Current-blocking grain boundaries in SRF cavities and RF dissipation due to nonlinear dynamics of Josephson vortices under strong RF fields

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Supported by DOE under grant # DE-SC100387-020

Outline

- Is there a grain boundary problem in SRF materials?

  - ○ Nb – usually not but it may appear due to segregation of impurities on GBs
  - ○ Nb_3Sn – likely yes, and it can be a serious problem at high fields

- How can current-blocking grain boundaries reduce the SRF breakdown field?

- Effect of grain boundaries on Q(H) slope.

- Strongly and weakly-coupled grain boundaries.

- Dynamics of mixed Abrikosov-Josephson vortices in strongly coupled GBs.

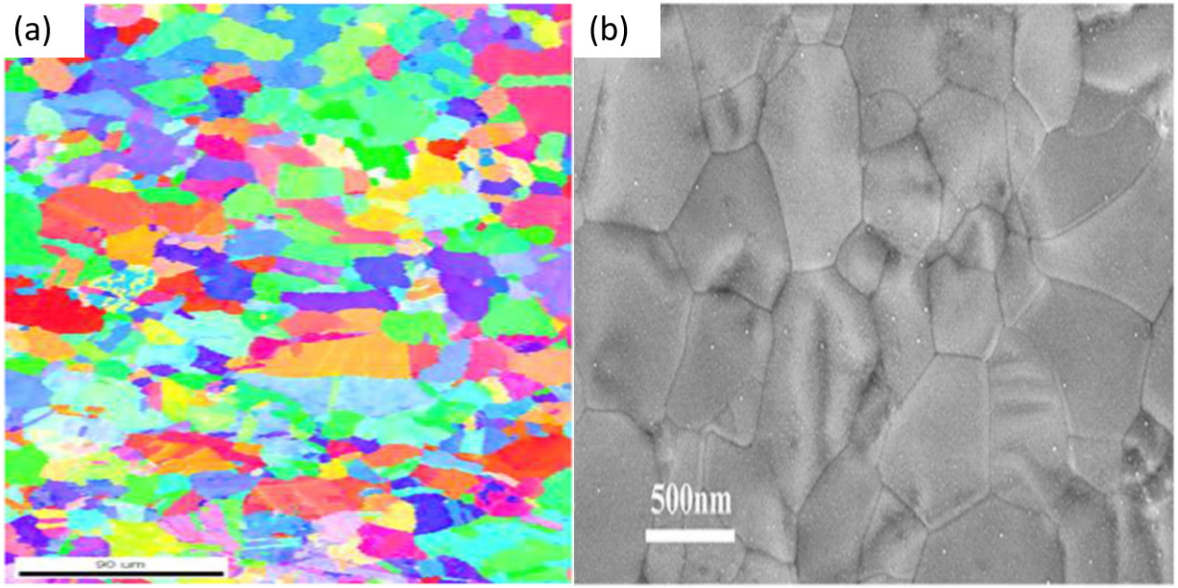
- Cherenkov instability and dynamic transition of of AJ vortices into phase slips.

- RF dissipation and deterioration of SRF performance by GBs

A. Sheikhzada and A. Gurevich:

1. **Physica C 506, 59-68 (2014)**
2. **Nature Scientific Reports 5, 17821 (2015)**
3. **Physical Review B 95, 214507 (2017)**

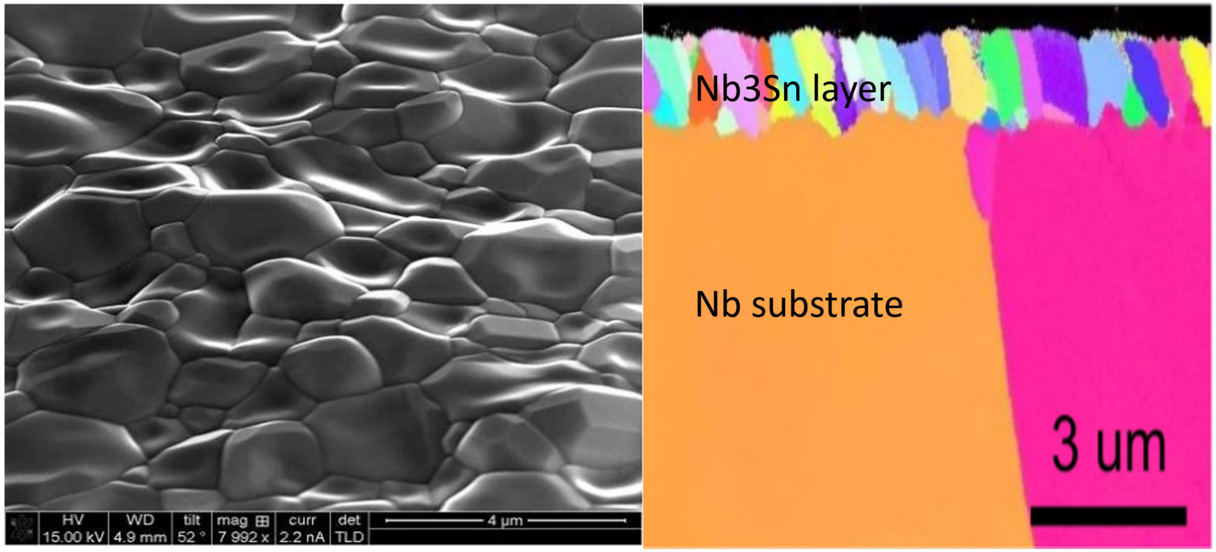
Do these grain boundaries impede RF currents?



EBSD map and optical microscopy of polycrystalline Nb films on Cu

A-M Valente-Feliciano, SUST 29, 113002 (2016)

GBs in Nb do not block RF currents up to H = Hc



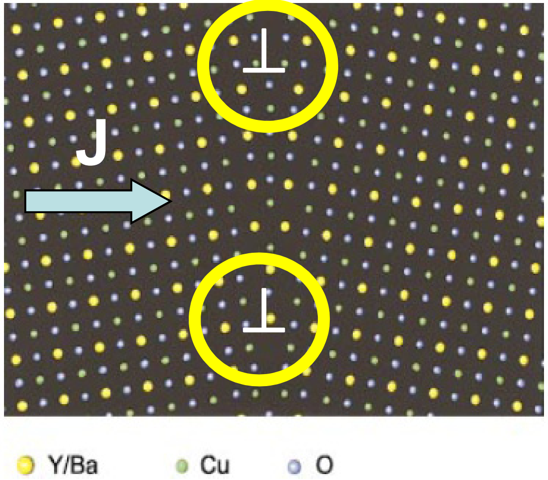
EBSD map and optical microscopy of polycrystalline Nb_3Sn films on Nb

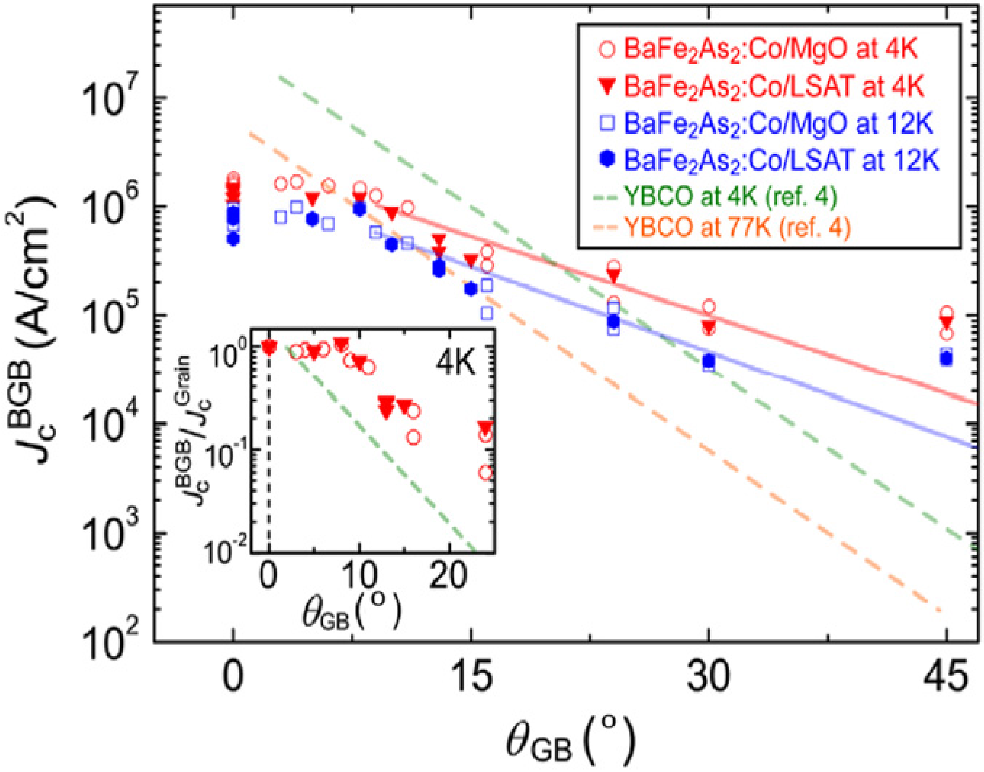
S. Posen and D. Hall, SUST 30, 033004 (2017)

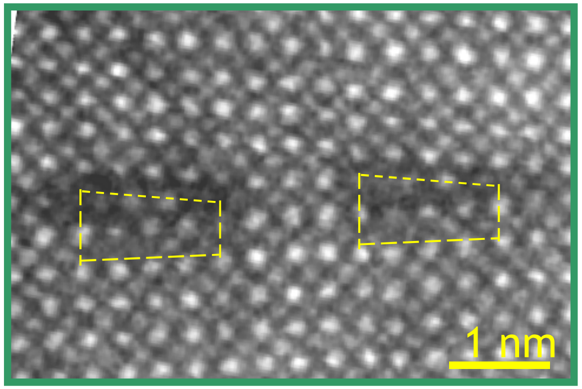
GBs in Nb_3Sn partly obstruct strong RF currents and pin vortices

GB problem in cuprates and pnictides

16^{O} [001] tilt grain boundary in YBCO







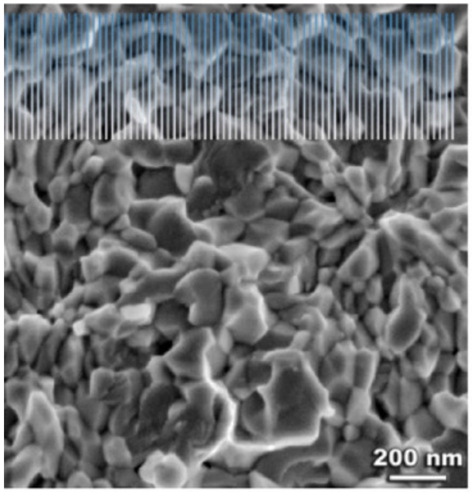
X. Song et al. Nature Mat. 4, 470 (2005)

Exponential decrease of J_c with the misorientation angle
GBs behave as weakly-coupled Josephson junctions

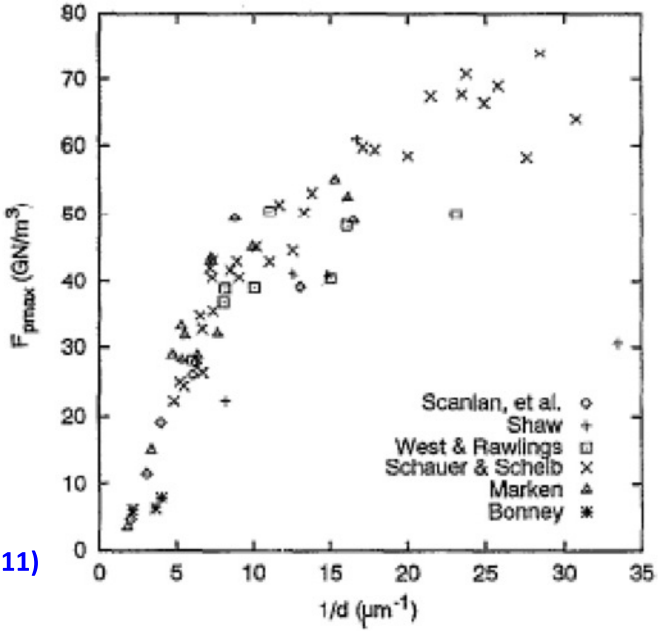
$J_c = 10^4 - 10^5$ A/cm^2 at 15-30^o are more then 3 orders of magnitude smaller than the SRF screening current densities at B_a = 100 mT:

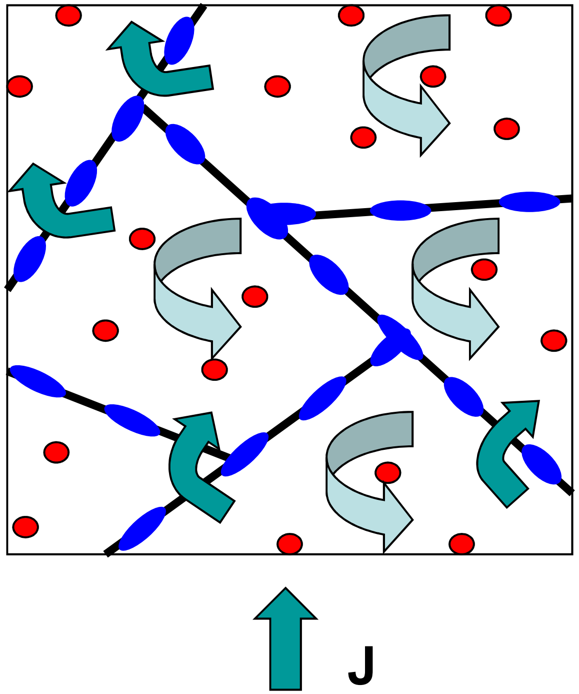
$$J_{SRF} \sim \frac{B_a}{\mu_0 \lambda} \sim 10^8 \frac{A}{cm^2}$$

Grain boundaries pin vortices in Nb_3Sn



Durrell et al, Rep. Prog. Phys. 74, 124511 (2011)



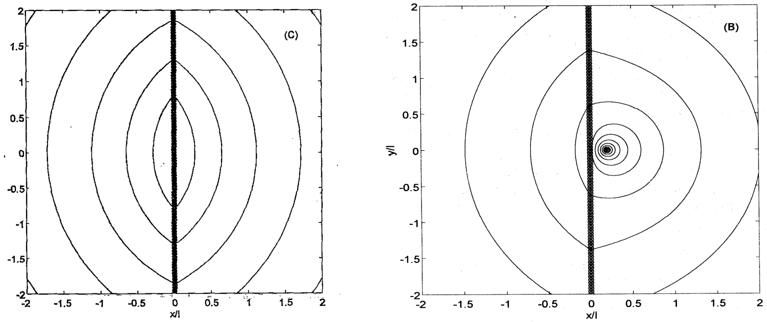


- ○ Vortices caged in the grains and pinned by GBs
- ○ GBs critical current density J_c is much smaller than the bulk deparing current density J_d:

$$J_c \ll J_d = H_c/\lambda$$

- ○ Bulk pinning force depends on the grain size d:

$$F_p = BJ_p \propto 1/d^2, \qquad d > \lambda,$$
$$F_p = BJ_p \propto 1/d, \qquad d < \lambda$$

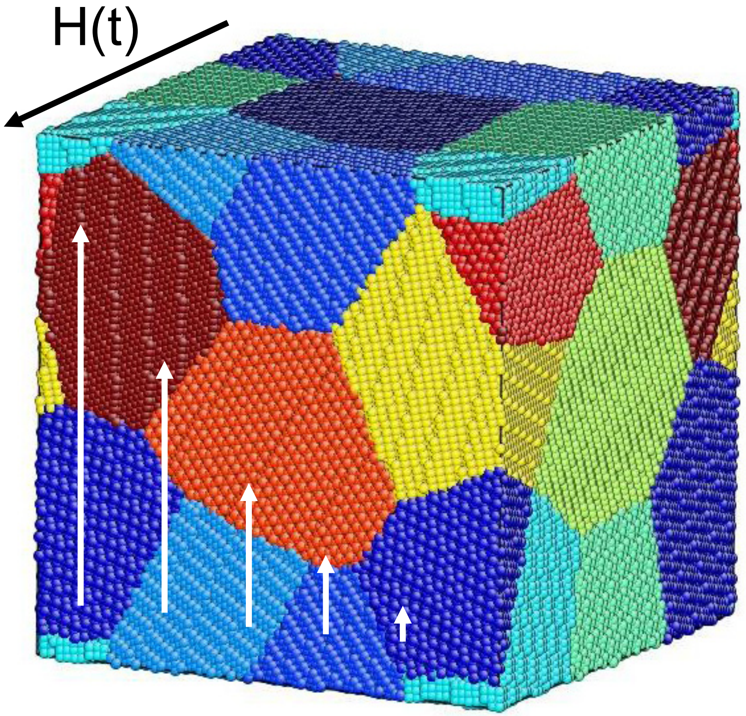


GB cuts currents circulating around a vortex causing its attraction to the GB at r < L:

$$J(r) \simeq J_d \frac{\xi}{r}, \quad L \simeq \xi \frac{J_d}{J_c}$$

Gurevich and Cooley, Phys. Rev. B 50, 13563 (1994)

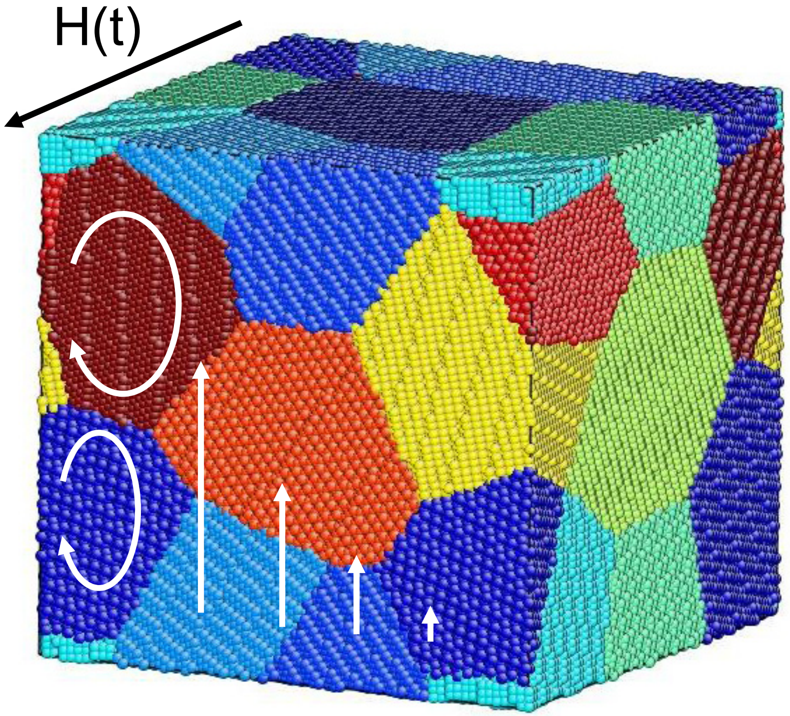
Grain boundaries impeding SRF currents



GBs are transparent to the RF current density

$$J(x) = (H/\lambda)e^{-x/\lambda}$$

Critical current density J_c of GB is larger than J(x) up to $H \approx H_c$



GBs are partly transparent to the RF current density

J_c of GB is not large enough to transmit J(x) above a penetration field:

$$H > H_p \simeq \lambda J_c \simeq H_c J_c/J_d$$

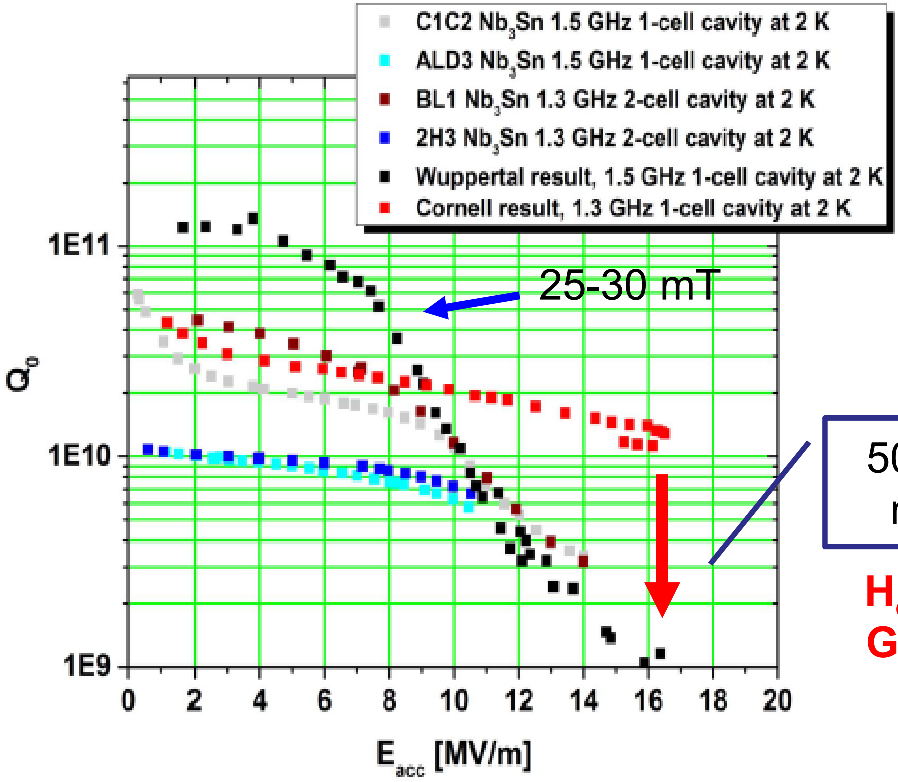
For **$J_c = 0.1J_d$,** Abrikosov-Josephson vortices penetrate in and out of GBs in Nb_3Sn at H > 20-50 mT

Penetration of vortices along GBs

Field onset of penetration for Josephson vortices

$$H > H_p \simeq \lambda J_c \simeq H_c J_c / J_d$$

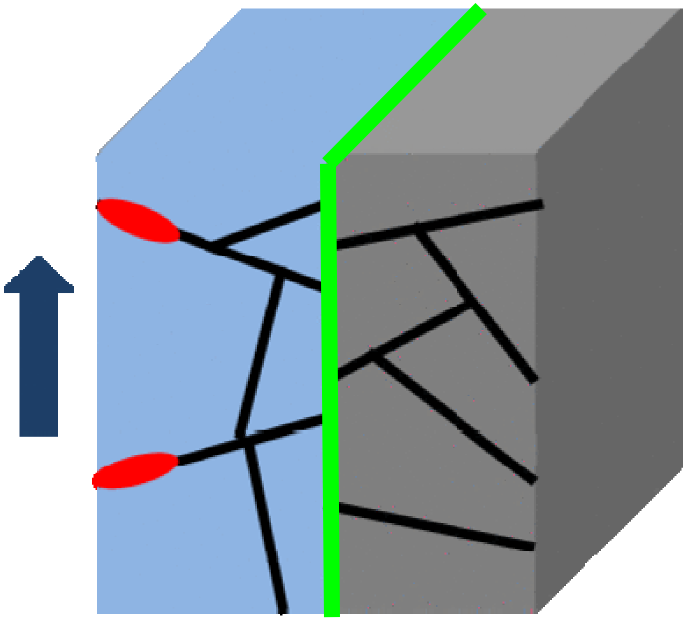
Higher H_c = 540 mT for Nb_3Sn can result in better high-field SRF performance only if GBs are strongly coupled, **$J_c > 0.2 J_d$**



25-30 mT

50-60 mT

H_{c1} or GBs?



Mismatch of GB structures in S coating layers and the Nb cavity: I layer intercepts AJ vortices

Penetration of AJ vortices along GBs does not go beyond the first S layer

Josephson vortex in a weak JJ

$$\ddot{\theta} + \eta\dot{\theta} = \theta'' - \sin\theta + \beta(t)$$

- sine-Gordon equation for the Josephson phase difference. Moving J vortex at η = 0:

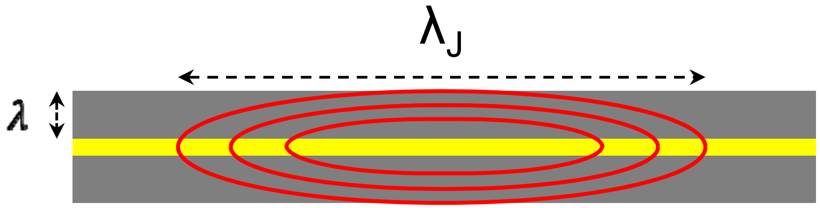
$$\theta(x,t) = 4\tan^{-1}\exp\left[\frac{x - vt}{\lambda_J\sqrt{1-(v/c_s)^2}}\right]$$

$$\lambda_J = \left(\frac{c\phi_0}{16\pi^2\lambda J_c}\right)^{1/2} \sim \sqrt{\xi\lambda}\left(\frac{J_d}{J_c}\right)^{1/2}$$

- $c_s = \omega_J\lambda_J$ (Swihart velocity)
- Weak low-J_c junction:

$$\lambda_J \gg \lambda, \quad J_c \ll \frac{J_d}{\kappa}, \quad \kappa = \frac{\lambda}{\xi} \simeq 20 - 40$$

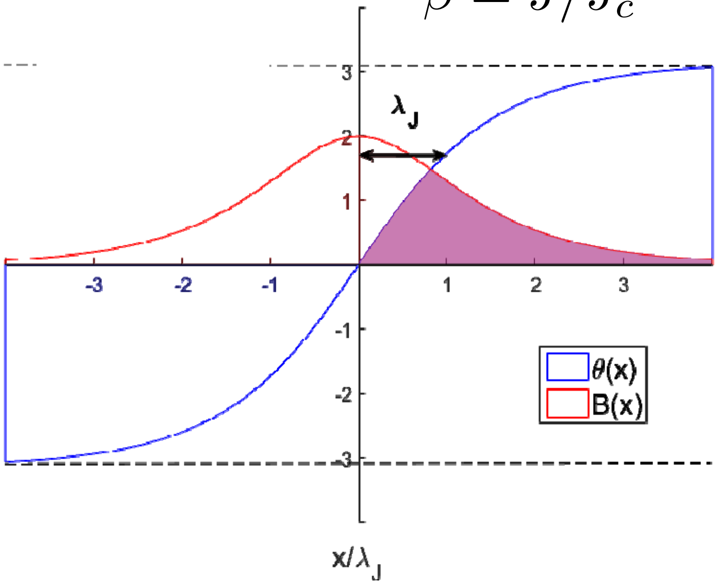
- Fields $H \ll H_c/\kappa \simeq 20 - 30$ mT for Nb_3Sn
- As v increases J vortex **shrinks** at η << 1 and **expands** at η >> 1



$$\omega_J = (2\pi c J_c/C\phi_0)^{1/2},$$

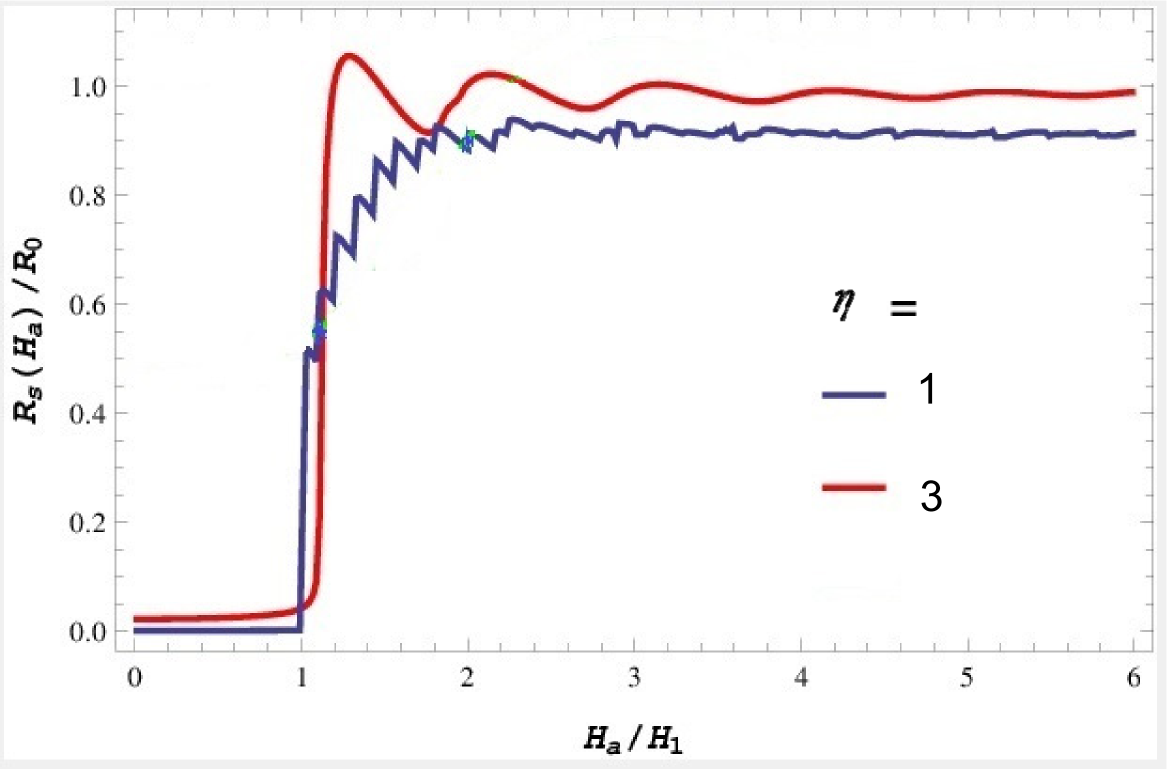
$$\eta = 1/RC\omega_J,$$

$$\beta = J/J_c$$



J vortex described by SG eq. cannot move faster that c_s and remains stable at any current $J < J_c$

Field-dependent surface resistance



- Sharp jump at the onset of penetration of J vortices
- $R_s(H)$ is not linear in the field amplitude.
- Penetration of J vortices can trigger transition to the normal state

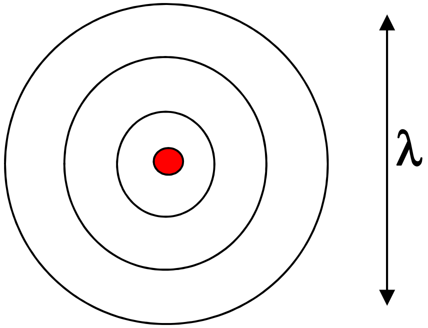
Strongly coupled GBs

- General eq. for the phase difference $\theta(x,t)$

$$\ddot{\theta} + \eta\dot{\theta} = \frac{\lambda_J^2}{\pi\lambda}\int_{-\infty}^{\infty} K_0\left[\frac{|x-u|}{\lambda}\right]\frac{\partial^2\theta}{\partial u^2}du - \sin\theta + \beta$$

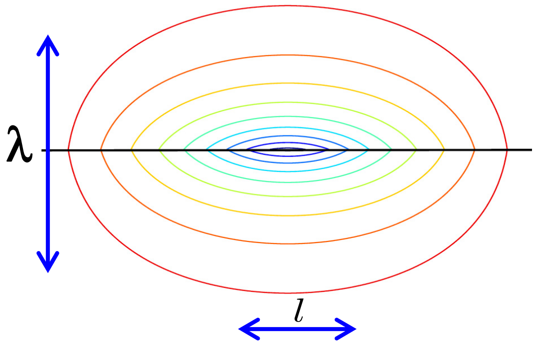
Gurevich, Phys. Rev. B 46, 3187 (1992); 65, 214531 (2002)

A



Low-J_c JJ: Josephson vortices in which $\theta(x,t)$ varies slowly over $\lambda \ll \lambda_J$ so that $K_0(|x-u|/\lambda) \to \pi\lambda\delta(x-u)$ and the integral eq. reduces to the sG eq.

AJ



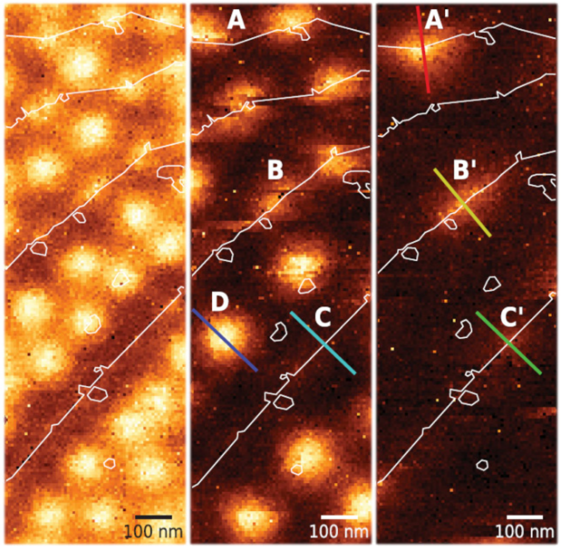
High-J_c JJ: Mixed Abrikosov-Josephson (AJ) vortices with no normal core but a phase core of length:

$$l = \frac{\lambda_J^2}{\lambda} \simeq \xi\frac{J_d}{J_c}$$

The general integral equation take into account Cherenkov radiation of vortices which is missing in the sine-Gordon equation

Observations of AJ vortices

- Transport measurements on grain boundaries, thin film junctions and layered superconductors
- STM imaging of AJ vortices in monolayer step junctions



VOLUME 88, NUMBER 9 PHYSICAL REVIEW LETTERS 4 MARCH 2002

Flux Flow of Abrikosov-Josephson Vortices along Grain Boundaries in High-Temperature Superconductors

A. Gurevich,[1] M. S. Rzchowski,[1,2] G. Daniels,[1] S. Patnaik,[1] B. M. Hinaus,[3] F. Carillo,[4] F. Tafuri,[4] and D. C. Larbalestier[1]
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(Received 27

PRL 111, 117002 (2013) PHYSICA

Evidence for Nonlocal Electrodynamics in Planar Josephson Junctio

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(Received 2 May 2013; published 13 September 2013)

We stud …mperature dependence of the critical current modulation $I_c(H)$ for two types of planar Josephson …Nb/CuNi/Nb and a high-T_c $YBa_2Cu_3O_{7-\delta}$ bicrystal grain-boundary junction. …ventional behavior, described by the local sine-Gordon equation. …tively different: the $I_c(H)$ modulation field ΔH bec… …he penetration of Josephson

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nature physics LETTERS

Direct observation of Josephson vortex cores

Dimitri Roditchev[1,2], Christophe Brun[1], Lise Serrier-Garcia[1], Juan Carlos Cuevas[3], Vagner Henrique Loiola Bessa[4], Milorad Vlado Milošević[4,5], François Debontridder[1], Vasily Stolyarov[1] and Tristan Cren[1]*

Superconducting cor
superconductors sep
barrier, allowing a dis

PRL 113, 247004 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Imaging Josephson Vortices on the Surface Superconductor Si(111)-($\sqrt{7}\times\sqrt{3}$)-In using a Scanning Tunneling Microscope

Shunsuke Yoshizawa,[1] Howon Kim,[2] Takuto Kawakami,[1] Yuki Nagai,[3] Tomonobu Nakayama,[1] Xiao Hu,[1] Yukio Hasegawa,[2] and Takashi Uchihashi[1,*]
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(Received 19 March 2014; published 10 December 2014)

ARTICLES nature materials

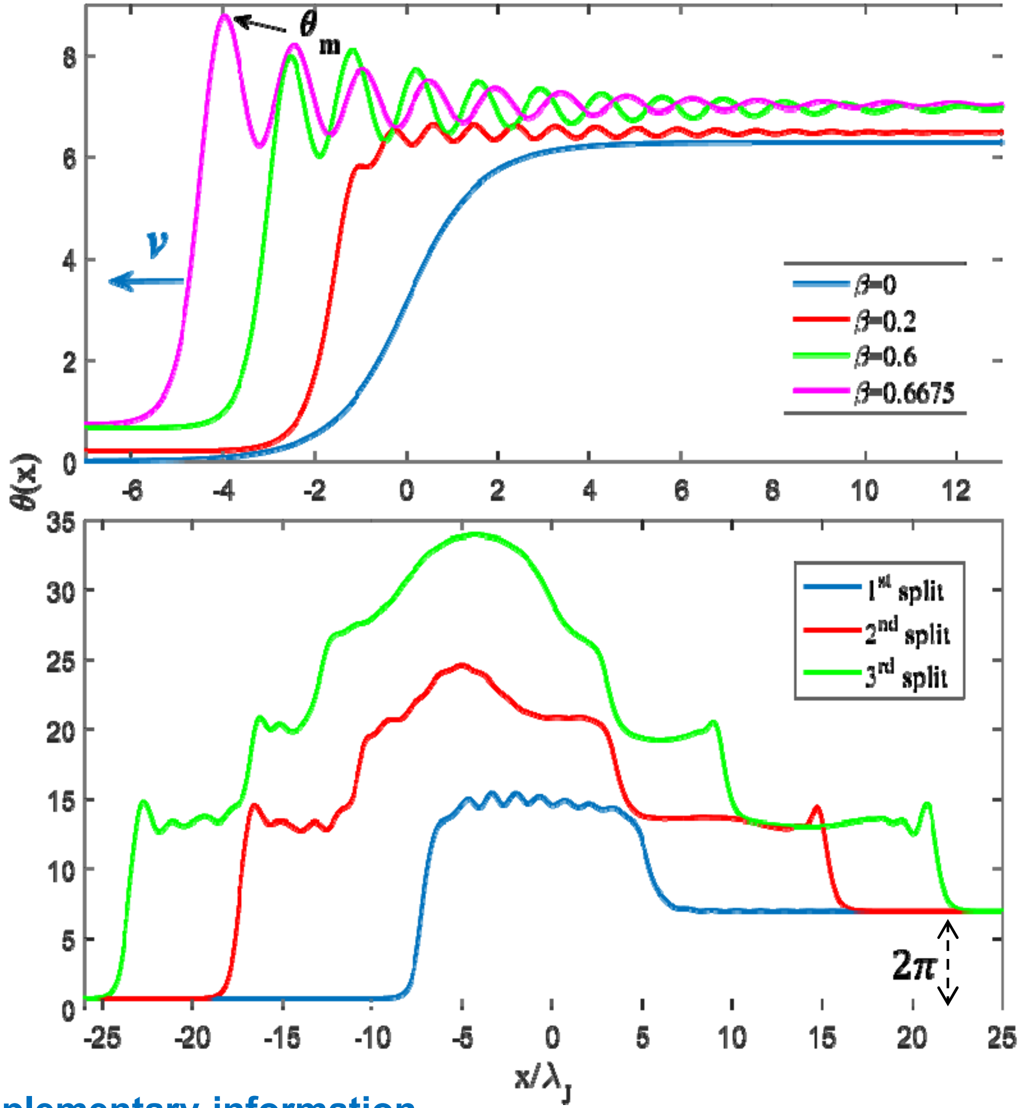
Transition from slow Abrikosov to fast moving Josephson vortices in iron pnictide superconductors

Philip J. W. Moll[1]*, Luis Balicas[2], Vadim Geshkenbein[3], Gianni Blatter[3], Janusz Karpinski[1], Nikolai D. Zhigadlo[1] and Bertram Batlogg[1]

Iron pnictides are layered high T_c superconductors with moderate material anisotropy and thus Abrikosov vortices are expected in the mixed state. Yet, we have discovered a distinct change in the nature of the vortices from Abrikosov-like to Josephson-like in the pnictide superconductor SmFeAs(O,F) with $T_c \sim$ 48–50 K on cooling below a temperature $T^* \sim$ 41–42 K, despite its moderate electronic anisotropy $\gamma \sim$ 4–6. This transition is hallmarked by a sharp drop in the critical current and accordingly a jump in the flux-flow voltage in a magnetic field precisely aligned along the FeAs layers, indicative of highly mobile vortices. T^* coincides well with the temperature where the coherence length ξ_c perpendicular to the layers matches half of the FeAs-layer spacing. For fields slightly out-of-plane (>0.1°–0.15°) the vortices are completely immobilized as well-pinned Abrikosov segments are introduced when the vortex crosses the FeAs layers. We interpret these findings as a transition from well-pinned, slow moving Abrikosov vortices at high temperatures to weakly pinned, fast flowing Josephson vortices at low temperatures. This vortex dynamics could become technologically relevant as superconducting applications will always operate deep in the Josephson regime.

Instability of underdamped J vortex

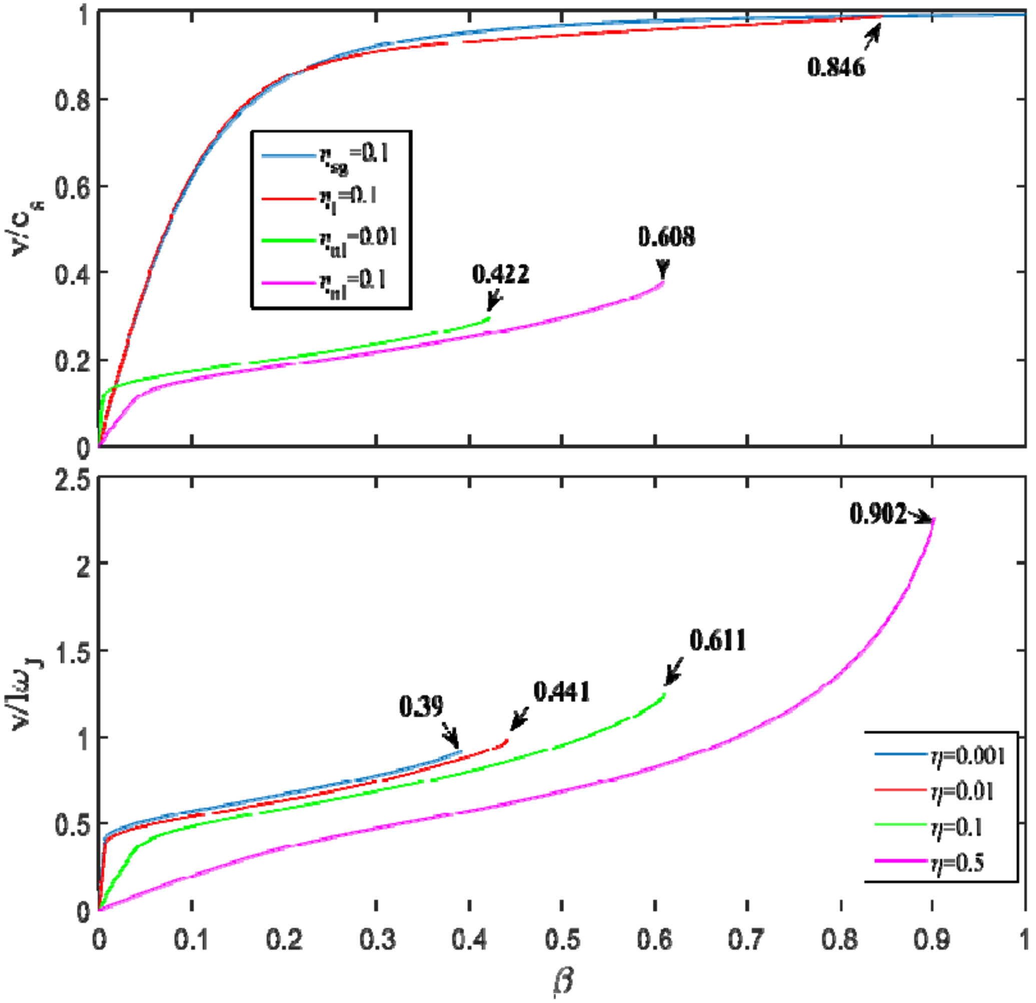
- Trailing tale of **Cherenkov radiation** with the amplitude increasing with β
- Instability occurs as a **π junction** critical nucleus with $5\pi/2 < \theta < 3\pi$ appears behind a moving vortex
- Cascade of **v-av pairs**
- Formation of an expanding **phase pile**, initial 2π phase difference is preserved
- Vortices at the edges move close to **Swihart velocity** or even higher

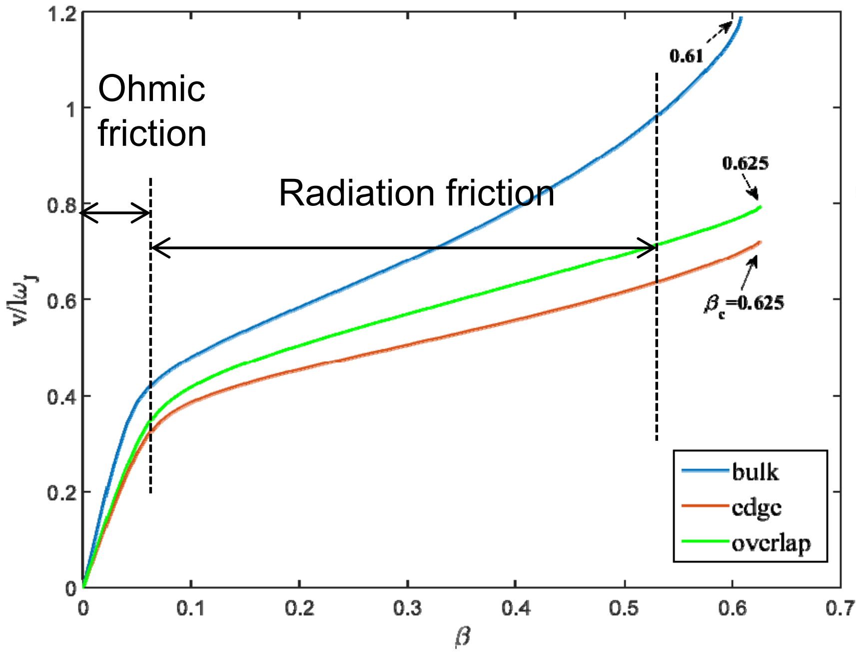


http://www.nature.com/articles/srep17821#supplementary-information

I-V characteristics

- Small currents → Ohmic friction
- Large currents → Cherenkov radiation friction
- Instability at $J \ll J_c$
- Similar behavior in different geometries





H_{c1} and superheating field for GB vortices

Weakly coupled GBs with $J_c \ll J_d/\kappa$

$$B_{c1}^J = \frac{\phi_0}{\pi^2\lambda\lambda_J} \approx B_c\sqrt{\frac{J_c}{\kappa J_d}}, \qquad B_s^J = \frac{\pi}{2}B_{c1}^J$$

Both B^J_{c1} and B^J_s are much smaller than B_c, particularly for Nb_3Sn with $\kappa = \lambda/\xi$ = 20--30

Strongly coupled GBs with $J_c > J_d/\kappa$

Gurevich, Phys. Rev. B 46, 3187 (1992)

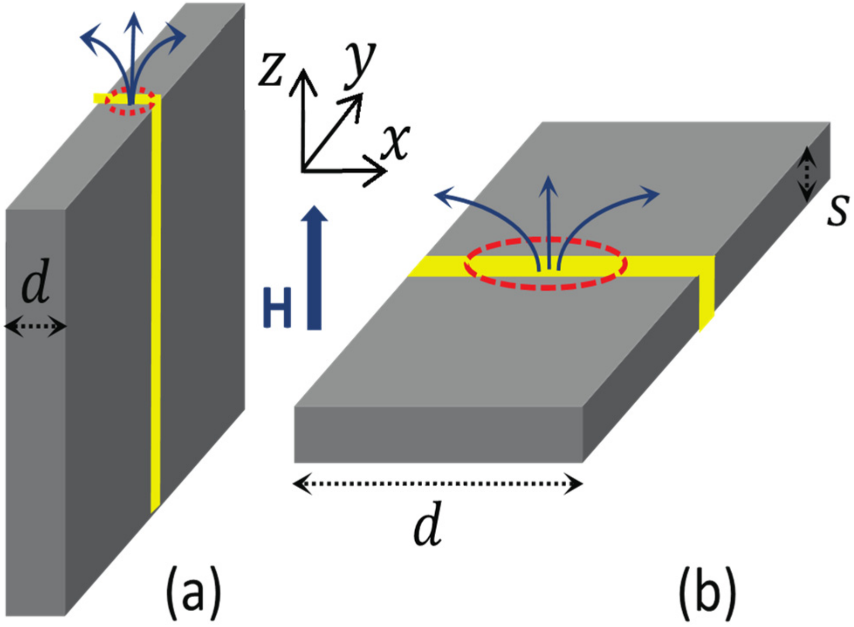
$$B_{c1}^{AJ} = \frac{\phi_0}{4\pi\lambda^2}\left(\ln\frac{\lambda}{l} + 0.423\right), \qquad B_s^{AJ} = \mu_0\lambda J_c = B_c\frac{J_c}{J_d}$$

Here $B_{c1}^{AJ} \simeq B_{c1}^{A}$ but the AJ superheating field B_s^{AJ} can be much larger than B_{c1}^{AJ} if:

1. J_c is of the order of J_d for a large – κ superconductor like Nb_3Sn
2. GBs do not have edge defects which locally reduce J_c down to $J_c \sim J_d/\kappa$

V-AV pair production in a GB in a film

- What happens when expanding phase pile hits the edges of the junction?
- How is the Cherenkov vortex pair production affected by the size effects?
- Acceleration of vortices due to their attraction to the edges causes additional radiation (vortex bremsstrahlung)
- Change of the structure of moving vortices in a finite junction
- Dynamic transition of driven vortices into phase slips



Vortices parallel or perpendicular to a thin film JJ

Numerical simulations

- Strongly-coupled GB in a thin film: length d is smaller than λ:

$$\ddot{\theta} + \eta\dot{\theta} + \sin\theta - \beta(x,t) = \epsilon\int_{-1/2}^{1/2} \ln\left|\frac{2}{\sin\pi x - \sin\pi u}\right|\theta''(u)du,$$

$$\epsilon = \frac{l}{\pi d} = \frac{c\phi_0}{16\pi^3\lambda^2 d J_c}$$

- Small gradient in $\beta(x,t) = (1-kx)\beta(t)$ due to weak screening facilitates penetration of vortices from the edge at $x = -1/2$.

- Both dc and ac currents $\beta(t) = \beta_0\cos\omega t$

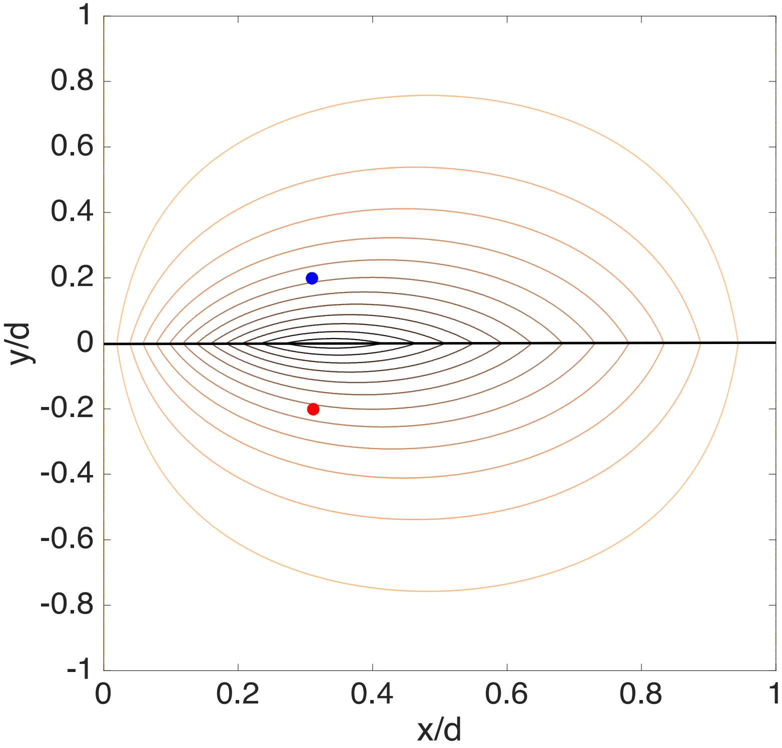
- Interaction of vortices with either edge or bulk defects

- Simulations were done at $\varepsilon = 0.002$, $k = 0.02$, $\omega = \pi/30$ and different η

Exact dynamic solution for η>> 1

$$\theta(x,t) = \chi + 2\tan^{-1}\left[\frac{\sin\pi u \sinh\pi l}{\cos\pi u\cosh\pi l - \cos\pi x}\right]$$

u(t) is the coordinate of the AJ vortex core
l(t) is the length of the AJ vortex core
χ(t) is the phase difference due to external current



Vortex solution disappears if :

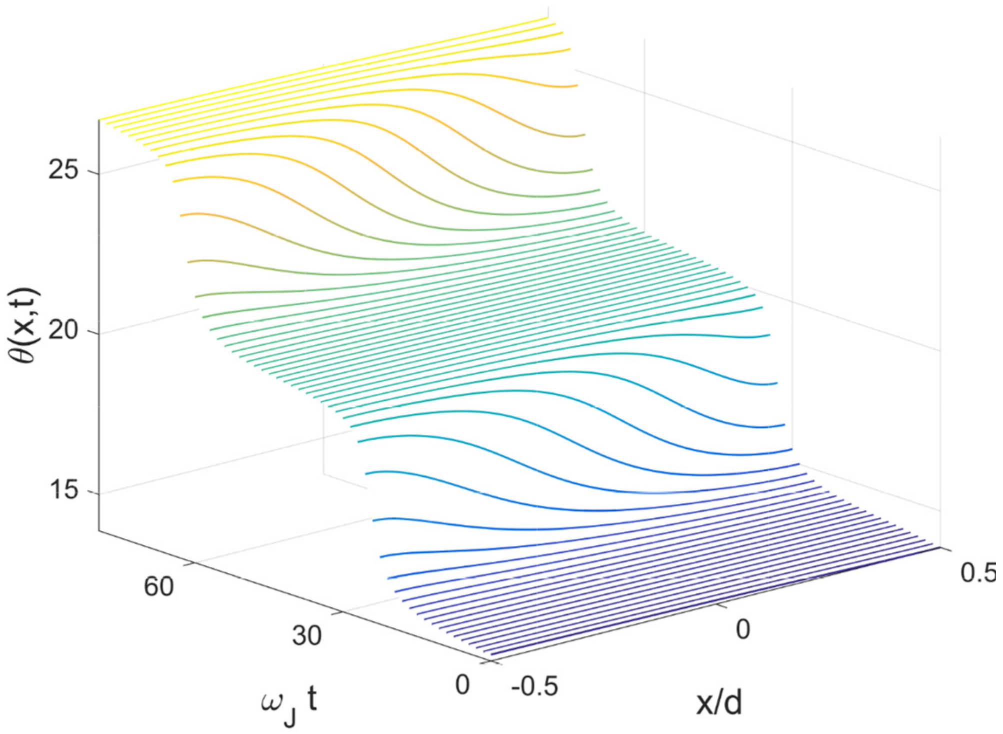
$$d < d_c = \frac{\pi l_0}{\sqrt{1-(J/J_c)^2}}$$

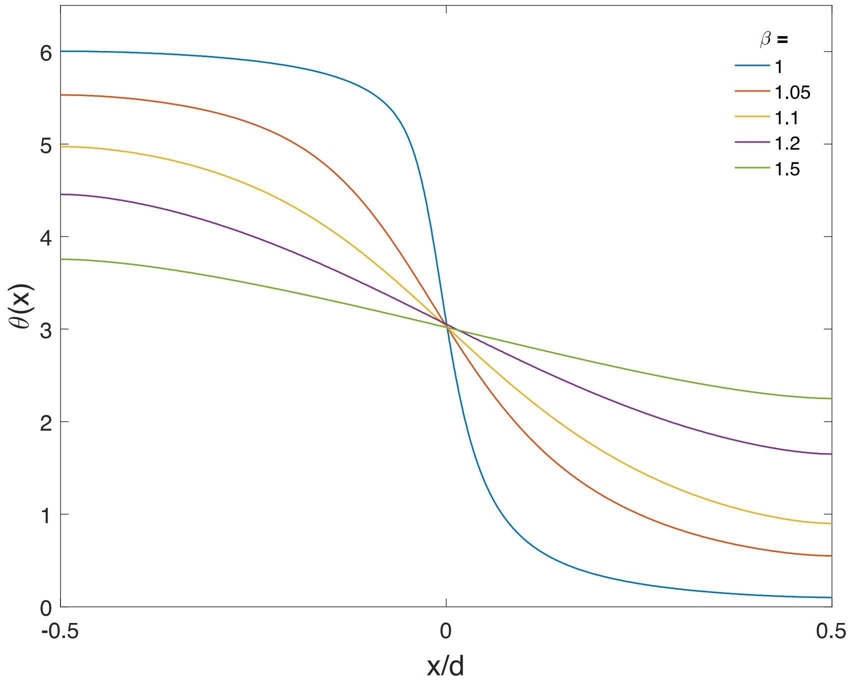
- Similar to A vortices in films

  (K.K. Likharev, RMP, 51, 101 (1979).

- Transition of the AJ vortex into a phase slip in which the whole junction switches to a uniform resistive state.

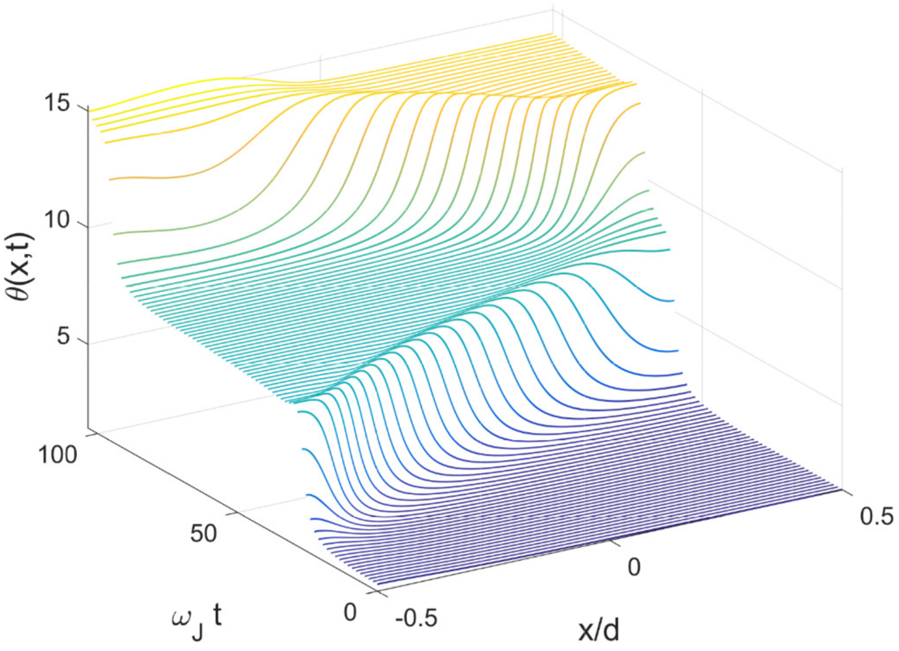
Overdamped GB (η=2)

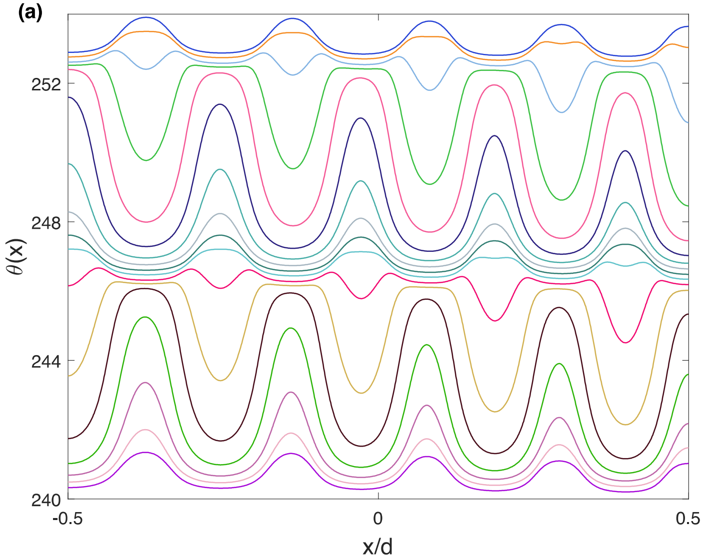


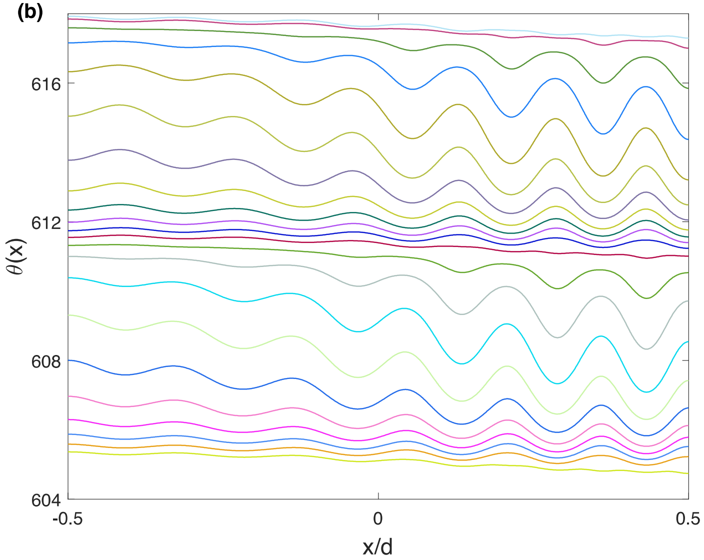


- Overdamped vortex expands as it moves faster
- Dynamic transition of a moving vortex to a phase slip as current increases
- Cherenkov radiation and vortex bremsstrahlung is suppressed
- No V-AV pair production

Weaker damping (η=1)



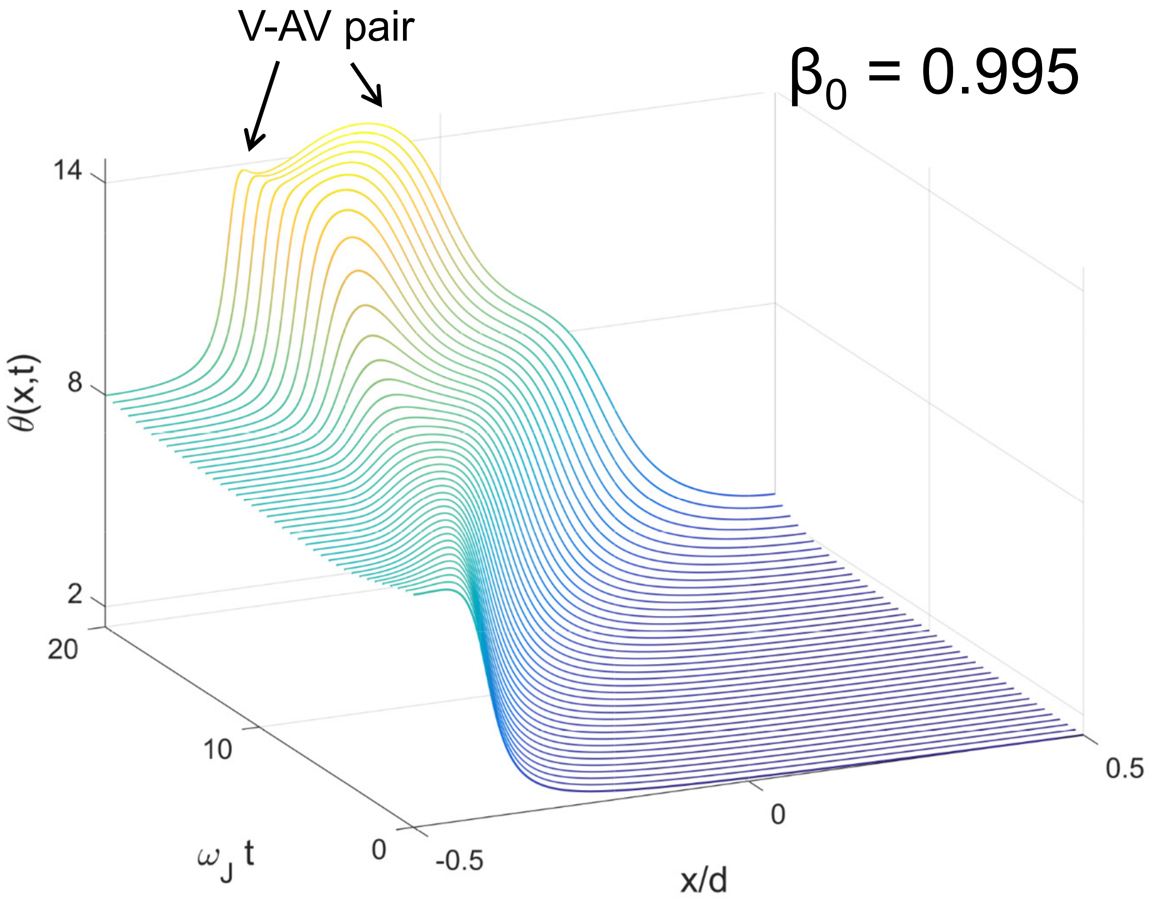




- Radiation wakes become apparent but no generation of V-AV pairs occurs
- Standing nonlinear waves as I increases
- Phase slips at higher currents

Moderately under-damped GB ($\eta = 0.7$)

- Vortex generates V-AV pairs at I slightly above the penetration threshold
- Multiple pair production and reflection from edges result in standing waves
- Standing waves evolve into phase slips as current increases
- V-AV pair production in a finite JJ occurs at larger than in infinite JJ

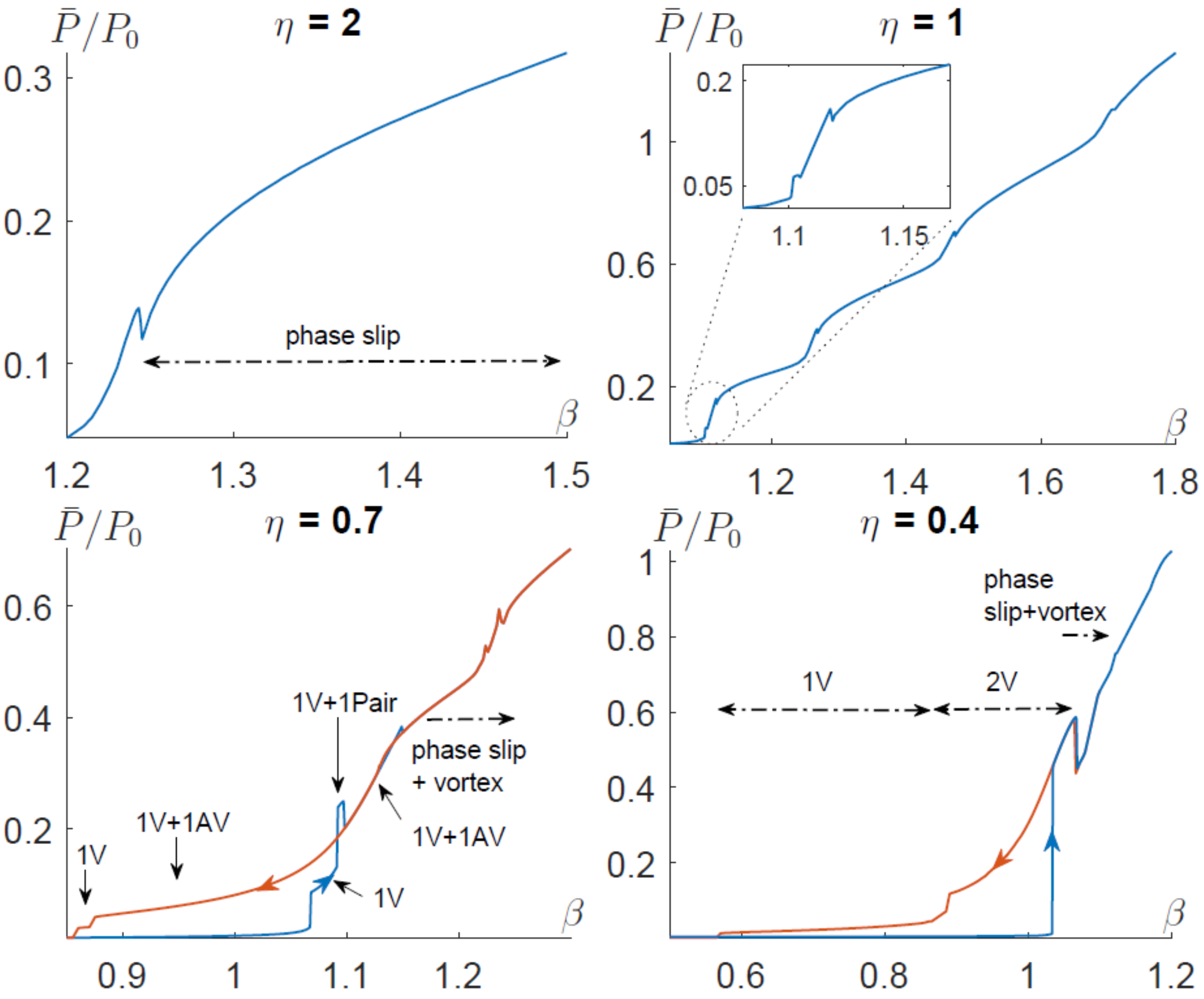


V-AV pair

$\beta_0 = 0.995$

RF power

- Transition from oscillalting to ballistic penetration of vortices as the field increases
- Staircase dependence of P(H) due to increasing the number of vortices in the junction
- Hysteretic dependencies of P(H) in underdamped junctions
- Dynamic transition of vortices into phase slips switches the entire GB into highly resistive state.

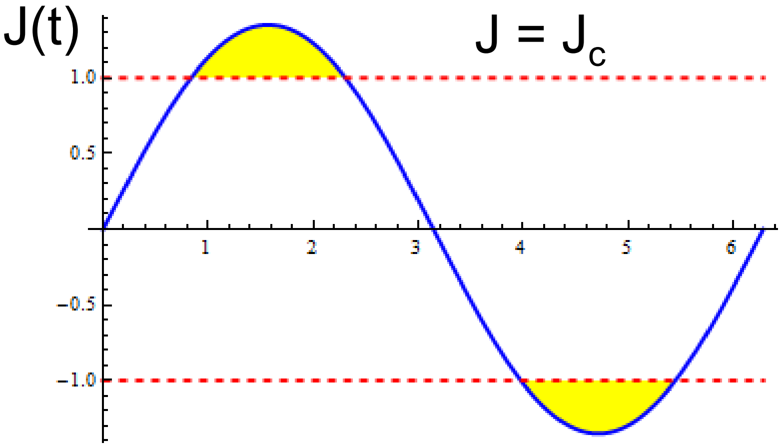


RF losses in the phase slip state

- Dynamic transition from vortices to phases slips occurs due to current-induced expansion of vortices in overdamped GB and Cherenkov instability in underdamped GBs.

- Dissipated power for $J(t) = J_0 \sin \omega t$

$$P \simeq \frac{R}{2}(J_0^2 - J_c^2)$$



Estimate for Nb_3Sn, assuming $R_\square \approx \rho t$, with $t = 1$ nm, $\rho = 1$ μΩm, $J_0 = 1.1J_c$, $J_c = 0.5J_d$ $J_d = B_c/\mu_0\lambda$, $B_c = 540$ mT, $\lambda = 100$ nm:

$P = 400$ MW/m^2, so that a single 1x1 μm GB dissipates 0.4 mW.

RF losses above the AJ superheating field in a polycrystal with strongly coupled GBs and a micron grain size can be some 6 orders of magnitude higher than $P = R_s B_a^2/2\mu_0^2$ for $B_a = 200$ mT and $R_s = 20$ nOhm.

GB losses above H_s^{AJ} are of the order of the losses produced by avalanche penetration of A vortices which quench the cavity

Summary

- Grain boundaries do not affect much the surface resistance at low fields but can become crucial performance-limiting defects in Nb_3Sn even at moderate fields.

- Achieving breakdown fields in Nb_3Sn clad Nb cavities above 50 mT may require strongly-coupled grain boundaries with $J_c \sim J_d$ which do not block RF currents up to $H \simeq H_c$

- New physics of vortices in strongly-coupled GBs: Cherenkov instability and vortex-antivortex pair production in underdamped GBs at currents below J_c

- Dynamic vortex-phase slip transition in thin film GBs under RF fields

- Hysteretic power losses as a function of RF field

- Explosive increase of RF losses above the GB vortex penetration field