Title
Time Dependent Focusing

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Time Dependent Focussing
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Background
Focussing Concept
NDCX II
Fusion Driver
Background

The VNL program now hinges on beam manipulations similar to those of light ion fusion:
neutralized drift compression
neutralized final focus

To be attractive WDM and fusion system concepts have evolved:

- low ion kinetic energy
- low ion mass
- high line charge density
- modular accelerators
- few (~20) drift lines
- high longitudinal compression
- highly stripped ions

→ Perveance $> 10^{-2}$ doesn't allow quadrupole transport in vacuum

Perveance may actually exceed unity in final focus!
Solenoidal transport in vacuum can handle much larger permeance, but there is a space charge limit:

\[
\frac{1}{4} < \left( \frac{10 \text{ mc}}{\text{m}} \right) \left( \frac{B}{10^7} \right)^2 \left( \frac{q}{10 \text{ cm}} \right) \left( \frac{133}{A/8} \right)
\]

- high space charge potential:

\[
\Phi_{\text{center}} = \frac{(90 \text{ kV})}{(10 \text{ mc/m})}
\]

- Use electron neutralization in solenoids — from plasma or co-streaming.

Not yet clear this really works when electrons must cross field lines.

If a design did not use neutralization, Grant would improve it by increasing \( \phi \) so it did require neutralization.
Some consequences of neutralization:

Momentum tilt is not removed by space charge prior to final focus.

Strong quadrupoles probably can't be used — problem for electron flow.

Solenoids may be "ok" — what happens to electrons when beam does not follow field lines?

Large tilts \((\Delta P/P \sim \pm 0.05)\) for large compression and short drift length.

A static final focus system has a severe chromatic aberration ("second order").

The focal spot position depends on momentum.
parallel-to-point focus

(We are actually considering)

thick solenoidal lenses

Random momentum spread blows up spot radius — can't fix with SLC type scheme using sextupoles

→ Must have sufficiently cold beam before compression

Systematic tilt moves focal spot — blows up the mean spot radius at fixed position

But systematic tilt can be compensated by time dependent upstream lenses (TDL)

\[(\text{spot motion from tilt}) + (\text{spot motion from TDL}) = 0\]
Focussing Concept (Drawing by GL)

Accelerator Drift

Strong final focus

Target

Time dependent lens for finite AP

Make ions with AP > 0 enter final focus with a finite converging angle

One period of envelope oscillation from pulsed lens to final focus
There is a connection between beam radius in drift and drift distance from pulsed lens to final focus!!

\[
\frac{d^2 \sigma}{d \tau^2} = - \left[ \frac{B_d}{z(B_0)} \right] \sigma + \frac{c^2}{\sigma^2}
\]

\(B_d = \text{drift field}\)

\(z(B_0) = \beta \gamma \frac{M_e}{q_e} = \text{ion rigidity}\)

\(\sigma = \text{beam radius}\)

\[
equilibrium ~ \sigma = \sqrt{\frac{z(B_0) c}{B_d}} \approx \sqrt{\frac{M_e e}{q_e B_0}}
\]

\[
envelope ~ oscillation:
\frac{d^2 \sigma}{d \tau^2} = - \left[ \frac{B_d}{z(B_0)} \right] \sigma - \frac{3 c^2}{\sigma^2} \sigma
\]

\[
\sigma = \cos (k \tau) \quad k^2 = \gamma \left[ \frac{B_d}{z(B_0)} \right] \quad (= 4 \kappa^2)
\]

Set \(k = \frac{2 \pi}{L_{\text{drift}} \overset{\text{Pulse}}{\rightarrow} \frac{1}{T_q}}\)

\[
\Rightarrow B_{\text{drift}} = k (B_0) = \frac{2 \pi (B_0)}{L_{\text{drift}}}
\]
Summary of concept:

Pulse head goes straight through
Pulse tail gets inward envelope kick and goes through one envelope oscillation

In between parts of the pulse get kicked and have less than one oscillation

For a given final strong lens find out how hard each part of pulse must be kicked to compensate focal position motion

This is not a linear dependence on ∆P

→ Find how the pulsed field must be ramped and see if it is possible
NDCX II Example

Ion = Na⁺⁹ (A = 23)

\[ E_{\text{read}} = 20 \text{ meV} \]
\[ E_{\text{tail}} = 24 \text{ meV} \]
\[ L_n = 2.3 \times 10^{-6} \text{ m-n} \]
\[ L_{\text{drift}} = 4.0 \text{ m} \]

\[ B_{\text{drift}} = 1.59 \text{ T} \]
\[ a_{\text{drift}} = 0.0079 \text{ m} \]
\[ B_{\text{final focus}} = 15 \text{ T} \]

Pulse Magnet length = 0.2 m

Spot radius of head = 0.0031 m

Cone Half angle of FF = 15°
envelope radius

envelope slope
Pulse Tail NDCX II

Uncompensated Envelope
Pulse Tail - NDCX II

Envelope radius

Compensated Envelope

Envelope slope
**NDCX-II Pulsed Fields**

<table>
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<tr>
<th>% of AP</th>
<th>Bpulsed</th>
<th>@spot</th>
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<tr>
<td>0</td>
<td>0 (T)</td>
<td>.000 309 (cm)</td>
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<tr>
<td>20</td>
<td>1.777</td>
<td>.000 369</td>
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<tr>
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<tr>
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<td>.000 811</td>
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</tbody>
</table>

We have compensated spot position.

If we minimize spot radius at target, we can get a smaller spot!

- An increase in beam radius entering final focus can decrease the spot more than the shift of focus increases it.
Driver Example

$I_{\text{on}} = K^{+19} \quad (A=39)$

$E_{\text{head}} = 611 \text{ MeV} \quad \gamma \approx \text{Tilt} = 0.1$

$E_{\text{tail}} = 739 \text{ MeV}$

$E_n = 5 \times 10^{-6} \text{ m-}r$

$L_{\text{drift}} = 400 \text{ m}$

$B_{\text{drift}} = 1.0203 \text{ T}$

$q_{\text{drift}} = 0.056 \text{ m}$

$B_{\text{final focus}} = 0.3 \text{ T}$

Pulsed magnet = 1.0 m

Spot radius of head = 0.00379 m

Cone half angle of FF = 0.006 radian
Uncompensated Envelope

envelope radius

envelope slope

envelope radius
Pulse Tail - Driver

envelope radius

Compensated Envelope

envelope slope
Note we need small cone angle to prevent very large amplitude envelope oscillations.

**Driver Pulsed Fields**

<table>
<thead>
<tr>
<th>% AP</th>
<th>B_{pulsed}</th>
<th>d_{spot}</th>
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<td>0 (T)</td>
<td>0.00379 (m)</td>
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