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Thin Film SRF Applications beyond Accelerators

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Outline:

- Introduction
- Electrodynamic properties of superconducting thin films: new results on MgB_2 and Nb
- Thin film based high-temperature superconducting resonators, filters and subsystems
- Cryogenic low-phase noise oscillators
- Millimetre wave / THz HTS Josephson devices: voltage standard and Hilbert transform spectroscopy
- Summary and outlook

Overview: Microwave to THz applications of superconducting films

- Cavities for particle accelerators (Nb, Nb_3Sn ?, NbN ?)
- Passive devices for wireless communications (YBCO, Tl and Hg ? based cuprates)
- Detectors for mm wave and THz radiation (Nb, NbN, YBCO, MgB_2 ?)
- Josephson voltage standards (Nb, YBCO ?)
- Josephson digital circuits (Nb, YBCO ?, MgB_2 ?)

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T-ray specs

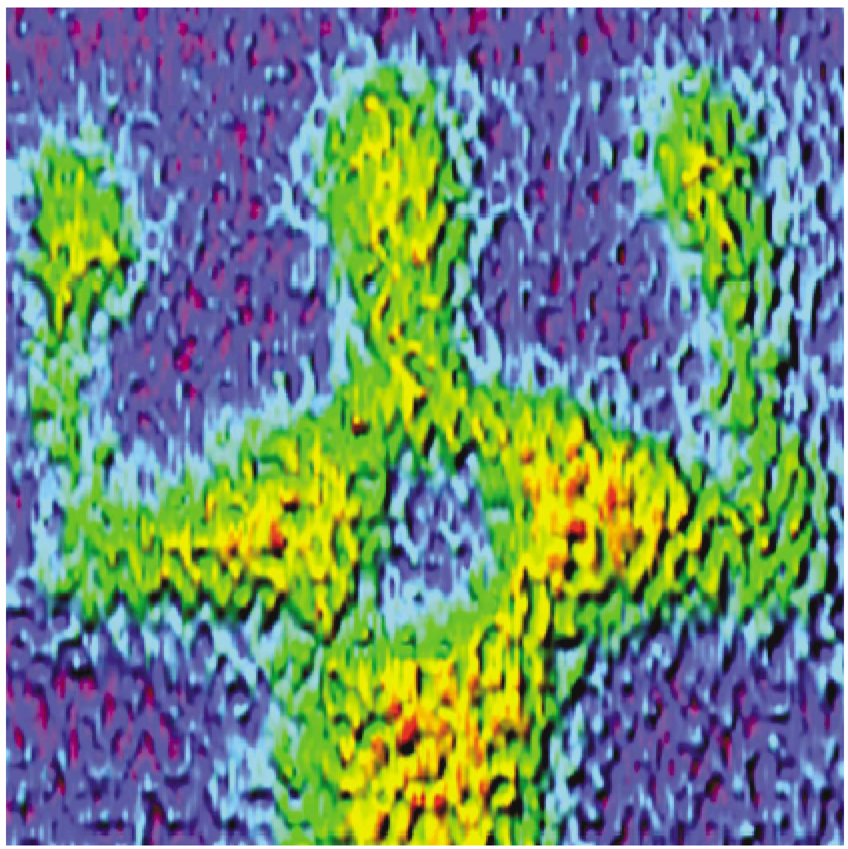
Radiation from a previously unexploited region of the electromagnetic spectrum could hold the key to a new generation of security devices. Catherine Zandonella investigates.

Suicide bombers, plastic explosives strapped to their bodies, approach the turnstiles at a packed football stadium. The security guards don't have time to search every spectator, and even if a metal detector were installed, it would miss the terrorists' deadly cargo. But a novel device that can see through the bombers' clothing succeeds were other systems fail. Security personnel are alerted, and surround the attackers before they can strike.

Such is the potential power of a new imaging technology. Terahertz devices, so named because they detect electromagnetic radiation in the terahertz frequency range (1 THz is 10^{12} Hz), promise to peer through clothing, revealing concealed weapons and explosives. The technique could also be used to seek out structural defects in materials, to detect skin cancer or to provide new information about astronomical objects.

For years, radiation with a frequency of between 0.1 THz and 10 THz languished unexplored. But recent advances in generating and analysing such radiation, together with an avalanche of research funding for antiterror applications, are now helping researchers to examine its applications.

Terahertz radiation, often called T-rays, lies between microwaves and infrared light in the electromagnetic spectrum. It can sail through paper and clothing, but not very far through skin or biological molecules, so objects hidden beneath clothing can be



Caught: this terahertz image clearly shows an object (blue) concealed beneath the person's clothing.

TAKEN WITH RUTHERFORD MK 2 IMAGING SYSTEM

from Nature 424, 14. August 2003

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Millimeter wave surface resistance of epitaxially grown $YBa_2Cu_3O_{7-x}$ thin films

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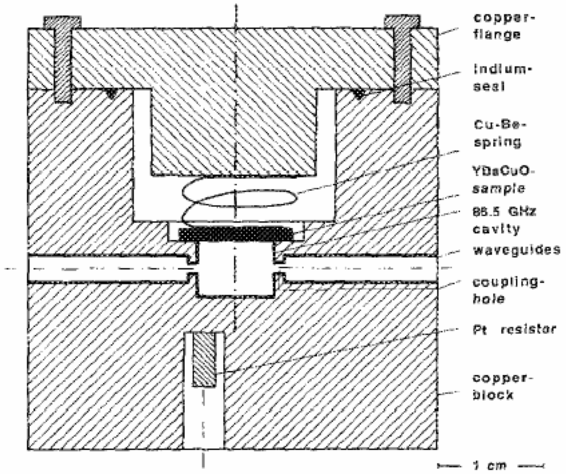
Fachbereich Physik, Bergische Universität, Gesamthochschule Wuppertal, D-5600 Wuppertal 1, West Germany

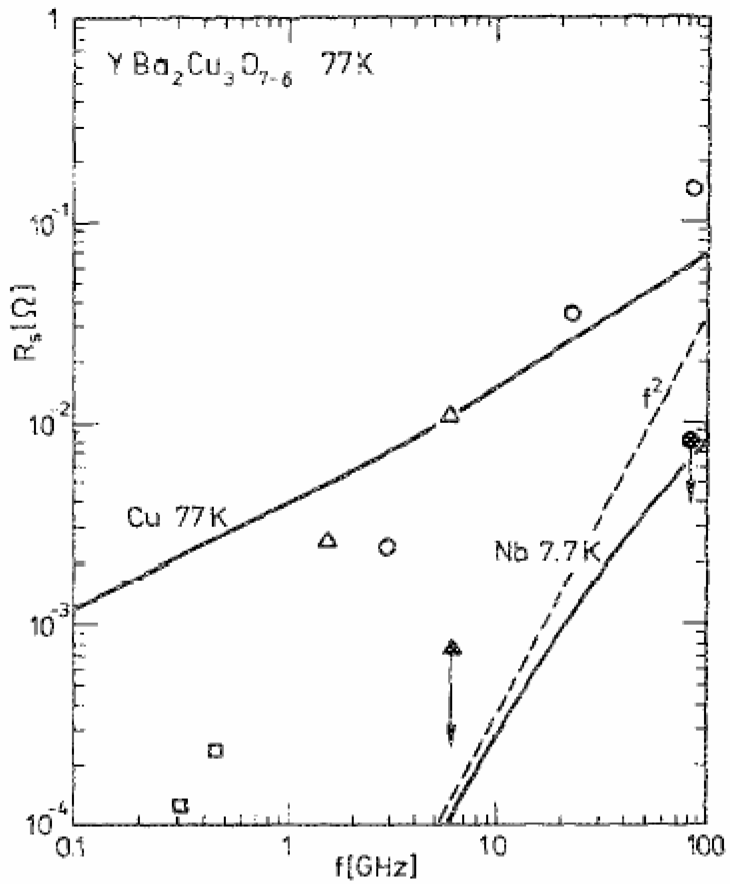
B. Roas[a] and L. Schultz
Siemens AG, Research Laboratories, D-8520 Erlangen, West Germany

U. Klein and M. Peiniger
Interatom GmbH, D-5060 Bergisch Gladbach 1, West Germany

(Received 10 November 1988; accepted for publication 22 December 1988)

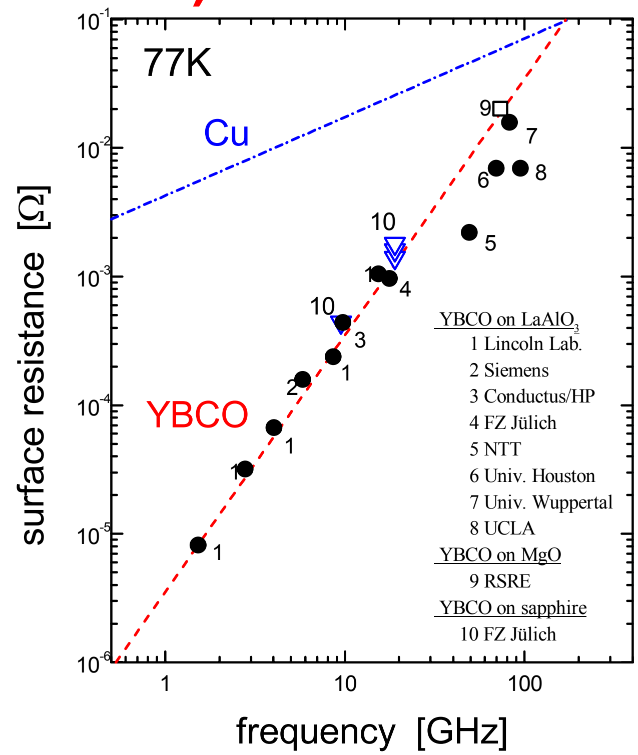
We have measured the surface resistance of two c-axis oriented $YBa_2Cu_3O_{7-x}$ thin-film samples in a copper host cavity at 86.7 GHz between 4.2 and 300 K. High quality films of 0.6 and 0.4 μm thickness have been grown epitaxially on $SrTiO_3$ by pulsed excimer laser ablation. Their millimeter wave absorption drops sharply at a transition temperature of 86 and 88 K to a corresponding surface resistance at 77 K of 18 mΩ and less than 8 mΩ, respectively. These values exceed the best results on polycrystalline samples and come close to the expectation from classical superconductors. Therefore, applications of high T_c superconductors up to THz frequencies can be envisaged now.





Thin films for high-frequency applications

$REBa_2Cu_3O_7$ ($T_c \approx 90$ K)



- thin film technology is mature
- Large area thin films commercially available, global market leader is THEVA in Germany

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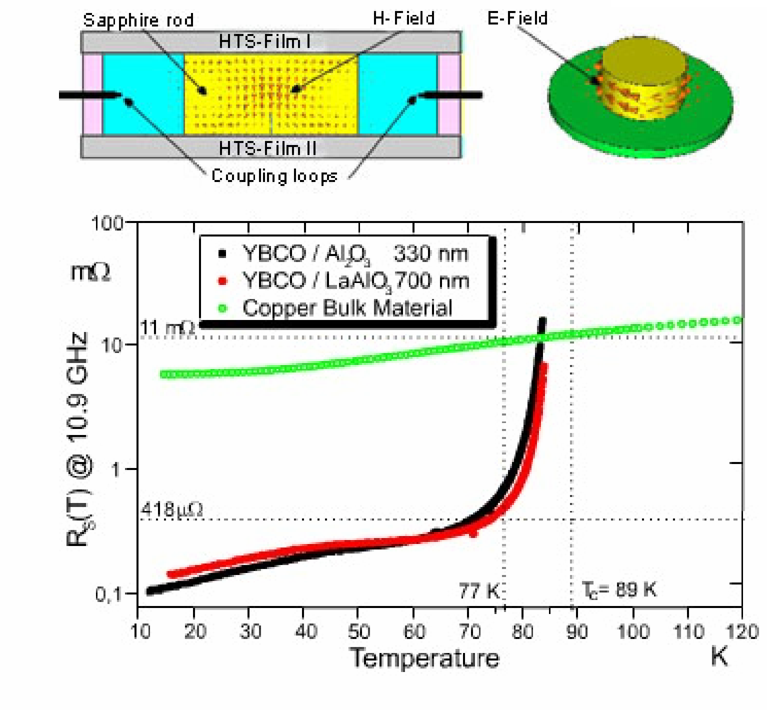
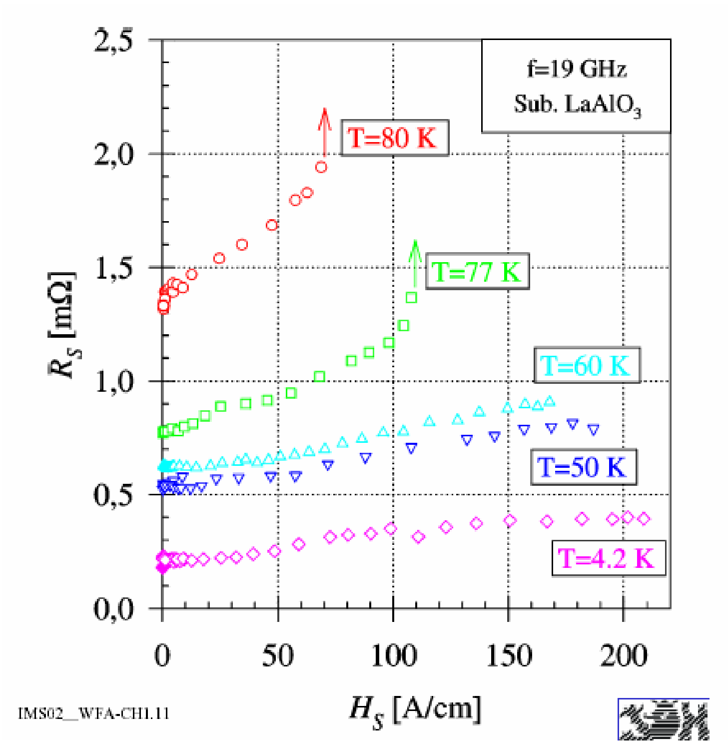




from **http://www.theva.com**

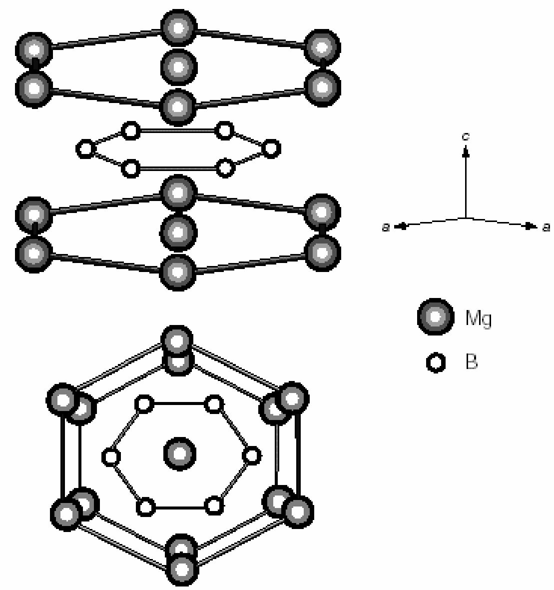
from M. Hein, TU Ilmenau

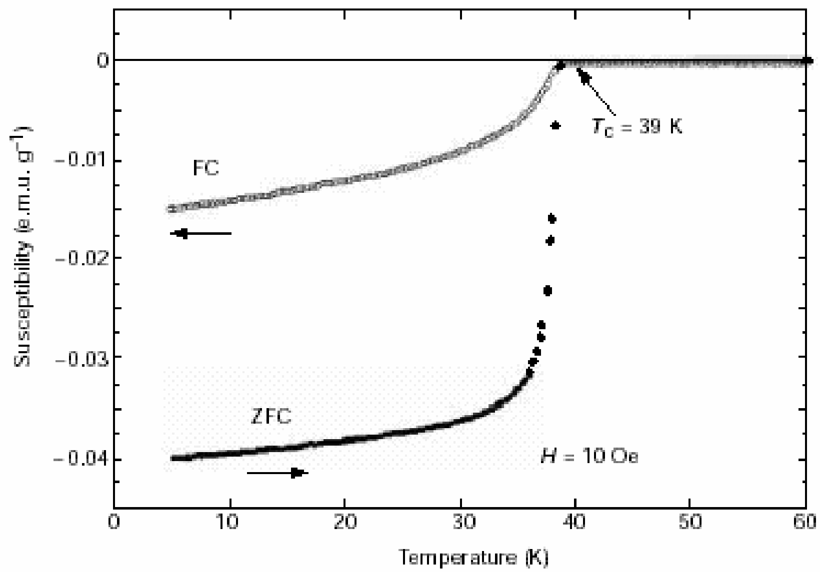
- d-wave nature of oxide high-temperature superconductors forbids exponential slope of R_s below $T_c/2$

$\Rightarrow$ no chance for accelerator applications

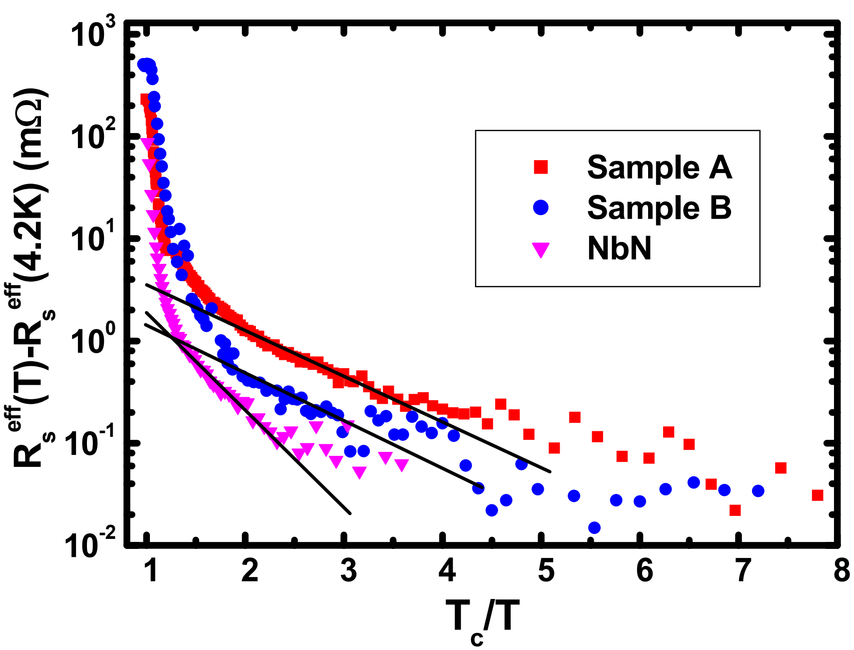
- Nonlinearities extremely sensitive to film quality because of short coherence length

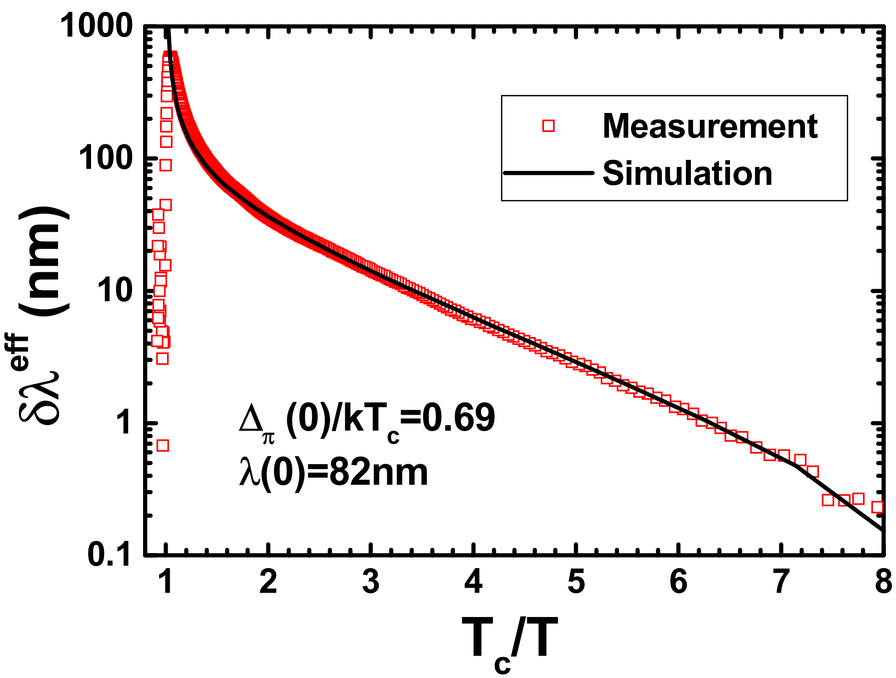
Magnesium Diboride - new hope ?





Jun Nagamatsu et.al., Nature 410, 63 (2001)





clear exponential dependences, but BCS fit to $\lambda(T)$
reveals Δ/kT_c between **0.7** and **1**

B.B. Jin et al., Phys. Rev. B. 66, 104521 (2002)

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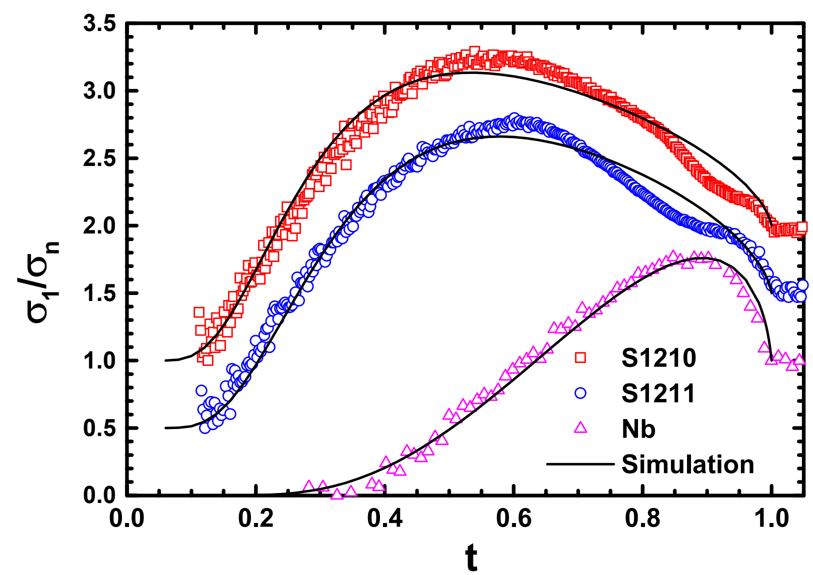
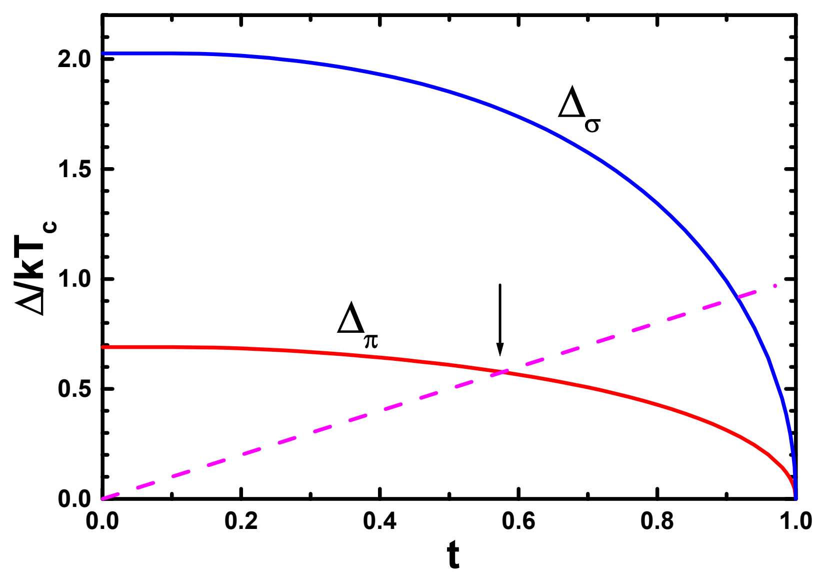
local limit: extract dynamic conductivity $\sigma_1(T)$ from $R_s(T)$ and $\lambda(T)$ employing

$$R_s(T) \approx \frac{1}{2}\omega^2 \mu_0^{\;2} \sigma_1(T) \lambda^3(T)$$





Consequence of two-gap BCS model: coherence peak shifted to lower temperatures

B.B. Jin et al., accepted for Phys. Rev. Letters

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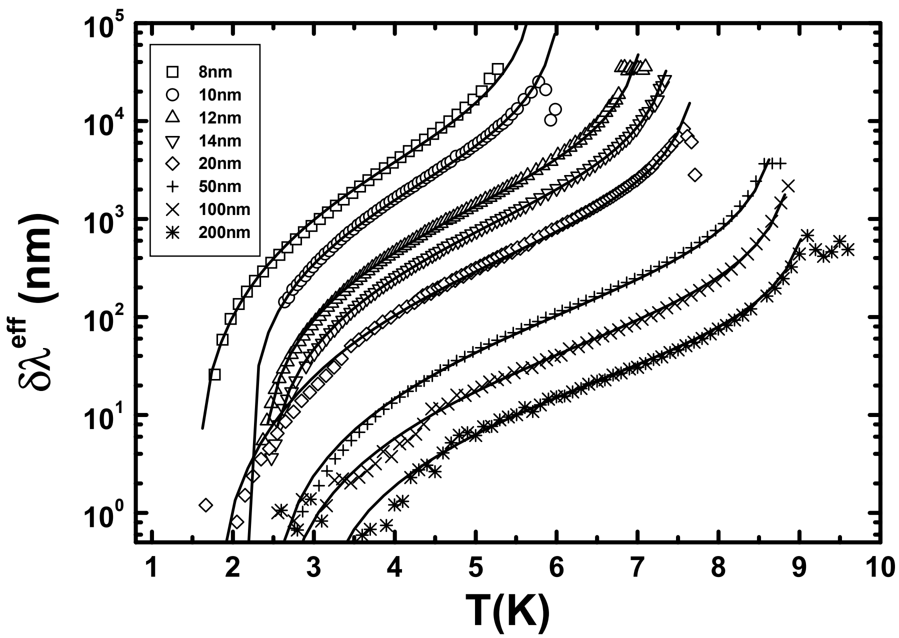
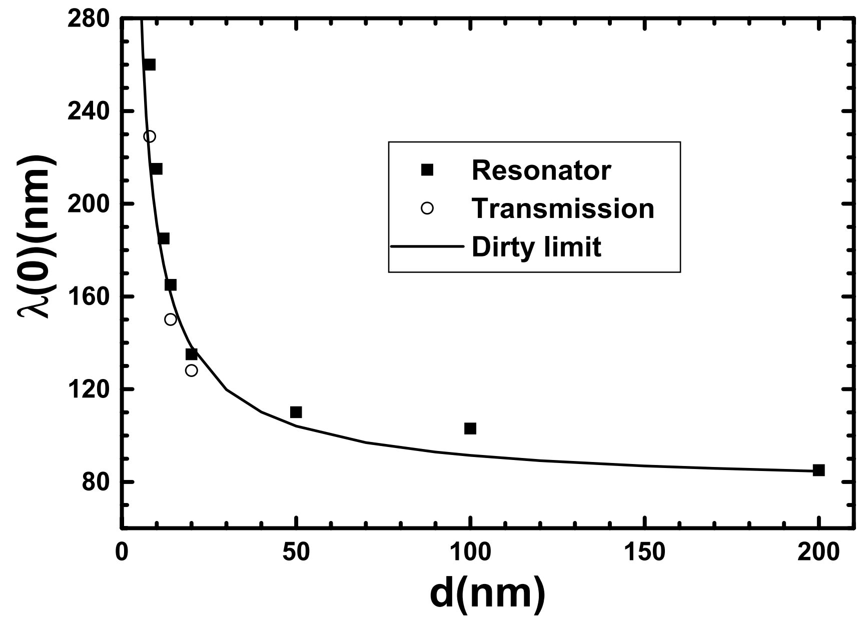
High-precision $\lambda(T)$ measurements on ultrathin niobium films





$$\lambda_0(d) = \frac{\lambda_{L,0}[\xi_0(d)/l(d)]^{1/2}}{\left\{1-\left[4l(d)/\pi^2\xi_0(d)\right]\ln[\pi\xi_0(d)/l(d)]\right\}}$$

$\Rightarrow$ sensitive test of proximity effect generated by normal conducting surface of interface layers

B.B. Jin et al., publication in progress

Q factor of a resonator composed of dielectrics and metall wall segments:

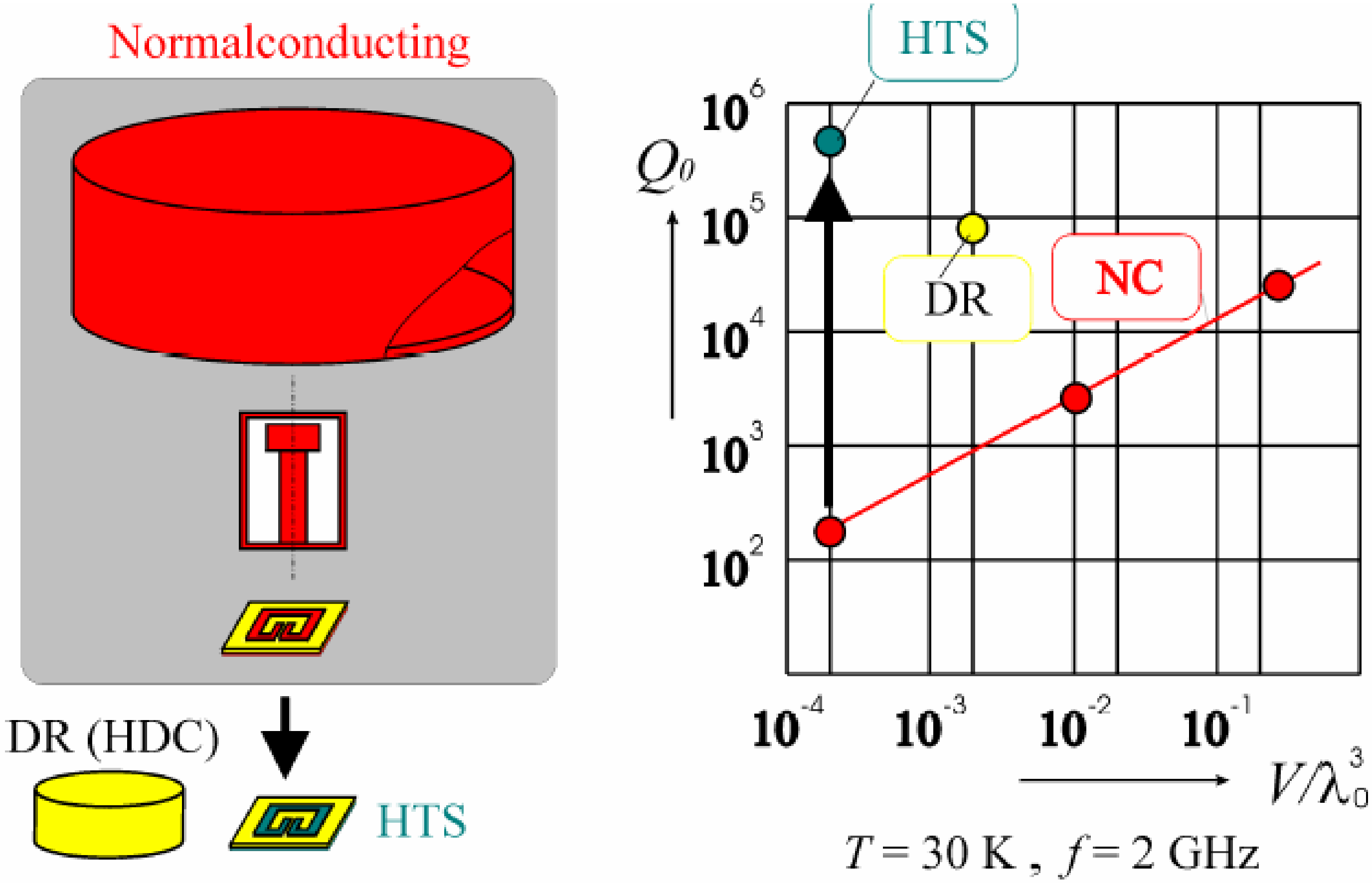
$$\frac{1}{Q_0} = \frac{R_s}{G} + \kappa \tan\delta$$

$G\ [\Omega] \propto V / \lambda_0^3$: geometric factor

κ: filling factor of electric field energy in dielectric material ($0 \leq \kappa \leq 1$)

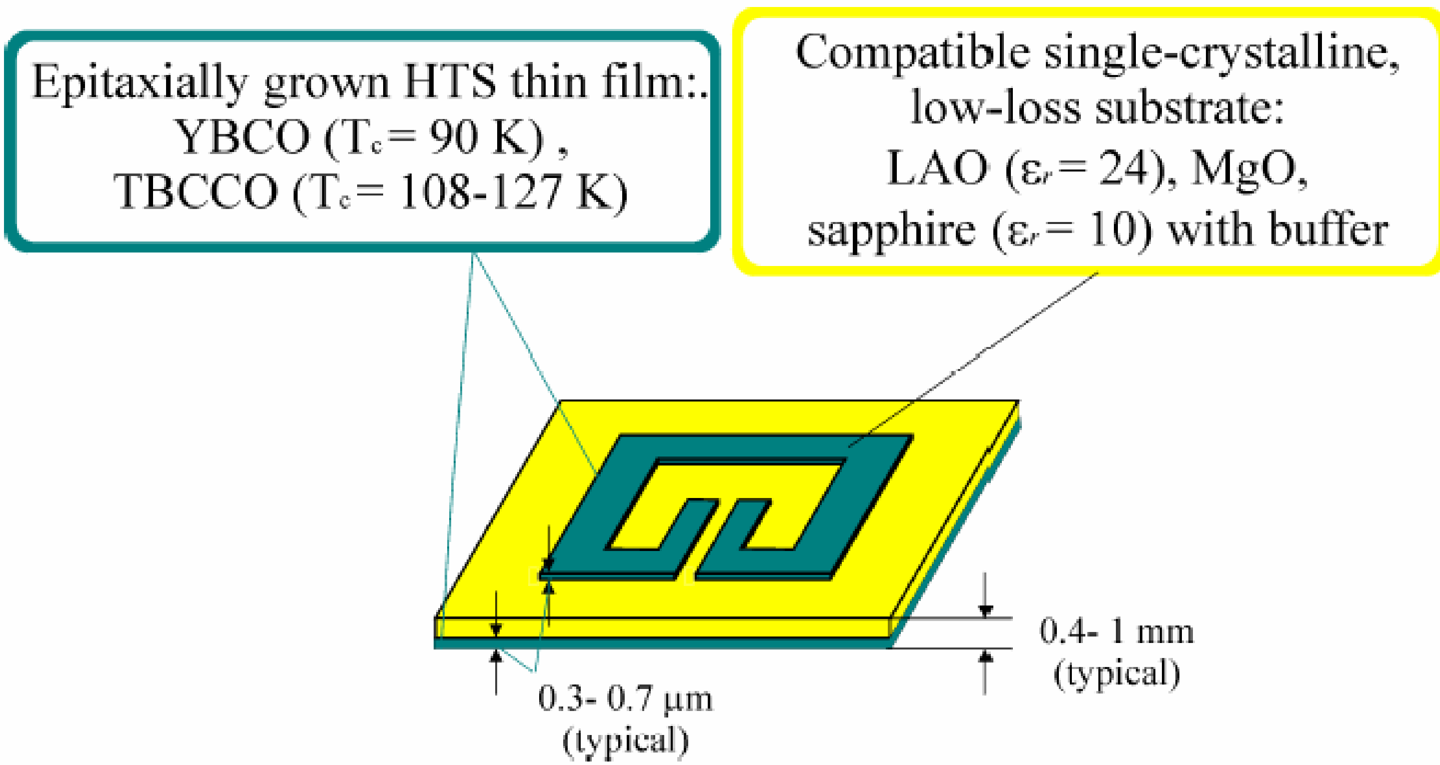
microstrip resonator: $\kappa \approx$ **1, *G* = 1 – 10 Ω**

dielectric resonator: $\kappa \approx$ **1, *G* = 100 – 10000 Ω**



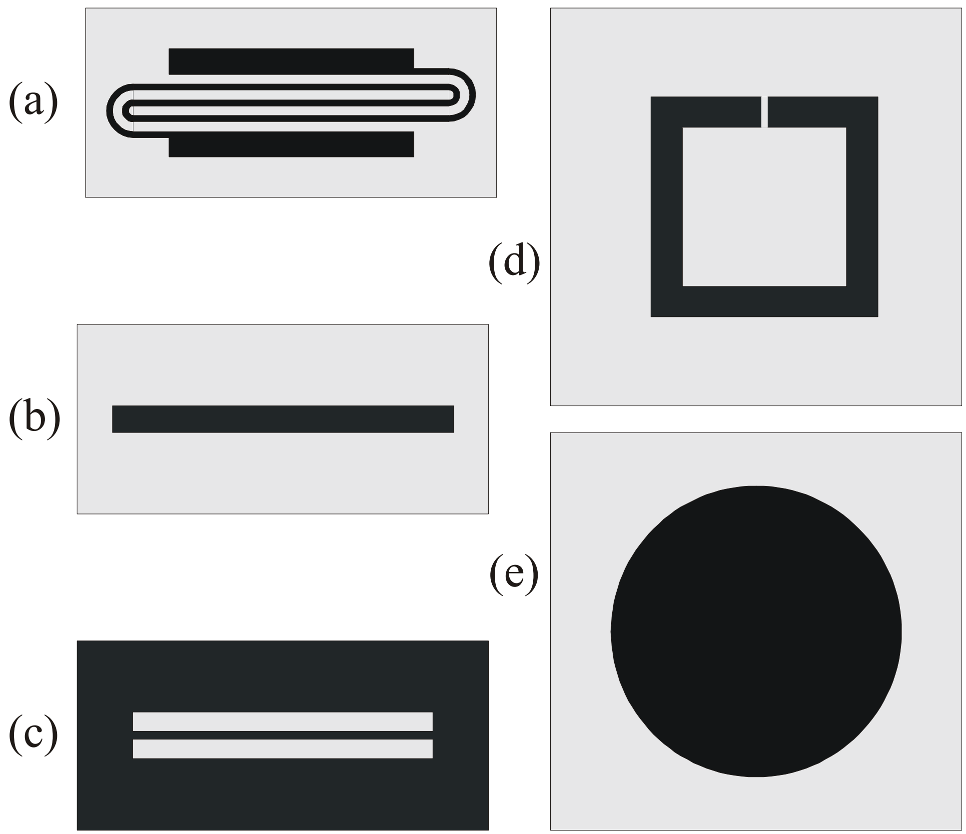
from IMS_2002, Seattle, tutorial workshops

Technology for planar HTS resonators and filters



from IMS_2002, Seattle, tutorial workshops

Planar HTS resonators



(a) quasi-lumped element
(b) micro strip
(c) coplanar waveguide
(d) folded microstrip with integrated capacitors
(e) 2D disk resonator

from N. Klein and H. Chaloupka, Encyclopedia of Materials, Elsevier

$Q \approx 10^4 - 10^5$: attractive for filters (< 5 GHz)

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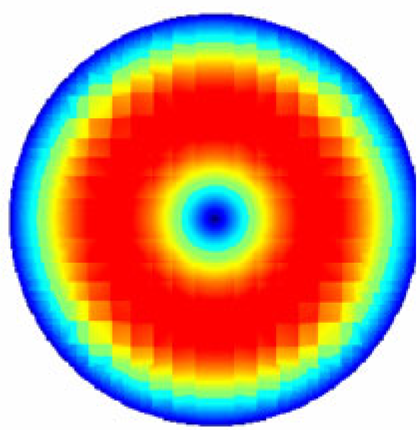
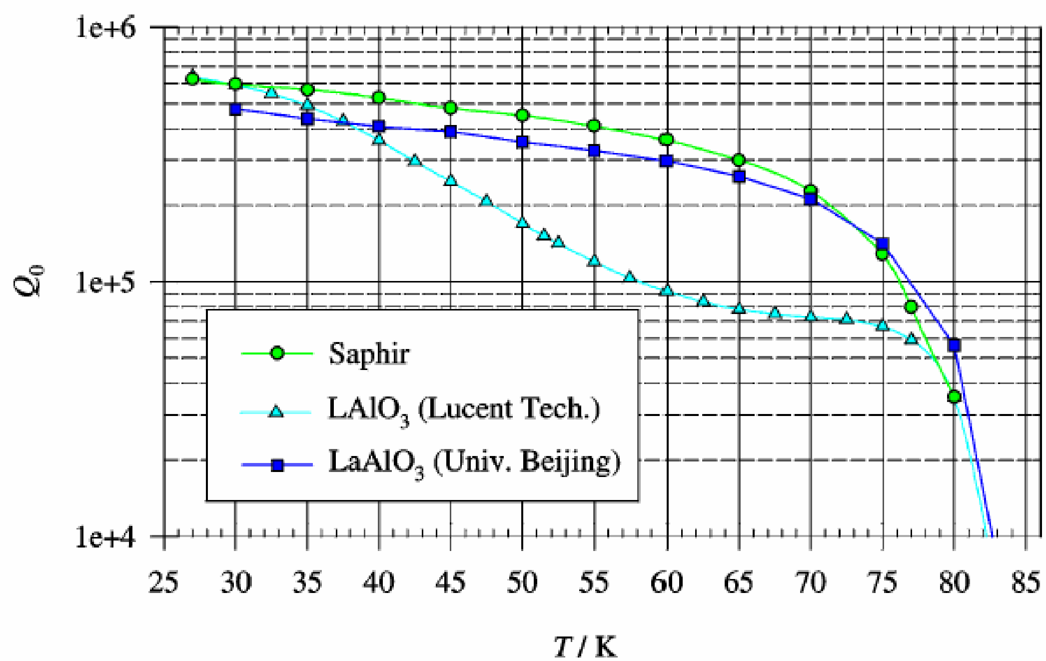
Properties of HTS disk resonator



Current distribution of TM_{010} mode



Measured temperature dependence of Q_0 (TM_{010} mode)

from IMS_2002, Seattle, tutorial workshops

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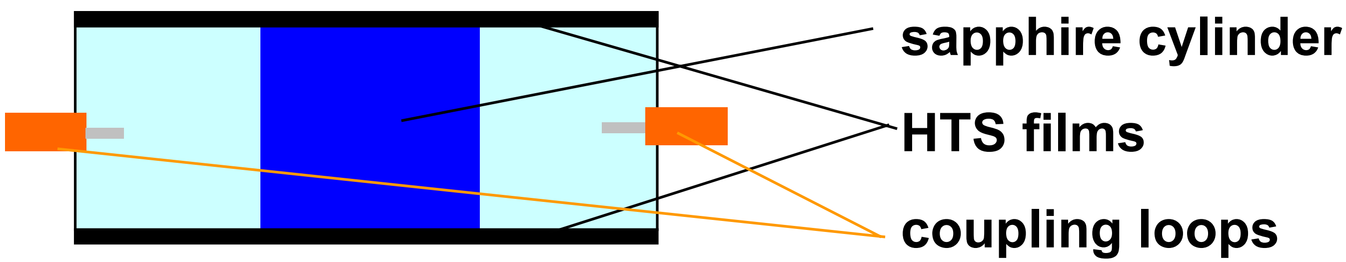
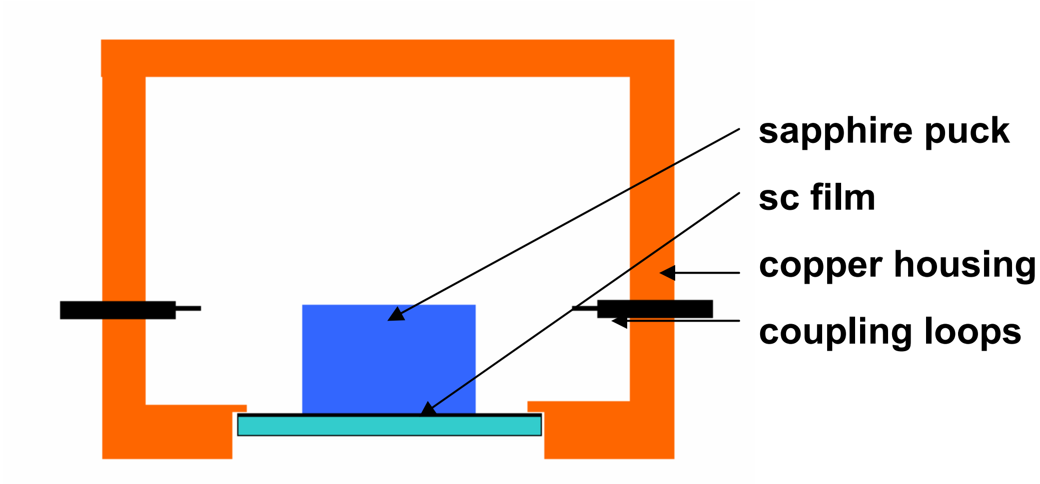
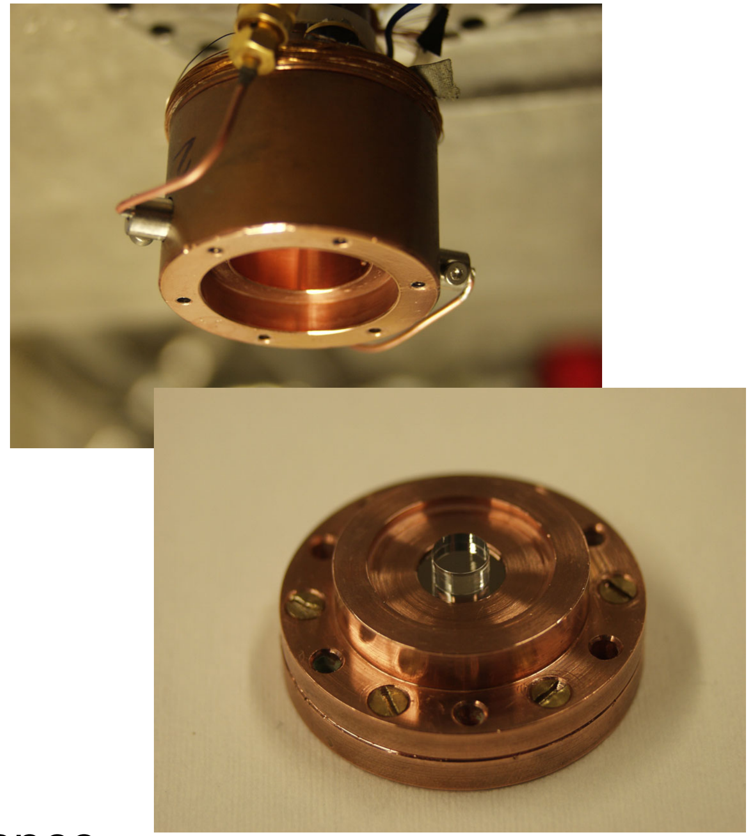
Puck $TE_{01\delta}$ resonator with two HTS endplates



Q **$\approx 10^5$ - 10^6**: attractive for surface impedance measurements of HTS films and low phase noise oscillators (5 to 30 GHz)

High-sensitivity microwave surface impedance measurement system for 7 to 20 GHz based on a sapphire dielectric resonator





N. Klein et al., Phys. Rev. Lett. 71, 2255 (1993), German and US Patent

- measure $Q(T)$ and $f\,(T)$ of high Q resonance
- calculate surface impedance $Z_s\,(T) = R_s\,(T) + i\omega\lambda_L(T)$ of sample from $Q(T)$ and $f\,(T)$
- R_s : surface resistance, determines losses

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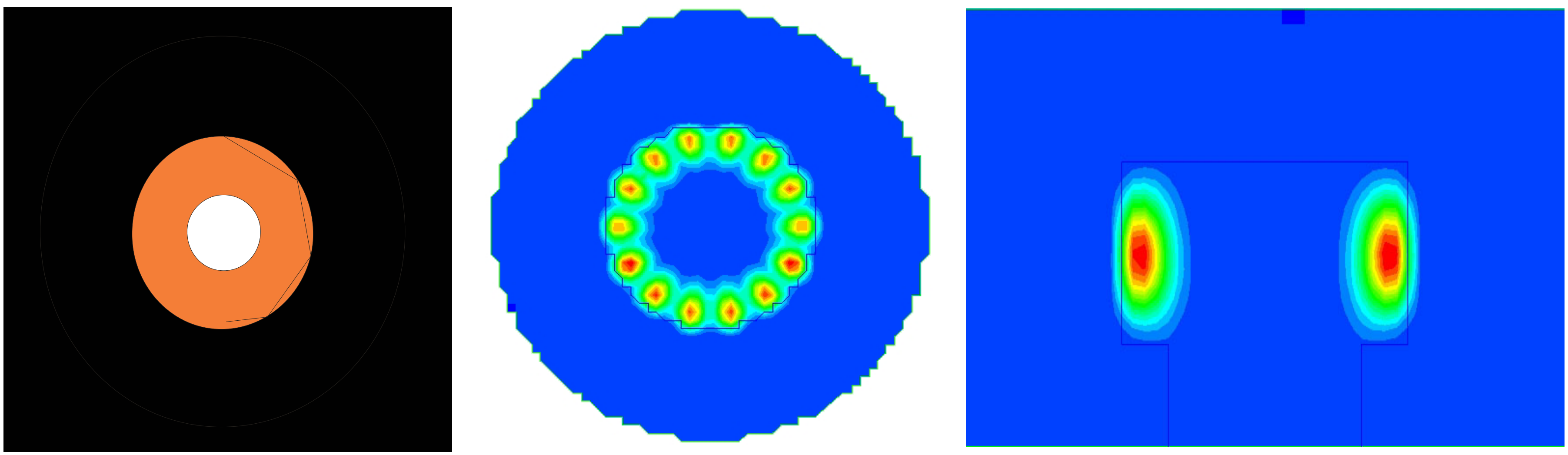
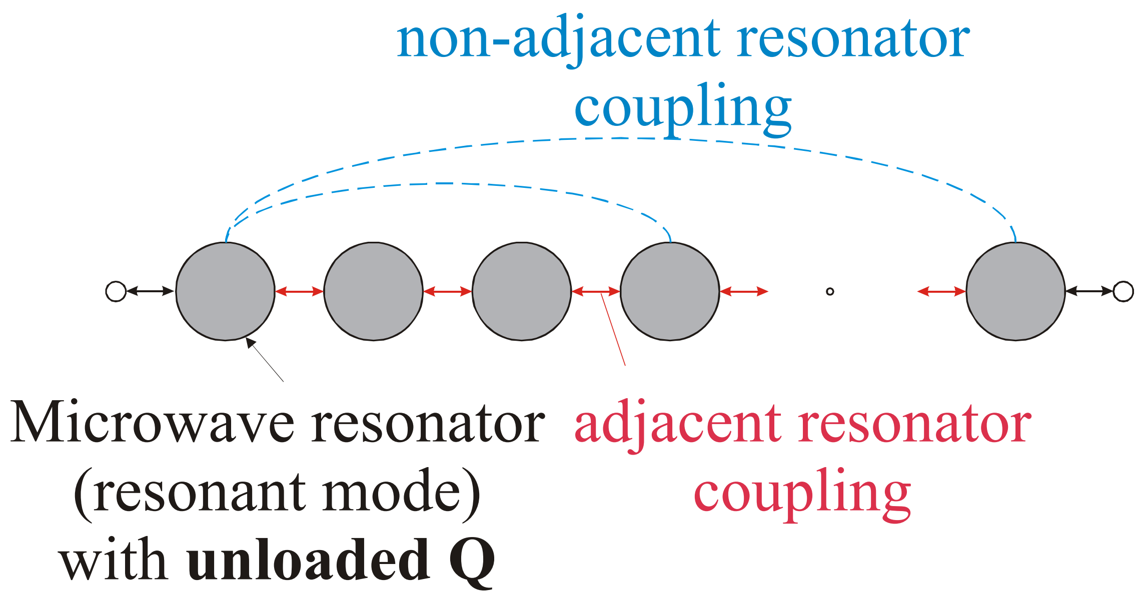
Whispering gallery mode in a dielectric puck



***Q* ≈10^6 - 10^7**: very attractive for mm wave low-phase noise oscillators (10 to 70 GHz)

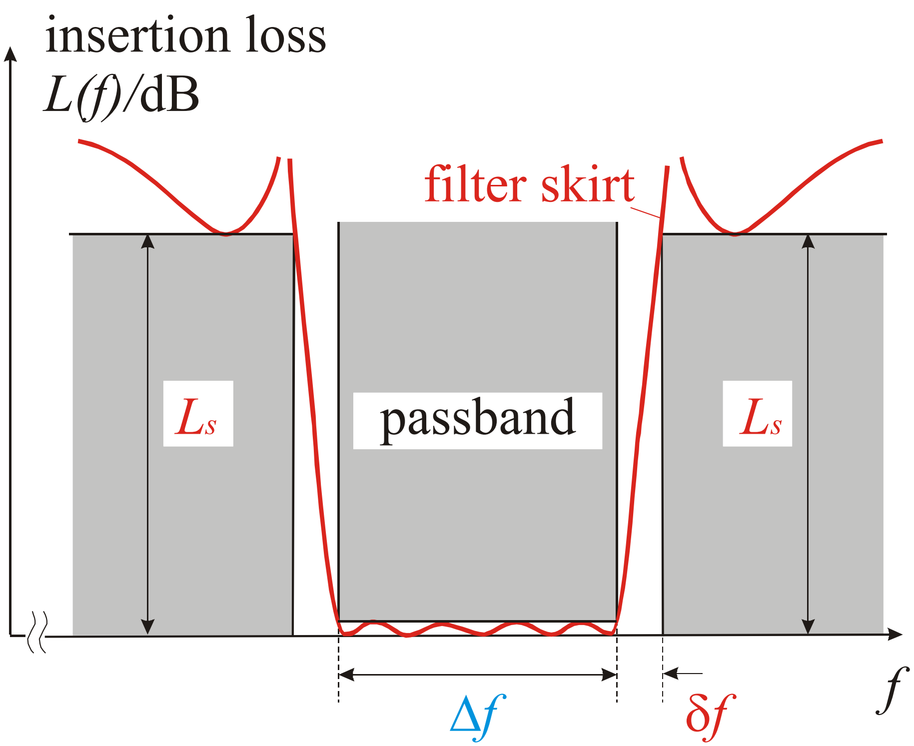
Filters: resonator coupling schemes

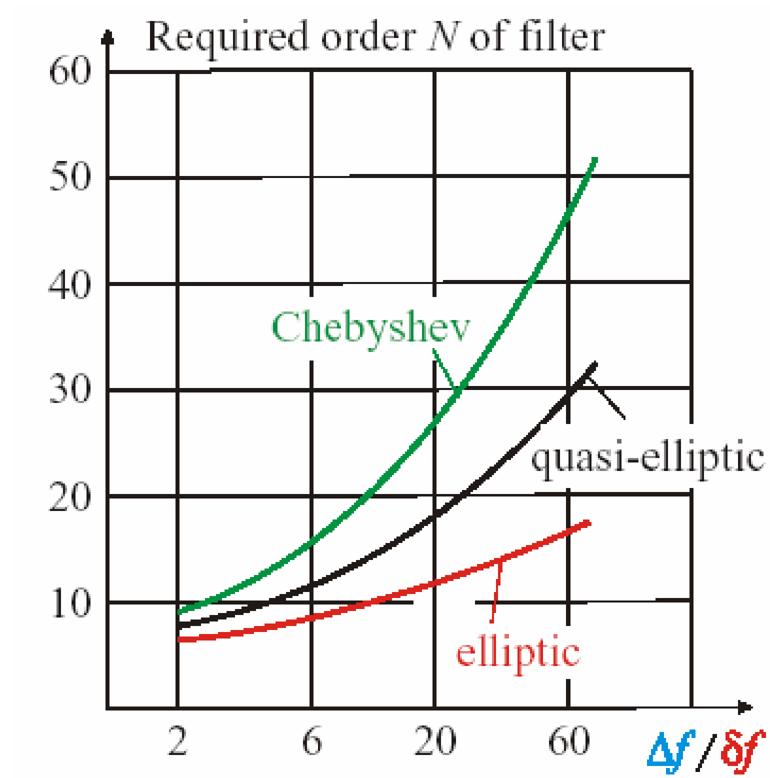


coupling only between adjacent resonators ⇒ Chebyshev- type characteristic

additional coupling between non-adjacent resonators ⇒ quasielliptic characteristic: damping poles at the passband edges ⇒ steeper skirts

Filters: steepness of skirts

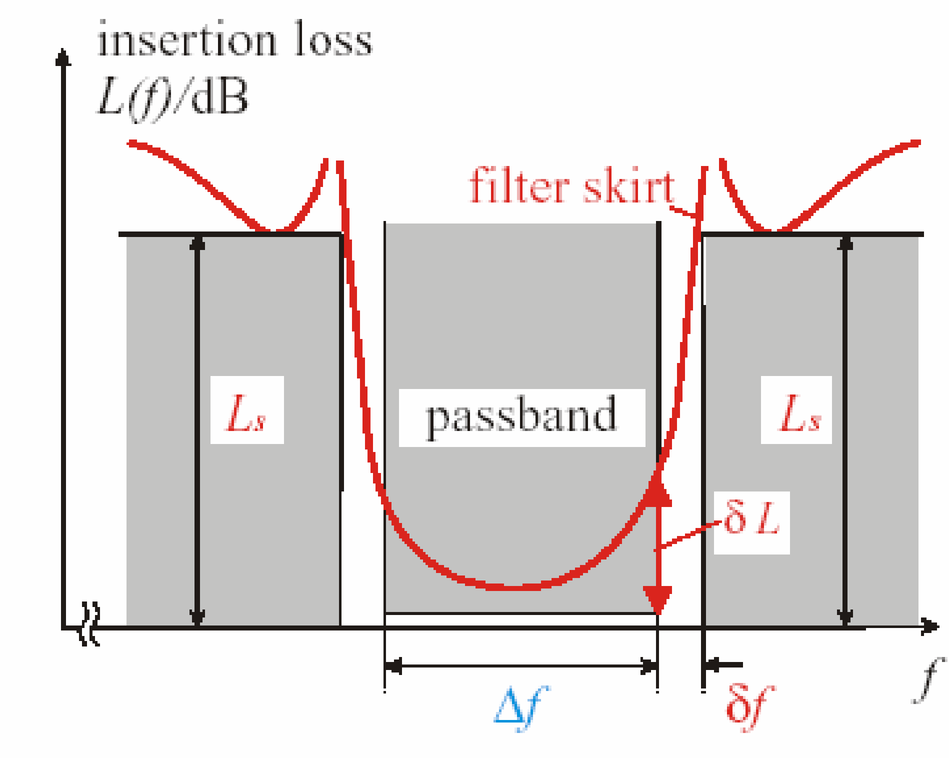




⇒ high number of poles required for high performance filters

1. N. Klein, H. Chaloupka, „Superconducting Microwave Applications: Filters“, Elsevier Encyclopedia of Materials: Science and Technology, ISBN: 0-08-043152-6, pp. 1-9 (2003)

Filters: steepness of skirts



***Q* requirement to avoid rounding effects:**

$$Q_{0,\min} \approx \beta \frac{L_s[\mathrm{dB}]}{\delta f[\mathrm{MHz}]} \frac{f_0[\mathrm{GHz}]}{\delta L[\mathrm{dB}]}$$

Chebyshev: β **= 750**
Elliptic: β **= 250**

example:

δL **=1 dB** L_S **= 100dB** δf **= 1MHz** $\Rightarrow$
$Q_{0,min}$ **= 50.000** for elliptic filter

1. N. Klein, H. Chaloupka, „Superconducting Microwave Applications: Filters", Elsevier Encyclopedia of Materials: Science and Technology, ISBN: 0-08-043152-6, pp. 1-9 (2003)

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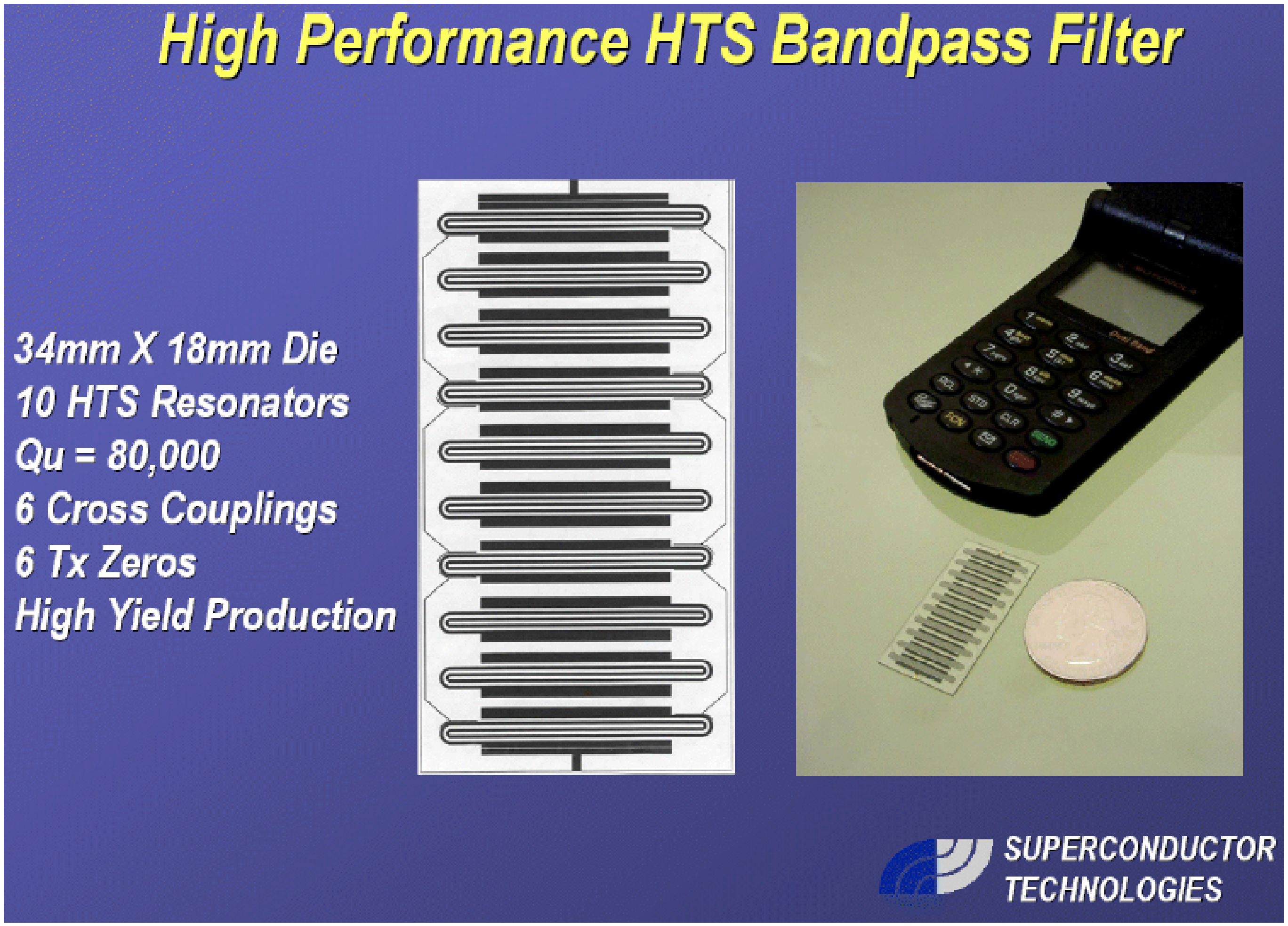
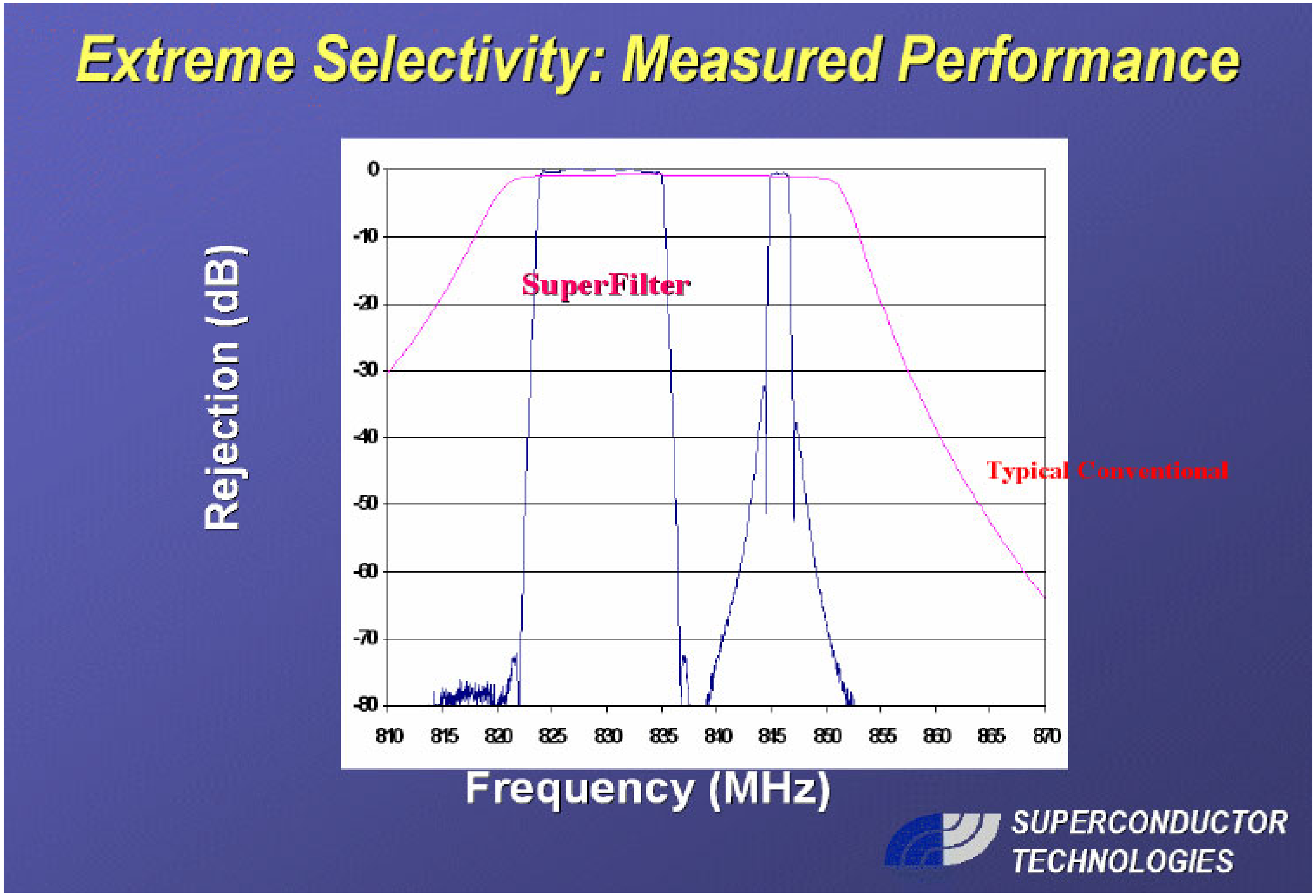


from IMS_2002, Seattle, tutorial workshops



from IMS_2002, Seattle, tutorial workshops

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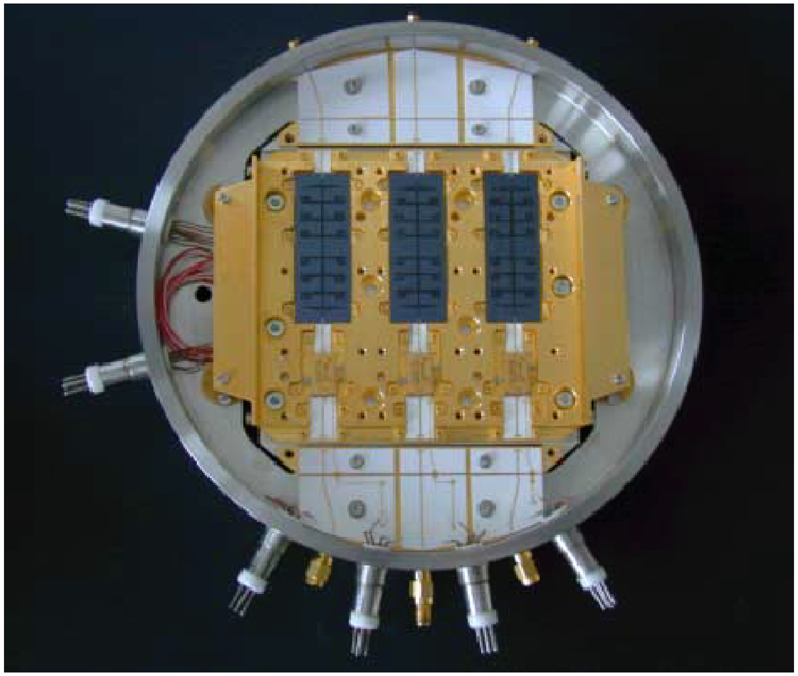

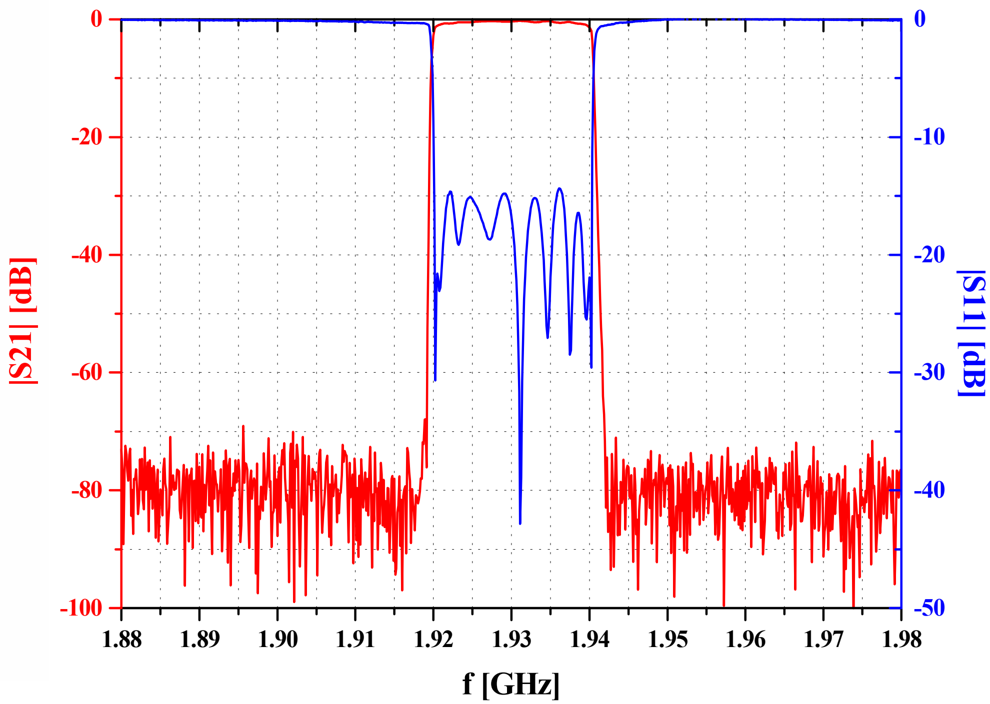

from Cryoelectra GmbH, Wuppertal

from IMS_2002, Seattle, tutorial workshops

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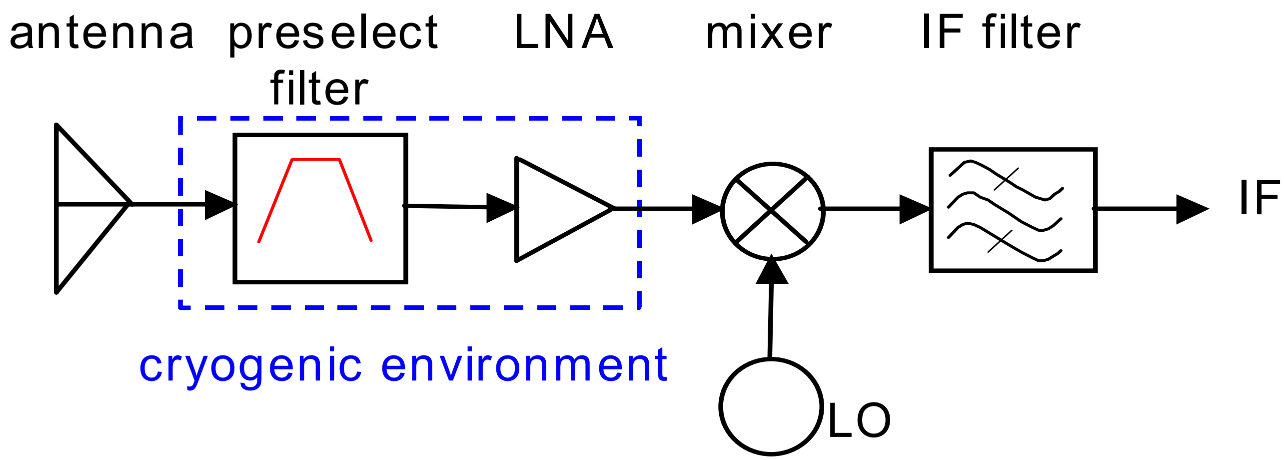
Sector of a basestation receiver frontend



Advantages of HTS / cryogenics

- higher receiver sensitivity due to reduction of filter insertion loss and lower noise temperature of LNA (rural areas)

- higher selectivity due to steeper filter skirts (crowded areas with strong interference problems)

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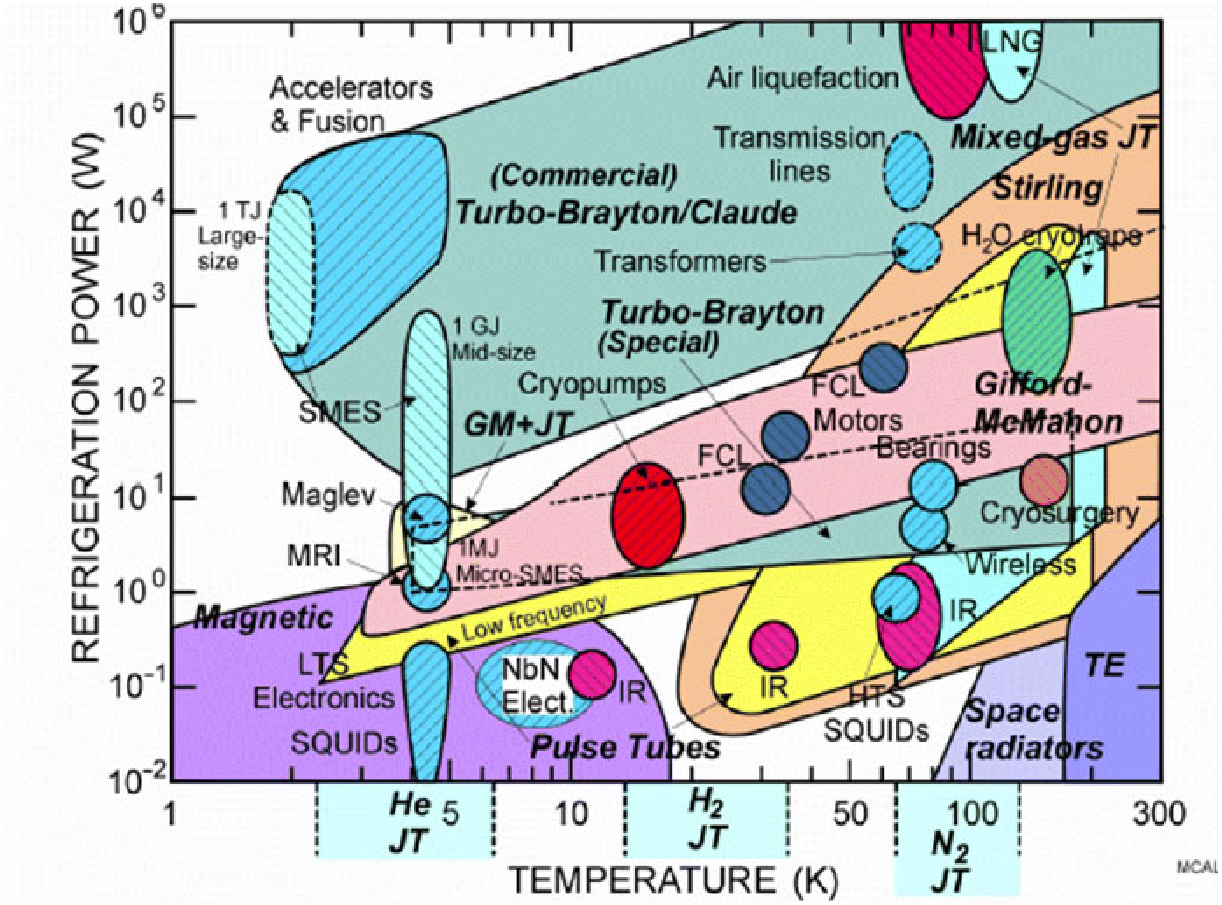
Enabling technology: cryocoolers



Courtesy of Ray Radebaugh, NIST-Boulder

Compact, high-efficient, reliable, and low–cost cryocoolers required for most of the high-frequency applications

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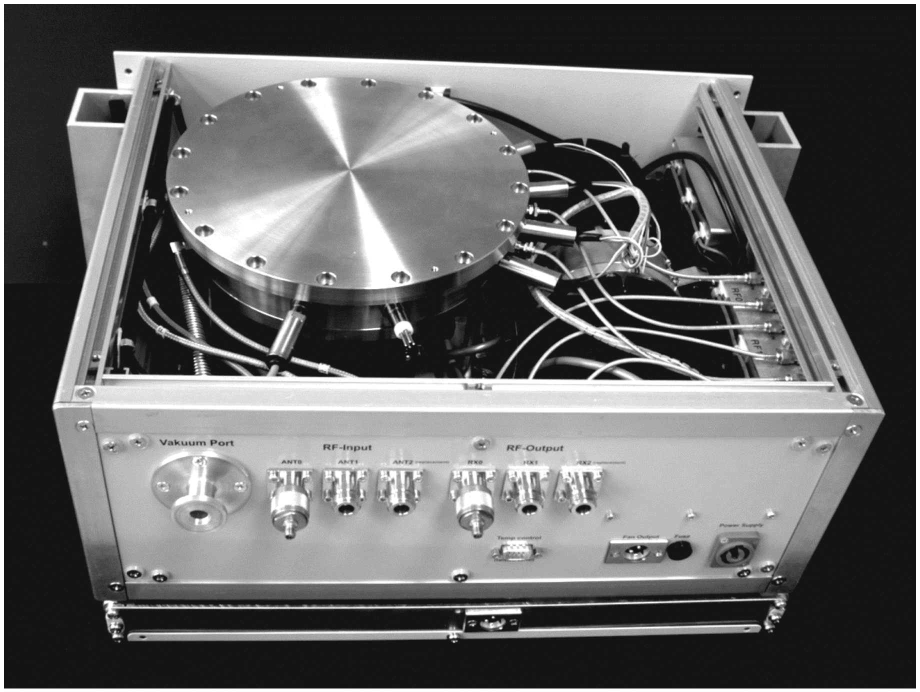

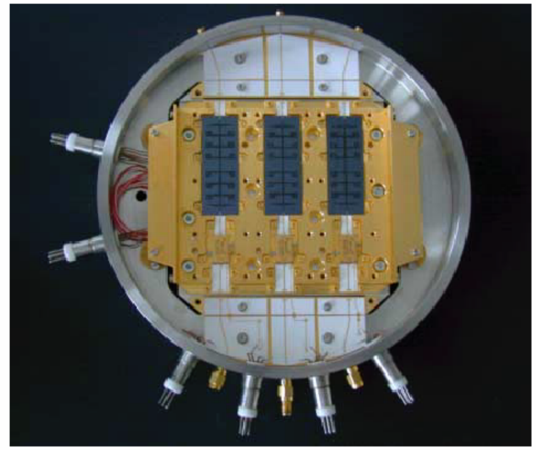

HTS subsystem developed by Cryoelectra GmbH, Germany with Stirling cooler developed at Leybold, Germany

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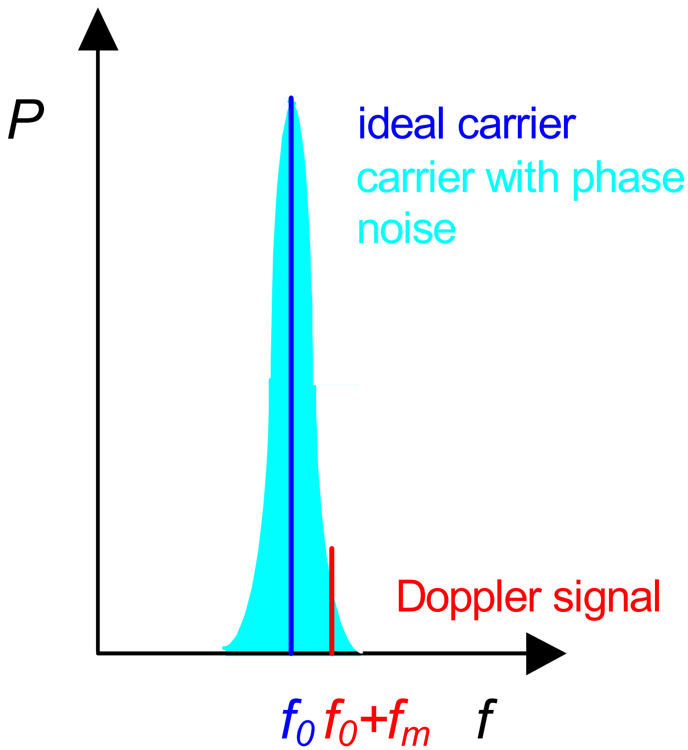
Product information from Superconductor Technolgies
http://www.suptech.com

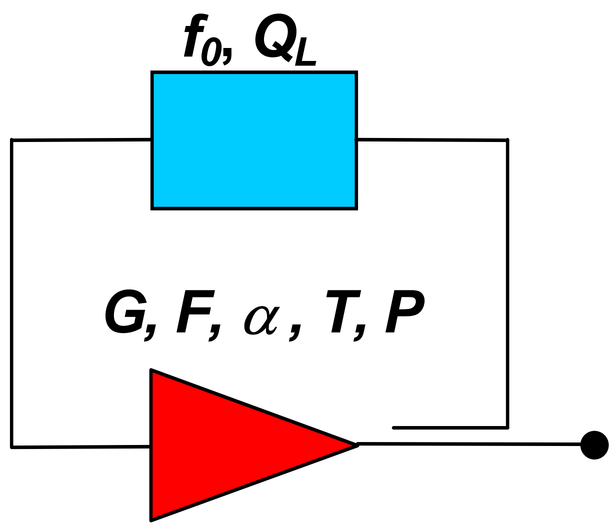
Cryogenic oscillators



- **Doppler radar**
- **passive microwave frequency standard**
- **high purity reference sources**

Leeson model: phase noise of a feedback oscillator

D.B. Leeson, Proc. IEEE vol. 54, pp. 329, 1966



$$L_{osc} = 10 \cdot \log\left[1 + \frac{f_0^{\,2}}{4Q_L^{\,2} f_m^{\,2}}\right] + 10 \cdot \log\left[\frac{\alpha}{f_m} + \frac{GFkT}{P}\right]$$

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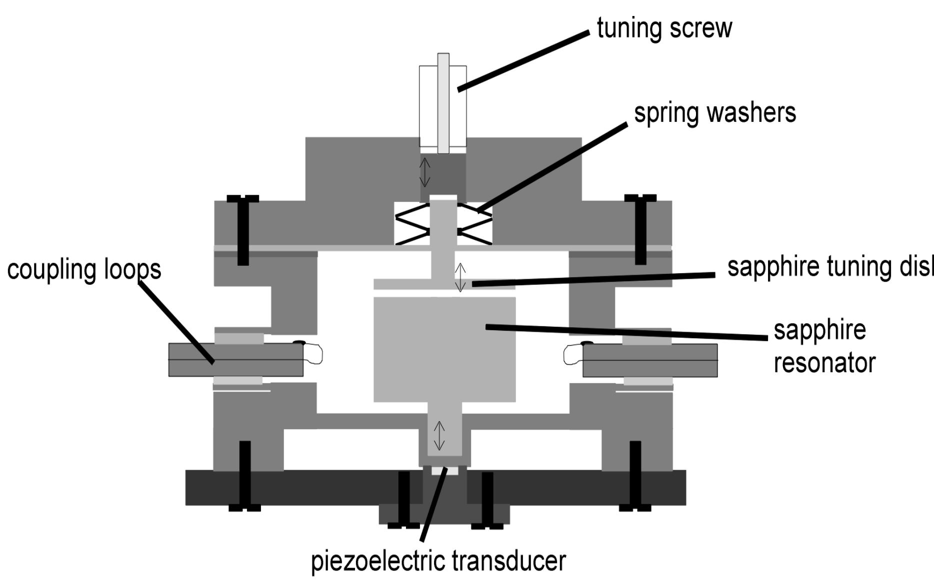
tuneable cryogenic WG – resonator for *f* = 23 GHz

Project with Bosch SatCom (Tesat-Spacecom), German Patent



- mechanical tuning range: **50 MHz**
- piezoelectric tuning range **50 KHz @ 60 V**

Extremely high $Q_0 \geq$ **5 · 10^6 @ *T* = 77 K**

S. Vitusevich et al., IEEE-Transactions on Microwave Theory and Techniques 51, 163 (2003)

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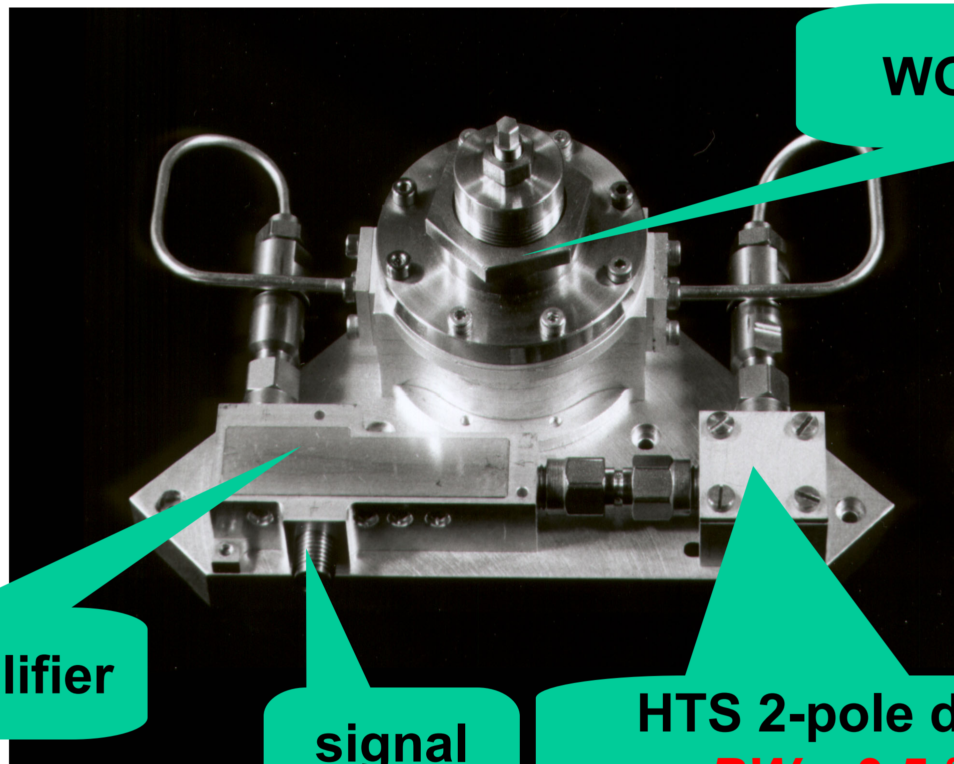
Cryogenic 23 GHz „near“ space qualified oscillator



S. Vitusevich et al., IEEE Transactions on Microwave Theory and Techniques 51, 163 (2003)

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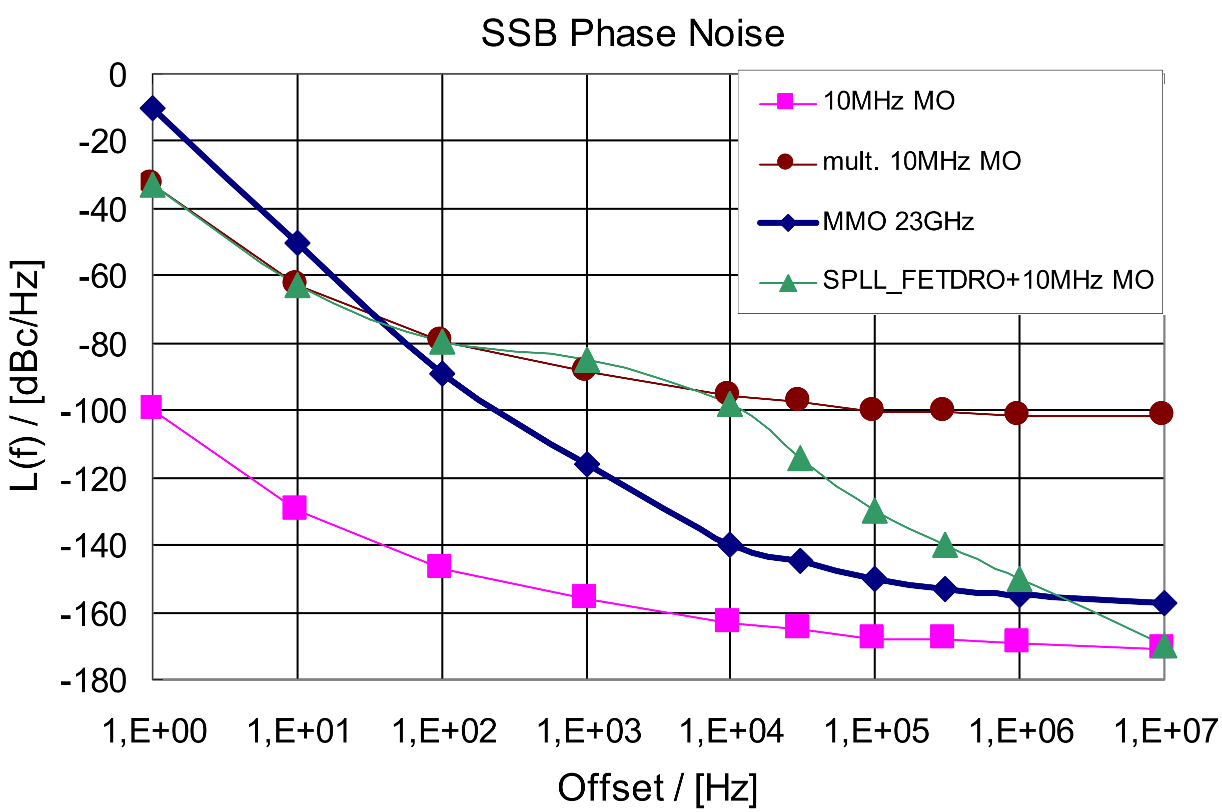
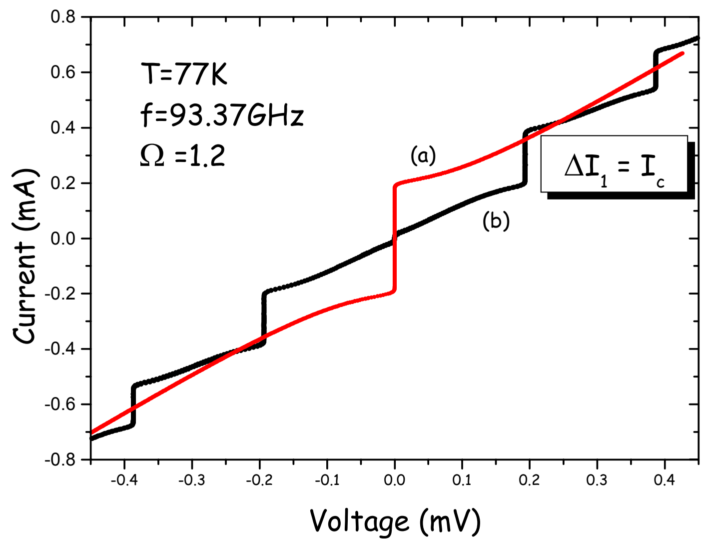
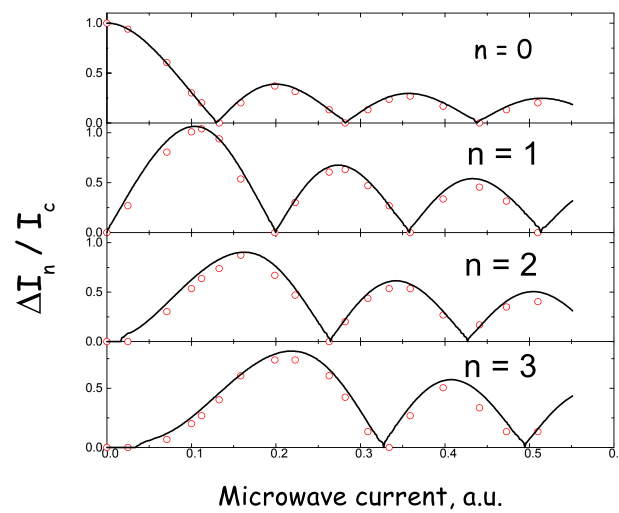
Cryogenic 23 GHz space qualified oscillator:
phase noise far below that of conventional oscillators



S. Vitusevich et al., IEEE Transactions on Microwave Theory and Techniques 51, 163 (2003)

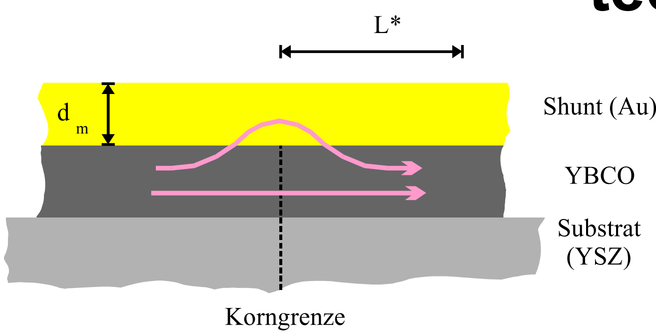
AC Josephson effect in HTS bicrystal junctions



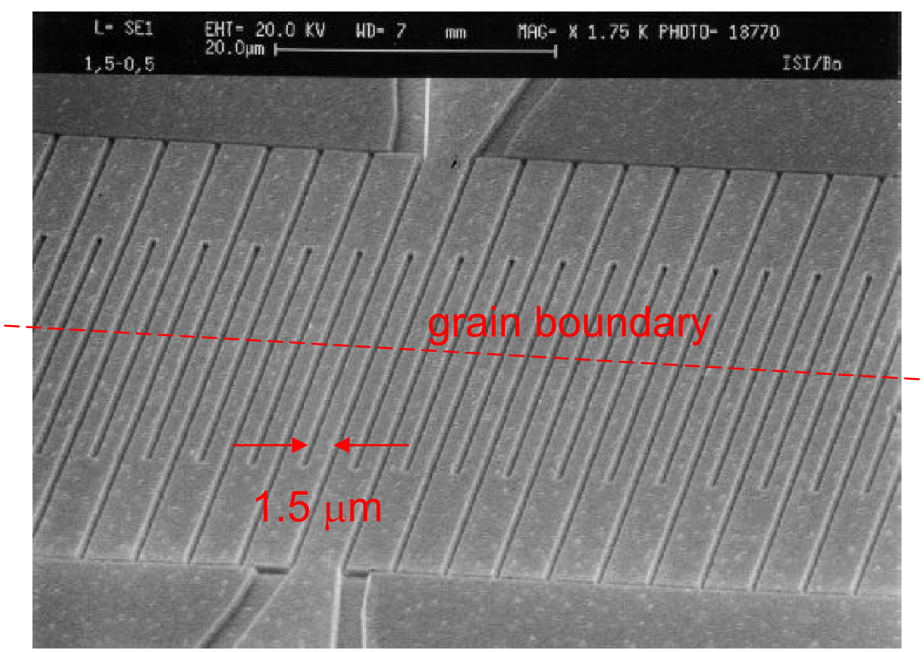


- Employ 1st Shapiro step to represent a dc/ac voltage with quantum accuracy $\Rightarrow$ towards an HTS voltage standard
- Employ differential IV characteristic to deconvolute the spectral response of incident THz radiation $\Rightarrow$ Hilbert transform spectroscopy

Novel approach: quantum voltage standard in HTS technology

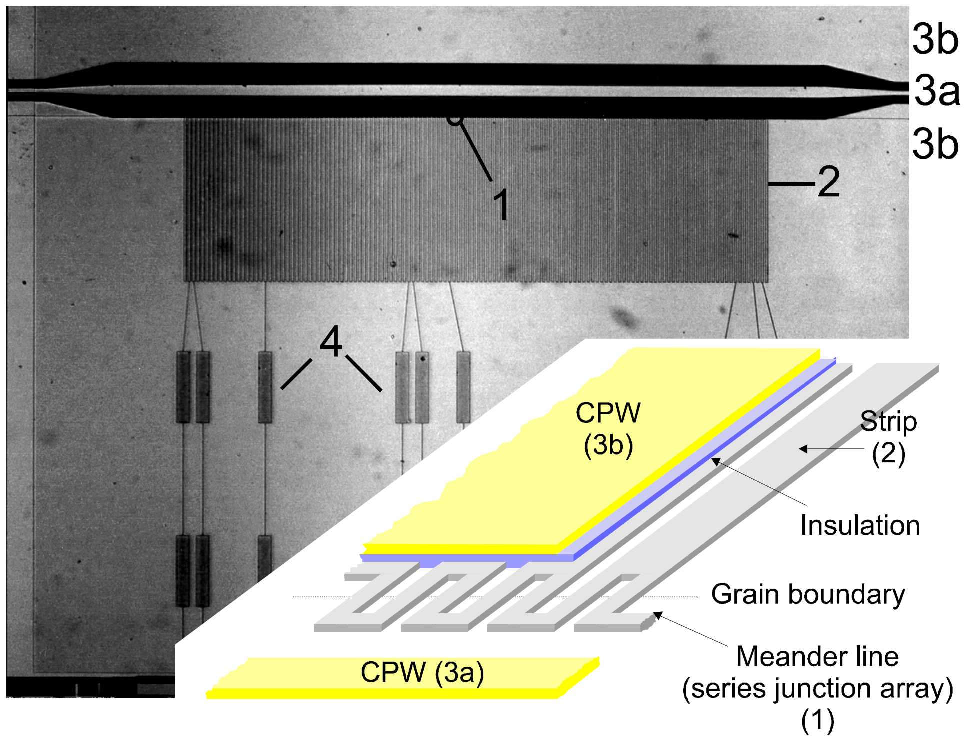


YBCO bicrystal junction with in-situ gold shunt : RSJ like I/V charactersitic with small (5 %) spread of R_n



Fabrication of an array of bicrystal junctions by submicometer lithography

Novel approach: quantum voltage standard in HTS technology



Irradiation of microwaves by a coplanar waveguide

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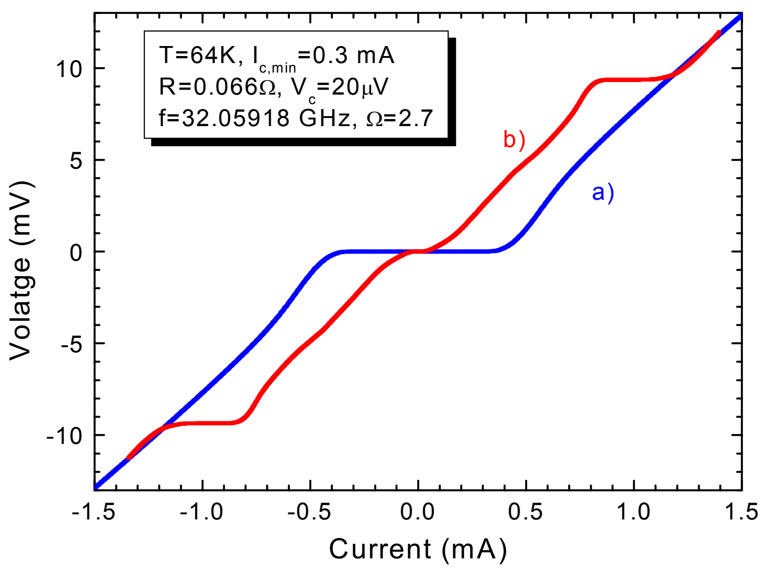
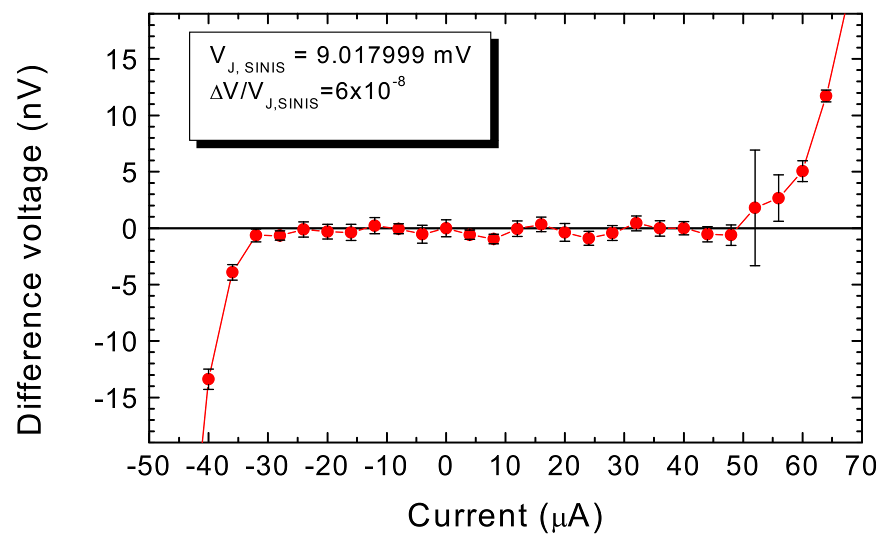
First experimental demonstration for a giant Shapiro step in an HTS bicrystal array of 136 JJ with metrologically relevant accuracy





A. M. Klushin, R. Behr, K. Numssen, M. Siegel and J. Niemeyer, APL, 80, p. 1972, 2002

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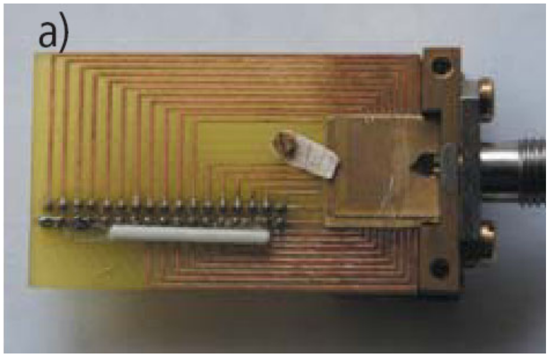
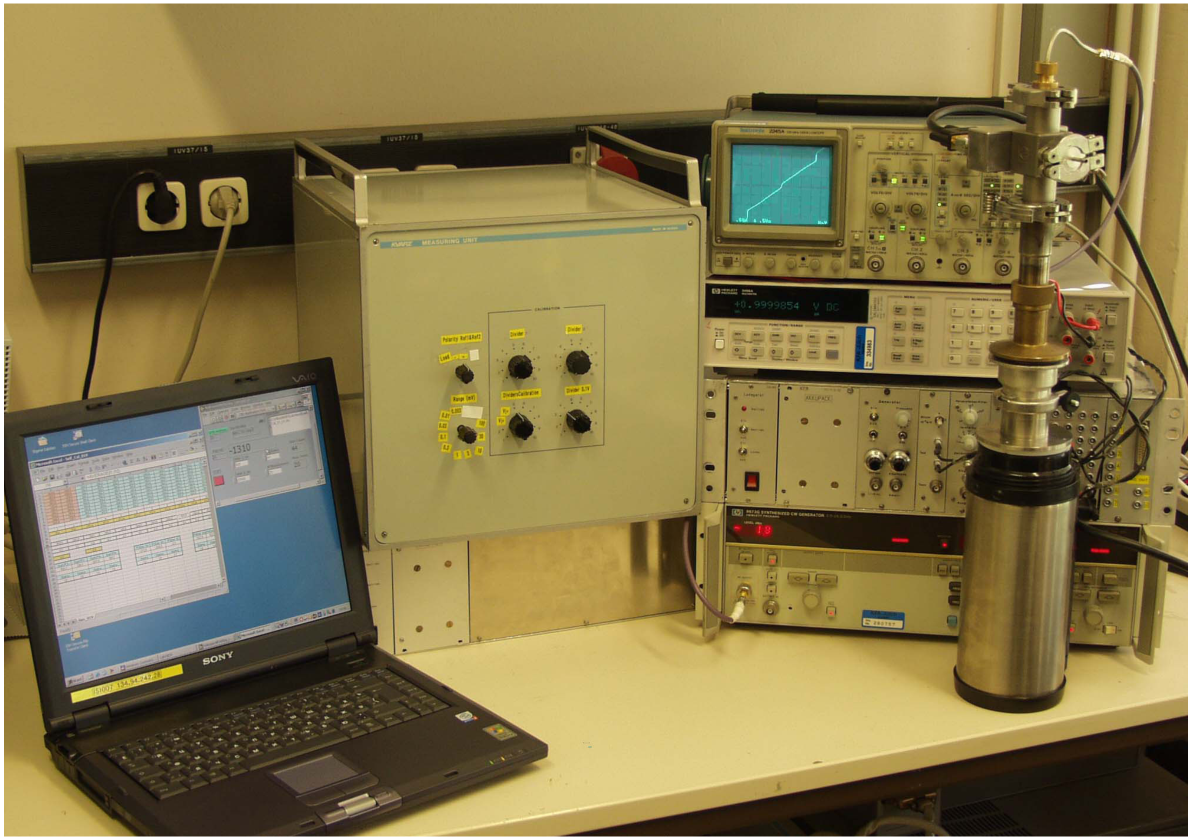
Laboratory prototype of an HTS voltage calibrator





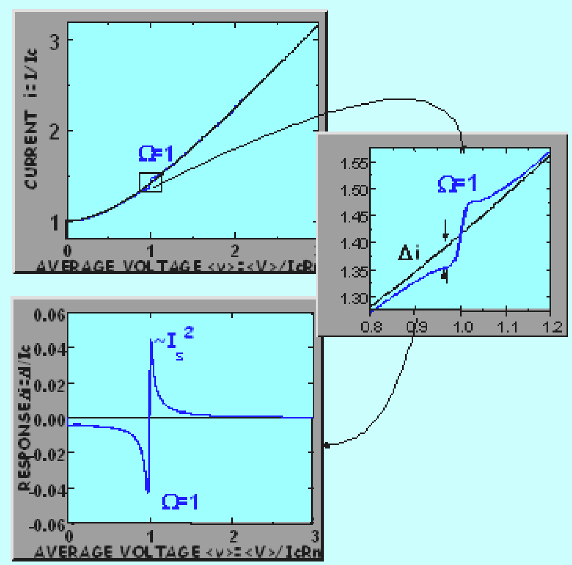
Hilbert Transform Spectroscopy

dc Response of Josephson Junction to Weak Monochromatic Radiation*

$$\frac{V(t)}{R_n} + I_c \cdot \mathrm{Sin}\left[2\pi \frac{2e}{h}\int_0^t V(t)dt\right] = I + I_s \mathrm{Sin}\, 2\pi f t$$

$I_s \ll I_c$

$$\Delta I(V) = \left(\frac{2e}{h}\right)^2 \frac{I_c^2 R_n^2}{4I(V)} \frac{I_s^2}{(f_j^2 - f^2)}$$



Response ΔI(V):
- resonance near hf/2e
- square-law detection
- additivity

*H.Kantor, V.L. Vernon. J.Appl. Phys. **43**,3174 (1972)

Hilbert Transform Spectroscopy

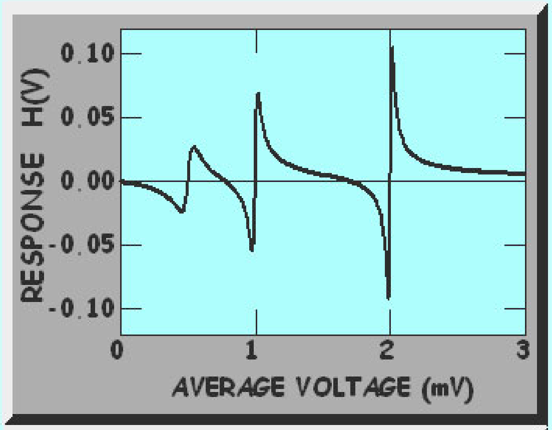
Response of Josephson junction to signal with arbitrary spectrum $S_{I_s^2}(f)$:

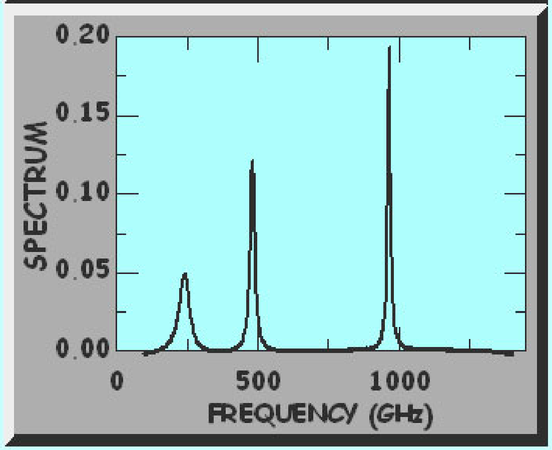
$$\Delta I(V) = -\left(\frac{2e}{h}\right)\frac{\pi \cdot I_c^2 \cdot R_n^2}{8 \cdot I(V) \cdot V} \cdot \left(\frac{1}{\pi}\right) \cdot P\int_{-\infty}^{\infty} \frac{S_{I_s^2}(f) \cdot df}{f - f_j}$$

$f_j = 2eV/h$

$$H(V) = \left(\frac{8}{\pi}\right) \cdot \left(\frac{h}{2e}\right) \frac{I(V) \cdot V \cdot \Delta I(V)}{I_c^2 \cdot R_n^2}$$

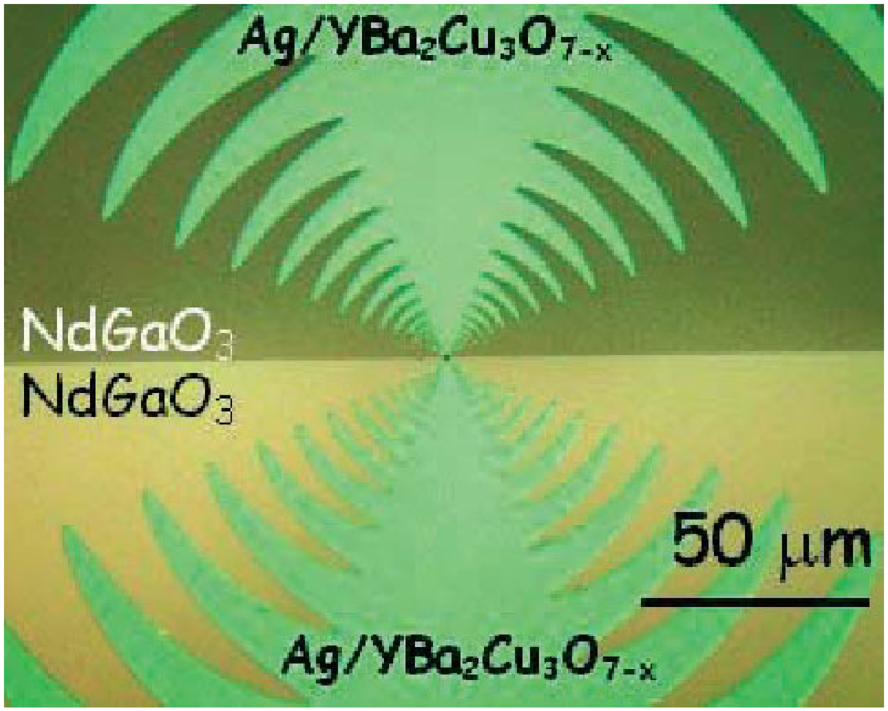
$$S_{I_s^2}(f) = \left(\frac{1}{\pi}\right) \cdot P\int_{-\infty}^{\infty} \frac{H(f_j) \cdot df_j}{f_j - f}$$

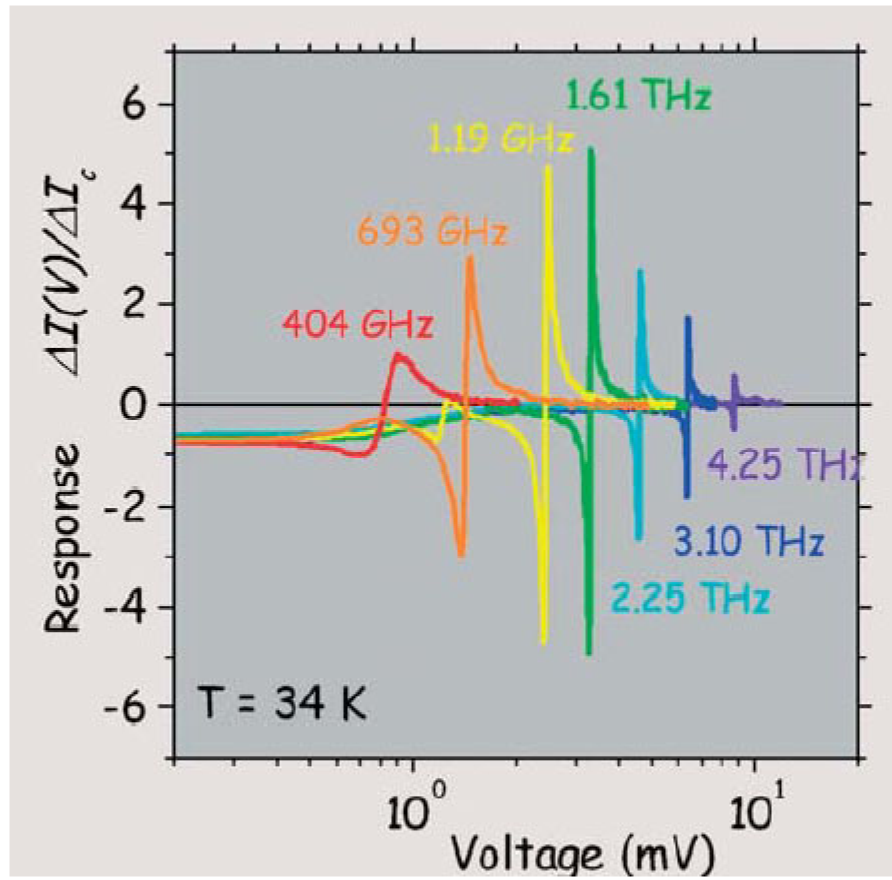




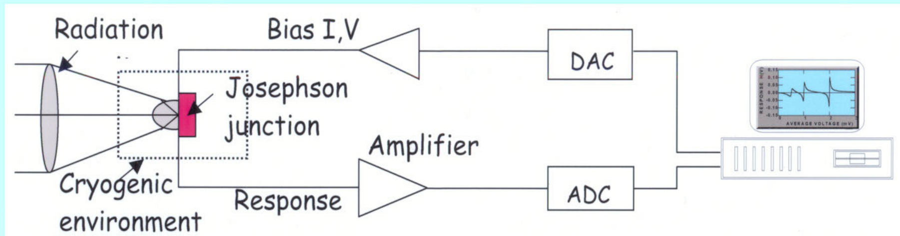
*Y.Y. Divin, O.Y. Polyanski, A.Y. Shul'man. Sov. Tech. Phys. Lett., v. 6, pp. 454-458, 1980.

Hilbert Transform Spectroscopy



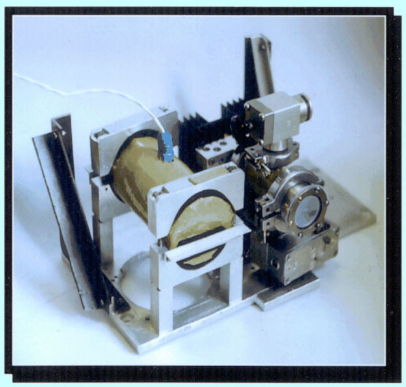


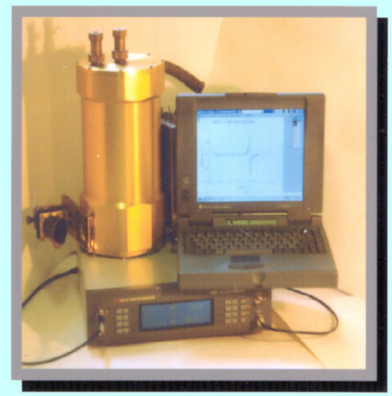
Hilbert-Transform Spectrometers



HT Spectrometer for Pulsed Subterahertz Radiation

HT Spectrum Analyzer Integrated into a Stirling Cooler





Quasioptical HT Spectrometer with LHe/LN Cryostat

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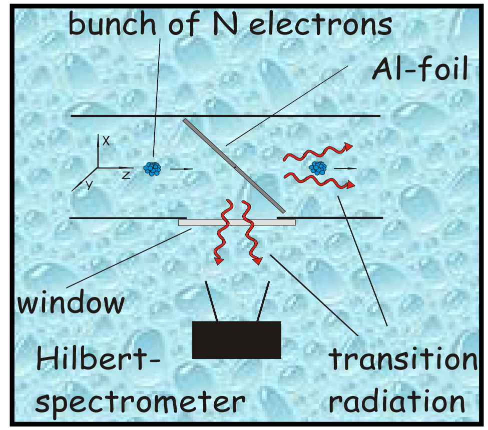
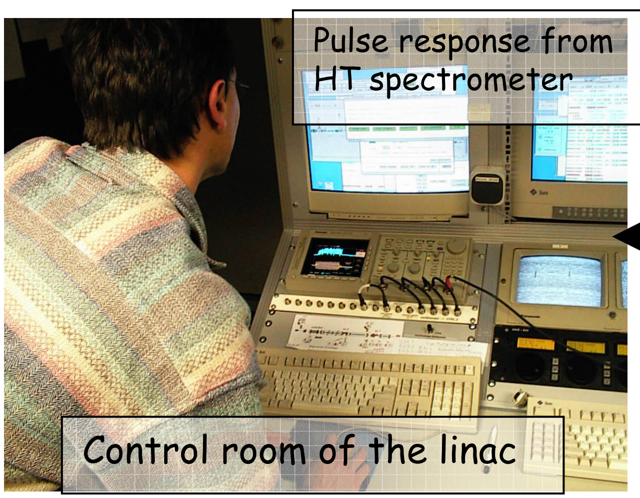
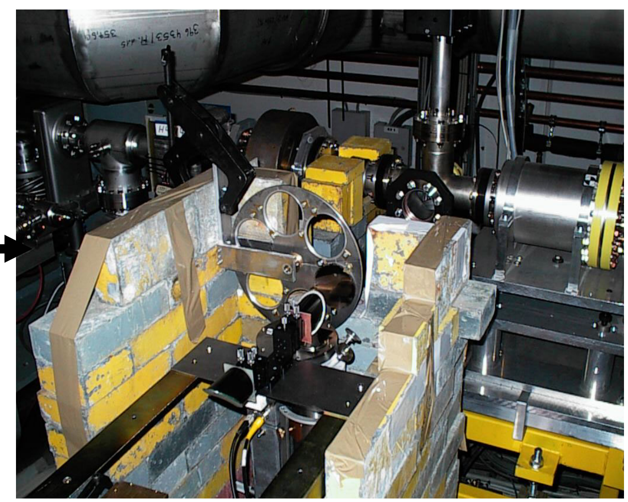
Hilbert Spectroscopy of Coherent Transition Radiation in TESLA Test Facility Linear Accelerator at DESY

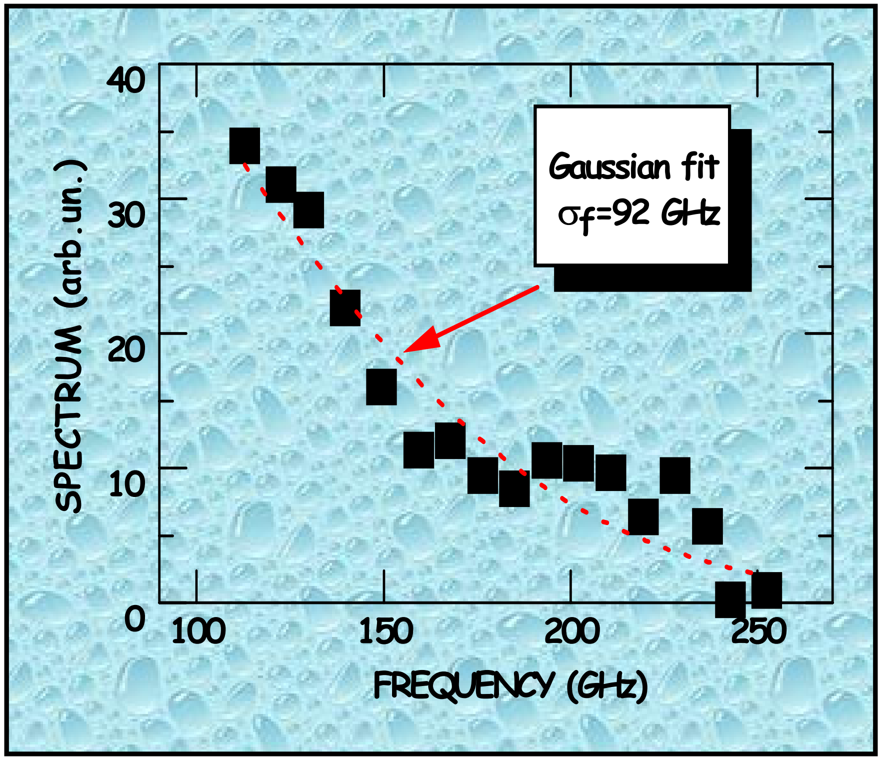


First measurements at DESY, 1997
- Thermoionic gun, N =2.3x10^8 electrons
- Macrobunch averaging
- Bunch length measured by HTS: σ_z = 0.4 mm

Measurements at DESY, 1999, 2001
- New Photoinjector, N =1.6x10^{10} electrons
- Pulse response detection from a single bunch







M. Geitz, K. Hanke, P. Schmueser, Y.Y. Divin, U. Poppe, V.V. Pavlovskii, V.V. Shirotov, O.Y. Volkov, M. Tonutti, DESY-TESLA Reports, 98-10 (1998).

Y.Y. Divin, U. Poppe, K. Urban, O.Y. Volkov, V.V. Shirotov, V.V. Pavlovskii, P. Schmueser, K. Hanke, M. Geitz, M. Tonutti, IEEE Trans. Applied Supercond.,1999, vol. 9, No.2, p.p.3346-3349.

M. Geitz, K. Hanke, P. Schmueser, Y.Y. Divin, U. Poppe, V.V. Pavlovskii, V.V. Shirotov, O.Y. Volkov, M. Tonutti, Proceedings 1999 Particle Accelerator Conf., New York, 1999 IEEE Publ , pp. 2178-2180

Summary and Outlook

- Passive filters have found a niche market in mobile communication
- Extremely narrowband and tuneable (MEMS) HTS filters are considered to be relevant for millitary applications
- Superconducting detectors are dominant for the THz range:
  Nb SIS mixers: < 700 GHz
  NbN Hot electron bolometers: < 1.5 THz
- HTS grain boundary Josephson junctions have a huge potential for millimetre wave and THz applications