Final Focus and Drift Compression Working Group Overview

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The Final Focus and Drift Compression group examined a wide variety of issues and several system scenarios, with the general objective of bringing beams from an accelerator to an experiment. The typical final pulse duration ($\tau \approx 1.0$ns) and spot radius ($r_s \approx 1.0$mm) present a challenging task that involves a number of innovations, to be outlined below. Short reports covering many aspects of a compression/focus system follow this overview. A typical parameter set, considered by the entire workshop, is as follows:

ion = Ne^+ (or Ne^{++})
kinetic energy = 19 MeV
β = .045
ion number =$1.4\text{x}10^{13}$
Total energy = 43J
Total charge = 2.2μC (or 15μC)

At the end of acceleration the pulse duration is about 100-200ns and it is to be compressed to 1.0ns by the imposition of a velocity tilt. This is a head-to-tail linear ramp of velocity (with only minimal errors allowed) such that the pulse tail nearly overtakes the pulse head at the experimental target. Pulse length in meters decreases from 1.35m to 1.35cm in x100 compression, and line charge density increases by the same factor. For charge state +1 the final density is 160μC/m, and the self-force would be enormous if this were done in vacuum – center to edge potential of 1.4MV! So it is assumed that the beam pulse may be neutralized by plasma or injected electrons, and the self-electric and self-magnetic fields are nearly eliminated. A residual potential of order 500 volts is expected since electrons must be accelerated to at least a fraction of the beam speed. The excess of electrons also neutralizes the space charge field in the longitudinal direction. Plasma should be "over-dense" to accomplish this condition, i.e. n_e>10 n_b in charge state +1. However this is not such a high density of plasma that scattering and stripping of the beam ions is expected to be appreciable, except very close to the target if extra plasma is created there; this is an issue for additional research.

The velocity tilt that is imposed at the start of drift compression is not removed by the space charge force near the final focus (as it is in the standard Heavy Ion Fusion approach) because the field is neutralized. Therefore the beam pulse must be focused with a large variation of momentum still present, and the resulting chromatic aberration must be considered. If a single, short focal length, solenoid is used to focus the beam, then tilts as large as $\pm$ 5% seem to be manageable, ie $\Delta\beta/\beta \le 0.10$. Such a tilt limit places a lower bound on drift distance.

$$\text{drift distance}=\frac{\text{initial pulse length}}{\text{tilt}}.$$

So for the example of x100 compression, a full tilt of $\pm$ .5% has drift distance =1.35x10=13.5m. Roughly speaking, the deviations from linearily in the tilt waveform must be smaller than the inverse of compression, so for compression by x100 with tilt

= ± 5%, the random velocity variations must be less than .1% times the beam velocity. This is a very significant restriction on accelerator design and technology.

Although it received relatively little attention at the workshop, an HEDP facility should be able to serve multiple users, say N=5, but not necessarily provide beam to more than one user at a time. This consideration implies N separate beam lines and a switchyard. The separate beam lines must be spaced far enough apart so that experiments are physically separated by at least a few meters, so the switching is through angles of order 20 radians or more. Chromatic problems must again be considered in switchyard design. It will be very helpful in this regard if beam trajectory bending by magnetic dipoles can be carried out inside the neutralizing plasma rather than upstream in the accelerator vacuum.

Beam transport during compression is generally assumed to use nearly continuous solenoid magnets of moderate strength (B ∼ 1.0T), whose purpose is to both guide the beam centroid and confine the beam's transverse thermal pressure. For a given emittance (edge unnormalized value = ε) and beam radius a, we need

$$B \geq \frac{2(B\rho)\varepsilon}{a^2},$$

where $(B\rho) = \beta\gamma mc/q$ is the ion's magnetic rigidity. For the 19MeV N_e^{+1}, we get $(B\rho)$=2.8 T-m. For $\varepsilon=10^{-5}$ (π) m-r and a=.02m, we need only B =2x2.8 x $10^{-5}/(.02)^2$ = .14T. However, the final focus lens may require a high field (B ≈ 15T) to produce a desired short focal length (f ≈ .4m). The short focus is needed to overcome the finite emittance, since the spot radius is limited to

$$r_s \geq \frac{\varepsilon}{\theta}$$

where θ is the convergence cone half angle to the target. For the relatively large θ = 50mr, and $\varepsilon = 10^{-5}$ mr, we have $r_s \geq 10^{-5}/.05 = .2mm$. This would be excellent, but the chromatic aberration is expected to considerable increase this value, as would a larger emittance.

At this stage we may summarize the situation as follows:

HEDP with accelerated ion beams
⇒ large space charge force ⇒ must neutralize
⇒ magnets must work in plasma and focal design be insensitive to tilt

Some broad physical issues are apparent:

How large are deviations from charge and current neutralization?
Is the beam-plasma interaction stable?
What are the effects of stripping, scattering and energy lose?
What is the tilt limit?
Does the neutralizing flow of electrons get significantly impeded by magnetic dipoles and quadrupoles?
On what time scale can a magnet be pulsed inside a neutralizing plasma (if needed)?

Further considerations of beam dynamics for design include:

Strip to high charge state advisable?
Matching of the beam envelope from the accelerator to the neutralized beam line
Mechanism for emittance growth during transport
Flexibility of final focus for experimenter
Achromatic switchyard
Flexibility of major parameters - ion mass, energy, current, pulse duration.

In designing a compression and focusing system various "tools" or "tricks" are available that can be invoked to match the beam from the accelerator to the requirements of the HEDP experiment. Several of these have been mentioned before, but here we wish to emphasize that there are varying levels of uncertainty, risk, and need for development. In fact the present VNL program is now largely oriented to their experimental and computational investigation.

A fundamental concern is the effect of a transverse magnetic field on neutralization by electrons. Suppose B_y is a dipole field of (say) 1.0 kG strength. We may reasonably assume electrons flow across the beam path along field lines to achieve a high level of charge neutrality. However current neutrality, which is also desired, is impeded. If current is also neutralized, the longitudinal drift speed of the electrons is

$$\beta_e = \beta_b \frac{n_b}{n_e} \ ,$$

and the induced electric field transverse to the beam is

$$E_x = \beta_e B_y = \beta_b \frac{n_b}{n_e} B_y .$$

This force acts to oppose the intended bend force $\left(= q\beta_b B_y\right)$, such that the total force on the beam is now

$$F = q\beta_b B_y \left(1 - \frac{n_b}{n_e}\right).$$

This may be "ok" if n_e and n_b are steady and predictable, or the force reduction may be made negligible by making n_e large with locally dense preformed plasma. The simulation code LSP was used to investigate the correctness of this simple model, with a surprising result: net bending force was close to that with <u>no</u> plasma. This is not understood.

Another simulation result is the predicted suppression of the two-stream instability by the application of a solenoidal field, which effectively eliminates fast growing transverse modes.

Stripping was estimated to be a marginal problem. The estimated cross section for 19MeV $Ne^+ \rightarrow Ne^{++}$on Hydrogen atoms is $\sigma = 3x10^{-17} cm^2$. Suppose the pressure is as high as 1.0 mT. Then the stripping distance is $\left(n_H \sigma\right)^{-1} \approx$1000 cm. For H pressure much, much less than 1.0mT (the usual situation) we may assume that the beam remains in charge state +1.

It may be desired to pre-strip the beam to q $\approx$+7, which is the equilibrium state (± 1). This lowers the rigidity by a factor of 7 and reduces the required strength of the final focussing magnet by the same factor. However about half of the beam ions would be lost in the stripping process.

An incomplete but illustrative list of tools and tricks includes:

- Neutralized drift compression
- Strong solenoid lens for final focus (~15T)
- Magnetic dipoles for:
  - Stopping upstream electron flow
  - Achromatic switchyard
  - Achromatic multiple beam illumination of target
- Instability suppression by solenoids
- Pulsed lenses to compensate chromatic aberrations
- Adiabatic funnel close to experiment

Conceptual system layouts were considered for a single beam accelerator and multiple (18) beam and (12) beam rf accelerators.

Case 1

The single beam system is relatively straight forward, with bends only in the upstream switchyard. However there are two general versions for the drift section, as shown in the following sequences (fig. 1)

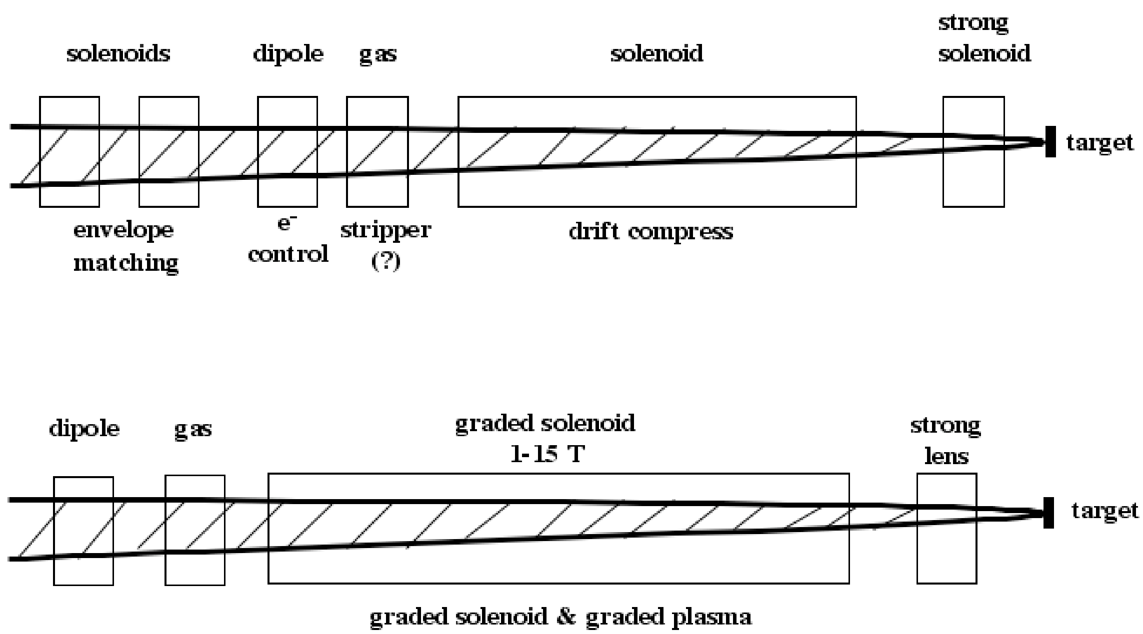

Figure 1

The idea behind the graded solenoid is to make an adiabatic match of the beam to drift system equilibrium conditions. This avoids the complications of upstream matching.

Case 2
rf acceleration – scheme 1

This presents 18 beams in a ring pattern, with tilt = ± .035, and x200 total compression. The compression distance is therefore 2.7m/.07 = 39m. The accelerator system is expected to produce the large value of emittance = 3□ mm-mr (rms-normulized) so the unnoralized edge value is 4□$_n$/□=2.7(□)x10^{-4} m-r.

Drift compression is in 18 separated lines, which are brought together a few meters from final focus using achromatic bend systems of a standard type using weak quadrupoles (see fig. 2). A special bend is inserted in each line to disperse the beam proportional to tilt in a way that compensates the chromatic effect at final focus. That is, a first order achromat for beam position is created. A strong, multibeam final lens (15 T solenoid) brings the spot radius to a 1.0 cm, followed by an adiabatic lens to produce a 1.0 mm final spot on target. This last element is described in a short note in the proceedings (see S.S Yu, "Adiabatic Plasma Lens -- A Current Density Booster"), and is an extrapolation by a factor 3 from what is achievable at present.

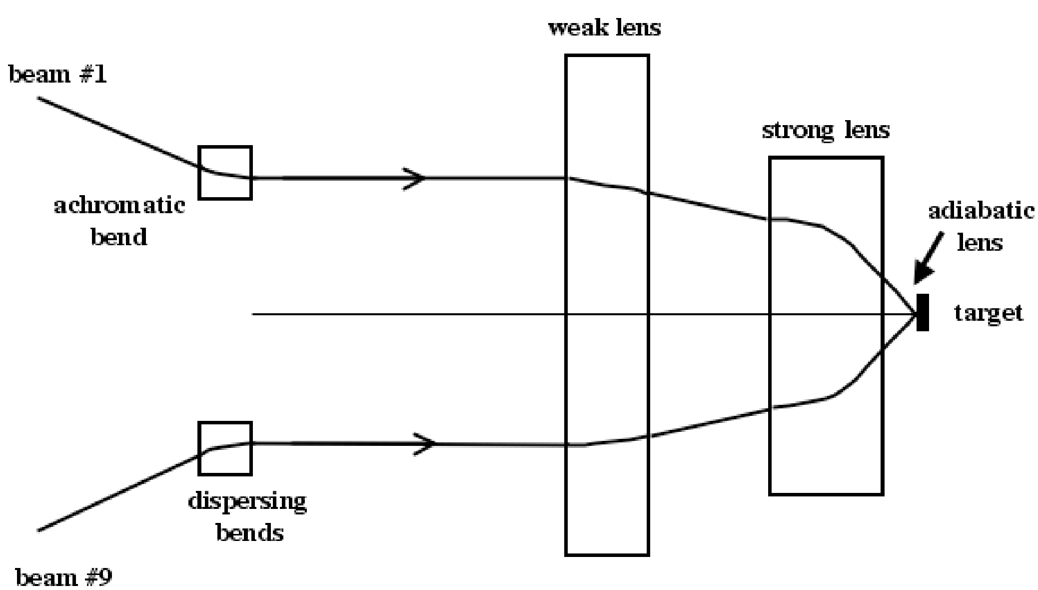

Figure 2

Case 3
rf accelerator – scheme 2

Here we merge 12 beams into one, and emittance is assumed to blow up to ~3x10^{-3}(π) m-rad. To achieve small spot radius on target $(r_s \approx 1.0mm)$ measures are taken upstream, with the use of pulsed lenses (in vacuum) to compensate chromatic effects (see fig. 3). All beams are focused at once in a large strong lens with large cone angle $(\theta \approx 200mr)$. This takes the collective radius down to 1.0 cm. A further decrease to 1.0 mm is achieved with the (hypothetical) adiabatic lens. In this scheme the tilt is ± 5% and the beam radius drops from 30cm to 1.0 cm in only 3.0m distance. It is expected that a significant halo will be produced, but a “good” pulse core will be available for experiments.

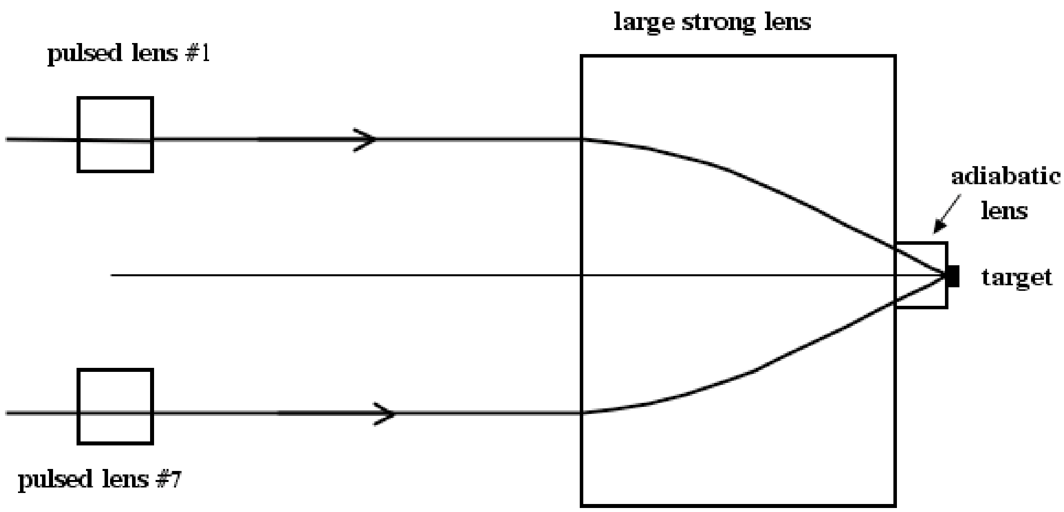

Figure 3