Solenoid Transport for Heavy Ion Fusion

by

Edward Lee

Lawrence Berkeley National Laboratory

Presented at
The Fifteenth International Symposium
on
Heavy Ion Inertial Fusion

Princeton, New Jersey
June 7-11, 2004

Solenoid Topics

Why consider solenoids now?

Basic solenoid features

Simple field models

Equilibrium (matched) dynamics

Envelope stability

Applications and issues

Why Consider Solenoids for HIF Now?

- Solenoids transport higher line charge density beams at low kinetic energy than quadrupoles:

$$T \lesssim 16\,MeV \qquad C_s^+$$

$$T \lesssim 40\,MeV \qquad N_e^+$$

- Solenoids are essential for several high current source concepts
- Solenoids may aid neutralized drift compression
- Final Focus for neutralized, highly stripped beams is simplified
- Transverse dynamics in vacuum transport is more stable and has less "flutter" than with quadrupoles and electron production from pipe walls may be suppressed

These Solenoid Features Suggest A Modular Driver Architecture

- $N \sim 24$ parallel separate accelerators in two opposed clusters

- Moderate mass ions are accelerated to relatively low energies (e.g. 200-300 MeV N_e^+)

- High line charge density is transported by solenoids during acceleration $\left(\lambda \sim 10 - 100\ \mu C/m\right)$

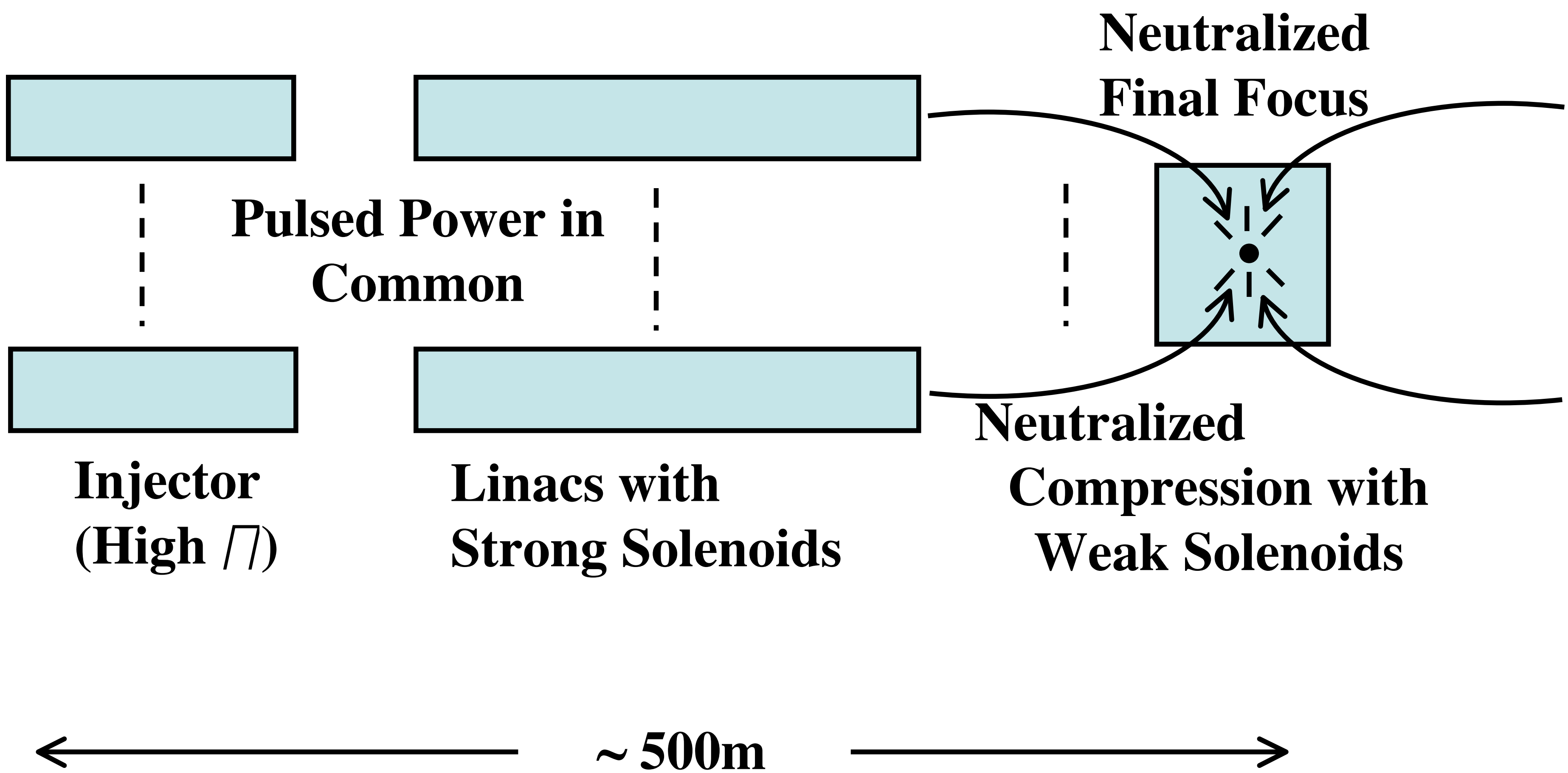
- Final Compression, Final Focus and Chamber Transport are neutralized to accommodate very high final line change densities

Modularity allows an attractive development path

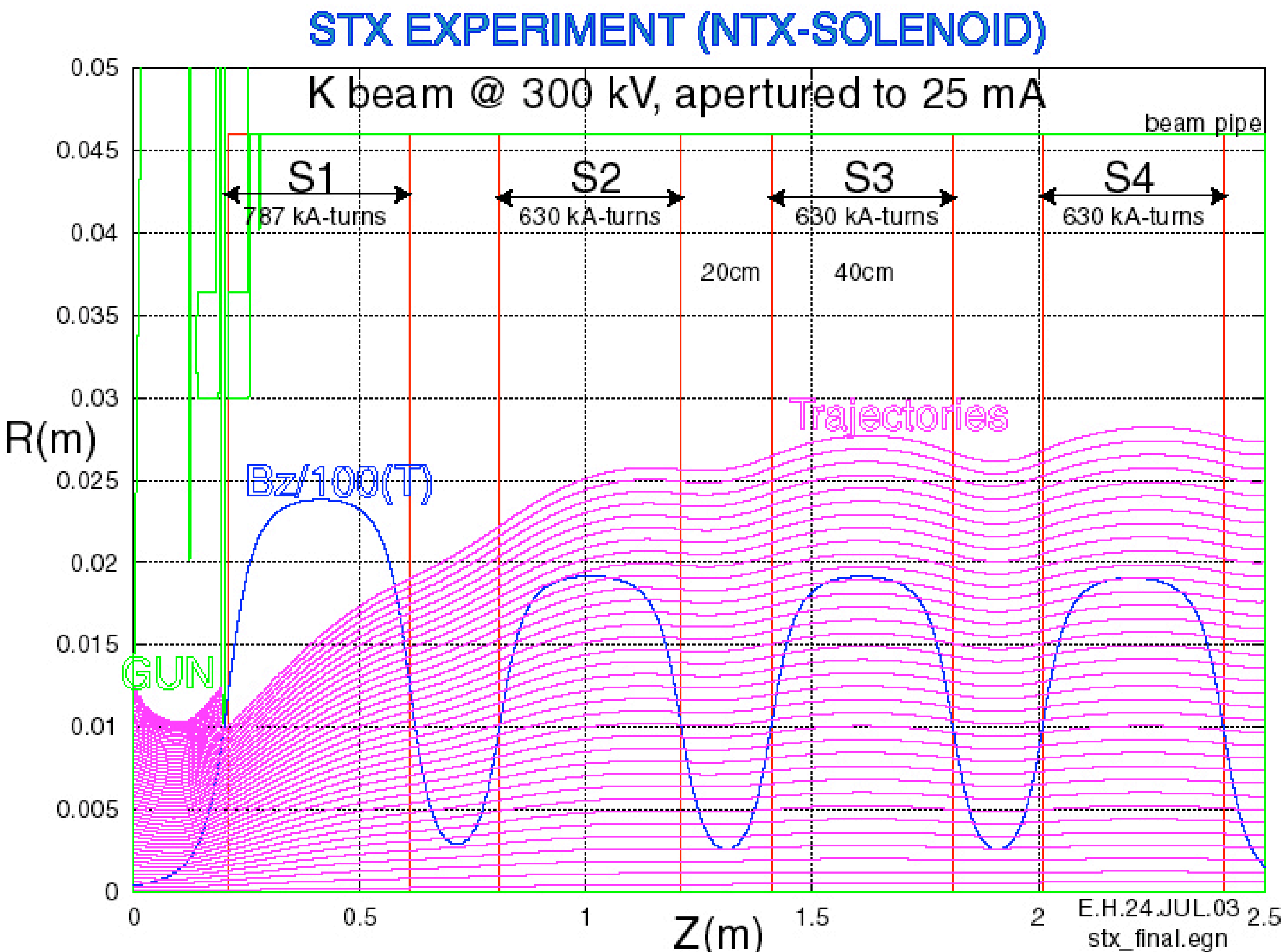
Related Talks at this Symposium

Tu I-11	R. Davidson	Instability
Tu I-12	E. Startsev	Instability
Tu I-13	J. Kwan	Ion Source
Tu I-15	C. Celata	Scientific Issues
W P-14	I. Kagonowich, et. al.	Neutralization
W P-15	D. Rose, et. al.	Two Stream
Th P-06	D. Welch	Neutralization
Th P-07	A. Bret, et. al.	Filamentation
Th P-13	E. Henestroza, et. al.	High [illegible] beam
Th P-20	S. Lund, et. al.	Emittance Growth
F I-01	S. Yu	Point Designs
F I-05	W. Meier	Modular vs Multibeam
F I-06	M. Leitner	IBX Option

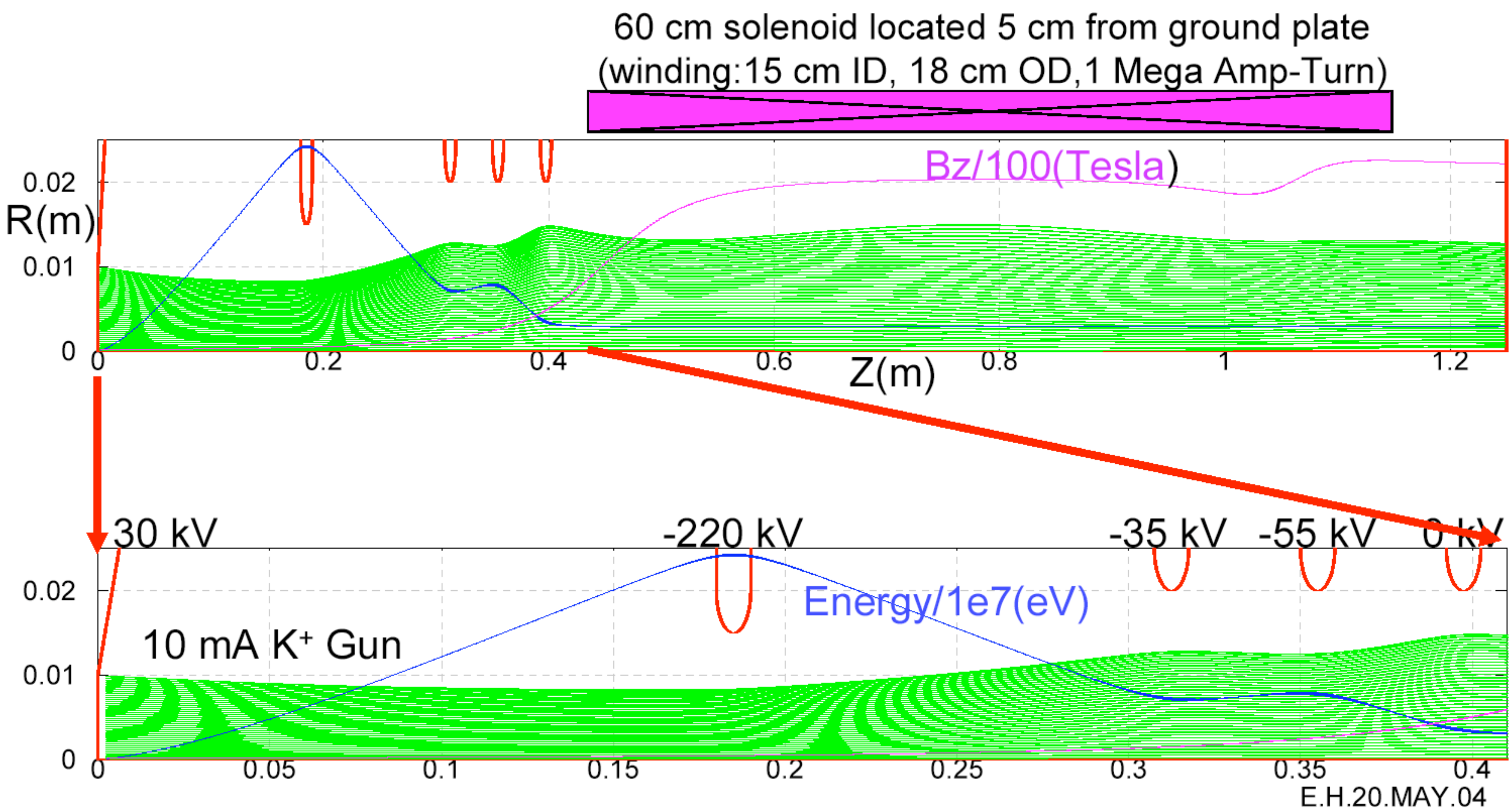
N ∏ 24 Short Linacs



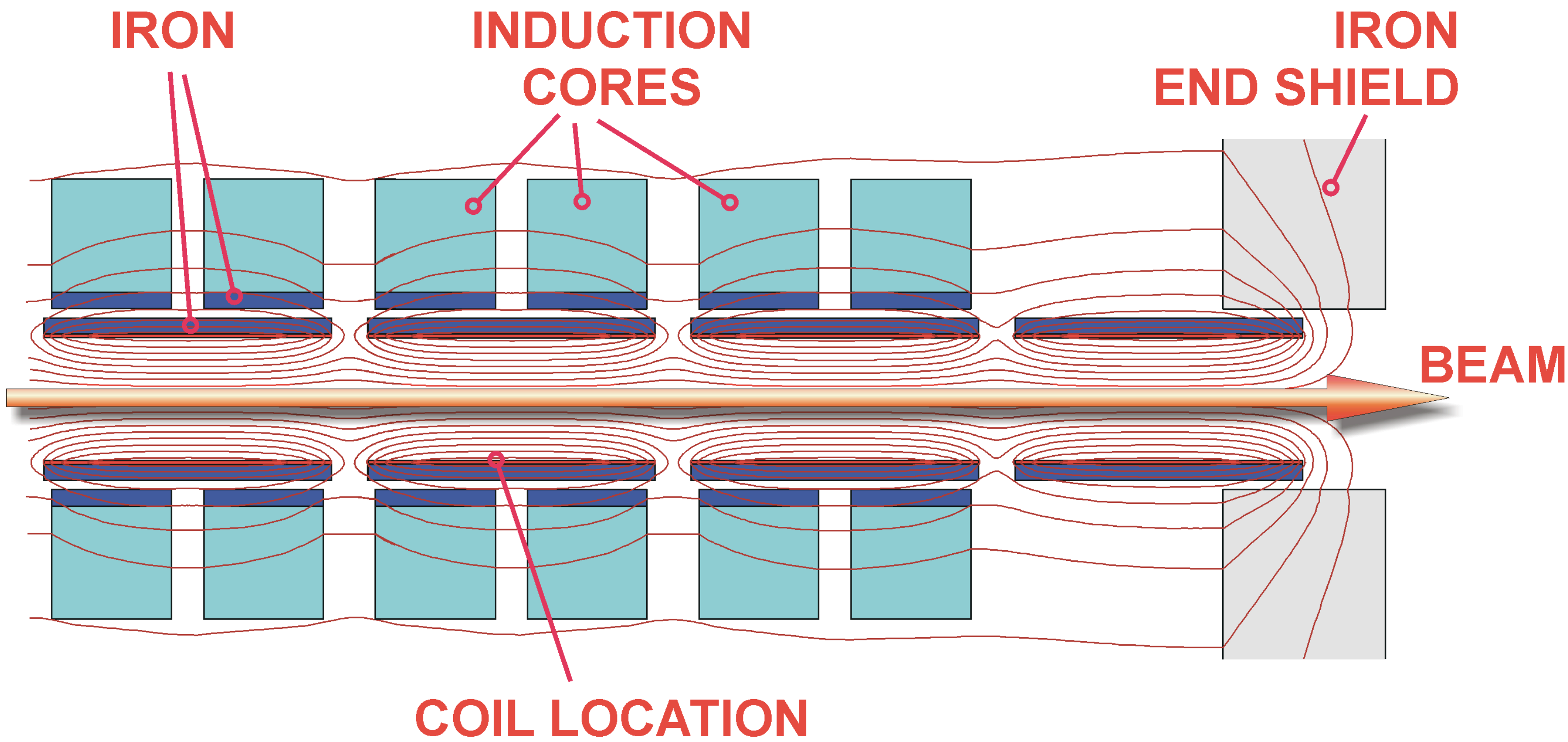
SOLENOIDAL TRANSPORT EXPERIMENT



ACCEL-DECEL INJECTOR (NDCX-1)
10 mA K^+ beam decelerated to 30 keV



Periodic Solenoid Layout



Basic Solenoid Transport Features

Transportable line charge density:

$$\lambda \simeq \frac{\pi\epsilon_0}{2}\frac{qe}{M}\overline{B_z^2}a^2 = \left(\frac{66.5\,\mu C}{m}\right)\left(\frac{20q}{A}\right)\overline{B_z^2}a^2$$

- **Use large** $\overline{B_z^2}$ $\left(\sim 50T^2\right)$
- **Use large apertures** $\left(R \gtrsim .1m\right)$
- **Use low mass**

Do not reverse B_z in a linac:

Reduces B_z^2

Return flux into cores

Increased aberrations

Increased envelope flutter

Path for electrons into beam

Basic Solenoid Features - Cont.

Return flux:

- **Cancel it among parallel linacs with opposed fields**
- **Design system ends to minimize asymmetric cross talk among linacs**

Variation in $\square_z(z)$ is caused by acceleration gaps

Periodic $\square_z(z) = \square_z(z + P)$

- **Allows simple matched envelope**
- **Minimizes effects of aberrations**
- P **must be small enough for stability**
- P **must be large enough to obtain desired** $\overline{B_z^2}$

Wire current $J_\square(r, z)$**: pair windings to cancel unwanted components**

Basic Solenoid Features (cont.)

B_z jumps across wire layer:

$$\Delta B_z = \mu_0 K \quad | \; | \quad 800\, kA/m \text{ per Tesla}$$

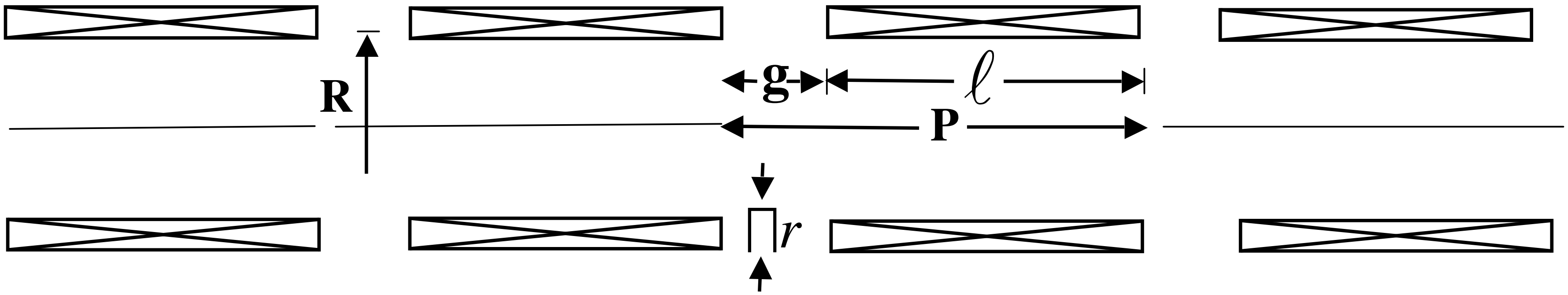
High fields are produced by a thin layer of superconducting cable (Cu stabilized).

$6T:$	$\Delta r \geq 6mm$	$NbTi$	$(800\, A/mm^2)$
$10T:$	$\Delta r \geq 16mm$	$NbSn$	$(500\, A/mm^2)$

A thicker wire layer may be desirable to avoid large fields at magnet ends

Permeable steel collar to control stray flux

Simple Field Calculations



Thin current layer centered at r=R:

$$K(z) = J_\theta \Delta r$$

On axis field:

$$B_0(z) = \frac{\mu_0 R^2}{2} \int_{-\infty}^{+\infty} \frac{dz' \, K(z')}{\left[(z - z')^2 + R^2\right]^{3/2}}$$

$$B_z = B_0 - \frac{B_0'' r^2}{4} + \frac{B_0'''' r^4}{64} - \ldots$$

$$B_r = -\underbrace{\frac{B_0' r}{2}}_{\text{Linear Part}} + \underbrace{\frac{B_0''' r^3}{16} - \frac{B_0''''' r^5}{384}}_{\text{Aberrations}} + \ldots$$

off axis (r<R)

Simple Fields (cont.)

Semi-infinite layer:

$$\square_0(z) = \frac{\mu_0 K}{2}\left[1 - \frac{z}{\sqrt{z^2 + R^2}}\right]$$

Build useful design fields from this case.

Lens of length ℓ :

$$\square_0^{Lens} = \frac{\mu_0 K}{2}\left[\frac{\left(z + \ell/2\right)}{\sqrt{\left(z + \ell/2\right)^2 + R^2}} - \frac{\left(z - \ell/2\right)}{\sqrt{\left(z - \ell/2\right) + R^2}}\right]$$

Lattice:

$$\square_0 = \sum_i \square_0^{Lens}(z - Pi)$$

An Ion is Focused by the Interaction of Its Azimuthal Velocity with Bz

$$F_r = qe(E_r + v_\theta B_z)$$

$$F_\theta = -qe B_z v_r$$

- **Azimuthal velocity v_θ is impressed on an ion when it passes through the fringe field.**
- **A beam <u>spins</u> in a cold equilibrium with space charge field E_r balanced by Bz (Brillouin flow).**
- **This is not like a magnetized plasma or most non-neutral plasma experiments.**
- **Dynamics are simplified in the Larmor frame (rotates at $\omega = -\omega_c/2$)**

Linear Dynamics – Larmor Frame

In the rotating frame

$$\frac{d^2 \underset{\sim}{r}}{dt^2} = -\frac{\Omega_c^2}{4}\underset{\sim}{r} + \frac{qe}{M}\underset{\sim}{E}_{\perp}$$

$$\frac{d^2 z}{dt^2} = \frac{dv}{dt} = \frac{qe}{M}E_z$$

– Basis for envelope theory –

B_o (z) is absorbed into Ω_c, B_r disappears

E_z is averaged field from gaps

E_r is from space charge and gaps

Axisymmetry $\rightarrow$ conserved canonical angular momentum

$$P_\theta = r\left(Mv_\theta + qeA_\theta\right) \cong r\left[Mv_\theta + \frac{qeB_0 r}{2}\right]$$

An Axisymmetric Envelope Equation is Derived from the Linearized Particle Equations

$$\frac{d^2a}{dz^2} = -\frac{k_c^2 a}{4} + \frac{Q}{a} + \frac{\varepsilon^2 + 4L^2}{a^3} - \frac{1}{v}\frac{dv}{dz}\frac{da}{dz} - \frac{1}{4v^2}\frac{d^2v^2}{dz^2}a$$

$a =$ **beam edge radius**

$v =$ **longitudinal velocity**

$k_c = \omega_c / v$

$Q = \dfrac{\lambda}{4\pi\varepsilon_0}\dfrac{2qe}{Mv^2}$ **= perveance**

$\varepsilon =$ **edge emittance (unnormalized)**

$L = \overline{P_\theta} / Mv$

Note that emittance and angular momentum are equivalent in effect. Try to avoid generating them!

Simple Brillouin Flow Gives the Maximum Transportable Line Charge Density

$$0 = \frac{d^2 a}{dz^2} = -\frac{k_c^2}{4} a + \frac{Q}{a}$$

Equilibrium from the envelope equation:

$$\lambda = \frac{\pi\epsilon_0}{2}\frac{qe}{M} B_z^2 a^2 = \left(66.5\,\frac{\mu C}{m}\right)\left(\frac{20}{A/q}\right) B_z^2 a^2$$

Looks great for large $B_z a \sim 1.0\ T\cdot m$

Looks terrible for small $B_z a \lesssim .1\ T\cdot m$

Note: velocity does not appear here, but for <u>periodic</u> B_z the velocity must be considered.

In A Linac We Want to Be Close To Matched (Periodic) Brillouin Flow

Consider $k_c(z) = k_0\left[1+\varepsilon\cos\left(2\pi z/P\right)\right]$

$$\frac{d^2a}{dz^2} = -\frac{k_c^2(z)}{4}a + \frac{Q}{a} \qquad , \qquad a(z) = a(z+P)$$

For $\varepsilon = 0$: $\qquad a = a_0 = 2\sqrt{Q}/k_0$

For small ε: $\qquad a = a_0\left[1 + \frac{\varepsilon\cos\left(2\pi z/P\right)}{\left(\frac{8\pi^2}{p^2k_0^2} - 1\right)} - \frac{\varepsilon^2}{4}\right.$

In a Linac We Want to Be Close To Matched (Periodic) Brillouin Flow (cont.)

$k_0P << \sqrt{8}$□□ **Normal match with very small flutter**

$k_0P >> \sqrt{8}$□□ **Reverse match (plasma-like) with large flutter**

k_0P □ $\sqrt{8}$□□ **“Trouble zone” (a<o); envelope mode in resonance with solenoid period**

Trouble Zone and Instability Are Related To Tune

Consider a single ion:

$$\frac{d^2x}{dz^2} = -\frac{k_c^2(z)}{4}x \qquad \textbf{(Larmor frame)}$$

$$x \propto \cos\left(\frac{\sqrt{\langle k_c^2\rangle}}{2}z\right)$$

$$\sigma_0 \approx \frac{\sqrt{\langle k_c^2\rangle}P}{2} \equiv \frac{k_0 P}{2} \qquad \textbf{(Undepressed Tune)}$$

- **"Trouble zone" corresponds to** $\sigma_0 \approx \sqrt{2}\pi = 255^\circ$
- **But single ion orbits are <u>parametrically</u> <u>unstable</u> in narrow bands around** $\sigma_0 = 180^\circ, 360^\circ, \ldots$
- **The cold beam envelope is unstable in a narrow band around** $\sigma_0 = \pi/\sqrt{2} = 127^\circ$

Envelope Instabilities Are Restricted To Narrow Bands In Tune Space

Simple axisymmetric mode:

$$a'' = -\frac{k_c^2(z)}{4}a + \frac{Q}{a} + \frac{\varepsilon^2}{a^3}$$

Satisfied by matched $a_m(z)$

$$a = a_m(z) + \delta a(z)$$

$$\delta a'' = -\left(\frac{k_c^2}{4} + \frac{Q}{a_m^2} + \frac{3\varepsilon^2}{a_m^4}\right)\delta a$$

$$\text{Note}\begin{cases} \sigma \simeq \varepsilon P/a_0^2 \\ \sigma_0^2 - \sigma^2 \simeq Q P^2/a_0^2 \end{cases}$$

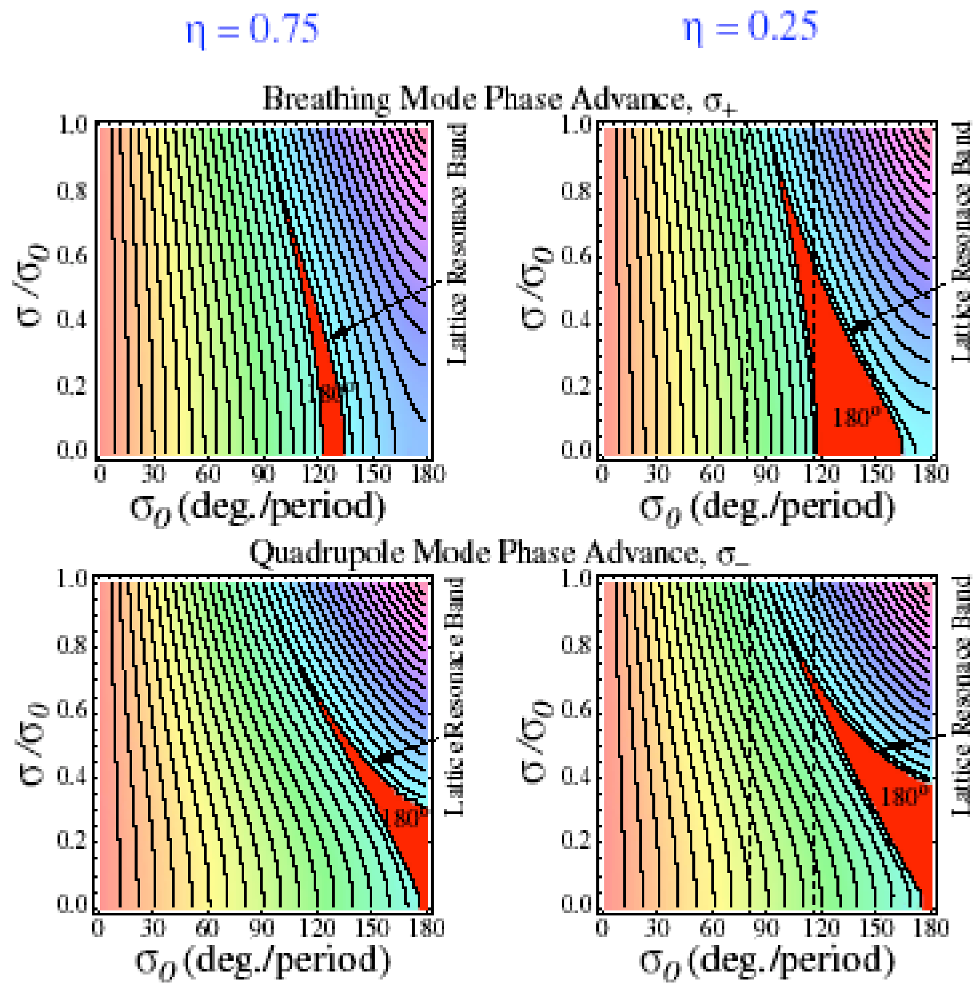
depressed tune

$$\delta a'' \simeq -\frac{1}{p^2}\left[\sigma_0^2 + \left(\sigma_0^2 - \sigma^2\right) + 3\sigma^2\right]\delta a$$

$$\delta a \propto \cos\left(\sqrt{2\left(\sigma_0^2 + \sigma^2\right)}\, z/P\right)$$

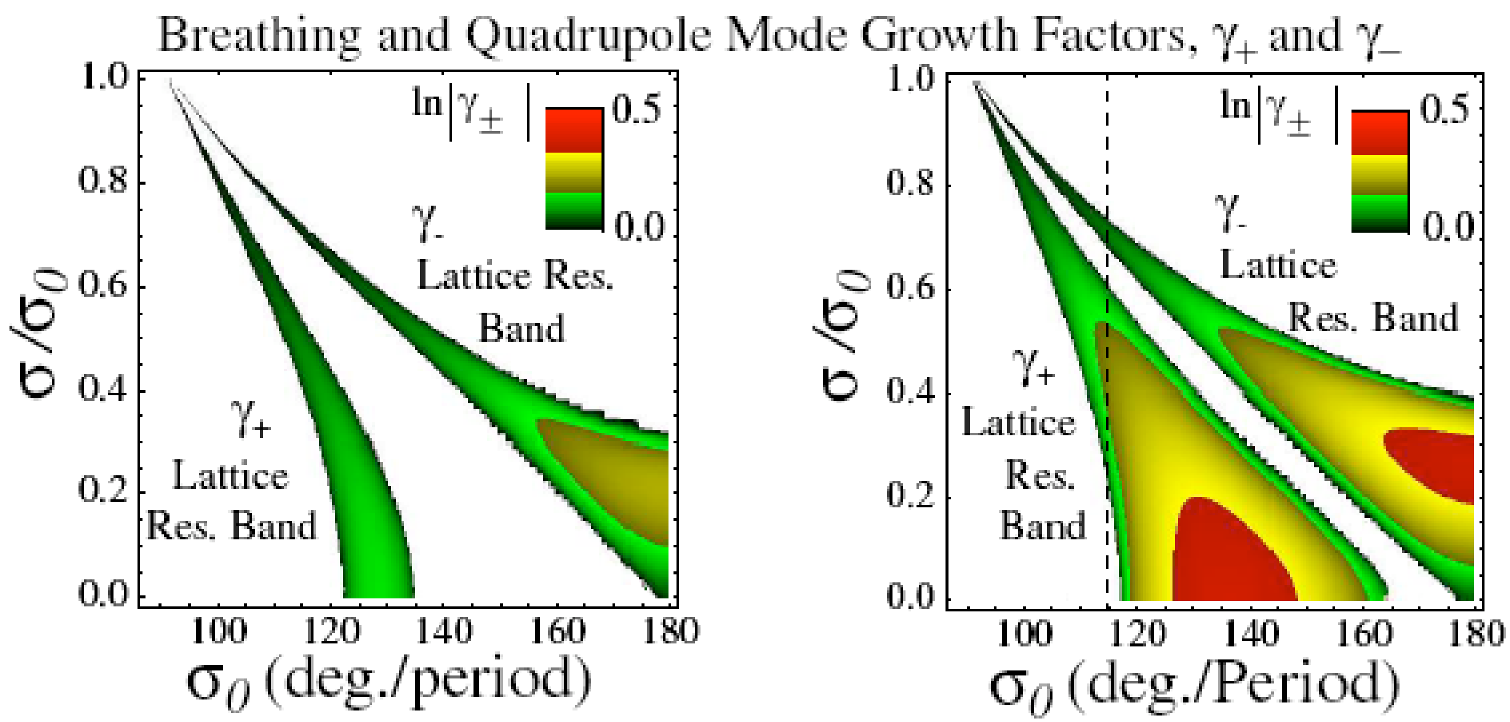
Unstable in band around $\sigma_0^2 + \sigma^2 = \left(\frac{\pi}{\sqrt{2}}\right)^2 = \left(127^\circ\right)^2$

Solenoid Focusing - parametric plots of breathing and quadrupole envelope mode phase advances for two occupancies



Solenoid Focusing - parametric plots of breathing and quadrupole envelope mode instability bands for two occupancies

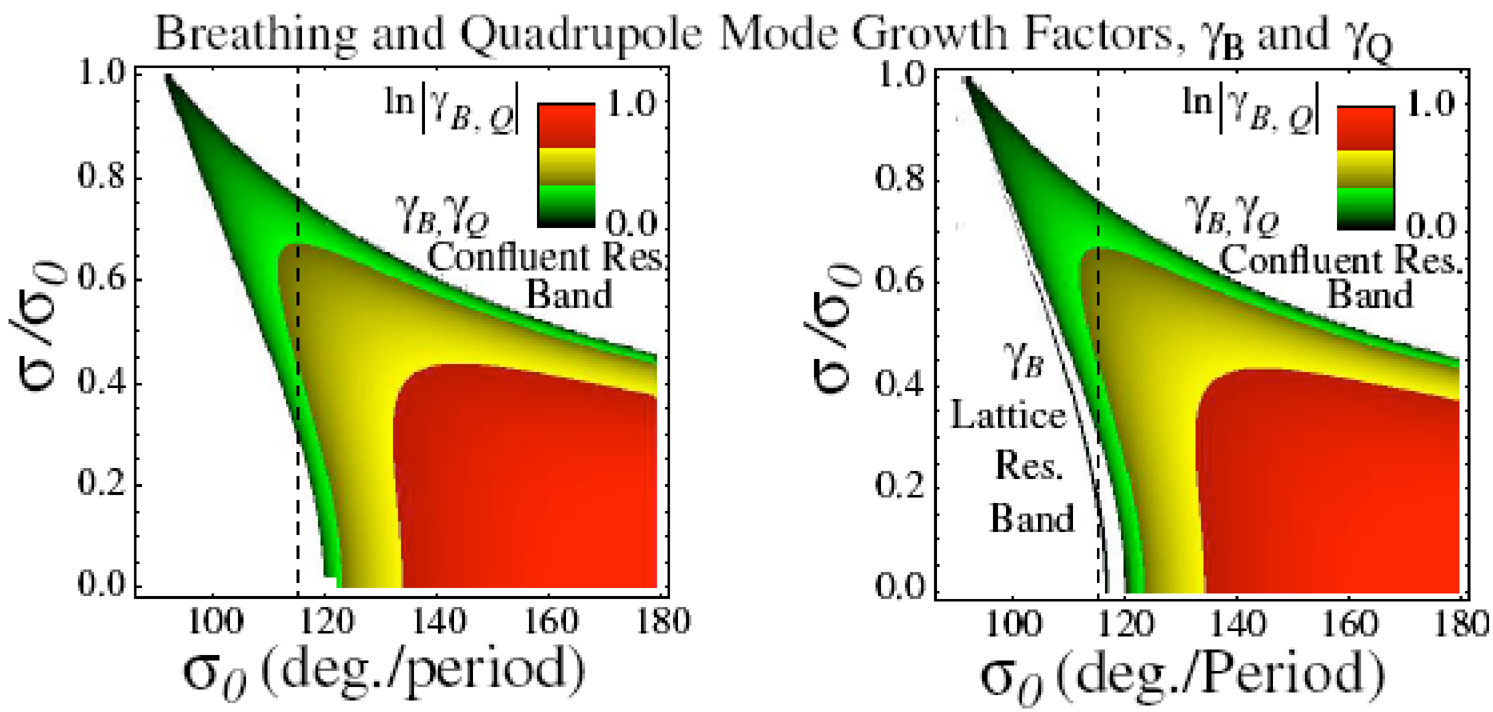
$\eta = 0.75$ $\eta = 0.25$



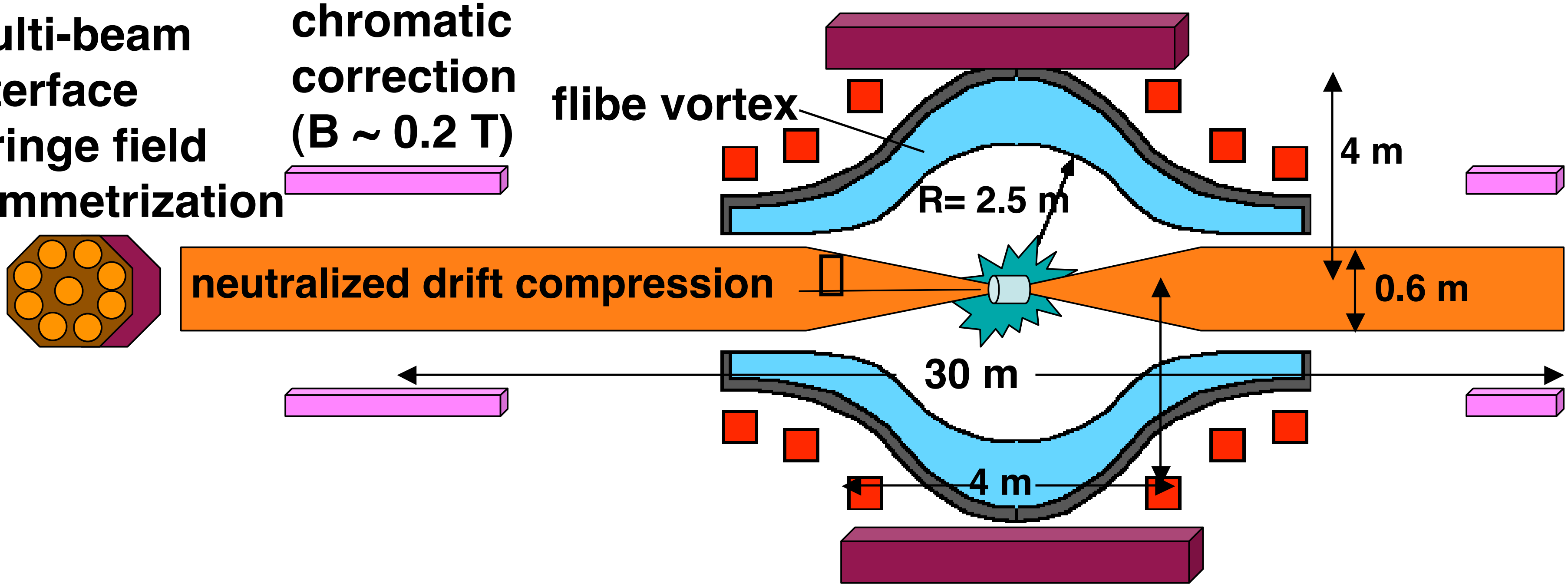
Quadrupole Focusing - parametric plots of breathing and quadrupole mode instability bands for FODO and syncopated lattices

$\eta = 0.6949,\ \alpha = 1/2$ (FODO)

$\eta = 0.6949,\ \alpha = 0.1$



A solenoid-based final focus system for a modular driver has attractive features



Large cone angle □ ~ 100 mr produces a small spot (~ 5 mm) on target for □ ~ 4□10^{-4} m-rad
Moderate fields allow normal magnets
Highly stripped ions (200-300 MeV Ne^{+10})
Fringe field aberrations minor

Some Issues

Magnets

- keep return flux out of cores
- field sufficiently uniform in (r,z)
- cryosystems compatible with cores

Beam dynamics in accelerator

- periodicity causes instability?
- mismatch, emittance growth
- electron production, halo production, scrape off
- longitudinal and transverse instability

Diagnostics

- can they be inserted into narrow gaps between solenoids?

Some Issues continued

Injector

uniformity of plasma and
adiabatic removal of electrons and beam
expansion gas load

Neutralization

how to do it adiabatically?
two stream instability?
hose instability?

Flux Return

how can flux be cancelled and its effect minimized at neutralization zone?

Some Issues continued

<u>$P_{\perp}$ Removal</u>

quadrupole design needed

analysis of deceleration compression with $P_{\perp} = 0$

<u>Pulse Power</u>

can pulsers be shared among 24 modules?

cross talk among modules

unstable interaction with beams?

<u>Final Focus</u>

chromatic aberration, compensate?

neutrality maintain in final lens?

design for N beams needed

Electron Behavior in Solenoids is Different from that in Quadrupoles

- No trapping from transverse magnetic field
- Strong sweeping by gap electric fields
- Possible protection of walls from beam halo by strong B_z
- Electrons trapped by beam potential are not removed by transverse magnetic field
- A solenoid can suppress avalanching in accelerating gaps and injector

- Much Research Needed Here -

Nonlinearity From Solenoid Fringe Field

$$B_z \approx B_0(z) - B_0''(z)\frac{r^2}{4}$$

- **Extra inwards kick in gaps $\sim$ r^3**

•For <u>matched</u> Brillouin flow this induces periodic corrections to $\square, \square, \ldots$

What happens to a mismatched or accelerated beam?

-Unknown at present
-Similar situation for quadrupole transport

How Well Can We Remove Cononical Angular Momentum?

- Finite $\square_{\square}$ is produce if anode feels the solenoidal field

- $\square_{\square} \longrightarrow$ extra spin; acts like emittance

- Quadrupoles violate conservation of $\square_{\square}$

Can $\square_{\square}$ be effectively removed by the downstream application of rotated or twisted quadrupole fields?

Neutralized Transport Issues

A weak solenoid is desired to confine and guide the neutralized beam

- **B_z may be modified by electrons swept by ion beam**
- **Vertical drift if pipe bent**
- **Two steam instability - so far not seen in simulation**
- **How to transition from accelerator?**
- **Transverse beam / electron modes may be supressed by B_z**

- Many Issues Unique to Solenoid Option -

Alignment / Corkscrew / Beam Breakup Mode

- Well-know set of coupled issues for electron induction linacs

- Predictions for Ions in solenoids needed

- Quadrupole transport of heavy ions was previously shown to produce very low Beam Break-up Instability growth

- What corrections / steering are effective in the HIF case?

- Since this is an issue in e^- induction linacs we must be prepared