RF Cavity Simulation for SPL

Simulink Model for single RF Cavity with Lorentz Detuning and RF Feedback Loop using I/Q Components

Acknowledgement:
CEA team, in particular O. Piquet (simulink model)
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This project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under the Grant Agreement n°212114
SPL High Power Operation

**General linac parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>HP-SPL</th>
<th>LP-SPL</th>
<th>Timestamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power</td>
<td>[MV]</td>
<td>&gt;4.0</td>
<td>0.192</td>
<td>31 March 2008</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>[Hz]</td>
<td>50</td>
<td>2</td>
<td>15 August 2007</td>
</tr>
<tr>
<td>Average pulse current</td>
<td>[mA]</td>
<td>20/40</td>
<td>0-20</td>
<td>28 November 2006</td>
</tr>
<tr>
<td>Peak pulse current</td>
<td>[mA]</td>
<td>32/64</td>
<td>32</td>
<td>15 August 2007</td>
</tr>
<tr>
<td>Source current</td>
<td>[mA]</td>
<td>40/60</td>
<td>40</td>
<td>21 April 2006</td>
</tr>
<tr>
<td>Chopping ratio</td>
<td>[%]</td>
<td>02</td>
<td>02</td>
<td>21 November 2006</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>[ns]</td>
<td>0.4(2)-1.2(3)</td>
<td>0.9</td>
<td>6 July 2009</td>
</tr>
<tr>
<td>Number of klystrons (704 MHz, 5 MW)</td>
<td>tbd</td>
<td>tbd</td>
<td>16 August 2007</td>
<td></td>
</tr>
<tr>
<td>Geometric cavity beta</td>
<td></td>
<td>0.65/1.0</td>
<td>0.65/1.0</td>
<td>24 April 2009</td>
</tr>
<tr>
<td>Number of cavities</td>
<td></td>
<td>60/184</td>
<td>60/144</td>
<td>2009-10-06</td>
</tr>
<tr>
<td>Additional cavities for debunching</td>
<td>0/16</td>
<td>0/16</td>
<td>2009-10-06</td>
<td></td>
</tr>
<tr>
<td>Cavities/klystron</td>
<td></td>
<td>tbd</td>
<td>tbd</td>
<td>22 April 2008</td>
</tr>
<tr>
<td>Cavities/cryostat</td>
<td></td>
<td>6/8</td>
<td>6/8</td>
<td>23 April 2008</td>
</tr>
<tr>
<td>Max. power/cavity</td>
<td>[MW]</td>
<td>1</td>
<td>0.5</td>
<td>21 April 2008</td>
</tr>
<tr>
<td>Length (4)</td>
<td>[m]</td>
<td>529</td>
<td>454</td>
<td>24 April 2009</td>
</tr>
</tbody>
</table>

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(1) assuming that the full klystron power is distributed to the cavities, which means splitting ratios up to 1 klystron/16 cavities
(2) expected nominal operation
(3) ultimate operation
(4) excluding Linac4, including 16 debuncher cavities at linac end, including extraction to ISOLDE and EURISOL

Parameters from SPL twiki web page (F. Gerigk)
https://twiki.cern.ch/twiki/bin/view/SPL/SPLparameterList

\[ f_{RF} = 704.4 \text{ MHz} \]
\[ I_b \simeq 40 \text{ mA} \]
\[ \phi_s = 15^\circ (\text{LINAC}) \]
\[ E_{acc} = 25 \text{ MV} \]
\[ length_{cav} = \beta \times \frac{\lambda_{RF}}{2} \times 5 (5 \text{ cell, } \pi \text{ mode}) \]
\[ V_{acc} = E_{acc} \times length_{cav} = 26.6 \text{ MV} \]
\[ P_b = V_{acc} \times I_b \times \cos(\phi_s) \simeq 1 \text{ MW} \]
\[ Q_L = \frac{V_{acc}}{R} \times I_b \times \cos(\phi_s) \simeq 1.3 \times 10^6 \]
\[ \frac{R}{Q} = 525 \text{ } \Omega \text{ (LINAC)} \]
\[ \tau_{\text{beampulse}} = 1.2 \text{ ms} \]
\[ \text{rep period} = 20 \text{ ms} \]
\[ I_g \simeq 40 \text{ mA} \]
\[ R_L = 680 \text{ M}\Omega \]
Simulink High-Level Model of Single Cavity with Feedback

- $f_{RF} = 704.4 \text{ MHz}$
- $I_b \approx 40 \text{ mA}$
- $\phi_b = 15^\circ$
- $P_b = 1 \text{ MW}$
- $Q_L = 1.3 \times 10^6$
- $\tau_{beam} = 1.2 \text{ ms}$
- $\tau_{rep \ period} = 20 \text{ ms}$
- $I_g \approx 40 \text{ mA}$
- $R_L = 680 \text{ M\Omega}$
Pulsed Source

- Frequency response modeled as a high bandwidth low-pass filter for I/Q
Circulator and Waveguide/Cavity Coupling

Future: refine and study how to include circulator mismatch
Cavity Model
Model Created using I/Q Differential Transient Relation Driven by Generator and Beam Current
Cavity Model (cont)

Simplified Diagram
Cavity differential equations plus beam loading instant \(\rightarrow\) voltage drops result in output curve for cavity voltage.

\[
V_{\text{cav bunch }_1} = \omega_{RF} \times \frac{R}{Q} (\text{circuit}) \times q_b \times \cos(\phi_s)
\]

\[
V_{\text{cav bunch }_Q} = \omega_{RF} \times \frac{R}{Q} (\text{circuit}) \times q_b \times \sin(\phi_s)
\]

\[
\frac{d\Delta \omega(t)}{dt} = -\frac{1}{\tau} (\Delta \omega(t) - \Delta \omega_r + 2\pi KE_{acc}^2)
\]

\[
R_L (2I_g + I_b)_{\text{inphase}} = \tau \frac{dV_{\text{inphase}}}{dt} + V_{\text{inphase}} - yV_{\text{quad}}
\]

\[
R_L (2I_g + I_b)_{\text{quad}} = \tau \frac{dV_{\text{quad}}}{dt} + V_{\text{quad}} + yV_{\text{inphase}}
\]
Beam Loading

- Infinitely narrow bunches induce an instant voltage drop in cavity
- Lump beam loading together in infinitesimal short “macro-bunches”, i.e. every 140 ns

- Voltage drop is equal to gene creating flattop operation

\[
V_{\text{cav bunch } I} = \omega_{RF} \times \frac{R}{Q} (\text{circuit}) \times q_b \times \cos(\phi_s)
\]
\[
V_{\text{cav bunch } Q} = \omega_{RF} \times \frac{R}{Q} (\text{circuit}) \times q_b \times \sin(\phi_s)
\]
RF Feedback

- PI controller model
- Output frequency response of feedback amplifier modeled as first order low-pass filter with 100 kHz bandwidth (1 MHz Klystron BW)

\[ K_p = 50 \]
\[ K_i = 0.01 \]
Results

• Cavity Voltage Amplitude and Phase

• Forward and Reflected Power

• Additional Power for Feedback Transients and Control

• Effect of Lorentz Detuning on Feedback Power
Cavity Voltage and Phase in the Absence of Lorentz Detuning (Closed Loop)

Feedback loop is closed 0.1 ms after generator pulse and 0.1 ms after end of beam loading pulse.

5 μs delay for Feedback Loop

Cavity phase optimized for 15 degree synchronous angle.
Effect of Lorentz Detuning on Cavity Voltage and Phase (Lorentz Frequency Shift)

\[
\frac{d\Delta \omega(t)}{dt} = \frac{-1}{\tau} (\Delta \omega(t) - \Delta \omega_r + 2\pi KE_{acc}^2)
\]
Effect of Lorentz Detuning on Cavity Voltage and Phase (Open Loop)

Decrease in accelerating voltage

Cavity Voltage

Linear phase shift for undriven cavity
Cavity Voltage and Phase With Lorentz Detuning
(Closed Loop Performance of Fast Feedback)

Lorenz force detuning and linear phase change when feedback is off and cavity is undriven.
Cavity Voltage and Phase Close-up

Cavity Voltage

Injection Time
(start of beam pulse)

Cavity Voltage Phase

Injection Time
(start of beam pulse)
Forward and Reflected Power without Lorentz Detuning

Oscillations due to transients during closing of the feedback loop and beam loading. Feedback loop is closed 0.1 ms after generator pulse and 0.1 ms after end of beam loading pulse.
Forward and Reflected Power and Feedback Power Consumption with Lorentz Force detuning

Oscillations due to transients during closing of the feedback loop and beam loading. Feedback loop is closed 0.1 ms after generator pulse and 0.1 ms after end of beam loading pulse.
Frequency Considerations

- Stability Observations using Gain and Phase Margin
- Effects of Delay on Transfer Function
Full Open-Loop System Bode Plot
(100 kHz feedback BW)

\[ f_{FB\_pole} = 100 \text{kHz} = 628 \text{krad/s} \]
\[ f_{Kly\_pole} = 1 \text{MHz} = 6.28 \text{Mrad/s} \]
\[ f_{cav\_2\_poles} = 318 \text{Hz} = 2 \text{krad/s} \]
\[ f_{cav\_zero} = 318 \text{Hz} = 2 \text{krad/s} \]

Gain Margin \( \approx 35 \text{ dB} \)

Effect of 5us Delay
Next Step

- Observe stability and frequency performance using analytical methods for finding optimum integrating gain $K$.

- Include and quantify effect from finite bunch length.

- Observe performance for multiple non-identical cavities and use adaptive feedforward.

- Observe cavity voltage response to $H$ source fluctuations.

- Quantify extra power required due to modulator droop and ripple.