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# **Pushing Nb Bulk Performances**

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EASISchool 3: Superconductivity and its applications 29 Sep 2020

#### **Particle acceleration with SRF cavities**

- Standing-wave structures accelerating trains of charged particles bunches moving in phase with the EM field
- Frequencies from ~100 MHz up to several GHz
- Tens of MV/m gradients with high Q factors >10<sup>10</sup>



# Advantage of superconducting RF

- SC cavities reduce the wall dissipation by many orders of magnitude with respect a NC cavity
  - − Cu 1.5 GHz:  $R_s$ (300 K)~10 mΩ,  $R_s$ (4 K)~1.3 mΩ
  - Nb 1.5 GHz:  $R_s$ (4 K)~500 nΩ,  $R_s$ (2 K)~20 nΩ
- Affordable continuous wave (CW) (continuous train of particles bunches is accelerated) and long pulse operation
- Larger beam pipe aperture for *better beam quality* (lower beam impedance)









# Advancement in SRF technology allows for the realization of state-of-the-art and future machines



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# We talk about bulk Nb, but the performance are still determined at the nanometer scale!



#### We want mirror-like surfaces to have good performance



# Surface processing is key!



# Extensive infrastructure needed for processing, testing and CM production







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 $E_{acc}$  (MV/m)

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# RF SUPERCONDUCTIVITY BASIS (JUST AS A REMINDER)

#### **Discovery of superconductivity and zero DC resistivity**

• H. K. Onnes discovers superconductivity in 1911



- Zero DC resistivity:
  - First London equation:

$$\boldsymbol{E} = \frac{d}{dt} \left( \frac{m}{n_s e^2} \boldsymbol{J} \right) = \frac{d}{dt} (\Lambda \boldsymbol{J})$$

H. K. Onnes, Comm. Leiden **120b**, **122b**, **124c** (1911) F. London and H. London, Proc. R. Soc. A **149**, 71 (1935)



#### **Meissner effect**

 A superconductor behaves as a perfect diamagnetic material

$$B = \mu_0(H + M) = 0 \quad \rightarrow \quad M = -H$$

• Second London equation:

 $\nabla \times (\Lambda J) = -B$  $B(x) = B(0)e^{-x/\lambda_L} \quad ; \quad \lambda_L = \sqrt{\frac{\Lambda}{\mu_0}} = \sqrt{\frac{m}{\mu_0 n_s e^2}}$ 

T>T T<T<sub>C</sub> - M H<sub>c</sub> Η



B in a superconductor decays exponentially with characteristic length  $\lambda_L$ 

W. Meissner *et al.*, Physica Naturwissenschaften **21**, 787 (1933) F. London and H. London, Proc. R. Soc. A **149**, 71 (1935)

#### Local and non-local description

- London (local description, valid if  $\lambda \gg \xi$ )
- Pippard (non-local description, valid always)
  - current density at each point depends on volume defined by the coherence length  $\xi$  which is function of the electron mean-free-path  $\ell$



## **Type-I and type-II superconductors**

- Type-I ( $\kappa = \lambda/\xi < 1/\sqrt{2}$ )
  - Below B<sub>c</sub> (thermodynamic critical field) Meissner state
  - Above  $B_c$  normal-conducting state
- Type-II ( $\kappa = \lambda/\xi > 1/\sqrt{2}$ )
  - Below  $B_{c1}$  Meissner state
  - Above  $B_{c1}$  mixed state
    - Magnetic flux vortices
  - Above  $B_{c2}$  normal-conducting state
- Nb has  $\kappa \gtrsim 1$ 
  - Marginally Type-II depending on electron mean-free-path



# **Microscopic (BCS) theory**

- Electrons (fermions) near E<sub>F</sub> have attractive interaction by exchanging phonons generating Cooper pairs (bosons)
- Pairs condensation at ground state  $E_F \Delta_0$ 
  - $\Delta_0 \cong 1.55 \text{ meV}$  (Nb)
  - coherence length  $\xi$ ~dimension of cooper pairs
- Unpaired electrons (quasiparticles) above the gap:
  - $n_n(T) \cong n_n \cdot e^{-\Delta/\kappa T}$





#### **Mattis-Bardeen surface resistance**

The surface resistance of superconductors is temperature dependent:

$$R_{BCS}(T,\omega,l) \sim \frac{A(l)\omega^2}{T} e^{-\frac{\Delta}{\kappa_B T}}$$

And it is due to:

- i. <u>Dissipation introduced by</u> <u>thermal-exited quasi-particles</u>
- ii. Absorption of photons by Cooper pairs and consequent pair breaking ( $\hbar \omega \ge 2\Delta$ )



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D. C. Mattis and J. Bardeen, Phys. Rev. 111, 412 (1958)

#### **Residual resistance**

In first approximation, the surface resistance has a T-independent term. Phenomenologically, we can define:

$$R_s(T) = R_{BCS}(T) + R_0$$

Where  $R_0$  is the residual resistance, due to:

- i. Trapped vortices
- ii. Sub-gap states
- iii. Niobium hydrides
- iv. Damaged layer

V. ...



# **Superheating field**

- Ginzburg-Landau definition
  - Upper magnetic field limit of Meisner state metastability
    - Type-I SC:  $B_{sh} > B_c$
    - Type-II SC:  $B_{c1} < B_{sh} < B_{c2}$
- Bean-Livingston definition
  - Field at which the energy barrier for vortex nucleation is zero
    - Definition valid for Type-II superconductors

Transtrum, et al. Phys. Rev. B **83**, 094505 (2011) J. Matricon and D. Saint-James, Physics Letters A **24A**, 14 (1967) C. P. Bean and J. D. Livingston, Phys. Rev. Lett. **12**, 14 (1964)



# ELECTROPOLISHED CAVITIES AND "HIGH-FIELD Q-SLOPE"

#### **Electropolished (EP) cavities**



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### Where does the HFQS come from?



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## Why 800 C baking?

- The baking at 800 C in vacuum was found to be the remedy to the socalled "Q-disease"
- Q-disease was proposed in the past to be caused by excess hydrogen, which forms nonsuperconducting niobium hydrides (Nb<sub>x</sub>H<sub>y</sub>) upon cooldown



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# **Niobium hydrides Nb<sub>x</sub>H<sub>y</sub> precipitation**

- Upon cooldown interstitial H in Nb (α phase) precipitates forming Nb<sub>x</sub>H<sub>y</sub>
- H concentration and cooldown speed determines dimension and density of precipitates





# Nb<sub>x</sub>H<sub>y</sub> precipitates formation in real-time

#### Laser confocal microscope with cryo-stage









#### **Details on Nb<sub>x</sub>H<sub>y</sub> precipitates**

50 um Hydrides first appear T=160K T=300K T=140K Large hydrides are the origin of Q-disease T=6K T=100K

F. Barkov, et al., Phys. Rev. ST Accel. Beams 15, 122001 (2012)
F. Barkov, et al., Y. Trenikhina, and A. Grassellino, J. Appl. Phys. 114, 164904 (2013)
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## **Details on Nb<sub>x</sub>H<sub>v</sub> precipitates**

50 um

## Second (smaller) phase of hydride forms ⇒ does it have something to do with HFQS?



160K



T=140K





Large hydrides are the origin of Q-disease

F. Barkov, et al., Phys. Rev. ST Accel. Beams 15, 122001 (2012)
 F. Barkov, et al., Y. Trenikhina, and A. Grassellino, J. Appl. Phys. 114, 164904 (2013)
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## Origin of the "high-field Q-slope"



Hypothesis: can it be the Q-disease "in miniature" – same mechanism, but nanohydrides instead of micron-size ones?

 Need free H near surface after 800 C baking!



### Near-surface H present even after 800 C degasing



A. Romanenko and L. V. Goncharova, 2011 Supercond. Sci. Tech. 24, 105017

Q-disease is eliminated by the 800 C H degassing (bulk H content drastically reduced), but the **near-surface H-rich layer remains** 

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Courtesy of A. Romanenko

#### Nano-hydrides formation upon cooldown

## Not 120C baked sample



# Courtesy of A. Romanenko

A. Romanenko, F. Barkov, L. D. Cooley, A. Grassellino, Supercond. Sci. Technol. 26 (2013) 035003 - selected for highlights of 2013



## Proximity effect model of the "high field Q slope"



A. Romanenko, F. Barkov, L. D. Cooley, A. Grassellino, Supercond. Sci. Technol. 26 (2013) 035003 – selected for highlights of 2013

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#### **Investigating with cavity cutouts**



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#### Courtesy of A. Romanenko

## **TEM evidence for nanohydrides**

#### Measurements performed at Univ. of Illinois Urbana-Champaign

Direct **nano-area electron diffraction (NED)** phase characterization of the surface of the SRF cavity cutouts before and after in situ mild vacuum bake at room temperature and at 94K







#### **<u>94K</u>**: stoichiometric Nb hydride phases!



TEM diffraction on cavity cutouts confirms the existence of nanohydrides

 Supports our proximity effect model

Y. Trenikhina, A. Romanenko, J. Zasadzinski, Proceedings of SRF'2013, TUP043



#### **Cryo-AFM evidence of nanohydrides**



120 C BAKING

#### **120 C baked cavities**



#### Courtesy of A. Romanenko

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### **Temperature mapping**



Array of 576 thermometers attached to the outside cavity walls allows mapping wall dissipation



#### Courtesy of A. Romanenko

### **Evidence for 120C baking effect**

#### Measurements performed at Univ. of Illinois Urbana-Champaign



120C baking leads to the decrease in size/density of the nanohydrides



## **120C bake leads to strong Meissner screening changes**

A. Romanenko, A. Grassellino, F. Barkov, A. Suter, Z. Salman, T. Prokscha, Appl. Phys. Lett. **104**, 072601 (2014)



#### Courtesy of A. Romanenko Positron annihilation studies on cavity cutouts

Collaboration with Bath University (UK) and Western University (Canada)

A. Romanenko, C. J. Edwardson, P. G. Coleman. P. J. Simpson. Appl. Phys. Lett. 102. 232601 (2013)



- Positron annihilation spectroscopy: 120C baking results in "doping" of the first ~50 nm from the surface with vacancies
  - So-called superabundant vacancy formation mechanism manifested in niobium [Y. Fukai and N. Okuma, Phys. Rev. Lett. 73, 1640 (1994)]

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### Effect of 120C baking

#### Courtesy of A. Romanenko

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A. Romanenko, C. J. Edwardson, P. G. Coleman, P. J. Simpson, Appl. Phys. Lett. 102, 232601 (2013)

#### Courtesy of A. Romanenko

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### Effect of 120C baking

## Cooling down of 120C baked niobium



Supports the proximity model

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NITROGEN DOPING AND "ANTI-Q-SLOPE"

## The discovery of N-doping



## **N-doping is game changing for CW accelerators!** Refrigeration cost is of the order of several tens of millions \$



## **Nitrogen doping**



## Nitrogen doping





#### **Origin of the anti-Q-slope**



A. Grassellino et al, Supercond. Sci. Technol. **26** 102001 (2013) - Rapid Communications A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

#### **BCS Surface Resistance**

$$R_S(2K) = R_{BCS}(2K) + R_0$$



M. Martinello et al., App. Phys. Lett. 109, 062601 (2016)

- ✓ Mean free path of N-doped cavities close to theoretical minimum of  $R_{BCS}$
- ✓ The reduced energy gap  $\Delta/\kappa_B T_c$ seems to increase with  $E_{acc}$  for Ndoped cavities causing the decreasing of  $R_{BCS}$



### Anti-Q-slope triggered by higher frequencies



- Anti-Q-slope (decreasing of  $R_{BCS}$  with  $B_p$ ) is triggered by higher frequencies and by high  $B_p$
- EP and 120 C baking cavities also show  $R_{BCS}$  decreasing with  $B_p$  for higher frequency

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M. Martinello et al., Phys. Rev. Lett. 121, 224801 (2018)

## **Comparison with Mattis-Bardeen model**

- Agreement with Mattis-Bardeen surface resistance ONLY at low B<sub>p</sub> values
- As expected, MB theory fails at high B<sub>p</sub> values



M. Martinello et al., Phys. Rev. Lett. 121, 224801 (2018)



## **Possible theories**

A. Gurevich, Phys. Rev. Lett. 113, 087001 (2014)

- Assumes a "frozen Fermi-Dirac distribution" of quasiparticles and a smeared density of states
- Can fit  $R_{BCS}$  vs  $B_p$  at 1.3 GHz
- Wrong dependence as a function of frequency!

Anti-Q-slope behavior in superconducting aluminum resonators was observed at very low  $B_p$  amplitudes (and low T, for Al Tc=1.2 K)

[de Visser, et al., Phys. Rev. Lett. 112, 047004 (2014)]

- Described as arising form non-equilibrium effects
  - Stimulated superconductivity due to microwave absorption
- Predicts correct dependence as a function of frequency
- The theory is built around low  $B_p$  approximation
  - No smearing of DoS is considered



-64 dBm

0.2

Temperature (K)

0.1

b

0.3

1.1

#### **Qualitative explanation: thermal equilibrium QP distribution**



#### Qualitative explanation: non-equilibrium QP distribution



#### Qualitative explanation: non-equilibrium QP distribution



#### Qualitative explanation: non-equilibrium QP distribution

How is this related with lower surface resistance?

Equilibrium distribution of QPs

Non-equilibrium distribution of QPs



# TRAPPED-FLUX SURFACE RESISTANCE

## Why do vortices dissipate under RF driving?

- Vortices oscillate driven by the RF current
- Random pinning centers in the

n

la

n

$$R_s(T, B_t) = R_{BCS}(T) + R_{fl}(T)$$

- Part of the EM energy in the resonator is converted into vortex motion
  - Power is dissipated by the vortex
    www we can define a vortex surface resistance R<sub>fl</sub>

PINNING

## **Trapped flux surface resistance**

In first approximation the trapped flux surface resistance is defined as:

$$R_{fl}(B_t) = S B_t = \eta_t S B$$

Where:

- $\eta_t$  is the flux trapping efficiency
- *S* flux sensitivity, in unit of  $n\Omega/mG$
- *B* the magnetic field applied during transition



## What is a pinning site?

- Pinning sites are *material imperfections or defects*:
  - Normal-conducting and dielectric inclusions
  - Grain boundaries
  - Dislocations
  - Local disorder
- Pinning  $\Rightarrow$  minimization of the system energy
  - Vortex = loss in condensation energy
  - Defect = weak or not superconducting site
- An efficient pinning center has *dimension* at least *comparable to the coherence length*  $\xi$ 
  - For niobium  $\xi \cong 10 38 nm$  (purity dependent)
  - $\xi$  is the characteristic variation length of the order parameter in the superconductor



## Possible pinning centers in niobium









- Normal-conducting and dielectric inclusions:
  3-D defects that introduce large κ variation (ex: nano-hydrides in the near-surface area)
- <u>Grain boundaries</u>: 2-D defects in the crystal structure, they define the interface between 2 grains.
  - Low-angle GBs: the misorientation between the two grains is <15 degrees</p>
- <u>Dislocations</u>: areas were the atoms are out of position in the crystal structure.
  - Tangles: after plastic deformation very small grain forms (cells) that are surrounded by tangles of dislocations
- <u>Local disorder</u>: 1-D defects (ex: impurities, vacancies)



## **Trapped flux surface resistance**

In first approximation the trapped flux surface resistance is defined as:

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Where:

- $\eta_t$  is the flux trapping efficiency
- *S* flux sensitivity, in unit of  $n\Omega/mG$
- *B* the magnetic field applied during transition


#### **Magnetic flux expulsion**



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### Fast cool-down helps flux expulsion



- Fast cool-down leads to <u>large thermal</u> <u>gradients</u> → efficient flux expulsion
- Slow cool-down leads to <u>small thermal</u> <u>gradients</u> → poor flux expulsion



A. Romanenko et al., J. Appl. Phys. **115**, 184903 (2014)

## Flux expulsion depends on bulk properties

- Flux expulsion is a bulk property → does not depend on surface treatment
- Not all materials show good flux expulsion, even with large thermal gradient during the SC transition → high T treatments allow to improve materials flux expulsion properties



## Analysis of "as received" materials

- Material that shows good flux expulsion properties after annealing at 800C has bigger grain size in the "as received" condition
- Material with bad flux expulsion properties shows larger density of low-angle GBs (misorientation < 15°)</li>
- Material with bad flux expulsion properties shows <u>larger density of</u> regions with very high <u>local misorientation</u>



#### Ningxia -bad flux expulsion-



## Analysis of "as

Material that shows go flux expulsion proper after annealing at 800



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Material expulsi shows I low-ang (misorie

the "as r Dislocations tangles observed in highly defective regions of as-received material with bad flux expulsion **Dislocation tangles dimension** comparable to  $\xi$  near Tc High likelihood to be efficient pinning centers during explusion

**Material** expulsion properties shows larger density of regions with very high local misorientation

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## Thermodynamic force during cooldown

The Gibbs free energy density defines the stability of vortices in the SC:

$$g = B(H_{c_1}(T) - H)$$

We can define the *thermodynamic force* acting on the vortex as:

$$f = -\frac{\partial g}{\partial x} = -\frac{\partial g}{\partial T}\frac{\partial T}{\partial x}$$

$$f = \frac{2BH_{c_1}(0)T}{T_c^2}\nabla T$$

M. Checchin, TTC, MSU 2017







## **Critical thermal gradient**

The *pinning force acting against the expulsion* is defined in terms of critical current density  $J_c$ :

$$f_p = |\bar{J}_c \times n\bar{\Phi}_0| = J_c B$$

The *minimum thermal gradient needed to expel vortices* is the critical thermal gradient  $\nabla T_c$ :



 $\nabla T_c \propto J_c \propto f_n$ 

M. Checchin, TTC, MSU 2017





## Statistical definition of trapping efficiency

- The probability of expelling vortices with the thermal gradient  $\nabla T_{c_i}$  is  $P(\nabla T_{c_i})$
- The trapping efficiency  $\eta_t$  is function of  $\nabla T_{c_i}$ :

$$\eta_t = \left[1 - P(\nabla T_{c_i})\right]$$

$$P(\nabla T_{c_i}) = \int_0^{\nabla T_{c_i}} p(\nabla T_c) \, d\nabla T_c$$

• The trapped field is then:

$$B_t = \eta_t B = B \left[ 1 - P \left( \nabla T_{c_i} \right) \right]$$

#### M. Checchin, TTC, MSU 2017





### **Comparison with experimental data**

### Good agreement with experimental data

Estimated J<sub>c</sub> in agreement with literature values for Nb  $(1 - 10 \text{ A/mm}^2)$ 



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#### **Trapped flux surface resistance**

In first approximation the trapped flux surface resistance is defined as:

$$R_{fl}(B_t) = S B_t = \eta_t S B$$

Where:

- $\eta_t$  is the flux trapping efficiency
- *S* flux sensitivity, in unit of  $n\Omega/mG$
- *B* the magnetic field applied during transition



#### **Trapped-flux surface resistance measurement**





Trapped flux surface resistance is calculated as:

 $R_{fl} = R_s(1.5 \, K, B_t) - R_s(1.5 \, K)$ 

- $R_s(1.5 K, B_t)$  measured after **slow cooldown** in a known amount of external magnetic field:  $B_t = B$
- *R<sub>s</sub>*(1.5 *K*) measured after fast cooldown in compensated magnetic field: *B<sub>t</sub>* = 0, *R<sub>fl</sub>* = 0
- Measurement are performed at 1.5 K to minimize error on T control ( $R_{BCS} \sim 0$ )



#### Sensitivity

- Bell-shaped trend of *S* as a function of the mean-free-path
- N-doping cavities present higher sensitivity than standard treated cavities
- Light doping needed to minimize trapped flux sensitivity
- Dependence of *S* as a function of the field



OF TECHNOLOGY

M. Martinello et al., App. Phys. Lett. 109, 062601 (2016)

## **Single-vortex motion equation**

In the condition  $B \ll B_{c2}$ , vortex-vortex interaction can be neglected, and the most general form of the vortex motion equation becomes:

$$M\ddot{u}(t,z) + \eta_0 \dot{u}(t,z) = \epsilon u''(t,z) + f_p(u(t,z)) + f_L(t,z)$$

Where:

- *M* is the vortex inertial mass
- $\eta_0$  is the vortex motion viscosity
- $\epsilon$  is the vortex line tension
- $f_p(u(t,z))$  is the pinning force
- $f_L(t, z)$  is the driving force (Lorentz force)

The surface resistance is defined as:

$$R_{fl} = \frac{2B_t \mu_0 f}{\lambda B_p} \int_0^{1/f} \cos \omega t \int_0^\infty \dot{u} \, e^{-z/\lambda} \, dz \, dt$$

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## Zero RF amplitude model

The vortex line tension term was neglected

 $M\ddot{u}(t,z) + \eta_0 \dot{u}(t,z) = \epsilon u''(t,z) + f_p(u(t,z)) + f_L(t,z)$ 

- Pinning force approximated to a linear elastic response along vortex oscillation axis (parabolic approximation of the pinning potential)
- Several pinning centers considered along the depth (z) with pinning potential shape
- Lorentzian function used to describe the pinning potential along z



#### Mean-free-path dependence

Small  $l - \underline{pinning regime} \eta \ll p$ :

$$\rho_1(l, U_0) \approx \frac{\eta(l)\omega^2}{p(l, U_0)^2}$$

 $\rho_1$  increases with l and  $\omega^2$ , decreases with the increasing of  $U_0$ 

Large  $l - \underline{flux} - \underline{flow} regime \eta \gg p$ :

$$\rho_1(l) \approx \frac{1}{\eta(l)}$$

 $\rho_1$  decreases with l, independent on  $\omega$  and  $U_0$ 



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### **Frequency dependence**

- $\omega \ll p/\eta \underline{pinning regime}$ :  $\rho_1(\omega) \sim \omega^2$
- $\omega \gg p/\eta \underline{flux-flow regime}$ :  $\rho_1 = constant$
- Intermediate  $\omega$ :
  - the frequency dependence is rather complex!
- As  $\omega$  increases:
  - higher peak value
  - peak at lower mfp values





#### **Pinning and Flux-flow regimes**



M. Checchin et al., Appl. Phys. Lett. 112, 072601 (2018)



#### **Pinning and Flux-flow regimes**





#### **Pinning and Flux-flow regimes**





### Minimizing $R_s$ at 16 MV/m

The best surface treatment *minimizes* all the surface resistance contributions:

$$R_s(T,B) = R_{BCS}(T) + R_{fl}(B) + R_0$$

For LCLS-II light doping was chosen:

- Very low values of R<sub>BCS</sub>
- Acceptable values of sensitivity
  - Low intrinsic residual resistance



#### **N-doping in Condition of Full Flux-Trapping**



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#### **N-doping in Condition of Full Flux-Trapping**



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...but, what about high gradient applications such as the ILC?



## Standard ILC cavity performance (no trapped field)



# **Standard ILC cavity performance** (5 mG trapped)



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# Standard ILC cavity performance (10 mG trapped)



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## Standard ILC cavity performance (20 mG trapped)



#### Fermilab High Luminosity ILC Workshop (May 2019)

- Significant luminosity improvements are made possible by SRF R&D advances since TDR
- Main result is given in table below by implementing technically feasible changes, ILC baseline luminosity of <u>1.35 x 10<sup>34</sup></u> can be increased

× 14.8

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- Increased number of bunches x 2
- Increased rep rate x 3

Increased  $Q_0 \times 2$ 

- Beam and IP parameters same as ILC baseline
- Effective luminosity with polarization advantage (x 2.5) is <u>20 x 10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup></u> (ILC) vs. 17 x 10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup> (FCC-ee, including multiplier of 2 for multiple interaction points)
- AC power 267 MW (ILC) vs. 282 MW (FCC-ee)
- Capital cost ~7.7B (ILC) vs. 10.5B (FCC-ee)
  - Not including labor or detectors

#### Details in <a href="https://arxiv.org/abs/1910.01276">https://arxiv.org/abs/1910.01276</a>



Based on CERN Courier, 24 January 2019 Details in https://arxiv.org/abs/1910.01276

## Arbitrary RF amplitude model

The vortex inertial mass was neglected since  $M \sim 0$ 

$$\begin{aligned} M\ddot{u}(t,z) + \eta_0 \dot{u}(t,z) &= \epsilon u''(t,z) + f_p(u(t,z)) + f_L(t,z) \\ u(0,z) &= 0 \\ u'(t,0) &= 0 \\ u'(t,Z_{max}) &= 0 \end{aligned}$$

- Pinning force is defined for each point in the vortex line as the summation over several pinning centers in the vortex oscillation place
- Each pinning center defined as





M. Checchin and A. Grassellino, Phys. Rev. Applied (2020)



## Frequency shift due to trapped flux

- Vortex oscillation generates induced currents in the SC
  - Effective penetration depth of the RF current increases
    - $\rightarrow$  lower cavity frequency
  - $\lambda_{fl}$  defines the vortex contribution to the current profile reach in the material
- We observe  $\Delta f_{fl}$  dependent on  $B_p!$ 
  - Higher  $B_p$  allows for more efficient depinning
    - Vortexes oscillates deeper
    - Penetration depth increases
    - Cavity frequency decreases
- $\Delta \lambda_{fl}$ , penetration depth variation due to vortex oscillation

$$\Delta\lambda_{fl} = -\frac{g\Delta f_{fl}}{\mu_0 \pi {f_0}^2}$$





## Works on trapped flux surface resistance

- Many models to describe the trapped flux sensitivity were performed over the years
- Her I just discussed works in which I was directly involved, but for completeness I would suggest to look up also the following references:
- Experiments:
  - C. Benvenuti et al., Physica C 316, 153 (1999)
  - D. Hall et al., IPAC 2017
  - D. Gonnella et al., J. Appl. Phys. 119, 073904 (2016)
- Models:
  - J. I. Gittleman and B. Rosenblum, Phys. Rev. Lett. 16, 734 (1966)
  - A. Gurevich and G. Ciovati, Phys. Rev. B 87, 054502 (2013)
  - S. Calatroni and R. Vaglio, IEEE Trans. Appl. Supercond. 27, 3500506 (2017).
  - S. Calatroni and R. Vaglio, Phys. Rev. Accel. Beams 22, 022001 (2019)
  - D. B. Liarte, et al. Phys. Rev. Applied 10, 054057 (2018).



## EXAMPLE OF REASERCH TO DEVELOPMENT TRANSFER: LCLS-II

# High-Q R&D allowed for the construction of the next generation of FELs facilities



#### Mike Dunne, LCLC-II and the future



The leap from 120 pulses per second to 1 million pulses per second will be transformative


### Mike Dunne, LCLC-II and the future





### Mike Dunne, LCLC-II and the future

### LCLS-II will transform our understanding of dynamics in real-world materials and chemical science systems



#### Charge dynamics on fundamental timescales

- Reveal coupled electronic and nuclear motion in molecules
- Capture the initiating events of charge transfer chemistry with sub-fs resolution



Ultrafast

#### Molecular dynamics with exquisite resolution

- Measure element-specific, local chemical structure and bonding
- Study efficient, robust, selective photo-catalysts



**High repetition rate** 

## Emergent phenomena in quantum materials

- Connect spontaneous fluctuations, dynamics and heterogeneities on multiple length- and time- scales to bulk material properties
- Study interacting degrees of freedom (e.g. unconventional superconductors)



Extreme brightness



### LCLS-II is being assembled as we speak

### **Tunnel View**



### Marc Ross, SRF 2019

M. Ross, SLAC. 19th SRF Conference, Dresden 01 July 2019



### **LCLS-II CM testing results**

Marc Ross, SRF 2019



## NITROGEN INFUSION AND MODIFIED 120 C BAKING

### **Nitrogen infusion**



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### Nitrogen infusion and 120 C baking differences



- Nitrogen infusion allows small traces of nitrogen at the near surface via low T diffusion (120 C)
  - Higher Q-factor due to interstitial N (basically a low T doping!)

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• Oxide is formed after nitrogen diffusion



### Impurity profiles in cavity cutouts by TOF-SIMS

Comparing EP cavity cutout with EP + 120 C 48h N-infused cavity cutout



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A. Romanenko et al., IPAC 2018, Vancouver, Canada

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### N-infusion performance dictated by first tens of nanometers

- Consequent HF rinses on N-infused cavities
  - Each HF rinse removes ~ 2 nm
  - Probing RF performance as a function of depth
- Performance reverted back to HFQS after ~ 15 nm of material removed
- In agreement with N-rich layer found with TOF-SIMS



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### **Similarities with 120 C baking**

- Both treatments have a high  $\kappa = \lambda/\xi$  diffused layer at the surface tens of nanometers thick!
- 120 C baking



### Modified 120 C baking



### Modeling of the maximum gradient

## Superheating field is determined from local critical current



QPs energy, We solve *simultaneously* momentum and 1. Eilenberger equation occupation for quasiparticle spectrum 2. Gap equation 1000for excitation gap EP + 120 C N-infused 1000 Nb<sub>2</sub>O<sub>5</sub> NbN<sup>-</sup> З. Impurity T-matrix equation ed intensity 100 ΕP - - Nb<sub>2</sub>O<sub>5</sub>-10 for the effect of disorder - - NbN Normaliz 0.1 4. Maxwell's equation 0.01 for *B*-field and current profiles 0.001 1E-4 0 20 40 60 80 100 120 140 160 180 To obtain superheating field, Sputter time (s) increase surface field until

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V. Ngampruetikorn and J. Sauls, Phys. Rev. Research 1, 012015(R) (2019)

current reaches critical value

### **Current density distribution in the superconductor**

### Disorder heterogeneity can enhance B<sub>sh</sub>



**Fermilab** 

V. Ngampruetikorn and J. Sauls, Phys. Rev. Research 1, 012015(R) (2019)

### **Enhancement of the accelerating gradient**



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V. Ngampruetikorn and J. Sauls, Phys. Rev. Research 1, 012015(R) (2019)





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## MULTILAYER STRUCTURES

### The boiling water analogy to vortex nucleation

That's why we want perfect surfaces in SRF cavities! We want to delay vortex penetration up to the superheating field

But real surfaces always have defects  $\Rightarrow$  need to find alternative solutions!

- Superconductor-superconductor (SS) structures
- Superconductor-insulator-superconductor (SIS) structures
  - Not enough time! Take a look to:
    A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006)
    T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017)



Let





A. D. Hernández and D. Domínguez, Phys. Rev. B **65**, 144529 (2002)

time

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### What does happen if another interface is added?



G. S. Mkrtchyan *et al.*, Zh. Eksp. Theor. Fiz. **63**, 667 (1972)

- The vortex is pushed by the S-S boundary to the direction of the material with a larger λ.
- A second BL-like barrier is acting at the S-S interface
- The force acting on the vortex as a function of depth can be calculated in the London and GL framework



### Layer thickness dependence



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M. Checchin et al., in proceedings of LINAC16, MSU, East Lansing, USA (2016) T. Kubo, LINAC 2014, Geneva, Switzerland (2014) T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

### Bulk µSR measurements of vortex penetration

#### **ETRIUMF**

Recently MgB<sub>2</sub> and Nb<sub>3</sub>Sn on niobium samples of different thickness have been tested.

Findings: A layer of a higher  $T_c$ material on niobium can enhance the field of first entry by about 40% from a field consistent with  $H_{c1}$  to a field consistent with  $H_{sh}$ .

This enhancement does not depend on material or thickness suggesting that superheating is indeed induced in niobium by the overlayer

#### Field of first flux entry on coated samples



<u>Superheating in coated niobium</u>, T Junginger, W Wasserman and R E Laxdal, <u>Superconductor Science and Technology</u>, <u>Volume</u> <u>30</u>, <u>Number 12</u>, Published 7 November 2017



## NEW FRONTIERS OF BULK NIOBIUM RESONATORS

### High Q SRF 3D cavities for improved coherence



M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)



 $Q > 10^{11}$ 

## 1-cell Fermilab cavities of various frequencies

Curtesy of A. Romanenko

~10 seconds of

coherence



### **Record high photon lifetimes achieved**



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### Dark sector search

**HF-Generator** 

- S. R. Parker et al, Phys. Rev. D 88, 112004 (2013)
- J. Hartnett et al, Phys. Lett. B 698 (2011) 346
- J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)

Emitter

Cavity

Shielding



 $Q_{DET}$ ,  $Q_{EM} > 10^{10}$  SRF can offer several orders of magnitude improvement in sensitivity to  $\chi$ 

🚰 Fermilab

Courtesy of A. Romanenko

### Dark SRF: "Run 0" has been successful

### **Everything worked!**

- ✓ Design
- ✓ Tuner operation
- Microwave scheme for matching the frequencies
- ✓ Actual data first acquisition







### Courtesy of A. Romanenko



## **New DOE-QIS center at Fermilab**





Home | Research | People | Partnerships

https://sqms.fnal.gov/

# Superconducting Quantum Materials and Systems Center

A national center for advancing quantum science and technology



# THE END!

for any question feel free to contact me at: checchin@fnal.gov

## **BACK UP SLIDES**

### Courtesy of A. Romanenko

### Muon spin rotation at PSI (Switzerland)



### Courtesy of A. Romanenko

### Muon spin rotation – measure B(z) directly



### **Positron annihilation Doppler broadening spectroscopy**



 $\gamma$ -ray (511keV  $\pm \Delta E$ )

Courtesy of A. Romanenko

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$$\mathbf{W} = (\mathbf{N}_{w1} + \mathbf{N}_{w2}) / \mathbf{N}_{total}$$

- S parameter corresponds to positron annihilation with valence electrons, W-> core electrons
- S is sensitive to open-volume defects, W-to chemical surrounding at the annihilation site
- Increase in S parameter indicates presence of vacancy defects