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NONLINEAR OPTICS FOR SUPPRESSION OF HALO FORMATION IN SPACE CHARGE DOMINATED BEAMS*

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Abstract

Traditional accelerator designs utilize linear focusing elements (quadrupoles, solenoids) to yield stable particle motion. Concurrently, high intensity rms-matched non-uniform beams are intrinsically mismatched with linear focusing structures. This inconsistency results in space charge induced beam emittance growth and halo formation. However, periodic structures of focusing-defocusing lenses with combined quadrupole and duodecapole field components provide an effective way to suppress halo formation [1]. This paper summarizes research activity aimed at optimizing the quadrupole-duodecapole channel for halo suppression. The performed analysis allows for matching of a realistic beam with the internal structure of the focusing field. Additionally, beam dynamics studies with a suppressed halo are presented and discussed.

EFFECT OF BEAM HALO

A beam halo is a comparativley small fraction of the beam (1% - 10%) which lies outside the beam core and simultaneously occupys a significantly larger phase space area than the beam core itself. Accordingly, beam halos constitute a dominant source of beam losses, which result in radio-activation and degradation of accelerator components. Modern accelerator projects that utilize high-intensity beams with final energies of 1-1.5 GeV and peak beam currents of 30-100 mA require the retention of the beam losses at a level of no more than 10^{-7}/m (less than 1 Watt/m) to avoid activation of the accelerator and to allow hands-on maintenance over long operating periods. Collimation of a beam halo cannot prevent beam losses completely, because the halo of a mismatched beam re-develops in phase space after a certain distance following collimation. Correspondingly, the main sources of beam halo formation in a linac are:

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

Initial formation of a space-charge induced beam halo is associated with filamenation in phase space due to intrinsic mismatching of a non-uniform beam with its linear focuing structure. Fig. 1 illustrates the injection of a space-charge dominated, non-uniform beam into a focusing channel with a linear field, which results in beam uniforming, beam emittance growth, and halo formation. Conservation of electromagnetic energy and kinetic energy of charged particles within an isolated volume element (Poynting's theorem), can be expressed for a non-relativistic particle beam as

$$\frac{d}{dt}\left(\frac{\varepsilon_o}{2}\int E^2\,dV + \sum_{i=1}^{N} W_{kin}\right) = 0 \ , \qquad (1)$$

where E is the total electrostatic field in the structure, W_{kin} is the kinetic energy of N particles:

$$\sum_{i=1}^{N} W_{kin} = \frac{N}{2m\gamma}[<p_x^2> + <p_y^2>] = N\frac{mc^2}{\gamma}\left(\frac{\varepsilon}{2R}\right)^2 \ , \qquad (2)$$

R is the beam radius, and ε is the normalized beam emittance. Reduction of energy stored in the beam due to beam uniforming results in an increase of beam emittance ("free energy" effect [2]). Furter develoment of a halo is associated with particle-core interaction within a focusing chennel.

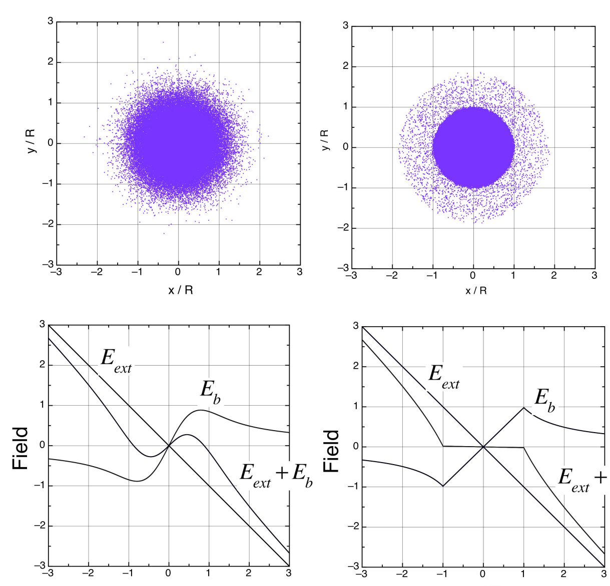

Figure 1: (left) Initial and (right) final particle distribution of a high-brightness beam in a continuous focusing channel: E_b – space charge field, E_{ext} –focusing field.

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QUADRUPOLE-DUODECAPOLE FOCUSING CHANNEL

Previous studies have shown that effective compensation of the nonlinear space charge effect can be achieved by adding a duodecapole field component in a quadrupole focusing structure [3]. Effective (time-independent) focusing potential of the quadrupole-duodecapole focusing structure is given by

$$U_{eff}(r,\phi)=\frac{r^2}{2}(\frac{\sigma_o\beta c}{L})^2[1+2\eta(\frac{r}{R})^4\cos 4\phi+\eta^2(\frac{r}{R})^8], \quad (3)$$

where σ_o is the transverse oscillation phase advance in a FODO quadrupole structure of the period L, and η is the normalized ratio of field components

$$\eta=\frac{G_6}{G_2}R^4 \ . \quad (4)$$

Because the effective potential is not azimuthally-symmetric, the matched beam has to be truncated along equipotential lines, which results in a diamond-shaped beam. The value of duodecapole component is dictated by the condition of equality of the field, Eq. (3), at the beam boundary, and the required focusing field for proper matching of the beam [1]:

$$\eta=-\frac{1}{36(1+\frac{2}{3b})} , \qquad b=\frac{2}{\beta\gamma}\frac{I}{I_c}(\frac{R}{\varepsilon})^2 . \quad (5)$$

A typical value of the normalized ratio of field components for compensation of nonlinear space charge effect on halo formation is $\eta=0.015-0.027$.

Figures 2 - 3 illustrate CST Particle Studio simulations of a proton beam with an energy of 35 keV, current 11.7 mA, normalized emittance of 0.0418 π cm mrad in a FODO quadrupole and quadruple-duodecapole channels. The channel is characterized by a period of L = 15 cm, lens length of D = 5 cm, quadrupole field gradient of G_2 = 0.03579 T/cm and a duodecapole component of G_6 = -0.14568 10^{-3} T/cm^5 (parameter $\eta=0.0156$). CST PS software simulates 3D beams with a full solution of Maxwell's equations. For the purposes of this study, a continuous beam was substituted by a finite-length beam portion with an initial length of 1.1×focusing period (16.5 cm). Because of the absence of longitudinal focusing, the selected bunch evolves in the longitudinal direction due to longitudinal space charge forces. For that reason, the simulation was restricted to 30 focuing periods. Figs. 2 - 3 illustrate initial and final transverse partcile distributions in the simulations. It is clear that the presence of a duodecapole component reduces the amount of halo particles significantly.

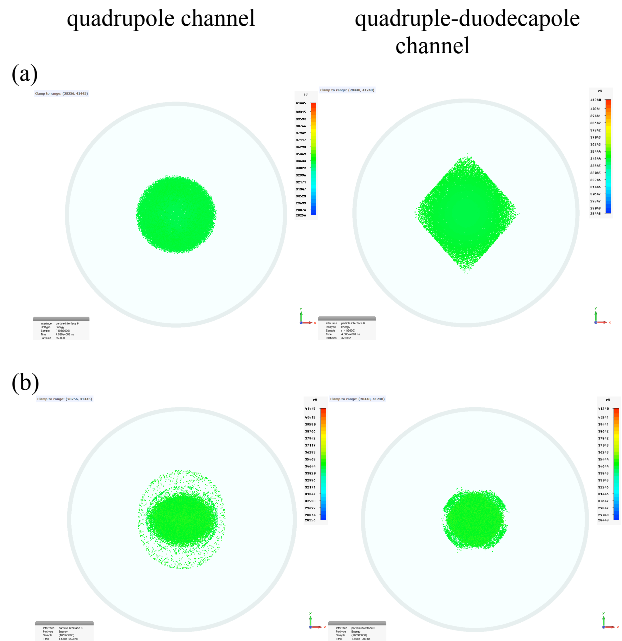

Figure 2: (a) initial and (b) final *x-y* particle distributions in a focusing channels containing 30 focusing FODO periods.

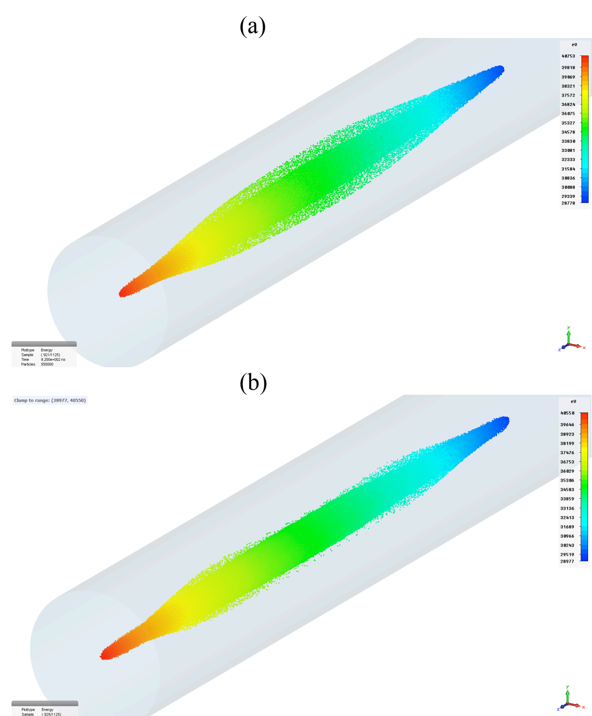

Figure 3: Final 3D distributions of the beam in 30 periods of (a) quadrupole channel, (b) quadrupole-duodecapole channel.

ADIABATIC MATCHING OF THE BEAM

An additional feature of the proposed structure is its ablity to adiabaticaly change the duodecaple component along the channel, which results in a transformation of a

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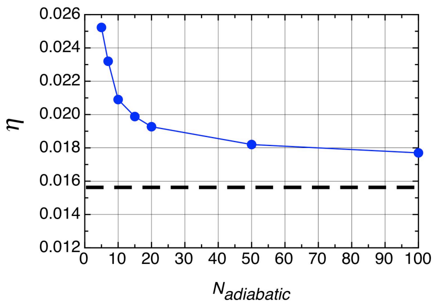

Figure 4: (blue) optimal starting values of parameter η, Eq. (4), versus number of FODO periods for adiabatic decline of duodecapole component, (dotted) the value of η for the channel with constant duodecapole component.

truncated, non-uniform beam, into a more uniform beam, matched with the quadupole focusing structure. Figs. 4 - 5 illustrate the results of a study of beam parameters as functions of the adiabatic decline distance using BEAMPATH code. Parameters of the beam and the structure were selected to be the same as that in Figs. 2 - 3, while duodecapole component dropped linearly from its initial value to zero at a certain distance, measured in number of focusing periods, $N_{adiabatic}$. The rest of the structure contained quadrupoles only. Results of the simulations were compared after 100 focusing periods of the structure.

It appears that the optimal starting value of the duodecapole component depends strongly on adiabatic distance. Fig. 4 illustrates the dependence of the initial normalized ratio of field components, Eq. (4), as a function of the adiabaticity parameter $N_{adiabatic}$. The dotted line corresponds to the case of constant duodecapole component along the channel. As can be seen, the reduction in the number of adiabatic lengths results in an increase of required duodecapole component.

Figure 5 illustrate particle distributions in phase space and in configuration space after 100 periods of the structure. Figure 5a illustrates halo formation of the beam in a pure quadrupole structure. Figure 5b illustrates the effect of suppression of the halo in quadrupole-duodecapole structure with constant value of the parameter $\eta = 0.0156$ along the channel. Figures 5c-5e illustrate the effect of adiabatic matching of the beam where the duodecapole component changed adiabatically to zero at the distance of $N_{adiabatic}$ focusing periods. It is clearly visible that the presence of the duodecapole component results in a significant reduction of the beam halo. Simultaneously, the reduction of adiabatic period $N_{adiabatic}$ results in a slight increase in the number of particles in the beam halo, which however remains significantly smaller than that in case of a pure quadrupole channel.

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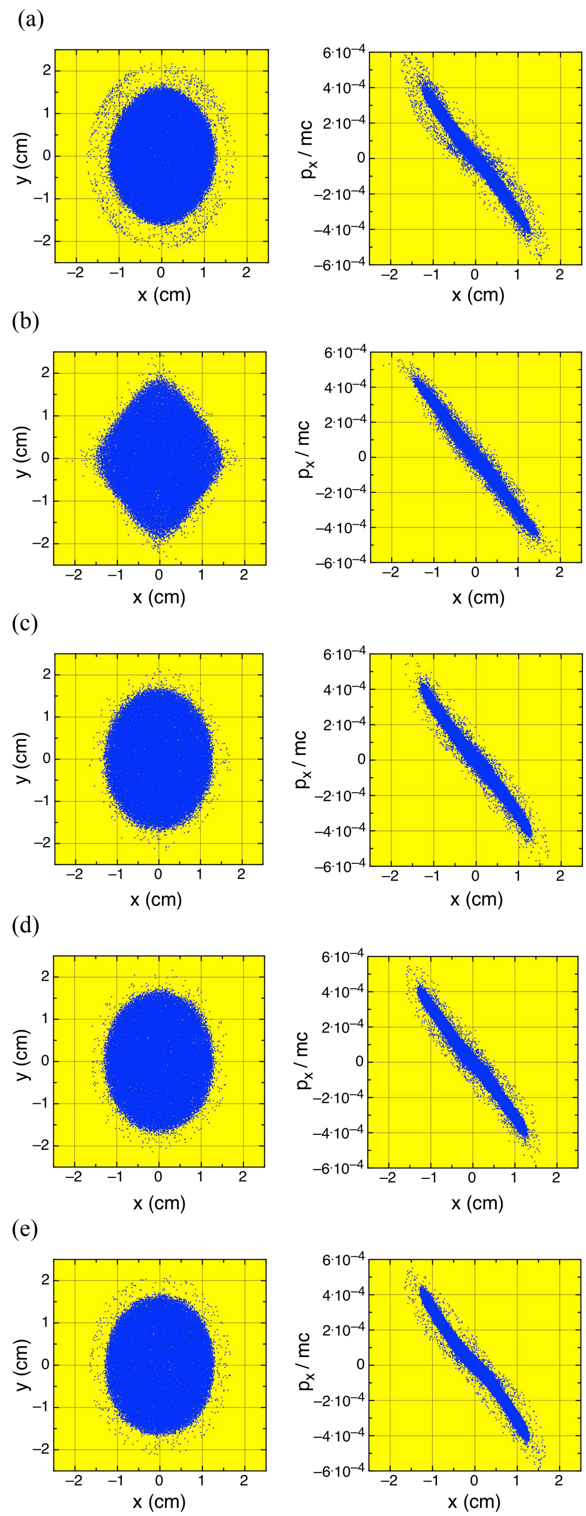

Figure 5: Particle distributions after 100 focusing periods: (a) pure quadrupole channel, (b) quadrupole-duodecapole channel with constant $\eta = 0.0156$, (c) quadrupole-duodecapole channel with initial $\eta = 0.0177$ and $N_{adiabatic}$=100, (d) quadrupole-duodecapole channel with initial $\eta = 0.0182$ and $N_{adiabatic}$ = 50, (e) quadrupole-duodecapole channel with initial $\eta = 0.0209$ and $N_{adiabatic}$=10.