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TAKASAKI ION ACCELERATORS for ADVANCED RADIATION APPLICATION

Focusing Charged Particle Beams Using Multipole Magnets in a Beam Transport Line

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Introduction

- **Use of multipole magnets in a beam line:**
  - Modulation of the transverse phase-space distribution
  - Transformation of the real-space intensity distribution
- **A "*uniform beam**" can be formed using octupole magnets.**
  - For low-rep-rate beam irradiation (BNL/NSRL)
  - For suppression of local target heating due to a high-intensity beam (GSI/UNILAC, IUCF, J-PARC, CSNS, ESS, IFMIF, etc.)
  - For low-fluence/short-time irradiation (JAEA Takasaki)

> *Nonlinear focusing method* is more capable
> for advanced irradiation
> as compared to *beam scanning method*.

**A beam with an almost uniform transverse intensity distribution*

Contents

- The transformation of the transverse distribution is studied using sextupole and octupole magnets.

$$x'' + K_{\mathrm{QUAD}} x + \frac{K_{\mathrm{SXT}}}{2!} x^2 = 0$$

$$x'' + K_{\mathrm{QUAD}} x + \frac{K_{\mathrm{OCT}}}{3!} x^3 = 0$$

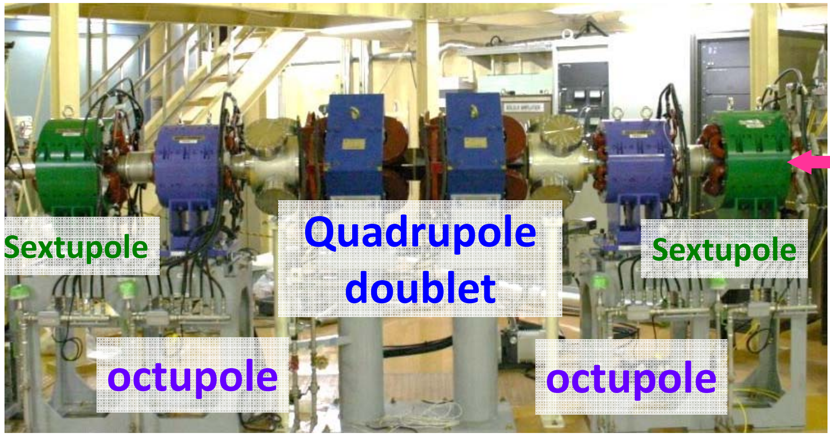
General equation of motion

$$\begin{cases} x'' + K_{\mathrm{QUAD}} x + \frac{K_{\mathrm{SXT}}}{2!}(x^2 - y^2) + \frac{K_{\mathrm{OCT}}}{3!}(x^3 - 3xy^2) + \cdots = 0 \\ y'' - K_{\mathrm{QUAD}} y - \frac{K_{\mathrm{SXT}}}{2!}(2xy) + \frac{K_{\mathrm{OCT}}}{3!}(y^3 - 3x^2 y) + \cdots = 0 \end{cases}$$

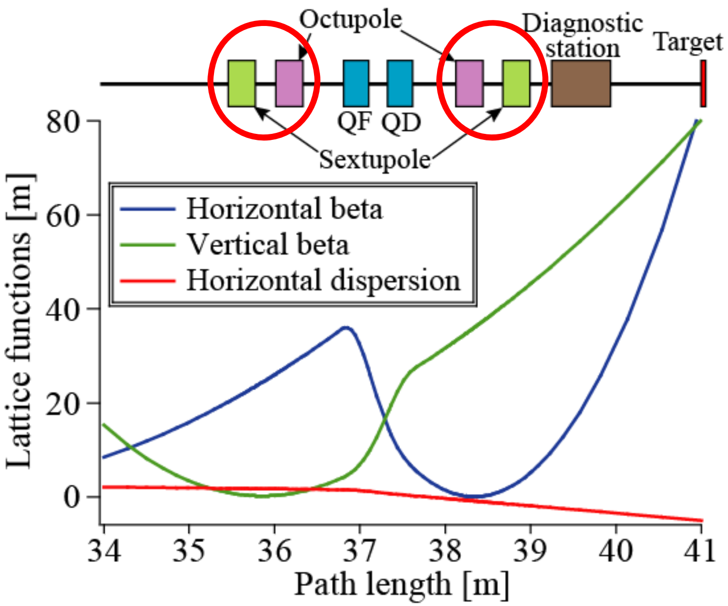
- Agenda
  - Tracking simulation, and its comparison with theory
  - Experiment at JAEA Takasaki Cyclotron (uniform-beam formation)

AVF cyclotron at JAEA Takasaki

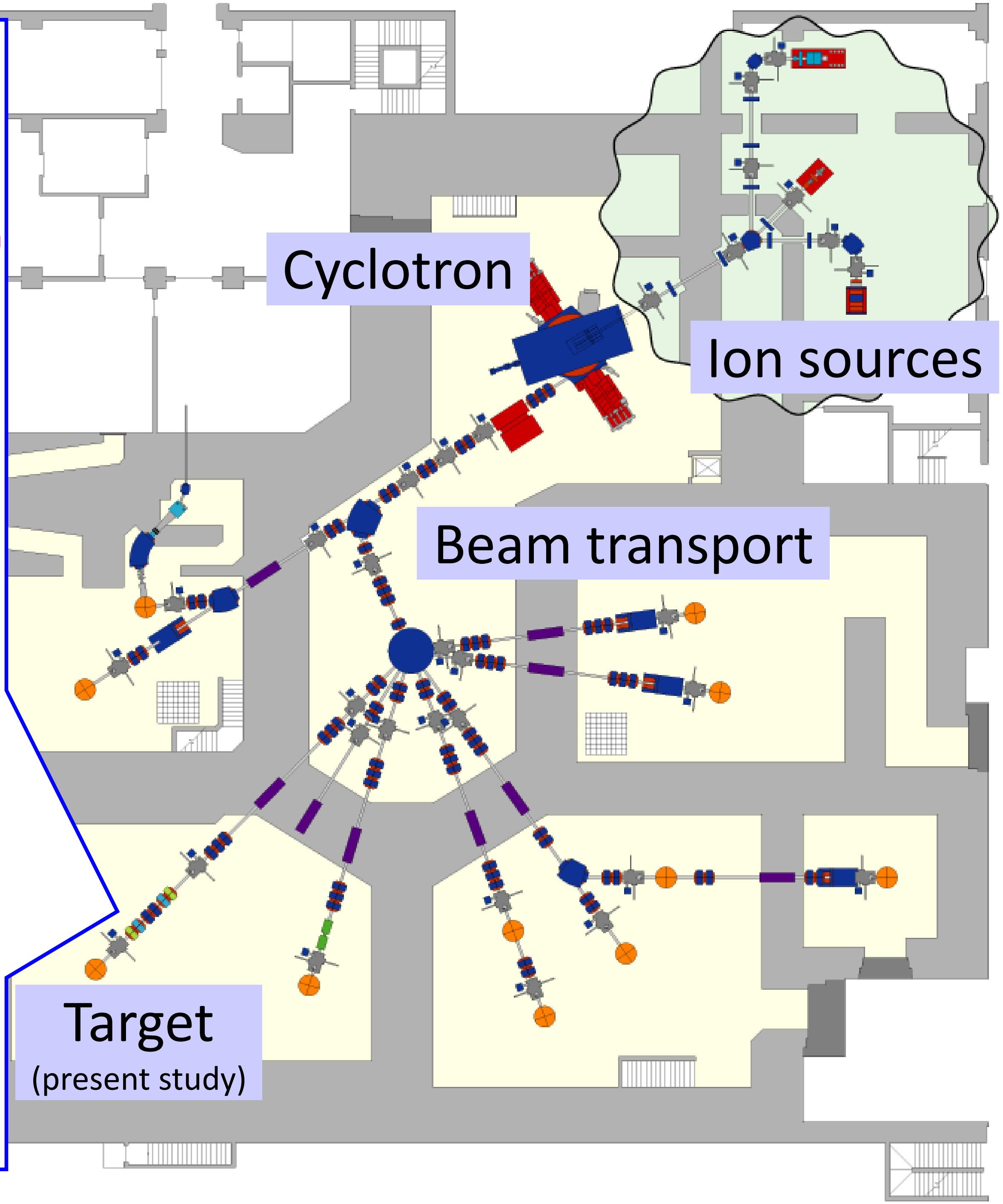
Multipole magnets



Typical beam optics for x-y coupling suppression

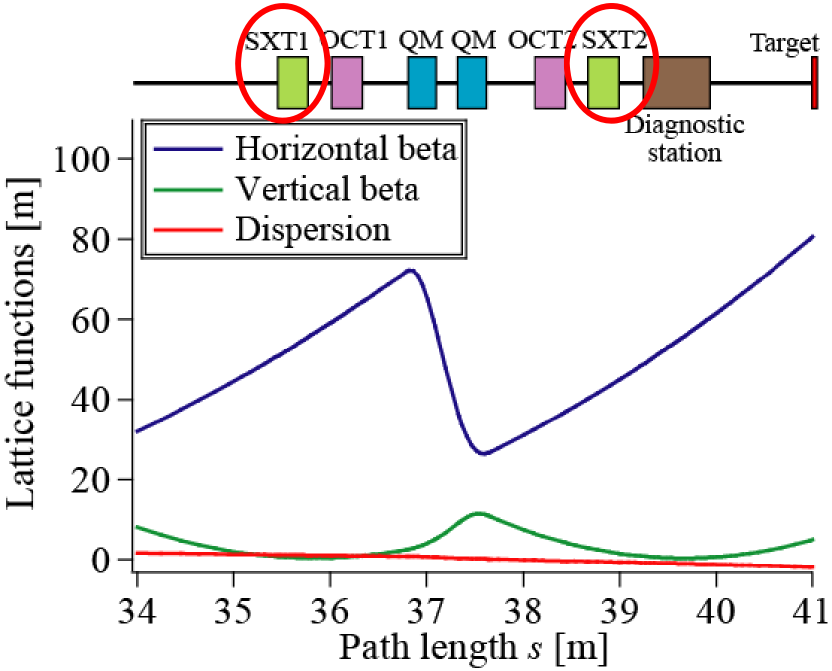


The beam cross-section is made flat at multipole magnet locations

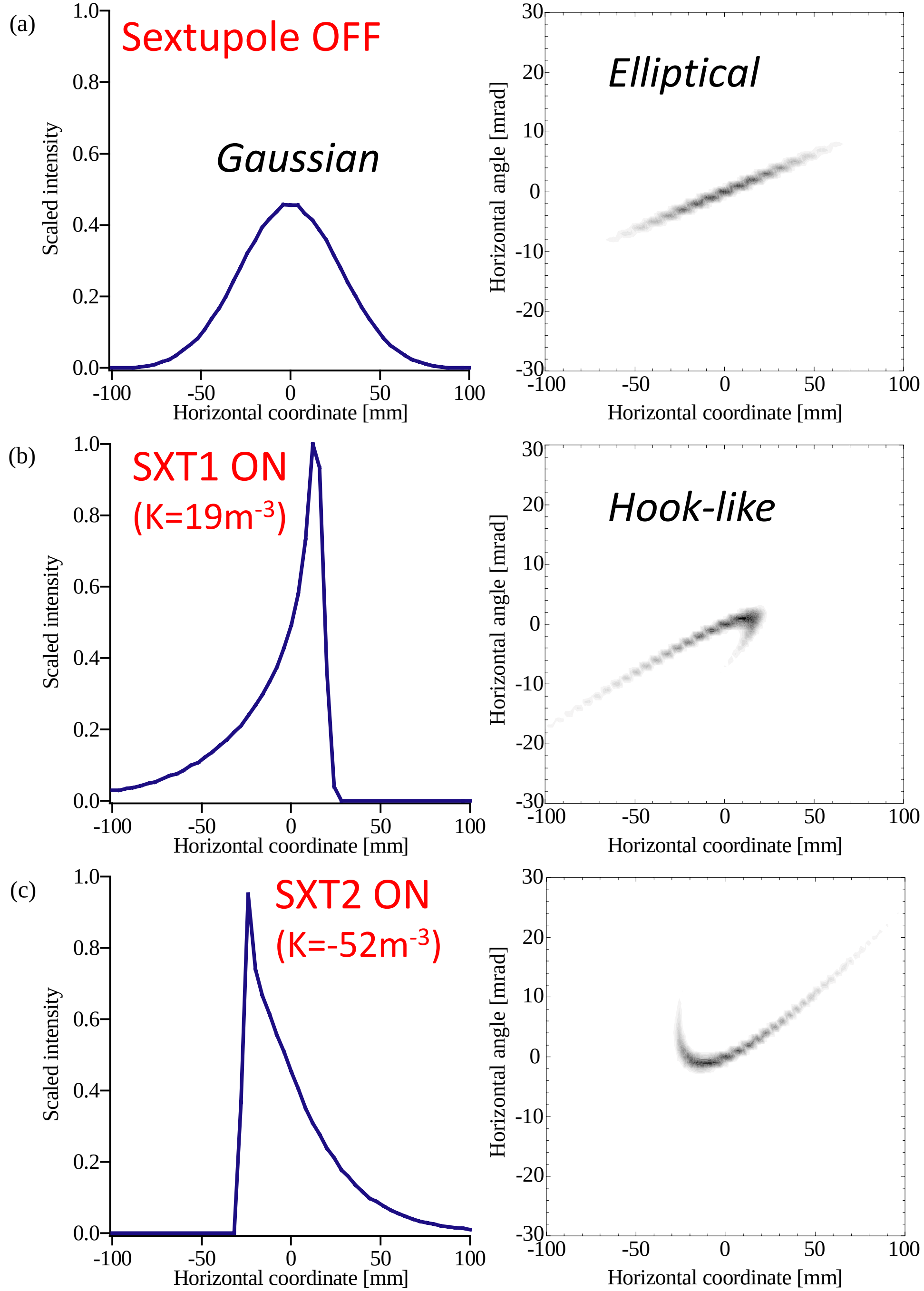


Simulation (1: Sextupole focusing)

- Single-particle tracking
  - From Cyclotron Exit to Target
  - Initial distribution: Gaussian
  - Rms emittance=10π mm.mrad
  - 1D (horizontal only)

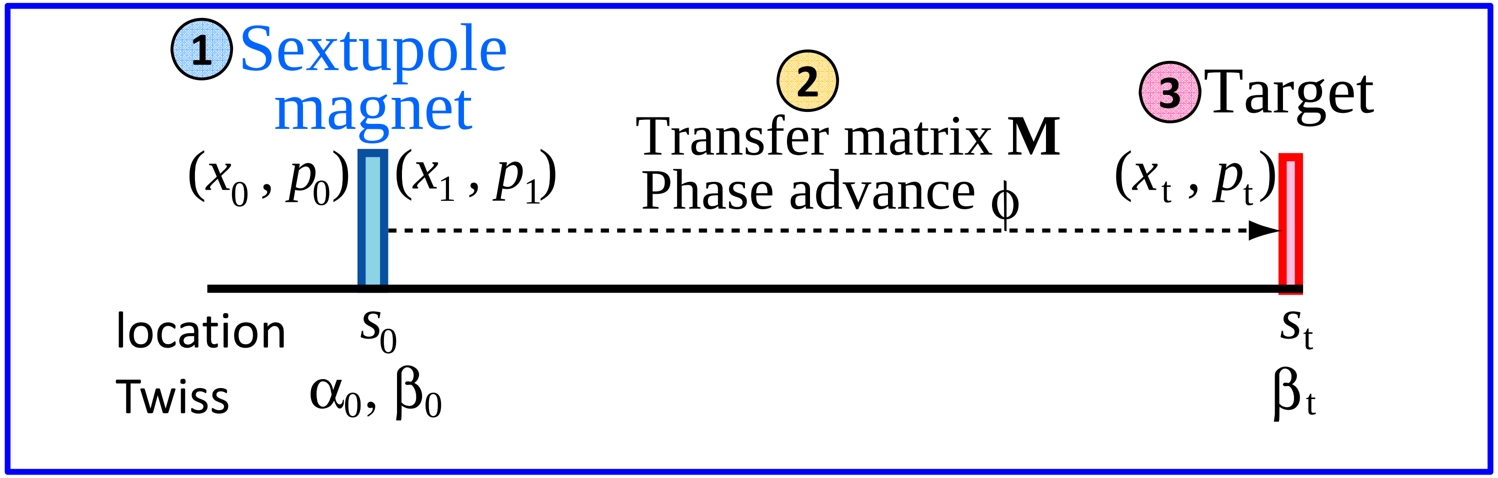


$$x'' + K_{\mathrm{QUAD}}x + \frac{K_{\mathrm{SXT}}}{2!}x^2 = 0$$



Theoretical analysis (1: Single-particle motion)

□ Model of the beam line



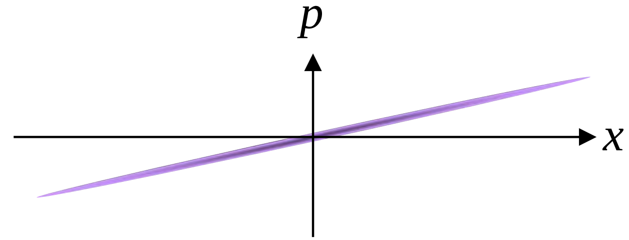
□ Single-particle motion

① $$\begin{cases} x_1 = x_0 \\ p_1 = p_0 - \dfrac{K_{\rm SXT} L_{\rm SXT}}{2} x_0^2 \end{cases}$$ (Thin-lens approx.)

② $$\begin{pmatrix} x_{\rm t} \\ p_{\rm t} \end{pmatrix} = \mathbf{M} \begin{pmatrix} x_1 \\ p_1 \end{pmatrix}$$

③ $$x_{\rm t} = \sqrt{\frac{\beta_{\rm t}}{\beta_0}} \cos\phi \, x_0 - \sqrt{\beta_0 \beta_{\rm t}} \sin\phi \frac{K_{\rm SXT} L_{\rm SXT}}{2} x_0^2$$

Approximation at ①



$$p_0 \approx -(\alpha_0/\beta_0) x_0$$

- "Linear" phase-space profile.
- Beam size is sufficiently large.

(Nonlinear force can be enhanced.)

Y. Yuri et al., PRSTAB2007

Theoretical analysis (2: real-space distribution)

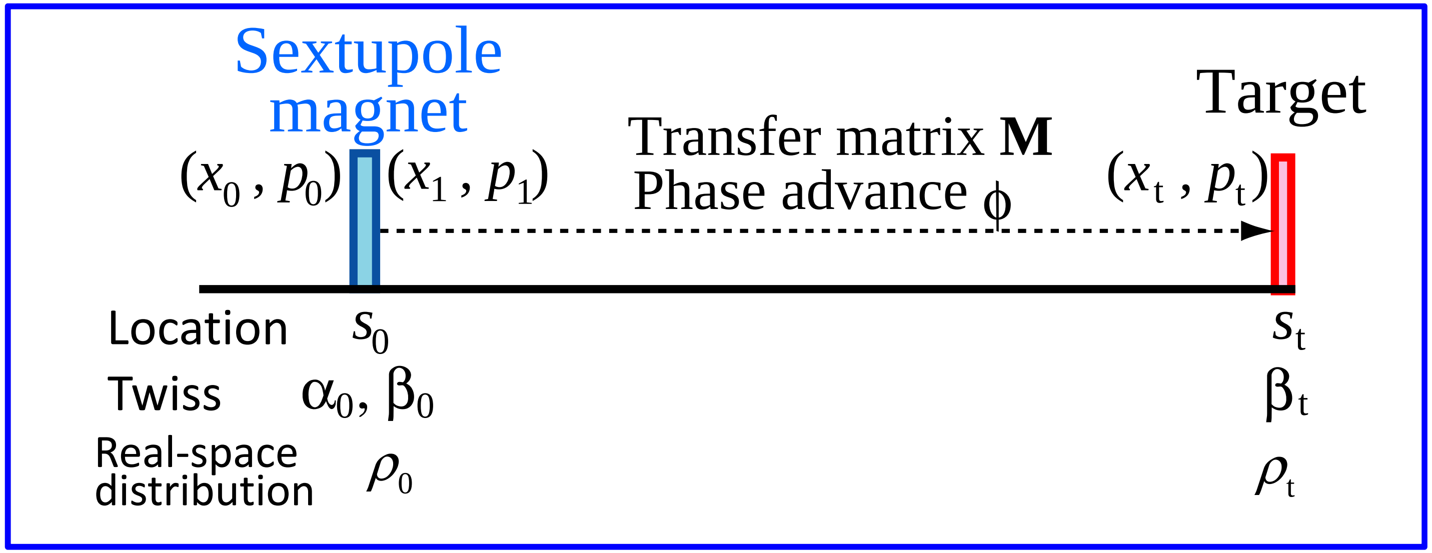
- Real-space distribution function

$$dN = \rho_0 dx_0 = \rho_{\rm t} dx_{\rm t} \quad \Rightarrow \quad \rho_{\rm t} = \rho_0 \left(\frac{dx_{\rm t}}{dx_0} \right)^{-1}$$

(Particle number is preserved.)

- Real-space distribution on the target:

$$\rho_{\rm t} = \rho_0 \left(\frac{dx_{\rm t}}{dx_0} \right)^{-1}$$
$$= \rho_0 \Big/ \left[\sqrt{\frac{\beta_{\rm t}}{\beta_0}} \cos\phi - \sqrt{\beta_0 \beta_{\rm t}} \sin\phi \left(K_{\rm SXT} L_{\rm SXT} \right) x_0 \right]$$



Y. Yuri et al., PRSTAB2007

Theoretical analysis (3: Moment)

Statistical information of the beam can be obtained from moments.

□ 1st-order moment: Beam centroid displacement

$$X \equiv \langle x_{\mathrm{t}} \rangle = \int x_{\mathrm{t}} \rho_{\mathrm{t}} dx_{\mathrm{t}}$$
$$= -\frac{1}{2} \varepsilon \beta_0 \sqrt{\beta_0 \beta_{\mathrm{t}}} \left(K_{\mathrm{SXT}} L_{\mathrm{SXT}} \right) \sin \phi$$

Displaced
due to sextupole force

□ 2nd-order moment: RMS beam radius (envelope)

$$\sigma \equiv \sqrt{\left\langle \left(x_{\mathrm{t}} - X \right)^2 \right\rangle} = \sqrt{\int \left(x_{\mathrm{t}} - X \right)^2 \rho_{\mathrm{t}} dx_{\mathrm{t}}}$$
$$= \sqrt{\varepsilon \beta_{\mathrm{t}}} \sqrt{1 + \frac{1}{2} \varepsilon \beta_0^3 \left(K_{\mathrm{SXT}} L_{\mathrm{SXT}} \right)^2 \tan^2 \phi} \left| \cos \phi \right|$$

Always increase
due to sextupole force

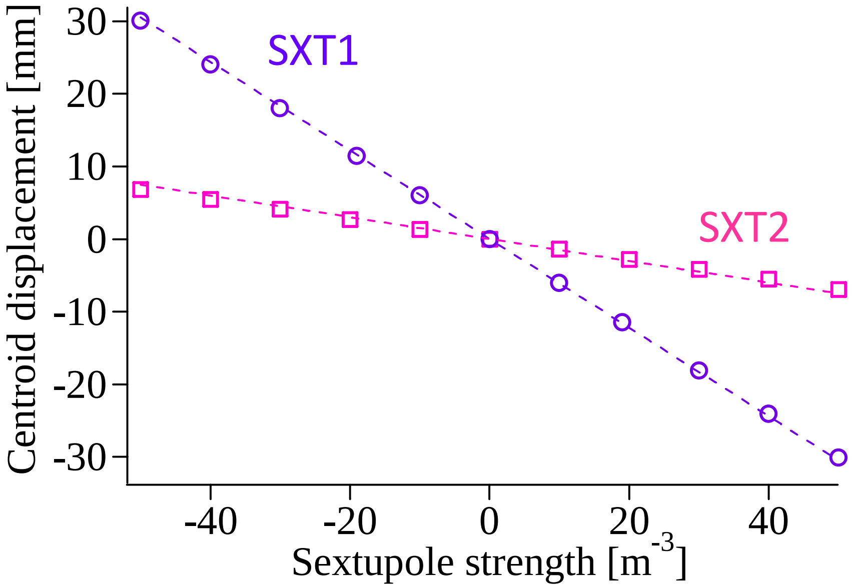
A Gaussian distribution has been assumed as an initial distribution ρ_0.

Y. Yuri et al., JPSJ2012

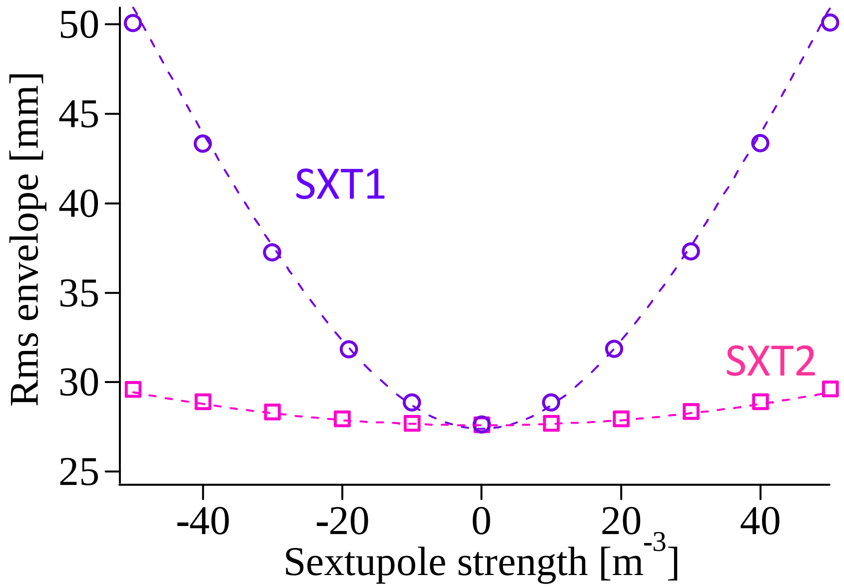
Beam centroid and rms envelope

- Comparing simulation results with the theoretical predictions.

Centroid displacement on the target



Rms envelope on the target



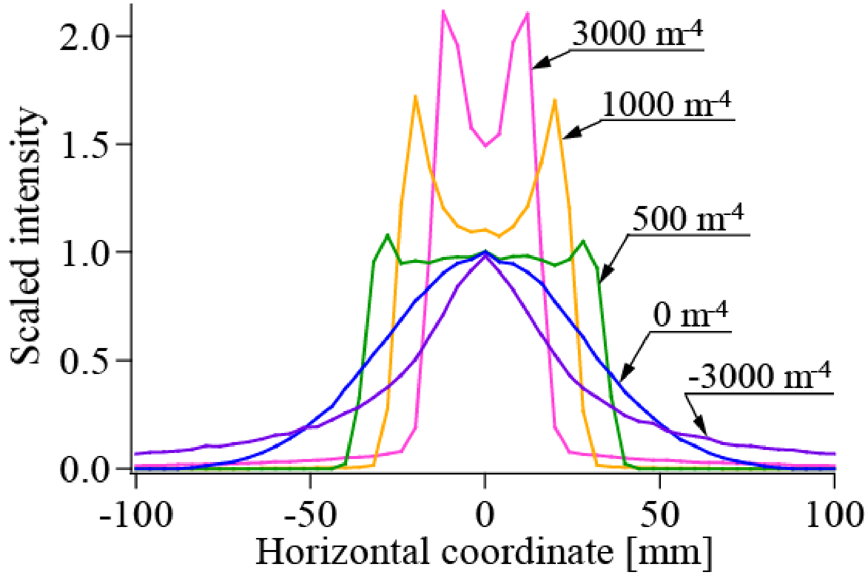
Dashed lines: Theory
○, □: Simulations

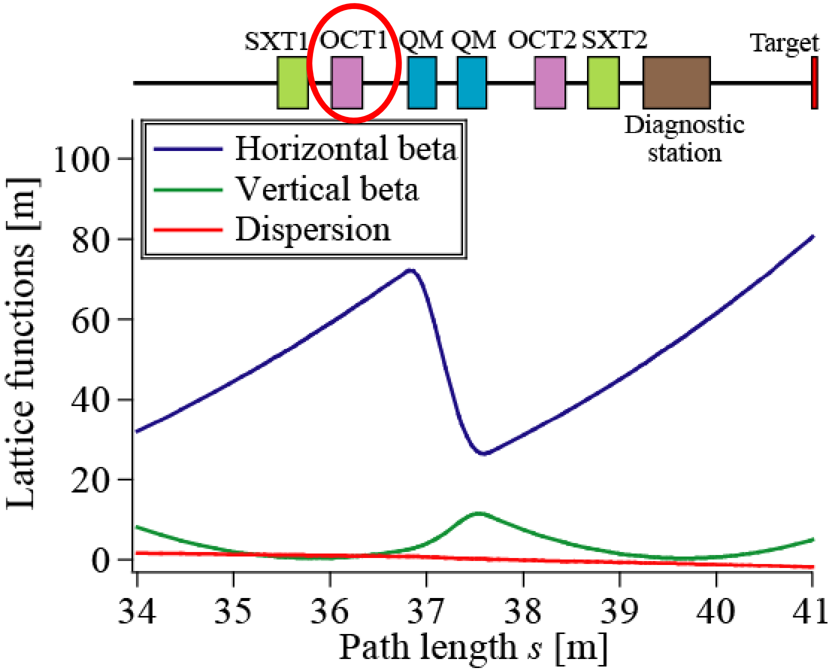
$$X = -\frac{1}{2}\varepsilon\beta_0\sqrt{\beta_0\beta_t}\left(K_{SXT}L_{SXT}\right)\sin\phi$$

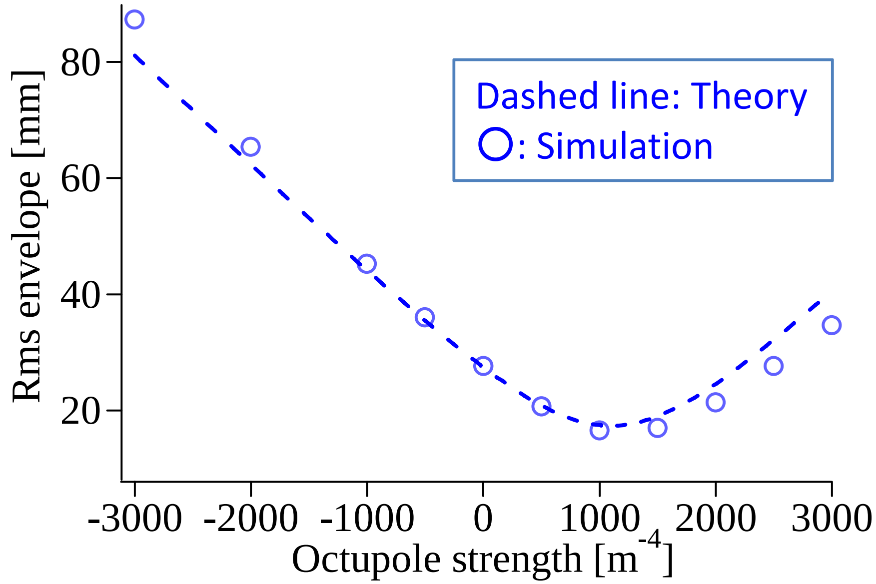
$$\sigma = \sqrt{\varepsilon\beta_t}\sqrt{1+\frac{1}{2}\varepsilon\beta_0^3\left(K_{SXT}L_{SXT}\right)^2\tan^2\phi}\,\left|\cos\phi\right|$$

Simulation (2: Octupole focusing)

- Single-particle tracking
  - From Cyclotron Exit to Target
  - Initial distribution: Gaussian
  - Rms emittance=10π mm.mrad
  - 1D (horizontal only)







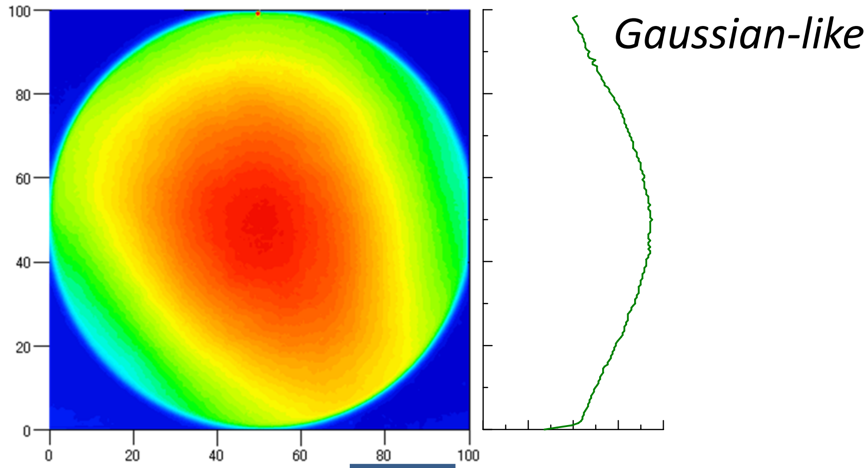
$$x'' + K_{QUAD}x + \frac{K_{OCT}}{3!}x^3 = 0$$

$$\sigma = \sqrt{\varepsilon\beta_t}\sqrt{1-\varepsilon\beta_0^2\left(K_{OCT}L_{OCT}\right)\tan\phi + \frac{5}{12}\left[\varepsilon\beta_0^2\left(K_{OCT}L_{OCT}\right)\tan\phi\right]^2}\,\left|\cos\phi\right|$$

Experiment @ JAEA (1: Octupole focusing)

- Beam experiment at JAEA Takasaki :
  - 10MeV protons from Cyclotron
  - Focused by octupole magnets
  - Measured on-target 2D profile using radiochromic films

Octupoles: OFF

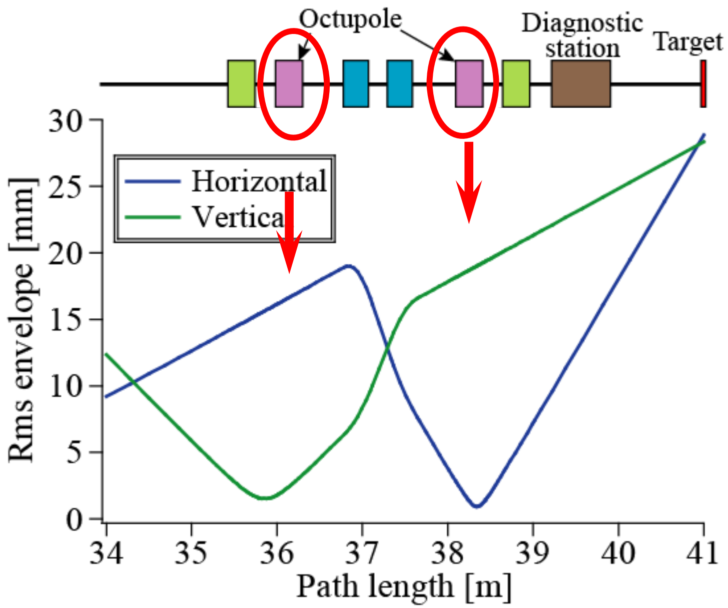


2D relative intensity

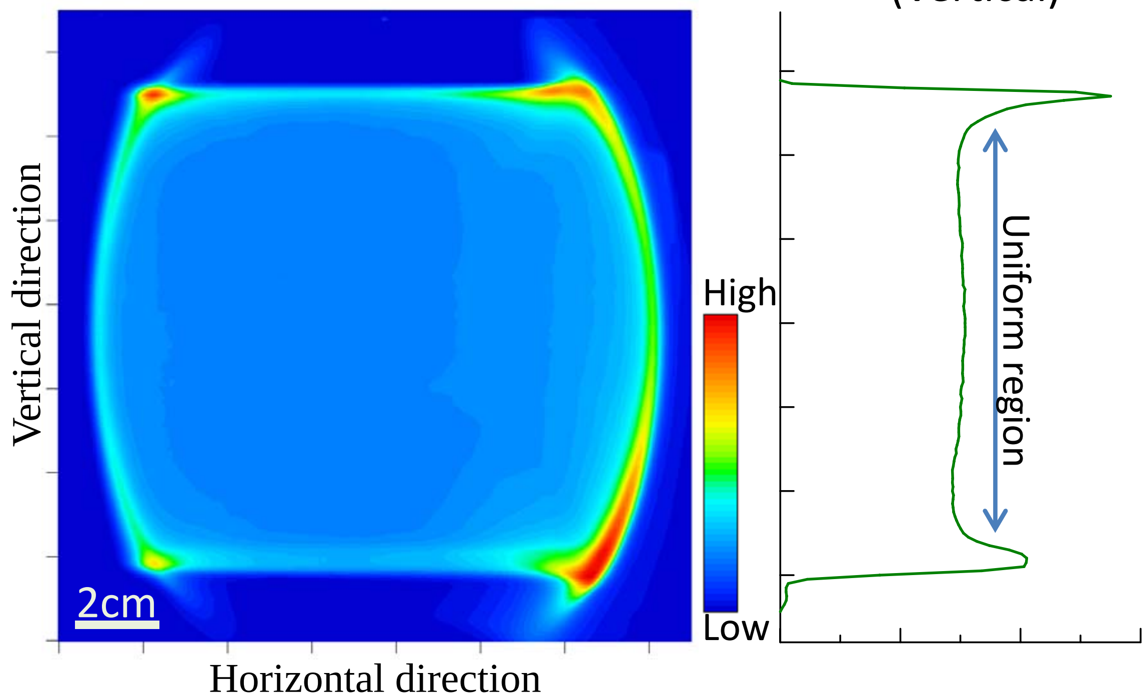
ON

1D relative intensity (Vertical)

Beam optics
for a large-area uniform beam



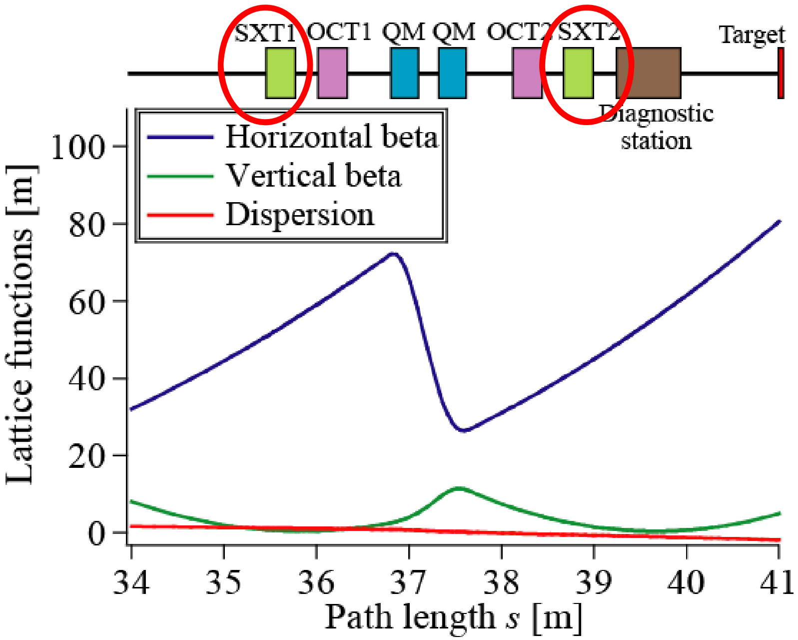
The beam cross-section is made flat at multipole magnet locations



Y. Yuri et al., NIMA2011

Experiment @ JAEA (2: Sextupole focusing)

- Beam experiment at JAEA Takasaki :
  - 10MeV protons from Cyclotron
  - <u>Focused by sextupole magnets</u>
  - Measured on-target 2D profile using radiochromic films



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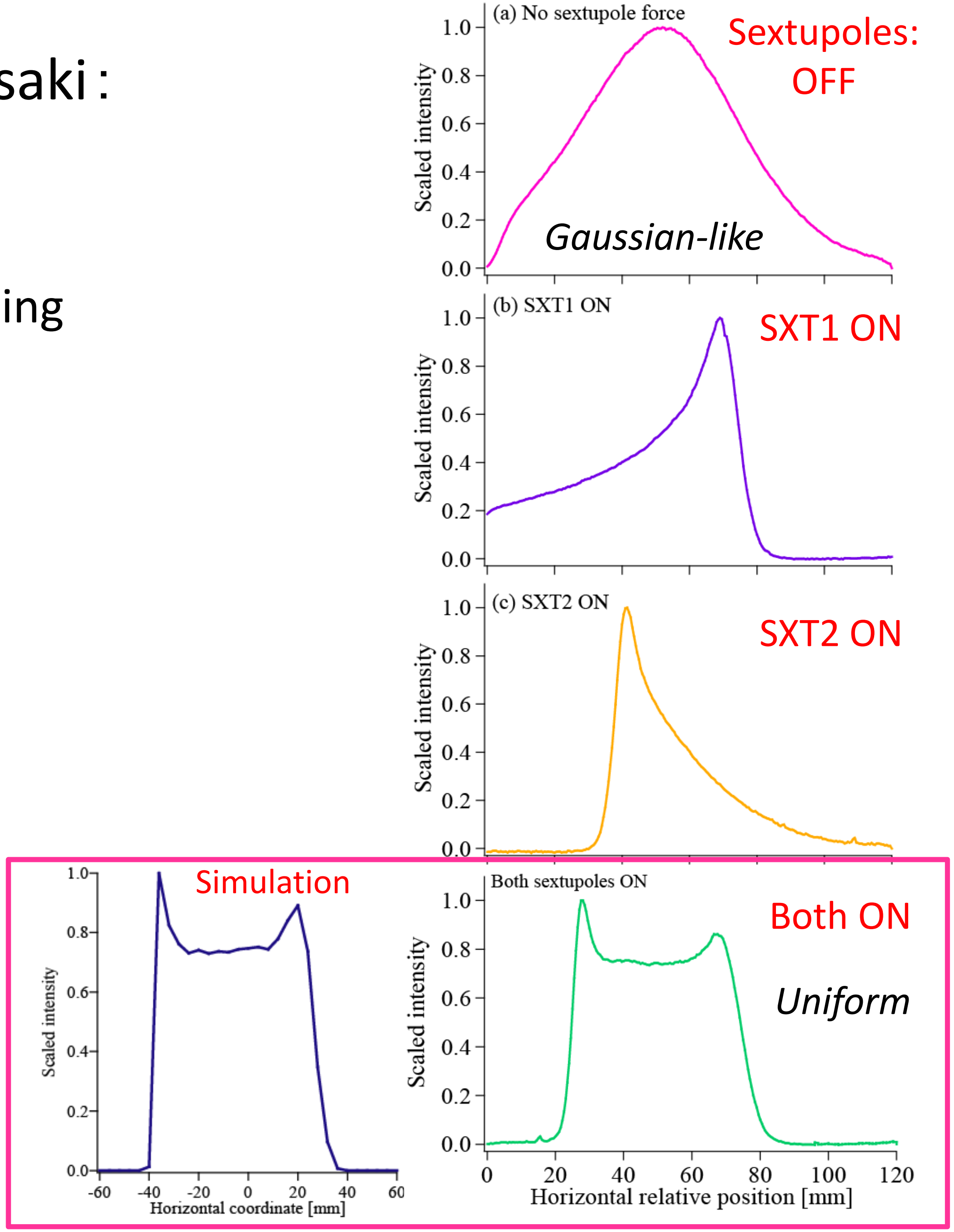

Summary

- We investigated the transformation of the transverse distribution by multipole magnets theoretically, numerically, and experimentally.
- The centroid displacement and rms envelope change of the beam focused by a sextupole or octupole magnet were shown.
- Furthermore, the intensity distribution can be transformed from a Gaussian one to a uniform one by octupole focusing or by combined sextupole focusing.
- Such uniform beams tailored by means of the nonlinear focusing method are used for applications in materials sciences (ion-track membranes, space-use device test, etc.) at JAEA Takasaki.