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Hilbert Spectroscopy as a Tool for pulsed Electron Beam Diagnostics

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1. ELAN –Workshop, Frascati, May 2004

Outline:

- Principles of Hilbert Spectroscopy
- High-T_C Josephson junctions
- Spectral range, resolution, speed ,dynamic range etc.
- Challenges and goals
- Applications
- e-beam diagnostics at the DESY TESLA Test Facility
- Transition radiation spectra and bunch form analysis
- Data aquisition system for pulsed radiation
- Conclusions and outlook

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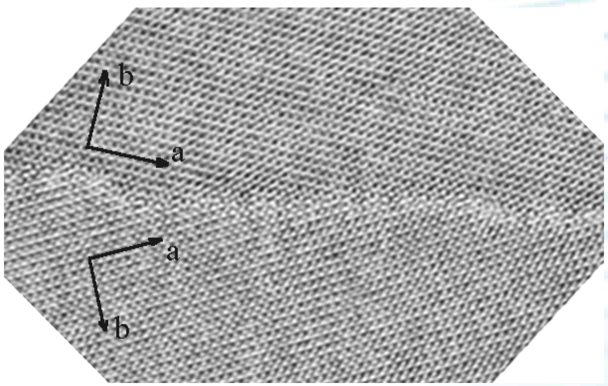
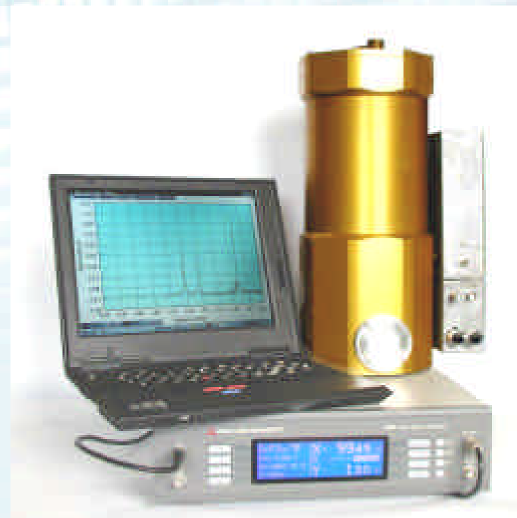
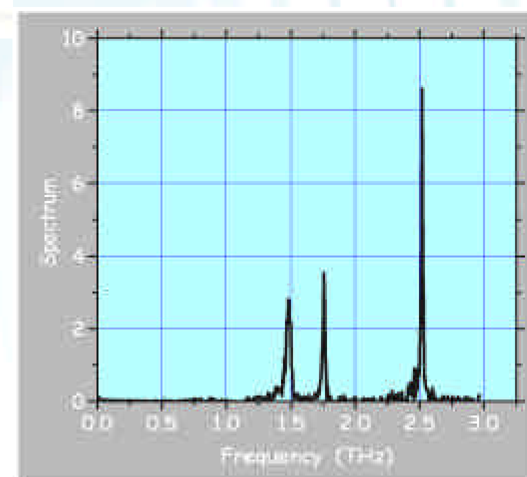
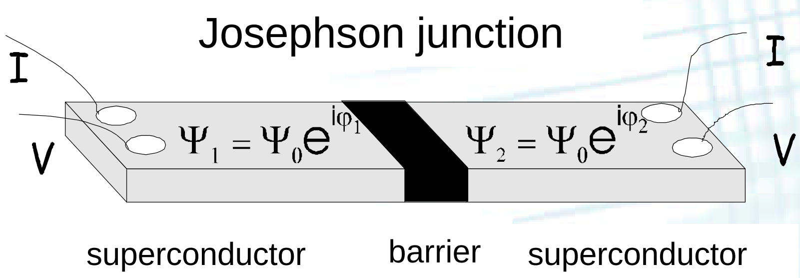
Terahertz Hilbert Spectroscopy using High-T_c Josephson Junctions: from Nanophysics to Applications







ac-Josephson Effect



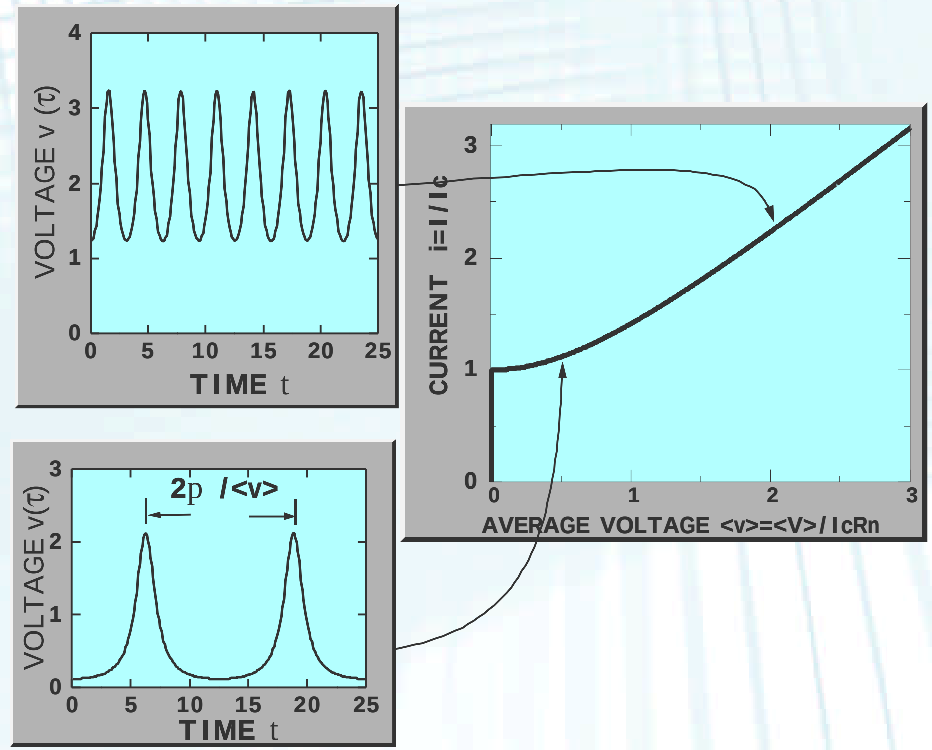
$$J_{pairs} = J_c \cdot \sin\varphi \qquad \varphi = \varphi_1 - \varphi_2$$

$$\frac{d\varphi}{dt} = \left(\frac{2e}{\hbar}\right) \cdot V(t)$$

$$I_{quasiparticles}(V,t) + I_{pairs}(V,t) = I$$

RSJ model

$$\frac{V(t)}{R_n} + I_c \cdot \sin\left[2\pi \frac{2e}{h} \int V(t)dt\right] = I$$



- Josephson junction is a voltage-controlled oscillator with $f/V = (2e/h) = 483.59$ GHz/mV
- When $I_cR_n = 2$ mV, $f_c \approx 1$ THz

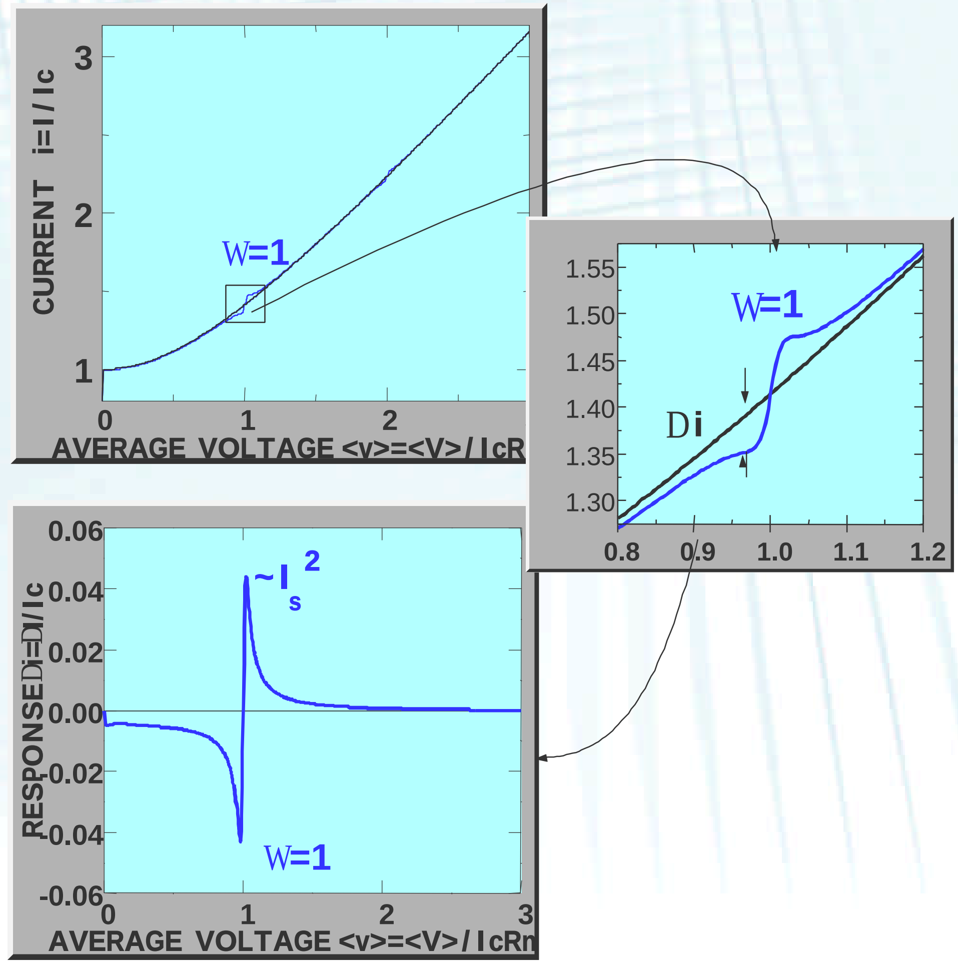
dc Response of Josephson Junction to weak monochromatic Radiation

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

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

Response $\Delta I(V)$:

- resonance near $hf/2e$
- square-law detection
- additivity



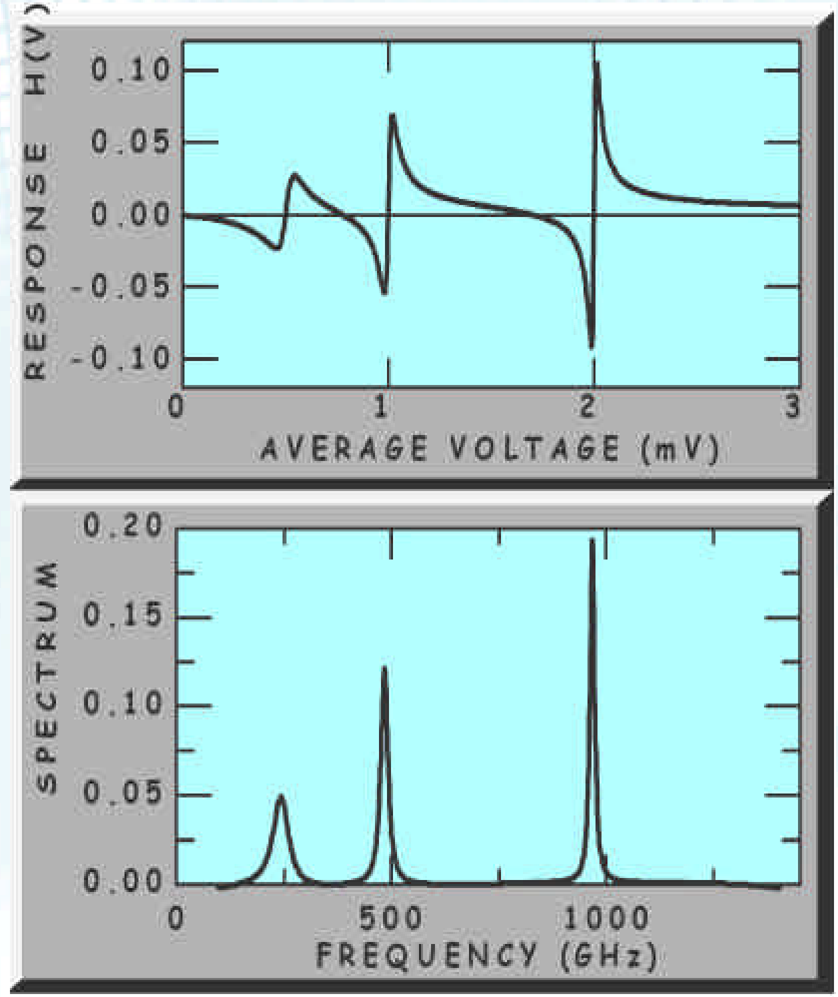
Principles of Hilbert spectroscopy

- Hilbert spectroscopy is based on the ac Josephson effect.
- Response of Josephson junction to signal with arbitrary spectrum

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

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

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



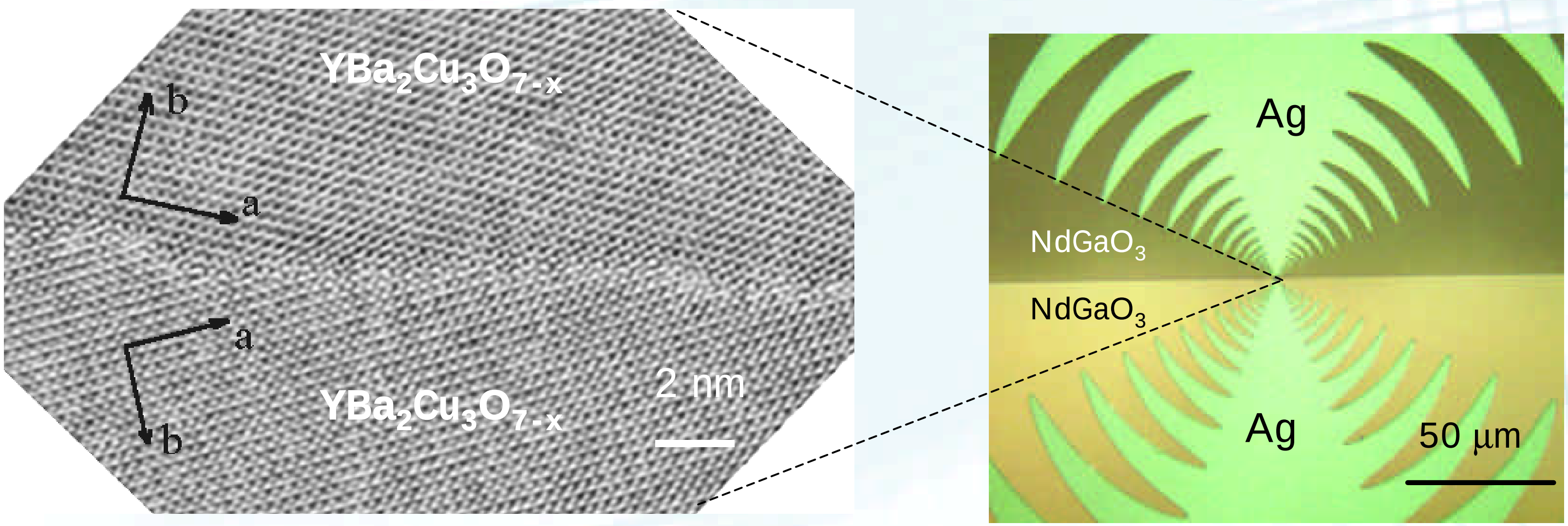
[001]-tilt $YBa_2Cu_3O_{7-x}$ Grain-Boundary Junctions for Hilbert Spectroscopy

- (110) $NdGaO_3$ bicrystal substrates
- dc sputtering of $YBa_2Cu_3O_{7-x}$
- $YBa_2Cu_3O_{7-x}$ grain boundary as a barrier

- R_n from 0.5 to 100 Ohm
- I_cR_n up to 3.7 mV @ 4 K

Nanostructure of [001]-tilt $YBa_2Cu_3O_{7-x}$ grain boundary

Integration with broadband terahertz antenna



In collaboration with the Institute of Radio Engineering and Electronics of RAS, Moscow

Y. Divin, et al. In Advances in Solid State Physics, 41, ed. B. Kramer (Springer, Berlin, 2001) pp. 301-313

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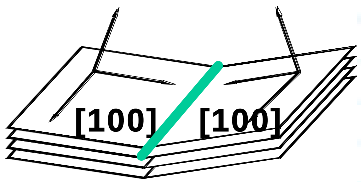
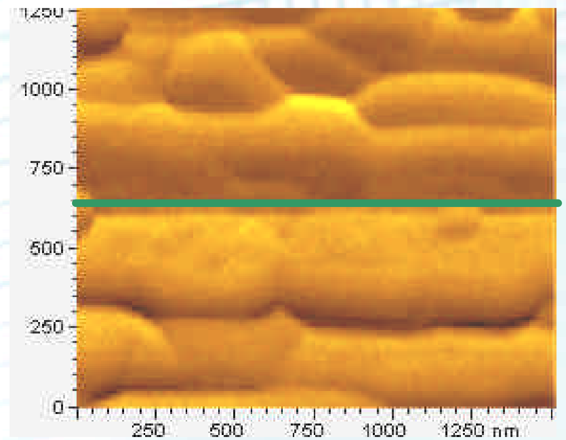
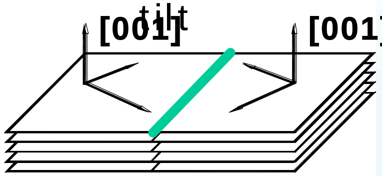
[100]-tilt vs [001]-tilt $YBa_2Cu_3O_{7-x}$ Grain-Boundary Junctions

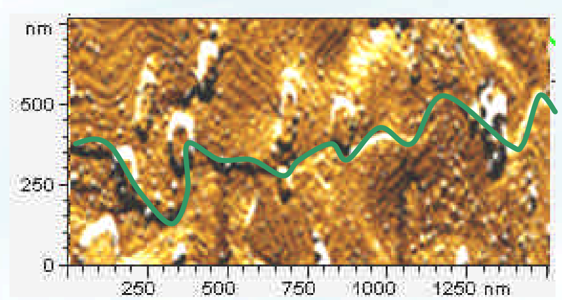
[100]-tilt



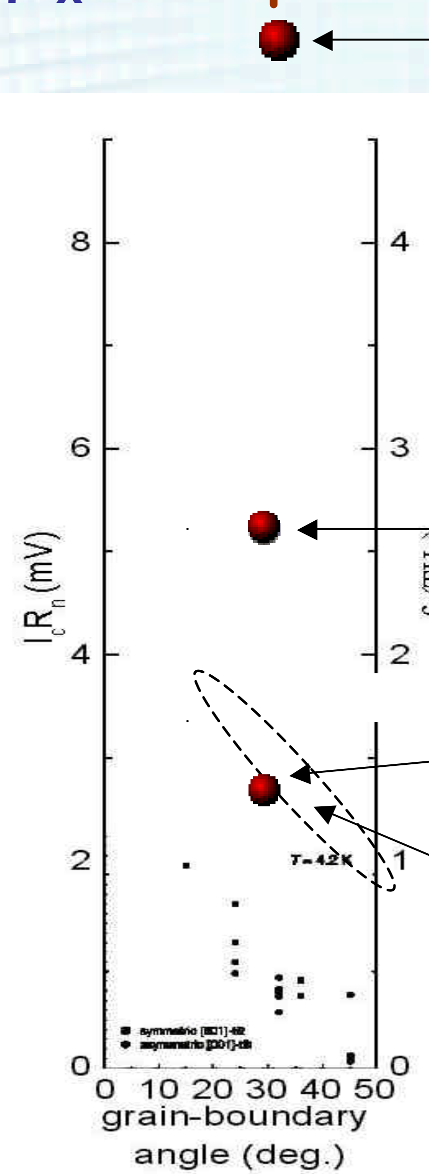


[001]-tilt





Our goal: 30 mV



Our data, [100]-tilt, 4 K
Y.Divin, U.Poppe, C.L.Jia, P.Shadrin, K.Urban. Physica C **372-376,** 115 (2002)

Our data, [001]-tilt, 4 K

Our data, [100]-tilt 77K

[001]-tilt, 4 K
H.Hilgenkamp, J. Mannhart
Rev. Mod. Phys. **74**, 485 (2002)

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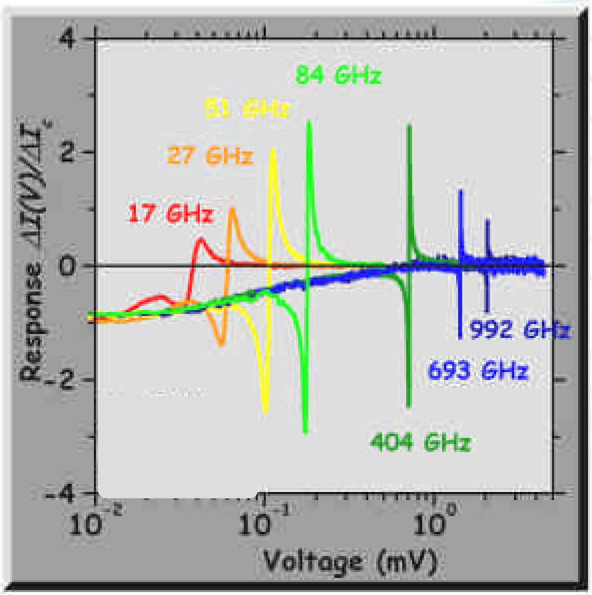
Spectral Range of the ac Josephson Effect

Our goals

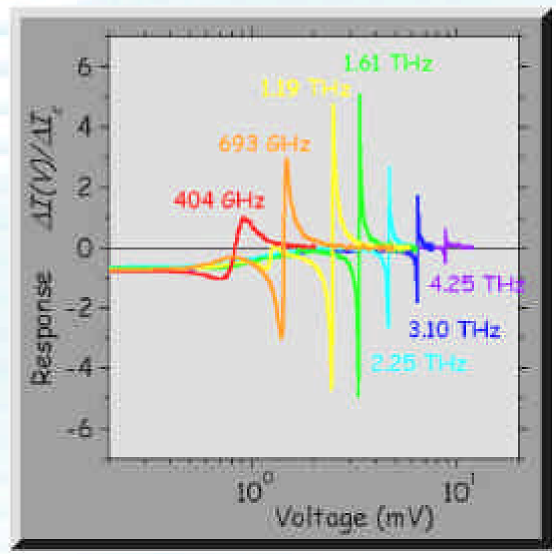
- Operation up to 30 THz
- Fundamental high-frequency limit

•Scaling with IcRn-values

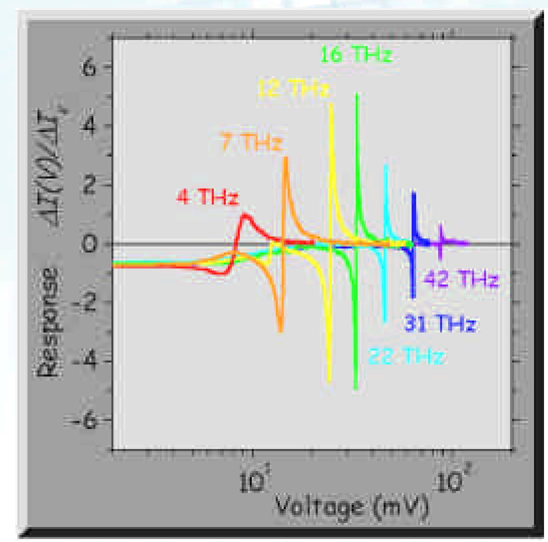
IcRn ~ 0.1 mV



IcRn ~ 1 mV



IcRn ~ 10 mV



Y.Y. Divin, U. Poppe, O.Y. Volkov, V.V. Pavlovskii.
Appl. Phys. Lett., v.76, n.20, p.p.2826-2828 (2000);
Y. Y. Divin, O.Y. Volkov, M.V. Liatti, V. N. Gubankov
IEEE Trans. Appl. Supercond., v.13, n.2, pp.676-679 (2003)

Comparison of Spectrometers

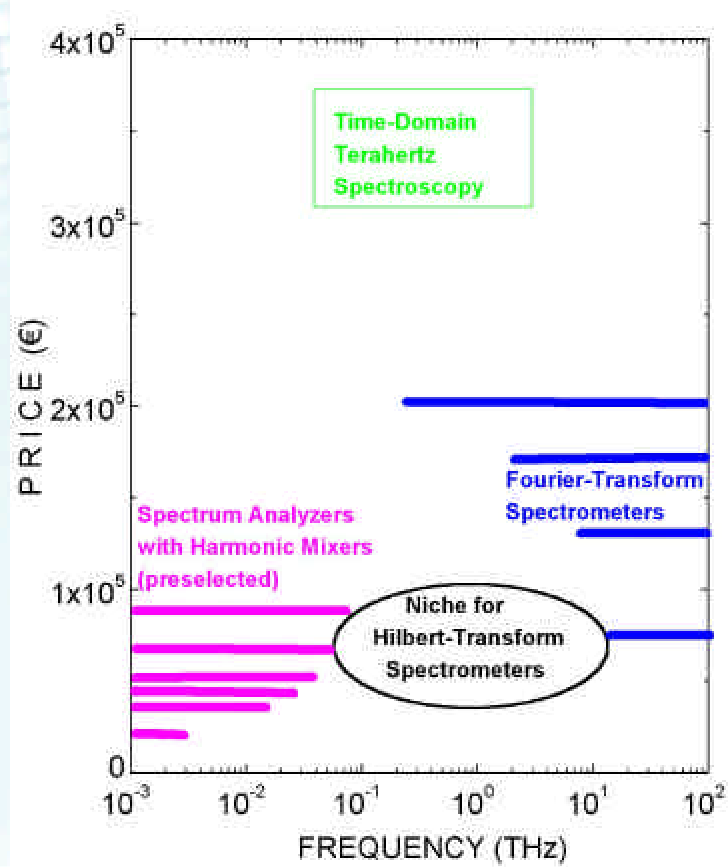
Advantage:

A transformation of the spectrum into an electrical signal is achieved:

•In **HTS** by a high-speed *nanoelectronic* device, a Josephson junction,

•in **FTS** by a low-speed bulk optical-mechanical device, an interferometer, and a broadband detector,

•in **TDS** by a detector with a low-speed bulk optical-mechanical delay line.



Terahertz Hilbert-Transform Spectrometers

HT spectrometer
using Stirling cooler

HT spectrometer
using LN cryostat.

Our goals:

- More broadband
- Faster
- More sensitive
- General-purpose and application-oriented

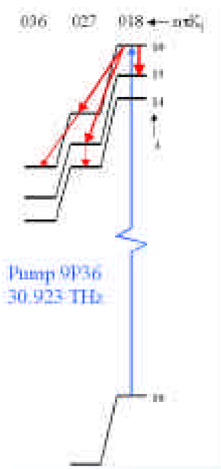
Y. Divin, O. Volkov, V. Pavlovskii, V. Shirotov, P. Shadrin, U. Poppe, K. Urban.
Advances in Solid State Physics, 41, ed. B. Kramer (Springer, Berlin, 2001) pp. 301-313

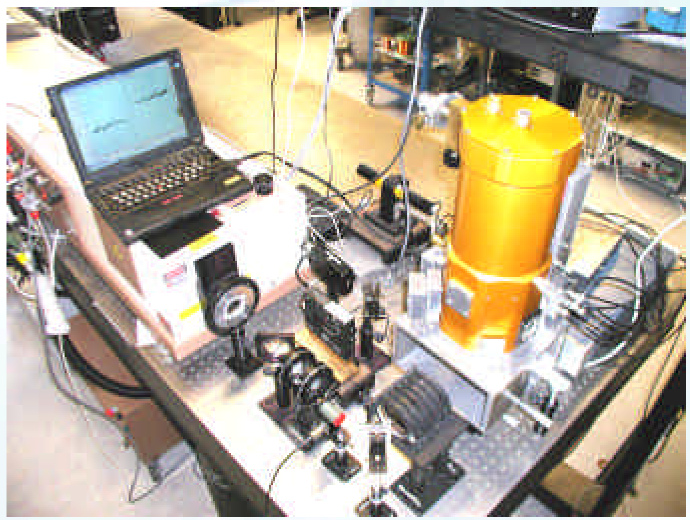
Applications of Terahertz Hilbert Spectroscopy

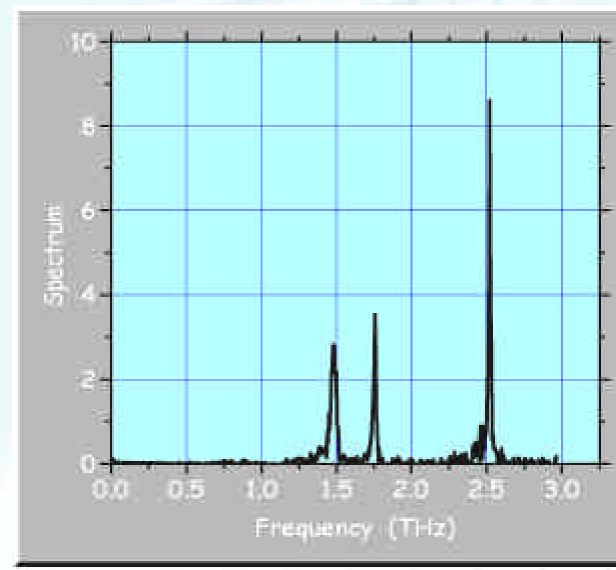
Spectral analysis of terahertz laser
(CH_3OH laser with CO_2 pump)

Our goal:

Spectral analysis of novel terahertz sources





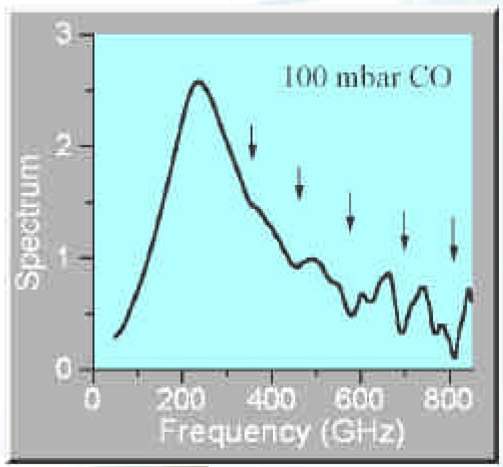


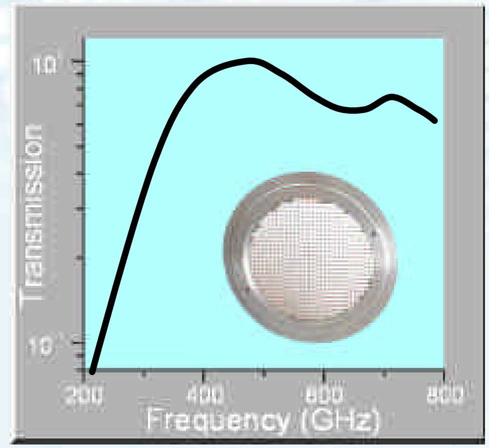
Y.Y. Divin, O.Y. Volkov, V.V. Pavlovskii, U. Poppe, K. Urban.
IEEE Trans. Appl. Supercond., vol. 11, n. 1, pp.582-585 (2001).

Applications of Terahertz Hilbert Spectroscopy

Transmission spectroscopy with broadband radiation source (high-pressure Hg lamp)

Our goal:
- Spectroscopy of
- dielectrics
- magnetic materials
- EBG structures
- biological substances
- at 100 GHz-10 THz





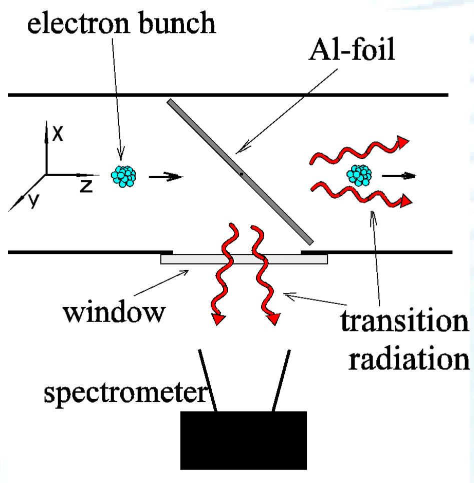
V.V.Shirotov, Y.Y.Divin, K.Urban
Physica C, v. 372-376, pp. 454-456 (2002).

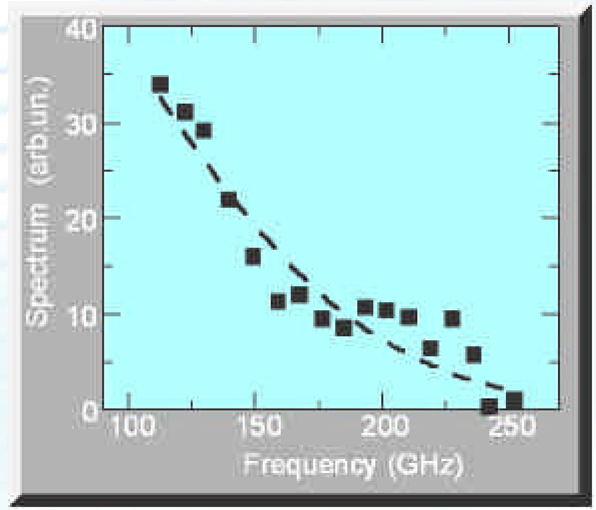
Applications of Terahertz Hilbert Spectroscopy

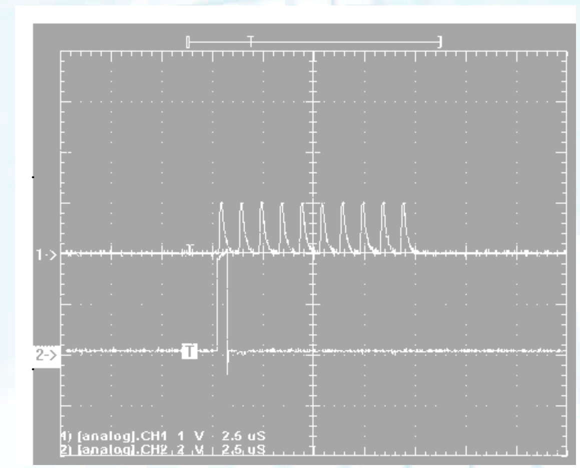
Frequency-resolved electron bunch diagnostics at linear accelerators*

Our goal:

Fast electron bunch analysis for next generation of large accelerators







In collaboration with TESLA Test Facility at DESY (Hamburg)

V. Shirotov, Y. Divin, U. Poppe, H. Larue, E. Zimmermann, A. Ahmet, H. Halling and K. Urban. IEEE Trans. Appl. Supercond., v.13, n.2, pp.172-175 (2003)

Challenges & Goals

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- Physics of high-Tc junctions
  - relation between nanostructure of barrier & ac Josephson effect
  - high-frequency limit of the ac Josephson effect
- Technology of high-Tc junctions
  - high I_cR_n-product for operation up to 10 THz
  - high spatial homogenuity for array application
- Development of spectrometers
  - fast spectrometer for novel terahertz sources (**pulsed** and continuous)

    for e-beams: transition radiation, synchrotron radiation, weak fields

    e-Beam Diagnostics

  - terahertz spectrometer for material science and biology

Spectroscopic measurements of coherent radiation for bunch length or bunch form diagnostics:

Fourier Transform spectroscopy (polarizing Martin Puplett)

Electro-optic sampling

.....

Hilbert-Transform spectroscopy:

Broad band: 50 GHz – 4.5 THz

Fast (no mechanical moving parts!)

Frequency resolution: ca.10^{-3}

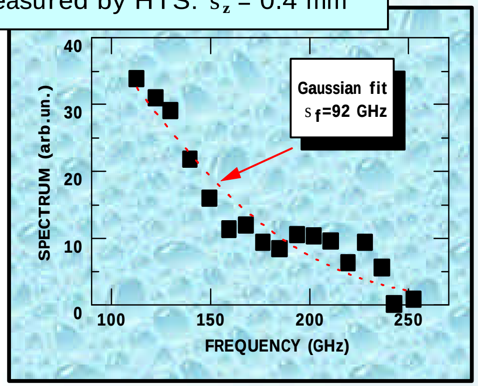
Dynamic range: 50dB

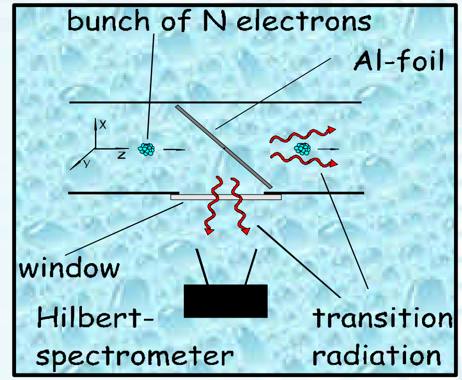
Min power: 1.8x 10^{-11} W for20 dB

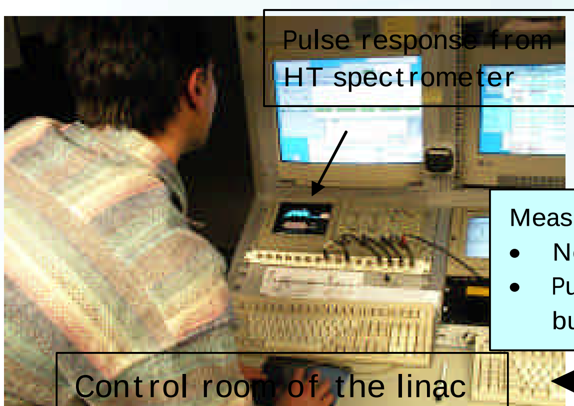
Hilbert Spectroscopy of Coherent Transition Radiation in TESLA Test Facility Linear Accelerator at DESY

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

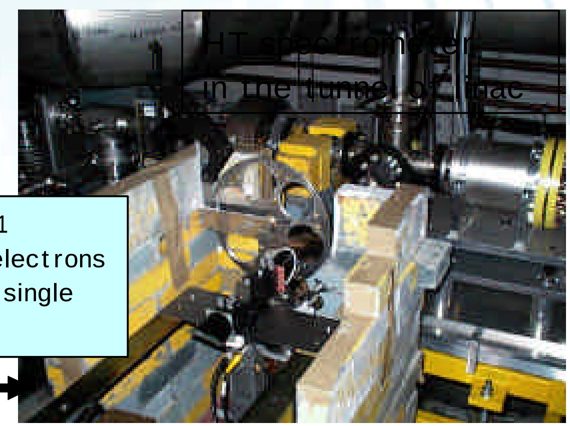
$$I_{total}(\lambda) = I_1(\lambda) \cdot \left[N + N(N-1) \left| \int \rho(\vec{r}) \cdot \exp\left(\frac{2\pi i (\vec{n} \cdot \vec{r})}{\lambda} \right) d^3 r \right|^2 \right]$$







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



First measurements at DESY, 1997

- Thermoionic gun, N =2.3x10^8 electrons
- Macrobunch averaging
- Bunch length measured by HTS: σ_z = 0.4 mm, σ_t = 1.2 ps, σ_f = 92 GHz

Measurements at DESY, 1999, 2001

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

Hypothetical spectrum: σ_z = 50 µm, σ_t = 0.17 ps, σ_f = 0.72 THz

Bunch form analysis needs ca. 4 THz

spectral intensity of transition radiation emitted by a bunch of N electrons

$$I_{total}(\lambda) = I_1(\lambda)\cdot\left[N + N(N-1)\left|\int \rho(z)\cdot\exp\left(\frac{2\pi i z}{\lambda}\right)dz\right|^2\right]$$

$I_1(l)$ is the intensity of transition radiation emitted by a single electron at given wavelength *l*

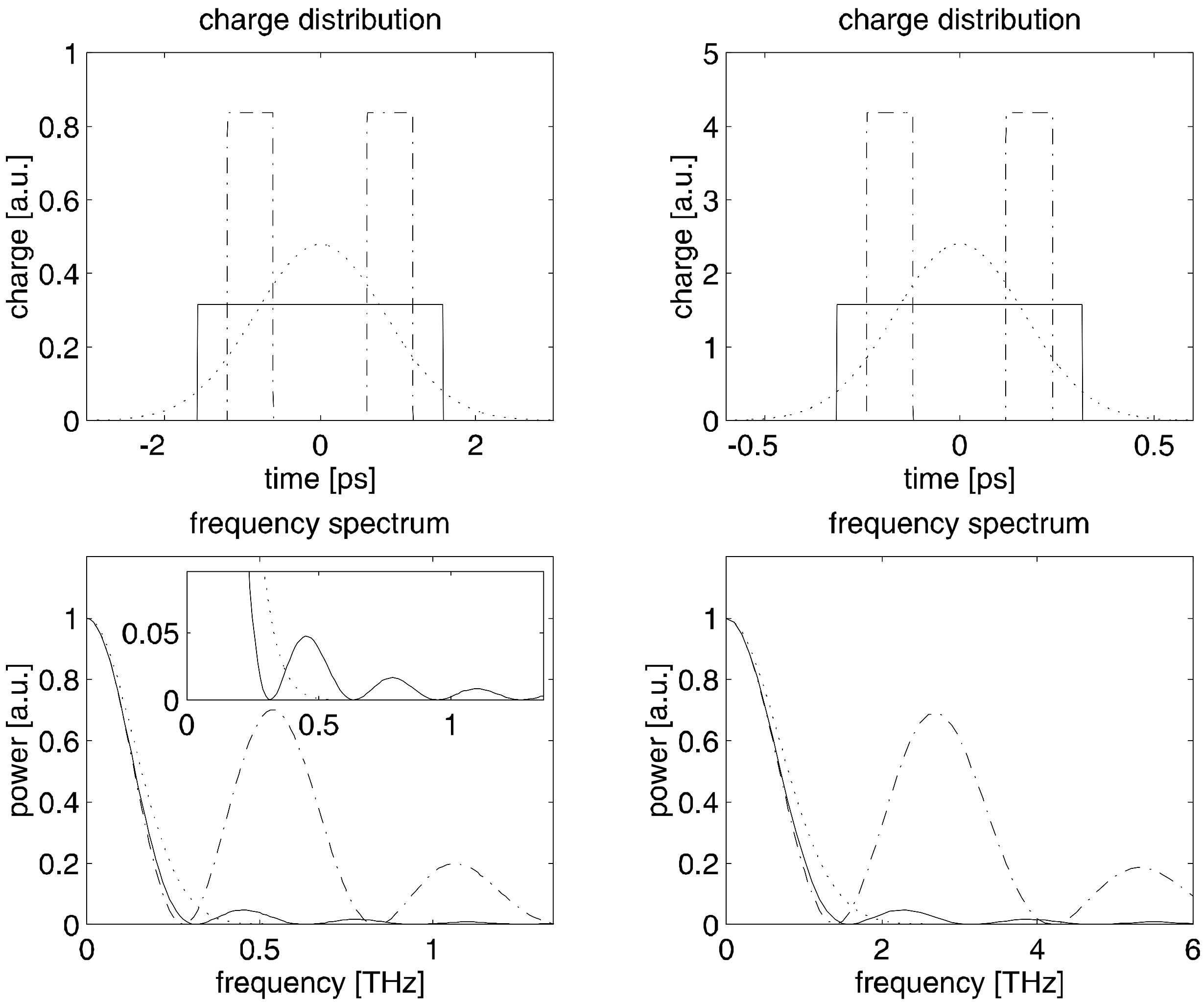
The integral is the longitudinal bunch form-factor, defined as the Fourier transform of the longitudinal charge distribution *r(z)* in the bunch.

When the charge distribution *r(z)* in the bunch is localized in space with a characteristic length L

$$I_{total}(\lambda) = N\cdot I_1(\lambda)$$ $\lambda \ll L$ uncoherent

$$I_{total}(\lambda) = N^2\cdot I_1(\lambda)$$ $\lambda \gg L$ coherent

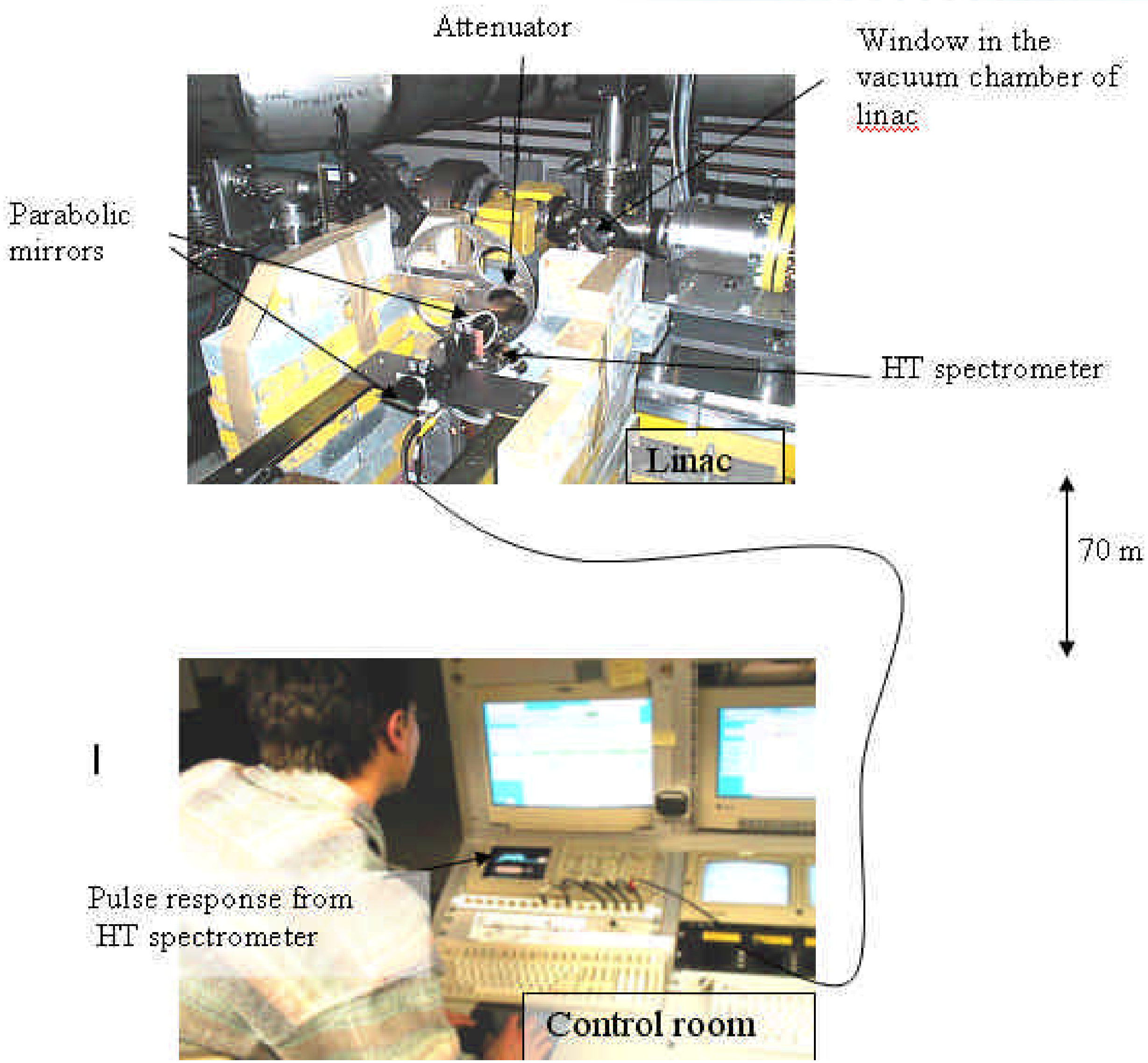
Bunch - form Diagnostics



Hypothetical longitudinal charge distributions in the bunch and the corresponding coherent radiation spectra.

The plots on the left correspond to rms bunch length of 250 µm, those on the right - to 50 µm.

Hilbert Spectrometer at the DESY Linac



Measurements of pulsed coherent transition radiation from electron bunch by Hilbert-transform spectrometer.

Compact HT-spectrometer with high-Tc Josephson junction operating at temperature of 80 K was used during the measurements.

TESLA Test Facility linear accelerator at DESY (Hamburg). 1999

Hilbert Spectrometer at the DESY TESLA Test Facility Linac

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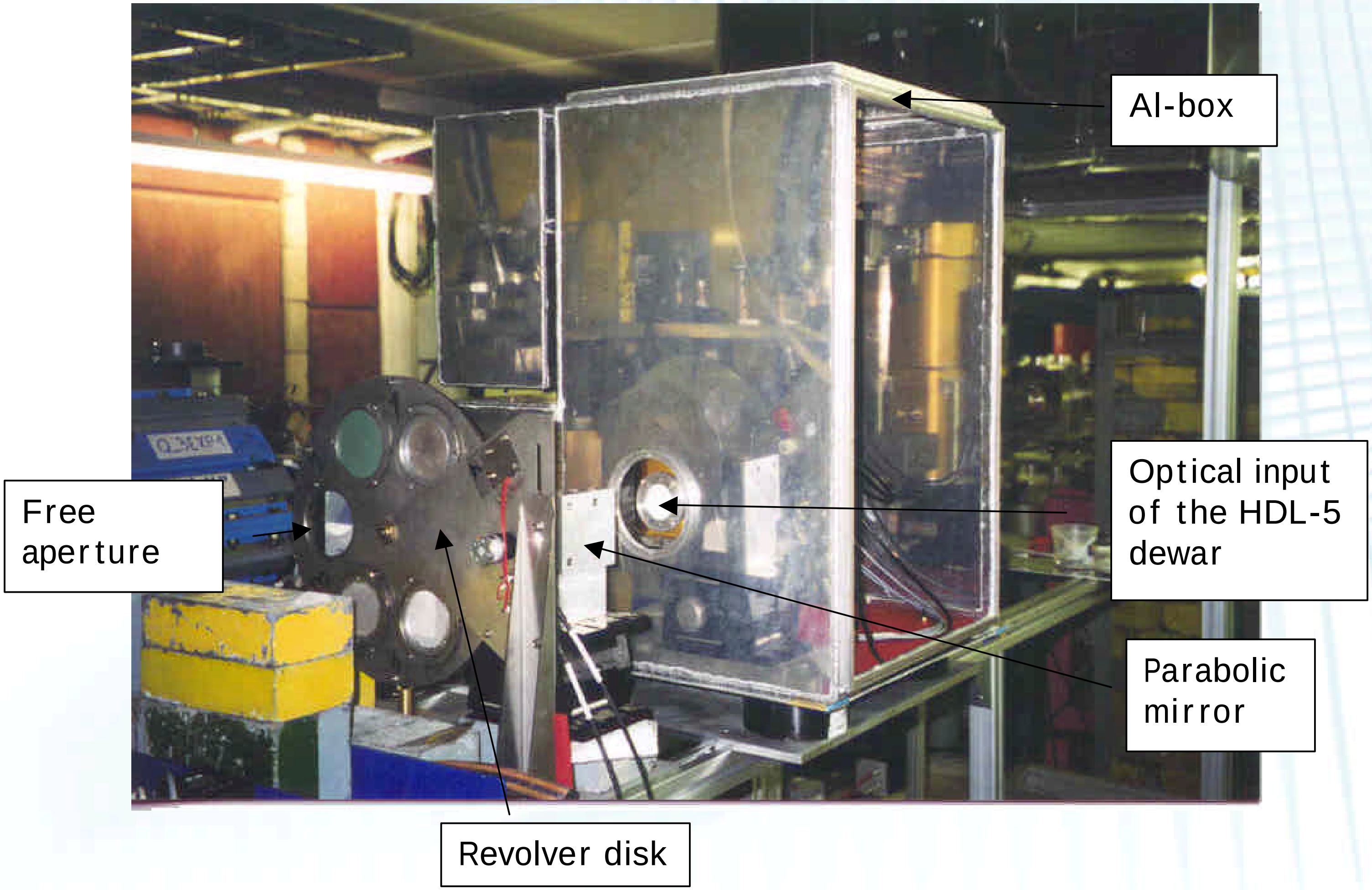

The view of the HT spectrometer from the optical input.

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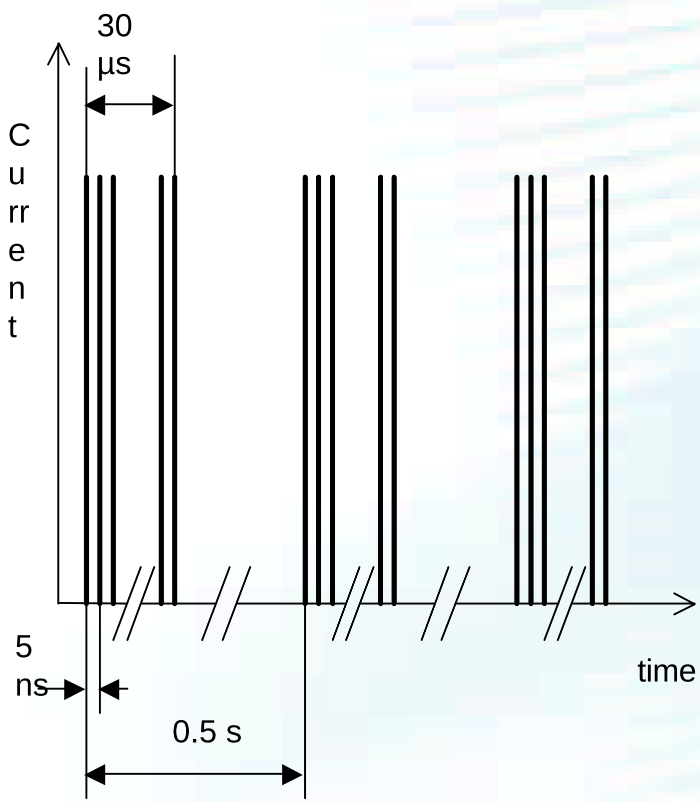
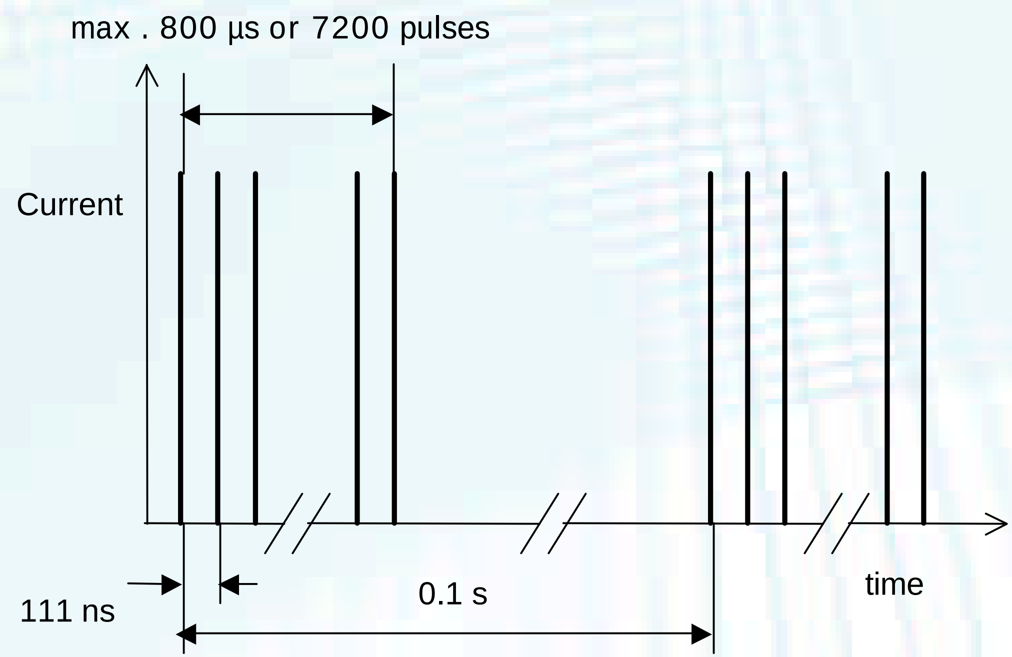
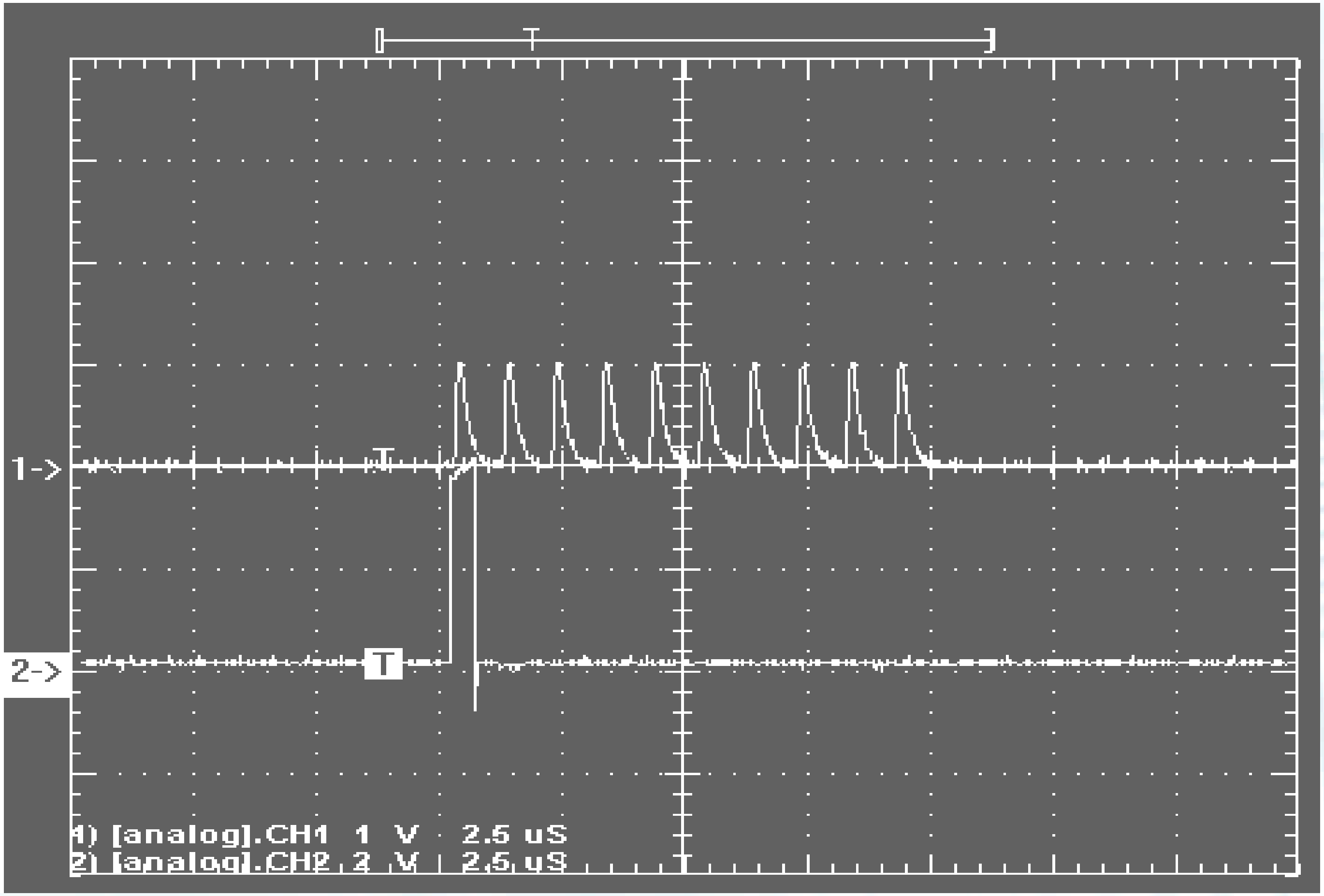
Time Diagrams for the Operation of the Electron Linac at TESLA Test Facility at DESY



previous configuration with thermoionic gun



planned configuration with a photo-injector
puls-trains with max. 7200 pulses



The time dependence of the response of Hilbert spectrometer to the pulse transition radiation at TESLA Test Facility (trace 1). The trace 2 is a trigger signal from the linac.

Conclusions:

- Fast Hilbert spectrometer based on high-Tc Josephson junctions for pulsed coherent transition radiation at TESLA Test Facility at DESY.
- Characterization in the laboratory :
  power dynamic range of 50 dB,
  spectral range from gigahertz range to terahertz range (50 GHz til 4.5 THz)
- Spectrometer with digital data transfer tested at TESLA Test Facility.
- Spectrum of transition radiation e.g. averaging 9 pulses bunches in one macrobunch delivered spectrum spreading from 50 to 500 GHz.

Outlook and Goals:

- Developed spectrometer allows measurements of whole spectrum during a single macrobunch, when a number of more than 500 bunches are provided (projected are 7200 bunches at TESLA).
- Hilbert spectrometer, integrated not into a liquid nitrogen cryostat but into a Stirling cooler.
- Extension to shorter pulses (ca. 10 THz, 100fs)

We are open for test measurements at different facilties participating in the ELAN-Care network which provide radiation in the terahertz range