テラヘルツ放射光利用の現状と大強度CSRテラヘルツ光への期待

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分子科学研究所UVSOR施設

Outline

- Introduction of UVSOR-II
- IR + THz beamline BL6B at UVSOR-II
  - Optics
  - Performance
- Application
  - THz spectroscopy of large samples
  - THz spectroscopy under high pressures
- Development of Coherent SR at UVSOR-II
- CSR-ERL?
- Conclusion and prospects

Collaborators and acknowledgments

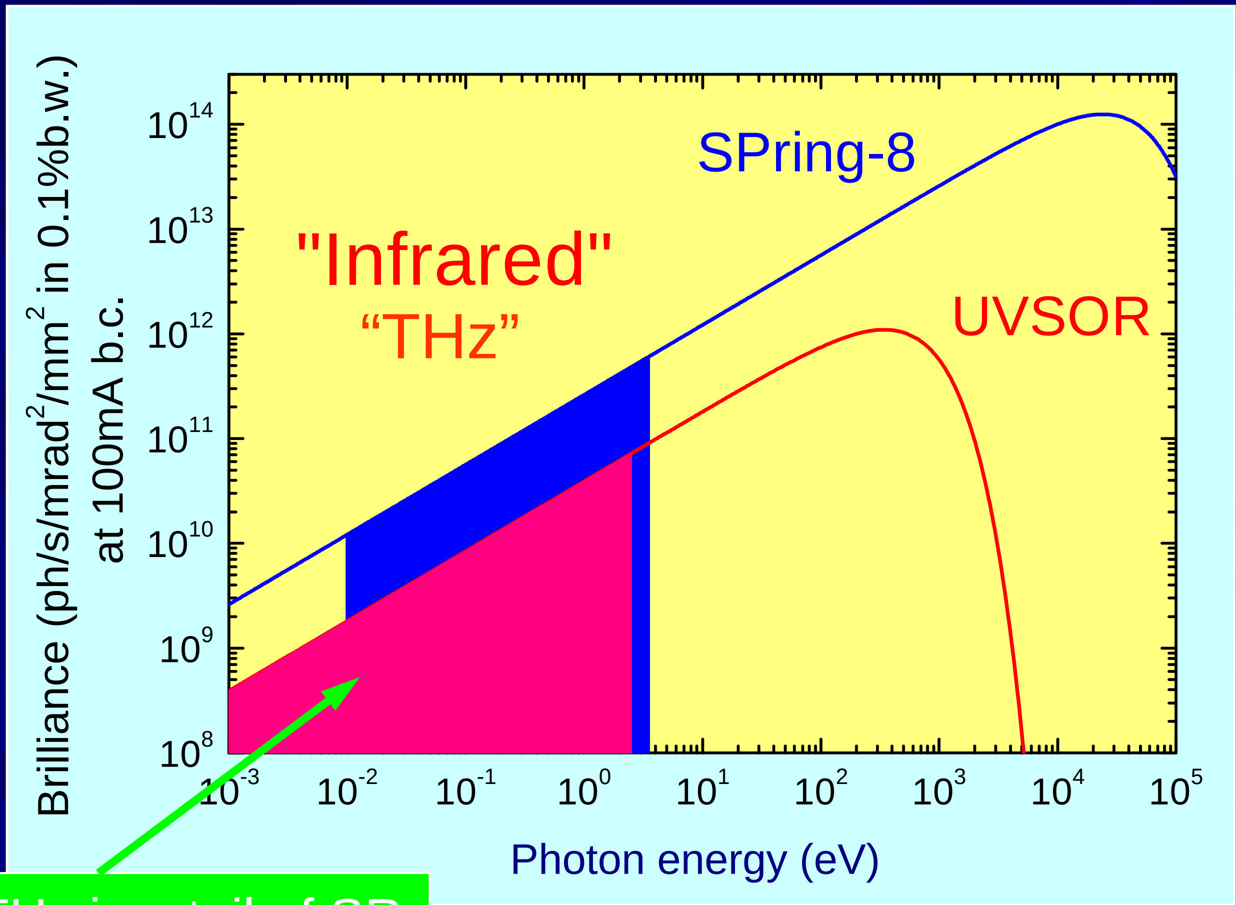
- Experiments
  - Spectroscopy at high pressures
    - T. Mizuno @ SOKENDAI+UVSOR
  - CSR
    - M. Katoh, A. Mochihashi, M. Shimada @ UVSOR
    - M. Hosaka, Y. Takashima @ Nagoya Univ.
    - T. Takahashi @ Kyoto Univ.
- Samples
  - SmS
    - N.K. Sato, K. Matsubayashi @ Nagoya Univ.
  - SmB_6
    - S. Kunii @ Tohoku Univ.

This work was performed at UVSOR and was partially supported by MEXT of Japan.

THz / Wavenumber / Photon energy?

$$1 \text{ THz} = 33 \text{ cm}^{-1} = 4 \text{ meV}$$

What's IR&THz synchrotron radiation?

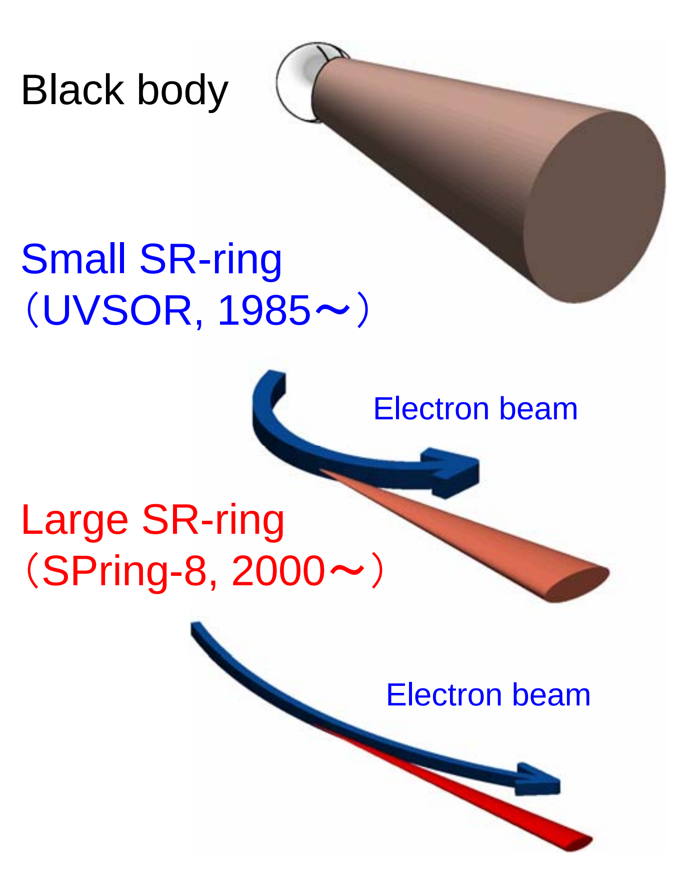


IR+THz is a tail of SR

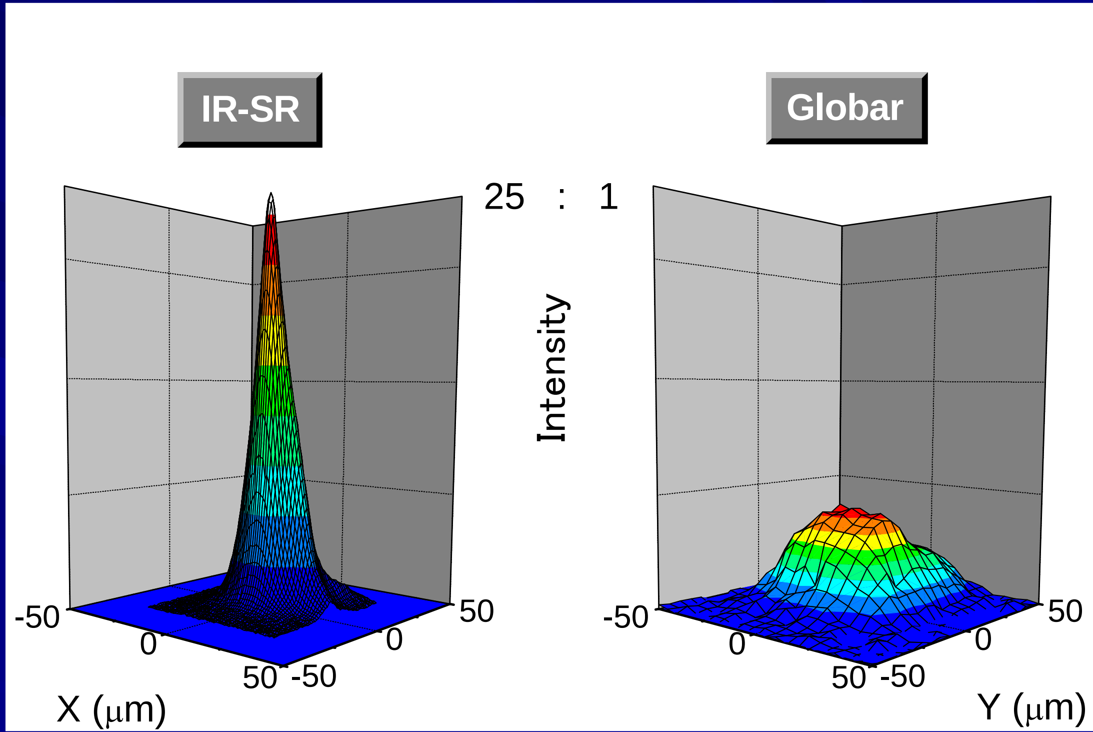
Properties of IR-SR
(compared to other light sources)

- High brilliance
  - For microspectroscopy
- Very broadband
  - For probing electromagnetic dynamics
- Linear / circular polarization
  - For linear / circular dichroism
- Pulse light (sub-nsec - μsec)
  - For time structure experiments

High brilliance property of IR-SR



Focusing at the sample position of IR microspectroscopy station of BL43IR at SPring-8



IR-SR is sharper than BB light source.

Peak intensity of SR is about 10^2 times higher than that of globar source.

IR-SR facilities in the world

Japan	UVSOR	6B	FIR, multipurpose, high pressure (solid state physics)
			MIR, multipurpose, IRMCD (solid state physics)
	SPring-8	43IR	MIR&FIR, microscopy under extreme conditions
			surface science, multipurpose, pump-probe
USA	NSLS	U2A	MIR, microscopy under high pressure (geology)
		U2B	MIR, microscopy for biology
		U4IR	FIR&MIR, surface science
		U10A	MIR, multipurpose (solid state physics)
		U10B	MIR, multipurpose, wide energy range
		U12IR	FIR, pump-probe (solid state physics)
	ALS	1.4.2	MIR, multipurpose, surface science
		1.4.3	MIR, microscopy (biology)
	SRC	031	MIR, microscopy
France	super-ACO	SIRLOIN	MIR, multipurpose
UK	SRS	13.3	FIR&MIR, microscopy, surface science
Sweden	MAX I	073	FIR&MIR, high resolution (gas)
Germany	ANKA		Edge radiation
	BESSY II		MIR, microscopy, CSR
Italy	DAΦNE	SINBAD	MIR, FIR
	Elletra		MIR
Taiwan	SRRC		MIR, microscopy
Switzerland	SLS		MIR&FIR microscopy
	ESRF		MIR, microscopy
Korea PLS, China NSRL,,,			under consideration

Red characters mean FIR is available.

Blue characters mean MIR is only available.

4th International Workshop on

Infrared Microscopy and Spectroscopy with Accelerator Based Sources

Second Announcement

WIRMS 2007

September 25 – 29, 2007
Awaji-Island, Hyogo, Japan

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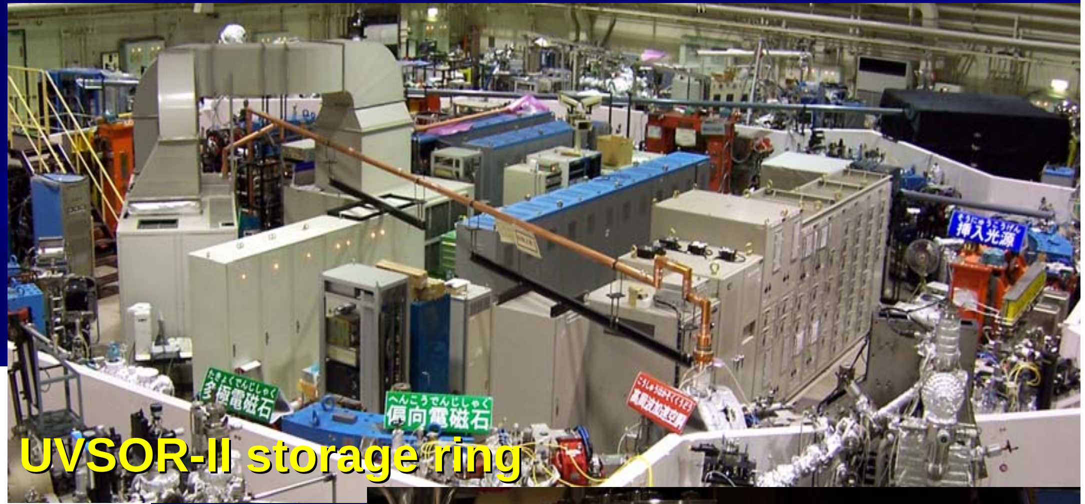
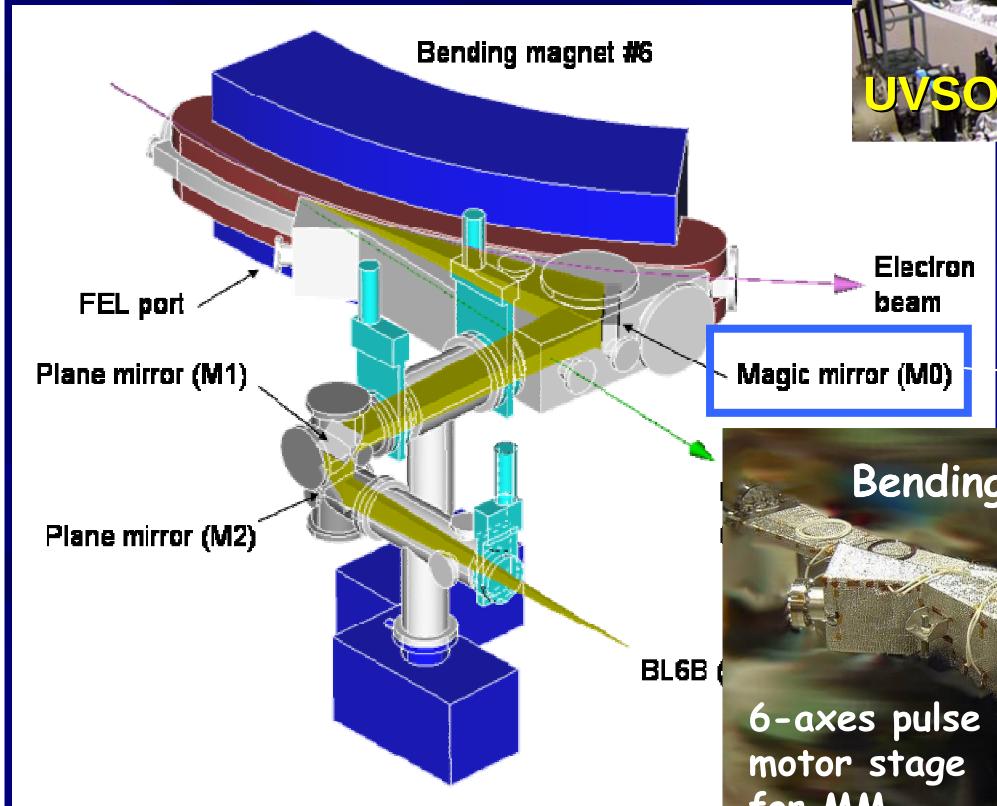
Reconstructed IR+THz beam line（BL6B） at USOR-II (since 2004)

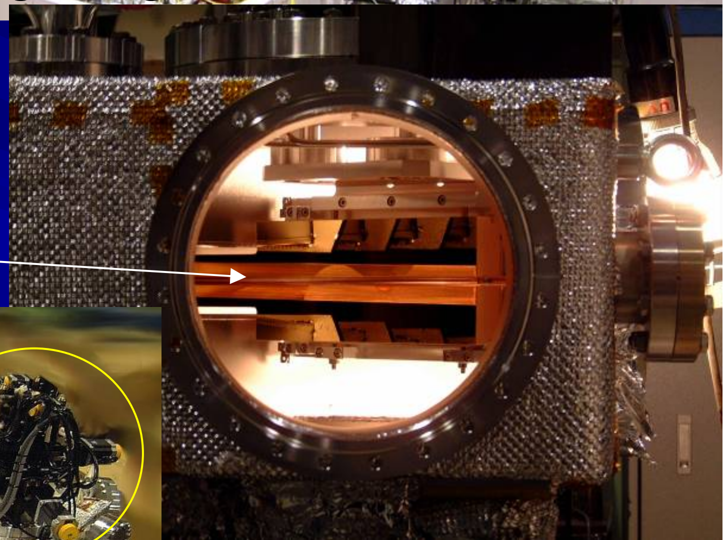
Acceptance angle of SR

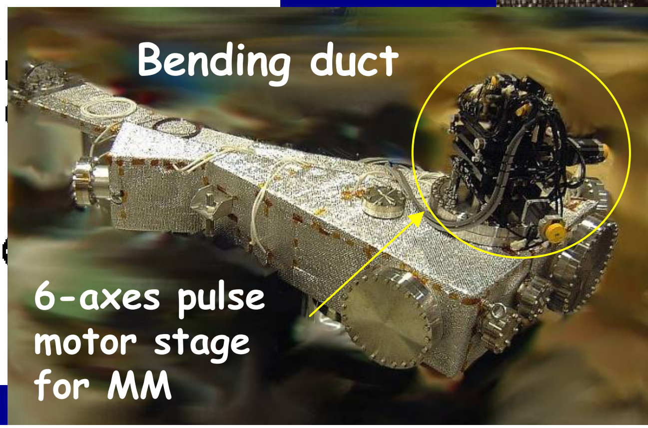
From 80(H) x 60(V) $mrad^2$

To **215(H) x 80(V) $mrad^2$**





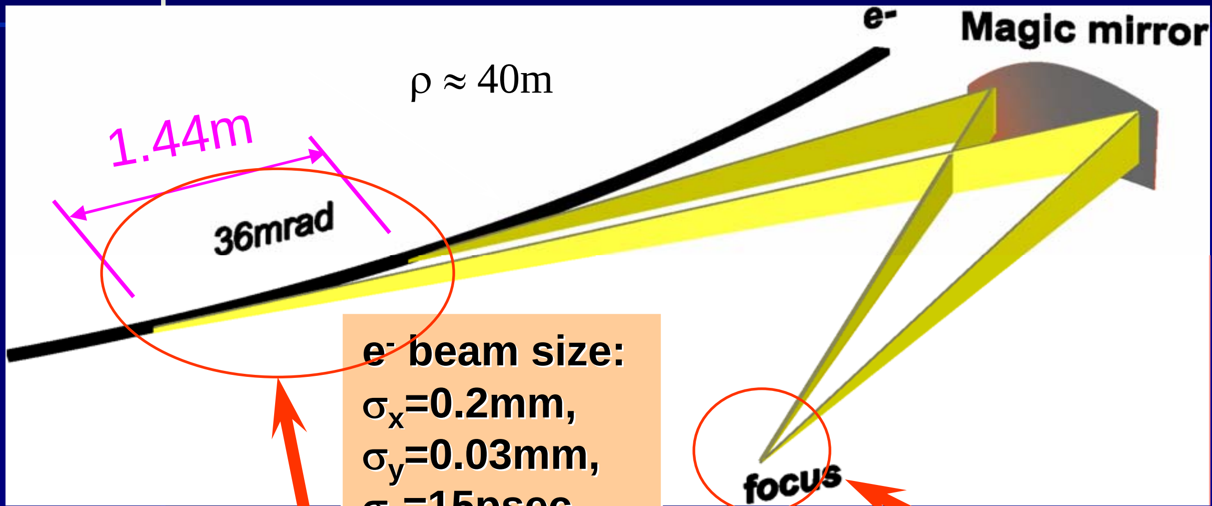


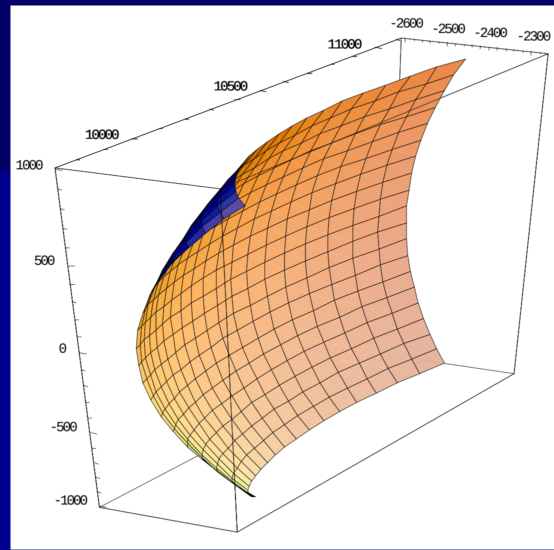


Magic mirror with vertical focusing

S. Kimura et al., NIMA **467-468**, 437 (2001).

cf. R. Lopez-Delgado and H. Szwarc, Opt. Commun. **19**, 286 (1976). ← in an orbital plane





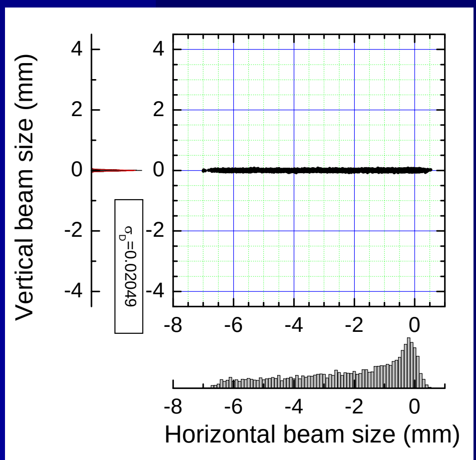
e⁻ beam size:

σ_x=0.2mm,

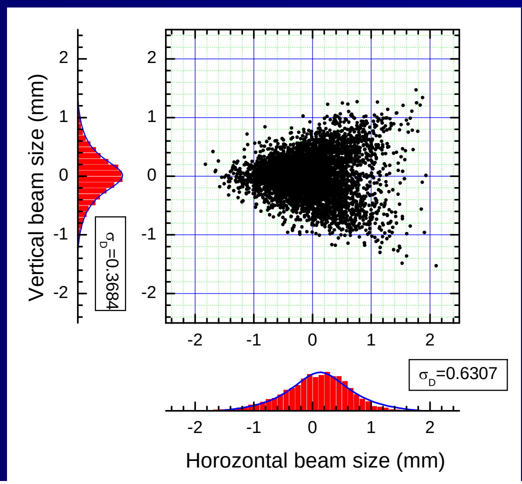
σ_y=0.03mm,

σ_z=15psec

Beam size at emission point



Beam size at focal point (hν~0.5eV)



$$\overline{AM}(\theta) = \frac{\frac{1}{2}\{(d_0 - \rho\theta)^2 - \rho^2 - a^2\} + a\rho\sin\theta}{d_0 - \rho\theta - a\cos\theta},$$

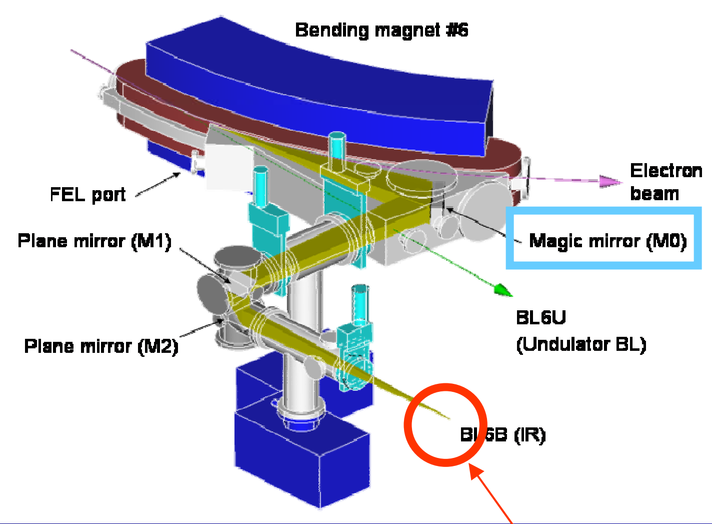
$$\overline{MI}(\theta) = \sqrt{\rho^2 + \overline{AM}(\theta)^2 + a^2 - 2a(\rho\sin\theta + \overline{AM}(\theta)\cos\theta)},$$

$$R(\theta) = \frac{2\overline{AM}(\theta)(d_0 - \rho\theta - \overline{AM}(\theta))}{d_0 - \rho\theta}\cos\left[\frac{1}{2}\cos^{-1}\left(\frac{\overline{AM}(\theta) - a\cos\theta}{\overline{MI}(\theta)}\right)\right],$$

and

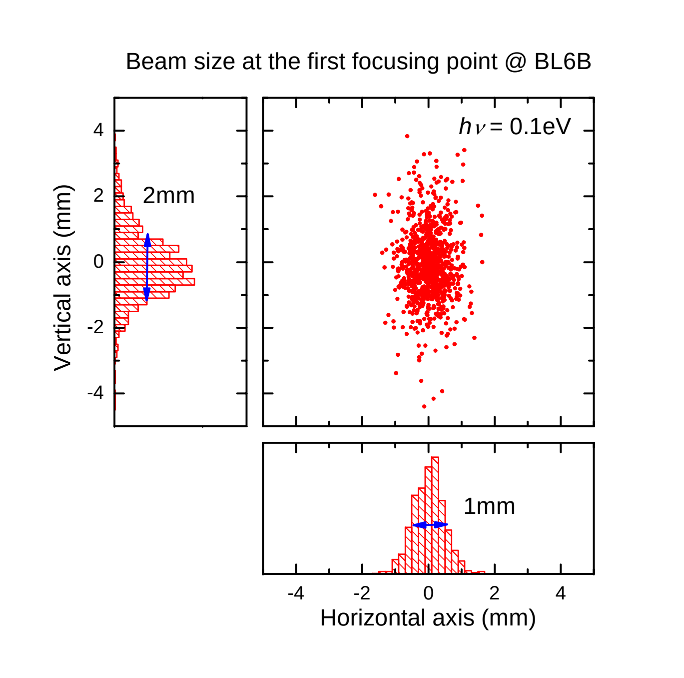
$$M\begin{cases} x(\theta, v) = \rho\cos\theta - \overline{AM}(\theta)\sin\theta + \dfrac{|R(\theta)|\{\sin\theta - (\rho\cos\theta - \overline{AM}(\theta)\sin\theta)/\overline{MI}(\theta)\}}{\sqrt{2 + 2(\overline{AM}(\theta) - a\cos\theta)/\overline{MI}(\theta)}} \\ \qquad \times\left\{1 - \cos\left(\tan^{-1}\dfrac{v}{R(\theta)}\right)\right\}, \\ y(\theta, v) = \rho\sin\theta + \overline{AM}(\theta)\cos\theta + \dfrac{|R(\theta)|\{-\cos\theta + (a - \rho\sin\theta - \overline{AM}(\theta)\cos\theta)/\overline{MI}(\theta)}{\sqrt{2 + 2(\overline{AM}(\theta) - a\cos\theta)/\overline{MI}(\theta)}} \\ \qquad \times\left\{1 - \cos\left(\tan^{-1}\dfrac{v}{R(\theta)}\right)\right\}, \\ z(\theta, v) = R(\theta)\sin\left(\tan^{-1}\dfrac{v}{R(\theta)}\right). \end{cases}$$

Beam size at the first focal point of BL6B

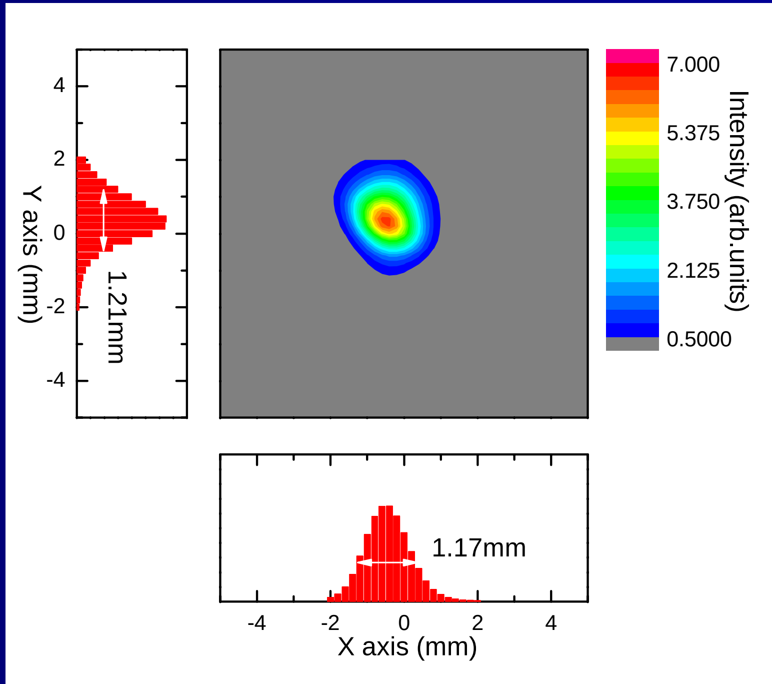


Here !

Calculation
($h\nu$=0.1eV)



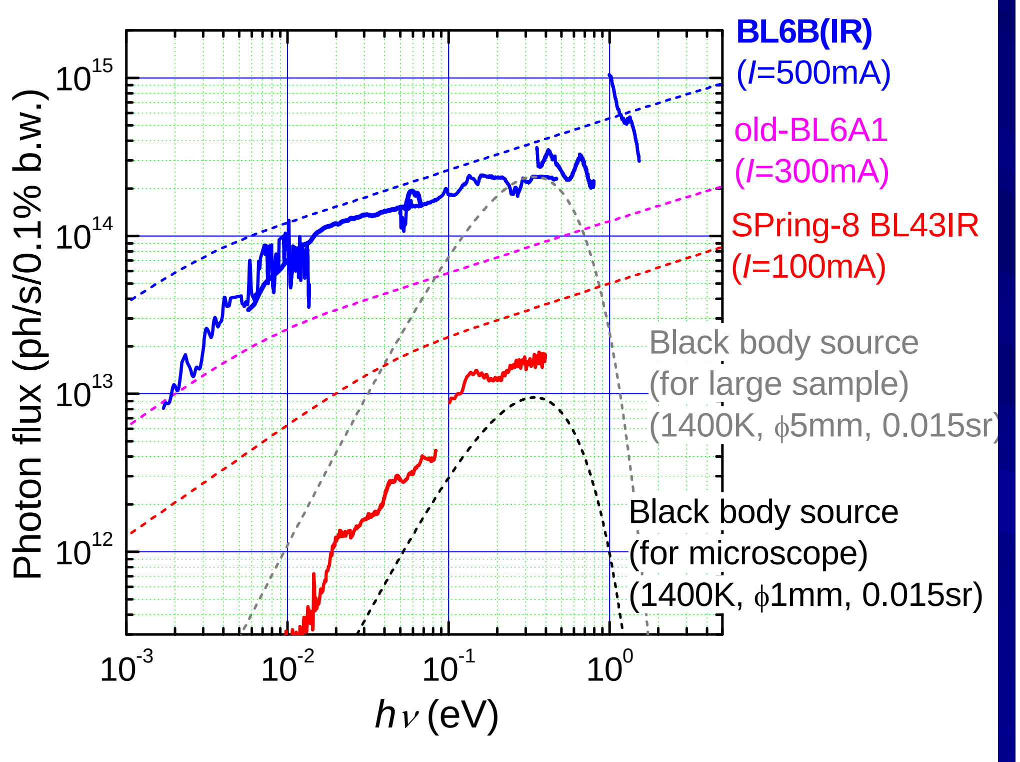
Experiment
($h\nu$=0.1~1eV)



Photon flux and brilliance

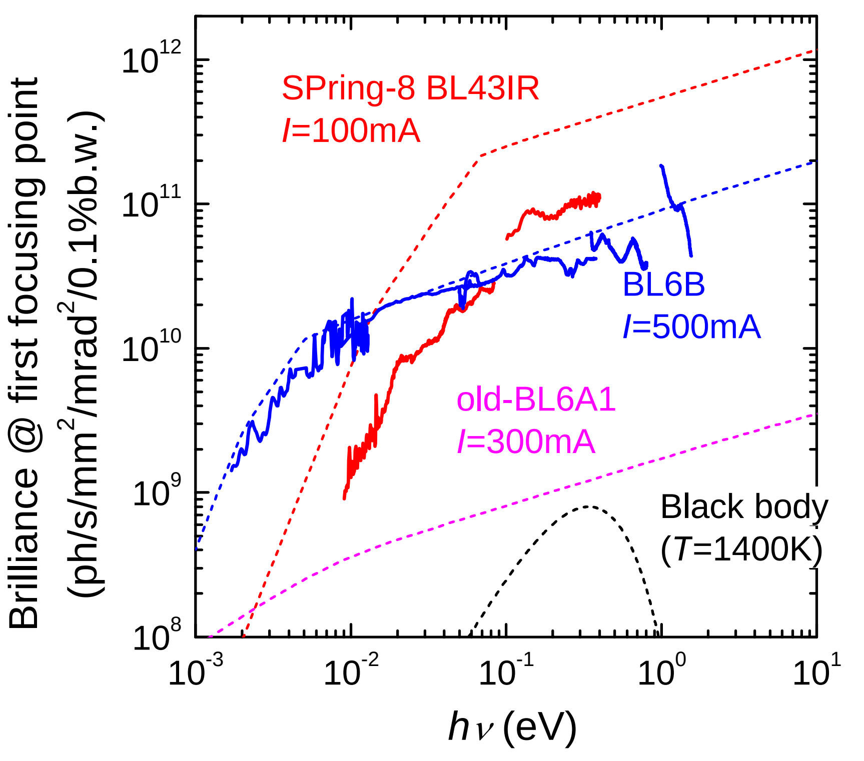
Photon flux

(due to large acceptance angle)



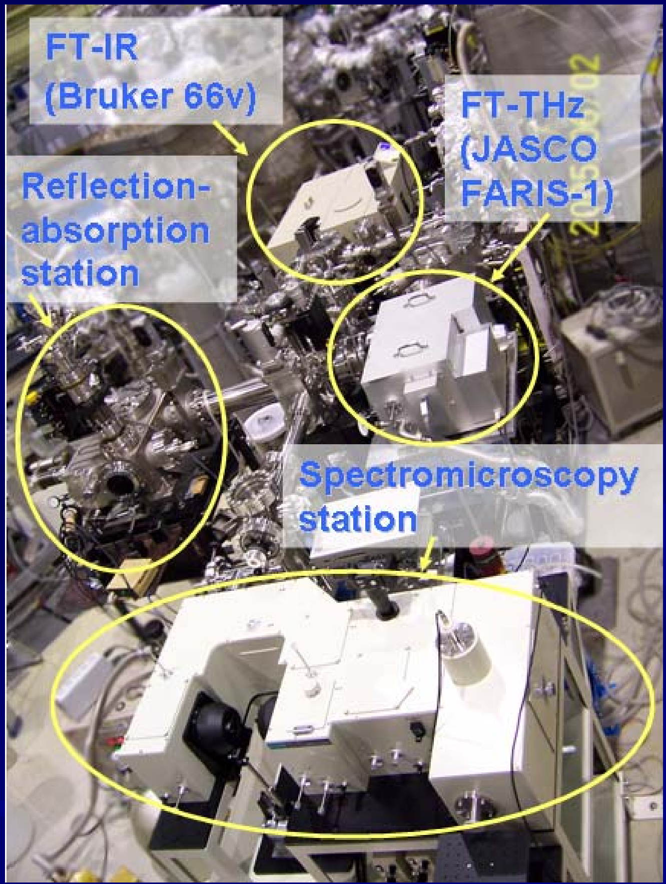
Brilliance

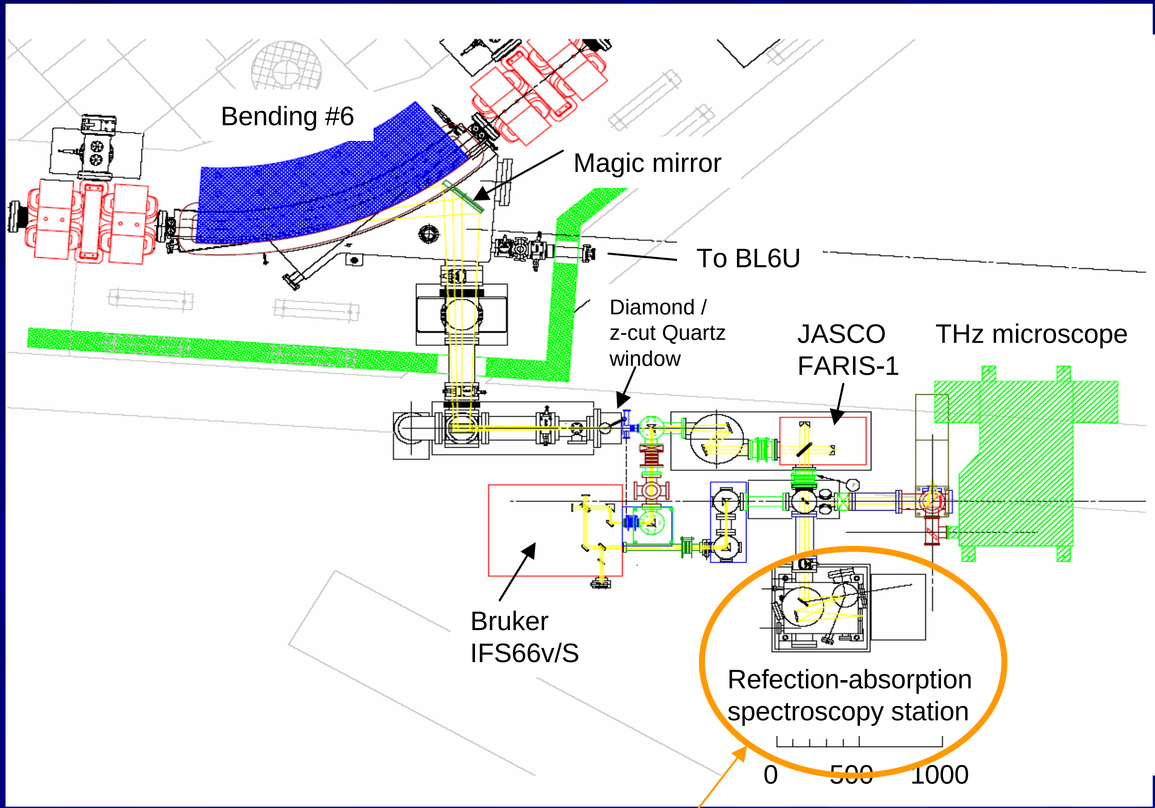
(performance of the magic mirror)



Si bolometer saturates in a multi-bunch operation !

End stations of BL6B at USOR-II





This chamber can be removed for the other experiments (IR-MCD, FIR-RAS and so on).

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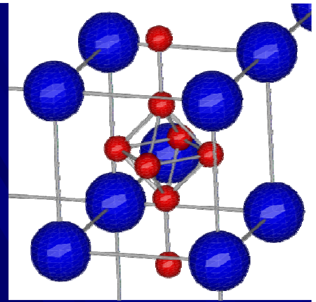
Physical properties of SmB_6



XPS ($I(Sm^{2+})$:$I(Sm^{3+})$=3:7)

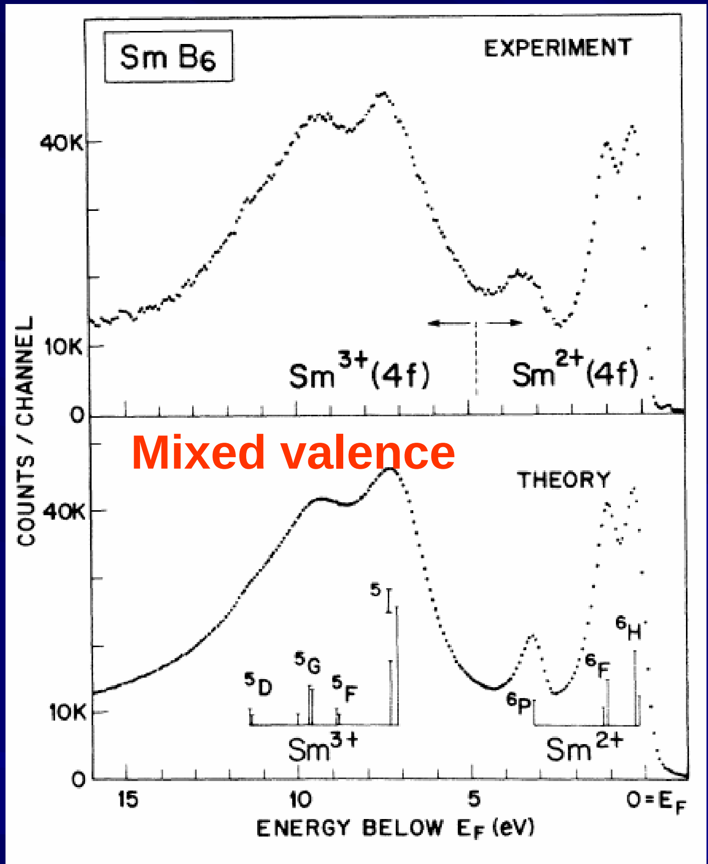


FIG. 2. Upper curve: difference curve of the data of Fig. 1; below: theoretical curve calculated using the intensity of final-state multiplets after Cox, Ref. 16.

[J.-N. Chazalviel et al.,

Phys. Rev. B 14, 4586 (1976).]

Electrical resistivity

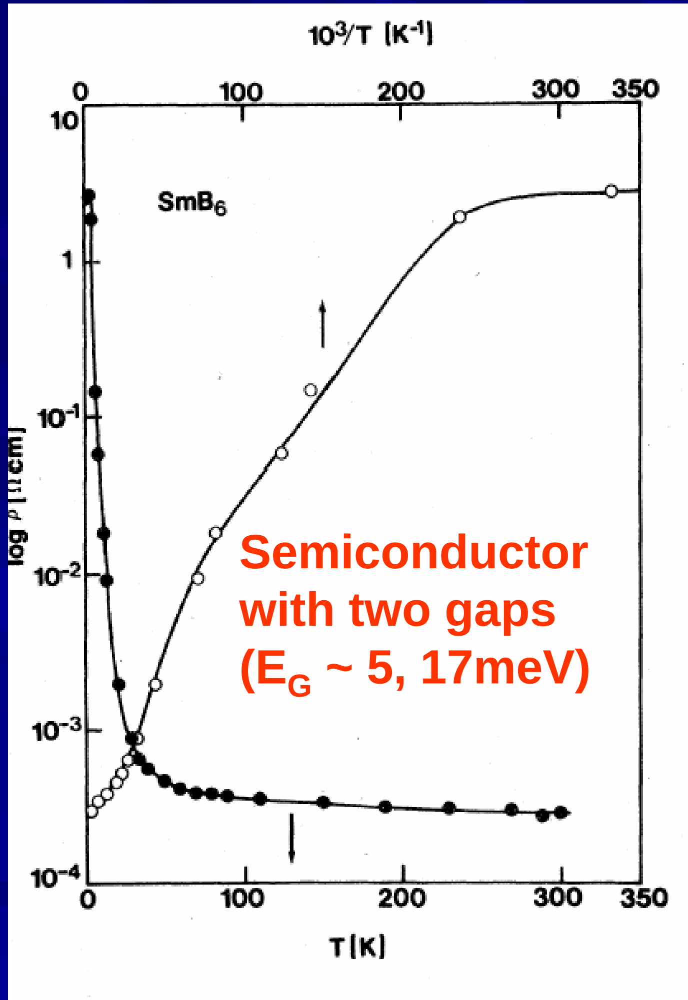


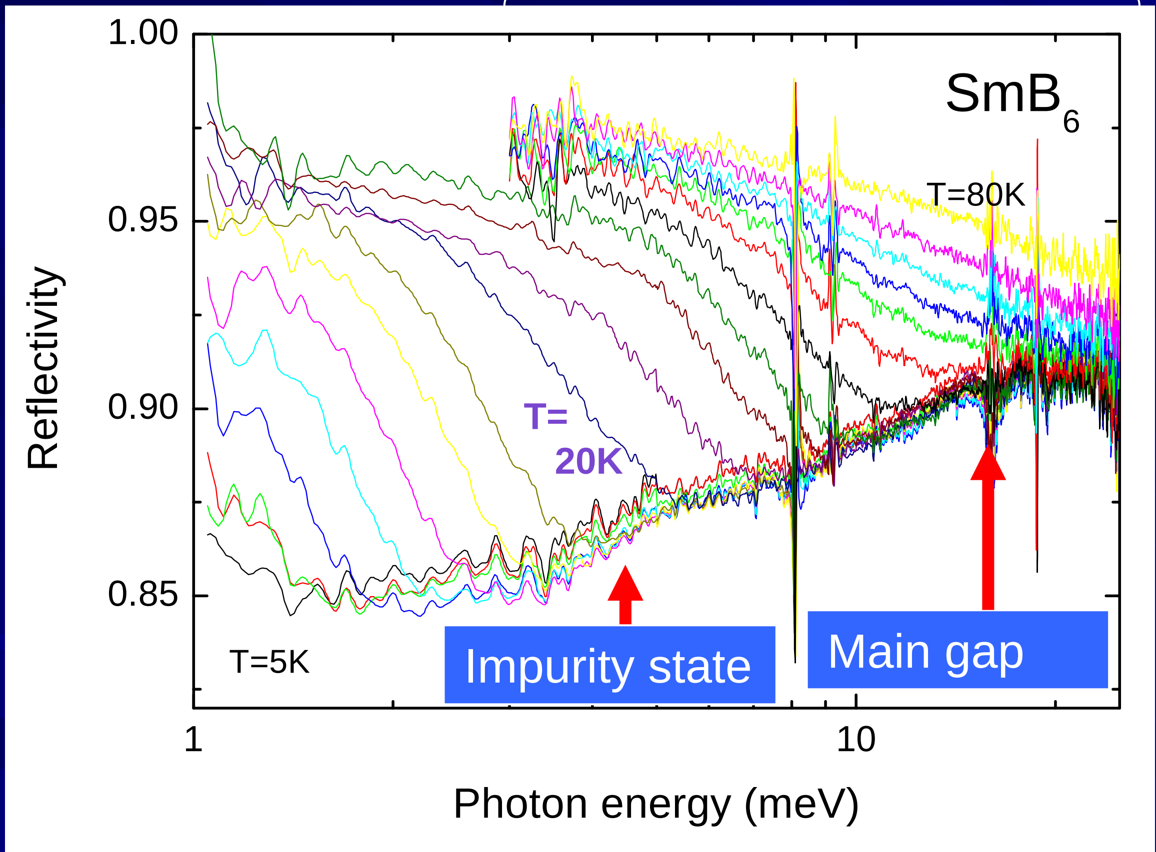
FIG. 1. Temperature dependence of resistivity of SmB_6.

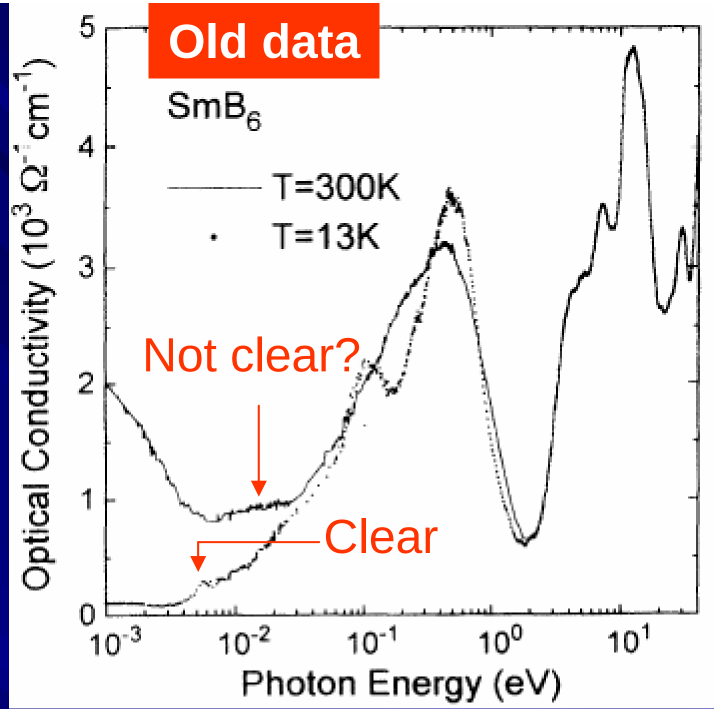
[J. W. Allen, B. Batlogg, and P. Wachter,
Phys. Rev. B **20**, 4807 (1979).]

Hot carriers in SmB_6

BL6B (UVSOR-II)

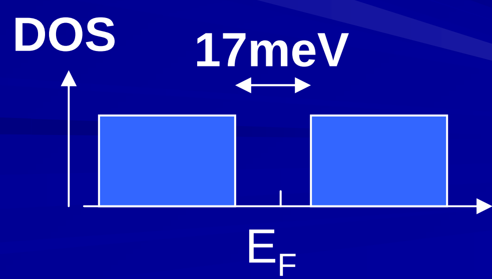
In Lab. (mercury lamp)





[S. K. et al., Phys. Rev. B **50**, 1406 (1994).]

Large spectral change is due to the thermally excited carriers across the small energy gap.



THz spectroscopy under pressures

Microscope

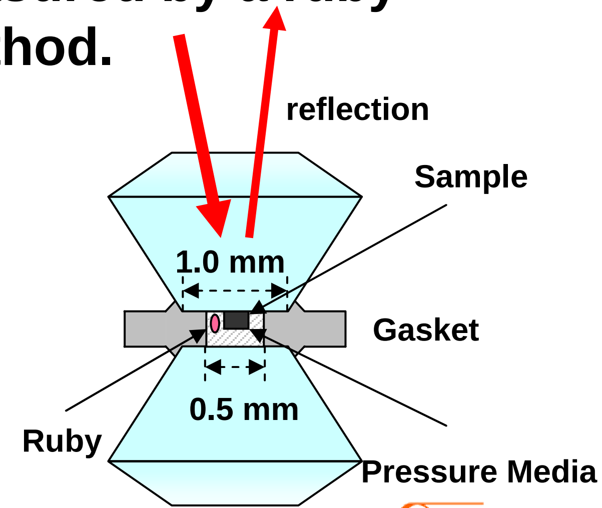
- Horizontal optical pass
- Energy range
  - Laboratory: 50 meV ～ 1.2 eV
  - UVSOR-II BL6B: 5 meV ～ 50 meV

Microsope @ BL6B

Diamond anvil pressure cell

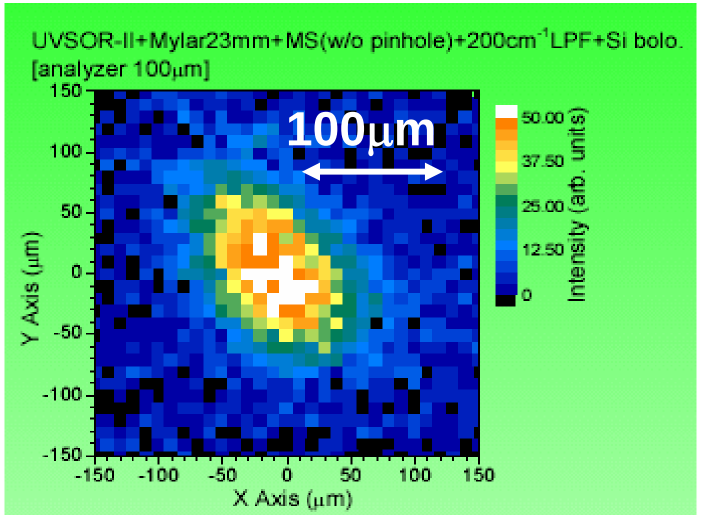
- Pressure media：Apiezon grease N
- Pressure is measured by a ruby fluorecence method.

Diamond anvil cell



DAC

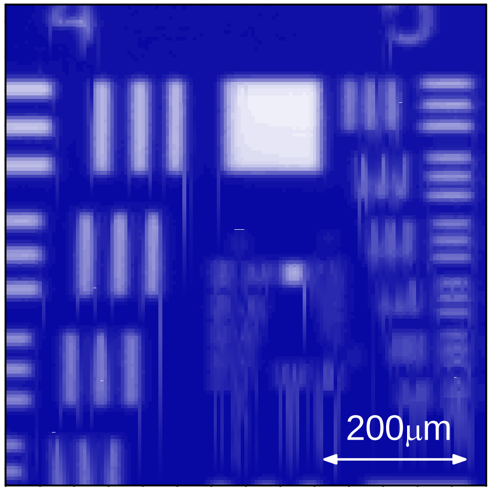
Spatial resolution of microscope in the THz region at BL6B



Spatial resolution of THz microscope at BL6B of UVSOR-II

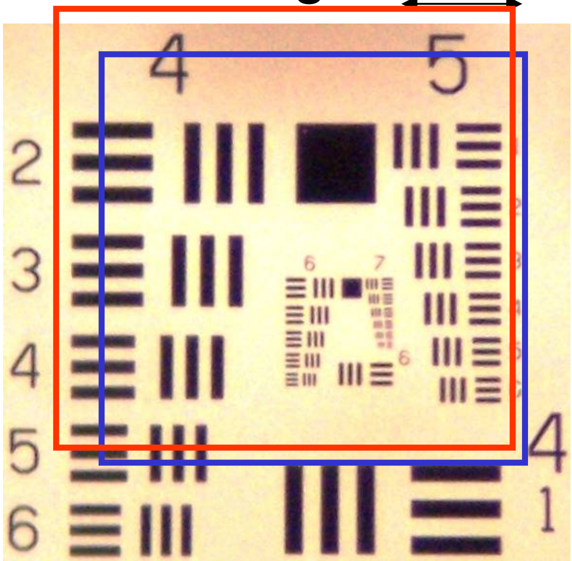
MIR

UVSOR-II
+ Ge/KBr
+MCT
(500-8000cm^{-1})



$\Delta r \sim 12\ \mu m$

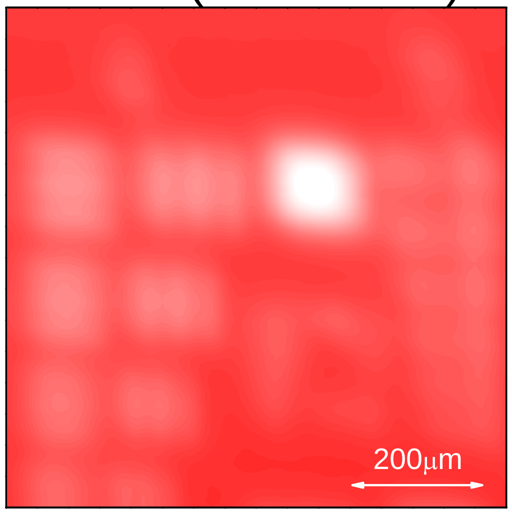
Visible image 200μm



USAF test target

FIR (THz)

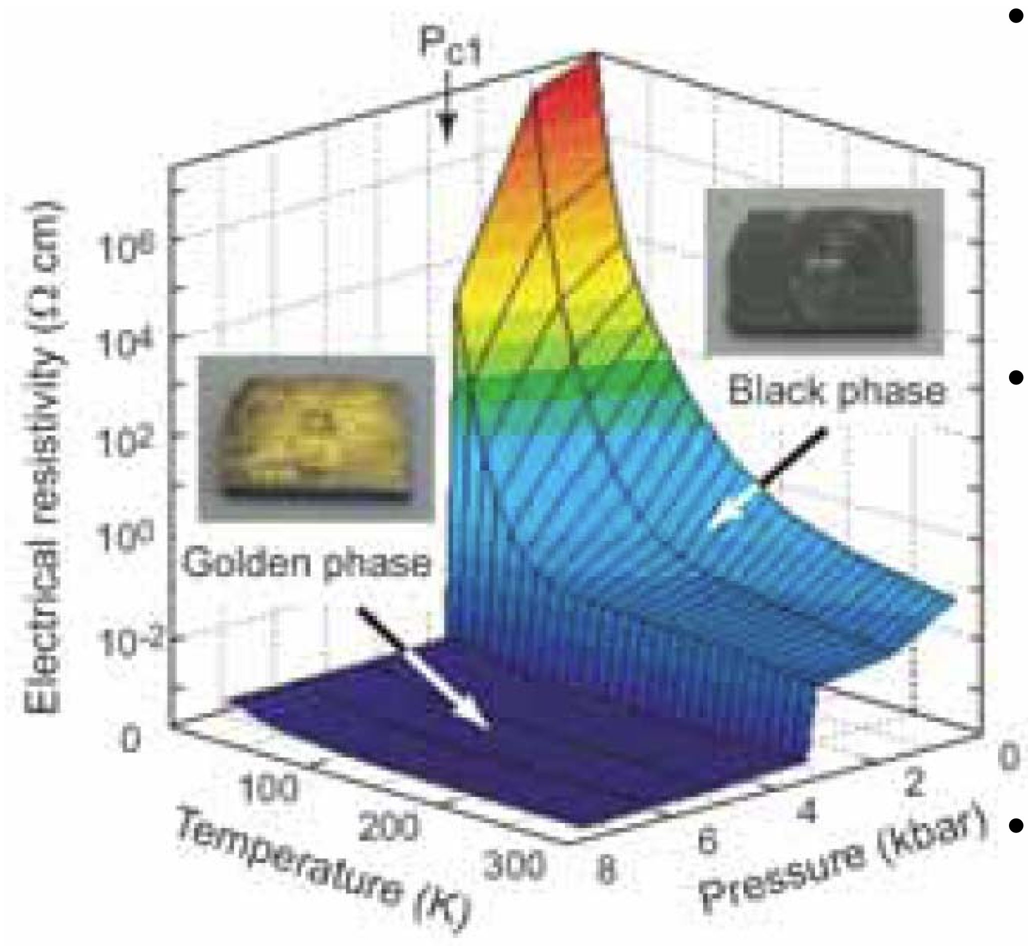
UVSOR-II
+ Mylar6μ
+Si bolo.
(50-600cm^{-1})



$\Delta r \sim 60\ \mu m$

Physical properties of SmS

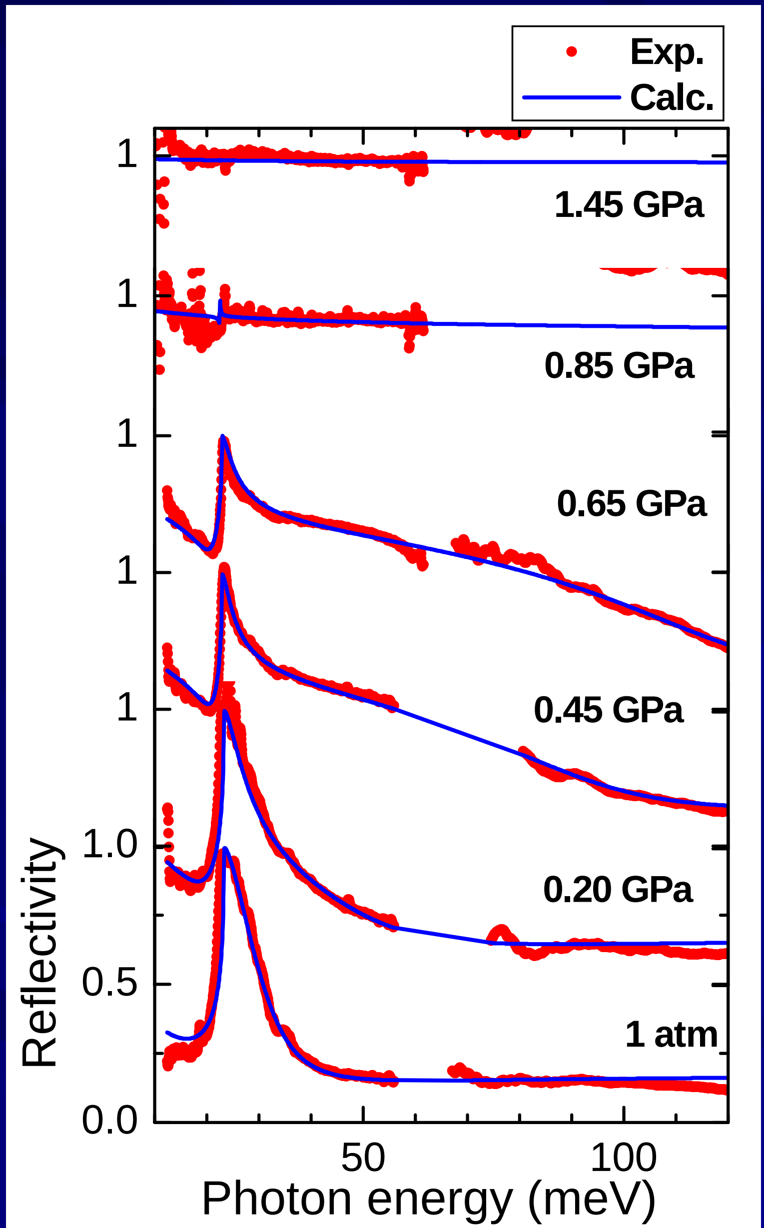
NaCl-type crystal structure

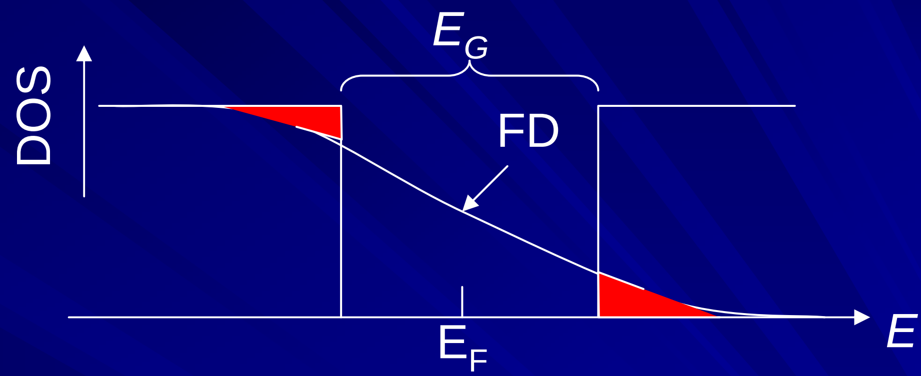


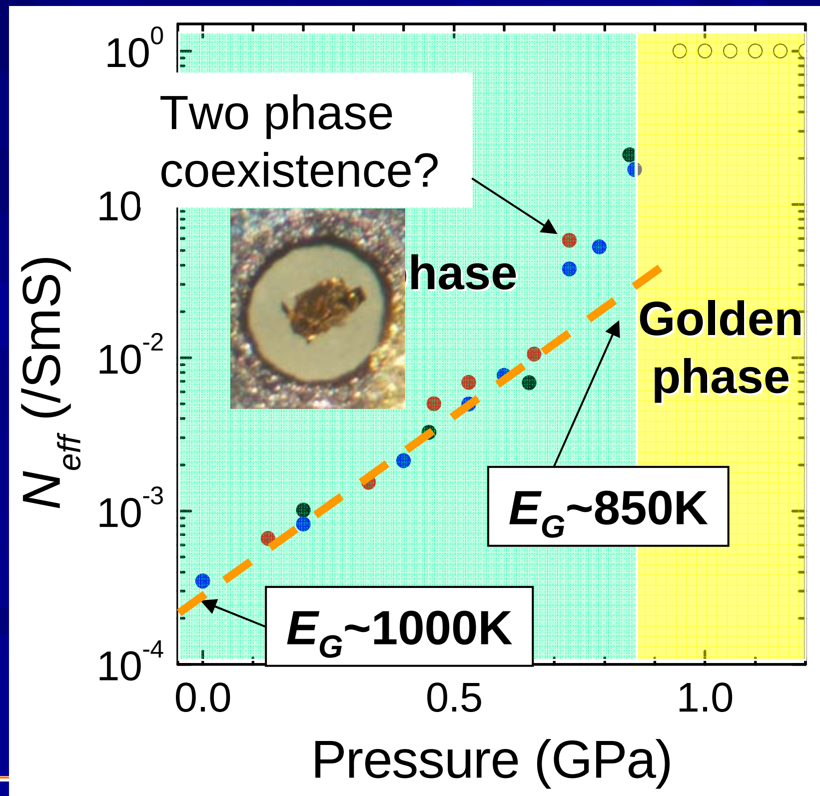
- P < 0.6 ~ 0.8 GPa:
  - •Black phase
  - •Semiconductor
    - •E_G~10^3 K ~ 86 meV
  - •Ionic crystal with Sm^{2+}
- P < 1.9 GPa
  - •Golden phase
  - •Strongly correlated semiconductor
    - •E_G~100 K ~ 9 meV
  - •Mixed valence of Sm^{2+} and Sm^{3+}
- P > 1.9 GPa
  - •Magnetic metal with Sm^{3+}

Pressure dependence of $R(\omega)$ in SmS

[T. Mizuno et al., in preparation.]

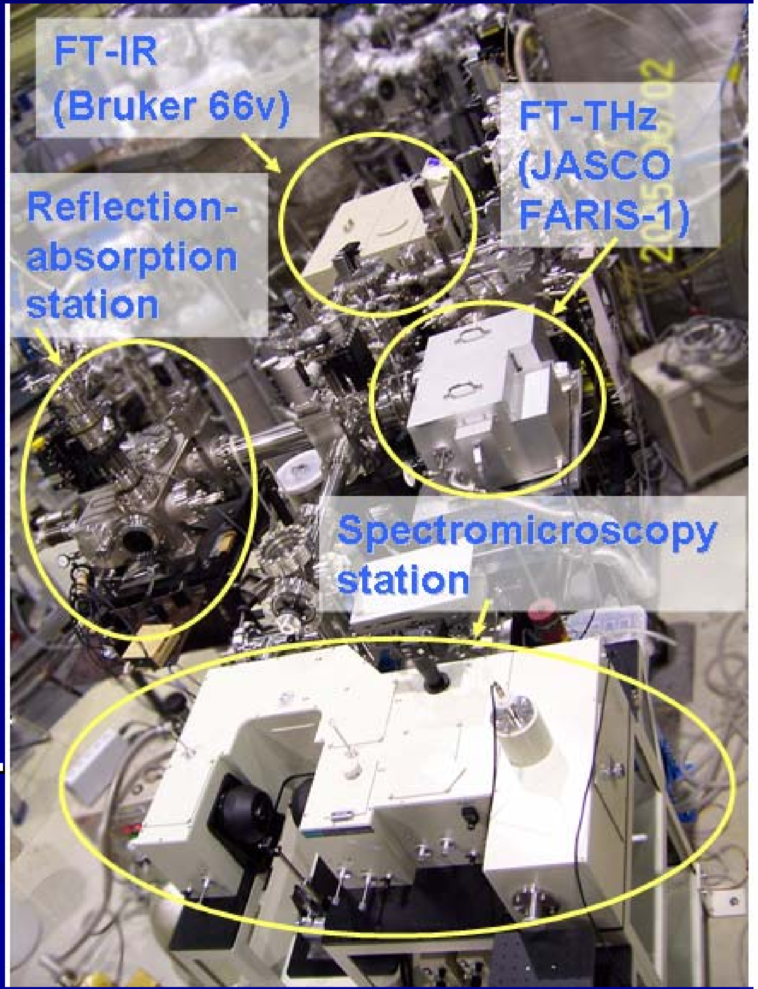






Scientific program at UVSOR-II BL6B

- Electrodynamics of solids @ multi-extreme conditions
  - Very low temperature (~0.4K)
  - High pressures (~20GPa)
  - High fields (~6T)
- THz microspectroscopy
- FIR-RAS of adsorbed molecules
- THz spectroscopy of protains
- THz excitation with coherent SR.
  - 10^3~10^4 higher intensity than the present IRSR.



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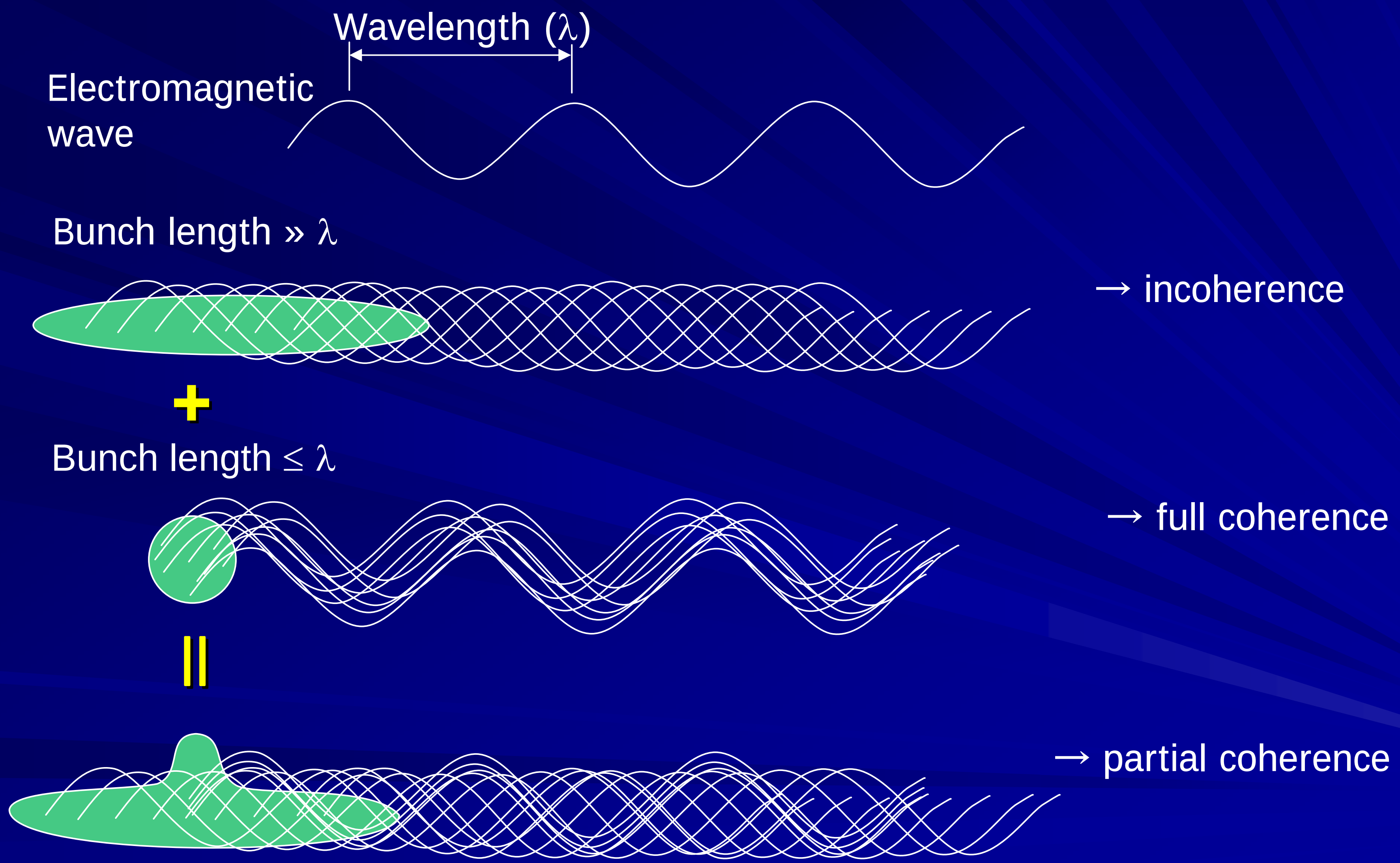
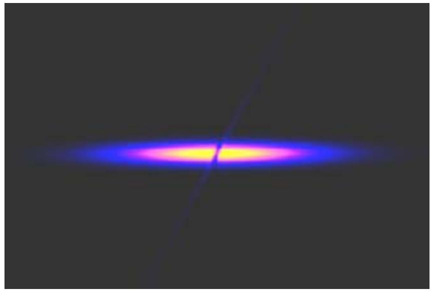
CSR from relativistic electron beam

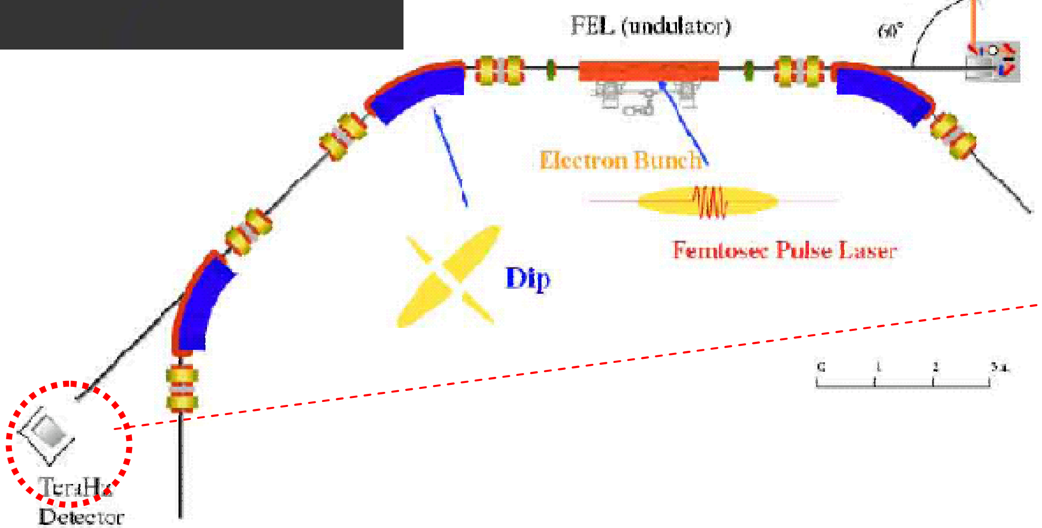


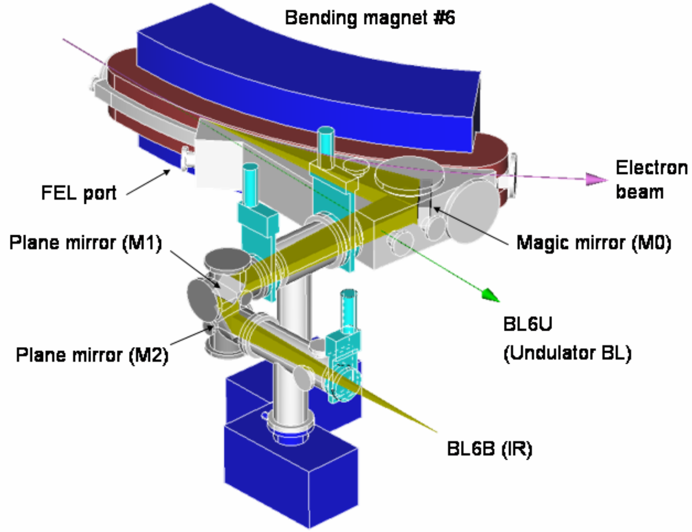
How can we make fine structures in electron bunches?

- Spontaneous electron bunch instability.
  - **Bursting mode.**
- Modulation induced by extra electric fields.
  - **Bunch slicing by short-pulse laser.**

Coherent Terahertz Pulses by Bunch Slicing

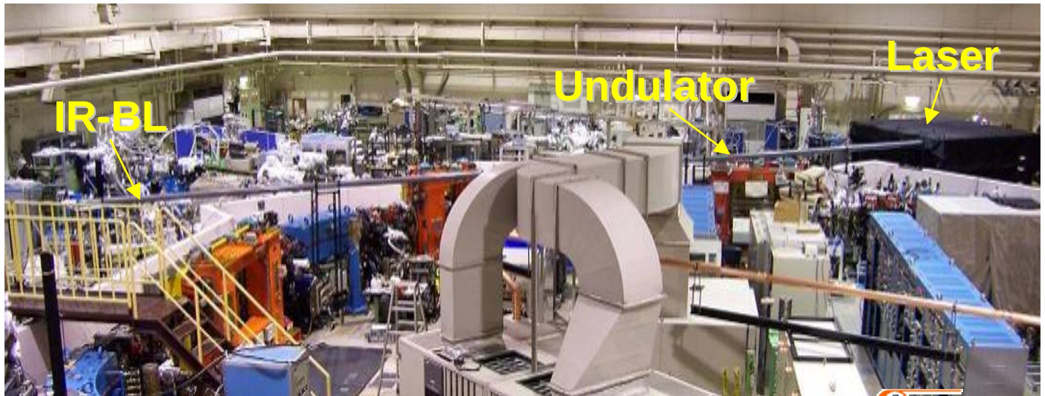


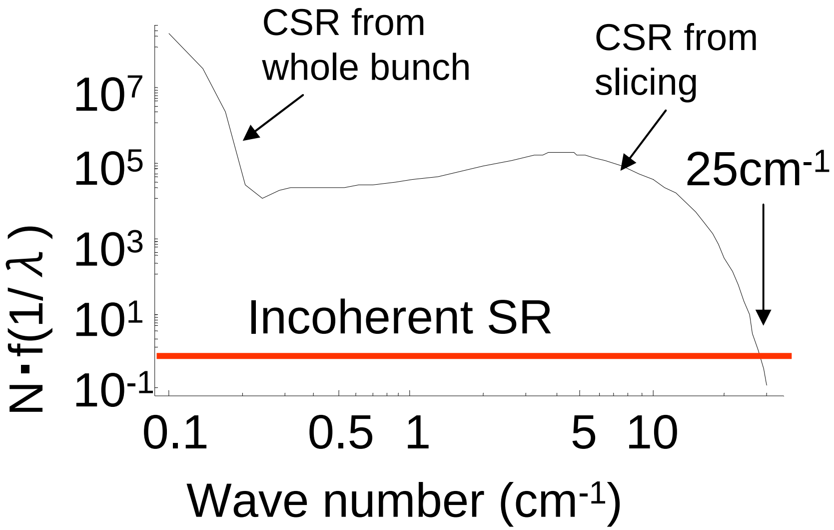




UVSOR-BL6B IR Beamline

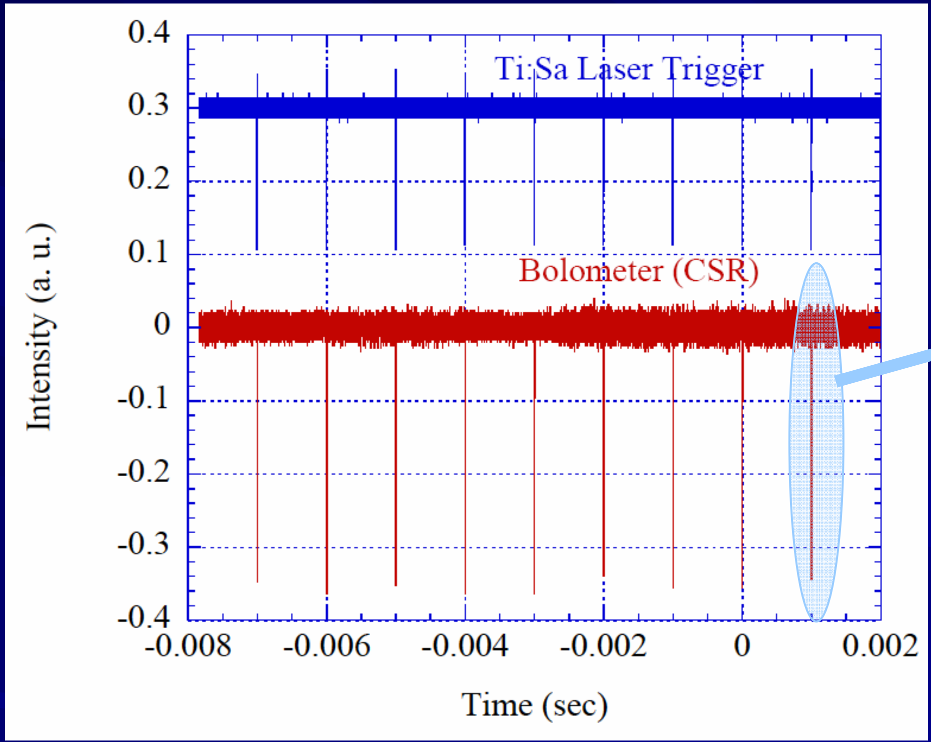
(S. Kimura et al., AIP Conf. Proc. 705 (2003),

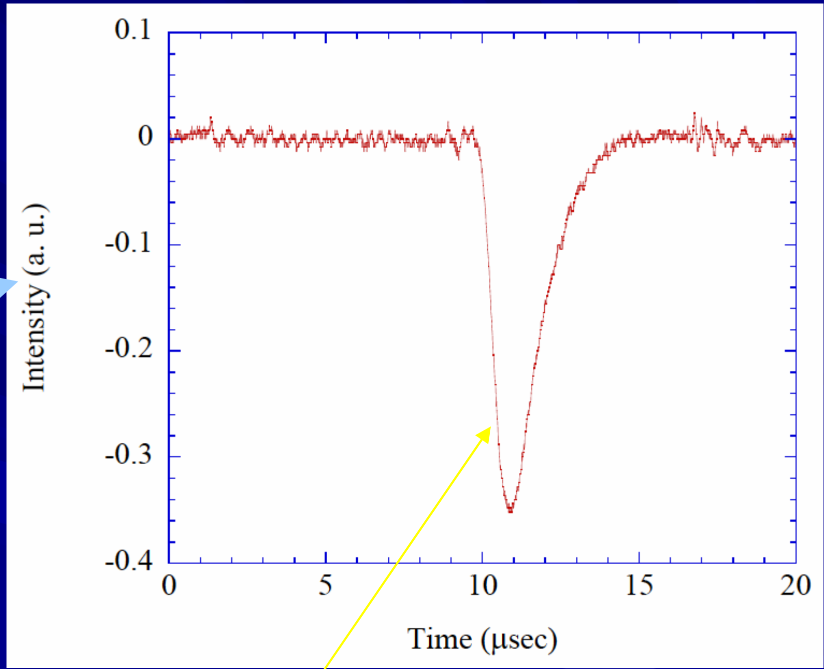




Coherent Terahertz Pulses by Bunch Slicing

[M. Katoh et al., Proc. EPAC06, 3377 (2006).]



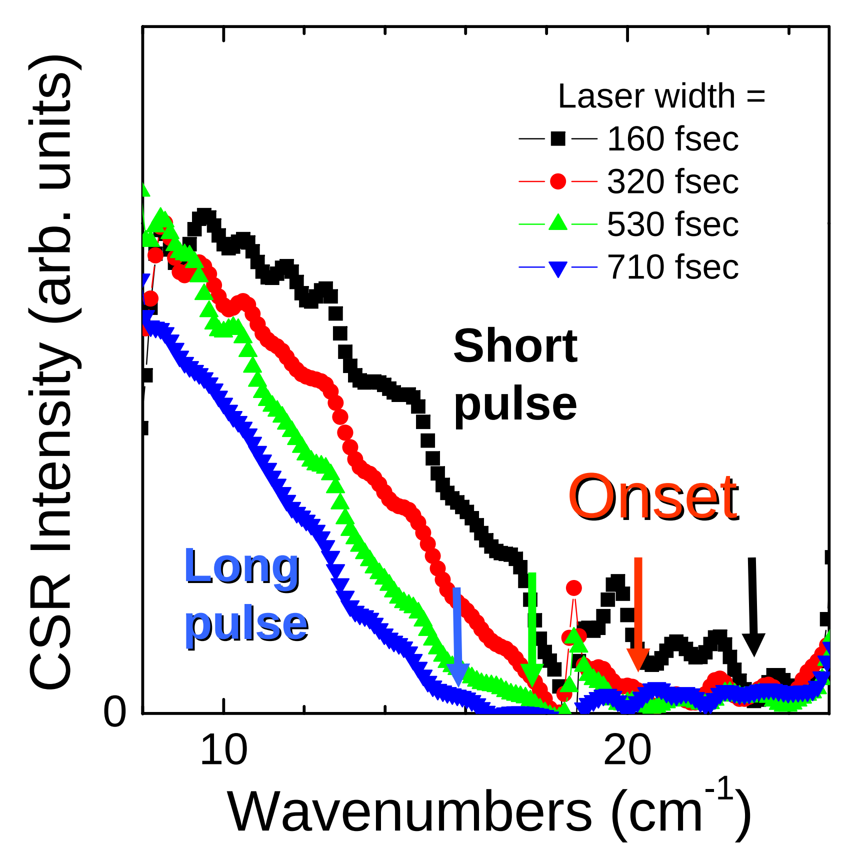


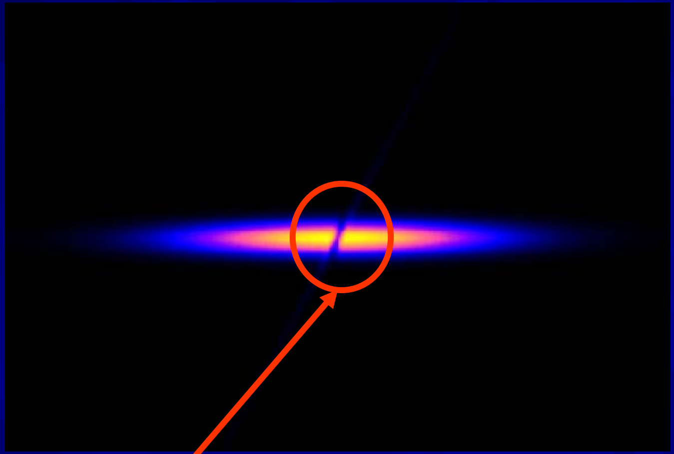
Stable and periodic.

The width originates from the InSb hot electron detector response.

Laser width dependence of CSR spectrum

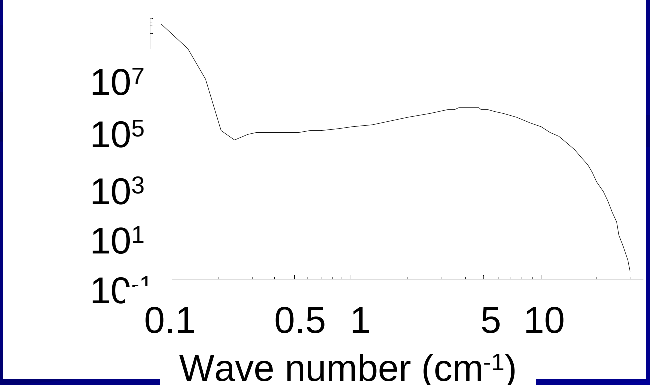
[M. Katoh et al., Proc. EPAC06, 3377 (2006).]





The dip is made by laser.

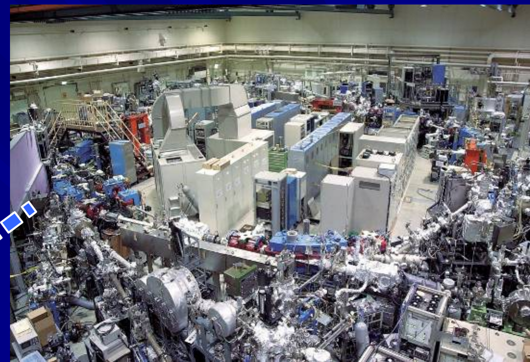
Onset shifts to the lower wavenumber side with increasing pulse width.



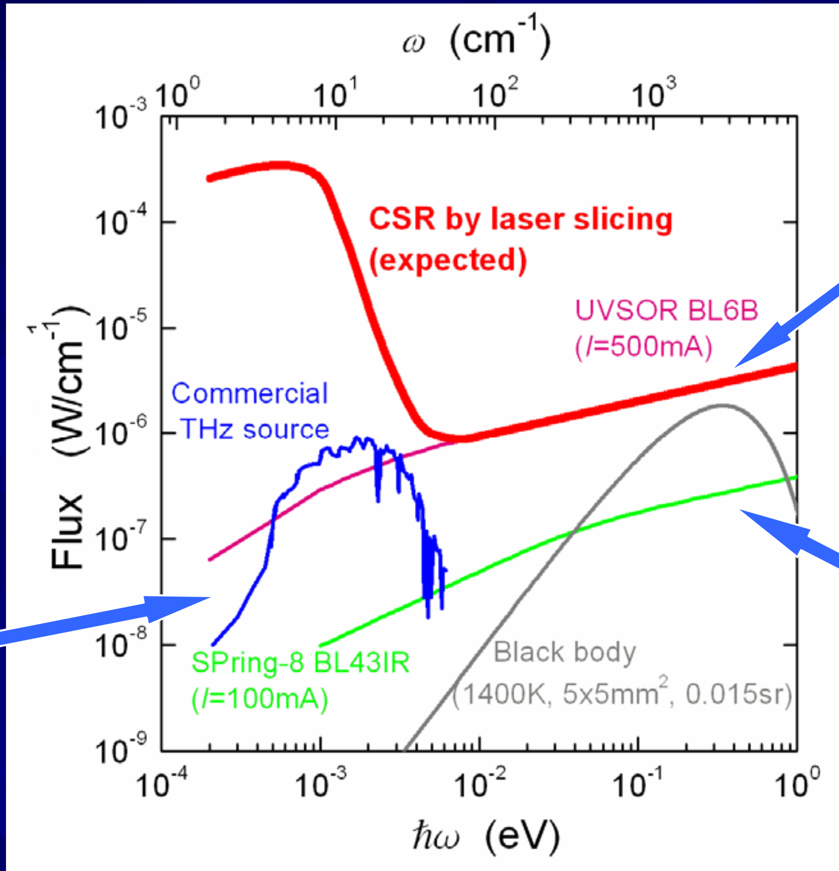
This is the evidence of the CSR originates from the dip induced by laser.

Average power of CSR

UVSOR-II BL6B



Commercial THz source



SPring-8 BL43IR

CSRの利用研究 @ BESSY-II

サブテラヘルツの大強度を利用

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

Observations in the THz Gap: The Josephson-Plasma Resonance of $Bi_2Sr_2CaCu_2O_8$

E.J. Singley[1], M. Abo-Bakr[2], D.N: Basov[3], J. Feikes[2], K. Holldack[2], H.-W. Hübers[4], P. Kuske[2], M. C. Martin[1], W.B. Peatman[2], U. Schade[2], G. Wüstefeld[2]

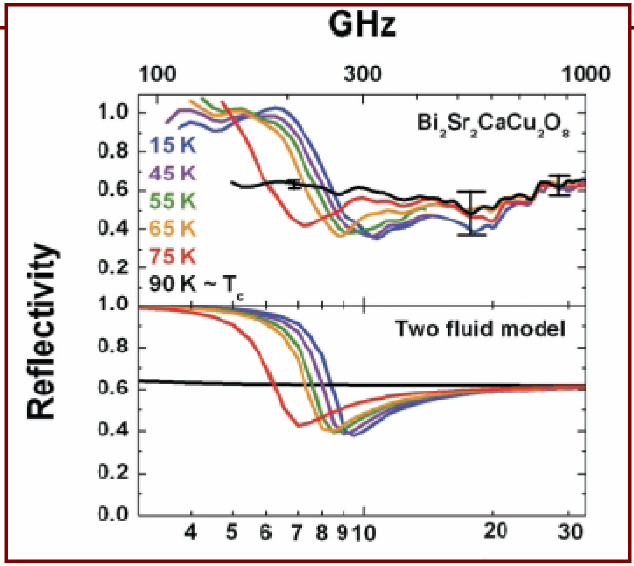
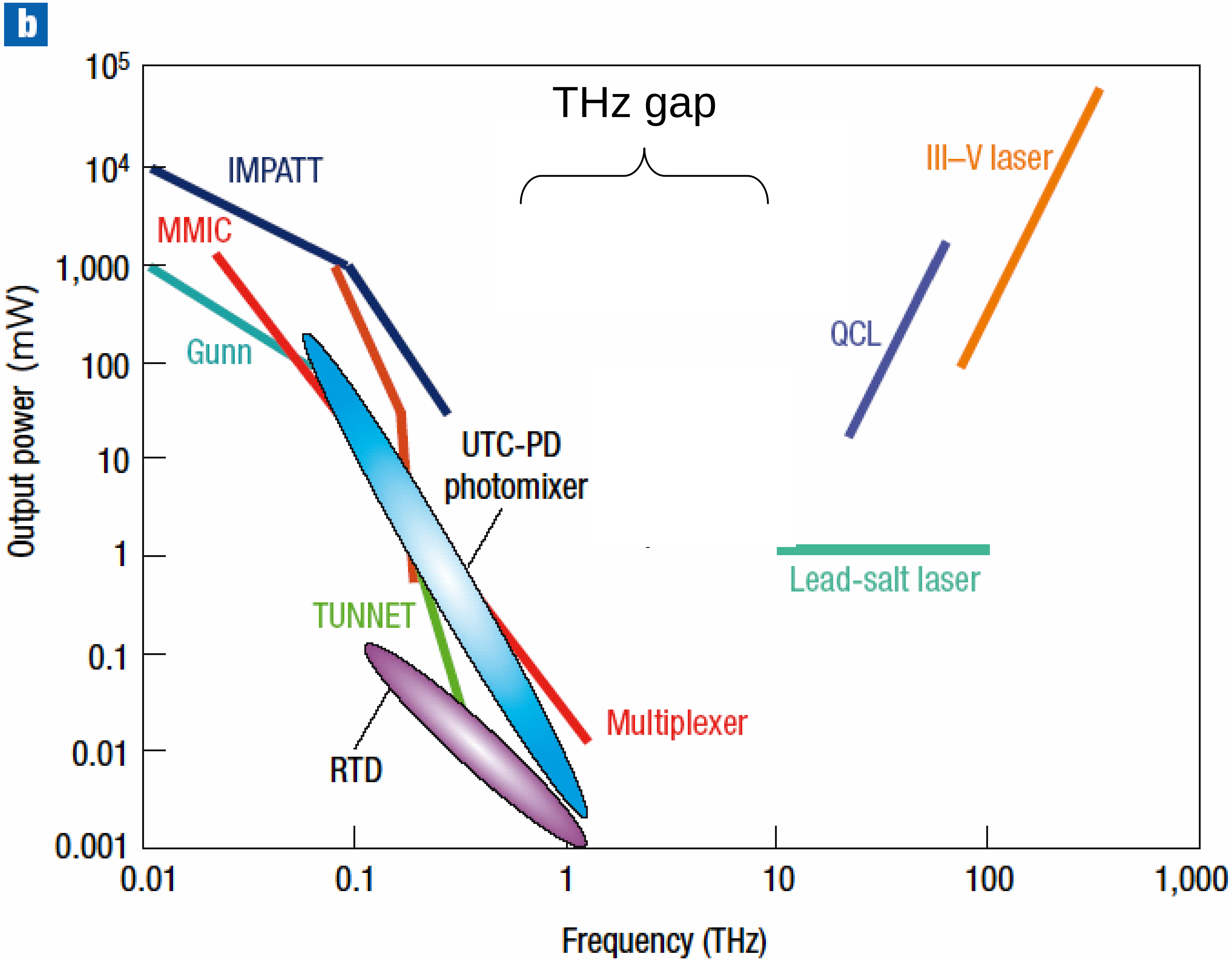


Fig. 3: Measured c-axis polarized near-normal reflectivity of $Bi_2Sr_2CaCu_2O_8$ (upper panel) for various temperatures at or below the superconducting transition temperature, T_c. A resonance that shifts with temperature and disappears above T_c is clearly observed. The lower panel shows the calculated reflectivity of a superconductor with a shifting Josephson-plasma resonance.

Outline

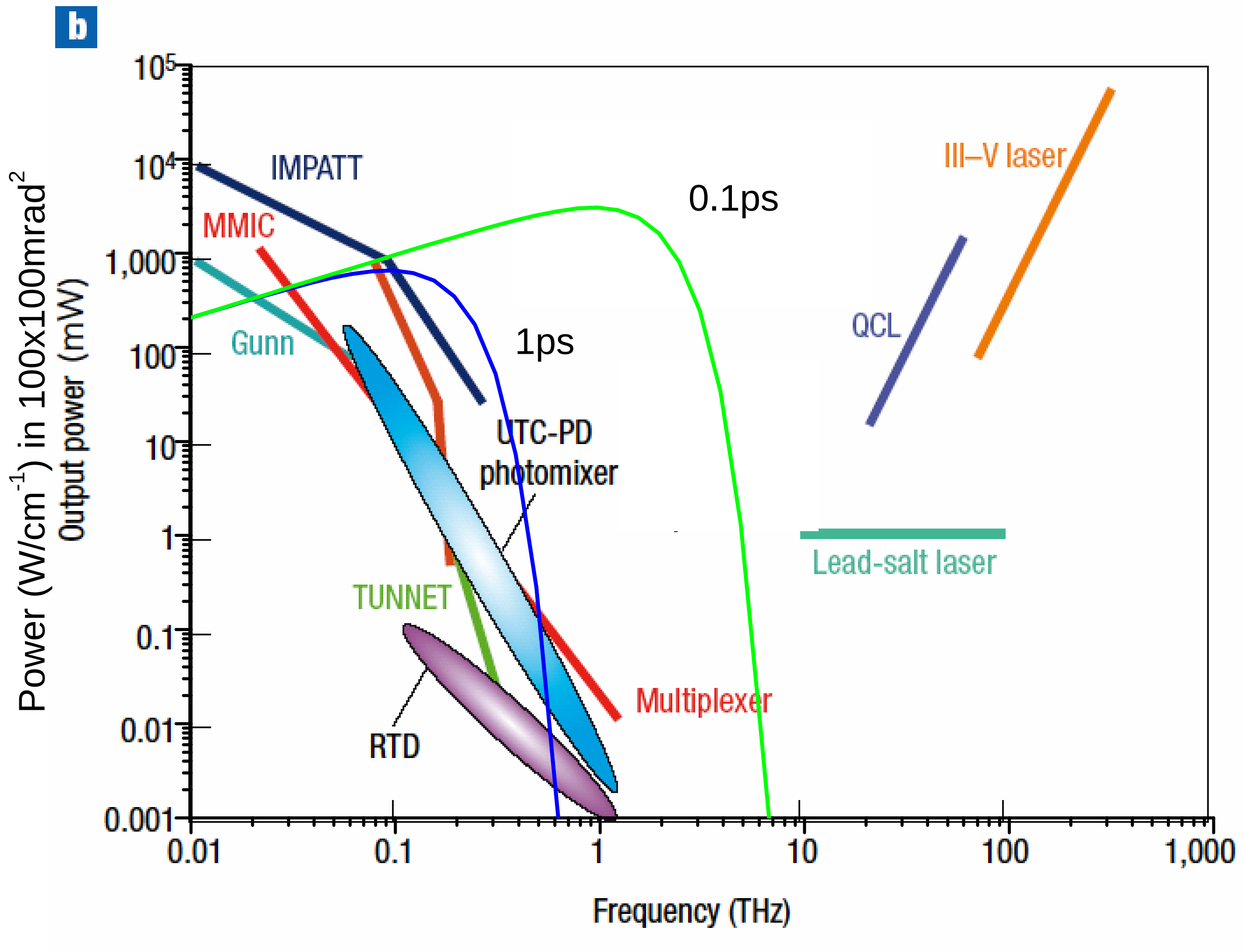
- Introduction of UVSOR-II
- IR + THz beamline BL6B at UVSOR-II
  - Optics
  - Performance
- Application
  - THz spectroscopy of large samples
  - THz spectroscopy under high pressures
- Development of Coherent SR at UVSOR-II
- CSR-ERL?
- Conclusion and prospects

High power CW THz sources



[M. Tonouchi, nature photonics **1**, 97 (2007).]

High power CW THz sources



[M. Tonouchi, nature photonics **1**, 97 (2007).]

Application of intense THz CSR

- Probe
  - Imaging in a wide spatial region
    - Ex.) Full human body.
  - Near-field microscopy
    - Phase separation of superconducting phase.
- Excitation
  - Nonlinear optics
    - Photo-induced phase transition.
  - Chemical reaction
    - Site-specific excitation.
    - Microwave effect.

An example of THz imaging
(QCL, narrow band imaging)

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 18, NO. 13, JULY 1, 2006

Real-Time Imaging Using a 4.3-THz Quantum Cascade Laser and a 320 × 240 Microbolometer Focal-Plane Array

Alan W. M. Lee, *Student Member, IEEE*, Benjamin S. Williams, *Member, IEEE*, Sushil Kumar, Qing Hu, *Senior Member, IEEE*, and John L. Reno

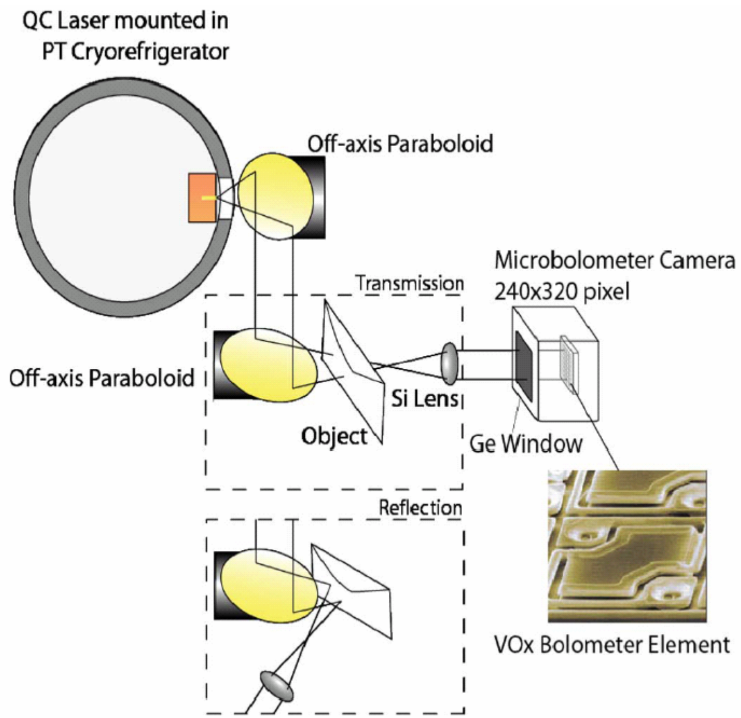


Fig. 1. Experimental setup of terahertz imaging system. Photo shows vanadium oxide microbolometer (courtesy of BAE systems, Lexington, MA). Cutaway depicts alternate reflection mode setup. (Color version available online at http://ieeexplore.ieee.org.)

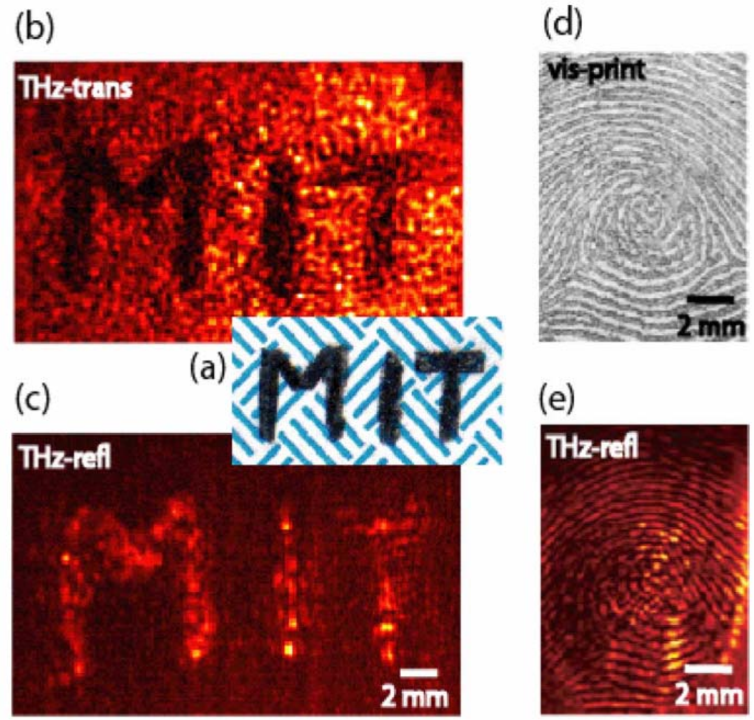


Fig. 3. Pencil letters written on inside of paper security envelope at visible frequencies. (a) Terahertz transmission mode, (b) one frame, and (c) terahertz reflection mode (20 frames). (d) Visible frequency thumb print and (e) terahertz reflection mode image of thumb of leading author (20 frames). (Color version available online at http://ieeexplore.ieee.org.)

An example of THz imaging
(broad band, multicolor imaging)

2007年(平成19年)4月22日 日曜日 朝日新聞

特殊な光を当てて絵画の真贋（しんがん）を見抜く――。こんな技術につながる手法の開発に情報通信研究機構（東京都小金井市）や東北大学などが成功した。電磁波のテラヘルツ波を利用し、絵を傷つけずに肉眼で区別がつかない顔料ごとの微妙な「色」の違いを見分ける手法で、電子情報通信学会の専門誌（電子版）に近く発表する。（小林哲）

名画の真贋 光が見抜く

電磁波利用 顔料の違い区別

研究機関など開発成功

テラヘルツ波は、光と電波の中間の性質をもつ遠赤外線の一種。物質に照射すると、成分ごとに特有の吸収率を示すことがわかっており、この特徴を読み取って含まれる成分を特定できる。同機構の福永香・主任研究員らは、イタリアの絵画修復業者から手に入れた古典顔料100種類以上にテラヘルツ波をあて、顔料ごとに反応の違いを分析、データベース化した。

その結果、肉眼で同じような白に見えても、19世紀まで主流だった鉛白と、その後に登場した亜鉛華、1920年以降に広まったチタンホワイトでは、特徴が異なることがわかった＝図参照。鉱物系顔料だけでなく植物系顔料や、オイルやアクリルなど展色材の種類も区別できるという。

こうした情報から絵画を傷つけずに顔料を特定できれば、描かれた時期や修復回数などを推定できる。古典絵画から近代の顔料が検出されれば、にせ物である疑いが強くなる。

福永さんは「食品添加物や公害物質の検出にも応用できる。装置を小型化して産業利用につなげたい」と話している。

The Asahi Shimbun

複数の白色顔料を用いたステンドグラス風の作品

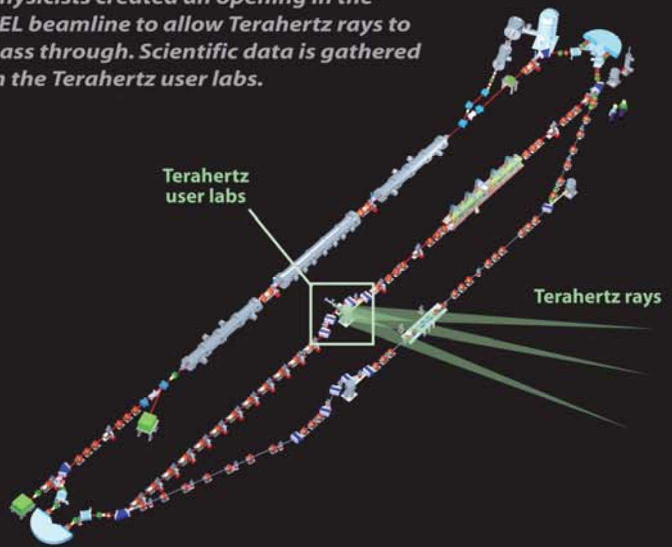
（情報通信研究機構の提供写真から作製）

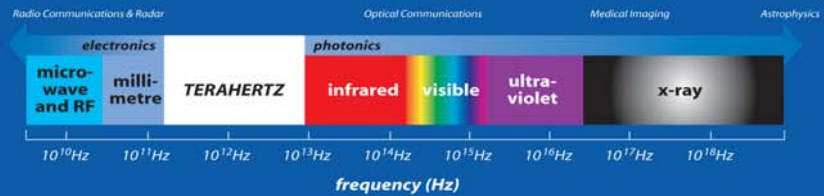
Terahertz Light

OFFICE OF SCIENCE

Catching T-rays

Physicists created an opening in the FEL beamline to allow Terahertz rays to pass through. Scientific data is gathered in the Terahertz user labs.





Terahertz light is a virtually unused portion of the light spectrum nestled between photonics and electronics. T-rays can "see" more color than humans can as they reflect different colors of light in various patterns, textures, and signatures. T-rays — a safe, non-ionizing form of electromagnetic radiation — can penetrate many solids, but not water or metals.

Physicists at Jefferson Lab's Free-Electron Laser Facility use magnetic fields to coax very short bunches of high-speed electrons into emitting Terahertz beams. These 100 watt terahertz beams are 100,000 times brighter than those produced at any other operating facility in the world.

T-rays add widely to the wave-based technologies — from the telegraph, radio and X-rays to computers, cell phones and medical MRIs — that have defined the last century and a half.

Potential Applications

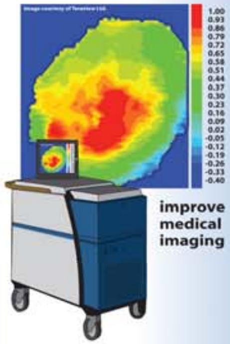
Security

fingerprint chemical and biological terror materials in packages, envelopes or air

find concealed weapons

locate hidden explosives and land mines

Medical Imaging

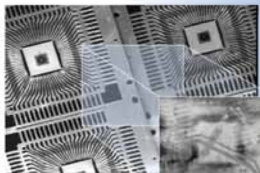


improve medical imaging

diagnose skin cancer

spot tooth erosion earlier than x-rays

Communications



see buried metal layers in semiconductors

widen frequency bands for wireless communi-cation

Quality Assurance

count items in packages

control quality of pharmaceuticals

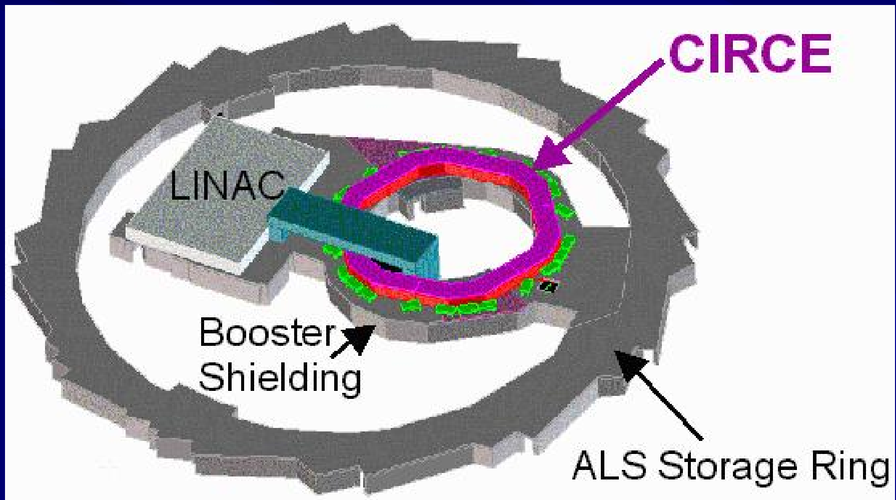
help airline pilots navigate through fog

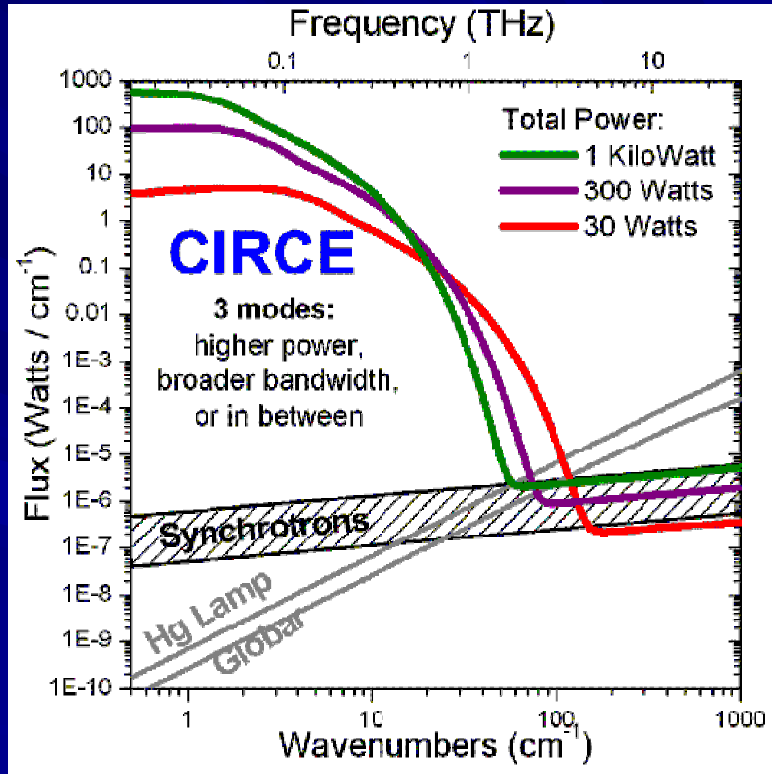
detect dangerous flaws in space shuttle components

CIRCE Project

Coherent InfraRed CEnter
Advanced Light Source

[http://circe.lbl.gov/]





This proposal was selected in BESAC 20 year BES Facilities Roadmap.

Conclusion and prospects

- Present use of THz-SR
  - Spectroscopy of solids under low temperature, pressures and magnetic fields.
  - Broadband spectroscopy of solids.
  - Microspectroscopy of solids, bio-materials etc.
- Future -- **Breaking the present concept.**
  - Use of intense THz-CSR.
    - Excitation light.
      - Ex.) THz pump - probe experiment of impurities, etc.
    - Advanced Probing.
      - Multicolor wide spatial region imaging.
      - Investigation of the local electronic structure of solids by THz-SNOM.