrupole magnet:
  - L = 0.1 m; K = -53.393 m^{-2};

2nd Triplet (DOFOD):
- Defocusing quadrupole magnet:
  - L = 0.04 m; K = 302.563 m^{-2}
- Focusing quadrupole magnet:
  - L = 0.04 m; K = -551.7324 m^{-2};



At 1m, after final quadrupole:
$\sigma_x = 0.74$ mm
$\sigma_y = 0.46$ mm

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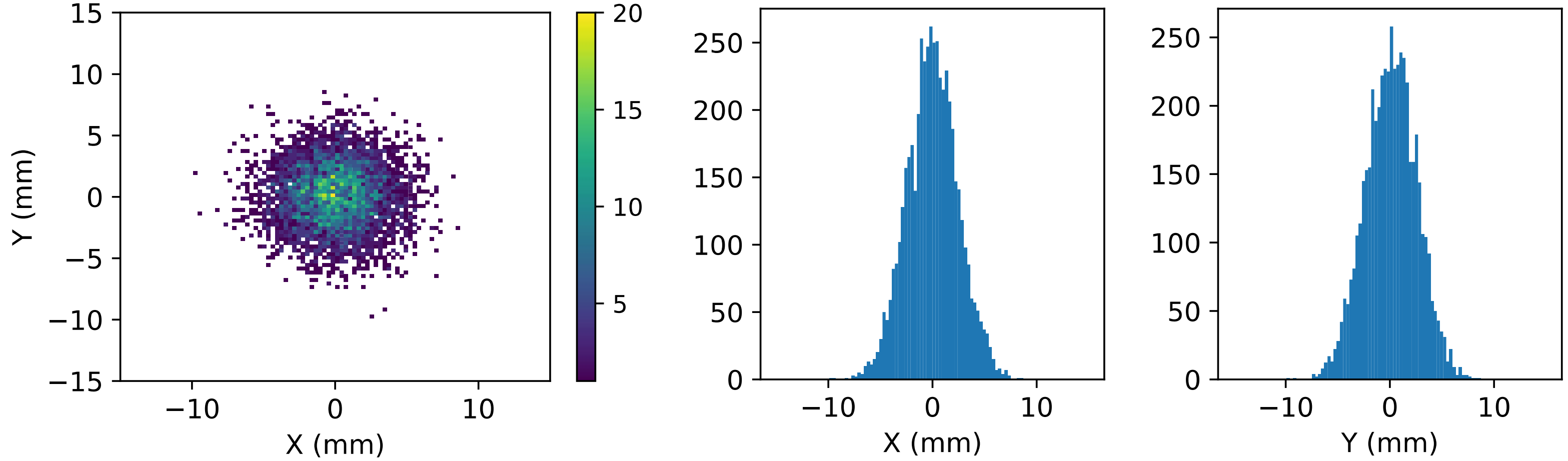
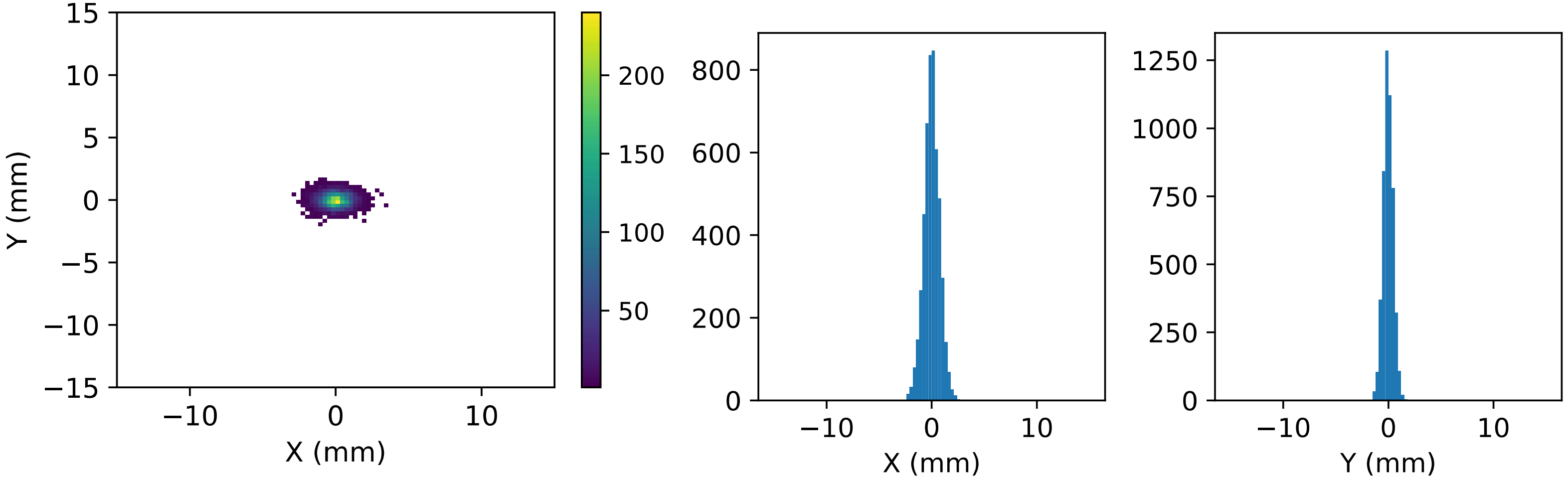
Minibeams

Transverse Profiles

- Before Quadrupole Triplets:



- After Quadrupole Triplets:



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Beam Uniformity

Octupole Optimisation

Target: 95% Uniformity in both Transverse axis

Optimising quads for:

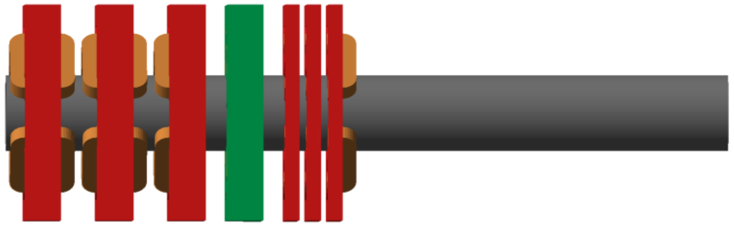
- Spot size at the end station (3.0, 2.0, 1.0 cm)
- $\beta_x >> \beta_y$ at the octupole
- $\phi_x \sim \pi$ between octupole and end station

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

$$2r_t = \sqrt{2\pi}\sqrt{\varepsilon\beta_t}|\cos\phi|,$$ [3]

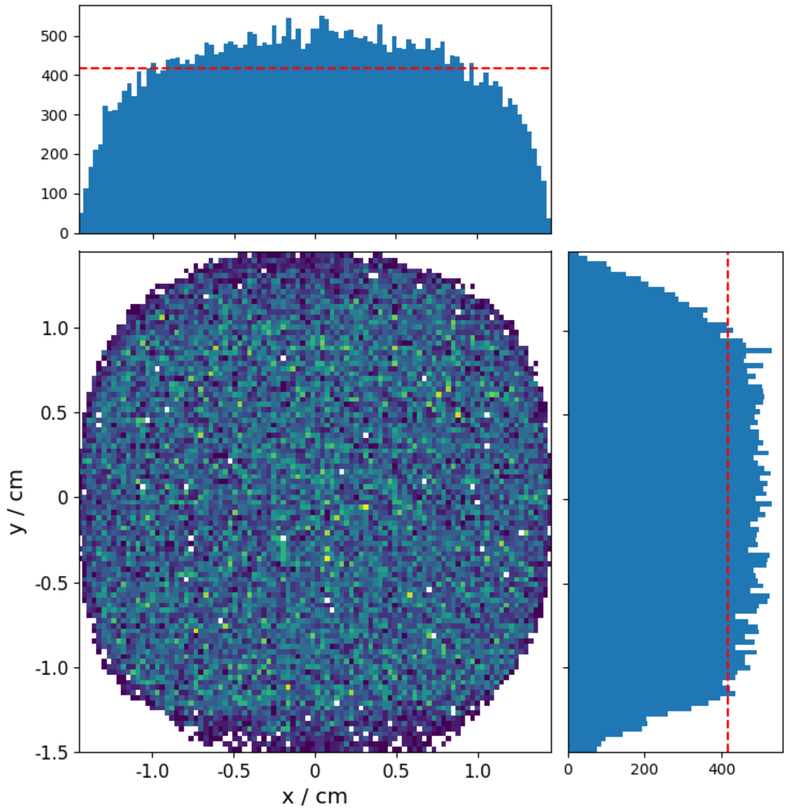
$$CV = \frac{\sigma}{\mu}$$

$$\%Uniformity = (1 - CV) \times 100$$



S1 beam delivery in the BDSIM visualiser
Quads in red, Octupole in green

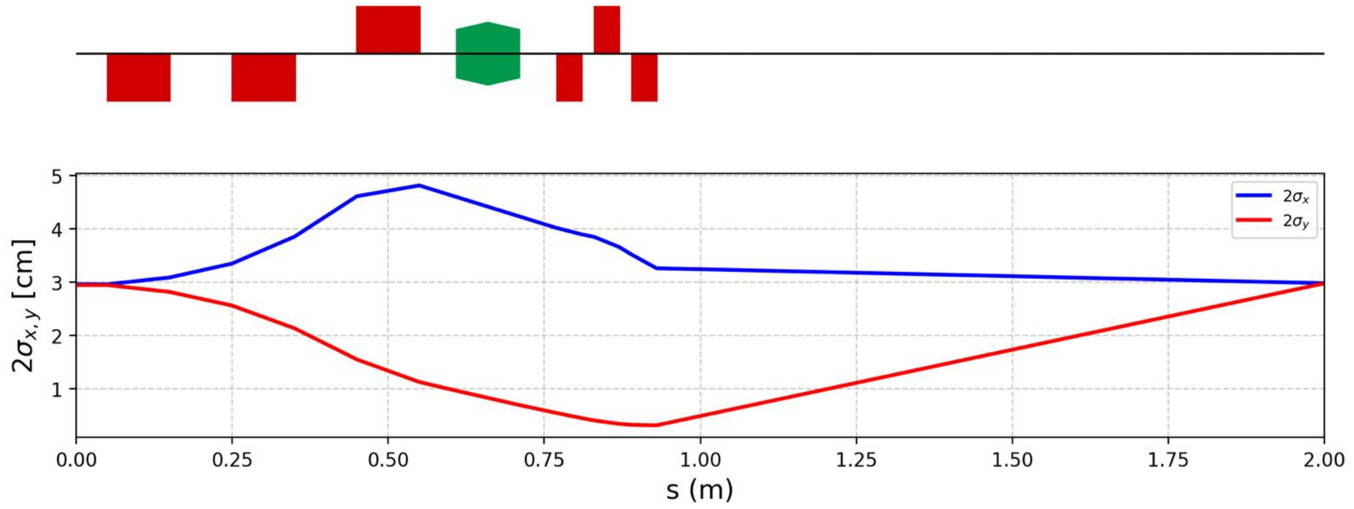
Starting with a 3.0 cm beam size out of the vertical arc.



X Uniformity = 74 ± 1.9 %
Y Uniformity = 68.2 ± 2.3 %
Beam Capture = 99.7%

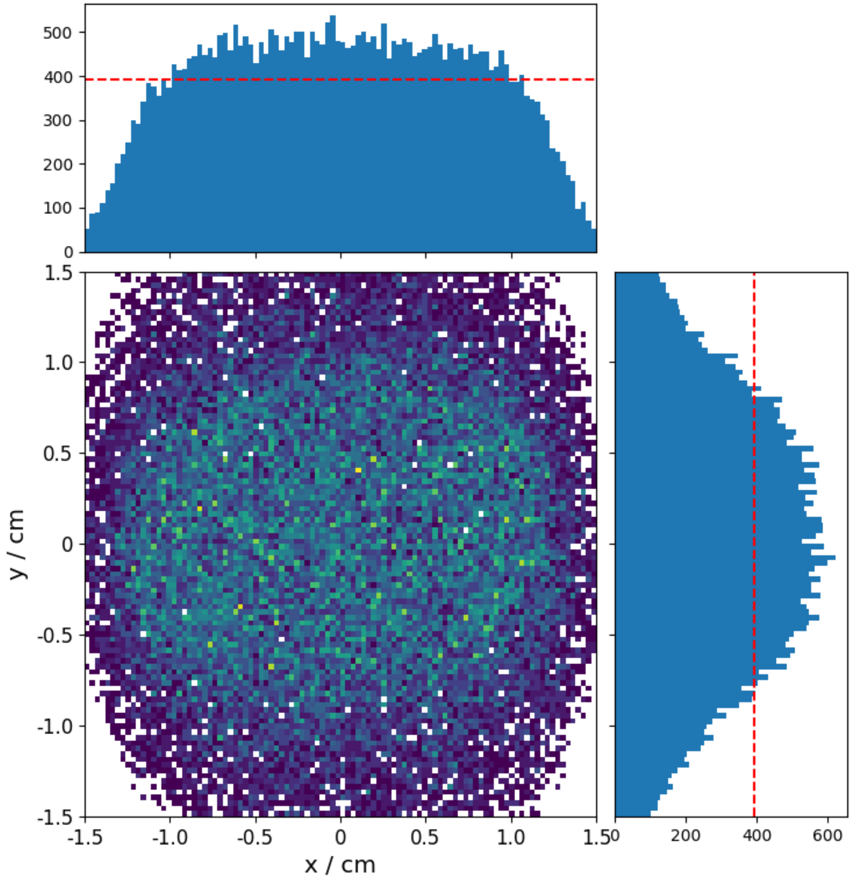
Beam Uniformity

3.0cm Spot Size Result



Element	QUAD_07	QUAD_08	QUAD_09	OCT_01	QUAD_10	QUAD_11	QUAD_12
k_n Strength [$m^{-(n+1)}$]	-8.85	-13.98	23.26	-3905	-7.96	31.34	-9.48

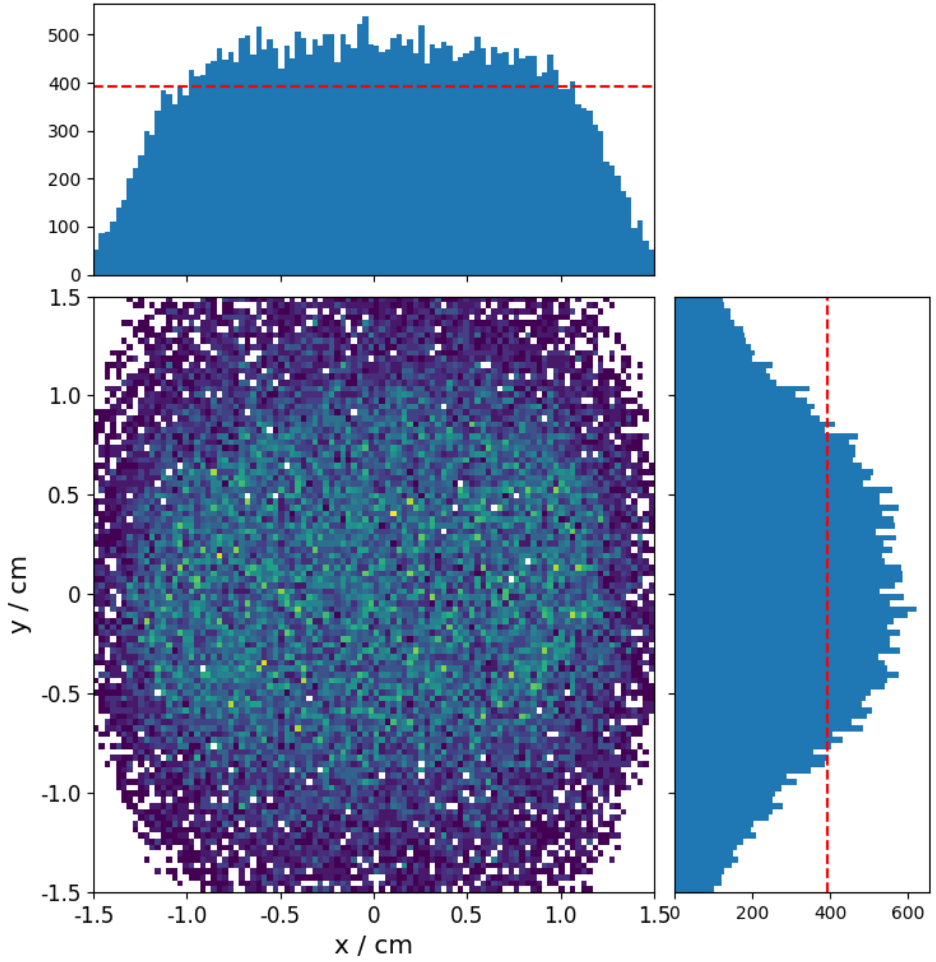
Second triplet required to be varied like EMQs to satisfy phase advance conditions and refocus to spot size at end station.



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

Beam Uniformity

3.0cm Spot Size Result



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

Max uniform width from current spot sizes

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

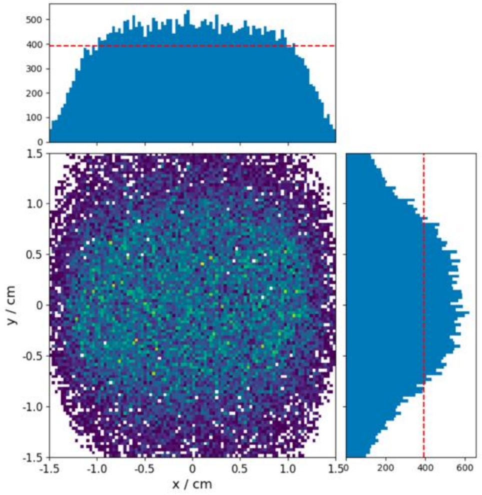
Required spot sizes for desired uniform widths

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

Beam Uniformity

Optimising for - Spot Size vs Uniform Width

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



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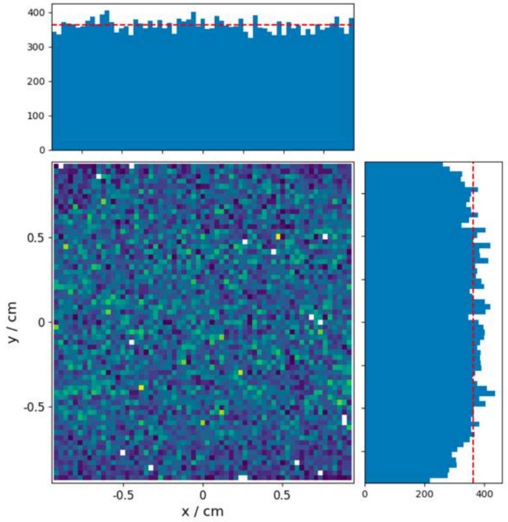
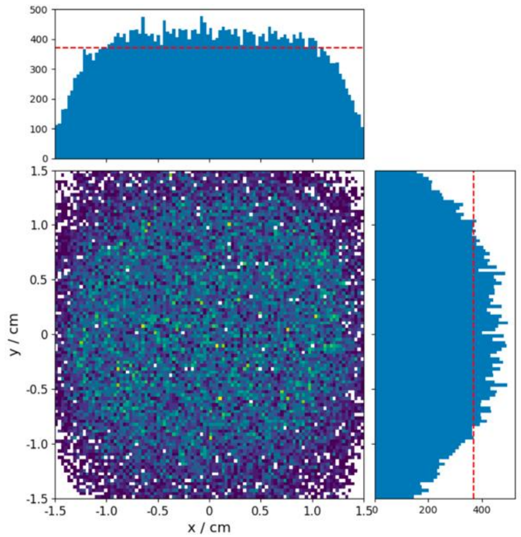
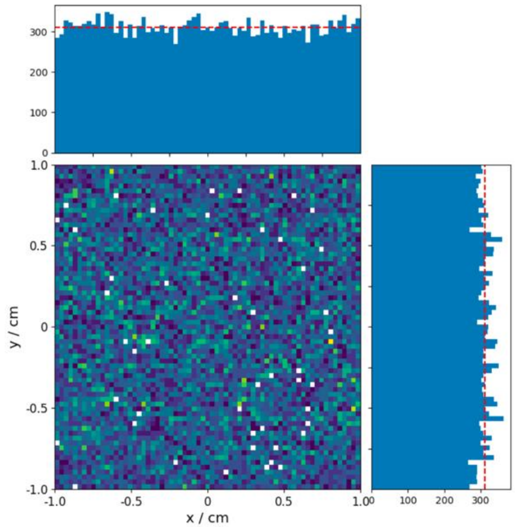


X Uniformity = 95.0 ± 0.5 %
Y Uniformity = 88.5 ± 1.0 %
Beam Capture = 55.7%

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, $2\sigma_{\varnothing}$ (cm)	Full Uniform Width, $2r_t$ (cm)
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Required spot sizes for desired uniform widths

Uniform Width, $2r_t$ (cm)	Spot Size, $2\sigma_{\varnothing}$ (cm)
3.0	4.79
2.0	3.19
1.0	1.60

Field Maps

Space Charge Simulations

GPT

- Modelling space charge is necessary for all LhARA designs, which requires simulation in GPT

Differences in the handling of magnet elements between BDSIM and GPT could be a source of uncertainty.

An additional step is required between the BDSIM and GPT stages

Field Maps

Bridging between BDSIM and GPT

Field Maps

- FieldMapper - Python library to generate BDSIM and GPT field maps.
- One consistent field map being used in both programs avoids differences arising from the way elements are handled

- The field maps created need to be validated, firstly against BDSIM and then GPT without space charge.
- If all three simulations produce identical results, the field map is valid.

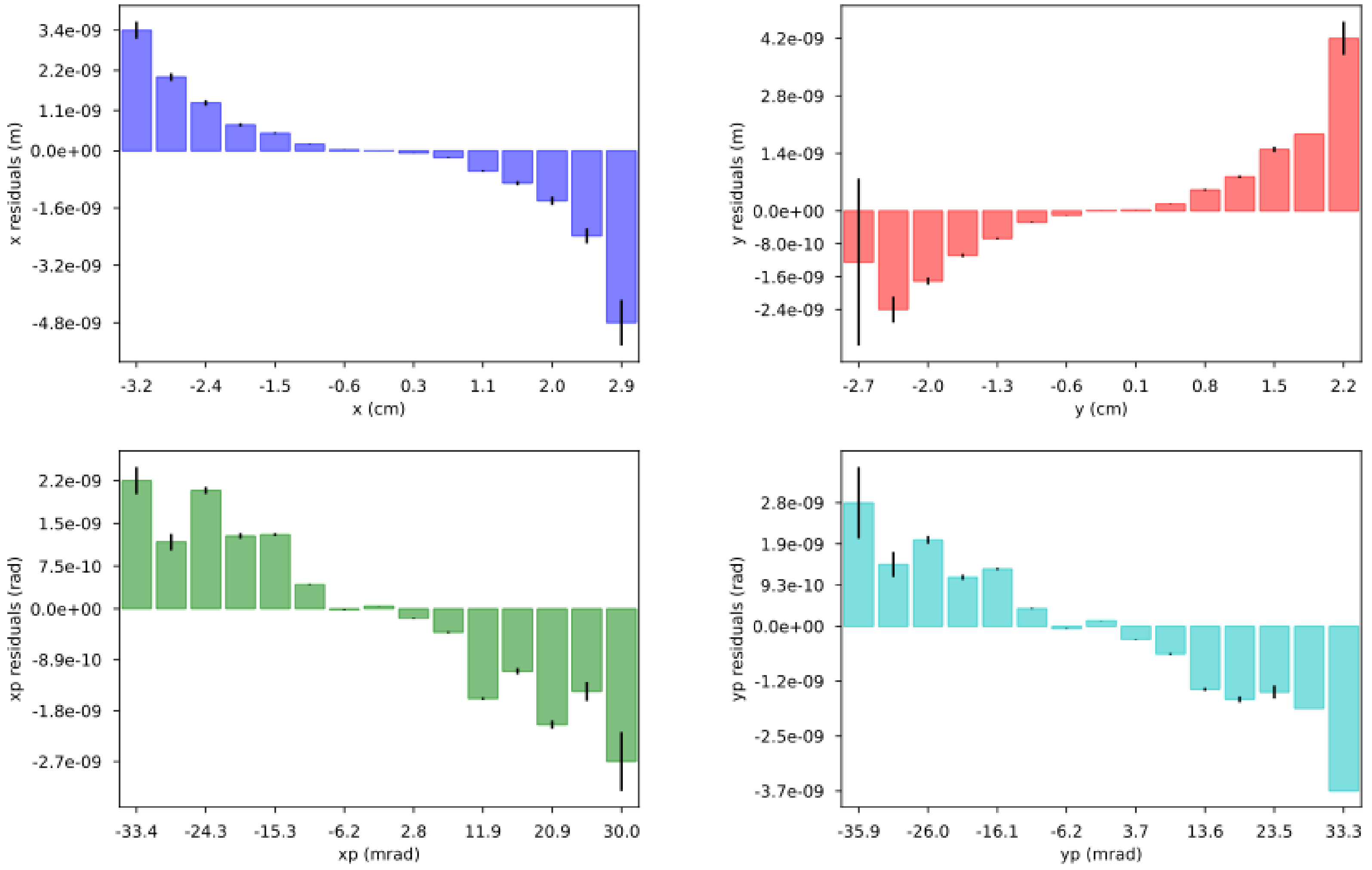
Field Maps

Validation

Validated multipole field maps with BDSIM to 10^{-8} precision

GPT Validation ongoing

- Currently residuals ~ 10^{-4}
- Investigating errors in model conversion from BDSIM -> GPT

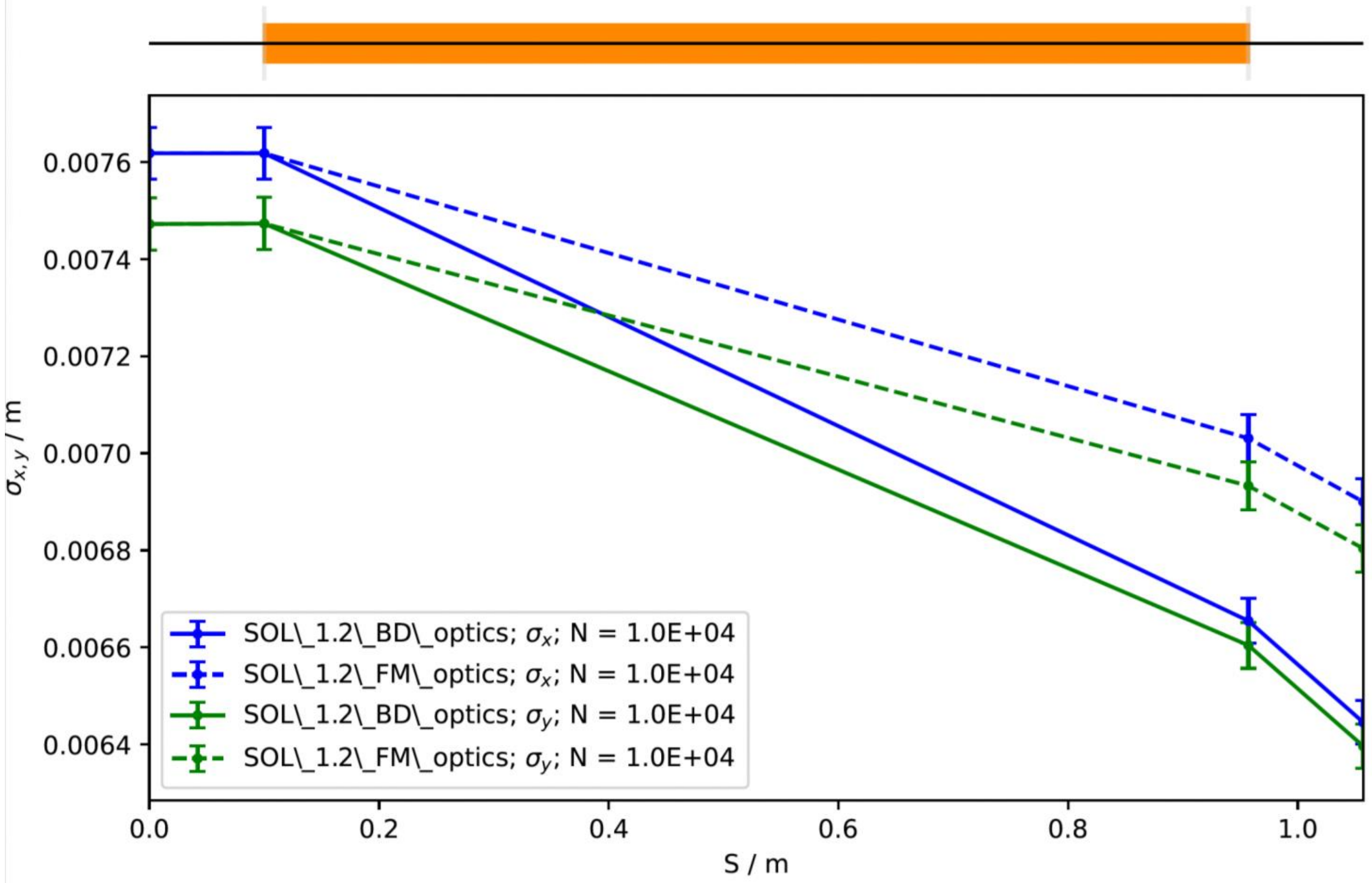


Field Maps
BDSIM Validation

Solenoid field map under-focuses compared to BDSIM element (Transfer Matrices)

Found to be a result of the way fringe fields are modelled by the field map vs the matrices.

Demonstrates the importance of modelling fringe fields for Solenoids/Gabor Lenses for LhARA Stage 1.



Summary

Conclusions and Next Steps

Conclusions

- The magnetic quadrupole triplet focusing system has achieved beam sizes satisfying the minibeam condition in the y-axis immediately after the focusing system
- The introduction of one octupole provides a uniformity > 93.5%, in both axes, for a spot size of 3.19 cm (2 cm uniform width) at the end station

Next Steps

- Optimisations for beam divergence and focal point of minibeam configurations
- Introduction of spot scanning dipoles for minibeams
- Optimisation of octupole k_3 and spot size around the values given by theory for better uniformity and beam capture
- Space charge simulations of beam delivery configurations with field maps
- Convergence of beam delivery designs optimised for flexibility between minibeams and uniform beams of conventional size

Thank You

Contributions:

IMPERIAL

Rehanah Razak
Ken Long

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Will Shields

References

[1] S. N. Dolya and V. I. Smirnov, “JINR Scientists Invented Effective Way of Medical Proton Beam Focusing,” Joint Institute for Nuclear Research, Mar. 1, 2022. [Online]. Available: https://www.jinr.ru/posts/jinr-scientists-invented-effective-way-of-medical-proton-beam-focusing/

[2] C. Fernandez-Palomo, S. Chang, and Y. Prezado, “Should Peak Dose Be Used to Prescribe Spatially Fractionated Radiation Therapy?—A Review of Preclinical Studies,” Cancers, vol. 14, no. 15, 2022, p. 3625. ISSN: 2072-6694. DOI: 10.3390/cancers14153625. URL: https://www.mdpi.com/2072-6694/14/15/3625.

[3] Yuri Y, Miyawaki N, Kamiya T, Yokota W, Arakawa K, Fukuda M. Uniformization of the transverse beam profile by means of nonlinear focusing method. Phys Rev ST Accel Beams. 2007 Oct 29;10(10):104001. URL: https://link.aps.org/doi/10.1103/PhysRevSTAB.10.104001

Beam Uniformity

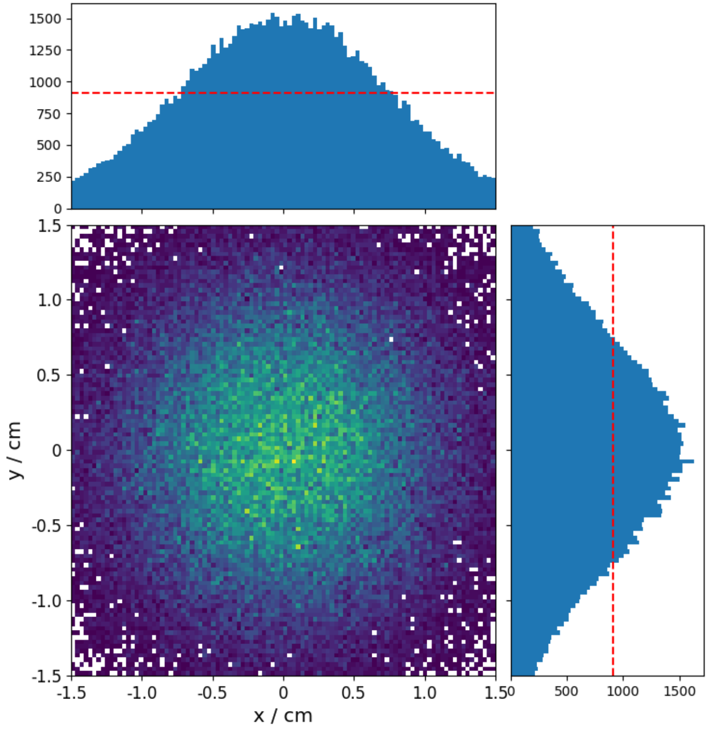
Calculation and Visualisation

Coefficient of Variation (CV)

$$CV = \frac{\sigma}{\mu}$$

$$\%Uniformity = (1 - CV) \times 100$$

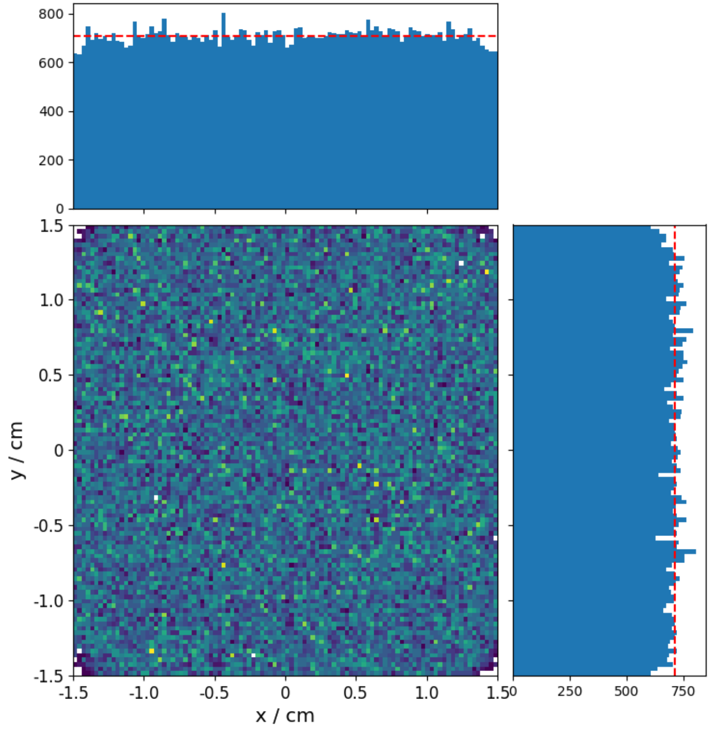
- Quick and simple to calculate
- Dimensionless and normalized
- No spatial information, so visualization is important for all assessments



3.0 cm Gaussian Beam

X Uniformity – 52.1%

Y Uniformity – 51.7%



3.0 cm Uniform Beam

X Uniformity – 95.8%

Y Uniformity – 95.1%

Beam Uniformity

Literature

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 104001 (2007)

Uniformization of the transverse beam profile by means of nonlinear focusing method

Yosuke Yuri, Nobumasa Miyawaki, Tomihiro Kamiya, Watalu Yokota, and Kazuo Arakawa
Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency, 1233 Watanuki-machi, Takasaki, Gunma 370-1292, Japan

Mitsuhiro Fukuda
Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
(Received 16 April 2007; published 29 October 2007)

$$K_{2(n-1)} = 0,$$

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

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

Paper: Yuri et al (2007)

- Equations for predicting the uniform region that can be generated from a non-linear magnetic field (e.g octupole) and the strength of the magnet required.
- Full width of the uniform region is dependent on σ at the target and phase advance between the multipole and the target, ϕ
- $n\pi$ phase advance gives the maximum value of $2r_t$ which can be used to calculate the maximum possible uniform width of a given beam size for LhARA.

Stage 1 Beam Delivery

Beam @ End of vertical arc

$NParts = 41000$

$\varepsilon_x = 6.84 \times 10^{-6}$ m

$\varepsilon_y = 5.36 \times 10^{-6}$ m

$\beta_x = 8.13$ m

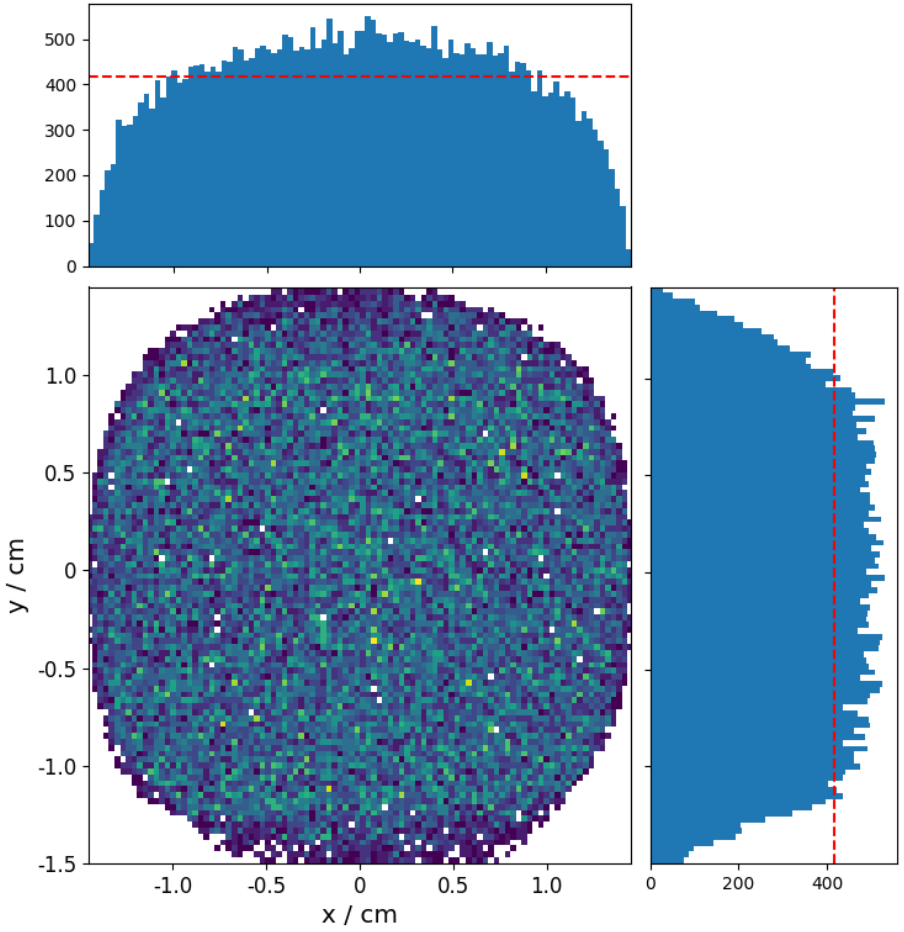
$\beta_y = 10.26$ m

$\alpha_x = 0.122$

$\alpha_y = -9.19 \times 10^{-6}$

Generated from the parameterized source definition.

Particle coordinates taken at the end of the vertical arc of Stage 1 Model.



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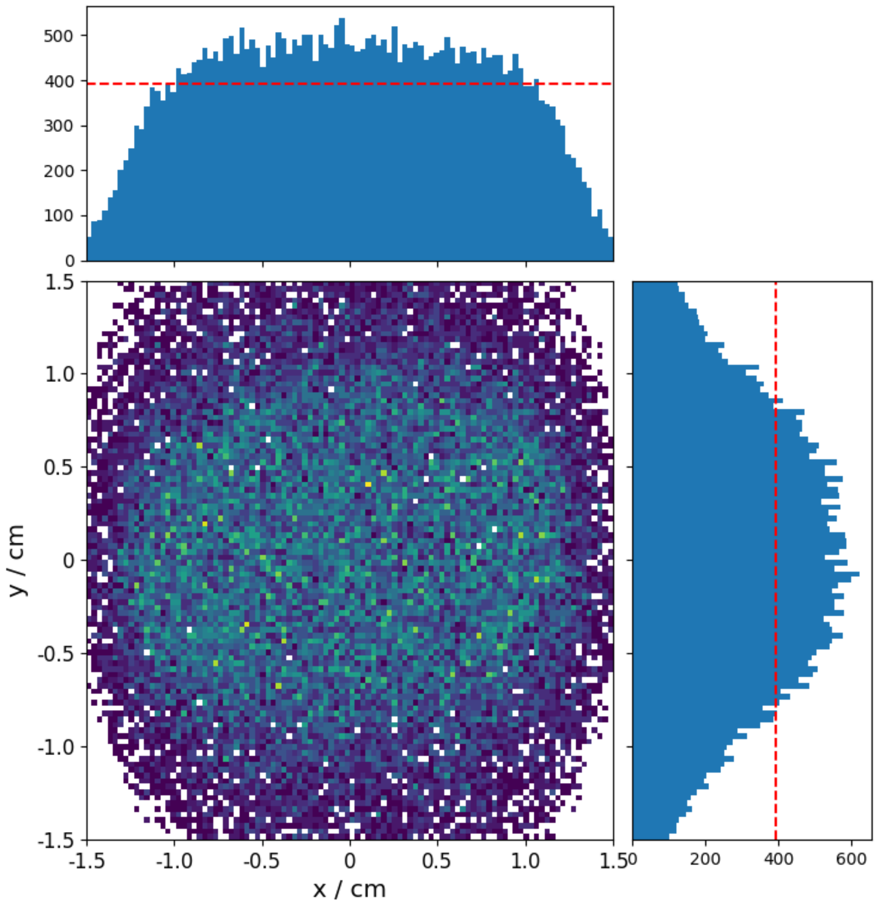
Beam Capture = 99.7%

Stage 1 Beam Delivery

3.0cm Spot Size – 1.88 cm Uniform Width ($2r_t$)



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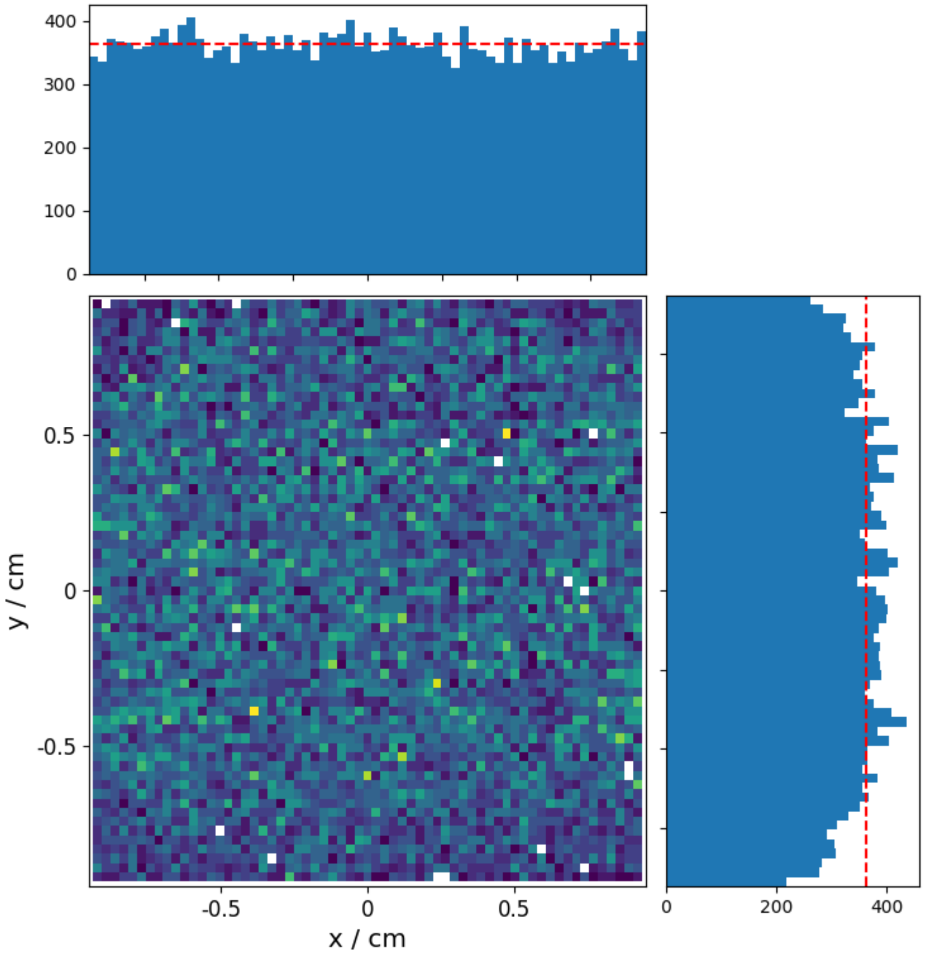

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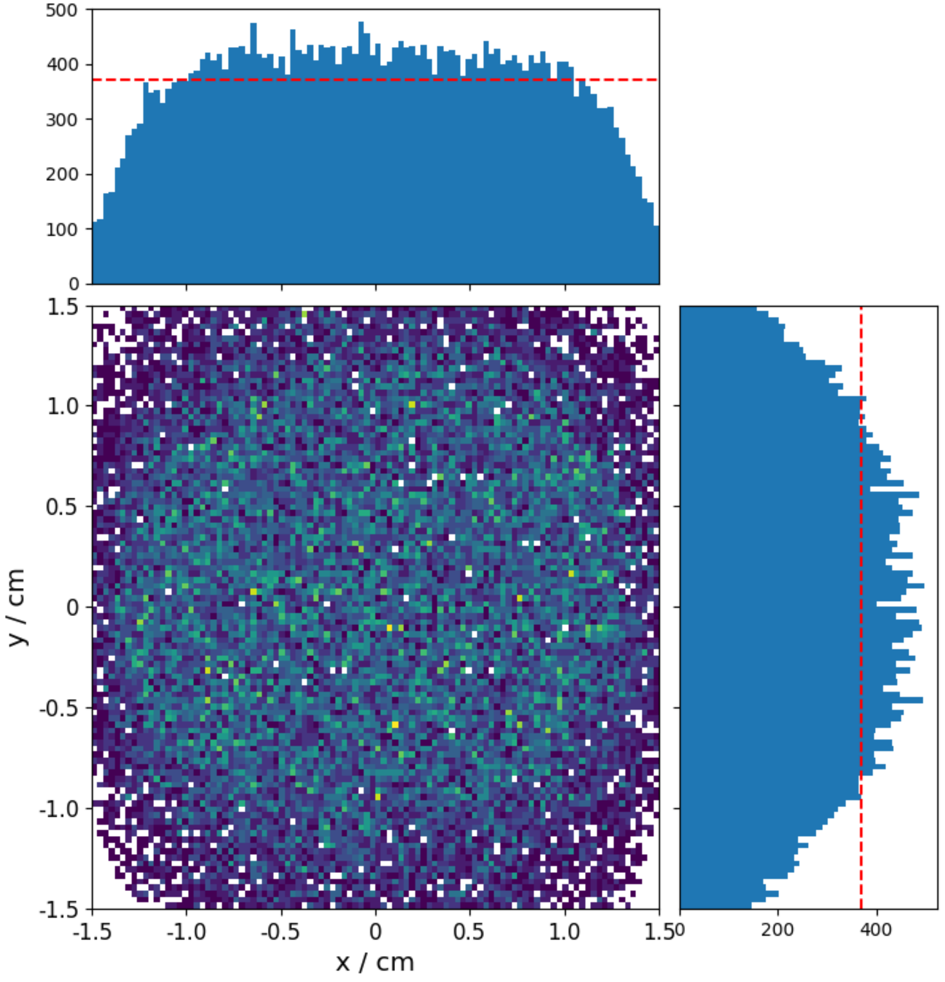
Stage 1 Beam Delivery

Optimising for $2r_t$ – 2.0cm $2r_t$



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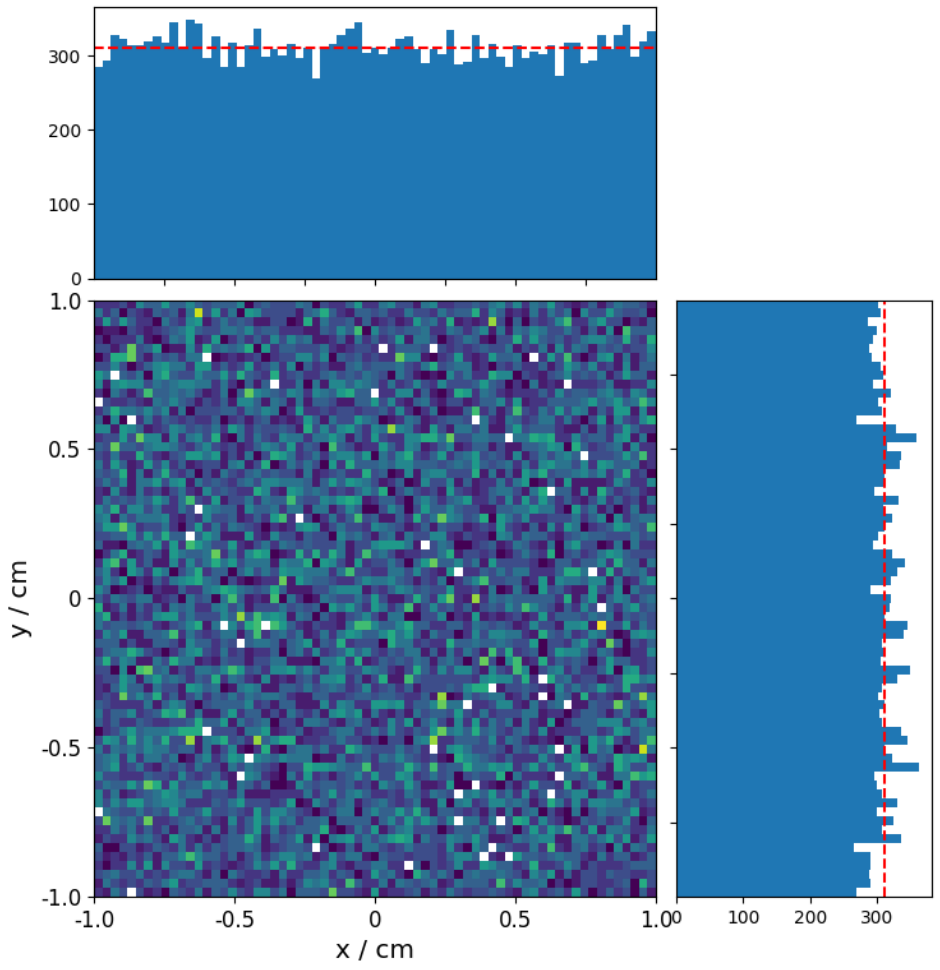

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Tables

2σ ⌀ (cm)	2Rt (cm)		% Uniformity		Beam Capture
	X	Y	X	Y	
3.0	1.87	1.67	94.9	88.6	55.7
2.0	1.24	1.04	94.6	70.2	58.3
1.0	0.59	0.29	75.9	33.7	61.7

2Rt	2σ ⌀ (cm)		% Uniformity		Beam Capture
	X	Y	X	Y	
3.0					
2.0	3.20	3.51	94.3	93.5	50.8
1.0	1.62	1.92	92.4	73.9	54.2

Stage 1 Beam Delivery

Optimising for Beam Uniformity

Plotted: XSuite vs BDSIM
3.0cm spot size