Localization of field emitter in a 9-cell cavity

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1. Motivation

2. Localization of field emitter in a 9-cell cavity

3. Summary
1. Motivation

- Field emission/dark current issue of concern for SRF cavity performance and SRF linac operation
  - ILC, pulsed, pushing high gradient, driven by $E_{pk}$
  - CEBAF and other future CW SRF linacs, driven by $DF$

- Complete understanding and reliable control of the issue is still needed in particular in multicell practical cavities
  - Dark current in multicell cavity
    - Where are the emitters
    - Origin of emitters
    - Impact to cryogenic load and machine operation
Goal

- Locate field emitter in multi-cell cavity
  - Develop a generic producer
  - Benchmark with vertically multicell cavity test
  - Close loop by optical inspection of predict emitter site
  - Provide feedback for cavity string assembly

- Ultimate goal— to reduce & eliminate filed emission in multi-cell cavity
2. Full Scale multicell cavities and FN Law

QM tunneling theory predicts exponential Fowler-Nordheim emission current density

\[ j(E) = \frac{A_{FN}(\beta_{FN}E)^2}{\varphi} \exp\left(-\frac{B_{FN} \varphi}{\beta_{FN}E}\right) \]
Trajectories of different Emitters
9-cell Model and Definition of Coordinate

IR-5-LF
IR-5-RT

I5 region, 15MV/m
β=150, Φ=4.2eV

(0,0)
3 Types of “Long Range” Trajectories

- Emission in region >>> “Reverse type”
- Emission in region >>> “Zigzag type”
- Emission in region >>> “Forward type”

Impact position VS impact energy distribution
Position and phase distribution

Position distribution

Phase distribution
1. R2 electron escaping rate is very high (0.5 at s=0.008m)
2. Most of electrons at hitting at cell 5 (emitter: IR5_RT)
3. R1 escaping is low compare with R2 (less than 8%)

\[ R_{\text{esp}} = \frac{N_{\text{esp}}}{N_{\text{total}}} \]

\[ R_{\text{hc}} = \frac{N_{\text{hc}}}{N_{\text{total}}} \]
Escaping from Left Flange
“Reverse type” trajectory

Escaping from Right Flange
“Zigzag type” & “forward type” trajectory
Emitter from reverse and zigzag regions [s] is very important considering the energy deposit in the cavity and escaping ratio of the electron.
Impact Energy with Iris

![Graph showing impact energy with Iris 2. The x-axis represents initial S [mm], and the y-axis represents impact energy [MeV]. The graph includes data points and bars representing different energy levels and initial positions.](image_url)
Bremsstrahlung

Electron Energy=25 MeV

Experiment: 9-cell cavity RI23

γ energy spectrum measurement system

High Voltage

② Detector ③ Amplifier ④ Attenuation ⑤ DAQ ⑥ computer

① Dewar

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① Dewar
Energy Spectrum from NaI(Tl) Crystal

End Point Energy Fitting

Pi mode 10MV/m Ep=4.3MeV

Pi mode 11MV/m Ep=6.8MeV

Pi mode 12MV/m Ep=9.4MeV

Pi mode 13.1MV/m Ep=11.14MeV
## End point Energy

### π measurement

<table>
<thead>
<tr>
<th>Field Gradient MV/m</th>
<th>End point Energy MeV</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.5</td>
<td>Field emission starts at about 9 MV/m</td>
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<tr>
<td>11</td>
<td>7.0</td>
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<tr>
<td>12</td>
<td>9.1</td>
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<tr>
<td>13</td>
<td>11.0</td>
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<tr>
<td>14</td>
<td>13.0</td>
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<tr>
<td>15</td>
<td>15.1</td>
<td>detector saturated</td>
</tr>
<tr>
<td>16</td>
<td>17.9</td>
<td>detector saturated</td>
</tr>
</tbody>
</table>

### 7/9 π mode measurement

<table>
<thead>
<tr>
<th>Field Gradient [end cell] MV/m</th>
<th>End point Energy MV/m</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>2.3</td>
<td>Field emission starts at about 13.5MV/m</td>
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<td>16.2</td>
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<tr>
<td>22</td>
<td>6.8</td>
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<tr>
<td>24</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>12.1</td>
<td>detector saturated</td>
</tr>
</tbody>
</table>
Field emitter location

1. $\pi$ mode Field emission onset about 9 MV/m

2. $6/9\pi$ mode Field emission onset 30MV/m (end cell)
3. $1/9 \pi$ mode Field emission onset 5.7 MV/m (end cell) (36 MV/m for middle cell)

Field emitter location

Iris 8

Iris 9

Initial S [mm]

Impact Energy [MeV]

reverse

zigzag
Field emitter location

4. $5/9 \pi$ mode Field emission onset  28MV/m (end cell)

$E_p = 36$ MV/m
Field emitter location

5. 7/9 π mode Field emission onset 13.5 MV/m (end cell)
Field emitter location

Radiation measurement

Field emission region is: Iris 9, -9.9mm~12.2mm [S]
Correlation between Simulation and Measurements

Calculated impact energy of field emission electrons and measured end point energy in $\gamma$ spectrum $\pi$ mode

Identification

Field emission onset
1. $\pi$ mode 9MV/m
2. 6/9 $\pi$ mode 30MV/m
3. 1/9 $\pi$ mode 5.7MV/m
4. 5/9 $\pi$ mode 28MV/m
5. 7/9 $\pi$ 13.5MV/m
6. Radiation at bottom is much higher than that at top

[Graph showing the correlation between field gradient and energy with experimental and simulation data marked.]
Correlation at another Pass-Band Mode

Calculated impact energy of field emission electrons and measured end point energy in $\gamma$ spectrum $7/9\pi$ mode
Radiation angular location measurement system

Emitter

Ring 1
Ring 2
Ring 3
Ring 4
Ring 5
Ring 6

Hamamatsu S1223-01
Detector Signal Angular Distribution

$E_{acc} = 14.9 \text{ MV/m}$
Detector Signal Angular Distribution

$E_{acc}=17.5$ MV/m

- **Ring 1**: Voltage plot against angular [Rad] showing a peak and dip pattern.
- **Ring 2**: Voltage plot against angular [Rad] showing a noisy, level pattern.
- **Ring 3**: Voltage plot against angular [Rad] showing a consistent, linear dip pattern.
- **Ring 4**: Voltage plot against angular [Rad] showing a smooth, consistent trend.
- **Ring 5**: Voltage plot against angular [Rad] showing a fluctuating pattern with multiple peaks and troughs.
- **Ring 6**: Voltage plot against angular [Rad] showing a fluctuating pattern with consistent peaks and troughs.

[Graphical representations of each ring's voltage distribution against angular position.]

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**Jefferson Lab**

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**Peking University**
Photon Simulation from emission electrons

Geant 4.9.4
Electrons escaping from the cavity

- Electron density distribution
- Electron energy distribution
Photon Distribution

- Left: Photon Energy vs Position [MeV] vs [mm]
- Right: Photon Energy vs Probability Density [KeV]
Detector response

Depletion: 50um @ 20 V

Depletion (Si)
3.6 eV / (electron and hole pair)

Electron range in silicon

Electron energy loss in silicon

SILICON

- Collision Stopping Power
- Radiative Stopping Power
- Total Stopping Power

Photon Energy [MeV]

Absorption Coefficient [b/atom]

Photoelectric
Compton
Pair
Detector response to photon

![Graph showing the detector response to photon energy.](Image)
Preliminary Simulation Result

Ring 1

Ring 2

Ring 3

Ring 4

Ring 5

Ring 6
Detector Signal Angular Distribution

$E_{acc} = 17.5$ MV/m
1. Emitter is one point chosen in the Zigzag region. More simulation of the emitter location within Zigzag region will be done in the next step.
2. The beta of the field emitter is 150. This data will be fitted by the measured diode data with different gradient.
3. The diode simulation model is simple. The wafer dimension and the window or the package did not consider in the simulation. For the next step, these factors will be considered.
4. Space charge effect is not consider for the field emission electrons.
Plan for the next step
Optical Inspection

Resolution: 7.4μm/pixel

No distinguished feather was observed within the limitation.
3. Summary

- Energy measurement in RI-23 9cell cavity are agreed very well with the simulation result.
- Angular location of field emitter are done by six diode rings.
- It has been demonstrated that field emitter can be located during vertical test; the method has potential to be generalized.
- Work also extended to calculate CEBAF 12 GeV upgrade cavities.