Diverse Beam Profile Shapings through Nonlinear Focusing of Multipole Magnets in a Beam Transport Line

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Feasibility of beam profile shaping using the nonlinear focusing force

- Equation of motion in the horizontal and vertical directions:

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

Quadrupole **Sextupole** **Octupole**

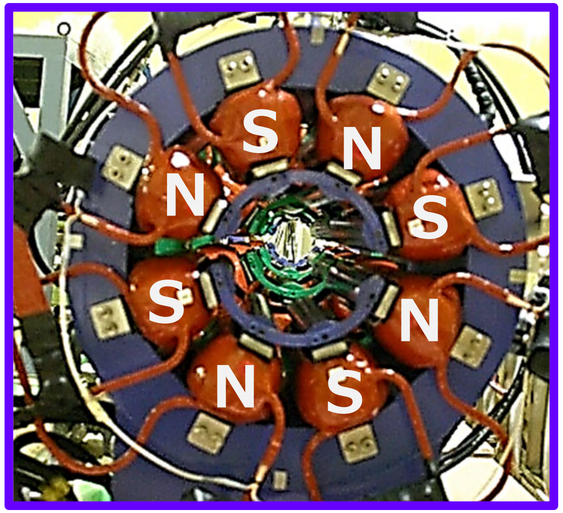
- Controlling the complicated particle motion properly,

➡ It should be possible to generate unique beam profiles that can never be realized by linear focusing.

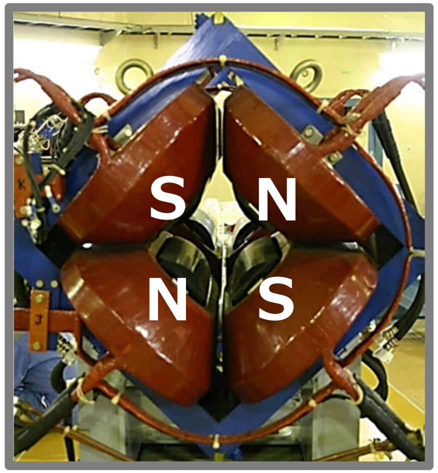
✓Uniform profile (NSRL@BNL, J-PARC, etc.)

✓**Hollow profile**

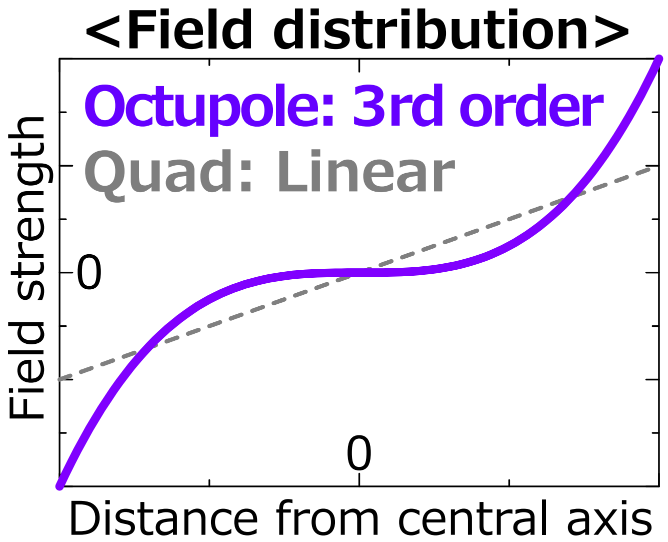
Beam shaping using octupole magnets



Octupole manet

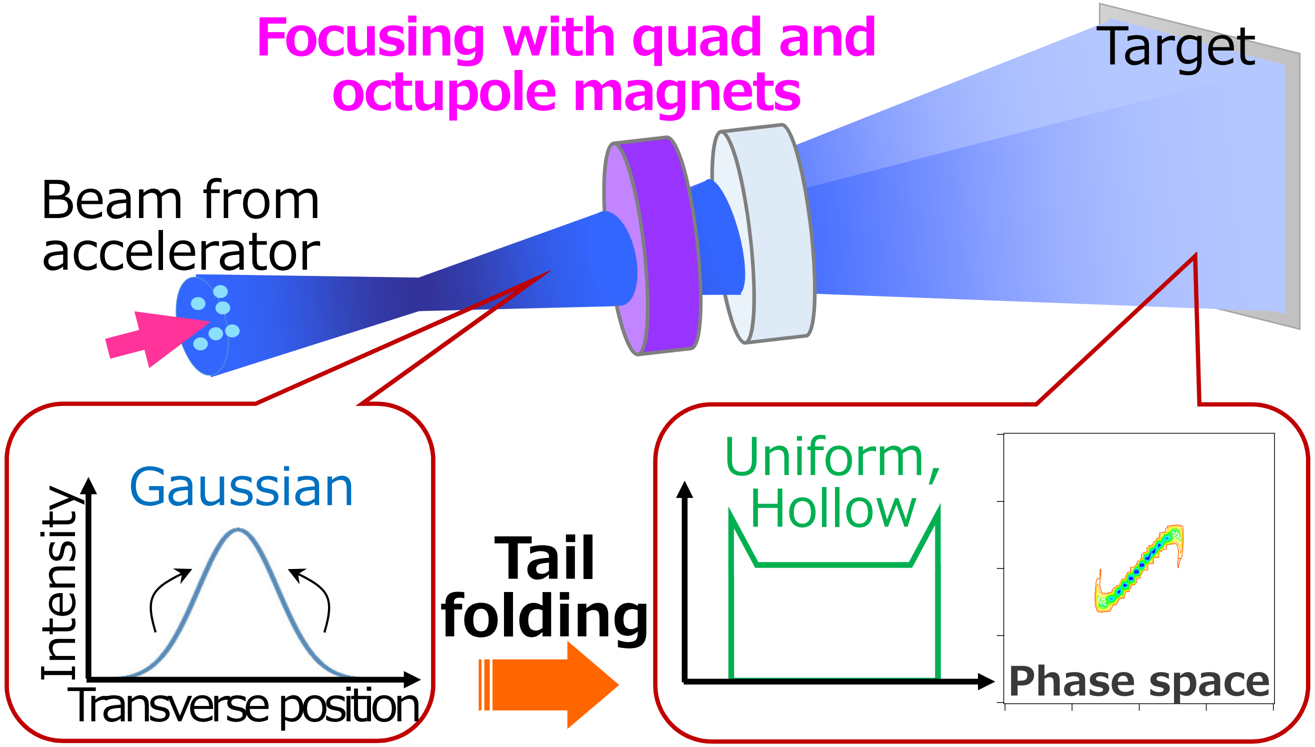


Quadrupole magnet



【Principle】

- The tail of the distribution can be folded by the nonlinear force.
- The phase-space profile is deformed into an "S"-shape.



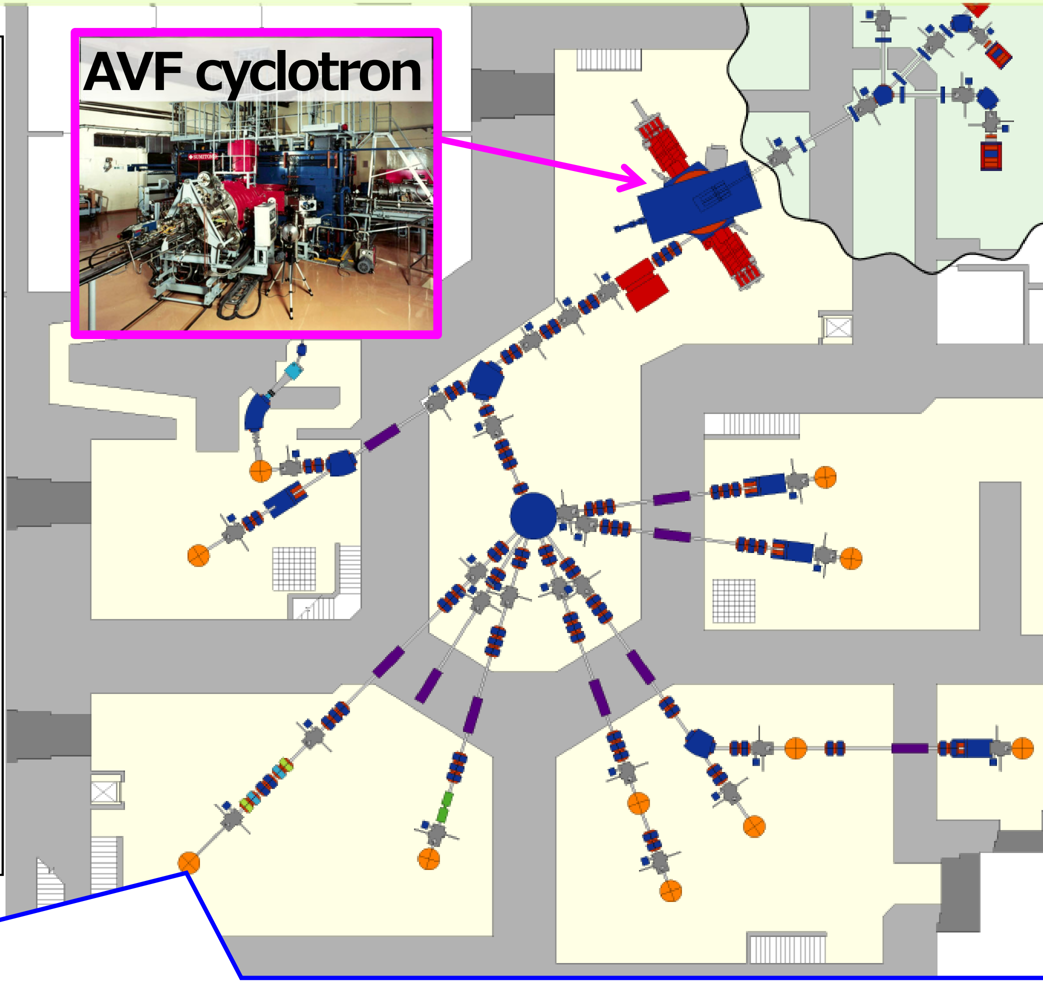
QST Takasaki's Cyclotron Facility

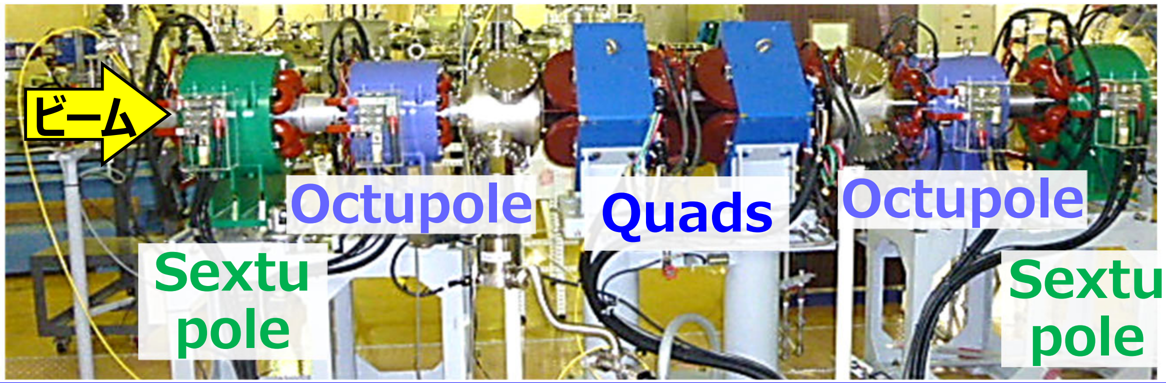
Bending limit K_b 110 MeV

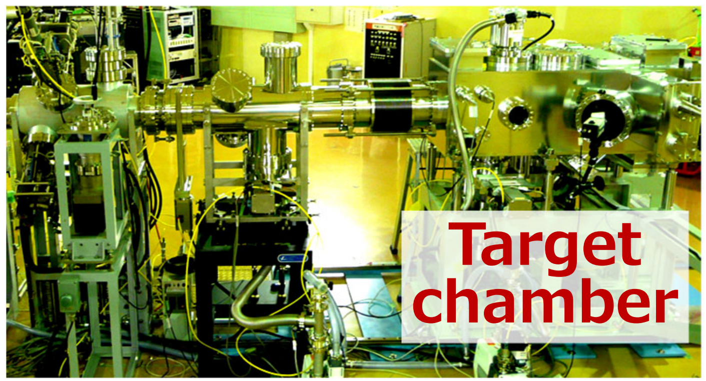
Ion species	Energy [MeV]
H	10 ~ 90
He	20 ~ 107
C	75 ~ 320
Ar	107 ~ 520
Kr	210 ~ 520
Xe	320 ~ 560

Main applications

- RI production
- Mutagenesis of plants
- Material modification
- Radiation testing of devices

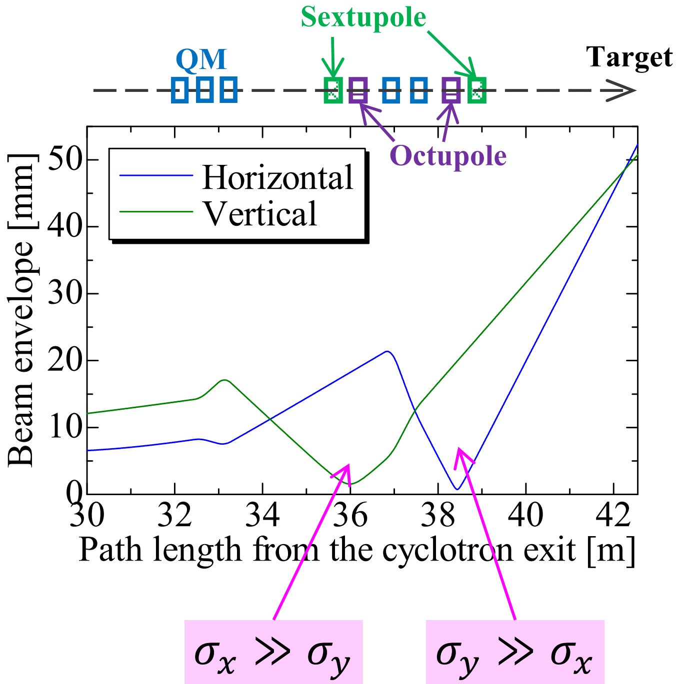






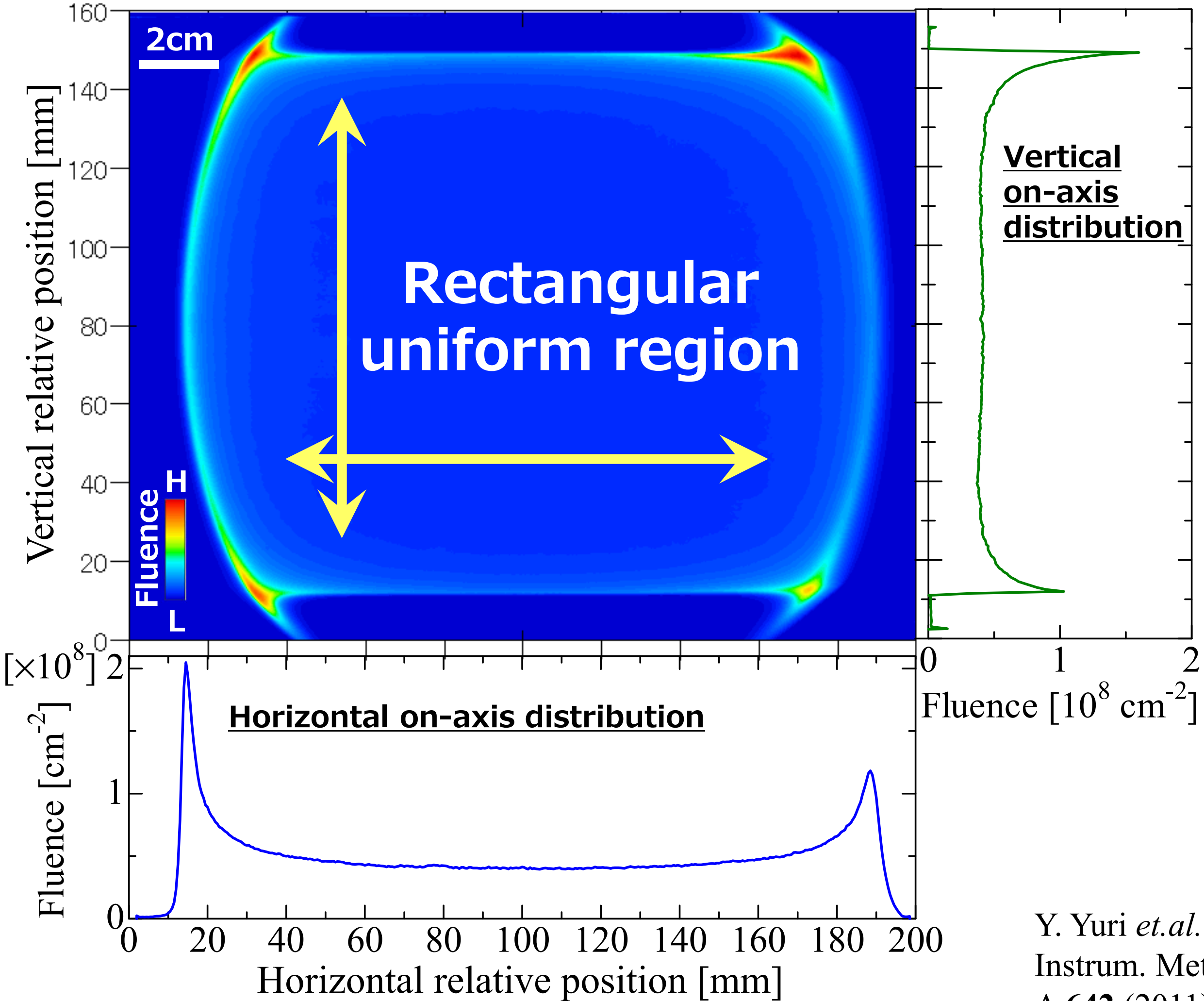
Existing nonlinear beam shaping: Uniform beam formation

【Beam optics】



X-Y coupling is reduced at OCTs

【2D profile (560MeV ^{129}Xe) 】



Y. Yuri *et.al.*, Nucl. Instrum. Methods A **642** (2011) 10.

Large-area uniform beam realized using octupole magnets

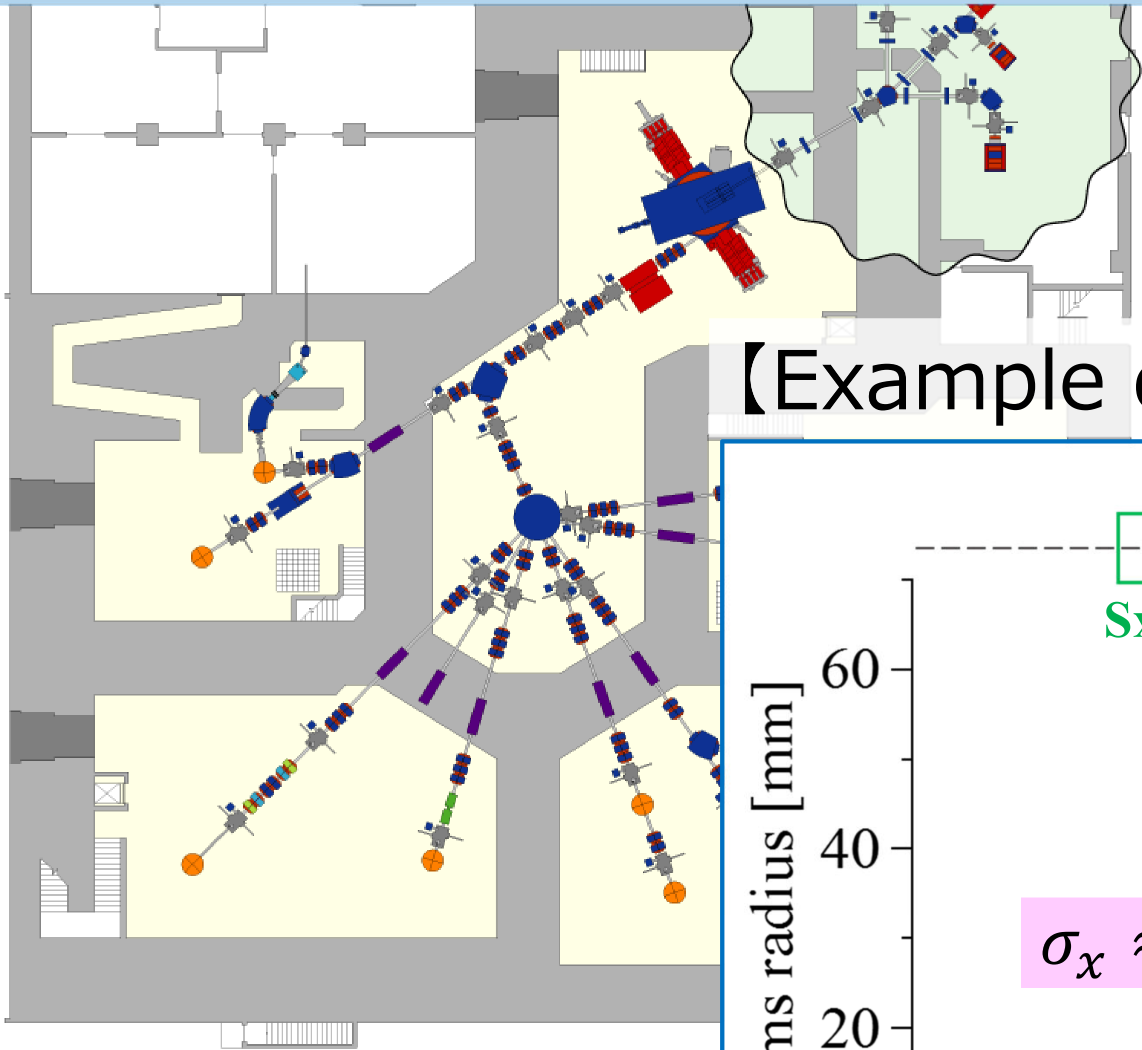
- ✓ Ion species: H, He, C, Ar, Xe
- ✓ Area: 20 ~ 200 cm^2
- ✓ Uniformity < 10%

Diverse beam shaping: Hollow beam formation

- ●Existing method (uniform beam formation)
  - ✓The peak is generated at the edge of the beam.
    - ⇒ Central uniform region is used for uniform irradiation.
  - ✓Horizontal-vertical coupling is suppressed.
    - ⇒ Rectangular cross-sectional shape

- ■New scheme
  - ✓Raise the intensity around the edge
    - ⇒ **Distribution can be made "hollow."**
  - ✓Betatron coupling
    - ⇒ **Various cross-sectional shapes** (other than a rectangle)

Beam experiment at QST Takasaki

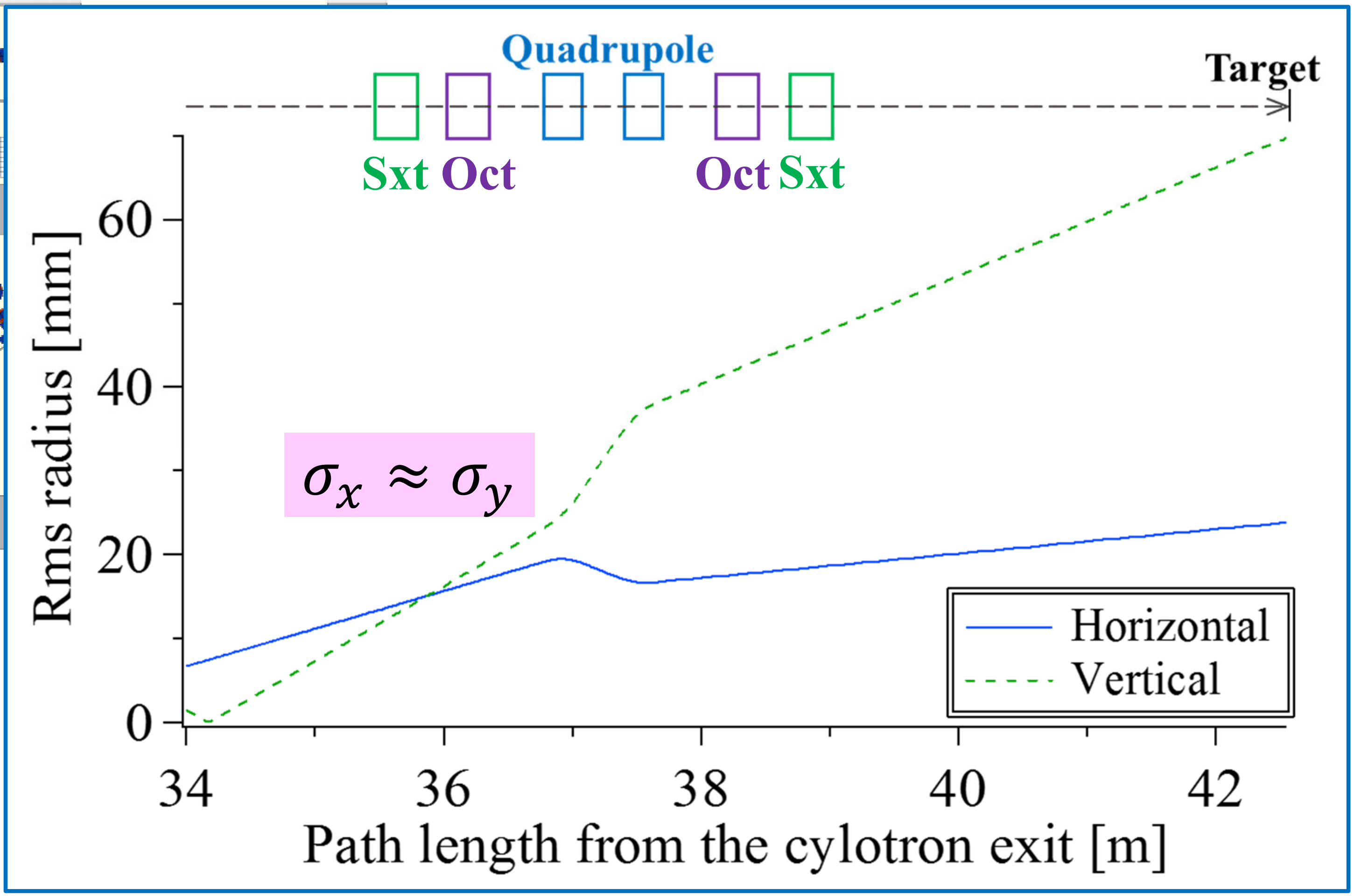


【Main conditions】

✓Ion species: 10 MeV proton
(Bρ=0.46 Tm, β=0.144, γ=1.011)

✓I~1 nA (No space-charge effect)

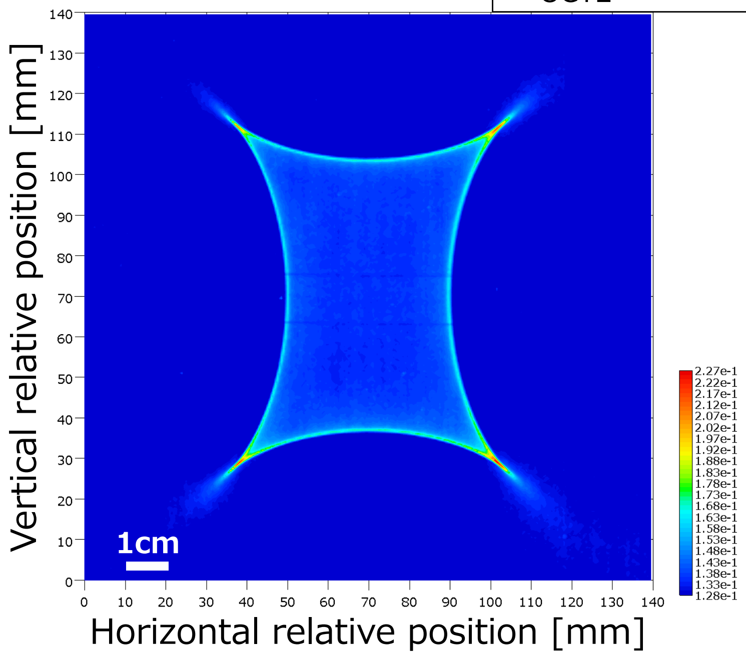
【Example of the linear beam optics】

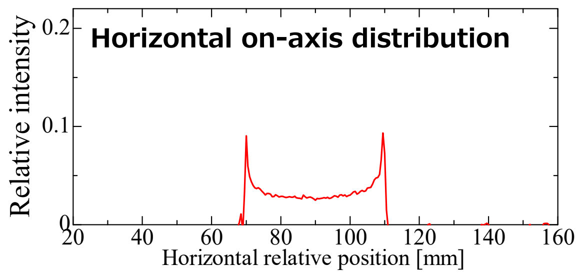


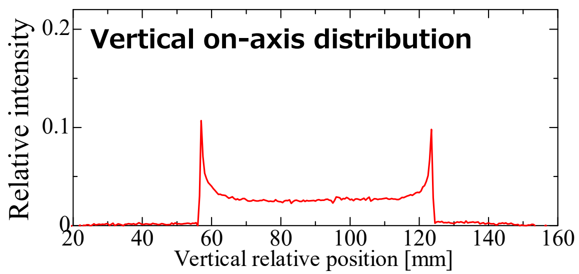
Experimental results (1)

One octupole: ON

$K_{OCT1}= 0[m^{-4}]$
$K_{OCT2}=3{,}100[m^{-4}]$

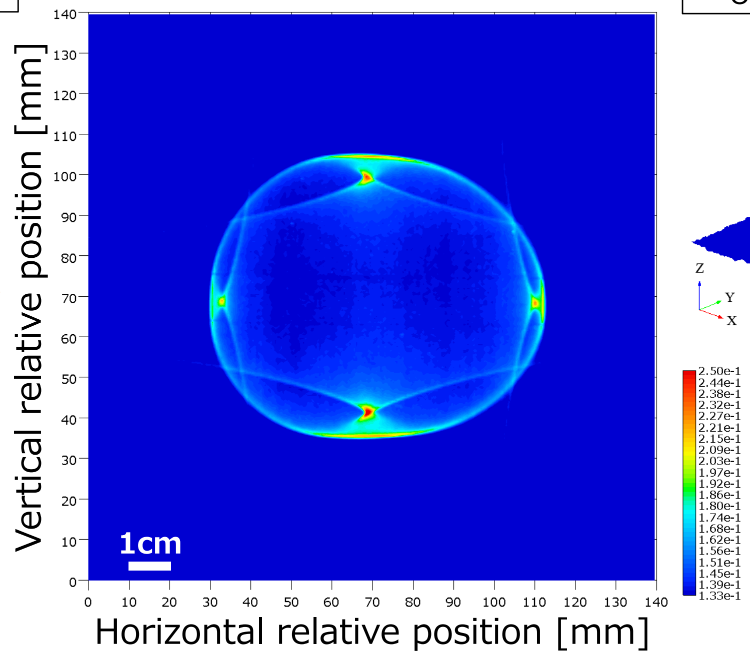


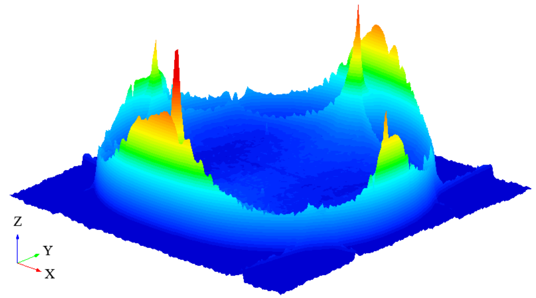


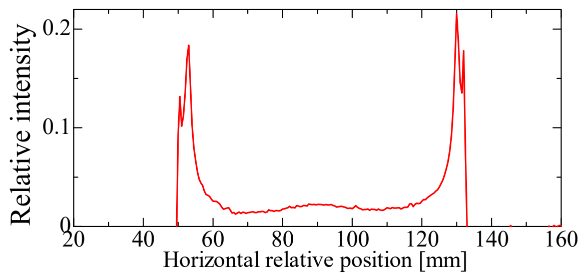


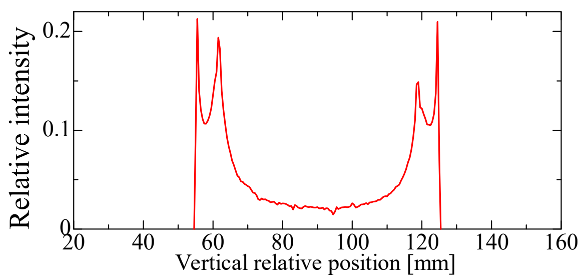
Two octupoles: ON

$K_{OCT1}=-10{,}500[m^{-4}]$
$K_{OCT2}= 3{,}100[m^{-4}]$









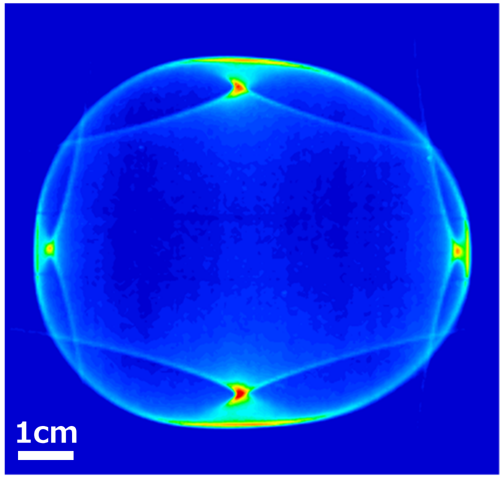
Size~8cm × 7cm
Peak width~1mm
Contrast~14 (max)

Hollow-beam formation demonstrated*!!*

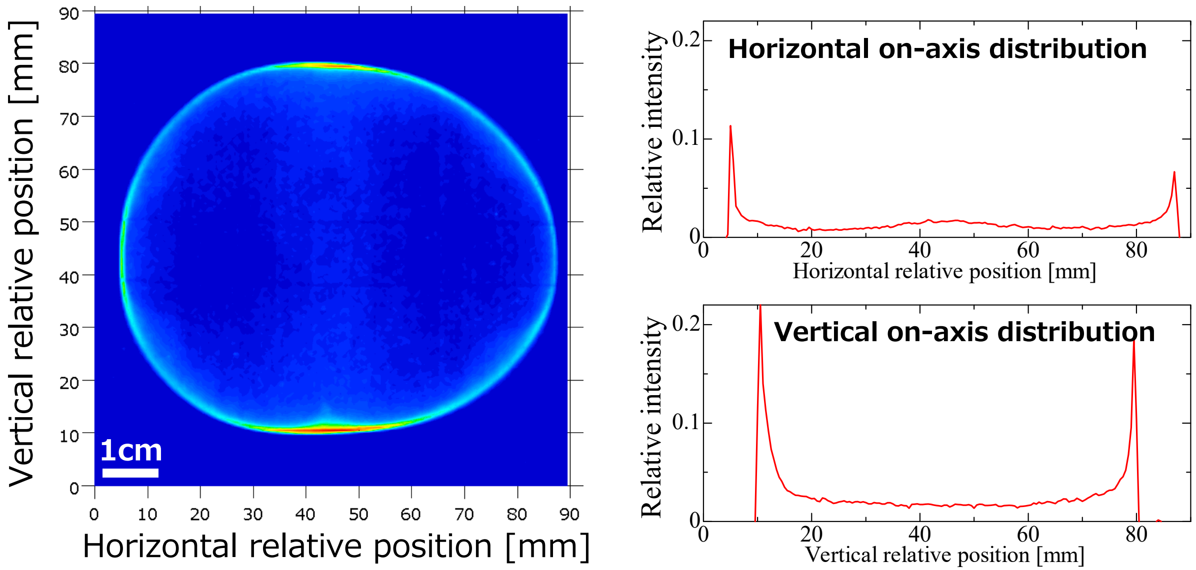
Experimental results (2)

K_{OCT1}=-10,500[m^{-4}]
K_{OCT2}= 3,100[m^{-4}]

Tail collimation using beam slits before octupole magnets



"Streaks"

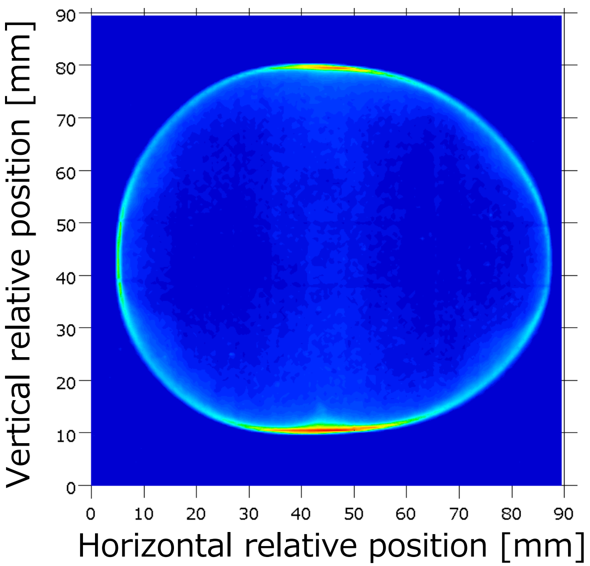


- ✓ **The streaks have been suppressed.**
- ✓ **These streaks are induced by strong X-Y coupling.**
- ✓ **Clearly hollow profile!!**

Experimental results (3)

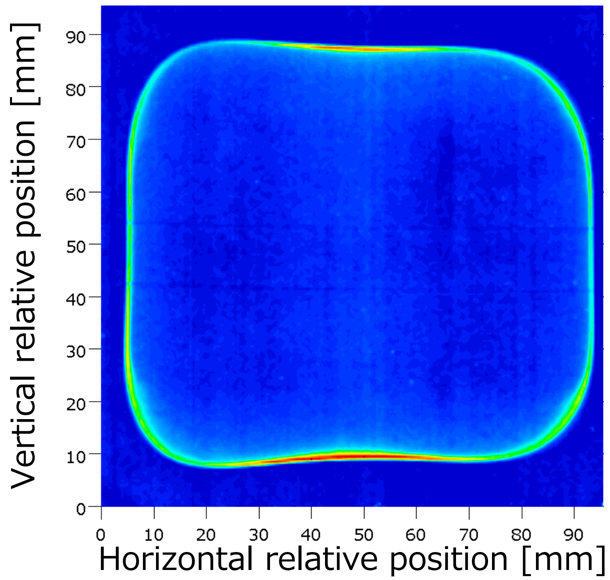
The cross-sectional shape changes depending on the octupole strength.

K_{OCT1}=-10,500[m^{-4}]
K_{OCT2}= 3,100[m^{-4}]



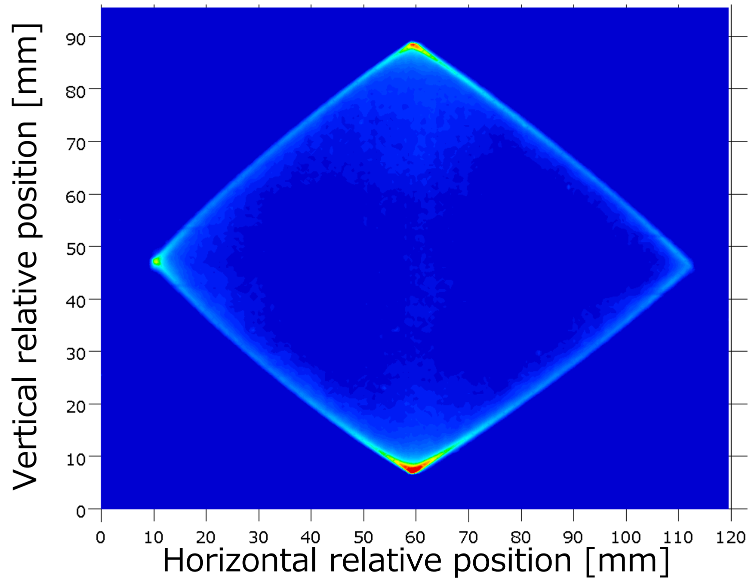
Ellipse

K_{OCT1}=-6,700[m^{-4}]
K_{OCT2}= 2,400[m^{-4}]



Rounded rectangle

K_{OCT1}=-11,300[m^{-4}]
K_{OCT2}= 2,300[m^{-4}]



Rhombus

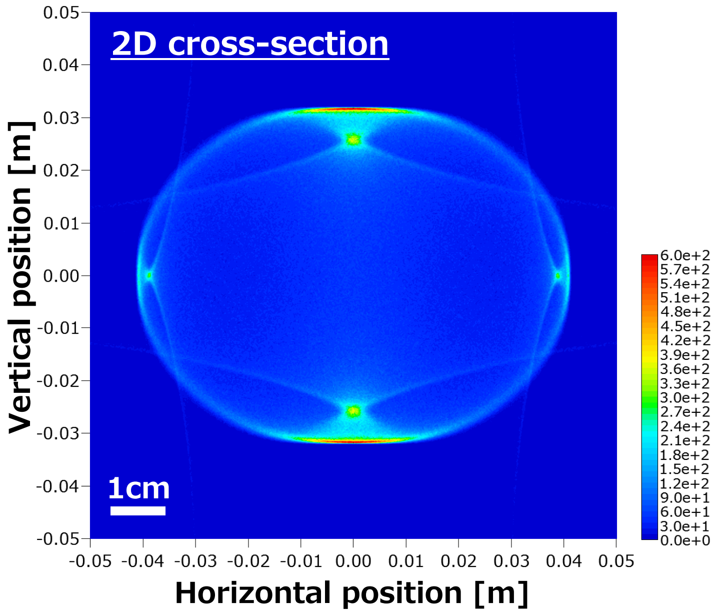
Hollow beams of various cross-sectional shapes can be generated easily using multipole magnets.

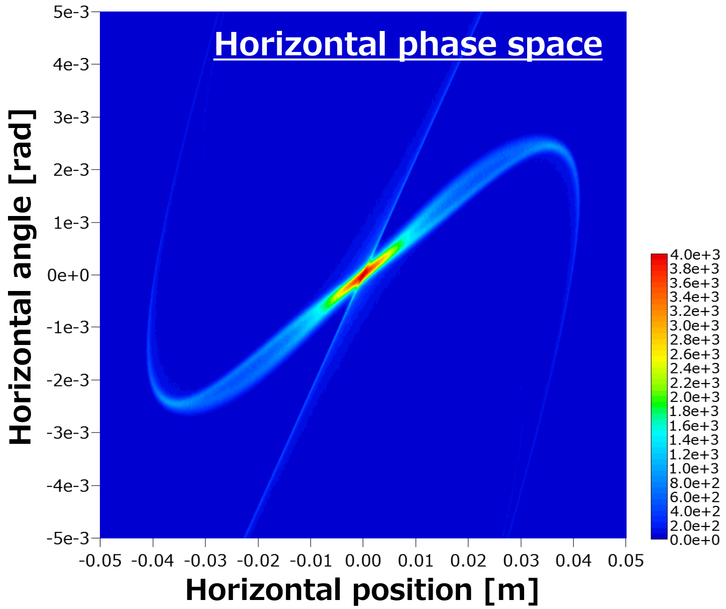
Particle tracking simulation

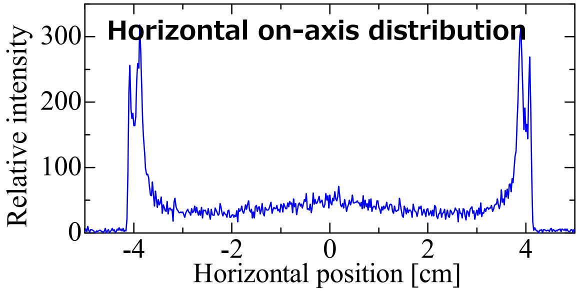
K_{OCT1}=-10,500[m^{-4}]
K_{OCT2}= 3,100[m^{-4}]

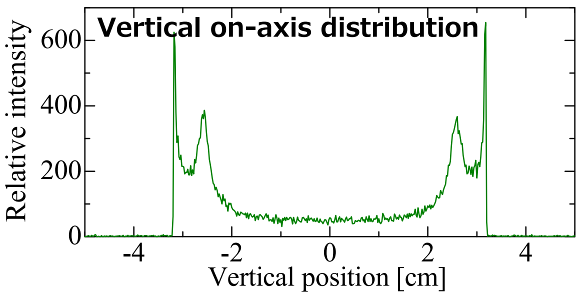
Numerical integration of EoM

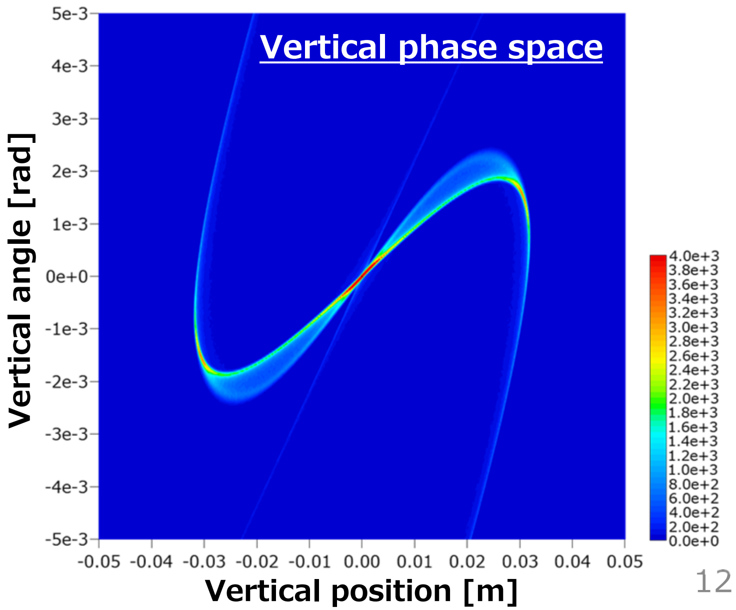
- ✓ Beam optics same as that of the experiment
- ✓ Ion species: 10MeV proton
- ✓ Initial conditions: Gaussian trans. distribution
- ✓ RMS emittance:
  - Hori. 2π mm.mrad
  - Vert. 1π mm.mrad
- ✓ dp/p=0
- ✓ No space charge





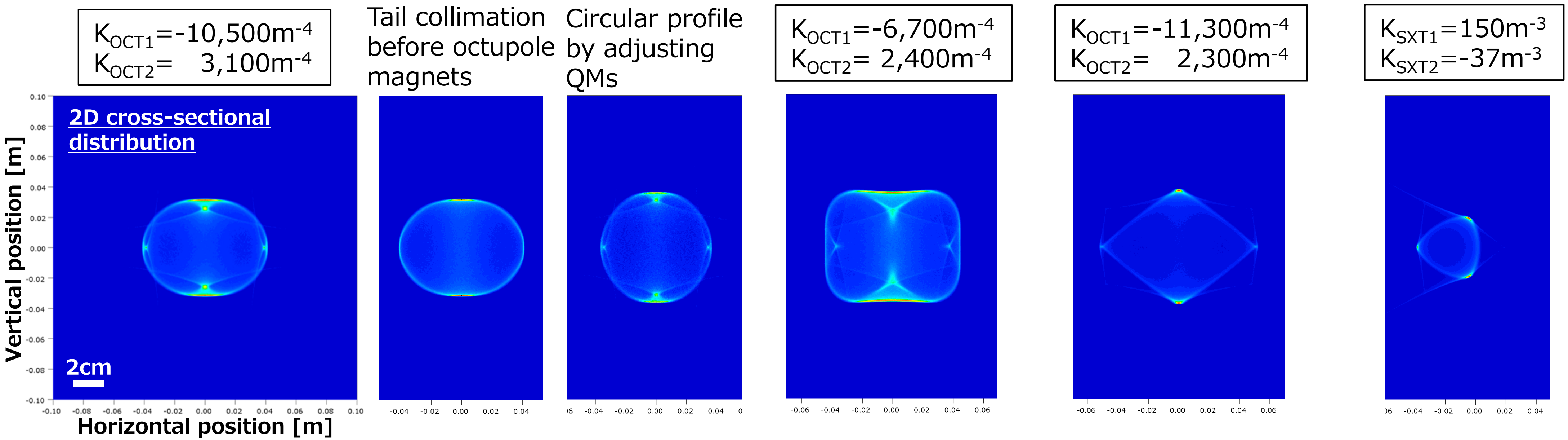






Contrast: 6~17
Edge peak width~1mm

Simulation results



Octupole focusing
→ Ellipse ~ Rectangle ~ Rhombus

Sextupole focusing
→ Triangle

Experimental results have been well reproduced.

Diverse beam profile shaping is possible, depending on the order and strength of multipole magnets.

Summary

✓We have demonstrated the formation of a hollow beam through the nonlinear force of multipole magnets.

Y. Yuri *et.al.*, Prog. Theor. Exp. Phys. **2019** (2019) 053G01.

✓Different characteristics have been revealed:

- Steep, narrow peak at the edge
- The cross-sectional shape depends on the order and strength of multipole magnets.

  Rectangle ~ Ellipse ~ Rhombus for octupole focusing

  Triangle-like for sextupole focusing

✓The proper use of the nonlinear force enables us to achieve unique beam shaping that cannot be realized by conventional linear focusing.

- Applicable to various beams of different parameters (species, energy, bunched or coasting, current, etc.) as the source of the nonlinear force is the magnetostatic field.

✓As an application of a hollow beam, irradiation of the hollow beam is now investigated toward efficient production of low-energy muons at RCNP, Osaka Univ.

QST National Institutes for Quantum and Radiological Science and Technology

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- ✓ JST OPERA (Quantum Innovation for Safe and Smart Society)

科研費 KAKENHI

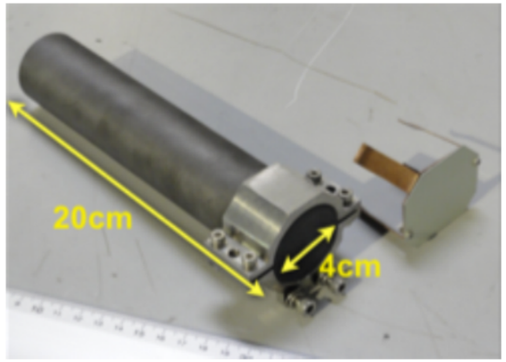
OPERA

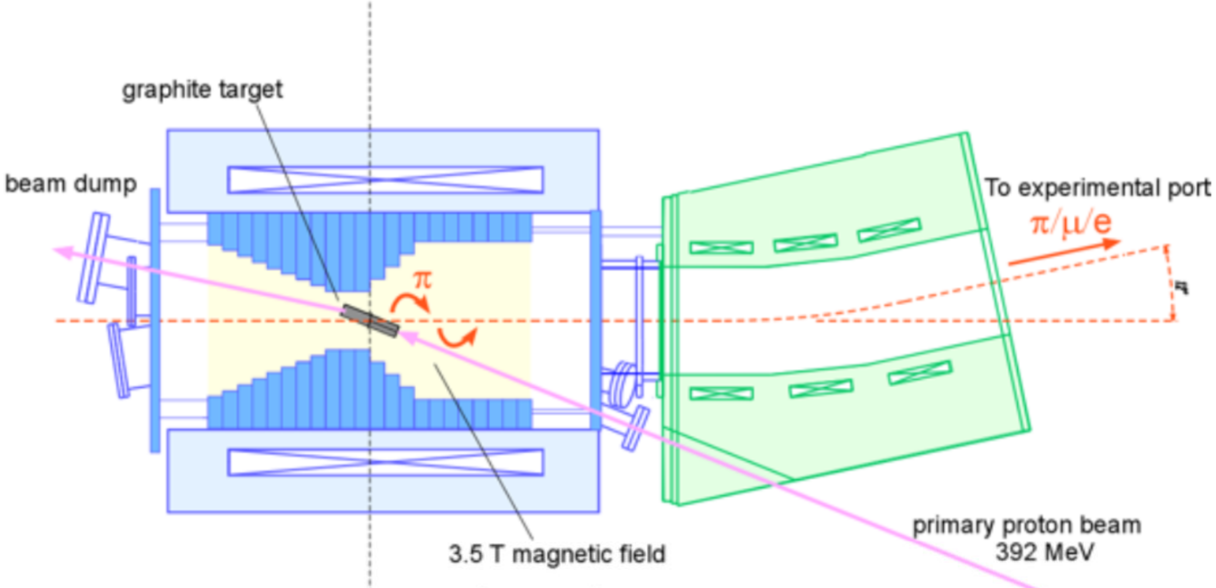
Supplements

A possible application of the hollow beam

Pion capture solenoid & Pion transport solenoid

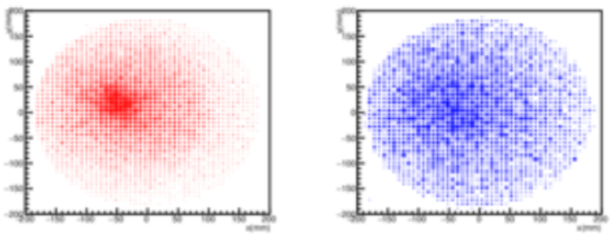
- Pion capture solenoid (3.5T)
  - — pion production target inside (1.5 interaction length)
  - — pion collection with large solid angles
- Pion transport solenoid (2.0T)
  - — Curved solenoid to capture and transport pion/muon
  - — Momentum selection with dipole collection field





Pion Capture Solenoid

Beam Profile by G4beamline simulation



Surface muon Inflight-decay muon

exit of the 36° curved solenoid
~ 3×10^8 positive muons
~ 1×10^8 negative muons

→ ~ 10^3 pion production efficiency

Previous studies of hollow beam formation

- Plasma lens (Z pinch discharge)
  - Short-pulsed heavy-ion beam (~100MeV/u)
  - Beam diameter~2cm
  - Edge peak width~5mm
  - Contrast~10
  - Axisymmetric target irradiation for HED/HIF
- Hollowing due to space-charge effect
  - High-current heavy-ion beams from ECR ion source
  - Coexistence of ion beams with a different M/Q ratio
- Hollow electron gun
  - keV electron beams

The generation method and availability of hollow beams are limited.

FIG. 1. 10 mm radius ringlike light output from a scintillator situated perpendicular to the axis 0.3 m behind the plasma lens.

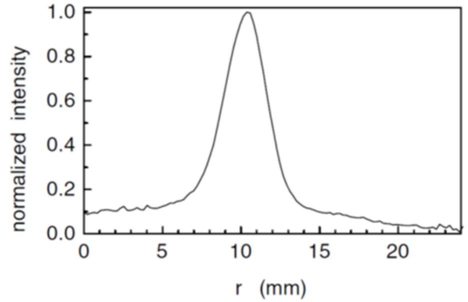


FIG. 6. Radial profile of the beam intensity distribution in the detection plane 0.3 m behind the plasma lens for the case of the optimum contrast of 10.

U. Neuner *et al.*, Phys. Rev. Lett. 85 (2000) p4518.

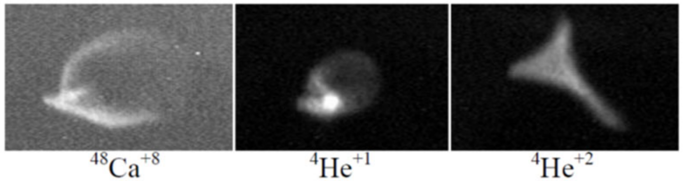


FIGURE 3. ECR is tuned to produce ^{48}Ca of about 100 eμA summed over all charge states. The support gas is helium of about 1200 eμA. Here, the solenoid and analyzing magnet are set first to select $^{48}Ca^{+8}$, then $^{4}He^{+1}$ and finally $^{4}He^{+2}$. Since the intensity of ^{48}Ca in charge states higher than 8+ is low, the ring in the first picture is produced by short focusing of both helium charge states.

J. W. Stetson *et al.*, CYC(2004)p483.

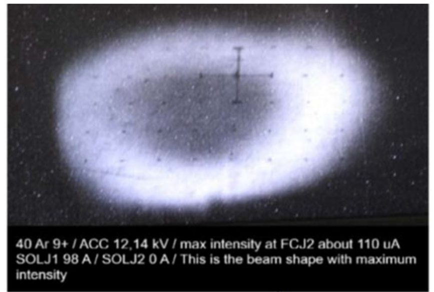


Figure 4: The beam profiles of Ar^{9+} ion beam after the analysing magnet.

H. Koivisto *et al.*, ECR(2008)p18.

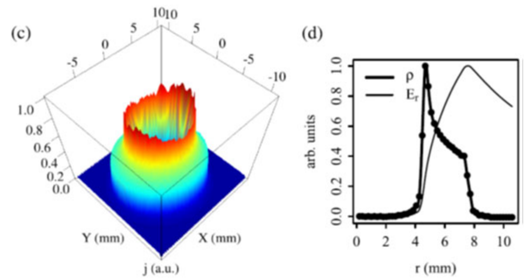


FIG. 2 (color online). Hollow electron gun: (a) top view; (b) side view; (c) measured current density profile; (d) measured charge density ρ and calculated radial electric field E_r.

G. Stancari *et al.*, Phys. Rev. Lett. 107 (2011) 084802.

Theoretical analysis (1D model)

Y. Yuri *et.al.*, Prog. Theor. Exp. Phys. **2019** (2019) 053G01.

1st Octupole Magnet (K_{O1}) → Transfer matrix **M**, Phase advance ϕ → **2nd Octupole Magnet (K_{O2})** → Transfer matrix **T**, Phase advance θ → **Target**

Twiss parameters: β_1, α_1 (1st Octupole); β_2 (2nd Octupole); β_t, α_t (Target)

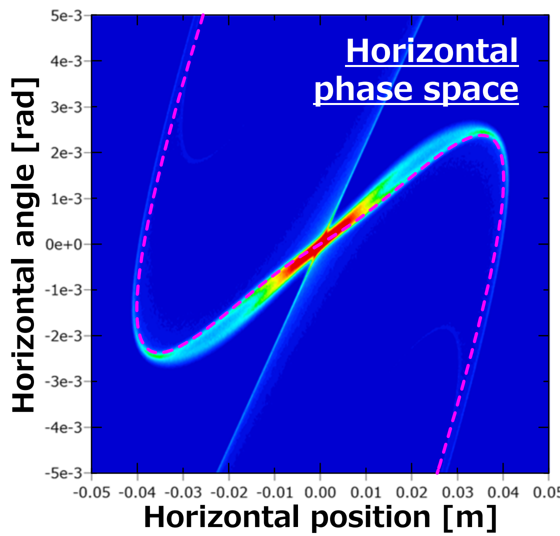
Particle coordinate:

$$\begin{pmatrix} x_1 \\ p_1 \end{pmatrix} \qquad \begin{pmatrix} x_2 \\ p_2 \end{pmatrix} = \mathrm{M}\begin{pmatrix} x_1 \\ p_1 - K_{O1}x_1^3/6 \end{pmatrix} \qquad \begin{pmatrix} x_t \\ p_t \end{pmatrix} = \mathrm{T}\begin{pmatrix} x_2 \\ p_2 - K_{O2}x_2^3/6 \end{pmatrix}$$

Approximation at 1st Octupole
$p_1 \approx -(\alpha_1/\beta_1)x_1$

✓ The on-target phase-space shape can be approximately characterized by the <u>Twiss parameters</u>, the <u>phase advance</u> and the <u>octupole strength</u>:

$$\begin{cases} x_t = \sqrt{\dfrac{\beta_t}{\beta_1}}\cos(\phi+\theta)\,x_1 - \dfrac{K_{O1}}{6}\sqrt{\beta_1\beta_t}\sin(\phi+\theta)\,x_1^3 - \dfrac{K_{O2}}{6}\sqrt{\beta_2\beta_t}\sin\theta\left(\sqrt{\dfrac{\beta_2}{\beta_1}}\cos\phi\,x_1 - \dfrac{K_{O1}}{6}\sqrt{\beta_1\beta_2}\sin\phi\,x_1^3\right)^3 \\[2ex] p_t = -\dfrac{1}{\sqrt{\beta_1\beta_t}}\{\sin(\phi+\theta)+\alpha_t\cos(\phi+\theta)\}x_1 - \dfrac{K_{O1}}{6}\sqrt{\dfrac{\beta_1}{\beta_t}}\{\cos(\phi+\theta)-\alpha_t\sin(\phi+\theta)\}x_1^3 \\[1ex] \qquad\qquad - \dfrac{K_{O2}}{6}\sqrt{\dfrac{\beta_2}{\beta_t}}(\cos\theta-\alpha_t\sin\theta)\left(\sqrt{\dfrac{\beta_2}{\beta_1}}\cos\phi\,x_1 - \dfrac{K_{O1}}{6}\sqrt{\beta_1\beta_2}\sin\phi\,x_1^3\right)^3 \end{cases}$$



The beam motion under nonlinear focusing has been theoretically predicted.