Ultracold electron source

extraction of electron bunches from an ultra-cold plasma

Collaboration “Accelerator Physics” group and “Quantum Gases” group
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Erice 2005
Ultradold waterbags...
Ultracold waterbags...

...red-hot potatoes?
Brightness limitations

☐ Nonlinear space charge forces

☐ Thermal emittance
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☑ Nonlinear space charge forces

☐ Thermal emittance
Transverse (5D) brightness:

\[ B_{\perp} = \frac{I_p}{(2\pi)^2 \varepsilon_{n,x} \varepsilon_{n,y}} \leq \frac{mc^2 J_p}{\pi kT} \]
collect **Rb atoms** from beam/vapor
- Laser cooling
- Magneto-Optical Trap (MOT)
- $N > 10^9$ atoms, $R = 1$ mm, $n = 10^{18}$ m$^{-3}$
- $T_{\text{atom}} < 0.001$ K

Erice 2005
Ultra-Cold Plasma (UCP)

- Laser cooling
- Magneto-Optical Trap (MOT)
- $N > 10^9$ atoms, $R = 1$ mm, $n = 10^{18}$ m$^{-3}$
- $T_{atom} < 0.001$ K

Ionize with pulsed laser ($\tau_{pulse} > 1$ ns)

$T_{electron} = 0.001$ K

$kT = 10^{-7}$ eV
Heating processes:

- **Correlation heating**: 
  \[ k_B T_e \approx \frac{e^2}{4\pi \varepsilon_0 n^{-1/3}} \]  
  timescale \[ \omega_p^{-1} = \sqrt{\frac{m\varepsilon_0}{ne^2}} \]  
  \[ n \leq 10^{18} \text{ m}^{-3} \implies T_e = 0.001 \text{ K} \sim 10 \text{ K in } \sim 100 \text{ ps} \]

- **Ponderomotive heating** by ionization laser pulse:
  \[ k_B T_e \approx \frac{e^2 E_{opt}^2}{4m\omega^2} \]
  \[ \frac{1 \text{ mJ}}{(1 \text{ mm}^2) \cdot (10 \text{ ns})} \implies T_e \approx 0.001 \text{ K} \]

- **Electron - neutral atom** scattering:
  Very small cross section \( T_e < 0.001 \text{ K} \)
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- **Electron - neutral atom** scattering:

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Magneto-Optical Trap (MOT)
3 October 2005:
Our first trapped sample of ultracold Rb gas
3 October 2005:
Our first trapped sample of ultracold Rb gas

window

Rb cloud (780 nm fluorescence)
Extraction of bunches

(I) MOT beams

(II) Excitation pulse

(III) Ionization pulse

(IV) Acceleration

Velocity bunching!
Waterbag recipe:

- Start with a **flat ellipsoid** can be ‘cut out’ with 2 intersecting laser beams;
- **pancake** ‘half-sphere’ laser intensity profile;
- **cigar** *parabolic* laser intensity profile;
- **automatic evolution into** 3D, uniform ellipsoid.
2 initial bunch geometries:

**Pancake** geometry: cutting out a thin transverse slice

![Pancake Geometry Diagram]

\[ Q = 10 \text{ pC} \]
\[ R = 2 \text{ mm} \]
\[ L = 15 \text{ m} \]
\[ T = 10 \text{ K} \]

**Cigar** geometry: cutting out a longitudinal needle

![Cigar Geometry Diagram]

\[ Q = 1 \text{ pC} \]
\[ R = 80 \text{ m} \]
\[ L = 1 \text{ mm} \]
\[ T = 10 \text{ K} \]
Acceleration geometry

 Vyuga et al., TU/e
Claessens et al., accepted for publication in PRL
## Beam parameters

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<th>pancake</th>
<th>cigar</th>
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<td>25 A</td>
<td>35 A</td>
</tr>
<tr>
<td>Emittance</td>
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B_{\perp} (A\cdot m^{-2}\cdot rad^{-2})

\sigma_E (eV)

carbon nanotubes

needle cathode

RF photogun

XFEL

pulsed
Thermal limit 10 K UCP cigar: $B_\perp > 10^{17}$ A·m$^{-2}$·rad$^{-2}$
Experimental realization
Technology challenge:
multi-100 kV voltage pulse with (sub-)ns risetime

Method:

• 30 kV DC power supply with commercial 10 ns solid state switch;
• ‘ferrite-sharpening’ technology _ 30 kV with sub-ns risetime;
• broadband transmission line transformer _ 200 kV with sub-ns risetime.
Under construction: 7X broadband transmission line transformer
The ultimate beam recipe...

Ionize **Bose-Einstein Condensate** _no correlation heating_

\[ T_{\text{electron}} = 0.001 \text{ K} \]

thermal De Broglie wavelength of electrons

\[ \lambda_{th} = \frac{h}{\langle p \rangle} = \frac{h}{\sqrt{2\pi mkT}} = 2 \mu m \]

larger than distance between electrons \( n^{-1/3} \leq 1 \mu m \)
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**Fermi degenerate electron beam!**