PITZ: Simulations versus Experiment

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Darmstadt, 19.12.2013

• Emittance and brightness vs. bunch charge
• Emission area homogeneity
• Emittance vs. main solenoid current
• “Fin structure” investigations – coaxial coupler kick?
• Photo emission studies – various cathode laser temporal profiles
• Recent problem: gun cavity resonance temperature drift
Emittance versus Laser Spot Size for various Charges

<table>
<thead>
<tr>
<th>Charge, nC</th>
<th>Measured, mm mrad</th>
<th>Simulated, mm mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.25±0.06</td>
<td>1.14</td>
</tr>
<tr>
<td>1</td>
<td>0.70±0.02</td>
<td>0.61</td>
</tr>
<tr>
<td>0.25</td>
<td>0.33±0.01</td>
<td>0.26</td>
</tr>
<tr>
<td>0.1</td>
<td>0.21±0.01</td>
<td>0.17</td>
</tr>
<tr>
<td>0.02</td>
<td>0.121±0.001</td>
<td>0.06</td>
</tr>
</tbody>
</table>

- Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
- Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
- Simulations of the emission needs to be improved

Minimum emittance $\sqrt{\epsilon_{nx}\epsilon_{ny}}$
Cathode laser pulse duration was **fixed at 21.5 ps (FWHM)** for all bunch charges!

Bunch charge reduction at fixed cathode laser pulse duration → space charge (SC) modification

\[
B_{\text{injector}} = \frac{I_{\text{injector}}}{\varepsilon_x \varepsilon_y} = \frac{Q \cdot NoP \cdot RR}{\varepsilon_x \varepsilon_y}
\]
Emission Area Homogeneity

Cs2Te cathode#110.2

Cathode QE map

\[
\min(\varepsilon_{n,x} \varepsilon_{n,y}) = 0.762 \pm 0.017 \text{ mm mrad}
\]

~emission area

E-beam ➔

X-Y

X-Px

Y-Py

Cs2Te cathode#11.3

Cathode QE map

\[
\min(\varepsilon_{n,x} \varepsilon_{n,y}) = 0.661 \pm 0.033 \text{ mm mrad}
\]

~emission area

E-beam ➔

X-Y

X-Px

Y-Py

Measured 1nC emittance vs. I_main

- x-emit (cath.#110.2)
- y-emit (cath.#110.2)
- xy-emit (cath.#110.2)
- x-emit (cath.#11.3)
- y-emit (cath.#11.3)
- xy-emit (cath.#11.3)

main solenoid current (A)
S↔M versus main solenoid current (1nC)

From magnetic measurements:
\[-B_{\text{max}}[T] = 0.0005893 \times I_{\text{main}}[A] - 0.00001169\]

ΔI(M-S)~9A!
S\leftrightarrow M versus main solenoid current (1nC)

- Measured X-Y
- Simulated X-Y

But:
- Magnetizable girder
- Weak Cu diamagnetism

\[ B_{\text{max}} \rightarrow B_{\text{max}} \times 0.977 \]

?Origin of these tails?
“Fin structure” investigations (Gun-4.3, not nominal setup)

Electron beam on HIGH1.Scr1 (EMSY, z=5.74m, Imain=363A)

booster on

booster off

[Ref] → Report on Gun-4.3 conditioning at PITZ in 2013
Coaxial Waveguide: TE_{11} (H_{11}) mode,

\[ f_c = \frac{k_c c}{2\pi} \approx \frac{c}{\pi(a+b)} = 1.331\,GHz \]

\[ f_{co} = \frac{k_c c}{2\pi} = 1.358\,GHz \]

\[ L_{att} = \frac{c}{2\pi \sqrt{f_c^2 - f^2}} = 121\,mm \]
RF field asymmetry?

H-fields x-cut plane

H-fields z-cut plane

MWS simulations: Igor Isaev

More detailed modeling/simulations are required...
Discrepancy in simulated and experimentally produced bunch charge

![Graph showing simulated and measured bunch charge vs. gun phase.](image)

- Laser rms spot size: 0.3mm(exp) vs. 0.4mm(sim)
- Main solenoid current $\Delta l(M-S) \sim 9A$
- RF gun phase: $+6\text{deg}(exp)$ vs. $\sim 0\text{deg}(sim)$ → field enhancement?
- Experiment → close to the SC limit!

Discrepancy in experimental and simulated optimum machine parameters:
- Laser rms spot size: 0.3mm(exp) vs. 0.4mm(sim)
- Main solenoid current $\Delta l(M-S) \sim 9A$
- RF gun phase: $+6\text{deg}(exp)$ vs. $\sim 0\text{deg}(sim)$ → field enhancement?
- Experiment → close to the SC limit!

Discrepancy in electron beam transverse profile (e.g. at EMSY1)

- Optimized photo injector → large fraction of the intrinsic cathode emittance in the overall emittance budget. (Slice) emittance formation → in the cathode vicinity!
Emission studies: Ecath·LaserSpotSize=const

Simultaneous variation of the rf field and the space charge density at the cathode by keeping the laser pulse energy and $E_{cath0} \cdot \sigma_{xy}^{laser}$ constant yields very similar extracted bunch charge for a rather wide range of the launch phase.

From the parallel plate capacitor (PPC) model:

$$Q_{\text{QE-\text{lim},PPCM}} = \pi \varepsilon_0 R^2 E_0 \sin \varphi_0 = \pi \varepsilon_0 R^2 E_{cath}$$
Emission G-FT program (February 2013): main idea

Laser temporal profile

- x 2 gun gradients (7.75MW and 4MW)
- x laser pulse energies (e-meter in tunnel 4; 20; 37nJ), same for the Gaussian and F-T profiles
- long. momentum measurements
- laser pulse energy (LT) scans for the MMMG phase

<table>
<thead>
<tr>
<th></th>
<th>7.75MW</th>
<th>4MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat-top (17ps)</td>
<td>case 1</td>
<td>case 3</td>
</tr>
<tr>
<td>Short Gaussian (2.7ps)</td>
<td>case 2</td>
<td>case 4</td>
</tr>
</tbody>
</table>
Emission studies: Field enhancement and QE-limited charge

\[ Q_{QE - lim} \propto Q_0 \left(1 - \frac{\phi_{eff}}{\hbar \omega}\right)^m \]

\[ \phi_{eff} = 3.5eV - 0.0379 \sqrt{E_{cath}(MV/m)}; \ h\omega = 4.81eV \]

\begin{tabular}{|c|c|c|}
\hline
\textit{E}_{laser} & \text{fitted } Q_0 \ (m=2) & \\
(nJ) & /4nJ & /Q0(4nJ) \\
\hline
4 & 1 & 2169 & 1.00 \\
20 & 5 & 11384 & 5.25 \\
37 & 9.25 & 20152 & 9.29 \\
\hline
\end{tabular}

- \[ m=2 \rightarrow \text{better fit for low SCD@cathode} \]
- \[ \text{Higher SCD} \rightarrow m<2 \]
The case of short Gaussian pulses and low gun gradient (4 MW in the gun) ➔ the strongest saturation of the charge production due to a stronger space charge effect.

The lowest space charge density case (− the flat-top and 7.75 MW in the gun) ➔ the most linear charge production curve.

It is interestingly enough the closeness of curves for the 4 MW gun power and flat-top laser pulse to the dependence for 7 MW and the short Gaussian pulse:

- projected space charge density for these two cases is different (in a factor of ~6)
- rf fields at the moment of emission is different (29 MV/m for 4 MW and 45 MV/m for 7.75 MW).
Laser transverse halo modeling-1: fitting measurements

Simultaneous fit of 4 curves using:

\[ Q_{\text{max}}(7.75 \text{MW}) = Q_{\text{max}}(4.0 \text{MW}) \cdot \frac{E_{\text{cath}_2} \cdot \sin \varphi_{\text{MMMG}_2}}{E_{\text{cath}_1} \cdot \sin \varphi_{\text{MMMG}_1}} \]

<table>
<thead>
<tr>
<th>Laser temporal profile</th>
<th>rf peak power</th>
<th>QE</th>
<th>( Q_{\text{max}} )</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat-top (17ps)</td>
<td>7.75MW</td>
<td>8.68%</td>
<td>457pC</td>
<td>12.9</td>
</tr>
<tr>
<td>Short Gaussian (2.7ps)</td>
<td></td>
<td></td>
<td>291pC</td>
<td>12.1</td>
</tr>
<tr>
<td>Flat-top (17ps)</td>
<td>4.0MW</td>
<td>8.12%</td>
<td>293pC</td>
<td>12.3</td>
</tr>
<tr>
<td>Short Gaussian (2.7ps)</td>
<td></td>
<td></td>
<td>187pC</td>
<td>21.8</td>
</tr>
</tbody>
</table>

The overall \( \chi^2 \) of the fit is 59.2, the reduced chi-squared statistic yields \( \chi_{\text{red}}^2 = \frac{\chi^2}{\nu} = 0.79 \), where the number of degrees of freedom \( \nu = N_{\text{points}} - N_{\text{fit.par.}} - 1 = 75 \).
Laser transverse halo modeling-2: fitting measurements

Simultaneous fit of 4 curves using:

\[ Q_{\text{max}}(7.75\text{MW}) = Q_{\text{max}}(4.0\text{MW}) \cdot \frac{E_{\text{cath2}} \cdot \sin \varphi_{\text{MMMG2}}}{E_{\text{cath1}} \cdot \sin \varphi_{\text{MMMG1}}} \]

\[ \rho_{\text{scl}}(\text{flat – top}) \approx 1.51 \]

The overall \( \chi^2 \) of the fit is 53.5, the reduced chi-squared statistic yields \( \chi^2_{\text{red}} = \frac{\chi^2}{\nu} = 0.73 \), where the number of degrees of freedom \( \nu = N_{\text{points}} - N_{\text{fit.par.}} - 1 = 73 \).
Recent problem: gun cavity resonance temperature drift

The resonance temperature drift/variation of ~4degC over two months of conditioning seems to be real:

- The same temperature difference observed at various gun iris sensors
- There is a direct linear correlation of the gun iris temperature with temperature of input and output water channels
- Water flow is almost constant for the monitoring measurements
- Estimated heat transfer is constant within error bars
- Cathode re-insertion/exchange experiments show that these manipulations cannot explain the observed temperature drift

Measurement benchmark:
3.6MW in gun (reflection=4%), 400us, 10Hz

NB: \( \frac{df}{dT} \approx -22 \text{kHz/degC} \)

? Inelastic deformation of the gun cavity?

? Can it be accurately simulated?
Conclusions

> PITZ ➔ for theoretical understanding of the photo injector physics (beam dynamics simulations vs. measurements)
  - rather good agreement on emittance minima between measurements and simulations
  - optimum machine parameters: simulations ≠ experiment
  - simulations of the emission needs to be improved

> “Fin structure” investigations ➔ asymmetry in RF fields in gun cavity due to the coaxial coupler kick has to be modelled and simulated in more details. Also – more dedicated measurements? Any ideas are welcomed!

> Photoemission studies at PITZ:
  - Key to understand the M-S discrepancies ➔ more precise modelling of the photoemission is needed (intrinsic cathode emittance formation)
  - Important for further optimization (e.g. 3D ellipsoidal pulses)
  - Recent studies using short Gaussian and long flattop cathode laser pulses:
    - transient effect ➔ depends on the laser temporal profile (parallel plate capacitor model)
    - field enhancement determined also by the peak field as well as by the space charge

> Long-term drift of the gun resonance temperature ➔ cavity deformations?