BESSY

Berliner Elektronenspeicherring-Gesellschaft
für Synchrotronstrahlung m.b.H.

THz Spectroscopy

with

Coherent Synchrotron Radiation

Ulrich Schade

BESSY

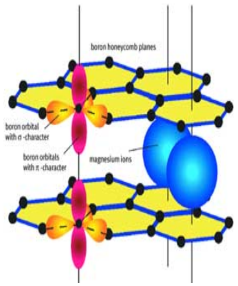
Leibniz Gemeinschaft

Condensed Matter Physics

Superconductivity
- Energy gap
- Symmetry of the order parameter
- Strength of coupling

Low-dimensional effects
- Dimensionality crossover
- Non-Fermi liquid normal states
- Broken symmetry ground states

Strongly correlated electrons
- Kondo problem
- Heavy electrons



Life Sciences

Protein dynamic
- Secondary and tertiary structure

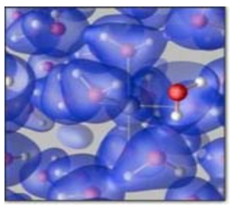
Metabolism
- Influence of nutrition, water
- Ion channels in cell membranes

Imaging
- 3D tomography of dry tissues
- Near-field

Physical and Analytical Chemistry

Polar liquids
- Hydrogen bond
- Van der Waals interactions
- Acoustic-Optic phonon mixing in water

Solutions
- Interactions between solvated ions and solvent



New Technologies

Medical diagnostic
- Early cancer detection

Industrial production
- Material inspection

Defense industry/Homeland security
- Detection of explosives and biohazards

Instrumentation

- Infrared Beamline at BESSY, THz Performance

THz Radiation from the Storage Ring BESSY

- Radiation Properties

Spectroscopic Application of the CSR

- Superconductors
- THz Near-field Spectroscopy

Conclusions

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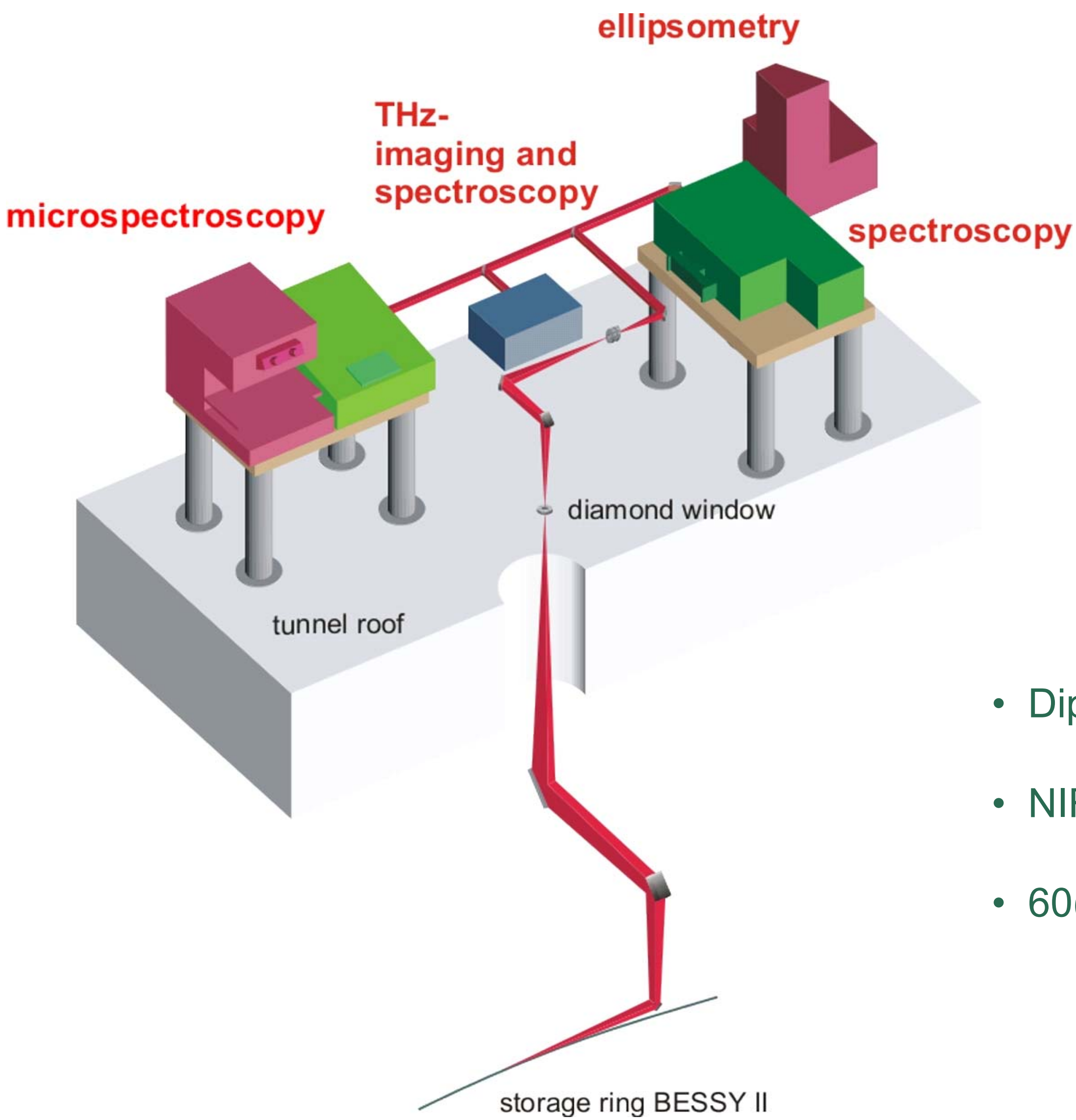
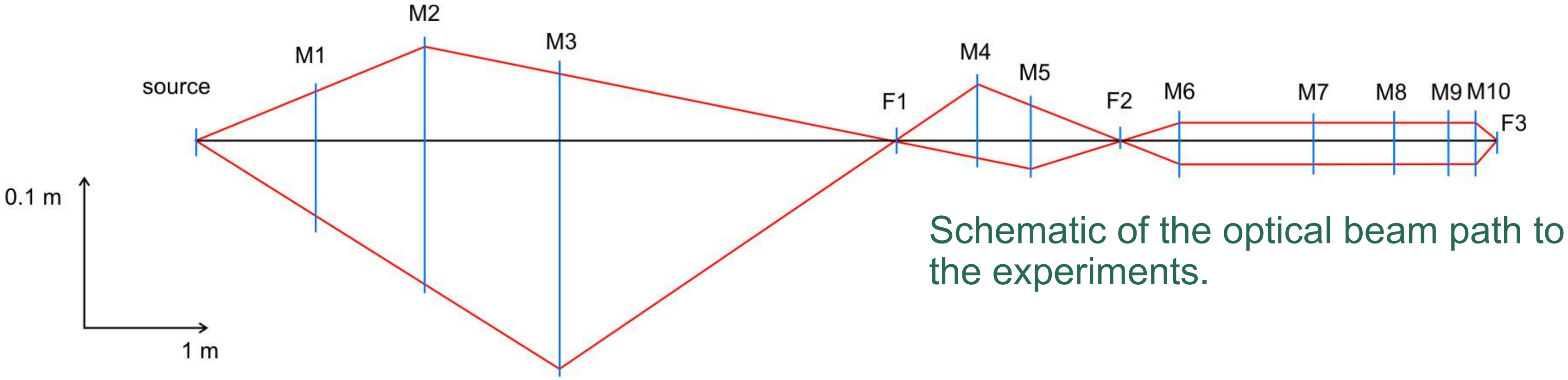


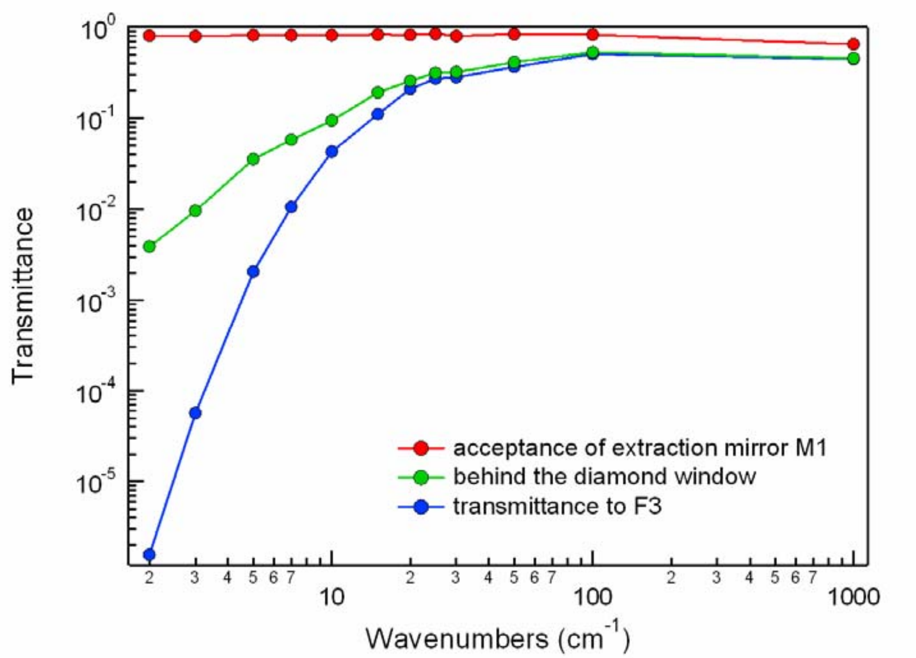
- Dipole radiation from dipole 2.2
- NIR to FIR
- 60(h) x 40(v) $mrad^2$ acceptance

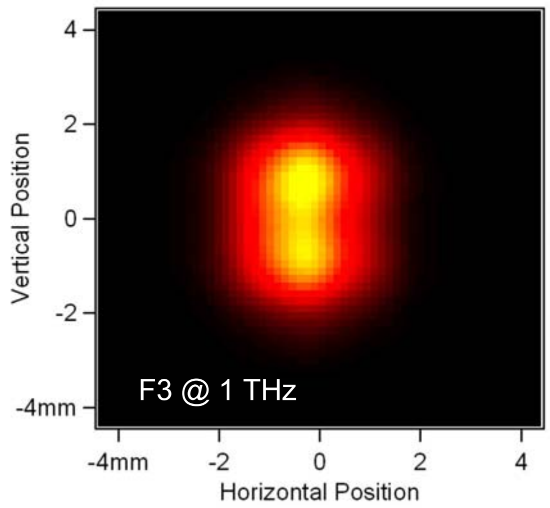
Schade et al., Rev. Sci. Instr. **73** 1568 (2002).

THz Transmission of IRIS Beamline



Schematic of the optical beam path to the experiments.





Calculated transmittance for different positions along the beam path (SRW code).

Instrumentation

- Infrared Beamline at BESSY, THz Performance

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Conclusions

CSR at higher frequencies observed than for Gaussian bunches expected

With increasing current of the bunch:

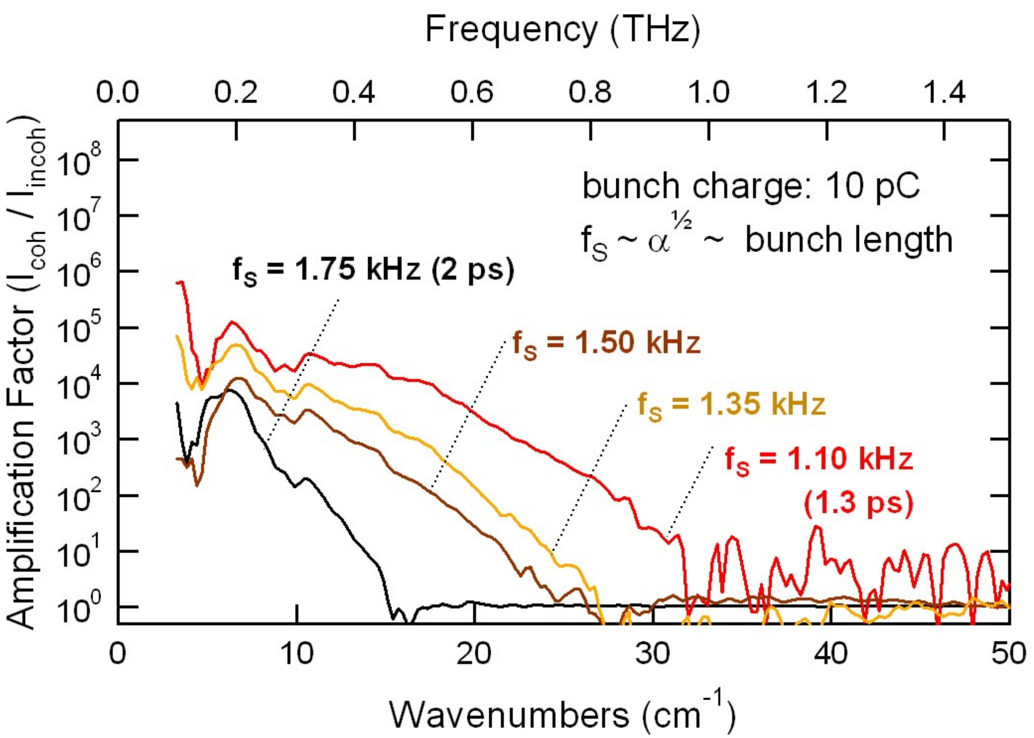
- the CSR spectrum extends to higher photon energies.
- the low-frequency noise in the THz beam drastically increases.

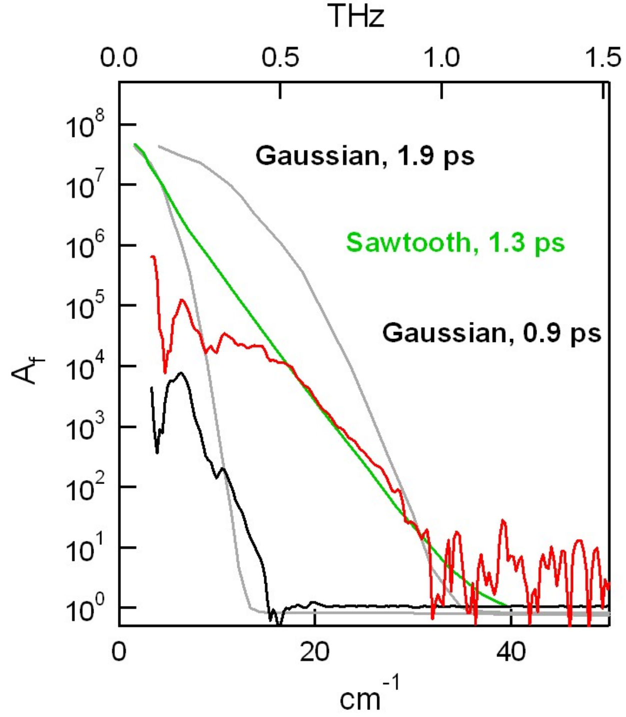
Present understanding:

Interaction of bunch with CSR-wakefield leads to:

- a static non-Gaussian deformation of the bunch (Bane, Krinsky and Murphy, 1996)
  → **steady-state CSR**

- bursting CSR emission above a current threshold (micro-bunching, Stupakow and Heifets, 2002)
  → **high power bursting CSR**

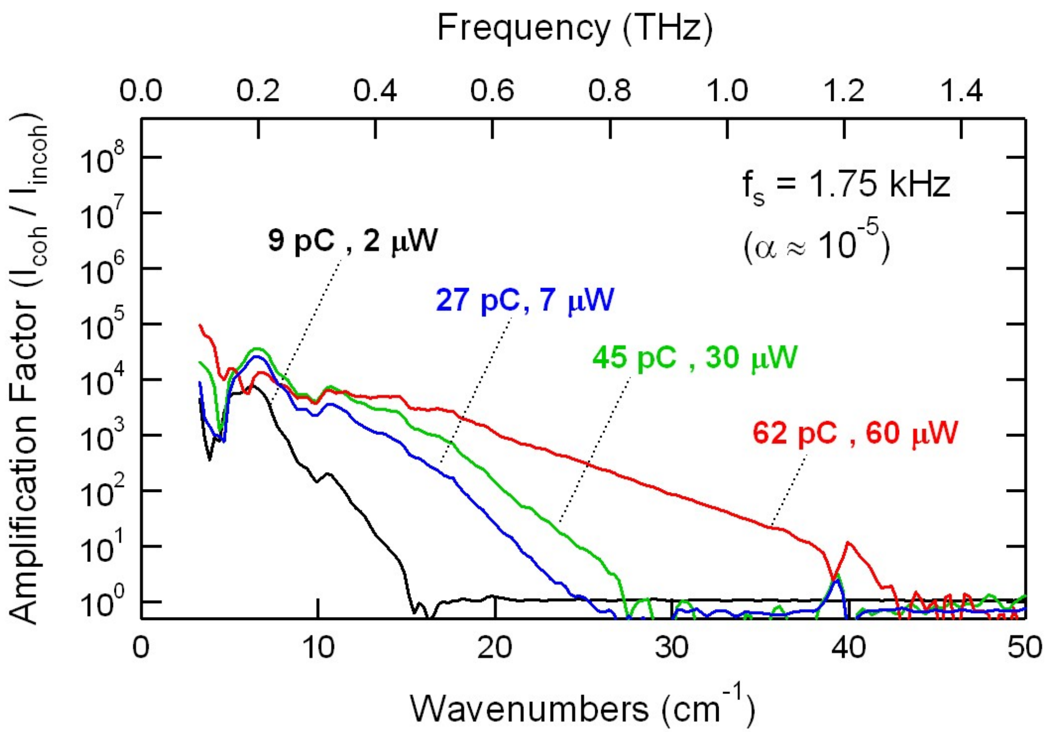




$$A_f = \frac{I_{coh}}{I_{incoh}} = N f_\nu \,, \quad f_\nu = \left| \int n(z)\, e^{i\pi\cos(\theta) z} dz \right|^2$$

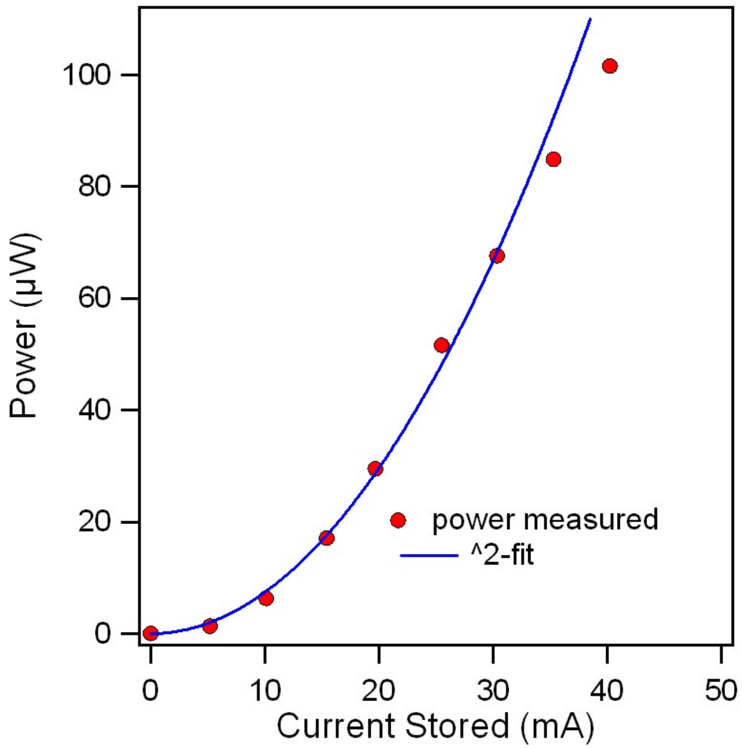
min. bunch length: 1.3 ps (0.5 mm)
max. charge: 10 pC

Coherent Amplification Factor



$$A_f = \frac{I_{coh}}{I_{incoh}} = N f_\nu \ , \quad f_\nu = \left| \int n(z)\, e^{i\pi \cos(\theta) z} dz \right|^2$$

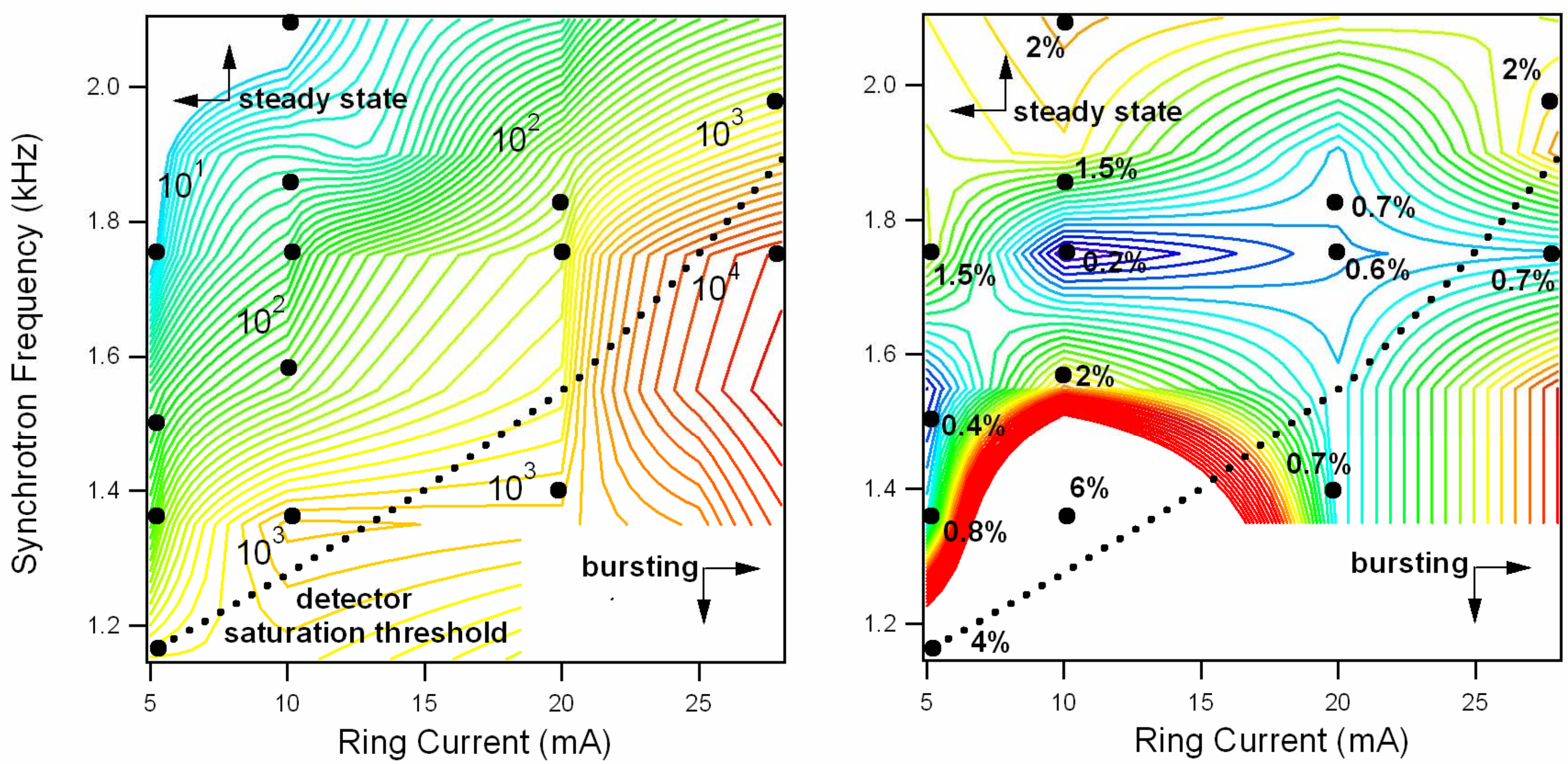
Total power of the coherent synchrotron radiation measured at F3.



Pulse energy: max 100 pJoule
Peak E-field: max 50 V/cm

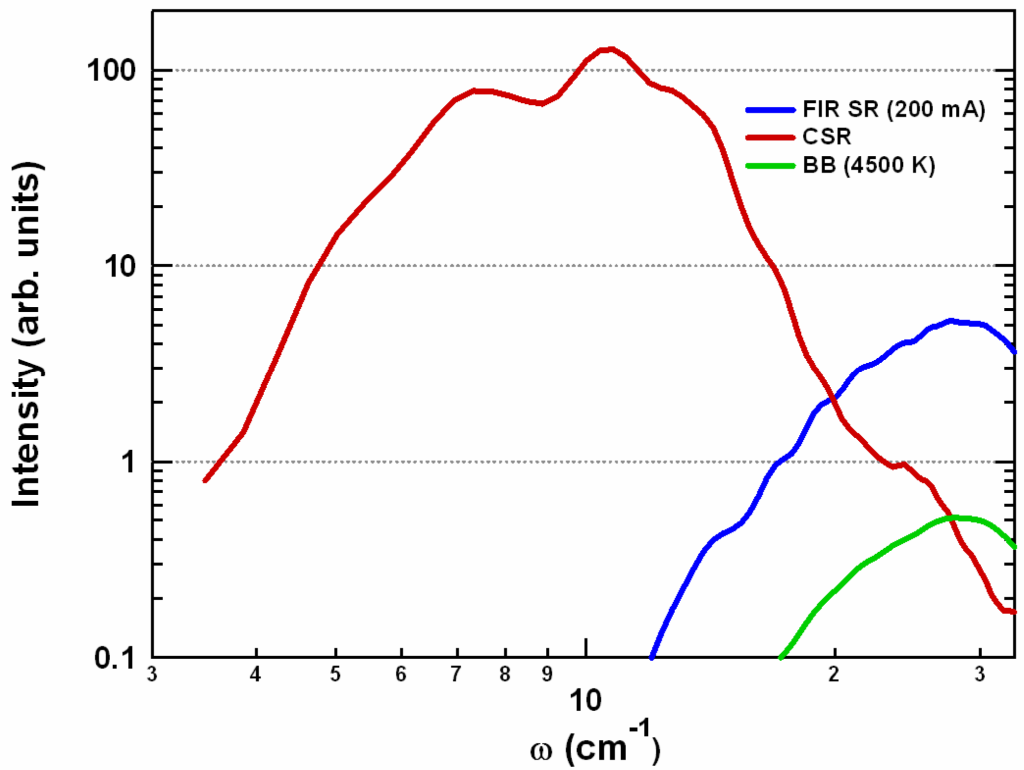
Integrated Spectral Intensity (a.u.) (5 -25 cm^{-1})

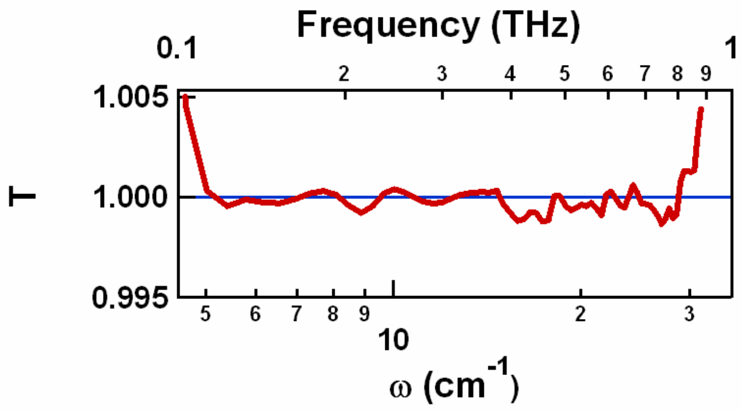
Noise (% rms from 100 % line) (7 -20 cm^{-1})



400 bunches stored, Bruker 66/v, 64 scans, $\Delta\omega$ = 0.5 cm^{-1}, 4.2 K Bolometer, 50-µm BS, 1.3 cm/s scanning velocity

Coherent Synchrotron Radiation in the low-α mode





"100%-line" for CSR

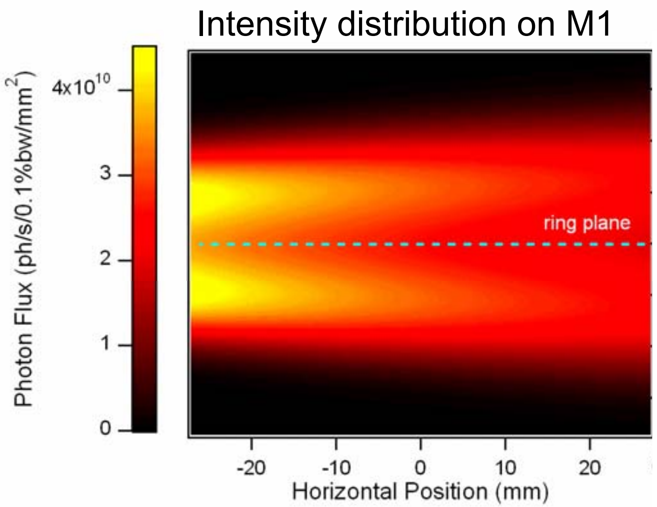
Source Comparison

256 scans, $\Delta\omega$ = 0.5 cm^{-1}, 1.4 K Bolometer, 5 mm aperture diameter

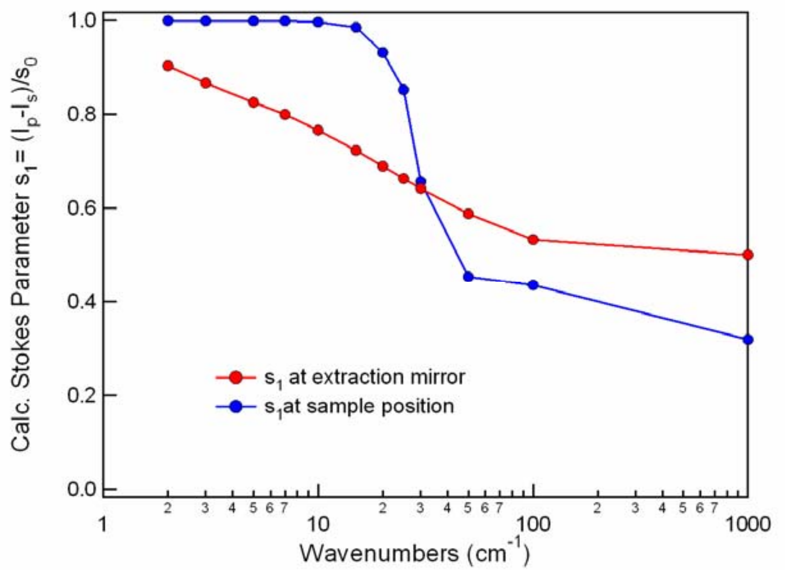
- long life time of the beam (>20 h)
- gain of 10^3 below 10 cm^{-1} (0.3 THz)
- highly reproducible

M. Ortolani et al., Phys. Rev. B **73**, 184508 (2006).

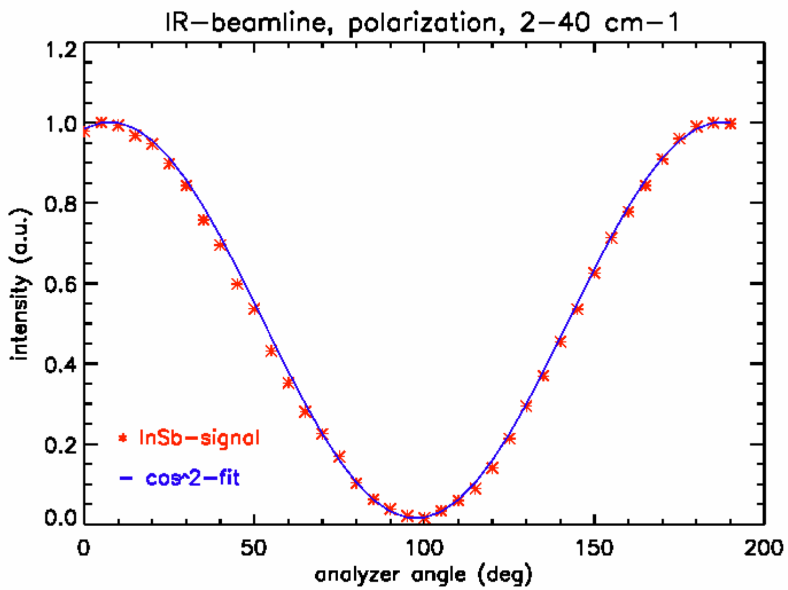
Polarization Characteristics of CSR



Polarization properties of IR synchrotron radiation from a bending magnet at 500 cm^{-1}.



Calculated s1 for the entrance and for the end focus of the beamline (SRW code).



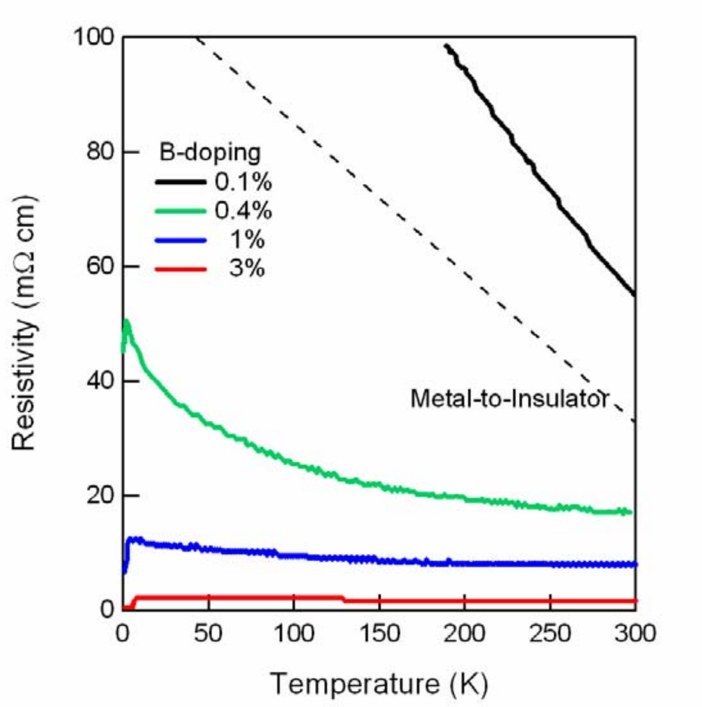
Normalized CSR intensity at F3 as a function of the azimuth angle of the analyzer.

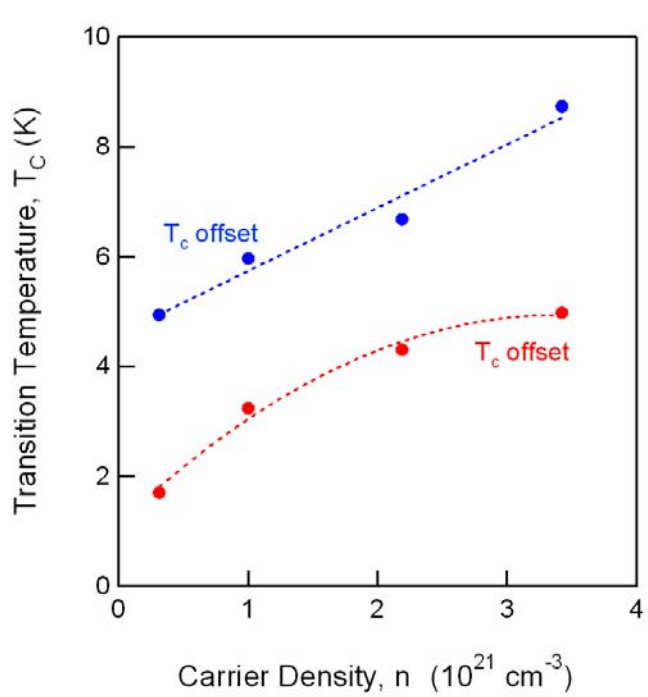
Application of the CSR:

- Superconductors
- THz Near-field Spectroscopy

Boron–doped Diamond

- Recently discovered superconductor: E.A. Ekimov, Nature **428**, 542 (Nov. 2004).
- Superconductivity appears at high B-doping beyond the Metal-to-Insulator transition.
- T_c increases to 8 K with increasing Boron concentration.



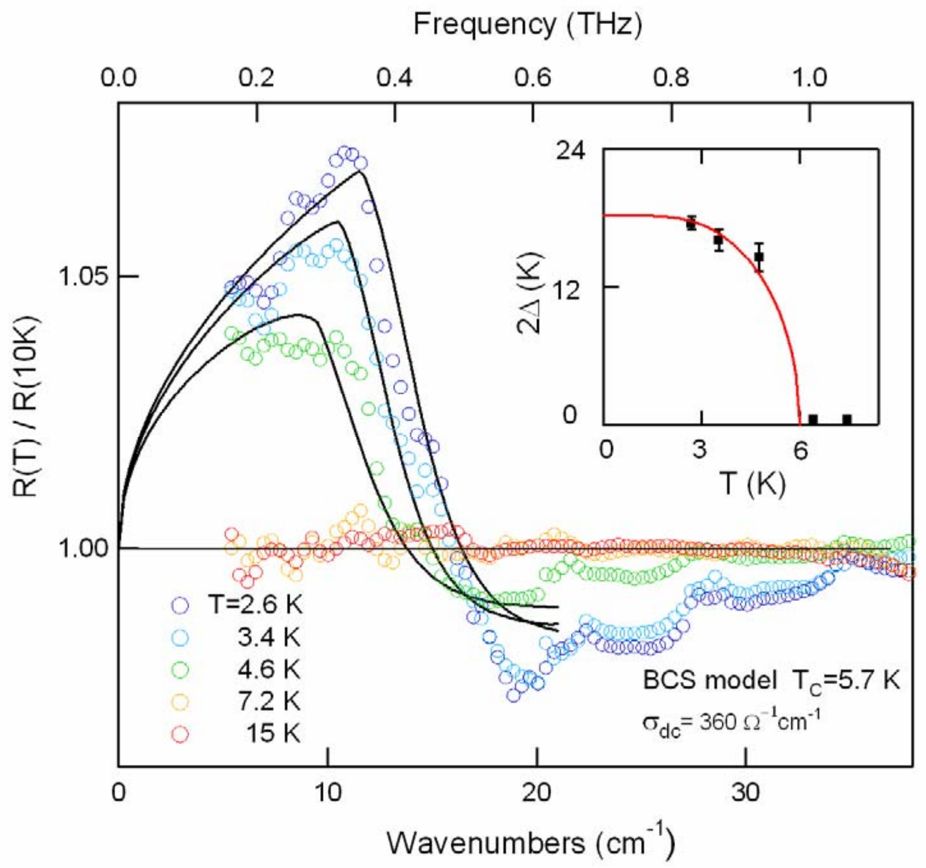


Size: 3 mm x 3 mm

Y. Takano et al., Diamond & Related Mat. **14**, 1936 (2005) and Nature **438**, 647 (2005).

Boron–doped Diamond

La Sapienza Università degli Studi di Roma NIMS BESSY



Increase of the normal-incidence reflectivity below T_c for $\omega < 2\Delta$ (total screening) observed.

The peak in the R_S/R_N ratio indicates the energy of the optical gap.

As a result of the BCS theory for weak electron-phonon coupling:

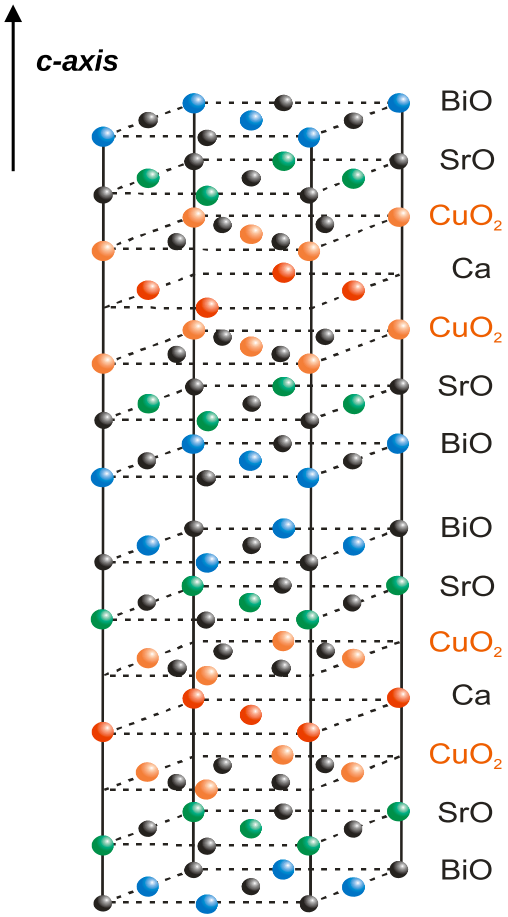
→ $2\Delta_0 = 3.53\ T_c$

Our sample: $\omega = 2\Delta = 12\ cm^{-1} = 17\ K$

→ $T_c = 5\ K$

M. Ortolani et al., Phys. Rev. Lett. **97**, 097002 (2006).

UCSD BERKELEY LAB BESSY



c-axis reflectance of optimally doped BSCCO 2212

- structural anisotropy
- high T_c (90 K) but low "gap energy"

T>T_C

- Charge transport is blocked by insulating layers.
- Behaves like an insulator with R <1.

T<T_C

- Cooper pairs tunnel through insulating layers, R ~ 1.
- Josephson Plasma Resonance (JPR) below 10 cm^{-1}

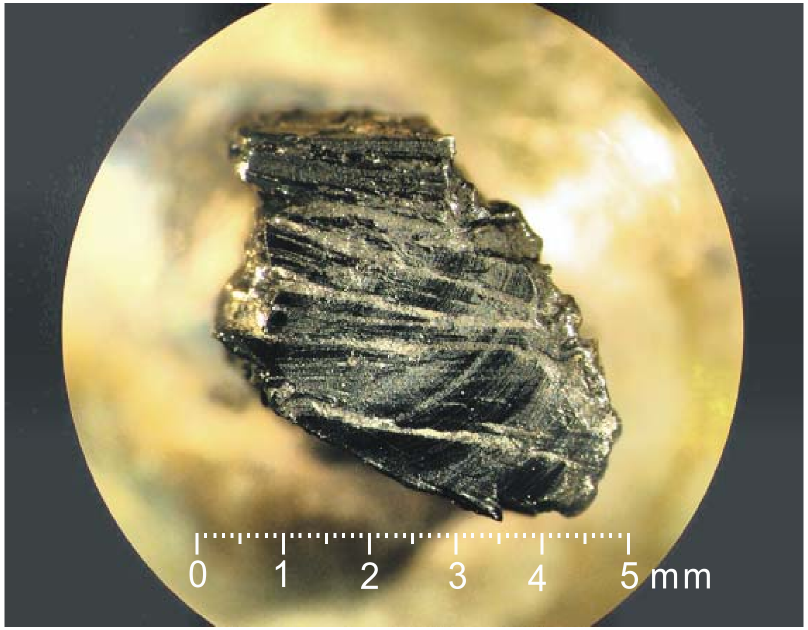
$$\omega_{JPR}^2 = \frac{4\pi n e^2}{m^*}$$

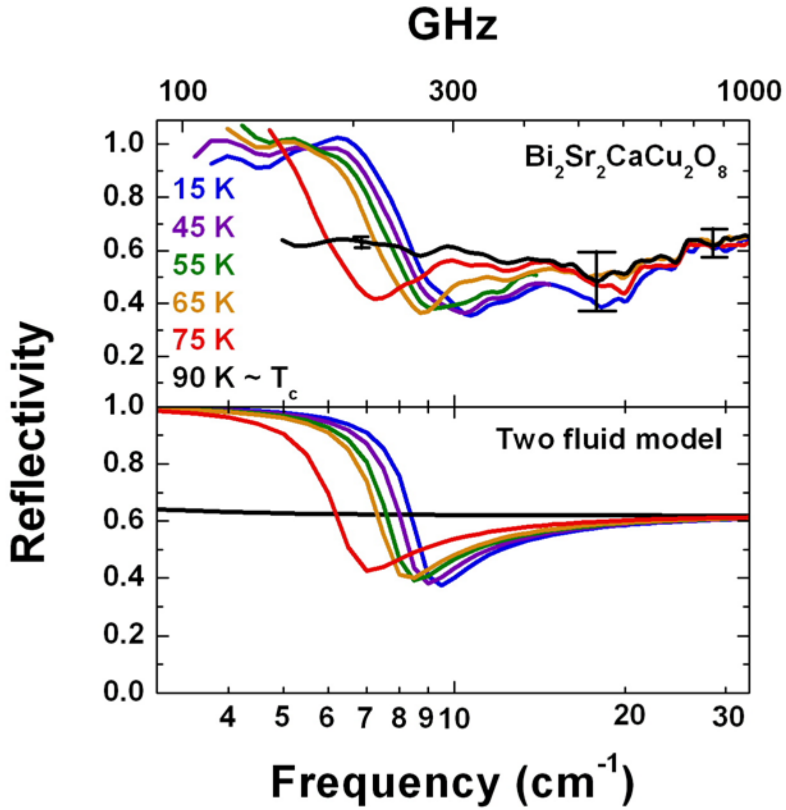
$Bi_2Sr_2CaCu_2O_8$: - extreme structural anisotropy

- highly insulating

High–T_C "Cuprate" Superconductor

Optimally doped $Bi_2Sr_2CaCu_2O_8$

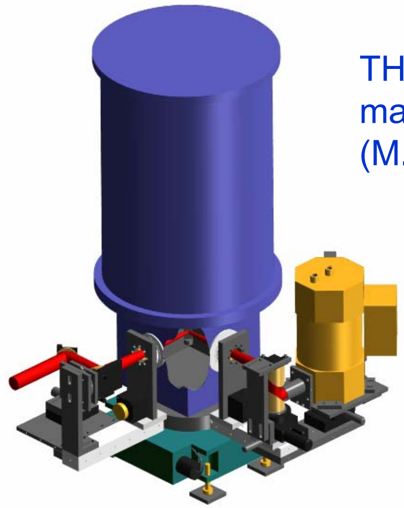




- First scientific experiment using coherent synchrotron radiation as a spectroscopic source.
- Absolute measurements of reflectivity with high photometric accuracy on small samples at low temperatures.
- Direct measurement of JPR in optimally doped $Bi_2Sr_2CaCu_2O_8$.
- Bridge between microwave magneto-absorption and conventional far-IR spectroscopy.

E. J. Singley et al., Phys. Rev. B. **69**, 092512 (2004).

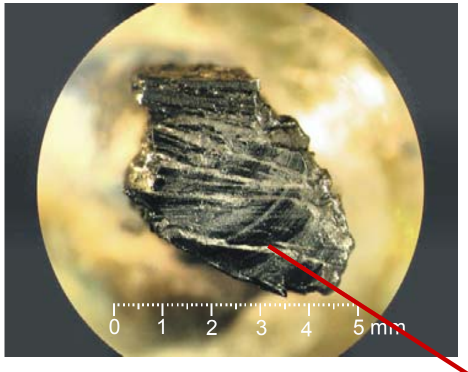
THz Problems Near-field Approaches Could Solve



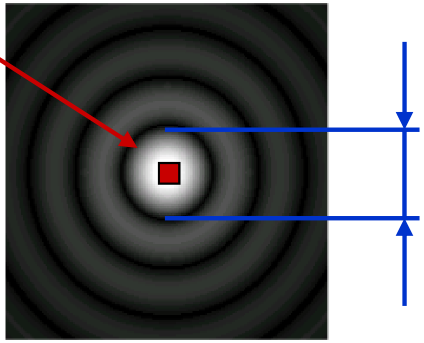
Small-Throughput Experiments
- complicated optical path (cryostat, magnets, etc.)
- large F#

Small Sample Geometry
- new and rare materials
- spatial resolution

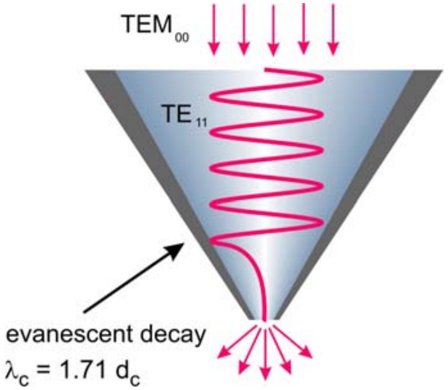
$Bi_2Sr_2CaCu_2O_8$

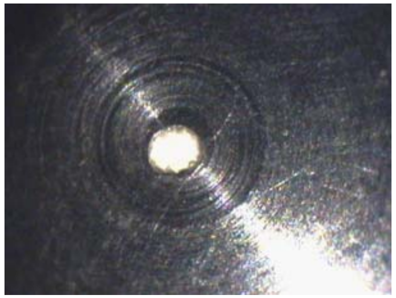


Large THz Focal Spot
- Frauenhofer diffraction (1. disk: 84 % intensity)



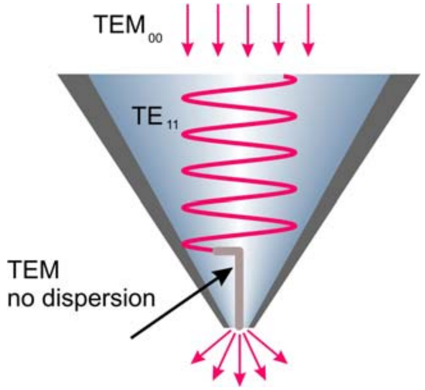
Aperture Cone



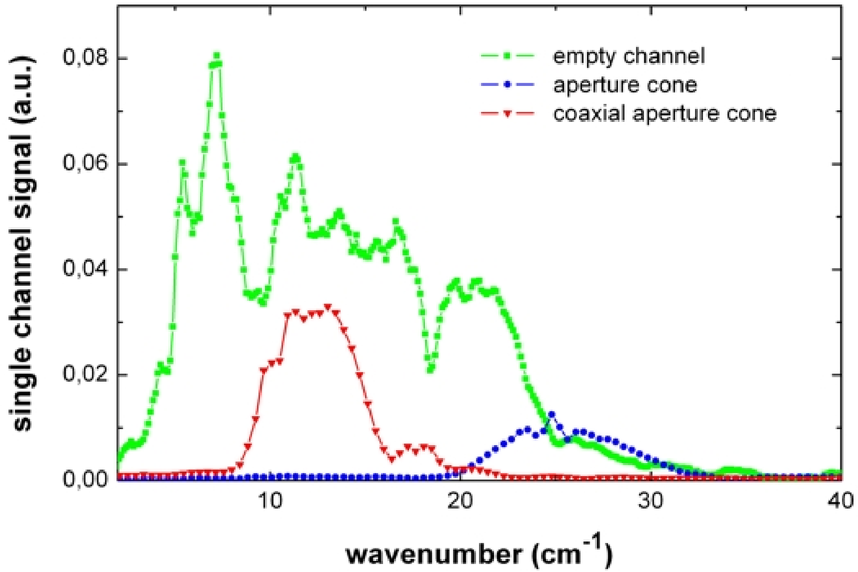


200 µm diameter aperture

Coaxial Aperture cone



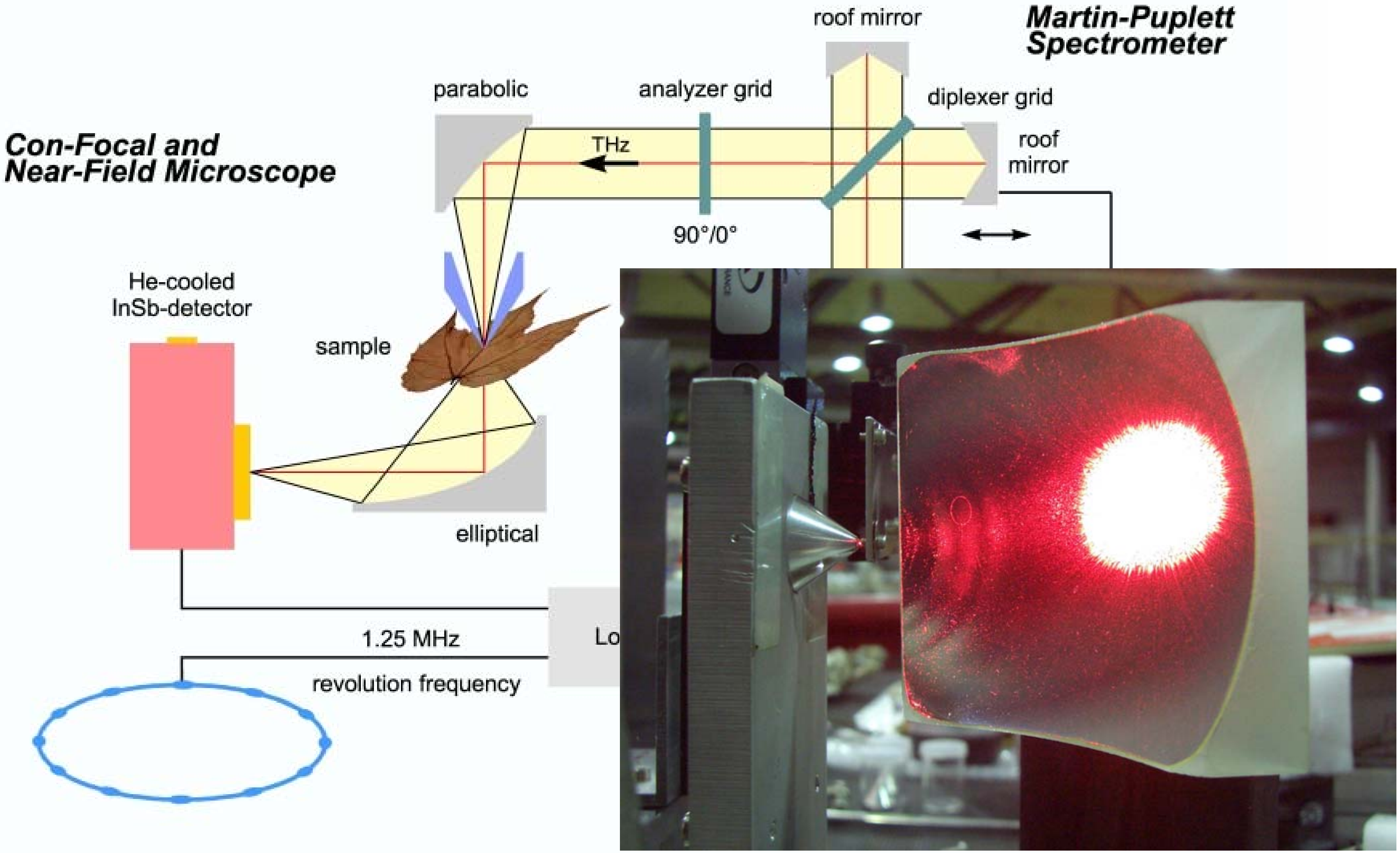
200 µm diameter aperture,
80 µm wire diameter



Spectra of the empty spectrometer (to be multiplied by 100), of the aperture cone and of the coaxial aperture cone.

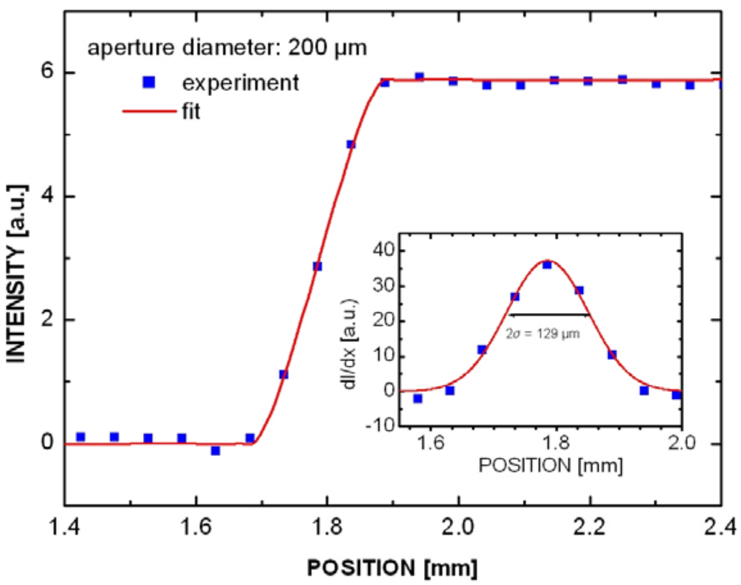
probe design according to: F. Keilmann, *Infrared Phys. & Technol.* **36** 217 (1995).

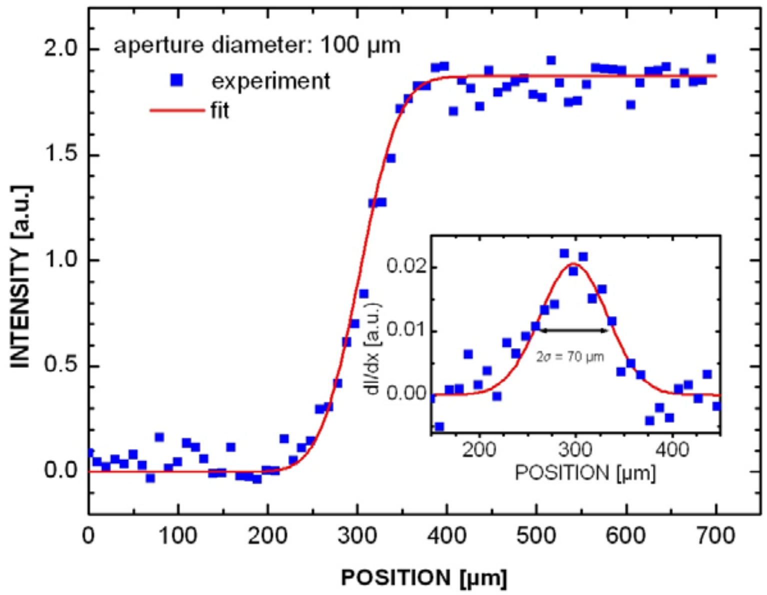
THz Near-field Imaging with CSR

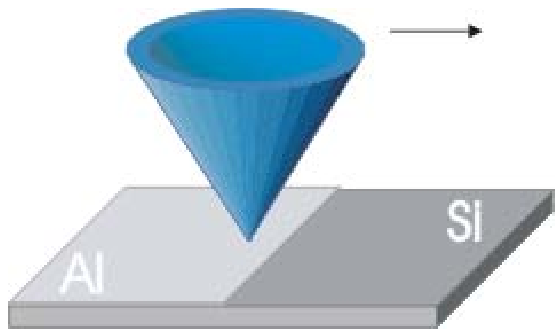


U. Schade et al., *APL* **84** 1422 (2004)

THz Near-field Imaging with CSR





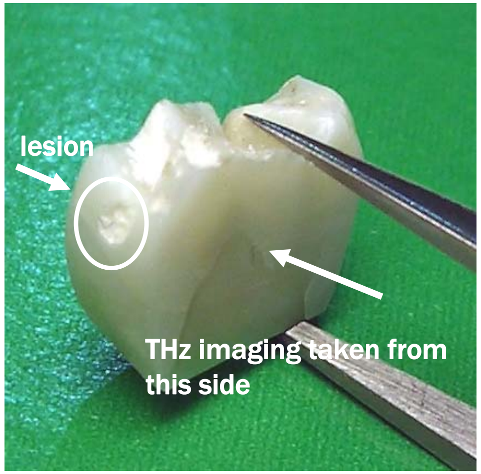


- "knife edge test" on Al-film on Si-substrate
- spatial resolution @ 1 mm wavelength (0.33 THz):

100 µm aperture: 70 µm ≈ 1/14 λ

200 µm aperture: 130 µm ≈ 1/8 λ
(@ 5 mm wavelength (0,066 THz): ≈ 1/38 λ)

Tooth decay diagnostics:

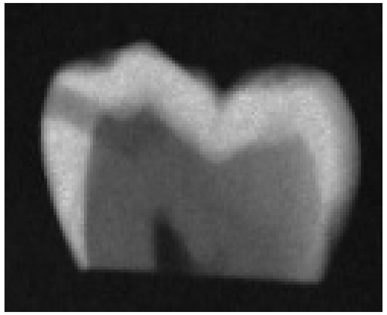


Simulated caries lesion (tooth decay) composed of hydroxyapatite powder.

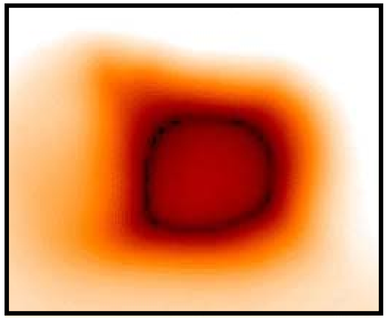
X-ray: little material contrast due to demineralization

NIR: good for enamel but dentin almost opaque

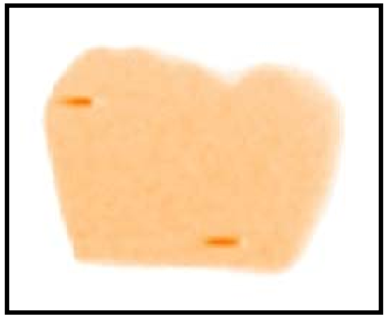
THz: ?



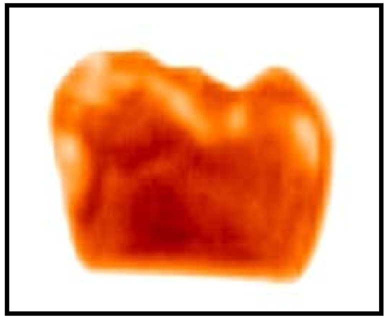
- shadow image
- x-ray



- far-field @ 1 mm (0.3 THz)
- con-focal geometry
- bursting mode



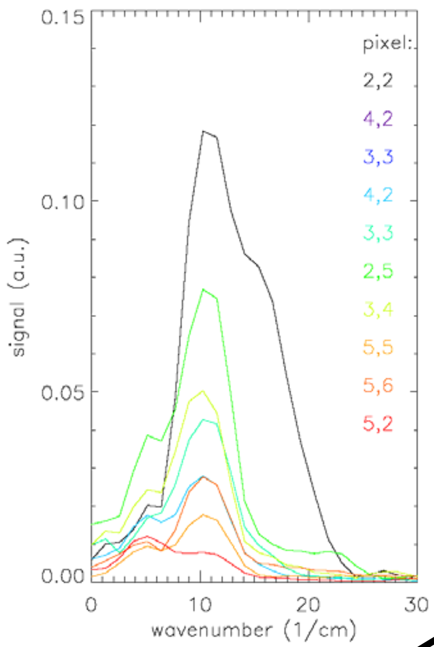
- near-field @ 1 mm
- 200 µm aperture
- bursting mode

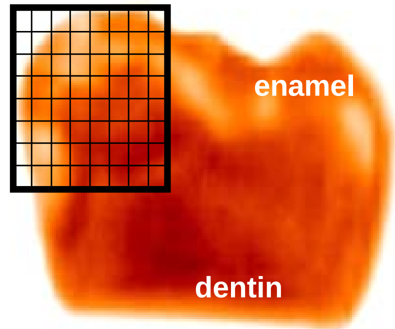


- near-field @ 1 mm
- 200 µm wire cone
- low alpha mode

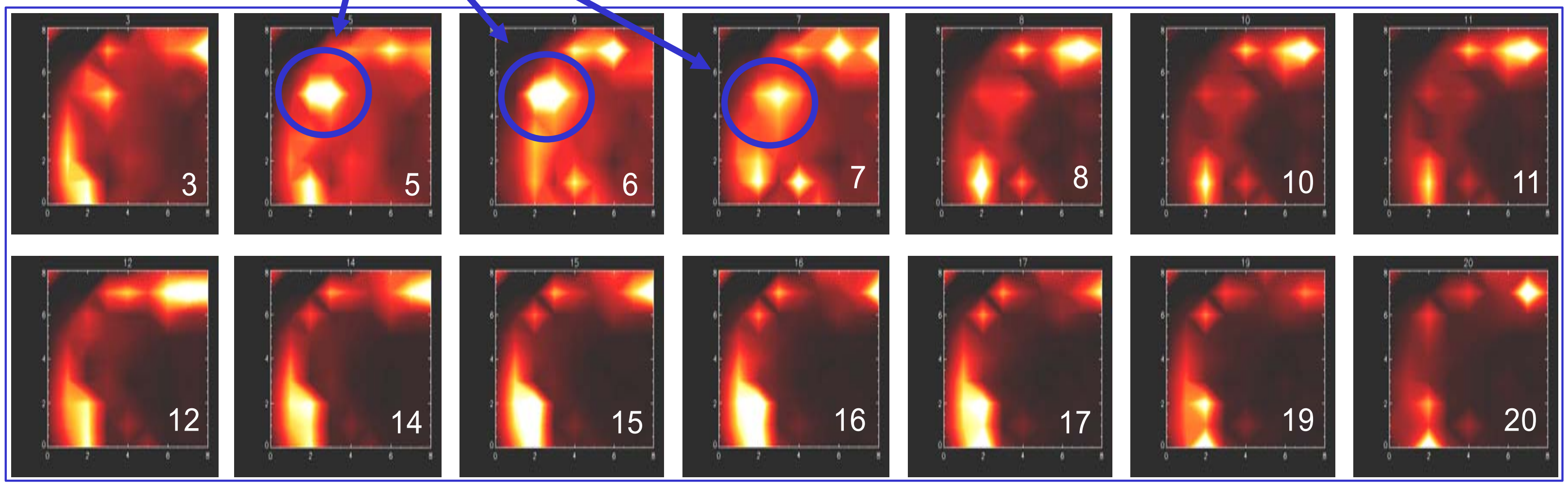
Spectral near-field images of the lesion region between 3 and 20 cm^{-1} (between 0.5 and 3 mm wavelength).

The corresponding wavenumber is indicated on top of each frame. Note that the simulated caries lesion is indicated by a lower absorption between 5 and 7 wavenumbers.





Integral THz Image



U. Schade et al., *Proc. SPIE Vol*. **5725** 46 (2005).

Coherent Synchrotron Radiation from low α operation at BESSY

FIR, low-noise, broadband, steady-state, high power, diffraction limited, polarized, pulsed

New science opportunities by employing FIR diffraction-limited spectromicroscopy

- superconducting gap (B-doped diamond, optimally doped BISCOO 2212)

Development of analytical methods

- near-field spectral imaging of biological and biomedical samples
- waveguide structures
- Martin-Puplett ellipsometer

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Dan Fried	UC SF
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