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Nonlinear Optics for Suppression of Halo Formation in Space Charge Dominated Beams

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Effect of Beam Halo in Linacs

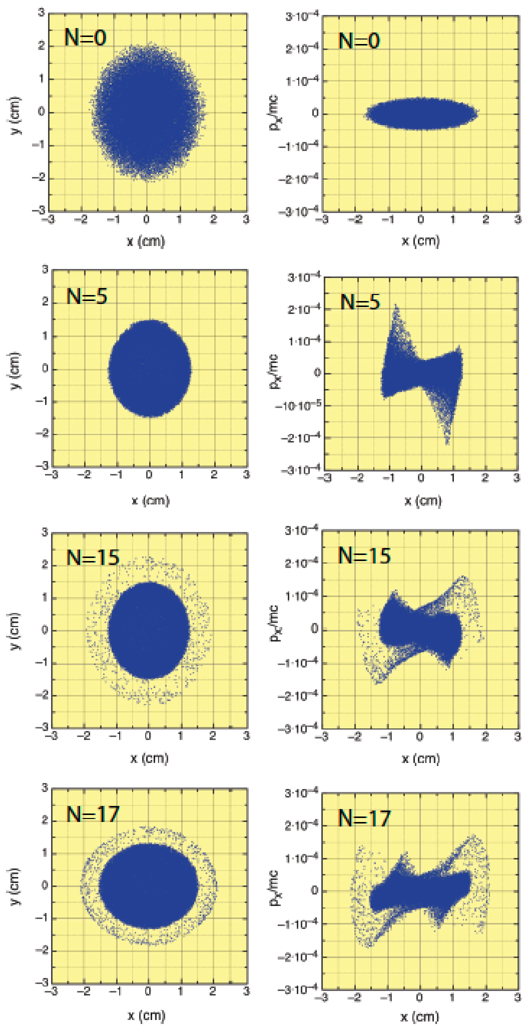
Beam halo is a small fraction of particles (1% – 10%) which lies outside of the beam core and results in radio-activation and degradation of accelerator components.

Modern accelerator projects using high-intensity beams require keeping the beam losses at the level 1 Watt / m or less to avoid activation of the accelerator.

Sources of Halo Formation in Linacs

1. Mismatch of the beam with accelerator structure
2. Transverse-longitudinal coupling in RF field
3. Misalignments of accelerator channel components
4. Aberrations and nonlinearities of focusing elements
5. Beam energy tails from un-captured particles
6. Particle scattering on residual gas, intra-beam stripping
7. Non-linear space-charge forces of the beam

Emittance Growth and Halo Formation of a Non-Uniform Beam in FODO Quadrupole Channel



Injection of a continuous non-uniform beam in a focusing channel with linear field results in

(a) uniformity of beam core
(b) beam emittance growth
(c) halo formation

<u>Example:</u>

Beam energy	**50 keV**
Beam current	**20 mA**
Beam emittance	**0.05 π cm mrad**
FODO period	**15 cm**
Lens length	**5 cm**
Quadrupole field gradient	**0.0428 T/cm**
Tune depression	**$\sigma/\sigma_o = 0.1$**

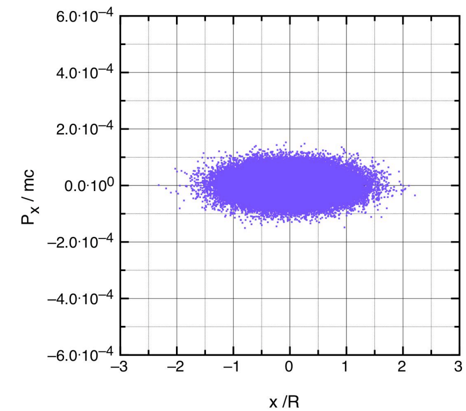
(Numbers indicate focusing period)

Self-Consistent Beam Equilibrium in Focusing Channel

<u>Self-consistent problem:</u>

Vlasov's Equation
$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \vec{x}}\frac{d\vec{x}}{dt} + \frac{\partial f}{\partial \vec{P}}\frac{d\vec{P}}{dt} = 0$$

Poisson's Equation
$$\Delta U_b = -\frac{\rho}{\varepsilon_o}$$



(Phys. Rev. E, Vol. 53, 1996, p. 5358)

Example: Beam with Gaussian distribution function

$$U_{ext} = U_{total} - \frac{U_b}{\gamma^2}$$

$$f = f_o \, exp(-2\frac{x^2+y^2}{R^2} - 2\frac{p_x^2+p_y^2}{p_o^2})$$

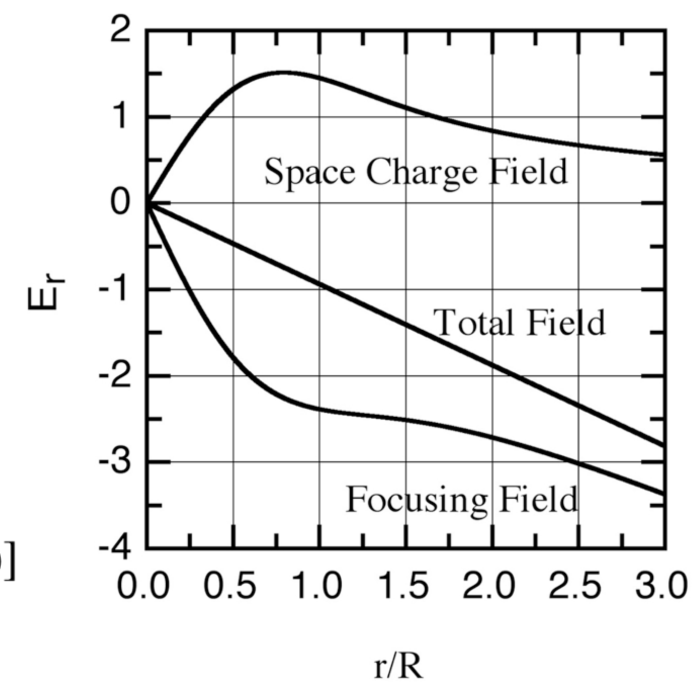
Total field
$$E_{tot} = -\frac{mc^2}{q}\frac{1}{\gamma}\frac{\varepsilon^2}{R^4} r$$

Space-charge field

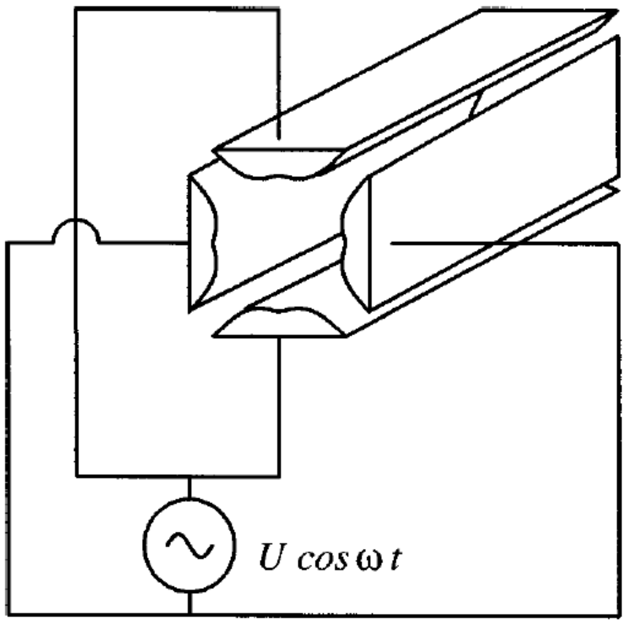
$$E_b = -\frac{\partial U_b}{\partial r} = \frac{I}{2\pi \varepsilon_o \beta c}\frac{1}{r}[1 - exp(-2\frac{r^2}{R^2})]$$

Required focusing field

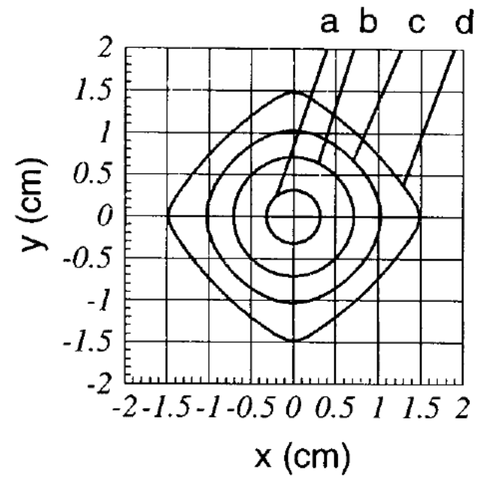
$$E_{ext} = -\frac{mc^2}{qR\gamma}[\frac{\varepsilon^2 r}{R^3} + 2\frac{I}{I_c \beta\gamma}\frac{R}{r}(1 - exp(-2\frac{r^2}{R^2}))]$$



Quadrupole-Duodecapole Focusing Structure



Proposed four vane quadrupole structure with a duodecapole field component (EPAC96, p.1236)



Lines of equal values of the function $C = \frac{r^2}{2} + \zeta r^6 \cos 4\theta + \frac{\zeta^2}{2} r^{10}$

for $\zeta = -0.03$: (a) $C = 0.05$, (b) $C = 0.25$, (c) $C = 0.5$, and (d) $C = 0.85$

Potential of the uniform four vanes structure:

$$U(r,\theta,t) = \left(\frac{G_2}{2} r^2 \cos 2\theta + \frac{G_6}{6} r^6 \cos 6\theta\right) \sin \omega t$$

Effective (time-independent) potential:

$$U_{eff}(\vec{r}) = \frac{q}{4m\gamma} \frac{E^2(\vec{r})}{\omega^2}$$

$$U_{eff}(r,\theta) = \frac{mc^2}{q} \frac{\sigma_o^2}{2} \left(\frac{r}{\lambda}\right)^2 \left[1 + 2\eta \left(\frac{r}{R}\right)^4 \cos 4\theta + \eta^2 \left(\frac{r}{R}\right)^8\right]$$

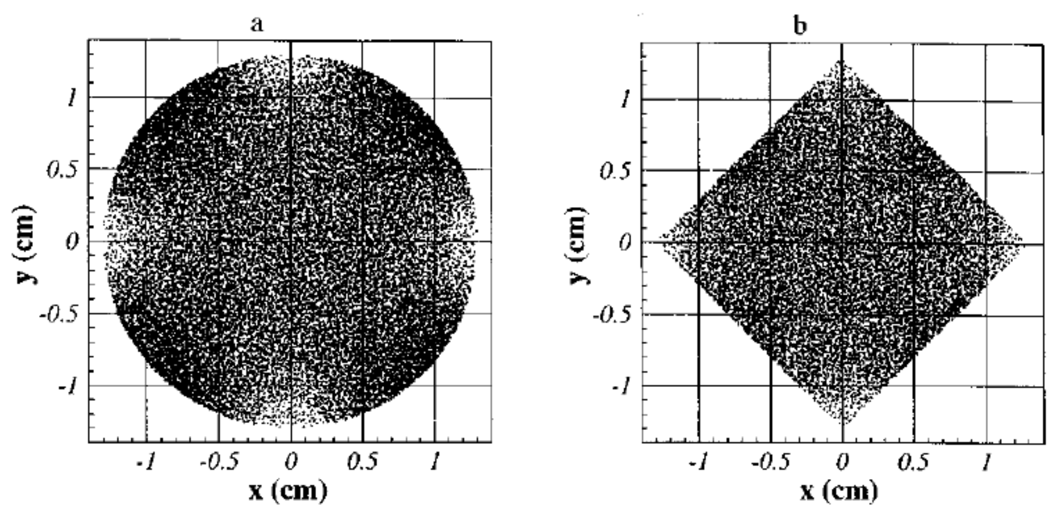
$$\eta = \frac{G_6}{G_2} R^4$$

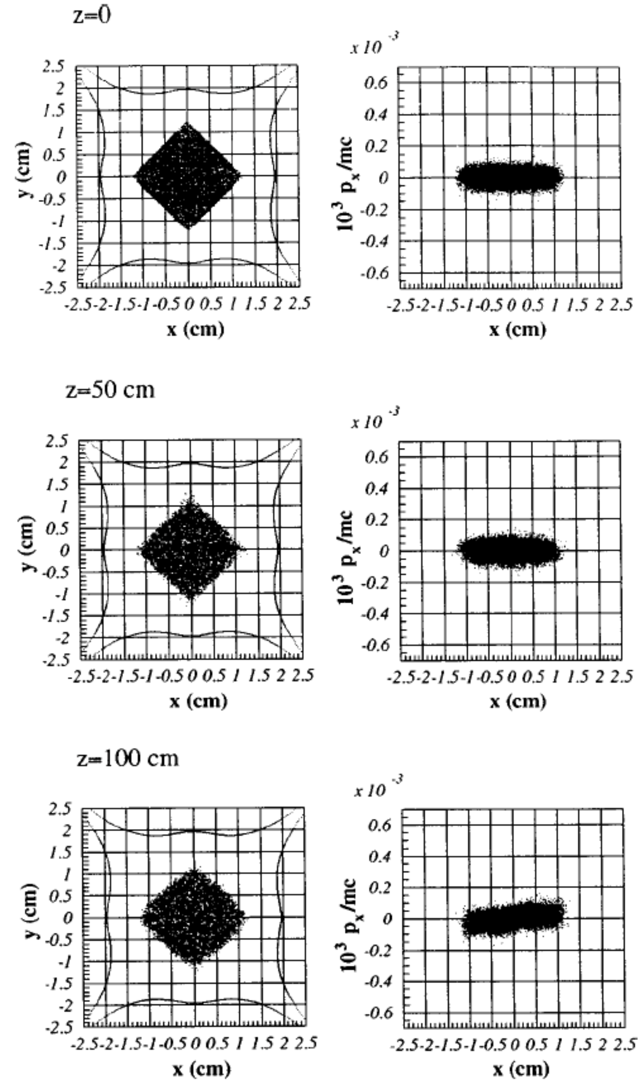
Space-Charge Density of the Matched Beam

Self-consistent space charge potential of the matched beam (Phys. Rev. E, Vol. 57, 1998, p. 6020)

$$U_b = -\frac{\gamma^2}{1+\left(\frac{\beta\gamma}{2}\frac{I_c}{I}\frac{R^2}{\varepsilon^2}\right)}\,U_{eff}$$

Space charge density $\rho_b = \rho_o(1+10\zeta r^4\cos 4\theta + 25\zeta^2 r^8)$





Dynamics of 150 keV, 100 mA, 0.06 π cm mrad proton beam in a structure with G_2 = 48 kV/cm^2 and G_6 = -1.3 kV/cm^6 .

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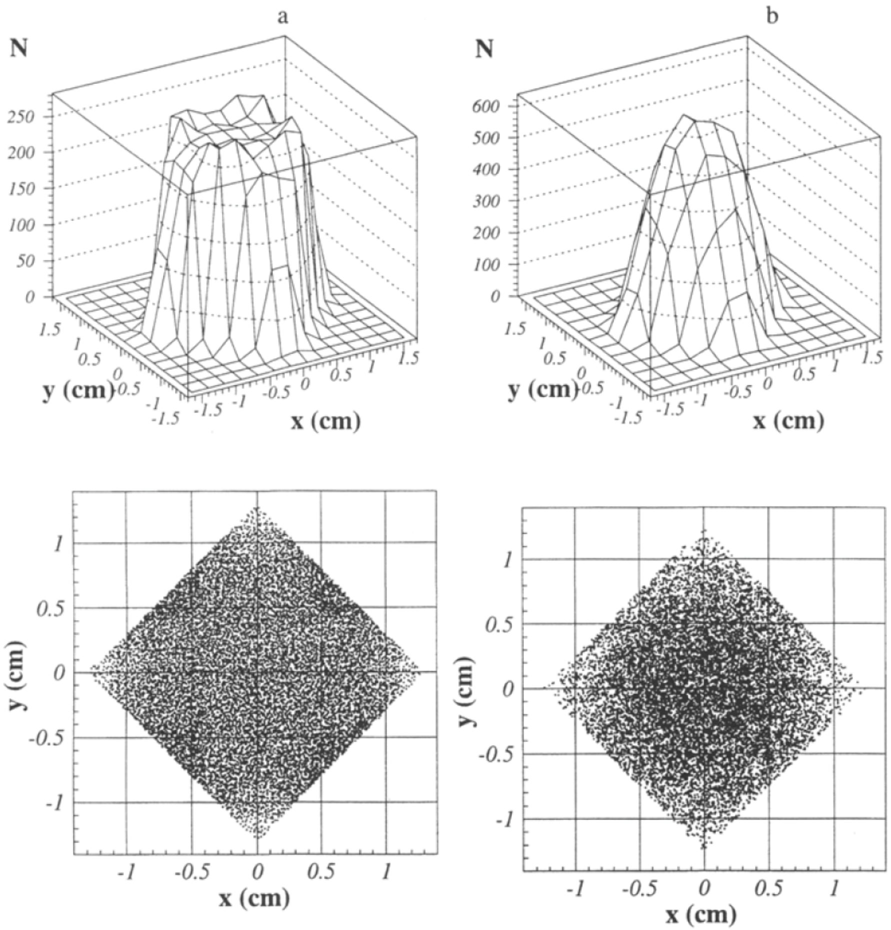
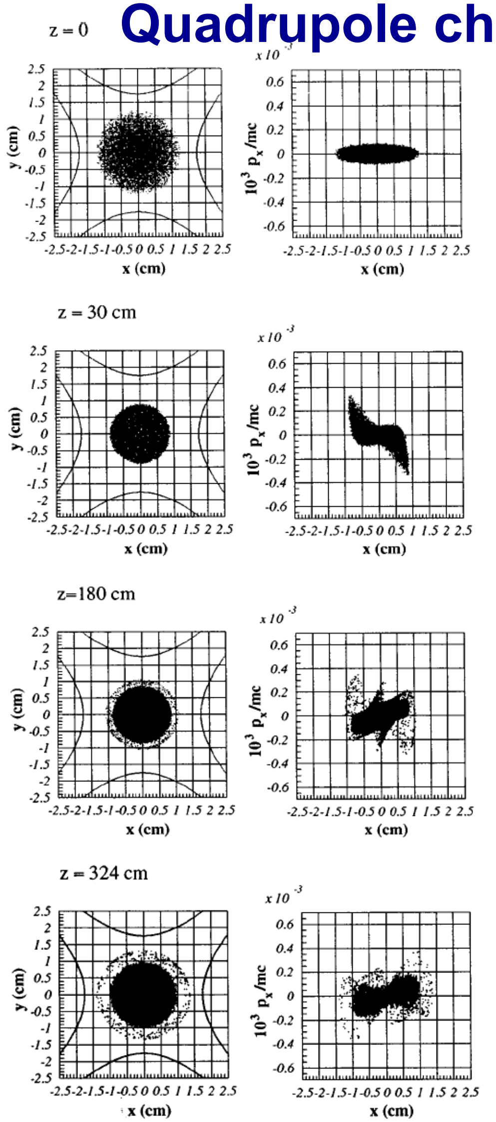
Matched and Realistic Truncated Beam Distributions

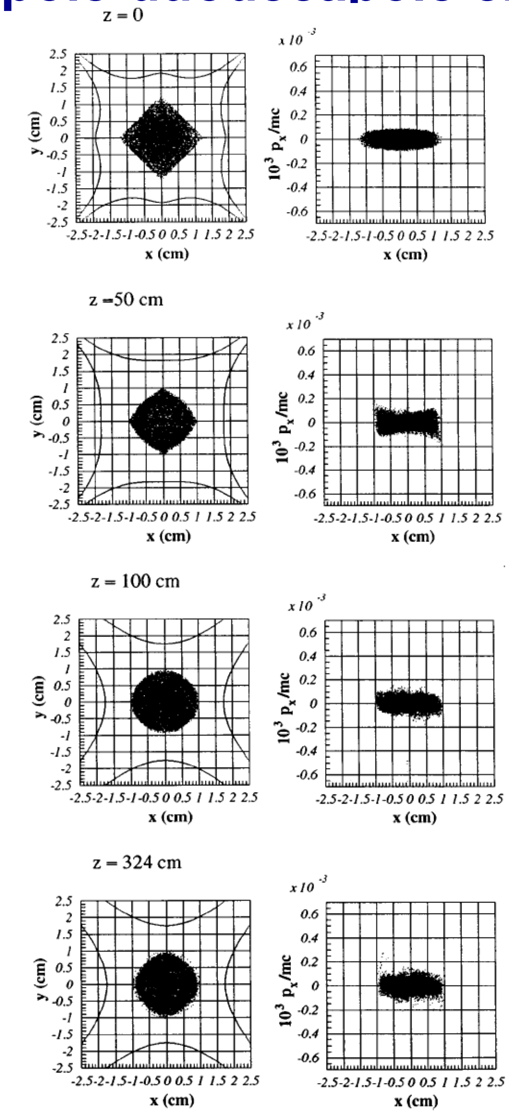


(a) Self-consistent particle distribution $\rho_b = \rho_o(1 + 10\zeta r^4 \cos 4\theta + 25\zeta^2 r^8)$ of the matched beam in quadruple-duodecapole channel with parameter ζ = - 0.03 and (b) beam with distribution $\rho_b = \rho_o[1-(r/R)^2]^2$ truncated along equipotential lines of effective focusing field.

Quadrupole channel



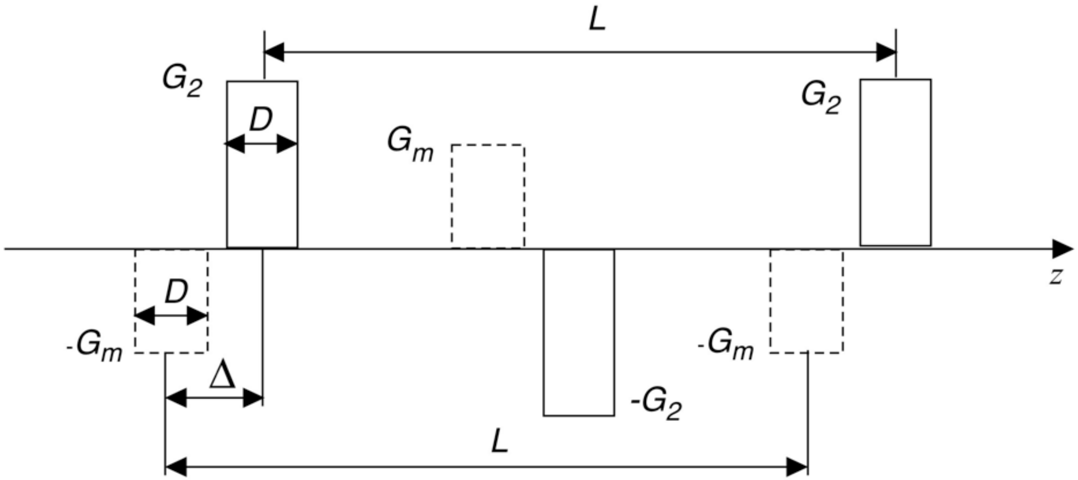
Quadrupole-duodecapole channel



Dynamics of 150 keV, 100 mA, 0.06 π cm mrad proton beam in a structure with G_2 = 48 kV/cm^2.

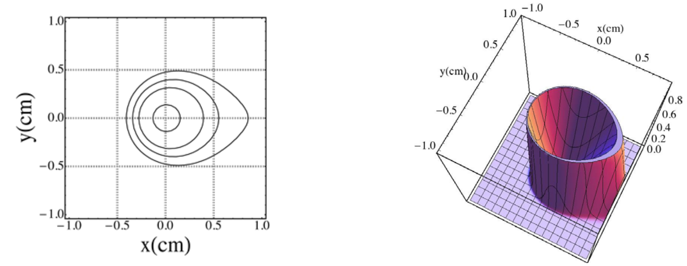
Adiabatic matching of 150 keV, 100 mA, 0.06 π cm mrad proton beam in a structure with G_2 = 48 kV/cm^2 , G_6 = -1.9 kV/cm^6 .

Combined FODO Structure with Arbitrary Multipoles*

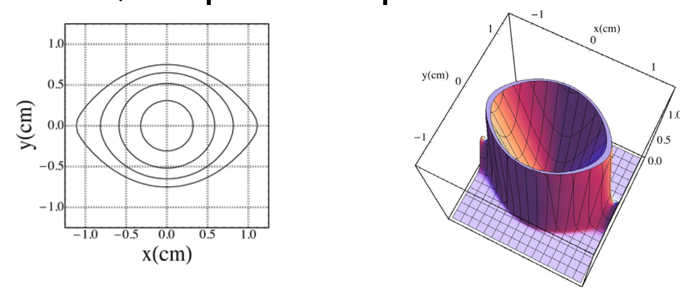


Combined FODO stricture with quadrupoles G_2 and multipoles G_m lenses.

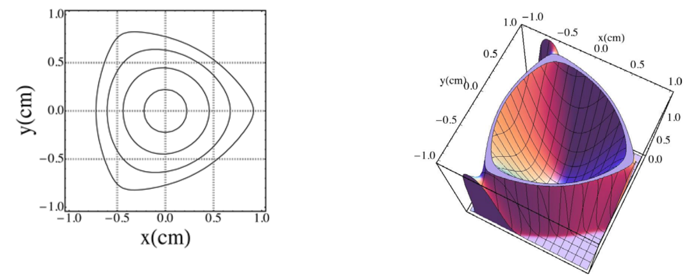
m = 3 Quadrupoles + Sextupoles



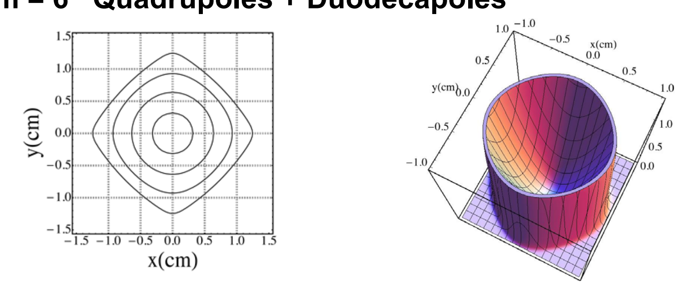
m = 4 Quadrupoles + Octupoles



m = 5 Quadrupoles + Decapoles



m = 6 Quadrupoles + Duodecapoles



Effective potential:

$$U_{eff} = \left(\frac{\sigma_o \beta c}{L}\right)^2 \left[\frac{r^2}{2} + f \varsigma r^m \cos(m-2)\theta + \varsigma^2 \frac{r^{2(m-1)}}{2}\right]$$

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FODO Quadrupole-Duodecapole Channel *

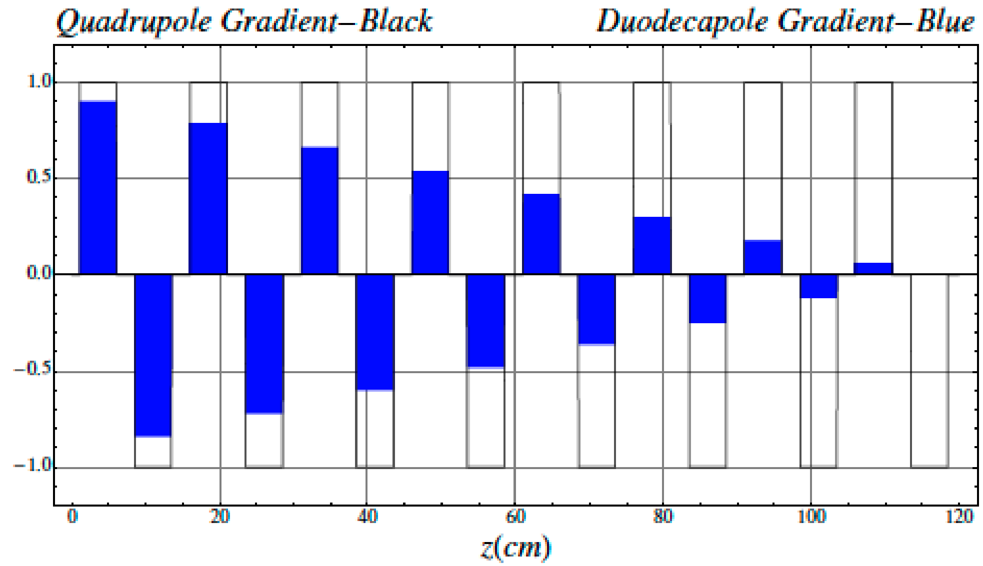

Figure 3: FODO quadrupole-duodecapole channel with combined lenses with the period of $L = 15$ cm, lens length of $D = 5$ cm, and adiabatic decline of duodecapole component to zero over a distance of 7 periods.

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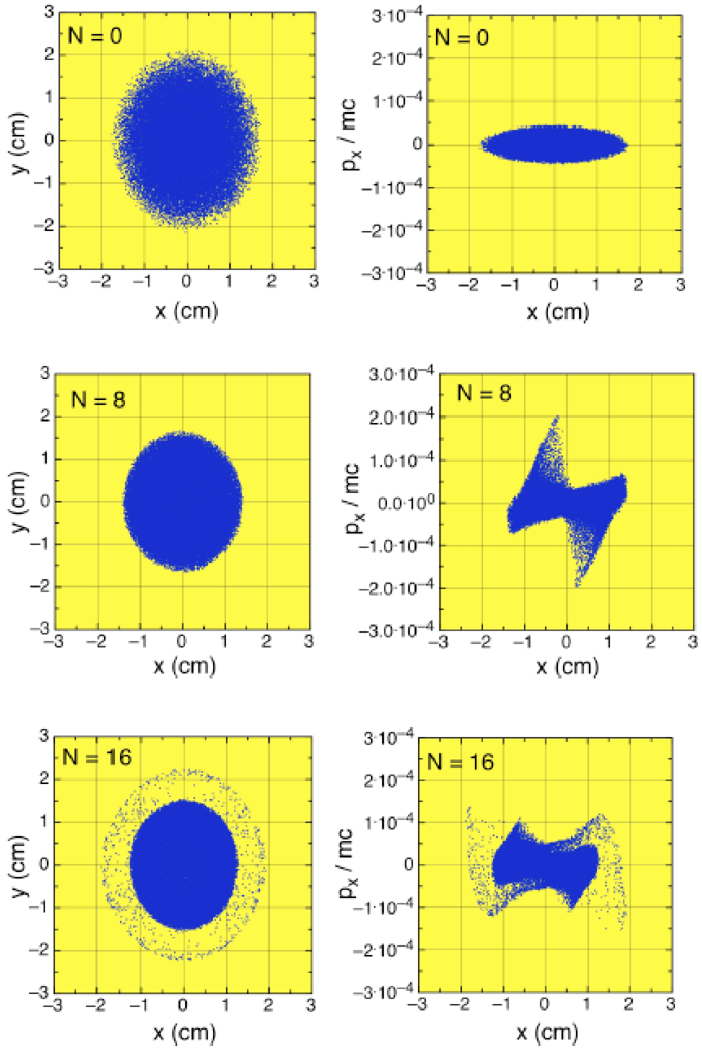
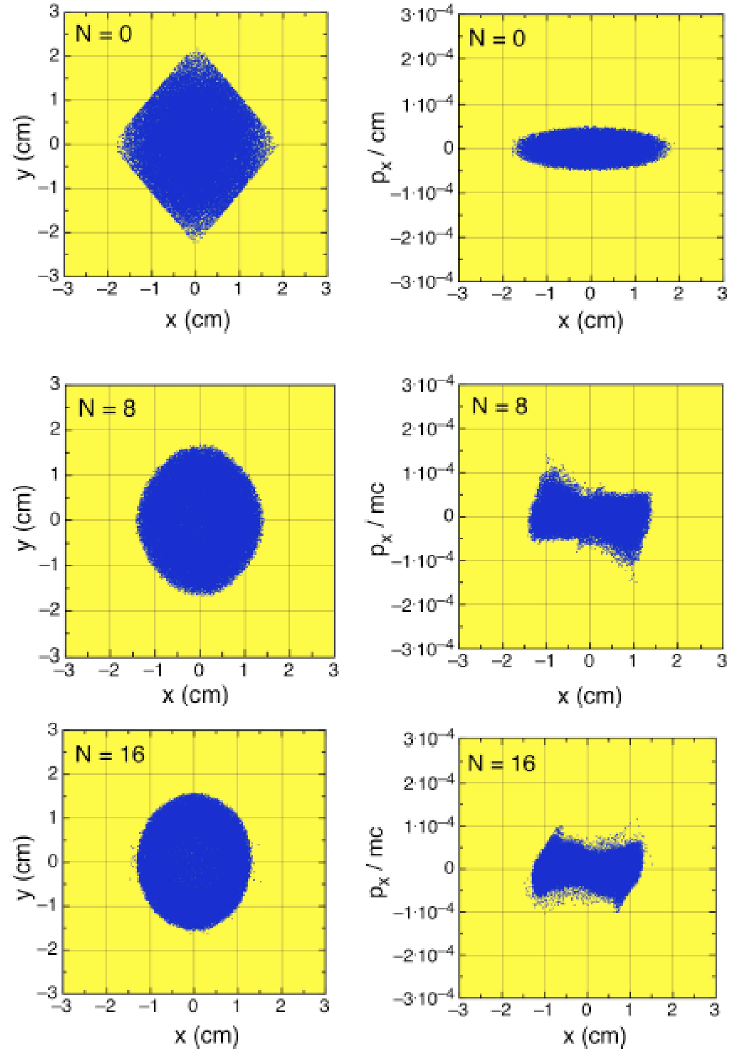
Quadrupole Channel



Quadrupole-Duodecapole Channel



Energy	**35 keV**
Current	**11.7 mA**
Emittance	**0.05 π cm mrad**
Quadrupole	**G_2 = 0.03579 T/cm**

Quadrupole G_2 = 0.03579 T/cm
Duodecapole G_6 = -1.76e-04 T/cm^5
Numbers indicate FODO periods

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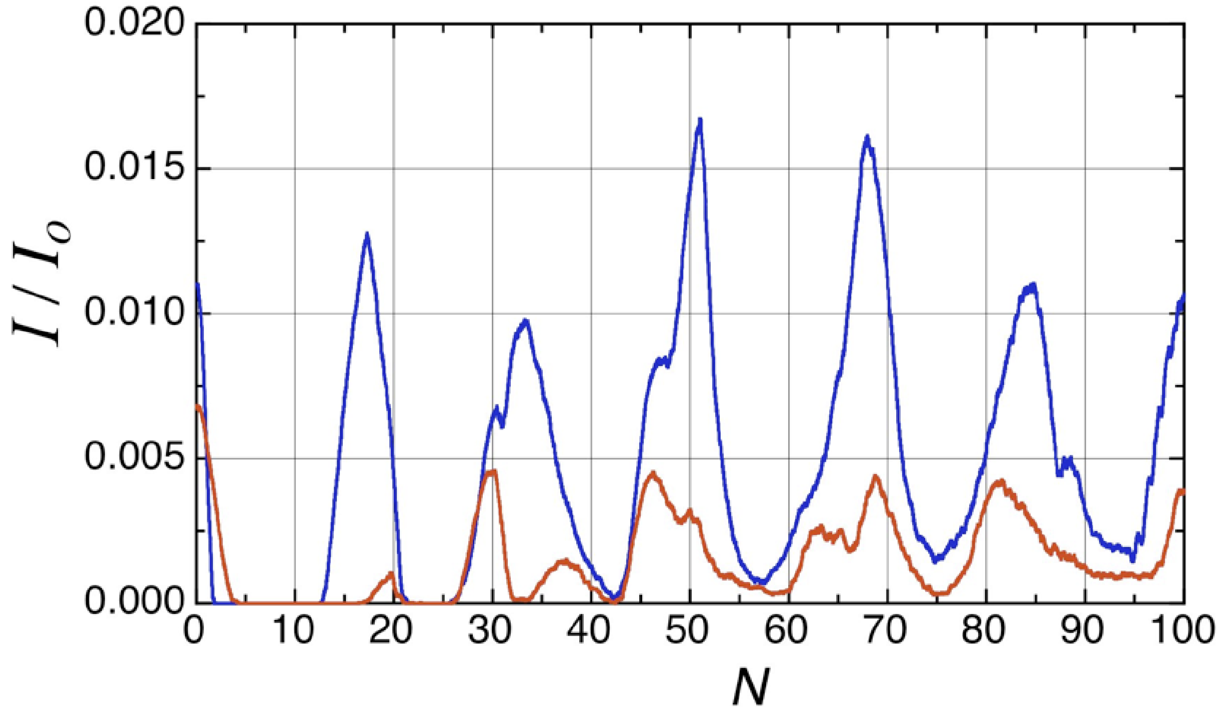
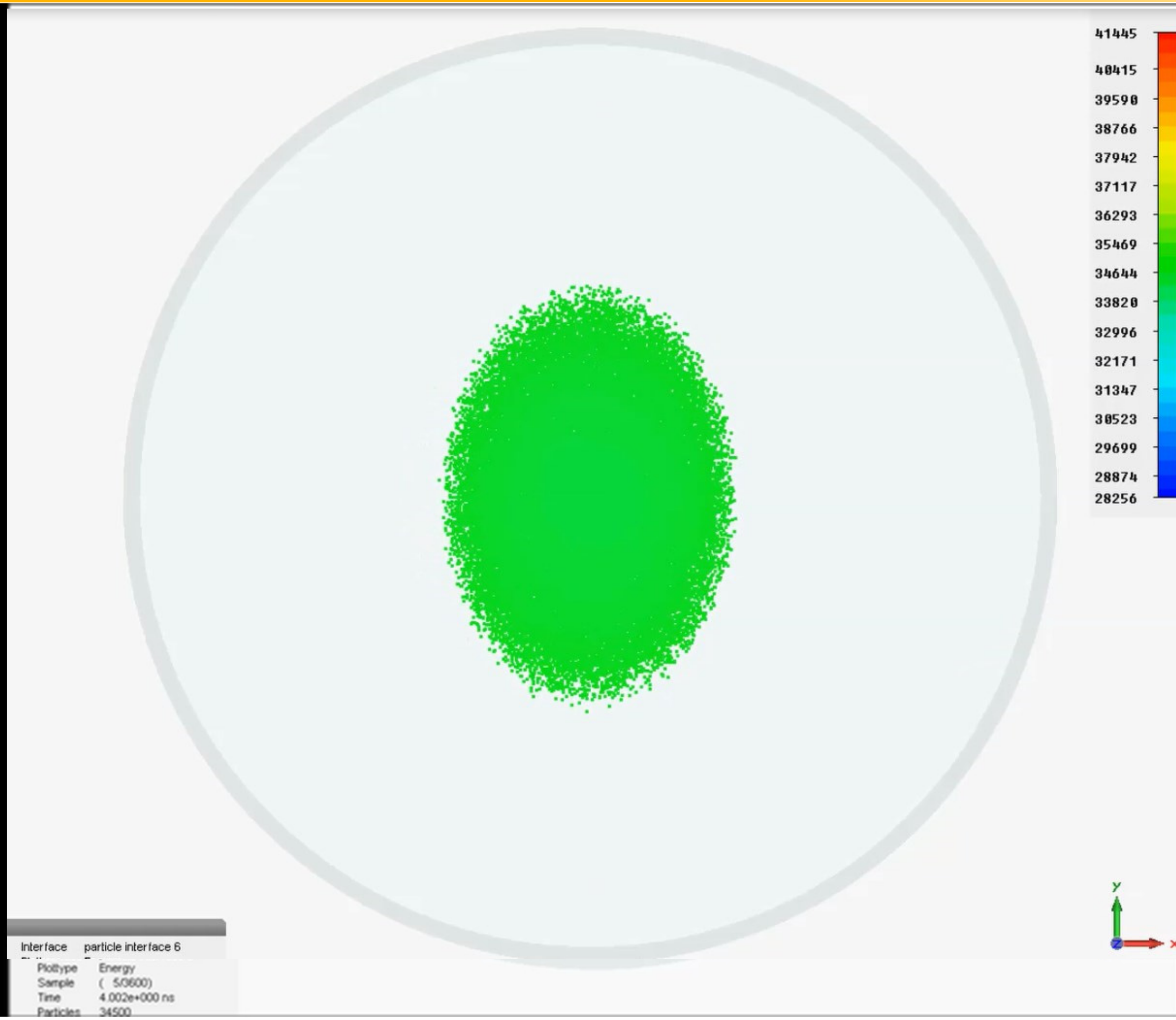
Suppression of Beam Halo



Fraction of particles outside the beam core $2.5\sqrt{<x^2>}$ x $2.5\sqrt{<y^2>}$ as a function of FODO periods: (blue) quadrupole channel, (red) quadrupole-duodecapole channel.

CST Particle Studio Simulation of Halo Formation in Quadrupole Channel



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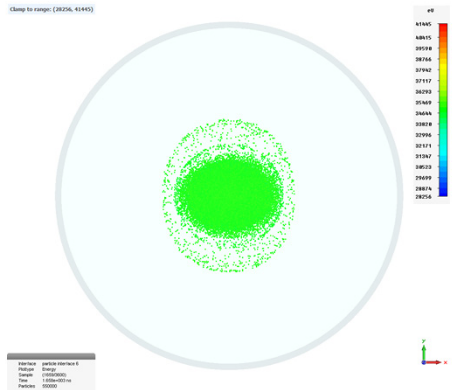
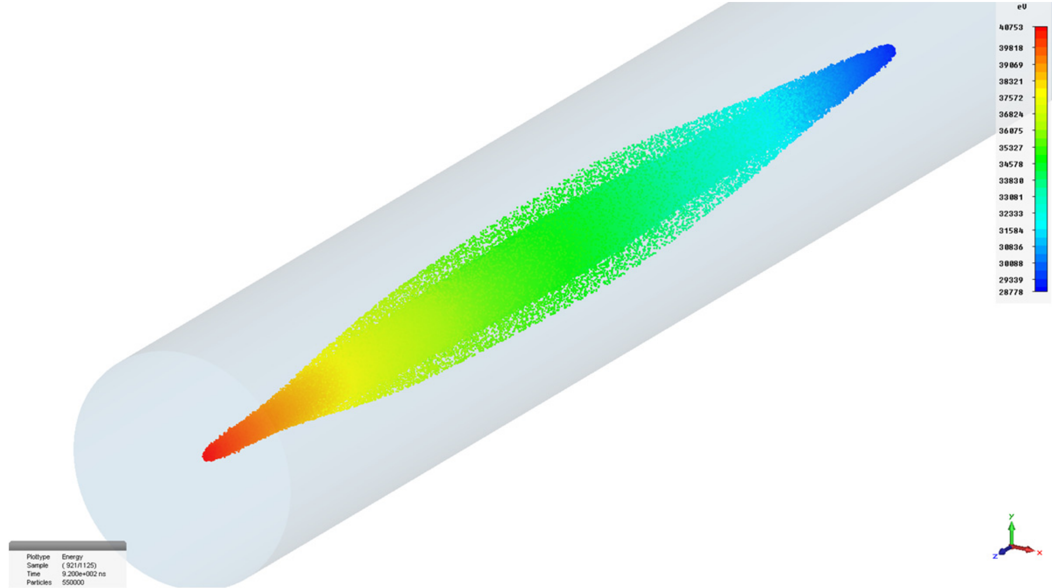
CST Particle Studio Simulation of Halo Suppression in Quadrupole-Duodecapole Channel

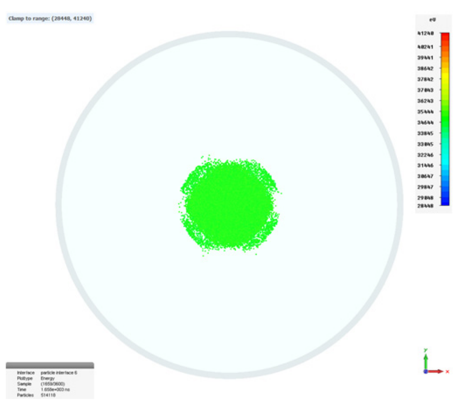
Final Particle Distributions in Focusing Channels

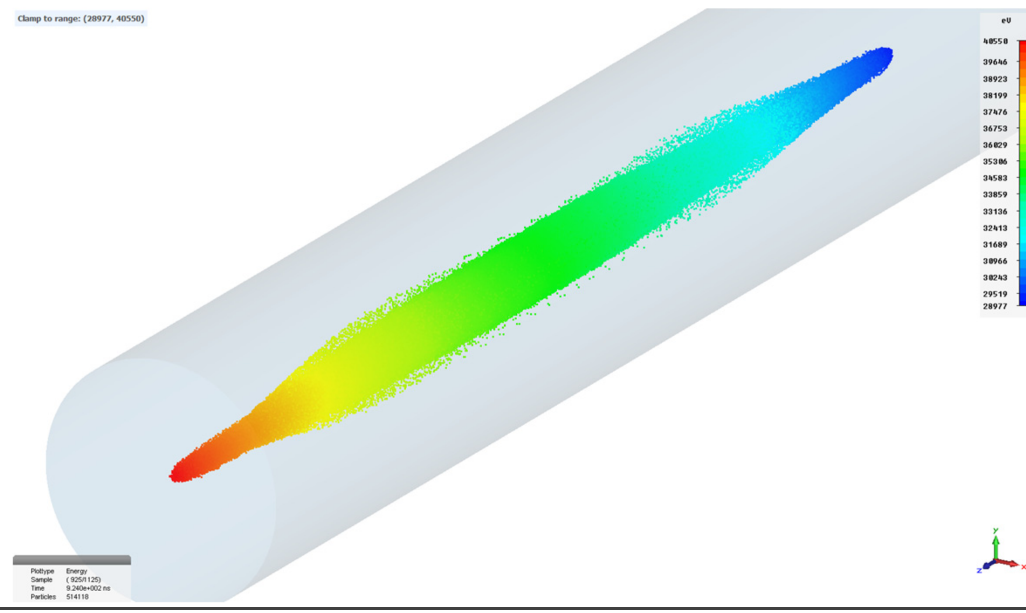
Quadrupole Channel





Quadrupole-Duodecapole Channel





Summary

1. Beam emittance growth and halo formation due to free-energy excess in high-brightness beams are unavoidable in linear focusing channel.

2. To prevent beam emittance growth and halo formation, focusing fields have to be a nonlinear function of radius.

3. Quadrupole-duodecapole focusing structure is an effective way to suppress beam halo formation.