Chapter 1:

Brief introduction of RF superconductivity

1.1 Histories using SRF technology for particle acceleration

1.2 Basics of Superconductivity

1.3 Issues and the state of the art

1.1 Histories using SRF technology for particle acceleration

1965; first acceleration of electrons in a SC lead-plated cavity at SLAC.

70's; Accelerator projects with niobium superconducting cavities at Stanford, Karlsruhe, CERN, Argonne, Cornell, KEK, U. Illinois, DESY, etc.

80's; Elliptical cavity to address multipacting issue. High quality niobium.
Ring → KEK, HERA. Large scale machine R&D and design/construction.

90's; Large Scale machine → CEBAF at JLab, LEP at CERN
TTF/TESLA at DESY; Extensive R&D for performance improvement

2000's; SNS at ORNL and many machines are proposed or under construction

Proposed or under-construction large scale machines
(mostly Linac using SRF cavities)
Proton machine; ESS, MYRRHA, Project-X
Heavy Ion machine; FRIB, IFMIF, EURISOL
Electron machine; XFEL, ERL, ILC

Technical motivation

In normal conducting cavity:

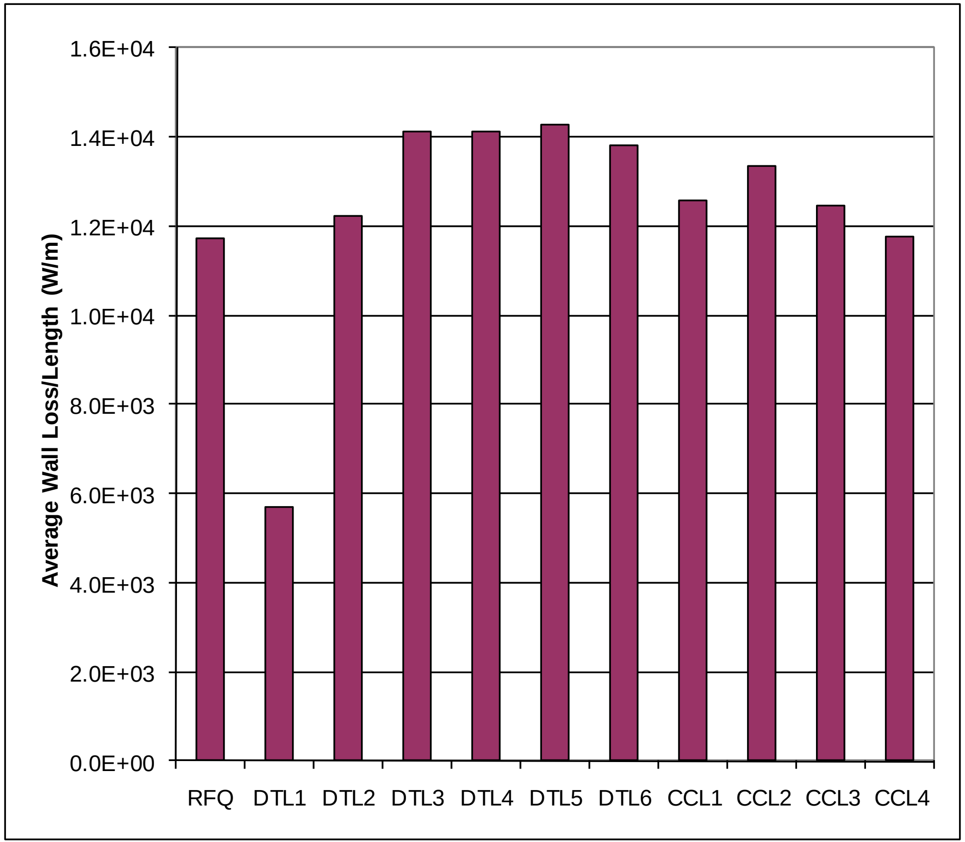
- RF power → wall dissipation + beam
  - Typically <25 % RF power goes to beam at 30 mA
  - In high duty or CW machine: lower accelerating gradient due to cooling and peak surface field
- bore radius is relatively small to get high shunt impedance
  - Beam loss becomes a fundamental limitation for hands-on maintenance as beam power goes up
- typical accelerating gradient ranges <3 MV/m for relatively long pulse (e.g. ~1 ms, 7 % RF duty), much lower for CW

In superconducting cavity:

- >99 % of RF power goes to beam
  - Surface resistance is lower by factor of 5~6 than in NC
- Higher accelerating fields for long pulse and CW operation.
  - 8 MV/m at CEBAF (CW), 15MV/m at SNS (1ms, 8% RF duty), 20-25 MV/m (2010s, CEBAF-U, EU-XFEL), 35 MV/m for ILC goal.
- Thermal management for CW operation is greatly relaxed.
- Bore radius is much larger: beam loss is not limiting power
  - Cavity can be designed without loosing RF efficiency
  - SNS is routinely running at 1 MW beam at much lower activation level than existing NC machine
- Needs cryogenic system.
- Needs great care and processing for high performance

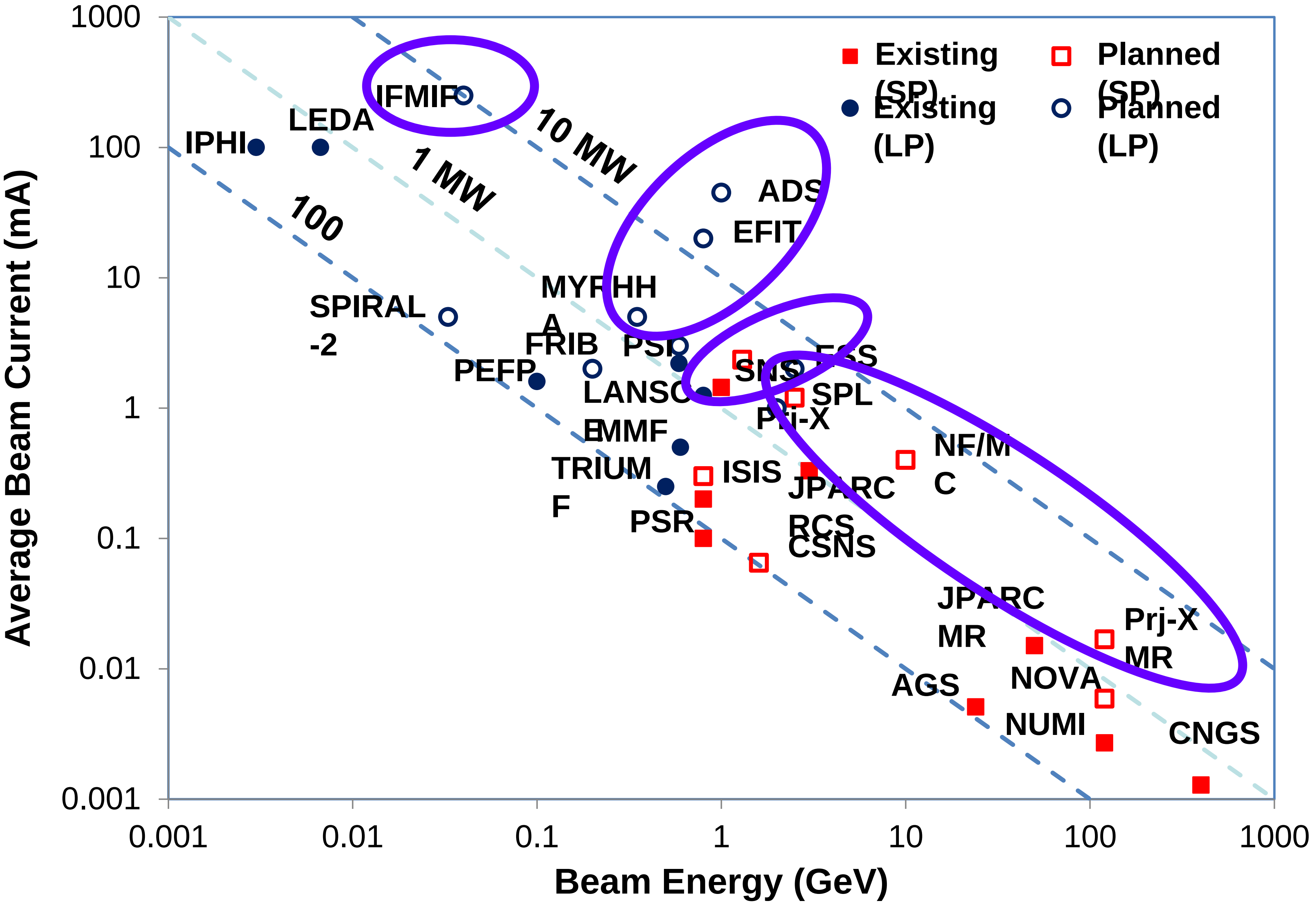
Ex) SNS normal conducting Structures

	L (m)	average EoT (MV/m)	ZT^2 (MOhm/m)	U (J)	Qo	duty=	0.07	
						Pw (W)	Pw,avg (W)	Pw,avg/L (W/m)
DTL1	4.152	1.518	28.22	4.78	35891	3.39E+05	2.37E+04	5.72E+03
DTL2	6.063	2.81	45.25	16.51	40074	1.06E+06	7.41E+04	1.22E+04
DTL3	6.324	2.966	43.54	21.84	43237	1.28E+06	8.94E+04	1.41E+04
DTL4	6.411	2.907	41.91	22.22	42492	1.29E+06	9.05E+04	1.41E+04
DTL5	6.294	2.886	40.83	22.05	43429	1.28E+06	8.99E+04	1.43E+04
DTL6	6.341	2.777	39.03	21.47	43316	1.25E+06	8.77E+04	1.38E+04
CCL1	11.839	1.983	21.89	6.63	16310	2.13E+06	1.49E+05	1.26E+04
CCL2	12.946	2.139	24.02	8.23	17418	2.47E+06	1.73E+05	1.33E+04
CCL3	14.001	2.14	25.71	9.41	18432	2.49E+06	1.75E+05	1.25E+04
CCL4	14.995	2.143	27.29	9.41	19311	2.52E+06	1.77E+05	1.18E+04

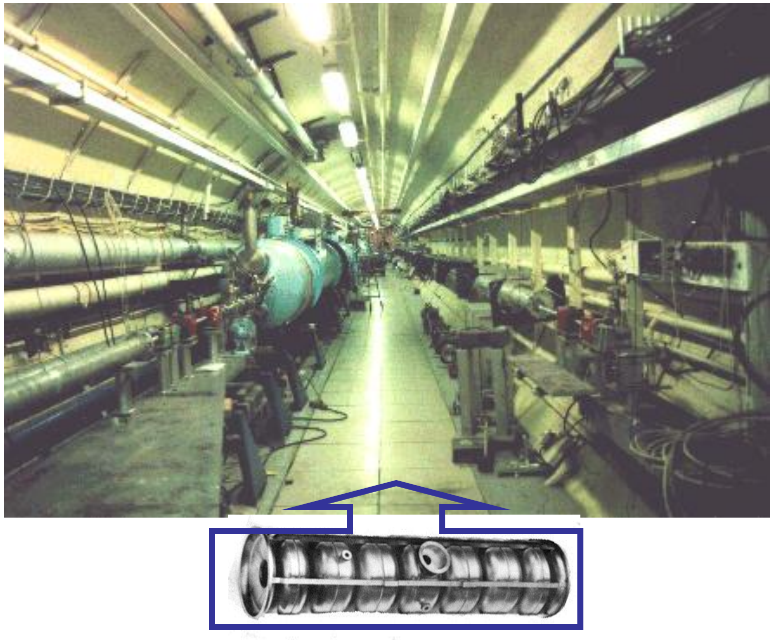


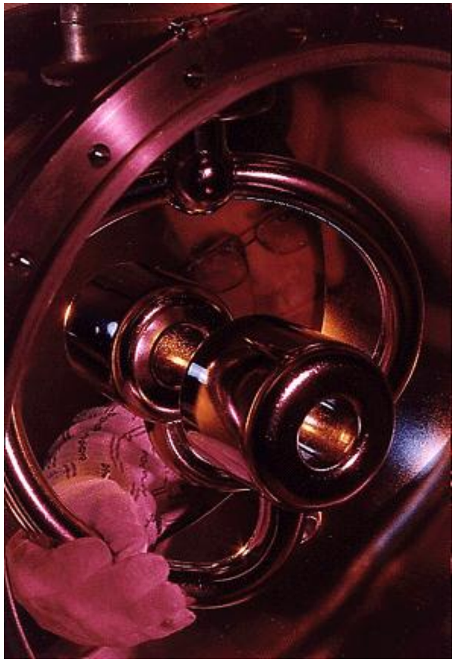
Proton/heavy ion accelerators

Most high power machines in the future are designed based on SRF technology



First Superconducting RF: 3-cell near 2856 MHz lead plated on Cu for electron acceleration in 1964-1965 (SLAC).
Early 70’s 1300 MHz (SCA project)





For Nuclear Physics
ATLAS: Argonne Tandem Linear Accelerator System
(Argonne National Lab)
The first acceleration of an ion beam with superconducting split ring resonator in 1978

CERN LEP (large electron-positron collider)

For high energy physics

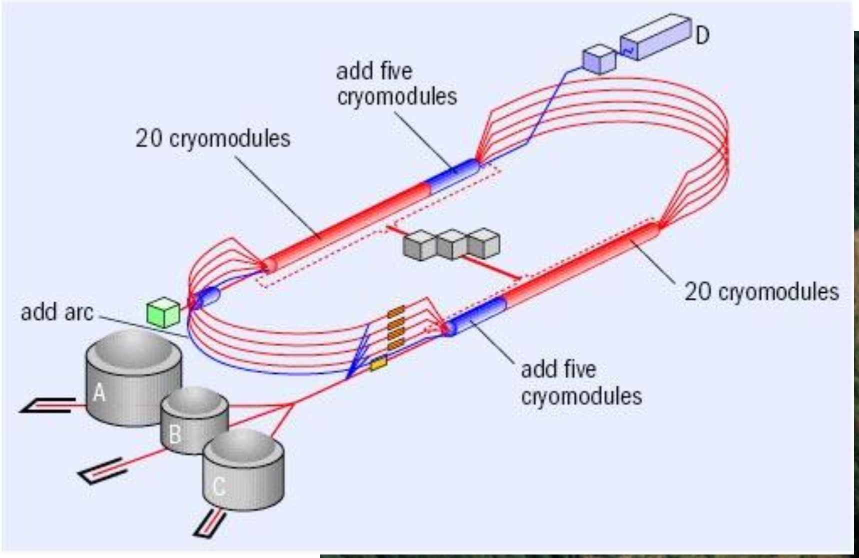
272 cavities, 352 MHz

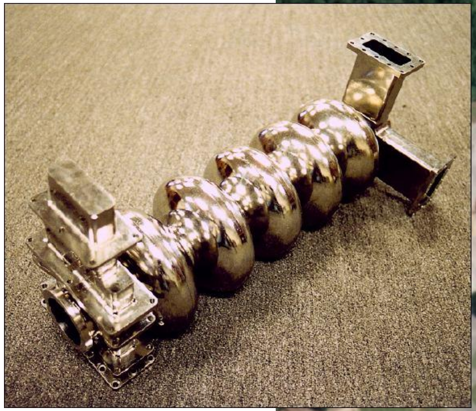
4 cells, Nb/Cu

preparation

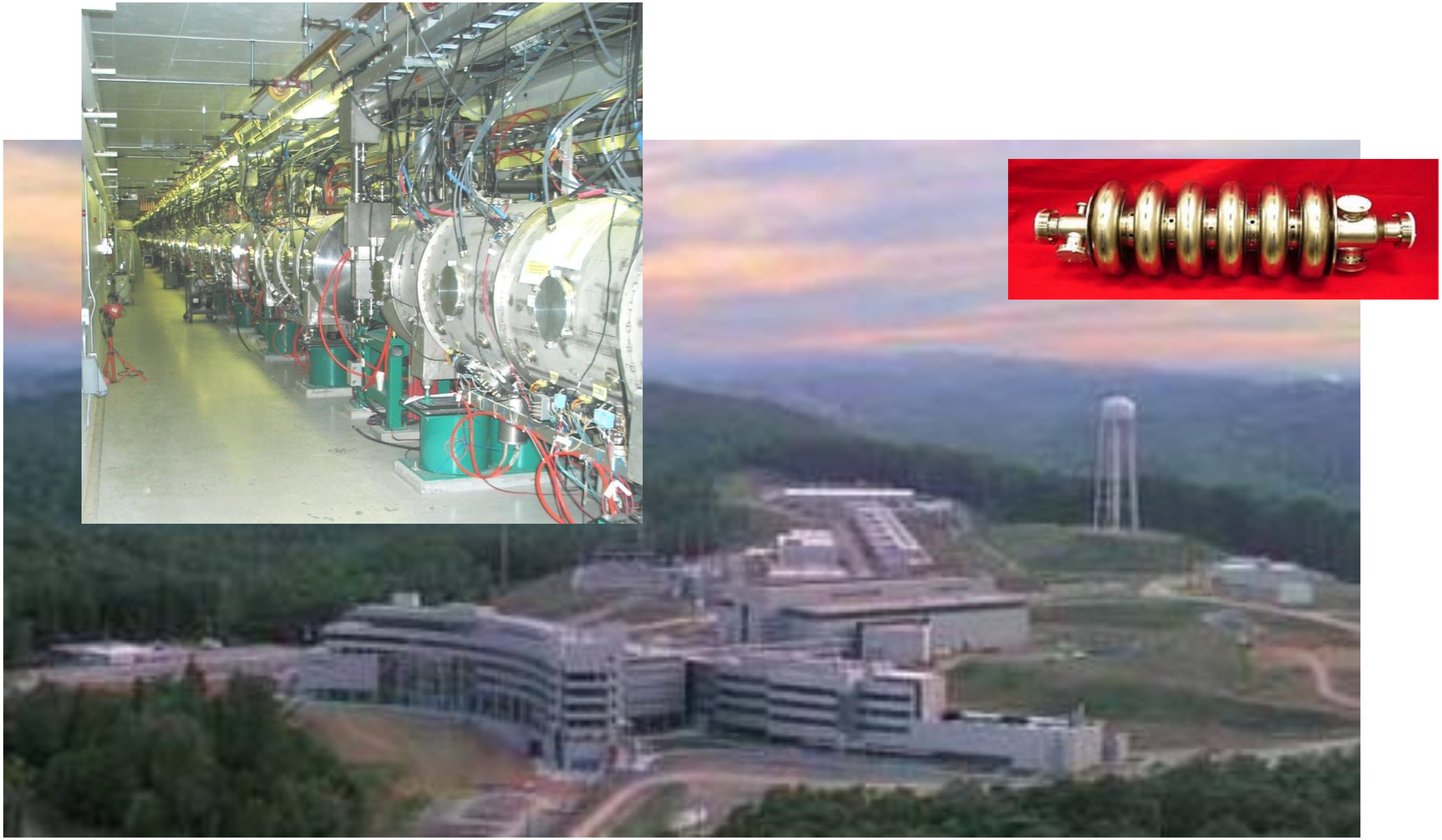
Retire…

For nuclear physics,
CEBAF (Continuous electron beam accelerator facility) at Jlab. 338 cavities, 1500 MHz, 5 cells Solid Niobium



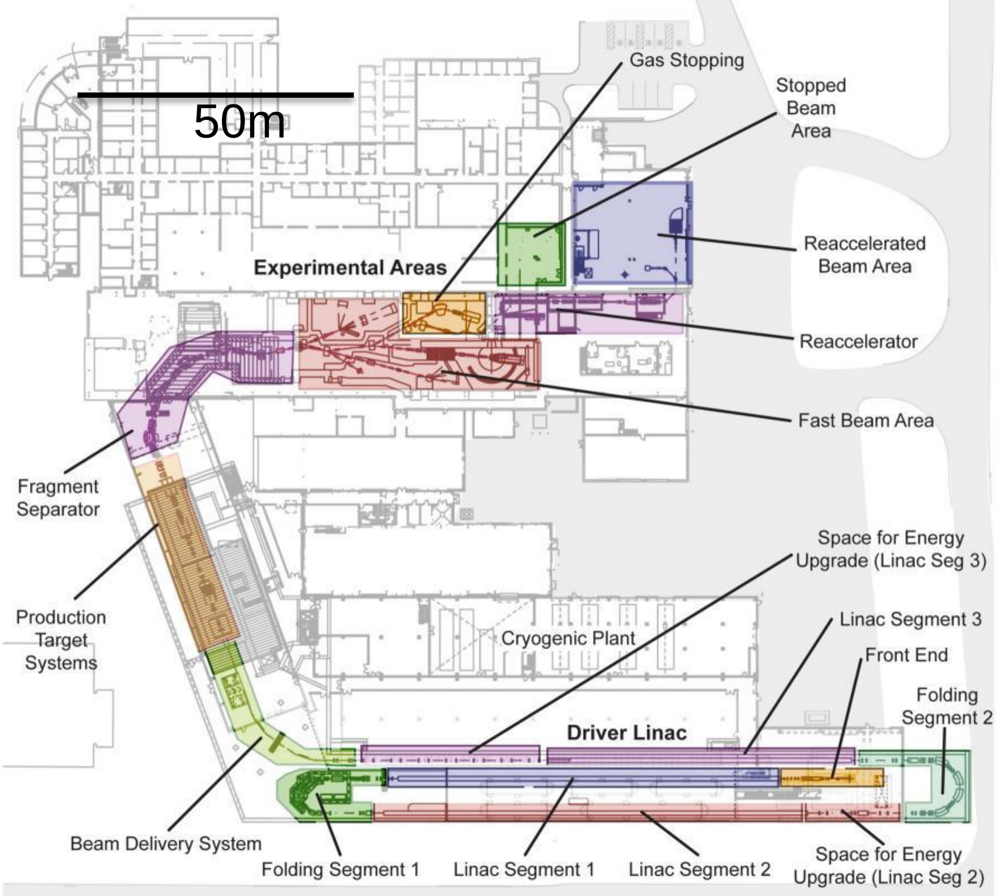


For Neutron production
SNS (Spallation Neutron Source) at ORNL.
81 cavities, 805 MHz, 6 cells Solid Niobium

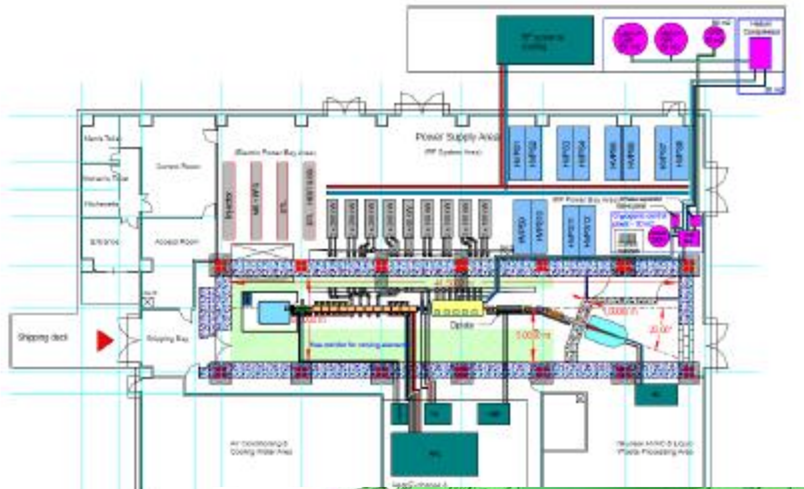


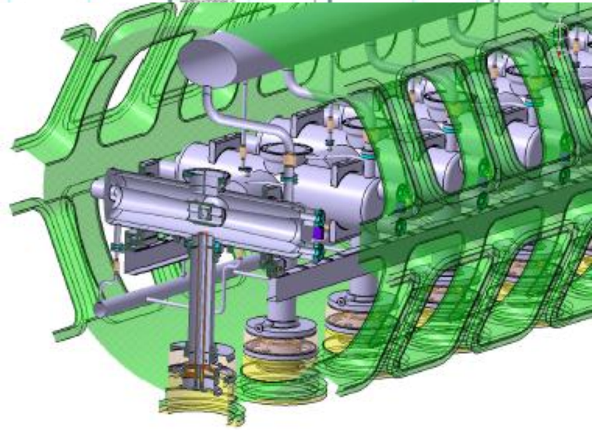
Future Machines for heavy ions

Nuclear Physics
FRIB (MSU) will use 336 low beta
SRF structures (β=0.041, 0.085, 0.285, 0.53)
for proton to Uranium acceleration (CW)

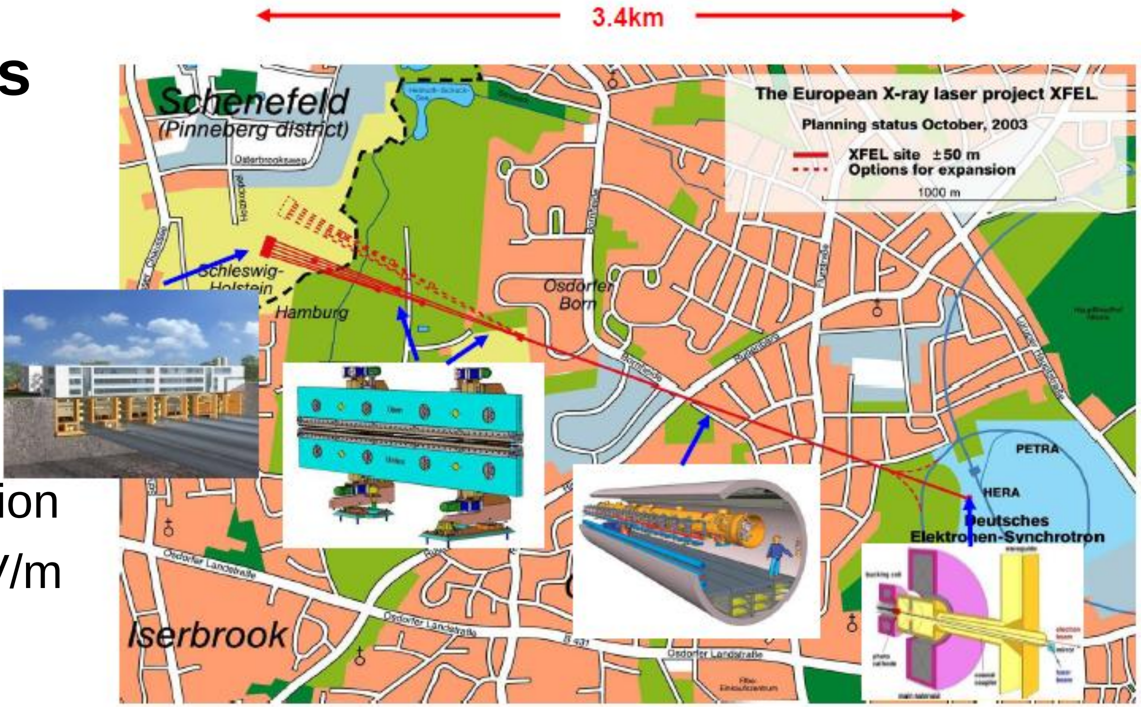


Fusion material test
IFMIF (ITER collaboration)
40 SRF low beta structures
for deuteron acceleration up to 40 MeV.
Two accelerator: 5 MW each CW





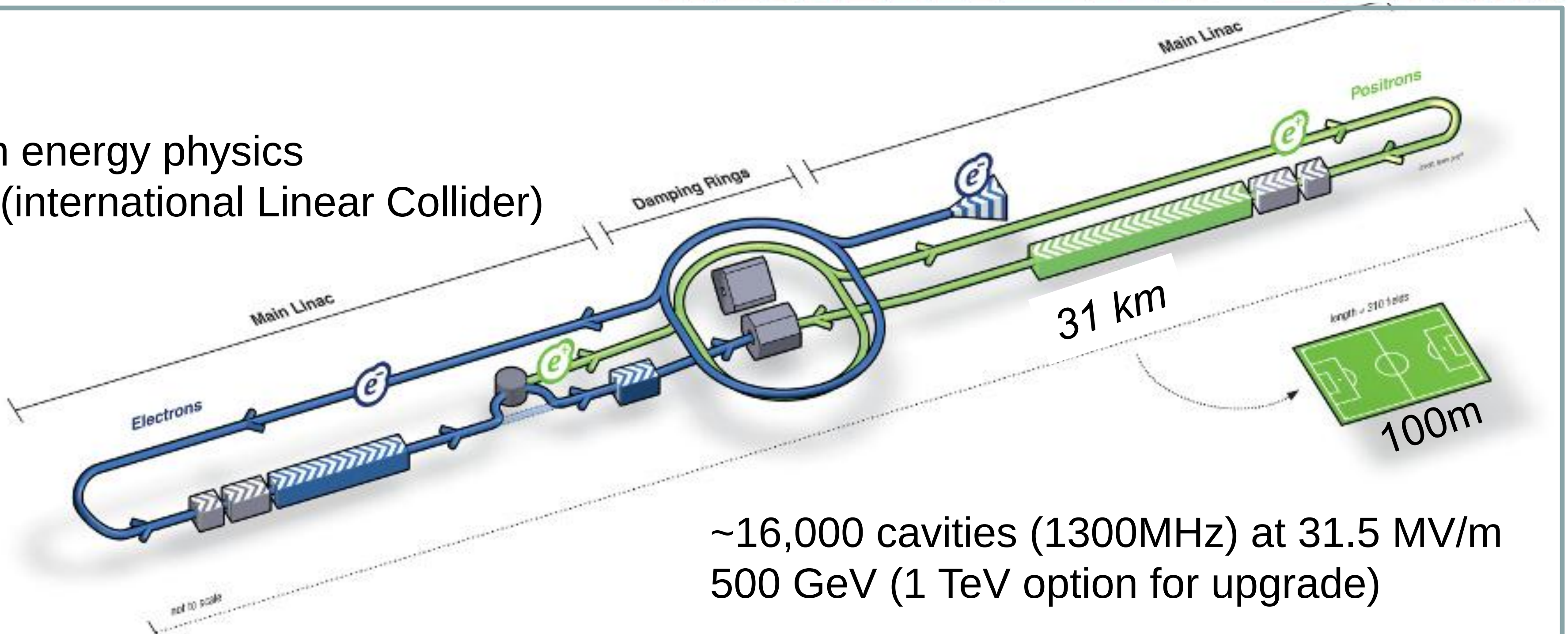
Future Electron machines



Free electron laser
XFEL (DESY/EU): under construction

928 cavities (1300MHz) at 23.6 MV/m
17.5 GeV (20 GeV max.)

High energy physics
ILC (international Linear Collider)



~16,000 cavities (1300MHz) at 31.5 MV/m
500 GeV (1 TeV option for upgrade)

1.2 Basics of Superconductivity

Discovery of superconductivity lies in the history of helium

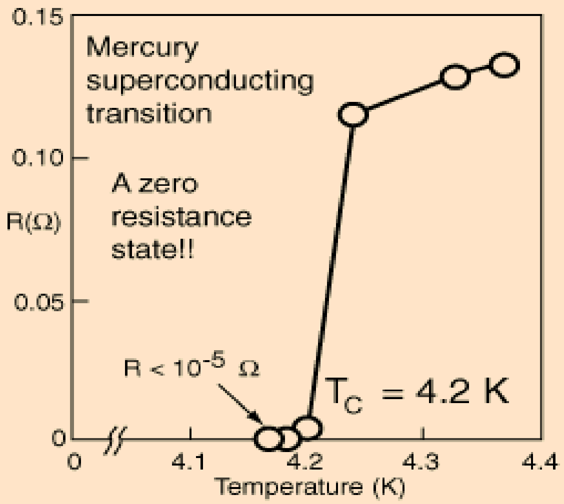
1868 (Jansen, Lockyer) discovery of helium in the Sun

1895 (Ramsay) discovery of helium on Earth, named ‘helium’ from Greek word for Sun

1906 (Onnes) first liquefaction of helium

1911 (Onnes) **discovery of superconductivity**

1910s (Onnes et al) attainment of temperature ~1K



H. K. Onnes, Commun. Phys. Lab.12,120, (1911)

1926 (Kapitza) solidification of helium

1934 (Kapitza) helium liquefaction in a gas-expansion cycle

1938 (Kapitza, Allen, Meisner) discovery of superfluidity of He-4

1939 (Borisov, Liburg) discovery of He-3

1960’s practical use of superconductivity.
creation of helium industries.
medical, big science (fusion, accelerator), defense, etc.

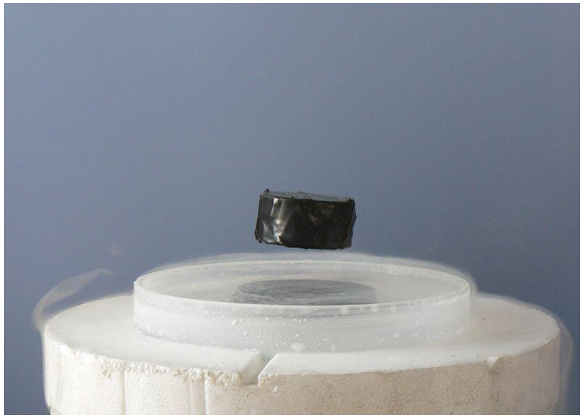
Present In particular, about all big science facilities use large cryogenic helium equipment
(fusion machines, large scale accelerators mainly for magnets and SRF cavities)

What is a superconductor?

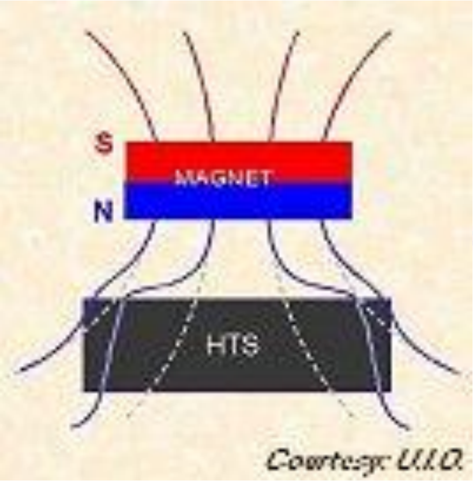
DC superconductivity

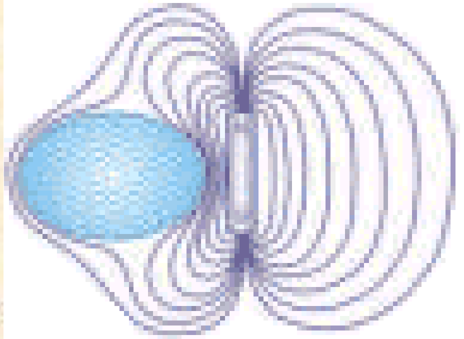
- Zero electrical resistance occurs in certain materials below a characteristic T, Tc
- Cooper pairs carry all current
- Cooper pairs form a coherent state (no scatter off impurities)
- It is a quantum mechanical phenomenon
- At T>0, phonon reaction breaks some pairs; normal electrons exist.
- Supercurrent has ‘0’ resistnace
- In DC operation, super electrons short out normal electrons
- One can characterize superconductivity with a phenomenon called ‘Meissner effect’.

Superconductor is not an idealized case of perfect conductor



Critical field



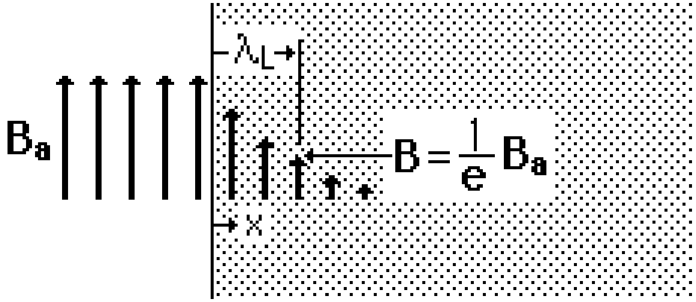


Flux exclusion (Meissner effect):
Perfect diamagnetism
prevents magnetic field from penetrating a pure superconductor up to a critical value, dependent on material and temperature.

London equation

London brothers gave phenomenological explanation of 'Meissner effect'

$$\nabla^2 H = \lambda_L^{-2} H$$ for minimum electromagnetic free energy in a superconductor



$$B_{inside} = B_a e^{-x/\lambda_L}$$

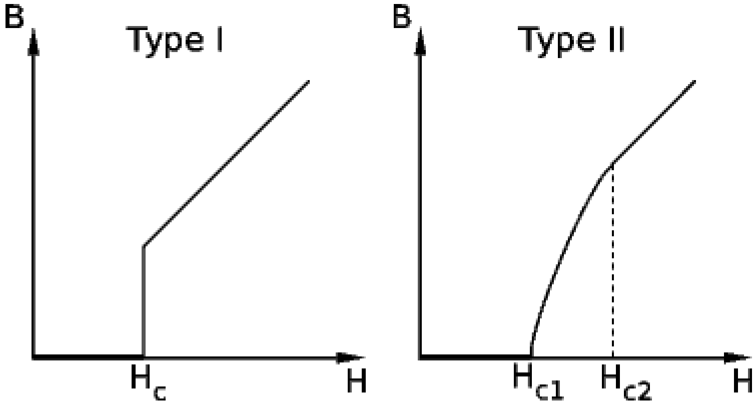
The London penetration depth is the distance required to fall to 1/e times the externally applied field B_a.

$$\lambda_L = \sqrt{\frac{\varepsilon_0 m c^2}{n e^2}}$$

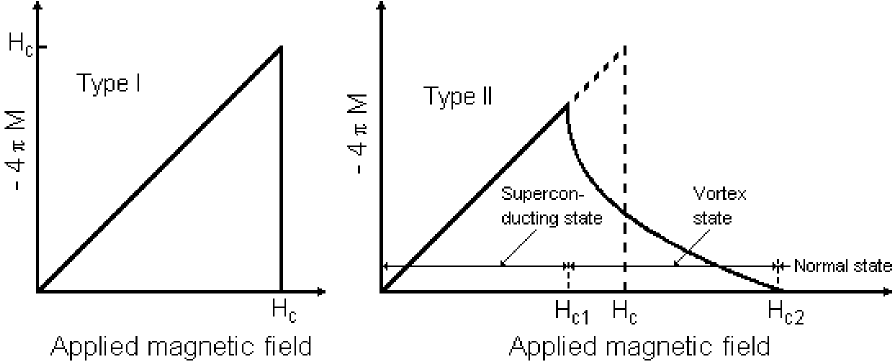
λ_L = London penetration depth
n = superconducting electron density

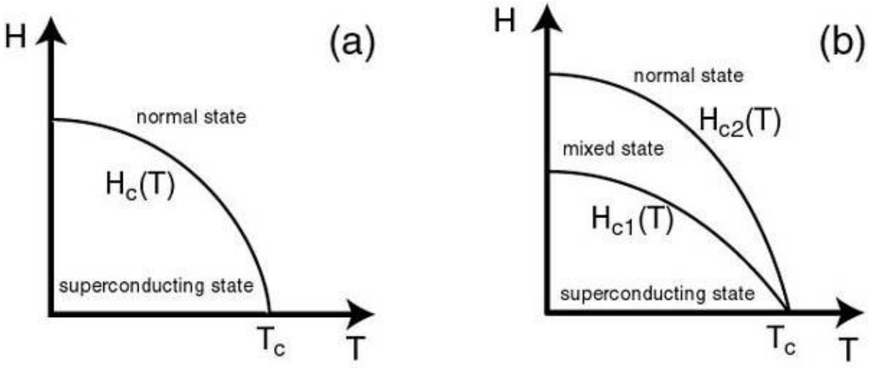
Type-I and Type-II Superconductors

Field inside



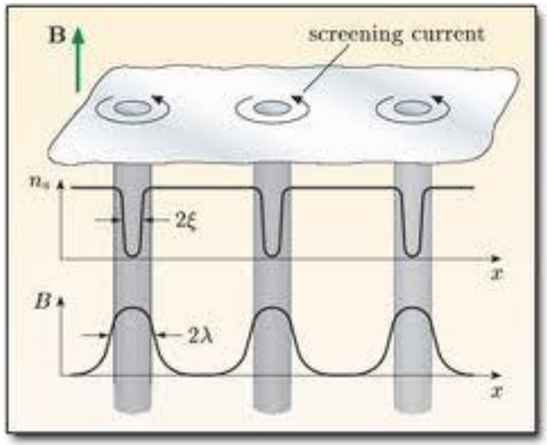
Magnetization





Type I;
-modeled well by the BCS theory
-shows perfect 'Meissner effect' up to the critical field

Type II;
-same as type I up to Hc1 (lower critical field)
-mixed state (normal and superconducting regions) exists between Hc1 and Hc2 (upper critical field); vortex state



Perfect conductor vs. superconductor

-Thermodynamic description of superconducting state; after finding ‘Meissner effect’
-If there’s only ‘perfect conductivity’, thermodynamically same state
-Perfect conductor; depends on history of the sample
-Superconductor; the final state is independent of the history
-Whether or not there is an applied magnetic field, the transition from the superconducting to the normal state is reversible, in the thermodynamic sense.
-thermodynamic state description for superconductor with Meissner effect

$$\mu_0 \frac{H_a^2}{2} > g_n(T,0) - g_s(T,0)$$

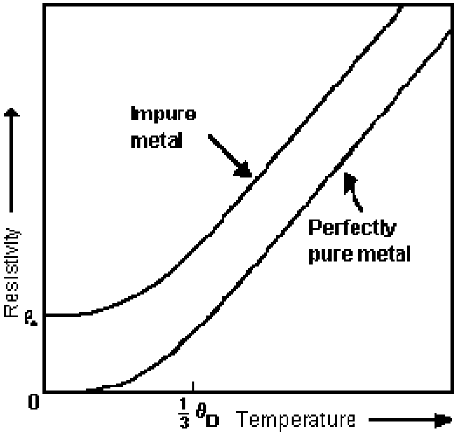
$$g_{s\,\mathrm{or}\,n}(T,H): \text{Gibb's free energy}$$

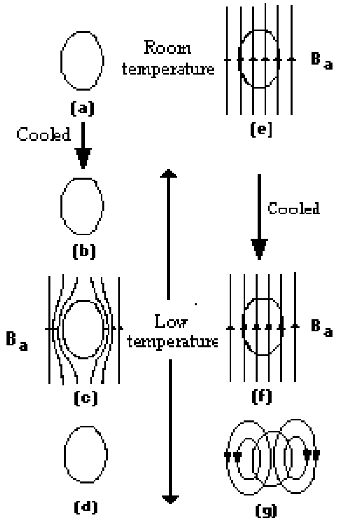
⇨

Thermodynamic Critical Field

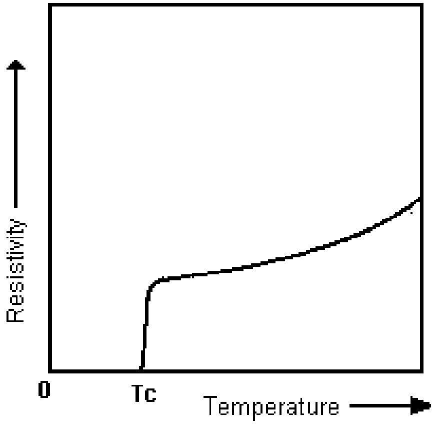
$$H_c = \sqrt{\frac{2}{\mu_0}\left[g_n(T,0) - g_s(T,0)\right]}$$

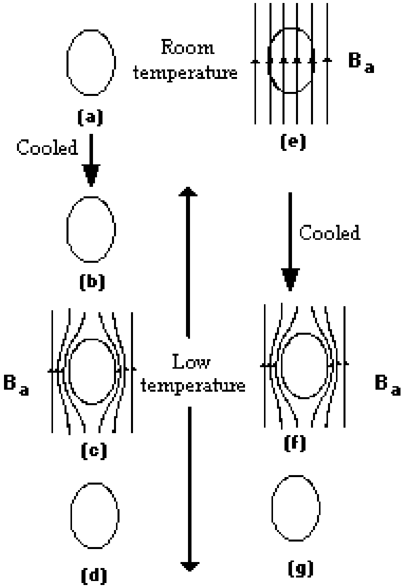
Perfect conductor



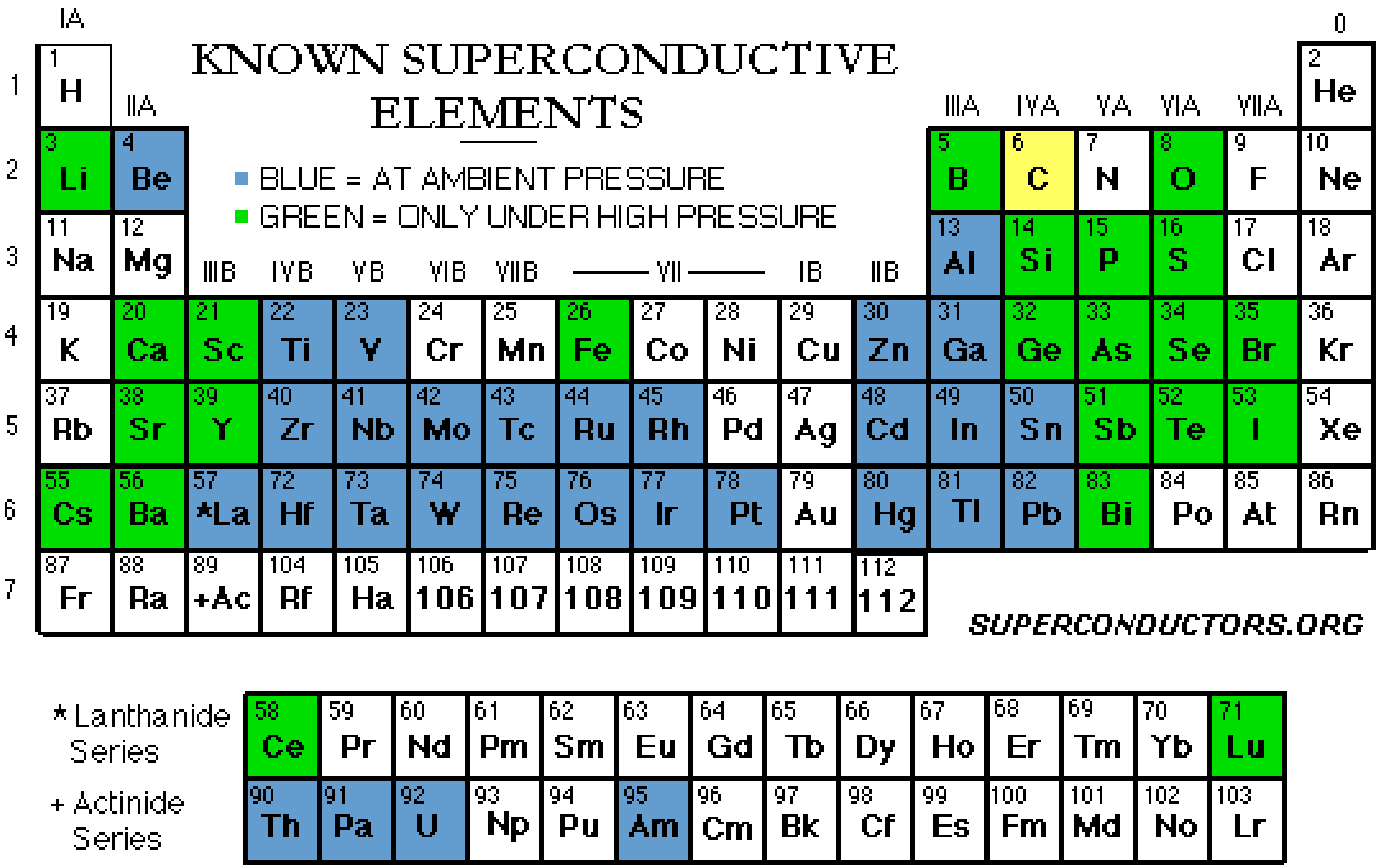


Superconductor





Superconducting elements
Type-I (except Nb, V, Tc here) Superconductors



KNOWN SUPERCONDUCTIVE ELEMENTS

🟦 BLUE = AT AMBIENT PRESSURE
🟩 GREEN = ONLY UNDER HIGH PRESSURE

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

SUPERCONDUCTORS.ORG

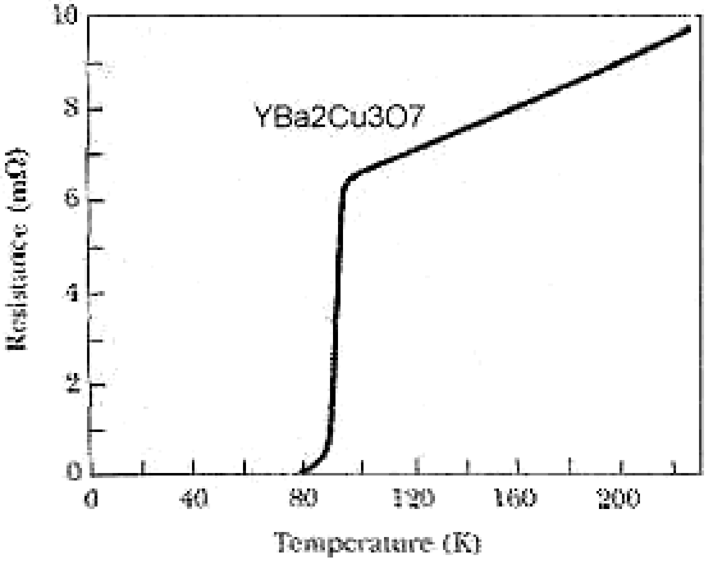
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

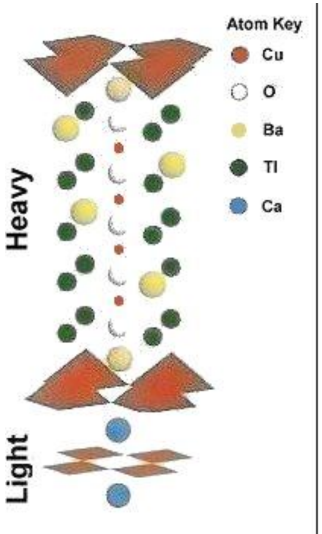
Type-II Superconductors

- Metal alloys: Nb_3Sn, NbTi, rare earth compounds up to 23 K
- High Tc superconductors:

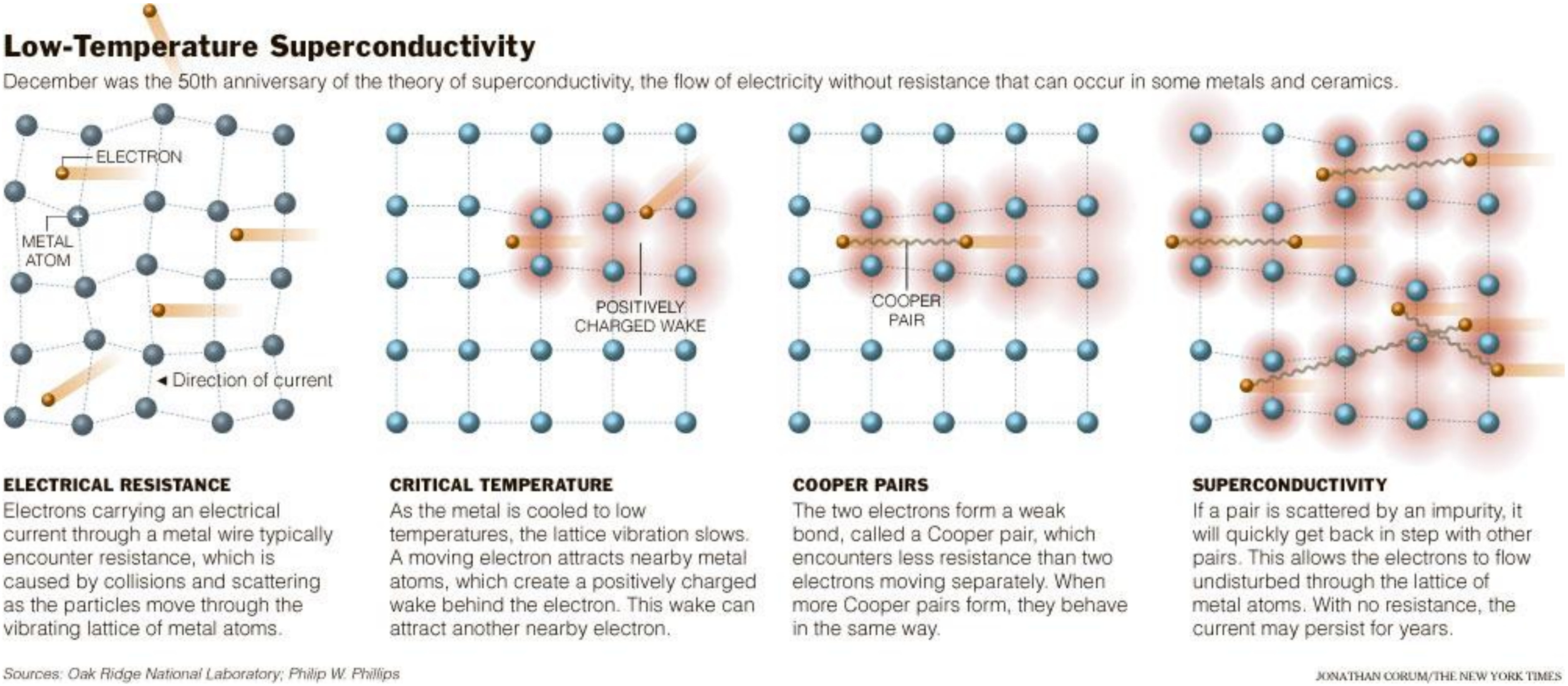
Hg0.8Tl0.2Ba2Ca2Cu3O8.33	**138 K**
Tl2Ba2Ca2Cu3O10	**128 K**
Bi1.6Pb0.6Sr2Ca2Sb0.1Cu3O$_y$	**115 K**
Ca1-xSrxCuO2	**110 K**
TmBa2Cu3O7	**90 K**
YBa2Cu3O7	**93 K**

- Highest Tc claimed; 254 K (+/- 2K) with $(Tl_4Ba)Ba_2Ca_2Cu_7O_{13+}$ in 9223 forms





Structure 9223



Low-Temperature Superconductivity

December was the 50th anniversary of the theory of superconductivity, the flow of electricity without resistance that can occur in some metals and ceramics.

ELECTRICAL RESISTANCE

Electrons carrying an electrical current through a metal wire typically encounter resistance, which is caused by collisions and scattering as the particles move through the vibrating lattice of metal atoms.

CRITICAL TEMPERATURE

As the metal is cooled to low temperatures, the lattice vibration slows. A moving electron attracts nearby metal atoms, which create a positively charged wake behind the electron. This wake can attract another nearby electron.

COOPER PAIRS

The two electrons form a weak bond, called a Cooper pair, which encounters less resistance than two electrons moving separately. When more Cooper pairs form, they behave in the same way.

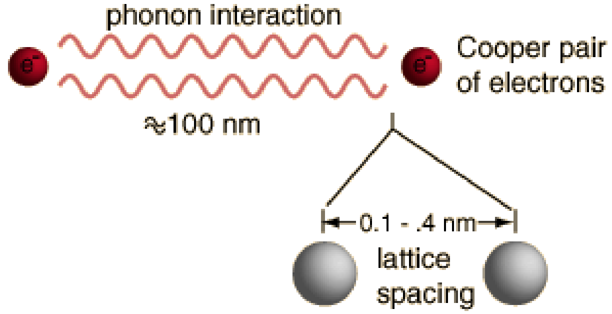
SUPERCONDUCTIVITY

If a pair is scattered by an impurity, it will quickly get back in step with other pairs. This allows the electrons to flow undisturbed through the lattice of metal atoms. With no resistance, the current may persist for years.

Sources: Oak Ridge National Laboratory; Philip W. Phillips

JONATHAN CORUM/THE NEW YORK TIMES

Lattice coupling of electron pairs (Cooper pairs); verified by isotope effect

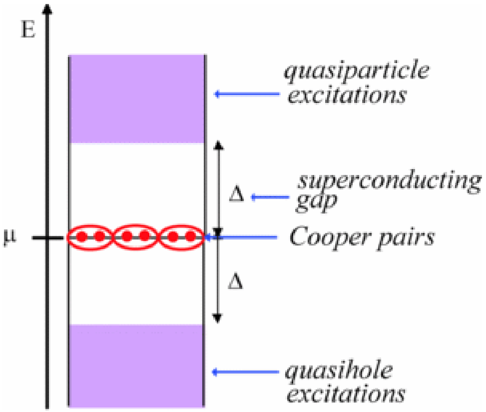


Pairing of electrons close to the Fermi level into Cooper pairs from a slight attraction between the electrons related to lattice vibration
→Phonon interaction

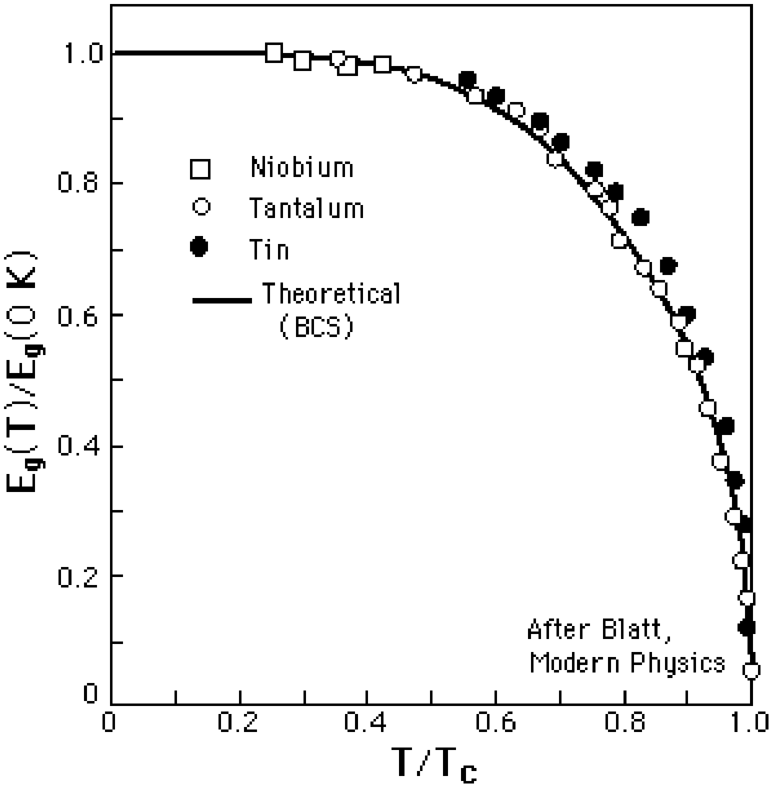
Single electrons → fermion (Pauli exclusion prin.)
Cooper pairs → bosons (condense into the same energy level. Leave an energy gap.

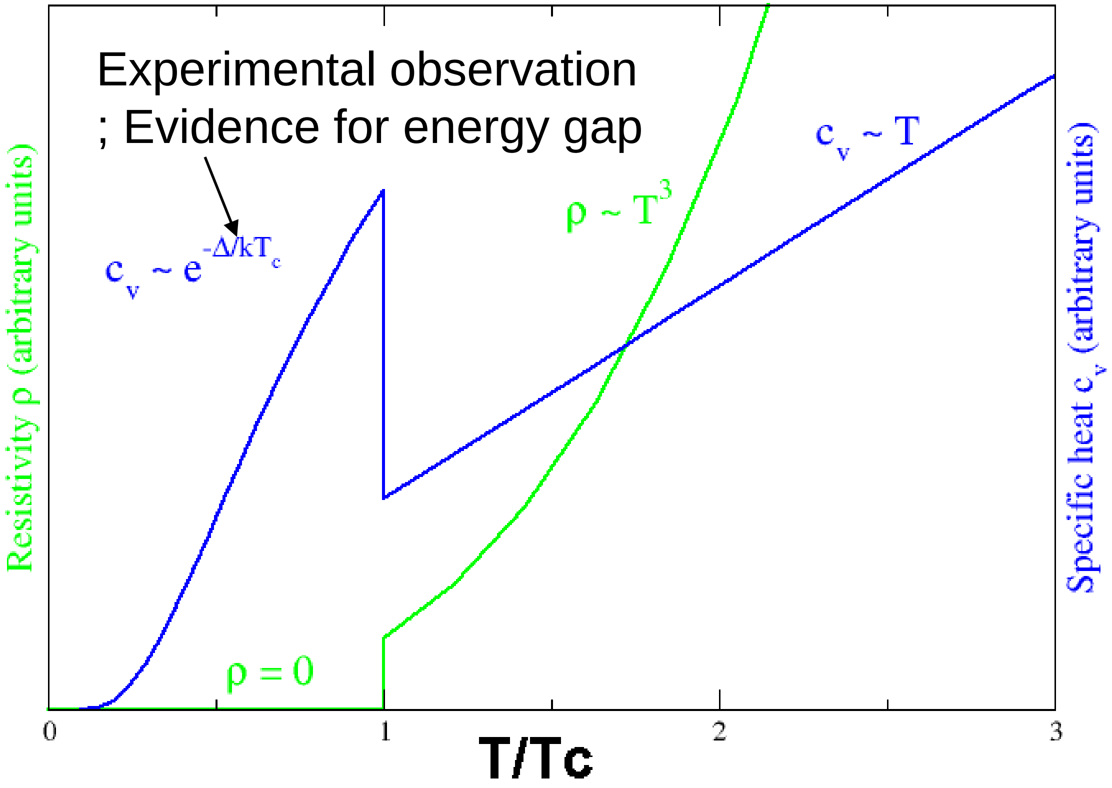
Energy gap and phase transition

Energy Gap, Δ



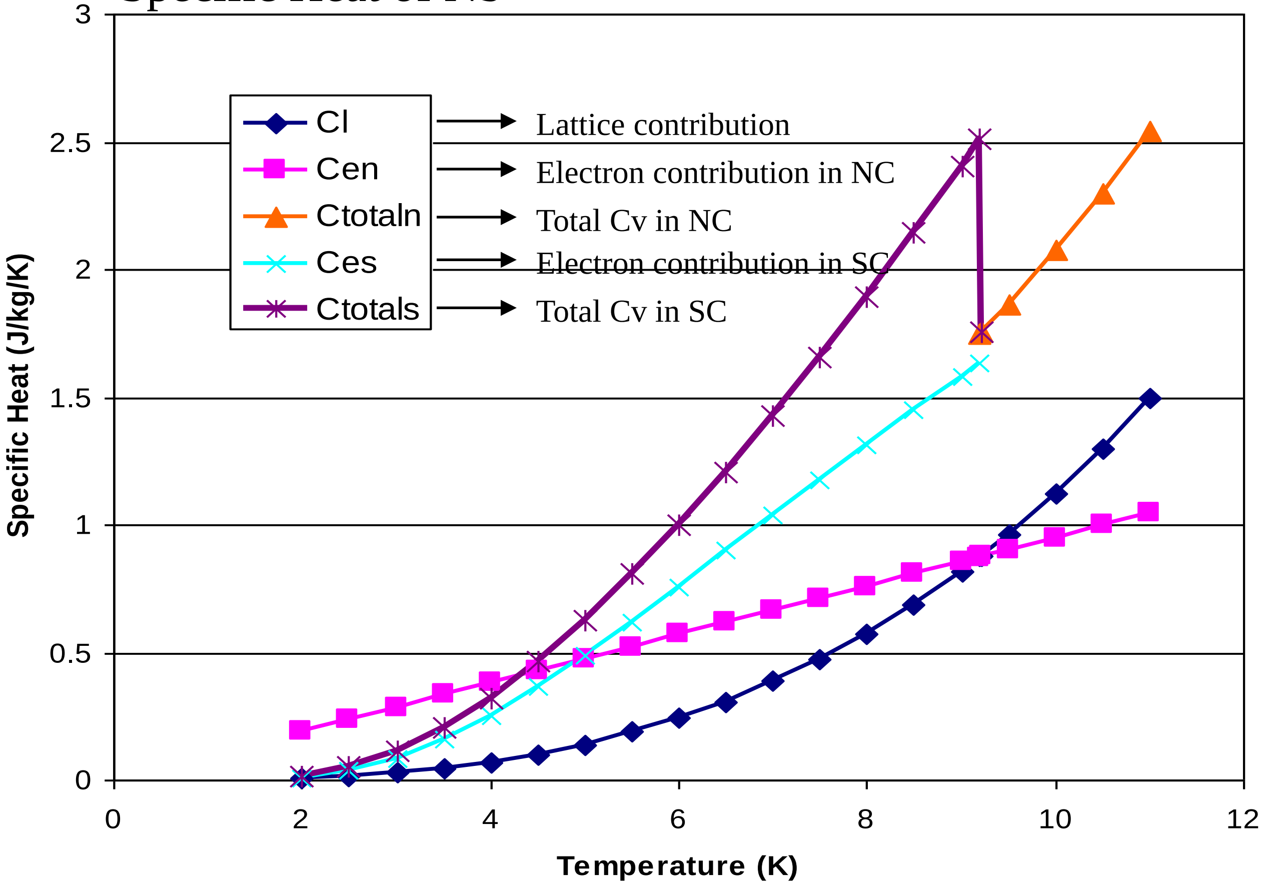
Existence of a critical magnetic field, and a critical temperature, and exponential nature of the heat capacity → energy gap → support BCS theory experimentally



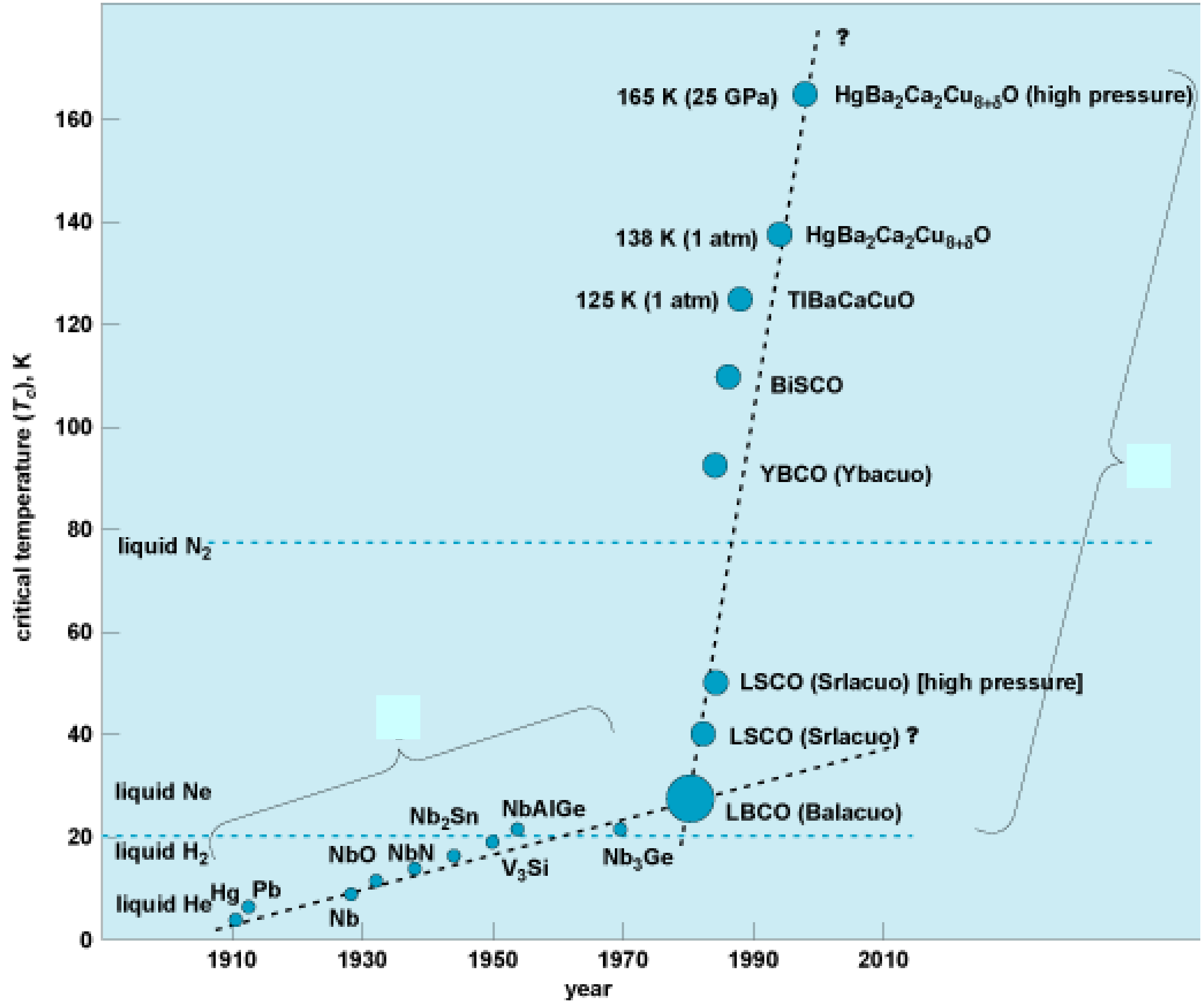


Experimental observation
; Evidence for energy gap

Specific Heat of Nb



Evolution of critical temperatures of superconducting materials



RF superconductivity

1934	Heinz London; predicted AC losses in a superconductor Nature, 133, p.497 (1934)
1940	H. London; First measurement of RF resistance in a superconductor (1.5GHz) -gradual decrement with T instead of sudden drop in DC Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 176, No. 967 (Nov. 27, 1940), pp. 522-533
1949	W. Fairbank; First RF surface resistance measurement in US (9.4GHz) Phys. Rev. 76, 8 (1949)
1955	G. Blevins, et al. superconductivity at millimeter wave frequency Phys. Rev. 100 (1955)
1956	millimeter and far infra-red absorption and transmission research
Finally…	
1957	**Bardeen, Cooper, Schrieffer published on** **‘Theory of Superconductivity’ Phys. Rev. 108, 5, pp.1175 – 1204 (1957)** **The ‘BCS theory’ → Novel Prize in 1972**
1958	Mattis and Bardeen published ‘Theory of the anomalous skin effect in normal and superconducting metals’ Phys. Rev. 111, 2, pp. 412-417 (1958)

RF surface resistance

In short, it has a finite surface resistance.

1. $R_{BCS}(f,T,A_{mat})$=

Cooper pairs do not have friction but have inertia.

→Not perfect screening under time varying H field.

→Induce time varying electric field

→Accel. & decel of normal electrons (normal current)

→Power dissipation

2. R_{res}

Temperature independent resistance by impurities

→Residual resistance (1nΩ~ 20nΩ)

Trapped magnetic flux pinning;

→controllable by shielding from earth magnetic field, stray field from magnets nearby, etc.

Formation of lossy layer on RF surface

BCS resistance

It depends on temperature.

It depends on frequency.

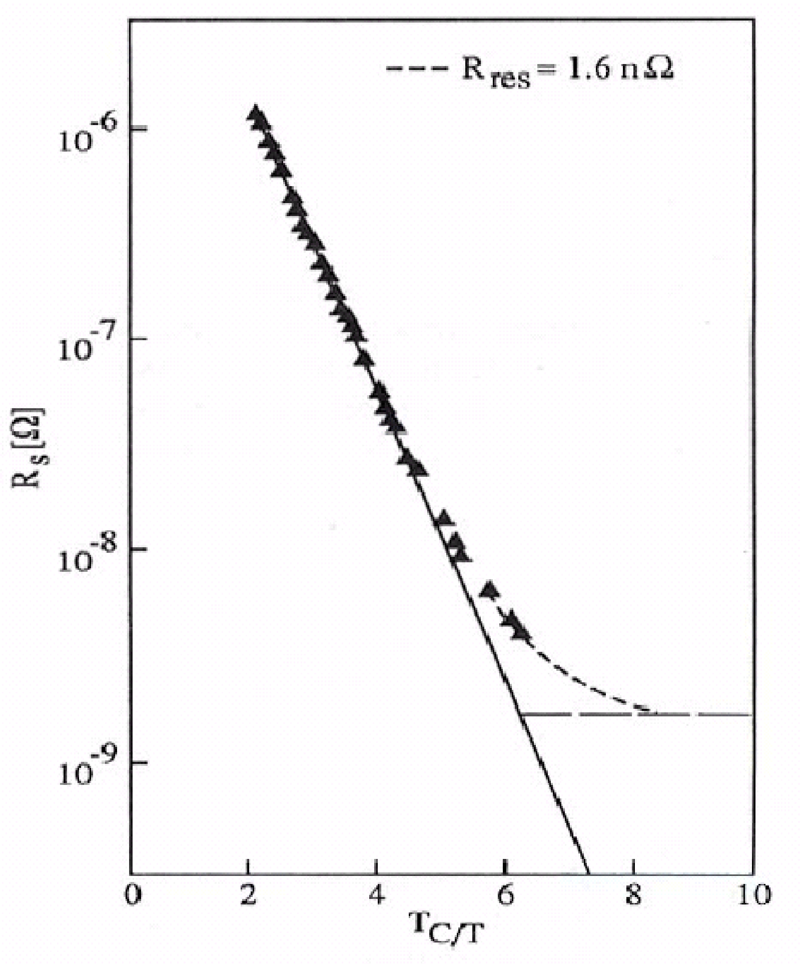
It depends on material characteristics.

Residual resistance: (here we included surface resistance due to all other sources in the category of ‘residual resistance’)

It depends on quality of the material. (impurities)

It depends on surface conditions. (hydride, oxide layer)

It depends on trapped magnetic field (ambient magnetic field)



Simplified semi-empirical formula; Good enough for T<Tc/2

$$R_S = R_{BCS} + R_{res} = 9\times10^{-5}\frac{f^2(\mathrm{GHz})}{T}\exp(-1.83\frac{T_c}{T}) + R_{res}$$ used in SUPERFISH

$$R_S = R_{BCS} + R_{res} = 8.9\times10^{-5}\frac{f^2(\mathrm{GHz})}{T}\exp(-\frac{17.67}{T}) + R_{res}$$ Good fitting function

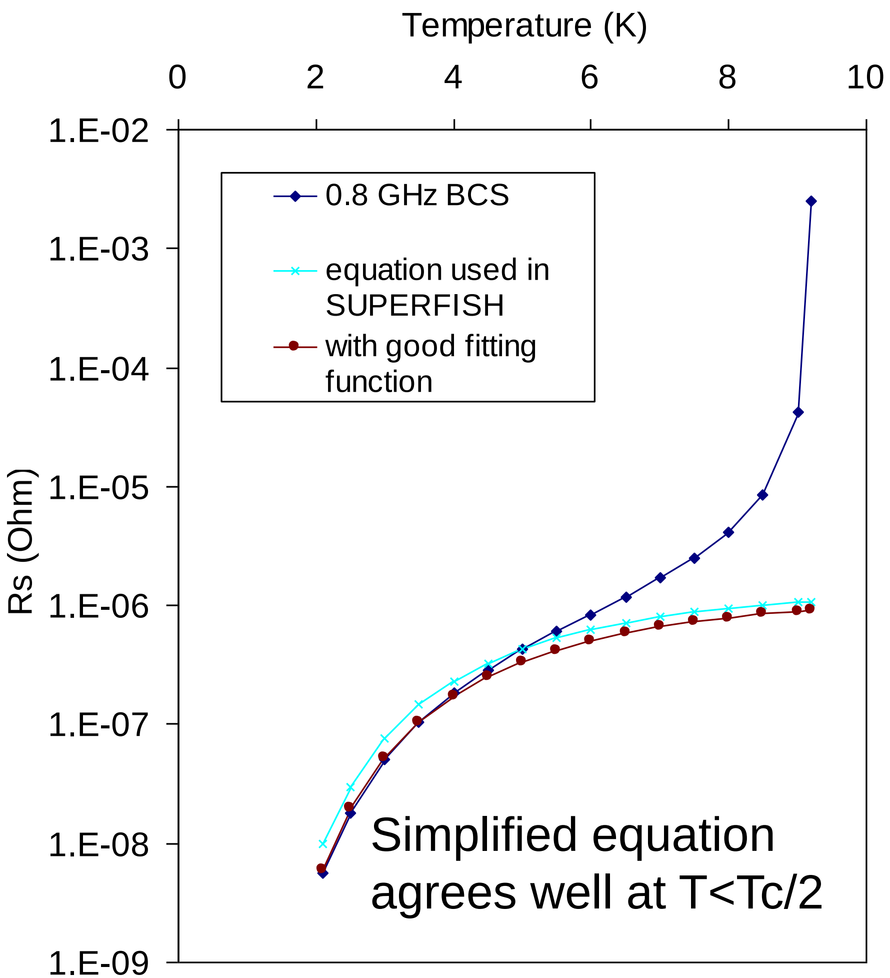
Residual resistance by ambient magnetic field for Nb

$$R_H \approx 9.5 H_{ext}(\mathrm{in\ Os})\sqrt{f\ (\mathrm{in\ MHz})}\quad \mathrm{in\ n\Omega}$$

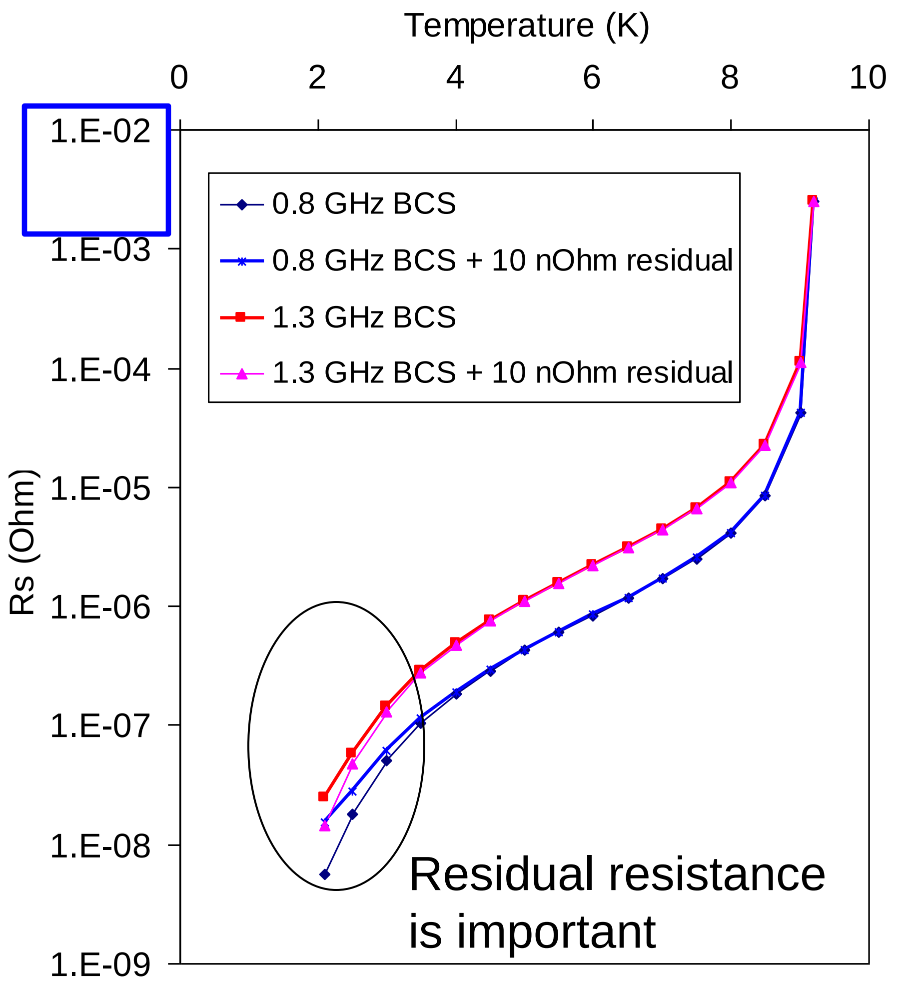
Ex.
Earth magnetic field~0.5 gauss (50 μT), 1300 MHz → R_H=171 nΩ
R_{BCS} at 2K, 1300 MHz → 15.8 nΩ

If SRF cavities have magnetic shields like
Bext~0.01 gauss (1/50 reduction)→ R_H=3.4 nΩ at 1300 MHz

Example: Niobium (Nb) Surface resistance



Simplified equation agrees well at T<Tc/2



Residual resistance is important

1.3 ‘State of the art’ and challenges

Fundamental questions on RF superconductivity

Fundamental questions on materials

Surface processing

Some known issues but difficulties of achieving good statistical performances in practice

Examples)

RF critical field (H_{c1}, H_{c2}, H_{sh} or something else)?

Theory? no good theory except BCS surface resistance

Field enhancement effect?

R&D are still in progress for a better surface processing recipe

Fundamental issues in practice

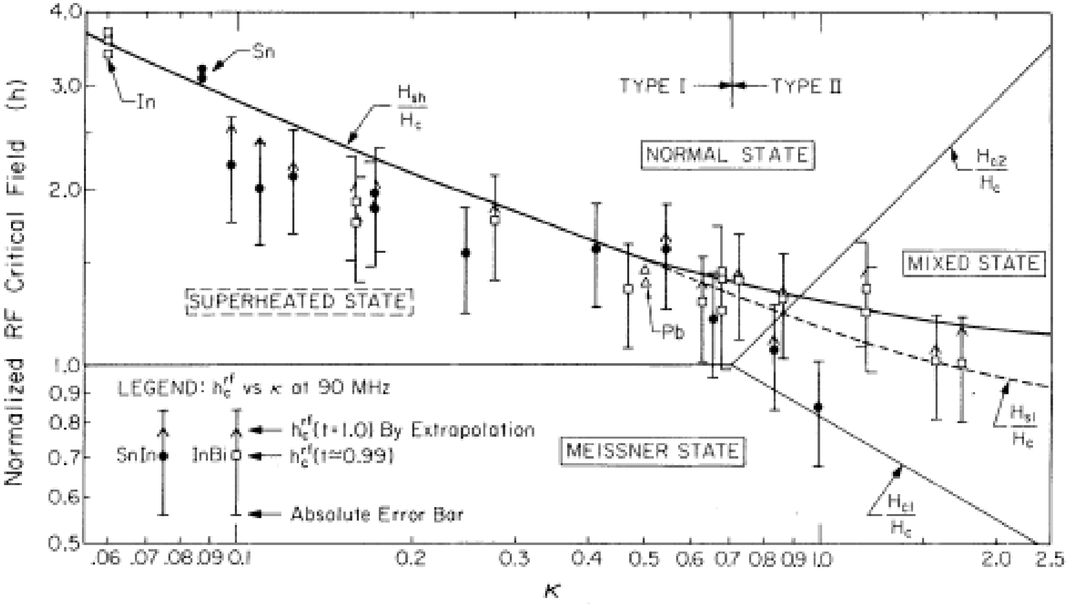
material uniformity, grain size/boundary, contaminations

Manufacturing cost, large scattering of performances?

Critical field: H_c, H_{c1}, H_{c2}, H_{sh}, or $H_?$

- Are a superconductor's DC and RF critical magnetic fields the same?
- If not, how are they related? how do they depend on the RF frequency?
- What do RF critical fields tell us about the superconductor?
- All questions are still open
- Up to now, Ginzburg Landau (GL) prediction is only one
  - Hsh=1.2Hc for Nb
  - Hsh=0.75Hc for high κ material
  - Phenomenological theory: valid only around Tc

$\kappa = \lambda/\xi$ Penetration depth/coherence length

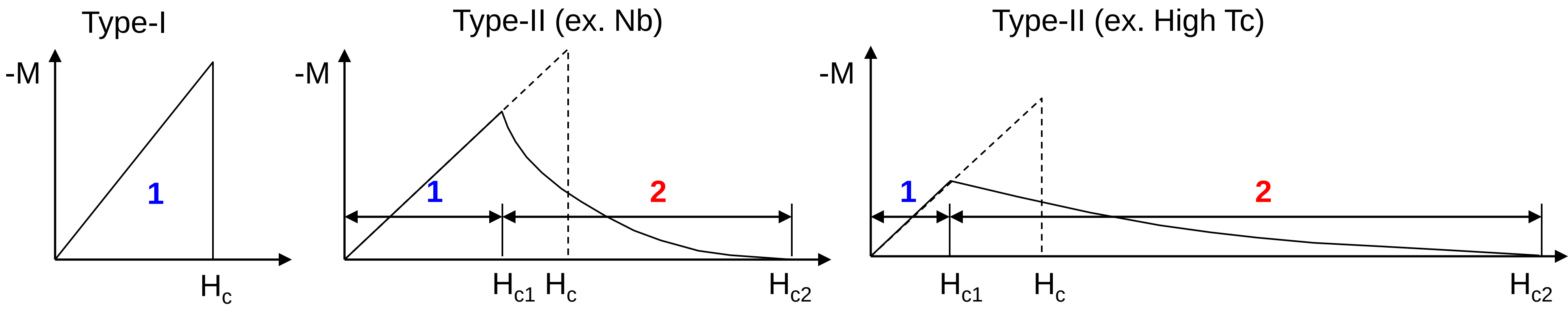


Yogi (1977)

FIG. 2. Normalized critical field as a function of the Ginsburg-Landau parameter $\mathcal{K}$. Data points are for h_c^{rf} at $t = 0.99$ for several metals and alloys. Full curve is calculation (Matricon and St. James, Ref. 1) of the dc superheating field h_p; dashed curve is the fluctuation-limited field estimated by Kramer (Ref. 1).

Comparisons of materials

Surface critical magnetic field is the primary parameter for SRF

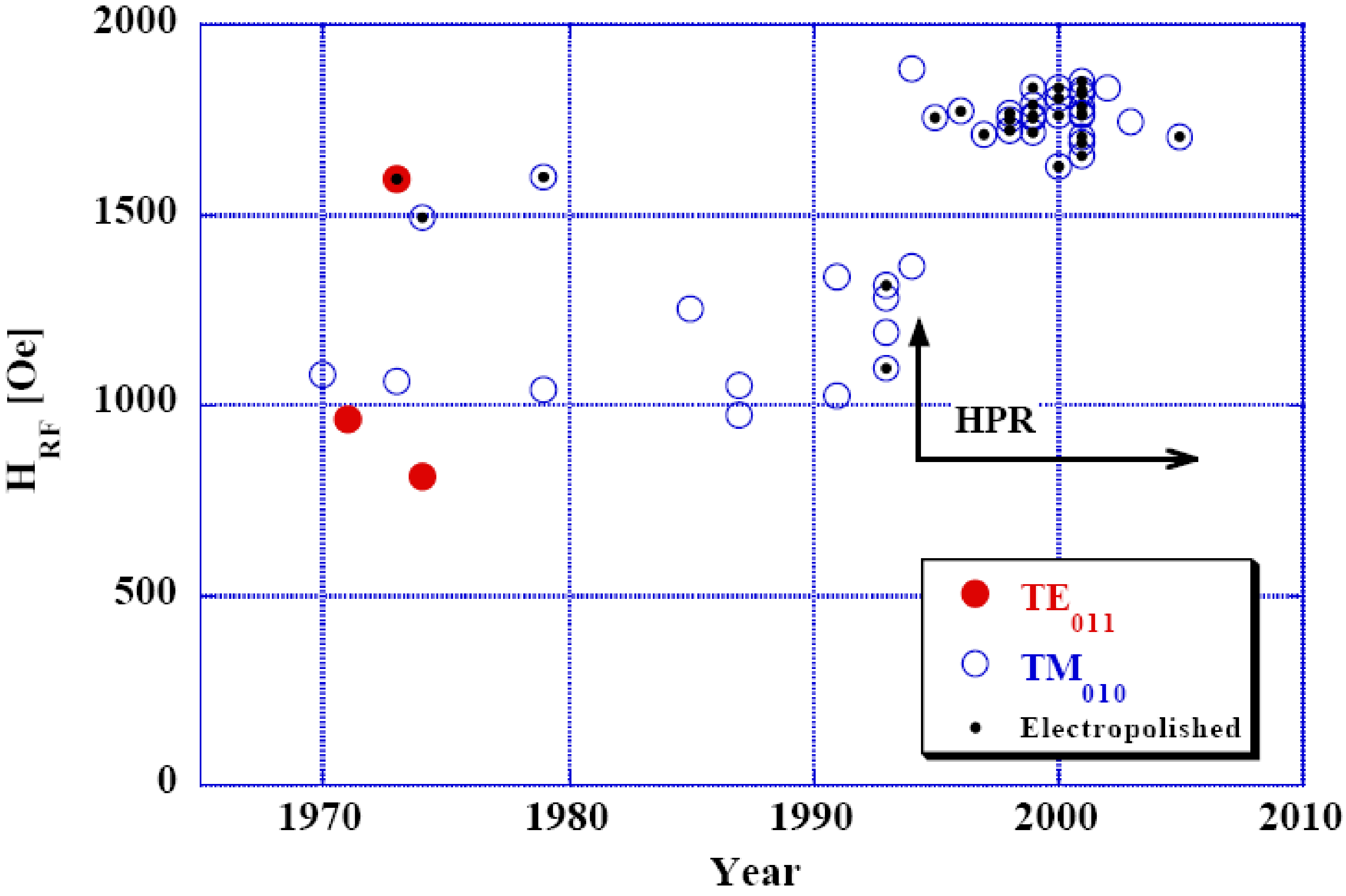


Region 1: complete Meissner effect, Very week dissipation.
Region 2: partial Meissner effect, strong vortex dissipation.

Material	**T_c (K)**	**H_c(0) [T]**	**H_{c1}(0) [T]**	**H_{c2}(0) [T]**	**λ(0) [nm]**
Pb	**7.2**	**0.08**	**Type-I**		**48**
Nb	**9.2**	**0.2**	**0.17**	**0.4**	**40**
NbN	**16.2**	**0.23**	**0.02**	**15**	**200**
NbTiN	**17.5**		**0.03**		**151**
Nb_3Sn	**18**	**0.54**	**0.05**	**30**	**85**
Mo_3Re	**15**	**0.43**	**0.03**	**3.5**	**140**
YBCO	**93**	**1.4**	**0.01**	**100**	**150**
MgB_2	**40**	**0.43**	**0.03**	**3.5**	**140**

Niobium:
Highest T_c among pure metals,
Highest H_{c1},
40-years of experiences,
Efforts from all SRF labs/univ.
Still not fully understood,
Practically best so far,

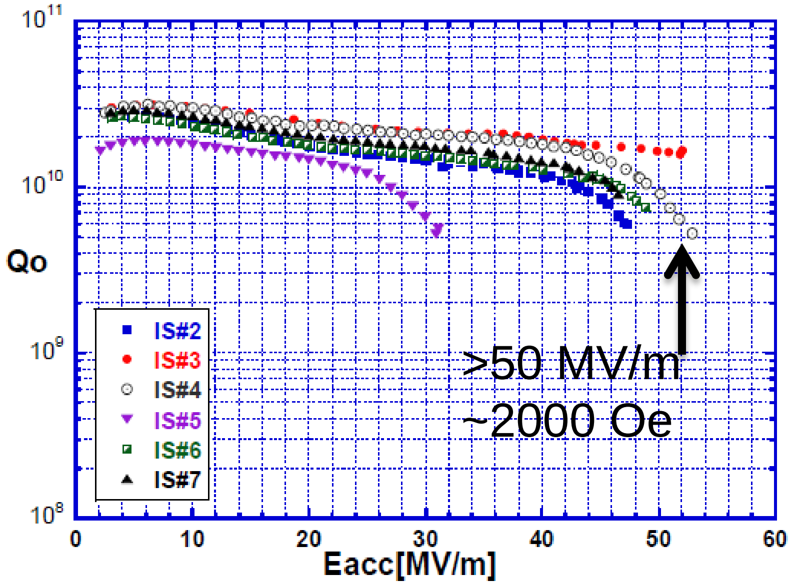
Performance progress



Niobium cavity is approaching its theoretical(?) limit

Hc=2000, Hsh=2300 (at 1.8 K), =2400 (at 0 K)

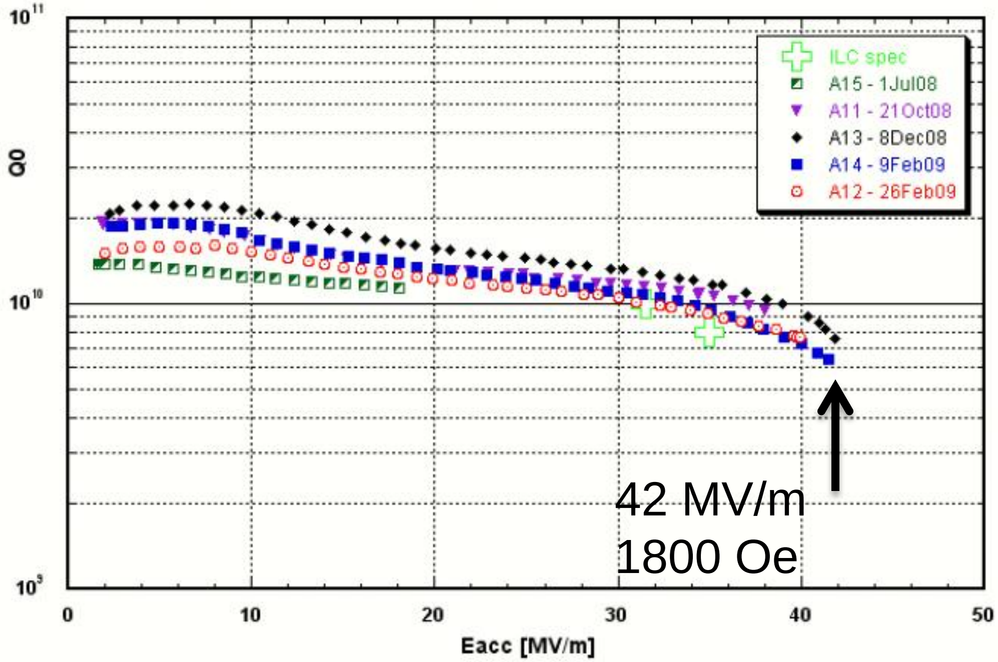
Single cell



>50 MV/m
~2000 Oe

K. Saito (KEK) for ILC efforts

Nine-cell



42 MV/m
1800 Oe

R. Geng (Jlab) for ILC efforts

New materials for higher performances and higher temperatures

Ex. Multi-layered superconductors for higher performances

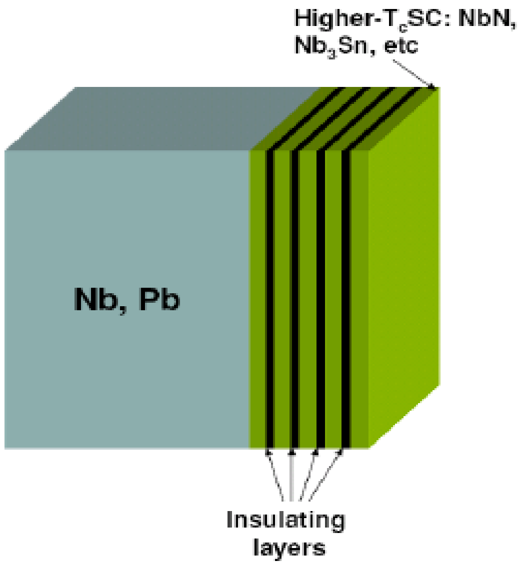
Enhancement of rf breakdown field of superconductors by multilayer coating

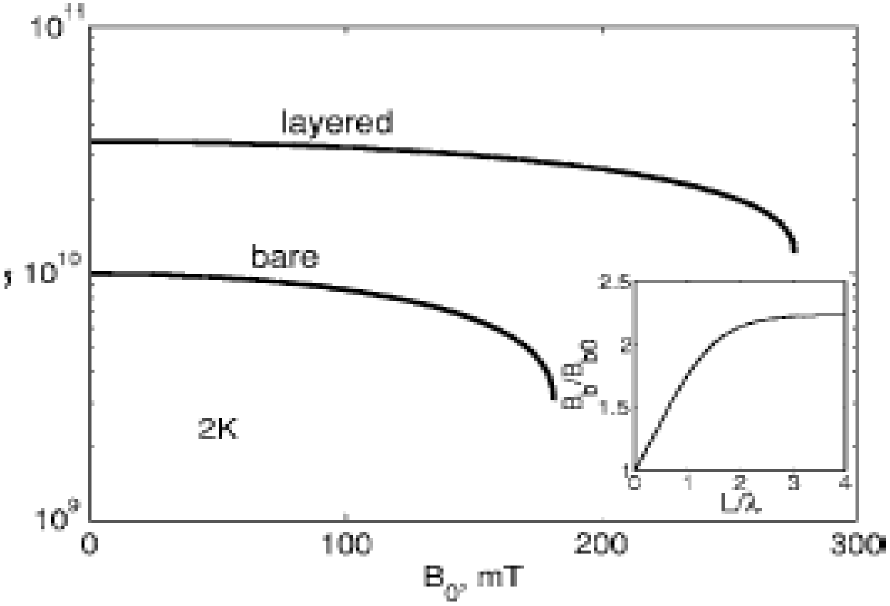
A. Gurevich

Applied Superconductivity Center, University of Wisconsin, Madison, Wisconsin 53706

Appl. Phys. Lett. 88, 012511 (2006)

Strong increase of H_{c1} in film





Superconducting rf properties
Practicality
Cost

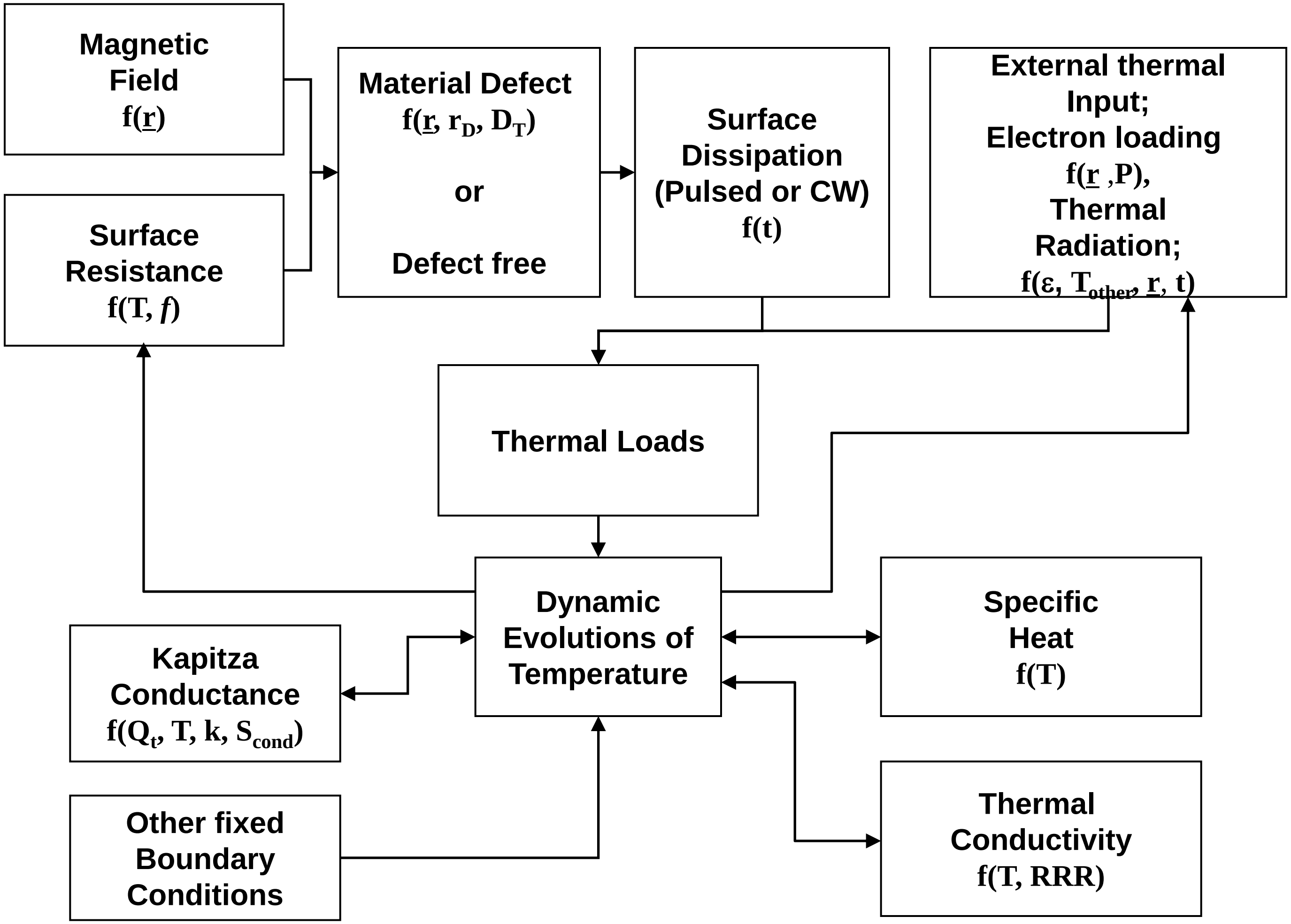
→

Still in questions.
But definitely need extensive efforts
for the new materials (say for 100 MV/m)

Thermal stability

- **Thermal load**
  - Surface
    - Surface resistance: BCS loss, residual resistance
    - Material defect: hot spot, field emitter, welding defects
    - grain boundary
  - Other sources
    - electron activity: multipacting, field emission
    - thermal radiation: warm coupler, other minor
- **Heat transfer and removal**
  - Niobium
    - thermal conductivity
    - Specific heat
    - niobium thickness
  - niobium-helium boundary
    - Kapitza resistance
- **Operation condition**
  - Operating frequency
  - Gradient
  - Duty factor
  - Operating temperature

Thermal stability realtions



Magnetic Field
$f(\underline{r})$

Surface Resistance
$f(T, f)$

Material Defect
$f(\underline{r}, r_D, D_T)$

or

Defect free

Surface Dissipation (Pulsed or CW)
$f(t)$

External thermal Input;
Electron loading
$f(\underline{r}, P)$,
Thermal Radiation;
$f(\varepsilon, T_{other}, \underline{r}, t)$

Thermal Loads

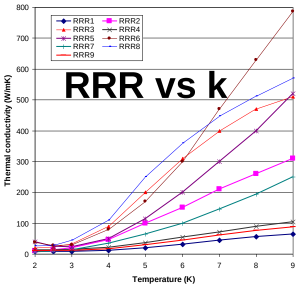
Dynamic Evolutions of Temperature

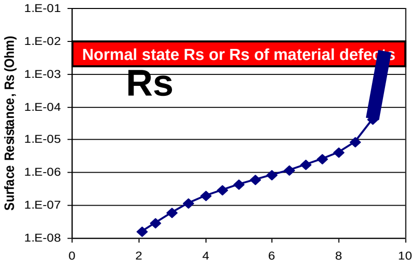
Kapitza Conductance
$f(Q_t, T, k, S_{cond})$

Other fixed Boundary Conditions

Specific Heat
$f(T)$

Thermal Conductivity
$f(T, RRR)$

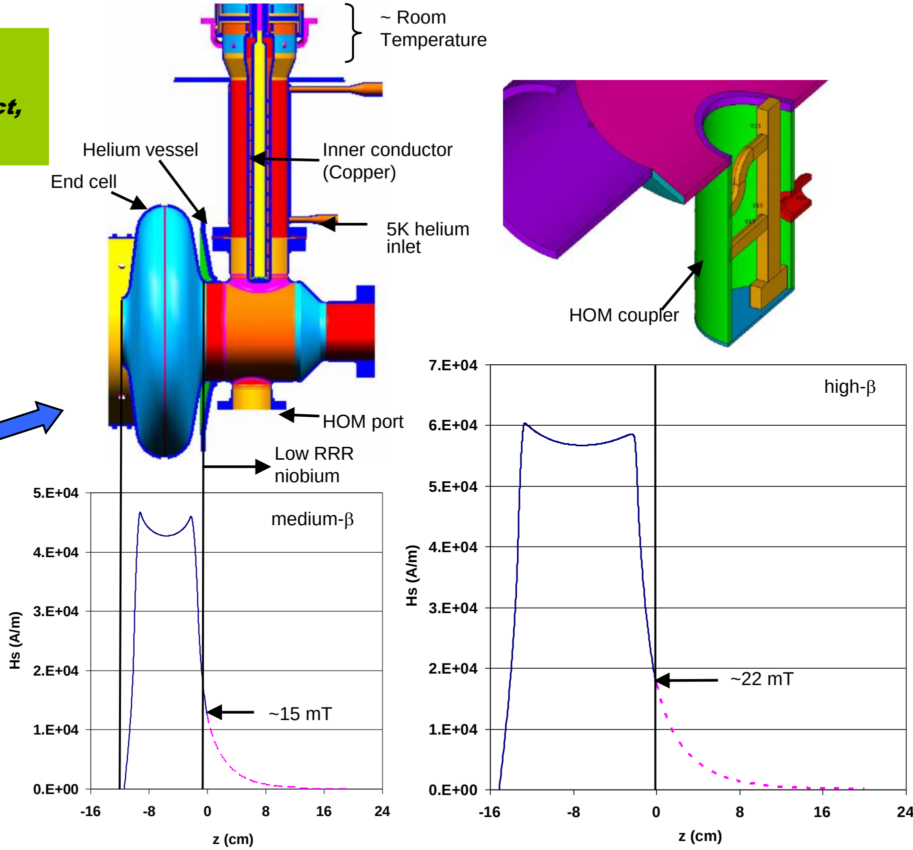


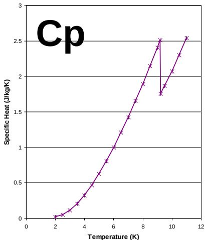


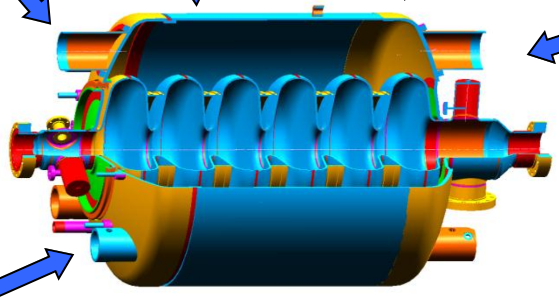
Kapitza Resistance,

Material defect,

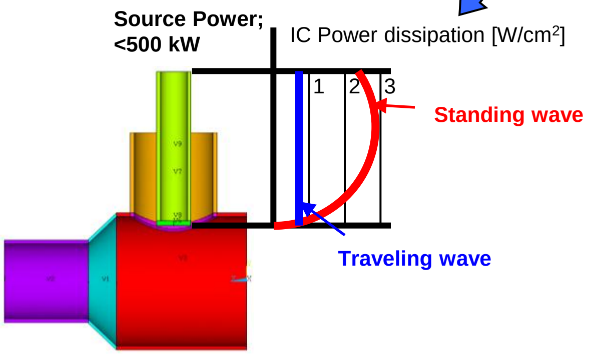
Other BC







Material defects
And/or
Electron loading
(field emission, MP)



Thermal stability

Static analysis

Dynamic analysis

Material defects can be anything in the history of surface preparations that has different characteristics

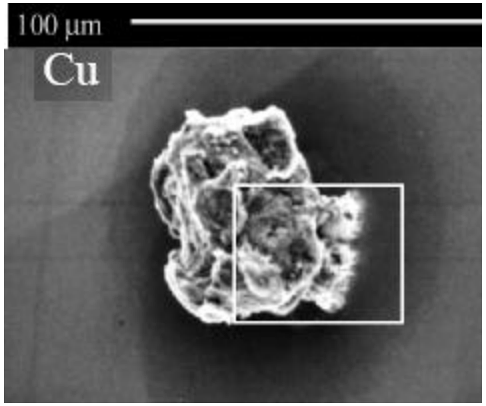
Usually have higher surface resistances (normal state), higher secondary emission yields, higher local surface electric field, etc.

Pure thermal breakdown due to material defect:

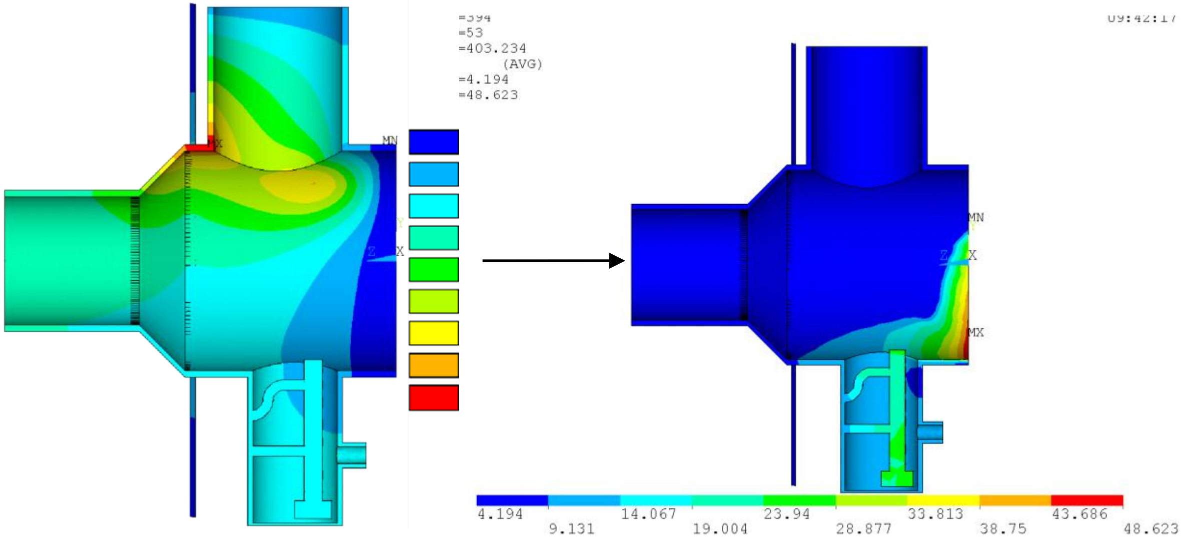
Thermal runaway;

heat generation > heat removal →normal region expansion

Defects on high field surface only allow several micron thermal runaway speed~μs

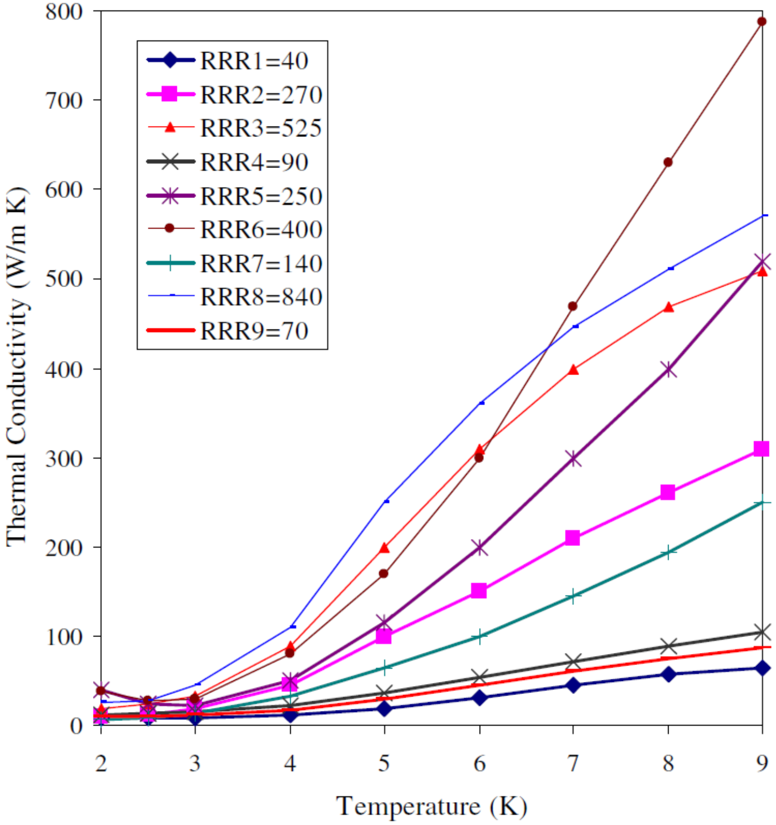


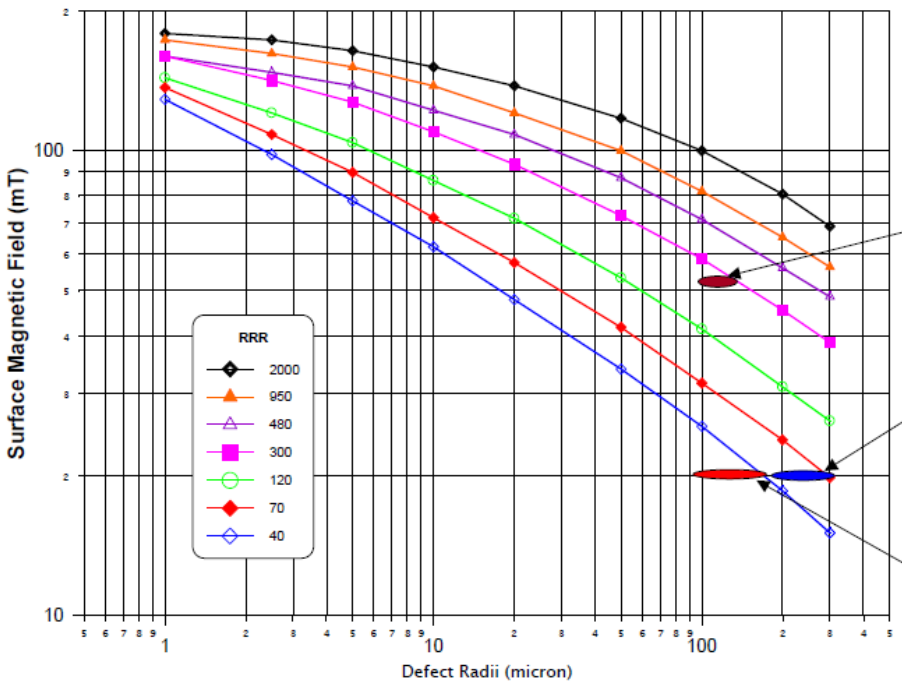
Visualization of thermal runaway on lower magnetic field



RRR (residual resistivity ratio), thermal conductivity and thermal stability

RRR =(resistivity at room temperature)/(resistivity at cryogenic temperature at NC state)





RRR vs. k
In page 4

RRR=200
Dynamic analysis
% high RRR
Variation is small

RRR=50
Dynamic analysis

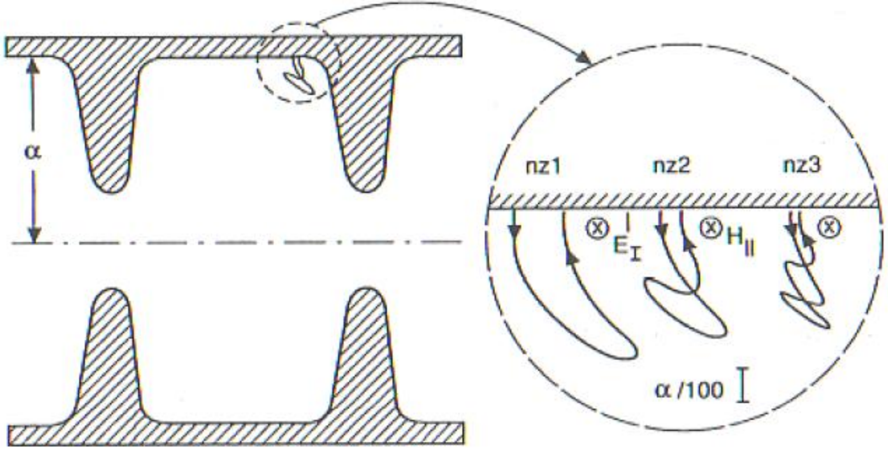
RRR=25
Dynamic analysis

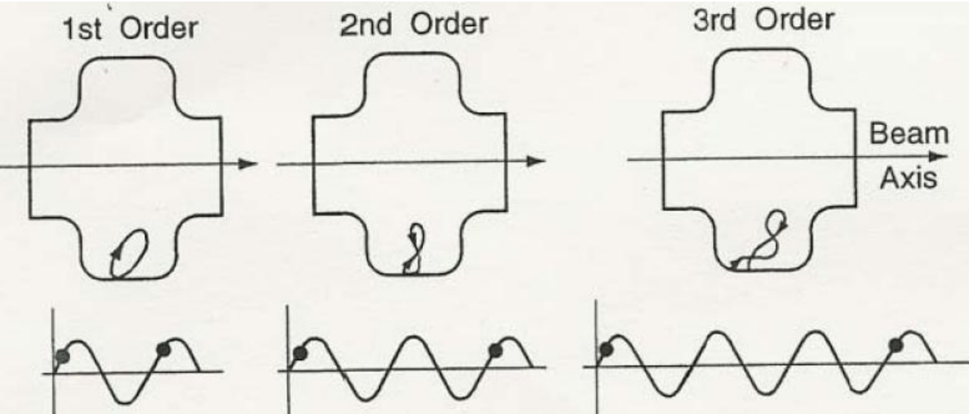
Multipacting

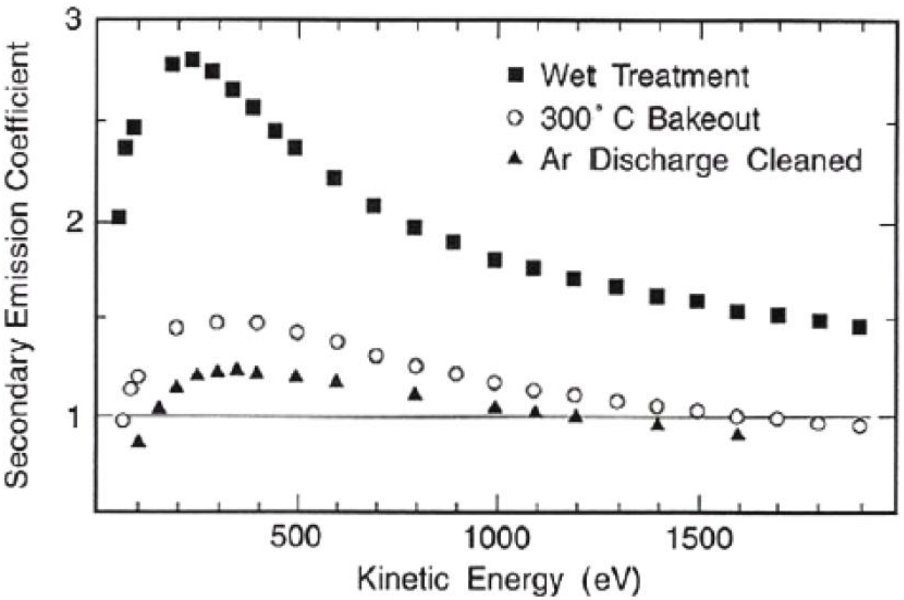
Resonant electron loading → strongly depends on geometry

Multipacting condition

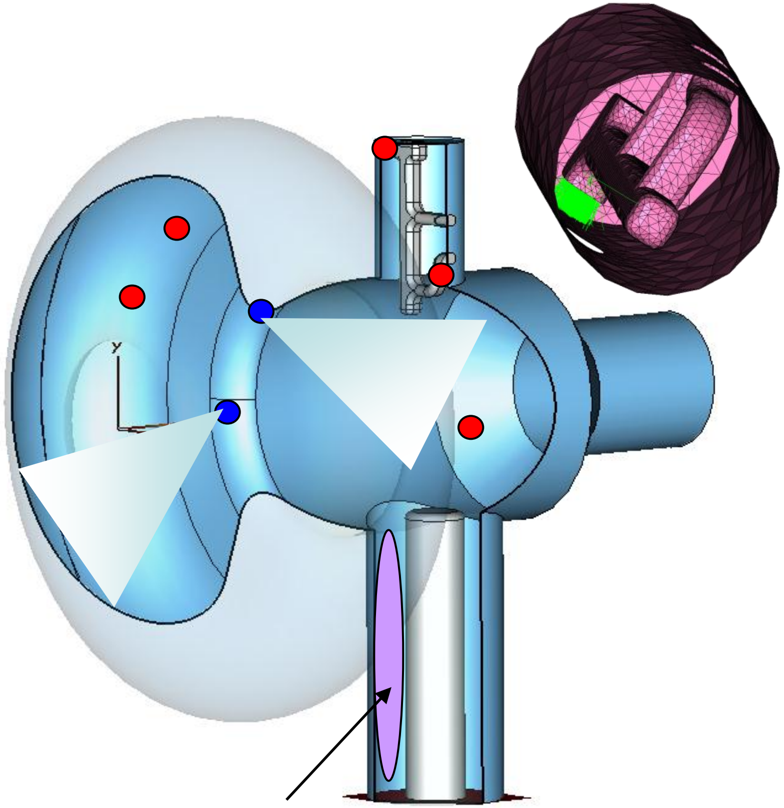
1. Closed trajectory
2. insensitive to the initial energy
3. SEY(E)>1 (Physical surface condition) ← lowering thru He processing & better surface cleaning process







Electron Loading



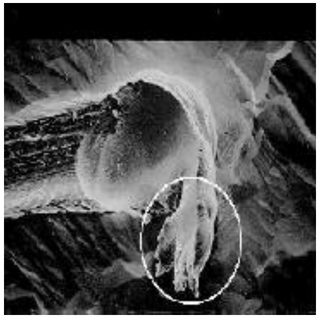
Easy to remove with DC biasing

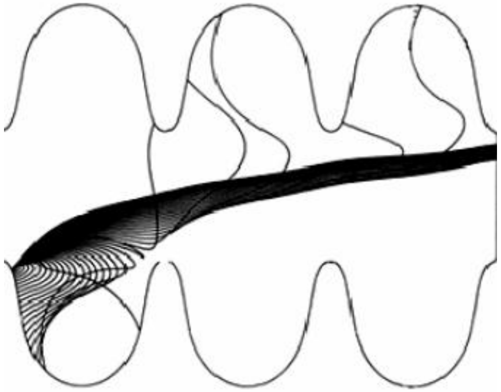
- Multipacting; secondary emission
  - resonant condition (geometry, RF field)
  - At sweeping region; many combinations are possible for MP
    - Temporally; filling, decay time
    - Spatially; tapered region
    - Non-resonant electrons → accelerated → radiation/heating
  - Mild contamination → easily processible
  - But poor surface condition → processing is very difficult in an operating cryomodule
- Field Emission due to high surface electric field

Result

End group heating/beam pipe heating + quenching/gas burst

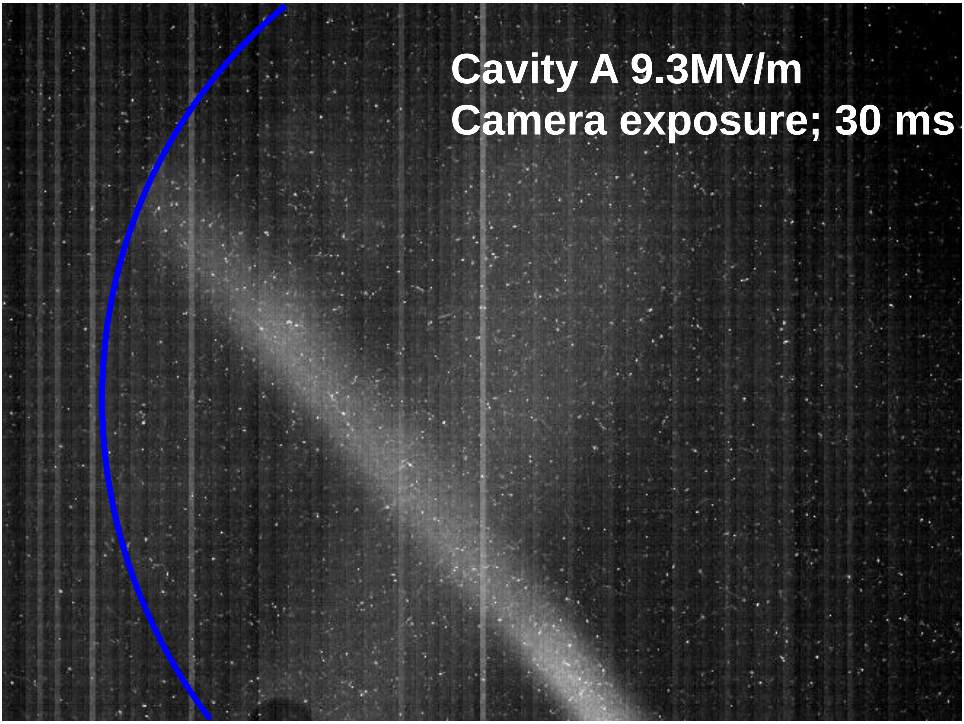
Field emission

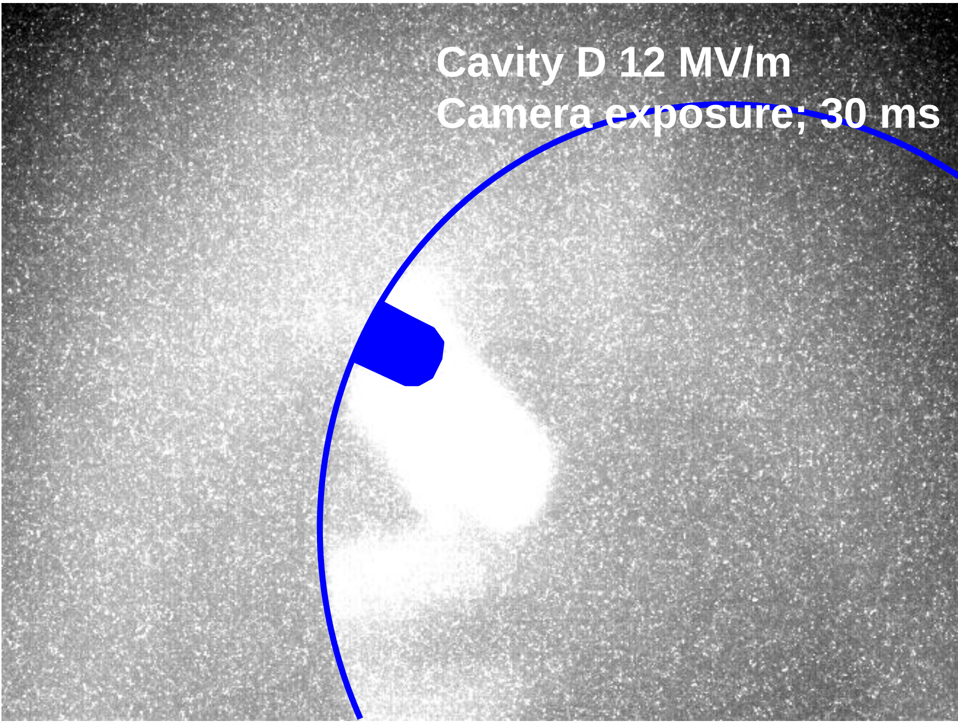




- Model
  - Protrusion-to-protrusion
  - Modification of constant and shape factor in FN equation by absorbed gases and oxide layer
  - Activation of field emitter at elevated temperature by changes of the boundary layer
- Complexity
  - Function of size, shape, kinds of particle, charge, substrate status, wettability, temperature, processing history……..
- No review of contamination and cleaning mechanisms

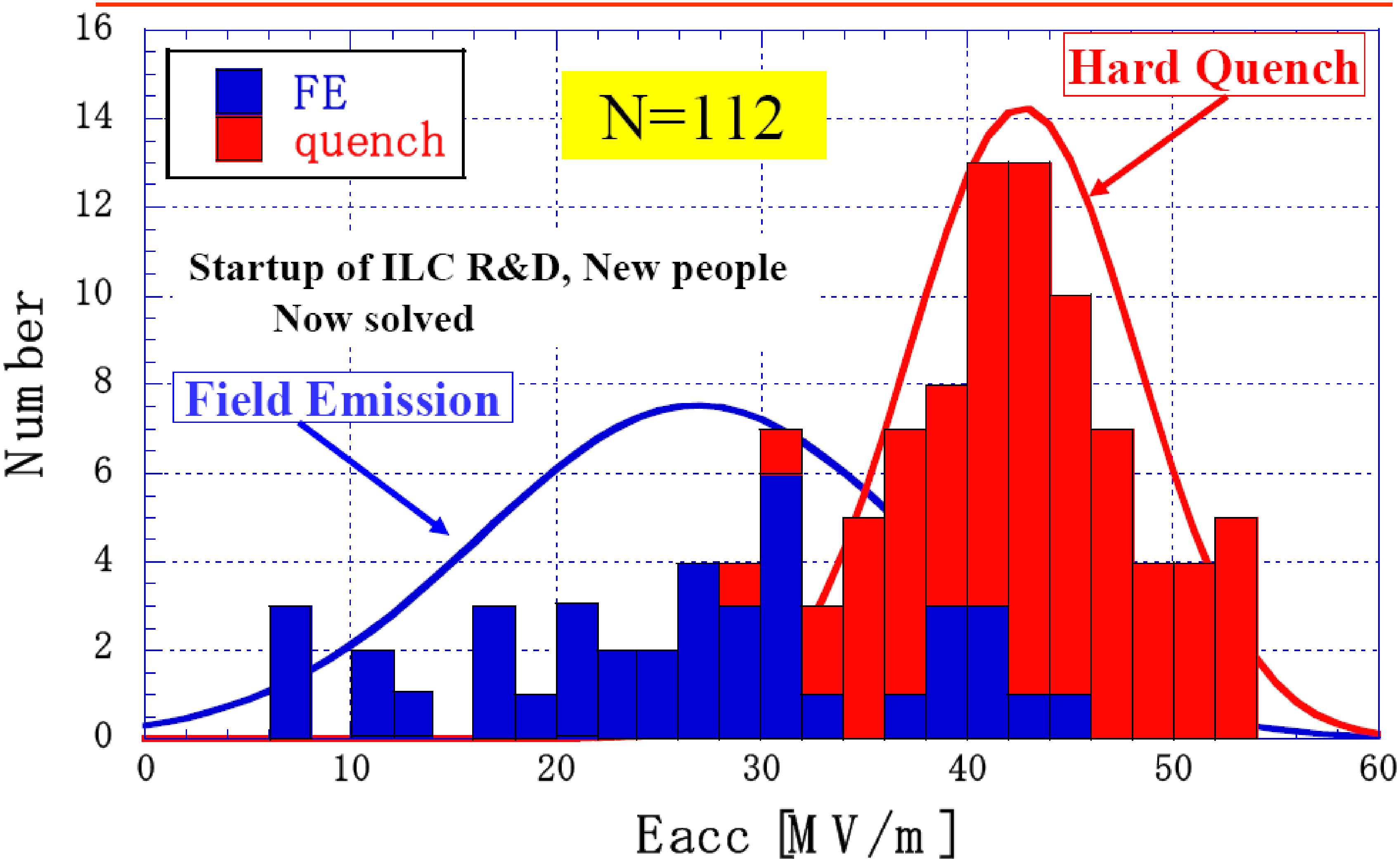
Phosphor screen images



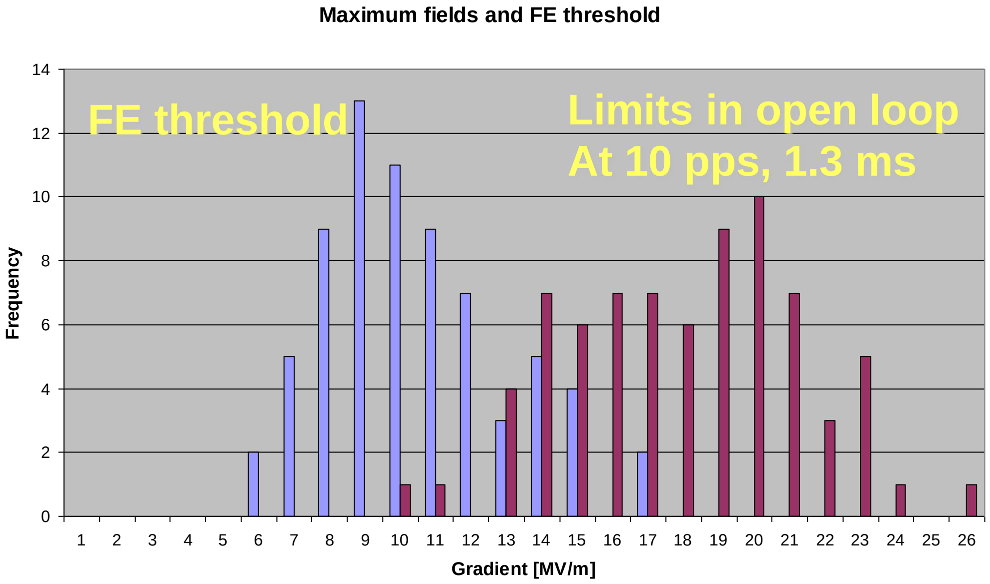


Performance scatter (I)

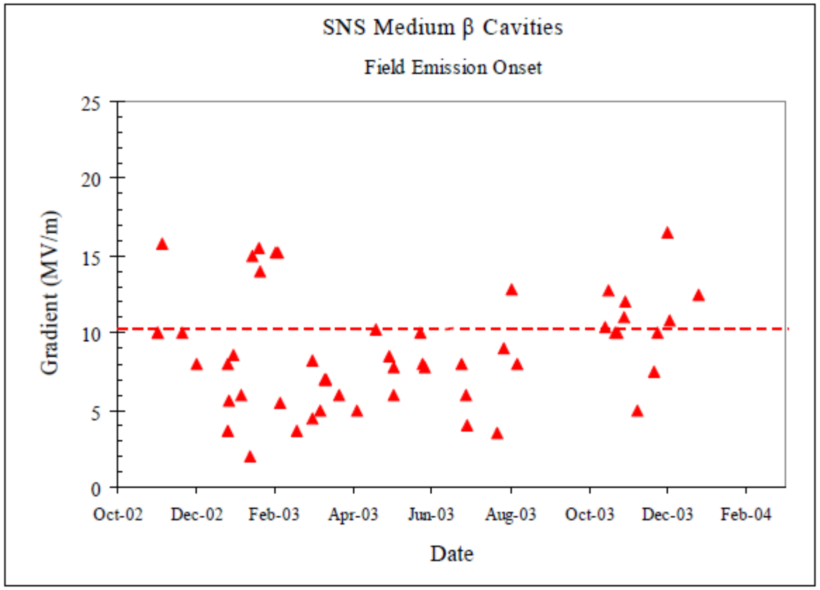
LL single cell study at KEK for ILC study (K. Saito)



Performance scatter (II)

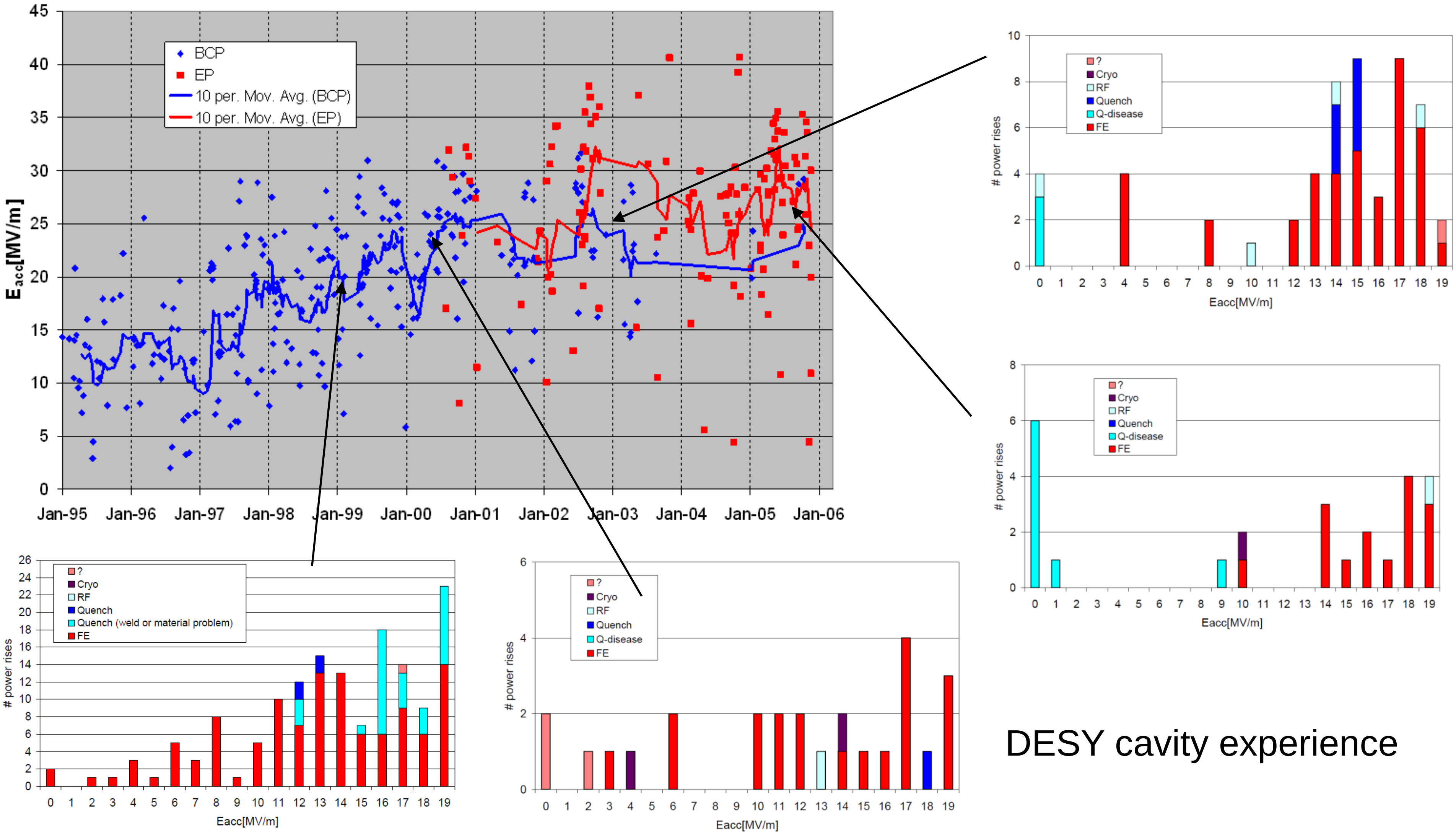


Measured at SNS



JLAB SNS cavity experience

Performance scatter (III)



DESY cavity experience

L. Lijie’s summary of DESY cavity databank, DESY, 2006

Great cares

Material preparation: high purity, high thermal conductivity

- refining; electron beam melting in vacuum
- gas/purity analysis
- vacuum annealing

Surface processing

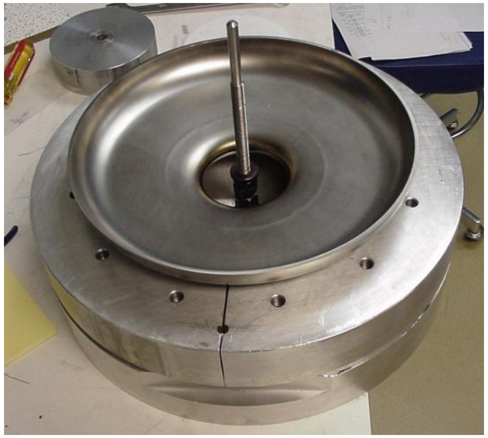
- surface polishing: chemical polishing, electropolishing
- clean environments as facilities in semi-conductor industries
  - high pressure rinse using ultra pure water
  - clean room
- Uniform processing/conditioning
- Repetitive processing/conditioning
- Understanding of processing/conditioning

Cavity Fabrication

Deep drawing & machining

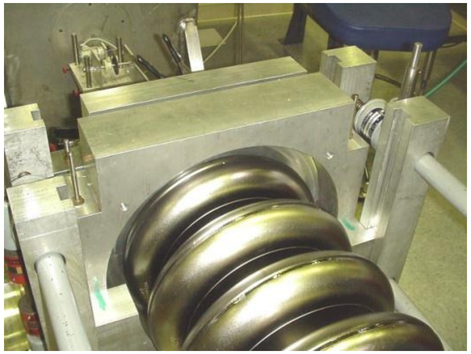
Dumb-bells

Frequency adjust



Welding

Tuning



Cavity Preparation

Buffered Chemical Polishing

High Pressure Rinsing

Assembly in clean room
(class <100)

Dewar insertion

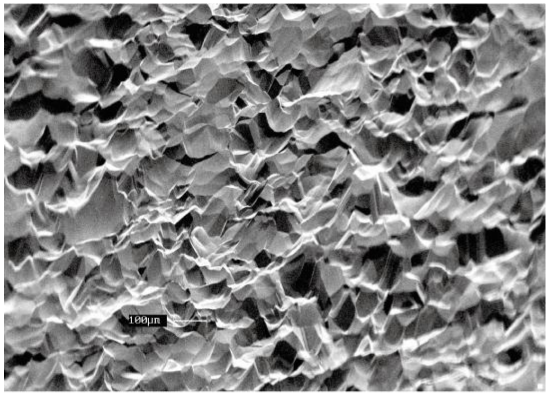
Electro-polishing & low temperature baking

Main Advantages

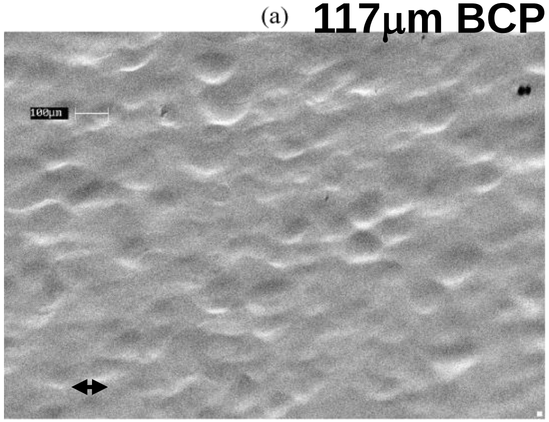
Much smoother surface

-No need of
 high temperature baking

-So better performance &
 more reliable



(a) **117µm BCP**



100 µm (b) **+90µm EP**

Electropolshing cabinet (Jlab)