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

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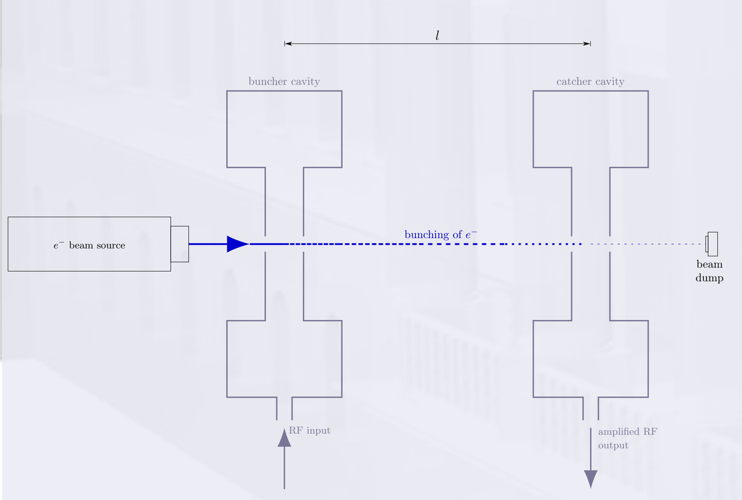
Abstract

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[1]. 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.

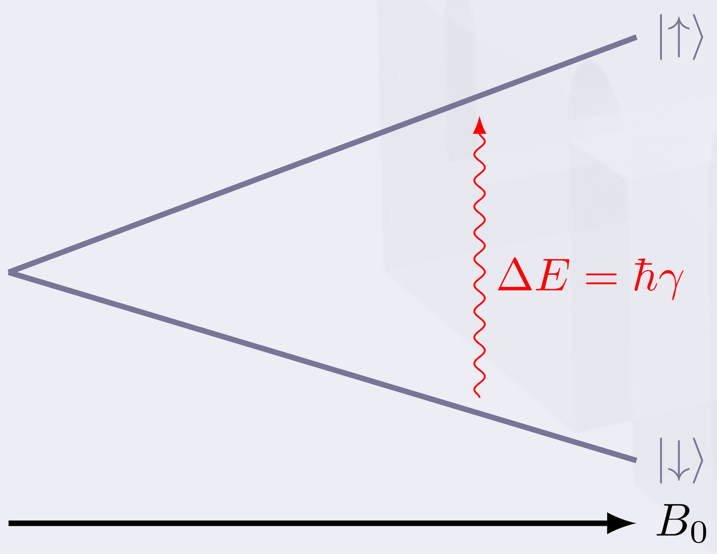
The Quantum Klystron

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 are accelerated into a linear tube
- Velocity modulation happens in a buncher cavity by the input signal
- A density modulated charge carrier wave forms through driftspace
- Outcoupling is done via a catcher cavity

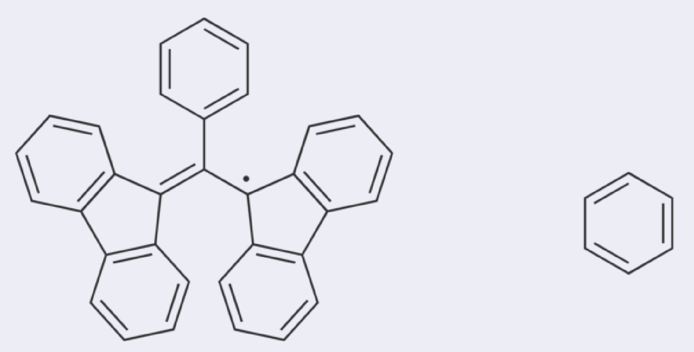


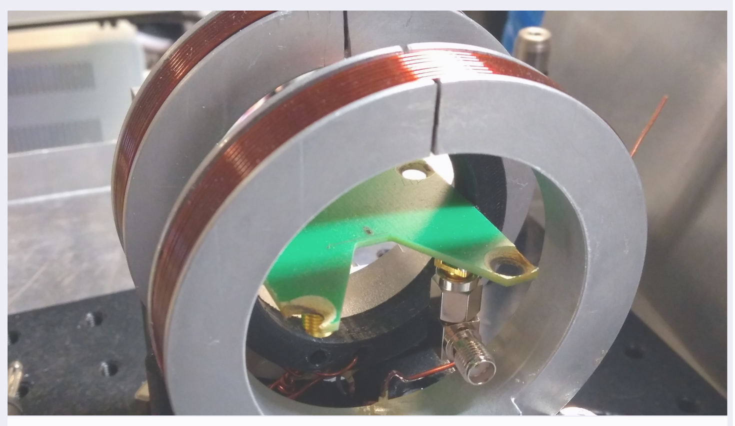
Quantum Klystron

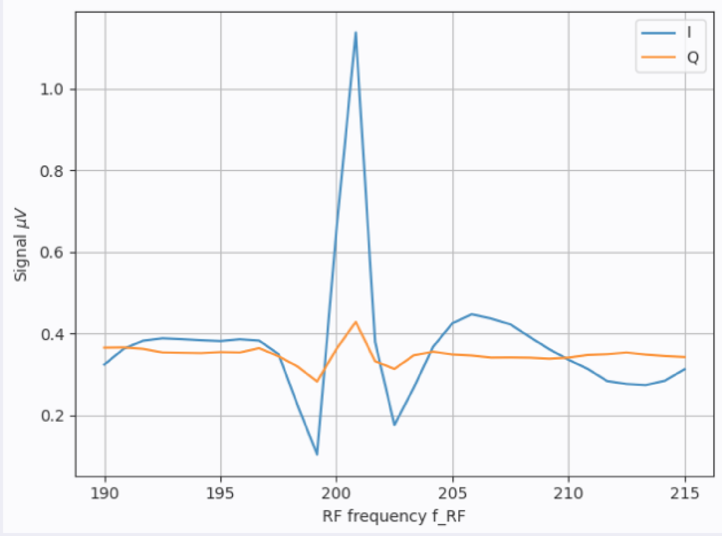
- We replace catcher cavity with a 2 level quantum system
- Then we drive the system using the *non-radiative electromagnetic near-field* of an electron beam.
- Either modulate in
  - *time domain* - bunching / density modulation
  - *spatial domain* - deflection
- Ability to draw arbitrary potentials (drive optical dipole, quadrupole, etc. transitions, spin systems, ...)
- High spatial resolution (de Broglie wavelength of modulated electron beam $\lambda_{DB} = 27.3pm$, wavelength of a 202 MHz electromagnetic wave $\lambda = 1.48m$)

Electron spin resonance with electron beams

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





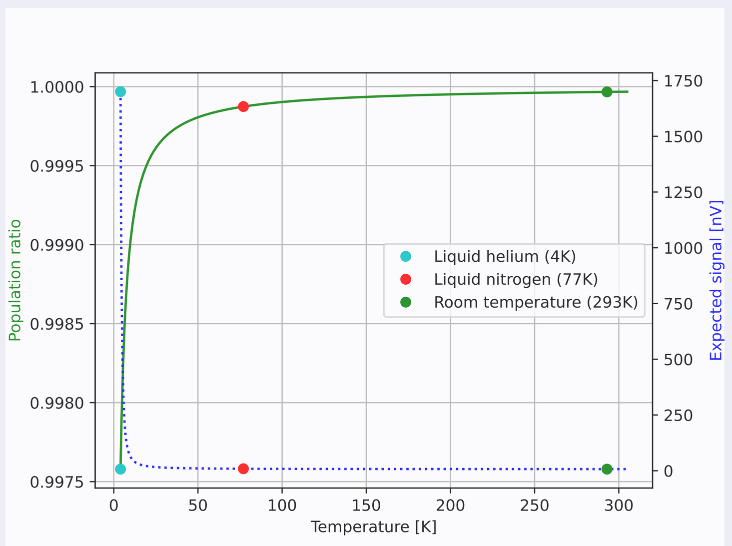


- As sample we use the Koelsch radical (α,γ-Bisdiphenylene-β-phenylallyl - BDPA)
- It has an unpaired spin $\rightarrow$ high spin density
- Excitation with microwave works at room temperature
- There is massive RF excitation background by radiated fields in our setup $\rightarrow$ differential measurements with and without electron beam or at different distances to the modulated beam are required

Temperature dependence

We want to move to a cryogenic environment. This is done due to the small signal generated by the modulated electron beam. The thermal population of spin states is heavily temperature dependent:

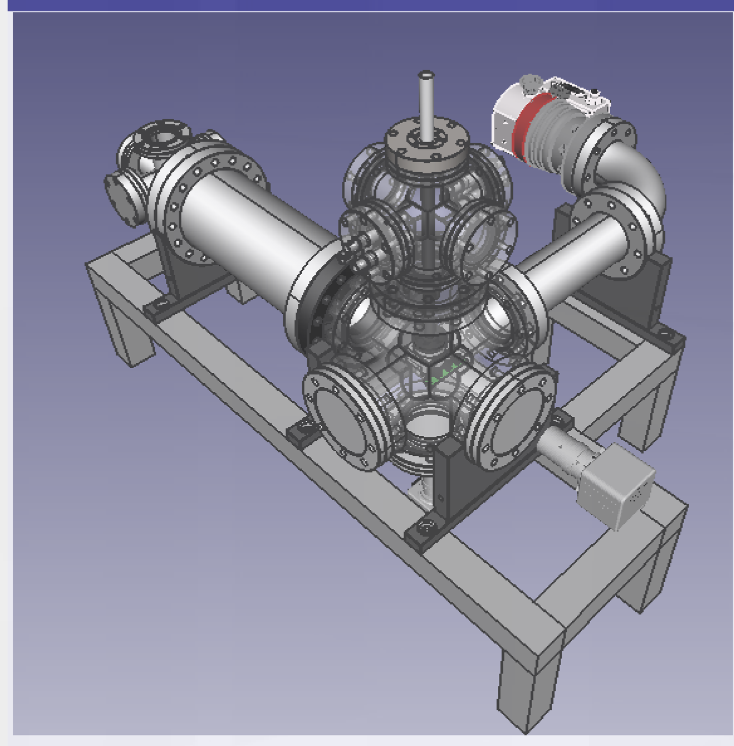
$$\frac{n_2}{n_1} = e^{-\frac{\Delta E}{k_B T}} = \left(e^{-\frac{\Delta E}{k_B}}\right)^{\frac{1}{T}}$$



- Room temperature:
  expect $22.9nV$ signal, $185.83\sqrt{Hz}$ SNR
- Moving to $77K$ (liquid nitrogen):
  expect $89nV$ signal
  expected gain ≈ 4, SNR gain ≈ 7.7
  simple to realize, our choice
- Moving to $4K$ (liquid helium):
  expect $1.7\mu V$ signal
  expected gain ≈ 75, SNR gain ≈ 649.5
  challenging to realize

Averaging increases the SNR by $\sqrt{N}$ for N iterations. Doubling SNR of the system decreases the number of required averages by a factor of four. A gain of 4 decreases measurement time by a factor of 16, a gain of 650 would decrease measurement time by about half a million

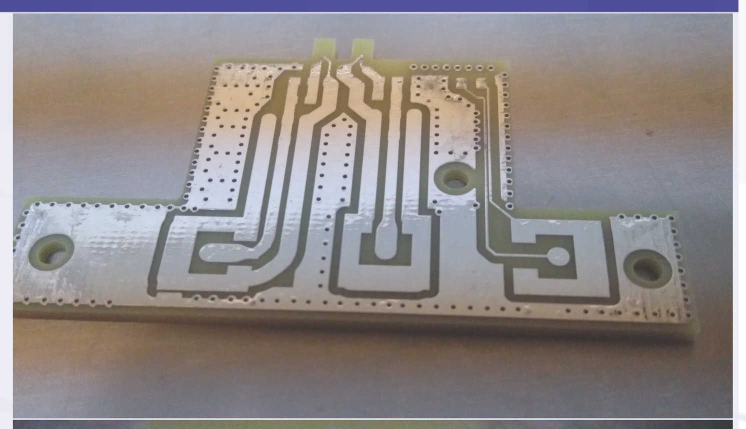
Experimental setup

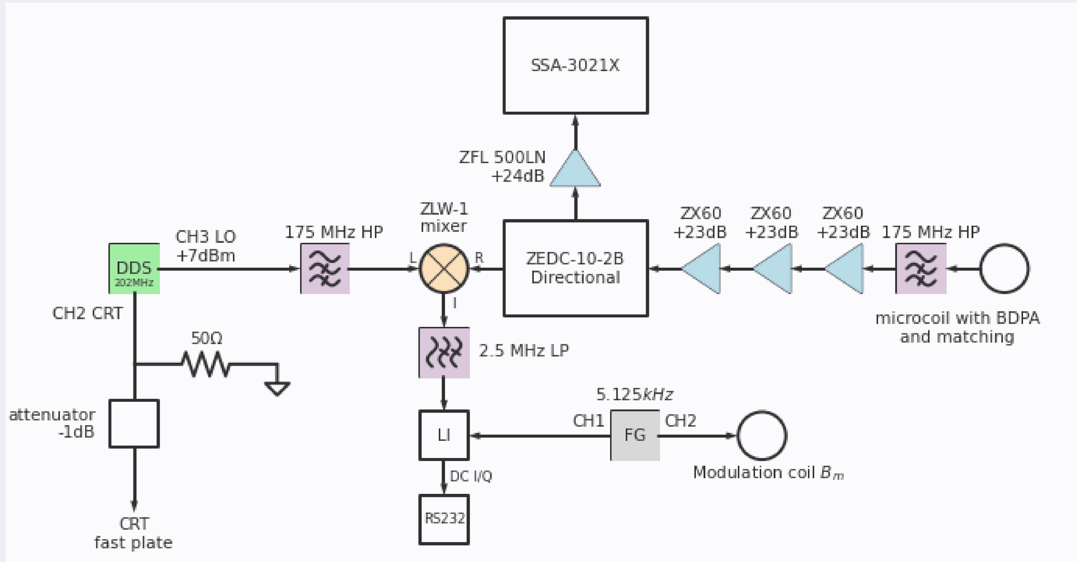


- The experiment runs in vacuum at 10^{-8} mbar or better
- As electron source we use a Barium-Strontium cathode, the beam is steered by electrostatic beam deflection. The source provides $\geq 10\mu A$ beam current at up to $2.2kV$ acceleration voltage.
- The beam modulation frequency is up to $\approx 250MHz$
- Camera imaging from two directions of phosphor screens inside the chamber and phosphor coated areas to determine and monitor beam parameters.
- Cooling is done with liquid nitrogen from a reservoire on top via a copper coldfinger through a teflon insulated steel pipe.

Readout and radio frequency setup

- We are using a carrier PCB thermally coupled to a copper coldfinger. The PCB contains the microcoils as well as an RF impedance match, copper areas and thermal vias to thermally couple to the coldfinger and high voltage protection via an RF choke.
- We plan to use a second coil for reference measurements.
- The BDPA sample is positioned inside the microcoil (2 windings, 2.58 x 1.14mm outer diameter, 1.5 x 0.5mm sample area) in a milled pocket.



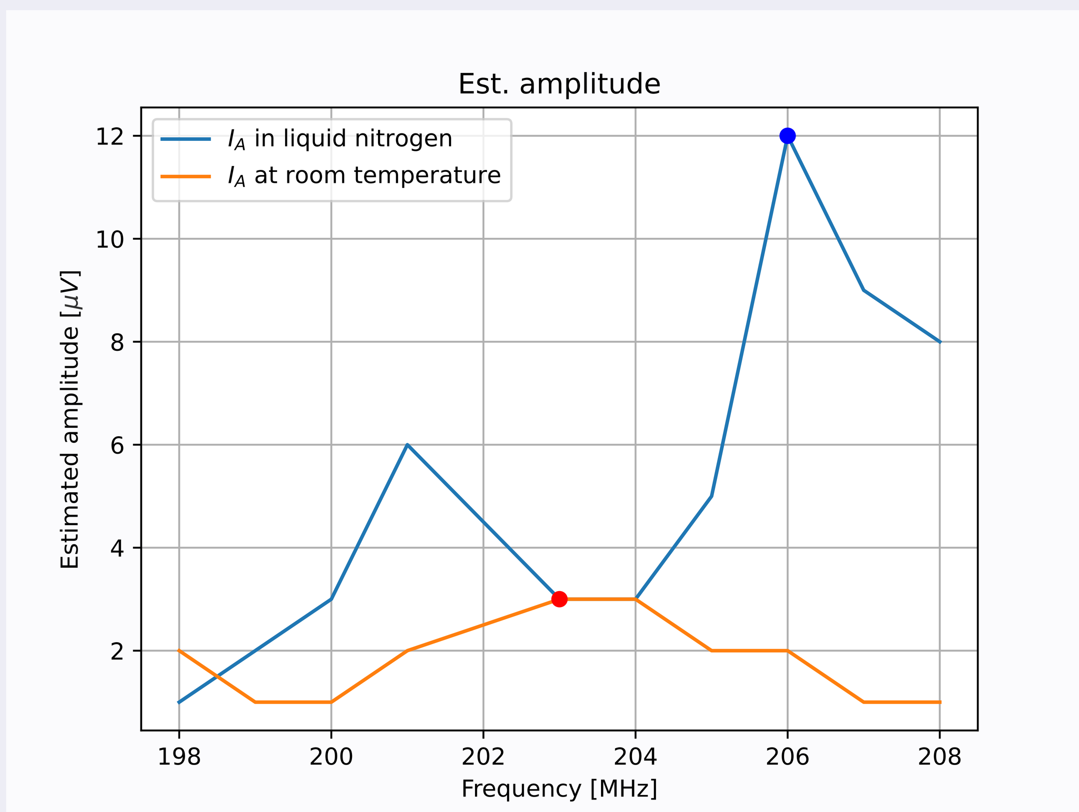


- We are using two independent channels of an AD9959 based DDS for local oscillator and beam deflection (excitation).
- Applying additional $5.123kHz$ modulation field B_m in same direction as B_0
- Performing lock-in detection for better noise suppression

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.

- Excited using microwaves at various frequencies via a directional coupler as in a traditional EPR setup.
- Scanned B_0 field
- Compared amplitudes of maximum detected EPR signals
- Resonance frequency shifted
- About gain of 4 for signal amplitude



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

[1] D. Rätzel, D. Hartley, O. Schwartz, P. Haslinger, A Quantum Klystron - Controlling Quantum Systems with Modulated Electron Beams. *Phys. Rev. Research 3, 023247 (2021)*