Atom lasers

MIT 1997

Yale 1998

NIST 1999

Munich 1999

FOMO summer school 2016
Florian Schreck, University of Amsterdam
Overview

What? Why?

Pulsed atom lasers

Experiments with atom lasers

Continuous atom lasers
What is an atom laser?

Laser

Light

Optical laser

Matter

Atom laser
LA\$SER$

Light Amplification by Stimulated Emission of Radiation

**Optical laser**

Stimulated emission

- ... photons
- Optical cavity
- Gain medium
- Pumping
- Optical outcoupler
- Optical Laser

**Atom laser**

Stimulated scattering

- ... atoms
- Atom cavity (trap)
- Pumping
- BEC
- Atom outcoupler

*Figure from [1] N.P. Robins, P.A. Altin, J.E. Debs, J.D. Close, Physics Reports 529, 265 (2013)*
## Atom laser vs. thermal beam

<table>
<thead>
<tr>
<th></th>
<th>Atom laser</th>
<th>Thermal beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial coherence</td>
<td>1 mode macroscopically occupied</td>
<td>many mode very weakly occupied</td>
</tr>
<tr>
<td>Longitudinal coherence</td>
<td>monochromatic = extremely small velocity spread</td>
<td>white = large velocity spread</td>
</tr>
<tr>
<td>Velocity</td>
<td>mm/s to cm/s</td>
<td>m/s to km/s</td>
</tr>
<tr>
<td>Correlation $g_2(0)$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Source area</td>
<td>1...100 μm diameter</td>
<td>0.1...10 mm diameter</td>
</tr>
<tr>
<td>Divergence</td>
<td>Heisenberg limited</td>
<td>typically several degrees</td>
</tr>
<tr>
<td>Flux</td>
<td>$10^5$ to $10^7$ atoms/s</td>
<td>Zeeman slowed: $10^{11}$ atoms/s</td>
</tr>
<tr>
<td>Brightness</td>
<td>$10^{24}$ atoms s$^{-2}$ m$^{-5}$</td>
<td>$10^{16}$ atoms s$^{-2}$ m$^{-5}$ (Rb 2D MOT)</td>
</tr>
</tbody>
</table>
Why atom lasers?

**Precision measurement**
- Atom interferometry
- Superradiant mHz-linewidth laser

**Studies of quantum mechanics**
- Dissipative driven systems
- Quantum turbulence

**Quantum technology**
- Conversion into chain of atoms
  → Quantum FIFO memory

**Technology**
- Cold e⁻ or ion sources
- Perpetual sympathetic cooling reservoir
- Lithography
Why atom lasers for interferometry?

Disadvantages compared to standard MOT based atom interferometers

• higher experimental complexity
• lower flux

Advantages

• Higher brightness: higher flux of usable atoms, e.g. atoms within flat region of Bragg beams
• Possibility of squeezing: trade atom-number stability for phase stability
• No Dick effect: if continuous atom laser used
The Dick effect

To measure quantity of interest with high precision, we need to average many measurements. Traditional atom interferometers work in pulsed mode.

Measure fluctuating quantity: Result

Dick effect

noise with same frequency as measurement repetition frequency is sampled incorrectly

Remedies

• alternate two measurement devices and average results
• measure continuously → use continuous atom laser
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Continuous atom lasers
State-of-the-art: pulsed atom laser

**Outcoupling mechanisms**
- radiofrequency outcoupling
- Raman outcoupling
- spilling from dipole trap
- outcoupling from lattice
Radiofrequency outcoupling

Starting point:
atoms in magnetic trap

First realization
Ketterle group, PRL 78, 582 (1997)

Outcoupling to non-magnetic state

short radiofrequency pulses
Magnetic field was unstable
→ short pulses used to broaden Fourier width
→ rf pulse addresses all atoms, irrespective of position in trap
→ each pulse creates “copy” of BEC in $m_F = 0$ state

Each copy falls and expands under influence of mean-field interactions

Figure from [1]
Continuous radiofrequency outcoupling

Very stable magnetic fields allow continuous outcoupling

I. Bloch, T.W. Hänsch, T. Esslinger, PRL 82, 3008 (1999)

Continuous radiofrequency has narrow Fourier width
→ outcoupling occurs at specific locations

Where?

Consider gravitational sagging:

Select outcoupling surface by rf frequency

surfaces of constant |B|
outcoupling surface

\[ m_F = 1 \quad \quad \quad \quad \quad \quad m_F = 2 \quad \quad \quad \quad m_F = 0 \]

magnetic potential

gravitational potential

total potential

BEC
Continuous radiofrequency outcoupling

Very stable magnetic fields allow continuous outcoupling

I. Bloch, T.W. Hänsch, T. Esslinger, PRL 82, 3008 (1999)

Figure from Bloch, Hänsch, Esslinger, Atom lasers and phase coherence of atomic Bose gases, RIKEN review 33 (2001)

solution of Schrödinger eqn. in linear potential = Airy function
Spatial mode

Mean-field influences expansion
→ spatial mode depends on outcoupling surface

Esslinger group, PRA 72, 063618 (2005)
Aspect group, PRL 96, 070404 (2006)
High-flux outcoupling


Uncoupled states

Rf dressed states
using strong rf

spilling

well-collimated

high-flux
$4 \times 10^7$ atoms/s
Raman outcoupling

Starting point:
- atoms in magnetic or dipole trap

Raman transition imparts momentum and changes internal state

First realization

Phillips group, Science 283, 5408 (1999)

Here: pulsed operation
(required by time-orbiting-potential magnetic trap)

20 kHz repetition rate: “quasi-continuous”
Radiofrequency vs. Raman outcoupling

Raman outcoupling imparts momentum to atom laser → less distortion of spatial mode by mean-field potential

<table>
<thead>
<tr>
<th>RF</th>
<th>Raman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial velocity: 0 cm/s</td>
<td>0.3 cm/s</td>
</tr>
</tbody>
</table>

Close group, PR A 77, 063618 (2008)
Outcoupling by spilling

Starting point:
atoms in dipole trap

Gradually reduce intensity of dipole trap beam

First realization
Weitz group, PRL 91, 240408 (2003)

Spilling from dipole trap

Rf outcoupling

No repulsive mean-field potential
→ better beam quality

Figures from [1]
Outcoupling from lattice


Interference of many Airy functions leads to atom laser pulses

(= Bloch oscillations in lattice with partial Bragg reflection)
Overview

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Pulsed atom lasers

Experiments with atom lasers

Continuous atom lasers
Experiments with atom lasers

Magnetic mirror & resonator

Guided atom lasers

Bragg mirrors and resonator

Coherence and correlations

\[ g^{(2)}(\tau) \]

\text{time } \tau \text{ (ms)}
Atom laser mirror and resonator

Esslinger group, PRL 87, 030401 (2001)

Raman briefly on
load atom laser into resonator
oscillations in resonator

Load resonator
Mirror

Raman always on
Guided atom lasers

Starting point: BEC in crossed beam dipole trap

Atom laser beam confined in vertical dipole trap → improved spatial beam profile
Atom laser beam splitter

Optically guided beam splitter

Guéry-Odelin group, PRL 109, 030403 (2012)

power laser $L_2$ / power laser $L_1$
Atom laser Bragg mirror

Lattice potential

propagation direction

propagating atom laser

Band structure

energy

quasimomentum

forbidden bands

→ no propagating matter wave at these energies

→ energy dependent mirror

Guéry-Odelin group, EPL 103, 50006 (2013)

no propagating matter wave at these energies
Atom laser Bragg mirror

Guéry-Odelin group, PRL 107, 230401 (2011)

(a) experiment

(b) theory

U₀/ER

x (mm)
Atom laser Bragg cavity

Guéry-Odelin group, EPL 103, 50006 (2013)
Procedure
1) Give atom laser velocity of 9.4mm/s using B-field gradient
2) Adiabatically ramp up resonator (in 0.1ms)
3) Let atom laser evolve
4) Image
Atom laser Bragg cavity

Guéry-Odelin group, EPL 103, 50006 (2013)

potential

propagation direction

Result

Bragg resonator

(a)

(b)

theory

experiment

$\alpha$

$\beta$

$D(x, t_{\text{prop}})$

$0$

$0.5$

$1$
Interfering two atom lasers

Outcoupling with two radiofrequencies

surfaces of constant $|B|$  

BEC, displaced by gravity

Esslinger group, Riken Review No. 33, 6 (2001)
Interfering two atom lasers

Interference of atom laser beams:

\[ n(z, t) \propto \frac{1}{\sqrt{|z|}} \left\{ 2 + 2V \cos \left(q\sqrt{|z|} + \frac{\Delta E t}{\hbar}\right) \right\} \]
Spatial coherence of source BEC

Choose distance between outcoupling surfaces by selecting rf frequencies.

Esslinger group, Riken Review No. 33, 6 (2001)
Temporal coherence of atom laser

Atom laser reflecting on mirror: in and outgoing wave packets interfere

Fringes would smear out if no temporal coherence → measure fringes to measure coherence
Fringes have spacing of 150nm → too small to be imaged

Perform spectroscopy
exploit variation in wavefunction overlap

Esslinger group, PRL 87, 16040 (2001)

Measurement procedure
1) Prepare atom laser in F=2, m_F=1
2) Reflect laser on magnetic mirror
3) Couple atoms to F=2, m_F=2 states with various turning points, determined by rf. Transfer probability given by overlap integral.
4) Separate m_F=1 and m_F=2 by letting them oscillate in their different potentials
5) Detect atoms, count m_F=1 and m_F=2

→ atom laser linewidth ~700 Hz
Spatial correlations

1D atomic beams with same density, but different spatial correlations:

- **Bunching**

- **uncorrelated**

- **Antibunching**

Correlations contain interesting information about quantum system. They can e.g. be used to distinguish different quantum phases.
Correlation function of atom laser

Esslinger group, PRL 95, 090404 (2005)

g^{(2)}(\tau) = \text{likelihood to detect a 2nd photon a time } \tau \text{ after having detected a 1st photon}
Correlation function of “thermal” beam

Use noisy radiofrequency for outcoupling to simulate thermal beam.
Overview

What? Why?

Experiments with atom lasers

Pulsed atom lasers

Continuous atom lasers
Cooling steps

Step 1: laser cooling

Step 2: evaporative cooling

Not easy to combine:

atom at standstill (BEC atom)

Laser cooling photons can heat up quantum gas
Perpetual BEC


Separate vacuum chamber in BEC production chamber and BEC storage chamber (“science chamber”)

Create BEC here

Store BEC here

Block MOT straylight by movable shutter

Transport and merging

Atom number in stored BEC

It should be possible to outcouple continuous atom laser (~10^5 atoms/s, phase jump when merging)
Atom laser with pumping mechanism

Creating continuous atom laser

State-of-the-art: **pulsed** atom laser

Vision: **time** → **space**: perpetual atom laser

Laser Cooling  
Evaporative Cooling  
Bose Einstein Condensation  
Outcoupling  
Depletion

Laser Cooling  
Evaporative Cooling  
Bose Einstein Condensation  
Outcoupling  
Depletion
Evaporative cooling of guided atoms

Guéry-Odelin group, PR A 72, 033411 (2005)
Evaporative cooling of guided atoms

Operating procedure
Every 100ms
- accumulate $10^9$ atoms in MOT
- push those atoms into magnetic guide

Reduce forward velocity by climbing hill
Let packets of atoms overlap to form beam

Perform evaporation while beam drifts along guide
detect atoms by fluorescence
determine
- flux
- forward velocity
- radial temperature

Phase-space density evolution
MOT: $10^{-5}$
start guide: $10^{-7}$
end guide: $10^{-6}$
Continuous loading of magnetic trap

Vogels group, PhD thesis Louise Kindt (2011)

Plan: add 8m quadrupole guide for evaporative cooling
Compact magnetic guide

Bend guide into the form of a spiral

Raithel group, arXiv:1202.0479
Continuous loading of magnetic trap


atoms accumulate in trap by elastic collisions

N = 4 x 10^7
T = 0.1 mK
PSD = 10^{-7}
High-flux source of guided atoms

Continuous loading of optical trap

Pfau group, PRL 106, 163002 (2011)

- Magnetic guide
- Optical guide
- Magnetic barrier
- Optical pumping

Only trapped atoms

$N = 2 \times 10^5$
$T = 0.2 \text{ mK}$
$PSD = 3 \times 10^{-6}$
Building a perpetual atom laser
Our new tricks

Strontium

Laser cooling on narrow transition

Transparency beam

Phase-space density = 0.1

BEC in thermal cloud
Narrow line cooling

hot blue MOT
T ~ 1 mK
PSD > 10^{-6}

blue MOT
461 nm
30 MHz

red MOT
689 nm
7.4 kHz

2 mm

cold red MOT
T ~ 1 µK
PSD ~ 0.1
Dipole trap

T ~ 1 µK
PSD ~ 0.1

laser cooling
Why not more?

Photons heat slowest atoms.

atom at standstill (BEC atom)

Let’s make atoms transparent!
Transparency beam

dipole trap

cooling laser

\[ ^1S_0 \rightarrow ^3S_1 \]

\[ ^3P_1 \rightarrow ^3P_J \]

cooling laser

potential

red MOT
689 nm
7.4 kHz

\[ ^1S_0 \rightarrow ^1S_J \]
Transparency beam

dipole trap

transparency beam

cooling laser

\[ ^3S_1 \]

\[ ^1S_0 \]

potential

transparency beam

cooling laser

red MOT

689 nm

7.4 kHz

\[ ^1P_1 \]

\[ ^3S_1 \]

transparency
Transparency beam

dipole trap

transparency beam

cooling laser

potential

transparency beam

\[ ^3P_1 \]

\[ ^1S_0 \]

cooling laser

\[ ^1P_1 \]

\[ ^3S_1 \]

\[ ^3P_J \]

red MOT
689 nm
7.4 kHz

without
with transparency beam
Laser cooling to BEC

- laser cooling alone removes entropy
- quantum gas in thermal cloud
Perpetual atom laser

Requirements:
1) Outcouple atom laser beam
2) Replenish reservoir

Potential landscape for perpetual atom laser:
Operation principle and design

Sr beam source
Zeeman slower

blue MOT
transfer tube
red MOT
atom laser in dipole trap guide
Building our perpetual atom laser

Spring 2015

Benjamin Pasquiou (Veni PI)
Chun-Chia Chen (PhD)
Shayne Bennetts (PhD)
Building our perpetual atom laser

Summer 2015
Building our perpetual atom laser

Winter 2015/16
Booting up our atom laser

Spring 2016
Booting up our atom laser

Spring 2016
Booting up the atom laser

- Atomic beam
- Blue MOT
- Zeeman slower
- Transfer tube
- Red MOT
- Atom laser in dipole trap guide
Atom transfer

blue MOT

atomic beam

transfer tube

red MOT
Zeeman slower on

blue MOT

atomic beam

probe beam

transfer tube

probe beam
Blue MOT on

atomic beam

probe beam

transfer tube

probe beam
Get colder

blue MOT

atomic beam

red molasses

probe beam

transfer tube

probe beam
Get slower

- blue MOT
- vertical molasses
- atomic beam
- red molasses
- probe beam
- transfer tube
- probe beam
Capture atoms

- blue MOT
- vertical blue molasses
- atomic beam
- red molasses
- transfer tube
- vertical slower and red MOT beams
Capture atoms

- blue MOT
- vertical blue molasses
- atomic beam
- red molasses
- transfer tube
- red MOT
- vertical slower and red MOT beams
**Perpetual red MOT**

- **blue MOT**
- **vertical blue molasses**
- **atomic beam**
- **red molasses**
- **transfer tube**
- **perpetual red MOT**
- **vertical slower and red MOT beams**

N = $10^9$ $^{88}$Sr
Flux = $10^8$ $^{88}$Sr/s
T = 50 µK
Perpetual narrow-line MOT

- **blue MOT**
- **vertical blue molasses**
- **atomic beam**
- **red molasses**
- **transfer tube**
- **red MOT**
- **vertical slower and red MOT beams**

**Parameters:**
- \( N = 10^7 \ ^{88}\text{Sr} \)
- \( T = 3 \ \mu\text{K} \)
- \( \text{flux} = 10^7 \ ^{88}\text{Sr}/\text{s} \)
- \( = 10^5 \ ^{84}\text{Sr}/\text{s} \)

(oven \( T = 410^\circ\text{C} \), design \( 540^\circ\text{C} \))
Time-sequential BEC

atomic beam

transfer tube

Time-sequentially created BEC

dipole trap

BEC lifetime without blue light: 7s
Stray-light protected BEC

Time-sequentially created BEC

BEC lifetime
- without blue light: 7s
- with blue light: 6s

Straylight protection works!
Towards perpetual BEC

blue MOT

atomic beam

red molasses

dipole trap

dimple beam
transparency beam

transfer tube

vertical blue molasses
Towards perpetual atom laser

- blue MOT
- vertical blue molasses
- atomic beam
- red molasses
- transfer tube
- dipole trap
- dimple beam
- transparency beam
- Raman (Bragg) outcoupled atom laser?
Towards perpetual atom laser

- blue MOT
- vertical blue molasses
- atomic beam
- red molasses
- transfer tube

Bessel beam guide + transparency beam
Why atom lasers?

**Precision measurement**
- Atom interferometry
- Superradiant mHz-linewidth laser

**Studies of quantum mechanics**
- Dissipative driven systems
- Quantum turbulence

**Quantum technology**
- Conversion into chain of atoms
  - Quantum FIFO memory

**Technology**
- Cold e\(^{-}\) or ion sources
- Perpetual sympathetic cooling reservoir
- Lithography
mHz-linewidth superradiant laser

**Normal clock laser:** frequency stability from length of cavity

**Superradiant clock laser:** frequency stability from ensemble spin of atoms

Need very longlived excited state to conserve spin orientation for long time.

→ Sr mHz-linewidth clock transition. Minutes lifetime.

How do we get sufficient flux of photons from such a long-lived state?
Phased antennas

Emission of $N$ antennas with random phase:

- Electric fields interfere randomly
- Total power is $N$ times power of one antenna
- Power scales with $N$

Emission of $N$ antennas with same phase, closer spaced than wavelength:

- Electric fields interfere constructively
- Electric field scales with $N$
- Total power scales with $N^2$
Superradiance

Consider emission of $N$ excited state atoms such that it cannot be known which atom emitted a photon

- e.g. all atoms within volume $\lambda^3$
- couple all atoms to same cavity mode

After one emission event, superposition state results of all combinations of one atom in ground state and all other in excited state

This is a Dicke state.
It will emit with higher probability into same mode as first photon.

Even stronger entanglement.
Even higher emission probability, just like for phased antennas.

A superradiant flash of light is the result.
Pulsed superradiant laser

Thompson group, arXiv:1603.05671

1.25 x 10^5
1.5 x 10^5
N = 2 x 10^5
1.25 x 10^5
10^5

Photon Output Rate $R$ (10^6 photons/s)

Intracavity Photons $M_c$

Time (ms)
mHz-linewidth laser

For continuous laser beam:
- overcome Doppler broadening by confinement in lattice (Lamb-Dicke regime)
- repump atoms to metastable state
- continuously cool atoms
- replenish lost atoms

Theory:
Why atom lasers?

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Quantum turbulence

sideview

atom laser sheet

barrier(s)

topview

Mach cones, vortices, ...

similar to Anderson group, arXiv:1303.4764
Quantum FIFO memory

- Create infinite row of individual atoms
- Store quantum information in atoms using cavity
- Retrieve quantum information later using second cavity

moving lattice with 2D BECs
row of individual atoms
select and blow out unwanted atoms
write cavity
read cavity
lattice in radial directions
→ Mott insulator transition
Sympathetic cooling

Goal: ultracold gas or quantum gas of atoms or molecules without laser cooling transition

Supersonic beam source → Stark or Zeeman decelerator → Magnetic trap stores cold atoms or molecules

Usages
- precision spectroscopy of target species
- ultracold chemistry
- Few- and many-body physics
Summary

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