Towards Driving Quantum Systems in Cryogenic Environments with the Near-Field of Modulated Electron Beams

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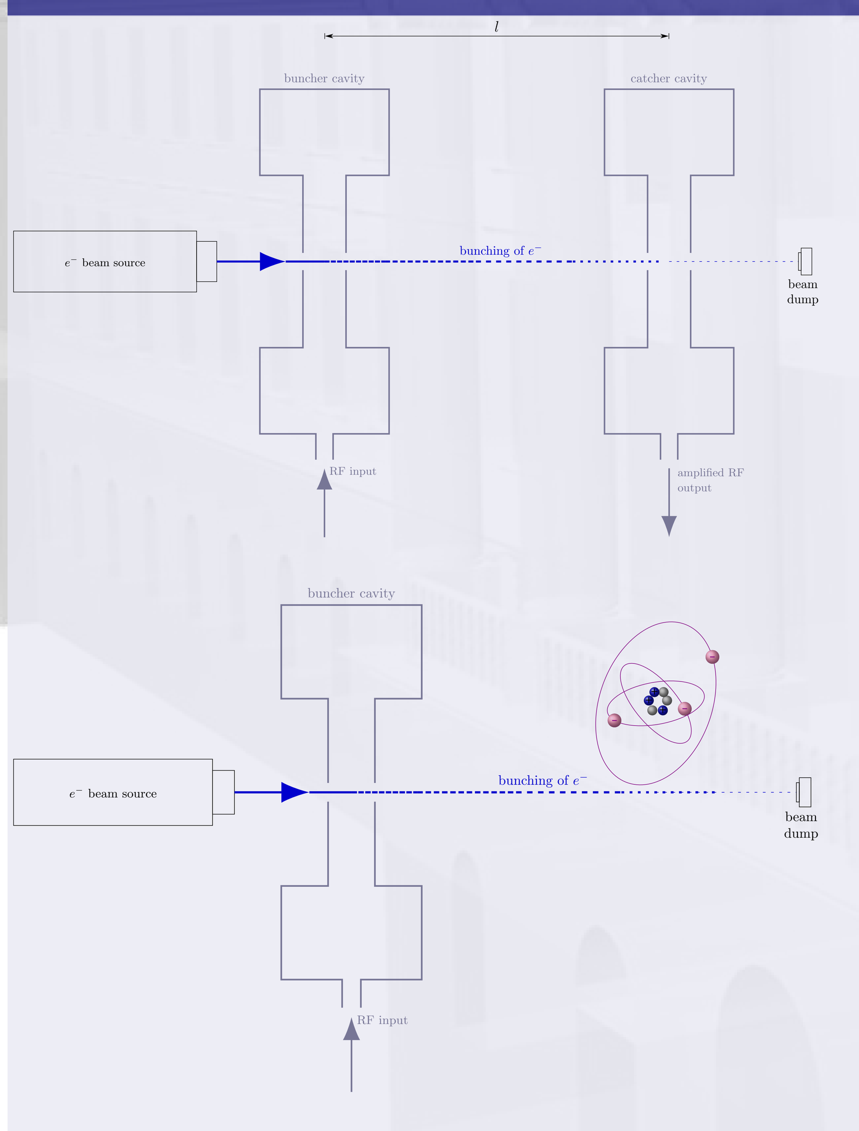
Abstract

Coherent electro-magnetic control of quantum systems is usually done by electro-magnetic radiation - which limits addressing single 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 electro-magnetic near-field of a spatially modulated electron beam to a quantum system in a coherent[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 modulated electron beam. The readout of the spin excitation resembles a standard continuous wave electron spin resonance experiment and is done inductively via a microcoil using a lock-in amplifier.

In the long term this experiment should demonstrate the feasability of coherent driving and probing of quantum systems far below the diffraction limit of electro-magnetic radiation by exploiting the high spatial resolution of an electron beam.

The Quantum Klystron



Klystron

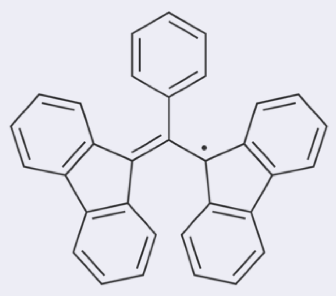
- Linear beam vacuum tube invented in 1935, used as RF and microwave amplifier
- Electron beam velocity modulated by microwaves in a (buncher) cavity
- Velocity modulation causes current modulation
- Outcoupling via a catcher cavity

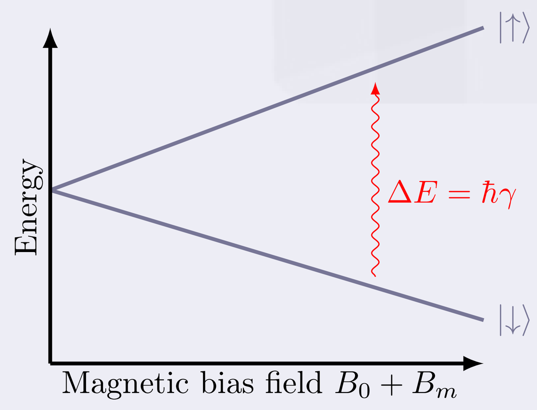
Quantum Klystron

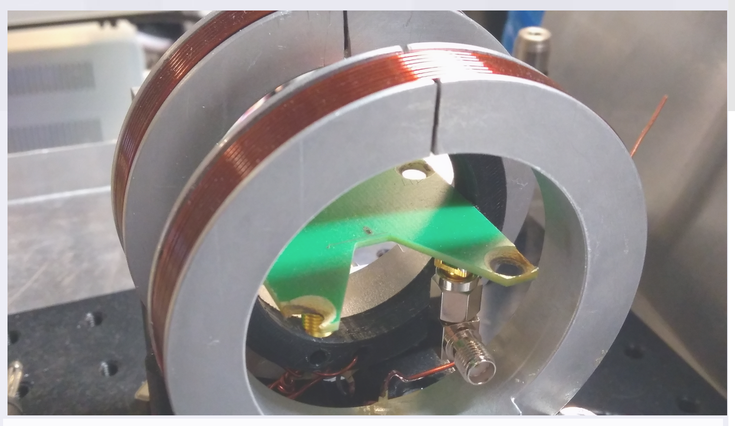
- Replace catcher cavity by a 2 level quantum system (QS)
- Drive the QS using the *non-radiative electro-magnetic near-field* of the electron beam.
  - Either modulate in
    - *time domain* - bunching / density modulation
    - *spatial domain* - deflection
- Paint arbitrary potentials (dipole, quadrupole or multipole transitions)
- High spatial resolution

Electron Spin Resonance with Modulated Electron Beams

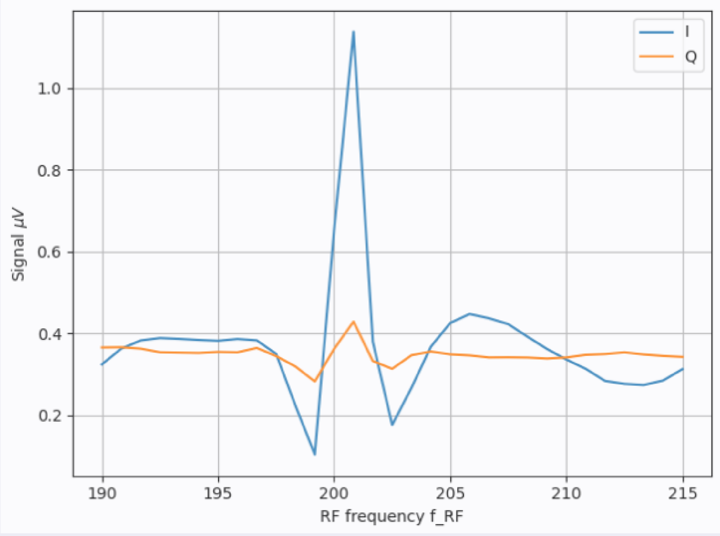
The experiment resembles an electron spin resonance experiment. In contrast to standard electron spin resonance setups where systems are excited using microwaves, we use the *non-radiative electro-magnetic near-field* of an modulated electron beam.







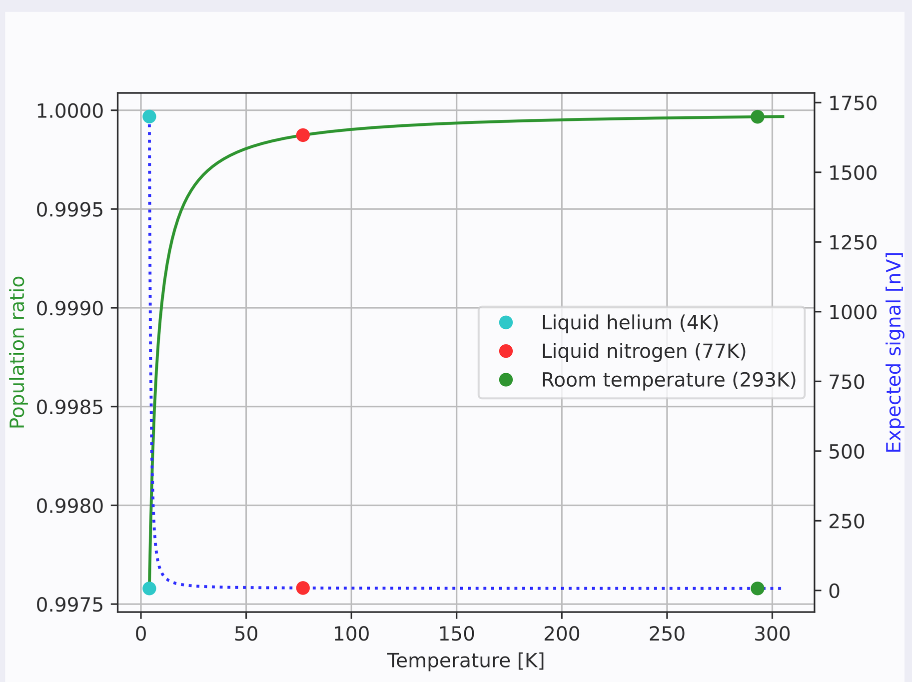
- Sample: $C_{33}H_{21}$ Koelsch radical (α,γ-Bisdiphenylene-β-phenylallyl - BDPA)
- high spin density (1 free spin per 51 atoms)
- Proof of concept experiment at room temperature (300K) and liquid nitrogen (77K)
- Background subtraction by differential measurement



Temperature Dependence

The thermal population ratio of spin states depends on temperature:

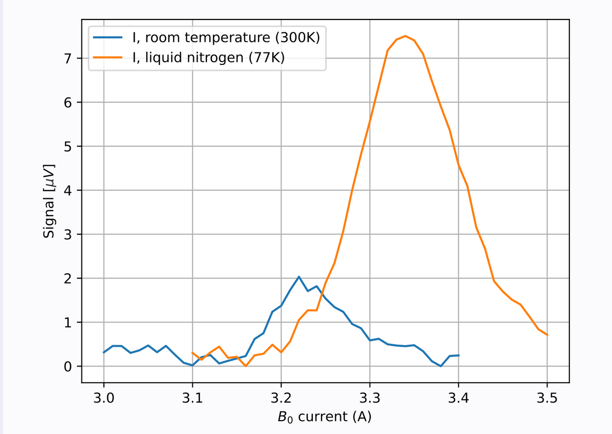
$$\frac{n_2}{n_1} = e^{-\frac{\Delta E}{k_B T}} = \left(e^{-\frac{\Delta E}{k_B}}\right)^{\frac{1}{T}}$$



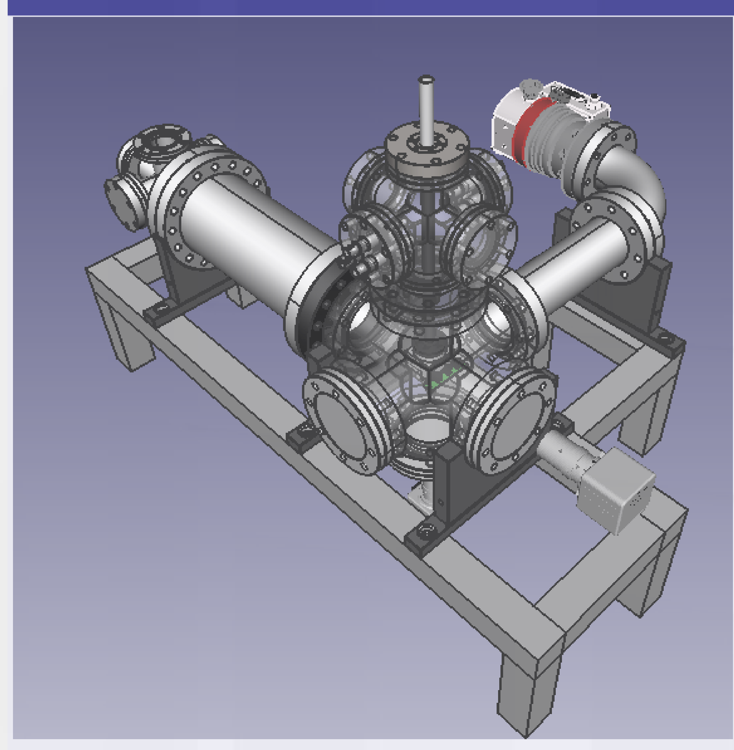
- $300K$ (room temperature): expected $22.9nV$ signal, $185.83\sqrt{Hz}^{-1}$ SNR
- $77K$ (liquid nitrogen): expected $89nV$ signal, $1221.46\sqrt{Hz}^{-1}$ SNR expected gain ≈ 4, SNR gain ≈ 7.7 simple to realize, our choice
- $4K$ (liquid helium): expected $1700nV$ signal, $103163.45\sqrt{Hz}^{-1}$ SNR expected gain ≈ 75, SNR gain ≈ 649.5

Averaging increases the effective SNR by $\sqrt{N}$ for N iterations. *Doubling SNR* of a single run 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.

- Initial tests by cooling BDPA sample in liquid nitrogen bath
- Scanned B_0 field, excited with microwaves (no electron beam)
- Compared amplitudes at 300K and 77K
- Resonance frequency of impedance match drifts
- Signal gain ≈ 4



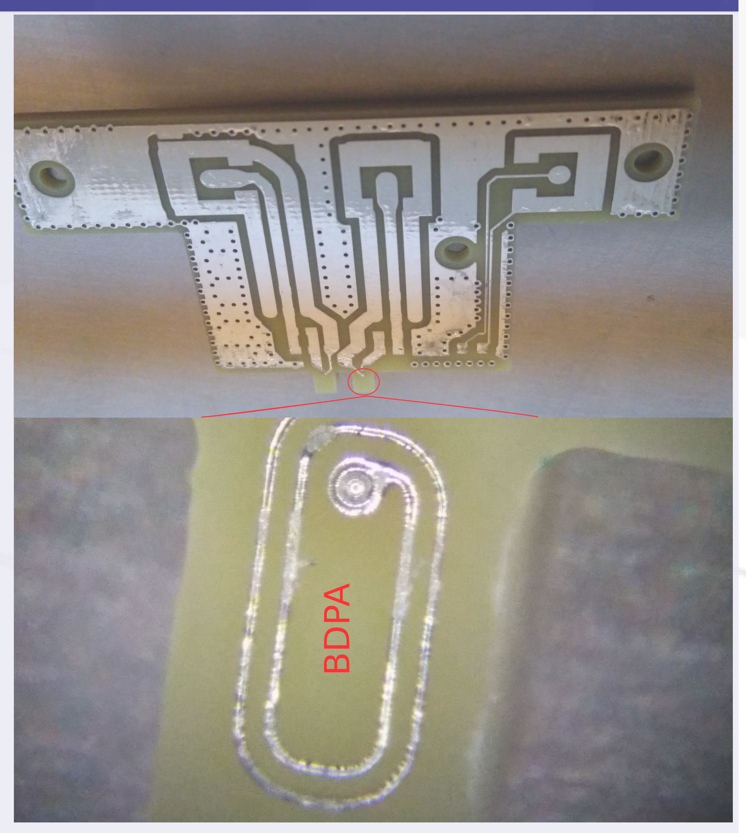
Experimental Setup

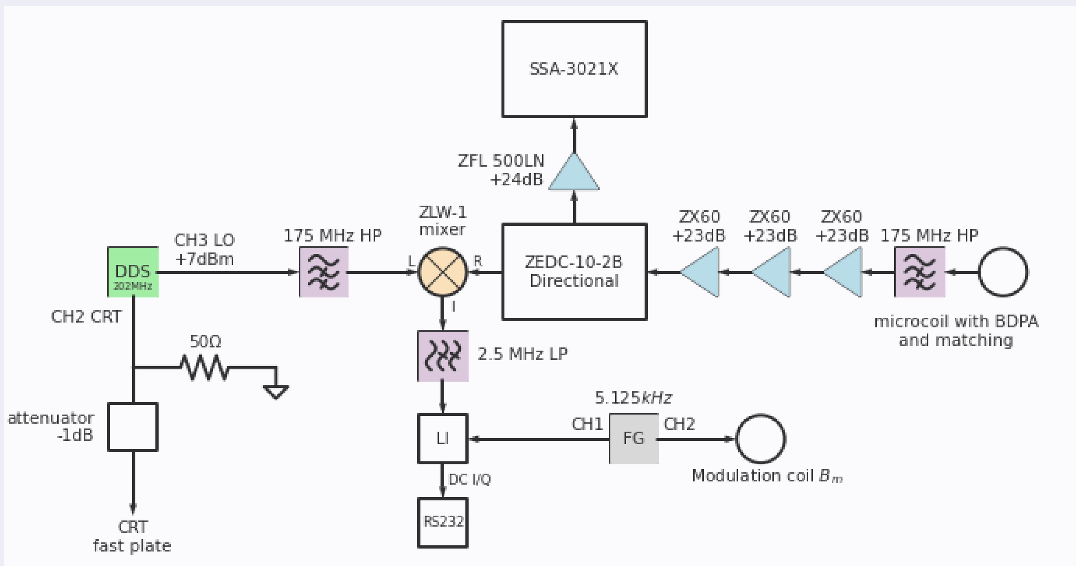


- Barium-Strontium cathode, electrostatic beam deflection. Current $\geq 10\mu A$ at up to $2.2kV$.
- Modulation frequency $\approx 250MHz$
- Two cameras imaging phosphor screens
- Cooling with liquid nitrogen
- Vacuum $\leq 10^{-8}$ mbar

Readout and Radio Frequency Setup

- Inductive readout by a microcoil on a printed circuit board (also including impedance match)
- Second microcoil for reference measurements
- BDPA inside microcoil (2 windings, $2.58mm$ x $1.14mm$ outer diameter, $1.5mm$ x $0.5mm$ sample area) in milled pocket

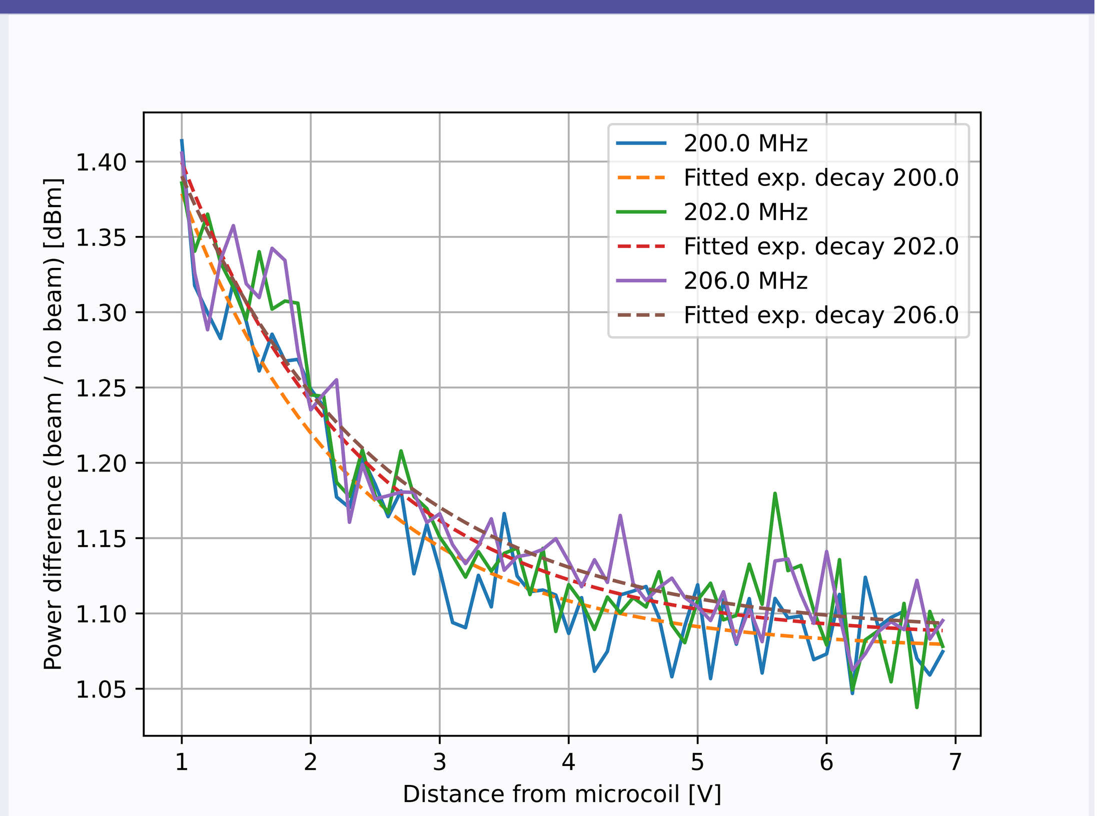




- Two independent channels of an AD9959 based DDS
- Applying $5.123kHz$ modulation field B_m parallel to B_0 for lock-in detection

First Runs at Room Temperature

- Electron beam at $2.2kV$
- Deflected at $202MHz$
- Scanning distance to microcoil (*slow position*)
- Beam wiggled by B_m field
- Coupling of *near-field* into microcoil
- Shows $\frac{1}{r}$ behaviour (Biot-Savart law)



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)*

FWF Österreichischer Wissenschaftsfonds
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