The LBNL setup for high brightness electron beams characterization and photocathode testing

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The LBNL High repetition rate VHF gun is a unique source of high brightness & high flux electron beams.

**X-FEL R&D (2010-2016)**

- X-rays
- The VHF gun at SLAC (2016-today)

**MeV-UED R&D (2014-today)**

- HiRES
- Not accessible
- GHZ-RF UED
- pulse length at sample (fs)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>186 MHz</td>
</tr>
<tr>
<td>Operation mode</td>
<td>CW</td>
</tr>
<tr>
<td>Gap voltage</td>
<td>750 kV</td>
</tr>
<tr>
<td>Field at the cathode</td>
<td>20 MV/m</td>
</tr>
<tr>
<td>RF Power</td>
<td>100 kW</td>
</tr>
<tr>
<td>Peak surface field</td>
<td>24.1 MV/m</td>
</tr>
<tr>
<td>Peak wall power density</td>
<td>25.0 W/cm²</td>
</tr>
<tr>
<td>Diameter/Length</td>
<td>69.4/35.0 cm</td>
</tr>
<tr>
<td>base pressure</td>
<td>~3 x 10⁻¹¹ Torr</td>
</tr>
</tbody>
</table>

**World-wide interest:**
- X-FEL @ DESY
- INFN-Mi, Italy (MARIX)
- Shanghai-Tech (Hard X-ray FEL facility)

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Working on the next generation CW-NCRF gun

### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>APEX</th>
<th>APEX-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [MHz]</td>
<td>186.7 (1300/7)</td>
<td>162.5 (1300/8)</td>
</tr>
<tr>
<td>Mode of operation</td>
<td>CW</td>
<td>CW</td>
</tr>
<tr>
<td>Number of cells</td>
<td>1</td>
<td>1 or 2</td>
</tr>
<tr>
<td>Peak power density [W/cm²]</td>
<td>22</td>
<td>&lt; 35</td>
</tr>
<tr>
<td>Max power/cell [kW]</td>
<td>100</td>
<td>&lt; 130</td>
</tr>
<tr>
<td>Launching field at photocathode [MV/m]</td>
<td>20</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>Beam energy [MV]</td>
<td>0.75</td>
<td>&gt; 1.5</td>
</tr>
</tbody>
</table>

APEX-like injector simulations:
A New tool for Ultrafast science with Atomic Resolution: High Repetition Rate Electron Scattering beamline

Electron beam energy: 700-900 keV
Repetition rate: 1-10^6 Hz
Temporal resolution: 250 fs-1000 ps
Electrons per pulse: 1-10^8
Relative energy spread: 10^-3 - 10^-4

Static diffraction patterns after beamline commissioning show high quality.

APEX beamline: Transverse and longitudinal beam characterization

HiRES beamline: Ultrafast Electron Scattering

single-Xtal gold

Bi-Xtal gold

Monolayer Graphene

Uncompressed LPS

Compressed LPS
Vacuum Load Lock system on the VHF gun

Adapted version of the INFN/PITZ/FLASH load-lock system

Vacuum “suitcase” compatible with airplane transportation (NEG pump)

transport from INFN-LASA to LBNL

Cs$_2$Te cathode

After shipping October 10, 2012

QE~13%
Photo-cathodes for APEX

PEA Semiconductor: Cesium Telluride Cs$_2$Te (In collaboration with INFN-LASA)
- $\sim$ps pulse capability
- relatively robust and un-reactive (operates at $\sim 10^{-9}$ Torr)
- successfully tested in NC RF and SRF guns
- high QE > 1%
- photo-emits in the UV ($\sim$260 nm) (4$^{\text{th}}$ harm. conversion from IR)
- for 1 MHz repreate, 1 nC, $\sim$ tents of W 1060nm required

First 3 cathodes successfully developed at INFN/LASA and delivered to LBNL.

PEA Semiconductor: Alkali Antimonides CsK$_2$Sb, (developed at LBNL)
- $\sim$ps pulse capability
- reactive; requires $\sim 10^{-10}$ Torr pressure
- high QE > 1%
- requires green/blue light (eg. 2$^{\text{nd}}$ harm. Nd:YVO4 = 532nm)
- for nC, 1 MHz repreate, $\sim$ few W of IR required

Cathodes under development at LBNL (H. Padmore’s group).
Promising lifetime and intrinsic emittance results (Cornell and LBNL).
Transfer chamber from preparation chamber to VHF gun in fabrication.
Oxygen contamination

Electron sputtering of cathode surface decreases the QE

“Rejuvenation” after long shutdowns:

CsK₂Sb Cathodes Demonstrated High QE in the Gun

CsK₂Sb cathodes (by Padmore’s group) have been used in the gun for over 3 years. The last cathode has been in the gun since June 2017 and we are now measuring QE=\(4 \times 10^{-4}\) at 515nm.

- **QE ~ 6% at 515 nm** (**\(\sim 6\%\) in the preparation chamber)**

- **Pixel size ~ 6.5 \(\mu\)m**

- **Laser position [pixels]**
  - **x-laser=700**
  - **y-laser=450**

- **Charge [pC]**
  - **QE (x-laser=700)**
  - **QE (y-laser=450)**

- **Laser pulse energy [nJ]**

- **Charge vs Laser pulse energy**

- **Central slice emittance vs beam charge**

- **100% slice over 100% laser rms**
  - 0.64 +/- 0.05 um/mm

- **95% slice over 95% laser rms**
  - 0.55 +/- 0.05 um/mm
Recipe:
1. Generate electron beams with picometer-range emittance
2. Nano-focusing of relativistic beams
3. Measurement and control of nano-beams
1- Generation and measurement of sub-nm emittance - first stage

TEM grid used to measure the beam emittance through the aperture

\[ \epsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \]

Pitch size = 340um

Emittance X = 3e-9 m
After second collimation large magnification is required to measure the beam phase space:

**PMQ triplet**

400 nm waist size with 600 pm emittance

**Single Quad flexure**

**Quad alignment <5 µm**

Alignment was carried out with Pulsed-wire technique

**Flip coils were used to measure**

The integrated field gradient

132 T/m
Nano-UED setup-large magnifications

- Targets with nanometer precision manufactured with Focused Ion Beam techniques.
- Used as Calibration in nano-scanning and imaging
- Poly-Au on SiN windows for measuring nano-beams

Knife-edge with 10 nm precision

- Calibration target for point-projection-imaging resolution analysis

FIB used to cut calibration Sample to obtain spatial resolution in nanobeam imaging spanning 1000-10 nm
The document discusses the direct characterization of nanometer-scale beam sizes using a knife edge scanning technique followed by 4D phase space reconstruction.

**Example of measurement:**
850 nm RMS

**Data Analysis**

1. Extract parameters at the detector (fit)
2. Back-mapping for initial guess
3. Global fit for beam evolution

**Mathematical Formulation:**

\[
 f(x, y) = \int_{-\infty}^{\infty} e^{-\frac{1}{2}y^2} \Theta(y - x_e - Ly')dy'dx'
\]

\[
 e^{-2 \left(\frac{y^2}{2\theta^2} + \frac{2xy}{\theta^2} + \frac{y'^2}{\theta^2}\right)} \left(1 + \text{erf} \left(\frac{P4 \cdot x + P5 \cdot y + P6}{\sqrt{2}}\right)\right)
\]

**FIB manufactured square windows:**
10 x 10 um

F. Ji, P. Musumeci, J. Navarro
Beam behavior around the waist #1: ~ round beam

\[ \epsilon_{n4D} = 0.0144 \text{ nm}^2 \text{ rad}^2 \]
Beam behavior around the waist: flat beam

\[ \epsilon_{n4D} = 0.0086 \, \text{nm}^2 \, \text{rad}^2 \]
Ultrafast Point Projection imaging

- Move the sample away from the waist -> projection imaging
- Typical Magnification: 145
- Typical Resolution 500 nm in consistent with the beam size analysis

Magnification = 145.3 ± 0.9
σ_{psf} (nm) = 527.7 ± 5.07
σ_{psf} (nm) = 408.9 ± 10.6

USAF-like target for e-beams
• APEX gun is a CW-RF electron gun, and has a load lock system!
  o Multiple cathodes can be tested (priority level given by the degree of relevance with the program)

• The two beamlines give access at multiple tools for beam characterization