Weak measurement of spin and its experimental realisation in atomic systems

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Plan of the talk

- Principle of weak measurement of spin.
- Method we are following.
- Experimental realization.
- Progress.

Focus on experimental not theoretical

Confusion in the literature

Strong measurement (von Neumann):

- Often referred to as collapsing the wave function.
- It is where we unambiguously measure the full set of eigenvalues of an observable.

Von Neumann. Mathematical foundations of quantum mechanics. Springer Verlag,1932.

Weak measurement (Aharonov et al):

- This is a two stage process; one weak, one strong.
- Each stage acting on one of non-commuting variables.
- It does not observe or measure the full set of eigenvalues of an observable.
- It measures a weak value.

Aharonov et al. Phys. Rev. Lett., 60:1351, 1988.

Why atomic particles?

The theory is based on the non-relativistic quantum mechanics using Schröedinger's equation.

Most experimental work used photons, i.e. Maxwell's equations.

The process has been observed using neutrons.

We wanted to confirm the weak measurement process using atoms.

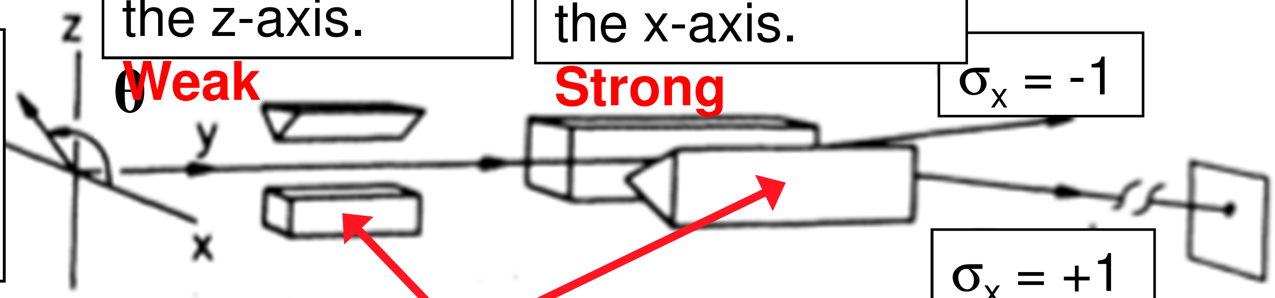
Weak measurement of spin: Method

I. M. Duck, P. M. Stevenson and Sudarshan, Phys. Rev. D, 1989

The particles enter along the y-axis with spin oriented at angle θ in the zx-plane.

The first S-G is oriented along the z-axis.

The second S-G is oriented along the x-axis.



Non-commuting variables spin z-axis, spin x-axis

- $\Delta_w = \mu\tan(\theta/2)$, $\mu \propto$ magnetic moment of the particle.
- Note what happens as θ approaches π, Δ_w gets very large.
- Need three magnets.
- What is meant by "weak"

Weak Stage
How weak is weak?

The initial wave packet is a superposition of the possible eigenstates.

The action of the weak stage cannot spread the packet sufficient to collapse the wave function.

Has the effect of producing a change in the phase.

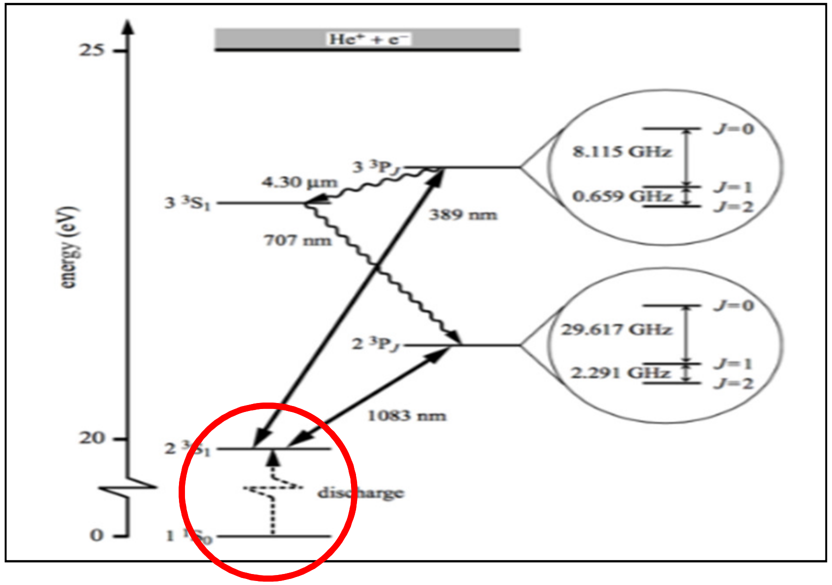
Each particle is emitted as a wave packet which has a width equal to the width of the beam.

The action of the weak stage cannot produce a divergence in the beam greater than its original width.

Our experimental interpretation

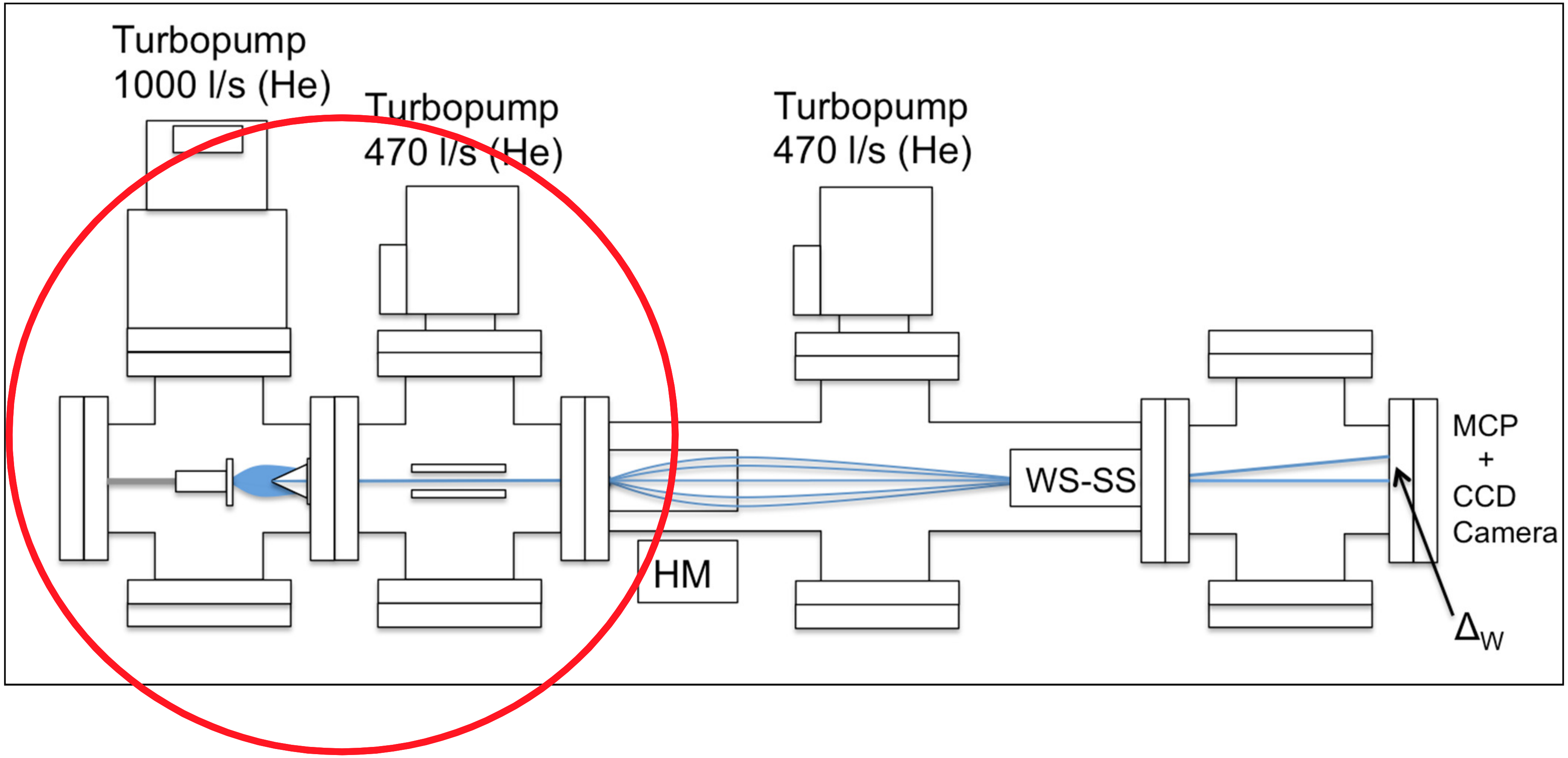
Metastable 2^3S_1 He, (He*)

K. Baldwin, Contemporary Physics, Vol. 46, No. 2, March–April 2005, 105 – 120



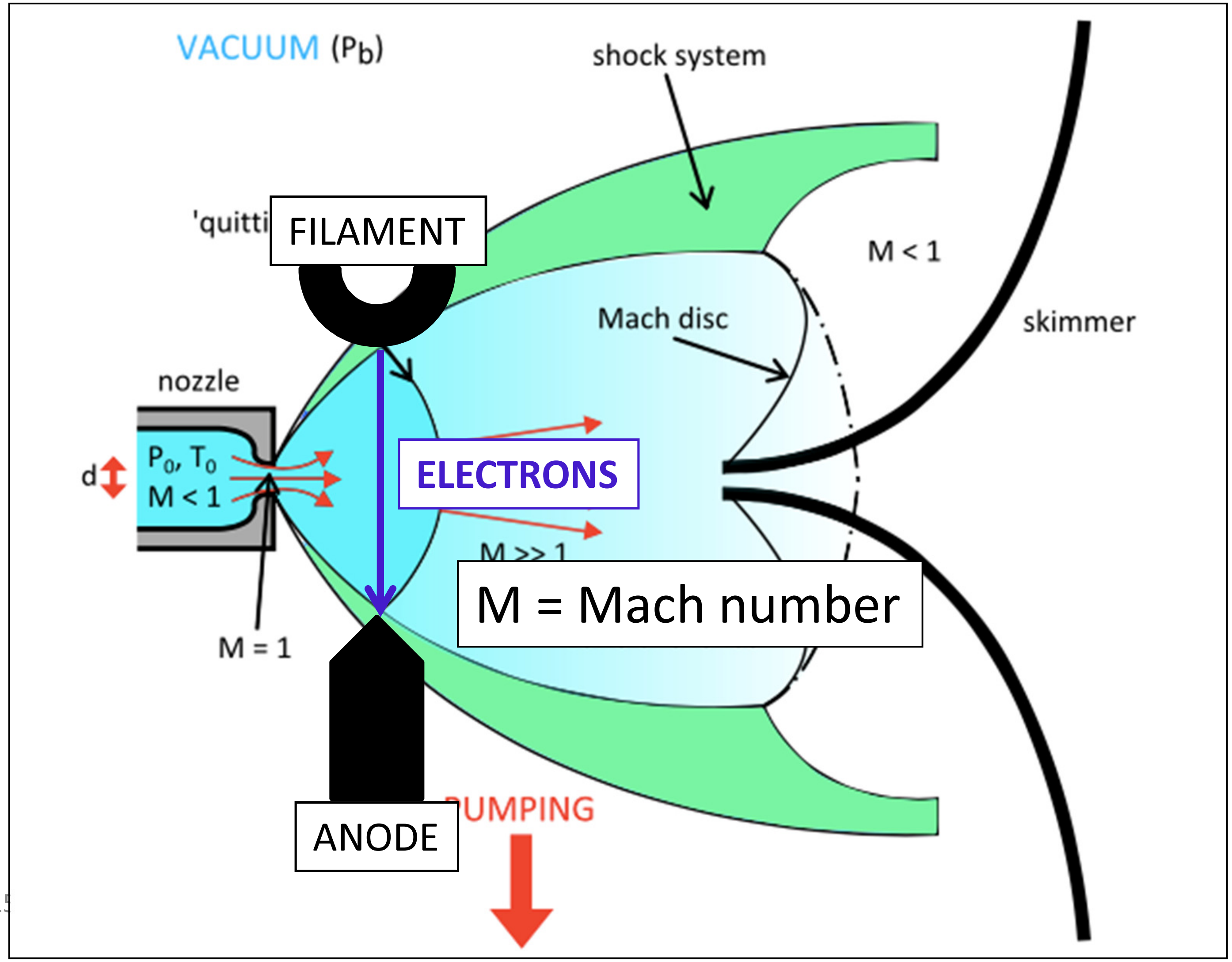
- This excited state can only be reached by collision.
- It is doubly forbidden to decay electromagnetically.
- Therefore a very long life-time: ~8,000s
- Magnetic moment 2 Bohr magnetons
- Triplet state: m = +1, 0, -1

Base design of the experiment

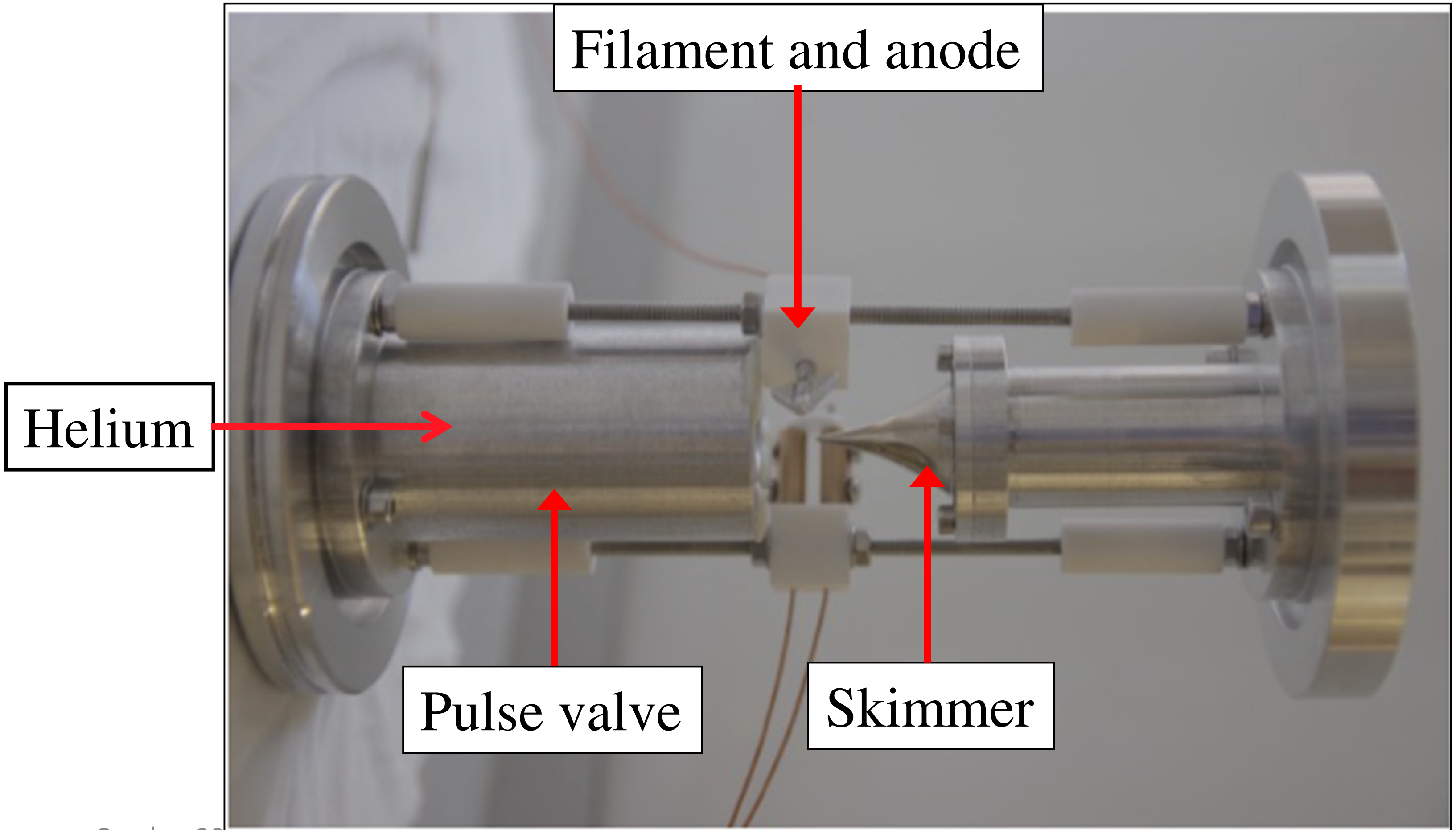


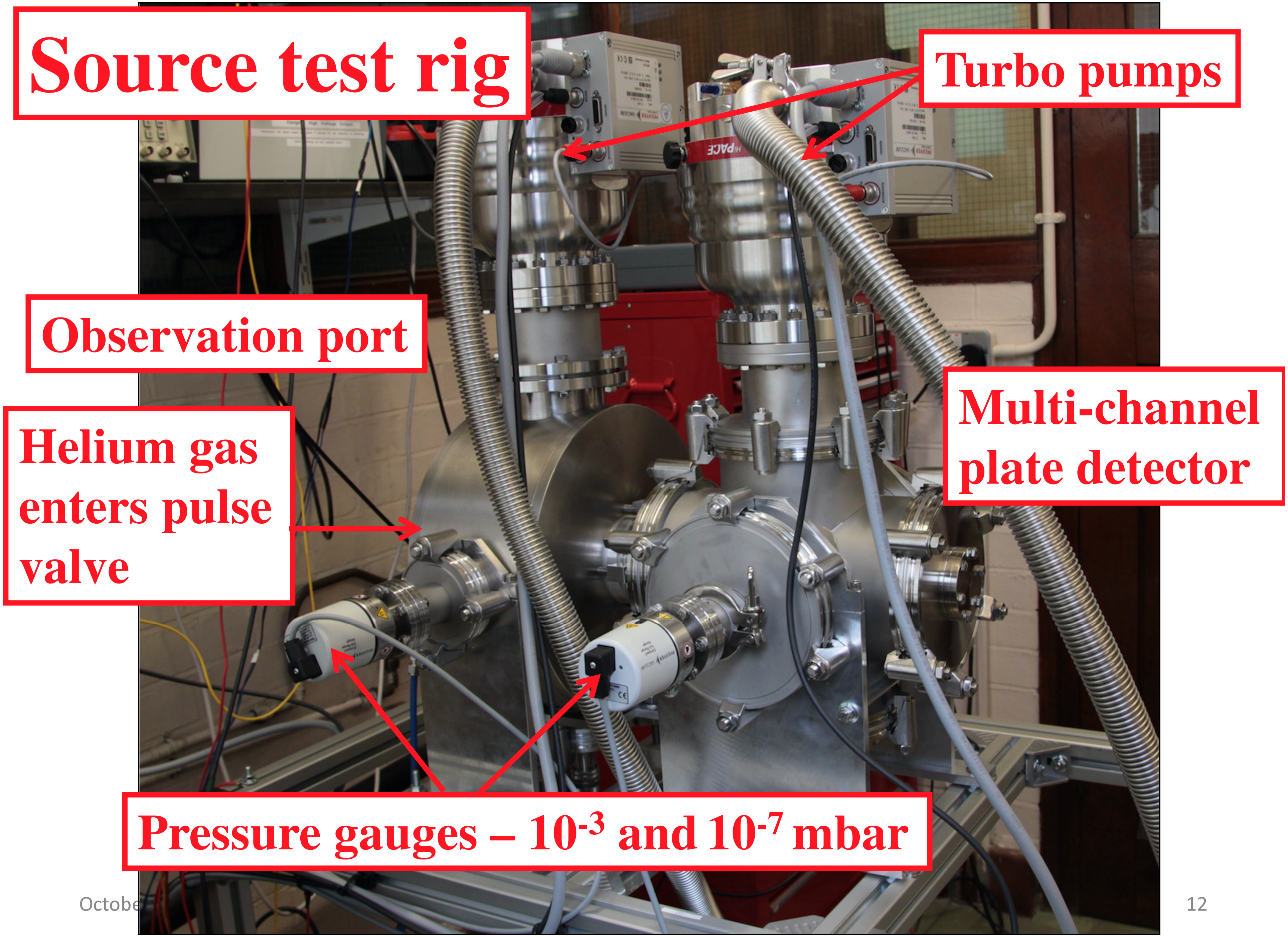
Schematic of a plume of He*

M Barr et al; A desktop supersonic free-jet beam source for a scanning helium microscope. *Measurement Science and Technology*, 23(10):105901, 2012.

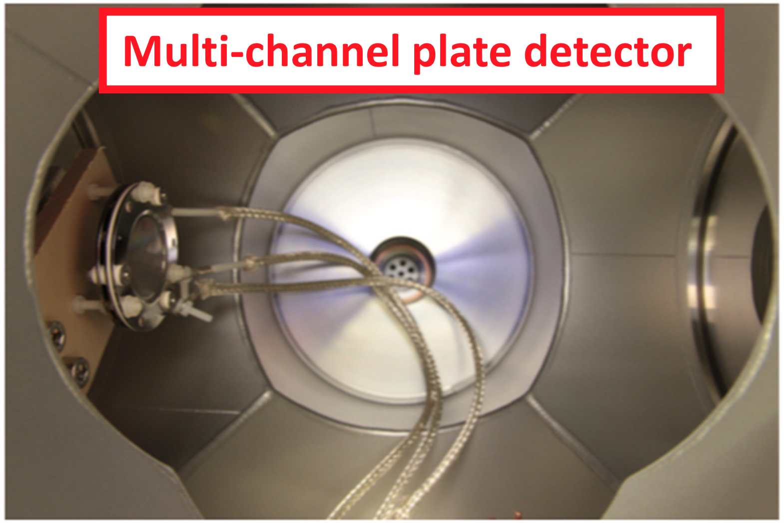


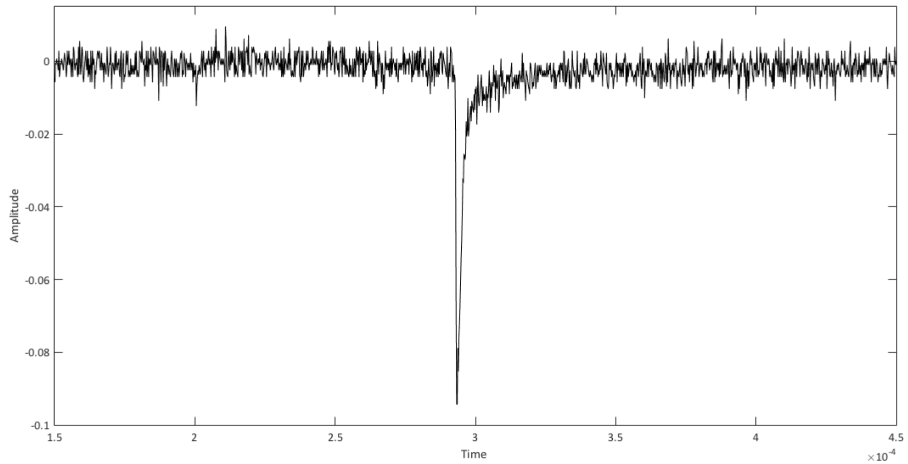
Engineered He* source




Source test rig
Turbo pumps
Observation port
Helium gas enters pulse valve
Multi-channel plate detector
Pressure gauges – 10^{-3} and 10^{-7} mbar

Observed source of He*





IQM2

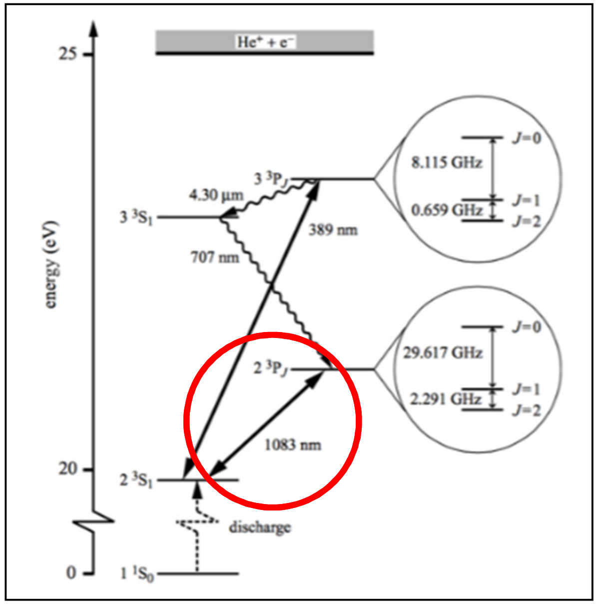
Pulsed supersonic beam

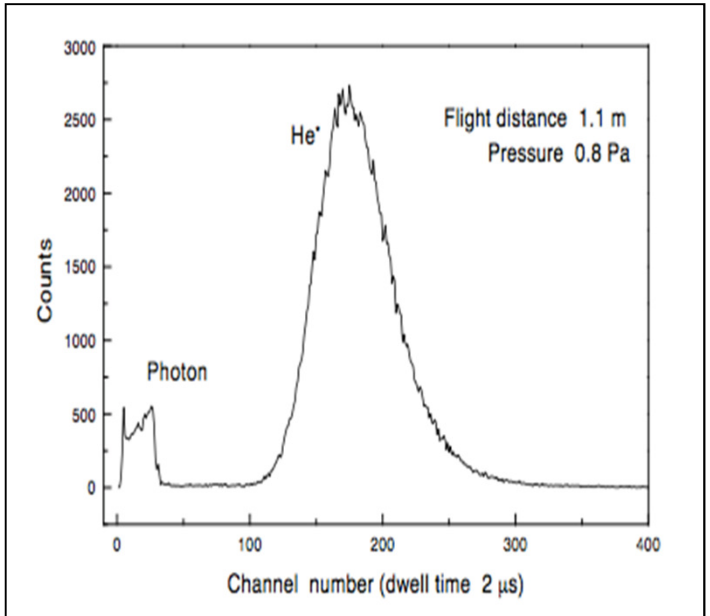
- Use a pulsed supersonic beam:
  - Velocity mean ~2km/s
  - Narrow velocity distribution.
  - Initial beam width ~2 mm
- Operating parameters:
  - Pulse frequency 50 Hz
  - Pulse width 200 μsec
  - Static pressure at input is 6 bar
  - Skimmer orifice size 0.25 mm.

Parameters of the beam

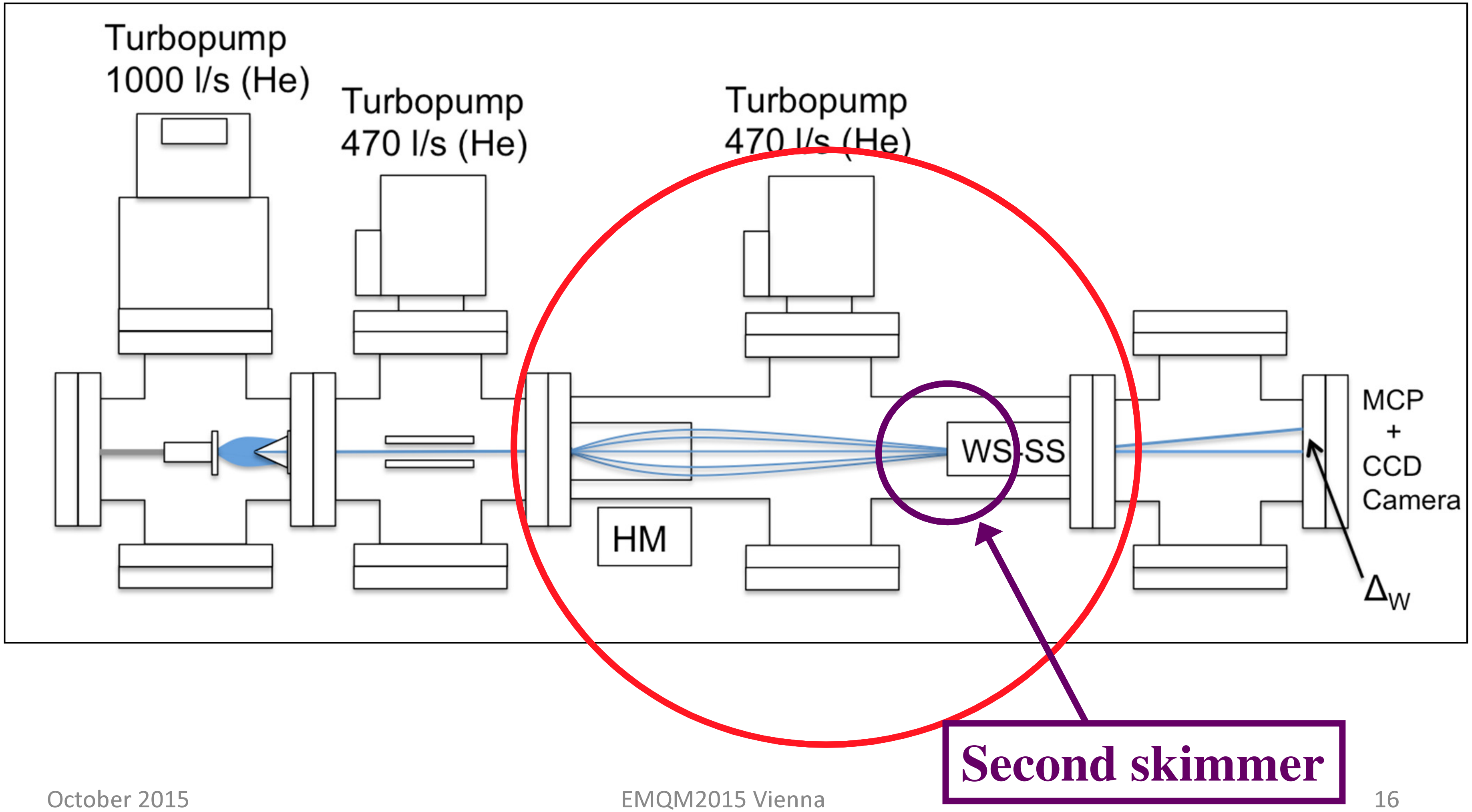
Y. Yamauchi, Meas. Sci. Technol. 9 (1998) 531–533.

Preliminary experiments on the beam:
- Estimate the flux.
- Estimate the density profile – laser excited transition 1083nm.
- Measure the momentum distribution – time of flight.

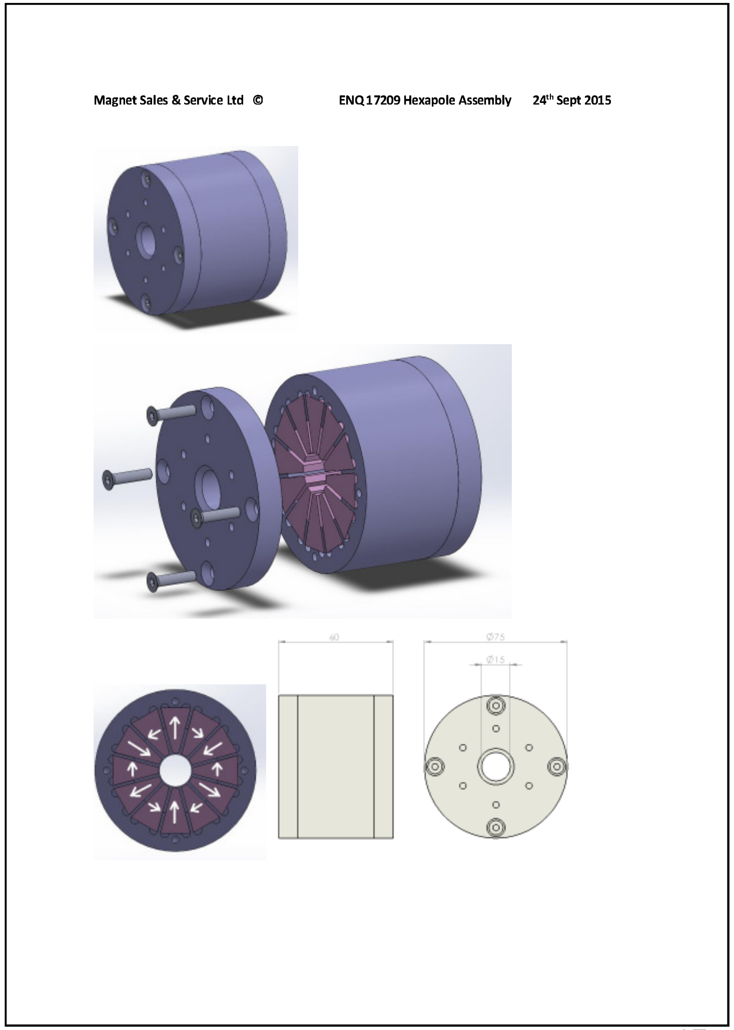




Base design of the experiment



Hexapole Magnet



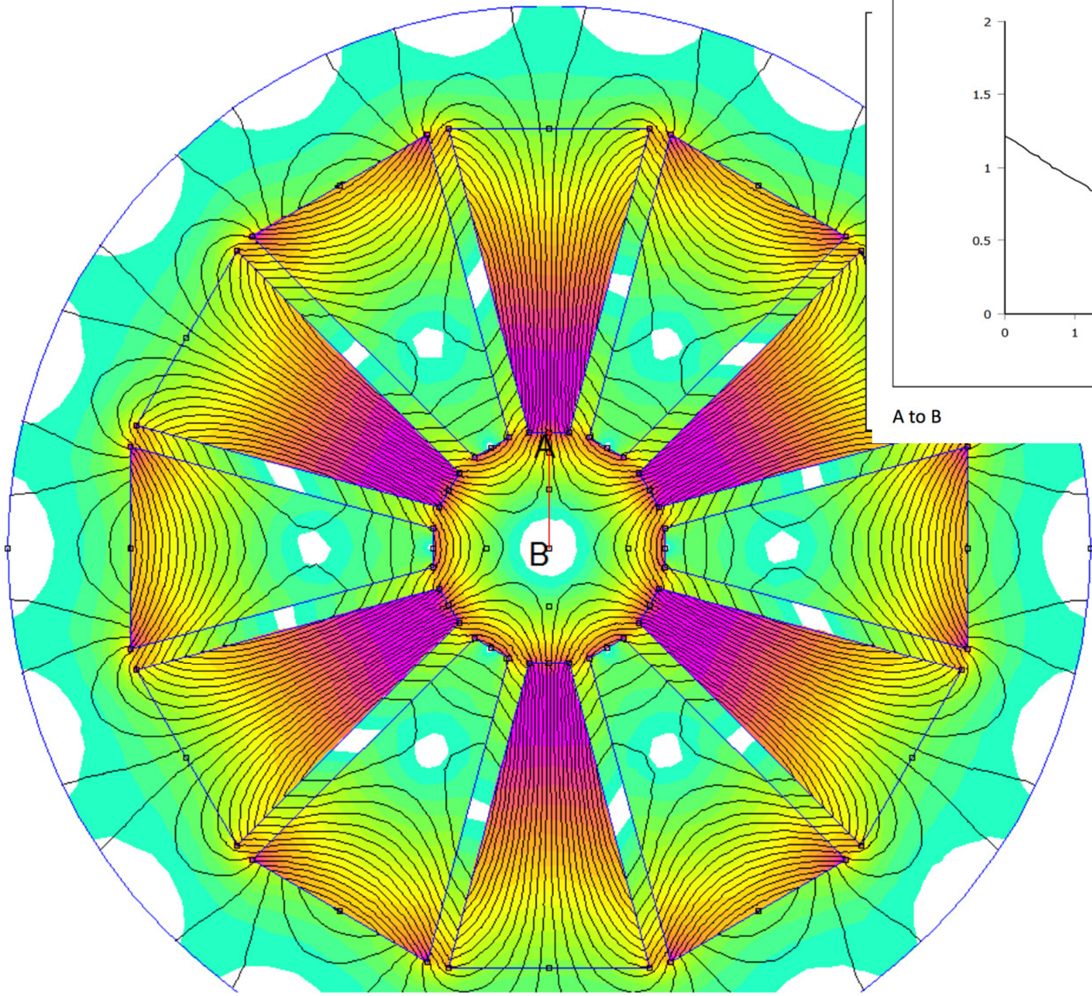
Purpose of the hexapole magnet is to:

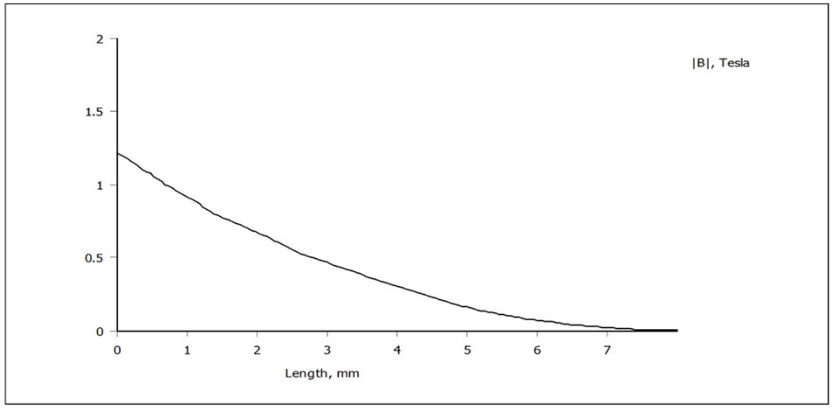
Focus m = +1 state onto a second skimmer.

Defocus m = -1 to miss the skimmer.

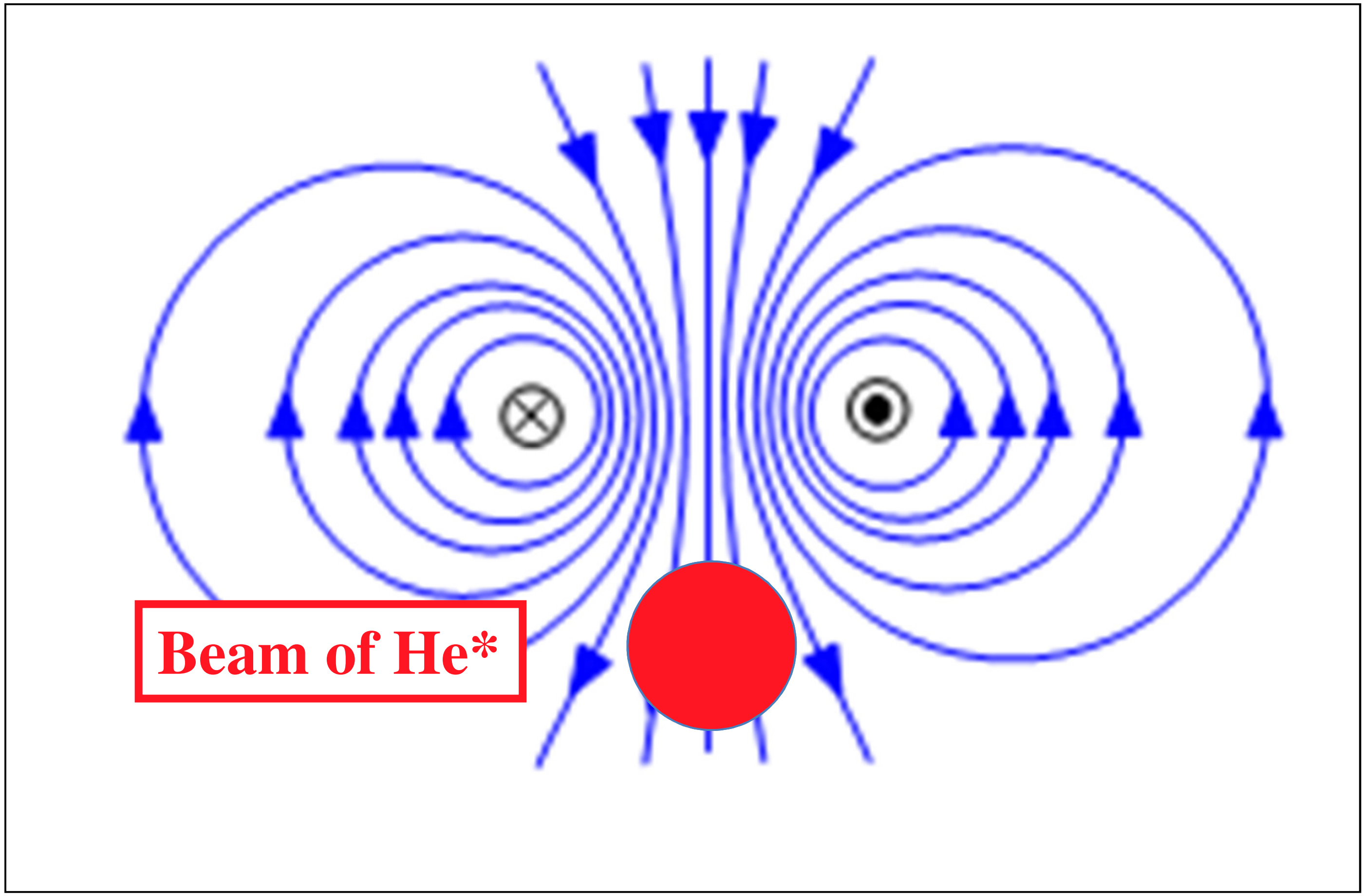
The m = 0 states will be unaffected.

Hexagonal magnet – field diagram

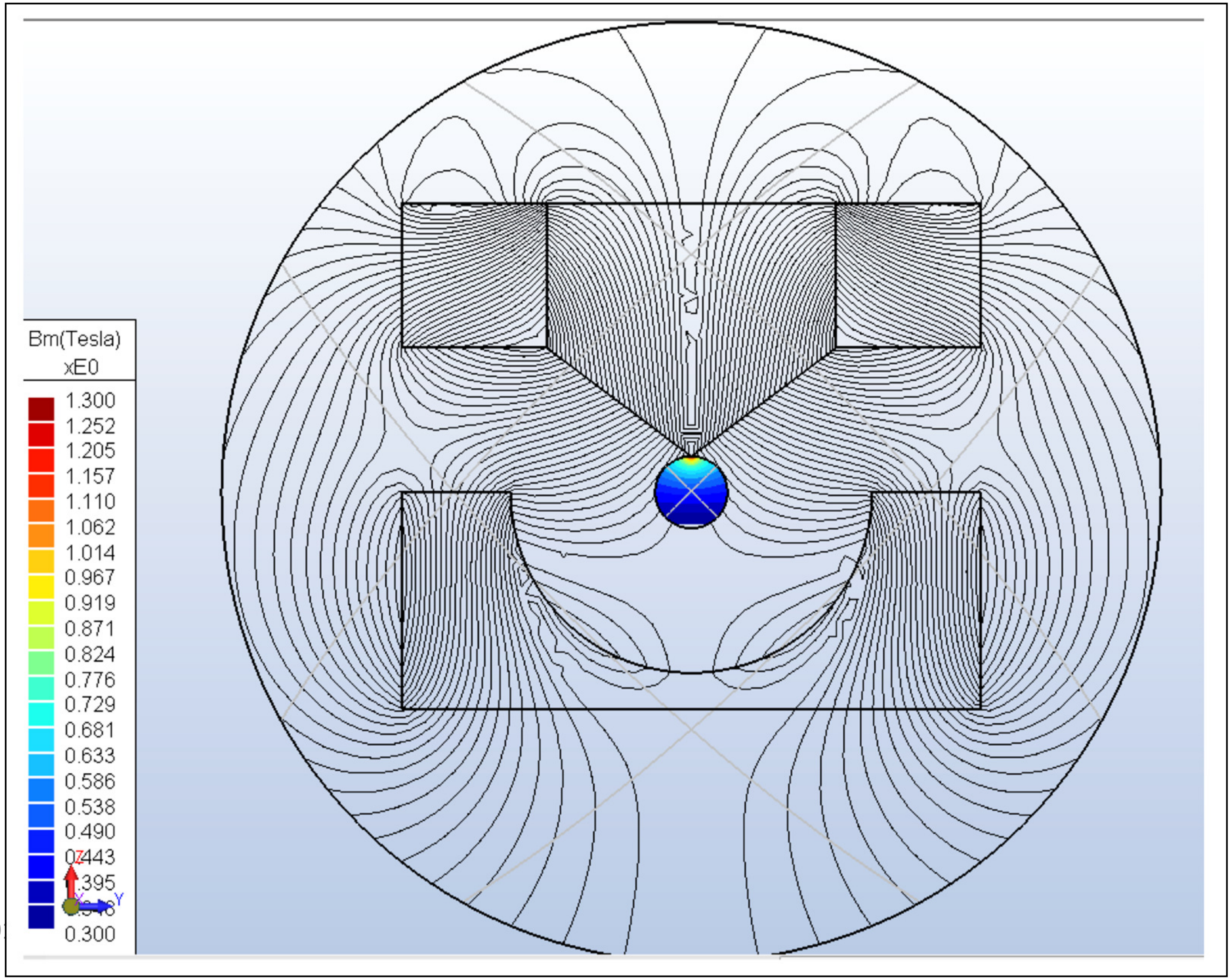




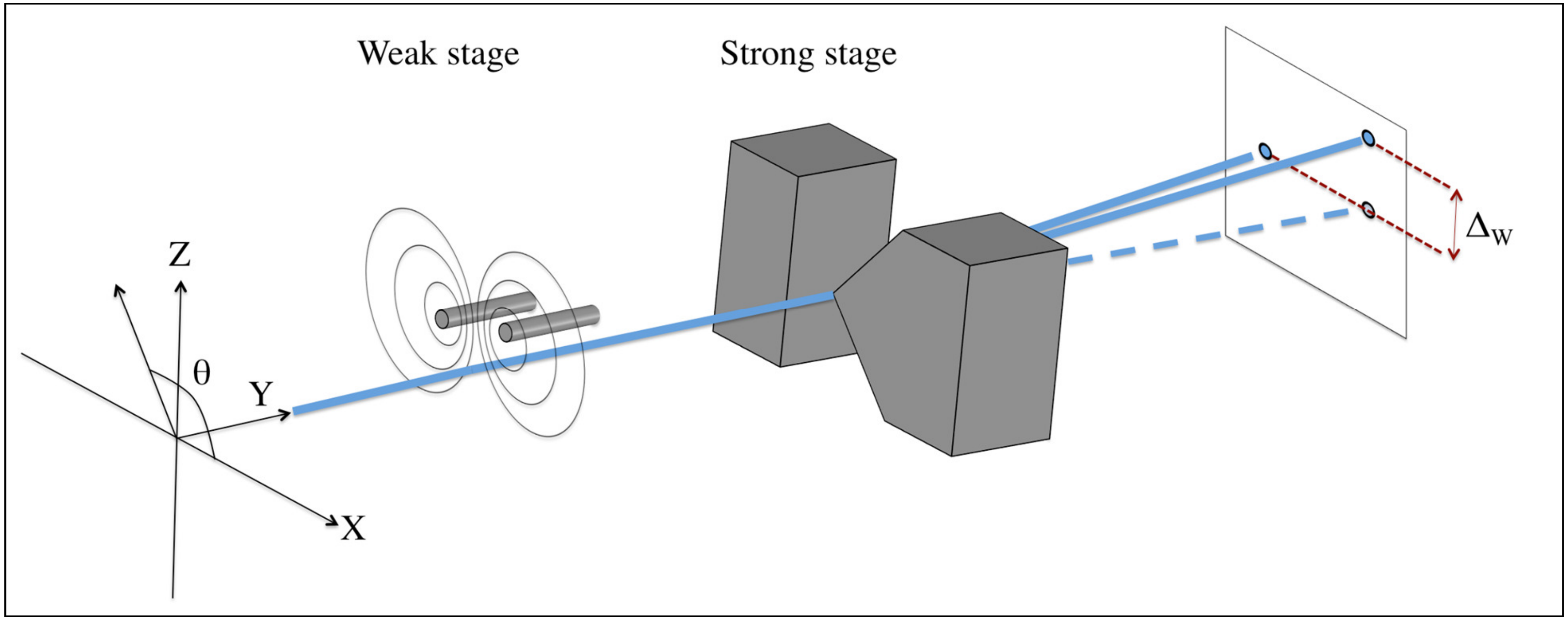
Magnet in weak stage – 2 wire



Magnet in strong stage



Weak measurement of spin

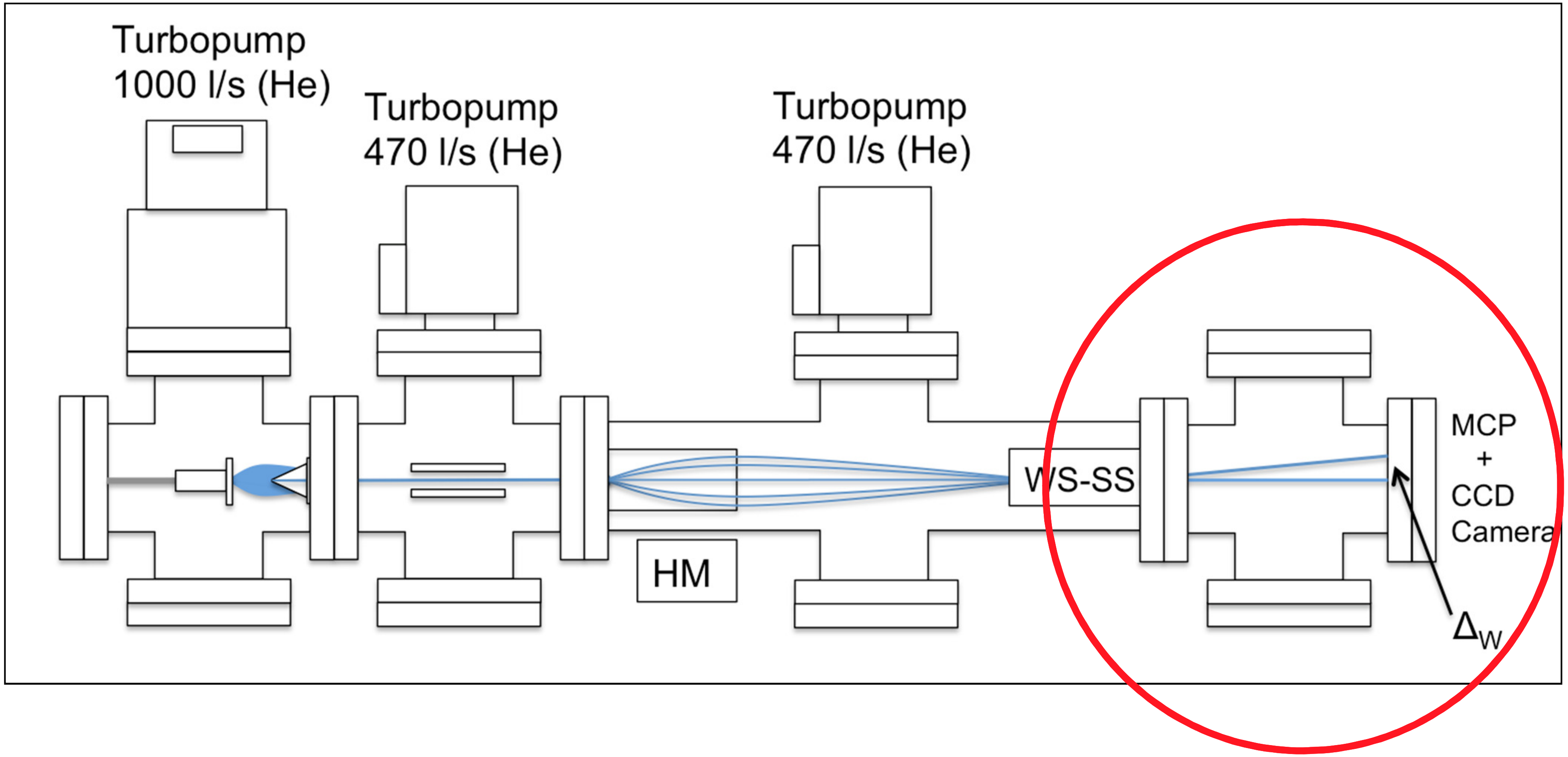


The weak value, Δ_w, can vary from zero to infinity.

We want to explore;

- **the limits on angle θ and the**
- **strength of the weak magnet**

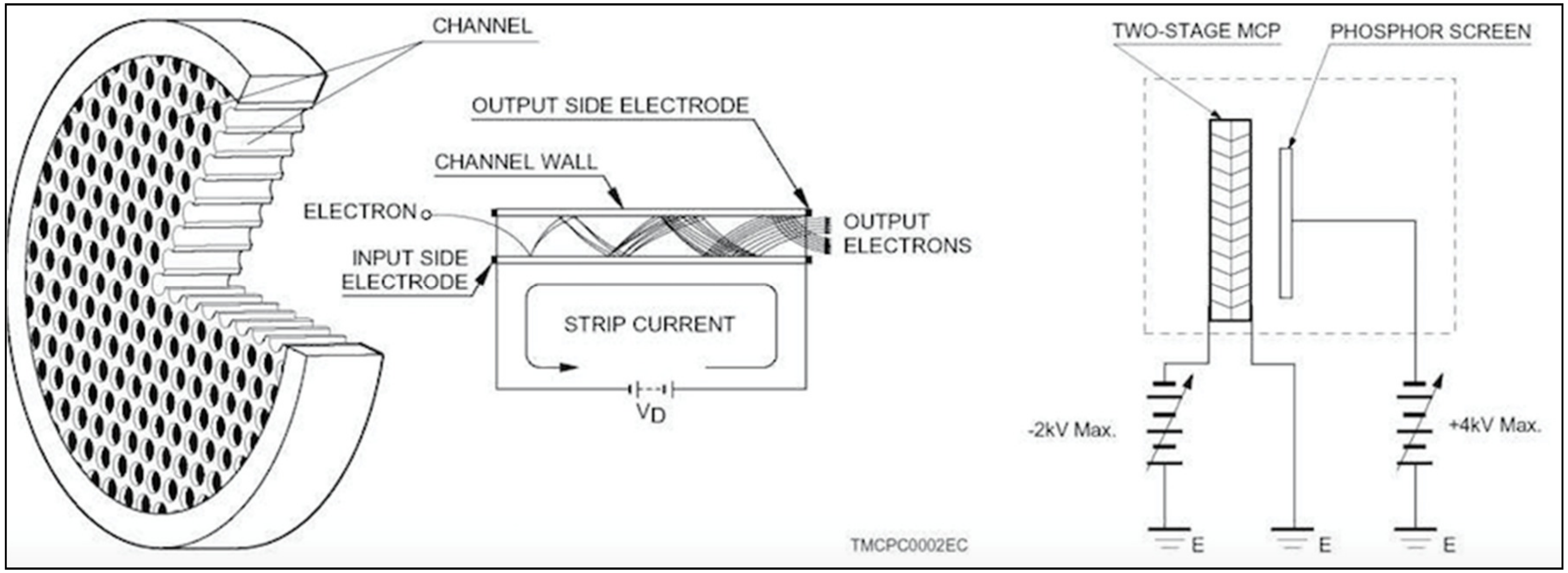
Detection chamber



Detection with an MCP/CCD

The He* has 20eV of energy and when it collides with the detector the electron will be ejected.

The 20eV electron will be detected using a multi-channel plate detector.



Conclusion

I have explained the difference between a weak and strong measurement from a experimental standpoint.

I have explained the method we are using to observe the weak measurement process using He* atoms.

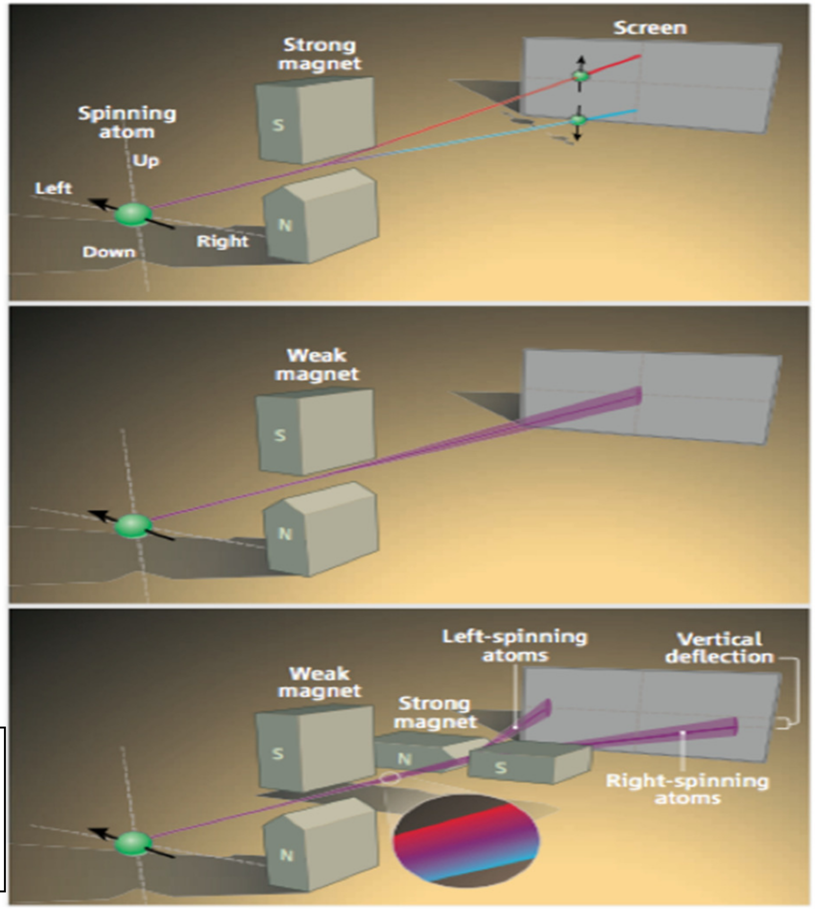
We want to explore how the magnitude of the magnetic field in the weak stage and the pre-selected angle θ changes the observed values of Δ_w.

We have made good progress and aim to have our first results in 2016.

Back up slides

Principal of weak measurement of spin

$$\phi_0(p_x) = \left(\frac{2\delta^2}{\pi\hbar^2}\right)^{1/4} \exp\left(-\frac{\delta^2 p_x^2}{\hbar^2}\right).$$



$$\phi_f(p_x) = \langle \chi_f | \chi_{\rm in} \rangle \left(\frac{2\delta^2}{\pi\hbar^2}\right)^{1/4} \exp\left[-\frac{\delta^2 (p_x - p_x'(\sigma_x)_w)^2}{\hbar^2}\right],$$

- $\Delta_w = \mu \tan(\theta/2)$, $\mu \propto$ magnetic moment of the particle.
- Note what happens as θ approaches π, Δ_w gets very large.
- Need three magnets.
- What is meant by "weak"

Exploitation of amplification effect

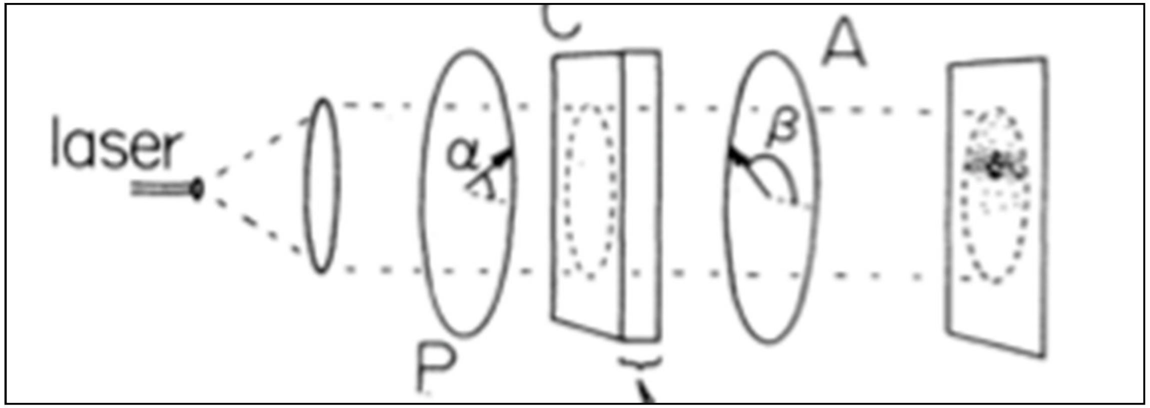
Dixon *et al*, Phys. Rev. Lett., 102 173601 (2009)

Measurement of the transverse deflection of an optical beam using a weak measurement amplification technique. They report to have measured the deflection to 400 ± 200 frads.

Hosten and Kwiat, Science, 319 787-790 (2008)

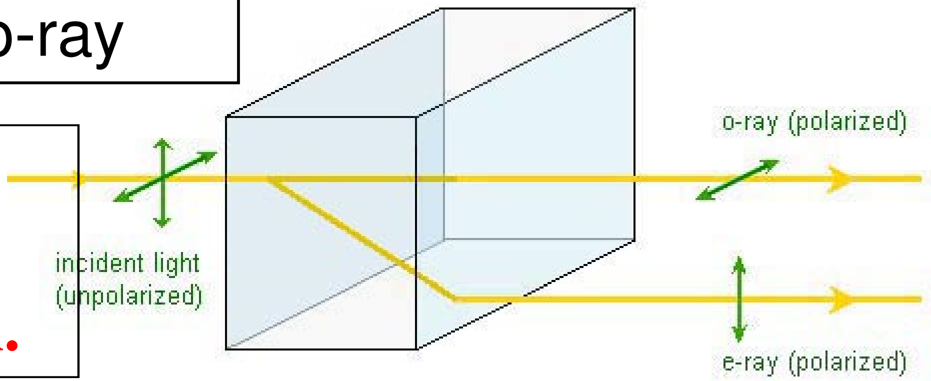
They report they have observed the optical spin-Hall effect using the amplification effect of weak measurement.

ical analogue of extended Stern-Gerlach appara



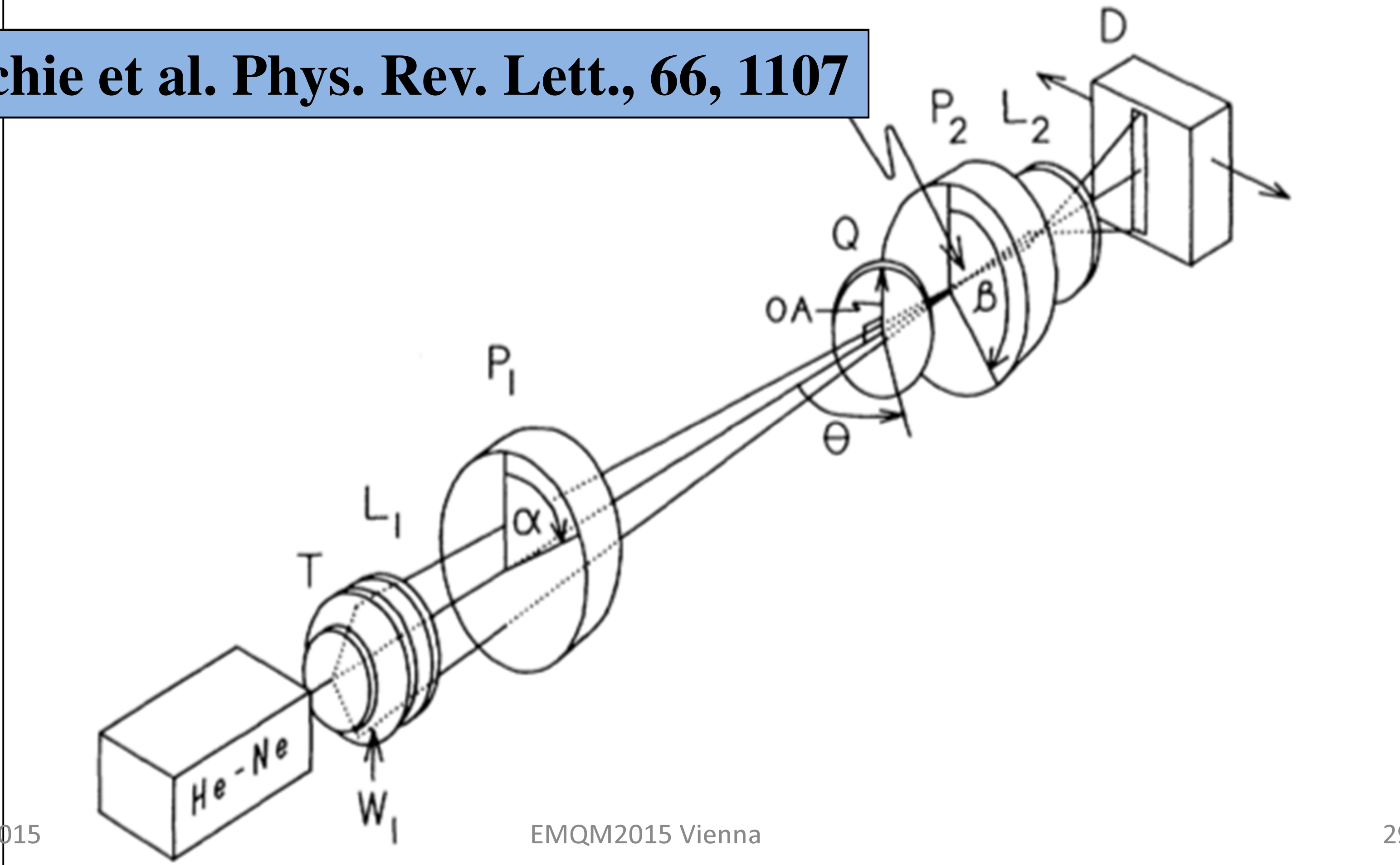
Weak stage is a thin birefringent crystal introducing a small phase change between the o-ray and the e-ray.

Using the width of the beam as reference for the allowed separation.



Realisation of the optical analogue

Ritchie et al. Phys. Rev. Lett., 66, 1107



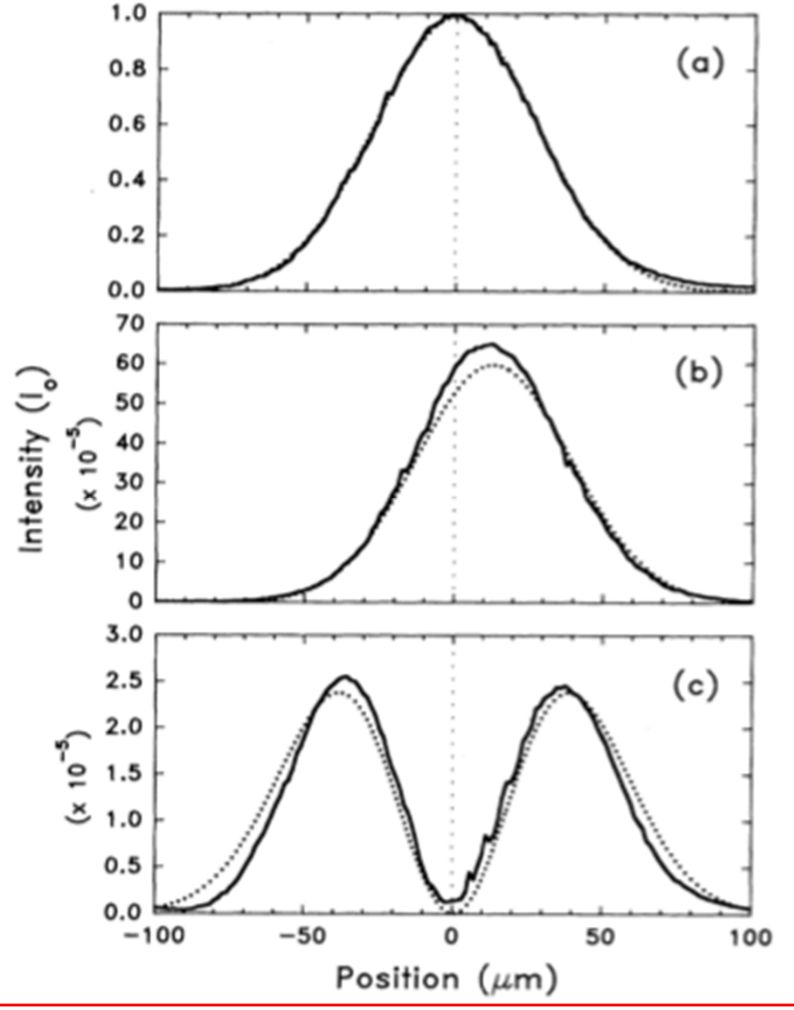
Results of the optical analogue

The wavelength of the light λ=0.64μm

$\alpha=\beta=\pi/4$, corresponding to aligned polarizers.

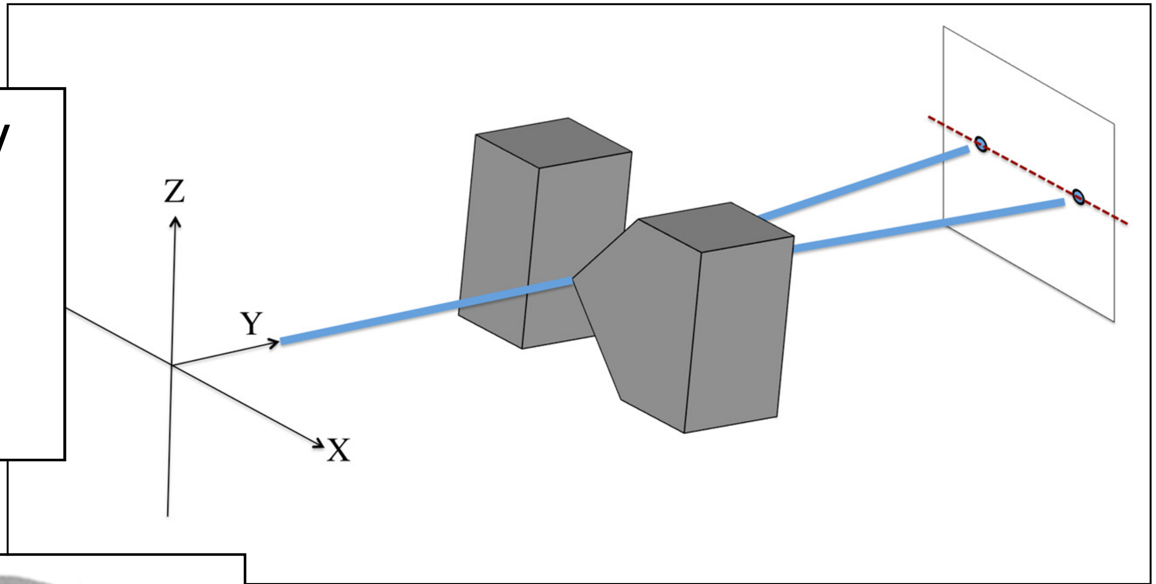
The centroid of the distribution is shifted by 20λ.

$A_w = \pm 60\lambda$.



Original Stern-Gerlach experiment (Strong measurement)

Silver atoms were originally used. They have one valence electron around a filled core and it behaved like a spin-1/2 particle.



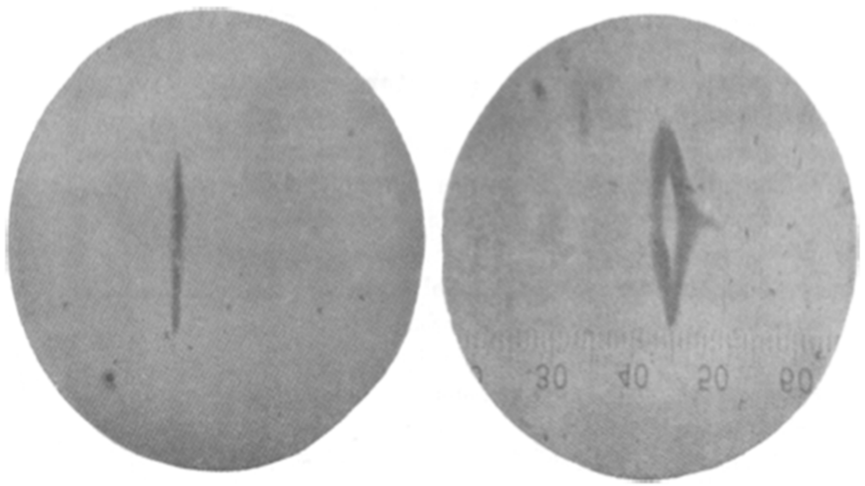


Fig. 2. Fig. 3.

Der experimentelle Nachweisder Richtungs quantelung im Magnetfeld. Z. Phys 9 (1922) 349-352

Measurement by von Neumann

In the chapter on measurement in his book he gives two types of measurement process:

1. Processes that collapse the wave function.

2. Processes that are described by the Schrödinger evolution. He calls these 'automatic changes that occur with the passage of time’.

He* selection rules

"However, by exciting rare gas atoms in electronic discharges, electron collisions can populate high lying states that are forbidden from decaying to the ground state by quantum mechanical selection rules."

"Neither the singlet nor triplet S states can decay to the ground 11S0 state via an electric dipole transition due to the L = +/- 1 selection rule (L being the orbital angular momentum quantum number which is zero for S states). However, decay of the 23S1 state is doubly forbidden because a transition to the ground state also requires that one of the electron spins has to flip to create a ground singlet state. "

Ensemble or individual

Ballentine: Quantum Mechanics, a modern development

Einstein (1949)

"One arrives at very implausible theoretical conceptions, if one attempts to maintain the thesis that the statistical quantum theory is in principle capable of producing a complete description of an individual physical system. On the other hand, those difficulties of theoretical interpretation disappear, if one views the quantum-mechanical description as the description of ensembles of systems."

Each particle is emitted as a wave packet which has a momentum spread equal to the momentum spread of the beam.

Remind ourselves about the measurement pro

Von Neumann. Mathematical foundations of quantum mechanics. Springer Verlag,1932.

An experiment has a system, ***S***, and detector, ***D***, coupled in such a way as to make the measurement. The Hamiltonian, ***H***, is written as the sum of three parts,

$$H = H_s(x) + H_D(y) + H_I(x,y)$$

The third term, H_I, produces a correlation between the system and the detector and has $H_I = -f\hat{q}\hat{A}$, where ***A*** is the variable to be measured with values a_n and ***q, p*** are generalised conjugate variables.

This term is switched on long enough to make the measurement and produce a strong correlation but not too long, **impulse measurement**. An example is the shutter of a camera. If it is left open for too long then the image is over-exposed.

An ideal measuring device has well defined initial and final values of *p* such that the pointer reading, $p_f - p_i$ gives the value of *A*.

Weak measurement

Sudarshan et al Phys. Rev. D, 1989

Aharonov et al. Phys. Rev. Lett., 60:1351, 1988.

In a non-ideal (real) measurement ***p*** has a width ***Δp*** the wave function of the detector will have the form:

$$|\Phi_{in}\rangle = \int exp(-\frac{p^2}{2(\Delta p)^2}dp]$$

The intial state of the system is prepared thus:

$$|\Psi_{in}\rangle = \Sigma_n \alpha_n |\mathrm{A_n}\rangle$$

After the measurement has taken place the final wave function has the form:

$$|\Phi_f\rangle = exp[-i\int H_I dt]|\Phi_{in}\rangle|\Psi_{in}\rangle$$

Putting these all together gives a sum of Gaussians one for each $\boldsymbol{a_n}$.

$$|\Phi_f\rangle = \Sigma_n \alpha_n \int exp[-\frac{(p-a_n)^2}{2(\Delta p)^2}]dp|A=a_n\rangle|p\rangle$$

A strong measurement depends on *Δp* being smaller than the spacing of the a_n making each Gaussian narrow and non-overlapping.

Consider the situation where $\Delta \boldsymbol{p}$ is much larger than the spacing between the $\boldsymbol{a_n}$. Instead of a set of widely separated Gaussians with narrow $\Delta \boldsymbol{p}$ we have a set of overlapping Gaussians with wide $\Delta \boldsymbol{p}$.

This will approximate a single large Gaussian-like function peaked at a mean value of $\boldsymbol{A}$ i.e. $\langle \boldsymbol{A} \rangle$.

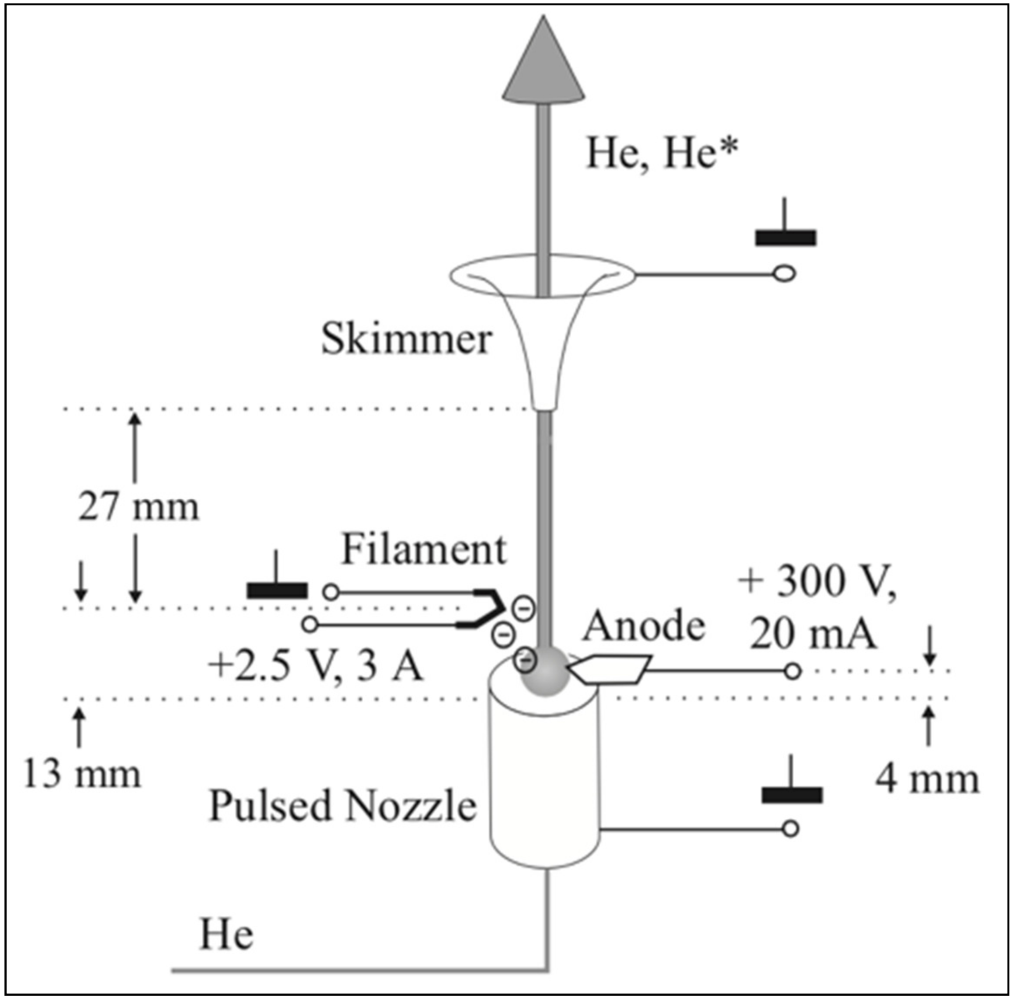
This measurement on its own gives little or no information.

If this type of measurement is carried out many times then it is possible to map out the distribution and obtain an estimate of the centroid. The accuracy depending only on the number of measurements.

Is this what we mean as an effective measurement?

Production of He*

Halfmann *et al*, Meas. Sci. Technol. 11 (2000) 1510 - 1514



Input pressure = 2000 mbar
Pulse width = 200 μsec
Pulse frequency = 50 Hz

Amplification?

A. K. Pan and A. Matzkin, Phys. Rev. A85, 022122

Gaussian wave function in x-space.

$$\psi_0(x) = \frac{1}{(2\pi\delta^2)^{1/4}} \exp\left[-\frac{x^2}{4\delta^2}\right].$$

Fourier transform to p-space.

$$\phi_0(p_x) = \left(\frac{2\delta^2}{\pi\hbar^2}\right)^{1/4} \exp\left(-\frac{\delta^2 p_x^2}{\hbar^2}\right).$$

Strong measurement

$$\phi_f(p_x) = \langle\chi_f|\chi_{\text{in}}\rangle \left(\frac{2\delta^2}{\pi\hbar^2}\right)^{1/4} \exp\left[-\frac{\delta^2(p_x - p'_{x\,[\text{illegible}]})^2}{\hbar^2}\right],$$

2-stage weak measurement.