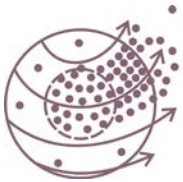
FEL-based study of *intervalley* elastic scattering of donor excited states in *multivalley* semiconductors

V.N. Shastin

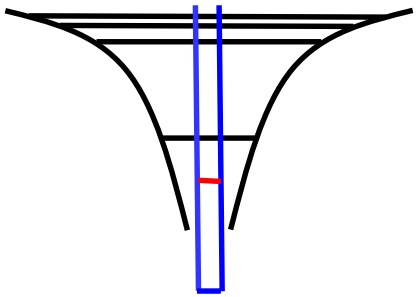


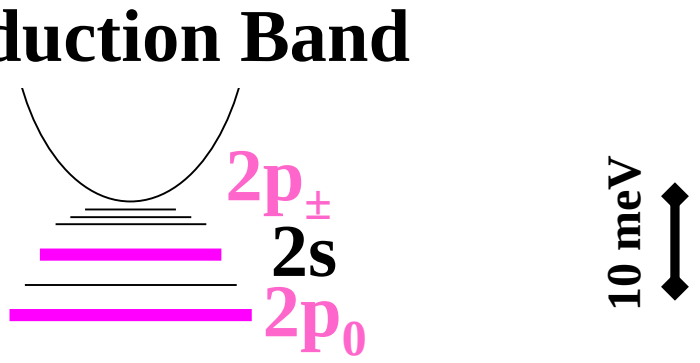
Лаборатория физики
полупроводниковых лазеров
на горячих носителях заряда

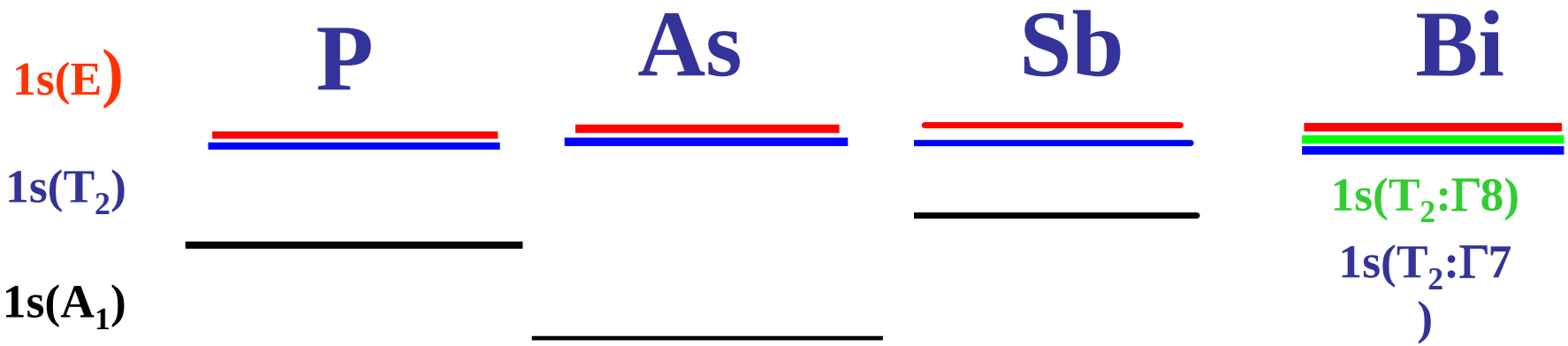
Outline

1) Introduction: donor states in silicon.
2) Populated inversion & lasing of group V donors under FEL excitation.
3) FEL pump-probe measurements of donor nonequilibrium states.
4) Laser action peculiarity & specificity of pump-probe response.
5) under resonant excitation of donor states.
6) Is there inter valley redistribution of bound electrons under elastic scattering?
7) Summary.

Group V Donors in Silicon



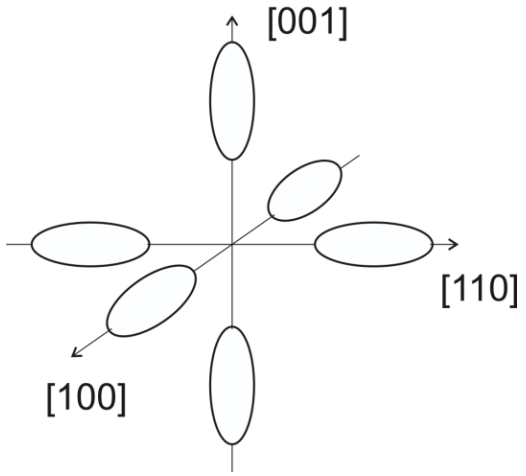


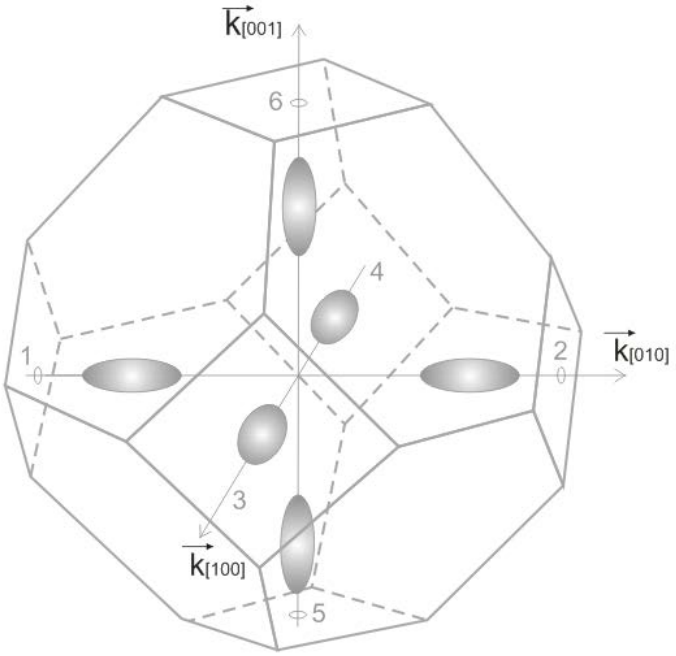


- Shastin V.N., Far Infrared Active Media Based on Intraband and Shallow Impurity States Transitions in Silicon, IRMMW Conference, Berlin (1996).

- S.G. Pavlov, R. Kh. Zhukavin, E. E. Orlova, V. N. Shastin, A. V. Kirsanov, H.-W. Hübers, K. Auen, H. Riemann, Stimulated emission from donor transitions in silicon, Phys. Rev. Lett., **84**, p. 5220 (2000)

Multivalley states in silicon.





Six-fold degeneracy

$\Psi(A_1) \sim (1,1,1,1,1,1)$

$\Psi(E) \sim (1,1,-1,-1,0,0)$

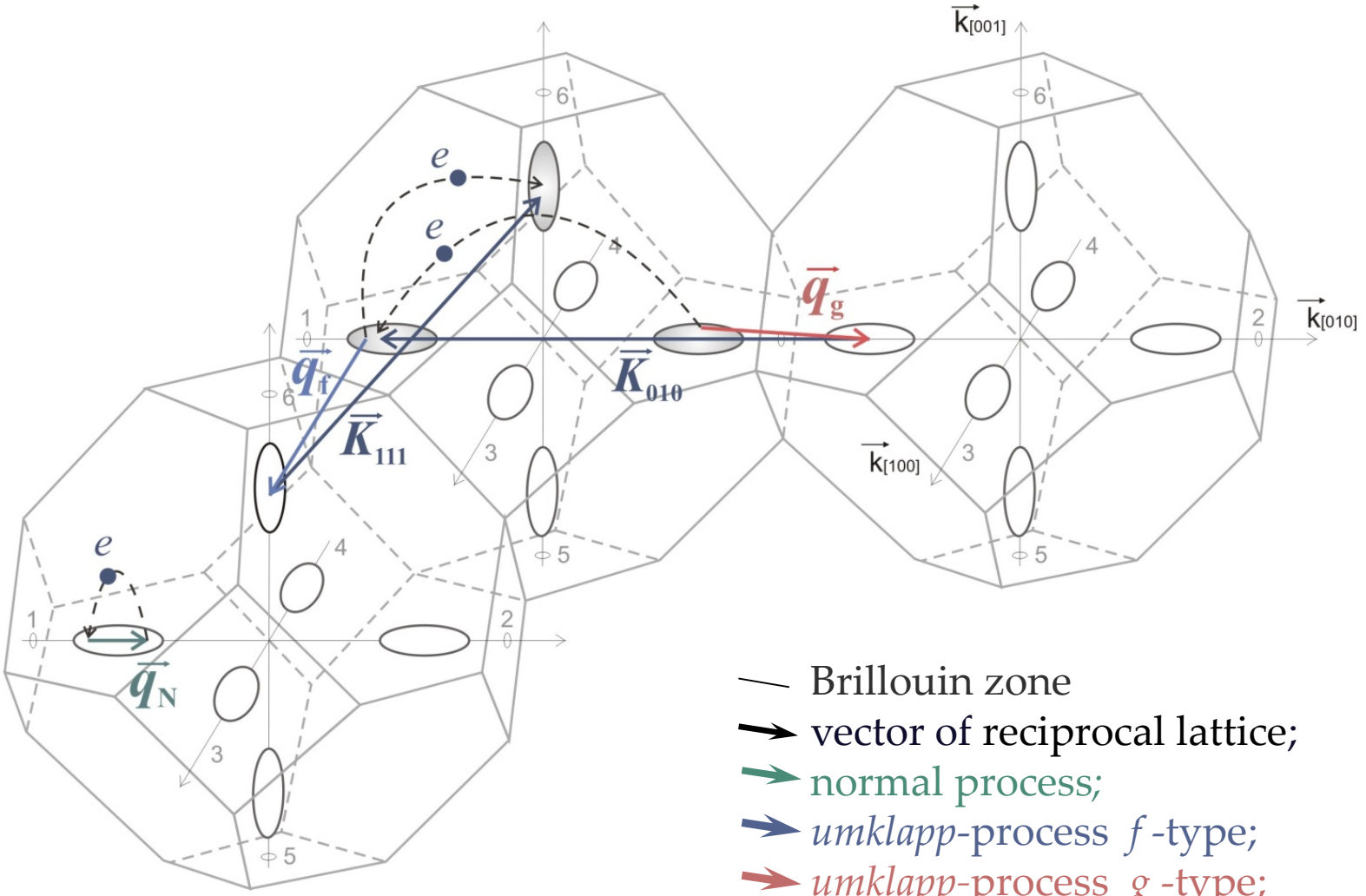
$(1,1,1,1,-2,-2)$

$\Psi(T_2) \sim (1,-1,0,0,0,0)$

$(0,0,1,-1,0,0)$

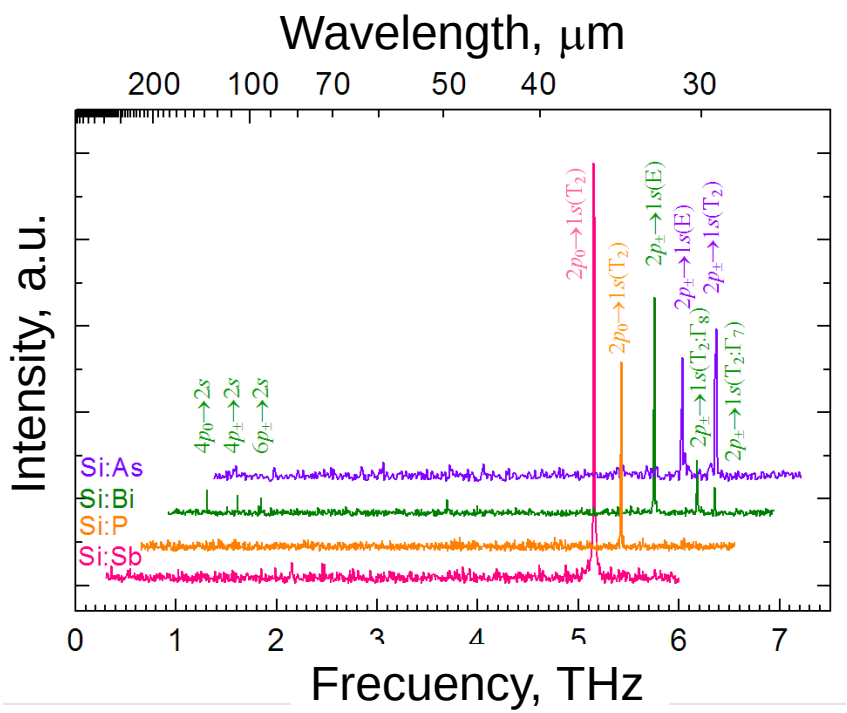
$(0,0,0,0,1,-1)$

Electron-phonon interaction

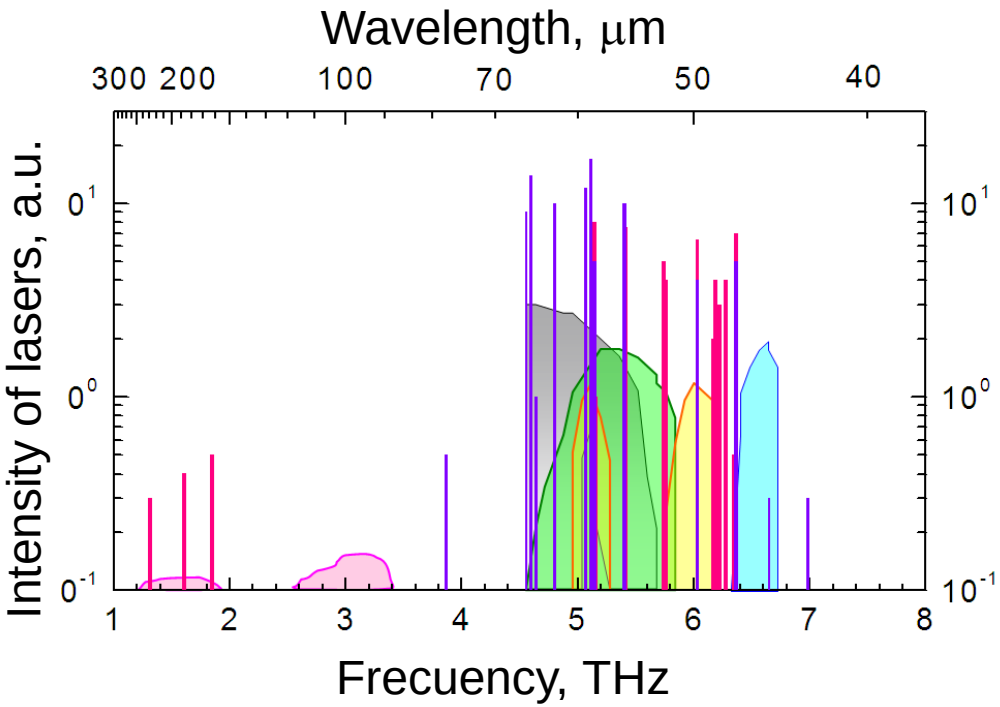


Laser lines of group-V donors in Si (summarized data)

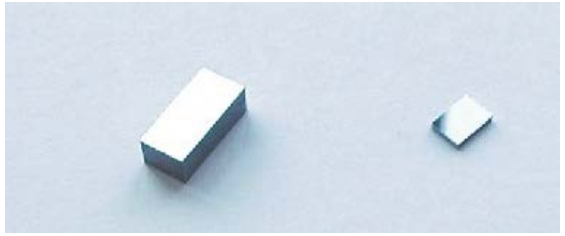
Normal lasing



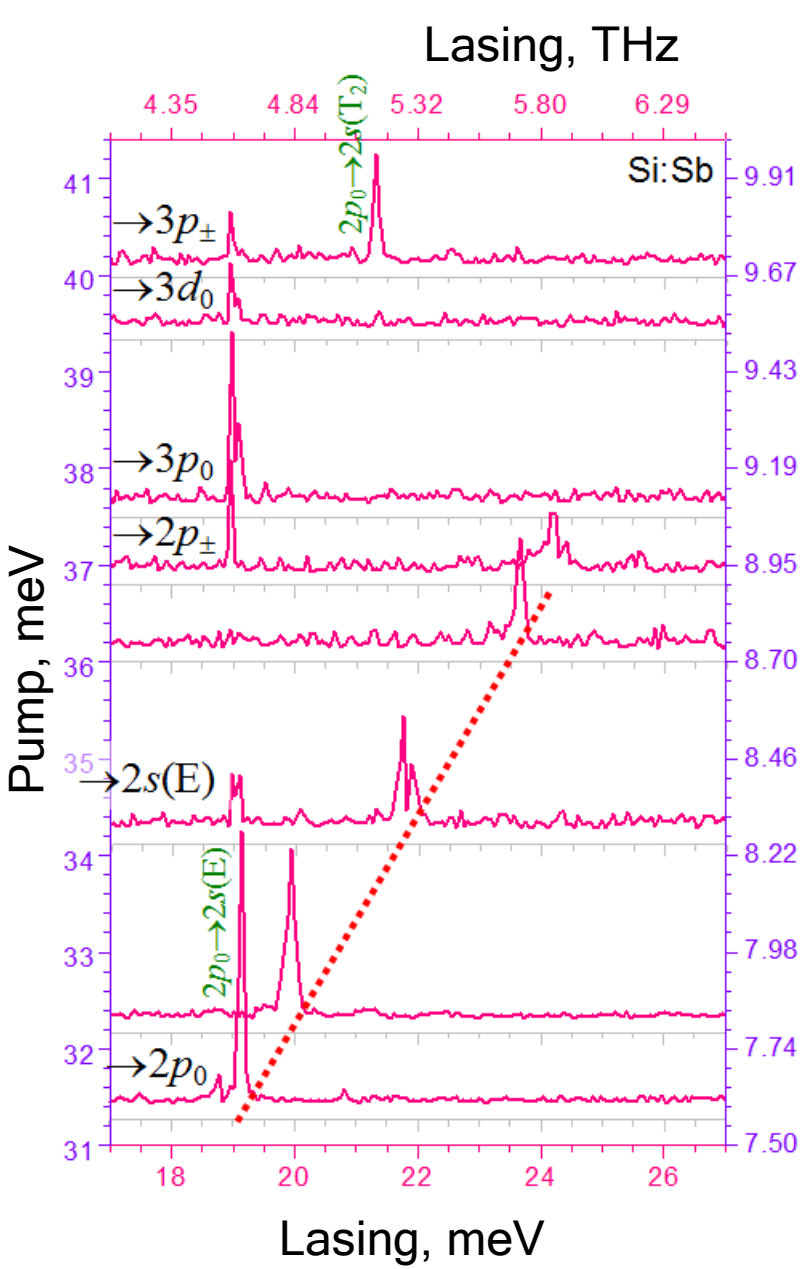
Normal + Raman lasing

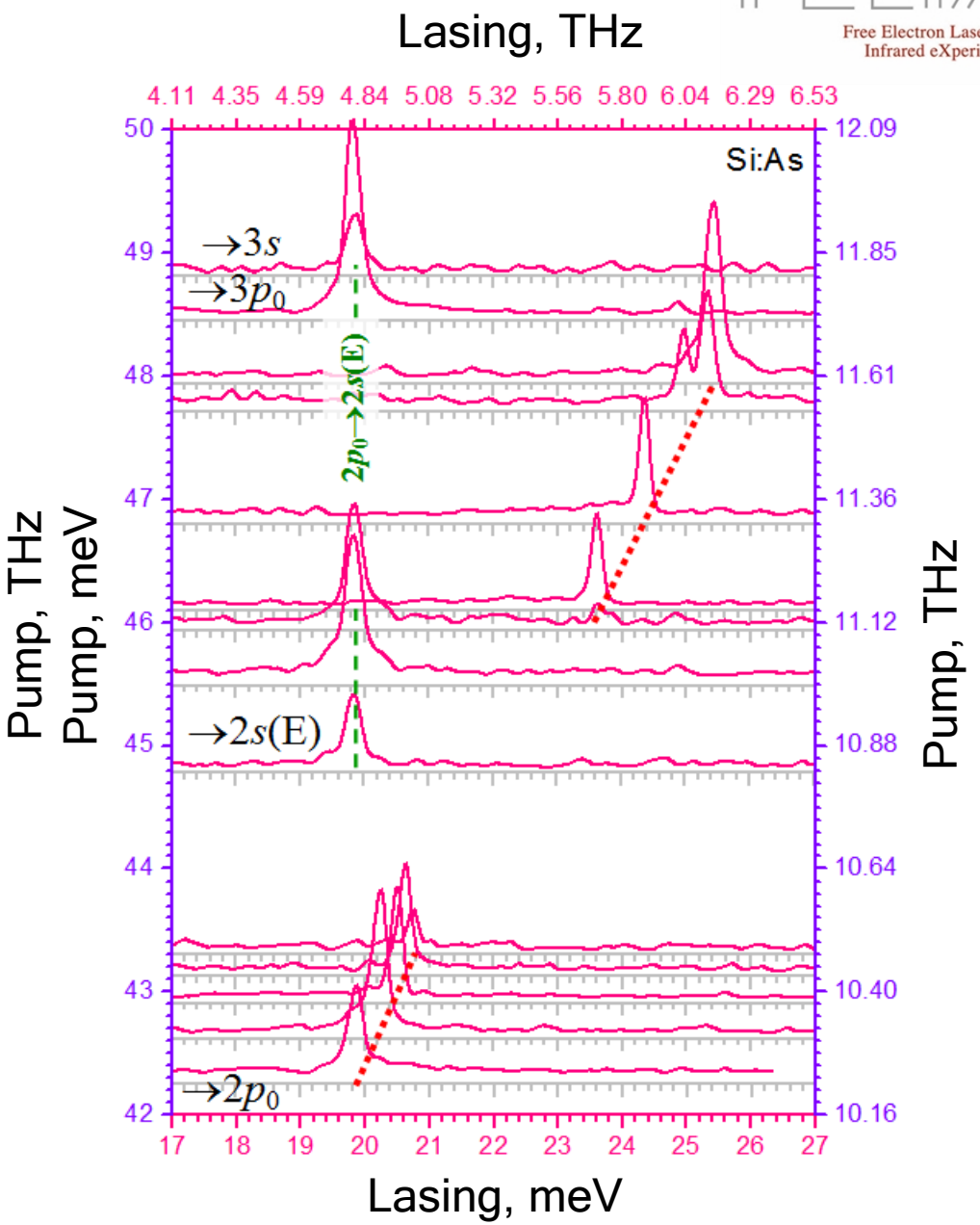


Stimulated terahertz emission from group-V donors in silicon under intracenter photoexcitation, V. N. Shastin *et.al.*, Appl. Phys. Lett. 80, 3512 (2002)



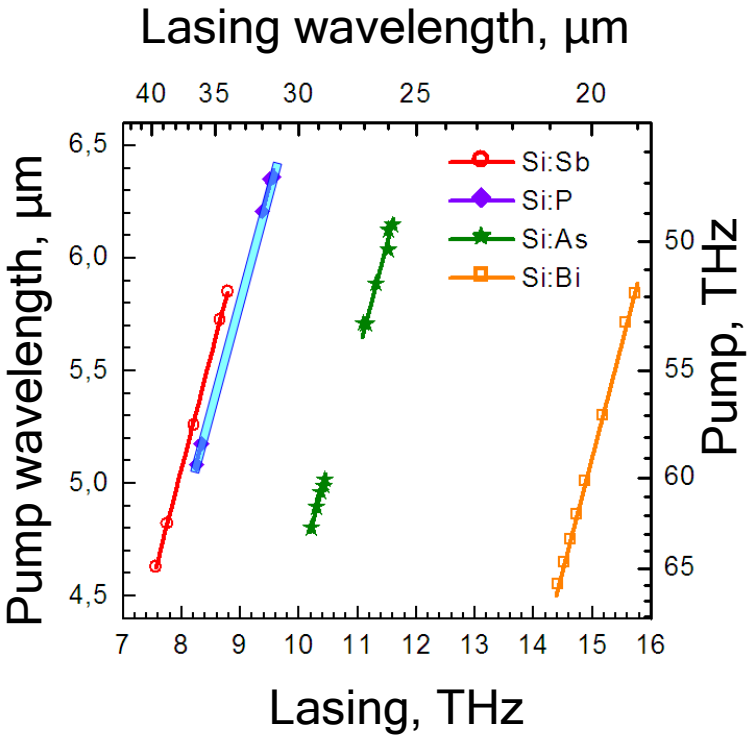
Raman lasing (Stokes process)

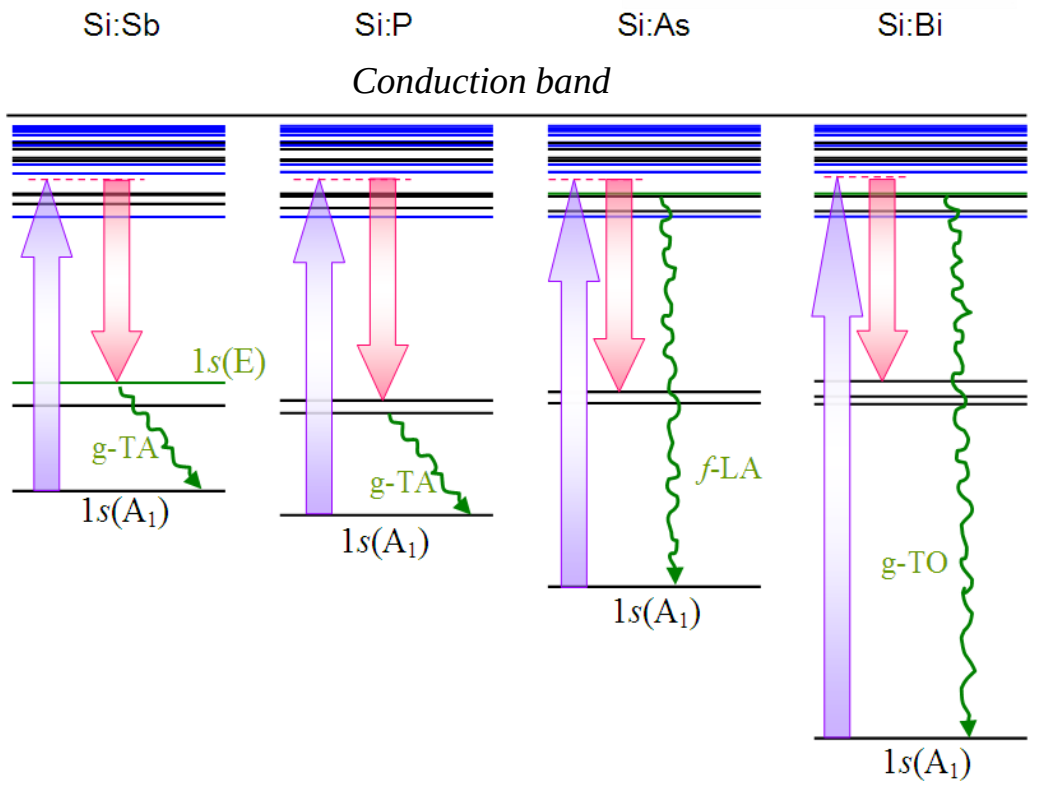




Raman lasing summary

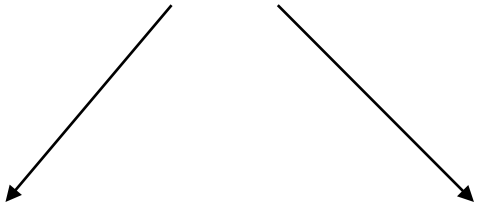
Free Electron Lasers for Infrared eXperiments





Terahertz Raman laser based on silicon doped with phosphorus
S. G. Pavlov *et.al.*, Appl. Phys. Lett. **92**, 091111 (2008)

FEL → Lasing



Normal lasing

Prof. H.-W.Hübers

Raman lasing

Dr. S.Pavlov

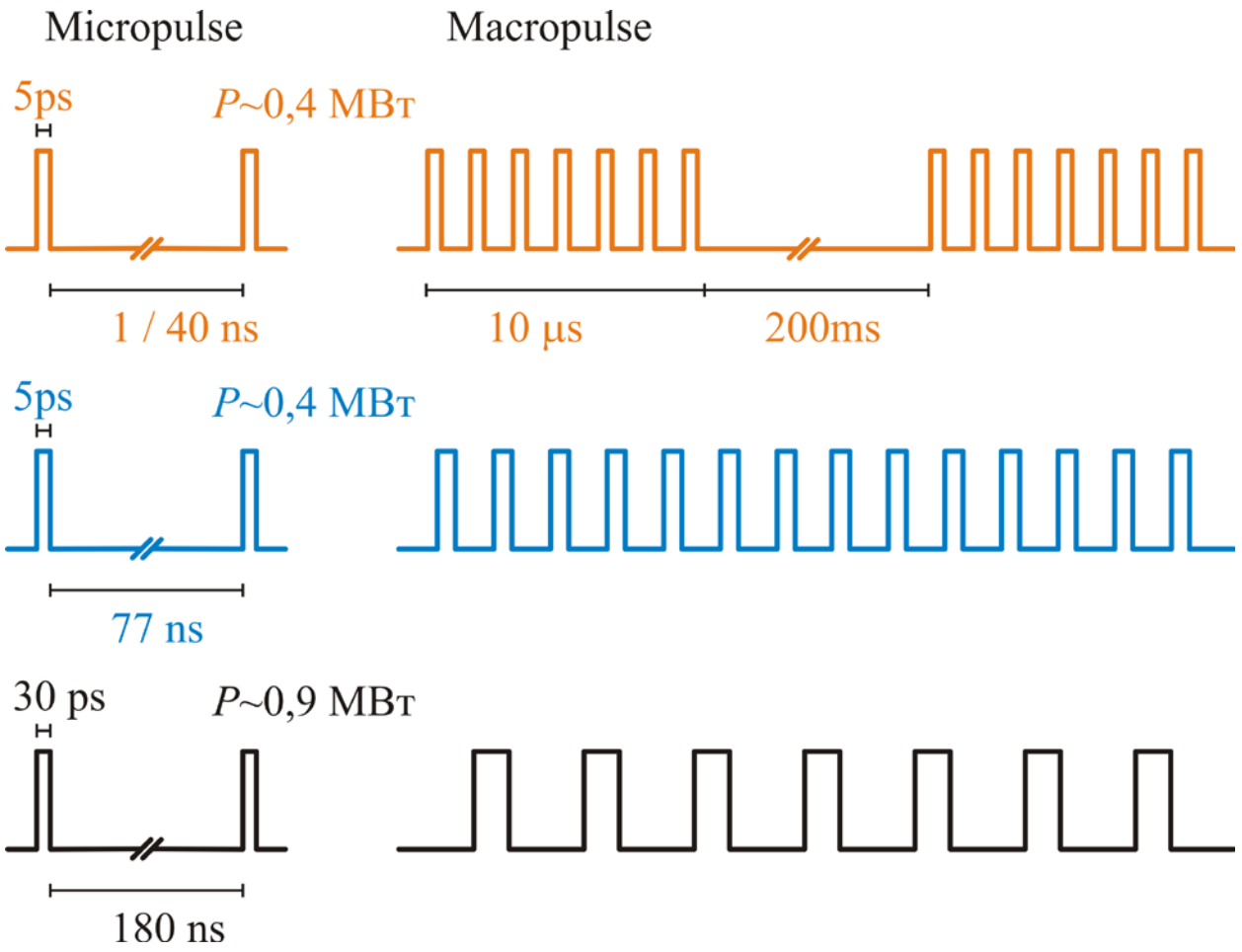
(German Aerospace Center)

FELIX
Free Electron Lasers for Infrared eXperiments

ELBE.

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

NovoFEL

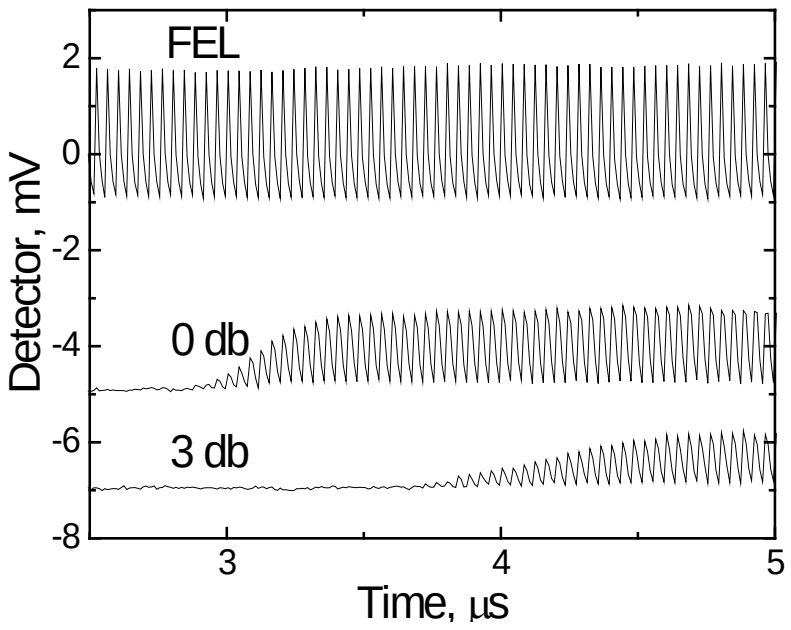


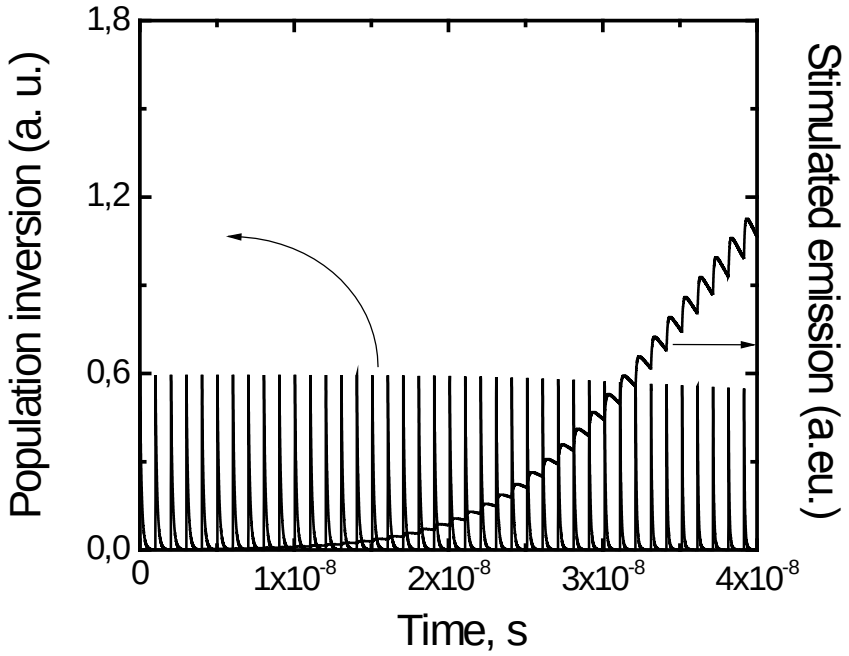
Output power instability ~10%

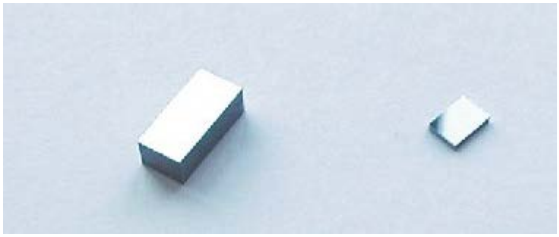
Lasing

Free Electron Lasers for Infrared eXperiments

Si:P $2p_0 \rightarrow 1s(T_2)$



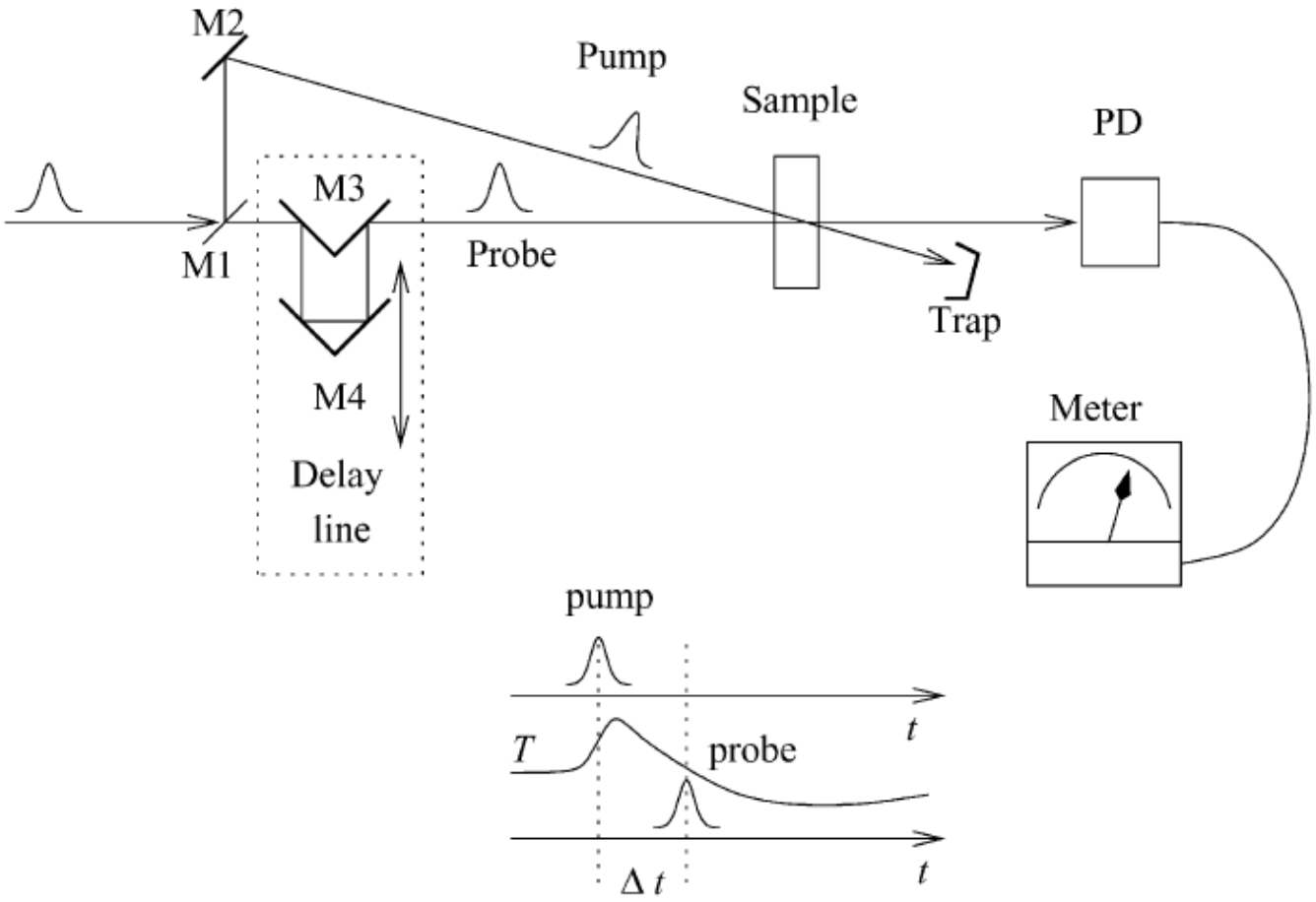




$\tau_{photon} \geq \Delta\tau$

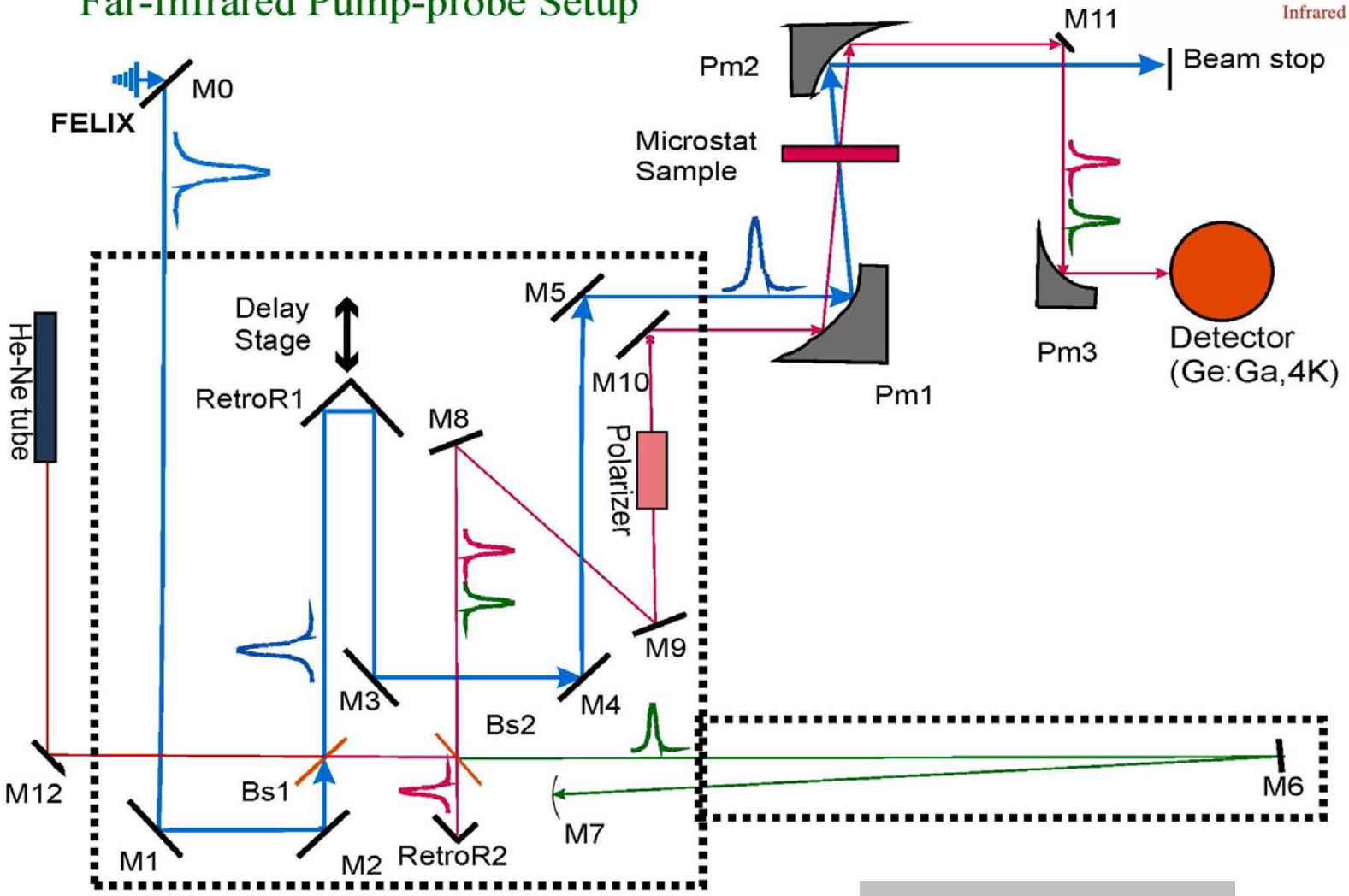
~10 ns

Pump-probe technique



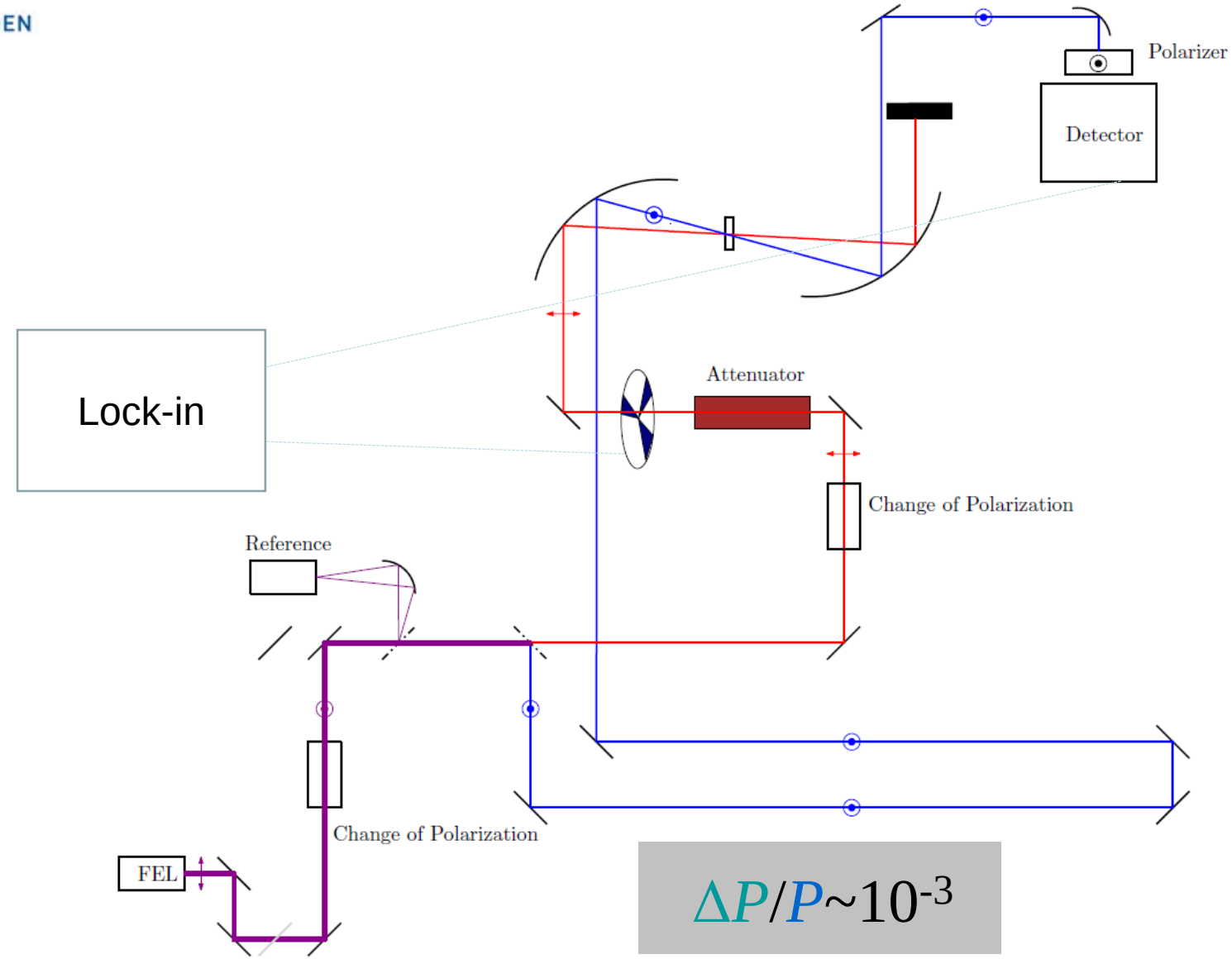
FELIX
Free Electron Lasers for Infrared eXperiments

Far-Infrared Pump-probe Setup



$\Delta P/P \sim 10^{-3}$

Pump-Probe-Experiment @ ELBE

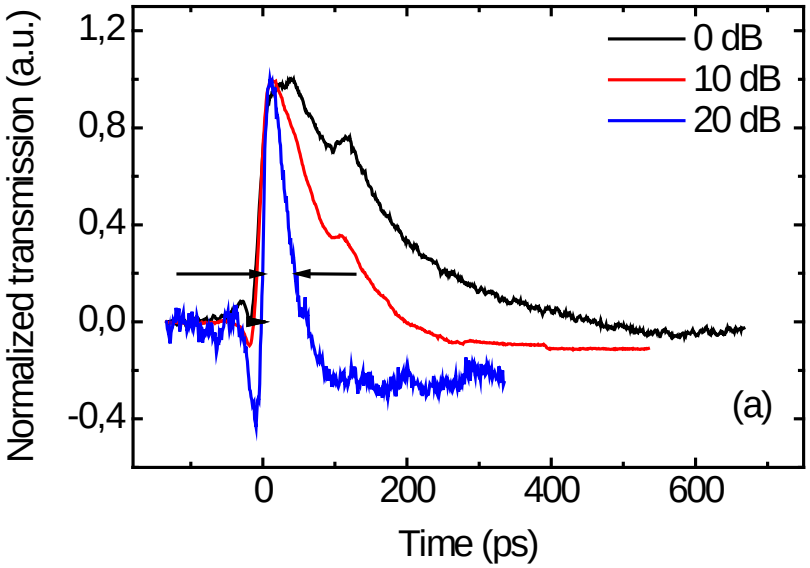


$\Delta P/P \sim 10^{-3}$

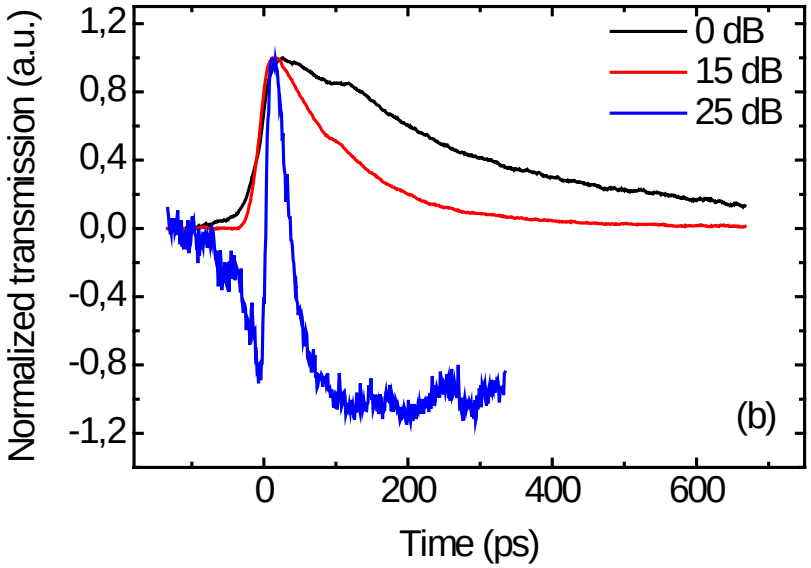
Pump-probe measurements on Si:P

Free Electron Lasers for Infrared eXperiments

$2p_0$



$2p_{\pm}$

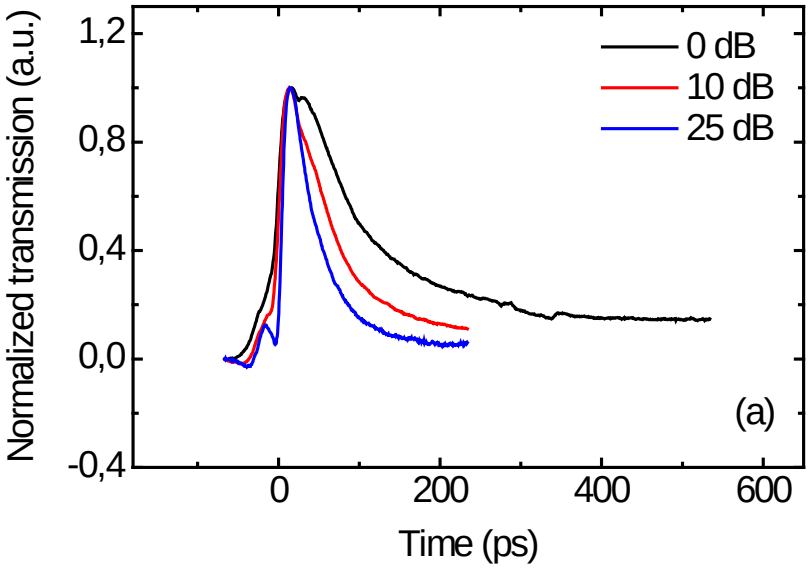


2001 – 2002 years

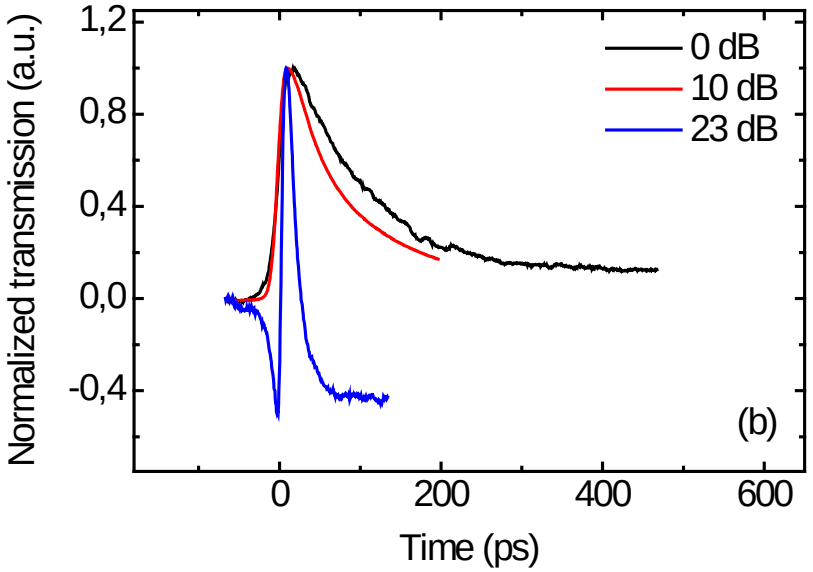
Pump-probe measurements Si:As

Free Electron Lasers for Infrared eXperiments

$2p_0$



$2p_{\pm}$

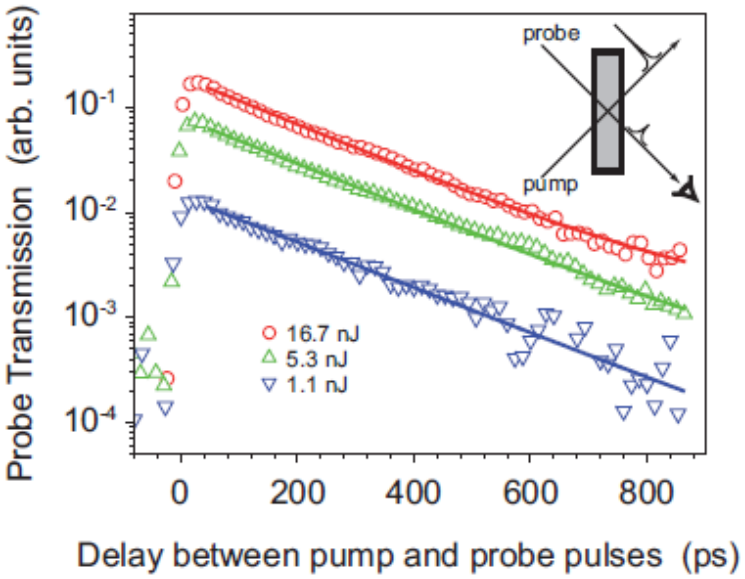


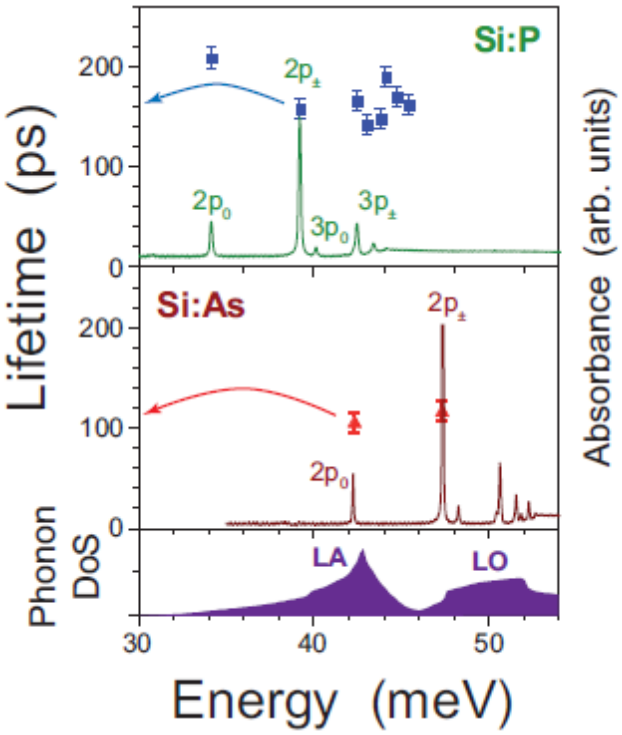
2001 – 2002 years

Pump-probe: shallow donors in silicon

Free Electron Lasers for Infrared eXperiments

Si:P : $1s(A_1) \rightarrow 2p_0$



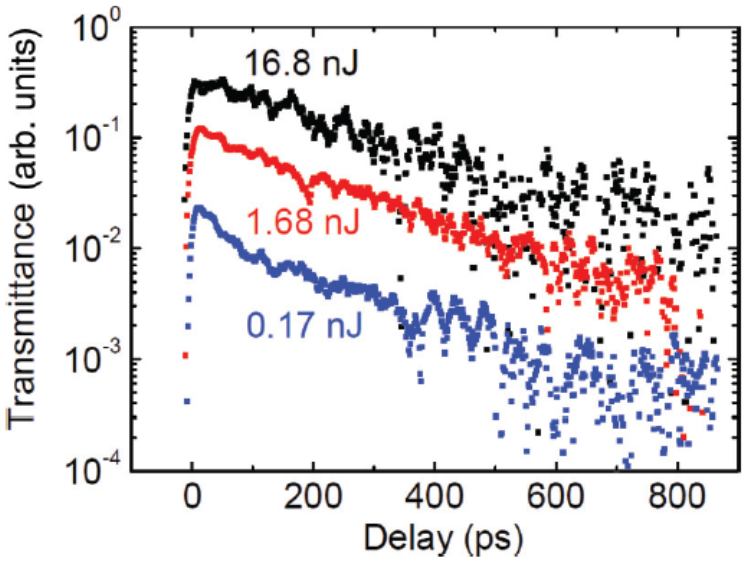


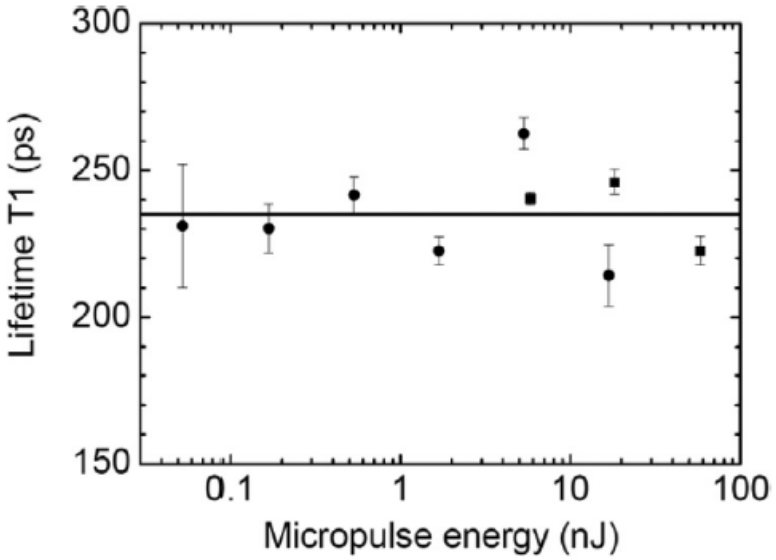
Silicon as a model ion trap: Time domain measurements of donor Rydberg states, N. Q. Vinh, P. T. Greenland, K. Litvinenko, B. Redlich, A. F. G. van der Meer, S. A. Lynch, M. Warner A. M. Stoneham, G. Aeppli, D. J. Paul, C. R. Pidgeon and B. N. Murdin‡, PNAS (2008)

Pump-probe: ^{28}Si:P

Free Electron Lasers for Infrared eXperiments

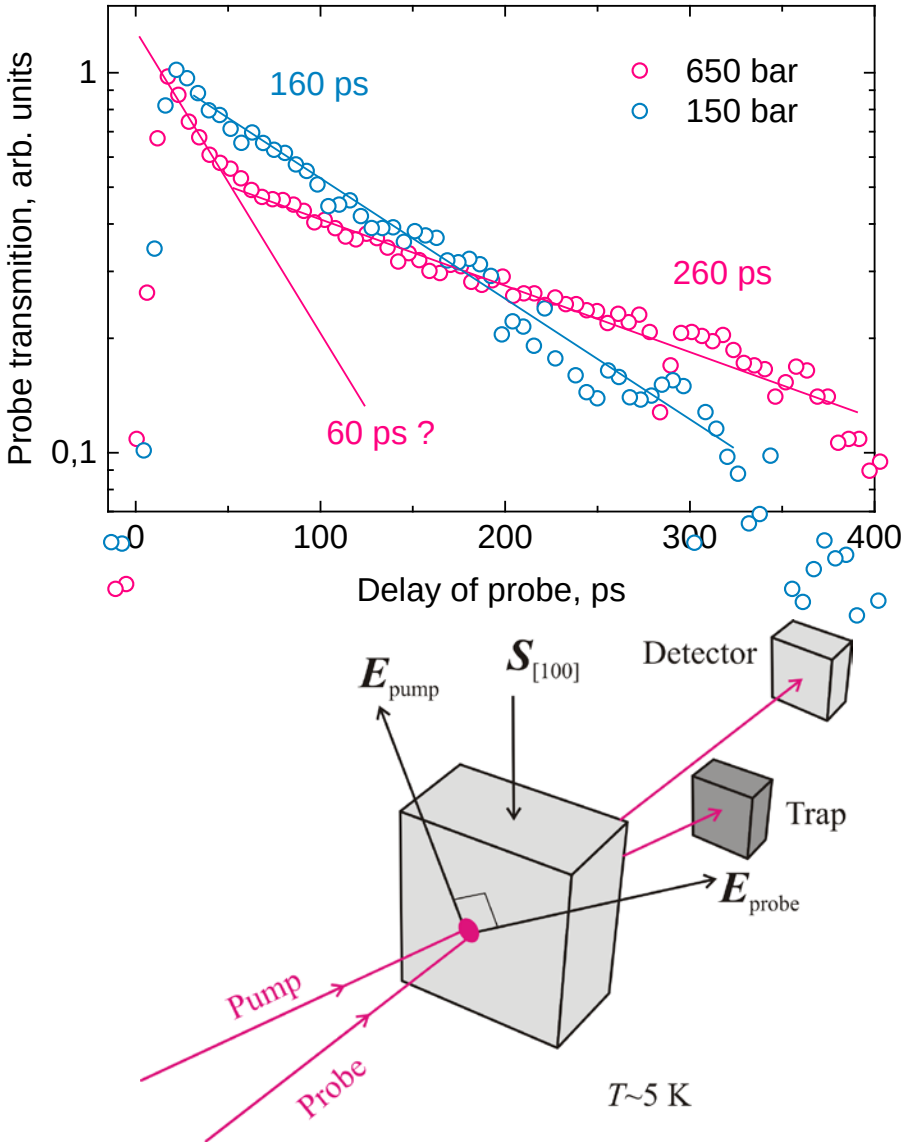
$1s(A_1) \rightarrow 2p_0$

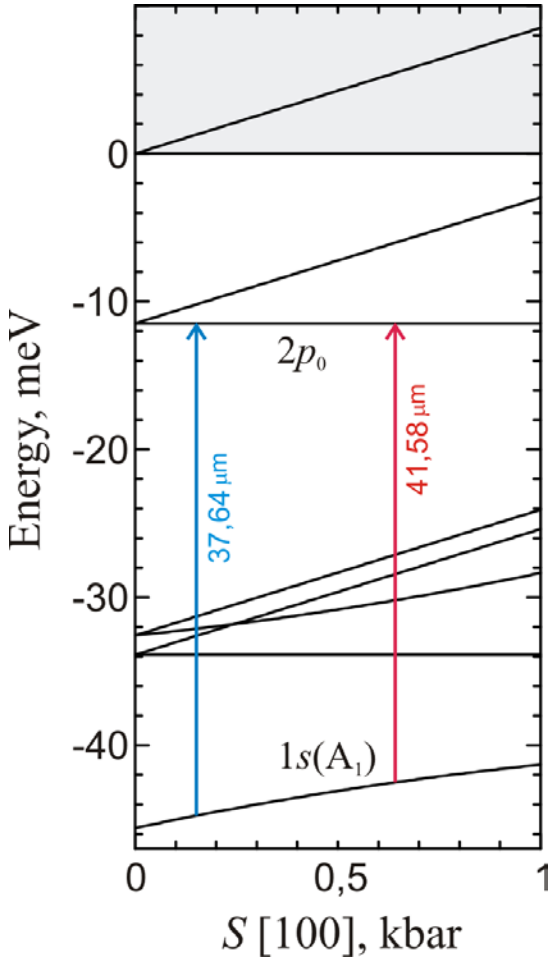




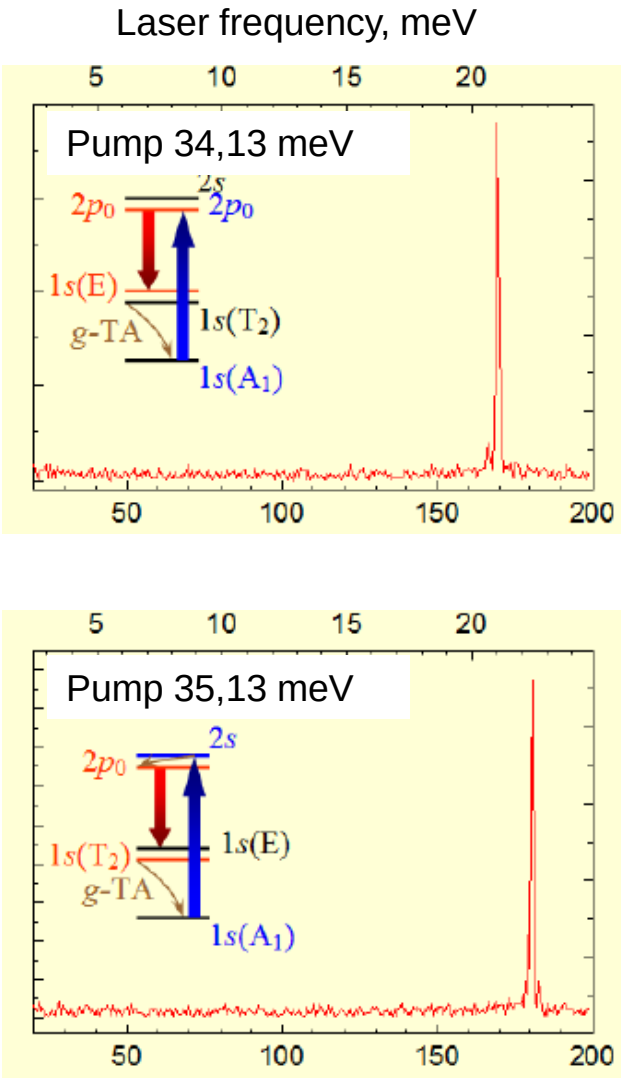
Isotope effect on the lifetime of the $2p_0$ state in phosphorus-doped silicon
H.-W. H¨ubers, S. G. Pavlov, S. A. Lynch, Th. Greenland, K. L. Litvinenko, B. Murdin, B. Redlich, A. F. G. van der Meer, H. Riemann, N. V. Abrosimov, P. Becker, H.-J. Pohl, R. Kh. Zhukavin, and V. N. Shastin,
PHYSICAL REVIEW B **88**, 035201 (2013)

Pump-probe: *uniaxially* stressed Si:P





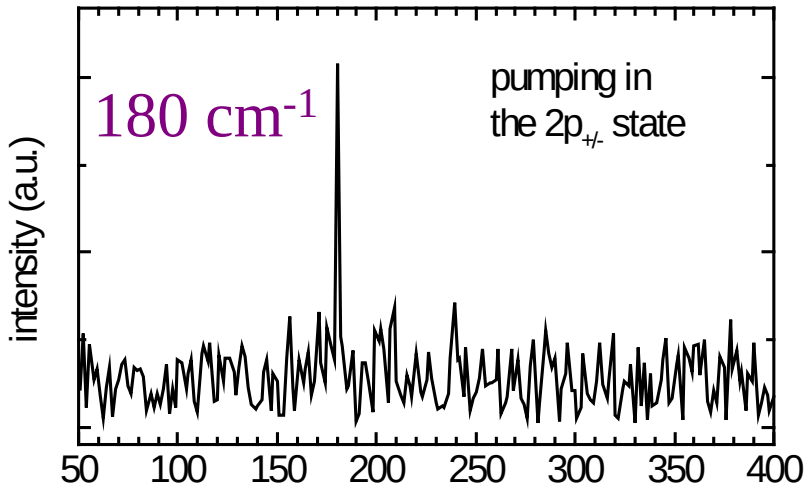
Dependence of Si:P laser frequency on the excited states

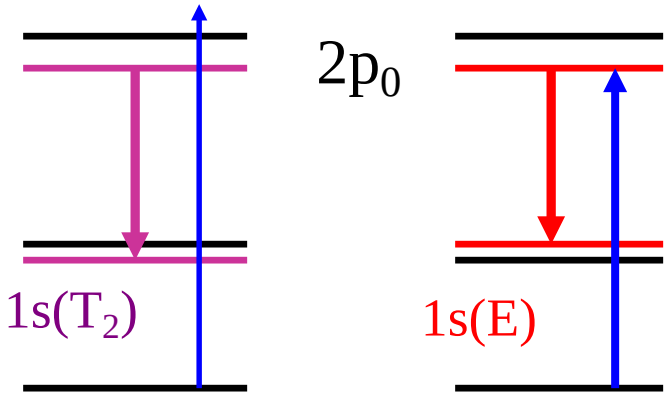


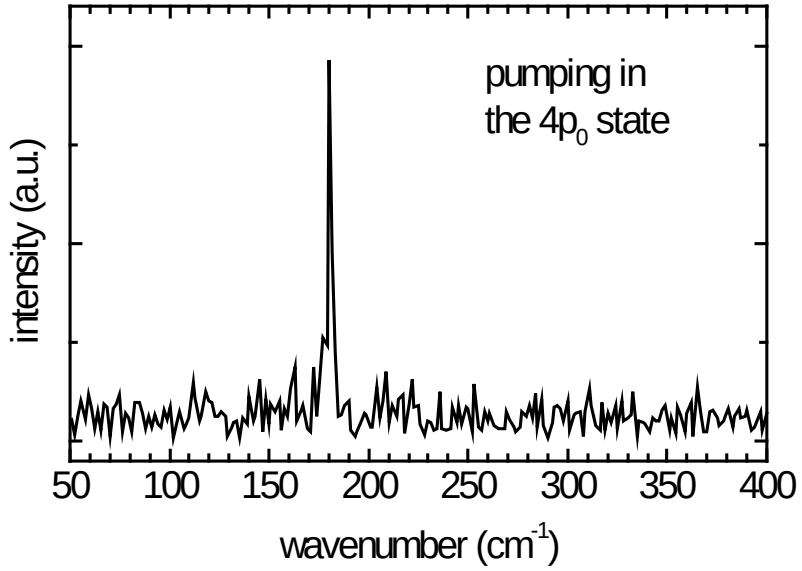
171 cm^{-1}

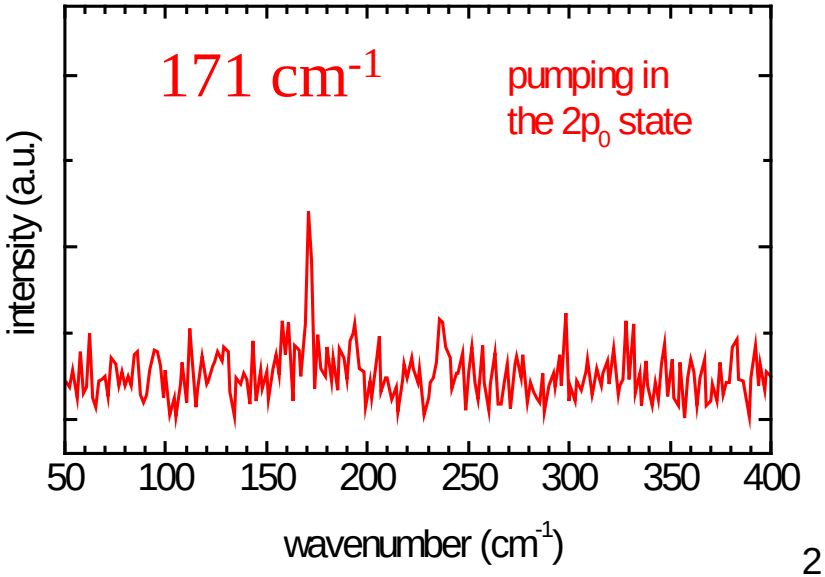
180 cm^{-1}

Si:P emission spectra under intracentre pumping



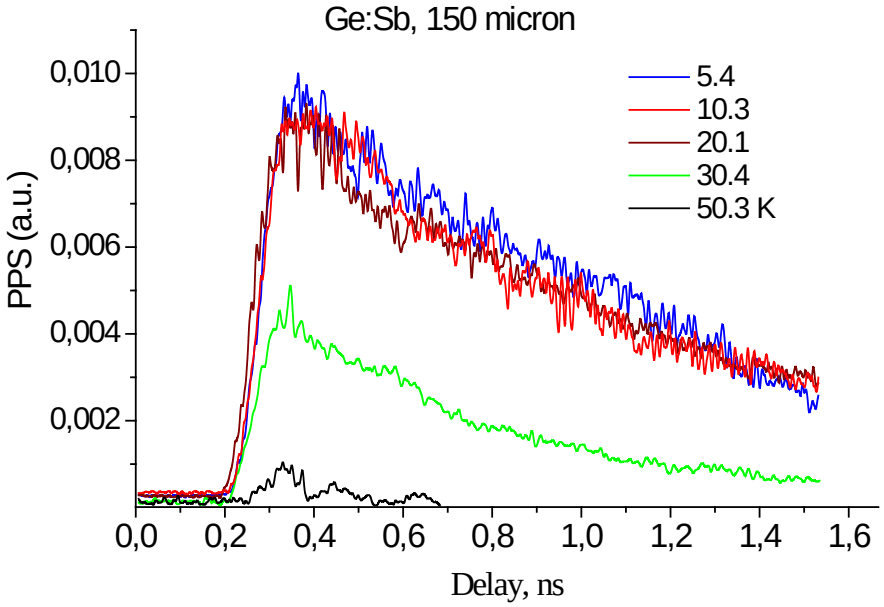


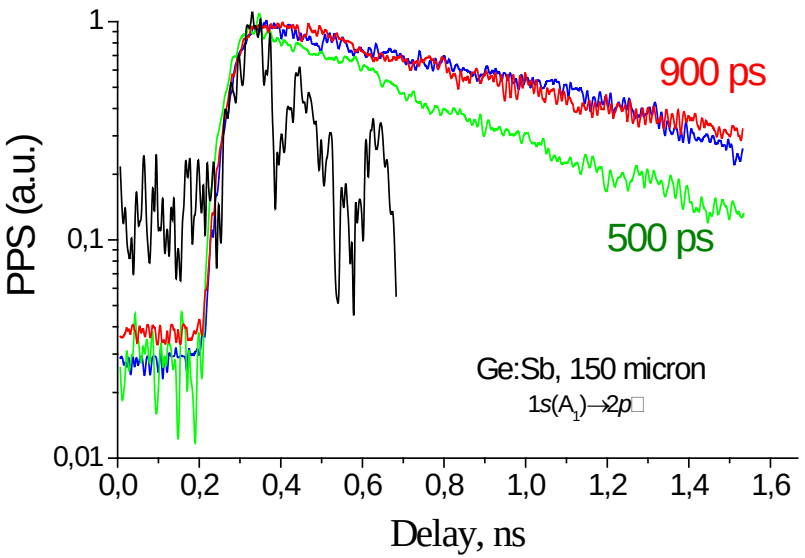




Pump-probe: Ge:Sb

NovoFEL





Summary:

1) FEL pump-probe measurement is an effective tool
for the study of non–equilibrium states of donors
as well as acceptors in semiconductors

2) During the short time of (~60ps and even less) elastic
scattering considerably change the distribution of electrons over
the donor valleys in silicon. Perhaps it is explained by a point imperfection
scattering of electrons in the real crystal.

Thank you for attention!