Terahertz LIFE

A proposal for a THz beamline at SPARC

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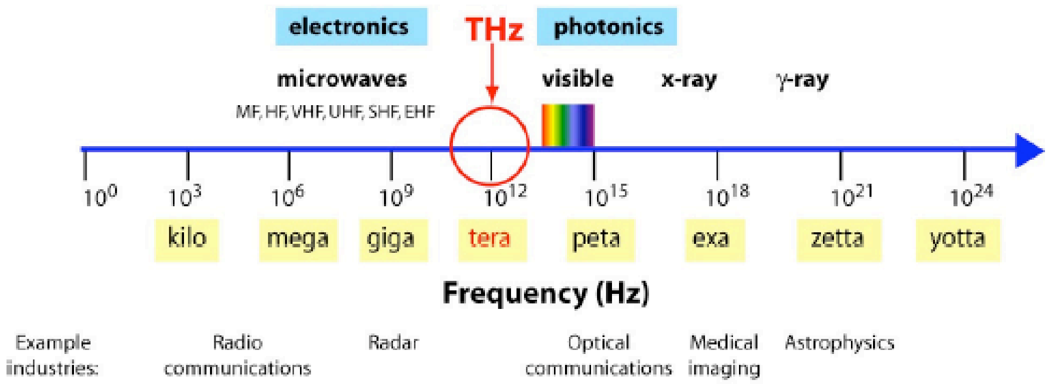
Outline

- THz gap
- Coherent THz emission in a FEL machine
- Scientific opportunities for linear and non-linear THz spectroscopy;
- THz@SPARC

The Terahertz gap

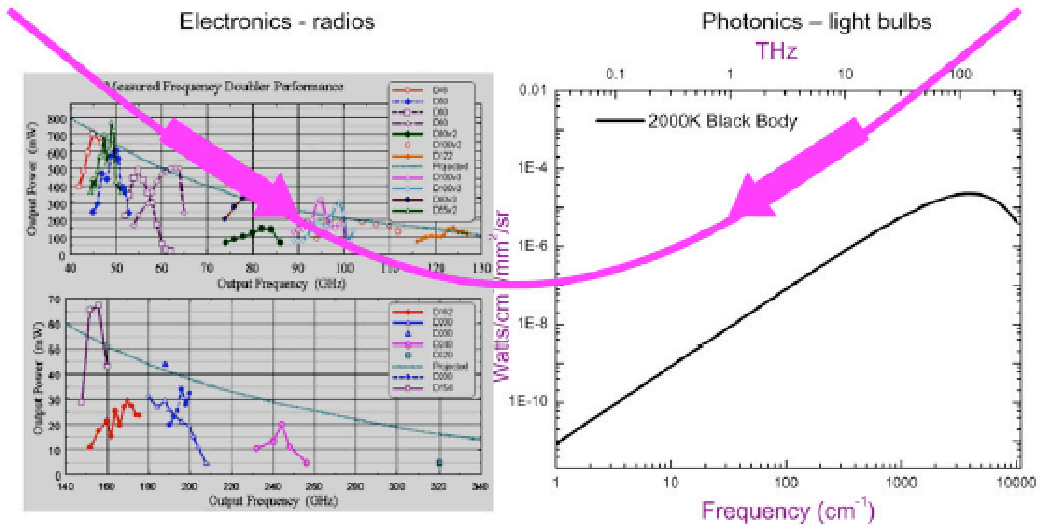
0.1 THz – 10 THz



1 THz ~ 1 ps ~ 300μm ~ 33 cm^{-1} ~4.1 meV ~ 47.6°K

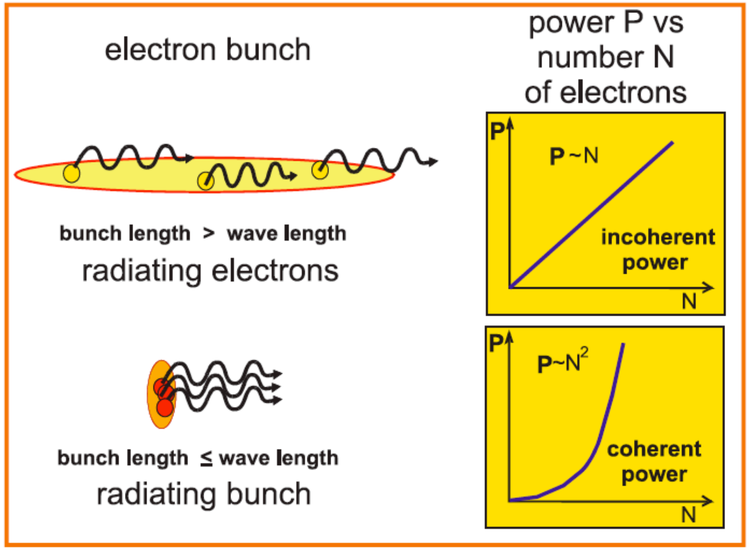
Figure 1. Schematic of the electromagnetic spectrum showing that THz light lies between electronics and photonics.

No electronics, few microwaves generators



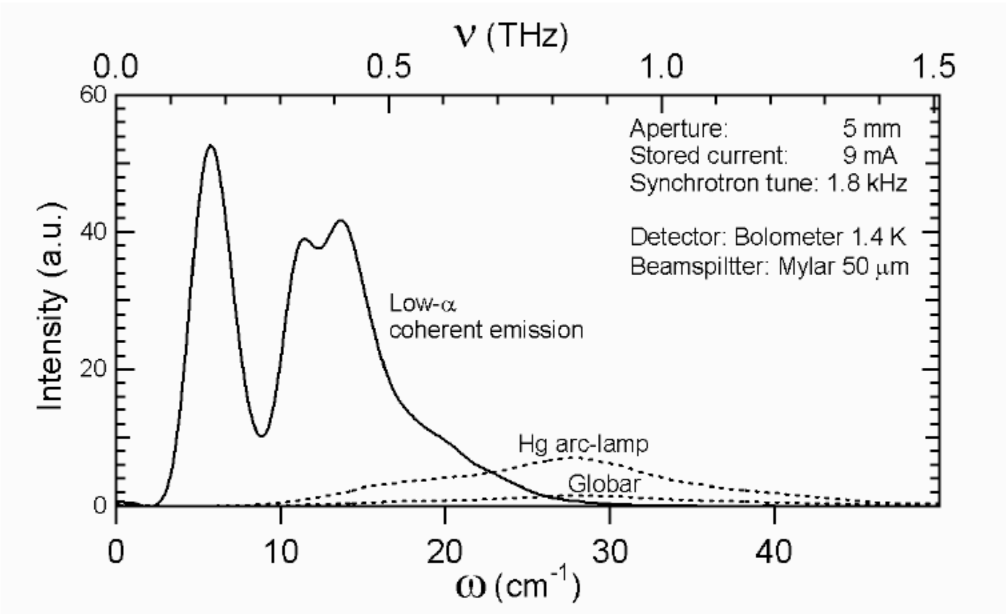
Vanishing thermal power, few tunable and pulsed lasers.

Coherent Synchrotron Radiation (CSR)

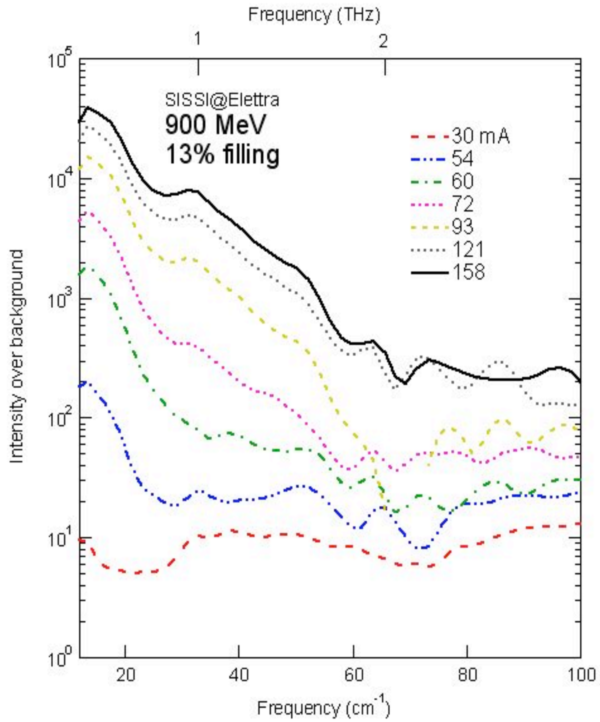


$$I = I_{incoh} + I_{coh} = (N(1 - f_\nu) + N^2 f_\nu) I_{incoh}$$

$$f_\nu = \left| \int n(z) e^{i\pi \cos(\theta) z} dz \right|^2$$



Low-α mode IRIS@Bessy-II: U. Schade et al, PRL 2003

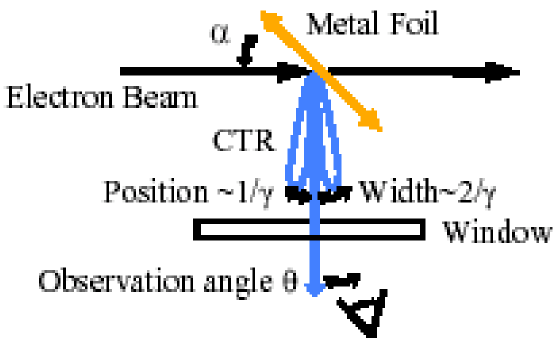


low-e beam energy

SISSI@Elettra: E. Karanzoulis, A. Perucchi, S.L et al, ,2007

Transition THz Radiation (CDR/CTR)

Transition Radiation occurs when an electron crosses the boundary between two different media

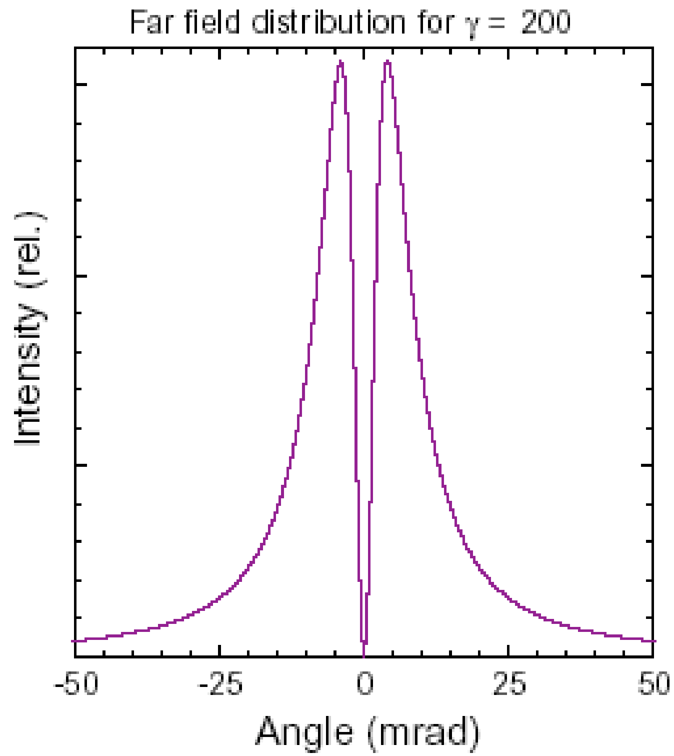


- Coherent Transition Radiation

N_e = number of electrons in single bunch
σ = bunch-length

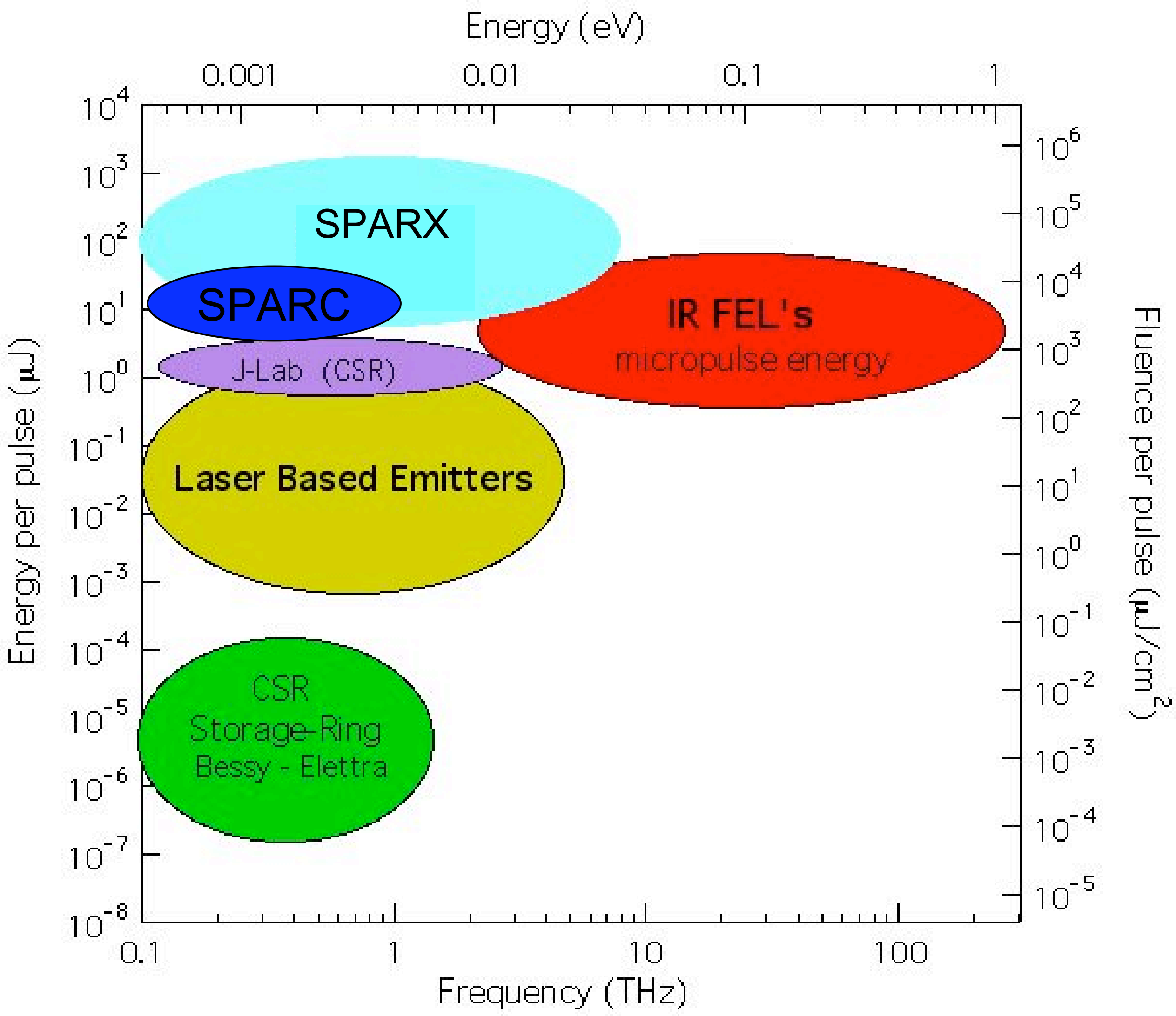
$$\frac{dI_{CTR}}{d\omega d\Omega} = \frac{e^2\beta^2}{\pi^2 c}\left(\frac{\sin\theta - \beta\cos\alpha}{(1-\beta\sin\theta\cos\alpha)^2 - \beta^2\cos^2\theta}\right)^2 N_e\left[1+N_e\exp[-\frac{\sigma^2\omega^2}{c^2}]\right]$$

- Position, width of maxima
- Coherence



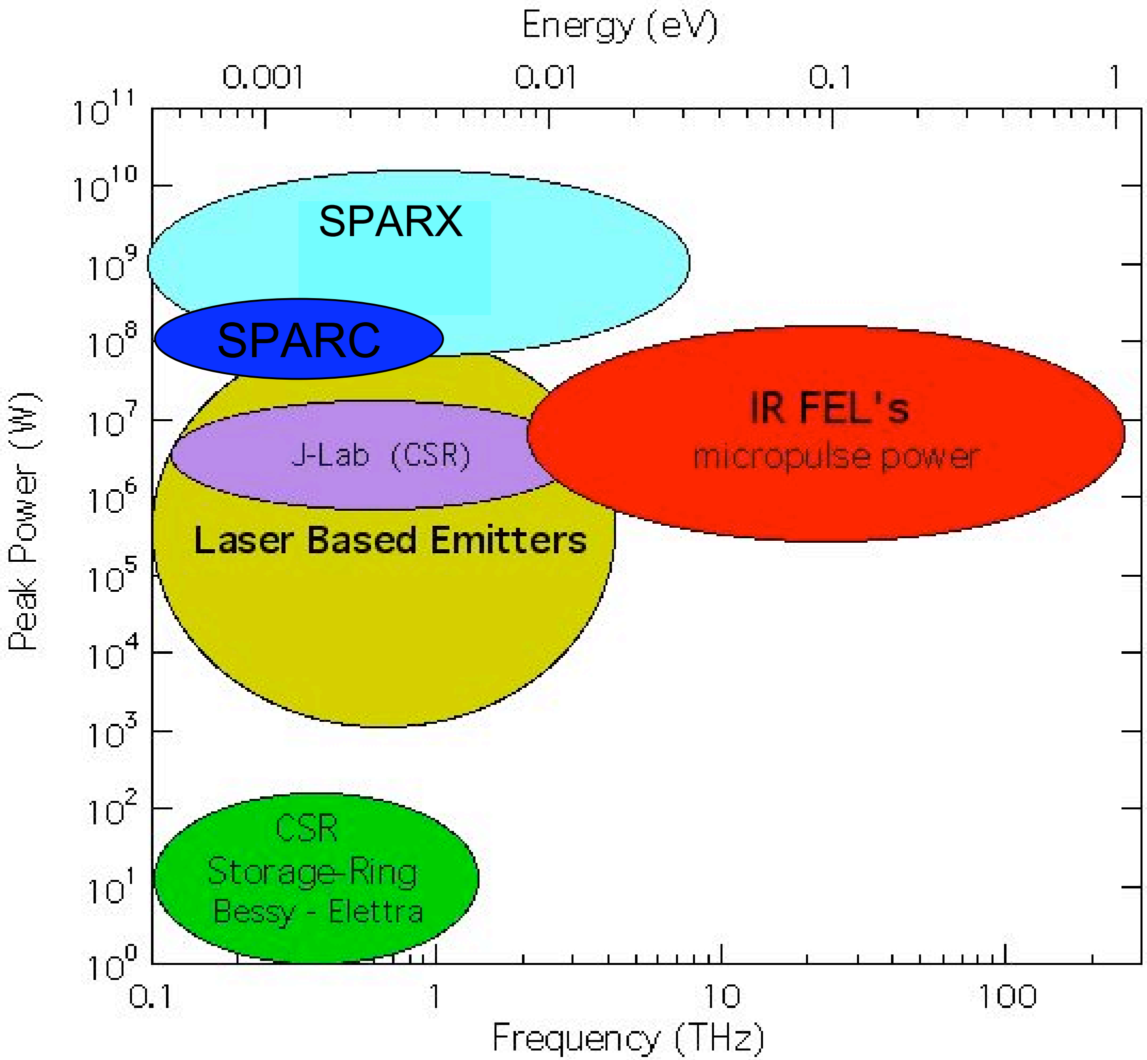
Intensity is 0 on axis and peaked at Θ~1/γ
Polarization is radial

Figures of Merit of THz sources: energy/pulse



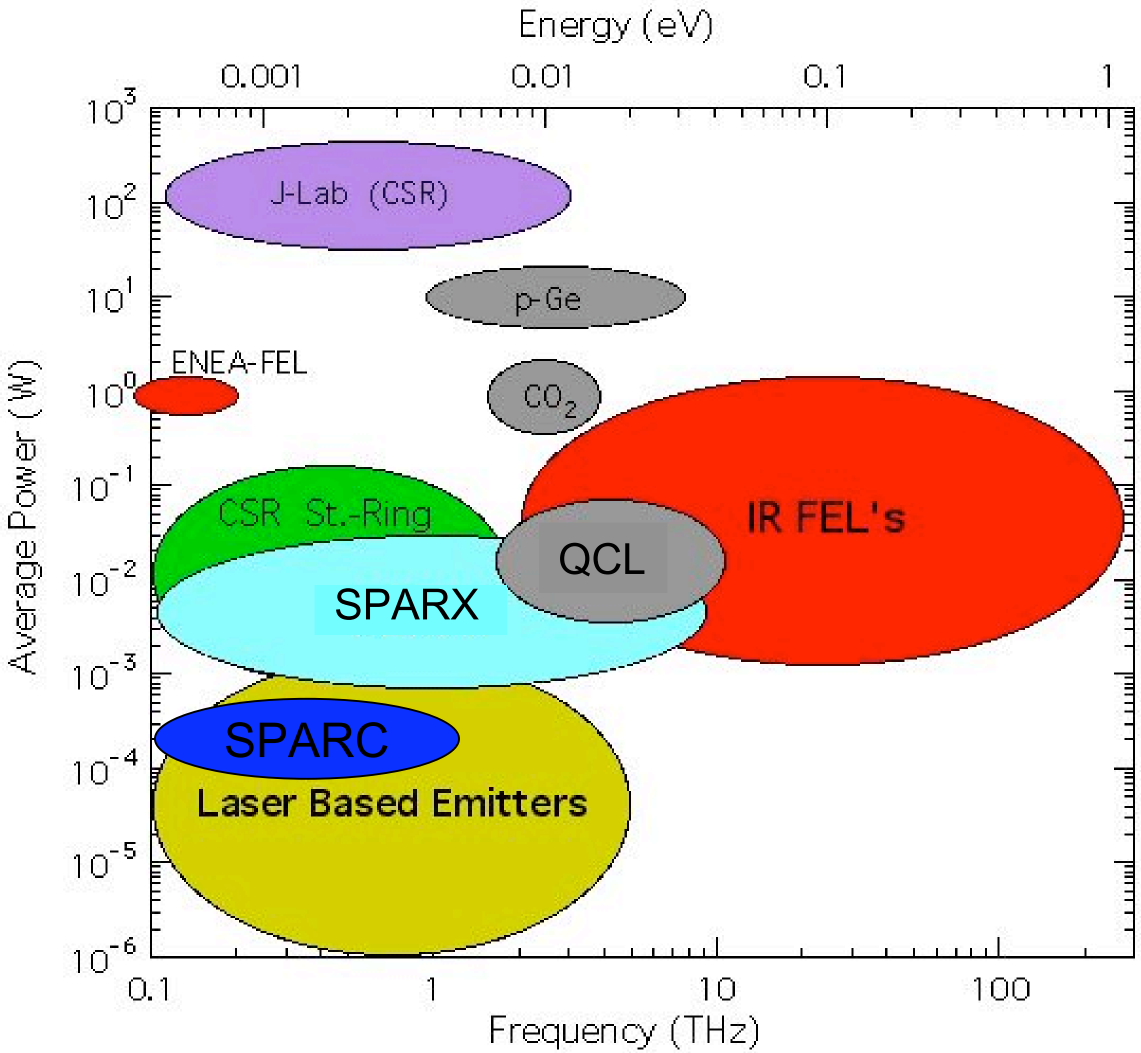
A. Perucchi et al, 2007

Figures of Merit of THz sources: peak power



A. Perucchi et al, 2007

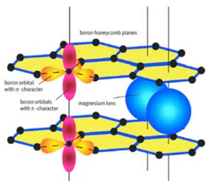
Figures of Merit of THz sources: average power



A. Perucchi et al, 2007

THz Science

Condensed Matter Physics



Superconductivity

- Energy gap
- Symmetry of the order parameter
- Direct determination of the superfluid density
- Dynamics of Cooper pairs

Low-dimensional materials

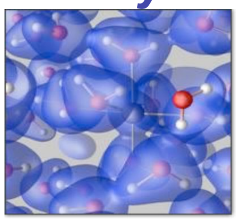
- Dimensionality crossover
- Non-Fermi liquid normal states
- Broken symmetry ground states

Coherent Phase Transitions

- Polarons
- Structural Phase Transitions

Magnetic sub-ps Dynamics

Physical and Analytical Chemistry



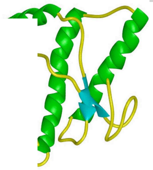
Polar liquids

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

Solutions

- Static and dynamic interactions between solvated ions and solvent

Life Sciences



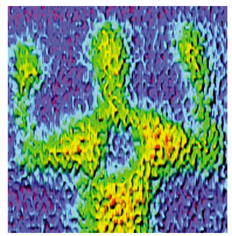
Macromolecules conformation

- Secondary and tertiary structure
- Coherent dynamic development

Imaging

- 3D tomography of dry tissues
- Near-field sub-wavelenght spatial resolution

New Technologies



THz technologies

Array THz detectors

Metamaterials

Medical diagnostic

- Skin cancer detection

Industrial production

- Material inspection
- Production line monitoring

Defense industry/Homeland security

- Detection of explosives and biohazards

THz Experiments

Frequency-Domain Spectroscopy

Average Energy (Power)

THz Pump- THz Probe non-linear time-domain experiments

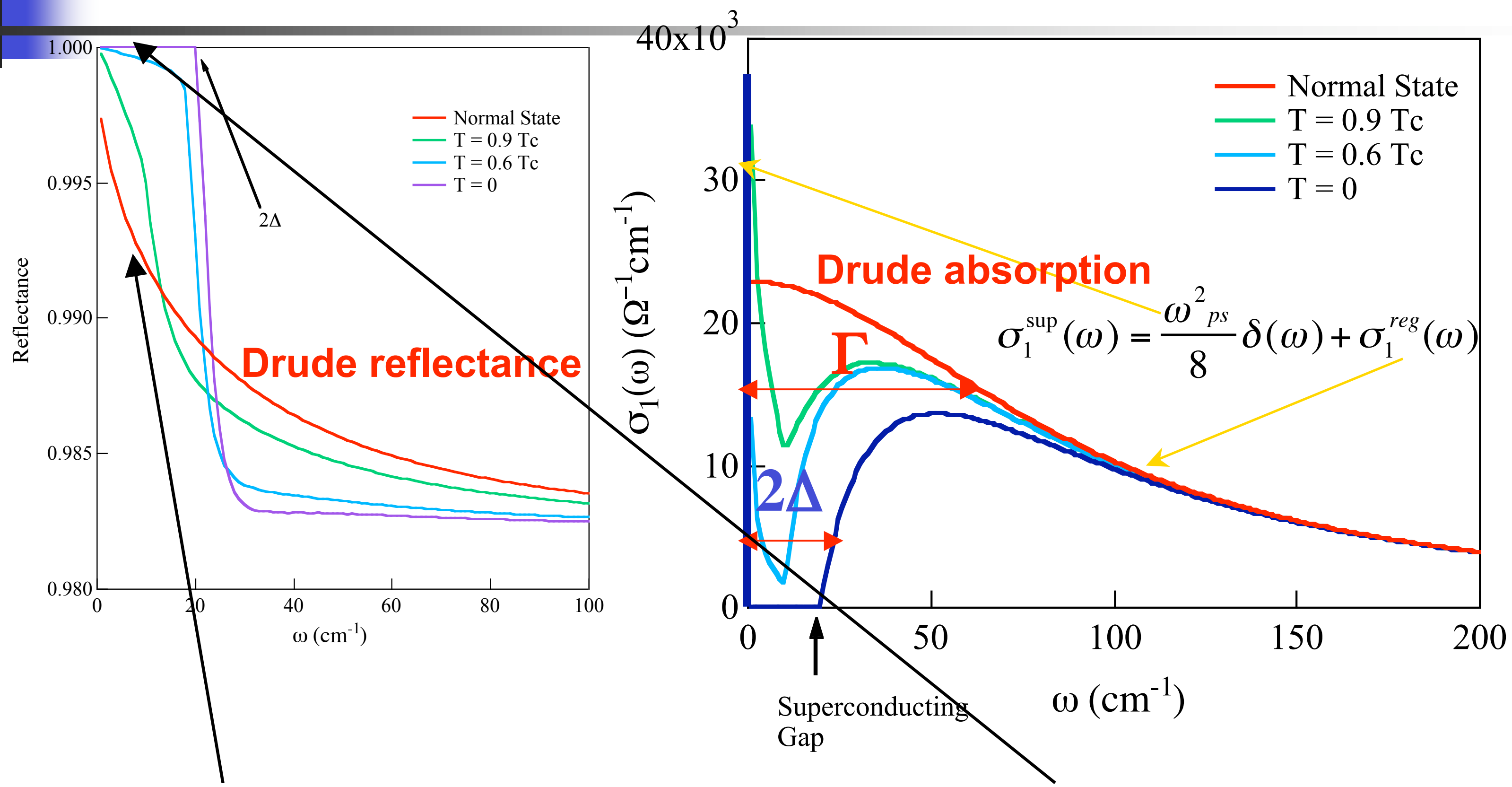
(THz Pump and IR+VIS Probes using IR+VIS emissions)

High Energy/Pulse

Basic optics of Superconductors

Minimum excitation energy:
Cooper-pair breaking 2Δ

Superconducting gap observed if:
- -sample in the dirty-limit ($2\Delta < \Gamma$)
- -Cooper pairs in s-wave symmetry



$\omega \leq \Gamma(T)$: $R_n(\omega) = 1 - [8\omega\Gamma(T)/\omega_p^2]^{1/2}$ $\omega \leq 2\Delta(T)$: $R_s(\omega) = 1$

Peak at 2Δ in Rs/Rn

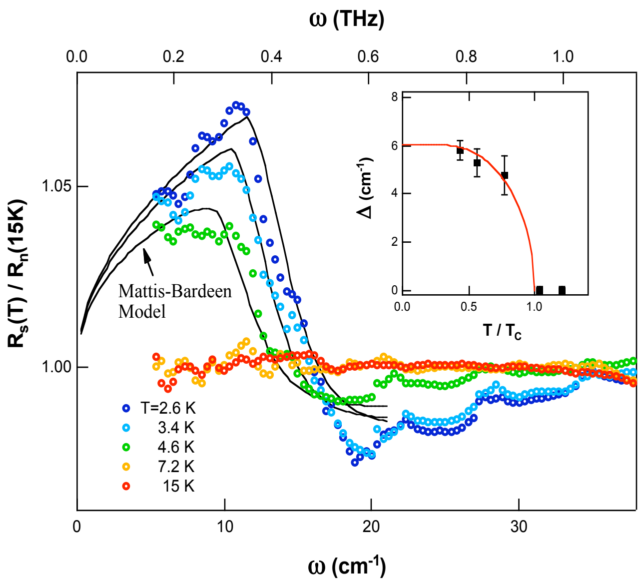
Frequency Domain THz Spectroscopy

Measuring the superconducting gap

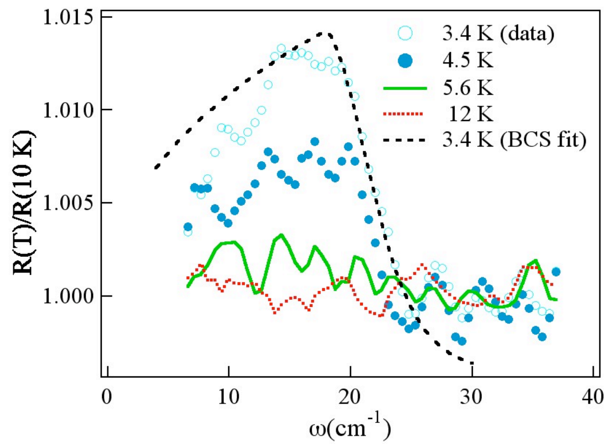
Superconducting Diamond Tc=5 K

CaAlSi Tc=7 K

Sm(O,F)FeAs Tc=39 K



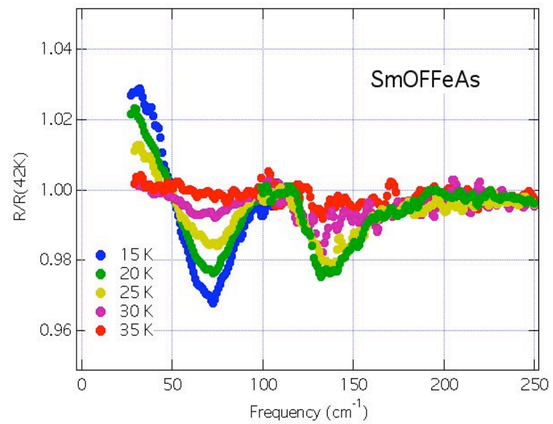
M. Ortolani, et al, PRL, 2006



Penetration depth @ 3.4 K = 120 nm

Superconducting gap @ 3.4 K = 9 cm^{-1} (1.1 meV)

S. Lupi et al, PRB, 2008



C. Mirri et al, SUST 2008

Pump-Probe Spectroscopy

1) **Optical Pump-Optical Probe Spectroscopy** Pump and Probe pulses (often at a single frequency) fall in the visible (near-IR)

- High energy excitation;
- Strong scattering effects;
- High energy dynamics;

Extrinsic dynamics

2) **Optical Pump-THz Probe Spectroscopy** Pump (single frequency) in the visible (near-IR) Probe in the far-IR and THz range;

- Similar inelastic effects in the Quasi-Particle decay like in (1) but investigation of the low-energy dynamics;

3) **THz Pump-THz Probe Spectroscopy** Accordable Pump pulses falling in the far-IR and THz;

•Possibility to resonate and/or selectionate several fundamental excitations;

•Intrinsic dynamics

4) THz Pump- IR+VIS SR Probe Spectroscopy

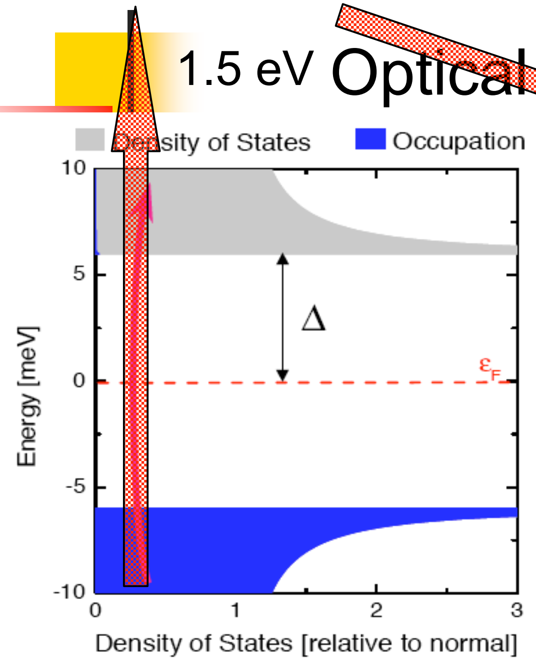
•Accordable Pump pulses falling in the far-IR and THz;

•Possibility to resonate and/or select several fundamental excitations;

•Intrinsic strongly-coupled different energy scale dynamics

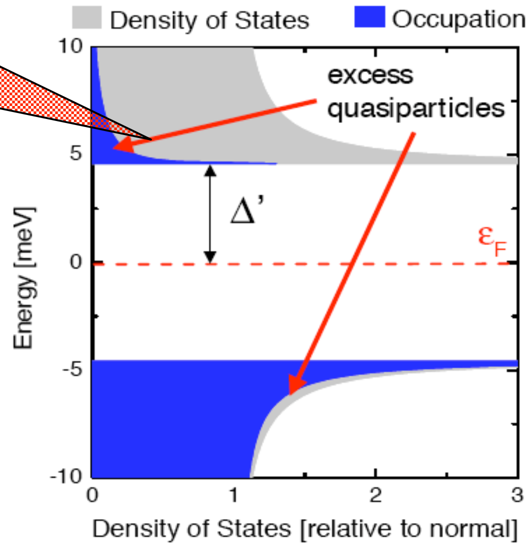
Time-Domain Spectroscopy in isotropic superconductors

1.5 eV Optical Pump - Optical Probe (THz Probe)



Step 1:
Photons (a pulse from near-IR laser) break pairs, creating high energy "quasiparticle" excitations.

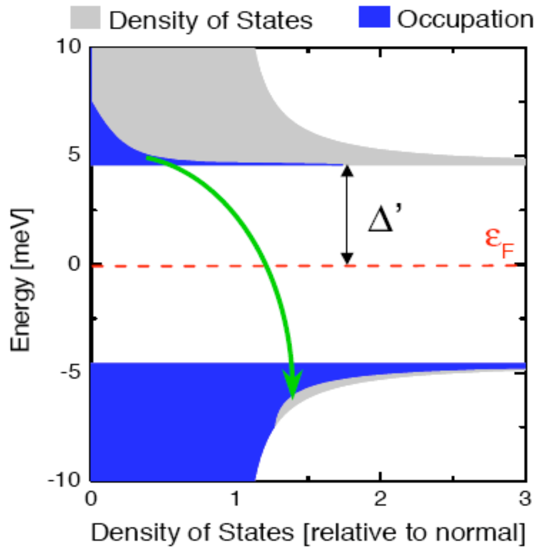
Photon energy 1.5 eV.



Step 2:
High energy quasiparticles scatter and relax toward gap edge. Many more pairs broken in this process (multiplication).

Weakened superconducting state appears as reduced gap; $\Delta' = \Delta - \delta$.

Note: Quasiparticle density is out of equilibrium, but energy distribution is approximately thermalized.

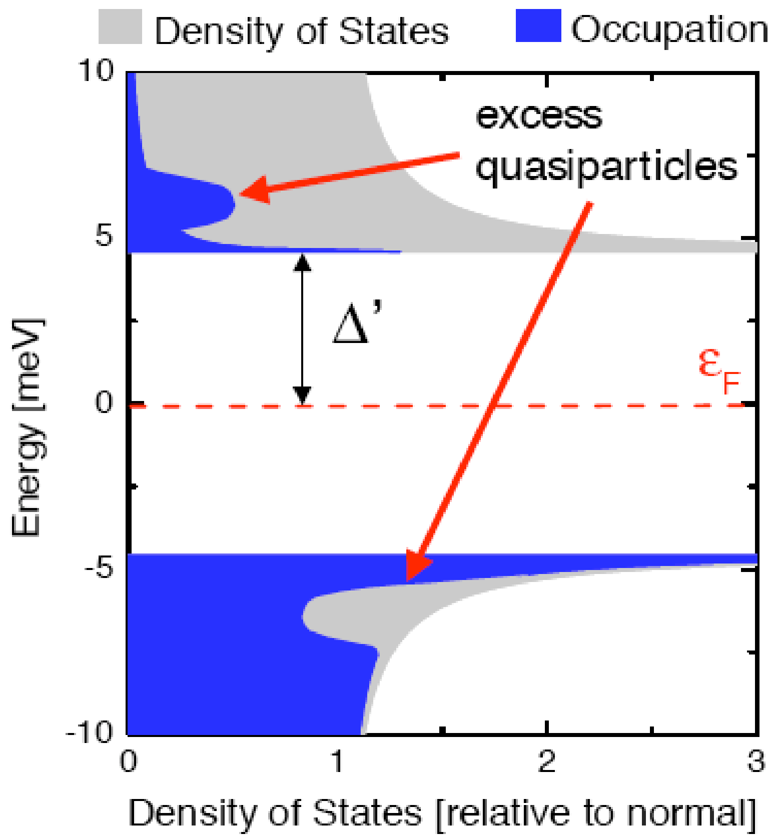


Step 3:
Excess quasiparticles recombine to form pairs and gap is restored to full value.

High-Energy Pump Pulse generates an extrinsic dynamical effect

Photoexcitation in isotropic superconductors

THz pump - THz probe



L. Carr et al, 2007

New Experiment

1) Resonating low-energy THz pump determines a non-thermal initial distribution reducing the bottleneck effect;

2) Probe with broad-band pulse provides information on how QP decay toward Cooper pairs;

3) Frequency-resolved spectra (using TDS) furnish both the real and immaginary part of each optical functions;

High Energy Probe Extension

THz Pump- IR+VIS SR Probe Spectroscopy

•Accordable Pump pulses falling in the far-IR and THz;

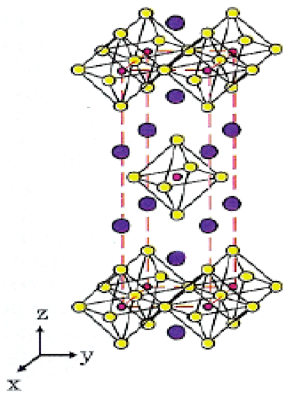
•Possibility to resonate and/or select several fundamental excitations;

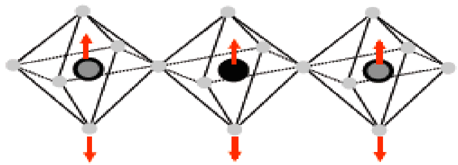
•Intrinsic strongly-coupled different energy scale dynamics

Multiple coupled energy scales in complex solids

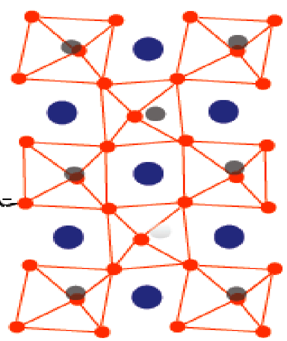
Oxides of Transition Metals

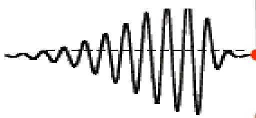
(e.g. Cu, Mn, Ni, V…)





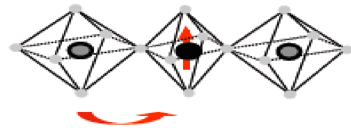
THz resonant Pumping
with a vibrational mode





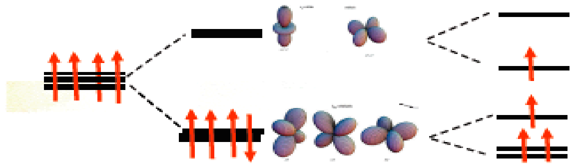
Electrons are strongly interacting

2) Strong Electron-lattice coupling



50 meV

3) Charge - Spin - orbital



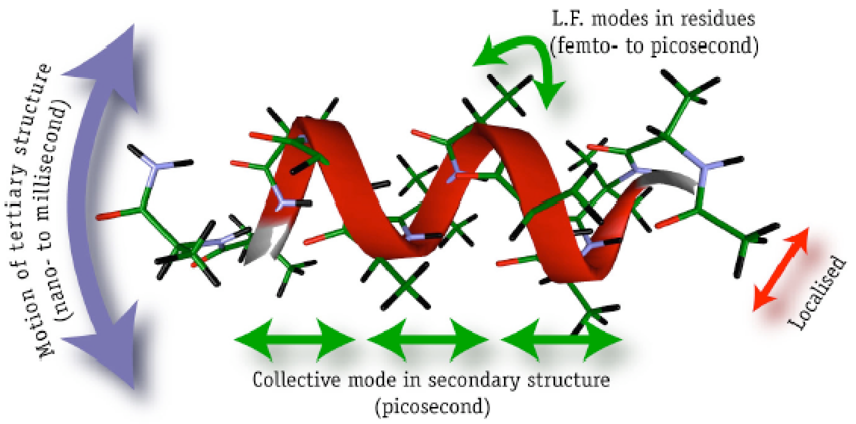
100 meV

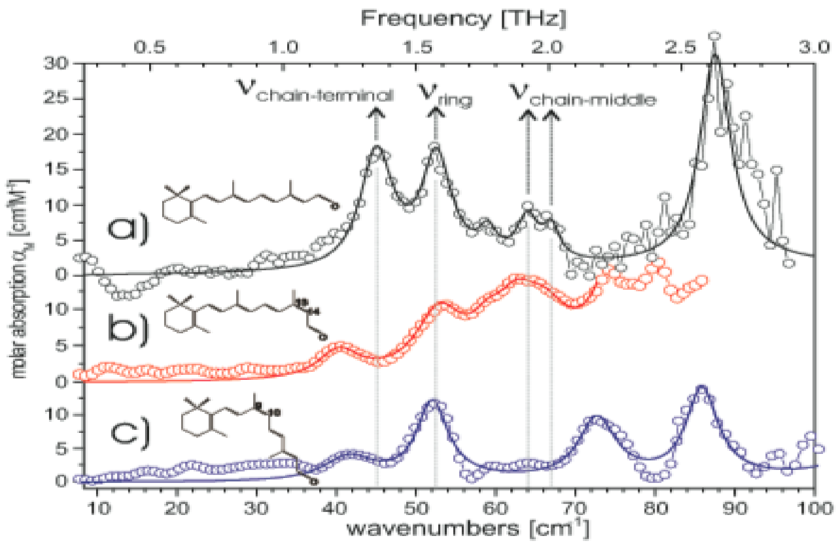
How does the electronic structure respond ?

How does the magnetic structure respond ?

How does the orbital structure respond ?

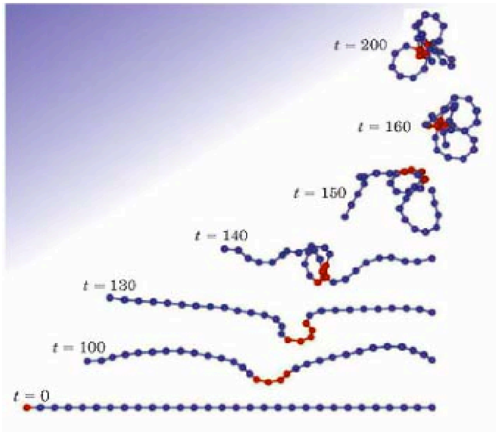
Conformational Collective modes of macromolecules





Conformational dynamics of DNA, proteins, lipids, result in collective THz modes. Structural changes are critically important in biological activity thus, if these modes are frozen out, the ability to change structure is lost.

High electric fields are predicted to generate localized modes!

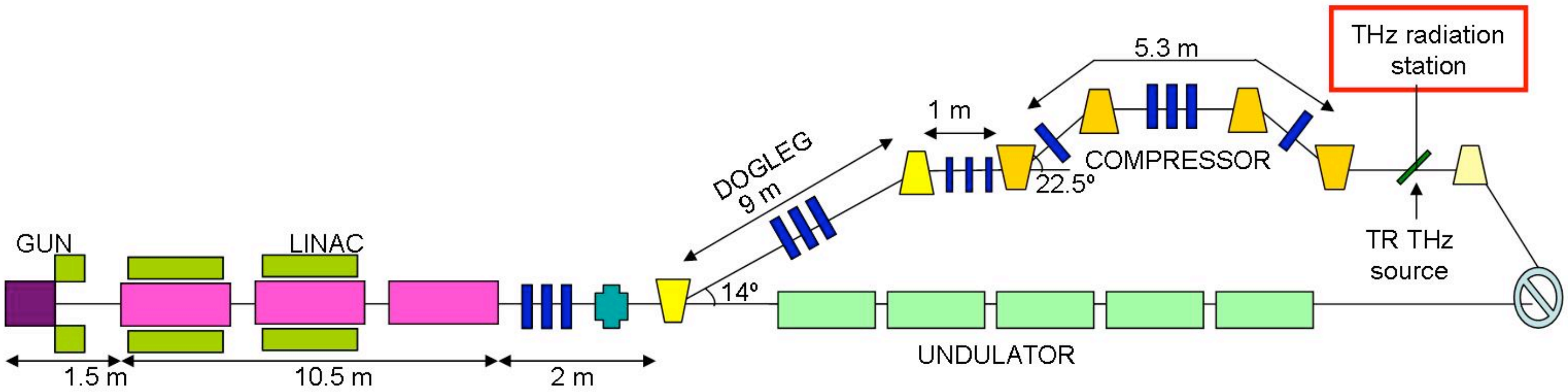


Dynamical evolution from disordered conformational states to ordering

Large pump THz E field may coherent induce conformational ordering and THz probe may measure its temporal evolution

A biopolymer chain buckles and folds on itself due to an instability produced by a nonlinear localized mode – Physics Today Jan. 2004 p43.
Mingaleev et al Europhys. Lett. **59** 403 (2002)

THz extraction& Requirements



1. THz emission covering a large spectral range: 0.1 to 10 (30) THz;
2. THz pulse duration in the sub-ps range;
3. Energy/pulse in the 10μJ-1mJ range;
4. Far-IR, Mid-IR and VIS probe using incoherent radiations;
5. Two sources: CDR+CSR to use the different polarization properties;
6. Optical coupling between the laser and the THz pulse: THz pump-VIS-UV probe;

Conclusion

- Relevant scientific cases for linear and non-linear THz science;
- Lack of broad-band ultra-fast sources in the THz and far-IR range: THz and far-IR radiations represent a strategic low-energy extension for UV-X FEL;
- **Extraction** of Coherent Radiation from short electron bunches from SPARC for linear and non-linear frequency and time domain spectroscopies;

Acknowledgments

- M. Ferrario (LFN-INFN)
- M. Castellano and E.Chiadroni (LNF-INFN)
- L. Palumbo (Univ. La Sapienza and LFN-INFN)
- M. Boscolo (LNF-INFN)
- G. Gallerano and A. Doria (ENEA)
- G. Williams (Jefferson Laboratory)
- E. Karanzoulis (ELETTRA)
- U. Schade (BESSY-II)