Addressing superconductivity with accelerator-based infrared and THz radiation sources

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Outline

1. Infrared Spectroscopy and Superconductivity
2. THz superconducting gaps
3. Addressing electron correlation with high-pressures
4. Non-linear THz spectroscopy
5. The TeraFERMI project
6. Conclusions and outlook
IR energy scales and Superconductivity

Basov, Timusk, RMP 2005
IR Spectroscopy and Superconductivity

- Extended Drude Model
- Energy Gap
- T-dependence of SW
- Universal scaling relation
- $K_{exp}/K_{LDA}$
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Infrared Synchrotron Radiation advantages

Carr et al. (Nature, 2002)

- Increased flux in the THz range
  ↑ Superconducting gaps

- Increased brightness in the whole IR range
  ↑ High-Pressure measurements in a DAC
Radiation is collected over a solid angle of 65 mrad (H) x 25 mrad (V)

M1 Plane mirror
M2 Ellipsoidal mirror
M3 Plane mirror
M4 Ellipsoidal mirror

a = 3.5 m  c = 8 m  e = 1.0 m
b = 1.0 m  d = 3.0 m  f = 1.0 m
Several bands crossing the Fermi level is not sufficient to have considerable many-band effects in superconductivity. Only when the bands have a very different physical origin, multigap effects take place. **Interband scattering has to be low!**

In 2001, multigap superconductivity has been demonstrated for the first time to take place in a real material, as MgB$_2$.

Multigap SC has been proposed for transition metals, A15 compounds, Copper-oxide high-Tc, Heavy Fermions, Pnictides

M. Norman, Physics (2008)
BCS-like electrodynamics

Superconductivity is ruled by *low-energy* electrodynamics:
The Superconducting Gap size and shape provide information on the nature and symmetry of pairing

\[
\frac{2\Delta}{k_B T_C} = 3.52 \quad \Rightarrow \quad T_C \approx 10 \text{ K} \quad \nabla \quad 2\Delta \approx 1 \text{ THz}
\]

**Synchrotron advantage at THz frequencies with both coherent and incoherent sources**

The Mattis-Bardeen (MB) relations are derived within the BCS theory, for a s-wave SC in the dirty limit (extension to arbitrary impurity scattering by Zimmermann)
MG Superconductors THz studies @ SISSI

MgB$_2$

Ortolani PRB (2008)

V$_3$Si

Perucchi PRB (2010)

Ba(Fe,Co)$_2$As$_2$

Perucchi EPJB (2013)
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Correlation strength and High Pressures
Ba-122 at High-Pressures

Baldassarre PRB (2012)

Wu et al. (2013)
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Non-linear THz optics at MV/cm

THz light couples with electronic, vibrational and magnetic excitations

Electronic response under giant quasi-static fields

Ultra-fast structural distortions and lattice control

Populating low-energy excited states

Ultra-fast magnetic switching (B~0.3 T)

E_c critical field

Dienst, 2011

Tudosa, 2004

1 From L. Carr

Rini, 2007

Populating low-energy excited states

Narrow-band THz excitation to limit starting population energy

Ultra-fast structural distortions and lattice control
Manipulating Mott Insulator-to-Metal Transitions

Filling-Controlled MIT:
- static (doping)
- dynamic (photoexcitation)

Bandwidth-Controlled MIT:
- static (pressure)
- dynamic (?)

THz pulses in the MV/cm range can drive lattice displacements in the pm range
Superconductivity close to an AF state: one general mechanism for HTSC?

“Conventional” BCS-like features (isotope effect, s-wave gap) together with the presence of strong correlation (large U, magnetism).

Retardation effects are poorly understood because of possible breakdown of adiabatic approximations (W~0.5 eV vs. $\omega_{ph}$~0.2 eV)

**Time-resolved studies of the electronic response upon lattice excitations**

Need of employing THz pulses
- **short** (on the fs time-scale)
- **broadband** (over the largest possible phonon range)
- **powerful** (MV/cm)
The THz Gap

Quantum Cascade Lasers

Backward-Wave-Oscillators

Gas Lasers (CO\textsubscript{2} and CO\textsubscript{2}-pumped)

Si/Ge Lasers

NO TIME STRUCTURE!!!
THz femtosecond sources

THz
Time Domain Spectroscopy

Photoconductive Antennas
GaAs, TiO$_2$, ...

Optical Rectification
ZnTe, GaP, LiNbO$_3$, etc.
Up to 10’s $\mu$J per pulse

RESTSTRAHLEN BAND GAP
(Optical Rectification in Organic Materials DAST, OH1, DSTM)

Optical Parametric Amplifiers
Tunable, Narrow-Band
Typically 1-10 $\mu$J per pulse above 15 THz
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The TeraFERMI idea

Exploiting the properties of the FERMI-FEL electron beam to produce:

* Short (sub-ps), Powerful (>MV/cm), Broadband (0.1-10 THz)

THz pulses to be used as a **Pump** beam for ultrafast nonlinear spectroscopies

Exploiting the already existing LINAC: Reduced construction and operation costs

**Parasitic THz emission:** TeraFERMI will not affect overall FEL available beamtime

THz light always available

Possibility for THz pump / FEL probe
Accelerator-Based Coherent THz emission

Extending the FEL’s advantages into the THz region

\[ N[1 + Nf(\omega)] \quad f(\omega) = \int_{-\infty}^{+\infty} \rho(t) \exp(-i\omega t) dt \]

- N ~ 6.24*10^7  @ 1pC  Storage-Rings
- N ~ 6.24*10^{10} @ 1nC Single-pass accelerators

Transition Radiation occurs when relativistic electrons cross the boundary between two media of different dielectric constant

The Ginzburg-Frank equation:

\[ \frac{d^2U}{d\omega d\Omega} = \frac{e^2}{4\pi^3\varepsilon_0c} \frac{\beta^2 \sin^2 \theta}{(1 - \beta^2 \cos^2 \theta)^2} \]
Expected Performance

- Energy: $10^{-4} \div 10^{-3}$ J / pulse
- Peak Power: $10^8 \div 10^{10}$ W
- Electric Fields: 1-100 MV/cm
- Magnetic Fields ~ T

1 nC charge
Flat-top profile
Performance under FEL operation

Frequency (THz)

Pulse Energy (µJ)

I (kA)

Time (fs)

Δt (fs)

Pulse Energy (µJ)

Frequency

I (kA)

Time (fs)

Δt (fs)
Conclusions

Exploiting synergies between accelerator-based THz sources

SISSI

Stable, high brightness IR-THz source
(10 mm to visible range)
Superconducting gaps, collective modes,
High-Pressure studies

TeraFERMI

Ultra-short, high-power THz pulses
between 1 mm - 20 μm (0.3 - 15 THz)
Access to the Reststrahlen-band gap!
Pumping on electronic, vibrational,
magnetic excitations
Phase separation phenomena are ubiquitous in strongly correlated electron systems.

\[ V_2O_3 \] (Lupi, 2010) \hspace{1cm} \[ VO_2 \] (Qazilbash, 2007)

Probing free carriers, SC gaps, vibrational modes on the local scale with nm resolution

\( \Rightarrow \) High brightness, THz broadband sources

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