Design of a Nonlinear Optics for Uniform Beam Distribution

For Accelerator Physics Term Project

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Outline

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- Brief Introduction to Uniform Beam Production
- Goals and Tasks
- Available Optics and Initial Beam Parameters
- ELEGANT Optics and Results
- Summary and Suggestions

Acknowledgements

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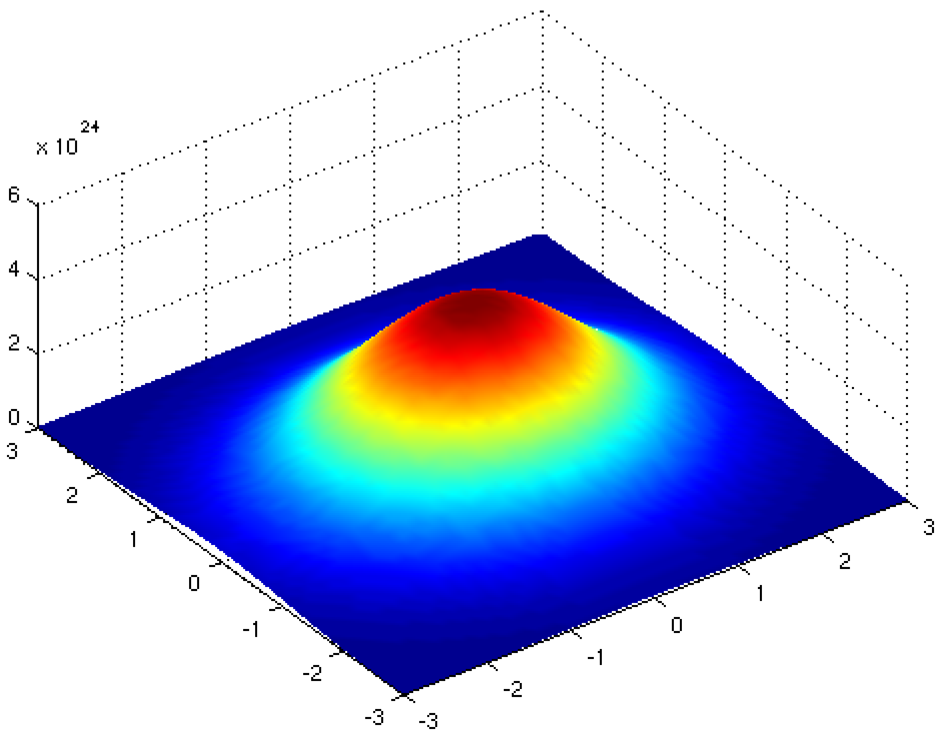
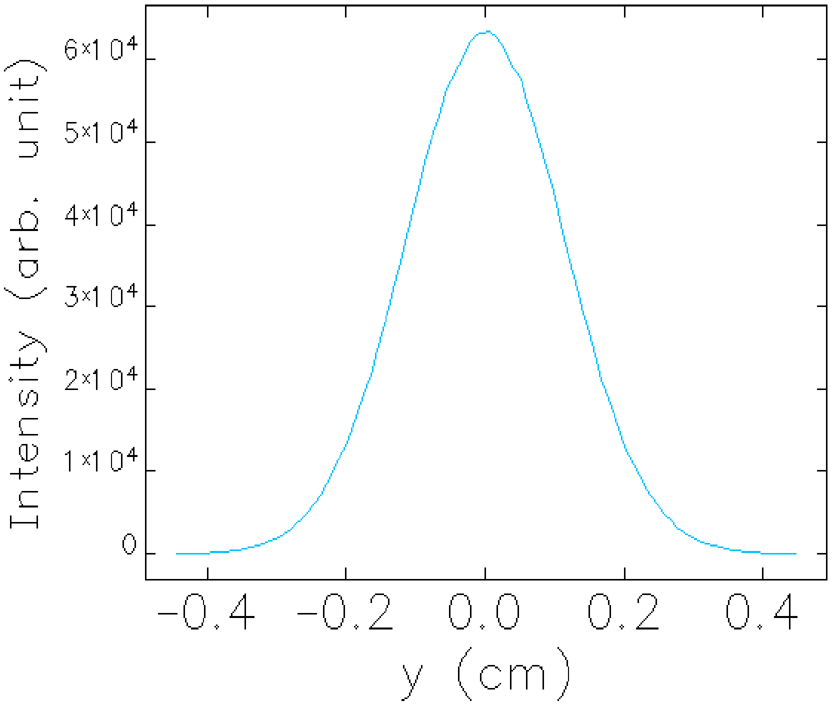
Also I would like to thank my adviser Prof. Dan Dale and all other faculties for interest to this topic

And many thanks to my classmates Jason D. Bond, Bibek Gautam, Bindu KC, Maimaitimin Mayierjiang, Shadike Saitiniyazi for technical details and support.

Introduction: Gaussian Beam Distribution

In many cases the usual beam distribution is Gaussian that is quite nonuniform with a bright center and a diffuse edges:





$$f(x,y) = Ae^{-\left(\frac{(x-x_O)^2}{2\sigma_x^2}+\frac{(y-y_O)^2}{2\sigma_y^2}\right)}$$

$$f(x) = ae^{-\frac{(x-b)^2}{2c^2}}$$

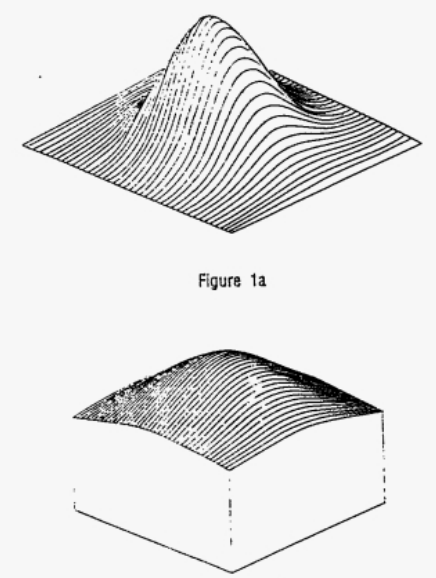
Introduction: Uniform Beam Distribution

However in many application, it's necessary to have uniform beam distribution such as:

- Radiation treatment of tumors
- Proton oncology
- ...other medical treatment application with need of uniform beam distribution
- Medical isotope production
- Food irradiation
- Radiation-damage study
- Ion implantation
- Nuclear waists transmutation
- Spallation neutron sources
- To prevent target damage and optimize target efficiency
- To minimize the cooling of target
- Electron to positron target converter   ...and many many other applications

Introduction: Uniform Beam Production

There are some methods for Uniform Beam Production:



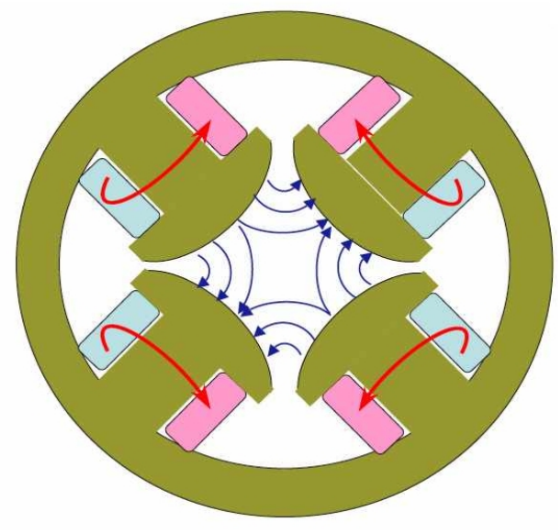
Figs. 1a and 1b. Fitting a Gaussian Distribution to a Rectangular Target

1. Defocussing the Gaussian beam
2. Collimating the Gaussian beam
3. Multiple Coulomb scattering.
4. "Rastering" of the beam.

But there are also some unwanted effects such as:

1. Waste of accelerator energy
2. Background noise from electron collimation
3. Creating the unwanted radioactivity
4. Requirement for complicated sweep system and long sweeping time

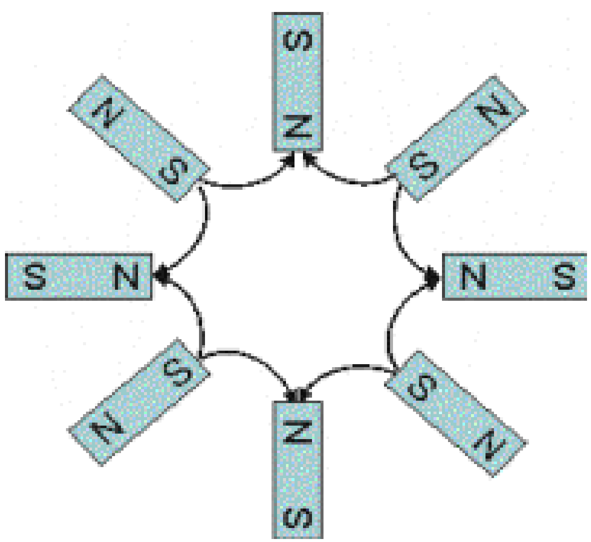
Introduction: Principal of Octupole Beam folding



$$k(s) \equiv \frac{\mu_0 q G_1}{pa} = \frac{q}{p}\frac{\partial B_y}{\partial x}\bigg|_{x=0} \equiv \frac{q}{p} g(s) \approx 0.2998 \frac{g(\mathrm{T/m})}{p(\mathrm{GeV/c})}$$

$$B_x(x,y) = gy, \quad B_y(x,y) = gx \quad \text{for perfect QMs}$$

The strength of the QM does not depend from the radius of QM. So there are not beam redistribution, only focusing, defocussing and bending effects



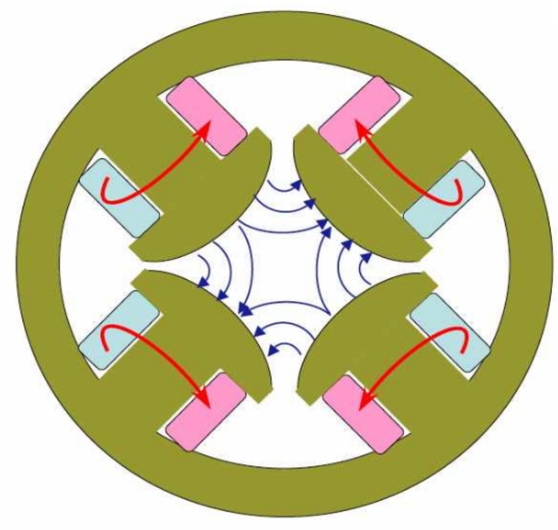
For the octupole n = 3:

$$H_x = (n+1)\frac{NI}{a}\left(\frac{r}{a}\right)^n \sin n\theta,$$

$$H_y = (n+1)\frac{NI}{a}\left(\frac{r}{a}\right)^n \cos n\theta$$

Octupoles can be used to transform a Gaussian distribution into a uniform distribution

Introduction: Principal of Octupole Beam folding



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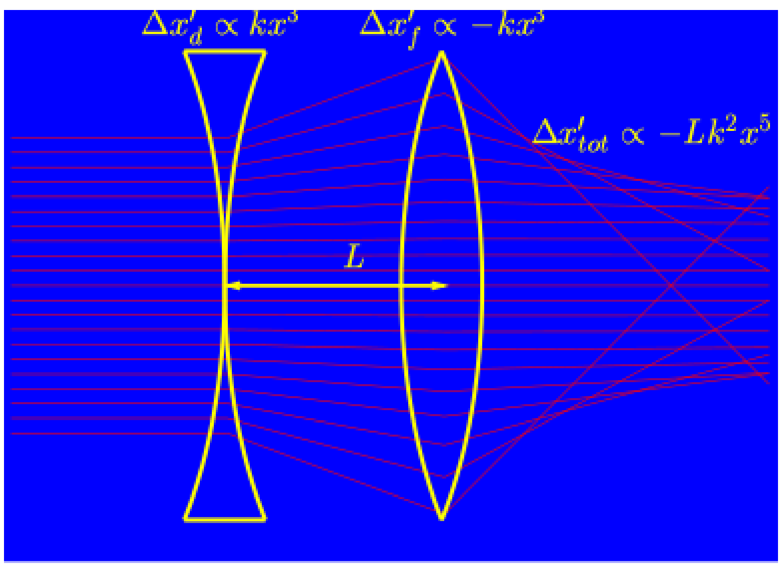


The particles that travel near the axis of the octupole are unaffected since the octupole field varies as the cube of its radius, while the particles away from the axis are deflected in nonlinear manner causing a flattening in the final particle intensity distribution

Figure 1: Principle of the octupole tail folding.

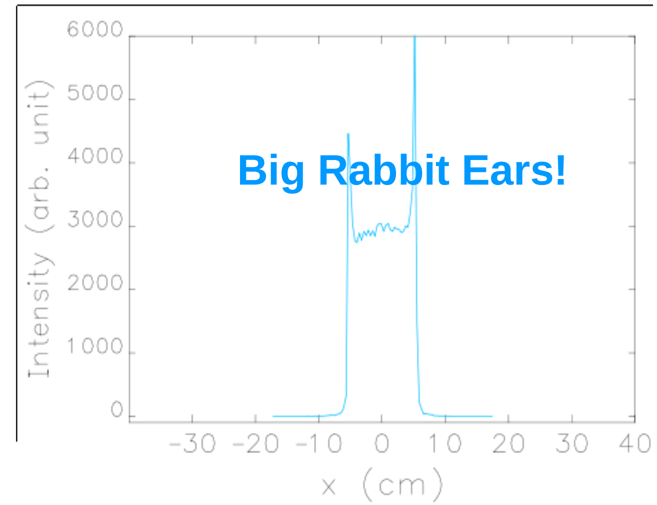
Goals and Tasks

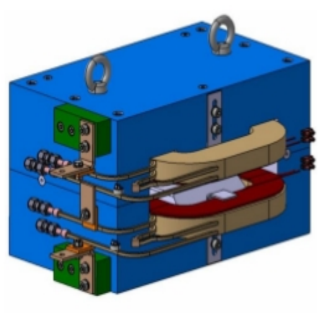
Design a Nonlinear Optics to make a Uniform Electron Beam Distribution

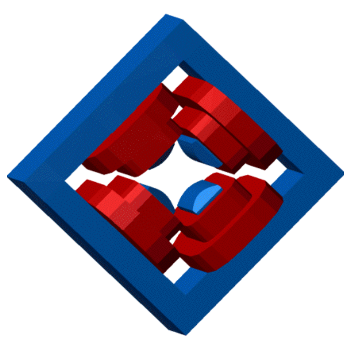
Final Beam Size is 40 mm x 40 mm

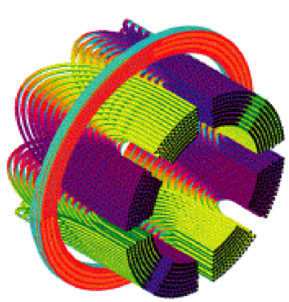
Rabbit Ears are as the smallest as possible

Beam Profile is as uniform as possible









Use available Beam Optics and Space:

- **Two 45 degree sector dipoles**
- **Effective length of BM = 0.2 m**
- **No more than 15 QMs**
- **Length of QM = 0.2 m**
- **Two Octupoles located after the 2nd DM**
- **Available Space = 10 m x 20 m**

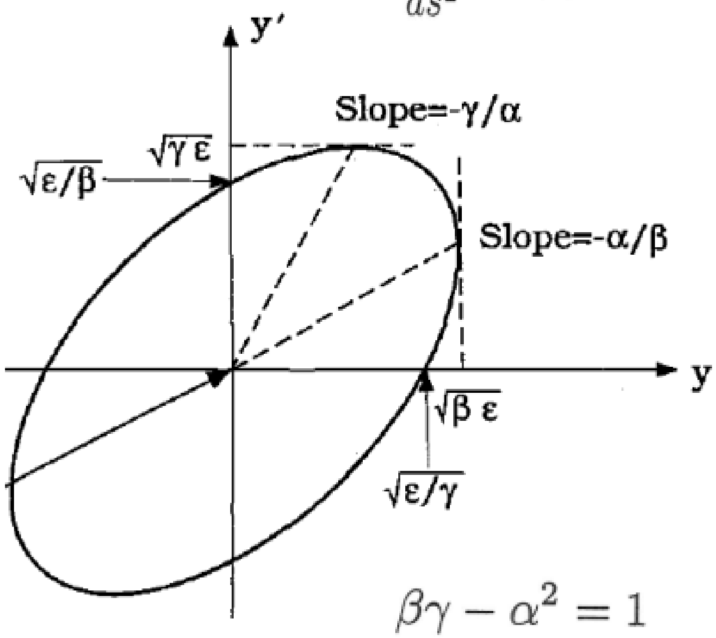
Initial Beam Parameters

$$\epsilon_n = \beta\gamma\epsilon \quad \approx \gamma\varepsilon \text{ for } \beta = \frac{v}{c} \sim 1$$

$$\gamma = E / m_0 c^2$$

- initial beam energy = 20 MeV
- initial normalized rms beam emittance = 5 μm
- initial rms relative energy spread = 0.2%
- initial rms bunch length = 20 ps
- initial horizontal beta function = 10 m
- initial vertical beta function = 10 m
- initial horizontal alpha function = -0.2
- initial vertical alpha function = 0.2
- available space for the beamline = 10 m x 20 m

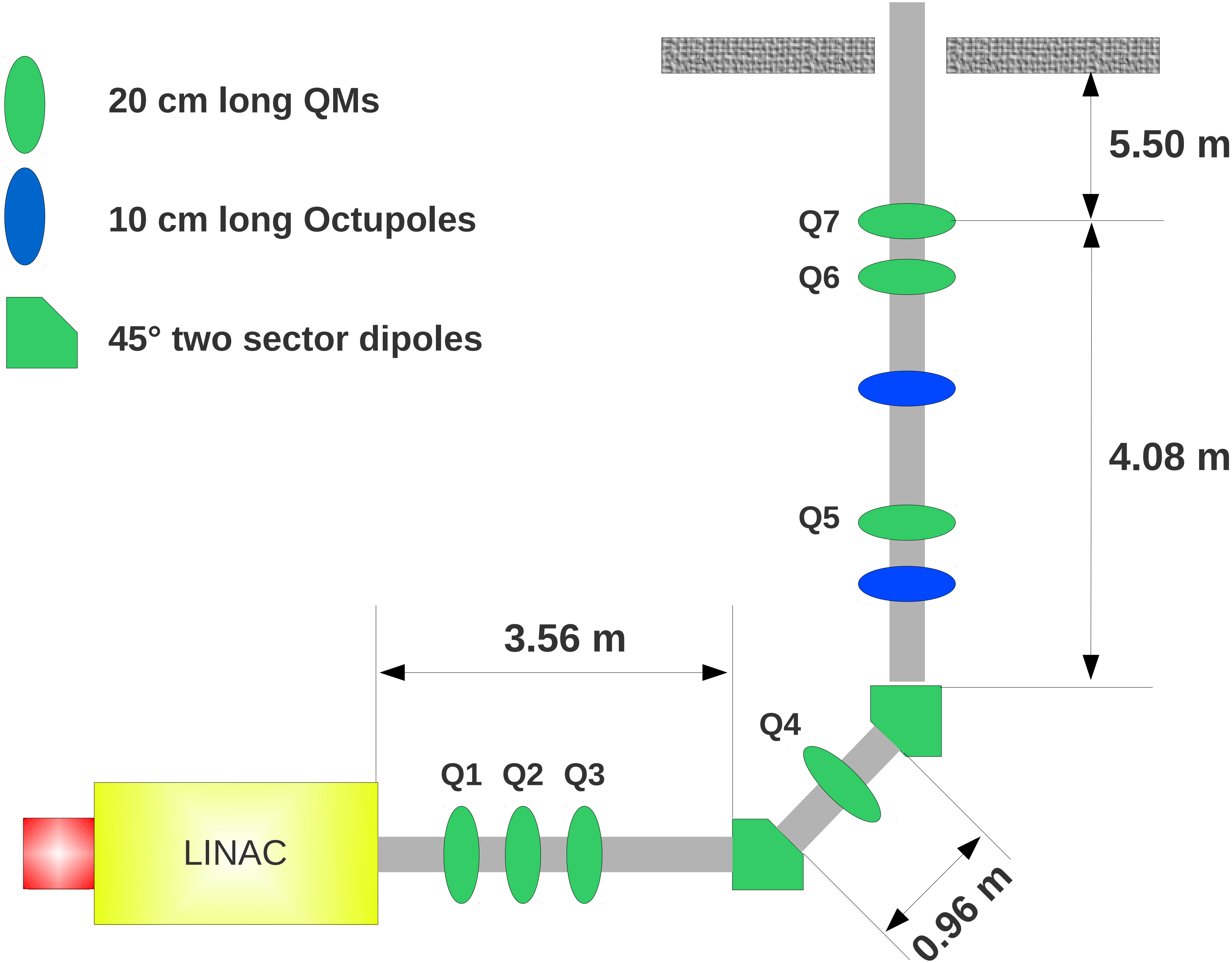
$$\frac{d^2 z}{ds^2} + k(s) z = 0$$



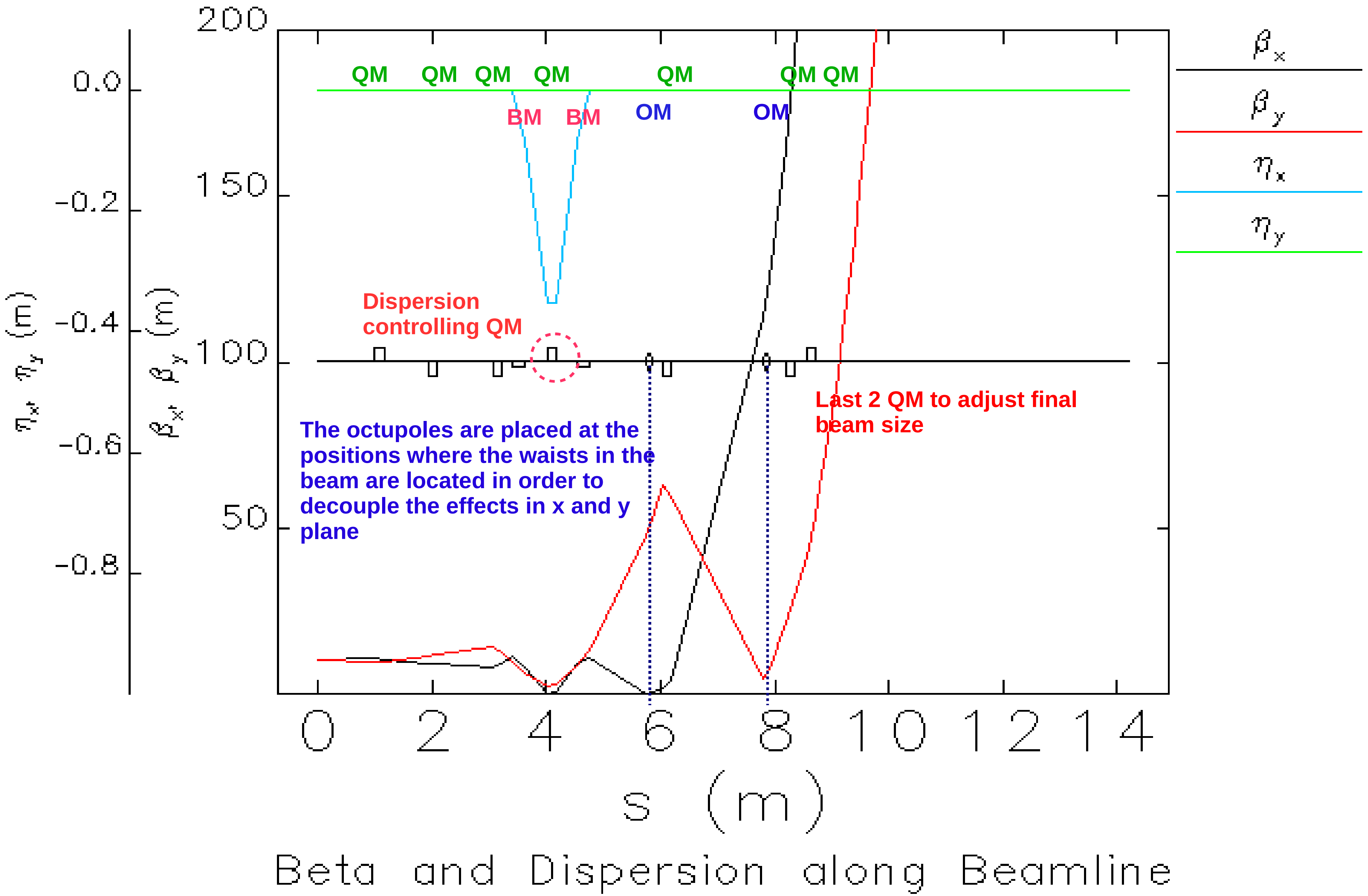
$$\beta\gamma - \alpha^2 = 1$$

$$\delta = \Delta p / p_0$$

Layout of Beamline №1



β-function and Dispersion along Beamline №1



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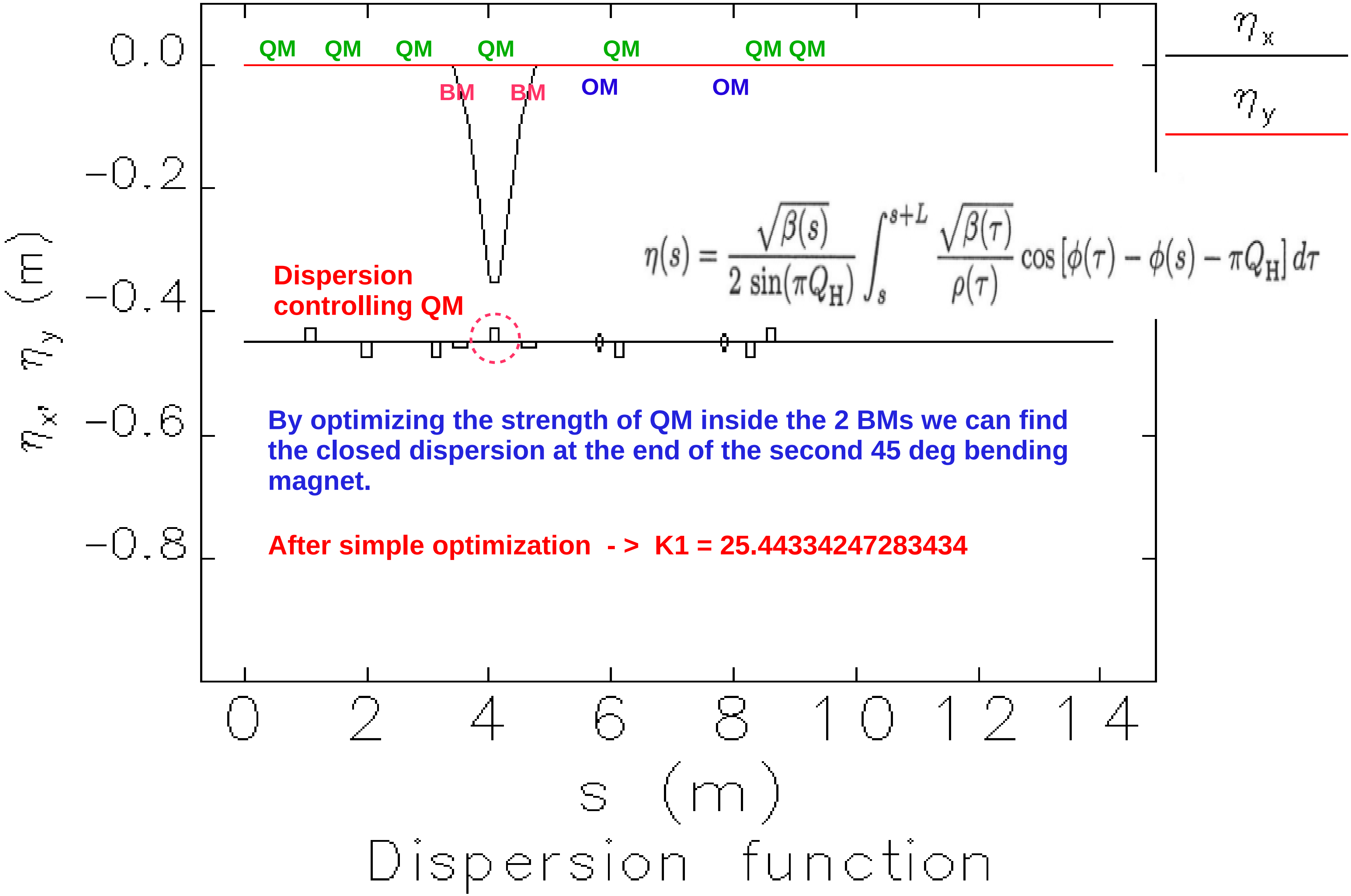
Dispersion correction. Beamline №1

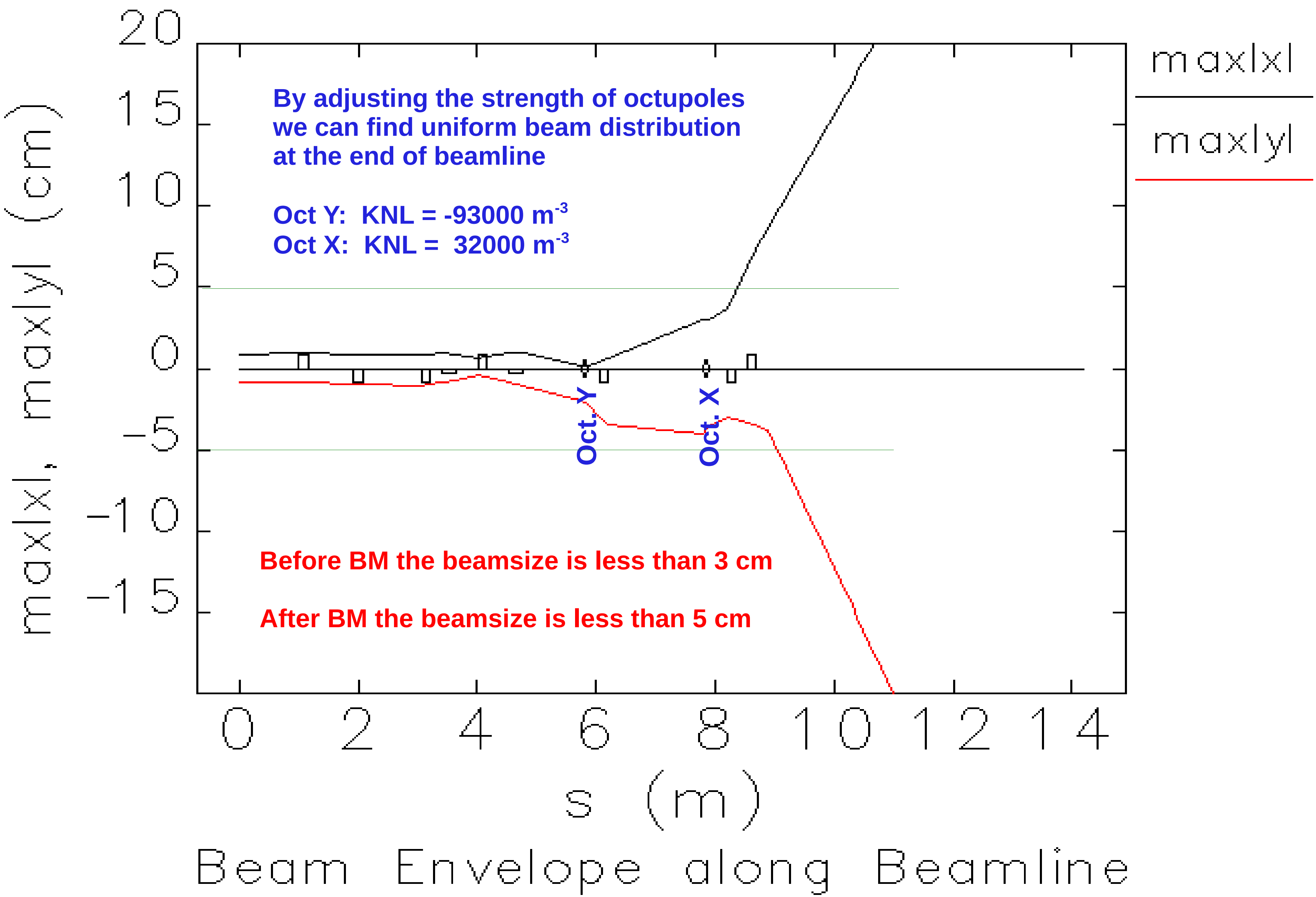


$$\eta(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi Q_H)} \int_s^{s+L} \frac{\sqrt{\beta(\tau)}}{\rho(\tau)} \cos\left[\phi(\tau) - \phi(s) - \pi Q_H\right] d\tau$$

By optimizing the strength of QM inside the 2 BMs we can find the closed dispersion at the end of the second 45 deg bending magnet.

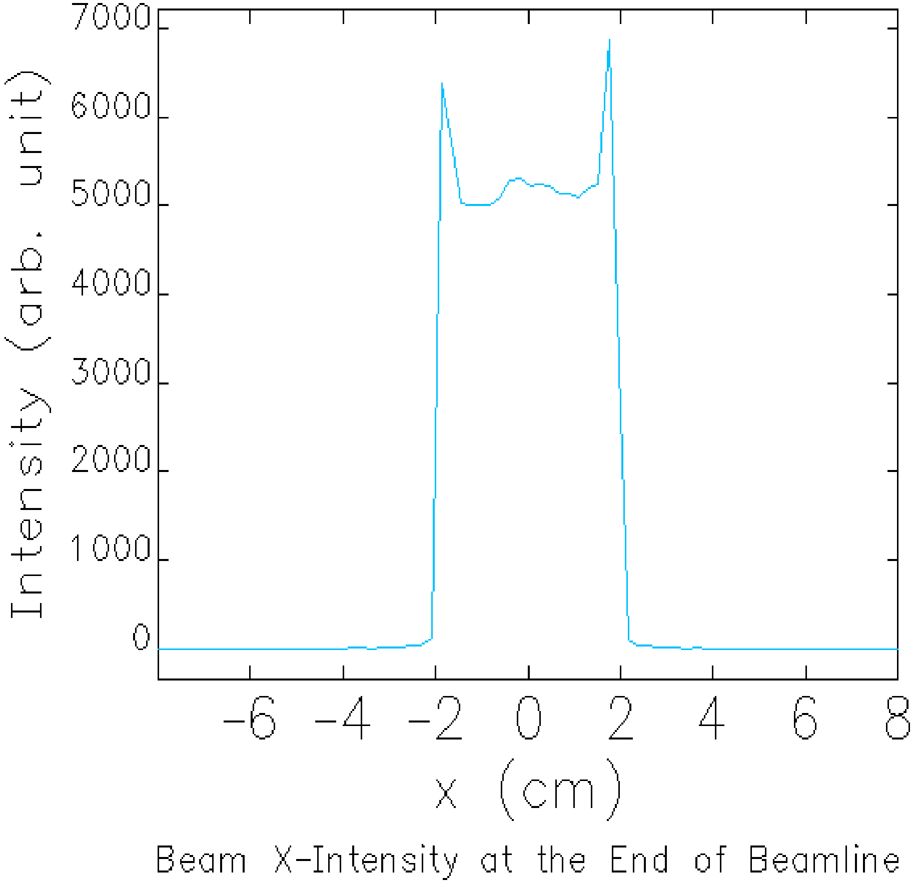
After simple optimization - > K1 = 25.44334247283434

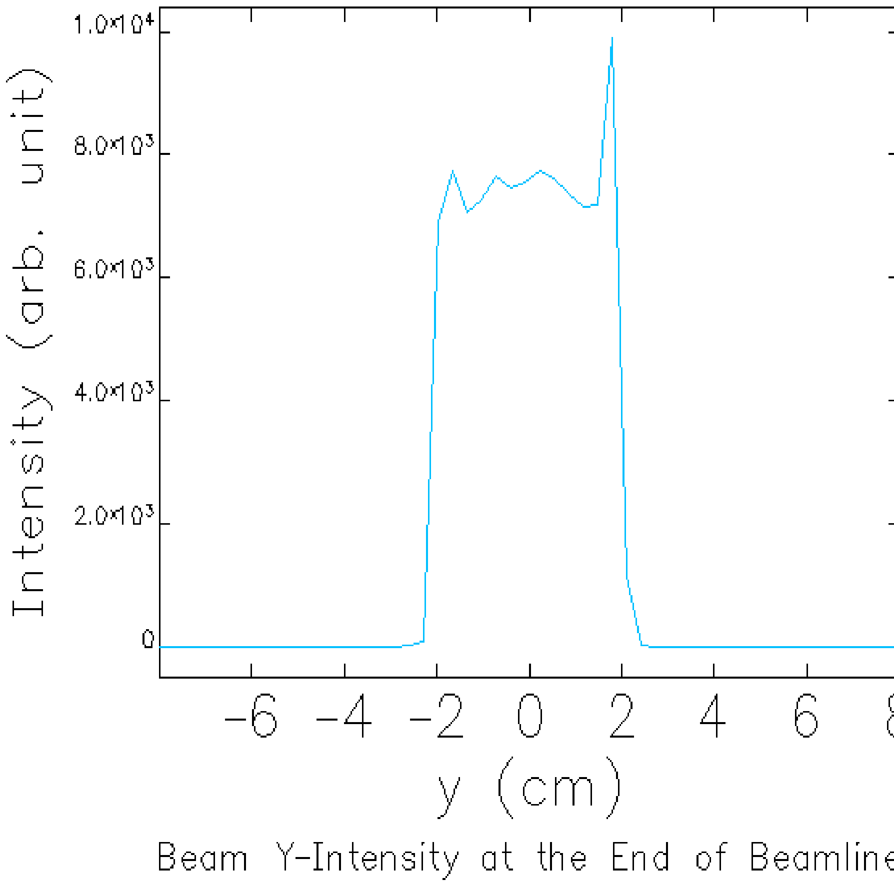
Beam envelope along Beamline №1



1D Intensity Profile at the End of Beamline №1

Uniform Beam Area = 4 cm x 4 cm

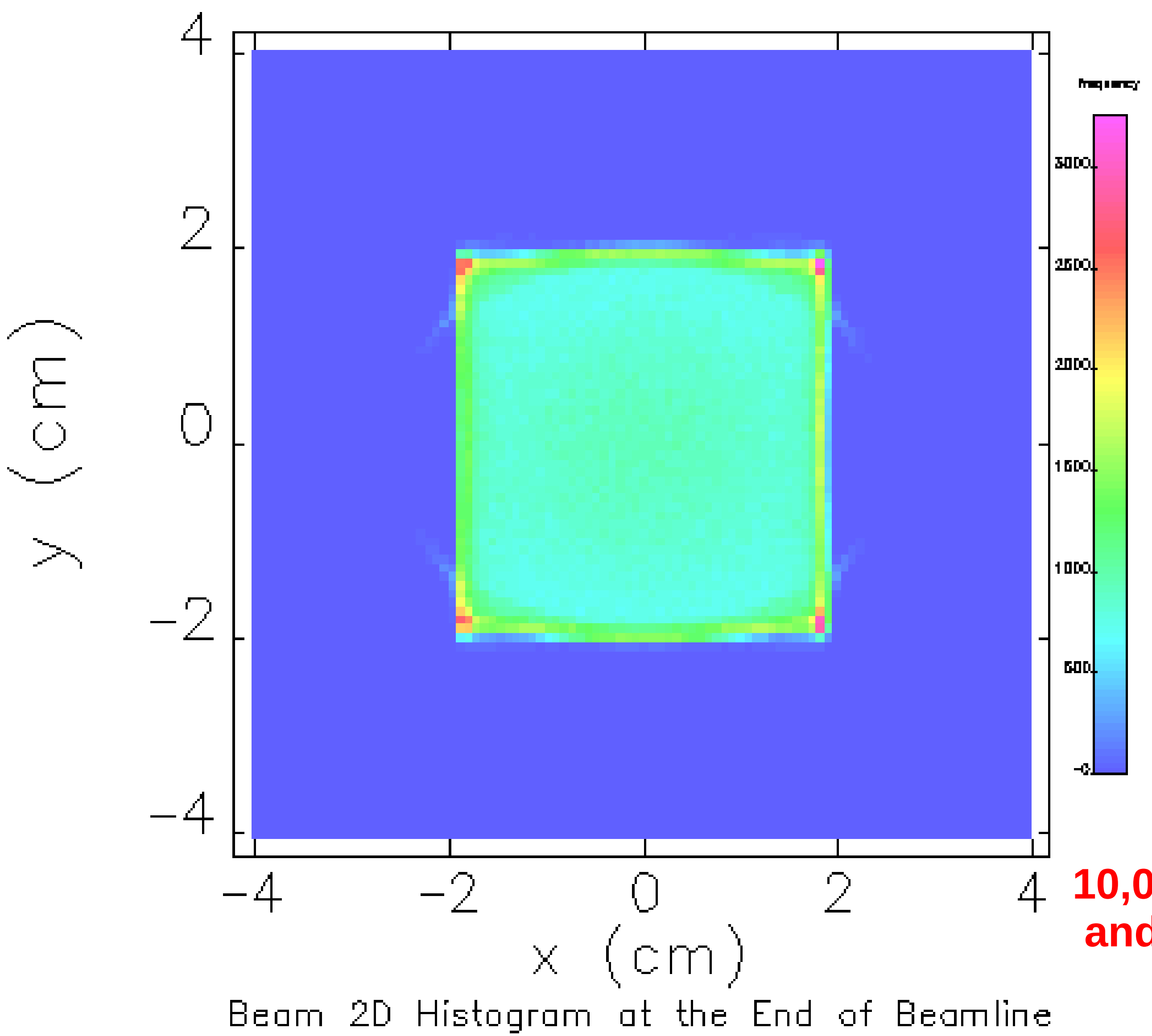




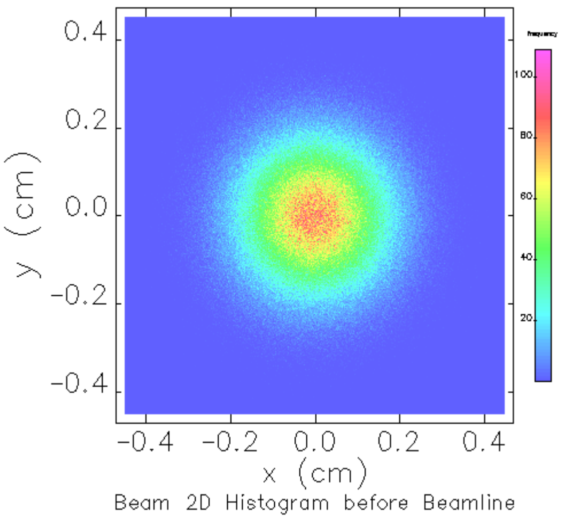
assumed initial beam = Gaussian shape

2D Intensity Profile at the End of Beamline №1

Final Uniform 4 cm x 4 cm Shape

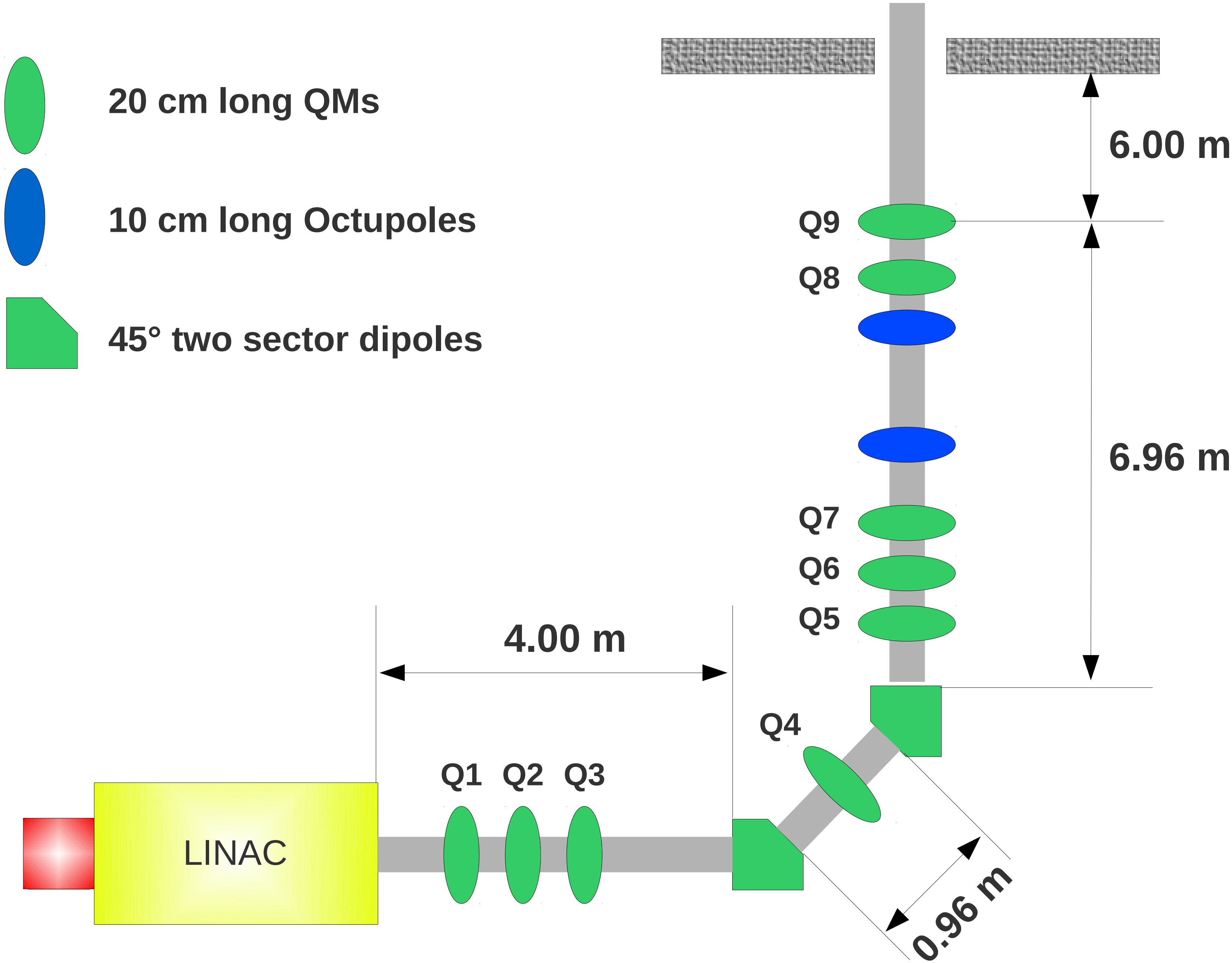


Initial Gaussian shape



10,000,000 particles was generated and transmitted through beamline

Layout of Beamline №2



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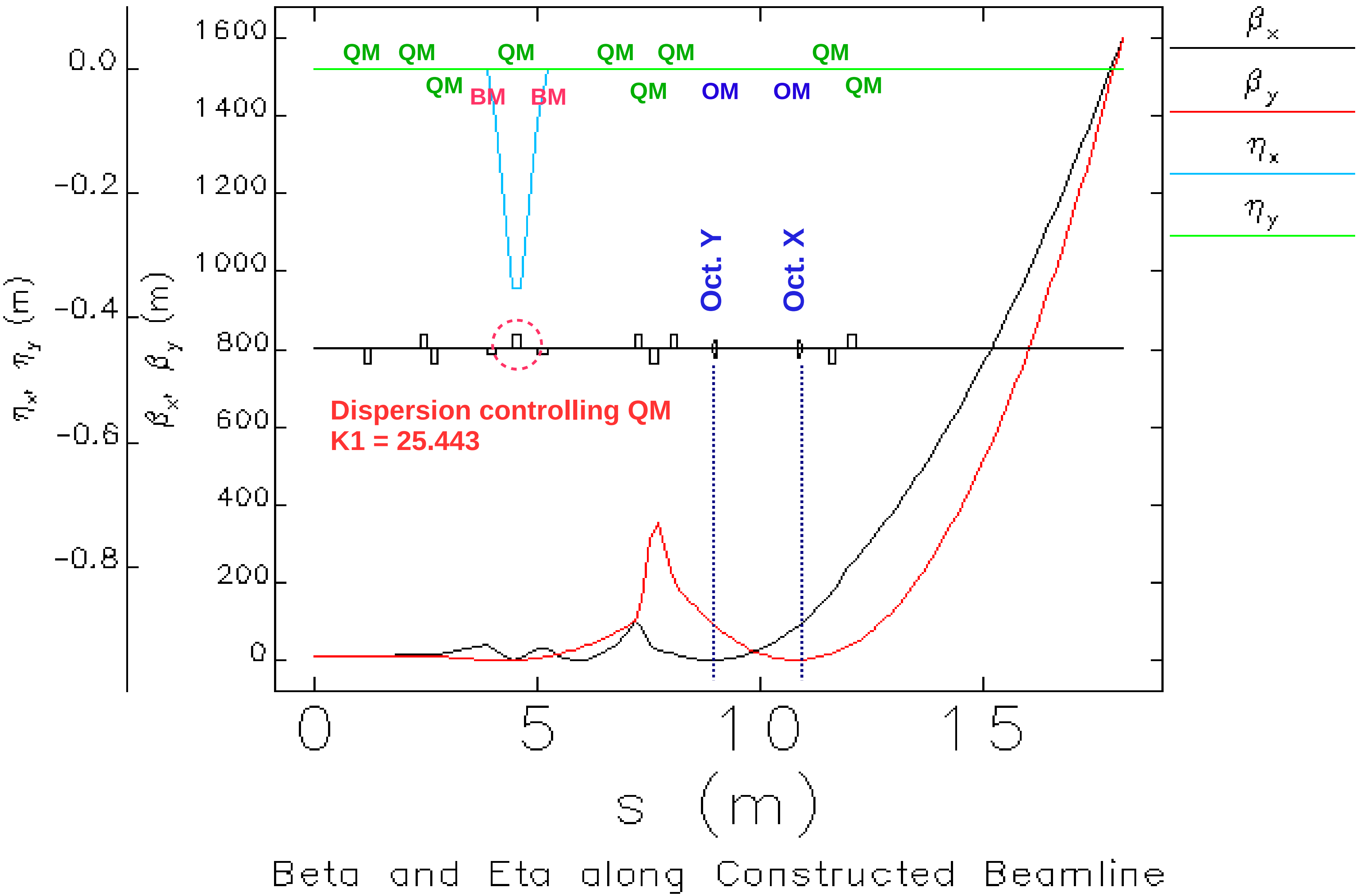
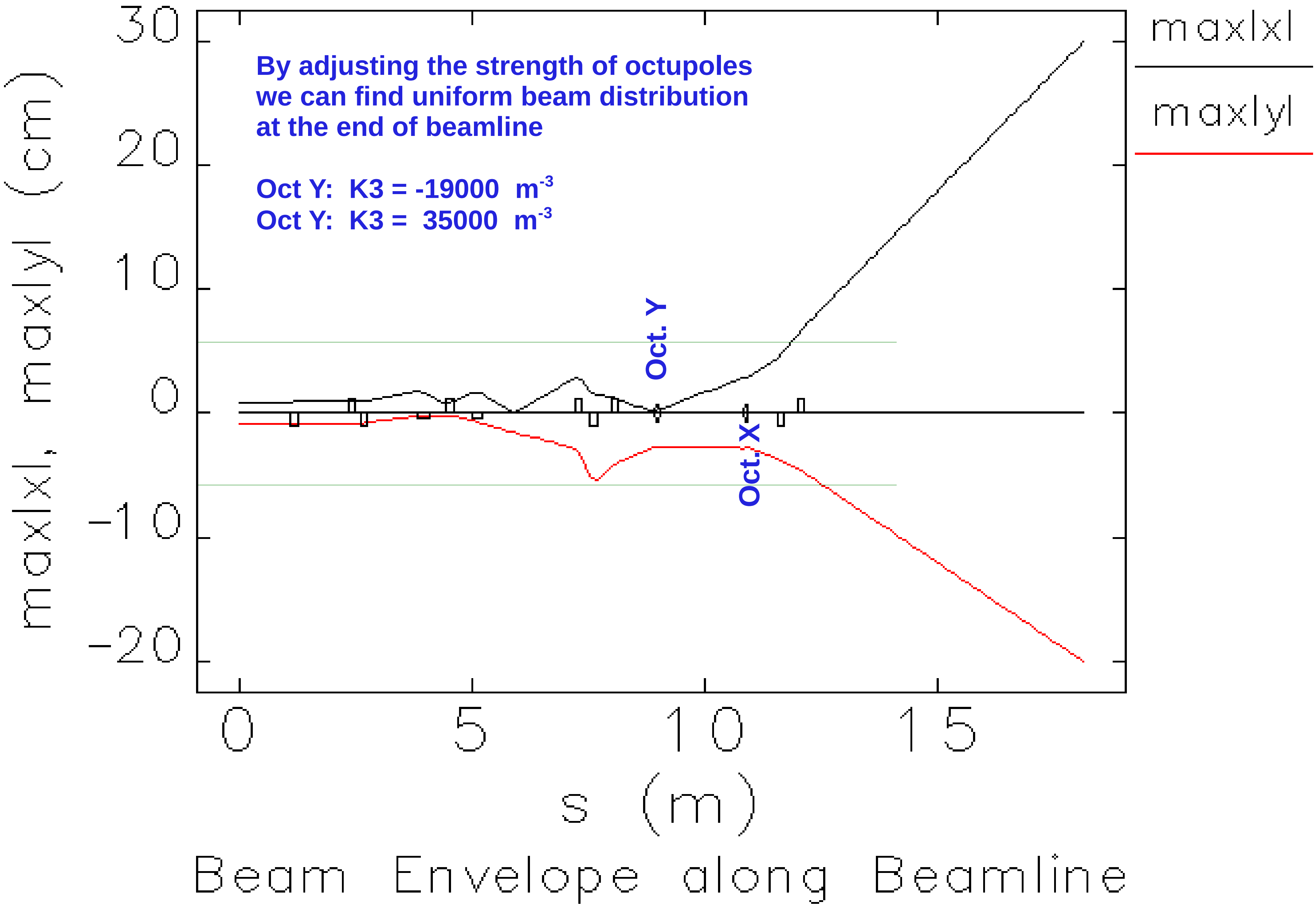
Beam Optics along Beamline №2



Beam Envelope along Beamline №2



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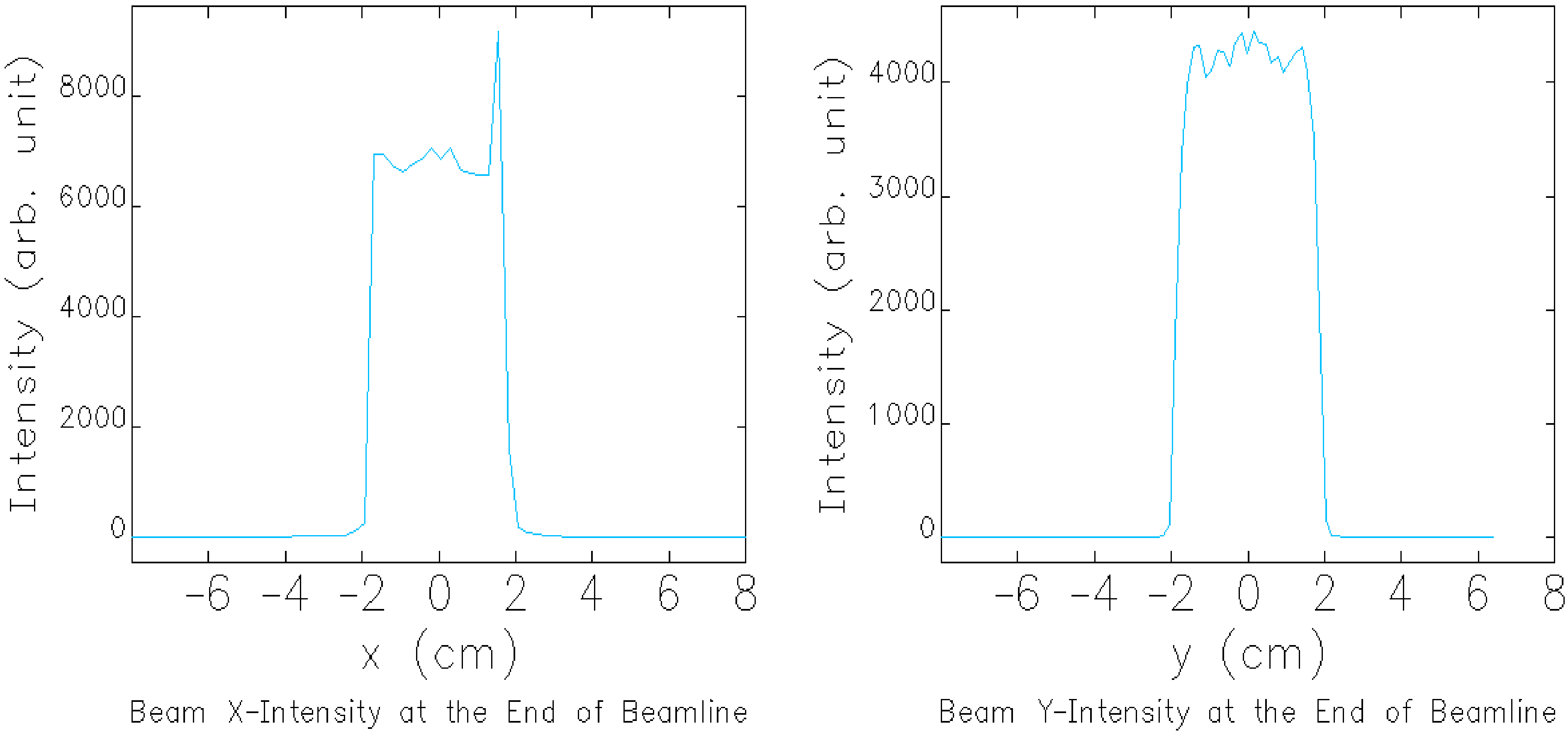
1D Intensity Profile at the End of Beamline №2

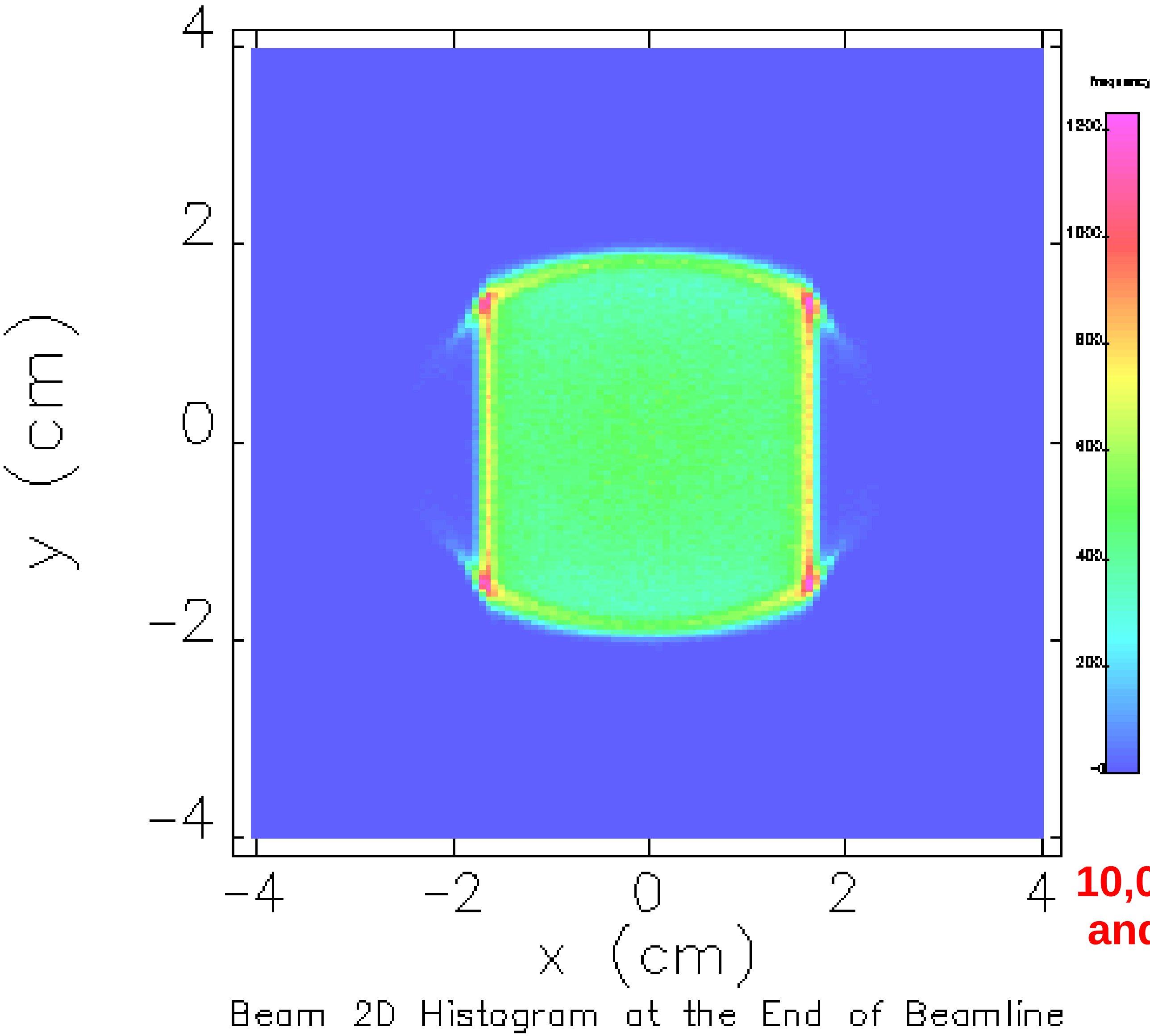
Uniform Beam Area = 4 cm x 4 cm



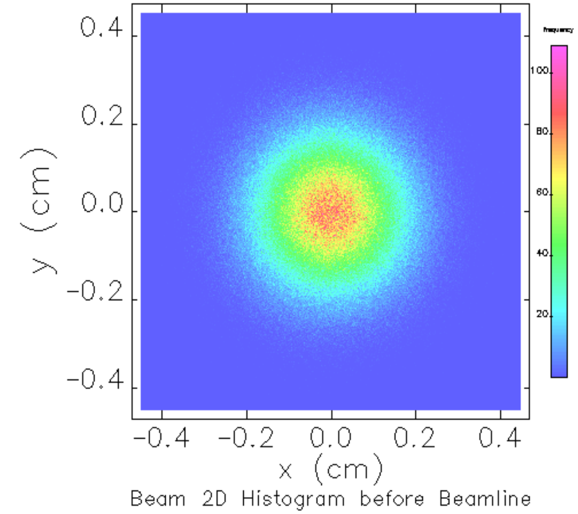
assumed initial beam = Gaussian shape

2D Intensity Profile at the End of Beamline №2

Final Uniform 4 cm x 4 cm Shape



Initial Gaussian shape

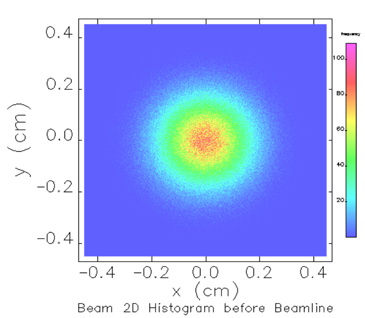


10,000,000 particles was generated and transmitted through beamline

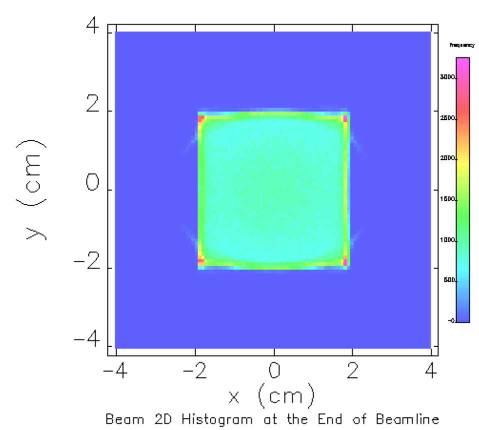
Comparison of Beamline №1 and Beamline №2

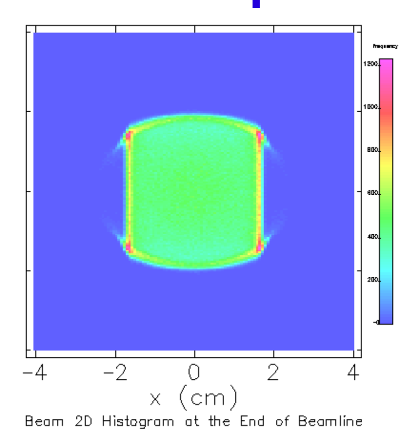
	Beam Line #1	Beam Line #2
Total Beamline Length	14.21 m	18.18 m
Beamline Length before before 1st DM	3.56 m	4.00 m
Beamline Length after after 2nd DM	9.58 m	12.96 m
Beamline Length after Last QM	5.50 m	6.00 m
Maximum Beam Size before 1st DM	1.2168 cm	1.6359 cm
Maximum Beam Size after 2nd DM	4.0566 cm	6.1527 cm
Maximum strength of QM	1.69 T/m	1.69 T/m
Strength of X Octupole	32000 m^{-3}	35000 m^{-3}
Strength of Y Octupole	-93000 m^{-3}	-19000 m^{-3}

Initial Gaussian shape



Final Uniform 4 cm x 4 cm Shape





Octupole Magnet Calculation.

- length = 0.1 m
- bore radius = 0.05 m

$$K_3 L_{OM} = \frac{L_{OM}}{B\rho} \times \left(\frac{\partial^3 B_y}{\partial x^3}\right) = 32000.00 \quad \text{m}^{-3}$$

$$\left(\frac{\partial^3 B_y}{\partial x^3}\right) = \frac{22\,000 \times B\rho}{L_{OM}} \simeq \frac{22000}{L_{OM}} \times \left(\frac{p\,(GeV/c)}{0.2998}\right) \simeq 21347.56 \quad \text{T/m}^3$$

$$T = \frac{1}{6}\frac{\partial^3 B}{\partial x^3} = 3557.92 \quad \text{T/m}^3$$

$$N I = \frac{T a^4}{4\mu_0} \times K_{iron} = 4866.31 \quad \text{A/pole}$$

where K_{iron} takes into account the saturation of the iron, $K_{iron} = 1.1$

Assuming $N = 40$ turns we have $I = 121.65$ A/pole

		KNL, m^{-3}	$\frac{\partial^3 B_y}{\partial x^3}$, T/$m^3$	N, turns	I, A
Beamline #1	X Octupole	**32 000**	**21347.56**	**40**	**121.65**
	Y Octupole	**-93 000**	**62041.36**	**60**	**235.71**
Beamline #2	X Octupole	**35 000**	**23348.89**	**35**	**123.83**
	Y Octupole	**-19 000**	**12 675.11**	**35**	**152.07**

Summary and Suggestions

Summary

1. Beamline to supply uniform 4 cm x 4 cm electron beam was designed.   But any size of uniform beam could be constructed by adjusting the strength of 2 last QMs

2. Two different approach to design beamline was used to show flexibility of used method.

3. A relatively small number of optics could be used to construct beamline.

4. We can utilize this technique in many areas such as uniform target irradiation for medical isotope production or electron to positron beam conversion at IAC and at Physics Department.

Suggestions

1. Further optics optimization to reduce the beam size can be done.

2. In case of second octupole we need to minimize the beam waist to reduce decoupling between two octupoles.

3. The beam distribution strongly depends on OMs location. The study up to 1 mm accuracy in position of octupoles should be done.

4. The effect of beam jitter on final beam distribution need to be performed.

Thank you for attention

Спасибо за внимание

谢谢

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धन्यवाद

teşekkürler