High intensity and low emittance gun

Paolo Michelato
INFN Milano - LASA
High brightness low emittance sources

- Many applications ask for high brightness
  \[ B \approx 10^{15} \text{ A/m}^2 \]
  - Energy Recovery Linac - ERL
    - High beam current (mean)
    - CW operation
    - Low emittance
  - FEL
    - Pulsed
      - Short, single pulse/long RF pulse, for multibunch
    - High peak current
    - Extreme low emittance (\( \approx 1 \text{ mm}\cdot\text{mrad} \) or less)
Normal Conducting RF GUN
(photocathode embedded in the RF cavity)

- “Low Frequency” RF gun with semiconductor cathode
  - LANL (433 MHz), LANL/AES (700 MHz), VHF (144 MHz)
- L-band with semiconductor cathode ($\text{Cs}_2\text{Te}$):
  - FLASH, PITZ, FNAL
- S-Band: BNL/UCLA/SLAC like, metal cathode
  - LCLS, SPARC, FERMI, and many others
- S-band with semiconductor cathode
  - KEK
The Boeing Gun: Still the Demonstrated State-of-the Art

Material Courtesy David Dowell and John Adamski

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
The Boeing Gun: Still the Demonstrated State-of-the Art

<table>
<thead>
<tr>
<th>Gun Type</th>
<th>NCRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector and ERL</td>
<td></td>
</tr>
<tr>
<td>RF Frequency (MHz)</td>
<td>433</td>
</tr>
<tr>
<td>PRF (MHz)</td>
<td>27</td>
</tr>
<tr>
<td>Charge/Bunch (nC)</td>
<td>4.75</td>
</tr>
<tr>
<td>Current (mA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>32 (132 Peak)</td>
</tr>
<tr>
<td>Injector Energy (MeV)</td>
<td>5</td>
</tr>
<tr>
<td>Transverse RMS Normalized Emittance</td>
<td>~ 7</td>
</tr>
<tr>
<td>Longitudinal RMS Emittance (keV-psec)</td>
<td></td>
</tr>
<tr>
<td>RMS Bunch Length (psec)</td>
<td></td>
</tr>
<tr>
<td>RMS Energy Spread (%)</td>
<td>~ 3</td>
</tr>
<tr>
<td>ERLP Energy (MeV)</td>
<td>N/A</td>
</tr>
<tr>
<td>ERL Energy Goal (MeV)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Electron Gun**

| DC Gun Voltage (kV)   | N/A    |
| Gun Accelerating Field (MV/m) | CsKsB |
| Cathode Material      |        |
| Drive Laser FWHM Pulse Length (psec) | 53   |
| Laser Wavelength (nm) | 527    |
| Laser Power at 5% QE (W) |        |

**Booster Accelerator**

| Type                  | N/A    |
| Geometry (Cavities x Cells) | 1 x 1.5 + 1 x 3 |
| Couplers per Cavity / Type | 2 / WG  |
| Coupler Power (kW)       |        |

**Status**

Retired

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
LANL-AES RF Gun Concept

High-Power RF Injector Performance
- 2.5 Cell Photoinjector Linac, 700 MHz, 7 MV/m, 2.7 MeV
- Following 4 Cell Booster Linac, 4.5 MV/m, 5.5 MeV
- 3.0 nC per bunch
  100 mA CW @ 33.3 MHz; 1.05 A CW @ 350 MHz
- 7 micron transverse, 200 keV-psec longitudinal rms normalized emittance, < 1% energy spread

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

© H. Bluemm
© A. Todd
# LANL-AES RF Gun Concept

![Diagram of 2.5 Cell Injector & Solenoids Showing Magnetic & Electric Fields](image)

## Gun Type

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector and ERL</td>
<td></td>
</tr>
<tr>
<td>• RF Frequency (MHz)</td>
<td>700</td>
</tr>
<tr>
<td>• PRF (MHz)</td>
<td>33.3 (350)</td>
</tr>
<tr>
<td>• Charge/Bunch (nC)</td>
<td>3.0</td>
</tr>
<tr>
<td>• Current (mA)</td>
<td>100 (1050)</td>
</tr>
<tr>
<td>• Injector Energy (MeV)</td>
<td>2.5</td>
</tr>
<tr>
<td>• Transverse RMS Normalized Emittance</td>
<td>6</td>
</tr>
<tr>
<td>Longitudinal RMS Emittance (keV-psec)</td>
<td>145</td>
</tr>
<tr>
<td>RMS Bunch Length (psec)</td>
<td></td>
</tr>
<tr>
<td>RMS Energy Spread (%)</td>
<td>0.5</td>
</tr>
<tr>
<td>ERLP Energy (MeV)</td>
<td>N/A</td>
</tr>
<tr>
<td>ERL Energy Goal (MeV)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

## Electron Gun

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Gun Voltage (kV)</td>
<td>N/A</td>
</tr>
<tr>
<td>Gun Accelerating Field (MV/m)</td>
<td>7 / 7 / 5</td>
</tr>
<tr>
<td>Cathode Material</td>
<td>Multi-Alkali</td>
</tr>
<tr>
<td>Drive Laser FWHM Pulse Length (psec)</td>
<td>18</td>
</tr>
<tr>
<td>Laser Wavelength (nm)</td>
<td>527</td>
</tr>
<tr>
<td>Laser Power at 5% QE (W)</td>
<td>5 (53)</td>
</tr>
</tbody>
</table>

## Booster Accelerator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>N/A</td>
</tr>
<tr>
<td>Geometry (Cavities x Cells)</td>
<td>1 x 2.5</td>
</tr>
<tr>
<td>Couplers per Cavity / Type</td>
<td>2 / WG</td>
</tr>
<tr>
<td>Coupler Power (kW)</td>
<td>500</td>
</tr>
</tbody>
</table>

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Photoinjector

- Laser driven RF gun
- L-band 1.3 GHz
- RF power 3.5 MW
- Pulsed 5 or 10 Hz
- RF pulse length 100 to 900 μs

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Pulse Trains

- 2 Pulse pickers, based on Pockels cells + polarizer → up to 1 MHz
- Pre-amplification (diodes) of 1.2 ms long train
- Power amplification with variable bunch pattern

After amplification (1 MHz)

Electron beam pulse train (30 bunches, 1 MHz)

Output of the laser oscillator (27 MHz)

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Laser System

- Nd:YLF based laser
- produces long pulse trains of up to 800 μs with up to 1 MHz
- laser system average power in the Watt range
- long trains require high QE cathodes ($\rightarrow$ Cs$_2$Te)
Laser System Overview

Diode-pumped Nd:YLF Oscillator

- Modulators (AOM EOM AOM)
  - 108 MHz
  - 1.3 GHz
  - 13.5 MHz
- Piezo tuning of cavity length
- Stabilized by quartz tubes
- Fiber-coupled pump diodes
- \( E_{\text{pulse}} = 6 \mu J \)

Faraday isolator
Pulse picker
Pockels cell
Remote controlled mirror box

Flashlamp pumped Nd:YLF amplifiers
- Fast current control
- Pulse picker
- Faraday isolator
- Relay imaging telescopes
- Fast current control
- \( E_{\text{pulse}} < 0.3 \text{ mJ} \)

LBO BBO IR \( \rightarrow \) UV
- \( E_{\text{pulse}} < 50 \mu J \)
- Remote controlled attenuator
- Double pulse generator

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy S. Schreiber, DESY
Laser System Overview

Diode-pumped Nd:YLF Oscillator

- Modulators (AOM EOM AOM)
  - 108 MHz
  - 1.3 GHz
  - 13.5 MHz

- Piezo tuning of cavity length
- Stabilized by quartz tubes
- Fiber-coupled pump diodes

- $f_{\text{round trip}} = 27 \text{ MHz}$

Diode pumped Nd:YLF amplifiers

- $E_{\text{pulse}} = 0.3 \mu\text{J}$
- Faraday isolator
- Pulse picker Pockels cell

Flashlamp pumped Nd:YLF amplifiers

- Fast current control
- Pulse picker
- Faraday isolator

- Relay imaging telescopes

- $E_{\text{pulse}} < 0.3 \text{ mJ}$

LBO BBO

IR $\rightarrow$ UV

- $E_{\text{pulse}} < 50 \mu\text{J}$

Remote controlled attenuator

Double pulse generator

Remote controlled mirror box

Imaging to the cathode

Beam shutter

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy S. Schreiber, DESY
Laser System Overview

Diode-pumped Nd:YLF Oscillator
- Modulators (AOM EOM AOM)
  - 108 MHz, 1.3 GHz, 13.5 MHz
- Piezo tuning of cavity length
- Stabilized by quartz tubes
- f_{round trip} = 27 MHz
- Fiber-coupled pump diodes
- E_{pulse} = 0.3 µJ
- Faraday isolator
- Pulse picker Pockels cell

Diode pumped Nd:YLF
- E_{pulse} < 0.3 mJ

Flashlamp pumped Nd:YLF amplifiers
- Fast current control
- E_{pulse} < 50 µJ

Remote controlled mirror box
- Imaging to the cathode
- Beam shutter
- Double pulse generator

Relay imaging telescopes
- Fast current control

LBO BBO
IR → UV

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Laser System Overview

Diode-pumped Nd:YLF Oscillator

- Modulators (AOM EOM AOM) 108 MHz 1.3 GHz 13.5 MHz
- Piezo tuning of cavity length
- f_{round trip} = 27 MHz
- Stabilized by quartz tubes
- Fiber-coupled pump diodes
- E_{pulse} = 6 µJ

Faraday isolator
Pulse picker
Pockels cell
Remote controlled mirror box
Imaging to the cathode
Beam shutter
Double pulse generator
Remote controlled attenuator
LBO BBO
IR → UV
E_{pulse} < 0.3 mJ
E_{pulse} < 50 µJ

Flashlam Nd:YLF amplifiers
Relay image telescope
E_{pulse} < 0.3 mJ

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy S. Schreiber, DESY
RF-Gun Phase Stability

- RF Gun has no probes $\rightarrow$ vector sum of forward and reflected power
- IlrF system based on FPGA, p-control and adaptive feedforward, latency 150 ns
- RF gun phase stability: 0.1 deg (rms) @ 1.3 GHz
  - peak-to-peak stability: 0.4 deg, measured with beam at small phases

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Continuous measurements of the emittance during a period of ~1.5 hours (1 nC, 127 MeV)

In this example, the projected normalized 90% rms emittance is 1.6 mm mrad

Jitter 2 - 3 % (rms)

→ jitter agrees with the statistical error

lasering slice emittance in the undulator estimated to be 1 to 1.5 mm mrad
The PITZ collaboration

- DESY, Zeuthen and Hamburg
- BESSY, Berlin
- CCLRC, Daresbury
- INFN – LASA, Milano
- INFN – LNF, Frascati
- INR, Troitsk
- INRNE, Sofia
- LAL Orsay
- MBI, Berlin
- TU, Darmstadt
- Uni, Hamburg
- YERPHI, Yerevan

PITZ: Photo Injector Test Facility in DESY Zeuthen
PITZ layout (until August 2007)

This setup was used for the measurements in 2006 / 2007:

- momentum + momentum spread
- transverse projected emittance
- dark current

High energy part

- EMSY
- WS
- streak

- Booster Section

Low energy part

- Gun Section
- Cs₂Te cathode
- Bucking Coil
- Main Solenoid
- 1.5 cells

High energy part:

- booster

Low energy part:

- gun + solenoids

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy F. Stephan, DESY PITZ
Photo cathode laser properties

- **Longitudinal profile:**
  
  FWHM = 20.22 ps; r1 = 6.58 ps; r2 = 6.67 ps; FTmod = 6.52%
  
  ![Graph showing intensity vs. time](image)

<table>
<thead>
<tr>
<th>FWHM [ps]</th>
<th>rise/fall [ps]</th>
<th>RMS [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>July '07</td>
<td>~20</td>
<td>~0.35</td>
</tr>
</tbody>
</table>

- **Energy stability:**

  \[
  \langle \text{RMS}_i \rangle = 2.0 \%
  \]

  \[
  \text{RMS(\text{mean}_i)} = 1.3 \%
  \]

- **Transverse profile:**

  \[
  \sigma_{x,y} : 0.05 \rightarrow 0.6 \text{ mm}
  \]

  ![Graph showing transverse profile](image)

  RMS = 7.5%

- **Pointing stability:**

  \[
  \langle \text{RMS}_x \rangle = 0.033 \text{ mm}
  \]

  \[
  \langle \text{RMS}_y \rangle = 0.032 \text{ mm}
  \]

  ![Graph showing pointing stability](image)

  Hybrid Detector: Quadrant diode + CCD matrix

  Averaged over 200 trains

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy F. Stephan, DESY PITZ
Emittance @1 nC, high gradient operation (summer 2007)

- in the minimum we obtained
  \[ \varepsilon_{x,n} = 1.25 \pm 0.19 \text{ mm mrad} \]
  \[ \varepsilon_{y,n} = 1.27 \pm 0.18 \text{ mm mrad} \]
  @1nC for 100% RMS emittance!

- ASTRA prediction:
  \[ \varepsilon_{x,y,n} = 1.28 \text{ mm mrad} \]

x-x' phase space:

Cathode: # 90.1
Gun gradient: \~60 MV/m
Gun phase: \[ \Phi_{\text{gun}} = \Phi_{\text{ref}} \]
Momentum from gun: \~6.44 MeV/c
Booster phase: \[ \Phi_{\text{booster}} = \Phi_{\text{ref}} \]
Total beam momentum: 14.5 MeV/c

With a cut at 5% of maximum measured phase space density (remove non-lasing electrons)
- normalized projected emittance = \~0.8 mm mrad

- first demonstration of beam quality required for European XFEL

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy F. Stephan, DESY PITZ
S-band gun

- Short RF pulse ($\mu$s)
- Rep. rate: up to hundreds of Hz
- High peak field (> 100 MV/m)
- Usually with metal cathode (Cu)
LCLS Injector Layout

- 6 MeV
- RF Gun
- Solenoid
- Gun Spectrometer
- L0a
- L0b
- RF Deflector
- Emittance Screens/Wires
- 135-MeV Spectrometer
- X-band RF acc. section
- L1S
- BC1
- TD11 stopper
- 2-km point in 3-km SLAC linac

- OTR screens (7)
- YAG screens (7)
- Wire scanners (7)
- Dipole magnets (8)
- Beam stoppers (2)
- S-band RF acc. sections (5)
LCLS RF Photo-Cathode Gun

- 1.6-cell S-band (2856 MHz - BNL/SLAC/UCLA)
- Copper cathode
- 120-Hz repetition rate
- 140-MV/m cathode field (max)
- Axially symmetric RF fields
- 15 MHz 0-π mode separation
- Dual RF-feed
- Built at SLAC

Courtesy D. H. Dowell, SLAC

D. Dowell
V. Dolgashev
E. Jongewaard
B. Kirby
J. Lewandowsky
R. F. Boyce

C. Limborg
Z. Li
A. Vlieks
J. Schmerge
J. Wang
L. Xiao
Gun-Solenoid Assembly

Cut-away view of LCLS Gun

Cathode weld assembly

Compliments E. Jongewaard

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy D. H. Dowell, SLAC
RF Gun1 Operating Since April 2007

LCLS RF Gun: Cathode Side

- focusing solenoid
- cathode flange
- dual rf power feed

LCLS Gun Installed at Sector 20

Courtesy D. H. Dowell, SLAC

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
**LCLS Gun Summary**

- Gun has operated reliably since April 2007
- Beam parameters meet the LCLS specifications
  - 1.2 micron@1nC; 0.9micron@0.5nC
- Initial problem of low QE resolved with “active” and “passive” laser cleaning.
  - Produced non-uniform emission…acceptable for now
- Recent maintenance upgraded gun RF probes for 120 Hz operation
- Gun2 is completed and reserved as a spare.
## Design and Typical Measured Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>sym</th>
<th>Design (1 nC)</th>
<th>measured (1.0 nC)</th>
<th>measured (0.25 nC)</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of linac e⁻ energy</td>
<td>$\gamma mc^2$</td>
<td>13.6</td>
<td>13.6</td>
<td>13.6</td>
<td>GeV</td>
</tr>
<tr>
<td>Init. bunch length (rms)</td>
<td>$\sigma_0$</td>
<td>0.9</td>
<td>1.2</td>
<td>1.0</td>
<td>mm</td>
</tr>
<tr>
<td>Min. final bunch length (rms)</td>
<td>$\sigma_f$</td>
<td>20</td>
<td>10</td>
<td>8</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Proj. norm. emittance* (inj.)</td>
<td>$\gamma \varepsilon_{x,y}$</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Proj. norm. emittance* (linac)</td>
<td>$\gamma \varepsilon_{L_{x,y}}$</td>
<td>1.5</td>
<td>2-6</td>
<td>1-2</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Slice norm. emittance* (inj.)</td>
<td>$\gamma \varepsilon_{x,y}$</td>
<td>1.0</td>
<td>0.9</td>
<td>0.8</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Slice energy spread (rms)</td>
<td>$\sigma_E$</td>
<td>&lt;5</td>
<td>&lt;10</td>
<td>&lt;6</td>
<td>keV</td>
</tr>
<tr>
<td>Single bunch rep. rate</td>
<td>$f$</td>
<td>120</td>
<td>10-30</td>
<td>10-30</td>
<td>Hz</td>
</tr>
<tr>
<td>RF gun field at cathode</td>
<td>$E_g$</td>
<td>120</td>
<td>115</td>
<td>115</td>
<td>MV/m</td>
</tr>
<tr>
<td>Laser energy on cathode</td>
<td>$u_l$</td>
<td>250</td>
<td>300</td>
<td>70</td>
<td>$\mu$J</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>$\lambda_l$</td>
<td>255</td>
<td>253</td>
<td>253</td>
<td>nm</td>
</tr>
<tr>
<td>Laser spot diam. on cathode</td>
<td>$2R$</td>
<td>2.0</td>
<td>1.6</td>
<td>1.2</td>
<td>mm</td>
</tr>
<tr>
<td>Cathode QE (pre Apr. '08)</td>
<td>$QE$</td>
<td>6</td>
<td>3.7</td>
<td>3.7</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>
Gun and cathode pictures

1.6 cell UCLA RF Gun

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy G. Penco, FERMI Elettra
SPARC @ INFN - LNF

<table>
<thead>
<tr>
<th>Charge</th>
<th>200 pC</th>
<th>900 pC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emittance</td>
<td>0.8 mm-mrad</td>
<td>2.2 mm-mrad</td>
</tr>
<tr>
<td>Energy</td>
<td>5.65 MeV</td>
<td>5.55 MeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>1 %</td>
<td>2.6 %</td>
</tr>
<tr>
<td>Pulse length</td>
<td>8 ps</td>
<td>12 ps</td>
</tr>
</tbody>
</table>

M. Ferrario, EPAC06

UCLA/BNL/SLAC type RF gun

SPARC movable emittance meter

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Ti:Sa system allows for impressive pulse shaping:
Example: photocathode laser at SPARC

1. With a DAZZLER:  
   - Time distribution at oscillator level  
   - Time distribution after the UV conversion

   ![Graphs showing time distribution](image1)
   
   C. Vicario et al, EPAC04

   ![Graphs showing time distribution](image2)
   
   H. Loos et al, PAC05

2. With gratings:  
   - UV cross-correlation with
   - 0.5 ps IR probe

   ![Diagram showing UV cross-correlation](image3)

   Taken from C. Vicario: Laser pulse shaping for high-brightness photoinjector
   CARE meeting, LNF, Nov15, 2006

ERL07: May 21, 2007
Ingo Will, G. Klemz, MBI Berlin: Drive lasers for photo injectors

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
L-band gun dark current

Gun 3.1 (standard cleaned)
- Cs2Te #58.1 (2006-05-08)

Gun 3.2 (standard cleaned)
- Cs2Te #42.4 (2007-08-05)

Gun 4.2 CO₂ cleaned
- Mo 2008-01-14: 60 µs
- Mo 2008-02-06: 400 µs
- Mo 2008-02-11: 700 µs (to be continued)

fairly fresh cathode measured towards end of gun operation time → still optimistic case

maximum dark current (µA)

all operation at 10 Hz rep. rate → meanwhile reached av. RF power up to 50 kW

some effect of fabrication error in cathode region of gun3.2 has been conditioned

≈43 MV/m

≈60 MV/m

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
L-band gun dark current

Gun 3.1 (standard cleaned)
- Cs2Te #58.1 (2006-05)

Gun 3.2 (standard cleaned)
- Cs2Te #42.4 (2007-08)

Gun 4.2 **CO₂ cleaned**
- Mo 2008-01-14: 60 µA
- Mo 2008-02-06: 400 µA
- Mo 2008-02-11: 700 µA

Some effect of fabrication error in cathode region of gun 3.2 has been conditioned

~43 MV/m

~60 MV/m

RF power up to 50 kW

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy F. Stephan, DESY PITZ
FLASH/PITZ RF L-Band gun: dark current investigation

Simple model using ASTRA code

Gun backplane, cathode and RF Cu Be contact spring

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
FLASH/PITZ RF gun: dark current statistics

Usually dark current decrease with the operation time (conditioning)

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
NC S-band metal cathode gun
Dark charge @ LCLS

LCLS dark charge vs. cathode peak field

Images of the cathode taken using a white light source and a camera (left), and an electron emission image on a YAG screen ($\approx 100$ cm from the cathode). The gun solenoid is adjusted to image the cathode electrons on the 100 micron thick YAG screen.
Dark current investigation @ LCLS

Image on the YAG

Electron trajectories computed using the linear model

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

D. H. Dowell, PAC07
FLASH RF gun: Cs$_2$Te cathode QE & lifetime 1/2

Cathode preparation in Milano and transportation to DESY

<table>
<thead>
<tr>
<th>Cathode ID</th>
<th>CW QE (%) @ 254 nm</th>
<th>Operation (days)</th>
<th>Charge (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#42.2</td>
<td>8.0</td>
<td>123</td>
<td>1.1</td>
</tr>
<tr>
<td>#23.2</td>
<td>9.6</td>
<td>195</td>
<td>1.7</td>
</tr>
<tr>
<td>#72.1</td>
<td>9.2</td>
<td>180</td>
<td>1.6</td>
</tr>
<tr>
<td>#73.1</td>
<td>7.9</td>
<td>114</td>
<td>1.0</td>
</tr>
<tr>
<td>#78.1</td>
<td>7.8</td>
<td>62</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Cathode growing recipe

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
FLASH RF gun: $\text{Cs}_2\text{Te}$ cathode QE & lifetime 1/2

Pulsed QE

\[ \text{QE} = 3.12\% \]

Charge (nC)

Laser Energy (uJ)

Linear fit

Space charge

Cathode growing recipe

L. Monaco, PAC07

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
FLASH RF gun: cathode QE & lifetime 2/2

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
FLASH RF gun: cathode QE & lifetime 2/2

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
FLASH/PITZ/FNAL: cathode “color”? A Puzzle!

Paolo Michelato, EPAC08, Genoa, June 23, 2008
NC S-band metal cathode gun: QE @ LCLS

- QE of copper was at the early beginning about 1 order of magnitude lower then the foreseen
- After laser cleaning reach about $4 \times 10^{-5}$ @253 nm

The measured charge vs. laser energy before (red) and after (blue) laser cleaning. The initial QE was $2.3 \times 10^{-5}$ and after mild laser cleaning it was $4.1 \times 10^{-5}$.

The approximate quantum efficiency (QE) during the last three months of commissioning. The vertical line indicates July 21 when the cathode was lightly cleaned with the drive laser at a higher fluence.
NC S-band metal cathode gun: QE @ SPARC

- QE of copper decrease with time, laser cleaning for rejuvenation.
- Investigation under way on Mg deposited by PLD (Pulsed Laser Deposition). QE @ 266 nm: $3 \times 10^{-5}$ but quadratic behavior of charge vs. laser energy (multi photon?)

---

**Cu cathode QE in the gun.** Before a gun venting (linac installation) QE was $7 \times 10^{-5}$. After the venting QE decrease of a factor 10. After laser cleaning QE recovered.

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
NC RF GUN challenges summary

• Dark current/dark charge
  – From cathode
  – From the contact between cathode and gun
• Cathode QE and vacuum (also for metallic cathodes!)
• Cooling and temperature stabilization
  – Main issue for CW (ERL or long pulse)
• Laser system
  – Transversal uniformity
  – Flat top
  – Jitter stabilization
  – ...

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
SC RF gun (embedded cathode)

• Quite attractive choice
  – Low power dissipation, high conversion efficiency from the plug to the beam.
  • CW operation possible!

• Projects
  – FZD/ELBE photoinjector (1.3 GHz), with Cs$_2$Te cathode
  – BNL/AES (703 MHz), with alkali (K$_2$CsSb) or diamond electron multiplier
  – Collaboration BNL/DESY/ JLAB for an “all metal all superconductive” RF gun (Nb or Nb + Pb)
SCRF gun cathode embedded

FZD/ELBE

BNL/AES

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

BNL/JLAB/DESY
SC RF gun (cathode embedded) cont.

• Photocathode choice
  • Semiconductor photocathode (alkali metal telluride, UV) or antimonide (green light)
    ‒ Proof of principle: OK
    ‒ One injector under conditioning: FZD/ELBE
    ‒ Still to be proved for long time operation
  • Metal cathode
    ‒ Cavity back wall (Nb)
    ‒ Pb film deposited on the Nb SC cavity back wall
• Diamond photocathode amplifier
Problems and open questions

- Cavity contamination (sputtered “particles” from cathode)
- Cathode operation at cryogenic temperature
- High field on the cathode: cathode have to be moved in and out the SC cavity
  - Cathode cooling
  - Cathode RF contact/choke filter joint
- Emittance compensation: not possible like in NC RF gun (solenoid).
SC gun: the first proof of principle

- Wuppertal experiment (1992)
  - SC cavity & Cs$_3$Sb cathode on Nb plug
  - Cathode stem insulated (thermally and electrically) by sapphire ring
  - Choke filter joint

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
successful Rossendorf ½ - cell gun with NC cathode


- Heat input:
  \[ P_{\text{diss}} = R_{\text{surf}} \int \frac{H^2}{2} \, dA \approx 5 \text{ W} \]
  
  dielectric loss \( \approx 15 \text{ W} \)
  
  laser power = 1 W

- isolated from Nb cavity
- liquid N2 cooling
- SC Nb choke filter prevents rf flow
Generation of high brightness electron beams

1. direct production of short pulses:
   laser & photo cathode

2. high acceleration field at cathode:
   radio frequency field

3. CW operation for high average current:
   superconducting cavity

**ELBE SRF PHOTO INJECTOR**

Institute of Radiation Physics • Jochen Teichert • www.fzd.de • Forschungszentrum Dresden-Rossendorf

Courtesy J. Teichert, FZD
<table>
<thead>
<tr>
<th>Mode</th>
<th>ELBE</th>
<th>High Charge</th>
<th>BESSY-FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>final electron energy</td>
<td></td>
<td>≤ 9.5 MeV</td>
<td></td>
</tr>
<tr>
<td>RF frequency</td>
<td></td>
<td>1.3 GHz</td>
<td></td>
</tr>
<tr>
<td>RF power</td>
<td></td>
<td>10 kW</td>
<td></td>
</tr>
<tr>
<td>operation mode</td>
<td></td>
<td>CW</td>
<td></td>
</tr>
<tr>
<td>drive laser</td>
<td></td>
<td>262 nm</td>
<td></td>
</tr>
<tr>
<td>photo cathode</td>
<td></td>
<td>Cs$_2$Te</td>
<td></td>
</tr>
<tr>
<td>quantum efficiency</td>
<td>≥ 1 %</td>
<td>≥ 2.5 %</td>
<td></td>
</tr>
<tr>
<td>bunch charge</td>
<td>77 pC</td>
<td>1 nC</td>
<td>2.5 nC</td>
</tr>
<tr>
<td>repetition rate</td>
<td>13 MHz</td>
<td>500 kHz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>laser pulse (FWHM)</td>
<td>4 ps</td>
<td>15 ps</td>
<td>50 ps</td>
</tr>
<tr>
<td>transverse rms emittance</td>
<td>1 mm mrad</td>
<td>2.5 mm mrad</td>
<td>3 mm mrad</td>
</tr>
<tr>
<td>average current</td>
<td>1 mA</td>
<td>0.5 mA</td>
<td>2.5 μA</td>
</tr>
</tbody>
</table>
Niobium Cavity

Nb RRR 300 cavity

\[ E_{\text{acc}} = 25 \text{ MV/m in TESLA cells}, \quad Q_0 = 1 \times 10^{10} \]  
(TESLA 500 specification)

110 mT maximum magnetic surface field

\[ E_{\text{peak}} (\text{TESLA cells}) = 50 \text{ MV/m} \]
\[ E_{\text{peak}} (\text{half-cell}) = 30 \text{ MV/m} \]
\[ E_{\text{cathode}} = 20 \text{ MV/m (retreated cathode)} \]
Installation of the SRF gun Cryostat in the shut-down June/July 2007
500 kHz laser for High-charge mode:

- Max. frequency: 0.5 MHz
- Lower frequencies for alignment
- Pulse duration: 12…15 ps
- Laser material: Nd:YLF, pumped by 8 fiber-coupled diodes

developed by Max-Born-Institut, Berlin
November 19th, 2007

RF:
- \( E_{\text{acc}} = 5 \text{ MV/m} \)
- \( f = 1300.38327 \text{ MHz} \)
- 150 Hz bandwidth
- \( P_{\text{diss}} = 6 \text{ W} \)

Laser:
- 263 nm, 100 kHz repreate
- 0.4 W power (4 \( \mu \text{J} \))
- 15 ps FWHM Gaussian
- \( \Delta x = 4 \text{ mm} \), \( \Delta y = 6 \text{ mm} \), Gaussian

Cathode: Cu
- Q.E. \( \approx 10^{-6} \)

Electron beam:
- 11 mm x 2 mm (FWHM) size on screen
- 50 nA average current
- 0.5 pC bunch charge
- 2.0 MV energy (estimated)

Field emission at 5.5 MV/m
FZD/ELBE SC RF gun

Test with $\text{Cs}_2\text{Te}$ cathode are under way

Next future:
- Cathode QE
- Dark current
- Reliable compatibility with SC cavity
- Gun reliability
- Cathode lifetime
- ...

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
BNL 703 MHz ERL SRF Photoinjector

Overview

- ERL operating at 703 MHz using SRF photoinjector and accelerating cavity
- Photoinjector designed to deliver 2 MeV beam, 5 nC/bunch at 9.38 MHz.
- Laser system designed to ramp up in power and rep rate, so various diagnostics will be possible
- Ideally operate in multiple modes
  - 93 MHz, 1.4 nC/bunch (130 mA) scale to 0.5A with 351 MHz laser
  - 9.38 MHz, 5 nC/bunch (50 mA) for RHIC II
  - Start-up mode 1 Hz and up, low bunch charge

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Gun Design

Assembly Support Fittings
Tuner Bellows
Cathode location
Double Quarter Wave Choke (cavity portion)
Helium Vessel
Helium Main Line
Opposing Pickup Ports
FPC Port Stiffener
10 cm Beam Pipe
Opposing FPC Ports

Andrew Burrill ERL Workshop 2007
Office of Science
U.S. DEPARTMENT OF ENERGY

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Photocathode choice and challenges

- $\text{CsK}_2\text{Sb}$ is cathode of choice, with a diamond amplified photocathode as the next generation cathode
- Lots of experience with $\text{CsK}_2\text{Sb}$ photocathode deposition, extensive R&D on diamond amplified photocathode

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode lifetime</td>
<td>No vacuum degradation</td>
</tr>
<tr>
<td>Thermal isolation</td>
<td>Actively cooled cathode stalk</td>
</tr>
<tr>
<td>Particulate and</td>
<td>Proper engineering and design</td>
</tr>
<tr>
<td>interface to gun</td>
<td></td>
</tr>
</tbody>
</table>
“All superconducting” RF GUN

Collaboration BNL, JLAB, DESY, Pekin Univ. FZR,...

Challenges:

• Superconducting RF structure
  – Pb coating compatibility

• Superconducting photocathode:
  – Nb back wall of the cavity
    • low QE, High laser power required
    • 5th harmonic (\( \lambda < 250 \text{ nm} \))
  – Deposited Pb on the back wall of the cavity
    • Cavity processing (HPR)
    • Cathode refurbishment
  – Moveable stem with Pb coating
    • Choke joint
III. SC cathode + SRF cavity

Assumption:
a superconducting metal cathode with theoretically “infinity” long life time should simplify the design.

The first approach:
photoemission from the cavity wall, so called “all niobium RF-gun”, proposed at BNL

The simplest way, but very low QE < 10^{-5} @ \lambda = 266 \text{ nm}

The second approach:
Bulk niobium cavity with the emitting spot of Pb, which is a commonly used sc (Tc=7.2 \text{ K})
III. SC cathode + SRF cavity

Measured QE at 300 K

Irradiating light sources:
ArF- laser: 193 nm, KrF-laser: 248 nm, 4-th harmonic Nd: YAG laser : 266 nm
Deuterium light source with monochromator (2 nm bandwidth): 190-315 nm

QE sufficient to generate ~0.5 nC at rep. rate ≤100 kHz
Fabrication Options:

Deposition of lead directly onto "cathode area" of cavity back wall via arc deposition (DESY cavity)

or

Use cavity with removable portion of the back wall (plug), which can be coated independently of cavity cleaning (Jlab cavity)

In both cases, cavities reached 40 MV/m with lead cathodes. The Q of both cavities was unchanged by the presence of lead.
Cavity Tests
Pb/Nb $\frac{1}{2}$ Cells
RF performance

- DESY Cavity with 4mm lead
- TJNAF Cavity with 7mm lead coated plug

$Q_0$

$E_{peak}$ [MV/m]

Courtesy J. Smedley
Charge Measurement

Photocurrent for both cavities measured in Jlab Vertical Test Area, by isolating the cavity and monitoring the current leaving.

QE for electroplated lead plug in Jlab cavity was $1.6 \times 10^{-4}$ (@248nm), in line with expected performance.

QE for Arc deposited lead cathode in DESY cavity was $1.4 \times 10^{-4}$ (@248nm), lower than expected, possibly due to uneven lead coating.

Courtesy J. Smedley
“All superconducting” RF GUN Summary

- Hybrid Pb/Nb cavities have been fabricated using two designs
  - Direct plating of Pb on cavity back wall via masked arc deposition
    - Avoids need for joints or seams
    - Challenging to do, cavity cleaning post deposition is challenging, may harm Pb
  - Use cavity with removable plug in back wall, that is coated separately
    - Easy to coat with lead, using a variety of techniques, easy to clean cavity
    - Requires a joint, which may limit electric field on cathode

- RF performance good for both designs, unchanged by presence of lead spot

- For plug gun, QE is $1.6 \times 10^{-4}$ (@248nm) in line with expected value for electroplated lead. The arc deposited spot on the DESY cavity has a QE of $1.4 \times 10^{-4}$ (@248nm).

- We were unable to cause a quench in the cavity, with 0.7W (>0.5 MW peak) of laser power delivered (the Q dropped by 20% in this case)
Conclusions

• NC RF gun are a mature technology, they can provide the beam quality for FEL, in terms of current, emittance, etc.

• NC RF gun for ERL: still critical for RF power dissipation.

• SC RF gun are close to demonstrate to be a reliable choice for ERL and FEL with semiconductor photocathodes (ELBE, BNL).

• SC RF gun “all superconductive” is a promising approach also in terms of reliability (no RF joint, no choke)

BUT...
High brightness low emittance with thermionic gun!

- Results obtained at RIKEN Spring-8 by T. Shintake
- CeB$_6$ thermionic cathode
- Beam peak current 300 A, emittance: 1 mm · mrad

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Thanks

• I first would thanks you for your attention and patience...
• I would apologize for having not included all the people and the projects around the world
• I would thanks all the people that have contributed in the collection of the information relative to the RF guns
The end
BNL Gun Cryomodule
Cathode insertion mechanism

Designed by AES

Paolo Michelato, EPAC08, Genoa, June 23, 2008.
Longitudinal Bunch Shape

- Measured with LOLA – S-band deflecting cavity
- Resolution 10 to 50 μm

- Development of spike(s) observed as predicted
- It’s the spike which carries the high peak current \( \sim 2 \text{ kA} \) and is actually lasing

\[ \Delta t_{\text{spike}} \approx 65 \text{ fs (FWHM)} \]
\[ Q_{\text{spike}} \approx 0.12 \text{ nC (23 %)} \]

Paolo Michelato, EPAC08, Genoa, June 23, 2008.

Courtesy S. Schreiber, DESY