SEY studies in CSNS

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- Measurement scheme
  - SEY and its dependence on incidence angle
  - Spatial distribution of secondary emission electrons
  - Spectrum distribution of secondary emission electrons
  - SEY depression as electron dose deposition
- Design and construct of SEE characteristics platform
- Experimental measurement and theoretical research
- Formula calculation and software simulation
- Summary and prospect
Impact of electron cloud effect

(1) During the operation of the accelerator, the electron cloud effect in the vacuum pipe can cause \textbf{beam instability}, resulting in a decrease in \textbf{beam lifetime}, generation of \textbf{the detector background} and so on.

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{simulated_bunch_size}
\caption{Simulated vertical bunch size blowup along the train}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{bpm_traces}
\caption{BPM traces of beam instability in the SNS accumulator ring}
\end{figure}

(2) The secondary electron multipacting effect occurring in the \textbf{high-frequency cavity} will cause frequent ignition of the high-frequency cavity, which severely limits the electromagnetic field intensity in the high-frequency cavity and even cause the failure of the high-frequency cavity system.

(3) Secondary electron emission \textbf{power deposition} in a beam screen in a superconducting low temperature environment may even result in quench protection of the entire superconductor system.
Source of electron cloud effect

(1) Electrons generated by beam loss;
(2) Electrons generated by ionization of residual gases in a vacuum chamber;
(3) Secondary electrons;
(4) For a proton accelerator such as CSNS, the stripping foil in the injection zone also generates a large amount of electrons;

Secondary electron emission (SEE) characteristics of material

The core of electron cloud effect research is to study the establishment process of electron cloud. The generation of secondary electrons plays a decisive role in the process of establishing the electron cloud and the final density. Therefore, this subject studies the secondary electron emission characteristics of the material.
Vacuum chamber material commonly used in accelerators

Stainless steel

Aluminum

Copper

TiZrV and TiZrHfV

Ceramic coated TiN (RCS ring of proton accelerator): Ceramic can suppress the eddy current effect produced by the rapidly changing magnetic field in the magnets of the RCS ring, but the secondary electron emission coefficient of the ceramic is relatively high, so the TiN film is to be plated on the inner wall of the ceramic vacuum chamber.
Significance

- Reference for **selecting the best vacuum chamber material**
- Providing measurement data to **improve accelerator coating process**
- Providing data for **simulation of electron cloud**
Complete secondary electron emission characteristics
SEY and its dependence on incidence angle
Spatial distribution of secondary emission electrons
Spectrum distribution of secondary emission electrons
SEY depression as electron dose deposition

Core: detector and sample holder
The detector is a three-layer structure: the outermost cap detector and wall detector are connected by an insulating ring, and the middle layer and the innermost layer are grid structures.
Sample holder: can be moved up and down in the vertical direction, and can be rotated in the axial direction from 0 to 180 degrees

$$\delta = \frac{n_{SE}}{n_{PE}}$$
Measurement scheme: SEY and its dependence on incidence angle

- **Conductive sample**

  **Sample method:** -20V bias on sample $\rightarrow I_t$ and +100V bias on sample $\rightarrow I_p$, $\delta = 1 - I_t/I_p$
  **Collector method:** +50V bias on collector $\rightarrow I_s$, +50V bias on collector and sample $\rightarrow I_p$, $\delta = I_s/I_p$

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**Sample method**

**Collector method**
Insulating sample

1. Impulsator: 150 µs, f=25 Hz TTL signal;
2. Faraday cup up, add +45 V bias on Faraday cup, single pulse mode, the pulse width is 150 µs, incident electron current is $I_p$;
3. Sample up, add +45 V bias on the complete detector, single pulse mode, secondary electron current $I_s$;
4. Before the next measurement, neutralize the charge accumulated on the sample surface: add -45V bias on the collector, periodic pulse mode, pulse duration 1~5 s, so that the secondary electron can return to the sample surface.

Neutralization method with negative bias on collector
Core: move the sample to different vertical positions to measure the current change on the cylinder type sidewall detector.

Method: \( M \rightarrow \alpha , \; I_\alpha ; \; N \rightarrow I_{\alpha + \Delta \alpha} \), \( \Delta \alpha \) and \( \Delta I_\alpha = I_\alpha - I_{\alpha + \Delta \alpha} \), 20° ~60°, 1°.

Measurement scheme:
Spatial distribution of secondary emission electrons

Difference method
The sample table is placed at the center of the hemispherical detector. By changing the grid voltage $U$, the secondary electrons with energy less than $eU$ are prevented, draw $E(eU)-\Delta I_s$ curve as spectrum distribution.
Design and construct of SEE characteristics platform

Measuring platform: vacuum system, measuring circuit system, data acquisition and equipment control system
Device advantage

• On the back of the rotatable sample holder, faraday cup (insulation sample measurement) and fluorescent target (focusing adjustment) can be installed according to the experimental requirements.

• Can measure the entire spatial distribution of secondary electrons

• Can measure the entire energy spectrum distribution of secondary electrons
**Beam Energy** | 100 eV-5000 eV
---|---
**Beam Current** | 1 nA-100 µA
**Energy Spread** | Approx 0.5 eV cathode thermal spread, calculated
**Spot Size** | 1 mm-100 mm

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**Energy stability**: ±0.01% per hour ±0.02% per 8 hours at full output; The dispersion of energy varying with filament temperature is as shown; Energy dispersion refers to the range of fluctuations centered around the set energy.

**Beam stability**: After warm up, ±0.1% per hour with Emission Current Control (ECC) or ±10% per hour without ECC.
Grid transparency:

manufacturer: 76% (vertical),
experimental measurement: 63%

Secondary electron spatial distribution is measured by secondary electron current’s relative variation under different spatial angle, and the range of almost constant grid transparency does not affect the measurement result.
Conclusion: The measurement results of the two methods are close, consistent with reference (Valizadeh, Reza, et al. 2014)

The sample method is easy to realize automatic measurement and control.

<table>
<thead>
<tr>
<th></th>
<th>Epm (eV)</th>
<th>δm</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample method</td>
<td>300</td>
<td>1.80</td>
</tr>
<tr>
<td>collector method</td>
<td>300</td>
<td>1.70</td>
</tr>
<tr>
<td>Valizadeh, Reza, et al. 2014</td>
<td>300</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Experimental measurement and theoretical research: SEY

- **Conductive sample**
  
  $I_p=300$ nA
  
  **Conclusion:** TiN (fresh) $<$ polished Si $<$ Cu $<$ polished Al $<$ TiZrHfV (nonactivated) $<$ TiN (exposed) $<$ Polished stainless steel 304 $<$ TiZrV (nonactivated). $E_{pm}$: 250 - 300 eV

Due to the material of SEY is not only related to the material composition but also surface roughness, surface pollution and so on, the measurement results of the same material under different measuring condition and different devices will have differences.

<table>
<thead>
<tr>
<th>样品</th>
<th>$E_{pm}$ (eV)</th>
<th>$\delta m$</th>
<th>$E_{pm}$ (eV) (reference)</th>
<th>$\delta m$ (reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiN (fresh)</td>
<td>230</td>
<td>1.66</td>
<td>300</td>
<td>1.5~2.4</td>
</tr>
<tr>
<td>Polished Si</td>
<td>200</td>
<td>1.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>300</td>
<td>1.90</td>
<td>300</td>
<td>1.90</td>
</tr>
<tr>
<td>Polished Al</td>
<td>300</td>
<td>1.97</td>
<td>300</td>
<td>2.55</td>
</tr>
<tr>
<td>TiZrHfV</td>
<td>250</td>
<td>2.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiN (expose for 3 month)</td>
<td>275</td>
<td>2.15</td>
<td>300</td>
<td>1.5~2.4</td>
</tr>
<tr>
<td>Polished stainless steel 304</td>
<td>250</td>
<td>2.23</td>
<td>300</td>
<td>2.25</td>
</tr>
<tr>
<td>TiZrV</td>
<td>250</td>
<td>2.32</td>
<td>250</td>
<td>1.3~2</td>
</tr>
</tbody>
</table>
Experimental measurement and theoretical research: SEY

- Insulating sample

Voltage signal $U_p$ at faraday cup measured by oscilloscope

Voltage signal $U_s$ at the collector measured by oscilloscope after neutralization

SEY of ceramic samples
Experimental measurement and theoretical research: SEY

- Insulating sample

**Conclusion:** The SEY of ceramic sample is very high, Primary energy $75 \text{ eV} \rightarrow 1.9$, $E_{pm}: 775 \text{ eV} \rightarrow 5.97$, constant with Dawson, P. H., 1966(6.4).

In order to reduce the eddy current effect on the vacuum chamber surface caused by the rapidly changing magnetic field in magnet in CSNS, ceramic is used as vacuum chamber material in the RCS ring, but the electron cloud effect caused by the high secondary electron yield will affect the stability of the proton beam, so the inner wall of the ceramic vacuum chamber was then plated with TiN films of suitable thickness with good vacuum properties and low secondary electron emission coefficient. After coated with TiN, $5.97 \rightarrow 1.66$, rose to 2.15(exposed to the air for 3 month) due to contamination.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$E_{pm}$ (eV)</th>
<th>$\delta m$</th>
<th>$E_{pm}$ (reference)</th>
<th>$\delta m$ (reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ceramic</td>
<td>775</td>
<td>5.97</td>
<td>650</td>
<td>6.4</td>
</tr>
<tr>
<td>Coated with TiN (fresh)</td>
<td>230</td>
<td>1.66</td>
<td>300</td>
<td>1.5~2.4</td>
</tr>
</tbody>
</table>
Oblique incidence

Conclusion: In the range of 0-60°, the SEY gradually increases with the increase of the incident angle θ, and has a cosine relationship with the incident angle. However, the SEY begins to decrease after the incident angle increased to 60°, which is consistent with the reference (Lin Zulun, 2013).

This may be because the measurement error increase with the increase of the incident angle θ.
Comparing the measurement results with the calculation results of the cosine function formula, it can be seen that the corresponding coefficients $n$ of several materials range from about 0.16 to 0.80:

$$y = \cos(\theta)^{-n}$$

Where $n$ is a parameter related to the material and the energy of the incident electrons.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.25~0.50</td>
</tr>
<tr>
<td>TiN</td>
<td>0.15~0.40</td>
</tr>
<tr>
<td>TiZrHfV</td>
<td>0.15~0.40</td>
</tr>
<tr>
<td>TiZrV</td>
<td>0.40~0.80</td>
</tr>
</tbody>
</table>
Experimental measurement and theoretical research: Spatial distribution of secondary emission electrons

\( E_p=600 \text{ eV}, \ I_p=500 \text{ nA} \)

**Conclusion:** According to the theory (Ciappa et al., 2012), the number of true secondary electrons at the unit solid angle conforms to the following formula. The parameters obtained by fitting the measurement results using the formula are shown in the following table.

\[
f(\theta) = \cos \theta (1 + a \sin^2 \theta + b \sin^4 \theta + \ldots)
\]

<table>
<thead>
<tr>
<th>Sample</th>
<th>( a )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>-2.10</td>
<td>1.63</td>
</tr>
<tr>
<td>TiN</td>
<td>-1.24</td>
<td>1.91</td>
</tr>
<tr>
<td>TiZrHfV</td>
<td>-1.09</td>
<td>2.03</td>
</tr>
<tr>
<td>TiZrV</td>
<td>-0.96</td>
<td>1.99</td>
</tr>
</tbody>
</table>

Fitting parameters for different samples

Secondary Electron Spatial Distribution in Cartesian and Polar Coordinate Systems
Measure the complete energy spectrum of secondary electrons and determine the proportion of different kinds of secondary electrons;

Calculated the full width at half maximum (FWHM) of the true secondary electron peak and the elastic reflected electron peak;

Using the gaussian function to fit the secondary electron peak and the elastic reflected electron peak.
Measure the complete energy spectrum of secondary electrons and determine the proportion of different kinds of secondary electrons.

Conclusion:
0 ~ 50 eV (secondary electron peak), \( E_p \) (elastic scattering peak).

<table>
<thead>
<tr>
<th>材料</th>
<th>( E_p ) (eV)</th>
<th>SE</th>
<th>ERE</th>
<th>IRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>150</td>
<td>80.2%</td>
<td>4.8%</td>
<td>15.0%</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>79.9%</td>
<td>3.1%</td>
<td>17.0%</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>76.8%</td>
<td>2.9%</td>
<td>20.3%</td>
</tr>
<tr>
<td>TiN</td>
<td>150</td>
<td>81.8%</td>
<td>3.3%</td>
<td>14.9%</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>78.7%</td>
<td>3.5%</td>
<td>17.8%</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>78.5%</td>
<td>3.0%</td>
<td>18.5%</td>
</tr>
<tr>
<td>TiZrHfV</td>
<td>150</td>
<td>83.5%</td>
<td>3.1%</td>
<td>13.4%</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>80.7%</td>
<td>2.7%</td>
<td>16.6%</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>78.5%</td>
<td>2.4%</td>
<td>19.1%</td>
</tr>
<tr>
<td>TiZrV</td>
<td>150</td>
<td>84.8%</td>
<td>2.8%</td>
<td>12.4%</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>84.2%</td>
<td>2.2%</td>
<td>13.6%</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>83.3%</td>
<td>1.8%</td>
<td>14.9%</td>
</tr>
</tbody>
</table>

Total secondary electron energy spectrum of different materials

The proportion of secondary electrons in each component (80%, 3%, 17%)
The position of the true secondary electron peak changes very little with the change of the energy of the incident electron, but the position of the elastic scattering peak increases with the increase of the energy of the incident electron.

Generation mechanism: extranuclear electron, primary electron
Calculated the full width at half maximum (FWHM) of the true secondary electron peak and the elastic reflected electron peak.

Conclusion: the position of energy spectrum peak is consistent with reference, and the half height and width is slightly larger than that of reference (Staib, Ph, and U. Dinklage, 1977)

<table>
<thead>
<tr>
<th>Ep (eV)</th>
<th>Cu</th>
<th>Al</th>
<th>Si</th>
<th>Stainless steel 304</th>
<th>TiN</th>
<th>TiZrV</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2.4</td>
<td>4.0</td>
<td>3.0</td>
<td>2.6</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td>200</td>
<td>2.2</td>
<td>3.6</td>
<td>3.2</td>
<td>2.4</td>
<td>2.6</td>
<td>2.2</td>
</tr>
<tr>
<td>250</td>
<td>2.2</td>
<td>3.6</td>
<td>3.0</td>
<td>2.4</td>
<td>2.6</td>
<td>2.2</td>
</tr>
<tr>
<td>300</td>
<td>2.2</td>
<td>3.6</td>
<td>2.8</td>
<td>2.2</td>
<td>2.6</td>
<td>2.2</td>
</tr>
<tr>
<td>500</td>
<td>2.2</td>
<td>3.6</td>
<td>2.6</td>
<td>2.2</td>
<td>2.4</td>
<td>2</td>
</tr>
<tr>
<td>800</td>
<td>2.0</td>
<td>3.4</td>
<td>2.6</td>
<td>2.4</td>
<td>2.4</td>
<td>1.8</td>
</tr>
<tr>
<td>1500</td>
<td>2.0</td>
<td>3.4</td>
<td>2.0</td>
<td>2.2</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td>2500</td>
<td>1.8</td>
<td>3.2</td>
<td>2.0</td>
<td>2.0</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The position of the true secondary electron energy spectrum peak (eV) (2~4eV)

<table>
<thead>
<tr>
<th>Ep (eV)</th>
<th>SE (eV)</th>
<th>ERE (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>5.6</td>
<td>10.1</td>
</tr>
<tr>
<td>200</td>
<td>5.4</td>
<td>14.5</td>
</tr>
<tr>
<td>250</td>
<td>5.4</td>
<td>18.6</td>
</tr>
<tr>
<td>150</td>
<td>6.0</td>
<td>12.7</td>
</tr>
<tr>
<td>200</td>
<td>5.8</td>
<td>22.7</td>
</tr>
<tr>
<td>250</td>
<td>5.0</td>
<td>25.2</td>
</tr>
<tr>
<td>150</td>
<td>4.9</td>
<td>11.8</td>
</tr>
<tr>
<td>200</td>
<td>4.7</td>
<td>17.9</td>
</tr>
<tr>
<td>250</td>
<td>4.6</td>
<td>19.6</td>
</tr>
<tr>
<td>150</td>
<td>5.1</td>
<td>9.6</td>
</tr>
<tr>
<td>200</td>
<td>4.4</td>
<td>12.9</td>
</tr>
<tr>
<td>250</td>
<td>4.2</td>
<td>19.0</td>
</tr>
</tbody>
</table>

True secondary electron and elastic scattering electron energy spectrum half high and wide (5 eV, 16 eV)
Using the gaussian function to fit the secondary electron peak and the elastic reflected electron peak

Satisfy: gaussian distribution; For: simulation of electron clouds

\[ f(x) = a_1 \times e^{-\frac{(x-b_1)^2}{2c_1}} + a_2 \times e^{-\frac{(x-b_2)^2}{2c_2}} + a_3 \times e^{-\frac{(x-b_3)^2}{2c_3}} + \ldots \]
**Experimental measurement and theoretical research**

\[ E_p=250 \text{ eV}, \ I_p=0.6 \ \mu \text{A} \]

**Conclusion:** the SEY of each material decreases with the increase of incident electron dose and finally becomes stable.

Analysis: Electron bombardment can cause changes in the surface of the material, removing contaminants and oxides on the surface of the material, and even forming a carbon film on the surface, making the measured SEY lower (Larciprete R, 2013).

Bombardment reducing SEY is an effective secondary electron suppression measure.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \delta_0 )</th>
<th>( \delta )</th>
<th>Dose ( \times 10^{-3} \text{C/mm}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>1.81</td>
<td>1.46</td>
<td>3.13</td>
</tr>
<tr>
<td>TiN</td>
<td>1.60</td>
<td>1.12</td>
<td>1.82</td>
</tr>
<tr>
<td>TiHfZrV</td>
<td>1.84</td>
<td>1.71</td>
<td>0.51</td>
</tr>
<tr>
<td>Stainless steel 304</td>
<td>1.76</td>
<td>1.69</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Formula calculation and software simulation

Formula

\[ \delta_{e0} = \frac{K}{\varepsilon} \int_0^1 \frac{G}{E_{p0}} e^{-\alpha s \cos \theta} ds = \frac{KG(e-1)}{\varepsilon e E_{p0} \alpha \cos \theta} \]  

(1)

\[ \delta = 0.5 \times \frac{E_{p0}}{\varepsilon} \times \frac{\lambda}{R} \left(1 - e^{-\frac{R}{\lambda}}\right) \]  

(2)

\[ \frac{\delta}{\delta_m} = 1.28 \left(\frac{E_p}{E_p^m}\right)^{-0.67} \left(1 - \exp(-1.614 \left(\frac{E_p}{E_p^m}\right)^{1.67})\right) \]  

(3)

Casino

Based on Monte Carlo simulation method: A computer experimental method for simulating the motion of real particles using the idea of probability statistics.

(DEMERSH, 2011)
Conclusion:
As the energy of the incident electrons increases, the yield of backscattered electrons first increases and then decreases, and the yield of true secondary electrons (SE) and the total secondary electrons (TSE) continue to decrease. As the incident electron energy increases, the proportion of true secondary electrons (SE) decreases, and the proportion of reflected electrons (RE) increases.

The work function used in the simulation is the default value of the software, Al is 4.28 eV and Si is 4.85 eV.
The calculation result of formula (3) is consistent with the trend of experimental measurement results. Software simulation is consistent with experimental data after 500 eV. The numerical differences are as follows:

$$\frac{\delta}{\delta_m} = 1.28 \left( \frac{E_p}{E_p^m} \right)^{0.67} (1 - \exp(-1.614 \left( \frac{E_p}{E_p^m} \right)^{1.67}))$$

(3)

The theoretical formula is a result of a series of formulae approximate derivation, so there is a certain gap between the true value.

The theoretical formula and software simulation only consider the nature of the sample material itself, and do not consider the state of surface contamination, adsorption, roughness, etc. Therefore, there is a certain gap between the actual value and the actual value.

In the theoretical formulas and software simulations, true secondary electron yields are calculated, however the experiment measures the total secondary electron yield. The value of the total secondary electron yield is the sum of the true secondary electron yield value and the value of the backscattered electron yield. From the measurement analysis, it can be seen that the proportion of backscattered electrons increases with increasing incident energy. Therefore, the experimental measurement is slightly larger than the calculated value of the formula and the difference between the two increases gradually with the increase of energy.
Summary

- The differential method was used to verify the measurement scheme of the secondary electron spatial distribution, and a multi-functional, high-efficiency secondary electron emission characteristic measurement platform capable of simultaneously measuring secondary electron yield, energy spectrum distribution, and spatial distribution was constructed.

- TiN (fresh) < polished Si < Cu < polished Al < TiZrHfV (nonactivated) < TiN (exposed) < Polished stainless steel 304 < TiZrV (nonactivated) < ceramic. Epm: 250 - 300 eV, δm: 1.66 ~ 2.32, ceramic after coated with TiN, 5.97 → 1.66

- δ has a cosine relationship with the incident angle in 0~60°.

- The spatial distribution satisfies cosine distribution.

- The spectrum distribution satisfies gaussian distribution.

- SEY of each material decreases with the increase of incident electron dose and finally come to be stable
Prospect

- Further study on the new materials such as graphene
- Add heating and baking equipment
- Add low temperature superconducting equipment
- Upgrade to on-line measuring device
Thank you for your attention and advice!