DESIGN CONSIDERATIONS FOR FINAL PULSE COMPRESSION WITH BENDING FOR HEAVY ION FUSION DRIVERS*

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Abstract
Immediately prior to final focus onto a fusion target, heavy ion driver beams are compressed in length by typically an order of magnitude (see e.g. [1] and [2]). This process is simultaneous with bending through large angles to achieve the required target illumination configuration. The large increase in beam current is accommodated by a combination of decreased lattice period, increased beam radius, and increased strength of the beamline quadrupoles. However, the large head-to-tail velocity tilt (up to 5%) needed to compress the pulse results in a very significant dispersion of the pulse centroid from the design axis. A principal design goal is to minimize the magnitude of the dispersion while maintaining approximate first order achromaticity through the complete compression/bend system. Configurations of bends and quadrupoles which achieve this goal while simultaneously maintaining a locally matched beam-envelope have been analyzed.

1 INTRODUCTION

Conceptual heavy ion driver systems for inertial fusion energy generally require multiple high power ion pulses of very short duration on the fusion target to achieve an efficient implosion of the fusion capsule. Typically, this might be made up of 84 separate beams of 2.5 GeV Cs^+, each with 2.0 kA and 10 ns duration. Such short pulses cannot be accelerated effectively using induction linac technology so drift compression by about an order of magnitude between the linac and the final focus system is employed. Several novel features of beam dynamics arise simultaneously in this compression zone. The high currents are confined by quadruples in a FODO configuration, with bends located in the drift sections to achieve the desired target illumination symmetry. To compress a beam pulse, a head-to-tail velocity tilt of several percent is applied during the final stages of acceleration in the linac. Current rises steadily during compression and this requires that either the quadrupole focal strength or the beam radius simultaneously increase. Roughly, the dimensionless generalized perveance Q is related to the lattice period length (P) and the mean beam edge radius ($\bar{a}$) by the the space charge limit:

$$\frac{2qI}{4\pi\varepsilon_0(\beta\gamma)^3 mc^3} \equiv Q \approx 1.4\frac{\bar{a}^2}{P^2} \tag{1}$$

where we have taken the undepressed lattice tune to be $\sigma_0 = 72^o$ per period. Here I is the beam current, q is the ion charge, m is the ion mass, $\beta\gamma mc$ is the ion momentum, and ε_0 is the permittivity of free space. If P is held at a low constant value to limit dispersion then $\bar{a}$ is seen to increase as $I^{1/2}$. A rough measure of the sideways displacement of the beam centroid (x) is obtained from the matched smooth limit formula

$$0 = x'' = -(\frac{\sigma_0}{P})^2 x + \frac{\Delta}{\rho}, \tag{2}$$

where ρ is the local mean curvature of the design orbit and Δ is local fractional momentum tilt. For example ρ=50 m, Δ = 0.02, P=3.0 m yields x= 2.3 mm. A critical question is whether the dispersion x(z) of a beam segment remains in a matched state with small amplitude oscillations while the lattice and beam parameters change. Furthermore, it is desirable that the entire pulse enters the final focus system essentially on axis, i.e. the system is in some sense achromatic. There is no simple principle of design that will guarantee these features for a single slice of a pulse, let alone for the entire pulse. However, there is ample evidence from numerical analysis that an "adiabatic" variation of lattice features will suffice. That is, if ρ, I, and P vary slowly on the scale of a betatron wavelength, the dispersion, as well as the beam envelope may remain in a nearly matched condition. As mentioned, there does not appear to be a developed mathematical basis for this strategy, so it must be examined by numerical examples.

In this study of the beam centroid dispersion and envelope during drift compression in bends, model equations are integrated using a simple Mathematica® code. The model assumptions are: 1. KV envelope equations for beam radii in the x (in bend plane) and y (vertical) directions; 2. A centroid equation which includes: image forces, off-momentum slices from velocity tilt, non-linear in Δ; 3. A longitudinal envelope equation, based on a constant g-factor model for calculating the longitudinal space charge force; 4. Discrete bend and quadrupole elements. The lattice period, focusing strength and perveance are allowed to vary with z. The goal is to try to minimize dispersion throughout the bend system and particularly the final centroid x and x' at exit of the bend system. For this study, the parameters were those typical of a Heavy Ion Fusion (HIF) "driver," see table 1.

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Parameter	Value
Charge state (q/e)	1
Ion Mass (amu)	132.9
Ion Energy (GeV)	2.43
Initial Current per beam at accel. exit (A)	103.4
Final Current per beam (A)	2254
Compression Factor	21.8
Final Perveance Q	0.000181
Velocity tilt (Dv/v)	-0.031
Total drift length (m)	502.3
Beam radius evolution	a ~ Sqrt[Q/Qo]
Lattice period evolution	L ~ constant

Table 1. Parameters used in this study. Parameters are typical of what is expected for an HIF "driver".

2 MODEL EQUATIONS AND EXAMPLE PARAMETERS

Four simultaneous equations are solved:

$$\frac{d^2\lambda}{dz^2}=\frac{12gqC}{4\pi\varepsilon_0\gamma^5 m v_0^2}\frac{1}{\lambda^2}-k_L\lambda, \tag{3}$$

$$\frac{d^2x}{dz^2}=\frac{1}{\rho_0}\left(1-\frac{p_0}{p}\right)-\frac{qG}{p}x+ +\frac{Q}{R}\left[\frac{x}{R}+\left(\frac{x^2+(a^2-b^2)/4}{R^3}\right)x\right], \tag{4}$$

$$\frac{d^2a}{dz^2}=\frac{\varepsilon_N^2}{\beta^2\gamma^2a^3}-\frac{qG}{p}a+ +2Q\left[\frac{1}{a+b}+\left(\frac{x^2+(a^2-b^2)/4}{2R^3}\right)\frac{a}{R}\right], \tag{5}$$

$$\frac{d^2b}{dz^2}=\frac{\varepsilon_N^2}{\beta^2\gamma^2b^3}+\frac{qG}{p}b+ +2Q\left[\frac{1}{a+b}-\left(\frac{x^2+(a^2-b^2)/4}{2R^3}\right)\frac{a}{R}\right]-\frac{b}{\rho_0^2}. \tag{6}$$

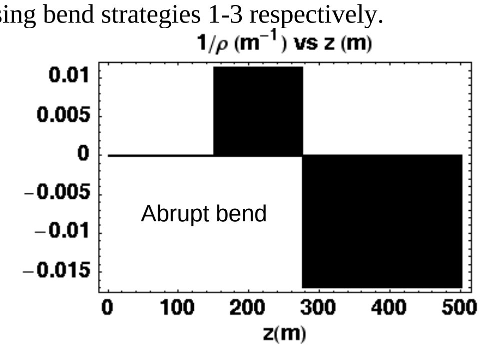
Here λ is the bunch length, x is thecentroid position, a, b are the envelopes in the x,y -directions, q is the ion charge, m is the ion mass, v_0, p_0,γ are the nominal ion velocity, momentum, and Lorentz factor of the ion; p is the particular ion momentum of the slice; ρ_0 is the instantaneous nominal radius of curvature of the bend, G is the quadrupole gradient; R is the pipe radius; k_L is the longitudinal focusing constant, ε_N is the normalized emittance, λ is the line charge density; C is the total charge in each beam, and ε_0 is the permittivity of free space. We assume that the pulse evolves self-similarly with a parabolic line charge density satisfying $\lambda=3C(1-4\zeta^2/\lambda^2)/(2\lambda)$ for $|\zeta/(\lambda/2)|\le 1$ and slice momentum satisfying $p/p_0=1+\lambda'\zeta/\lambda$, where ζ is the slice position relative to the bunch center, with ζ/λ constant for each slice.

3 BEND STRATEGIES

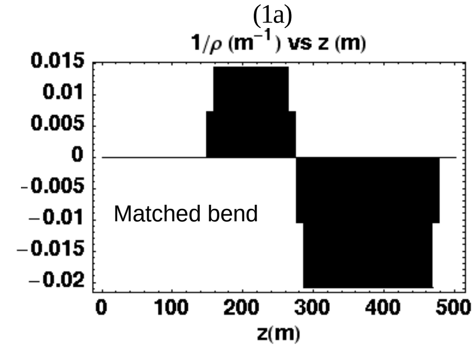
We consider three design strategies for placing bends in a drift compression lattice: 1.Abrupt bends, in which all bends are full strength. This is the simplest configuration from which to compare improved designs; 2. Matched bends: Here we choose bends of half-strength over a distance equal to one-half undepressed betatron period. The centroid will enter the full strength section, at the peak of the amplitude of a half-strength bend centroid betatron orbit, with $x'\approx 0$ (in the smooth focusing approximation). This will be close to the matched condition for a full strength bend, and hence subsequent bends are at full strength. 3. Adiabatic bend: In this design strategy, a gradual ramp-up of bend strength over several betatron periods is carried out, keeping centroid and envelope oscillations "matched" at low amplitude.

4 COMPARISON OF THE BEND STRATEGIES

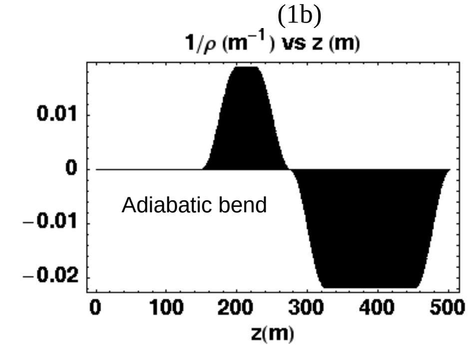
Figures 1a, 1b, and 1c illustrate the layout of instantaneous radius of curvature of the bend centroid using bend strategies 1-3 respectively.



(1a)



(1b)



. (1c)

Figure 1. Inverse instantaneous radius of curvature (m^{-1}) as a function axial distance (m) for (a) an abrupt bend, (b) a matched bend, and (c) an adiabatic bend, using

driver parameters of table 1. Peak strength is shown, with bend occupancy of 0.65.

The bunch length l is undergoing compression in all three scenarios and is found by integration of equation 3. Figure 2 illustrates the evolution of l with z.

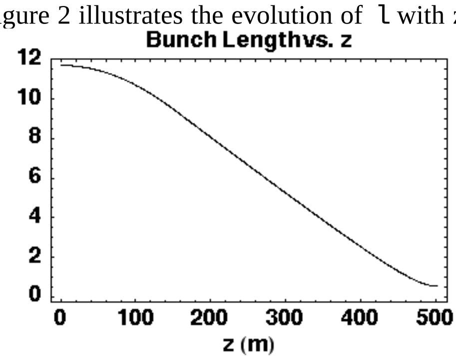
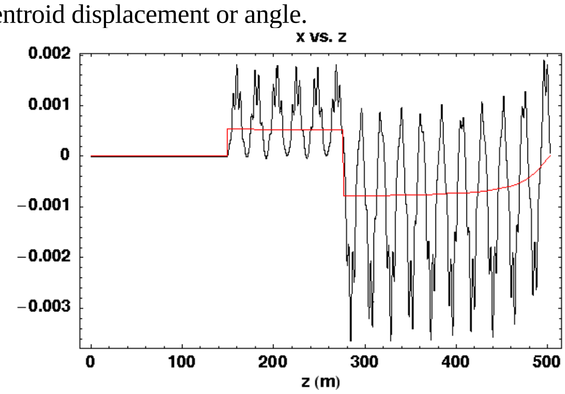
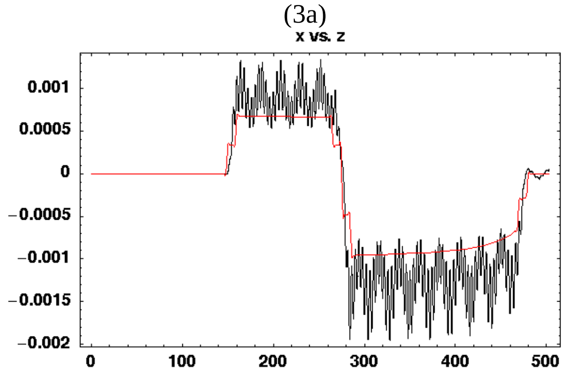


Figure 2.Bunch length l vs. z for all 3 bend strategies.

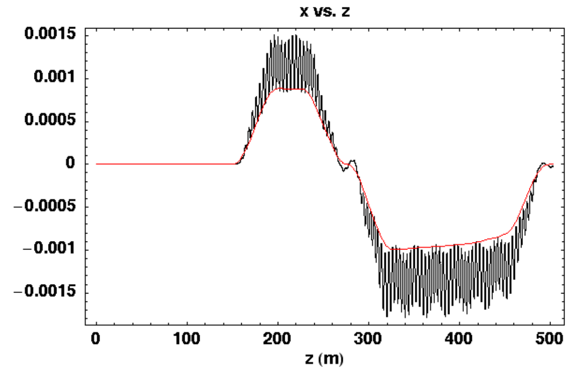
The evolution of the centroid for off-momentum slice of the beam varies according to which bend scenario is selected. Since bunch compression intrinsically requires the velocity of the beam to systematically vary from tail to head, velocity dispersion is an essential feature of bunch compression. From figure 3, it is apparent that the abrupt turn-on of the bend has greatest dispersion and largest x' upon exit from the bend, whereas the "matched" and "adiabatic" designs have smaller excursions and terminate the bend with little residual centroid displacement or angle.



(3a)



(3b)



(3c)

Figure 3, Evolution of centroid for the beam slice half-way between center and head, in bend design scenarios (a) abrupt, (b) matched, and (c) adiabatic. The solid (non-oscillating) line in each figure represents the instantaneous smooth limit result given by eq. (2).

5 SUMMARY AND CONCLUSIONS

In this paper we have shown the effect of three different bending scenarios on the beam centroid for different longitudinal slices of the beam, (and hence different longitudinal velocities).

An abrupt turn-on of the bend induces a centroid mismatch for off-momentum slices, and does not return the slice to the center of the beamline upon exit of the bend. This would increase the requirement on pipe radius throughout the drift compression section and would lead to an enlargement of the spot on target if not corrected using time dependent steering.

Matched designs in which the bend ramps at about half-strength for half of a betatron period reduce both maximum radius and final centroid displacement, as do adiabatic designs in which the bend strength ramps up and down over several betatron periods. Adiabatic designs appear more robust however, allowing greater flexibility in choice of tune, with minimal penalty in bend length or bend strength.

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