Two step photo-ionization of a laser cooled and compressed thermal atomic beam for use in a focused ion beam

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Ultracold Atoms and their Prospects for High Resolution FIB Nanomachining

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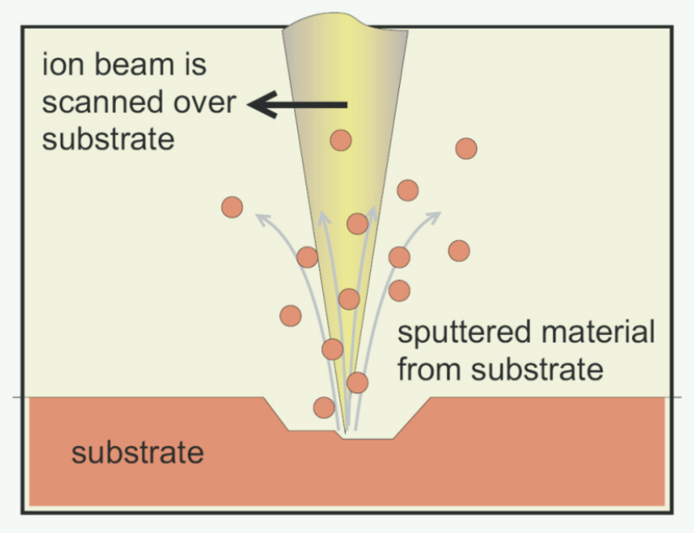
Introduction

- **Goal:** Design and fabrication of a focused ion beam (FIB) based on photoionization of a laser cooled and compressed thermal beam of rubidium to reach nm spot sizes
- **Applications:** Imaging and altering structures at the nanometer length scale. By scanning the beam over a substrate material can be removed (milling), a precursor gas can be deposited or the substrate can be imaged by looking at secondary/back scattered electrons/ions.

FIB milling



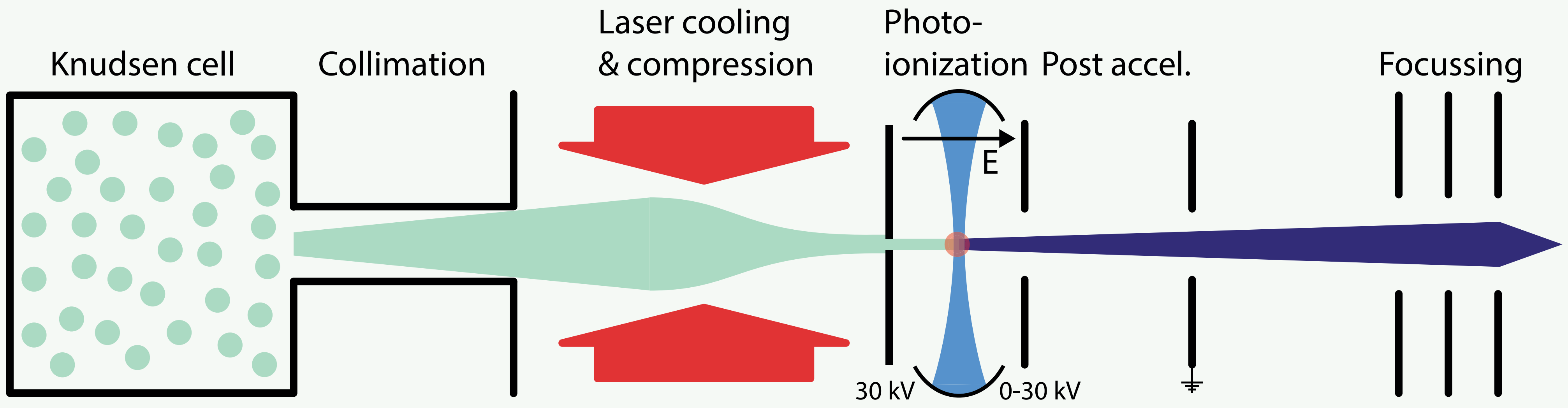
- **Other FIB sources:**
  - Liquid metal ion source (LMIS), uses heavy Gallium ions (good for milling), but only has resolution of 5 nm.
  - Gas Field Ionization Source (GFIS), uses light helium or neon atoms, but has a high resolution of < 1 nm.
- **Important beam parameters:**
  - Reduced brightness B_r: current density per unit of area and solid angle
  - Longitudinal energy spread σ_U

$$B_r = \frac{1}{U}\frac{\partial^2 I}{\partial A \partial \Omega}$$

Higher B_r and lower σ_U give a smaller spot size.

Commercial (LMIS) FIB system:

Proposed setup

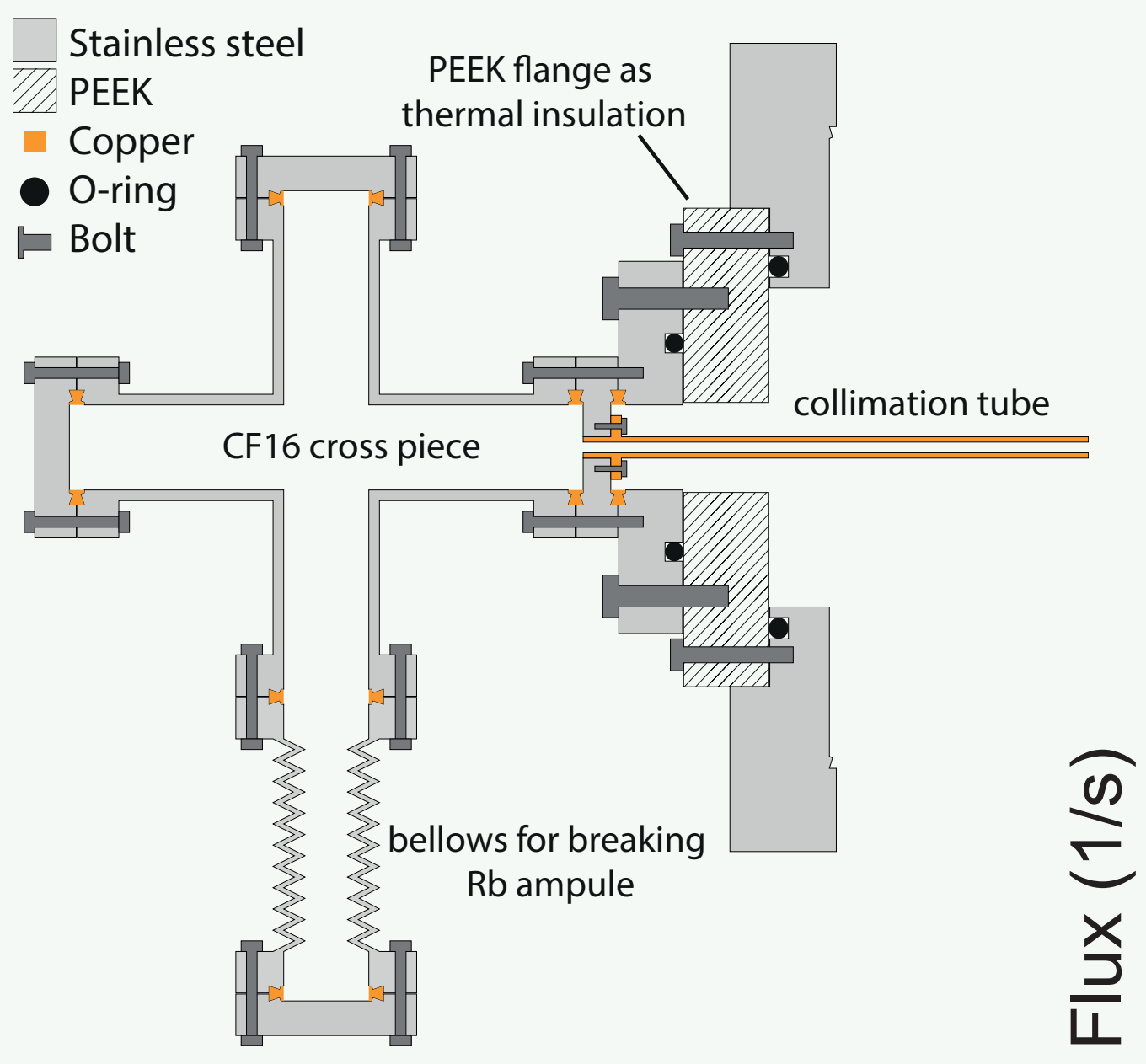


- ^{85}Rb is heated in a Knudsen cell. Due to the created vapor pressure rubidium will flow through a tube to the rest of the setup.
- A collimation tube is used to send back part of the atoms that can not be laser cooled and compressed, in order to increase the lifetime of a future FIB instrument.
- A Magneto-optical Compressor (MOC), consisting of a quadrupole magnetic field in combination with circularly polarized laser beams intensifies the atomic beam.
- An aperture is used to select the atomic beam. A build-up cavity creates an intense enough laser to ionize the complete transmitted beam. This happens inside an electric field to immediately accelerate the interacting ions.
- A commercial FIB electrostatic lens system will be used to focus the beam. Combined laser cooling [1] and charged particle tracing [2] simulations predict a nanometer sized probe.

[1] S.H.W. Wouters et al., PRA **90**, 063817 (2014)
[2] G. ten Haaf et al., JAP **116**, 244301 (2014)

Knudsen source: design and flux

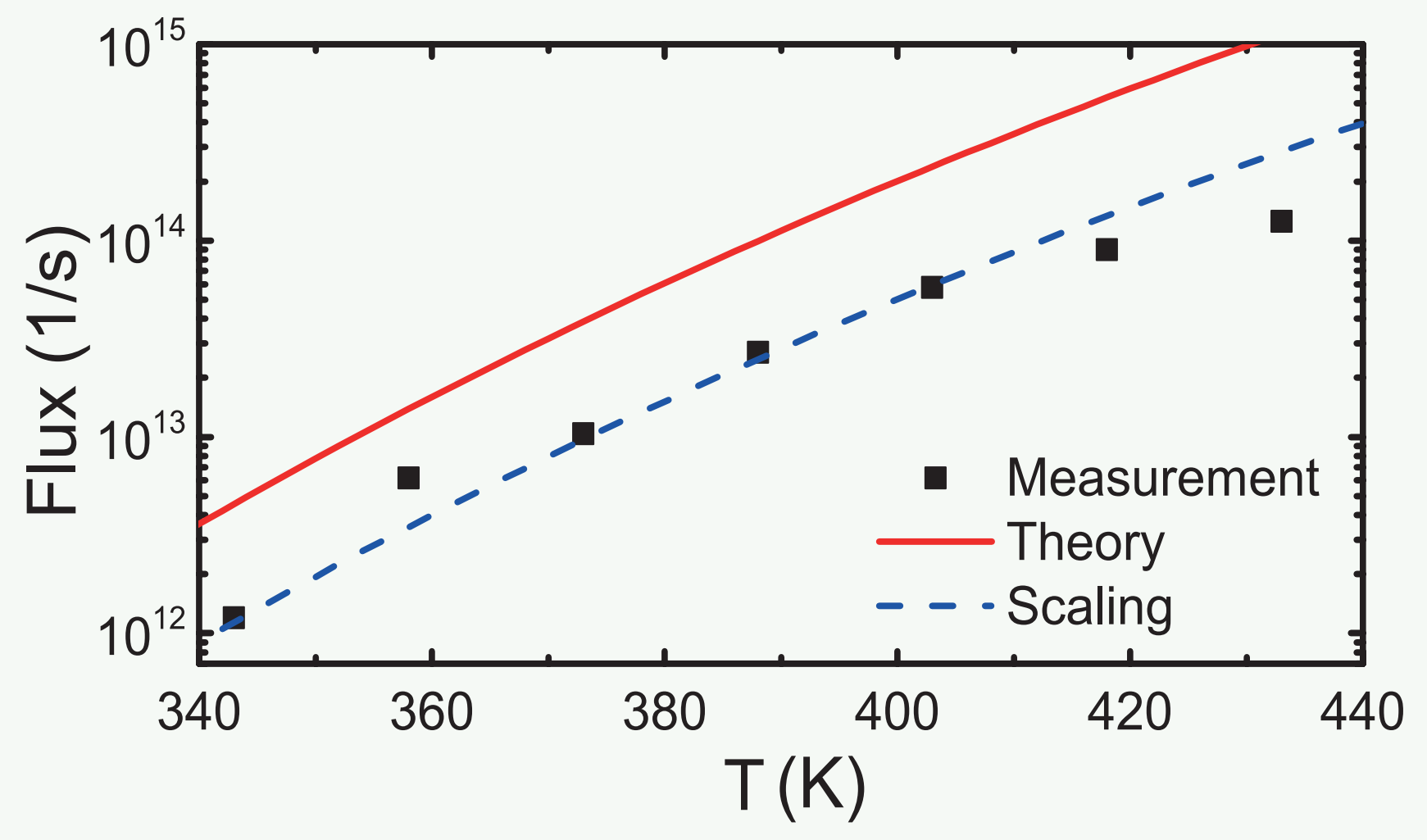
Design



- Bandheaters can heat the cross and bellows up to 160°C and an additional heating wire wrapped around tube heats the tube to 200°C to prevent clogging.
- Collimating tube design chosen over recirculating skimmed oven because of its simple design

Flux measurements

- Measured flux [3] a factor of 4 lower than predicted by molecular flow theory [4]. However, this is not a big problem since it is simply overwon by increasing the Knudsen cell temperature by 20 K.
- At higher temperatures (>400 K) collission in the tube cause the flux to decrease, hence the larger discrepancy with theory.



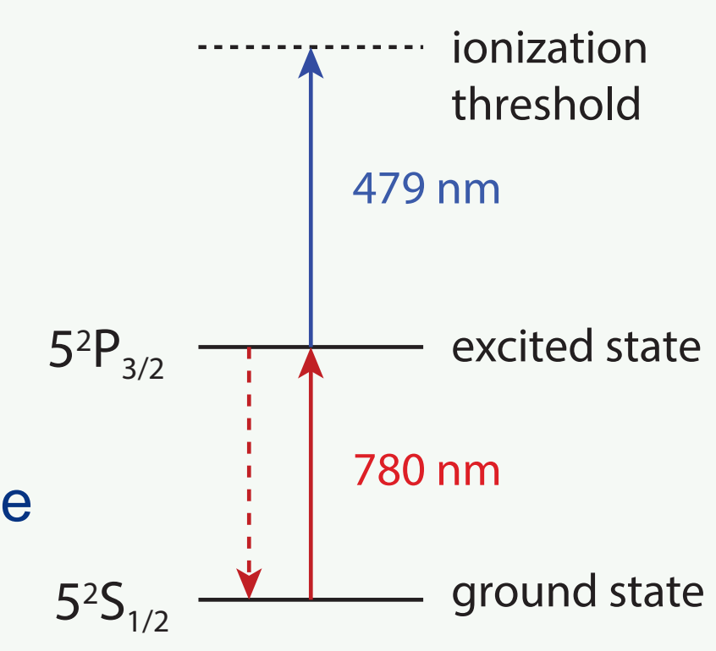
[3] S.H.W. Wouters et al., Rev. Sci. Instr. 87, 083305 (2016)
[4] D.R. Olander and V. Kruger, *Molecular beam sources fabricated from multichannel arrays. iii. the exit density problem.* J. Appl. Phys. **41**, 2769 (1970)

Ionization: process and realization

Two-step ionization

- Two lasers overlapped spatially at the position of the atomic beam.
- For largest brightness nearly complete ionization wanted

Atomic level scheme ^{85}Rb

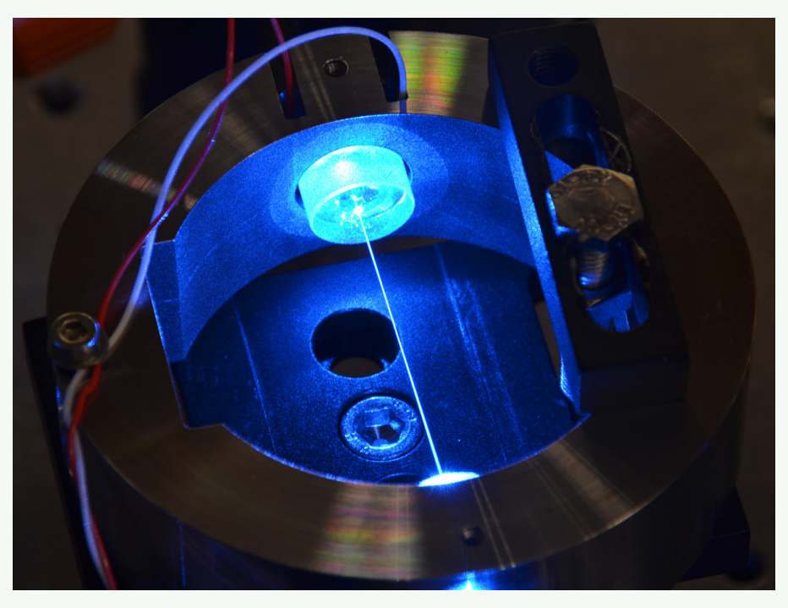


- Numerical calculations of the ionization process showed an ionization laser (479 nm) intensity of 10^{10} W/m² will ionize ≈80% of the beam within approximately 3 μm

Build-up cavity

- Reflectance = 99.7%, max. theor. build up = $\frac{\textit{circulating power}}{\textit{incident power}} = \frac{1}{1-R} = 333$
- Cavity length chosen to give an 18 μm waist. Two lenses used for mode coupling.
- Pound Drever Hall [5] technique used to lock the length of the cavity to an integer times the half wavelength.
- Build up of (190 ± 30) measured by locking the cavity and comparing the transmitted power through the cavity to the incident power.

Build up cavity realization



- So 300 mW laser gives 2×10^{10} W/m², enough for ionizing ≈80%.

[5] E.D. Black, Am. J. Phys. 69, 79 (2001)

Conclusion and outlook

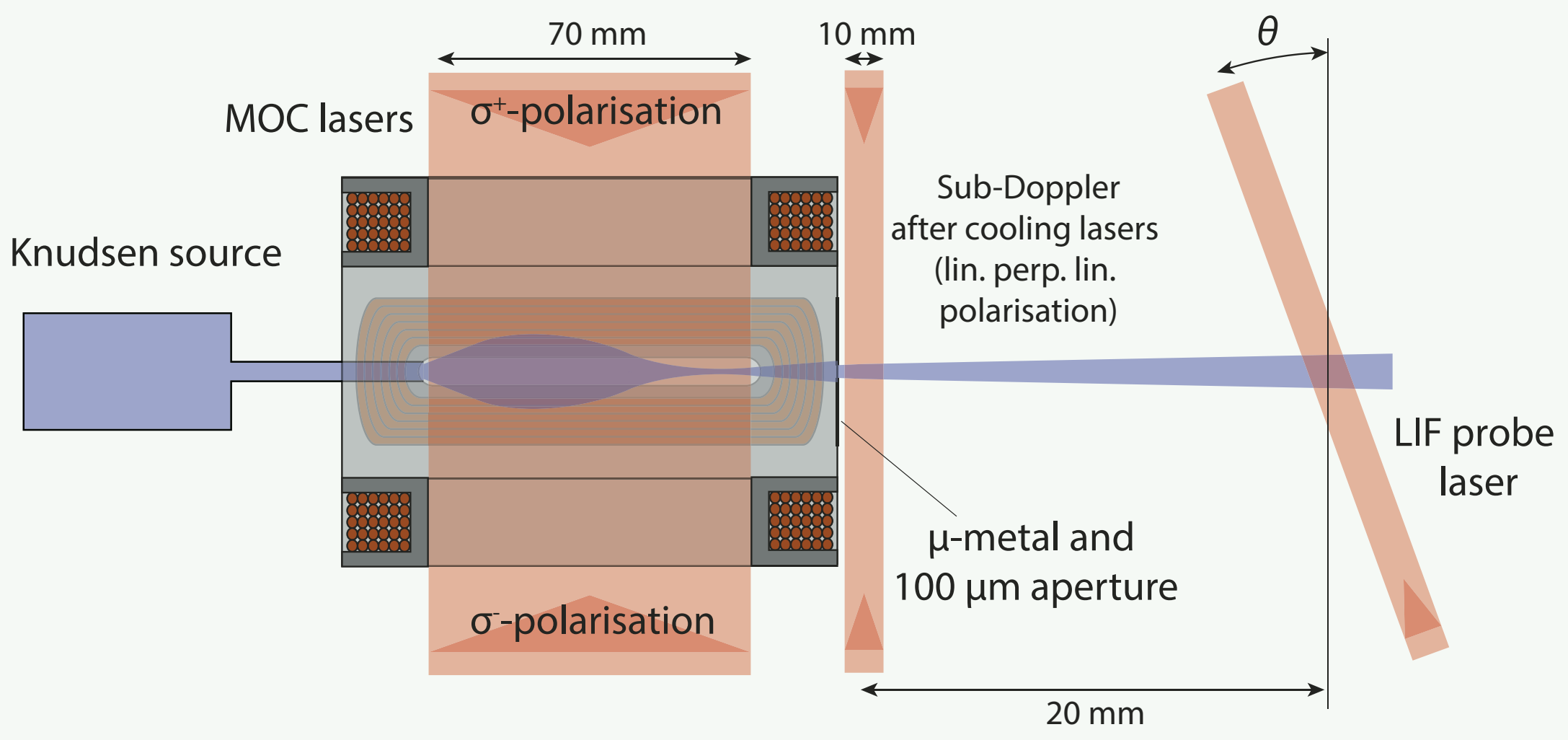
- Flux from Knudsen cell scales as expected and is sufficient for our purpose.
- Magneto-optical compression experiments show that an equivalent reduced brightness of10^6 A/m²/sr/eV can be achieved in a single 70 mm laser cooling stage, additional sub-Doppler cooling improves the equivalent reduced brightness to 6×10^6 A/m²/sr/eV.
- Build-up cavity is realized in which an ionization intensity of 2×10^{10} W/m² can be reached, which can ionize 80% of the atomic beam.

Next steps:

- Ion beam creation in tailor made vacuum vessel to accomodate accelerator and build up cavity
- Energy spread analysis with retarding field analyzer (0.1 eV FWHM energy spread expected @ 1pA)
- Mounting source on FIB collumn (FEI sidewinder) and determine ion beam brightness

Magneto-optical Compression (MOC)

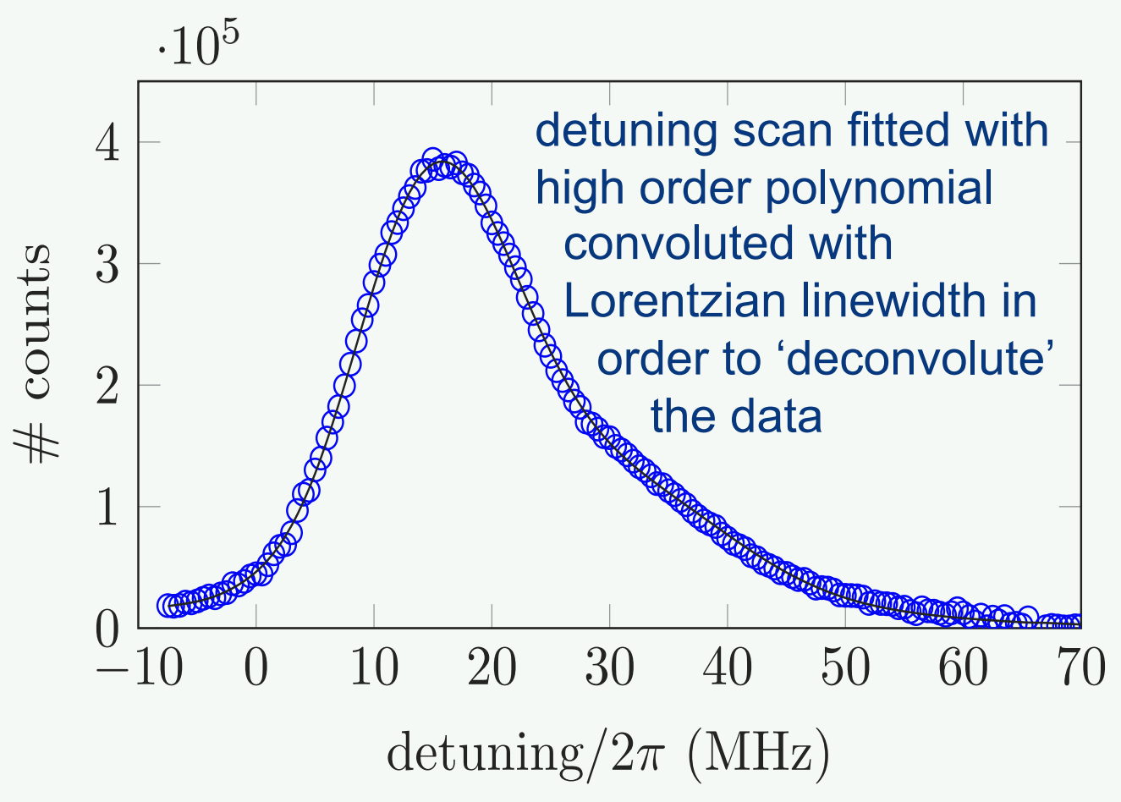
Experimental setup

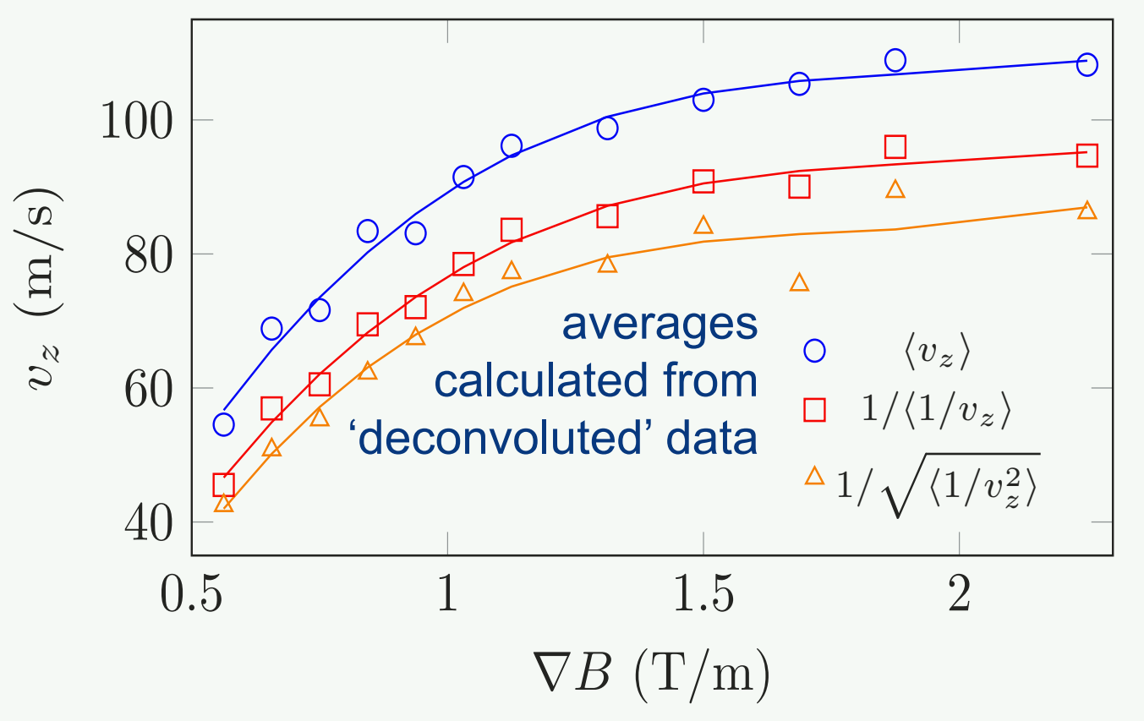


- 100 μm diameter aperture to select 'useful' central part of the beam
- Imbalance in current through opposing quadrupole coils to overlap magnetic axis with aperture
- Lasers with linear perpendicular linear polarisation configuration were added to improve on the temperature of the beam
- Laser induced fluorescence (LIF) of atoms imaged on camera to measure beam flux and size
- Probe laser perpendicular to beam (θ = 0) for temperature and flux measurements and θ = 0.3 rad for longitudinal velocity distribution measurement.

Longitudinal velocity distribution

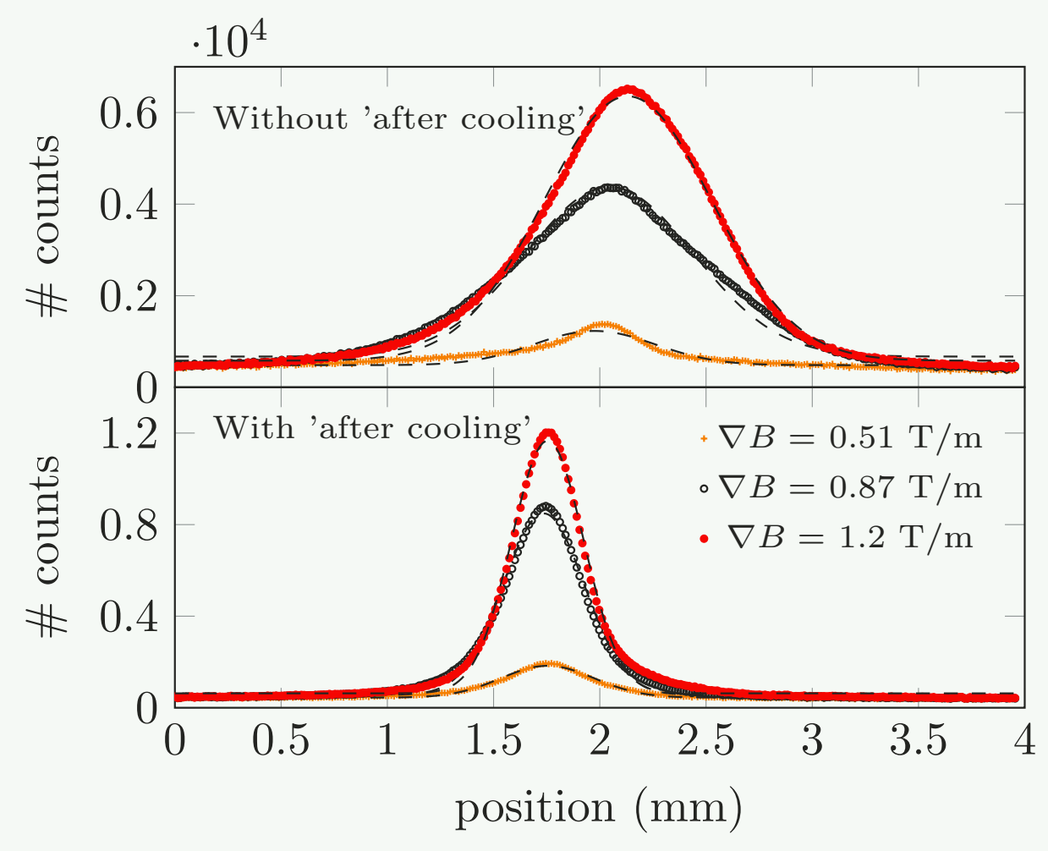
- Longitudinal velocity required for accurate determination of flux (because of transit time through the probe laser) and temperature (because extracted from divergence)
- Longitudinal velocity of cooled beam lower than input from Knudsen source because slow atoms are captured more easily than fast atoms



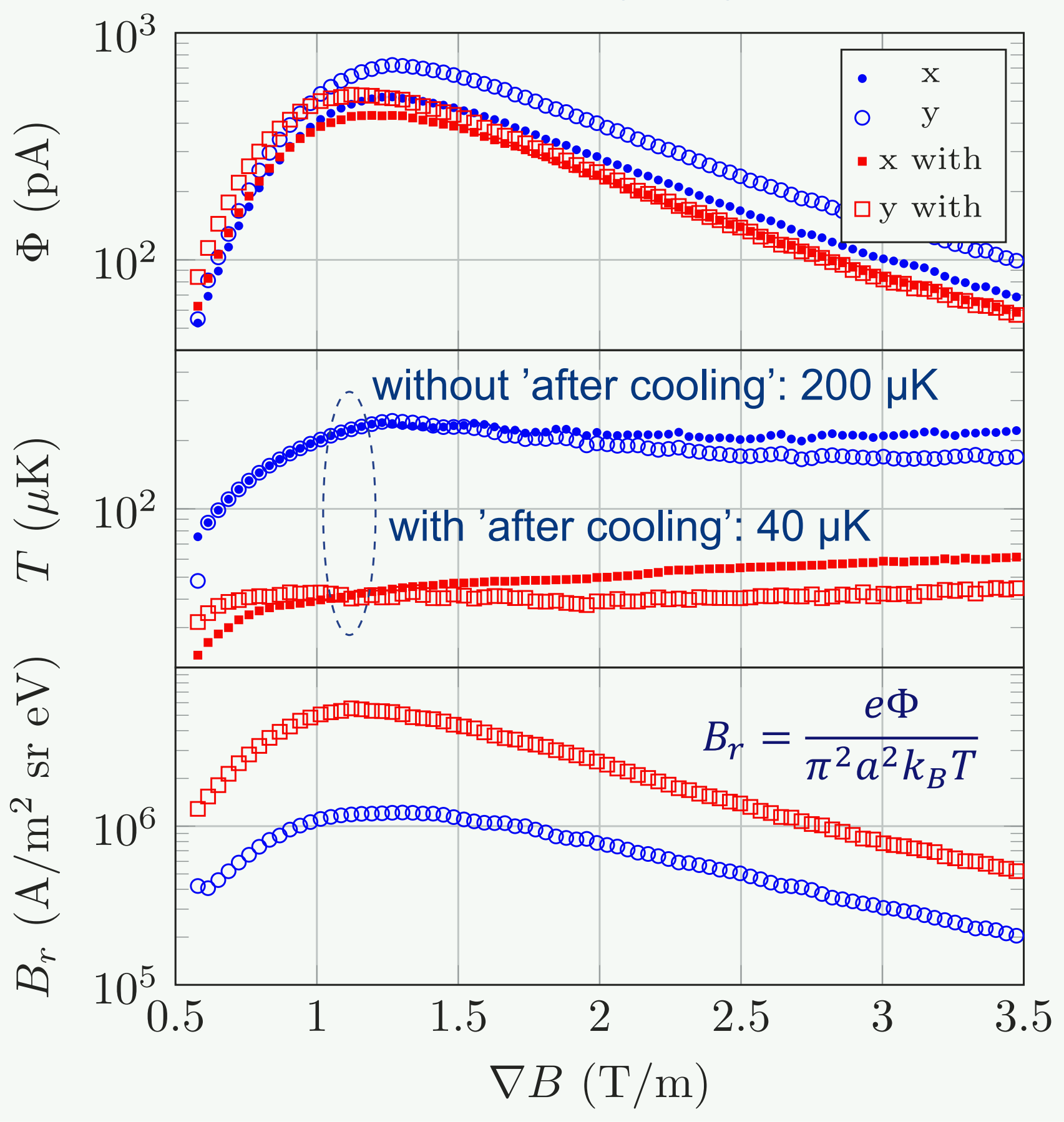


Equivalent reduced brightness

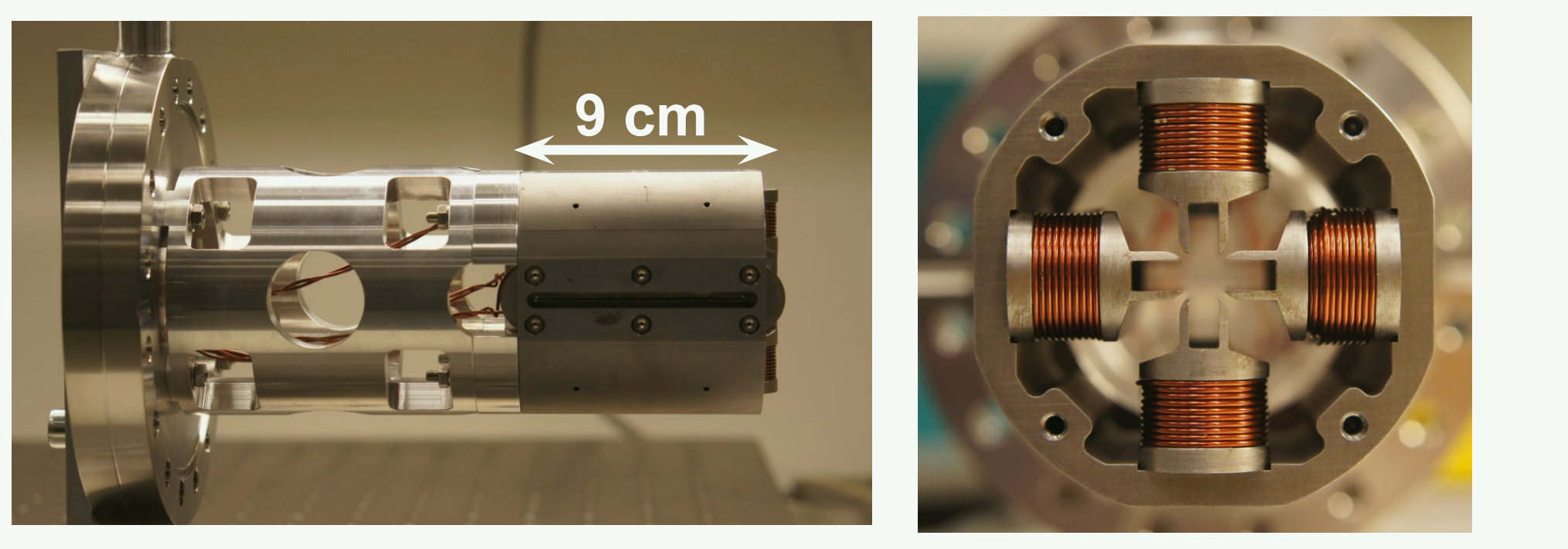
Beam profiles @ different magnetic gradients



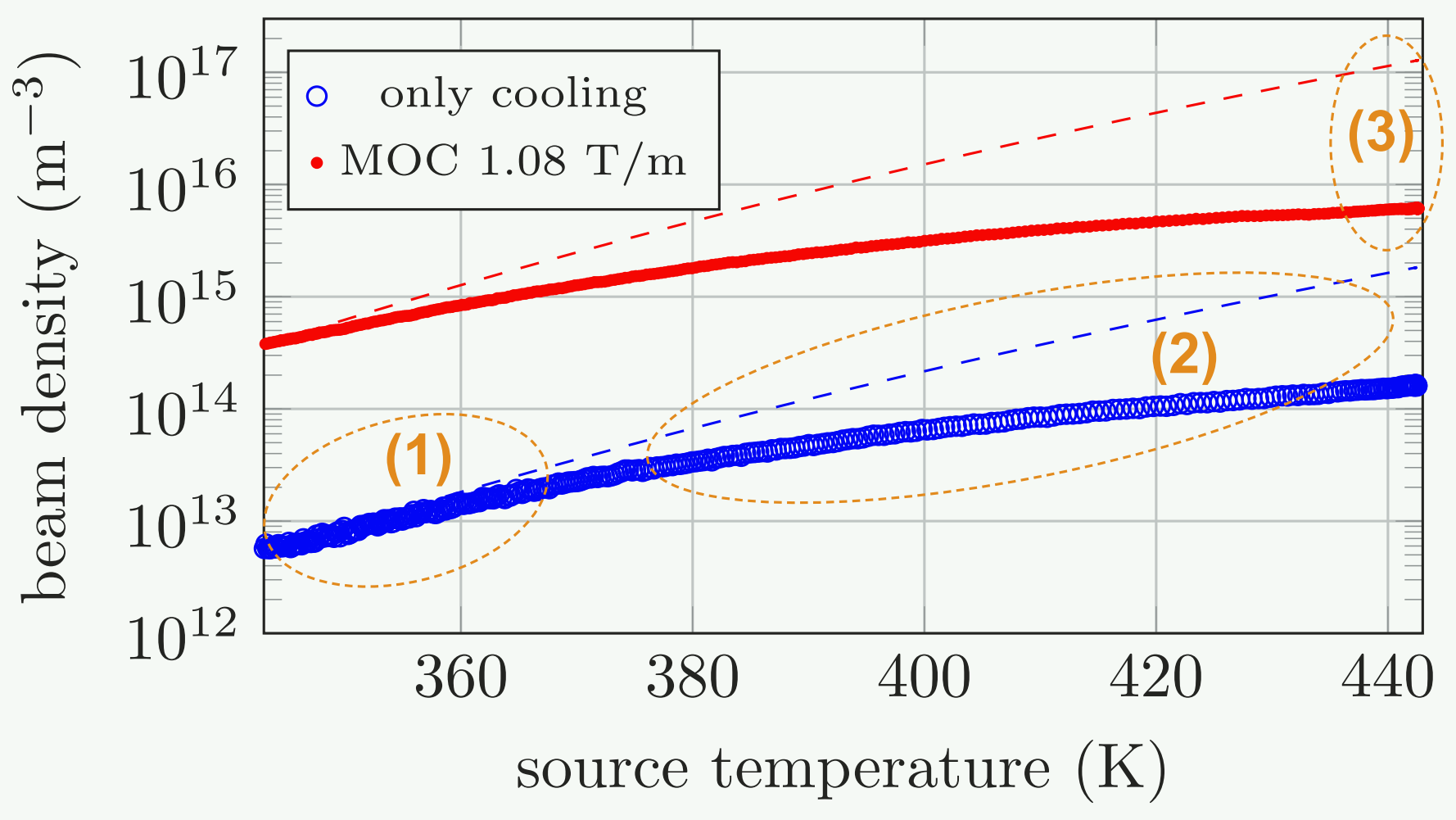
Beam parameters vs. magnetic gradient



Compact in-vacuum quadrupole magnet



Beam density vs. source temperature



- Without interactions the density in the beam would scale according the flux from the Knudsen source (dashed lines).
- At low source temperatures **(1)**, scaling agrees with data when only cooling the beam, i.e. without compression.
- At higher temperatures **(2)**, scaling doesn't hold anymore due to atomic collisions inside the collimation tube that lowers the amount of useable flux that can be captured in the cooled beam.
- When also compressing the beam the discrepancy with the scaling is larger **(3)**, possibly due to radiation trapping or inelastic collisions between ground and excited state atoms.

Equivalent brightness of 6×10^6 A/m²/sr/eV with 500 pA equivalent current!

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