Atom Chip Loading from Atomic Beam

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Focusing of an Atomic Beam

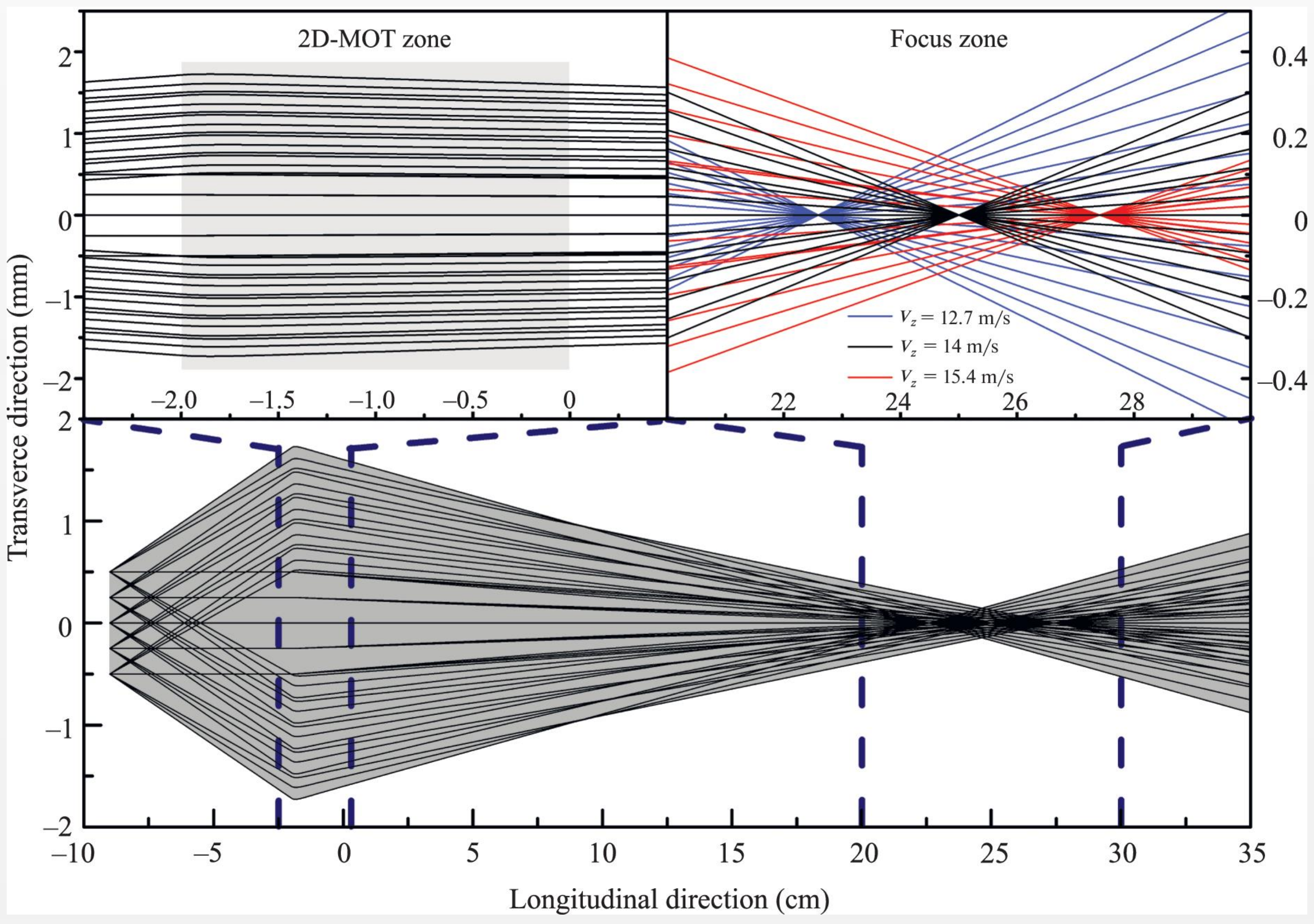


Fig. 1. Focusing of an atomic beam. The trajectories of atoms were calculated for various longitudinal ($v_z = 12.7, 14, 15.4\ m/s$) and transverse ($v_x = 0.22, 0, -0.22\ m/s$) velocities of atoms [1].

We propose focusing of the LVIS atomic beam by 2D MOT into the trapping region of the atom chip (Fig. 1, 2) to increase atomic flux and, consequently, the number atoms in the atom chip's MOT.
In overdamped regime the focal length of such focusing element is given by:

$$\mathrm{f} = \frac{\mathrm{k v_z}}{\alpha \mathrm{g}},$$

where α = 2π ×1.4MHz/G is the Zeeman shift of the resonance absorption line in the magnetic field $B = g \cdot x$, k – laser field wavevector, $\mathrm{v_z}$ – longitudinal velocity of the atom. Remarkably, f does not depend on initial transverse velocity of an atom, what makes focusing possible. However, f depends on longitudinal velocity $\mathrm{v_z}$, what can be called "chromatic aberration". We demonstrated that, in spite of "chromatic aberration", low-velocity atomic beam can be focused into a spot 250μm in diameter [1]. This would increase the loading rate by a factor of 160 in our experiment geometry.

Momentum Diffusion

The momentum of an atom fluctuates in a laser field. This is due to fluctuations in the direction of spontaneous emission and the number of photons scattered by stimulated transitions. The mean square of momentum fluctuations $\langle(\Delta p)^2\rangle$ characterizes the diffuse broadening of the atomic momentum. A quantitative representation of the rate of diffusion broadening of the momentum can be obtained using the momentum diffusion tensor:

$$D_{ij} = \frac{1}{2}\frac{\langle \Delta p_i \Delta p_j \rangle}{\Delta t}, \text{ where } \Delta p_i = p_i - \langle p_i \rangle,\ i = x, y, z.$$

If the radiation propagates along axis *x*, *y* or *z*, then the tensor D_{ij} contains only diagonal elements. To calculate the momentum diffusion during atomic beam focusing due to interaction with laser beams along *x*-axis (see Fig. 2), it is necessary to solve the Fokker-Planck equation for the velocity distribution function of atoms $w(t, v_x)$:

$$\frac{\partial w}{\partial t} = -\frac{\partial}{\partial v_x}(A_x w) + \frac{\partial^2}{\partial {v_x}^2}\left(\frac{D_{xx}}{M^2} w\right),$$

where v_x – projection of the atom's velocity on the x-axis, A_x – acceleration of an atom caused by forces in a 2D MOT, $D_{xx}(x, v_x)$ – momentum diffusion tensor, M – mass of an atom.

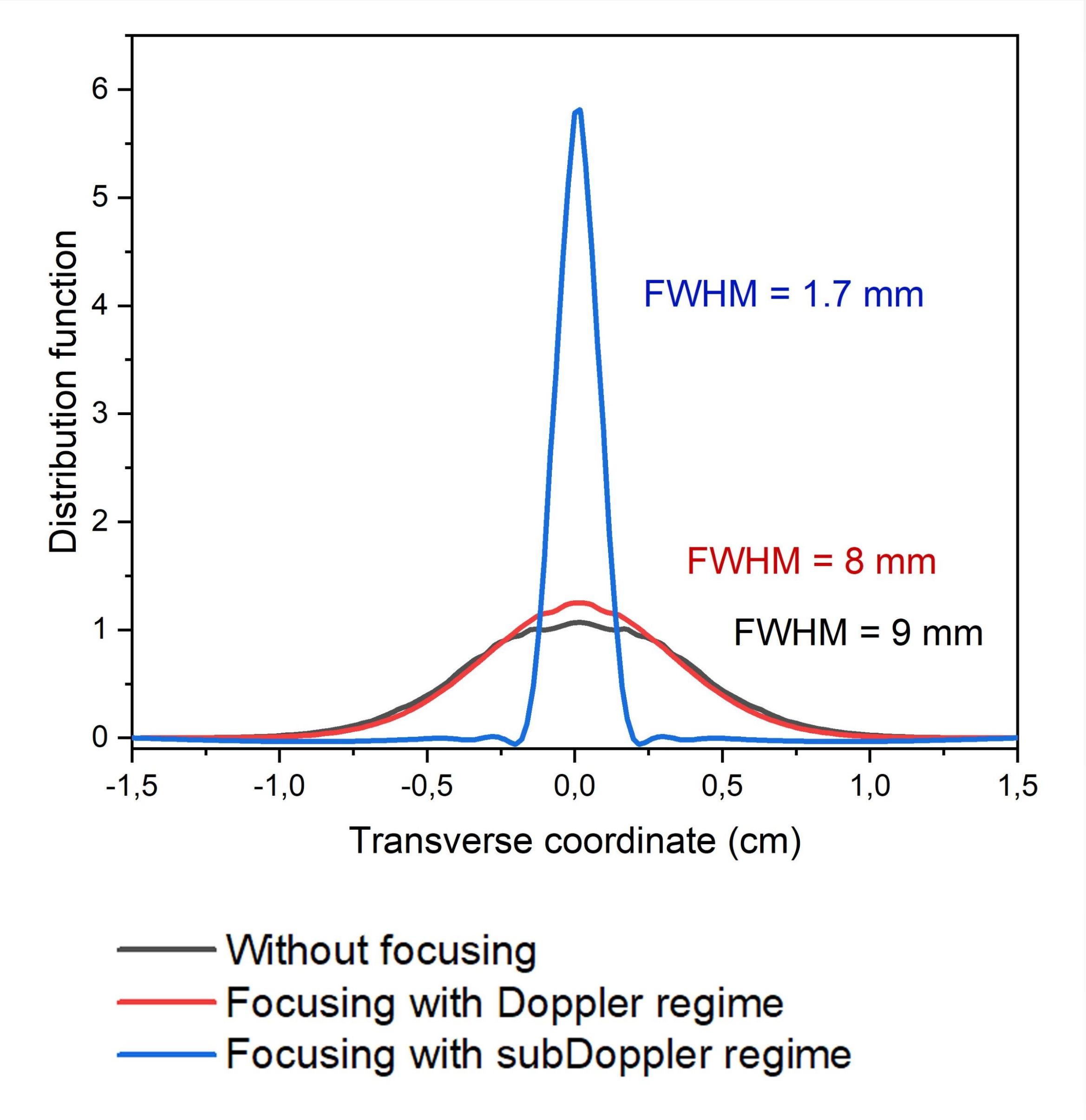


Fig. 4. Calculated distribution functions along x-axis in the focal plane f = 25 cm.

Fig. 4. shows the results of numerical solutions of the Fokker-Planck equation for cases without focusing (black), with focusing in a 2D MOT with a Doppler cooling mechanism (red), and with focusing with a sub-Doppler cooling mechanism (blue). This shows that focusing with the Doppler cooling regime is inefficient due to the large momentum diffusion.

At large detuning $|\delta| \gg \gamma$, where 2γ is the decay rate, the diffusion coefficient is $D_{xx}(0{,}0) = \frac{23}{17}\hbar^2 k^2 \gamma \frac{G\gamma^2}{\delta^2}$, [3] where G is the saturation parameter, so $D_{xx}(0{,}0) \sim \frac{1}{\delta^2}$. Thus, at large detuning, the diffusion coefficient is small. This leads to the use of the sub-Doppler cooling regime (see Fig.4).

Atom Chip Loading

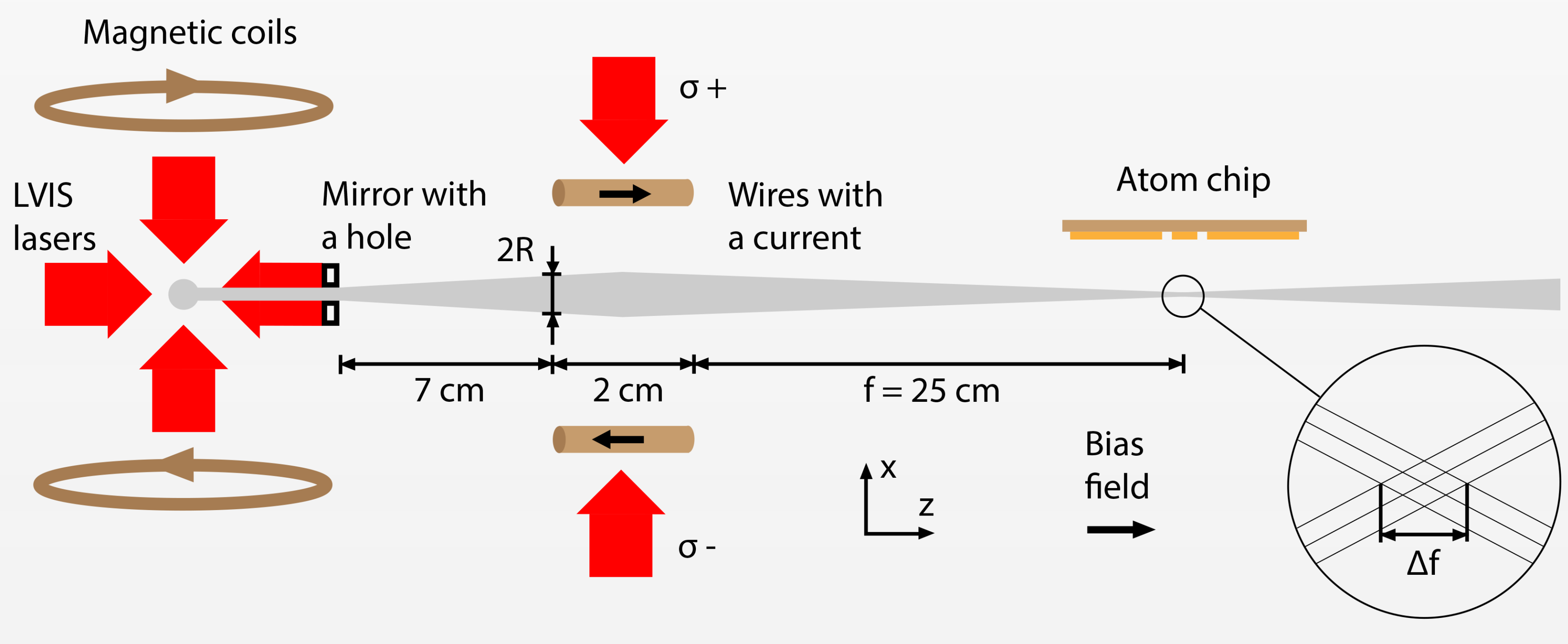


Fig. 2. Scheme of the experimental setup [1]. The atomic beam is formed using a low-velocity intense source (LVIS) and focused using a 2D MOT to the localization area on the chip [2].

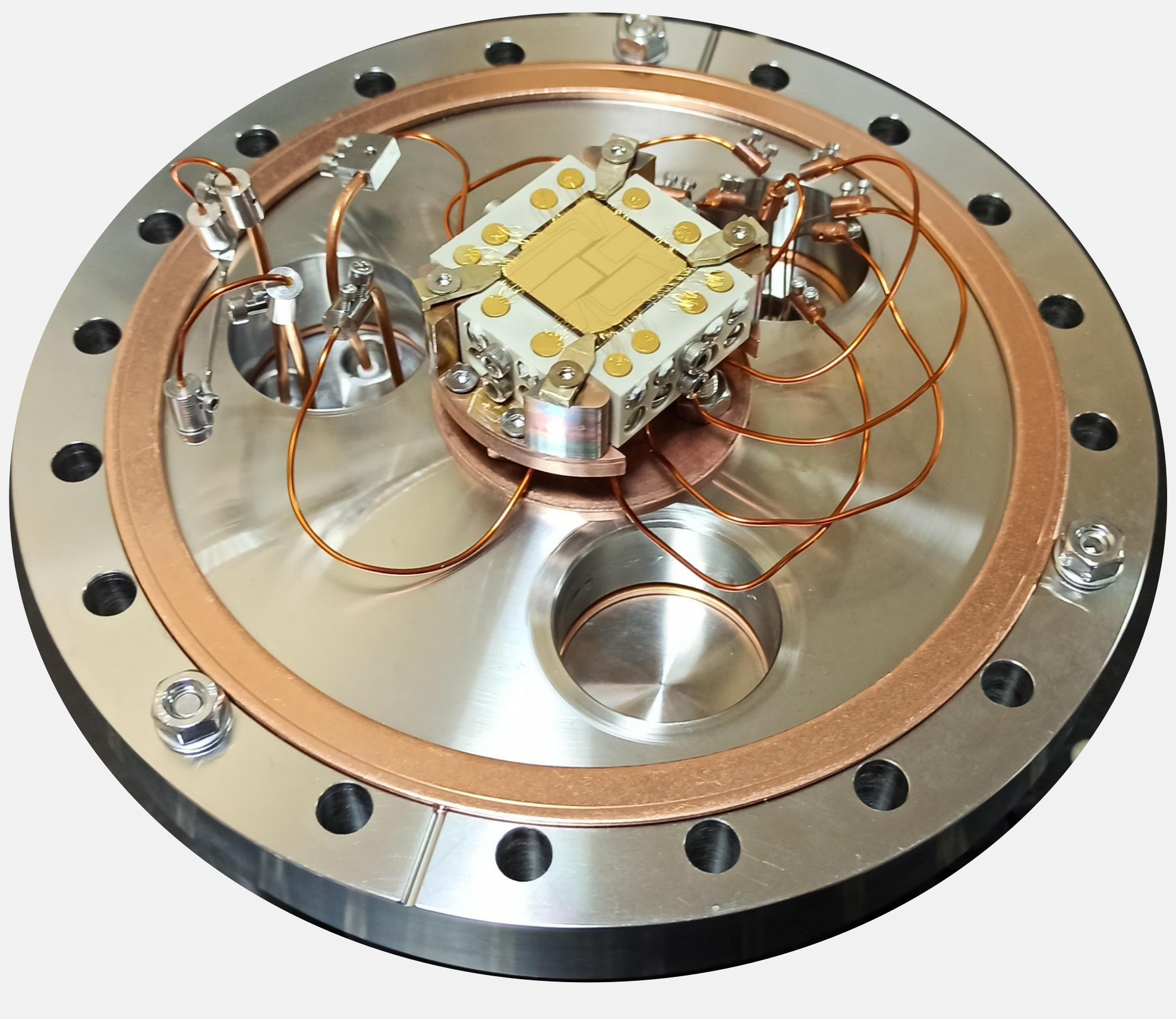


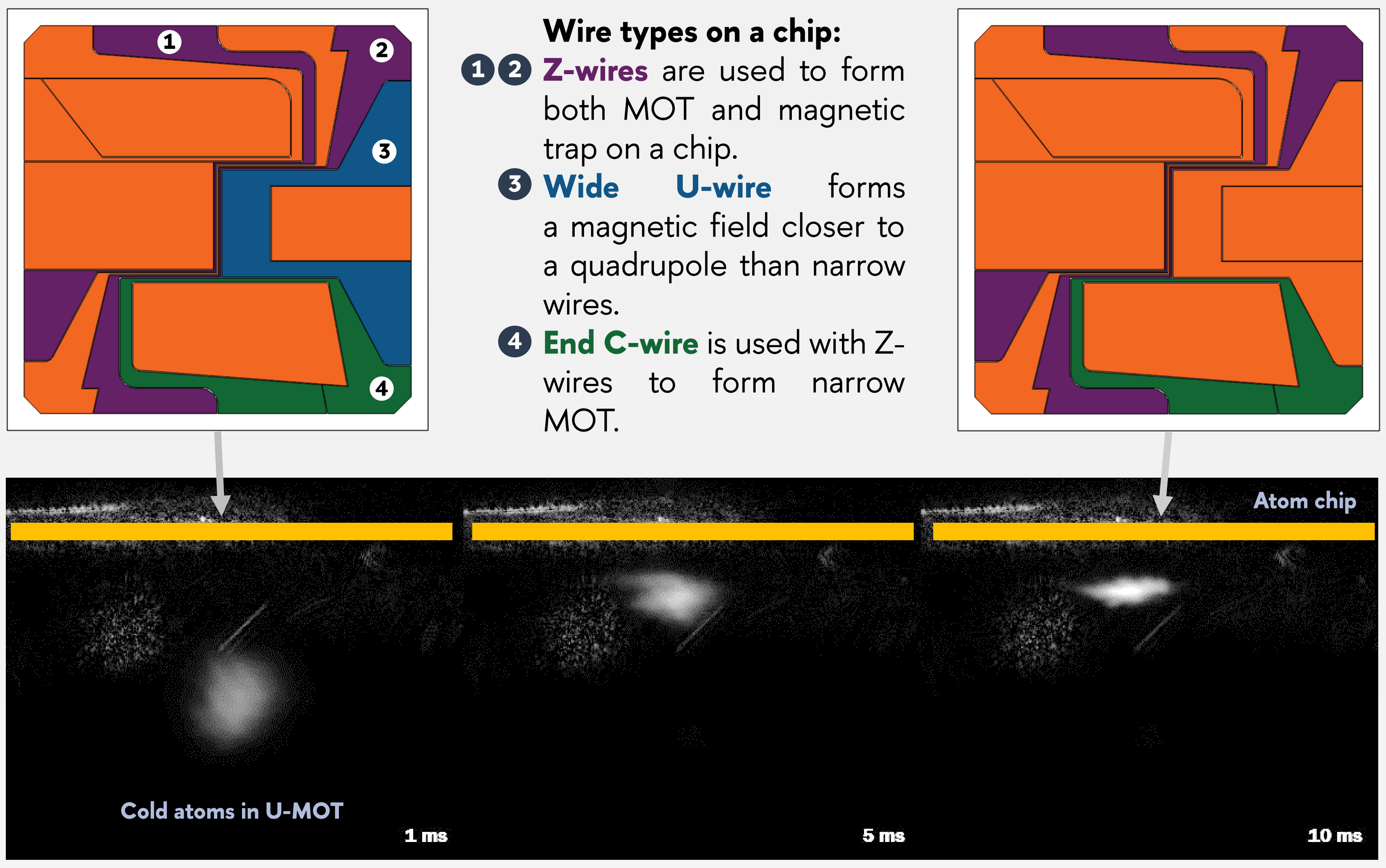
Fig. 3. The atom chip assembled on a vacuum flange.

We expect that focusing of an atomic beam will increase efficiency of loading single-layer atom chip with a small localization area [2].

On the other hand, it is possible to enlarge the trapping region of the chip. Fig. 3. demonstrates the modified version of an atom chip with an additional U-wire (see 3 on Fig. 5), which is wider, then wires in previous version.

According to numerical simulations, trap with such wide U-wire would capture 1.7 times more atoms than usual U-MOT on a chip.

Wide-wire U-MOT



Wire types on a chip:
①② **Z-wires** are used to form both MOT and magnetic trap on a chip.
③ **Wide U-wire** forms a magnetic field closer to a quadrupole than narrow wires.
④ **End C-wire** is used with Z-wires to form narrow MOT.

Fig. 5. Atom chip design with wide U-wire and experimental photos of trapped cold atoms in U-MOT on an atom chip.

On the first stage of experiment the wide U-MOT is formed with narrow Z- and C-wires and wide U-wire running simultaneously. Wide wire on our chip can carry 10 A current in continuous regime. When the MOT is fully loaded, the wide U-wire is turned off. The total chip current is significantly reduced, so the position of the minimum of the magnetic field is shifted closer to the chip surface. The cloud of cold atoms moved to a new position in about 10 ms and compressed. The resulting atomic ensemble is then used to load a magnetic trap on a chip formed only by Z-wires.

References

[1] A. E. Afanasiev, D. V. Bykova, P. I. Skakunenko and V. I. Balykin, JETP Lett. 115, 509–517 (2022).
[2] A. E. Afanasiev, A. S. Kalmykov, R. V. Kirtaev, A. A. Kortel, P. I. Skakunenko, D. V. Negrov and V. I. Balykin, Opt. Laser Technol. 148, 107698 (2022).
[3] Jin Woo Jun, Soo Chang, Taeg Yong Kwon, Ho Seong Lee, and V. G. Minogin, Phys. Rev. A 60, 3960 (1999).

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