Beam Breakup and the Conceptual Design of Guided and Unguided Accelerators

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Beam breakup mode

- Off axis beam entering accelerator gap excites dipole ($M=1$) TM mode
- Mode has an E_z that can extract energy from the beam
- Mode has a transverse $\vec{B}$ that gives the beam an oscillating transverse impulse
- Oscillating transverse impulse develops into transverse displacement in B_z field between gaps
- Beam enters next gap with a larger displacement than at previous gap—thus displacement grows

The beam break-up instability

Laser guiding option

- **Advantages**
 - **Strong focusing**
 - **Anharmonic focusing**
 - **Demonstrated suppression of BBU**
- **Issues**
 - **Brightness preservation**
 - **Channel formation at high rep rate**
 - **Development of high rep rate laser**

Quadrupole channel option

- **Advantages**
 - **Strong focusing**
 - **No rep rate problems**
 - **Time invariant focusing**
- **Issues**
 - **Engineering**

I PHASE MIX DAMPING OF BEAM OFF-AXIS DISPLACEMENTS

- Consider a line charge as the focusing field for beam electrons

- Beam electrons far off axis will oscillate slower than electrons near axis

- This "orbital phase mixing" changes coherent displacements into random motion (entropy), or increased emittance

60-B-6

I PHASE MIX DAMPING BY LASER PRE-IONIZED CHANNEL

- Future ETA experiments (summer '83) will produce the anharmonic potential by pre-ionizing a preferred channel in a very low pressure gas (~ 1 micron)

A pre-ionized channel is formed within a circular beam transport pipe

The electron beam ejects secondary electrons and forms a preferred axis ion channel (strongly anharmonic potential)

The off-axis beam is centered and beam oscillations are phase mixed damped

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Without laser guiding (using conventional magnetic solenoids) growth of transverse beam motion degrades ATA beam

- Oscilloscope traces from small magnetic induction loops located along the accelerator show growth of transverse beam motion that results from the beam coupling to a resonant (800MHz) transverse mode of the accelerator modules (all traces horizontal 10nS/div, vertical arbitrary)

With electrostatic transport transverse beam motion within ATA is stabilized and suppressed

- Oscilloscope traces on left are from magnetic induction loops at different accelerator locations. Data from one beam pulse is shown in each column. The two columns indicate reproducibility. The oscilloscope trace in the bottom right is accelerator output current (2kA/div. 10 nS/div.).

Laser guiding parameters

Laser

- Wavelength 249 nm (KrF)
- Pulsewidth 28 ns FWHM
- Energy 0.4 J
- Spatial profile 20×12 mm, 12×7 mm
- Divergence $50 \mu\text{r}$
- Centroid jitter $100 \mu\text{r}$
- Repetition rate 0.2 - 1 Hz
- Timing ~ 150 ns before e-beam

Benzene

- Pressure 0.1 - 0.5 μm
- Flow rate 1 - 6 scc/min
- Replenishment rate 0.3 - 2 Hz
- Ionization fraction 1 - 3%

Difference in ATA operation when beam transport and focusing is accomplished by conventional solenoids versus laser guiding

Quadrupole channels

$$B_x = gy \phi(z)$$

$$B_y = gx \phi(z)$$

g is the "gradient"

Equations of motion:

$$\frac{\partial^2 y}{\partial z^2} + \frac{eg}{\gamma mc^2} y \phi(z) = 0$$

$$\frac{\partial^2 x}{\partial z^2} - \frac{eg}{\gamma mc^2} x \phi(z) = 0$$

For a periodic channel fourier analyze $\phi(z)$

Alternating singlets

FODO

$$\phi(z) = \frac{4}{\pi} \sum_{m=0}^{\infty} \frac{\sin \frac{\pi w(2m+1)}{L} \cos \frac{2\pi z}{L} (2m+1)}{2m+1}$$

Periodic doublets

FDOFD

$$\phi(z) = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{\left[\cos \frac{2\pi n}{L} \left(w + \frac{d}{2} \right) - \cos \frac{\pi n d}{2L} \right]}{n} \sin \frac{2\pi n z}{L}$$

$$\begin{aligned} y(z) &= a \cos(\mu x + \theta) \left[1 + \epsilon \sum_{n=1}^{\infty} \frac{A_n}{h^2} \cos nz \right] \\ &= a \cos(k_{\beta} z + \theta) \left[1 + \frac{k^2}{k_o^2} \sum_{n=1}^{\infty} \frac{A_n}{n^2} \cos \frac{2\pi n z}{L} \right] \end{aligned}$$

$$k_{\beta} = \mu \epsilon k_o = \frac{\mu k^2}{k_o} \quad \mu^2 = \frac{1}{2} \sum_{n=1}^{\infty} \frac{A_n^2}{n^2}$$

$$k_{\beta} = \frac{\mu}{2\pi} \frac{egL}{\gamma mc^2}$$

For an FODO lattice

$$k_{\beta} = \frac{\sqrt{2}}{\pi^2} \sin \frac{\pi w}{L} \left[\frac{egL}{\gamma mc^2} \right]$$

Continuous BBU model

$$\left[\frac{\partial^2}{\partial \tau^2} + \frac{\omega_o}{Q} \frac{\partial}{\partial \tau} + \omega_o^2 \right] \Delta = \frac{\omega_o^2 G \xi}{\gamma}$$

$$\frac{\partial}{\partial z} \left[\gamma \frac{\partial \xi}{\partial z} \right] + \gamma k_\beta^2 \xi = \gamma \Delta$$

ω_o = Angular frequency of mode

ξ = Beam centroid displacement

L_g = Average gap separation

$$\Delta = \frac{1}{L_g} \left[\frac{\Delta p_\perp}{p_z} \right]$$

$$G = \frac{\omega_o (z_\perp / Q) l}{L_g l_o}$$

Solve model equations by Fourier transform in τ

$$\frac{\partial^2 \tilde{\Psi}}{\partial z^2} + \left[k_\beta^2 - \frac{h(\omega)}{\gamma} \right] \tilde{\Psi} \cong 0$$

$$\xi(z, \omega) = \frac{\tilde{\Psi}(z, \omega)}{\sqrt{\gamma}}$$

$$h(\omega) = \frac{\omega_o^2 G}{\omega_o^2 - \omega^2 + \frac{i\omega\omega_o}{Q}}$$

For resonant excitation (steady state gain)

$$\xi \sim \exp \left[-i \int_0^z \left[k_\beta^2 + \frac{iGQ}{\gamma} \right]^{1/2} dz' \right]$$

For strong focusing growth is given by

$$\xi \sim \exp \left[GQ \int_0^z \frac{dz'}{2k_\beta \gamma} \right]$$

For $\gamma(z) = \gamma_0 + \lambda z$

$$k_\beta = \frac{k}{\gamma} \quad \xi \sim \exp \frac{GQ(\gamma - \gamma_0)}{2k\lambda}$$

$$k_\beta = \frac{k}{\sqrt{\gamma}} \quad \xi \sim \exp \frac{GQ(\sqrt{\gamma} - \sqrt{\gamma_0})}{2k\lambda}$$

$$k_\beta = k \quad \xi \sim \exp \frac{GQ \ln(\gamma/\gamma_0)}{2k\lambda}$$

ATA 250 kV induction cell

Cavity model

Response for ATA cavity

$$\omega_0 Z_{\perp} = - \frac{4w}{b^2} \text{Im} P_1(\omega)$$

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Results of cavity model

Minimum of the negative imaginary part of the cavity response as a function of gap width w over pipe radius b from the cavity model. The quantity $\omega_o Z_{\perp}$ is the critical parameter which determines growth of the beam breakup instability

Proposed accelerator output beam specifications

Current = 3 kA

Energy = 300 MeV

Brightness = 2×10^6

Emittance = 0.055 rad-cm, edge

Pulse length > 50 ns

Rep rate 100 Hz continuous

5 kHz for 30 seconds

Beam $\Delta X \lesssim 0.01$ cm

Conceptual point design

- Cell coupling (all cells)

$$\text{I.D.} = 5.875 \text{ in}$$

$$b = 7.48 \text{ cm}$$

$$\text{Gap} = 0.25 \text{ in}$$

$$w = 0.635 \text{ cm}$$

$$\omega_o Z_{\perp} = 2X \frac{4w}{b^2} (0.6) = 0.055 \text{ cm}^{-1}$$

$$(\text{ATA value} = 0.27 \text{ cm}^{-1})$$

- Low gamma section: $\gamma_o = 5$ to $\gamma_T = 50$ solenoids

- Tune

$$\begin{array}{l} B_z = 1 \text{ kG at } \gamma_o = 5 \\ \quad = 3 \text{ kG at } \gamma_F = 15 \\ \quad = 3 \text{ kG flat up to } \gamma_T = 50 \end{array} \left. \begin{array}{l} \text{Linearly} \\ \text{ramped} \end{array} \right\}$$

$$\xi = \frac{\xi_o}{2} \exp \left[\frac{1}{I_o} \frac{mc^2}{\Delta E g} \frac{\omega_o Z_{\perp}}{K_{os}} \left\{ \gamma_T - \gamma_F + \gamma_F \frac{\ln \gamma_F}{\gamma_o} \right\} \right]$$

$$K_{os} = \frac{eB}{mc^2}$$

$$\boxed{\xi/\xi_o = 1.3}$$

- Intermediate γ : $\gamma_o = 50$ to $\gamma_F = 200$

Doublets, FDOFO

Tune: $g = 0.29$ kg/cm ($B_{\text{pole}} = 2.2$ kg) at γ_o

$g = 1.16$ kg/cm ($B_{\text{pole}} = 8.8$ kg) at γ_F

Linearly ramped to give $\lambda_\beta = 5.0$ meters

$$\xi = \frac{\xi_o}{2} \left(\frac{\gamma_F}{\gamma_o} \right)^{\frac{1}{2} \left[\frac{1}{I_o} \frac{\omega_o z_\perp}{k_p} \frac{mc^2}{\Delta E_g} - 1 \right]}$$

$$\xi/\xi_o = 1.5$$

$$f = 1.35$$

- High γ section: $\gamma_o = 200$ to $\gamma_F = 588$

Singlets, FODO . . .

Tune: $g = 0.44$ kg/cm ($B_{\text{pole}} = 3.3$ kg) at γ_o

$g = 1.28$ kg/cm ($B_{\text{pole}} = 9.75$ kg) at γ_F

Linearly ramped to give $\lambda_\beta = 7.0$ meters

$$\xi/\xi_o = 2.1$$

$$f \cong 1.7$$

**HIGH
BRIGHTNESS
TEST
STAND**
60-C 06-85 121A

**Typical Section
of
Low Gamma 10 Cell Module**

10 cell block – intermediate gamma section (25 MeV - 100 MeV)

Predicted on axis gradient profile

8 cm doublet

**Quadrupole
Magnets**

Ferrite

**Alumina
Insulator**

**HIGH
BRIGHTNESS
TEST
STAND**

4510-CB-05-1210

**Fan Out
Enclosure**

Fan Out Bus

Cell Feed

Ferrite

**Typical Section
of
High Gamma 10 Cell Module**

Predicted on axis gradient profile for 16 cm wide quadrupole