(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 4 618 108 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
17.09.2025 Bulletin 2025/38

(21) Application number: **24382260.8**

(22) Date of filing: **11.03.2024**

(51) International Patent Classification (IPC):
G21K 1/00 *(2006.01)*

(52) Cooperative Patent Classification (CPC):
G21K 1/006

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
GE KH MA MD TN

(71) Applicant: **Lace Lithography AS**
5007 Bergen (NO)

(72) Inventors:
- **Sidhu, Adrian Parveet James**
  08002 Barcelona (ES)
- **Salvador Palau, Adrià**
  08005 Barcelona (ES)

(74) Representative: **LIGL IP Consult AS**
Apotekergata 10
0180 Oslo (NO)

(54) PARTICLE BEAM VELOCITY SHAPER AND METHOD FOR SHAPING THE VELOCITY OF A PARTICLE BEAM

(57) 1. A particle beam velocity shaper (1) and a method for shaping the velocity of an incoming particle beam (b) with a beam direction (z), wherein particle beam velocity shaper (1)comprises;
- a magnetic field generator (30) arranged to provide a magnetic field (B) in the beam direction (z),
- one or more electromagnetic radiation sources (20a, 20b,...) configured to generate two or more beams of coherent light (21a, 21b,...), wherein the beams of coherent light (21a, 21b,...) coincide at least partly with the particle beam (b).

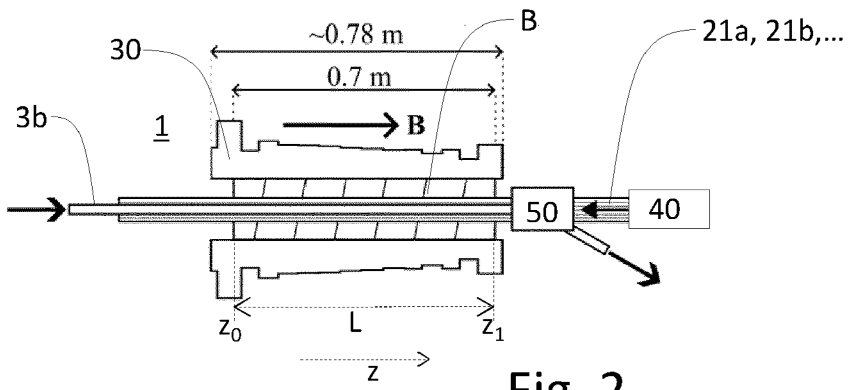

Fig. 2

Processed by Luminess, 75001 PARIS (FR)

Description

TECHNICAL FIELD

[0001] The present invention relates to the field of particle beam velocity shapers, and more specifically to the field of modifying the velocity profile of particle beams, such as atomic or molecular beams.

BACKGROUND

[0002] Atomic beam velocities can be manipulated by lasers via momentum transfer from the laser photons to the individual atoms in the beam. This type of laser manipulation is termed Doppler cooling when used to slow and cool the atoms. This phenomena is characterized by the dissipative force or radiation pressure force, given by

$$\vec{F}_{\text{diss}} = \frac{\hbar\vec{k}\Gamma}{2}\frac{s_0}{1 + s_0 + \left(\frac{2\Delta}{\Gamma}\right)^2}.$$

[0003] The ultimate operational objective in using lasers to manipulate atomic velocities is to ensure the laser photons are on resonance with some two-level transition in the atom. This is done by ensuring that the effective detuning $\Delta = 0$ in the denominator to maximize the dissipative force. In prior art Zeeman slowers this is achieved by applying a magnetic field. Further, the prior art Zeeman slowers use a laser with a fixed frequency, red-detuned to the resonance frequency of the atomic transition to account for the Doppler shift, to capture and slow all atoms with a velocity below a capture velocity.

[0004] Phillips, William D. and Harold J. Metcalf. "Laser Deceleration of an Atomic Beam." Physical Review Letters 48 (1982): 596-599, OBSERVED deceleration OF NA ATOMS caused by absorption of counterpropagating resonant laser light.

[0005] EP1871149A1 discloses a Zeeman slower with a coil for creating a magnetic field in the longitudinal direction, where the coil has an increasing inner diameter along the longitudinal axis.

[0006] Zeeman slowers with spin-flip magnetic arrangements are also known where the magnetic field changes direction in the longitudinal direction. This requires optical pumping of the atom beam into opposite spin states along the slower.

[0007] One of the problems with prior art Zeeman slowers, is that the efficiency is low, i.e., the intensity of the output beam is low compared to the intensity of the input beam. Further, the Zeeman slowers are quite long, which means that the internal beam losses increases and that the devices may be more difficult to align and handle in a system setup.

SHORT SUMMARY

[0008] A goal of the present invention is to disclose a method and a system solving the problems related to prior art.

[0009] Some of the advantages that may be obtained by the invention are listed below.

[0010] In particular the invention is efficient, in that a large fraction of the incoming particles are captured and participate in the produced particle beam.

[0011] The length of the beam velocity shaper device can be reduced compared to the prior art Zeeman slower.

[0012] The complexity of the magnetic field generator may be reduced, since there may be no need for spin-flip of the magnetic field.

[0013] The intensity of the particle beam at the output of the beam velocity shaper device may be increased due to less internal losses and a higher capture rate.

[0014] The output particle beam has several distinct and well-defined wavelengths.

[0015] A large part of the particles in the output beam will have a high velocity while still having a very well-defined velocity distribution.

[0016] The latter two items may be beneficial for some applications, e.g., applications making use of particle diffraction.

[0017] The invention solving the above-mentioned problems is a particle beam velocity shaper and a method for shaping particle beams according to the independent claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018]

Fig. 1 illustrates a cross section of a prior art spin-flip Zeeman slower where the left-hand circularly (LHC) polarized light induces σ^+ transitions, until the magnetic field becomes negative, wherein it induces σ^- transitions. Note that in this design for the prior art Zeeman slower, an optical pumping region between the positive and negative magnetic fields has not been included, which would result in an even longer slower chamber. The inner coil/chamber diameter is 8 cm, and the coils are typically made of copper wire. Other types of magnets are also used.

Fig. 2 illustrates an embodiment of the particle beam velocity shaper 1 according to the invention with multiple beams of coherent light (21a,21b, ...), in this case red-shifted lasers that are left-hand circularly (LHC) polarized to induce σ^+ transitions throughout the chamber where the magnetic field is always positive w.r.t. the beam propagation direction. The inner coil/chamber diameter is 8 cm and the coils of the magnetic field generator 30 are typically made of copper wire. The beam velocity shaper device of Fig. 2 is to scale with the prior art slower in Fig. 1.

Fig. 3a illustrates an embodiment of a laser input mechanism (50) where a laser deflector 51 is used to deflect the particle beam b, and hence the beams of coherent light (21a, 21b,...) can enter on-axis with the particle beam b.

Fig. 3b illustrates more details of an embodiment of the beam input system (40) used in Fig. 2. The purpose of the beam input system is here to provide a beam comprising four time multiplexed beams of coherent light (21a, 21b,...) with different frequencies. A nanosecond laser 20a with a wavelength of 1083 nm sends pulses on the order of 98 ns / 4 ~ 25 ns (since there are 4 detunings in this case) The 25 ns pulse is then split into four different pulses using beam splitters (42). Three of the pulses are sent through delay lines (43) of increasing length. The delay is 98 ns * (3/4) ~75 ns delay. The upper pulse is not delayed. The first delay line, for the second pulse, delays the pulse by Δt = 25 ns, the second delay line for the third pulse delays the third pulse by 2*Δt = 50 ns, and the third delay line delays the fourth pulse by 3*Δt = 75 ns. Since delay lines typically reflect laser beams between mirrors, the delay lines are here represented with an increasing number of reflected laser beams. Each pulse, including the first, non-delayed pulse is sent through a respective modulator 44 to detune it, and then all four beamlines are coupled into a beam coupler (44), such as an optical fibre coupler. The output of the beam coupler ensures that all four pulses are sent down the same beamline, and into the laser input mechanism (50) as illustrated in Fig. 3a.

Fig. 4 illustrates the magnetic field produced by a series of coils wrapped around the main chamber cylinder with a diameter of 8 cm for the beam velocity shaper device in Fig. 2. The top figure shows in a graph the target field (solid line, calculated with the Zeeman slower theory) and the optimized field (dashed line, produced by coils and calculated with the Biot-Savart law). The bottom figure shows a cross section of the top half of a particle beam velocity shaper with the coil configuration where each step represents a separate coil with radial thickness given by coil radius and z-axis depth given by the step length. The solid line is the top boundary of the cylindrical chamber. The current density of the coils is $J = 10^6$ A/m^2 , meaning this setup requires active cooling, e.g. water cooling, which the diameter of 8 cm accounts for.

Fig. 5 illustrates examples of four velocity profiles of different detunings within the same chamber and same magnetic field profile. The upper plot in each graph is the velocity profile with detuning Δ_L^B , the detuning the magnetic field is tuned to according to the Zeeman slower theory. In this example, to capture all atoms between 1300 m/s and 700 m/s, the chamber length must be L>1.9 m for the single-frequency case, while for the four-frequency case the chamber length must be L~0.59 m, a reduction in required length of almost 70%. The dotted vertical lines visualize the boundary conditions.

Fig. 6 is a numerical simulation of the four-frequency beam velocity shaper to the lower right in Fig. 5. The chamber length is set to L=0.587 m, according to the chamber length L determined analytically, as seen in Fig. 5. The output beam has four distinct monochromatic peaks.

Fig. 7a and 7b shows initial and final velocity distributions, respectively of the numerical simulation results seen in Fig. 6 for the four-frequency beam velocity shaper. The total number of particles is 1000.

Fig. 8a illustrates an incoming velocity distribution used for comparing the output velocity distribution of a prior art Zeeman slower in Fig. 8b and a particle beam velocity shaper in Fig. 8c and 8d. Please note that the conditions used here are different from the example with the results presented for Figs. 5 and 6 previously. Specifically, in this example we use a Gaussian beam where the intensity profile is Gaussian instead of just constant intensity, and we use a tapered magnetic field as opposed to the ideal magnetic field.. It can also be noted from this example that the prior art Zeeman slower is almost three times longer than the inventive beam velocity shaper under realistic conditions. While Fig. 8c illustrates the velocity distribution in the case where multiple laser beams are directed in the opposite direction of the particle beam, i.e. slowing the particles, Fig. 8d illustrates the velocity distribution where multiple laser beams are directed in the direction of the particle beam, i.e., speeding up the particles, and Fig. 8e shows longitudinal particle velocities vs. longitudinal particle distance at each simulation for the speeding example. The vertical line is the end of the magnetic field.

EMBODIMENTS OF THE INVENTION

[0019] In the following description, various examples and embodiments of the invention are set forth in order to provide the skilled person with a more thorough understanding of the invention. The specific details described in the context of the various embodiments and with reference to the attached drawings are not intended to be construed as limitations. Rather, the scope of the invention is defined in the appended claims.

[0020] The embodiments described below are numbered. In addition, dependent embodiments defined in relation to the numbered embodiments are described. Unless otherwise specified, any embodiment that can be combined with one or more numbered embodiments may also be combined directly with any of the dependent embodiments of the numbered embodiment(s) referred to.

[0021] Chamber length and length of magnetic field L are used interchangeably in this document and should be seen as the active part of the beam velocity shaper in the beam direction z, i.e. the region where the magnetic field B is present and where photons may resonate with particles in the particle beam. As seen in the upper graph of Fig. 4 the actual, or optimized field does not match the target field exactly. For simplicity the chamber length and the target field have a length L. The active magnetic field is slightly longer than the length L. This means that even outside the target area, photons can still resonate with particles, but the effect is greatly reduced due to the inhomogeneity of the magnetic field.

[0022] In an independent embodiment ED1-1, the invention is a particle beam velocity shaper (1) for an incoming particle beam (b) with a beam direction (z), wherein particle beam velocity shaper (1)comprises;

- a magnetic field generator (30) arranged to provide a magnetic field (B) in the beam direction (z),
- one or more electromagnetic radiation sources (20a, 20b,...) configured to generate two or more beams of coherent light (21a, 21b,...), wherein the beams of coherent light (21a, 21b,...) coincide at least partly with the particle beam (b).

[0023] ED1-2. Particle beam velocity shaper (1) of claim ED1-1, wherein the beams of coherent light (21a, 21b,...) coincide at least partly with the particle beam (b) in any cross section of the particle beam (b) inside the magnetic field (B).

[0024] ED1-3. Particle beam velocity shaper (1) of ED1-1 or ED1-2, wherein the beams of coherent light (21a, 21b,...) have corresponding two or more wavelengths (λ1, λ2, ...) that are different from each other.

[0025] ED1-4. Particle beam velocity shaper (1) of any of ED1-1 to ED1-3, wherein the magnetic field (B) extends at least a length (L) in the beam direction (z), where the length (L) is the distance between an input and output of a target magnetic field (z0, z1).

[0026] ED1-5. Particle beam velocity shaper (1) of any of ED1-1 to ED1-4, wherein the magnetic field (b) is spatially varying in the beam direction (z).

[0027] ED1-6. Particle beam velocity shaper (1) of any of ED1-1 to ED1-5, wherein the two or more beams of coherent light (21a, 21b,...) are configured to transfer momentum to particles (p) with different velocities in the particle beam (b).

[0028] ED1-7. Particle beam velocity shaper (1) of any of ED1-1 to ED1-6, configured to induce transitions in the particles of the same type along the entire length L of the magnetic field. E.g. only σ+ or σ- transitions.

[0029] ED2-1. Particle beam velocity shaper (1) of ED1-4, wherein an exit velocity (vca) of a first beam of coherent light (21a) at the output of the magnetic field (z1) is equal to a input velocity (vcb) of a second beam (21b) of coherent light at the input of the magnetic field (z0).

[0030] ED2-2. Particle beam velocity shaper (1) of ED2-1, wherein vi+1(z=0) = vi(z1), where vi(z) is the i-th velocity profile of the i-th beam of coherent light of the two or more beams of coherent light (21a, 21b,...).

[0031] ED2-3. Particle beam velocity shaper (1) of ED2-1, wherein vi-1(z=0) = vi(z1), where vi(z) is the i-th velocity profile of the i-th beam of coherent light of the two or more beams of coherent light (21a, 21b,...).

[0032] The order of i in slowing is opposite to the order of i in speeding. So if one direction is chosen for i=0 to i= n, where n is the number of detunings, and i=0 is the largest velocity profile, ED2-3 could be used for speeding-up particles and ED2-2 could be applied for slowing particles.

[0033] ED3-1. Particle beam velocity shaper (1) of ED1-4, wherein each of the one or more beams of coherent light (21a, 21b,...) have corresponding velocity capture ranges (vcra, verb, ...), wherein each of the velocity ranges are defined as the difference between the capture velocity at the input of the magnetic field (z0) and the capture velocity at the output of the magnetic field (z1) for the respective beam of coherent light (21a, 21b,...). Please see Fig. 5 where an example of velocity capture ranges (vcra, verb, ...) for each of the beams of coherent light are illustrated.

[0034] ED3-2. Particle beam velocity shaper (1) of ED3-1, wherein a total velocity capture range (vcr) is defined as the difference between the highest capture velocity at the input of the magnetic field (z0) and the lowest capture velocity at the output of the magnetic field (z1). Please see Fig. 5 where an example of the total capacity velocity range has been illustrated.

[0035] ED3-3. Particle beam velocity shaper (1) of ED3-2, wherein all velocities of the total velocity capture range (vcr) exist within the velocity capture ranges (vera, verb, ...).

[0036] ED3-4. The particle beam monochromator of any of ED3-1 to ED3-3, wherein a majority of the particles of the velocity distribution falls within the total velocity capture range vcr.

[0037] ED4-1. Particle beam velocity shaper (1) of any of ED1-1 to ED3-3, wherein the magnetic field B decreases in the beam direction z and the polarization of the two or more beams of coherent light (21a, 21b,...) are LHC polar.

[0038] ED4-2. Particle beam velocity shaper (1) of any of ED4-1, wherein particle beam velocity shaper (1) is configured to induce σ+ transitions.

[0039] ED4-3. Particle beam velocity shaper (1) of any of ED1-1 to ED3-3, wherein the magnetic field B increases in the beam direction z and the polarization of the two or more beams of coherent light (21a, 21b,...) are RHC polar.

[0040] ED4-4. Particle beam velocity shaper (1) of ED4-3, wherein particle beam velocity shaper (1) is configured to induce σ- transitions.

[0041] ED5-1. Particle beam velocity shaper (1) of any of ED1-4 to ED4-4, wherein the particle beam at the output of the magnetic field (z1) has a velocity distribution vdo with two or more distinct output monochromatic peaks.

[0042] ED6-1. Particle beam velocity shaper (1) of any of ED1-1 to ED5-2, comprising three or more electromagnetic radiation sources (20a, 20b,...) configured to generate three or more beams of coherent light (21a, 21b,...).

[0043] ED6-2. Particle beam velocity shaper (1) of ED6-1, wherein the beams of coherent light (21a, 21b,...) have corresponding three or more wavelengths (λ1, λ2, ...) that are different from each other.

[0044] ED6-3. Particle beam velocity shaper (1) of ED6-2, wherein the at least three or more wavelengths (λ1, λ2, ...) are separated from each other in two equal steps in terms of wavelength at the input of the magnetic field (z0) and/or at the output of the magnetic field (z1).

[0045] ED7-1. Particle beam velocity shaper (1) of any of ED1-1 to ED6-3, wherein the electromagnetic radiation sources are lasers and the beams of coherent light (21a, 21b,...) are laser beams.

[0046] ED7-2. Particle beam velocity shaper (1) of any of ED1-1 to ED6-4, wherein the beams of coherent light (21a, 21b,...) are circularly polarized.

[0047] ED7-3. The beam velocity shaper of any of ED1-1 to ED7-2, wherein the direction of the beams of coherent light (21a, 21b,...) is opposite the beam direction (z).

[0048] In this case, each of the two or more beams will slow the particles over the length of the magnetic field.

[0049] ED7-4. The beam velocity shaper of any of ED1-1 to ED7-2, wherein the direction of the beams of coherent light (21a, 21b,...) is the same as the beam direction (z).

[0050] In this case, each of the two or more beams will speed up the particles over the length of the magnetic field.

[0051] ED8-1 Particle beam velocity shaper (1) of any of ED1-1 to ED7-2, comprising a beam input system (40) configured to feed the two or more beams of coherent light (21a, 21b,..) into the magnetic field (B).

[0052] ED8-2 Particle beam velocity shaper (1) of ED8-1, wherein the beam input system (40) is configured to pulse the two or more beams of coherent light (21a, 21b, ...) sequentially into the magnetic field (B).

[0053] ED8-3 Particle beam velocity shaper (1) of ED8-1 or ED8-2, wherein the beam input system comprises a modulator (41a, 41b,...) for each of the two or more beams of coherent light (21a, 21b,...), wherein the modulators are configured for detuning the two or more beams.

[0054] ED8-4 Particle beam velocity shaper (1) of any of ED8-1 to ED8-3, comprising a beam coupler (44) configured to multiplex the two or more beams into a multiplexed beam.

[0055] ED8-4 Particle beam velocity shaper (1) of ED8-3 or ED8-4, wherein a pulse time is equal to or smaller than the lifetime of the resonant transition of the particles in the particle beam divided by the number of beams of coherent light (21a, 21b,...).

[0056] ED8-5 Particle beam velocity shaper (1) of any of ED8-1 to ED-5, wherein the beam input system (40) does not block the particle beam (b).

[0057] ED8-6 Particle beam velocity shaper (1) of any of ED8-1 to ED8-5, comprising an input mechanism (50), comprising a laser deflector configured to deflect the particle beam (b). This will allow the multiplexed beam to be directly fed into the chamber of the beam velocity shaper (1).

[0058] In an independent embodiment EM1-1, the invention is a method for shaping the velocity of an incoming particle beam (b) with a beam direction (z), comprising;

- providing a magnetic field (B) in the beam direction (z),
- generate two or more beams of coherent light (21a, 21b,...), wherein the beams of coherent light (21a, 21b,...) coincide at least partly with the particle beam (b).

[0059] EM1-2 The method of EM1-1, comprising features of any of ED1-1 to ED8-5.

[0060] The velocity profiles, detunings, and chamber length necessary to capture atoms between velocities v_{start} and v_{end} with n different detunings are given in the following equations for slowing the particles.

[0061] The ith velocity profile (with i=1,2,...,n) associated with detuning Δi, together ensuring that Δ=0 throughout the chamber for the respective velocity range, is given by

$$v_i(z) = \frac{\Delta_L^B - \Delta_i + k_z^B v_B(z)}{k_i}$$

where Δ_L^B is the detuning the magnetic field is tailored to, $k_z^B = k_z + \Delta_L^B / c$ is the effective wavenumber associated to Δ_L^B, k_z is the wavenumber of the non-detuned laser (assuming the laser is perfectly parallel/ antiparallel to the z axis), $v_1(z) \equiv v_B(z)$ is the velocity profile associated with detuning $\Delta_L^B \rightarrow v_1(z) \equiv v_B(z) = \sqrt{v_c^2 - 2az}$ with v_c the capture velocity of the magnetic field (not the actual capture velocity), and $k_i = k_z + \Delta_i/c$ is the effective wavenumber associated to Δ_i. The above reduces to $v_B(z)$ when $i = 1$ since $\Delta_1 = \Delta_L^B$. Note that the parameters of the magnetic field are not physical, but rather numbers to define the ideal magnetic field profile. The detuning Δ_i is given by

$$\Delta_i = \frac{\Delta_L^B + k_z^B v_{start} - k_z v_i(0)}{1 + \frac{v_i(0)}{c}}$$

where $v_i(0) = v_{start} - (i - 1)\Delta v$ and $\Delta v = \frac{v_{start} - v_{end}}{n}$. Finally, the chamber length L is given by

$$L = \frac{2v_{start}\Delta v - \Delta v^2}{2a}$$

Where $a = (s_0/[1 + s_0]) \cdot a_{max}$, $s_0 = I/I_0$ is the on-resonance saturation parameter (effectively the laser intensity) and where I_0 is the saturation intensity of the transition and $a_{max} = \frac{\hbar k_z \Gamma}{2m}$ is the maximum possible acceleration resulting from the dissipative force. Γ is the lifetime of the two-level transition and m is the mass of the atom.

[0062] These equations can be found by using the boundary conditions $v_{j+1}(0) = v_j(L)$ for j=1,2,...,n-1, $v_1(0) = v_{start}$, and $v_n(L) = v_{end}$.

[0063] The following example is generally applicable to all atom beams and most molecular beams.

[0064] Consider a beam of metastable helium-4 (from now on simply helium) in metastable state 2^3S_1 with a mean longitudinal (atom beam axis/z axis) velocity of 1000 m/s and a full width at half maximum (FWHM) of 400 m/s, with the longitudinal velocity being Gaussian distributed. The slowing transition in metastable helium accessed by lasers is $2^3S_1 \rightarrow 2^3P_2$ with ΔJ=1. The transition wavelength is 1083 nm. In the presence of an applied magnetic field, the magnetic transition accessed is MJ=1→MJ=2 in the case of a σ+ slower, and MJ=-1→MJ=-2 in the case of a σ- slower. For a spin-flip Zeeman slower, which is the standard prior art slower used for metastable helium, the initial transition is M3=1→MJ=2 when the magnetic field is positive and MJ=-1→MJ=-2 when the magnetic field is negative. Note that $\mu' = (g_2 M_{J_2} - g_1 M_{J_1})\mu_B = \mu_B$ in the case of |J,MJ ⟩:|1,1⟩→|2,2⟩ and $2^3S_1 \rightarrow 2^3P_2$ (g1=2, g2=3/2), and in the case of |1,1⟩→|2,2⟩ this is negative.

[0065] Now comparing a prior art Zeeman slower with the beam velocity shaper. The aim in this example for the prior art Zeeman slower is to slow as many atoms as possible to 660 m/s, which with a capture velocity of 1340 m/s, should capture ≳ 95% of the atoms (two standard deviations of the original Gaussian distribution).

[0066] A Gaussian laser intensity profile and a tapered magnetic field profile have been applied to the simulations used to produce the results of this example. This means that the simulations mirror reality more closely, and that the efficiency of the beam velocity shaper is also decreased. Despite this, the beam velocity shaper still shows great advantages over the prior art Zeeman slower.

[0067] The parameters shared between both devices are:

- Frequency of the laser: 1083 nm corresponding to the $2^3S_1 \rightarrow 2^3P_2$ transition in helium-4, but as mentioned, this is easily generalisable. The absolute laser frequency does not matter, only the detuning (the offset of the laser frequency w.r.t. the $2^3S_1 \rightarrow 2^3P_2$ resonance frequency) and the |J,MJ⟩ values matter;
- Initial magnetic field: $B(z = 0) = 35$ mT ;
- Laser intensity: $s_0 = 3$ corresponding to an intensity of $I = 3I_0 = 3(\hbar c k^3 \Gamma / 12\pi) = 3(0.17\ \mathrm{mW/cm^2}) = 0.51\ \mathrm{mW/cm^2}$;
- Laser intensity distribution (intensity vs. space in the transverse plane): Gaussian;
- Laser intensity FWHM (of Gaussian): 5 cm;
- Laser transition linewidth: ~ 10.2 MHz.

[0068] The prior art Zeeman slower has the following parameters:

- Chamber length: L=2 m (theory suggests L=1.93 m for ideal case);
- Capture velocity: $v_c = 1340$ m/s;
- Laser detuning: ΔL=-748 MHz. This is the detuning which is required from the magnetic field $B(z) = B_0 + B_1\sqrt{1 - \frac{2az}{v_c^2}}$ with $B_0 = \frac{\hbar \Delta_L}{\Delta(g_j m_j)\mu_B}$, $B_1 = \frac{\hbar}{\Delta(g_j m_j)\mu_B}(k_z v_c + \frac{\Delta_L v_c}{c})$, if $B(z = 0) = 35$ mT and the capture velocity is set to $v_c = 1340$ m/s.

[0069] The beam velocity shaper device has the following parameters (note that the intensity between the beam velocity shaper and the prior art slower is constant, four detunings does not mean quadrupled intensities):

- Chamber length: L = 0.7 m (theory suggests L = 0.61m for ideal case);
- Capture velocities: vc = 1340 m/s, 1170 m/s, 1000 m/s, 830 m/s;
- Laser detunings (ordered w.r.t. capture velocities): ΔL = -748 MHz, -591 MHz, - 434 MHz, -277 MHz. Again the first detuning is the detuning required by the magnetic field profile B(z) with $B(z = 0) = 35$ mT and $v_c = 1340$ m. The rest of the detunings are determined from the theory above.

[0070] The results of the beam velocity shaper in Fig. 9, will now be compared to the results of the prior art Zeeman slower in Fig. 8, according to the parameters given above.

[0071] The number of particles which are collimated with the prior art Zeeman slower is hard to estimate, as the two relatively clear peaks are still surrounded by a large number of particles in velocity space. However, even when approximating the two peaks to be well defined, only $\sim \frac{450}{10000} = 4.5\%$ of the particles are slowed and have a well-defined velocity distribution. The full width at half maximum (FWHM) of the peak at -785 m/s is around 6 m/s. This width is determined by setting the bin number equal to the number of particles.

[0072] What is interesting to note is that the prior art Zeeman slower does not reach the end target velocity of 660 m/s. Given an initial magnetic field of B(z=0)=35 mT, a capture velocity of vc=1340 m/s, a detuning of Δ_L = -748 MHz and a chamber length of L=1.93 m, the ideal theoretical case gives ~660 m/s as a final velocity. Seeing as this chamber is larger by a few centimetres, this should be smaller. In fact, the peak predicted by theory can be seen a t -625 m/s. However, the largest peak at -785 m/s, is a result of atoms going off-resonance with the laser, due to a combination of their high longitudinal velocities and an increasingly sharper magnetic field gradient.

[0073] The beam velocity shaper case, despite the realistic constraints (a Gaussian beam and a tapered magnetic field), performs considerably better than the standard slower. Around $\sim \frac{7500}{10000} = 75\%$ of the beam is slowed into well-defined peaks. From left to right, the peaks have FWHMs of around 3 m/s, 3 m/s, and 1.5 m/s.

[0074] In the example above, the laser beams are counter propagating with regards to the particle beam (b). In this embodiment the particles will have a decreasing velocity through the through the chamber as seen e.g. in Fig. 5. However, in another embodiment the laser beams can be arranged in the direction of the particle beam. In this case the particles velocity will increase through the chamber and the curves in Fig. 5 would slope upwards instead of downwards. Fig. 8d illustrates the output velocity distribution for this case. The same peaks are present, but this time their longitudinal velocity has shifted upwards, with a shift corresponding to about two times the velocity capture range (vcra, verb,....) of one of the velocity profiles in the length L of the magnetic field B. The parameters are mostly identical to the counter propagating beam velocity shaper with the exception of:

- Capture velocity and detuning of magnetic field: 1500 m/s, -896 MHz (high capture velocity and magnetic field detuning to increase capture efficiency);
- Actual laser detunings: 1100 MHz, 1257 MHz, 1414 MHz, 1571 MHz, all blue detuned/ positively detuned. In this embodiment, the laser input mechanism 50 and the beam input system 40 would be arranged before the particle beam enters the chamber.

[0075] In the exemplary embodiments, various features and details are shown in combination. The fact that several features are described with respect to a particular example should not be construed as implying that those features by necessity have to be included together in all embodiments of the invention. Conversely, features that are described with reference to different embodiments should not be construed as mutually exclusive. As those with skill in the art will readily understand, embodiments that incorporate any subset of features described herein and that are not expressly interdependent have been contemplated by the inventor and are part of the intended disclosure. However, explicit description of all such embodiments would not contribute to the understanding of the principles of the invention, and consequently some permutations of features have been omitted for the sake of simplicity or brevity.

Claims

1. A particle beam velocity shaper (1) for an incoming particle beam (b) with a beam direction (z), wherein particle beam velocity shaper (1)comprises;

    - a magnetic field generator (30) arranged to provide a magnetic field (B) in the beam direction (z),
    - one or more electromagnetic radiation sources (20a, 20b,...) configured to generate two or more beams of coherent light (21a, 21b,...), wherein the beams of coherent light (21a, 21b,...) coincide at least partly with the particle beam (b).

2. The particle beam velocity shaper (1) of claim 1, wherein the beams of coherent light (21a, 21b,...) coincide at least partly with the particle beam (b) in any cross section of the particle beam (b) inside the magnetic field (B).

3. The particle beam velocity shaper (1) of claim 1 or 2, wherein the beams of coherent light (21a, 21b,...) have corresponding two or more wavelengths (λ1, λ2, ...) that are different from each other.

4. The particle beam velocity shaper (1) of any of claims 1 to 3, wherein the magnetic field (B) extends at least a length (L) in the beam direction (z), where the length (L) is the distance between an input and output of a target magnetic field (z0, z1).

5. The particle beam velocity shaper (1) of claim 4, wherein an exit velocity (vca) of a first beam of coherent light (21a) at the output of the magnetic field (z1) is equal to a input velocity (vcb) of a second beam (21b) of coherent light at the input of the magnetic field (z0).

6. The particle beam velocity shaper (1) of claim 5, wherein each of the one or more beams of coherent light (21a, 21b,...) have corresponding velocity capture ranges (vcra, verb, ...), wherein each of the velocity ranges are defined as the difference between the capture velocity at the input of the magnetic field (z0) and the capture velocity at the output of the magnetic field (z1) for the respective beam of coherent light (21a, 21b,...).

7. The particle beam velocity shaper (1) of claim 6, wherein a total velocity capture range (vcr) is defined as the difference between the highest capture velocity at the input of the magnetic field (z0) and the lowest capture velocity at the output of the magnetic field (z1).

8. The particle beam velocity shaper (1) of claim 7, wherein all velocities of the total velocity capture range (vcr) exist within the velocity capture ranges (vcra, verb, ...).

9. The particle beam monochromator of any of claim 6 to 8, wherein a majority of the particles of the velocity distribution falls within the total velocity capture range vcr.

10. The particle beam velocity shaper (1) of any of claim 6 to 9, wherein the magnetic field B decreases in the beam direction z and the polarization of the two or more beams of coherent light (21a, 21b,...) are LHC polar, or wherein the magnetic field B increases in the beam direction z and the polarization of the two or more beams of coherent light (21a, 21b,...) are RHC polar.

11. The particle beam velocity shaper (1) of claims 1 to 10, wherein the particle beam at the output of the magnetic field (z1) has a velocity distribution with two or more distinct output monochromatic peaks.

12. The particle beam velocity shaper (1) of any of claims 1 to 11, comprising three or more electromagnetic radiation sources (20a, 20b,...) configured to generate three or more beams of coherent light (21a, 21b,...), wherein the at least three wavelengths ($\lambda 1$, $\lambda 2$, ...) are separated from each other in two equal steps in terms of wavelength at the input of the magnetic field (z0) and/or at the output of the magnetic field (z1).

13. The particle beam velocity shaper of any of ED1-1 to ED7-2, wherein the direction of the beams of coherent light (21a, 21b,...) is opposite the beam direction (z), or wherein the direction of the beams of coherent light (21a, 21b,...) is the same as the beam direction (z).

14. A method for shaping an incoming particle beam (b) with a beam direction (z), comprising;

- providing a magnetic field (B) in the beam direction (z),
- generate two or more beams of coherent light (21a, 21b,...) and feed them into the magnetic field, wherein the beams of coherent light (21a, 21b,...) coincide at least partly with the particle beam (b).

15. The method of claim 14, comprising features of any of any of claims 1 to 13.

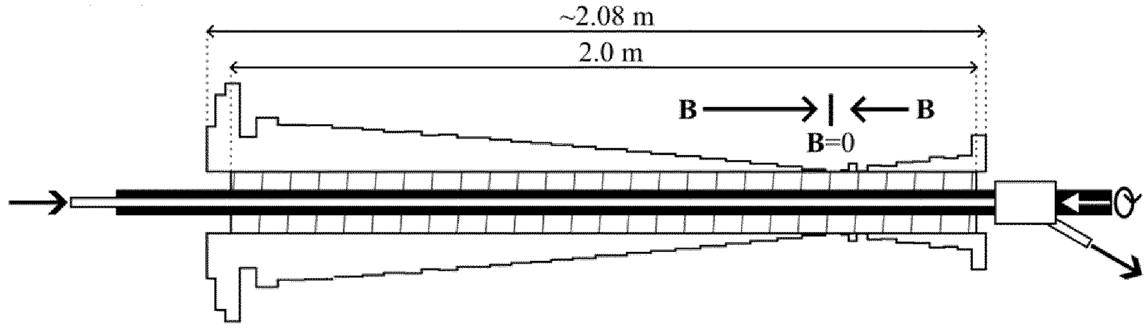

Fig. 1 (Prior art)

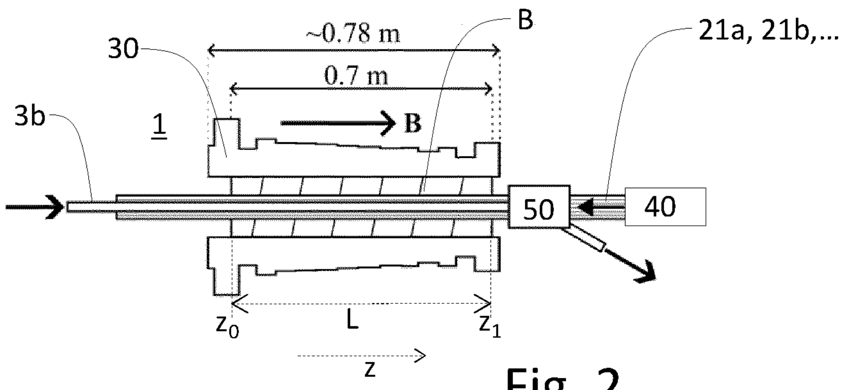

Fig. 2

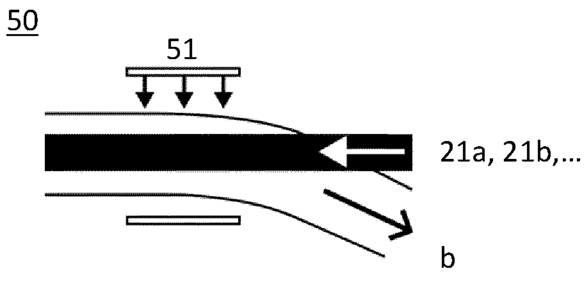

Fig. 3

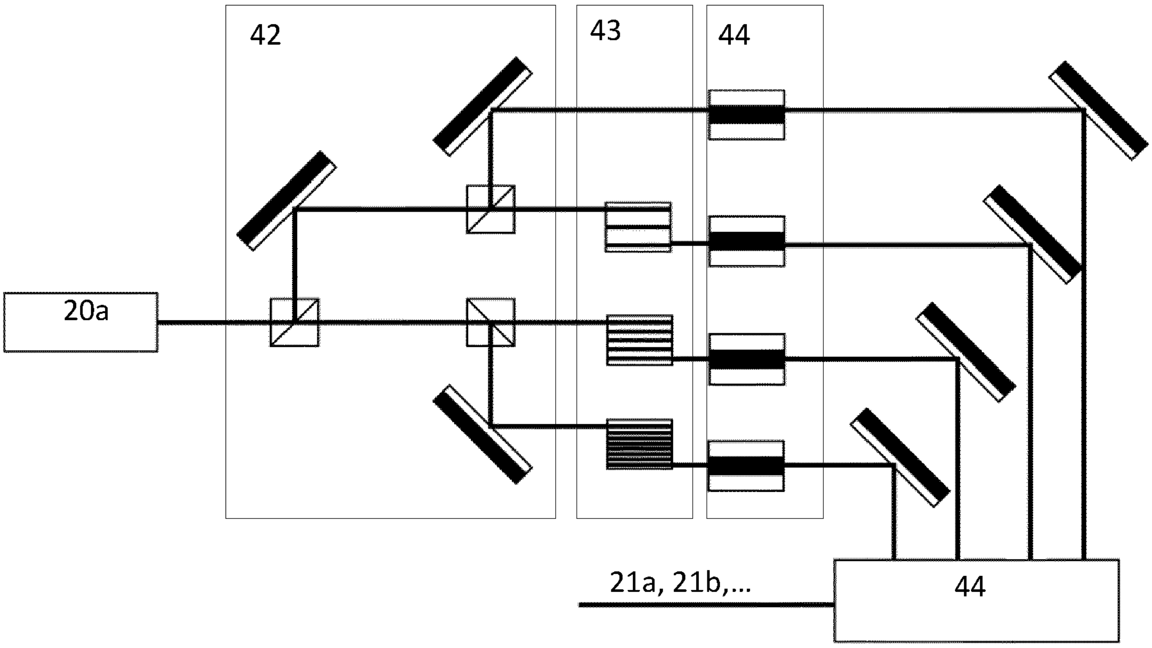
42
43
44
20a
21a, 21b,...
44

Fig. 3b

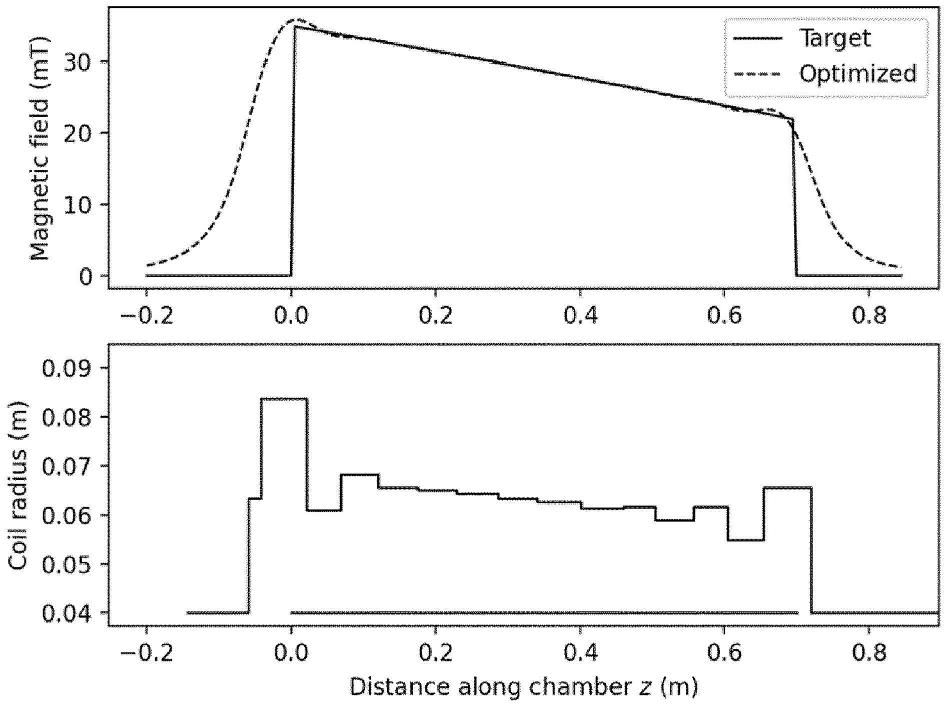
Target
Optimized
Magnetic field (mT)
0
10
20
30
−0.2
0.0
0.2
0.4
0.6
0.8
Coil radius (m)
0.04
0.05
0.06
0.07
0.08
0.09
Distance along chamber z (m)

Fig.4

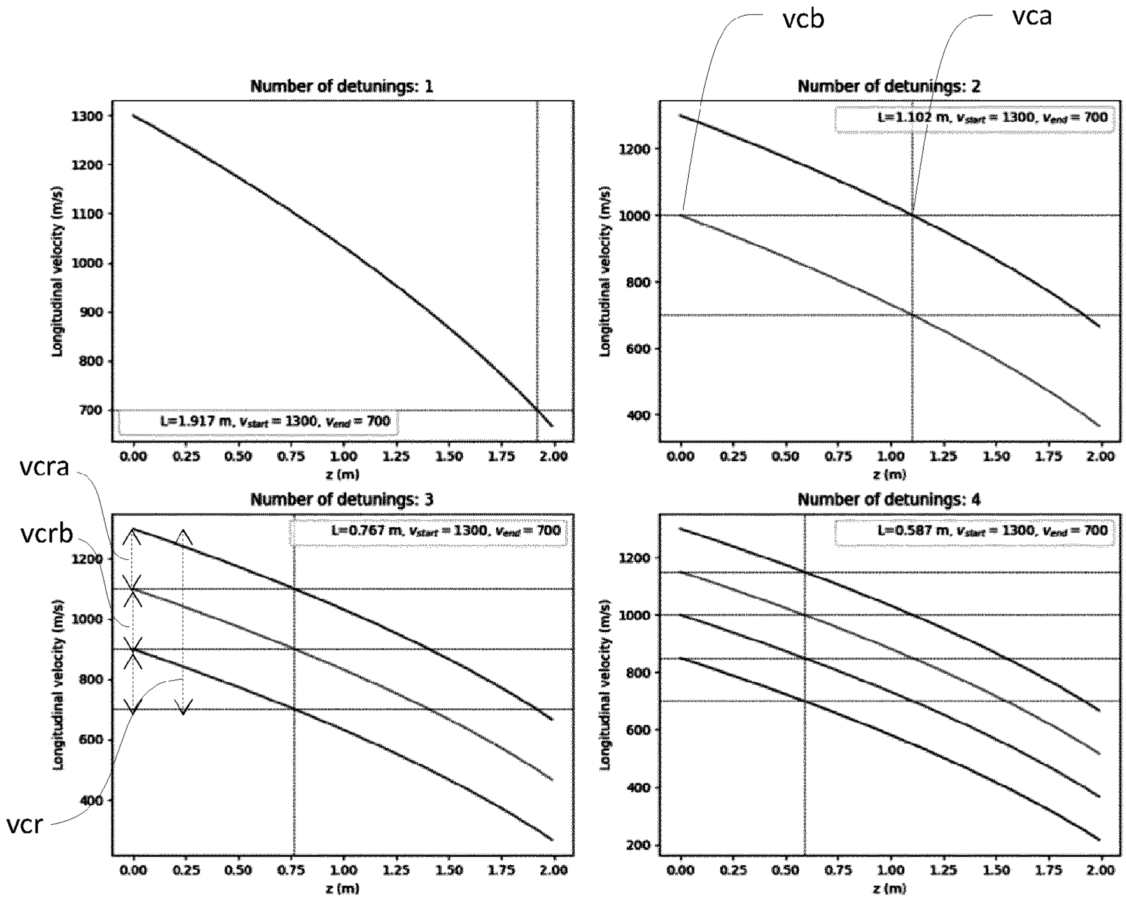
vcb
vca
Number of detunings: 1
L=1.917 m, v_{start} = 1300, v_{end} = 700
Number of detunings: 2
L=1.102 m, v_{start} = 1300, v_{end} = 700
Number of detunings: 3
L=0.767 m, v_{start} = 1300, v_{end} = 700
Number of detunings: 4
L=0.587 m, v_{start} = 1300, v_{end} = 700
vcra
vcrb
vcr
Longitudinal velocity (m/s)
z (m)

Fig. 5

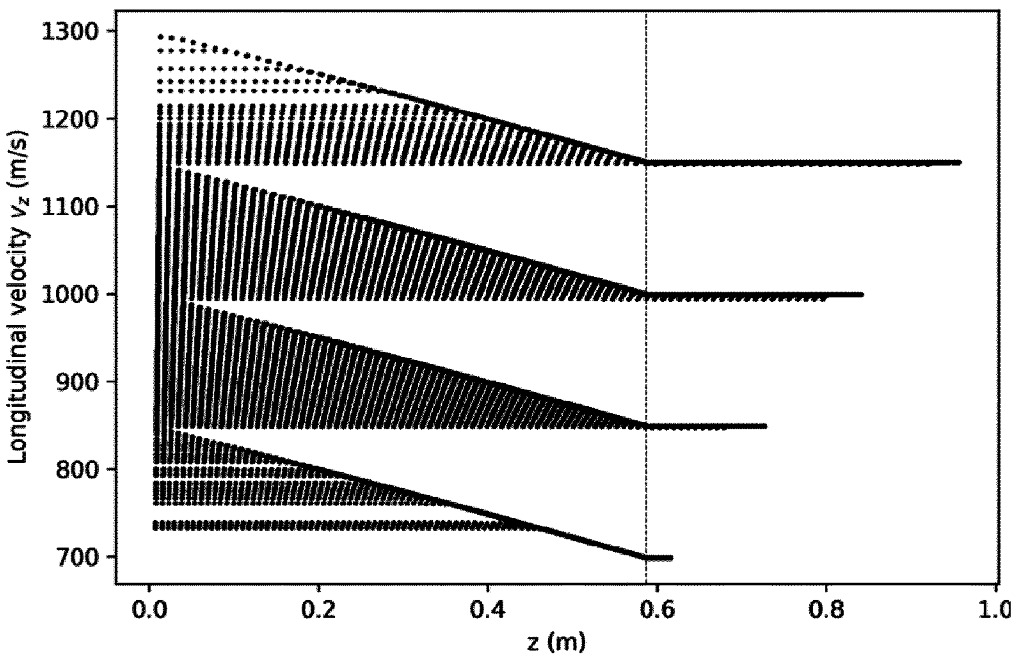
Longitudinal velocity v_z (m/s)
z (m)

Fig. 6

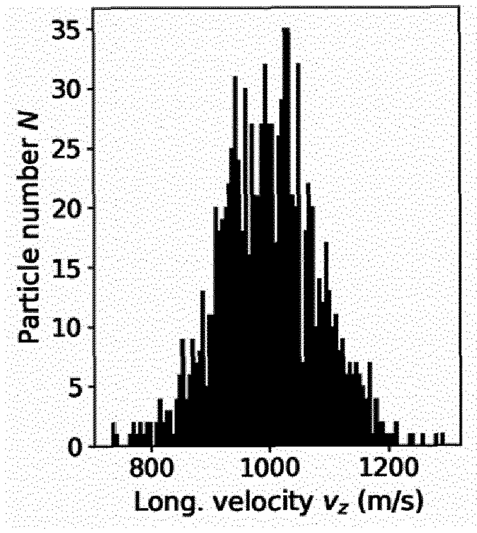

Fig. 7a

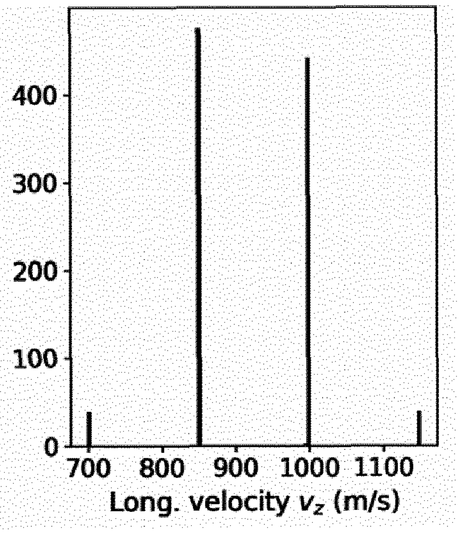

Fig. 7b

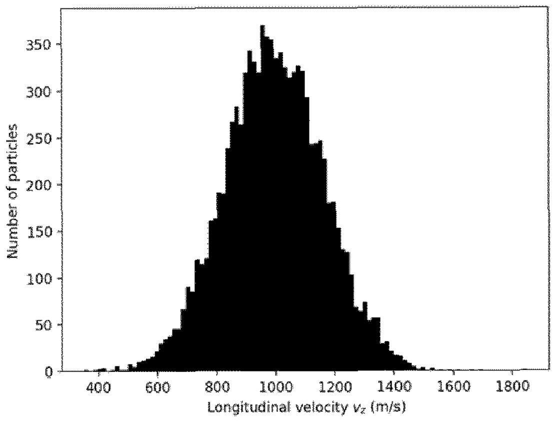

Fig. 8a

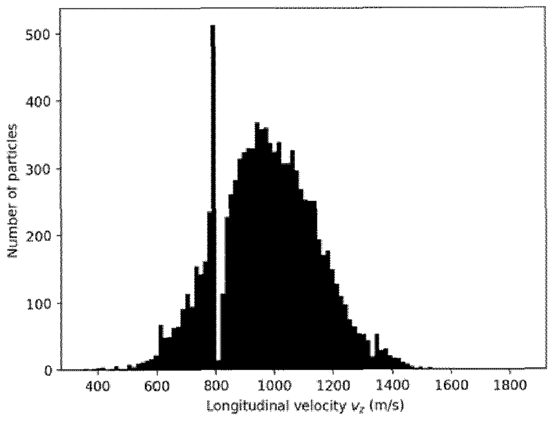

Fig. 8b

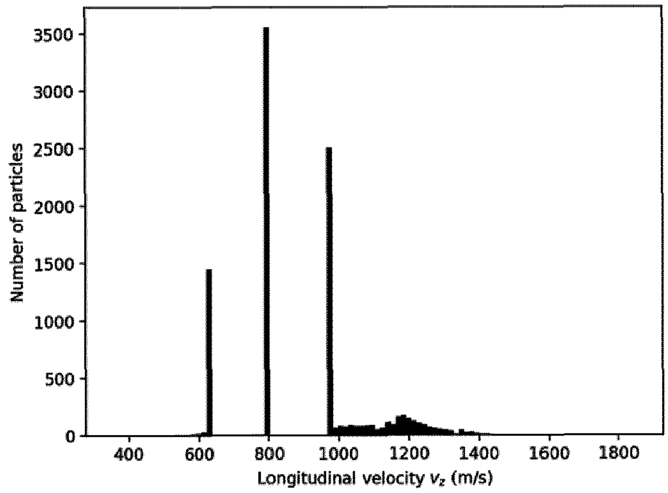

Fig. 8c

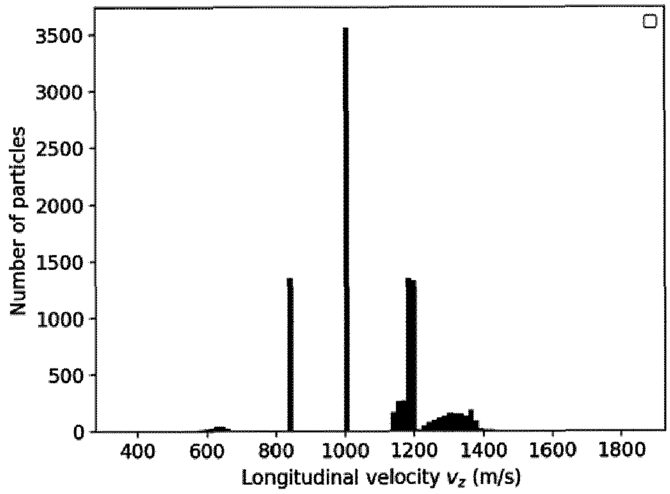

Fig. 8d

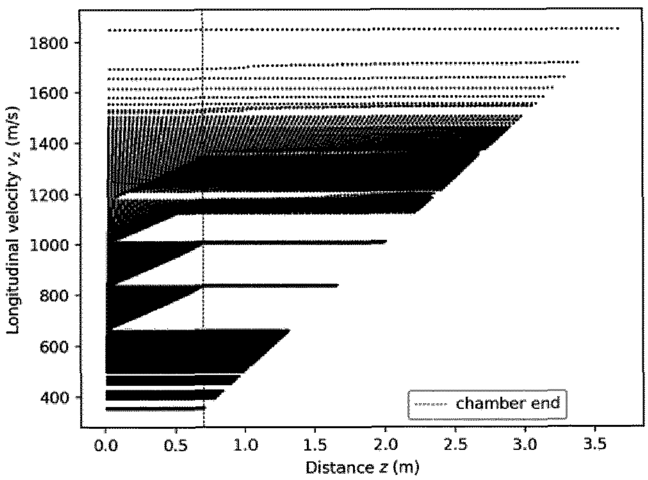

Fig. 8e

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 24 38 2260

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	RIDINGER A ET AL: "Large atom number dual-species magneto-optical trap for fermionic6Li and40K atoms", THE EUROPEAN PHYSICAL JOURNAL D, SPRINGER BERLIN HEIDELBERG, BERLIN/HEIDELBERG, vol. 65, no. 1, 27 April 2011 (2011-04-27), pages 223-242, XP036683006, ISSN: 1434-6060, DOI: 10.1140/EPJD/E2011-20069-4 [retrieved on 2011-04-27]	1-10,13, 14	INV. G21K1/00
A	* pages 226-228 *	11	

X	ALEJANDRO LEFRÁN TORRES MANUEL ET AL: "Proposal for Zeeman slowing of Rb2 molecules in a supersonic beam, inducing internal cooling", JOURNAL OF PHYSICS B, ATOMIC MOLECULAR AND OPTICAL PHYSICS, INSTITUTE OF PHYSICS PUBLISHING, BRISTOL, GB, vol. 56, no. 6, 6 March 2023 (2023-03-06), XP020445815, ISSN: 0953-4075, DOI: 10.1088/1361-6455/ACBDD6 [retrieved on 2023-03-06]	1-3, 5-10, 12-15	
A	* the whole document *	11	TECHNICAL FIELDS SEARCHED (IPC)
	-----		G21K
X	C-H FENG ET AL: "Compact and high flux strontium atom source", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 1 October 2023 (2023-10-01), XP091628018, * pages 1,7 *	1-9, 13-15	

1

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	4 September 2024	Giovanardi, Chiara

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- EP 1871149 A1 **[0005]**

Non-patent literature cited in the description

- **PHILLIPS, WILLIAM D.** ; **HAROLD J. METCALF.** Laser Deceleration of an Atomic Beam. *Physical Review Letters*, 1982, vol. 48, 596-599 **[0004]**