Low-Z anode wires testing for particle accelerator electrostatic septa

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Purpose

To reduce extraction losses in slow extraction electrostatic septa, it is beneficial to use a low-Z septum instead of an array of WRe (26%Re) wires as used up to now.

A laboratory test set-up was built, allowing the high voltage (HV) testing of anodes using wires made of different materials.
Cathode design

Cathode (60 x 80 mm) was designed to limit field amplification when placed opposite the existing anode. Several cathodes with the same profile were made, using stainless steel (304L) and titanium (grade 2).

Of note: the E field mentioned in the following slides, is the average field between cathode and anode wires, i.e.

$$ E = \frac{U_{\text{cathode}}}{d_{\text{cathode–anode}}} $$
(Existing) Anode layout

Springs, to allow retraction of any broken wires behind the stainless steel HV deflectors.
## Tested anode wire materials

<table>
<thead>
<tr>
<th>Wire material</th>
<th>Ø [µm]</th>
<th>Density [kg/l]</th>
<th>Alloy reference</th>
<th>state</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>100</td>
<td>19.7</td>
<td>WRe (26%)</td>
<td>Annealed</td>
<td>Reference material</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>100</td>
<td>7.9</td>
<td>316 L</td>
<td>Tempered hard</td>
<td>Not yet tested.</td>
</tr>
<tr>
<td>Titanium</td>
<td>100</td>
<td>4.42</td>
<td>TA6V</td>
<td>Annealed</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>125</td>
<td>2.7</td>
<td>AlMgSi (98/1/0.6 %)</td>
<td>As drawn</td>
<td></td>
</tr>
<tr>
<td>Carbon Nano Tube</td>
<td>100</td>
<td>1.3</td>
<td>CNT wire made of 7µm CNT strands</td>
<td>Measured density ±0.2 kg/l</td>
<td></td>
</tr>
</tbody>
</table>
CNT wire investigation

- No broken wires. Very robust mechanically.
- Once a spark occurred, the cathode seems to become an electron emitter. The current could be increased 10-fold (or more) without increasing voltage or provoking a spark. Further conditioning became impossible.
- After conditioning, Carbon deposit was observed on the cathode using an electron microscope.
Zoom of a wire in low field region after conditioning. Strand damage from installation only.

Zoom of wire in high field region after conditioning. Degradation of some strands was visible.

Cathode: surface aspect at 1k magnification and detail of the molten material at the inclusion edge at 10k magnification.

Inclusions were found on front (i.e. high field) face of the cathode, but none on the back side.

Hypothesis: the included CNT debris acts as electron emitter.
Aluminium wire

• In total more broken wires (12) during conditioning, although the initial tests with low current showed less wires broken w.r.t. what was expected due to its low melting temperature.
• The fields achieved are definitely the highest achieved compared to CNT or titanium.
• Cathode seems to have suffered after conditioning, i.e. observed more surface irregularities than with other tests (Al deposits?, not yet determined).
• The surface of some wires that saw field are heavily deformed after conditioning.
Aluminium wires, after conditioning 1/2

Wire surface of wire after exposure to high field; no surface damage observed.

State of Al wires in the array after conditioning; some wires changed colour.
Aluminium wires, after conditioning 2/2

Extremity of a wire broken during conditioning.

‘White’ wire after exposure to high field on the right side and low field on the left. Droplets created on surface. Conditioning damage?
Titanium wire

- A few broken wires during conditioning. Mainly because higher currents were used to condition (up to 200 µA instead of several 10s of µA).
- When a Ti wire broke (4) using a ti cathode, welding of an end onto the cathode has occurred, shorting the system.
- Broken Ti wires (2) didn’t weld onto a stainless-steel cathode.
- The titanium revealed itself as a very springy wire: it was very hard to tension the wires straight (i.e. nicely parallel) on anode support.
## Achieved E fields

<table>
<thead>
<tr>
<th>Cathode Material</th>
<th>Anode Material</th>
<th>Gap width [mm]</th>
<th>Achieved voltage [kV]</th>
<th>Average gap field [MV/m]</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. steel.</td>
<td>WRe</td>
<td>10</td>
<td>25</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>St. steel.</td>
<td>WRe</td>
<td>30</td>
<td>50</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>WRe</td>
<td>10</td>
<td>130</td>
<td>13</td>
<td>Fields achieved too low for application</td>
</tr>
<tr>
<td>St. steel.</td>
<td>CNT</td>
<td>10</td>
<td>30</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>CNT</td>
<td>10</td>
<td>18</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>CNT</td>
<td>30</td>
<td>33</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>St. Steel</td>
<td>Ti</td>
<td>10</td>
<td>120</td>
<td>12</td>
<td>Useable field</td>
</tr>
<tr>
<td>St. Steel</td>
<td>Ti</td>
<td>20</td>
<td>140</td>
<td>7</td>
<td>Feedthrough limited?</td>
</tr>
<tr>
<td>Ti</td>
<td>Ti</td>
<td>10</td>
<td>100</td>
<td>10</td>
<td>Useable field</td>
</tr>
<tr>
<td>Ti</td>
<td>Al</td>
<td>20</td>
<td>115</td>
<td>5.8</td>
<td>Feedthrough limited?</td>
</tr>
<tr>
<td>Ti</td>
<td>Al</td>
<td>10</td>
<td>110</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>Al</td>
<td>5</td>
<td>55</td>
<td>11</td>
<td>Useable range of fields</td>
</tr>
<tr>
<td>St. Steel</td>
<td>Al</td>
<td>10</td>
<td>105</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>St. Steel</td>
<td>Al</td>
<td>5</td>
<td>53</td>
<td>10.6</td>
<td></td>
</tr>
</tbody>
</table>
Summary

• The test set-up seems more adapted to small gap tests.

• CNT doesn’t seem to be a valid alternative, since after sparking, carbon debris is deposited on the cathode, preventing further conditioning.

• Aluminium wires broke, but less than what was expected based on their low melting temperature. However, significant surface damage was observed after conditioning.

• With titanium wires in combination with a Ti cathode, it was observed several times that a broken wire extremity welded onto the cathode, unlike the same wires opposite a stainless-steel cathode.

• For future use in slow extraction septa, other criteria play a role as well. Beam interaction will provoke wire heating for example and loss of mechanical properties, which may lead to wire break down as well.
Outlook

- Initial testing of titanium wires didn’t reveal any showstoppers. Now, we are looking for a more ductile titanium alloy, to allow stringing of the wires sufficiently straight on the anode support.

- Another alternative that we would like to study is graphene. Clamping the graphene foils will need a new fixation to be designed.
References

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