Materials and gradient
Some properties of pure metals in low temperature region
Cold RF-photo GUN design

Vladimir Vogel,
Motivation

Super conductive Linac ≠ Normal temperature RF Gun

\[ P_{\text{cavity}} \sim G^2 \times R^* \times T_{RF} \]

Low emittance \(\rightarrow\) high gradient

Dissipated power \(\rightarrow\) low temperature (DESY RF GUN #5, Tiris = 72°C + 46°C pulse heating)

Gradient \(\rightarrow\) new materials, (we have only one RF GUN !!!)

Dark current \(\rightarrow\) new geometry + new materials
Breakdown mechanisms

For a cylindrical protrusion heat conduction is described by:

\[ C_V \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + J^2 \rho \]

Let’s get approximate solution it in two steps:

1. Solve it in steady-state (i.e. left hand side is zero) for a threshold current density required to reach melting temperature \( T_m \)

2. Solve time dependent equation in linear approximation to get the threshold time required to reach melting temperature

Williams & Williams, J. Appl. Rhys. D, 5 (1972) 280
Breakdown study, pulse DC

Ranking materials by crystal structure?

H. Timkô, CERN

dc breakdown conditioning and breakdown rate of metals and metallic alloys under ultrahigh vacuum

A. Descoeudres, T. Ramsvik, S. Calatroni, M. Taborelli, and W. Wuensch

*European Organization for Nuclear Research, CERN, 1211 Geneva 23, Switzerland

(Received 8 January 2009; published 24 March 2009)
Some property of pure metals in normal temperature

- **Thermal conductivity (W/m*K):**
  - C: 0
  - Al: 100
  - Cu: 200
  - W: 300
  - Ta: 400
  - Nb: 500
  - Mo: 0
  - Cr: 100
  - Co: 200
  - V: 300
  - Ti: 400
  - SS: 500
  - Ir: 600

- **Young's modulus (10^{-10} * N/m^2):**
  - C: 0
  - Al: 10
  - Cu: 20
  - W: 30
  - Ta: 40
  - Nb: 50
  - Mo: 60
  - Cr: 70
  - Co: 80
  - V: 90
  - Ti: 100
  - SS: 110
  - Ir: 120

- **Resistivity (10^8 * Ohm*m):**
  - C: 0
  - Al: 10
  - Cu: 20
  - W: 30
  - Ta: 40
  - Nb: 50
  - Mo: 60
  - Cr: 70
  - Co: 80
  - V: 90
  - Ti: 100
  - SS: 110
  - Ir: 120

- **Expansion (10^6 *1/K):**
  - C: 0
  - Al: 5
  - Cu: 10
  - W: 15
  - Ta: 20
  - Nb: 25
  - Mo: 30
  - Cr: 35
  - Co: 40
  - V: 45
  - Ti: 50
  - SS: 55
  - Ir: 60
Ranking materials: RF, high gradient

Temperature ~ 300 K

$Ey^* (l_{ar})^{0.5}$

CLIC HIGH-GRADIENT TEST RESULTS
CERN, Geneva, Switzerland
Gradient in the pressurized cavity.

Maximum stable gradient as a function of the Young's modulus for different materials. RF frequency 805 MHz, Hydrogen pressure ~ 100 bar. (data from (#), for Iridium the approximation)

DC dark current

Field gradient (MV/m)

SS  Cu  Ti  Mo

gap 1 mm, F. Le Pimpec and al., NIM A 574
gap 0.5 mm, F. Furuta and al. NIM A 538
Some properties of pure metals in low temperature

**Thermal conductivity**

\( \text{Au, Ag, Ir, W, Pt…} \)

- Helium: 4.22 K
- Hydrogen: 20.3 K
- Neon: 27 K

L.A. Novickiy, I G. Kozhevnikov
“Thermo physical properties of materials in the low temperature region”
Moscow 1975. In Russian
Some properties of pure Cu, W, Mo and Ir in low temperature

\[ \tau = 1 \text{ mSec} \]

\[ D_{th} = \sqrt{\frac{\tau \cdot \lambda}{\gamma \cdot C_p}} \]
Cupper, thermal conductivity

http://www.copper.org/resources/properties/cryogenic/homepage.html
Electrical resistivity of Copper and Molybdenum

**BROOKHAVEN NATIONAL LABORATORY**

**SELECTED CRYOGENIC DATA NOTEBOOK**

**VOLUME II**

**SECTIONS X-XVIII**

Compiled and Edited by
J.E. Jensen  W.A. Tuttle
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1. Worcester Polytechnic Inst. and National Bureau of Standards, Cryogenic
2. Institute of Technology, Rapperswil, Switzerland

**ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER**
### Thermal losses in the Gun for different materials

**DESY RF GUN5** (V. Paramonov, K. Floettmann,..)  
\[ f = 1300 \text{ MHz}, \; Trf = 1 \text{ mS}, \; H_{\text{p max}} = \sim 100kA/m \]

\[
Lt = \left(\frac{\lambda \cdot \tau}{(\gamma \cdot Cp)}\right)^{1/2}
\]

\[
\Delta Ts = \left(\frac{\rho \cdot f \cdot \mu}{\gamma \cdot \lambda \cdot Cp}\right)^{1/2} \cdot (Hp)^2
\]

<table>
<thead>
<tr>
<th></th>
<th>T (K)</th>
<th>( \rho ) (Ohm*m)</th>
<th>( Cp ) (J/kg*K)</th>
<th>( \lambda ) (W/m*K)</th>
<th>( \delta ) (m)</th>
<th>( Lt ) (m)</th>
<th>( \Delta Ts ) (K)</th>
<th>P (W/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>300</td>
<td>~ 5*10^{-11}</td>
<td>~ 7</td>
<td>~6000</td>
<td>9.8*10^{-8}</td>
<td>9.8*10^{-3}</td>
<td>46.2</td>
<td>4.7*10^7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RRR~400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>20</td>
<td>~ 8*10^{-11}</td>
<td>~3.5</td>
<td>~360</td>
<td>29.2*10^{-8}</td>
<td>3.2*10^{-3}</td>
<td>32</td>
<td>3.2*10^6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RRR~600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>20</td>
<td>~ 1.2*10^{-10}</td>
<td>~2</td>
<td>~1600</td>
<td>15.2*10^{-8}</td>
<td>6.5*10^{-3}</td>
<td>18</td>
<td>3.9*10^6</td>
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<tr>
<td></td>
<td></td>
<td>RRR~450</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ir</td>
<td>20</td>
<td>~ 1.0*10^{-10}</td>
<td>~3</td>
<td>~1900</td>
<td>13.9*10^{-8}</td>
<td>5.3*10^{-3}</td>
<td>11.3</td>
<td>3.5*10^6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RRR~450</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Freyrl, Haefar "Tieftemperatur technologie" 1981, p. 5.1.1-1(11/74)
- Л.А. Новицкий, И.Г.Кожевников "Теплофизические свойства материалов при низких температурах", Moscow 1975.
- Thermophysical properties of matter, IFI/PLENUM, NEW YORK-Washington 1970

*Not included anomalous skin effect!!!*
Anomalous skin effect

\[ \delta = \sqrt{\frac{\rho}{\mu_0 \pi * f}} \]

\[ \Lambda = \frac{h * 3^{1/3}}{\rho * e^2 * n^{2/3} * (8\pi)^{1/3}} \]

\[ R_{an} \approx \left( \frac{c^2 \cdot \Lambda \cdot \rho}{\beta \cdot f} \right)^{-1/3} \cdot f(R) \cdot g(N) \]

\[ R \sim \text{reflection factor for electrons} \]
\[ N \sim \text{RRR} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( d/L ) T=300 K</th>
<th>( d/L ) T=20 K</th>
<th>( d/L ) T=300 K</th>
<th>( d/L ) T=20 K</th>
<th>( Q_{20}/Q_{300} ) 11.4GHz</th>
<th>( Q_{20}/Q_{300} ) 1.3GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>27</td>
<td>2.4*10^-3</td>
<td>16</td>
<td>0.81*10^-3</td>
<td>4.4 (exp)</td>
<td>~ 6.2 (estim)</td>
</tr>
<tr>
<td>Mo</td>
<td>47</td>
<td>2.3*10^-3</td>
<td></td>
<td>4.4 (exp)</td>
<td>4.4 (exp)</td>
<td>~ 6</td>
</tr>
</tbody>
</table>

**DESY GUN 5**
**60 MV/m ~ 6.18 MW**

**Cold GUN**
**60 MV/m - ~ 1 MW**
Conditioning of pure metals in pulse DC mode

Conditioning curves of pure metals

assumption: ‘good material’ = refractory ; oxides easily reduced

CLIC Breakdown Workshop – CERN, May 2008
Cold GUN, regimes for conditions and for the normal operation

Mo, Ir, W, $T = 20 \text{ K}$

\[
\lambda_{20} \approx 3 \cdot \lambda_{300}
\]

\[
\frac{d\lambda_{20}}{dT} \geq 0
\]

\[
c_{p_{20}} = 0.1 \cdot c_{p_{300}}
\]

\[
\frac{dc_{p_{20}}}{dT} \geq 0
\]

\[
\alpha_{20} = 0.04 \cdot \alpha_{300}
\]

\[
Rs_{20} \approx \frac{1}{6} \cdot Rs_{300}
\]

\[
\frac{dRs_{20}}{dT} \approx 0
\]

No reason for the breakdown in the standard BD model !!!

\(\begin{align*}
& 1. \quad 20 \text{ Kelvin, working point, feedback “ON”} \\
& 2. \quad 77 \text{ Kelvin, point for condition, feedback “OFF”}
\end{align*}\)
Problem: must be a possibility to change photocathodes in the RF GUN!!

1. From W, Ir and Mo we can easy make only very simple shapes like a disks.
2. At the moment we can only get from the industry very pure thin sheets of W, Ir and Mo with maximal sizes just about 100 mm.

Solution #1

To make the first half cell of cavity as an oversized, operated on TM 020 mode at the working frequency.

+ * a removable connection can be done without problems for TM020 mode in cavity, because there is a circumference where we don’t have any of radial current,

* the oversize cavity has a higher Q factor and can be cooled better due to larger surface.

- * this type of cavity can only be done for a frequency more than 2.9 GHz because of the limitation on max size of available metals.
Oversize cavity:

Example:
TM020 in first half cell
TM010 in second cell

1. No tangential current for TM020, slot for cathode changing, damping of HOMs
2. More space for input couplers.
3. No cathode holder, direct Cs2Te film on the replaceable part of cavity.
4. Cathode part of cavity can be made from very hard material
Problem: must be a possibility to change photocathodes in the RF GUN !!

1. From W, Ir and Mo we can easy make only very simple shapes like a disks.
2. At the moment we can only get from the industry very pure thin sheets of W, Ir and Mo with maximal sizes just about 100 mm.

Solution #2

For removable connection, we can use a fact that a factor of thermal expansion for Cu for one side and W, Ir and Mo for the other have a big difference.

+  * 1.3 GHz cavity can be produced using existing 100 mm sheets from the industry
  * over electrical fields that arise due to inaccuracies of fabrication in the contact area could be shielded by inner angle in the cavity.
  * easy to test on the existing DESY cryostats

-  * limitation of working cycles because of a peening.
Removable connection of two kinds of metals (Cu + W, Ir or Mo) in one cavity

Spring (Be bronze)
Cs2Te film
Cathode holder (Mo)

GUN #5

Cu
W

Spring (Be bronze)
Cs2Te film
Cathode holder (Mo)
Over fields through of removable connection.
“COLD GUN” team in DESY

Klaus Flöttmann, Siegfried Schreiber, Dirk Lipka, Xenia Singer

and Sven Lederer
Conclusion

Heating and thermal expansion in the normal conductivity RF-photo electron gun are the main limitations to achieve high accelerating gradient and consequently a low emittance beam. Some pure materials show a significant increase in thermal conductivity with a small coefficient of temperature expansion at temperatures around 20 degrees Kelvin. Possible materials are Molybdenum, Iridium or Tungsten. However, machining of these materials is very difficult. Therefore we propose a simplified shape for RF gun. We expect to achieve a significant increase in gradient for similar RF powers as used in the present DESY RF-gun. On the other hand, it would also be possible to increase the duty cycle keeping a moderate gradient and to decrease heat losses, frequency shift and dark current.

Thank you for attention!
**F** = 5.25GHz

ON POSSIBILITY OF DEVELOPMENT OF HIGH-PERFORMANCE HIGH-FREQUENCY CRYOGENIC RESONANCE SYSTEM FROM YTTRIUM DOPED COPPER

V.A. Kutovoy, A.I. Komir, ISSN 1562-6016. ВАНТ. 2012. №4(80)

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Рис.9. Относительное изменение поверхностного сопротивления меди марок MoB, MoBВ, MoBВ+0,02Y в зависимости от температуры

<table>
<thead>
<tr>
<th></th>
<th>$\delta/L$, T=300 K 1.3 GHz</th>
<th>$\delta/L$, T=20 K 1.3 GHz</th>
<th>$\delta/L$, T=300 K 11.4 GHz</th>
<th>$\delta/L$, T=20 K 11.4 GHz</th>
<th>$Q_{20}/Q_{300}$ 11.4GHz Cu+0.02 Y</th>
<th>$Q_{20}/Q_{300}$ 5.25GHz Cu+0.02 Y</th>
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<tbody>
<tr>
<td>Cu</td>
<td>27</td>
<td>2.4*10^{-3}</td>
<td>16</td>
<td>0.81*10^{-3}</td>
<td>4.4 (exp)</td>
<td>6.1(exp)</td>
</tr>
<tr>
<td>Mo</td>
<td>47</td>
<td>2.3*10^{-3}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Результаты приведены для $Q_{20}/Q_{300}$ 1.3GHz ~ 6.2 (estim)
Liquid Hydrogen
\[ T_{\text{boiling}} = 20.3 \, \text{K} \]
\[ C_p = \frac{8000}{12000} \, \text{J/kg*K} \]
\[ \Theta_{\text{evaporation}} \sim 454 \, \text{kJ/kg} \]
\[ \rho = 71 \, \text{kg/m}^3 \]

\textbf{H}_2: For 1 kW evaporative cooling:
\[ 8 \, \text{kg/hour} \]
liquid cooling (\( \Delta T = 2 \, \text{K} \)):
\[ 180 \, \text{kg/hour} (2.5 \, \text{m}^3/\text{hour}) \]

Liquid Neon
\[ T_{\text{boiling}} = 27 \, \text{K} \]
\[ C_p = 1880 \, \text{J/kg*K} \]
\[ \Theta_{\text{evaporation}} \sim 84-89 \, \text{kJ/kg} \]
\[ \rho = 1207 \, \text{kg/m}^3 \]

\textbf{Ne}: For 1 kW evaporative cooling:
\[ 42 \, \text{kg/hour} \]
liquid cooling (\( \Delta T = 2 \, \text{K} \))
\[ 862 \, \text{kg/hour} (0.7 \, \text{m}^3/\text{hour}) \]
Fig. 4. Impulse breakdown voltage as a function of the gap length. Parameters: temperature of the plane electrode and polarity.

Fig. 3. DC breakdown voltage as a function of the gap length. Parameters: temperature of the plane electrode and polarity.
Breakdown for copper at 77 K and 293K
Breakdown voltage for Aluminum Copper and Gold

Prebreakdown currents and breakdown voltages in vacuum at cryogenic temperatures

R N Allan and A J Salim
Department of Electrical Engineering and Electronics, UMIST, Sackville Street, Manchester, M60 1QD

Figure 4. Logarithmic plots of breakdown voltage characteristics for gold, copper and aluminium electrodes.

<table>
<thead>
<tr>
<th>Curve</th>
<th>Electrode material</th>
<th>Temperature (K)</th>
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<tbody>
<tr>
<td>A</td>
<td>Aluminium</td>
<td>4.2</td>
</tr>
<tr>
<td>B</td>
<td>Aluminium</td>
<td>77.3</td>
</tr>
<tr>
<td>C</td>
<td>Aluminium</td>
<td>300</td>
</tr>
<tr>
<td>D</td>
<td>Copper</td>
<td>4.2</td>
</tr>
<tr>
<td>E</td>
<td>Copper</td>
<td>77.3</td>
</tr>
<tr>
<td>F</td>
<td>Copper</td>
<td>300</td>
</tr>
<tr>
<td>G</td>
<td>Gold</td>
<td>77.3</td>
</tr>
<tr>
<td>H</td>
<td>Gold</td>
<td>300</td>
</tr>
</tbody>
</table>
Surface temperature rise as a function of the initial gun temperature.

1 ms RF pulse
Gradient 60 MV/m,
$f = 1.3$ GHz,
material copper, $RRR = 100.$