First experimental measurement of the speed distribution of ballistically-evaporated atoms

2017 CAP Congress
Ryan Groome
9rrg2@queensu.ca

Department of Physics, Engineering Physics, and Astronomy
Queen's University
Supervisor: Dr. Kevin Robbie

May 30, 2017

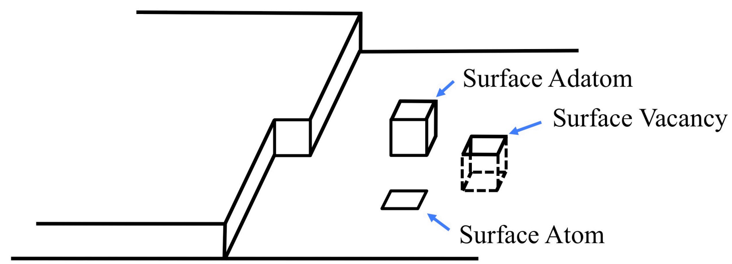
Outline

- Introduction
- Instrumentation
  - Electron-beam evaporator
  - Mechanical velocity selector
  - Quartz crystal microbalance
- Preliminary experimental measurements
- Summary

Introduction

- The Maxwellian distribution is often used for describing the speeds of ballistically evaporated atoms [1, 2]
- We identify that ballistic evaporation of a vapour from its condensed phase is entirely different than effusion of a gas from an oven
- **We hypothesize that the speed distribution of evaporated atoms is not governed by the Maxwellian distribution due to the electromagnetic interaction between ballistically evaporating atoms and the surface**

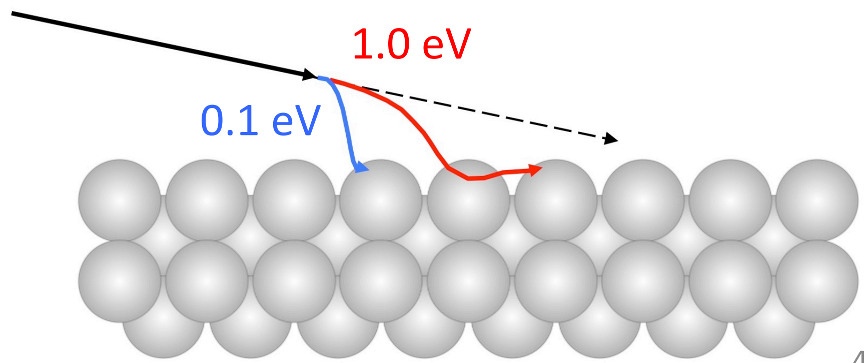
Vapour $\neq$ Gas



Motivation

- Does the kinetic energy of condensing vapour atoms affect the structure and physical properties of nanostructured thin film materials?
- Several new studies investigate “steering” [3,4]
  - significant deflection for low energies and small incidence angles: affects surface roughness of deposited films

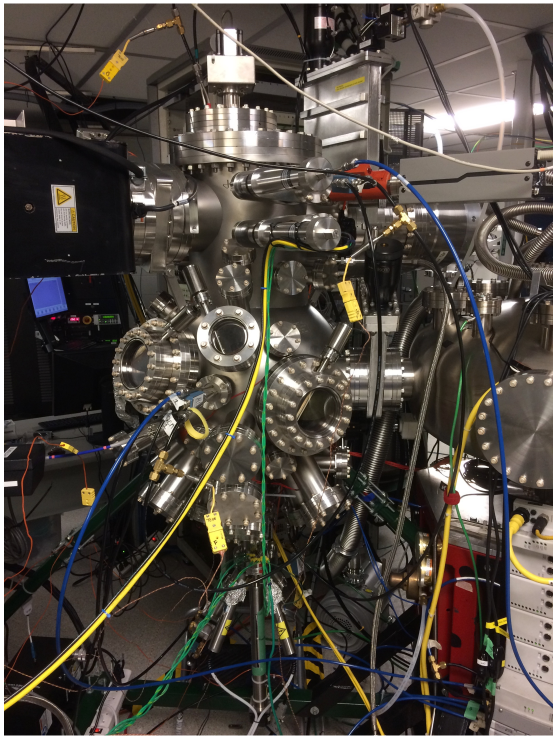
- Thin film engineers may gain further control by adjusting the initial energy of condensing atoms!



Research objectives

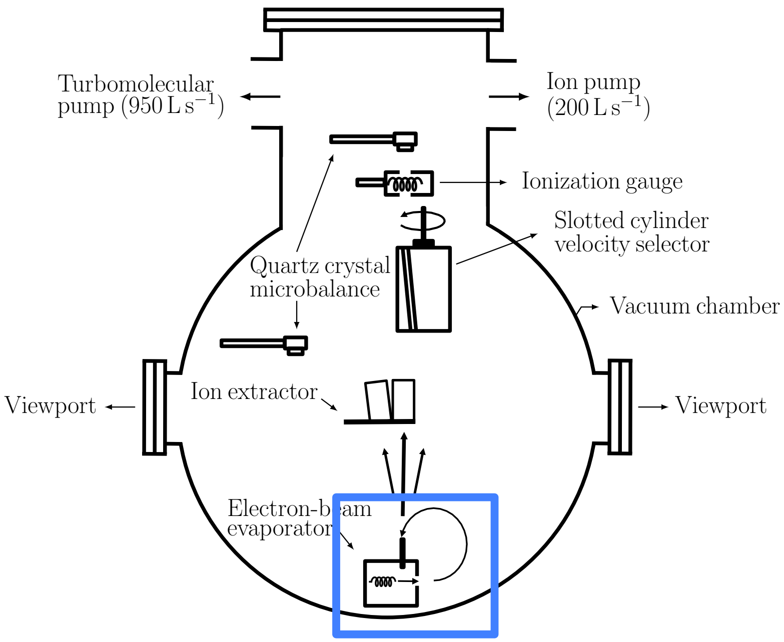
- Primary objective
  - Develop experiment to measure the speed distribution of ballistically-evaporated atoms using an electron-beam evaporator

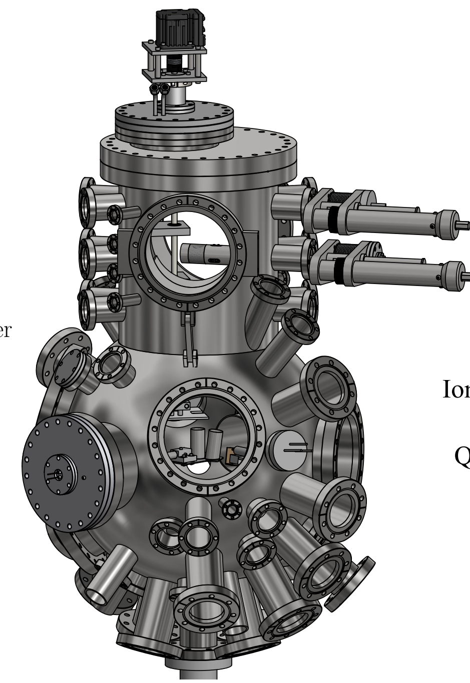
- Secondary objectives
  - Measure the speed distribution of atoms emitted from a high temperature effusion cell
  - Demonstrate differences in physical characteristics of thin film coatings condensed from velocity-selected vapours

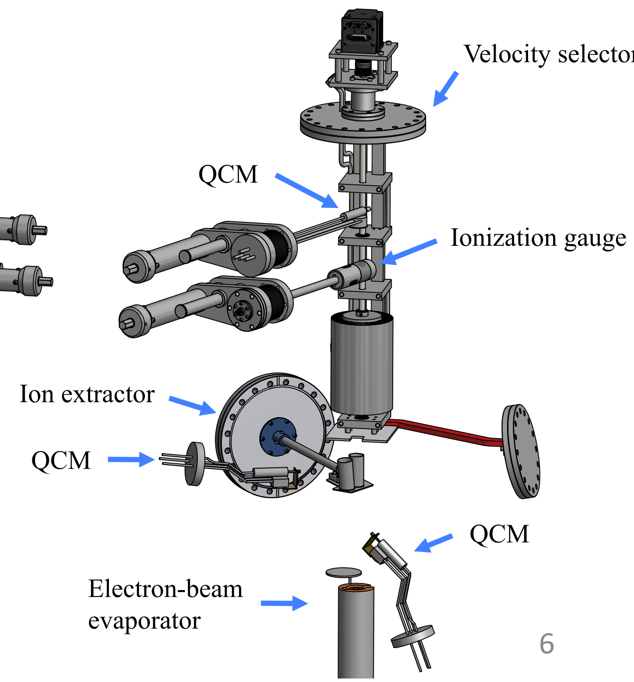


Electron-beam evaporation experiment

- Experimental apparatus designed to detect velocity-selected atomic vapour that is ballistically-evaporated from a surface in vacuum

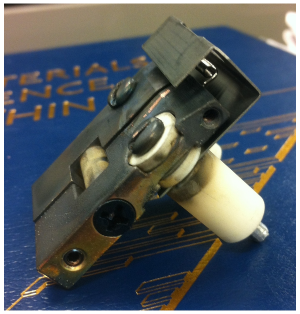


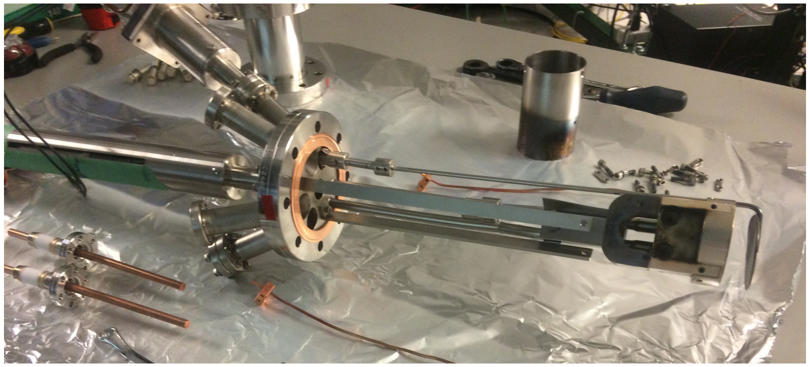




Electron-beam evaporator

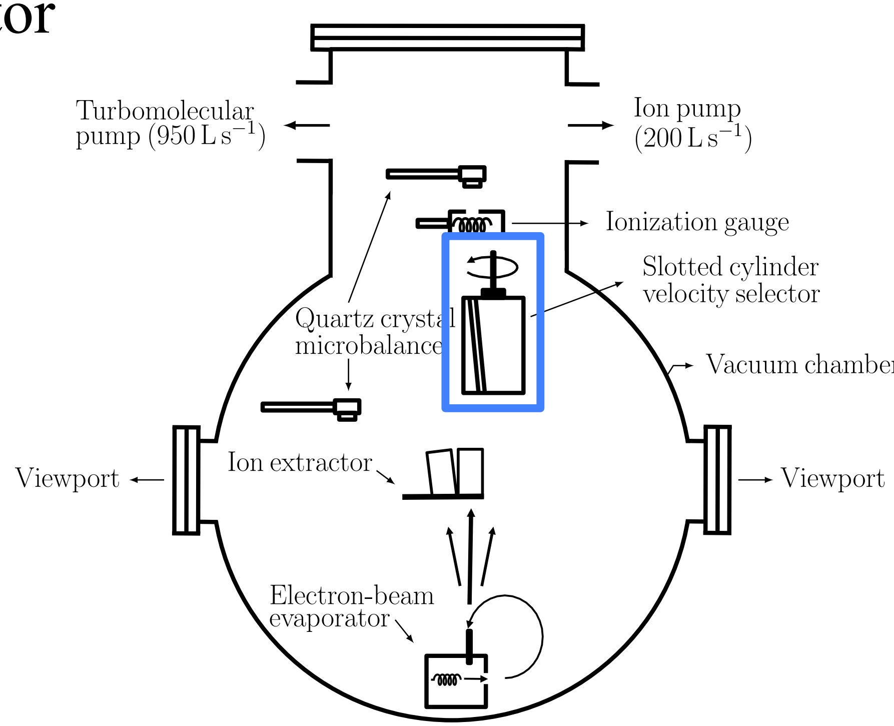
- We use a commercially available 3 kW rod-fed bent-beam electron gun (Thermionics Lab Inc)
- Electrons are emitted from a heated filament and then accelerated in a 10 kV potential
- The beam is then bent by ~270° using a permanent magnet that directs it towards the surface of the evaporant



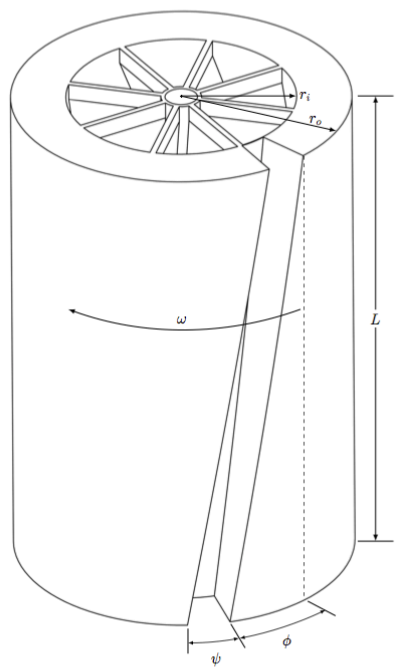


Electron-beam evaporation experiment

- Mechanical velocity selector



Velocity selection



$$v_o = \frac{\omega L}{\phi} \qquad v_{min,max} = \frac{\omega L}{\phi \pm \psi}$$

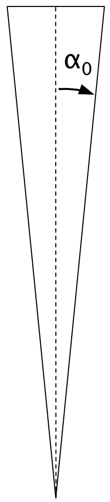
- We use a rotating slotted cylinder velocity selector (spindle) to selectively transmit atoms within a restricted range of speeds
- The total fraction of atoms transmitted at the rotation frequency ω is

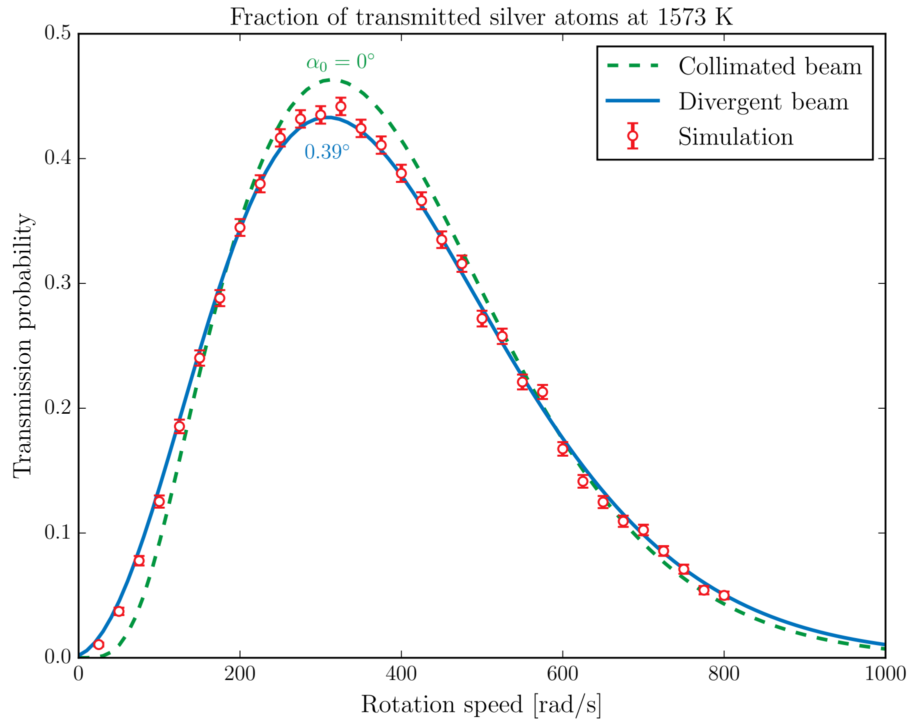
$$T(\omega) = \int_{v_{min}(\omega)}^{v_{max}(\omega)} I(v)B(v,\omega)dv$$

where $I(v)$ is the speed distribution of evaporated atoms, and $B(v, \omega)$ is the fraction of atoms traveling at speed v that are transmitted

Velocity selection

- Transmission of divergent thermal atomic beams

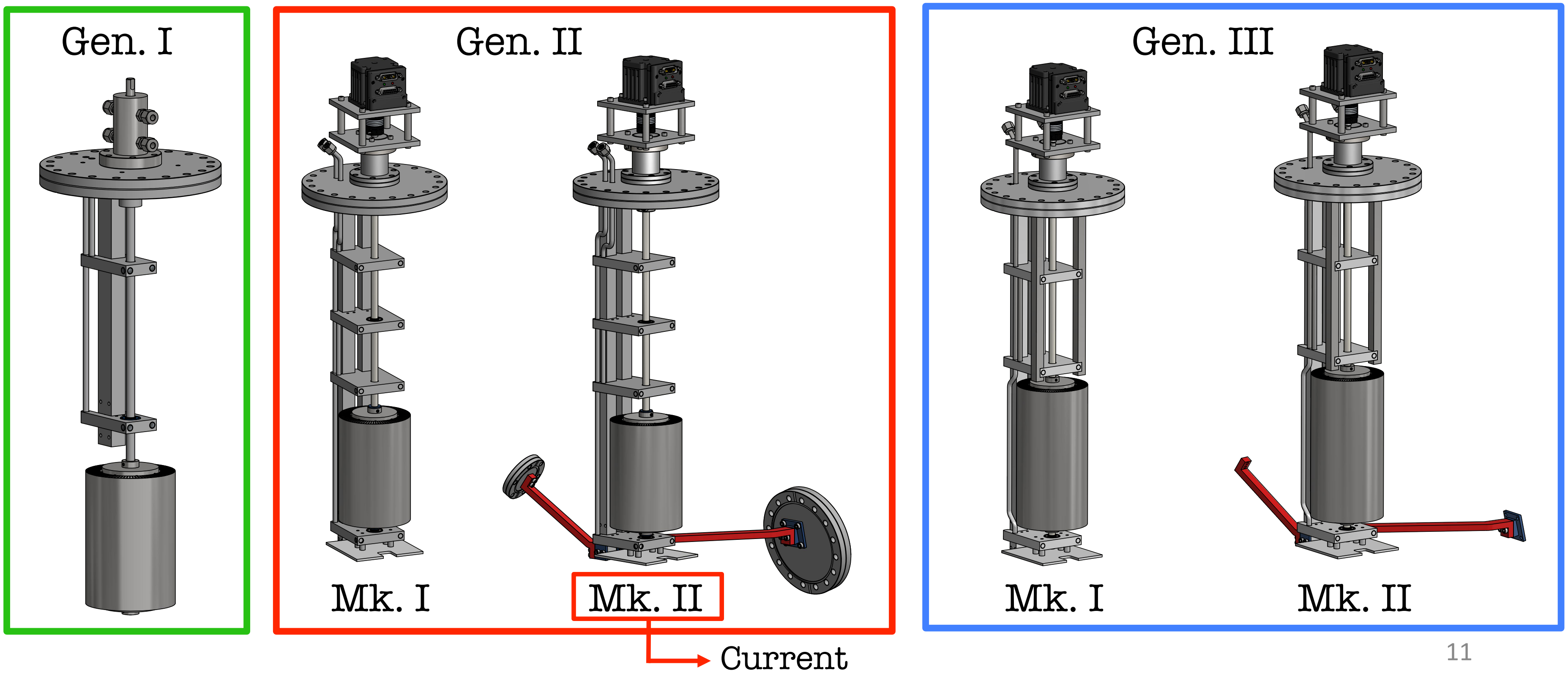




Monte Carlo simulation:

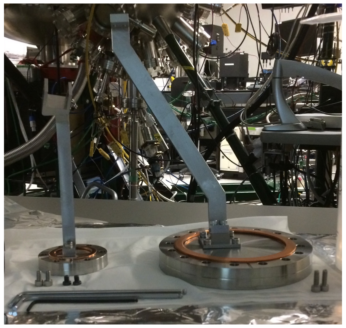
- 5000 atoms per rotation speed
- 50 ns time step
- 62.8 cm source to detector distance
- 1.5 mm source diameter

Generations of the velocity selector apparatus



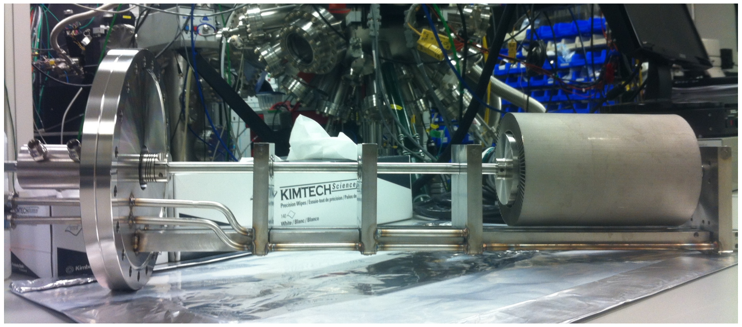
Velocity selectors

Gen. II



Mk. II additions

Experiments in progress...



Gen. III

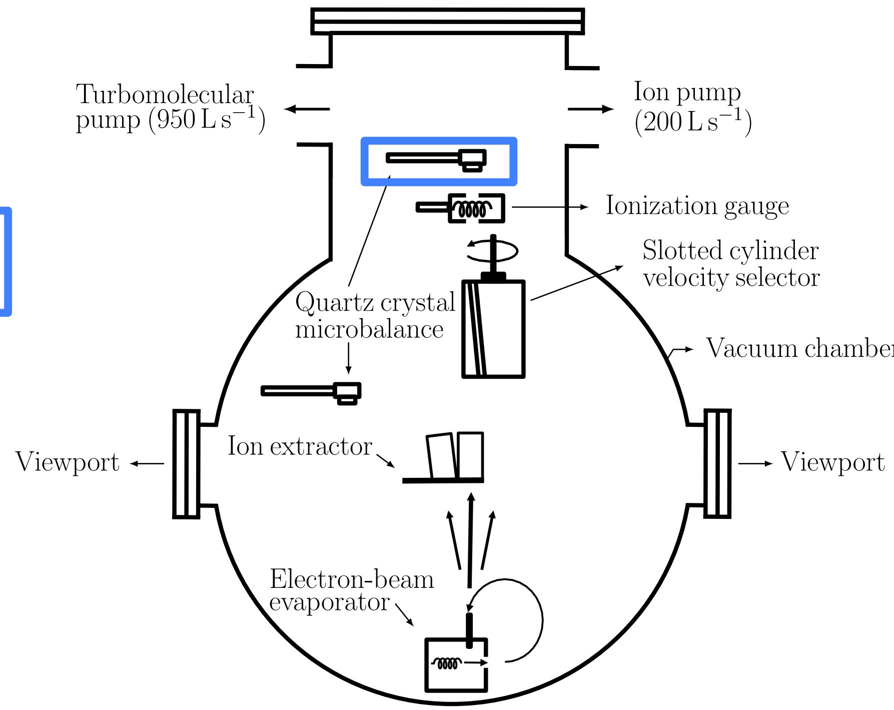
Installation coming soon...

Electron-beam evaporation experiment

- Detectors:
  - Hot-filament ionization gauge
  - Quartz crystal microbalance

Typical deposition rate sensitivity:

~ 1 ng / cm^2 / s



Quartz crystal microbalance (QCM)

- The change in mass per unit area is related to the measured frequency shift using the Z-match method

$$\frac{\Delta m}{A} = \frac{N_q \rho_q}{\pi Z f} \arctan\left(Z \tan\left(\frac{\pi(f_u - f)}{f_u}\right)\right)$$

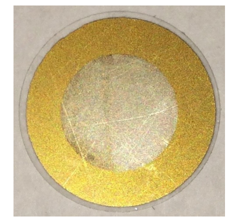
N_q: Frequency constant

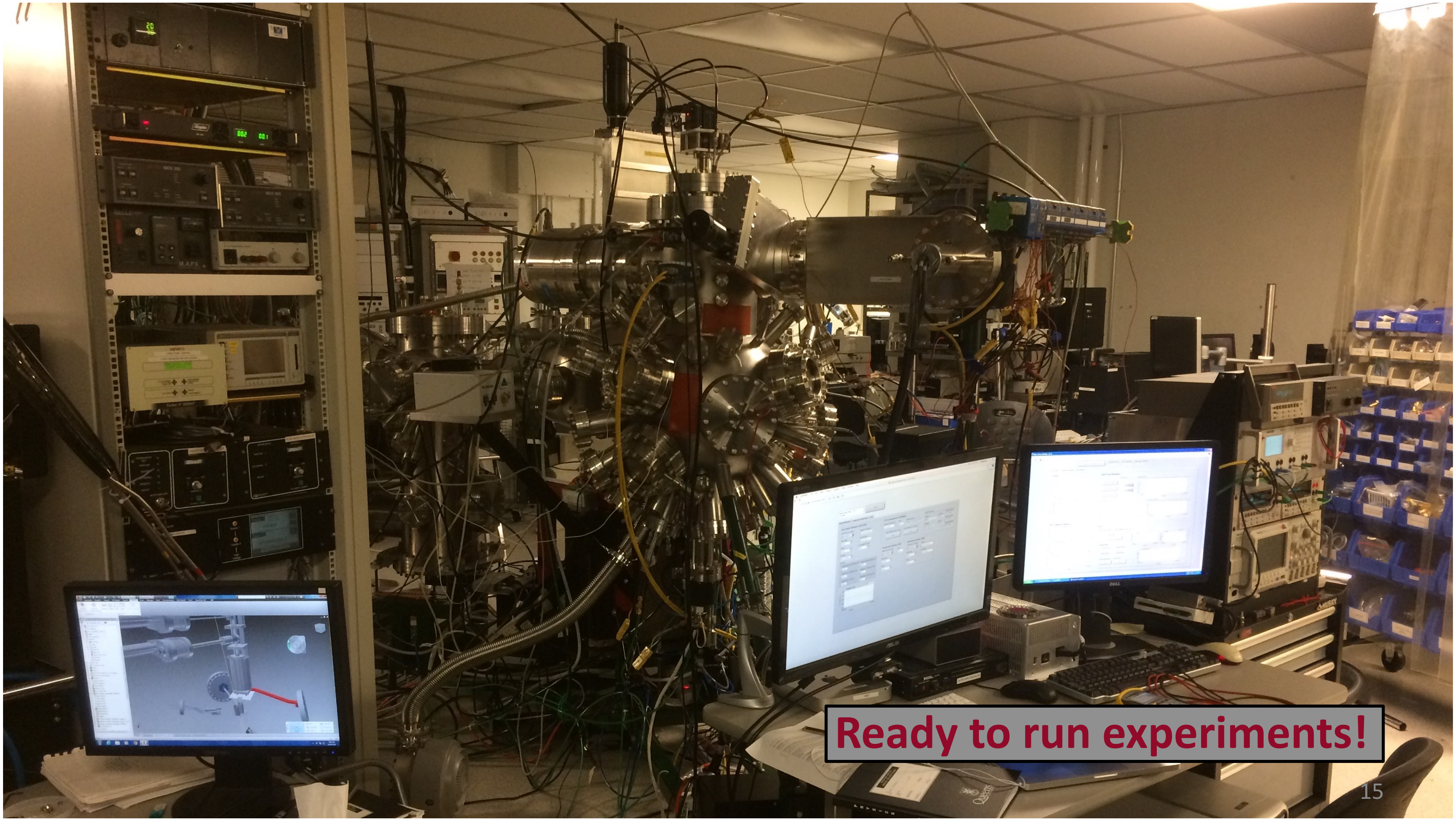
ρ_q: Density of quartz

f: Resonant frequency of loaded crystal

Z: Acoustic impedance ratio

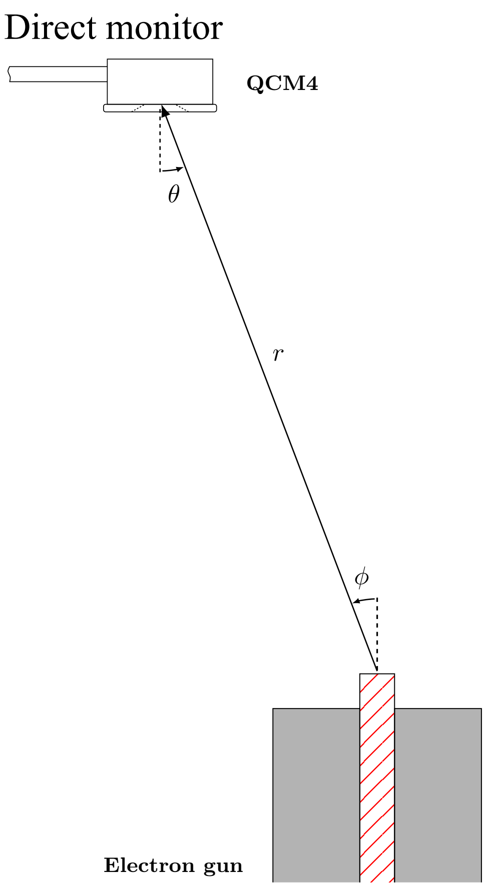
f_u: Resonant frequency of unloaded crystal

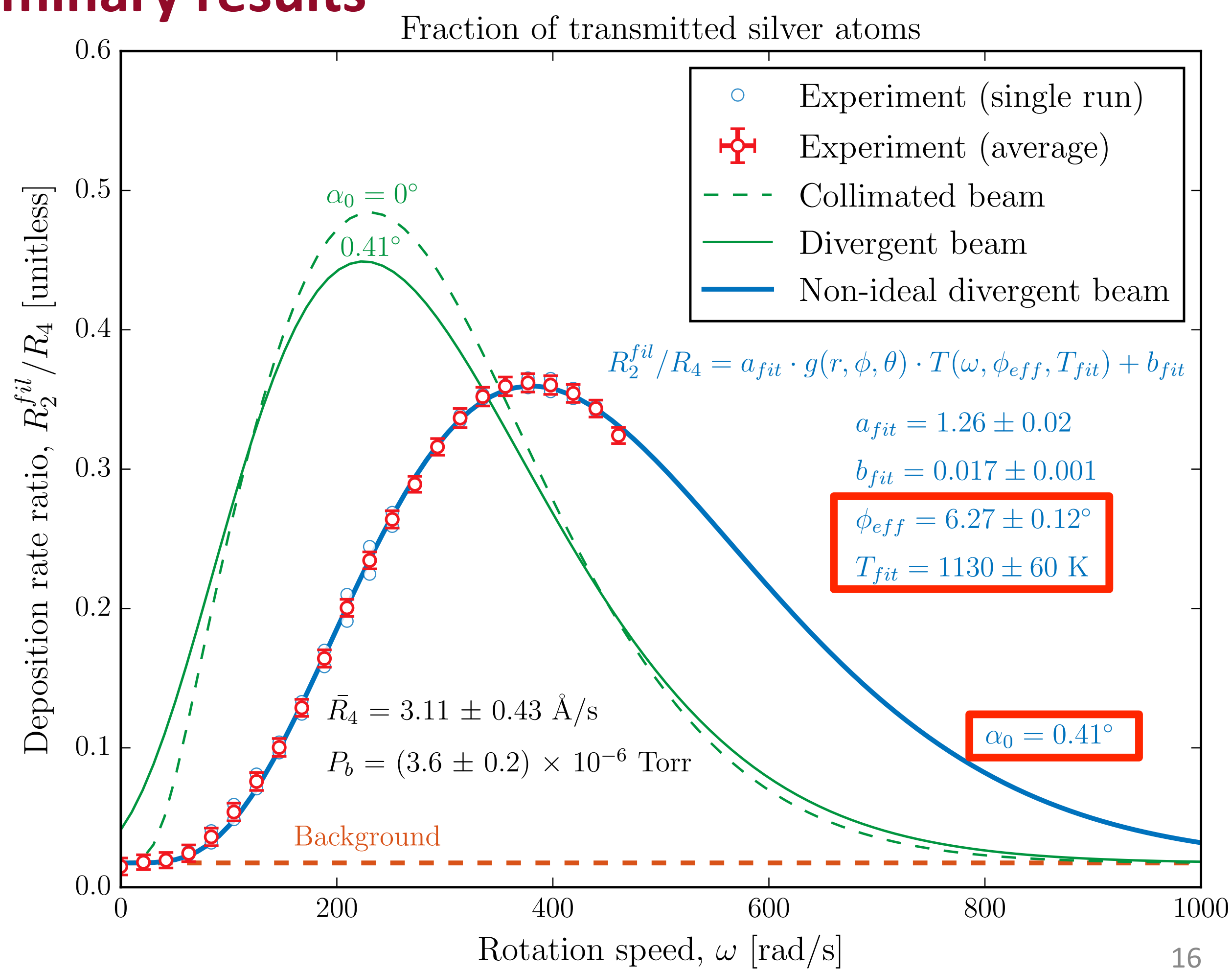




Ready to run experiments!

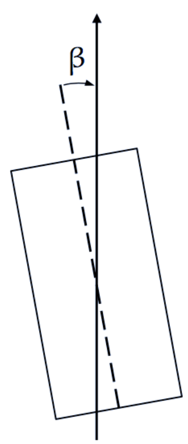
Electron gun: preliminary results



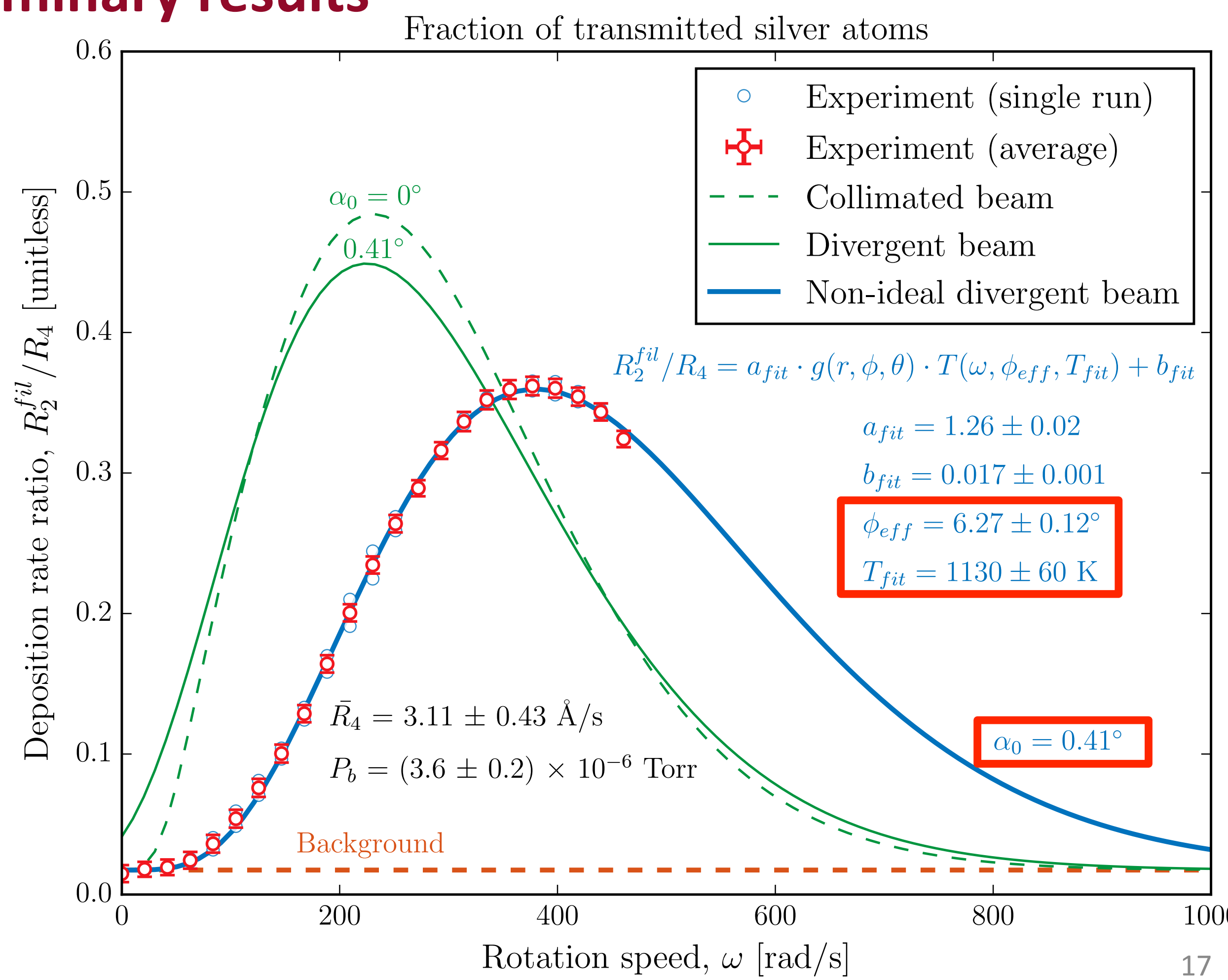


Electron gun: preliminary results

Must quantify experimental parameters…

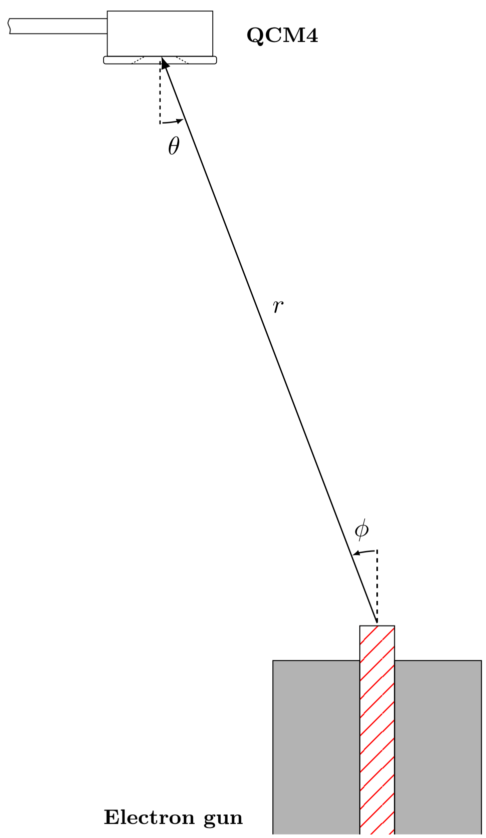


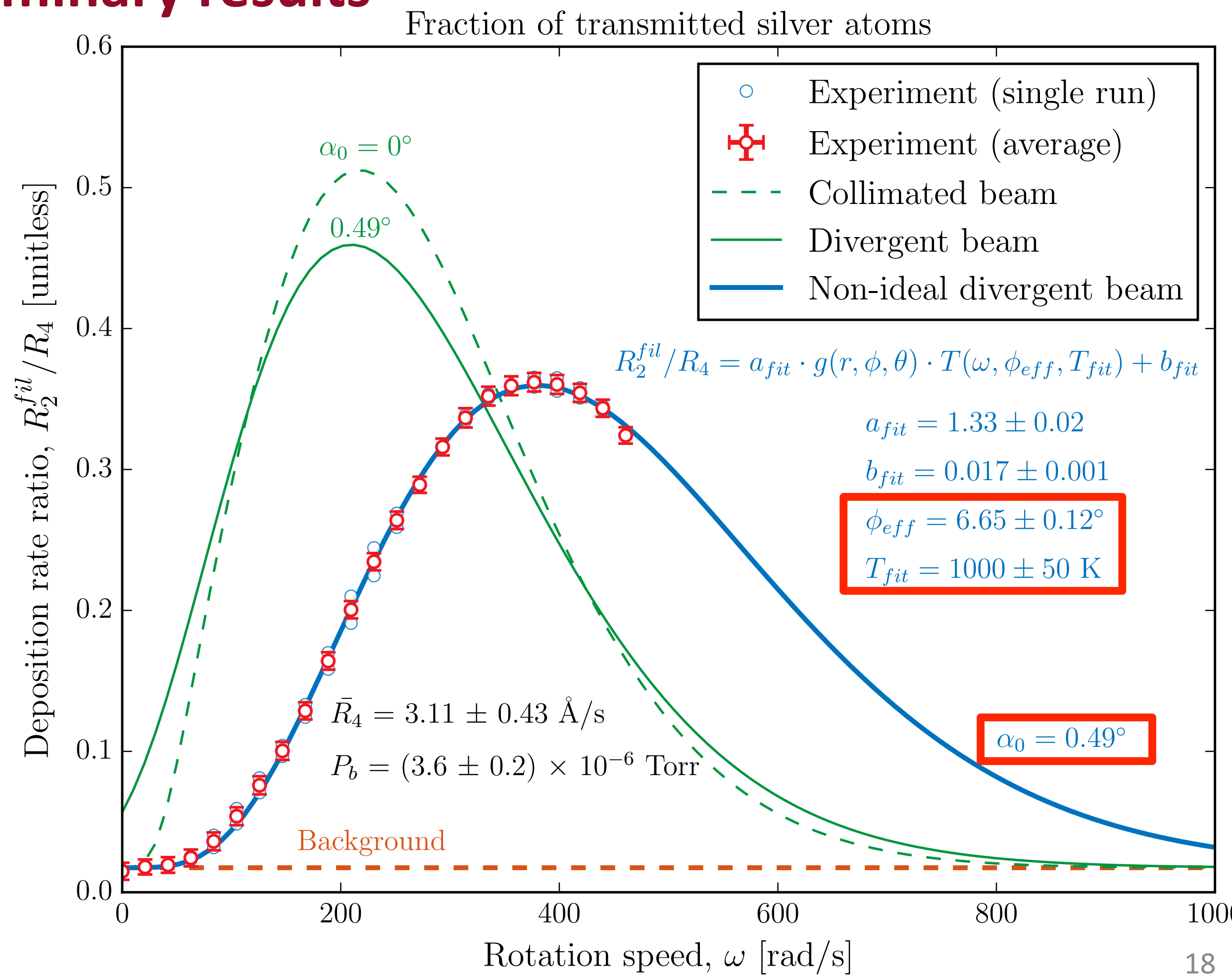
$$\phi_{eff} = \phi + \frac{\beta L}{r_0}$$



Electron gun: preliminary results

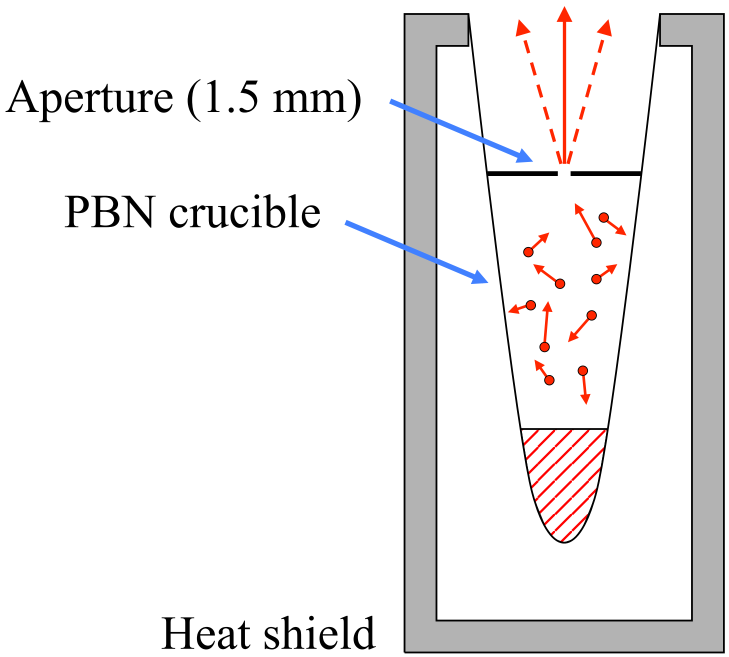
Direct monitor





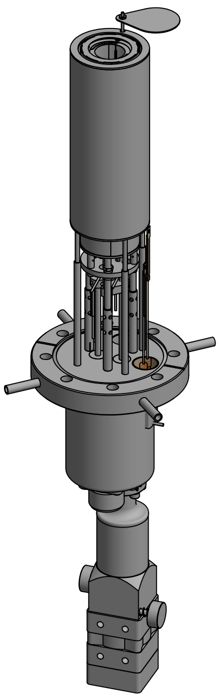
High temperature effusion cell (HTEC)

- Commercially available HTEC (from STV Associates)

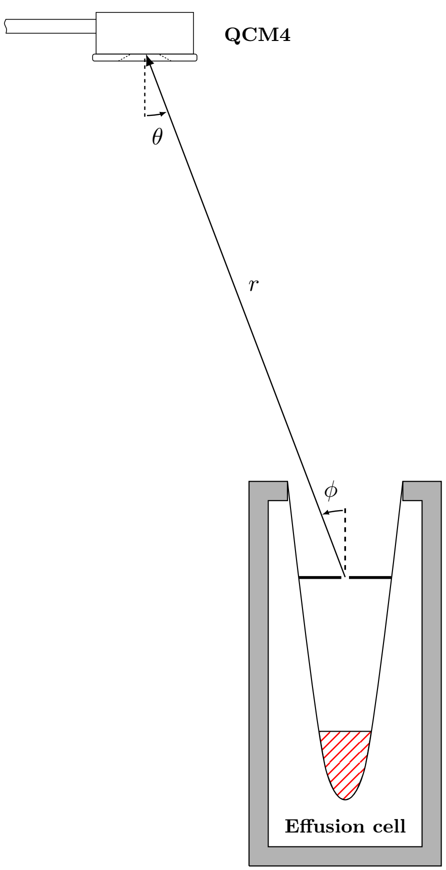


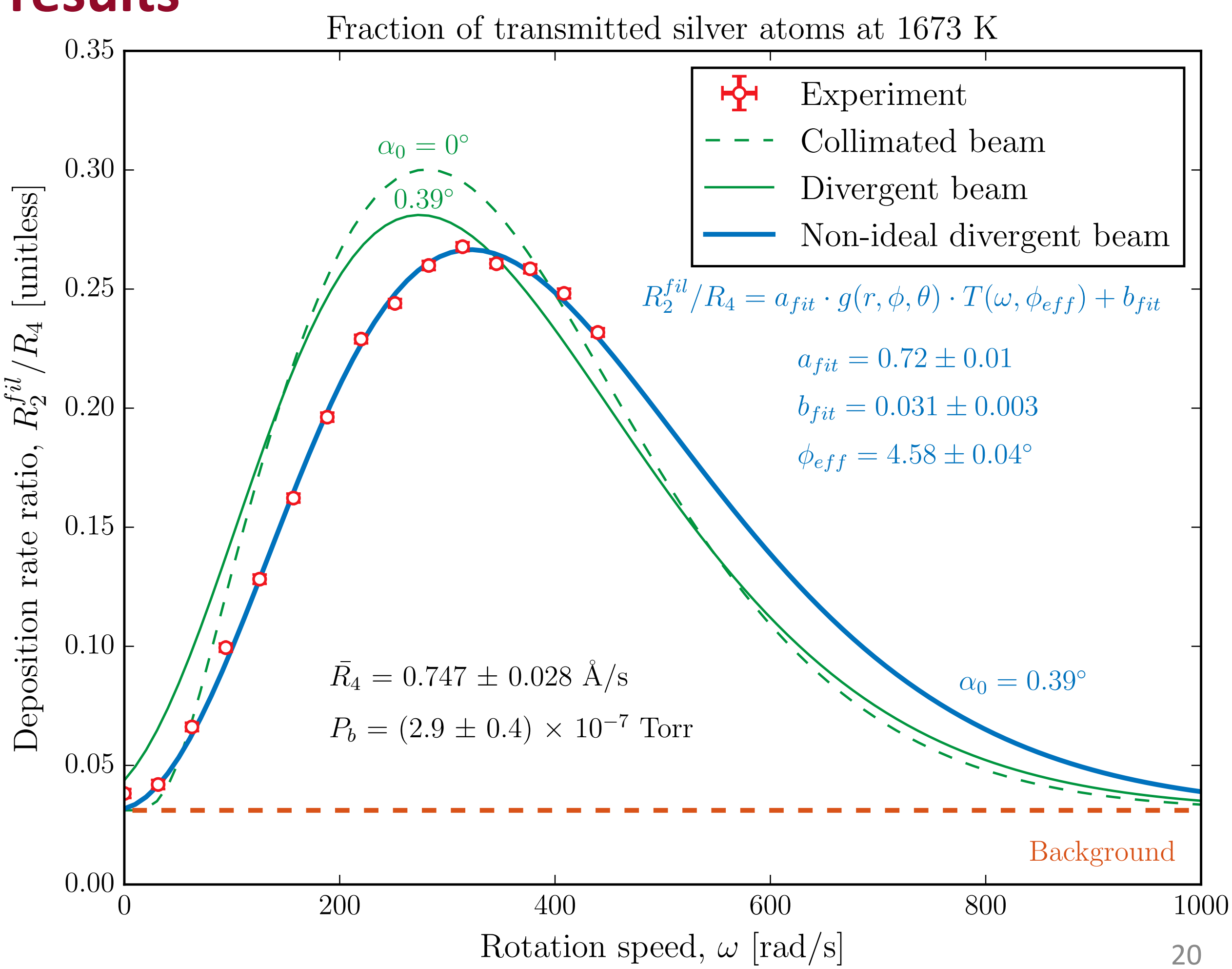
For Ag at 1600 K,

- Equilibrium vapour pressure ~ 1 Torr
- Mean free path ~ 1 mm

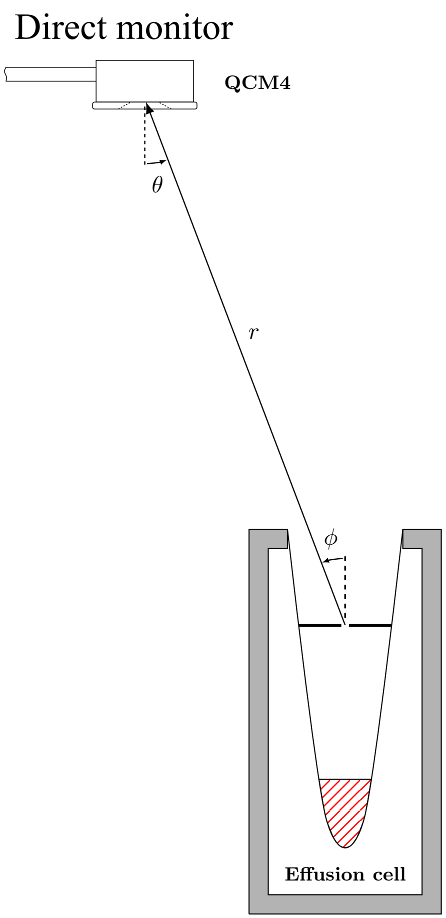


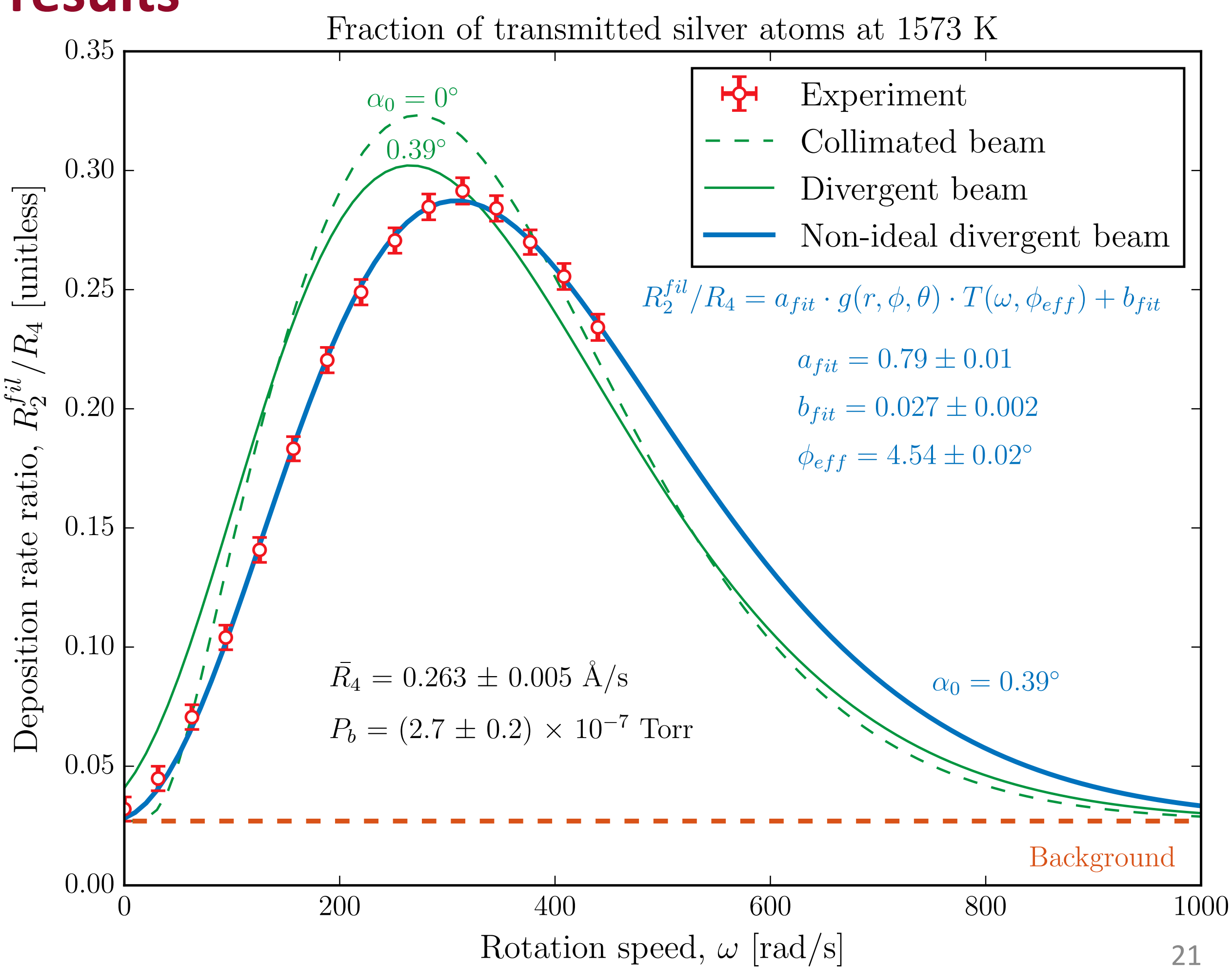
HTEC: preliminary results





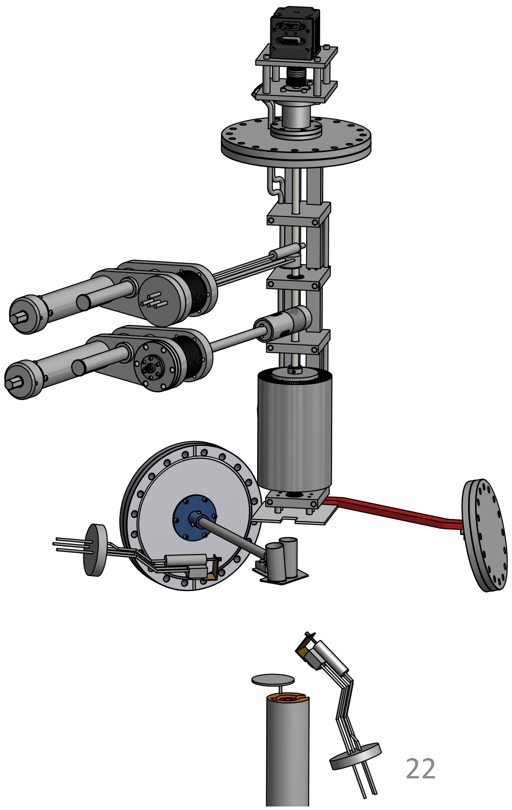
HTEC: preliminary results





Summary

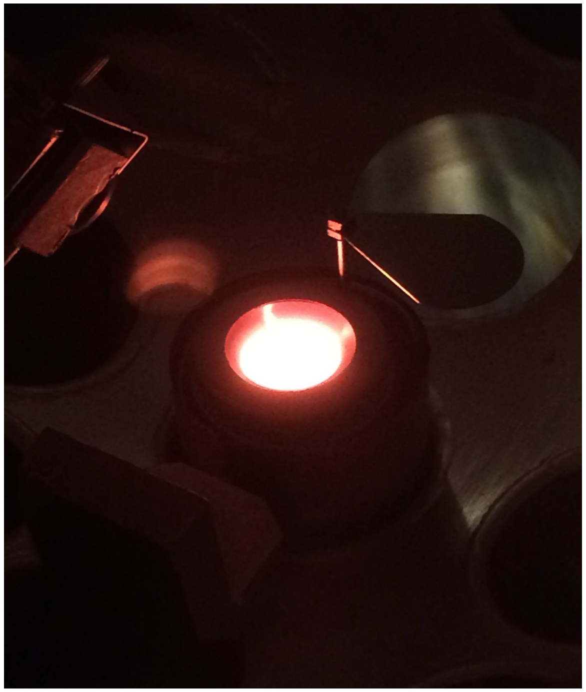
- Experimental apparatus is substantially complete
  - Vapour is produced using an electron-beam evaporator or a HTEC
  - Atoms are selectively transmitted through a mechanical velocity selector
  - Transmitted atoms are detected using a QCM
- Differences are observed between electron-beam evaporation and oven evaporation
- Theoretical model can be fit to experimental data, but more constraints are needed!



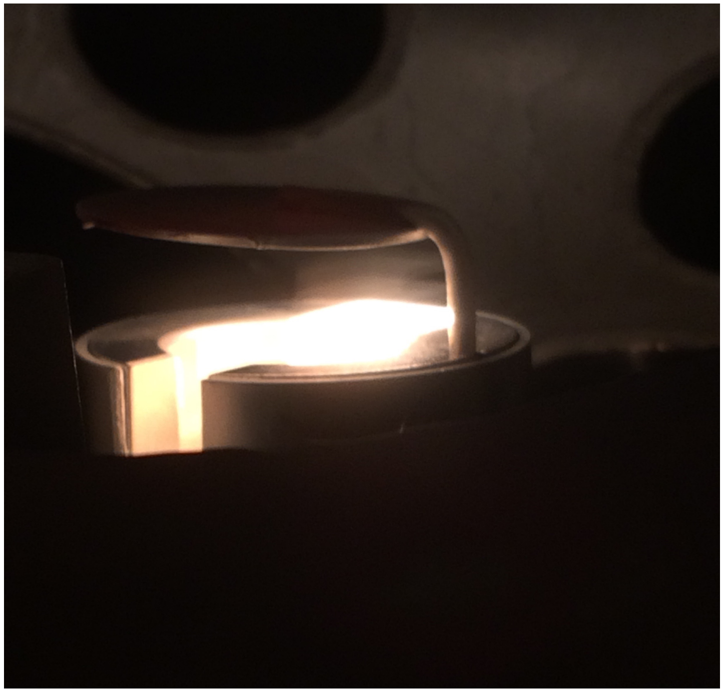
References

1. O. Knacke and I. Stranski. The Mechanism of Evaporation. Progress in Metal Physics, 6:181-235, 1956.
2. L. Koffman, M. Plesset, and L. Lees. Theory of Evaporation and Condensation. Physics of Fluids, 27(4):876-880, 1984.
3. S. van Dijken, L. C. Jorritsma, and B. Poelsema. Steering-enhanced roughening during metal deposition at grazing incidence. Physical Review Letters, 82(20): 4038–4041, 1999.
4. M. Ceriotti, R. Ferrando, and F. Montalenti. Impact-Driven Effects in Thin-Film Growth: Steering and Transient Mobility at the Ag(110) Surface. Nanotechnology, 17(14):3556–3562, 2006.

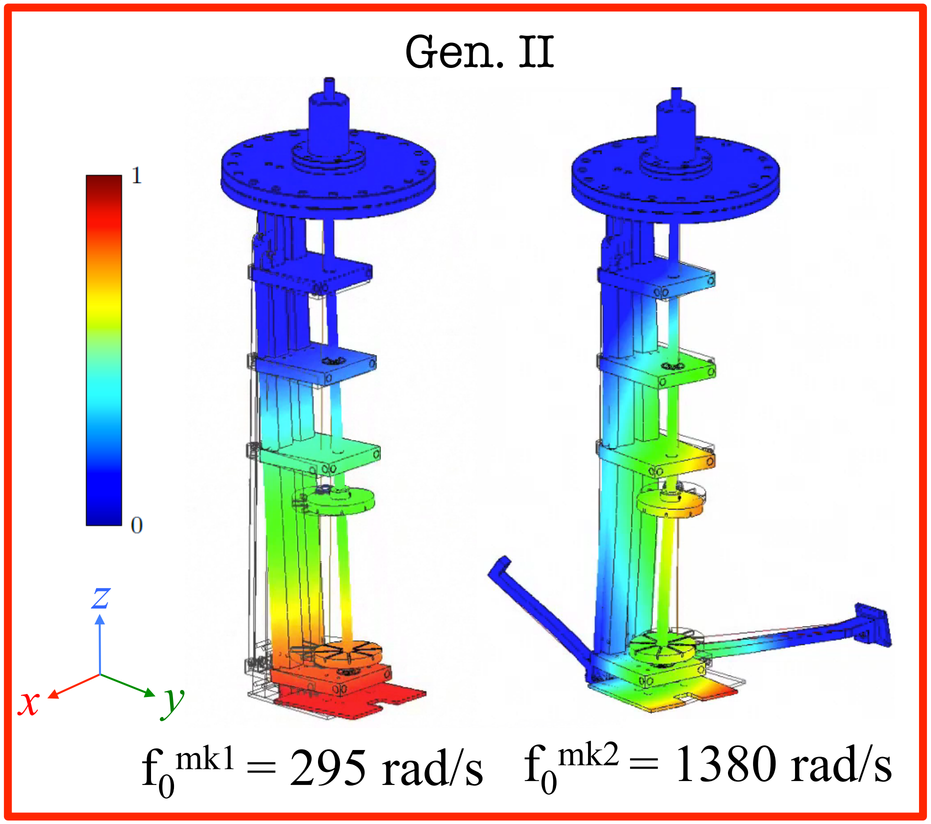
Questions

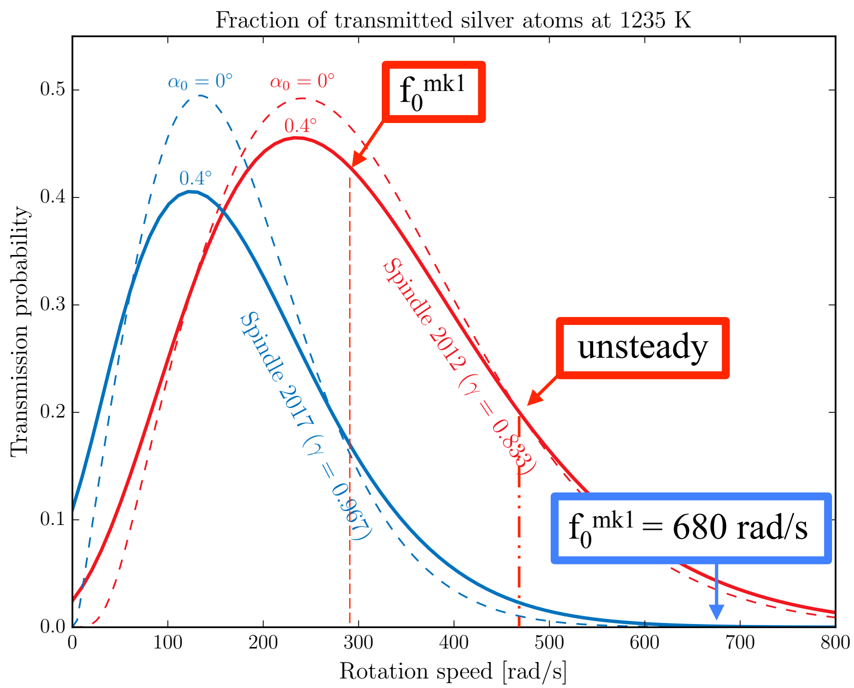


Questions?!



Bonus slide: simulated mode shapes



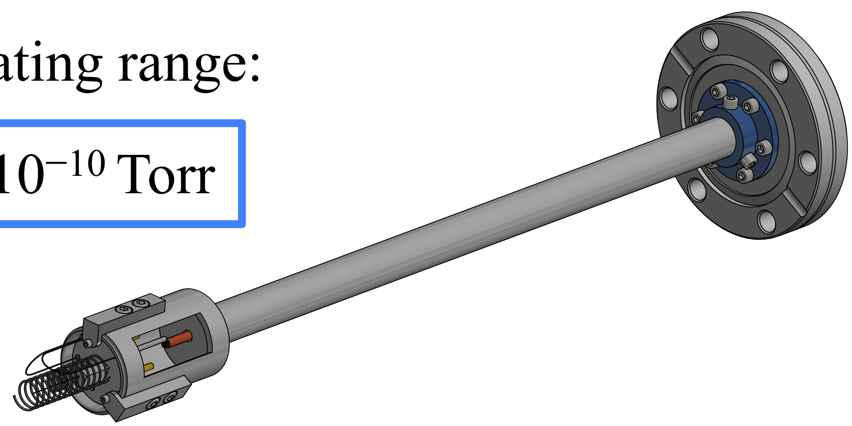


Bonus slide: hot-filament ionization gauge

- Energetic electrons ionize residual gas atoms which are then collected at an electrode
- Ion current is directly proportional to the number density of atoms in the detection region, and is thus an indication of pressure

Standard operating range:

10^{-3} Torr to 10^{-10} Torr



Bonus slide: ion extractor

- Ion trap extracts the plasma from the expanding vapour (for electron-beam evaporation experiment)