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Doppler cooling reduces momentum spread of atoms only.

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→ Does not reduce spatial spread.
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Magneto-Optical Trap (MOT)

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Solution:
Spatially tune the laser-atom detuning with the Zeeman shift from a spatially varying magnetic field.

~10 G/cm
~14 MHz/cm
Magneto-Optical Trap

2-level atom

\[ |e\rangle \]

\[ |g\rangle \]

\[ \delta \]
Magneto-Optical Trap

2-level atom

magnetic gradient

| e ⟩

| g ⟩

δ

E

z

B
Magneto-Optical Trap

4-level atom

$|g\rangle \rightarrow \text{“F=0”}, \ |e\rangle \rightarrow \text{“F=1”}$

magnetic gradient

$\frac{\partial F}{\partial z} = 0$

$B$
Magneto-Optical Trap

4-level atom
|g⟩ → “F=0”, |e⟩ → “F=1”

magnetic gradient

E

|g⟩

|e⟩

m_f=+1

m_f=0

m_f=-1

z

B

m_f=0

m_f=0

m_f=0

m_f=0

m_f=0

m_f=0
4-level atom
$|g\rangle \rightarrow \text{“} F=0\text{”}, \ |e\rangle \rightarrow \text{“} F=1\text{”}$
magnetic gradient

Magneto-Optical Trap
4-level atom
$|g\rangle \rightarrow "F=0", \ |e\rangle \rightarrow "F=1"$

magnetic gradient

Magneto-Optical Trap
4-level atom
\( |g\rangle \rightarrow \text{"F=0"}, \ |e\rangle \rightarrow \text{"F=1"} \)

magnetic gradient

\( m_F = 0 \)

\( m_F = +1 \)

\( m_F = -1 \)

\( \sigma^+ \)

\( \sigma^- \)

Magneto-Optical Trap
Magneto-Optical Trap (MOT)
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$10^9 \, ^{87}\text{Rb atoms}$
**PROBLEM:** Accelerator produces only $10^6$ Fr atoms/s.

→ Very difficult to work with.

**SOLUTION:** Attach a Francium Magneto-Optical Trap to the accelerator.

→ Cold Francium is concentrated in $\sim 1 \text{ mm}^3$ volume.
→ With $T < 100 \mu \text{K}$, Doppler broadening is negligible.
→ Long integration times.
→ Minimally perturbative environment (substrate free).
**PROBLEM:** Accelerator produces only $10^6$ Fr atoms/s.

→ Very difficult to work with.

**SOLUTION:** Attach a Francium Magneto-Optical Trap to the accelerator.

→ Cold Francium is concentrated in ~1 mm$^3$ volume.
→ With $T < 100$ μK, Doppler broadening is negligible.
→ Long integration times.
→ Minimally perturbative environment (substrate free).

MOT collection efficiency ~ 1 %

MOT with ~$10^5$ $^{210}$Fr atoms
Figure A.2: Branching ratios for $^{87}$Rb. Multiply by the circled number in the left(right) column to get the branching ration for the D2(D1) line.