Particle simulations of collective effects in high intensity charged particle beams

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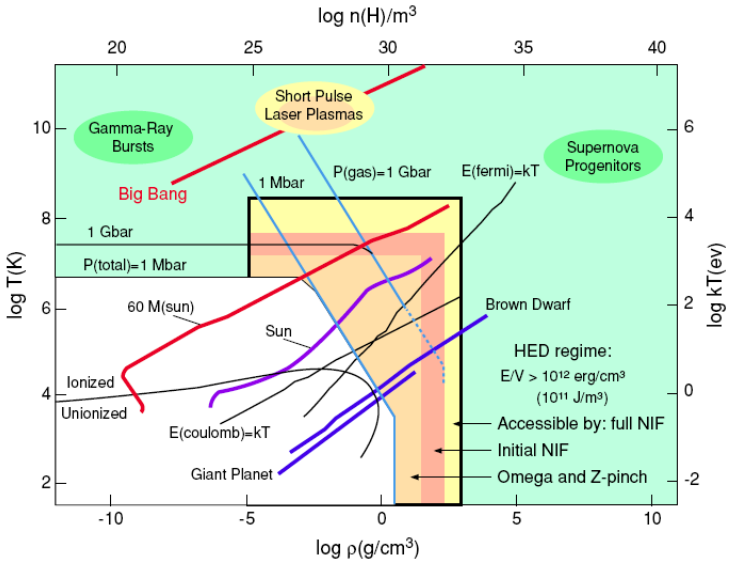
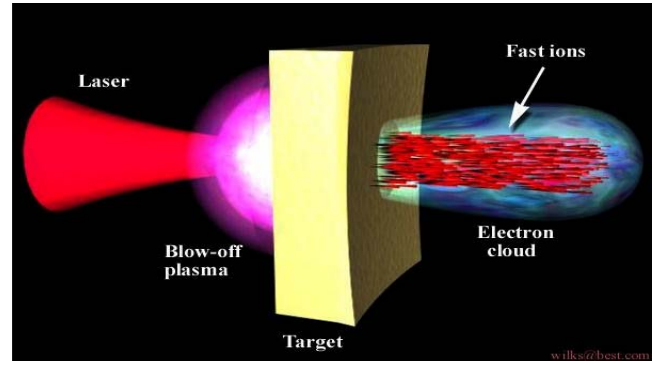
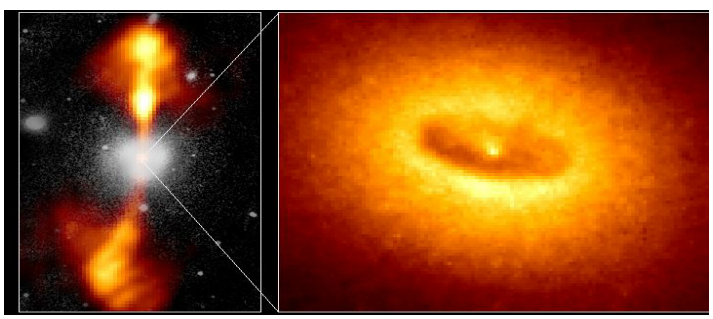
Beam physics application --- high energy density physics

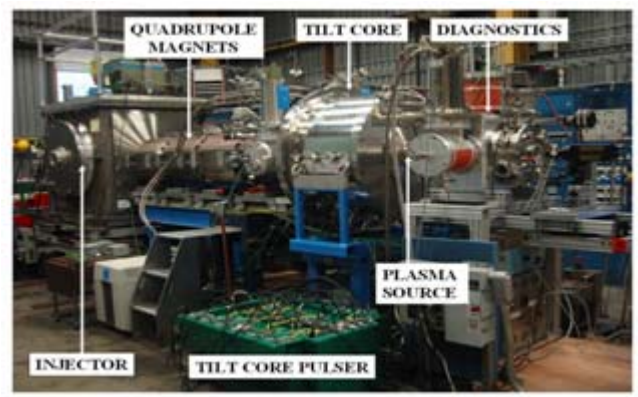




Gamma ray bursters experiment

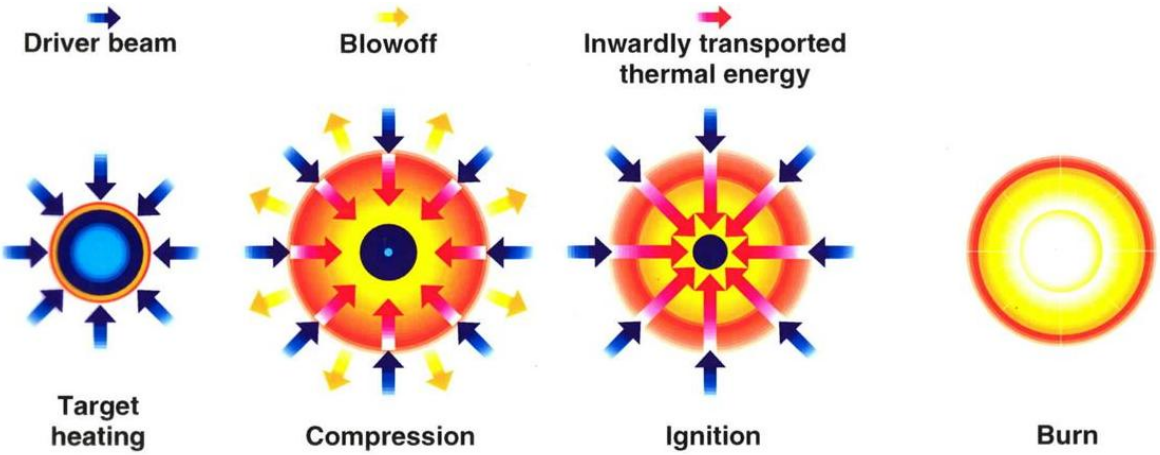


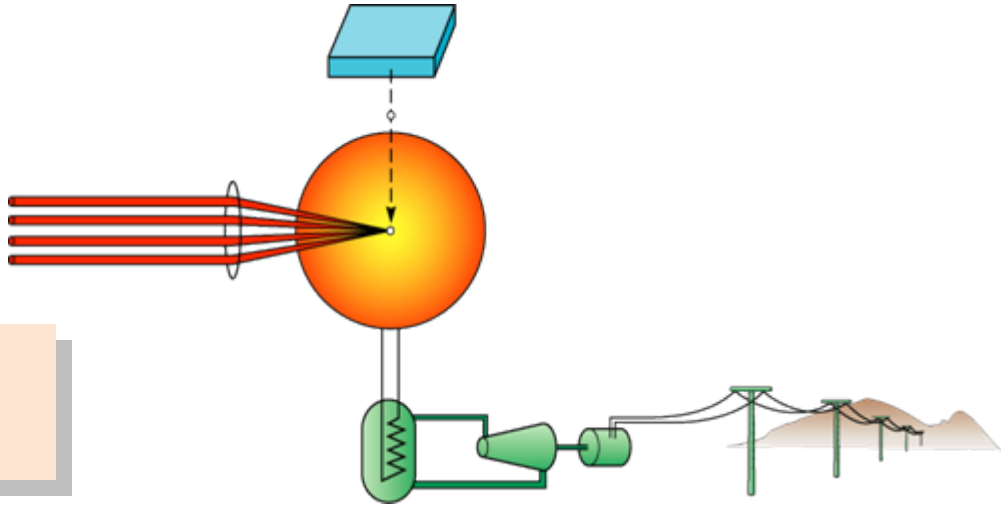
Photoionized plasmas in an accreting massive black hole



Neutralized drift compression experiment for ion beam driven HEDP

Beam physics application --- heavy ion fusion

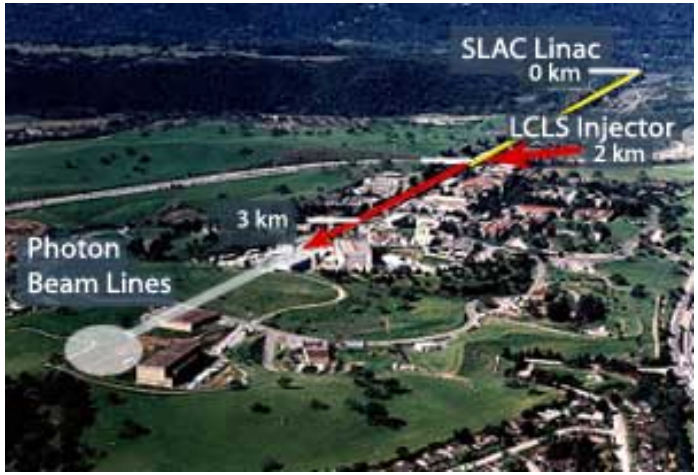


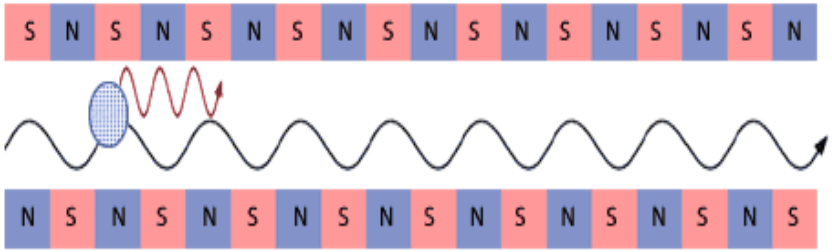


Beams strike "hohlraum," producing x-ray bath for fusion capsules.

Beam physics application --- modern high intensity accelerators

Spallation Neutron Source





Linear Coherent Light Source

Nonlinear Vlasov-Maxwell equations for high intensity beams

Collective dynamics described by the Vlasov equation

$$\left\{\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{x}} - \left[m_b\left(\omega_{\beta b}^2\mathbf{x}_\perp + \omega_z^2 z\mathbf{e}_z\right) + e_b(\nabla\phi - v_z c\nabla_\perp A_z)\right]\cdot\frac{\partial}{\partial \mathbf{p}}\right\} f(\mathbf{x},\mathbf{p},t) = 0$$

External focusing field:

$$\mathbf{F}_{foc} = -m_b\omega_{\beta b}^2\mathbf{x}_\perp - m_b\omega_z^2 z\,\mathbf{e}_z$$

distribution function on phase space

Self-electric and self-magnetic fields <u>self-consistently</u> determined from Maxwell's equations.

$$\nabla^2\phi = -4\pi e_b\int d^3p f(\mathbf{x},\mathbf{p},t),$$

$$\nabla^2 A_z = -4\pi c e_b\int d^3p v_z f(\mathbf{x},\mathbf{p},t).$$

$f(\mathbf{x},\mathbf{p},t)$ and (ϕ, A_z) nonlinearly coupled

δf particle simulation method reduces noise

$$f = f_0 + \delta f,$$
$$\phi = \phi_0 + \delta\phi,$$
$$A_z = A_{z0} + \delta A_z.$$

(f_0, ϕ_0, A_{z0}) – equilibrium

$(\delta f, \delta\phi, \delta A_z)$ – perturbation

Fully nonlinear

$$\frac{dw_i}{dt} = -(1 - w_i)\frac{1}{f_0}\frac{\partial f_0}{\partial \mathbf{p}} \cdot \delta\left(\frac{d\mathbf{p}_i}{dt}\right),$$
$$\delta\left(\frac{d\mathbf{p}_i}{dt}\right) \equiv -e_b\left(\nabla\delta\phi - \frac{v_{zi}}{c}\nabla_\perp \delta A_z\right),$$

Weight function $w \equiv \dfrac{\delta f}{f}$

dynamically determines δf

Statistical noise **significantly** reduced by a factor of $\dfrac{\delta f}{f}$

Beam Equilibrium Stability and Transport (BEST) Code

Physics

- Perturbative particle simulation method to reduce noise.
- Linear eigenmodes and nonlinear evolution.
- 2D and 3D equilibrium structure.
- Multi-species; electrons and ions; accommodate very large mass ratio.
- Multi-time-scales, frequency span a factor of 10^5.
- 3D nonlinear perturbation.

Computation

- Message Passing Interface
  - Multiple-1D domain decompositon (OpenMP by users).
- Large-scale computing: particle x time-steps ~ 0.5 x 10^{12}.
- Scales linearly to 512 processors on IBM-SP3 at NERSC.
- NetCDF, HDF5 parallel I/O diagnostics.

Nonlinear Equilibrium

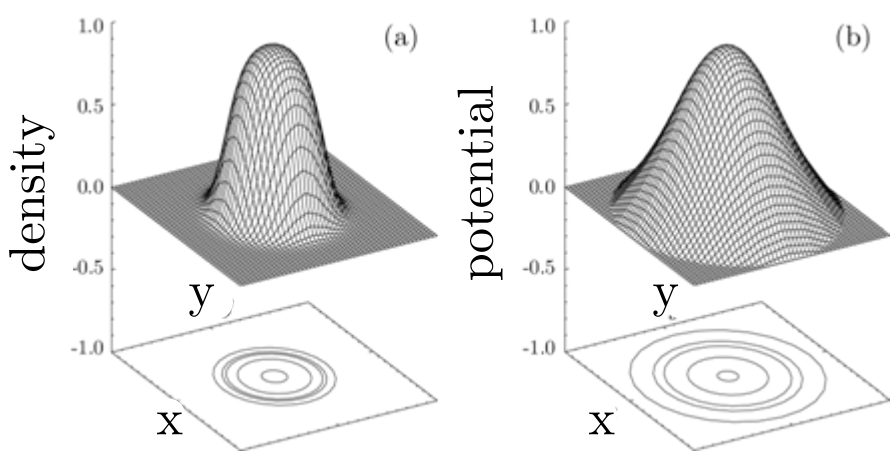
$$H = \frac{p^2}{2m_b} + e_b\phi + \frac{1}{2}m_b\left(\omega_{\beta b}^2 r^2 + \omega_z^2 z^2\right),$$

$$f_0 = f_0(H) = \frac{\hat{n}_b}{(2\pi m_b T)^{3/2}} \exp\left(\frac{-H}{T}\right),$$

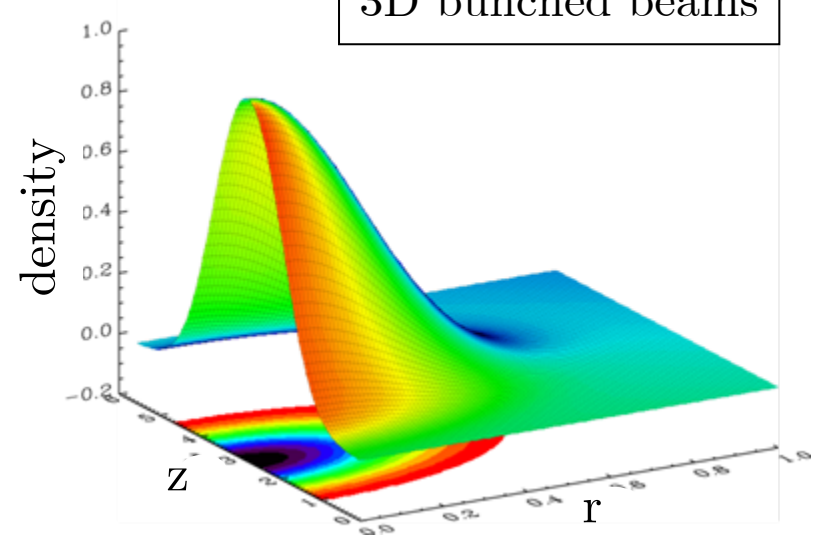
$$\nabla^2\phi_0 = -4\pi e_b \hat{n} \exp\left[-\frac{m_b\left(\omega_{\beta b}^2 r^2 + \omega_z^2 z^2\right)}{2T} - \frac{e_b\phi_0}{T}\right],$$

Chaotic orbits.
Linear Stability
theory not possible.

2D coasting beams



3D bunched beams

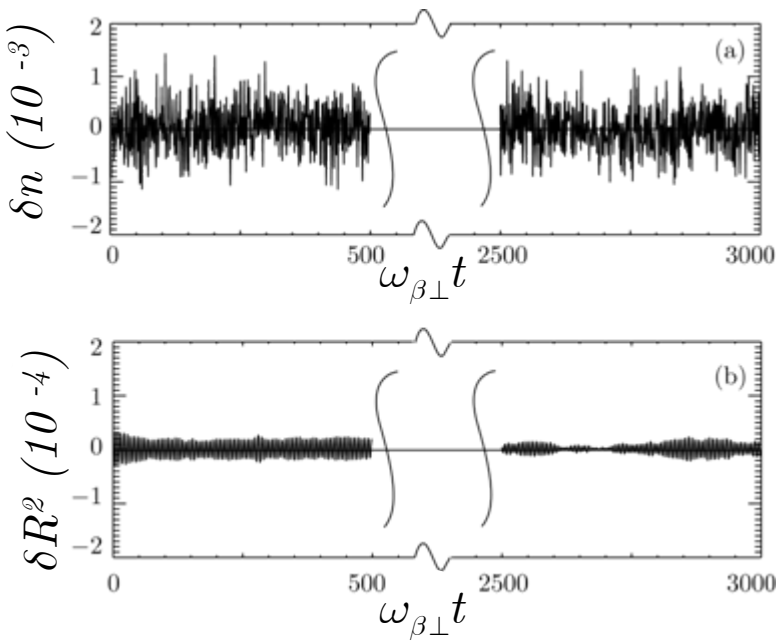


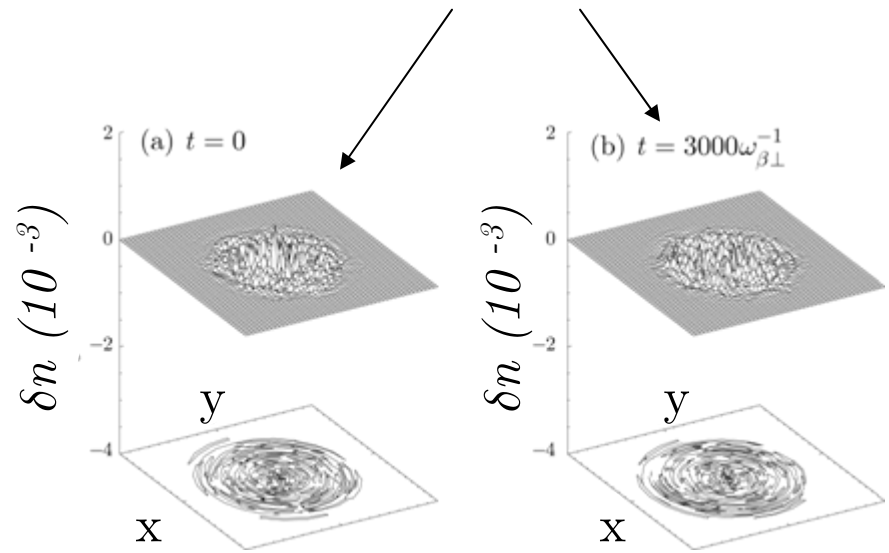
Long-time nonlinear perturbations

Theorem [Davidson, 1998]:

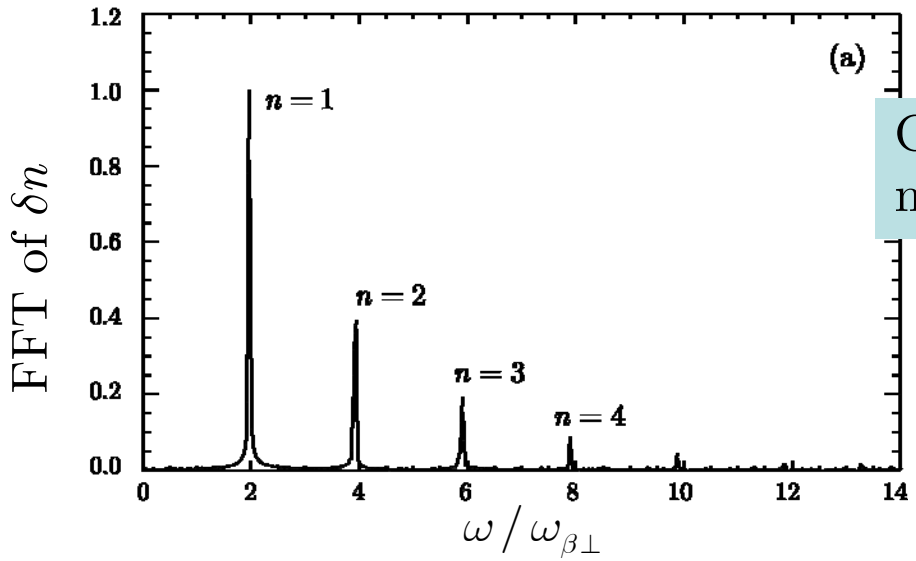
Linear and nonlinear stability $\Leftrightarrow \dfrac{\partial f_0(H)}{\partial H} < 0.$

contain perturbation spectrum

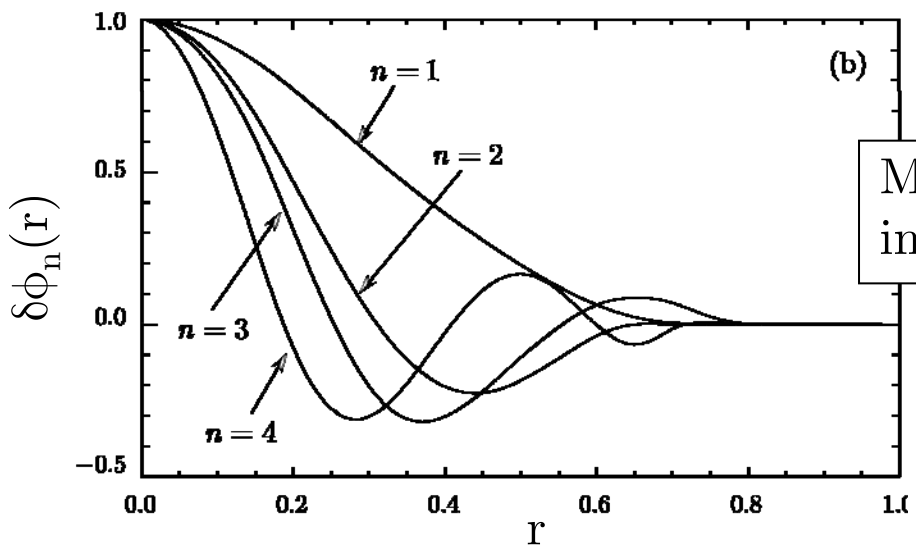




Collective interior mode excitation



Collective dynamics manifest by eigenmodes

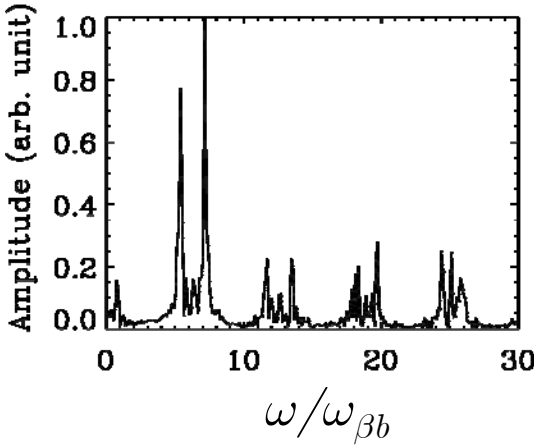


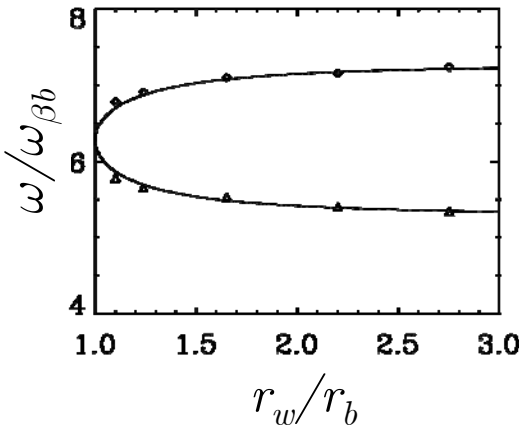
Mode structure confined inside the beam

Collective surface mode excitation

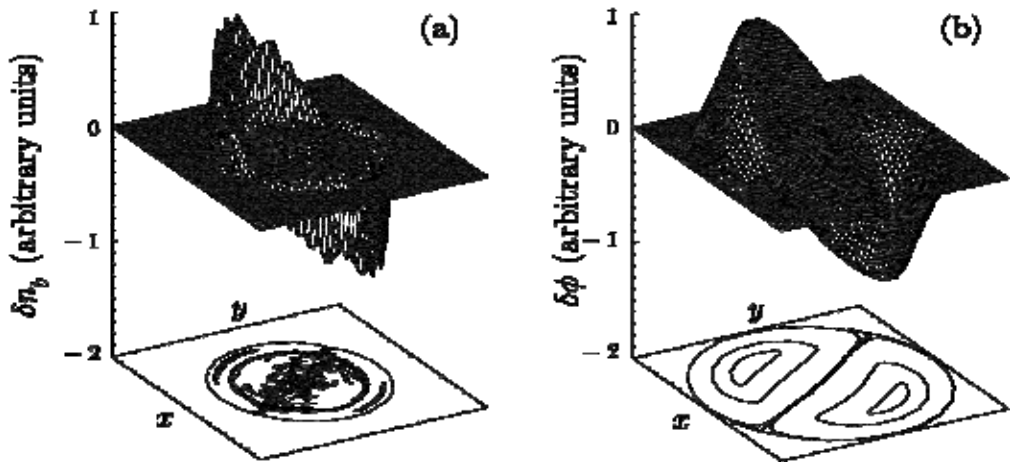
Dispersion relation:

$$\omega = k_z V_b \pm \frac{\hat{\omega}_{pb}}{\sqrt{2}\gamma_b}\sqrt{1 - \frac{r_b^2}{r_w^2}}$$

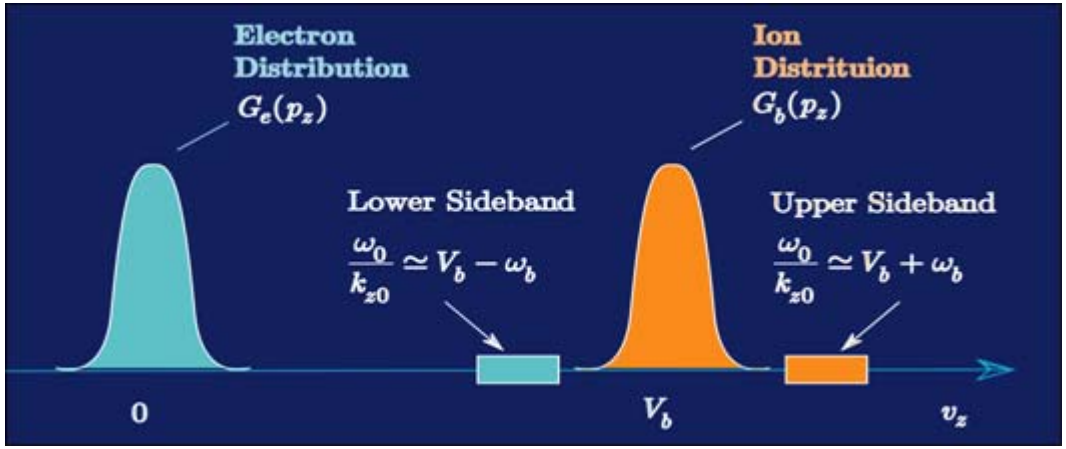


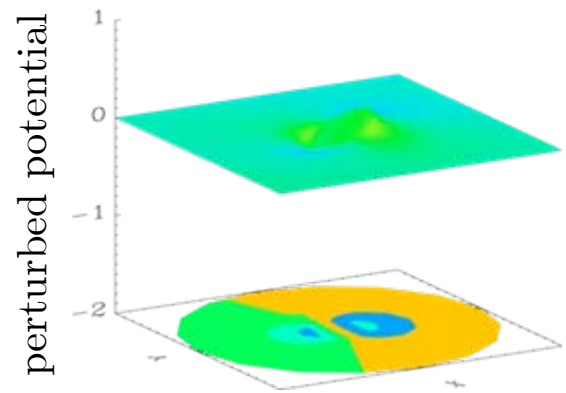


Dipole mode structure



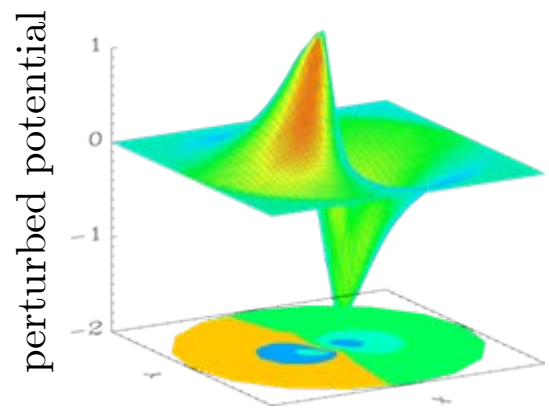
Electron-ion two-stream instability





$t = 0$

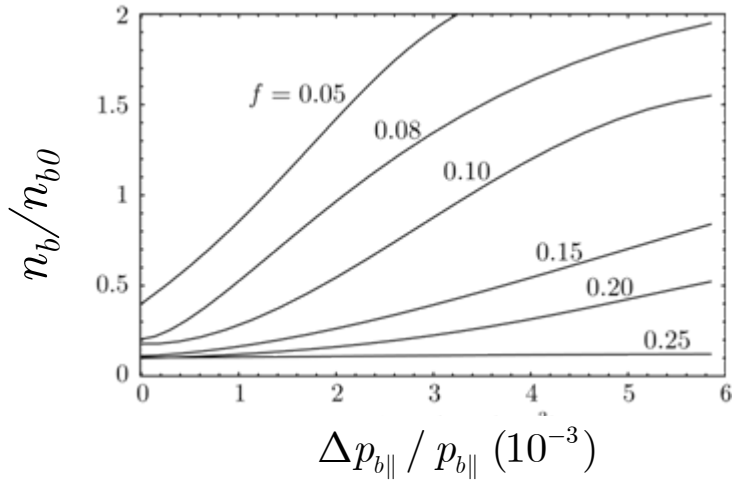
- Surface mode destabilized by background electrons.
- Observed in high intensity proton beams.
- Could be a show stopper for high intensity accelerators, e.g. SNS.
- Transverse geometry and dynamics are important.
- Important damping mechanisms (Landau damping) included.



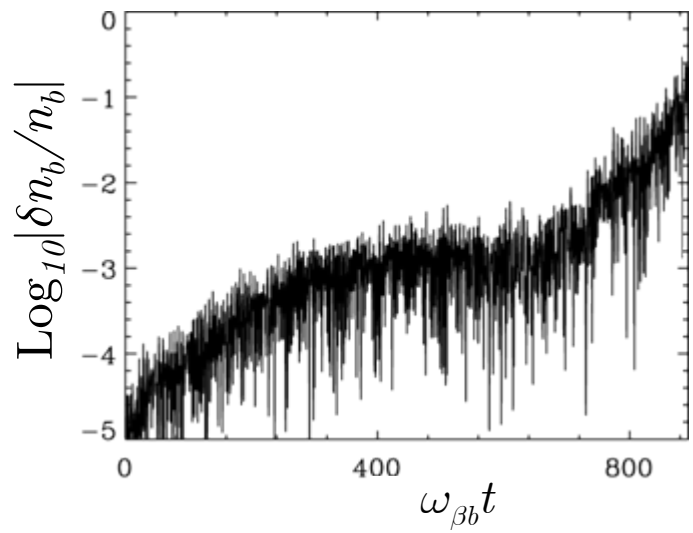
$t = 200 / \omega_{\beta b}$

Instability properties predicted by BEST simulations

- Instability threshold observed.
- **Agrees well with experiment observations** (Proton Storage Ring)
  - Mode structure
  - Growth rate
  - Real oscillation frequency

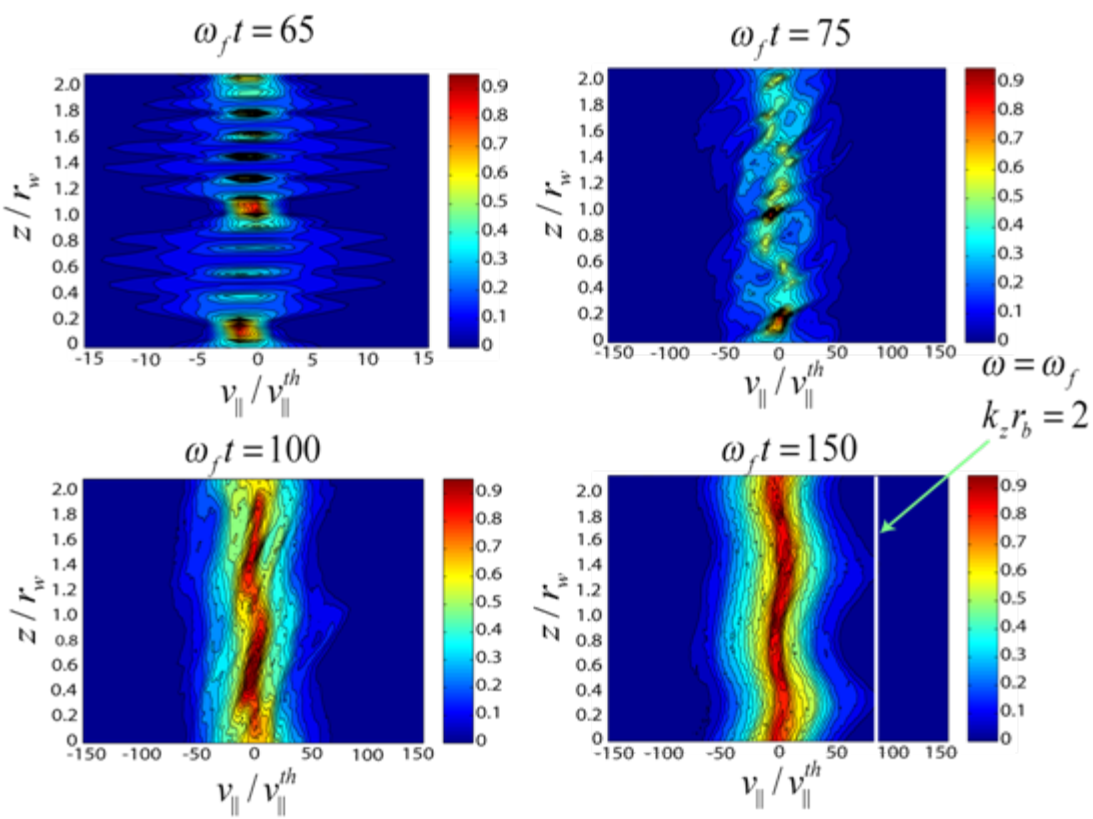


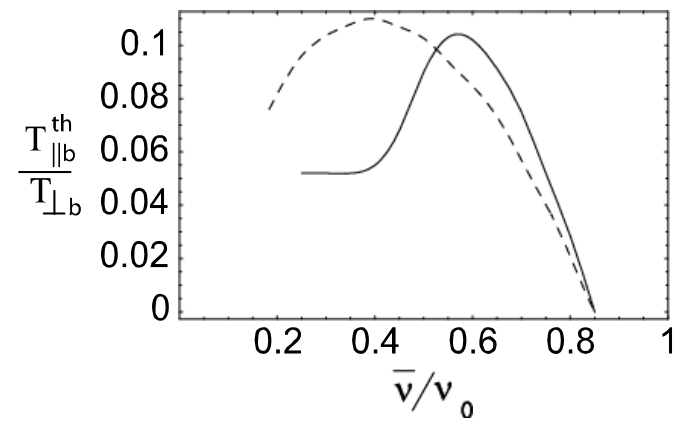
- Late time nonlinear growth observed.
- There are two-phases to the instability.

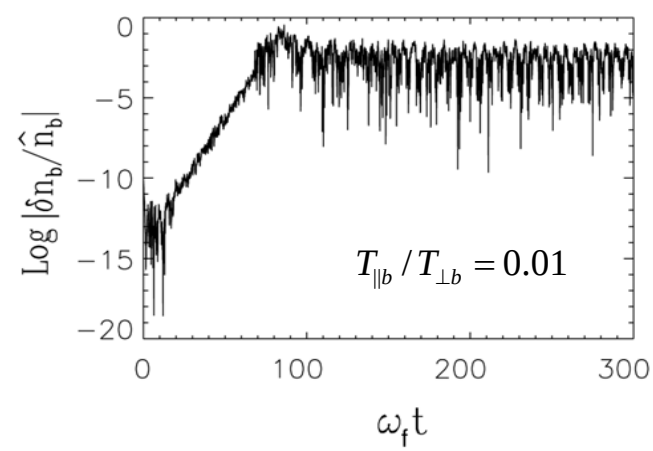


Strong Harris instability for beams with large temperature anisotropy

- Moderate intensity → largest threshold temperature anisotropy.
- Nonlinear saturation by particle trapping → tail formation.



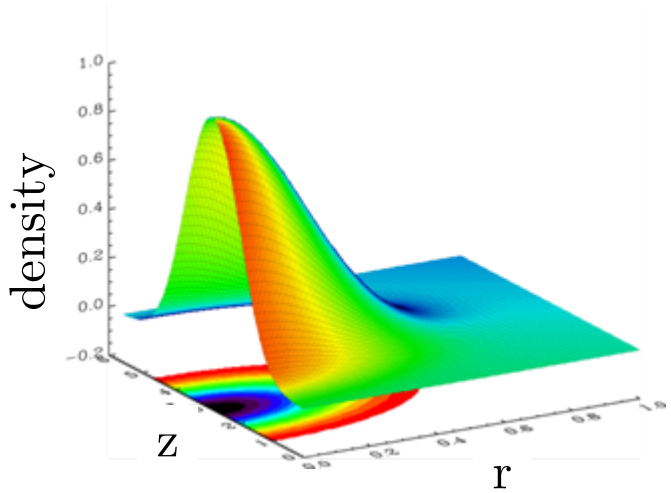


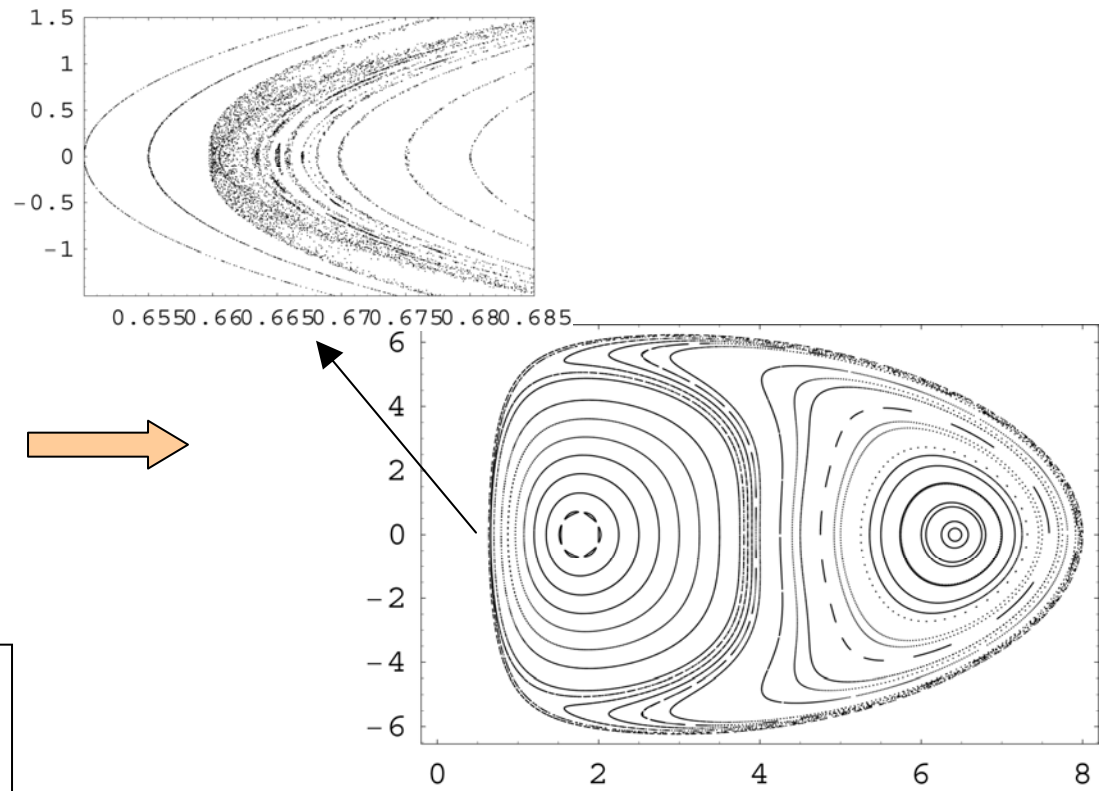


Collective excitation in 3D bunched beams

$$\nabla^2\phi_0 = -4\pi e_b \hat{n} \exp\left[-\frac{m_b\left(\omega_{\beta b}^2 r^2 + \omega_z^2 z^2\right)}{2T} - \frac{e_b\phi_0}{T}\right],$$

3D anisotropic quasi-equilibrium





Nonlinear space-charge effects reduce integrability of orbits in 3D

Chaotic particle dynamics

Conclusions

- **Vlasov-Maxwell equations for high intensity beam physics.**

- **Nonlinear δf particle simulation method significantly reduces noise.**

- **Major progress in simulation studies using BEST code.**
  - Electron-cloud-induced two-stream instability.
  - Temperature anisotropy instability.

- **Exciting future task areas include:**
  - Collective excitations and instabilities in bunched beams.
  - Beam-beam and beam-plasma collective interactions.

- **Impossible without NERSC. Thank you.**