Phase-sensitive Spectroscopy of Positronium n=2 Fine-structure Intervals

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Positronium Spectroscopy

Positronium (Ps) is the bound-state of the electron and positron and is therefore described to high-precision by bound-state quantum-electrodynamics (QED)

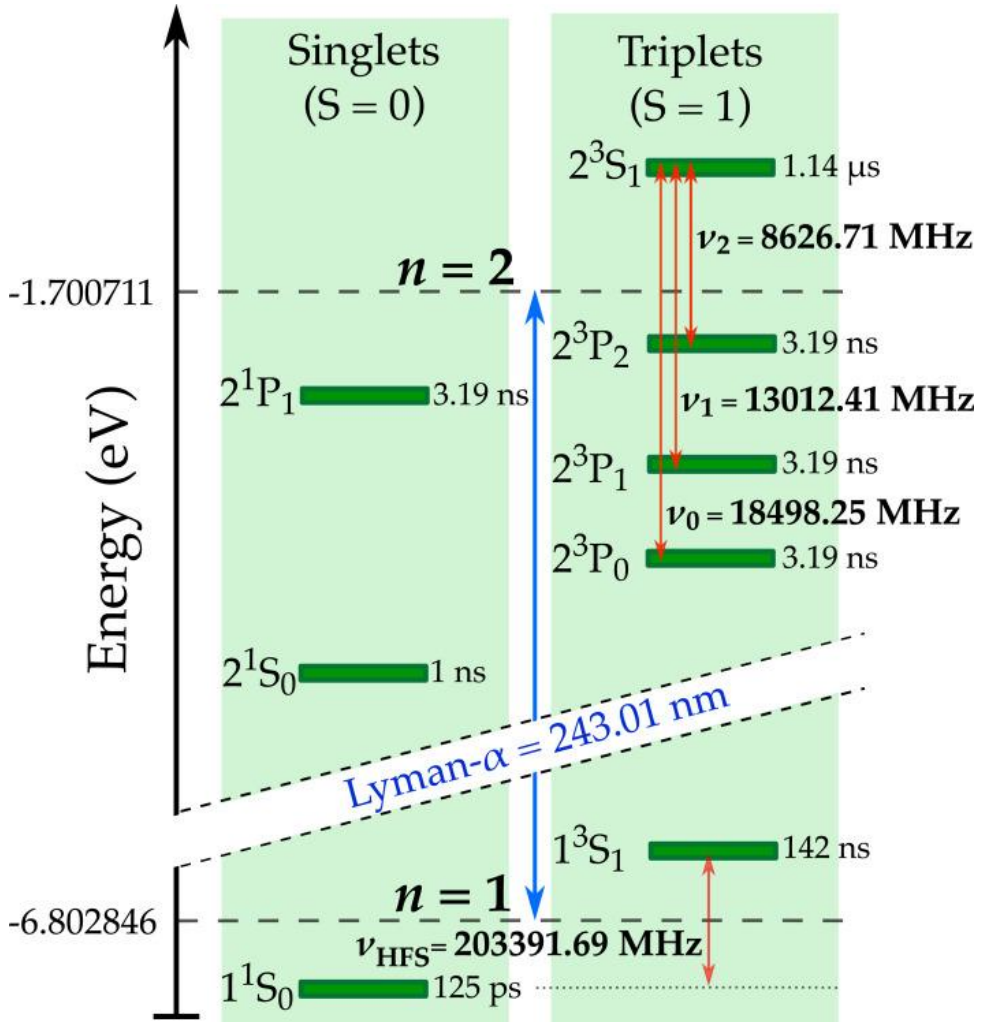
Theory:

2^3S_1 -> 2^3P_0: 4.3 ppm
2^3S_1 -> 2^3P_1: 6.1 ppm
2^3S_1 -> 2^3P_2: 9.3 ppm

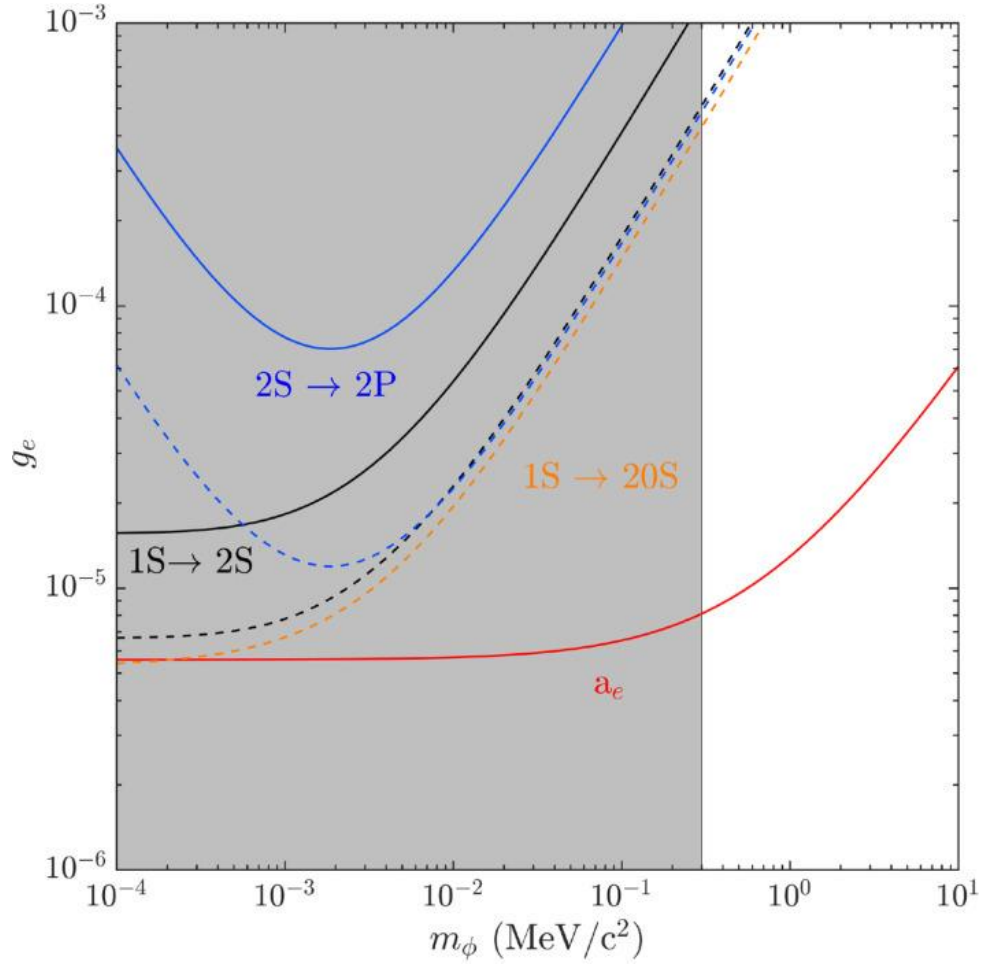
Experiment:

2^3S_1 -> 2^3P_0: 36 ppm
2^3S_1 -> 2^3P_1: 130 ppm
2^3S_1 -> 2^3P_2: 110 ppm

Adkins *et al.* PR **975** (2022)
Sheldon *et al.* PRL **131** (2023)



Positronium Spectroscopy



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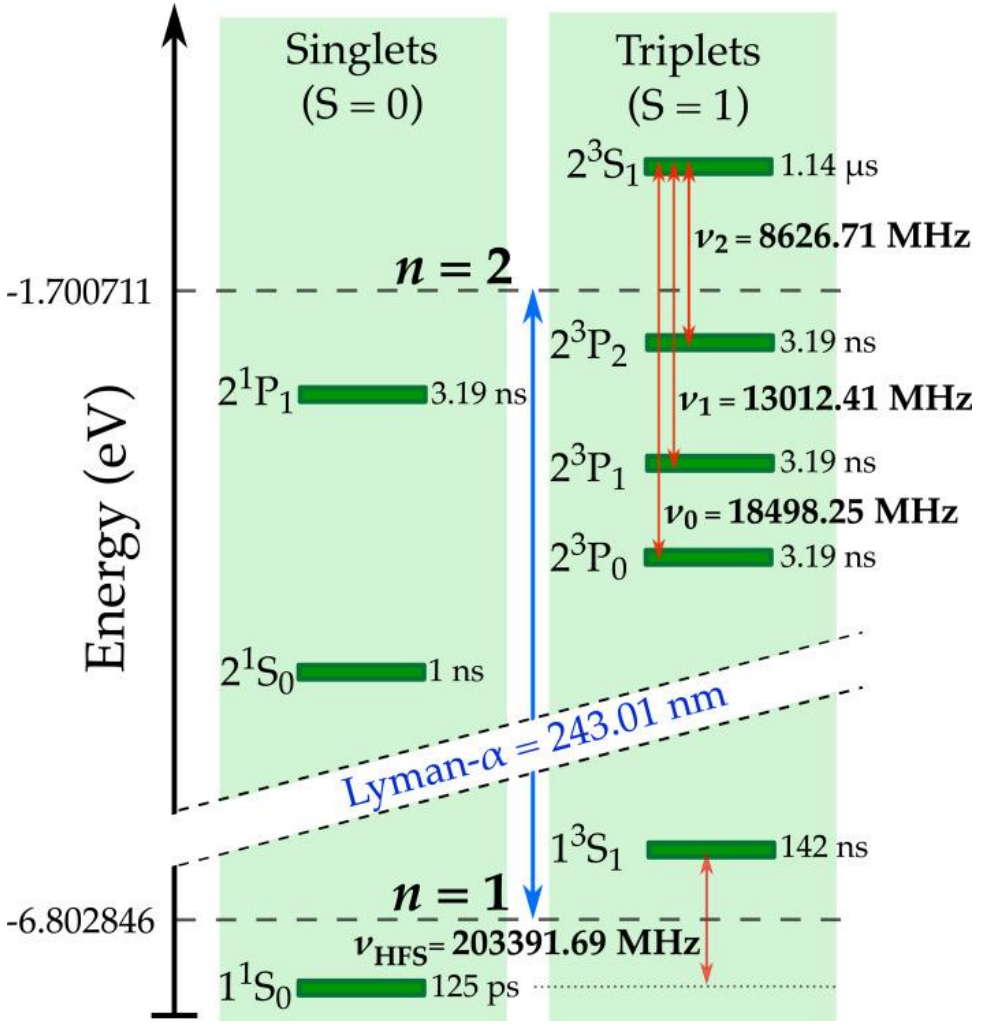
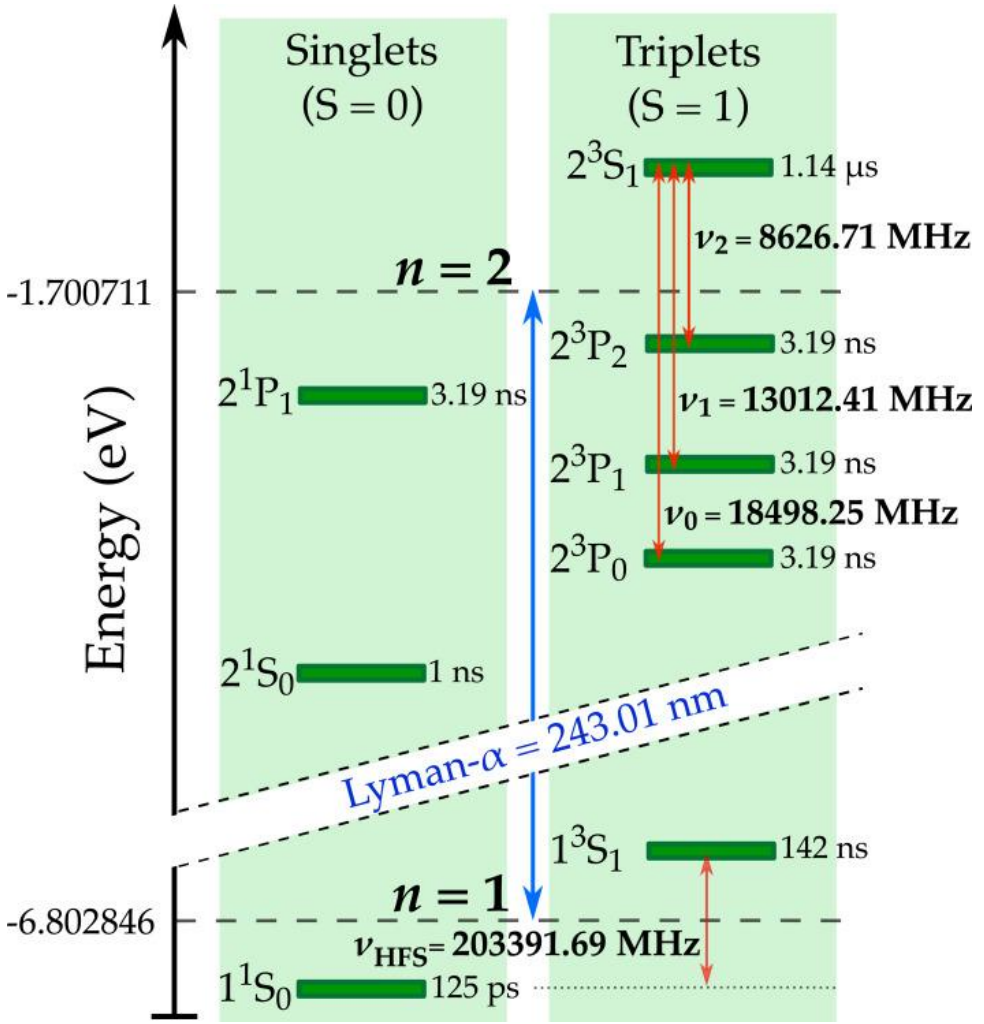


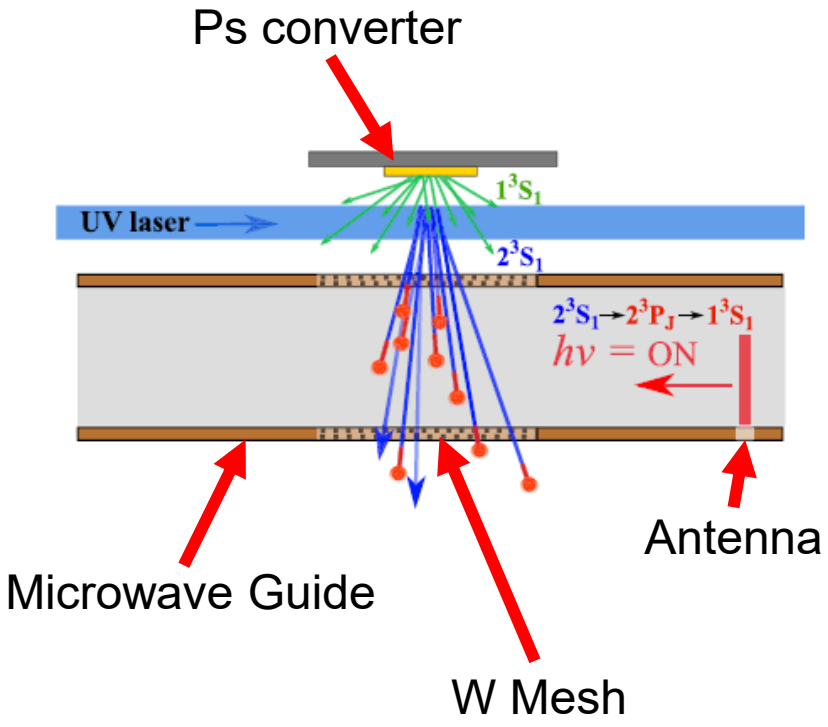
Positronium Spectroscopy

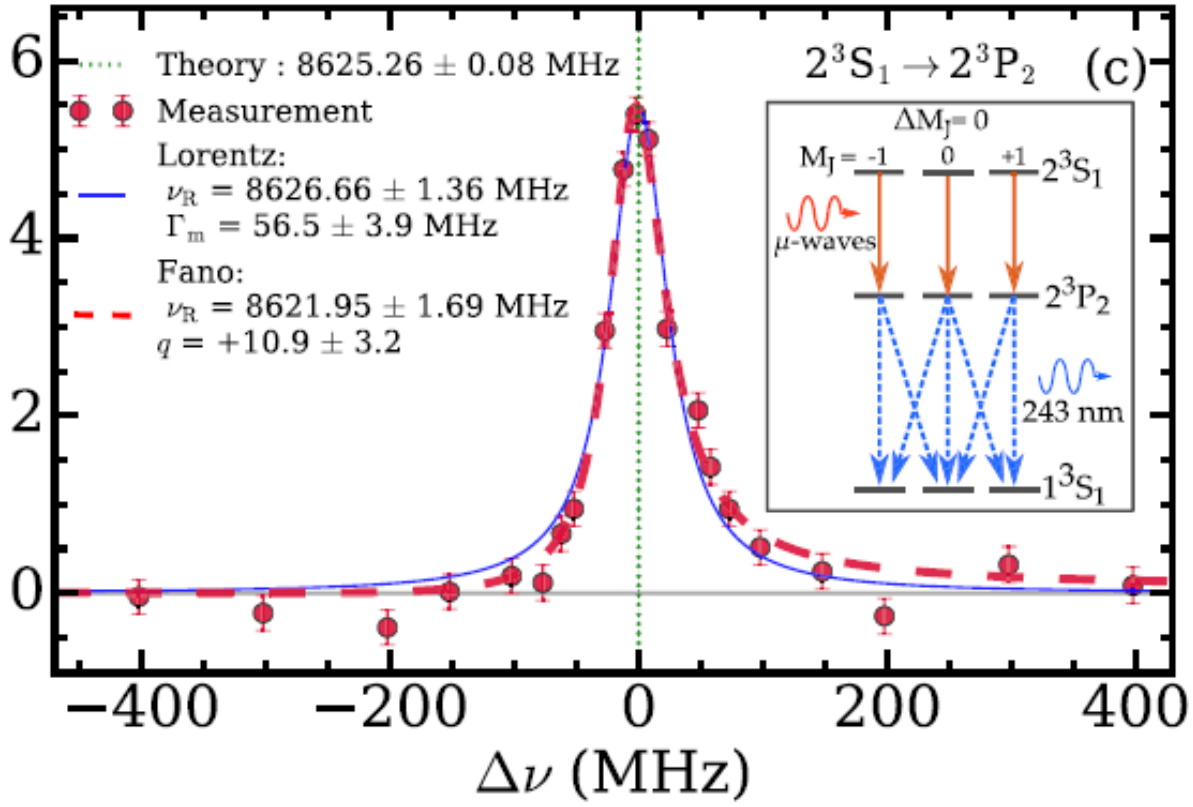
Challenges:

- Low metastable (2^3S_1) Ps production and/or detection efficiencies
- Broad natural line width of fine-structure transitions
- High velocities due to light mass leads to significant velocity dependent systematics (e.g. Doppler)



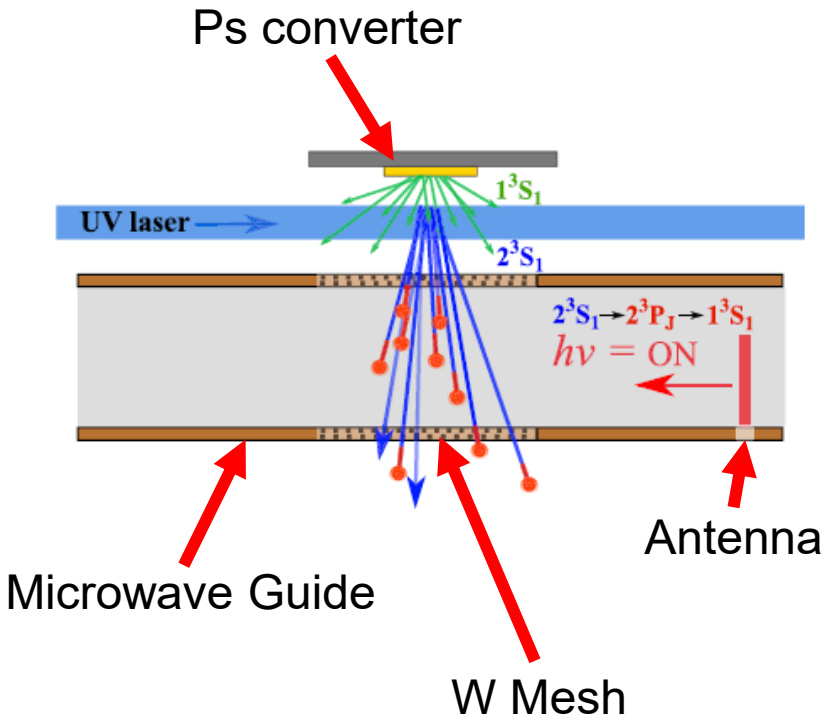
Previous Measurements

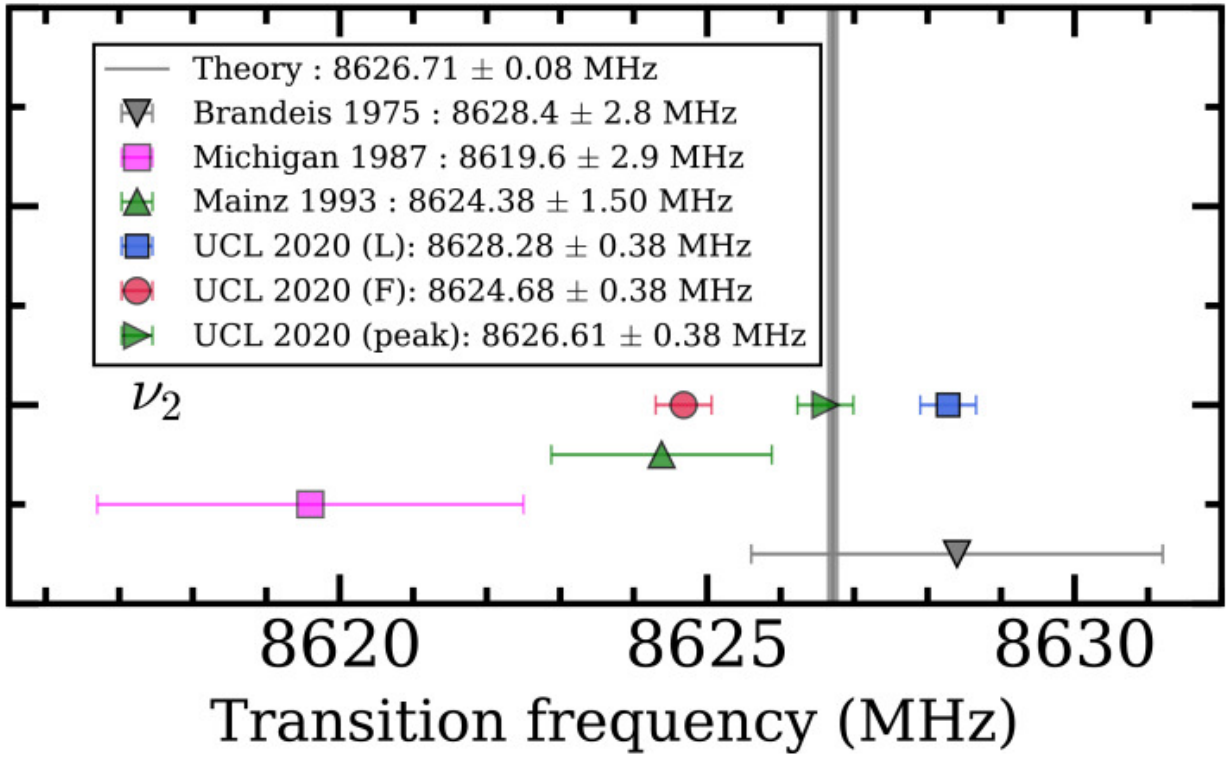




Gurung *et al.* PRL **103** 042805 (2022)

Previous Measurements





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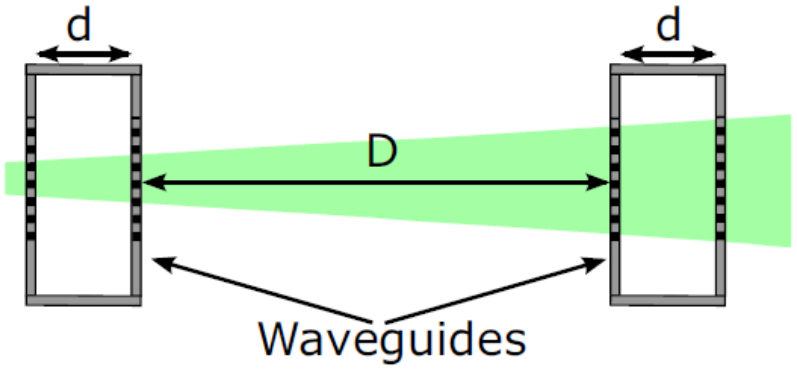
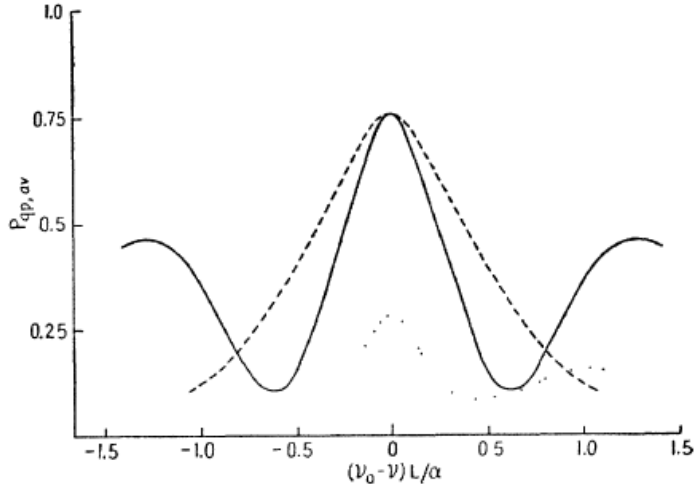
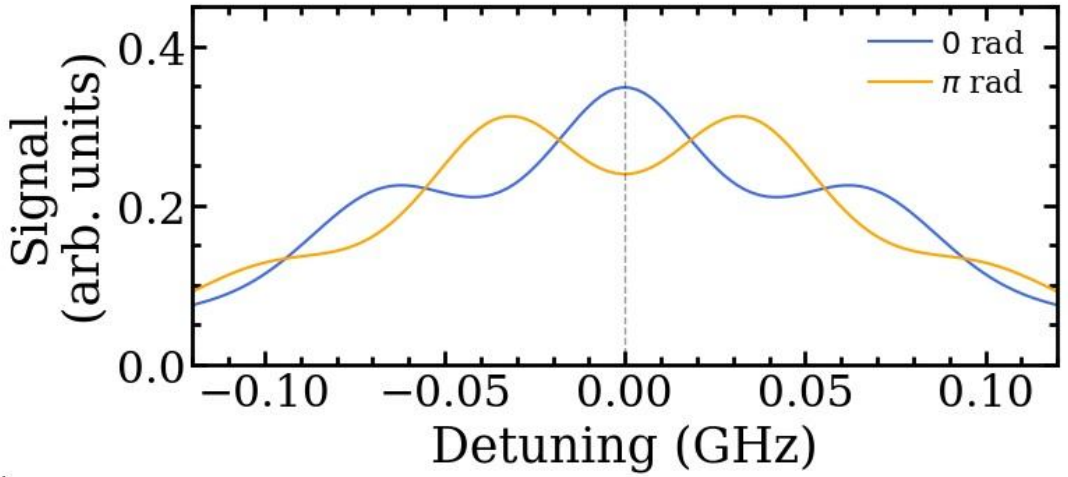
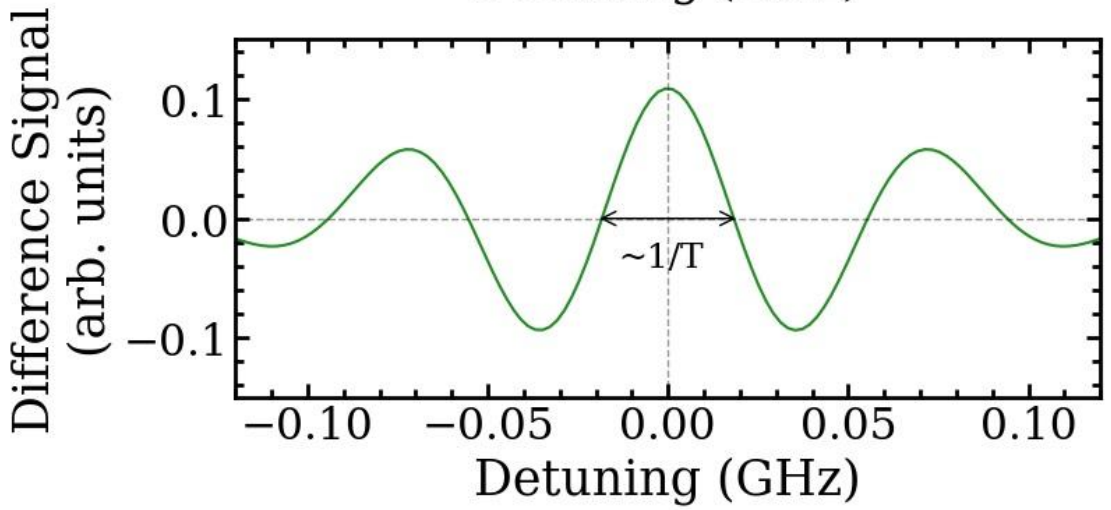
Separated Oscillatory Fields (SOF)



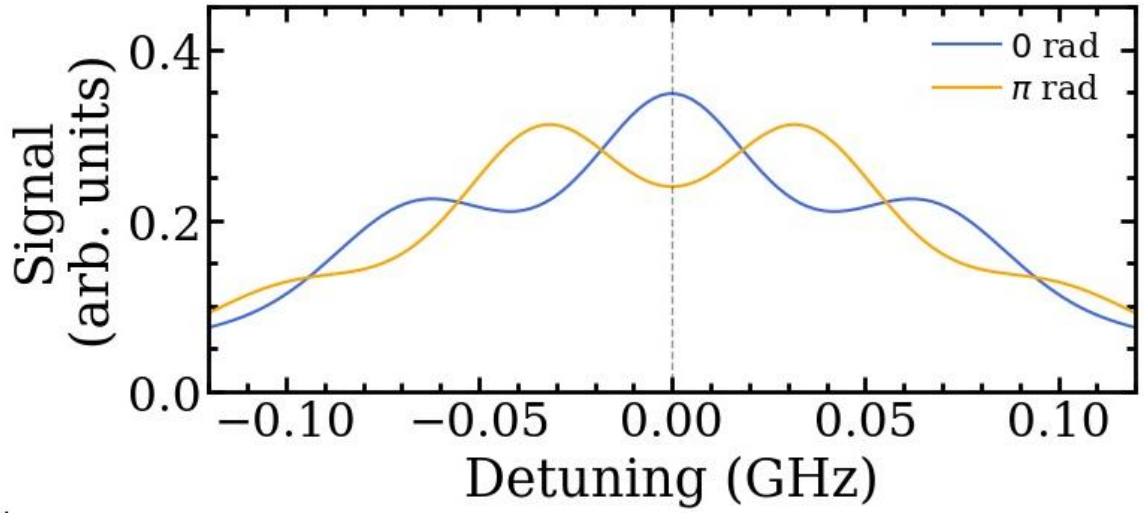


Ramsey PR **76** 996 (1949)





Phase Variation SOF (PVSOF) Method



$$S \propto A(\Delta, T)\cos(2\pi\Delta T + \phi)$$

$$\text{with} \quad \phi = \begin{cases} 0 \\ \pi \end{cases}$$

Klein *et al.* PRA **36** 3494 (1987)

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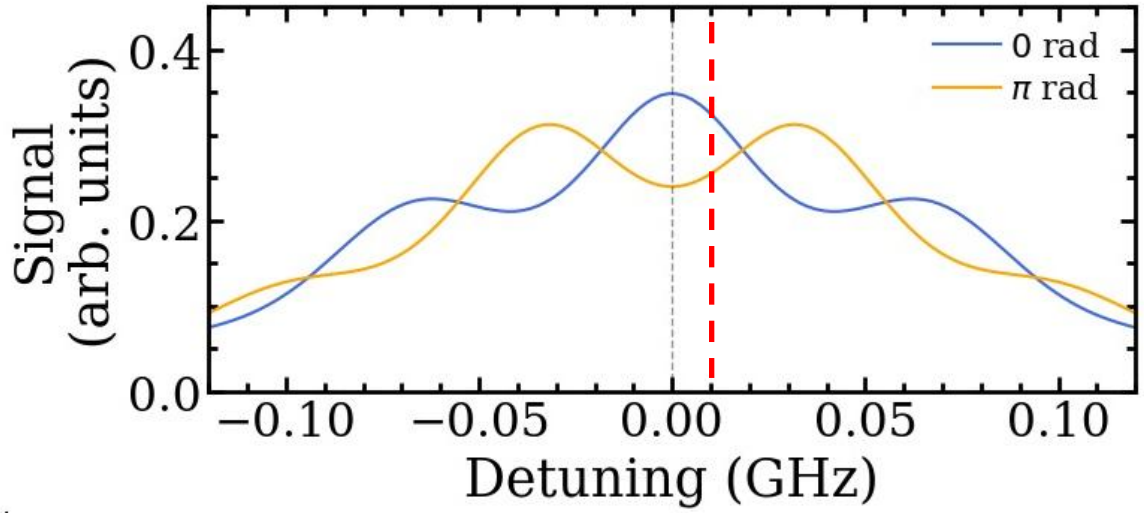

$$S \propto A(\Delta, T)\cos(2\pi\Delta T + \phi)$$

$$\text{with } \Delta \text{ fixed}$$

$$\Rightarrow S_{\max} : \phi_{\max} = -2\pi\Delta T$$

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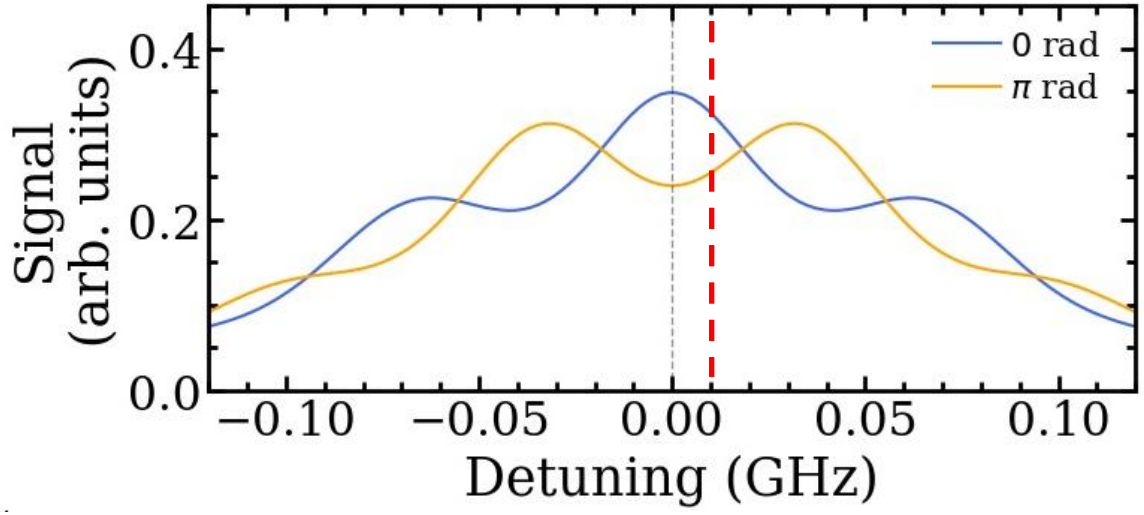

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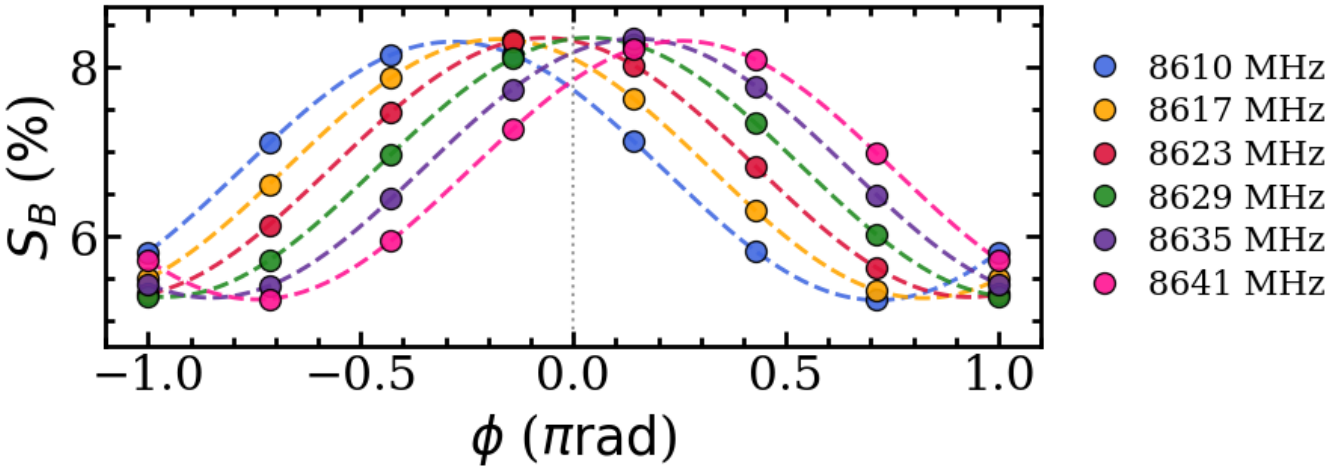
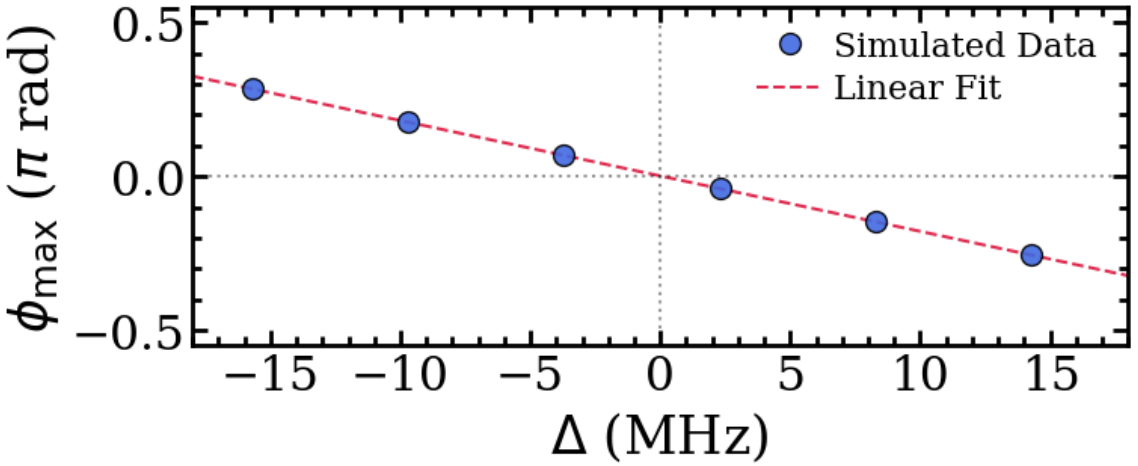
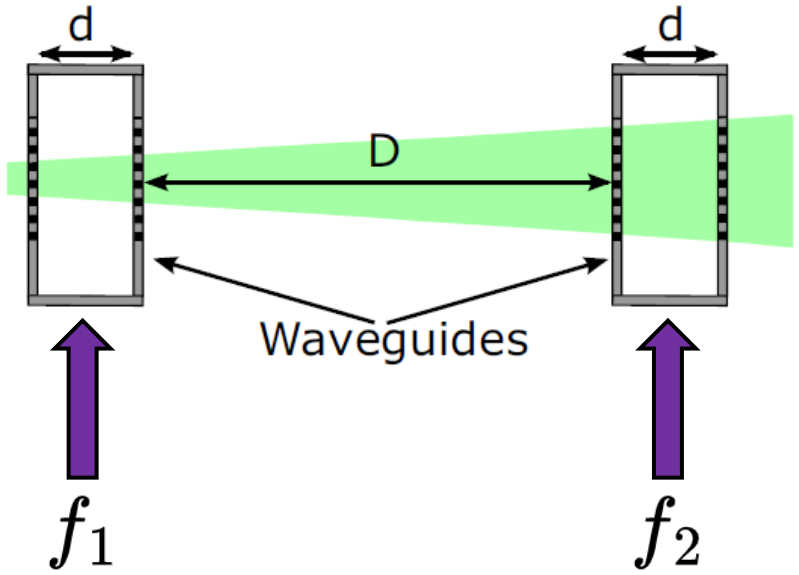




Klein *et al.* PRA **36** 3494 (1987)

Frequency Offset SOF (FOSOF) Method



$$\mathrm{SOF} : f_1 = f_2$$

$$\mathrm{FOSOF} : f_1 - f_2 = \delta f$$

Vutha & Hessels PRA **92** 052504 (2015)

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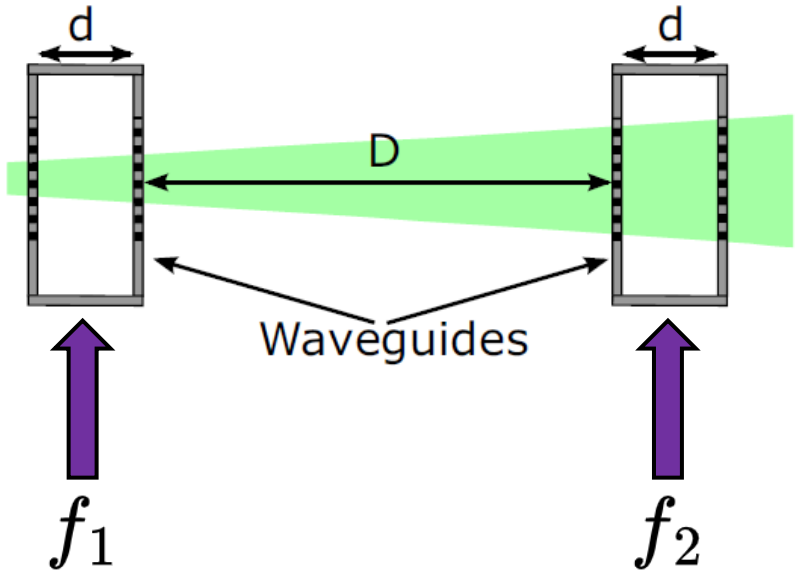

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Vutha & Hessels PRA **92** 052504 (2015)

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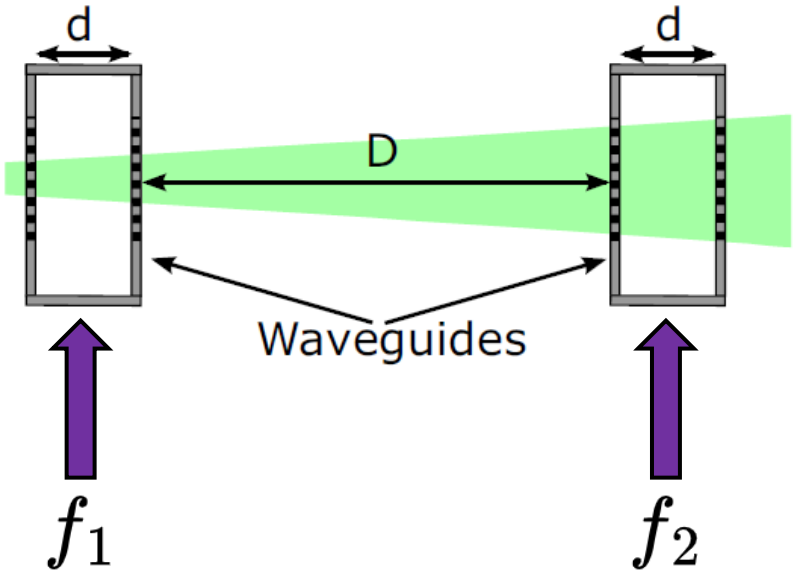

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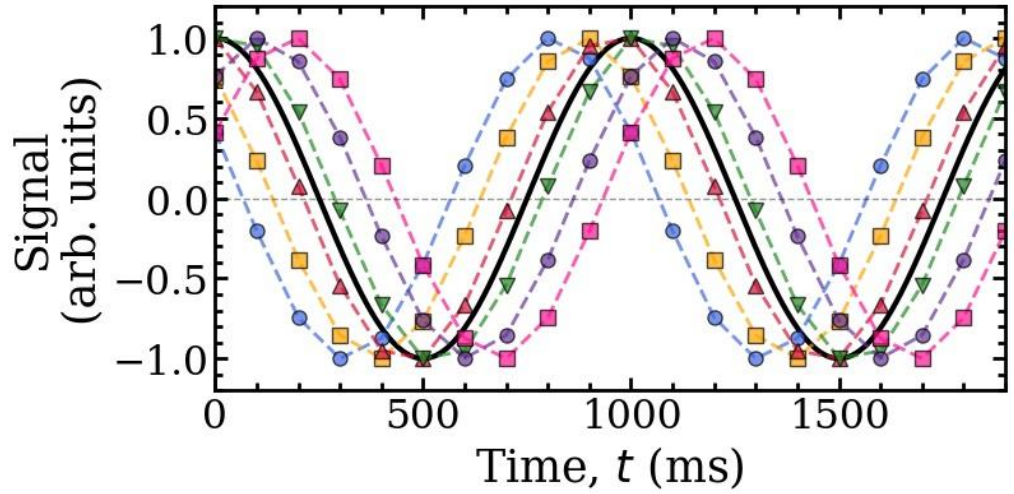

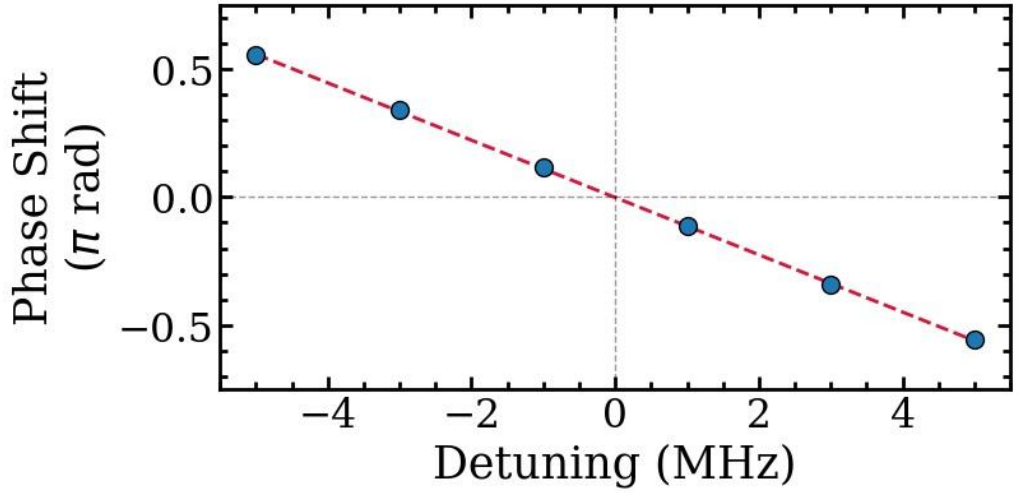

Vutha & Hessels PRA **92** 052504 (2015)

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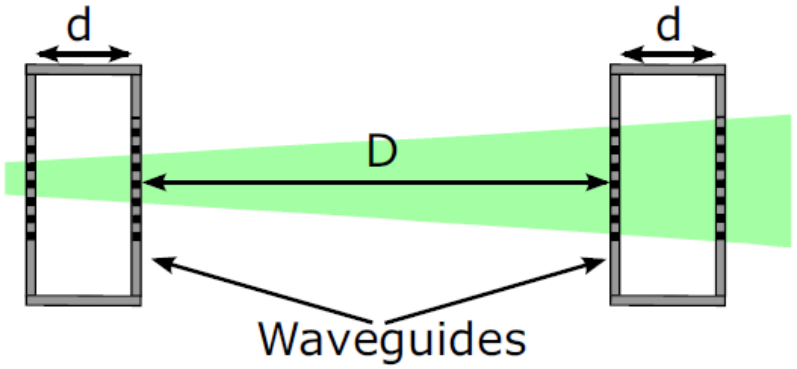
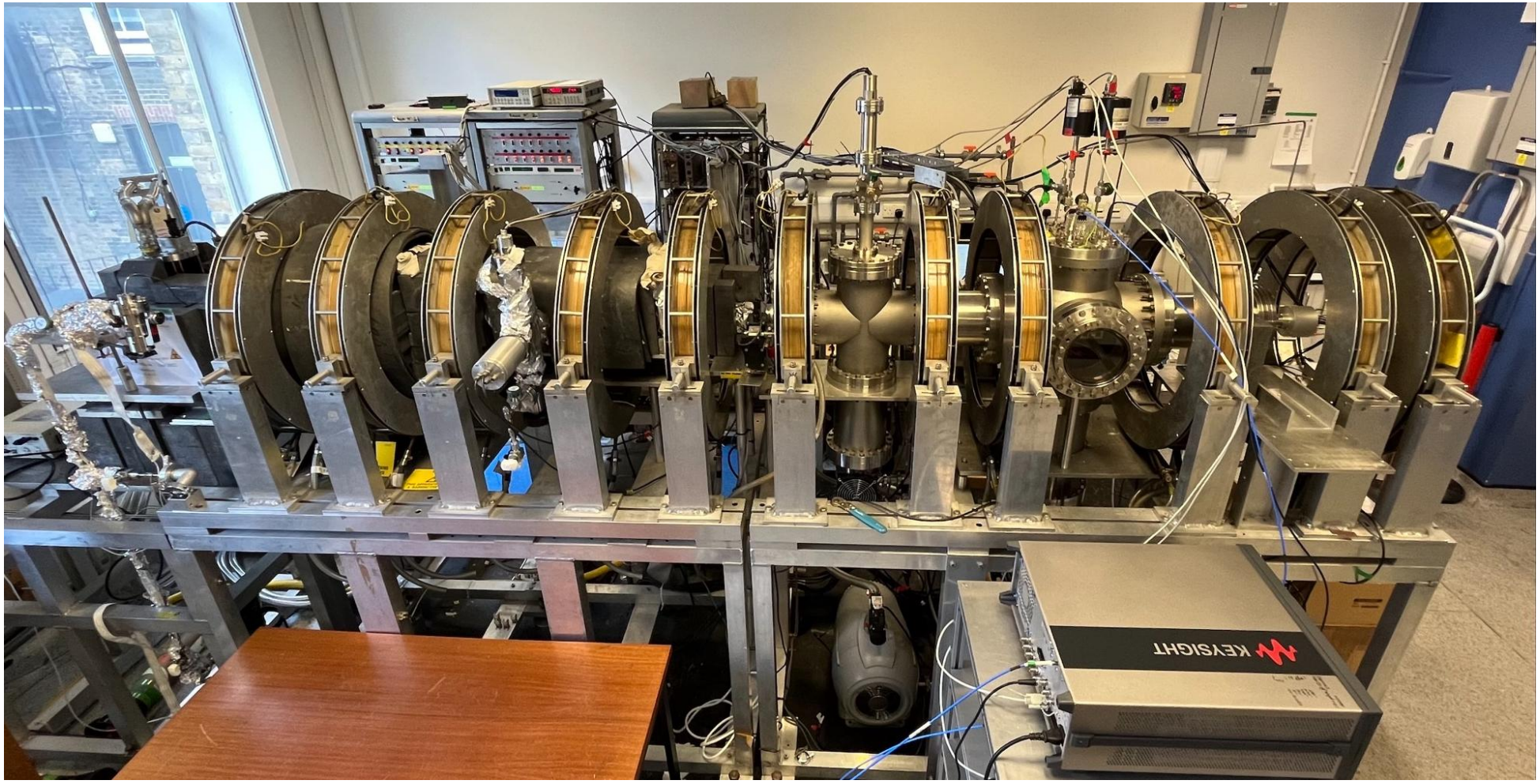


$$\tau_{\text{superposition}} \approx 3\ \text{ns}$$

SOF methods require energetic (10-100 eV) beam of metastable (2^3S_1) positronium atoms

Experimental Setup



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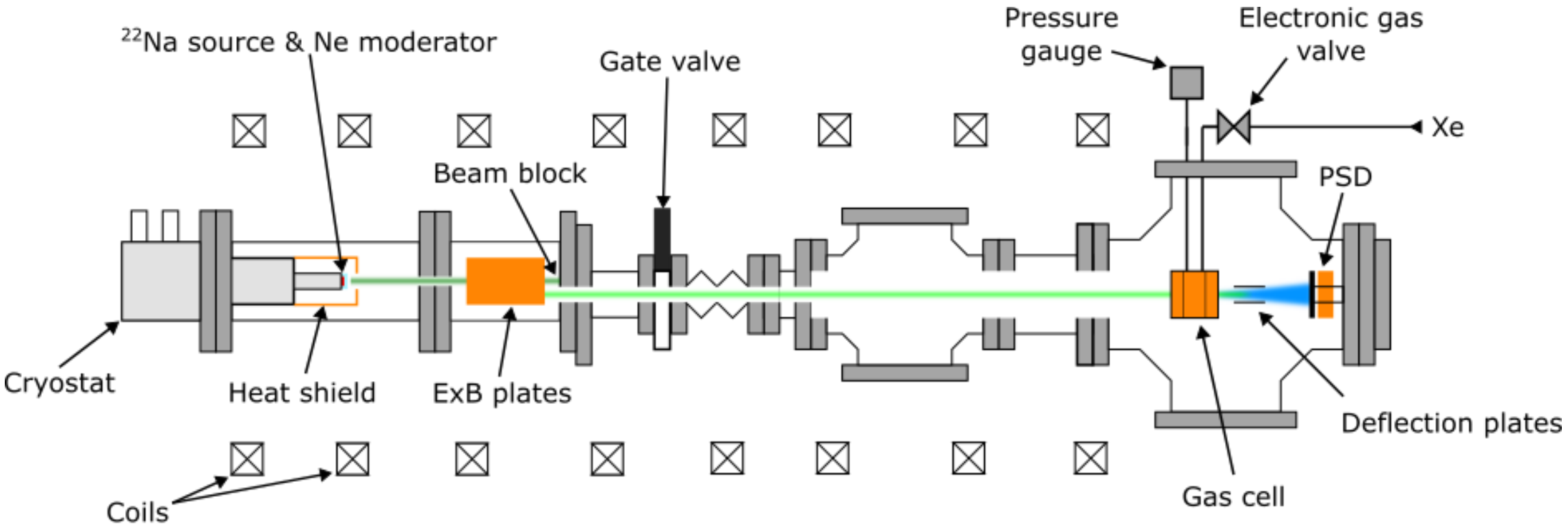


D. M. Newson *et al.* RSI **94** 083201 (2023)

Ps Beam Characterisation

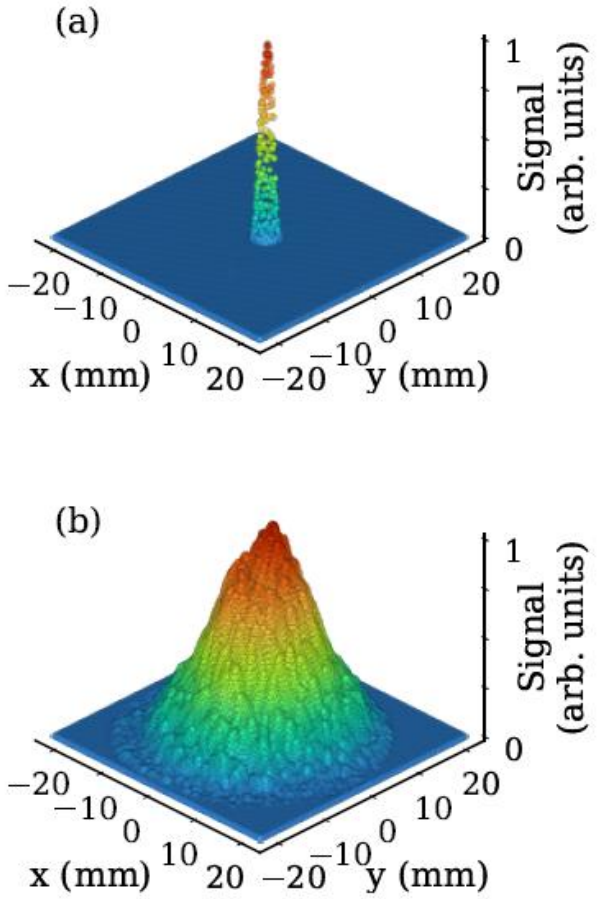
$$e^+ + \mathrm{Xe} \rightarrow \mathrm{Ps}^{(*)} + \mathrm{Xe}^+$$

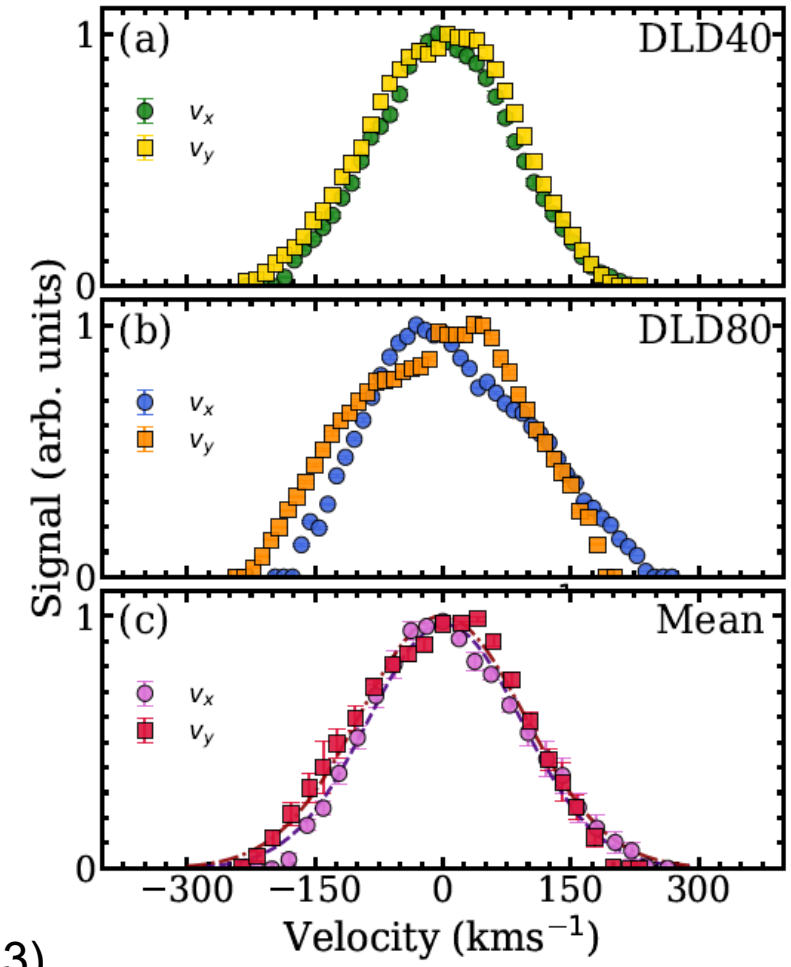
$$E_{\mathrm{Ps}} = E_+ - E_I + 6.8\,\mathrm{eV}/n_{\mathrm{Ps}}^2$$

Velocity of Ps beam can be determined, with the assumptions:

(i) $v_{\parallel} \approx \sqrt{E_{\mathrm{Ps}}/m_e}$

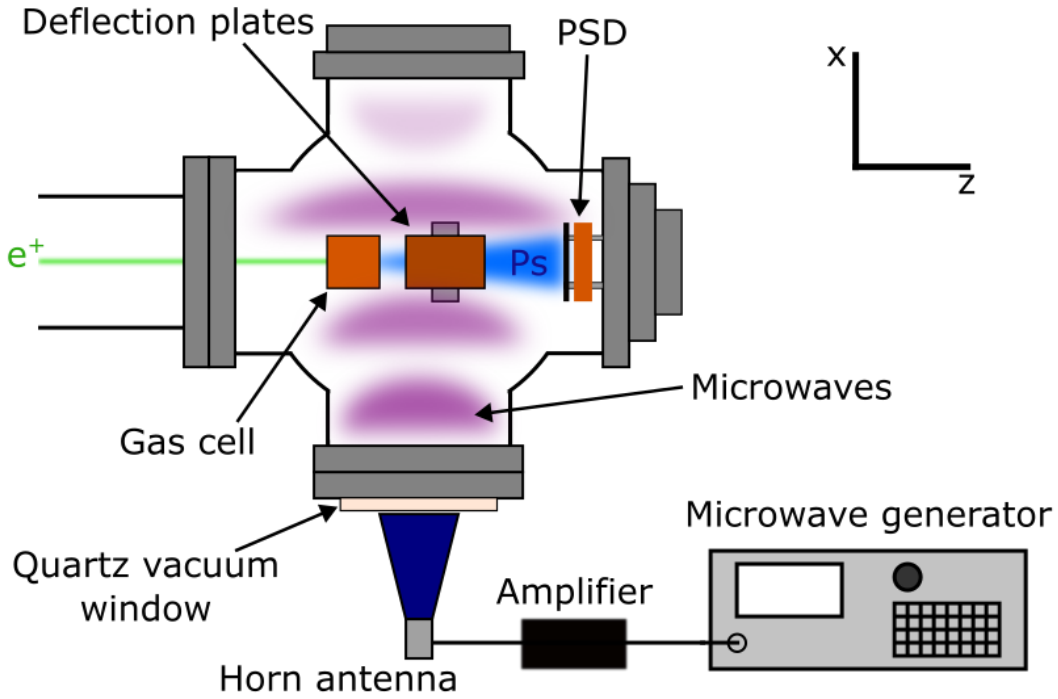
(ii) Spatial distribution is symmetric about centre

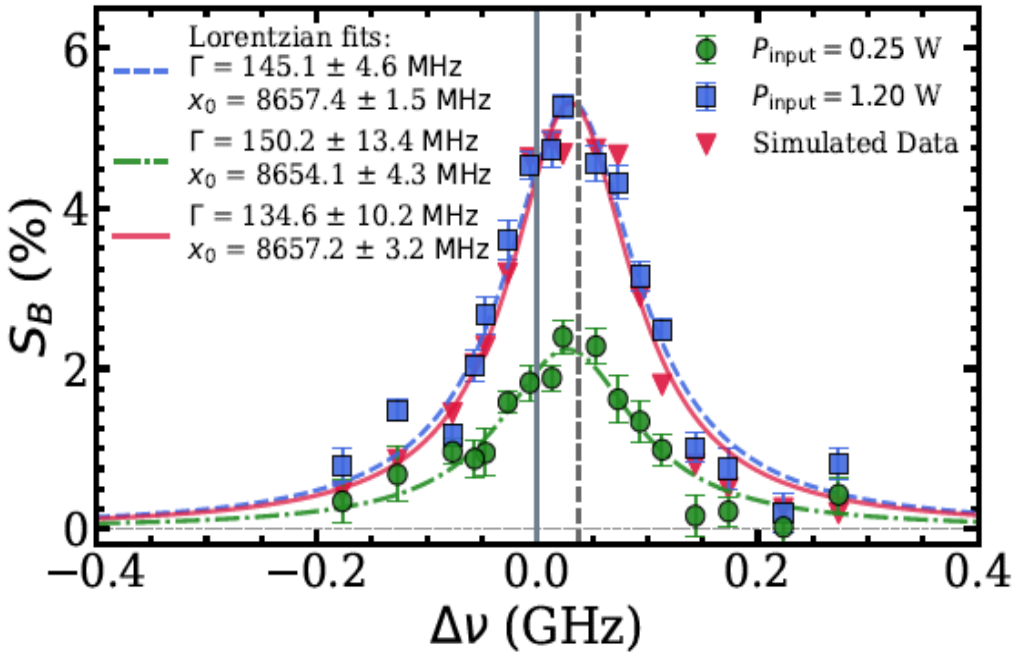




D. M. Newson *et al.* RSI **94** 083201 (2023)

Ps* Beam Characterisation





$$S_{\mathrm{B}} = \frac{S_{\mathrm{OFF}} - S_{\mathrm{ON}}}{S_{\mathrm{OFF}}}$$

S_{OFF}: microwaves off
S_{ON}: microwaves on

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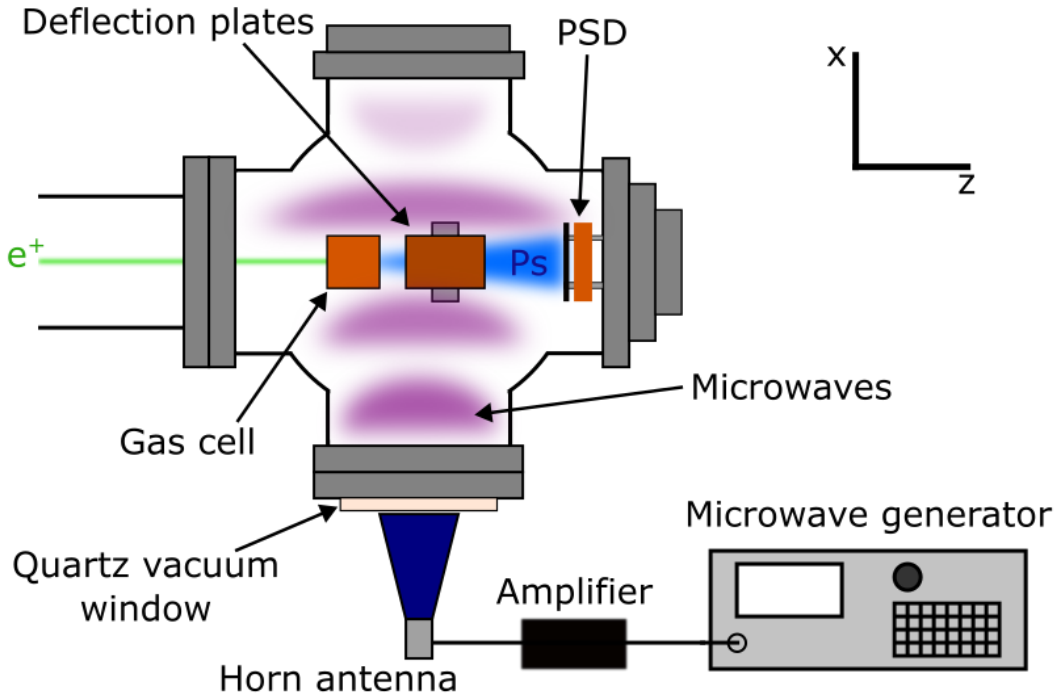
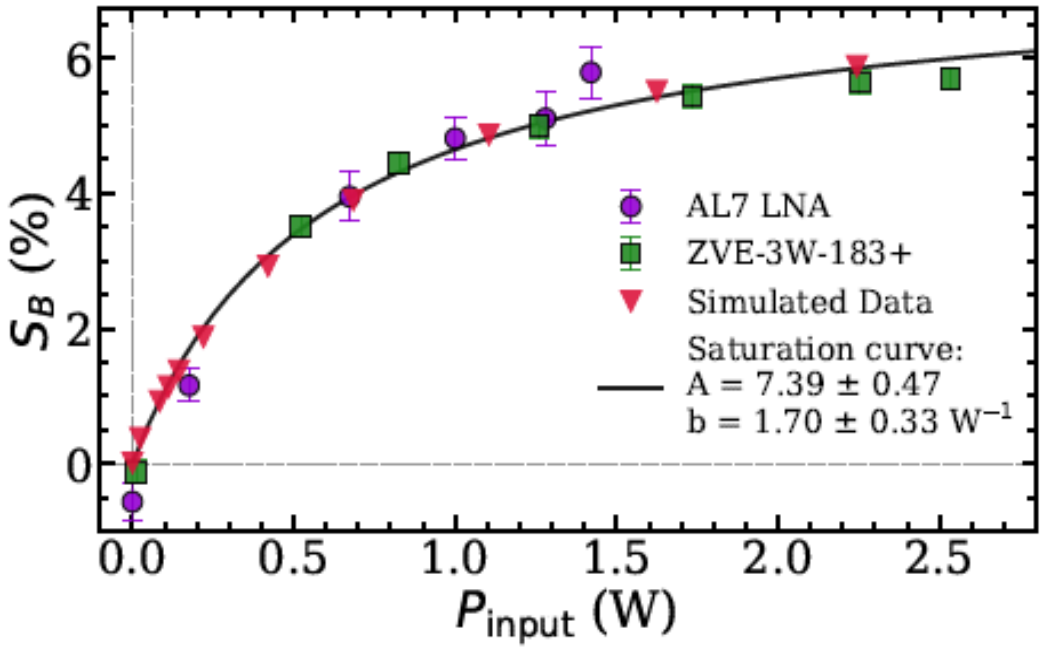
Ps* Beam Characterisation





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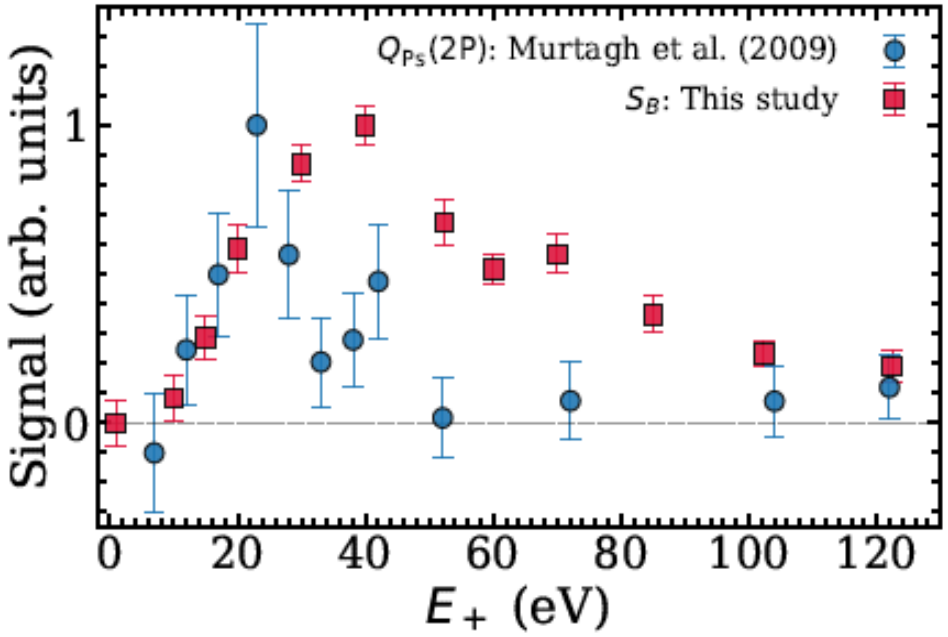

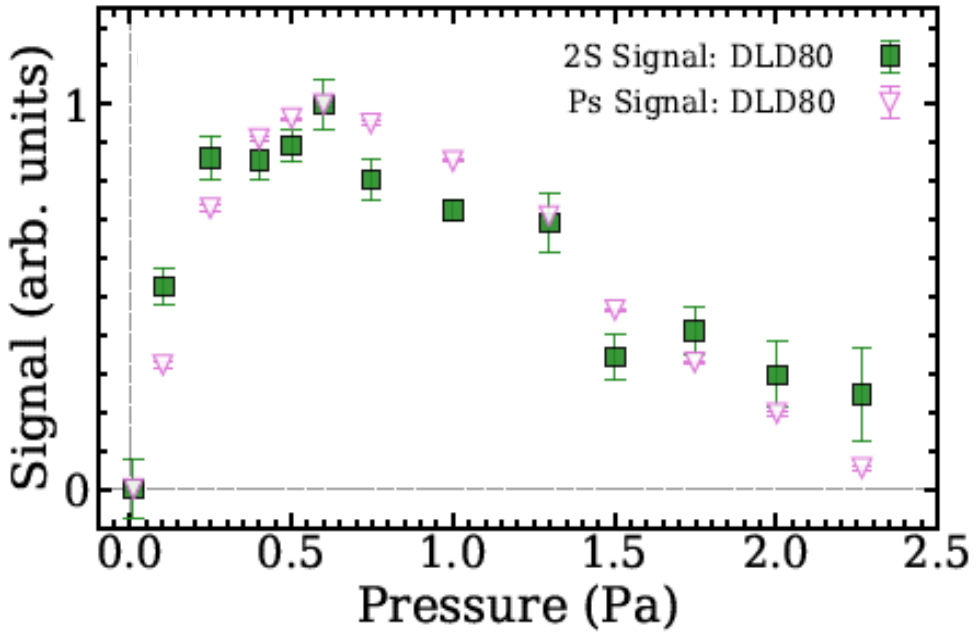

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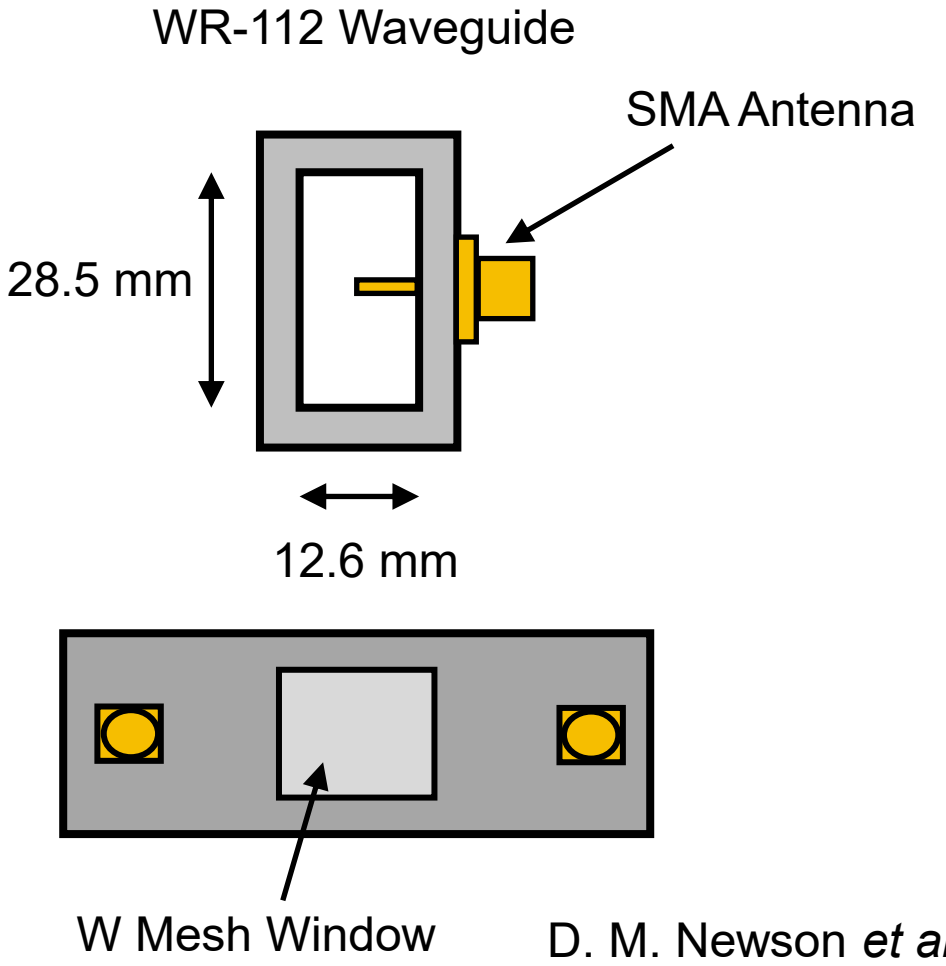

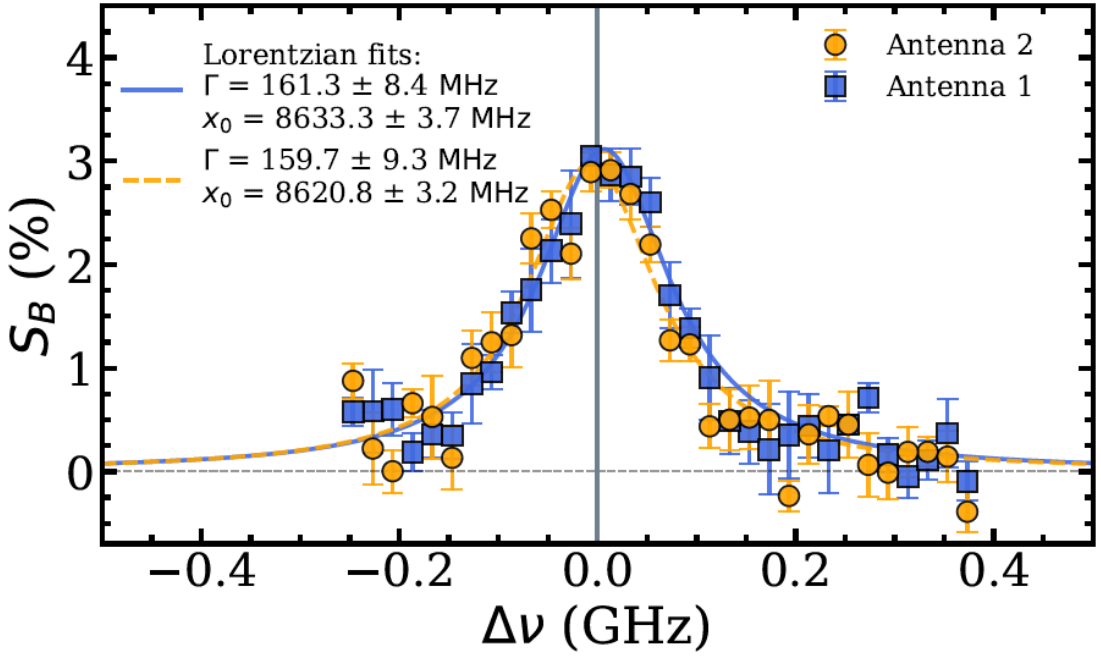

$$\nu_2 = 8626.05 \pm 2.65 \text{ MHz}$$

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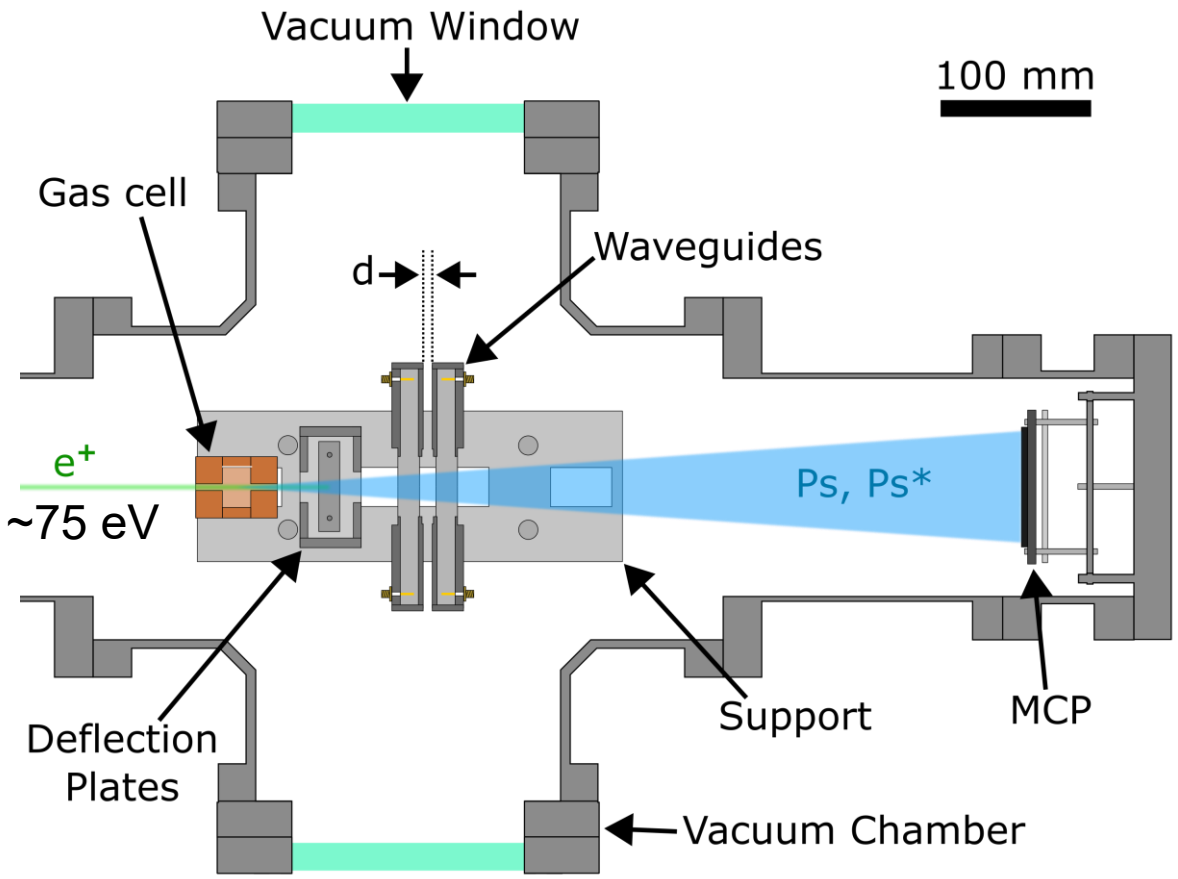
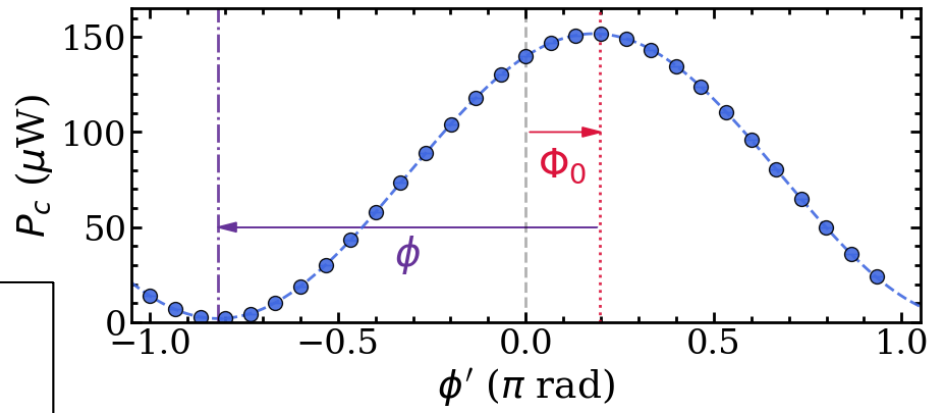
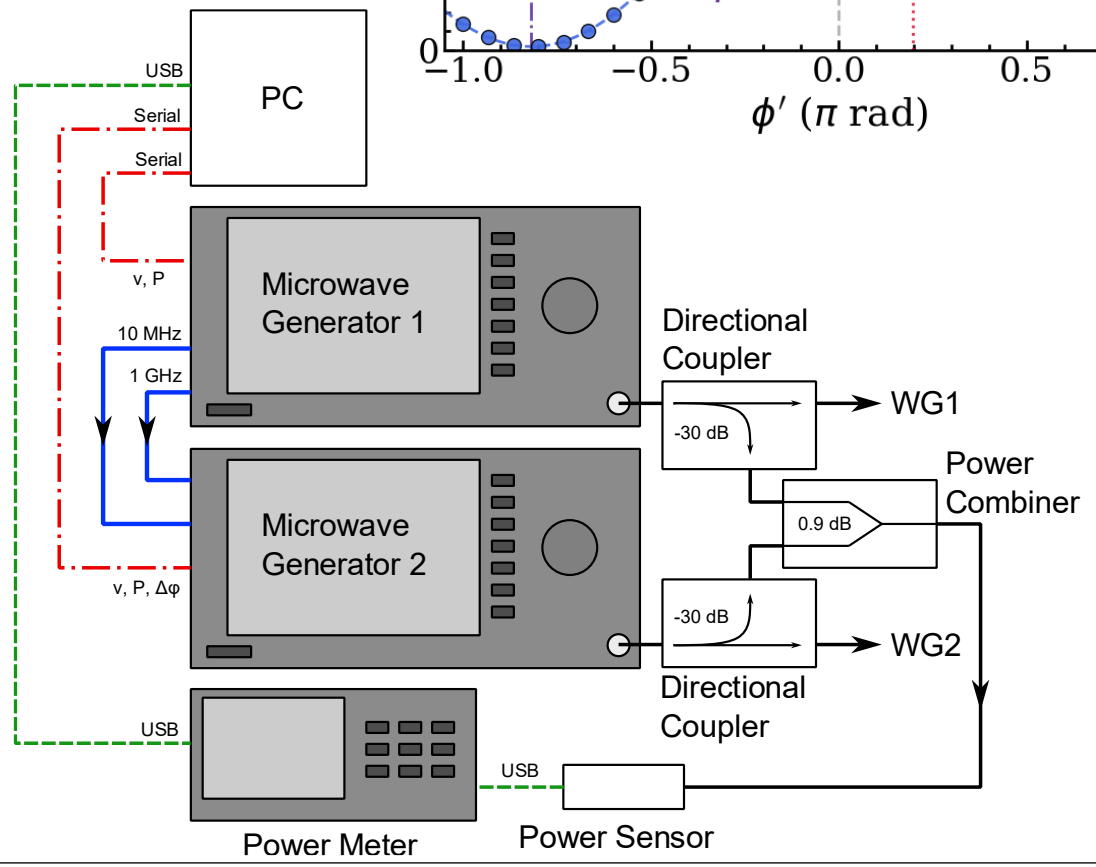
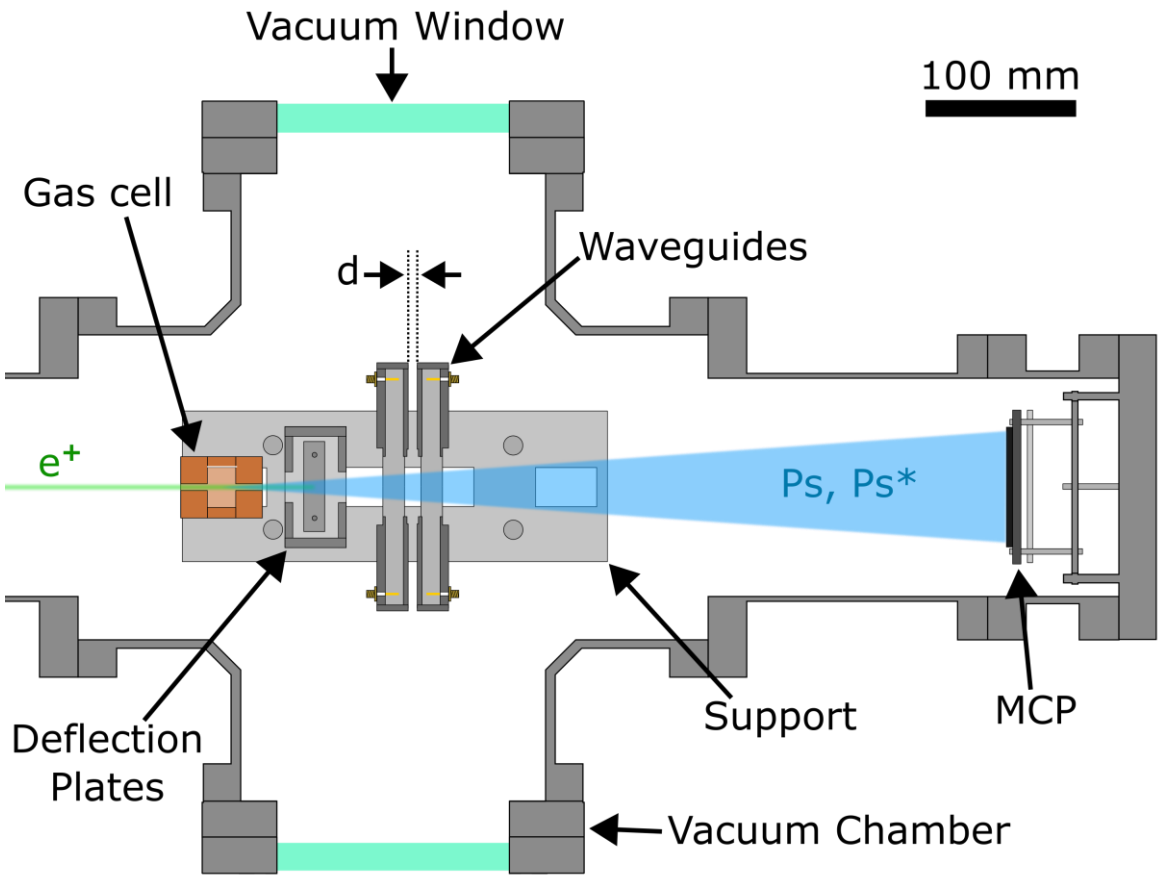
Experimental Setup - PVSOF

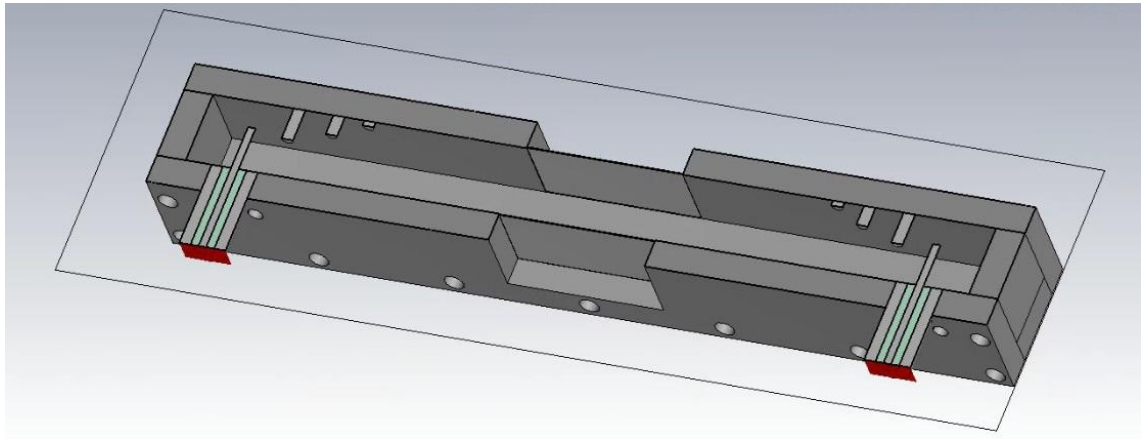


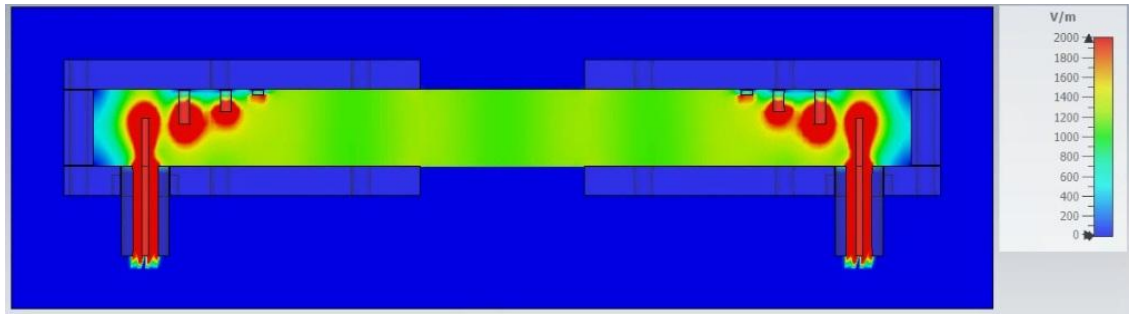




Experimental Setup - Waveguides







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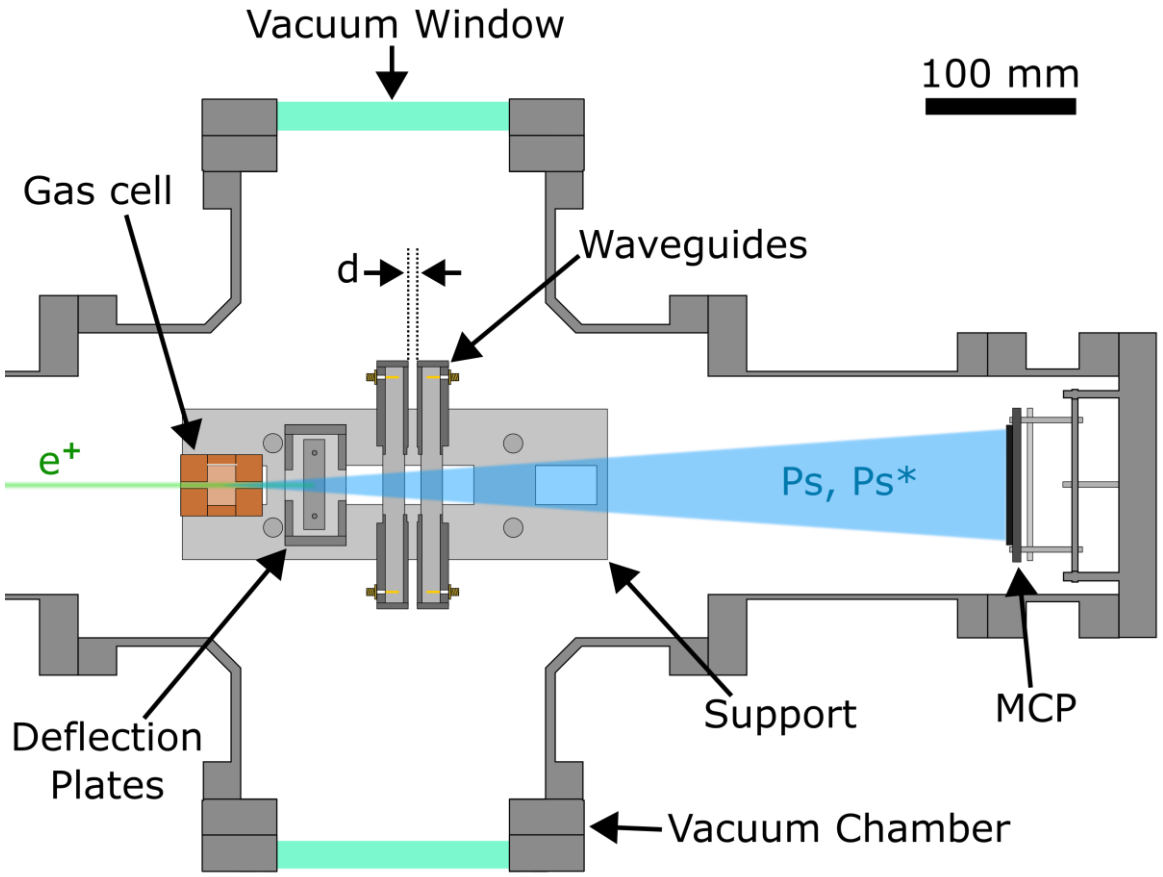
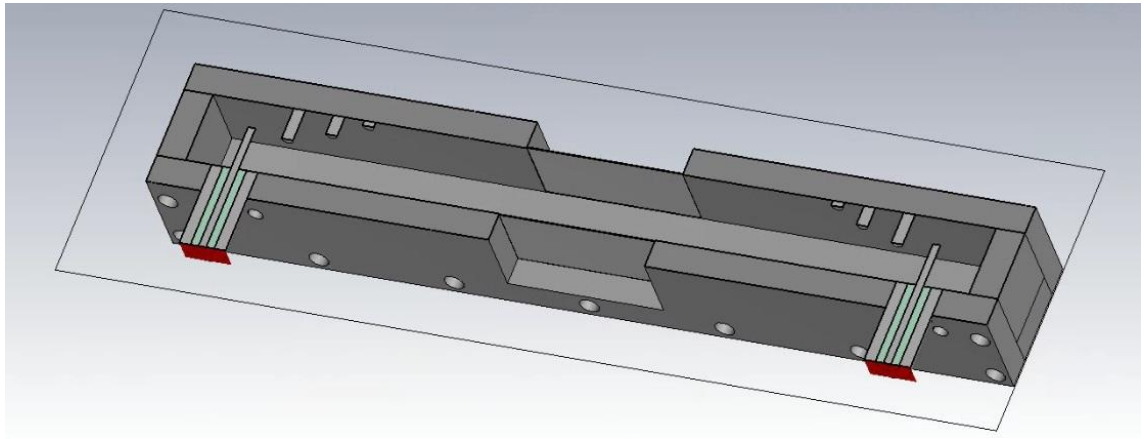
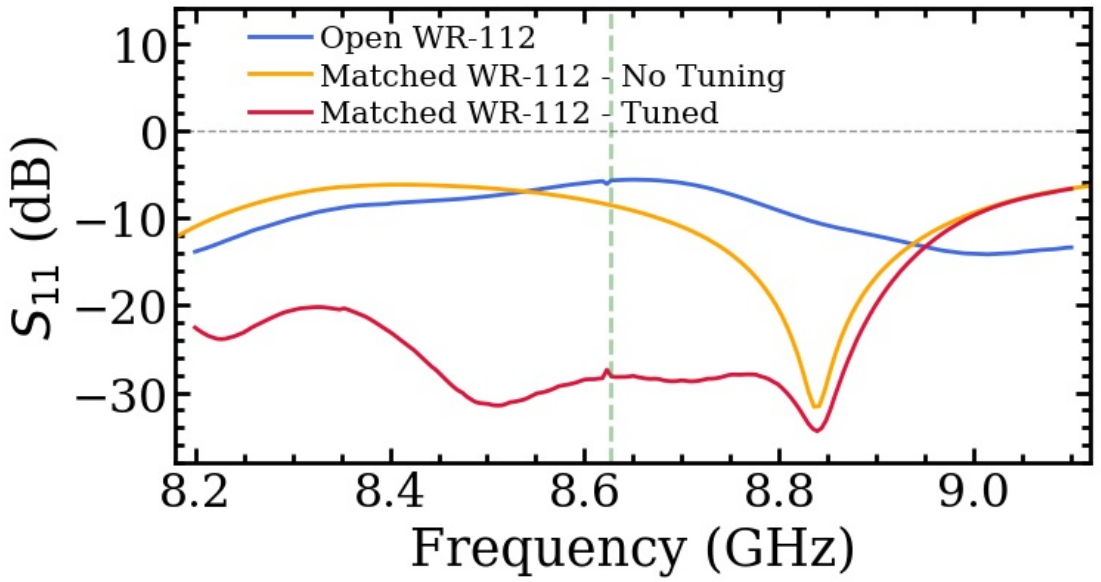
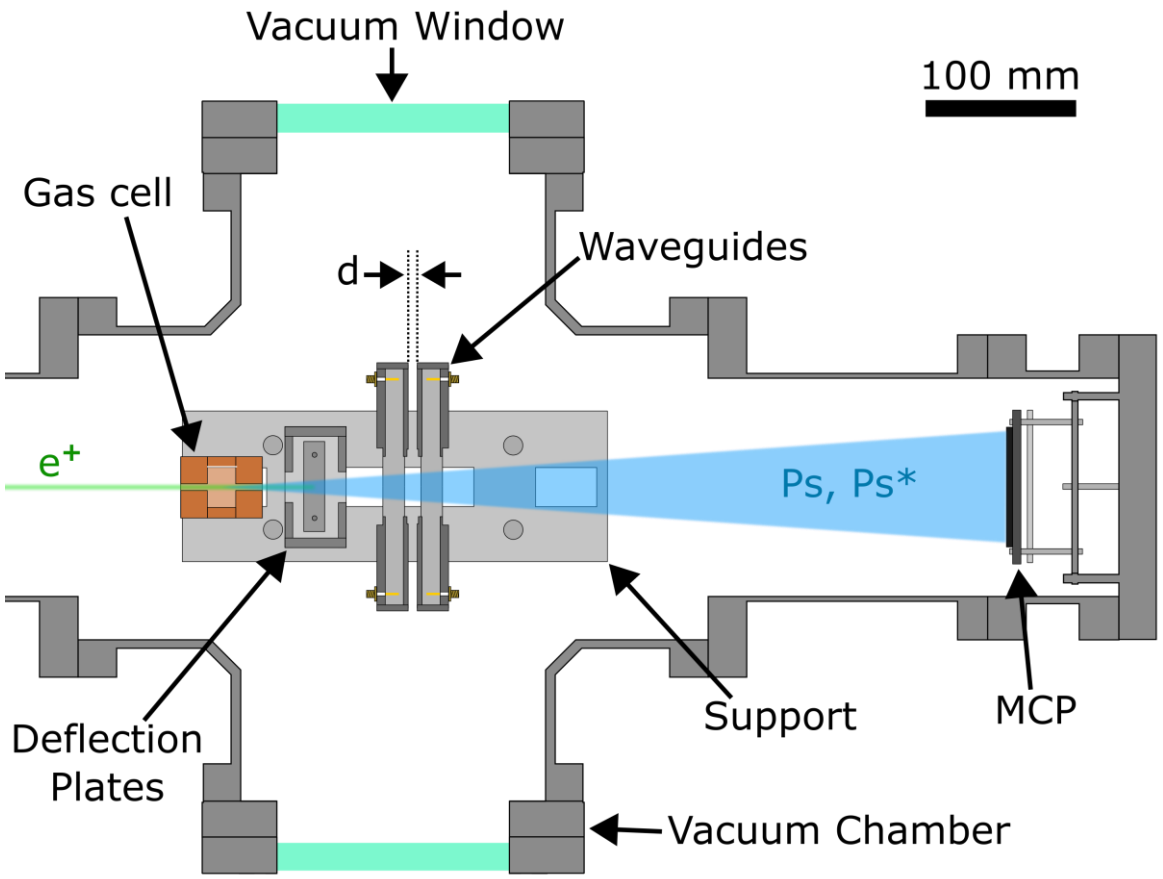


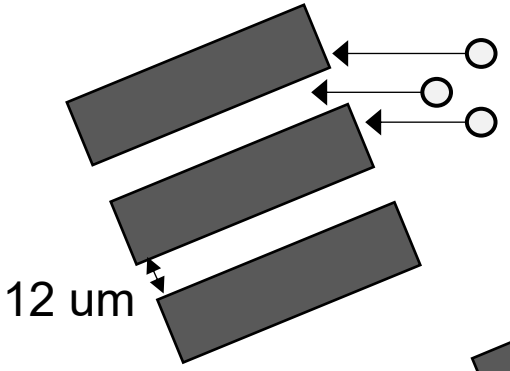


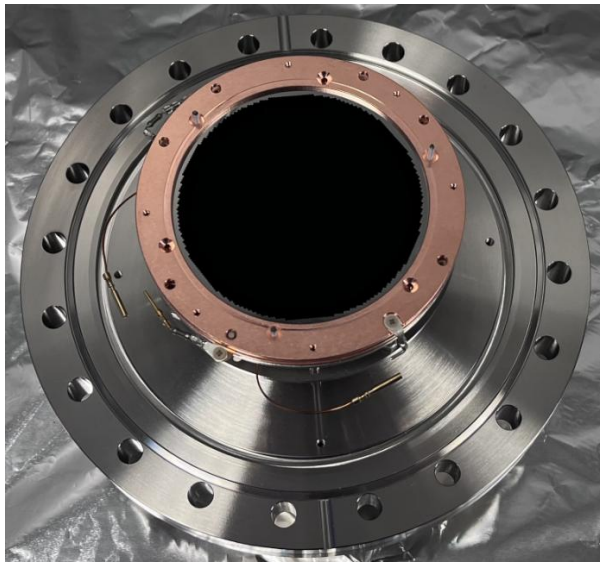


Experimental Setup – Funnelled MCP

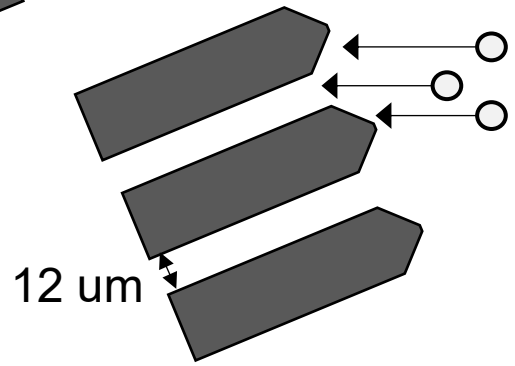


Standard channels
open area ratio ~60 %





Funnelled channels ~90 %



Results - Phase Variation SOF

Measurement Sequence:

- Measure PSD signal with no gas in cell (background, 100 s)
- Set gas cell pressure, frequency, power & relative phase offset
- Record PSD signal with microwaves on (600 s)
- Record PSD signal with microwaves off (600 s)

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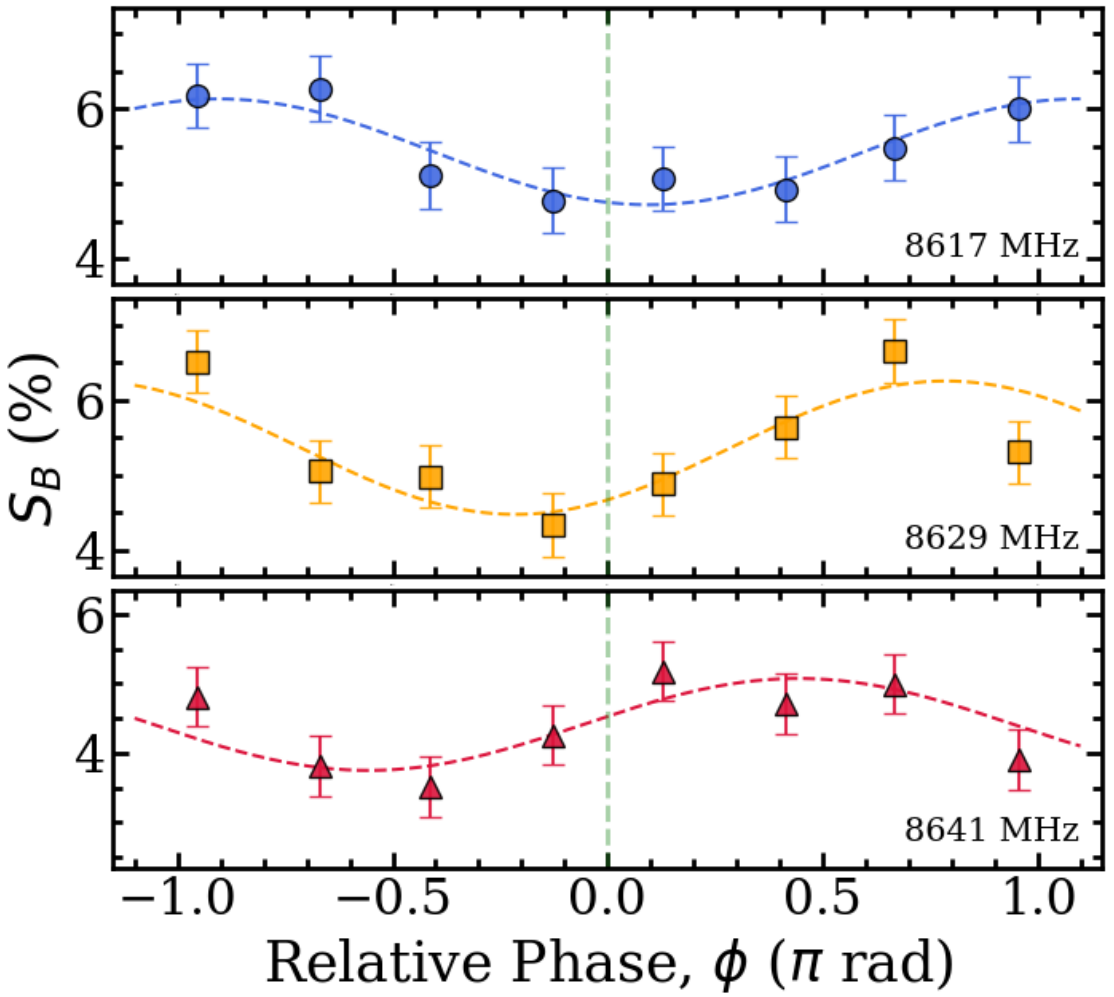
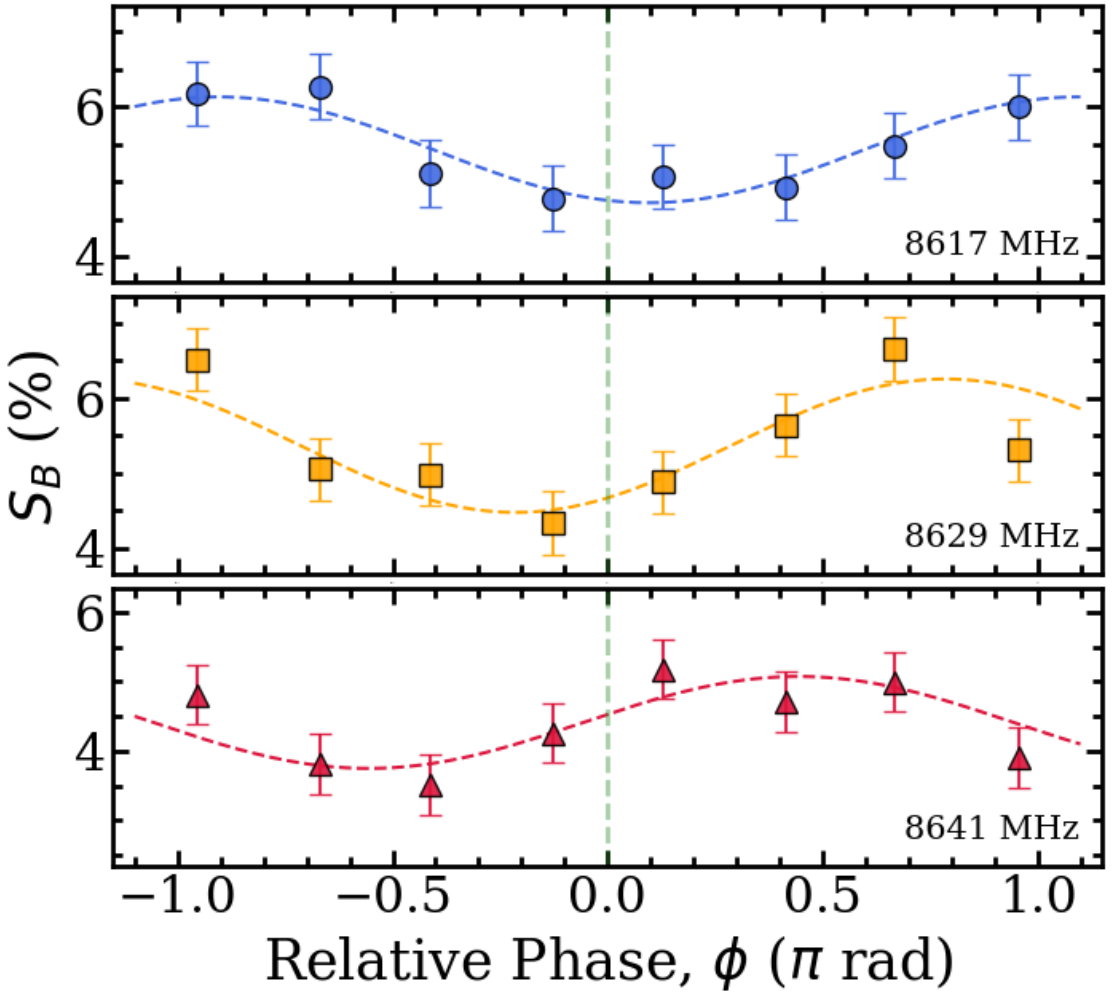


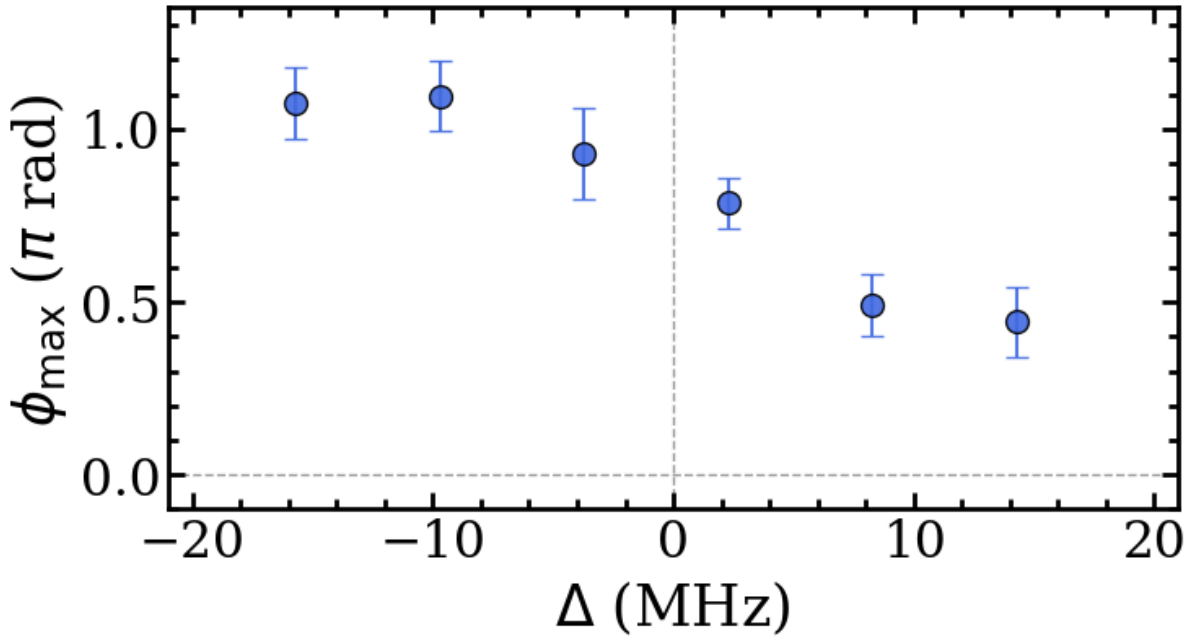
Results - Phase Variation SOF

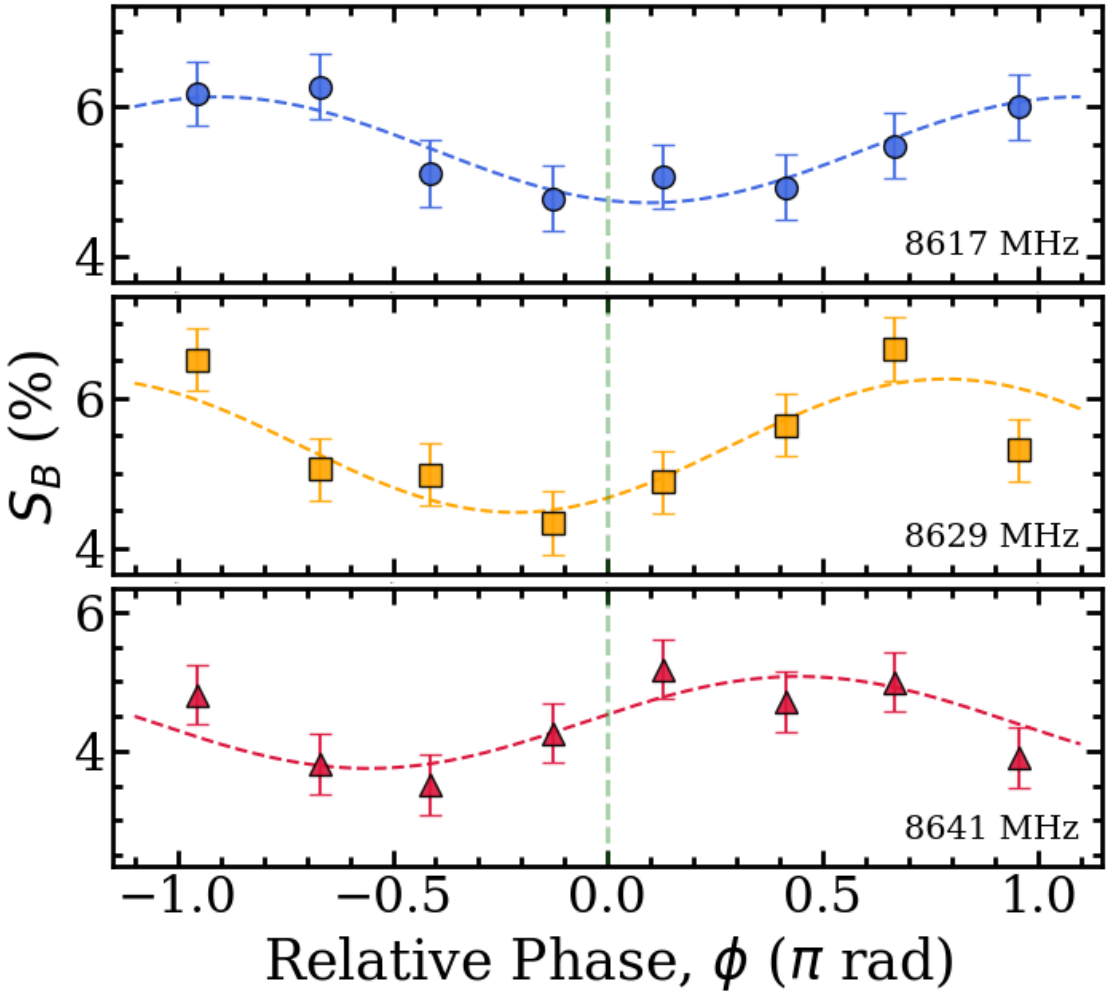
Observation of Ps* interference signal



Results - Phase Variation SOF

Extract phase of modulation versus detuning:





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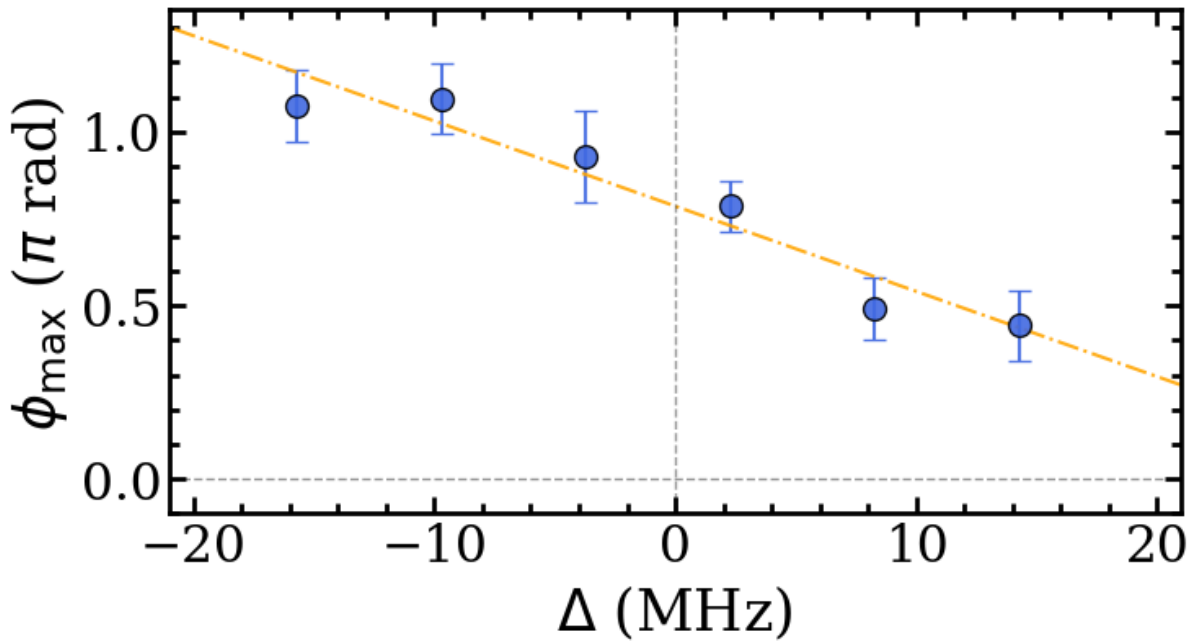
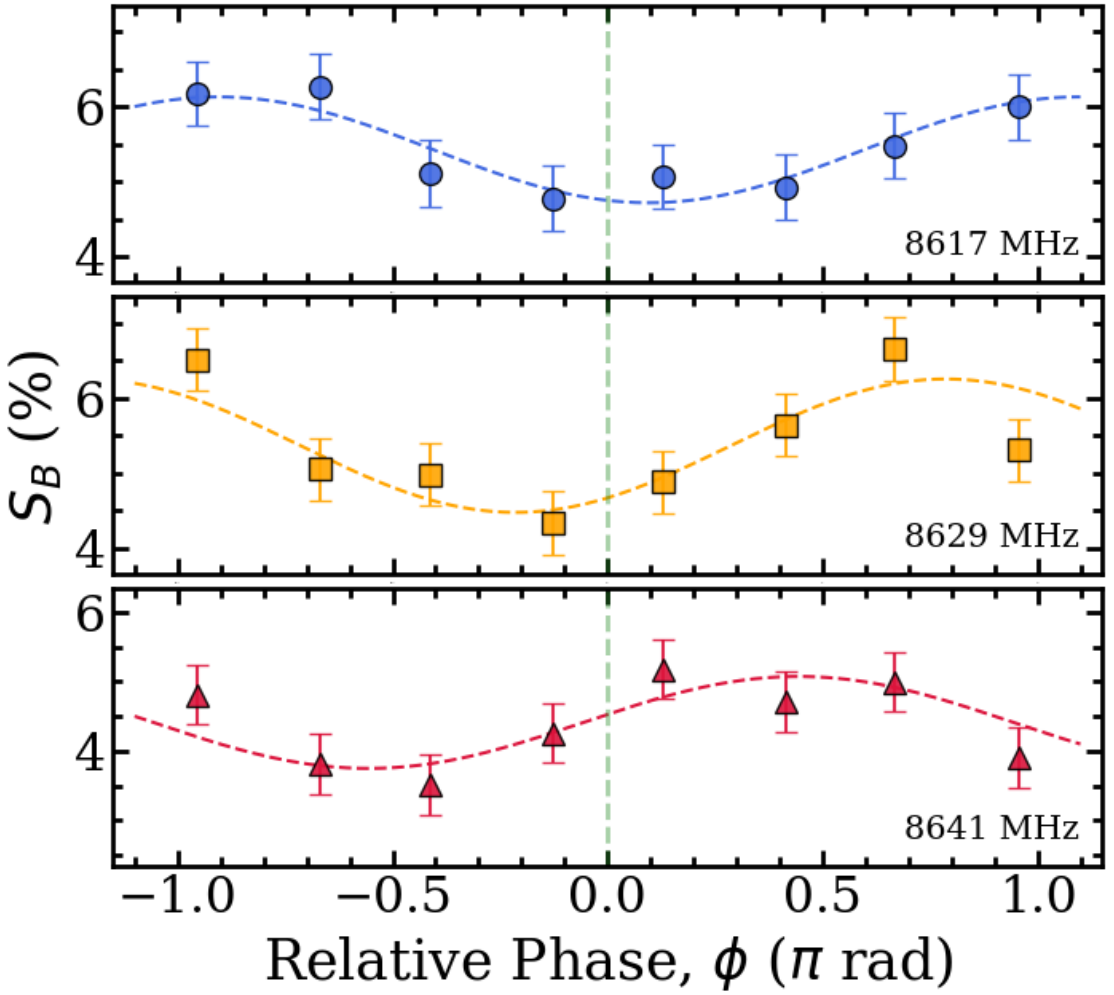
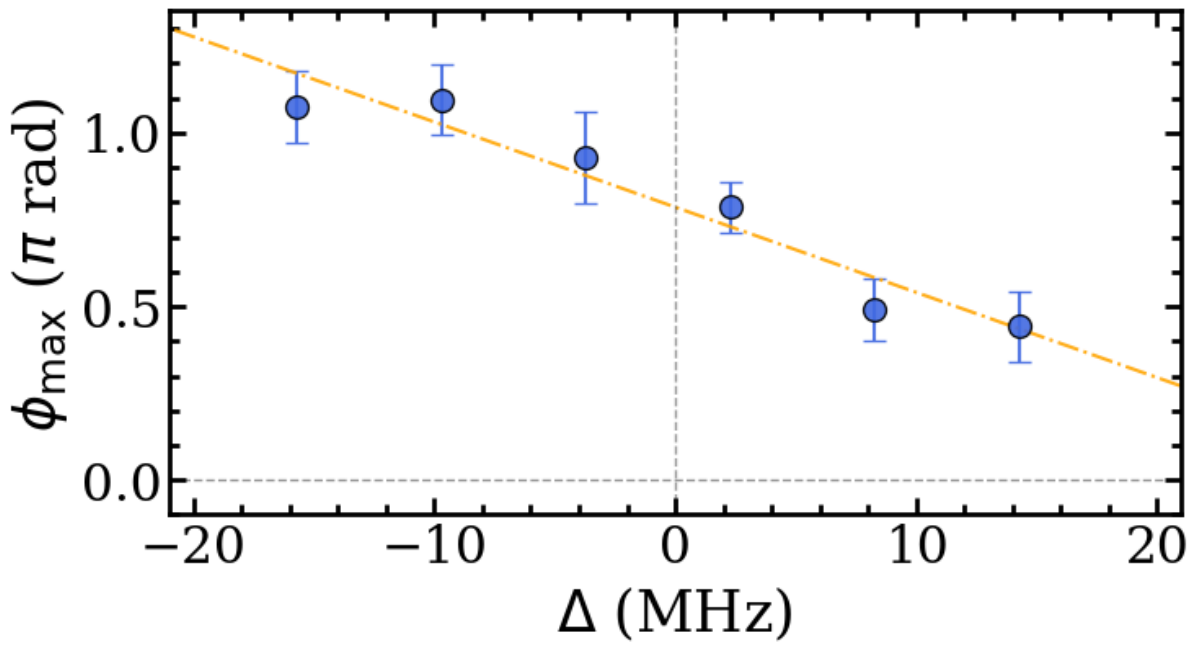




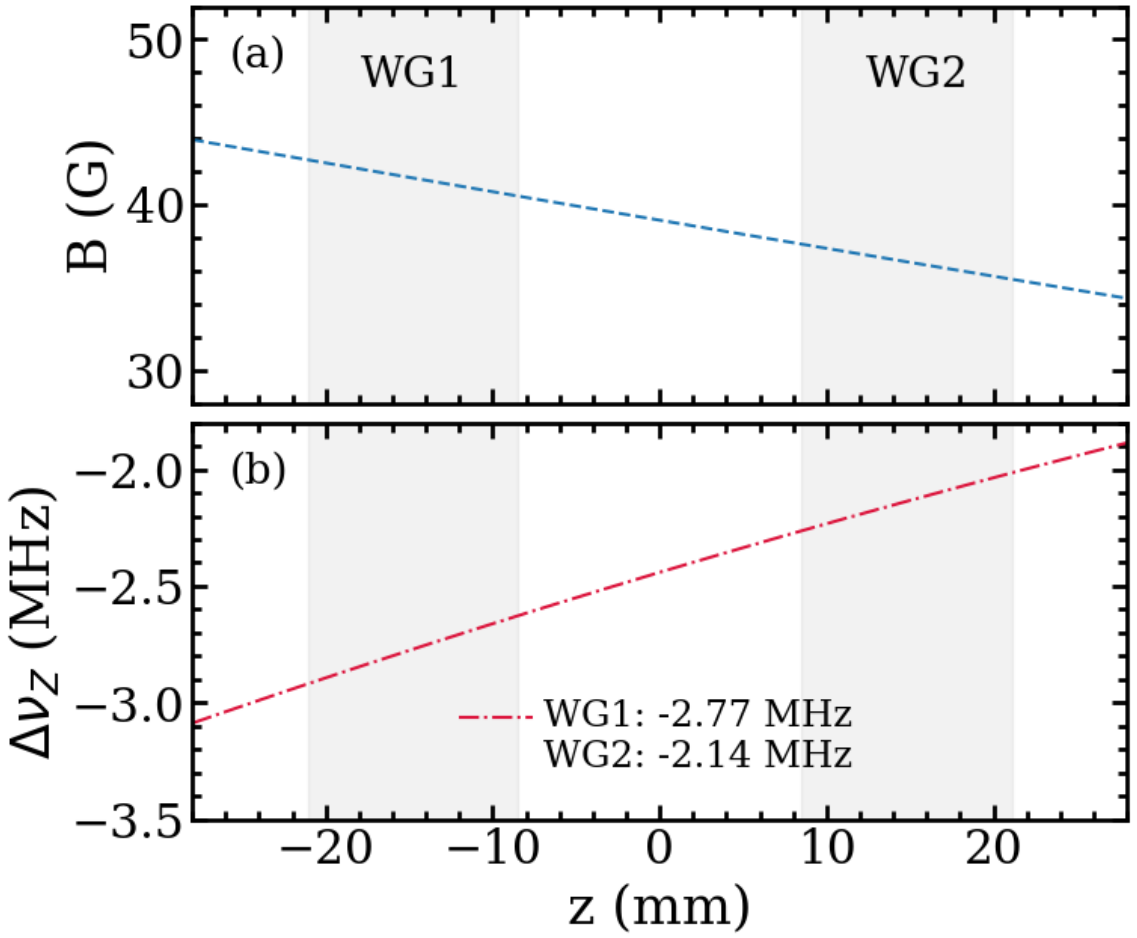
Systematic Effects

Linear trend but data shifted relative to zero phase axis



- Zeeman Shift
  - Residual positron guiding field
- Relative Phase Shifts of Driving Fields
  - Impedance differences from waveguide construction, cables etc.

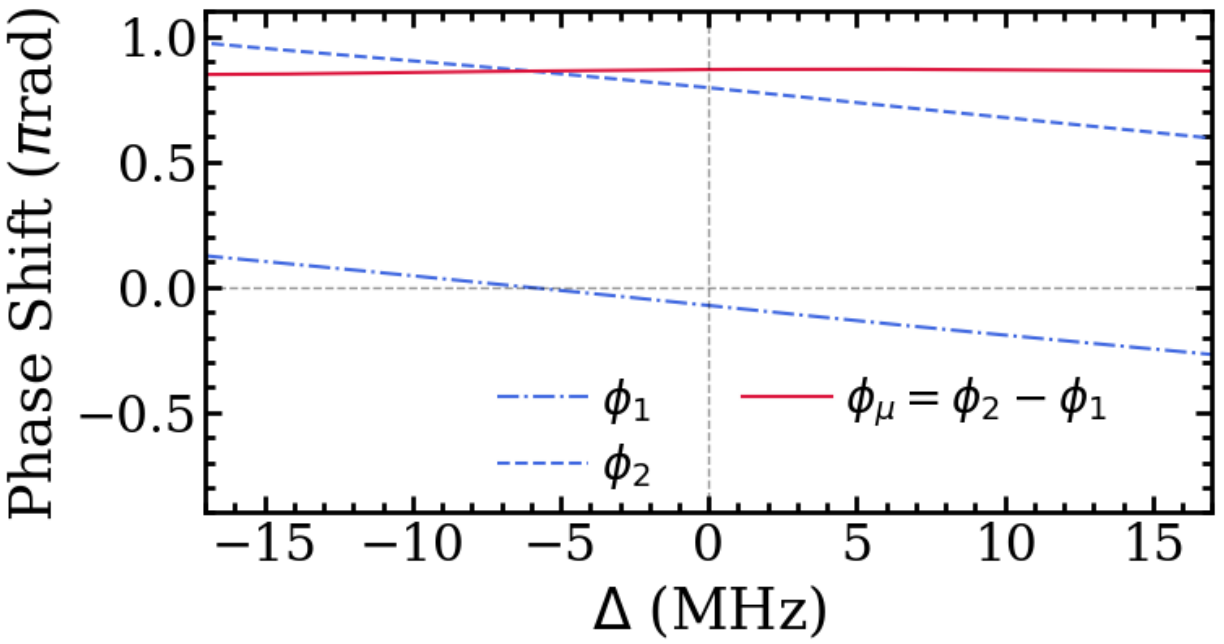
Systematic Effects



- Zeeman Shift
  - Residual positron guiding field
- Relative Phase Shifts of Driving Fields
  - Impedance differences from waveguide construction, cables etc.

Systematic Effects

Measured phase shift of each waveguide port-to-port with VNA



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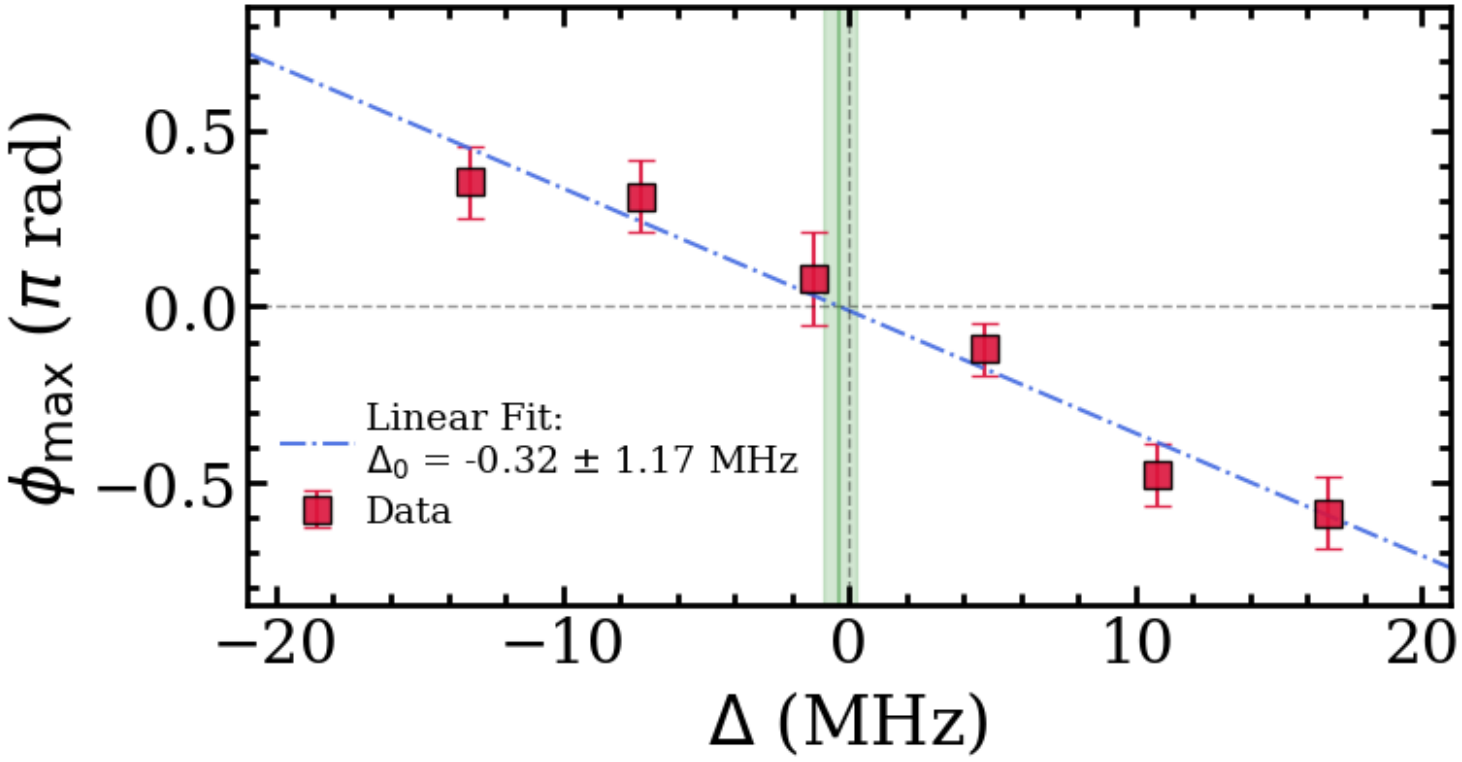
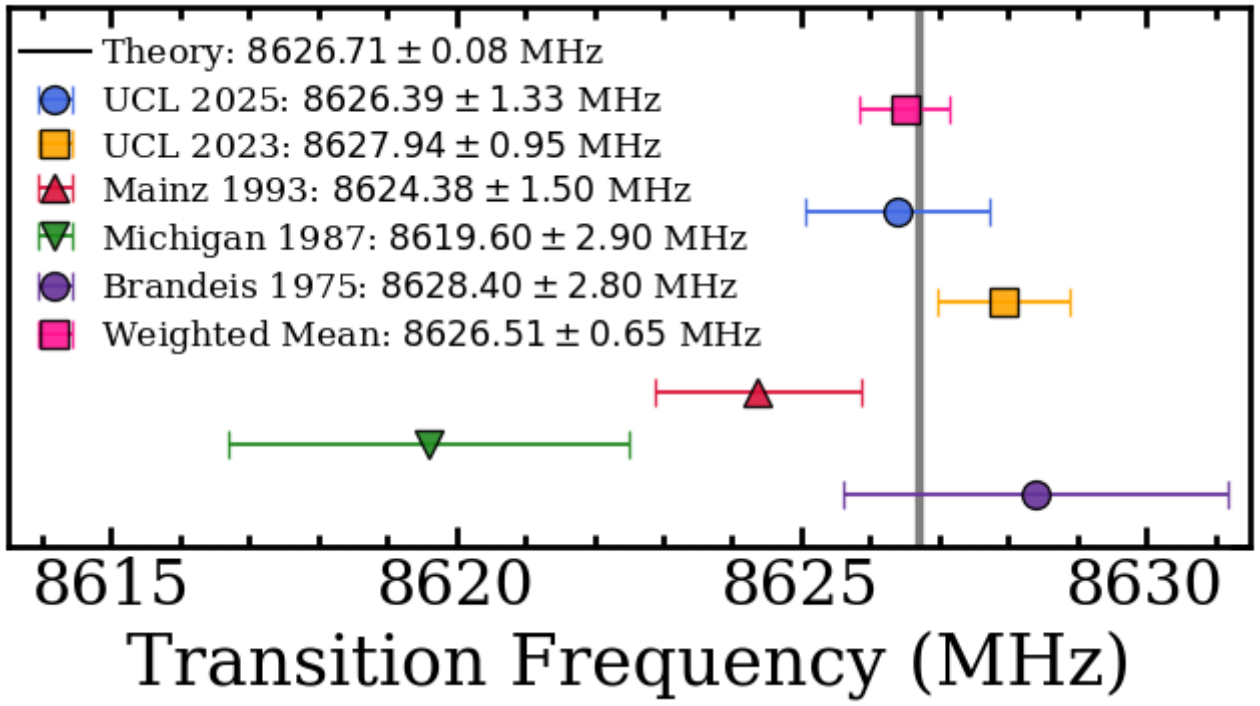
Results - Phase Variation SOF



$$8626.39 \pm 1.17_{\text{stat}} \pm 0.80_{\text{sys}} \text{ MHz}$$

Results - Phase Variation SOF



$$8626.39 \pm 1.17_{\text{stat}} \pm 0.80_{\text{sys}} \text{ MHz}$$

Improvements

- Higher positron/Ps beam rate
- Doppler-free measurement
- Minimise/eliminate magnetic field

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- Higher positron/Ps beam rate
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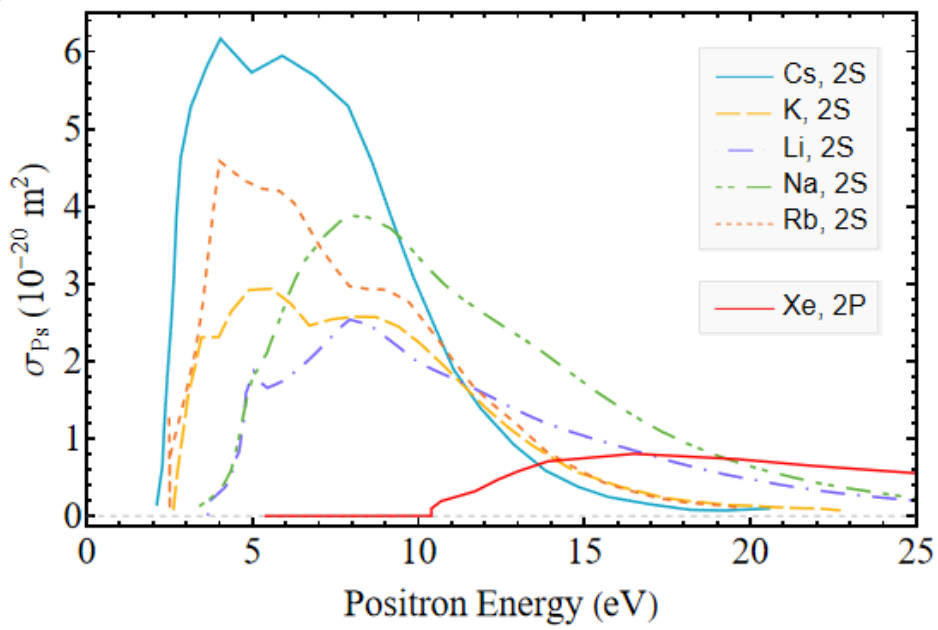
Facility based positron beams:

- Reactor
- LINAC

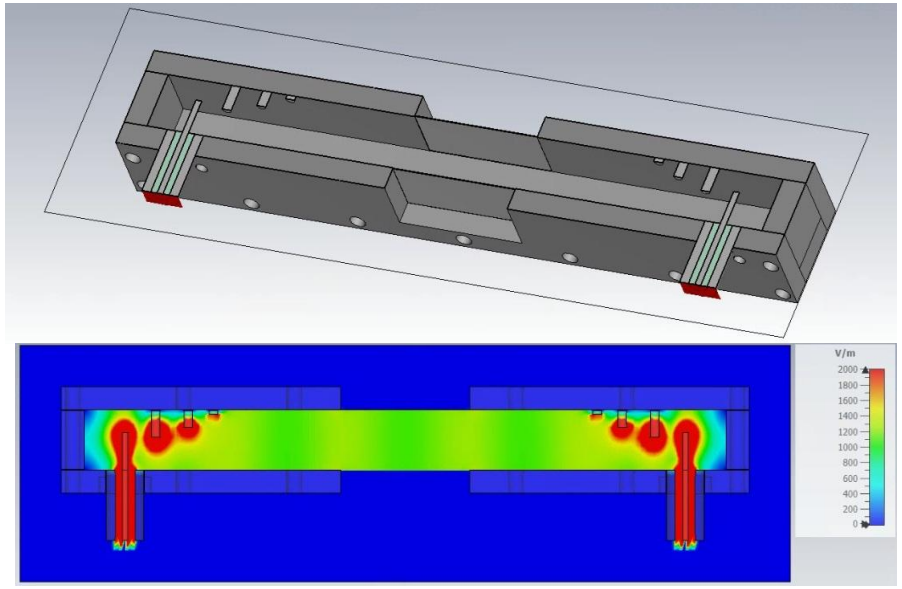
Improved Ps* production efficiencies:



Improvements

- Higher positron/Ps beam rate
- Doppler-free measurement
- Minimise/eliminate magnetic field

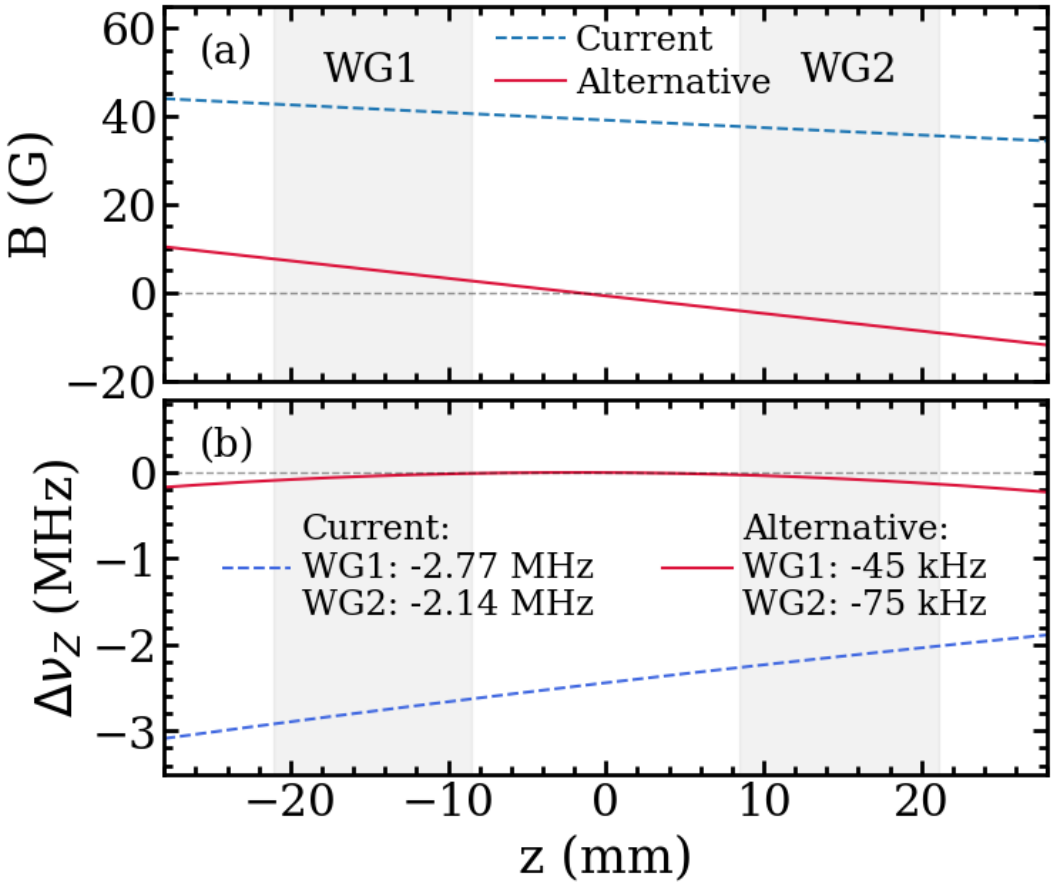
Average measurements with driving signals applied to right/left waveguide antennas



Improvements

- Higher positron/Ps beam rate
- Doppler-free measurement
- Minimise/eliminate magnetic field

Cancel magnetic field around waveguides:



Summary

- Produced energy tuneable beam of metastable positronium suitable for spectroscopic methods requiring fast atoms (PVSOF, FOSOF)
- Observed Ps* interference signal with separated oscillatory fields
- Measured fine-structure transition frequency using PVSOF technique and characterised dominant systematic effects
- Next steps:
  - Minimise systematics: magnetic field-free, Doppler-free measurements
  - Understand quantum interference effects (10-100 kHz shifts) in PVSOF
  - Apply technique to other fine-structure intervals (13.01 GHz, 18.5 GHz)
  - FOSOF technique

Acknowledgements

Group members:
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Derek Thomas
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Thank You For Your Attention

PHYSICAL REVIEW LETTERS **136,** 033001 (2026)

Editors' Suggestion

Phase-Variation Ramsey Spectroscopy of the $2^3S_1 \rightarrow 2^3P_2$ Interval in Positronium

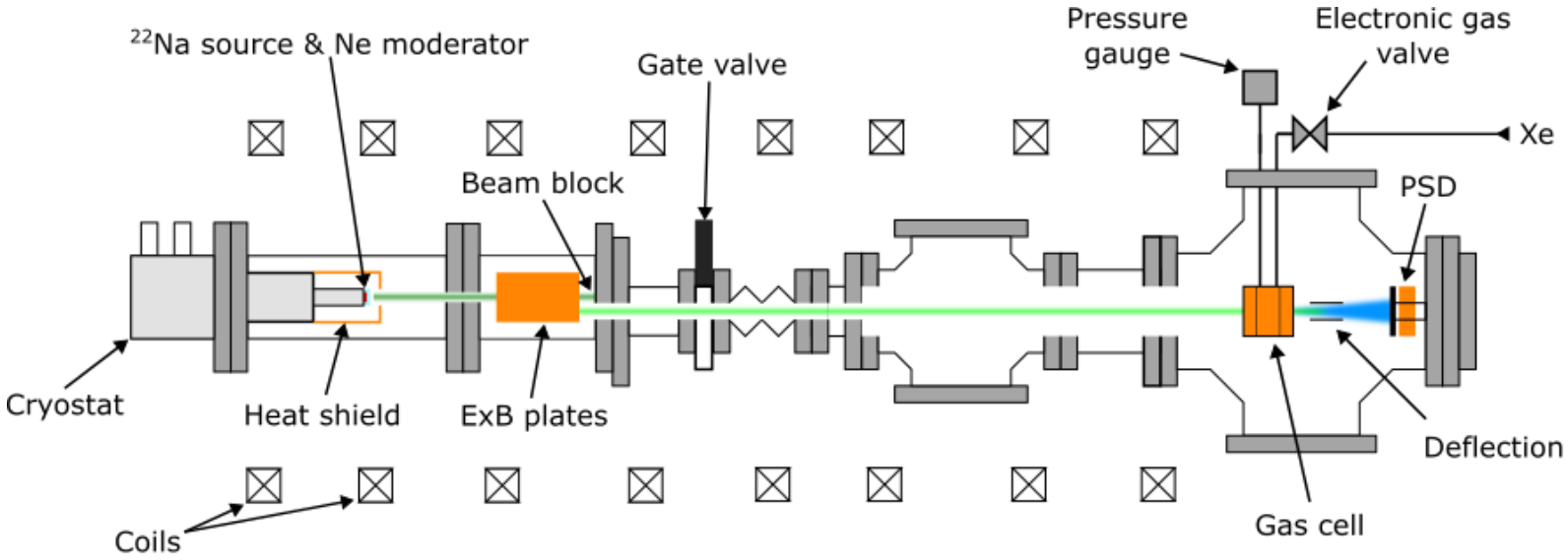
D. M. Newson and D. B. Cassidy

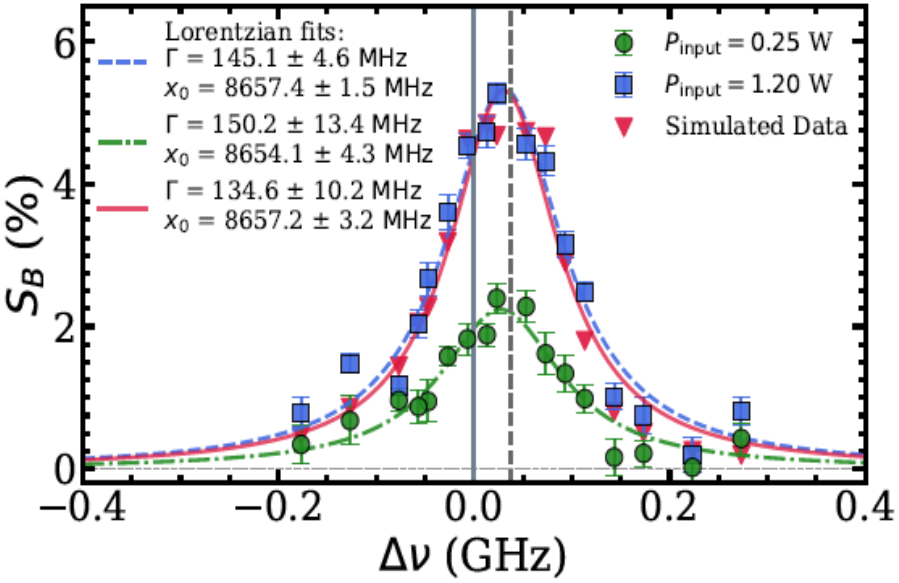
Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, United Kingdom

(Received 7 October 2025; accepted 2 January 2026; published 22 January 2026)

Ps* Beam

$$e^+ + \mathrm{Xe} \rightarrow \mathrm{Ps}^{(*)} + \mathrm{Xe}^+$$
$$E_{\mathrm{Ps}} = E_+ - E_I + 6.8\,\mathrm{eV}/n_{\mathrm{Ps}}^2$$





An energy tunable continuous 2^3S_1 positronium beam

Cite as: Rev. Sci. Instrum. 94, 083201 (2023); doi: 10.1063/5.0167125
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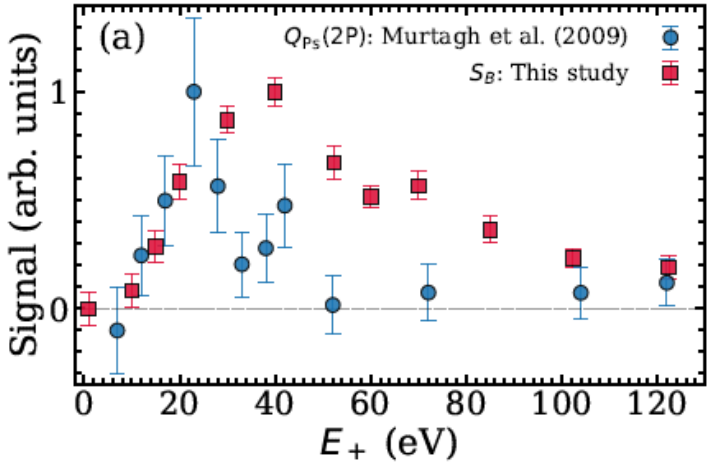
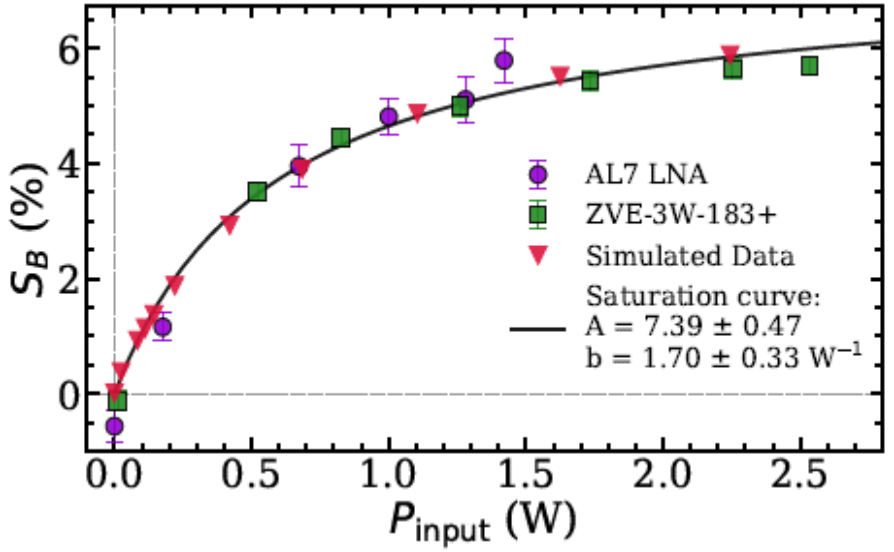
D. M. Newson, T. J. Babij, and D. B. Cassidy[a)]

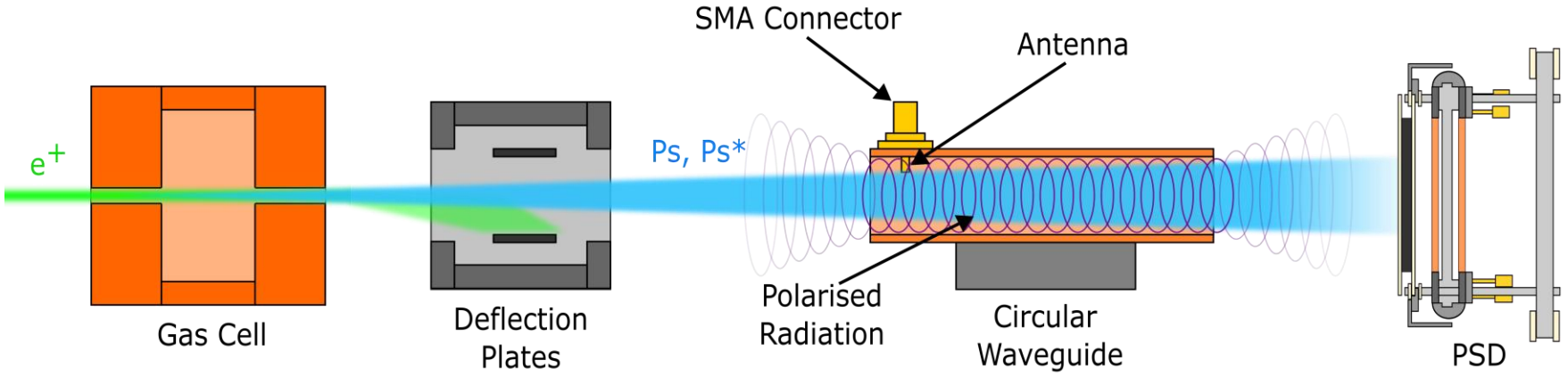
AFFILIATIONS

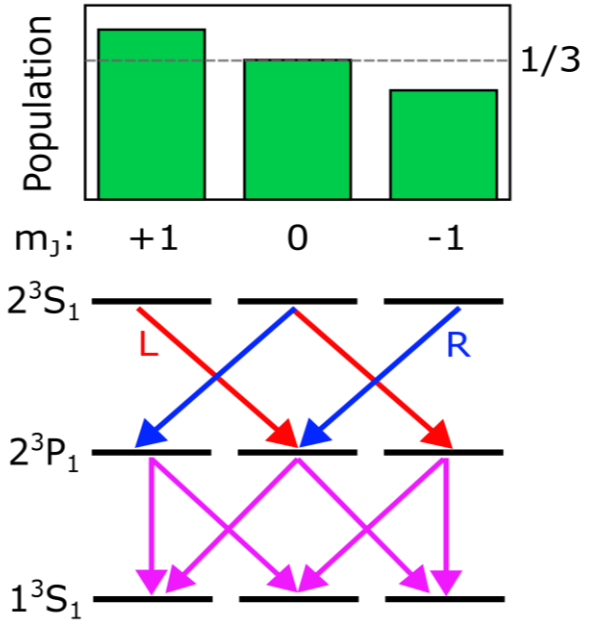
Department of Physics and Astronomy, University College London, Gower Street,





Polarimetry Measurements



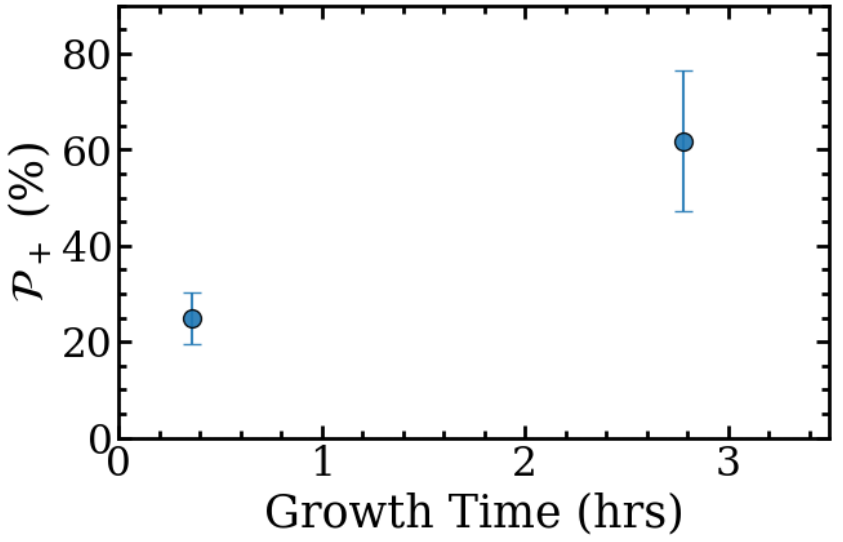


PHYSICAL REVIEW LETTERS **133,** 233004 (2024)

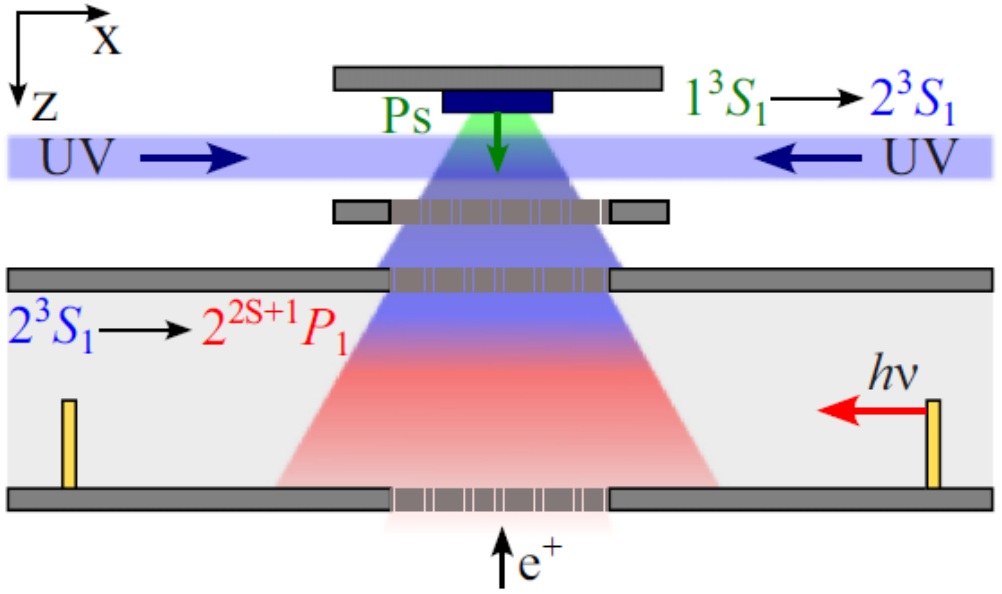
Measurement of the Spin Polarization of a Slow Positron Beam Using Circularly Polarized Microwave Radiation

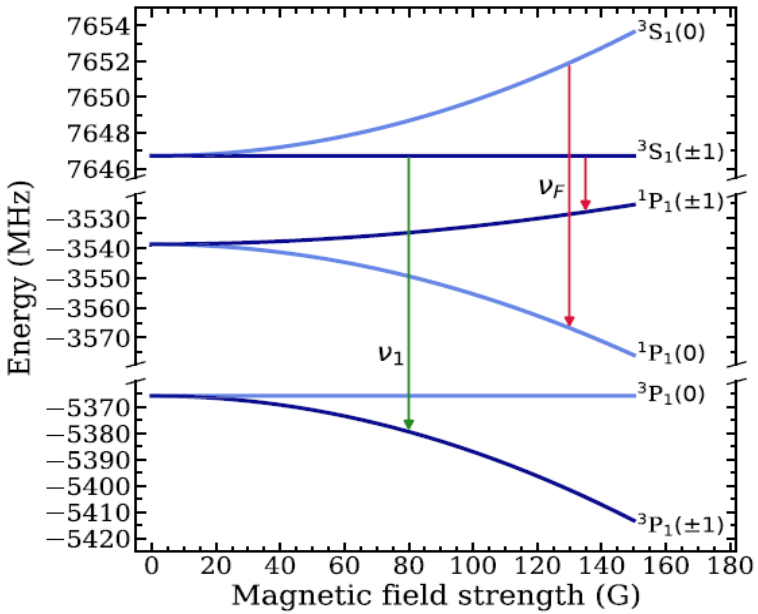
D. M. Newson and D. B. Cassidy
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

(Received 13 September 2024; accepted 6 November 2024; published 4 December 2024)

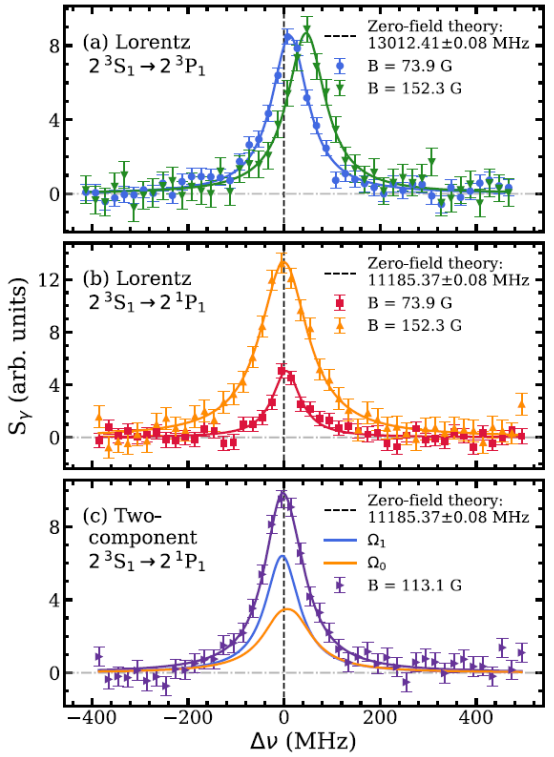


C-Violation Tests





$$A_X = \frac{\langle 2\,^1P_1|H_X|2\,^3P_1\rangle\langle 2\,^3P_1|E1|2\,^3S_1\rangle}{E_F}$$



PHYSICAL REVIEW A **112**, 062801 (2025)

Test of charge-conjugation symmetry via microwave spectroscopy of positronium

R. J. Daly,[1] K. P. Habdas,[1] D. M. Newson,[1] J. Pérez-Ríos,[2] R. E. Sheldon,[1] and D. B. Cassidy[1]
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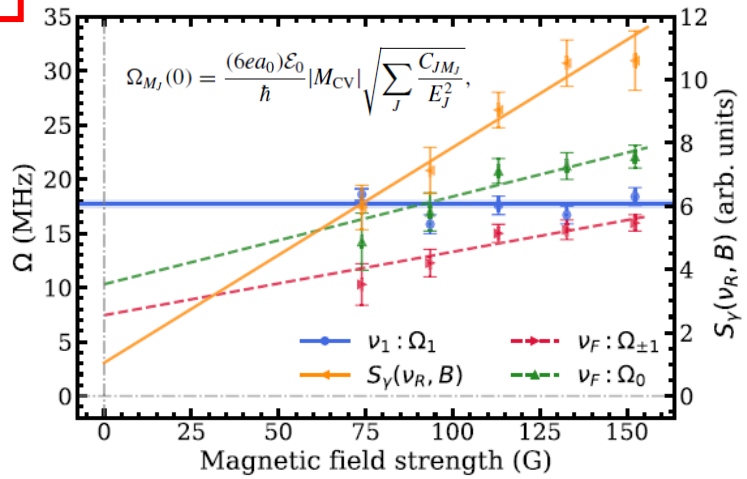
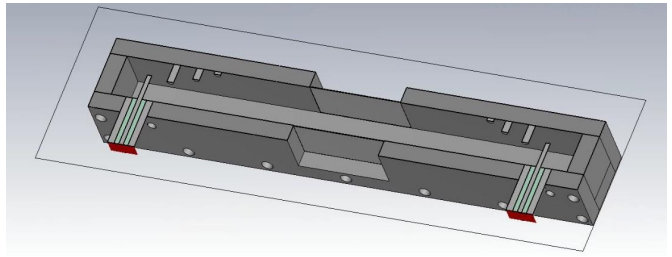
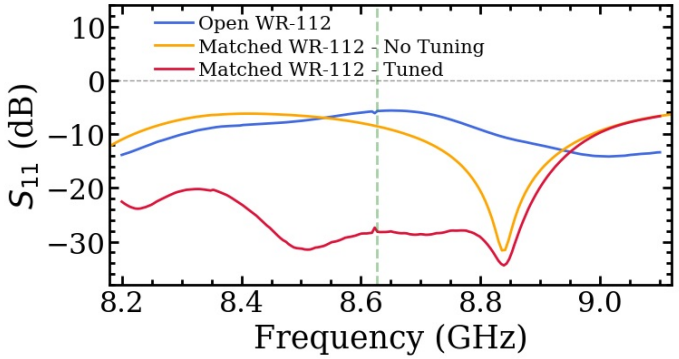
[2]*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794, USA*

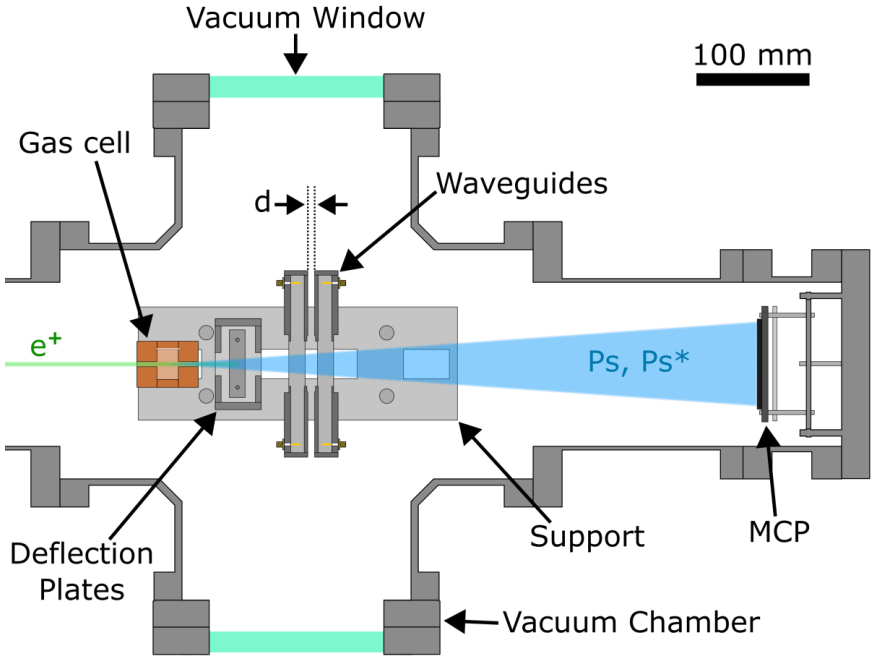
(Received 23 July 2025; accepted 30 October 2025; published 1 December 2025)

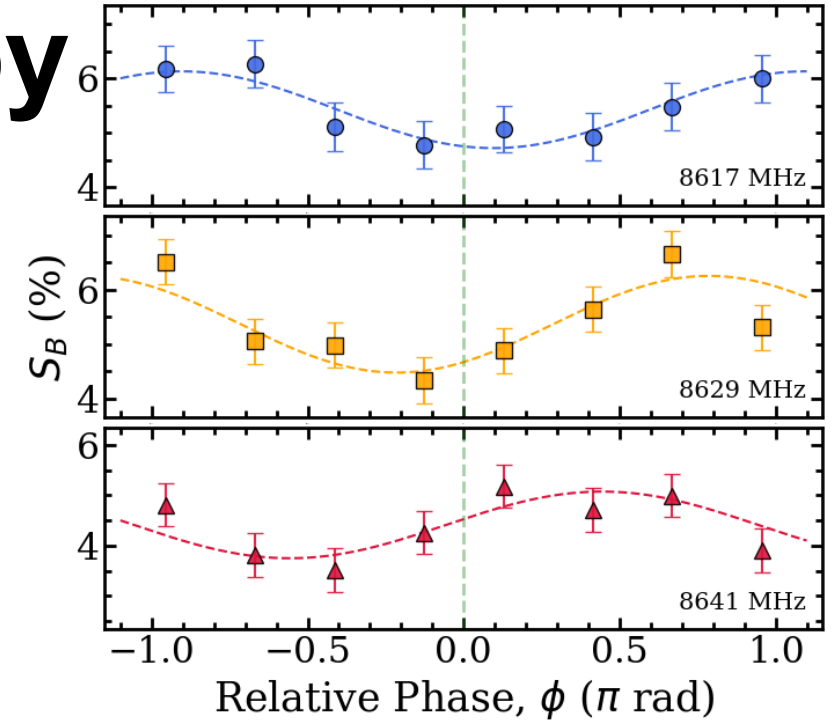


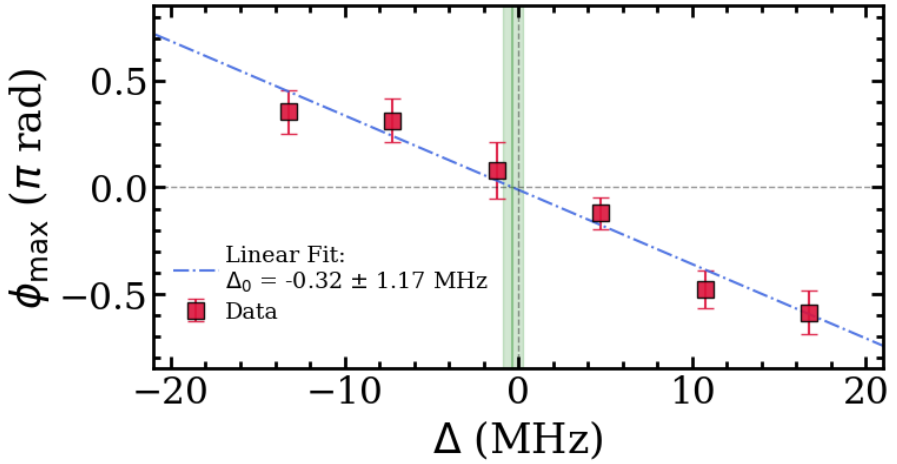
Phase-Sensitive Spectroscopy











PHYSICAL REVIEW LETTERS **136,** 033001 (2026)

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