Towards driving Quantum Systems in cryogenic environments with the Near-Field of Modulated Electron Beams

T. Spielauer[1], M. Kolb[1], T. Weigner[1], J. Toyfl[1], G. Boero[2], P. Haslinger[1]

[1]VCQ, Technische Universität Wien, Atominstitut, Stadionallee 2, 1020 Vienna, Austria; [2]EPFL, BM 3110 Station 17, CH-1015 Lausanne, Switzerland

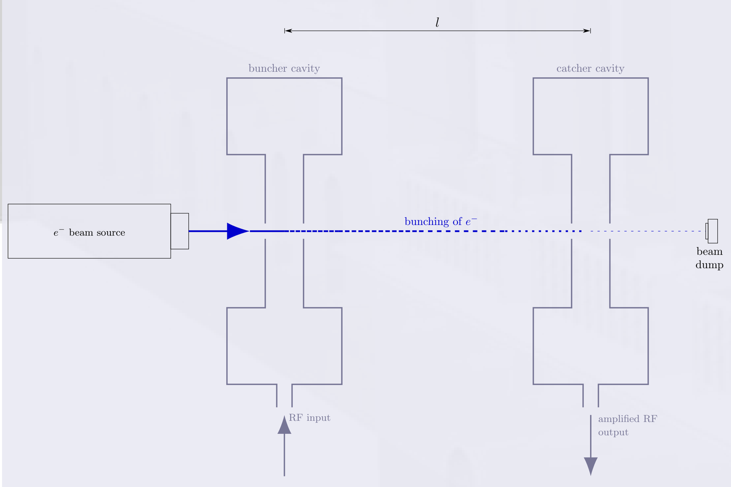
Abstract

Coherent electromagnetic control of quantum systems is usually done by electromagnetic radiation - which does not permit addressing single site-selected quantum systems, especially in the microwave range. In our proof of concept experiment we want to couple for the first time the non-radiative electromagnetic near-field of a spatially modulated electron beam to a quantum system in a coherent way as has been proposed lately. As the quantum system we use the unpaired electron spins of a free radical organic sample (Koelsch radical α,γ-Bisdiphenylene-β-phenylallyl) that is excited via the near-field of the aloof electron beam. The readout of the spin excitation resembles a classic continuous wave electron spin resonance experiment and is done inductively via a microcoil using a lock-in amplifier.

The long term perspective of this experiment is the ability to coherently drive and investigate quantum systems in a spatial volume way below the diffraction limit of traditional electromagnetic wave based excitation schemes. The spatially confined excitation using an electron beam could also be realized within an electron microscope. Within the last year we have been able to improve the setup, couple the electron beam to the microcoil and reduce noise sources as well as started preparations to cool down the microcoil setup to cryogenic temperatures for enhanced signal to noise ratio.

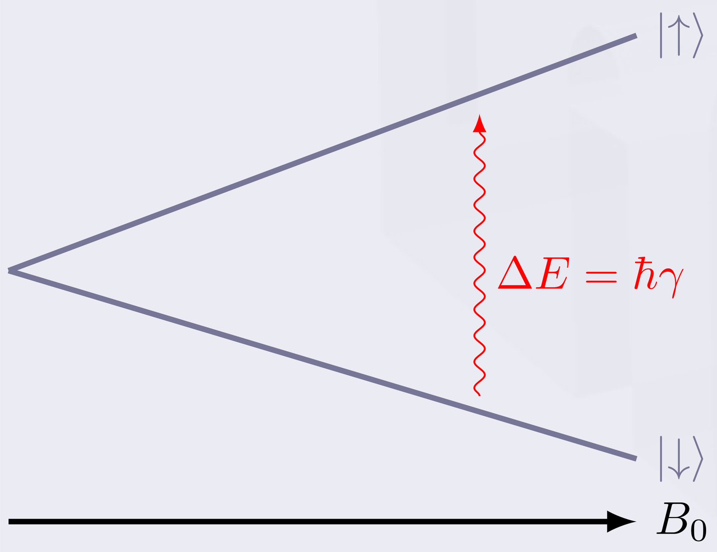
The Quantum Klystron

We call our experiment the *Quantum Klystron*, referencing an established technology, the Klystron.



Klystron

- Linear beam vacuum tube invented in 1935, used as RF and microwave amplifier
- Electrons accelerated into a linear tube
- Velocity modulation in buncher cavity by input signal
- Density modulated charge carrier wave forms through driftspace
- Outcoupling via catcher cavity

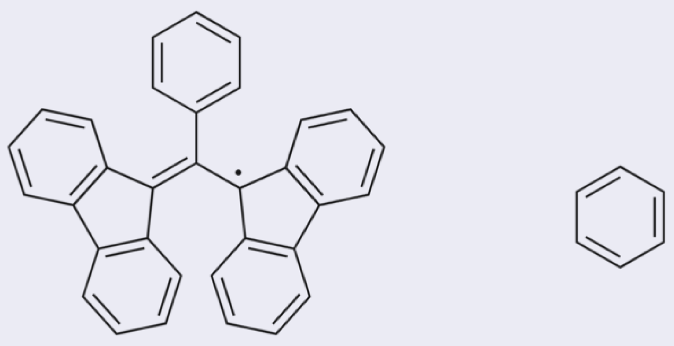


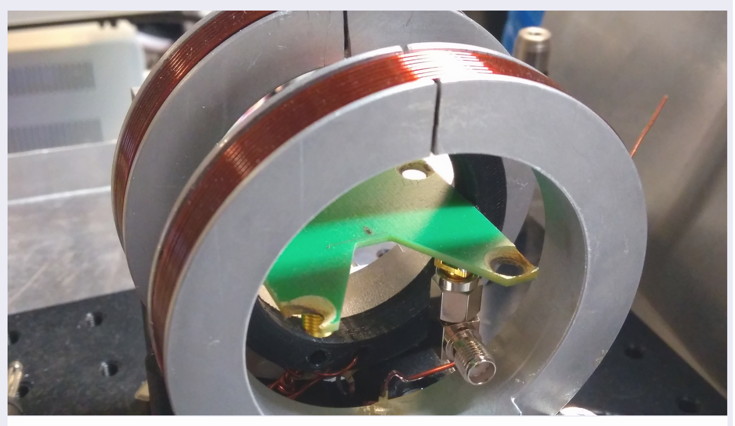
Quantum Klystron

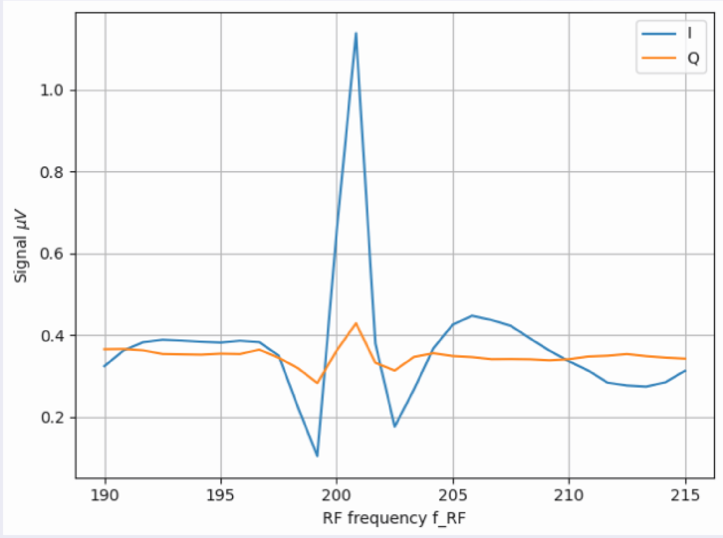
- Replace catcher cavity with 2 level quantum system
- Drive system using *non-radiative electromagnetic near-field* of electron beam.
- Either modulate in
  - *time domain* - bunching / density modulation
  - *spatial domain* - deflection
- Ability to draw arbitrary potentials (drive optical dipole, quadrupole, ... transitions, spin systems, ...)

Electron spin resonance with electron beams

Our experiment resembles an electron spin resonance experiment. In contrast to classic electron spin resonance where systems are excited using microwaves we use the *non-radiative electromagnetic near-field* of an electron beam.

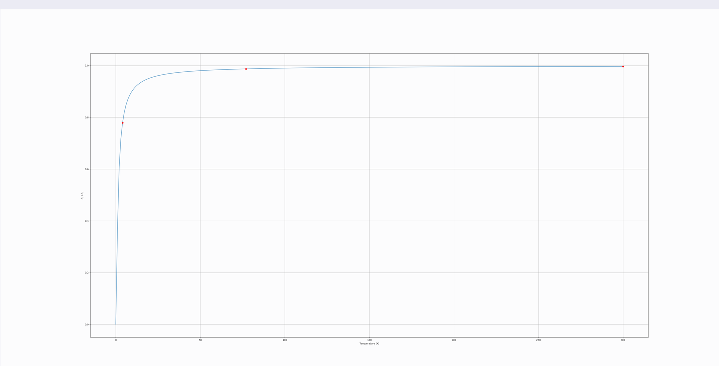






- Koelsch radical α,γ-Bisdiphenylene-β-phenylallyl
- Unpaired spin $\rightarrow$ high spin density
- Excitation with microwave works at room temperature
- RF excitation background by radiated fields $\rightarrow$ differential measurements with and without electron beam required

Temperature dependence

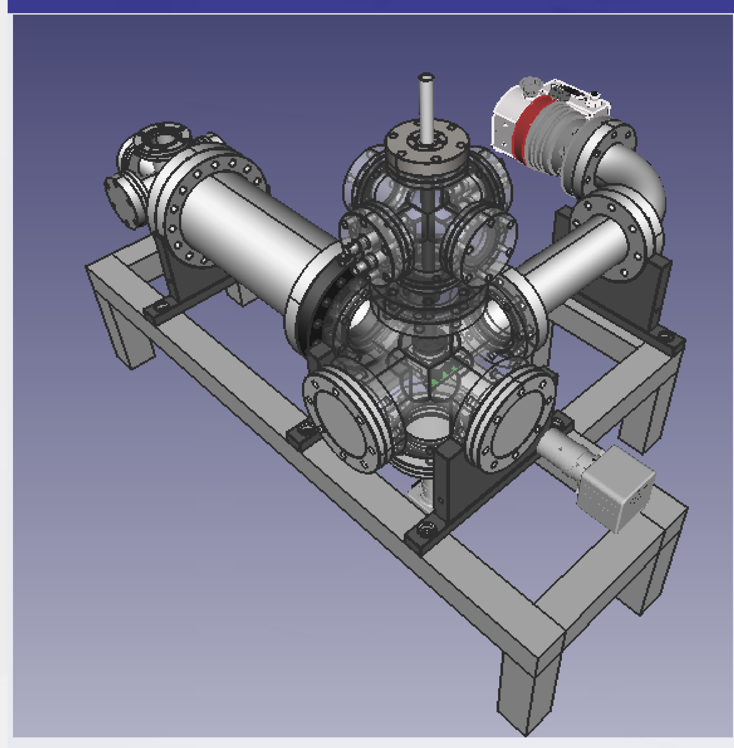


- Thermal population of spin states heavily temperature dependent
- $\frac{n_2}{n_1} = e^{-\frac{DeltaE}{k_B T}} = \left(e^{-\frac{\Delta E}{k_B}}\right)^{\frac{1}{T}}$
- Moving to $77K$ (liquid nitrogen): expect $8.9nV$ signal expected gain ≈ 4, SNR gain ≈ 7.7 simple to realize
- Moving to $4K$ (liquid helium): expect $1.7\mu V$ signal expected gain ≈ 75, SNR gain ≈ 650 challenging to realize

Contact

Thomas Spielauer
Technische Universität Wien, Atominstitut
thomas.spielauer@tuwien.ac.at

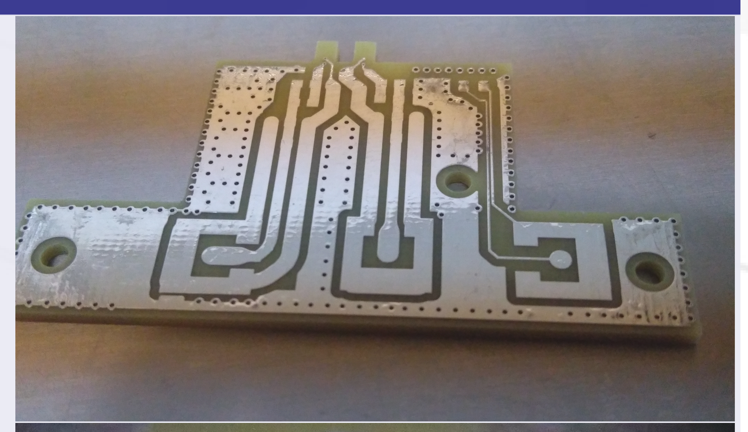
Experimental setup

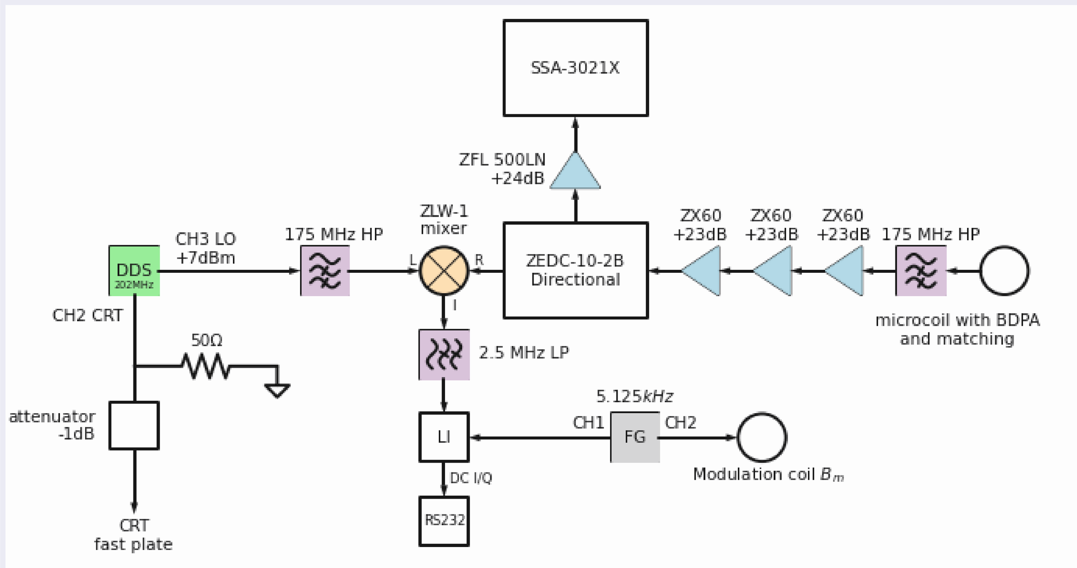


- Running in vacuum at 10^{-8} mbar or better
- Electron source (Barium-Strontium cathode, electrostatic beam deflection) with $\geq 10\mu A$ beam current at up to $2.2kV$ acceleration voltage
- Beam modulation frequency up to $\approx 250MHz$
- Camera imaging of phosphor screens to determine and monitor beam parameters
- Cooling with liquid nitrogen reservoire and copper coldfinger

Readout and radio frequency setup

- Using carrier PCB thermally coupled to a copper coldfinger. The PCB contains the microcoils as well as en RF impedance match, copper areas to thermally couple to the coldfinger and high voltage protection.
- We use a second coil for reference measurements
- Sample is positioned inside microcoil (2 windings, 2.58 x $1.14mm$ outer diameter, 1.5 x $0.5mm$ sample area)





- Using two independent channels of an AD9959 based DDS for local oscillator and beam deflection (excitation).
- Applying additional $5.123kHz$ modulation field B_m in same direction as B_0
- Performing lock-in detection

First tests on test setup

We did some initial tests on our setup by simply cooling a PCB containing our BDPA sample in a liquid nitrogen bath. The sample then was excited using microwaves coupled in via a directional coupler as in a traditional setup. We saw the expected increase in signal amplitude as well as a shift of our impedance match that we have to compensate for.

References & Acknowledgements

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