Current-induced phase textures and pairbreaking in multilayers and two-gap superconductors

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Outline

- **Systems with two <u>different</u> weakly coupled current-carrying parallel channels:**
  - **Multilayer structures**
  - **2 – gap superconductors (π and σ bands in MgB_2)**

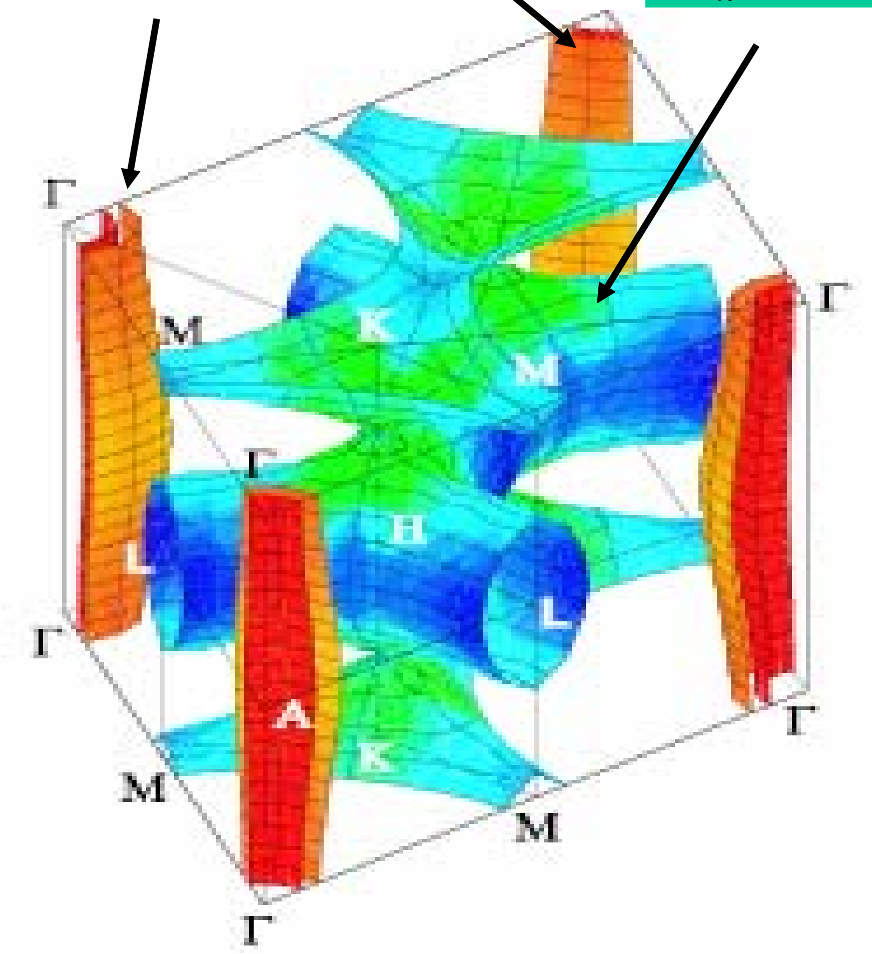
- **How does current destroy superconductivity?**
  - **Current-induced decoupling of channels and formation of equilibrium phase textures**
  - **Current sharing and suppression of current pairbreaking in the weaker channel**
  - **Global pairbreaking**

- **Manifestations**
  - **Current - controlled 4 terminal devices**
  - **Current - induced interband phase textures in MgB_2**

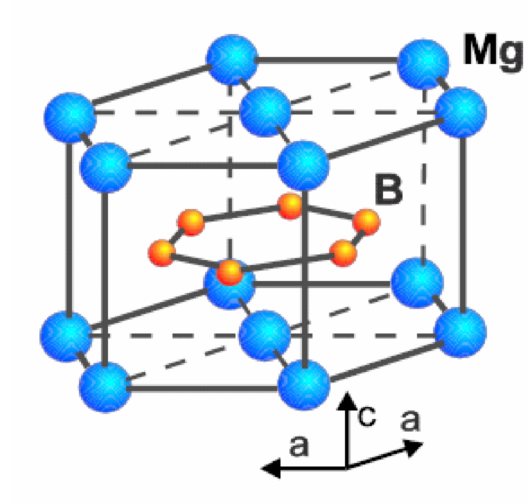
Two-gap superconductivity in MgB_2

Big gap,
$\Delta_\sigma \approx 7$ meV

Small gap,
Δ_π = 2.3meV



Liu, Mazin and Kortus (2002);
Choi et al, (2002)



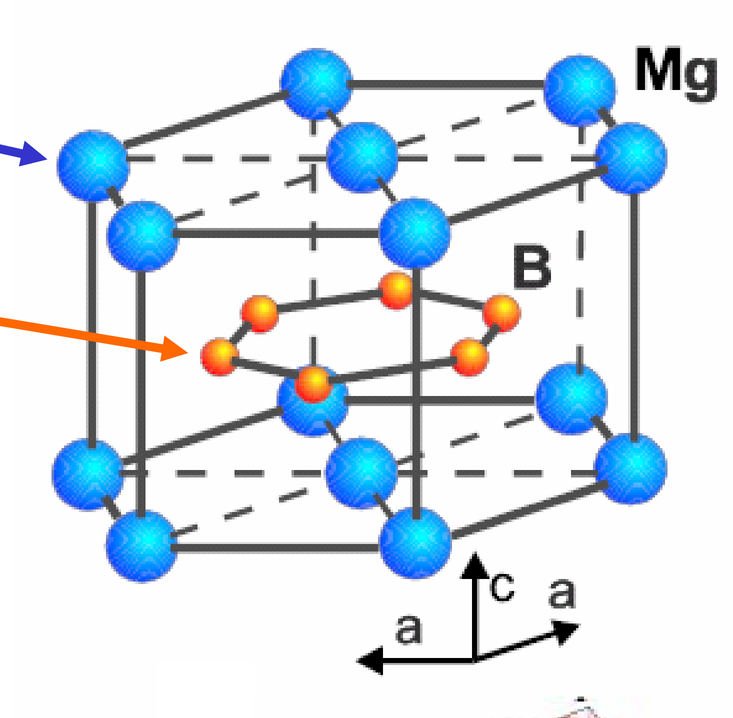
- 2D big gap for in-plane σ-orbitals s and 3D small gap for out-of-plane π-orbitals
- Weak interband coupling due to orthogonal p_z and p_{xy} orbitals of B

High T_c = 40K, but
low H_{c2} of MgB_2 single crystals:

$H_{c2}^{\perp}(0) \approx 3.5$ T
$H_{c2}^{||}(0) \approx 13$ T

Tunable impurity scattering

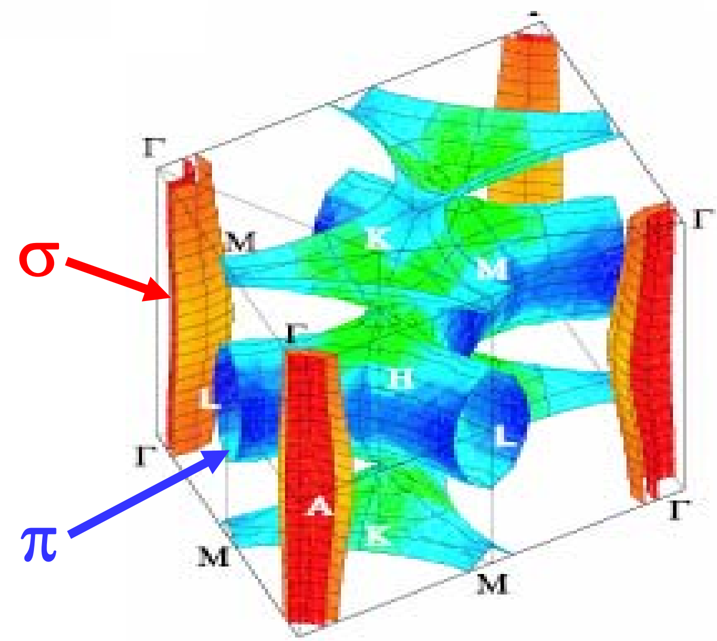
- Mg - substitution: 3D intraband π scattering
- B - substitution: 2D intraband σ scattering
- Weak interband scattering
- Selective atomic substitution produces quenched impurity or vacancy structures



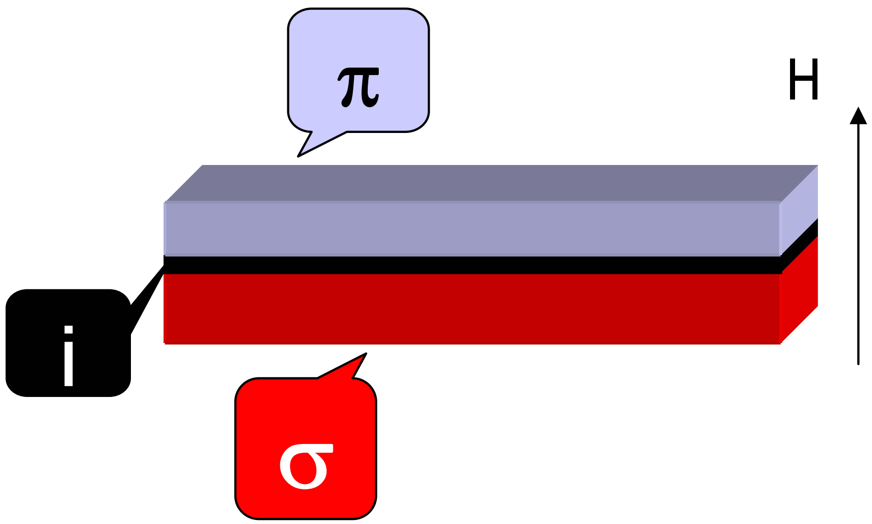
Anisotropic intraband diffusivities:

$D_\sigma^{(c)} << D_\sigma^{(ab)}$, $D_\pi^{(c)} \approx D_\pi^{(ab)}$

D_σ/D_π is a variable material parameter

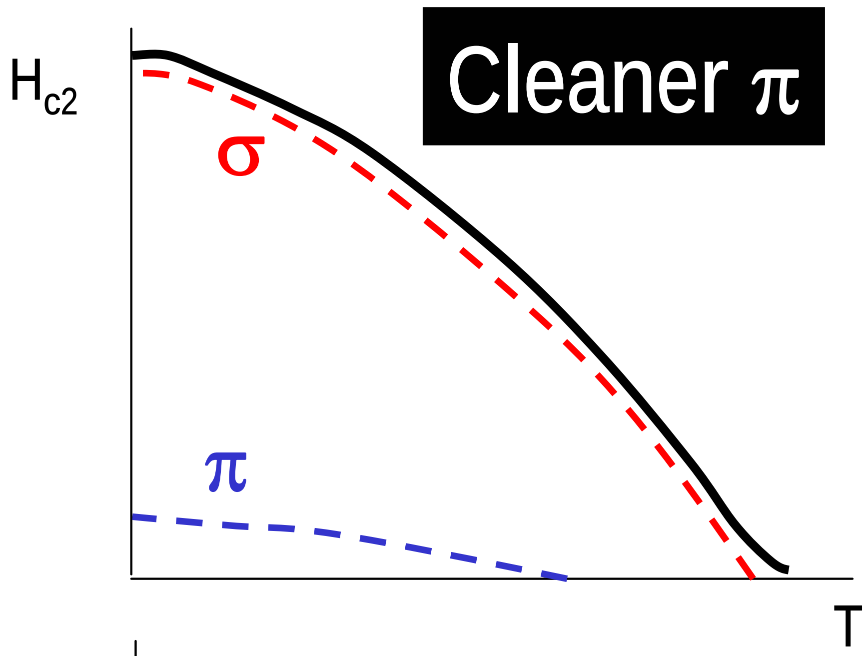


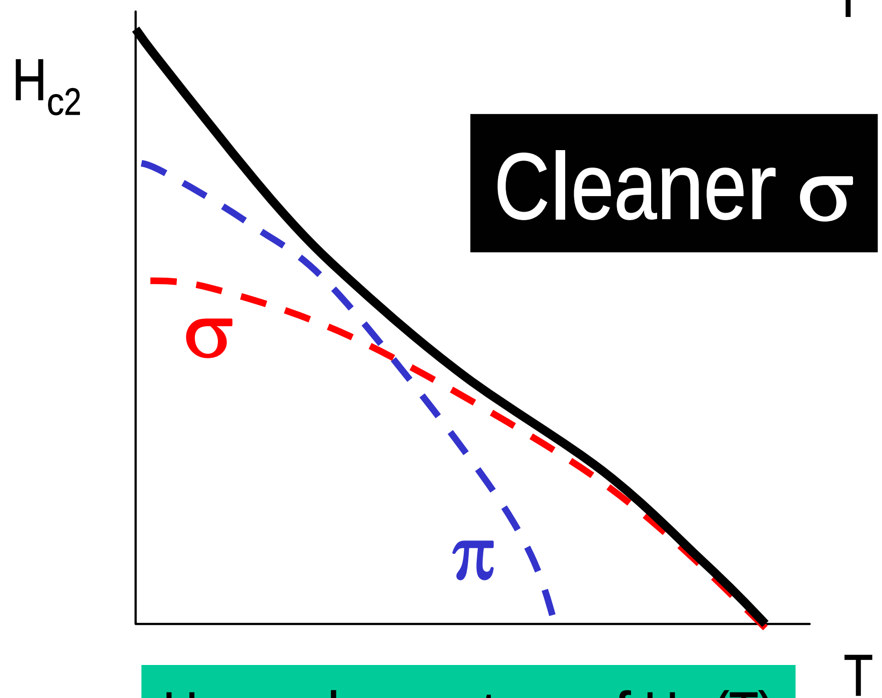
Toy model for MgB_2



- Two weakly coupled thin films (σ and π)
- $T_c^{(\sigma)} > T_c^{(\pi)}$
- Weak Josephson coupling analogous to interband coupling

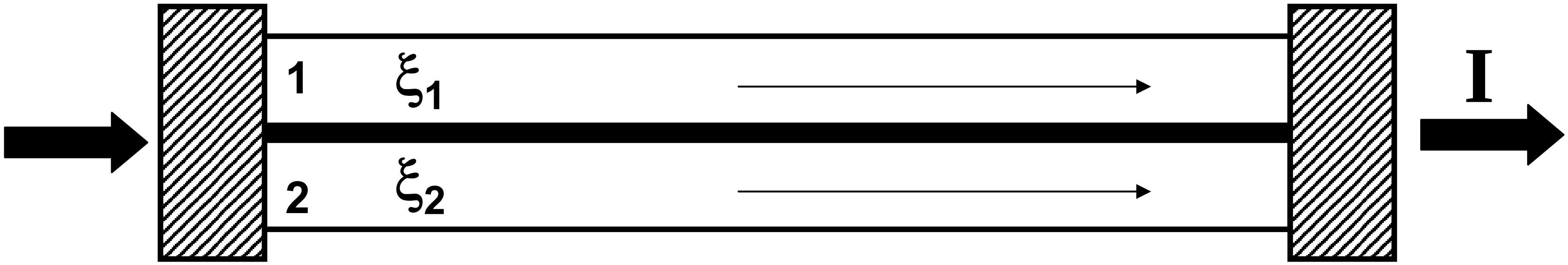
More details on H_{c2} in multilayers in:
S. Takahashi and M. Tachiki, PRB 33, 4620 (1986)
For MgB_2 see: AG, PRB 67, 184515 (2003)





Upward curvature of $H_{c2}(T)$

Phase locked current state



Same phases $\chi_1 = \chi_2$ to minimize the Josephson energy,

$$W_J = (\hbar J_c/2e)[1 - \cos(\chi_1 - \chi_2)]$$

Current-carrying state: $\Psi_1 = \Delta_1 \exp(i\chi_1)$, $\Psi_2 = \Delta_2 \exp(i\chi_2)$,

$$\nabla\chi_1 = \nabla\chi_2 = \mathbf{q}$$

$$\mathbf{Q} = \nabla\chi + 2\pi\mathbf{A}/\phi_0$$

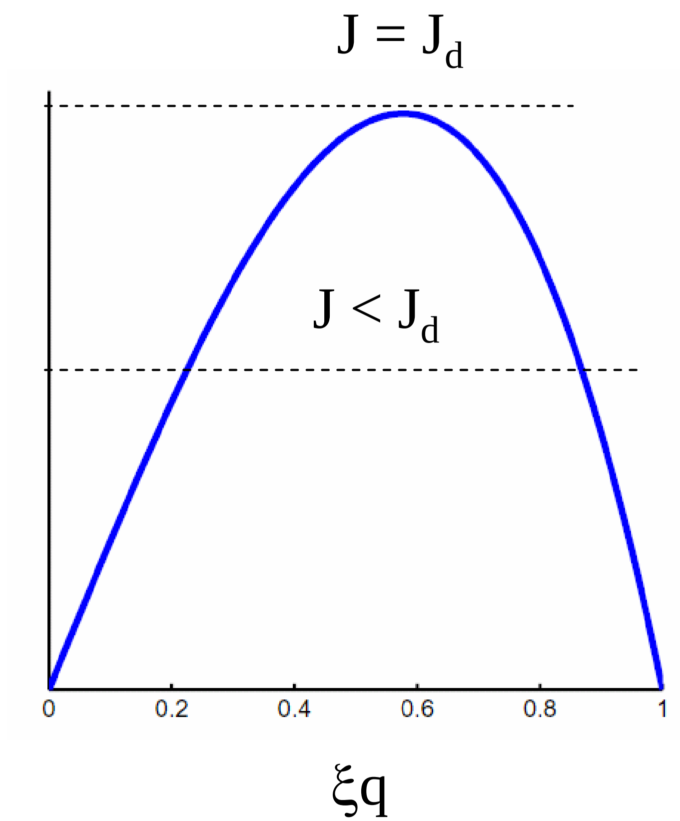
$$Q = -\frac{8\pi^2}{c\phi_0}\left(\frac{\Lambda_1^2}{d_1} + \frac{\Lambda_2^2}{d_2}\right)I$$

What happens at higher currents?

GL depairing current density

- GL current-carrying state with $\psi = \psi_0 \exp(-iqx)$, in a thin filament.

$$\psi_0^2 = 1 - \xi^2 q^2, \qquad J = \frac{c\,\psi_0^2 \phi_0 q}{8\pi^2 \Lambda^2}$$



- Current density as a function of q:

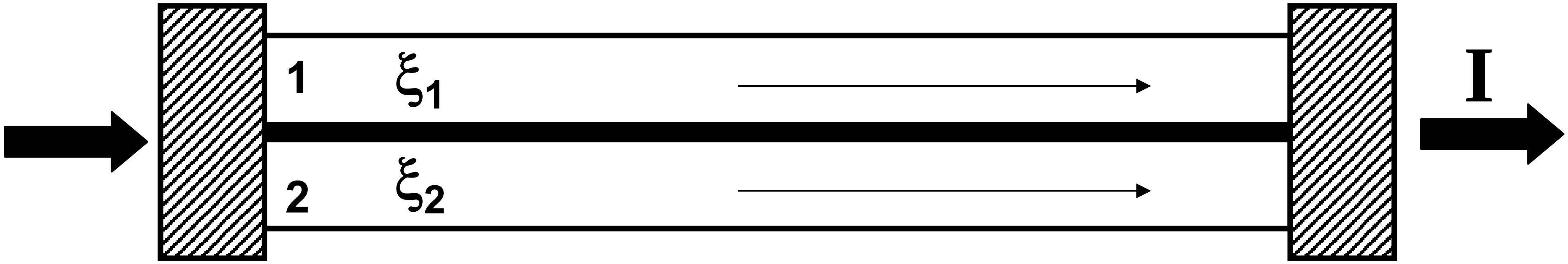
$$J = \frac{c\,\phi_0 q}{8\pi^2 \Lambda^2}(1 - \xi^2 q^2)$$

Suppression of ψ by current

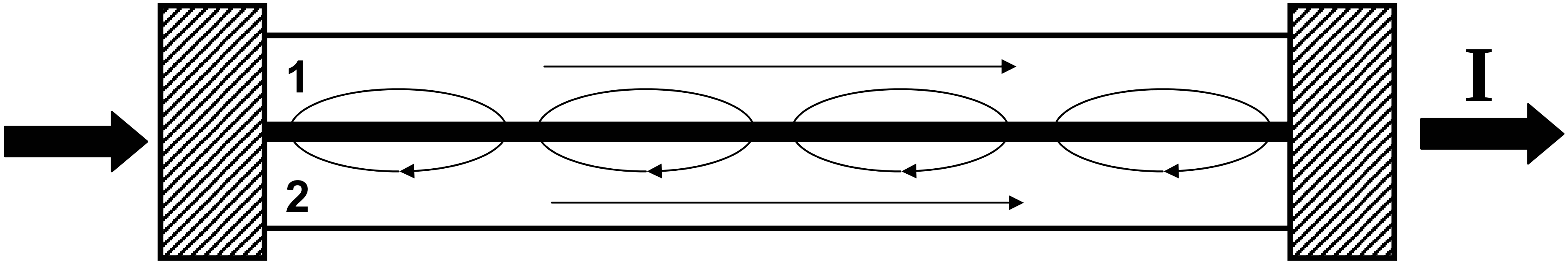
- Maximum J at $\xi q = 1/\sqrt{3}$:

$$J_d = \frac{\phi_0}{12\sqrt{3}\pi^2\Lambda^2\xi} \simeq 0.54\frac{H_c}{\Lambda} \propto \left(1 - \frac{T}{T_c}\right)^{3/2}$$

Transition to a phase slip state

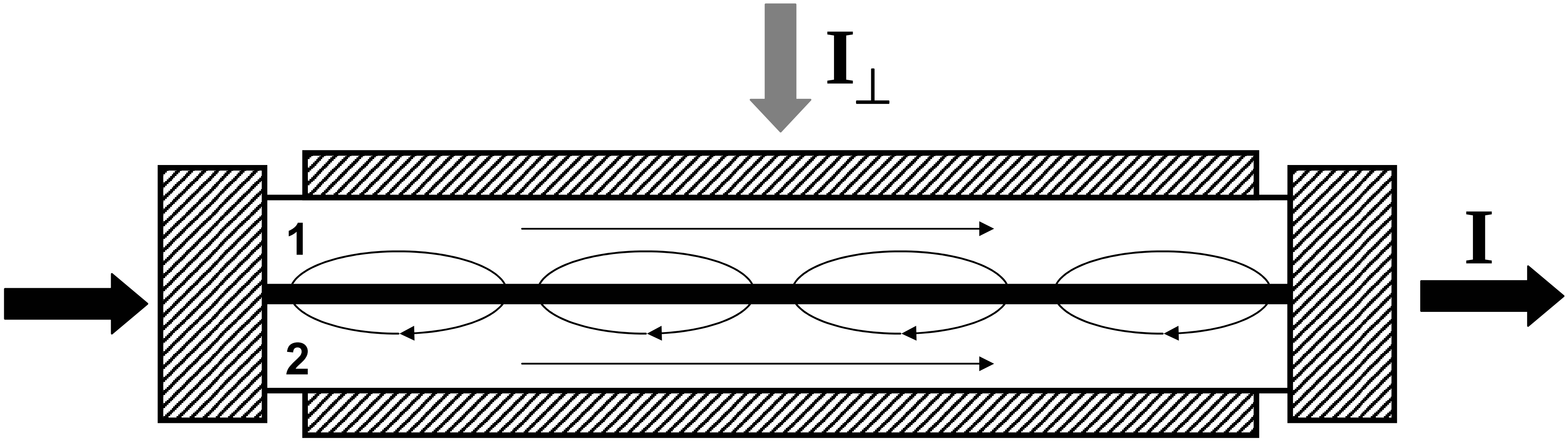


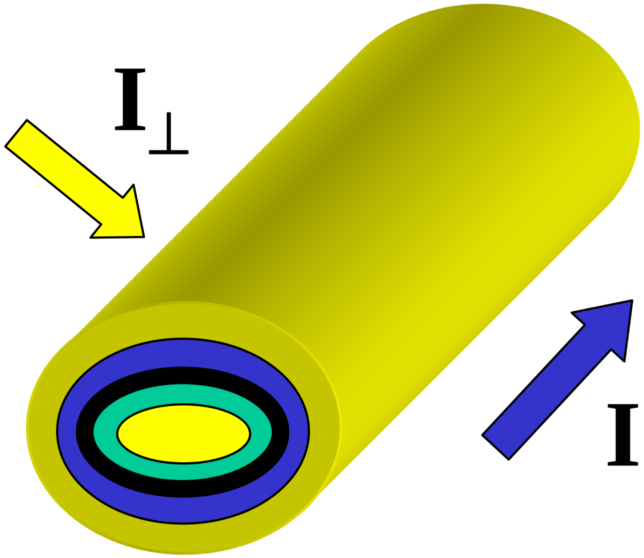
- What happens if $Q\xi_2 \sim 1$ in film 2, but $Q\xi_1 << 1$ in film 1?
- Film 2 cannot go normal
- Current redistribution enforces different Q_1 and Q_2 competing with the Josephson energy



- Current-induced vortex structure (interlayer phase texture) provides current sharing between films 1 and 2
- For weak Josephson coupling, the lock-in transition occurs at $I << I_d$

Four terminal devices





- Period of vortex structure is controlled by parallel current I
- Dynamics of vortices is controlled by perpendicular current $I_{\perp}$
- Parametric amplifier
- **No magnetic field is needed**

GL theory

$$F = -\alpha_1\Delta_1^2 + \frac{\beta_1}{2}\Delta_1^4 + g_1\left|\left(\nabla + \frac{2\pi i \vec{A}}{\phi_0}\right)\Psi_1\right|^2 - \alpha_2\Delta_2^2 + \frac{\beta_2}{2}\Delta_2^4 + g_2\left|\left(\nabla + \frac{2\pi i \vec{A}}{\phi_0}\right)\Psi_2\right|^2 - \gamma\Delta_1\Delta_2\cos\theta$$

- Thermodynamic potential for slow variation of $\theta(r) = \chi_1 - \chi_2$ and fixed I

$$G = -\frac{\alpha_1^2 d_1}{2\beta_1}(1-\xi_1^2 Q_1^2)^2 - \frac{\alpha_2^2 d_2}{2\beta_2}(1-\xi_2^2 Q_2^2)^2 - \varepsilon_J\cos\theta + cAI$$

$$I = -\frac{\phi_0}{\pi c}\left[\varepsilon_1 Q_1(1-\xi_1^2 Q_1^2) + \varepsilon_2 Q_2(1-\xi_2^2 Q_2^2)\right]$$

- Energy scales: $\varepsilon_1 = \alpha_1^2\xi_1^2 d_1/2\beta_1$, $\varepsilon_2 = \alpha_2^2\xi_2^2 d_2/2\beta_2$, $\varepsilon_J = \gamma\Delta_1\Delta_2$

Expand G to quadratic terms in small $\nabla\theta$

Energy of phase textures

$$G_\theta = \varepsilon_J \left[\frac{L_\theta^2}{2} (\nabla \theta)^2 - \cos\theta - (\vec{Q}\nabla\theta) h(Q) - \beta\theta \right]$$

$$\beta = I_\perp / I_c$$

Similar to the energy of a long Josephson contact. The effective magnetic field h is due to asymmetric pairbreaking. Both L_θ and h depend on current

$$h = \frac{8\varepsilon_1\varepsilon_2(\xi_2^2 - \xi_1^2)Q^2}{[(1-3\xi_1^2Q^2)\varepsilon_1 + (1-3\xi_2^2Q^2)\varepsilon_2]\varepsilon_J},$$

$$L_\theta^2 = \frac{4\varepsilon_1\varepsilon_2(1-3\xi_1^2Q^2)(1-3\xi_2^2Q^2)}{[(1-3\xi_1^2Q^2)\varepsilon_1 + (1-3\xi_2^2Q^2)\varepsilon_2]\varepsilon_J},$$

$$I = -Q[(1-\xi_1^2Q^2)\varepsilon_1 + (1-\xi_2^2Q^2)\varepsilon_2]8\pi c / \phi_0$$

- Nonlinear pairbreaking for $\xi_1 \neq \xi_2$.
- Large h and L_θ >> ξ_2 due to weak Josephson coupling
- L_θ^2 (Q) changes sign at

$$Q_{c2} = 1/\sqrt{3}\xi_2$$

Spinodal current instability at Q_{c2}

- Expansion to higher order derivatives:

$$G = \varepsilon_J [\frac{\lambda^2 L_0^2}{4}(\nabla^2\theta)^2 + \frac{L_0^2}{2}(1-3Q^2\xi_2^2)(\nabla\theta)^2 - \cos\theta - (\vec{Q}\nabla\theta)h]$$

- where $\boldsymbol{\ell} \sim \xi_2$, and $L_0^2 = 4\varepsilon_2/\varepsilon_J >> \xi_2$.

- Periodic weak disturbance $\theta_0\cos(kx)$, with $k^2 = (3Q^2\xi_2^2 - 1)/\boldsymbol{\ell}^2$

- Linear instability at Q_{c2} at finite wave vector k_m

$$Q_{c2} = \frac{1}{\xi_2\sqrt{3}}\left(1 + 2\lambda\sqrt{\frac{\varepsilon_J}{\varepsilon_2}}\right), \qquad k_m = \frac{1}{2}\left(\frac{\varepsilon_J}{\lambda^2\varepsilon_2}\right)^{1/4}$$

- No small amplitude solutions above Q_{c2} (analog of H_{c2} for vortices)

Explosive current redistribution at Q_{c2} well below the usual depairing current

Equilibrium phase textures

$$\tau^2\ddot{\theta} + \tau_r\dot{\theta} = L_\theta^2\nabla^2\theta - \sin\theta + \beta$$

Textures are energetically favorable for $Q > Q_{c1}$ analogous to H_{c1} for JJ

Different from nonequilibrium textures caused by electric field, AG & V. Vinokur, PRL 90, 047004 (2003)

- A single 2π kink, $\theta(x) = 4\tan^{-1}\exp(x/L_\theta)$ appears if $2\pi Qh(Q) > 8L_\theta$:

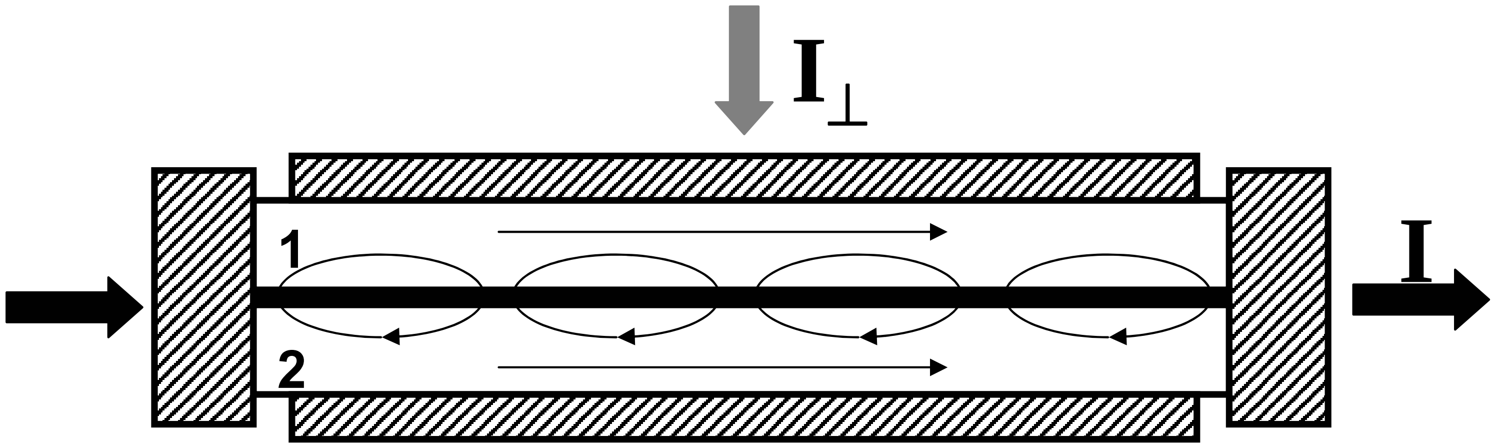
$$Q_{c1} = \left[\frac{(\varepsilon_1+\varepsilon_2)\varepsilon_J}{\pi^2\varepsilon_1\varepsilon_2(\xi_2^2-\xi_1^2)^2}\right]^{1/6} << Q_{c2}, \qquad I_{c1} = \frac{8\pi c}{\phi_0}(\varepsilon_1+\varepsilon_2)Q_{c1}$$

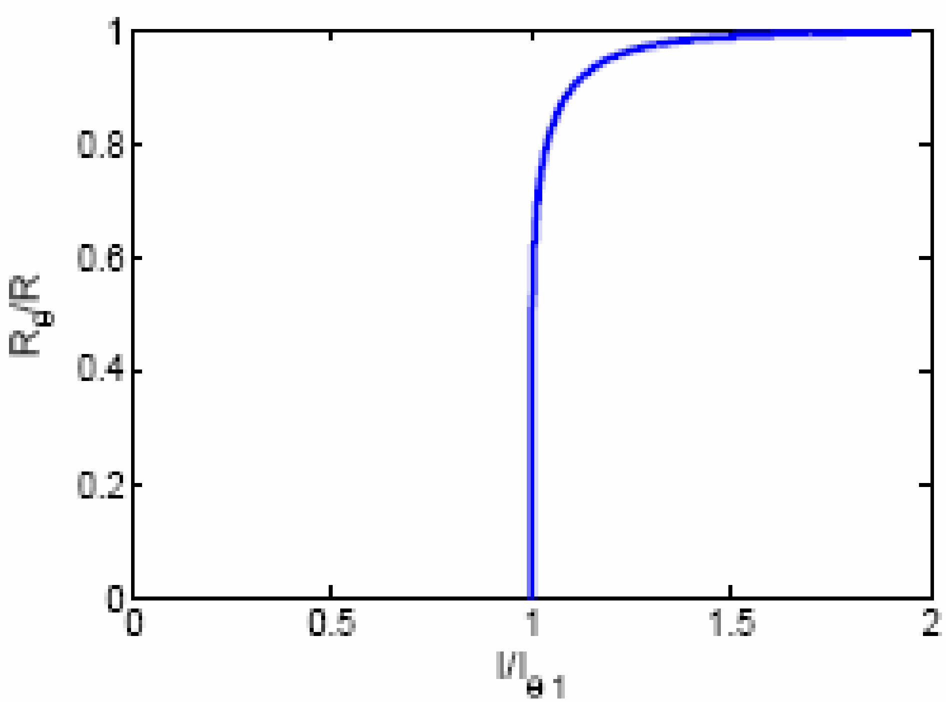
- Periodic phase texture $\theta(x) = \mathrm{am}(x/pL_\theta, p)$.

- Parametric relation which defines the period $a(I)$ $(0 < p < 1)$:

$$a = 2L_\theta pK(p), \qquad I^3 = I_{c1}^3 E(p)/p$$

Phase-unlocked resistive transition



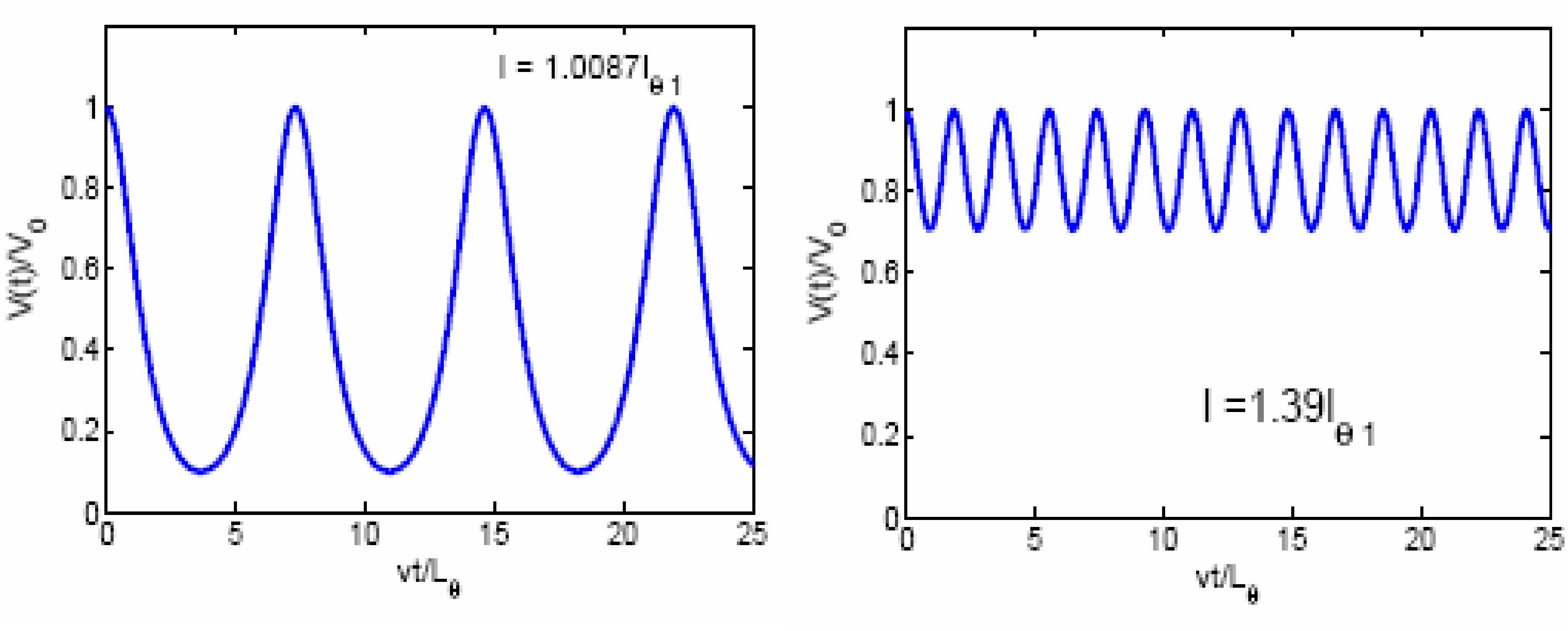


- Switching to ohmic flux flow for $I > I_{c1}$

$$\bar{V} = R_\theta I_\perp, \qquad R_\theta = \frac{\pi^2 R p L_\theta}{2E(p)a(p)}$$

- Resistive transition controlled by longitudinal current

Oscillating Josephson voltage



- Josephson ac voltage voltage: **$V = (\phi_0 v/2\pi c)am'(vt/pL_\theta, p)$**
- Washboard frequency proportional to the transverse current $I_\perp$

Two-gap superconductors

Dirty limit, two-gap Usadel equations:

AG, PRB 67, 184515 (2003)

$$\omega f_1 - \frac{D_{\alpha\beta}^{(1)}}{2}[g_1\Pi_\alpha\Pi_\beta f_1 - f_1\nabla_\alpha\nabla_\beta g_1] = \Delta_1 g_1 + (f_2 g_1 - f_1 g_2)\gamma_{12}$$

$$\omega f_2 - \frac{D_{\alpha\beta}^{(2)}}{2}[g_2\Pi_\alpha\Pi_\beta f_2 - f_2\nabla_\alpha\nabla_\beta g_2] = \Delta_2 g_1 + (f_1 g_2 - f_2 g_1)\gamma_{21}$$

Here $D_{\alpha\beta}$ are intraband electron diffusivities, $\Pi = \nabla + 2\pi iA/\phi_0$, $|f_m|^2 + g_m^2 = 1$, γ are interband scattering rates, λ_{nm} are the BCS coupling constants

- **Gap equations:**

$$\Delta_m = 2\pi T \sum_{\omega>0}^{\omega_D} \sum_{s=1,2} \lambda_{ms} f_s(\omega, \Delta_s)$$

- **Current density:**

$$J_\alpha = -4\pi eT\ \mathrm{Im} \sum_\omega [N_1 D_{\alpha\beta}^{(1)} f_1^+ \Pi_\beta f_1 + N_2 D_{\alpha\beta}^{(2)} f_2^+ \Pi_\beta f_2]$$

Phase textures for all T

$$G_\theta = \varepsilon_J \left[\frac{L_\theta^2}{2} (\nabla \theta)^2 - \cos\theta - (\vec{Q} \nabla \theta) h(Q) \right]$$

$\varepsilon_J = \gamma \Delta_1 \Delta_2$

$2\gamma = N_1 \lambda_{12}^{-1} + N_2 \lambda_{21}^{-1}$

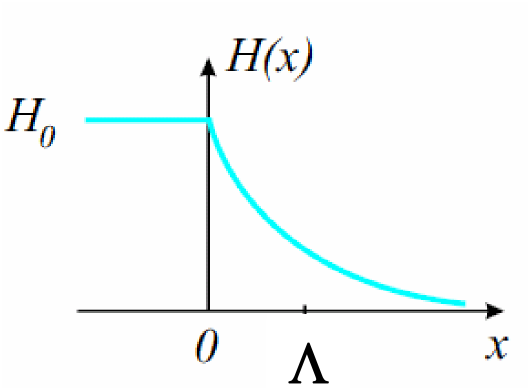
Small Q expansion for all T: $h = f(T)Q^3$. Example for T = 0

$$L_\theta^2 = \frac{\pi N_1 N_2 \Delta_1 \Delta_2 \xi_1^2 \xi_2^2}{4\gamma (N_1 \Delta_1^2 \xi_1^2 + N_2 \Delta_2^2 \xi_2^2)}, \qquad J_{c1} \cong J_2 \left[\frac{\gamma \xi_2 L_\theta (N_1 \Delta_1^2 \xi_1^2 + N_2 \Delta_2^2 \xi_2^2)}{N_1 N_2 \Delta_1 \Delta_2 (\xi_2^2 - \xi_1^2)} \right]^{1/3}$$

$\xi = (D/\Delta)^{1/2}$ are dirty coherence lengths at T = 0, and $J_2 = c\phi_0 / 8\pi^2 \Lambda^2 \xi_2$ is the depairing current density for the weaker band.

Interband phase textures in MgB_2

- For the parameters of MgB_2, J_{c1} is not much smaller than J_{c2}.
- Static interband phase textures $\theta(x)$ along the current direction at $Q \approx 1/\xi_\pi\sqrt{3}$



Screening current: $cH/4\pi\Lambda \approx c\phi_0/8\pi^2\Lambda^2 \xi_\pi\sqrt{3}$

Band decoupling magnetic field

$$H_\theta = \frac{\phi_0}{2\sqrt{3}\pi\Lambda\xi_\pi} \cong H_c\frac{\xi_\sigma}{\xi_\pi} \cong 0.3H_c \cong 0.13T$$

- Textures facilitate vortex penetration over the surface barrier
- Breakdown of linear London electrodynamics, mechanism of nonlocality and nonlinearity
- Nonlinearity of the rf surface impedance at $H \approx H_\theta$

Conclusions

- Two - stage superconductivity breakdown by current:
  - $I < I_{c1}$ - phase-locked state
  - $I_{c1} < I < I_d$ - band (layer) decoupling, current redistribution resulting in static phase textures
  - $I > I_d$ - global pairbreaking

- Current - controlled 4-terminal devices
  - Current switching and ac flux flow oscillators
  - Parametric generators and amplifiers

- Interband phase textures in MgB_2
  - Dc current pairbreaking
  - Vortex penetration
  - Effect on vortex lattice and the vortex core structure
  - Pinning and critical currents
  - Nonlinearity of the rf surface impedance