Linear Particle Accelerator Control Performance

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Johnny Tang
Overview of the Spallation Neutron Source Accelerator
Overview of the Spallation Neutron Source (SNS) Accelerator
How does it work?

Front-End Systems, 7m long
Generate 2.5 MeV H- Beam of Minipulses, 68% beam, 32% gap, made by chopper, every 945ns for 1 ms long, 60 times per second

Injection Kickers

Extraction Kickers

Beam Travel Length
FE 7m
LINAC
HEBT
Ring

Current

minipulse

945 ns

1 ms macropulse @ 60 Hz
How does it Work?

LINAC Systems, 300m long
Accelerate the H- beam pulse to 1 GeV

Current

945 ns

minipulse

1 ms macropulse @ 60 Hz

Injection Kickers

Extraction Kickers

Beam Travel Length

FE 7m
LINAC 300m
HEBT
Ring
How does it Work?

HEBT Systems, 170m long
Transport the 1 GeV H- Beam of Minipulse to the strip foil at the Ring Injection;
H- stripped to protons

Injection Kickers

Extraction Kickers

Beam Travel Length
FE 7m
LINAC 300m
HEBT 170m
Ring

945 ns
1 ms macropulse
**How does it Work?**

**Accumulator Ring Systems, 248m circumference**
Compress 1 ms long beam pulse to 650 ns; Preprogrammed Inj. Kickers move each mini-pulse transversely to meet beam specs. (*Inj. Painting Process*)

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**Injection Kickers**

**Mini-pulse**

**Beam Travel Length**
- FE: 7m
- LINAC: 300m
- HEBT: 170m
- Ring: 248m

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**H- Beam**

945 ns

1 ms macropulse

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**Proton Beam in the ring**

**Current**

1 ms
How does it Work?

The 14 Extraction Kickers fire simultaneously at the circulating beam gap to cause the beam to be deflected downward and then to be delivered to its target.

Protons are accumulated in a 650 ns bunch in 1060 turns.

Current

1ms

Beam Travel Length

- FE: 7m
- LINAC: 300m
- HEBT: 170m
- Ring: 248m
- FE to Inj.: 477m
- Inj to Ext.: 124m
How does it Work?

Tb – Beam Travel Time

Tev -Timing Event Travel Time

Tkick – Event and Signal Travel Time and Tdelay

Tkick + Tdelay = Tev + Tb

Beam Travel Length
- FE 7m
- LINAC 300m
- HEBT 170m
- Ring 248m
- FE to Inj. 477m
- Inj to Ext. 124m
Resonance Control Philosophy

- The LLRF system controls the rf frequency at the klystron
- Each tank is tuned to resonate at 402.5 MHz under vacuum at a predetermined temperature
  - Cavity resonant frequency is determined by its detailed geometry
  - Cavity geometry & resonant frequency can be modified thermally @ ~7kHz/C
- The RCCS system controls the cavity resonant frequency by
  - Controlling tank temperature and ....
  - Removing the heat dissipated by the cavity rf fields
- Frequency excursions are minimized to limit the reflected power
Drift Tube Linac (DTL)
RCCS Water Cart
Each Tank Resonates at 402.5 MHz Under Vacuum at a Predetermined Temperature

DTL-1 Thermal Resonance Curve Under Isothermal Conditions

<table>
<thead>
<tr>
<th>DTL Tank</th>
<th>Peak Power (kW)</th>
<th>Average Power (kW)</th>
<th>Isothermal Temperature at Resonance (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>339</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>1,058</td>
<td>74</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>1,277</td>
<td>89</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>1,292</td>
<td>90</td>
<td>20*</td>
</tr>
<tr>
<td>5</td>
<td>1,284</td>
<td>90</td>
<td>20*</td>
</tr>
<tr>
<td>6</td>
<td>1,254</td>
<td>88</td>
<td>20*</td>
</tr>
</tbody>
</table>

* design value
Control Valves Vary the Coolant Temperature while Maintaining Constant Flow

DTL-1 3-Way Control Valve

DTL-1 Chilled Water Flow Control

DTL Tank 1 RF Structure
Tank 1 Control Valves are Oversized

- We set chilled water valve to minimum controllable flow
  - 30 gpm to minimize heat transfer

- At full rf power flow to the heat exchanger must be <10 gpm
  - To maintain the tank at 26 C
  - Where valve is highly nonlinear
RCCS Control Modes

- LLCF Control System is now ready for frequency agile mode of operation
  - In frequency agile mode, RF control system will monitor the structure’s resonant frequency and adjust the LLCF Control System output drive frequency to the klystron to match it. The RF control system will thus continuously change the RF frequency as the cavities warm up, and follow the cavity resonant frequency to the desired operational resonant frequency.
  - RCCS will stay in temperature control mode during the frequency agile mode of operation.
Two Modes of Controls

Control Mode

Two sets of gains, loop time and Bias

PID

$CV = K_p E + K_i \int_0^t E dt + K_d \frac{dPV}{dt} + BIAS$

Valve Position

$E_f = PV - 0$

$E_I = PV - SP$

Supervisory control: adjust temp SP to minimize Ferr and Ref Pwr

Temperature Measurement

DTL Cavity

Water Temp Change

LLRF System Resonance Frequency Error

$ET = PV - SP$

$Ef = PV - 0$

Control Mode

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY
DTL 1 RCCS Control Performance

Graph showing various parameters and trends over time.
RCCS 3-way Valve Control Performance
Control Software Improvement Made – Con’t

- PID Gain Tuning with Matlab and EPICS
  - Matlab EPICS Interface established
  - PID gain optimization routines and tuning procedure are under development with Matlab and simulink
  - RCCS modeling work is under its way

EPICS

RCCS 3-Way Valve PID Control Block diagram

Matlab

Tank Temperature Control Optimization

$Q(\text{kw}) = 0.263 \cdot \Delta T(\text{deg.reeC}) \cdot FT(\text{gpm})$

$FT(\text{gpm}) \propto CV1(\% \text{open})$
SUMMARY of RCCS Control Issues

- Primary finding is that cooling capacity is too great, causing valves to operate outside their controllable range

- Mechanical changes to be implemented on DTL1/3 to reduce cooling capacity
  - Reduce size of 2-way valve (consulting manufactory)
  - Improve 3-way valve control resolution

- Control system improvements being implemented to mitigate the mechanical problems and ultimately resolve the RCCS issues
  - Frequency Agile mode controls with LLRF system
  - RCCS Temperature & Frequency Control Mode auto-switch
  - PID gain tuning procedure and optimization – ExperTune ???

- Initial release of RCCS model with Simulink
  - Validation during the August commissioning
  - Develop an adaptive PID control algorithm with the model
Discussion

• PID gain automatic tuning for ControlLogix PLC based PID Control System
• Can ExperTune Help?