SNS Superconducting Linac Operational Experience and Upgrade Path

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Victoria, Canada

Sang-ho Kim
Spallation Neutron Source
ORNL

For the SNS Team
Outlines

- Status
- Operational Experiences
- Power Ramp-Up
- Power Upgrade Project
- Summary
SNS Accelerator Complex

Front-End:
Produce a 1-msec long, chopped, H-beam

1 GeV LINAC

Accumulator:
Compress 1 ns to 100 ns long pulse to 1 ns pulse

Ion Source
RFQ DTL CCL SRF, $\beta=0.61$ SRF, $\beta=0.81$

2.5 MeV 87 MeV 186 MeV 387 MeV 1000 MeV

Chopper system makes gaps

945 ns 1 ms macropulse

Current

1 ms

Liquid Hg Target

OAK RIDGE
National Laboratory
SNS Accelerator Complex

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11 (33)

SRF cavities & Cryomodule were designed and built at Jlab 805 MHz, 1.3 ms, 7.8 % RF duty

12 (48)

Liquid Hg Target

Oak Ridge National Laboratory
SNS SRF cavity

Major Specifications:

- $E_a = 15.8 \text{ MV/m at } \beta = 0.81$
- $E_a = 10.1 \text{ MV/m at } \beta = 0.61$
- $Q_o > 5 \times 10^9 \text{ at } 2.1 \text{ K}$
SNS SCL status

- Completed CM installation (April-June 2005)
- SCL commissioning with beam (Aug.-Sep. 2005)
- Formal production run (since Oct. 06)
- 2 K transition; 30 Hz production run (Jun./07-Sep./07)
- 60 Hz production run at 2.1 K (Since Nov./07)
- Present run; 550 kW beam on target at 60 Hz, ~900 MeV, 76 cavities in service

- Presently SCL is one of the most reliable systems
  - Drastically improved trip rates by better understanding of cavity/cryomodule/other systems
  - Trip rate from the cavity/cryomodule side is approaching zero
## Major Parameters achieved vs. designed

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design</th>
<th>Individually achieved</th>
<th>Highest production beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy (GeV)</td>
<td>1.0</td>
<td>1.01</td>
<td>0.9</td>
</tr>
<tr>
<td>Peak Beam current (mA)</td>
<td>38</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Average Beam Current (mA)</td>
<td>26</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>Beam Pulse Length (μs)</td>
<td>1000</td>
<td>1000</td>
<td>580</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Beam Power on Target (kW)</td>
<td>1440</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Linac Beam Duty Factor (%)</td>
<td>6</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Beam intensity on Target (protons per pulse)</td>
<td>$1.5 \times 10^{14}$</td>
<td>$1.3 \times 10^{14}$</td>
<td>$0.53 \times 10^{14}$</td>
</tr>
<tr>
<td>SCL Cavities in Service</td>
<td>81</td>
<td>79</td>
<td>76</td>
</tr>
</tbody>
</table>
Operating Status

Mainly limited by Electron loadings (mostly FE) and their affections between cavities (+ lack of RF power at high intensity beam)

- Medium beta CMs are performing above spec.
- High beta CMs are running 3 MV/m lower than spec.
Operational Experiences
**SNS SCL**

- **The first pulsed operational machine at a relatively high duty**

- **We have learned and are learning many aspects**
  - Operating temperature
  - Heating by electron loadings (cavity, FPC, beam pipes)
  - MP & Turn-on difficulties
  - HOM coupler issues
  - Tuner
  - Beam loss

- **Strong emphasis on a high availability as an user facility**
  - Update/upgrade/implement what we learned in a simple, reliable and robust way
  - Change system configuration as needed
  - Software upgrade for better interlocks, alarms, monitoring, llrf
Operating Temperature

Pulsed nature of the SNS operation & relatively low operating frequency → cavities at 4.5 K up to the critical field. Both calculations and experiments tell → there’s no difference in performances of the SNS SRF cavities when the operating temperature < 4.5 K.

Optimization can be done for the future machines → Static loss, duty, frequency, plant capital, op cost, etc.
Electron Loading and Heating

- FE; due to high surface electric field
- MP; secondary emission
  - At resonant condition (geometry, RF field)
  - At sweeping region; many combinations are possible for MP
    - Temporally; filling, decay time
    - Spatially; tapered region
    - Non-resonant electrons → accelerated → radiation/heating
  - Mild contamination → easily Processible
  - But bad surface → processing is very difficult in a cryomodule (operational)

Initial VTA or CM HP tests could have a significant conditioning effects for both

Usually ended-up
End group heating/beam pipe heating + quenching/gas burst
Quenching pattern examples in the end group

Low RRR & long path to the thermal sink
→ Thermal margin is relatively small,
→ Intermediate stage at the end-group
→ Results in thermal quench/gas burst
Field Emission?

If this cavity is limited at this condition, what is the limiting factor? Field emission?
MP! And then later on Field Emission!

VTA

MP
FE

Qo

Gradient (MV/m)

Radiation (arb. unit)

1.0E+11

1.0E+10

1.0E+09

1.0E+08

0

5

10

15

20

25

0

5

10

15

20

25

1.0E+05

1.0E+04

1.0E+03

1.0E+02

1.0E+01

1.0E+00

1.0E-01

1.0E-02

1.0E-03

1.0E-04
Field emission

17b in open loop
Eacc=16.5

17b in open loop
Eacc=17.5

Pulsed operation
Waveform tells us what is happening inside

Ex. 17b individual

Radiation waveform

17b Radiation at Eacc=16.5 (Elim=17.5 MV/m due to FE!)
Multipacting

HOM signal

Electron probe

HOM signal from RF only

RF power (W)

Cavity field

Forward power

Reflected power

Time (us)

At the end of pulse or decay

During cavity filling

Implies that MP in one cavity can excite the others

E-probe signal

OAK RIDGE
National Laboratory

for the Department of Energy

Lake OS, Victoria Canada
**Turn on and MP**

**MP at around coupler** → vacuum response, e-probe
→ Also electrons can travel whole cryomodule and excite MP at the neighboring cavities
Ex. Here 1a by itself does not have MP. MP excited by electrons from 1c.

**Very difficult turning on cavities during the first year of operation**
**CCG reading; No response or too much, does not match with e-probe signal**
SNS cavity operating regime

After initial commissioning and conditioning
→ surface conditions are quite stable
re-distribution of gases (slow & fast)
→ processible

Gradient settings in SNS SCL;
Not uniform gradients as designed
But as high as individually achievable
Without HOM feedthrough

Both feedthroughs of 19b HOMA and B; removed and blank-off
Add thermal diodes (TD) at around multipacting regions

CM19 test at Test Cave;
All individually tested up to ~16 MV/m at 4 K, 30 Hz, 1ms, in open loop, (about the same gradient we got in the linac tunnel at 30 Hz, collectively)
→ in service in the tunnel; all at 15 MV/m (best CM)
Cavity test without HOM feedthrough

Large electron activities

CCG

$\Delta f$ or $\tau$

Eacc 16MV/m
Cavity test without HOM feedthrough

HOMA bottom TD signal led all other TDs, (Coupler vacuum) aggressive electron activity excitation of the whole cavity changes of bandwidth (or Qex, Δf), drops Eacc down by several % quench (> a few kW of RF → electrons → deposit on the surfaces)
E-probe & HOM signals during CM 19 test

All showed similar behavior

19b (no feedback) showed very aggressive electron activities

processing was possible with no feedback

e-probes while ramping up the gradients

HOM
Electron activities $\rightarrow$ damage HOM coupler

- Any electron activity
  - Destroy standing wave pattern
    - (or notching characteristics)
  - Large fundamental power coupling
  - Feedthrough/transmission line damage
  - Irreversible

Electric Field

10~14 MV/m
Turn-on and High power commissioning

- First turn on must be closely watched and controlled (possible irreversible damage)
  - Initial (the first) powering-up, pushing limits, increasing rep. rate (extreme care, close attention)
    - Aggressive MP, burst of FE → possibly damage weak components
    - Similar situation after thermal cycle (and after long shut down too)
      → behavior of the same cavity can be considerably different from run to run

- Subsequent turn-ons (after long shut-down) also need close attention: behavior of the same cavity can be considerably different from run to run → gas re-distribution

- Cryomodules/strings must be removed and rebuilt if vented/damaged
Collective limits (clear indication at higher rep. rate)

- Electrons from Field Emission + MP:
  - steady state electron activity (+ sudden burst)
  - affects other cavities
  - electron landing place (relative phase, amplitude)
  - leads continuous gas activity, even though all signals look quiet
  - heating starts → end group quench and/or
  - hits intermediate temperature region (5-20K); $H_2$ evaporation (burst of gas)
  - redistribution of gas → changes cavity/coupler conditions

Ex. CM13 individual limits: 19.5, 15, 17, 14.5 MV/m
Ex. CM13 collective limits: 14.5, 15, 10.5 MV/m
Individual limits and collective limits

Individual: powering a cavity at a time
Collective: powering all cavities in a CM at the same time
Large performance variations cavity to cavity
Electron loading (FE, MP) amount from the Cryogenic loads
Electron loading (FE, MP) amount from the Cryogenic loads

Set 1; Below radiation threshold (~9MV/m)
Set 2; 80% of individual limits
Set 3; 88% of collective limits
Avg(set2)-Avg(set3)~1MV/m

Total dynamic heat loads due to different sources
Tuner

- Slow tuner
  - Stepping Motor + Harmonic Driver

- Piezo Tuner
  - Piezo tuners installed compensate for the Lorentz detuning
  - Not yet used in operations
  - May be activated on selected cavities if necessary
  - If piezo stack fails, the cavity cannot be operated
- Performances of MB cavities are very good.
  collective limits: medium~14.9 MV/m, high~14.3 MV/m
  individual limits: medium~16.9 MV/m, high~17.8 MV/m (closed loop)
  individual limits: medium~18.8 MV/m, high~19.1 MV/m (open loop)
- Some cavities have multiple limiting factors.
- ~14 cavities are limited by coupler heating, but close to the limits by radiation heating.
- Operating gradients are around 85~95% of $E_{\text{lim}}$. 
Operations constraints: improving performance since turn on

- Drastically improved trip rates by better understanding of:
  - underlying physical phenomena (outgassing, arcs, discharges, radiation, field emission, beam strike, dark current etc.) \( \rightarrow \) 60 Hz collective limits
  - components response (arc detectors, HOM couplers, Cold Cathode Gauges, coupler cooling, end group heating) \( \rightarrow \) determine what are meaningful
  - controls (LLRF logic, programming, choice of limits and stability parameters) \( \rightarrow \) apply what we learned to the real control system...debugging software, 20 Hz update of LLRF control, improving interlock systems, etc

- Continue to improve performance and ultimate beam power by:
  - Optimizing gradients, modulator voltages, matching of klystrons to cavities, circulator settings, available forward power for beam loading etc.
Further Power Ramp-Up
Power Ramp-up Experiences

- Power ramp up over the last two years
  - 5 to 550 kW (figure out many technical/physics problems)

- Power ramp-up; identify issues/problems
  - ‘Remember’; the machine power is about an order of magnitude higher than the existing ones → not only beam related but also machine/equipment related issues. Some are new technologies, the first operational attempts, etc.
  - tested machine/systems and learned limits and limiting conditions → set up the machine improvement plan (bottom-up power ramp-up plan; reaching 1MW-grade operational performance in a year from now)
  - Further power ramp-up → still challenging

- Availability is an increasing concern
  - User facility (operational machine)
Power Ramp-up for last 2 yrs
(*beam experiences; WE202 J. Galambos*)
Beam power ramp-up with high availability + reserve

- Current \(\rightarrow 38\) mA peak (26 mA average)
- Energy \(\rightarrow 1\) GeV + reserve (3~4 %)
- Pulse length \(\rightarrow 1\) ms
- Rep. rate \(\rightarrow 60\) Hz

= 1.44 MW on target
Beam power ramp-up w/ high availability + reserve

- Current \( \rightarrow \) ion source, beam loading (HVCM, RF), beam loss, chopper, LLRF
- Energy \( \rightarrow \) SCL
- Pulse length \( \rightarrow \) HVCM, ion source, chopper, beam loss, cavity filling time
- Rep. rate \( \rightarrow \) stress for all at full duty
SCL for the Goal

For design beam power in SCL

- 1 ms beam pulse
  - 1350 us HVCM $\rightarrow$ 1280 us RF (300us filling + 30us FB stabilization + 950us beam)
  - Shorter filling time (need more RF) 950us $\rightarrow$ 1000us

- 1-GeV energy + energy reserve (~40 MeV)
  - All cavities in the tunnel in service $\rightarrow$ 940~950 MeV (no reserve)
  - SCL HB cavity performances should be improved (+2.5~3 MV/m)

- 26-mA average current (or 38-mA midi-pulse current) at 1-GeV operation
  - Need more RF available for the design beam current
HVCM & RF configuration for SCL cavities

~25kW of RF at saturation/kV of HVCM

- Add one more HVCM to get 75 kV operation w/ reliability (next year)
  - 10 pack configuration
  - Enough RF power up to design beam loading
  - Cavity filling time can be shortened from 300 us to 250 us
Beam Energy; repair and spare
(J. Mammossor TH103)

- 76 out of 81 are in service
- Continuous repair efforts
  - 2 CM removed. One back to service, the other is waiting for further repair and test in test cave (will back soon)
  - One cavity in the tunnel is disabled due large fundamental power through HOM coupler
- Spare cryomodules in progress (expect 1 ½ years)
- Early next year we expect 80 or 81 cavities for operation
  - Output energy; about 950 MeV
  - Surface improvements; for 1 GeV + energy reserve (high beta cavities)
    - R&D for In-situ processing; just started
    - He-processing/Plasma processing
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Plasma in HB cavity
Power Ramp-Up Plan

More emphasis on machine availability but still there are many challenges.
Power Upgrade Project (PUP)
# Power Upgrade Project (PUP) + Accelerator Improvement Project (AIP)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SNS Baseline</th>
<th>Power upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy [MeV]</td>
<td>1000</td>
<td>1300</td>
</tr>
<tr>
<td>Beam power [MW]</td>
<td>1.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Chopper beam-on duty factor [%]</td>
<td>68</td>
<td>70</td>
</tr>
<tr>
<td>Linac beam macropulse duty factor [%]</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Average macropulse H-current, [mA]</td>
<td>26</td>
<td>42</td>
</tr>
<tr>
<td>Peak macropulse H-current, [mA]</td>
<td>38</td>
<td>59</td>
</tr>
<tr>
<td>Linac average beam current [mA]</td>
<td>1.6</td>
<td>2.5</td>
</tr>
<tr>
<td>SRF cryo-module number (medium-beta)</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>SRF cryo-module number (high-beta)</td>
<td>12</td>
<td>12+8 (+1 reserve)</td>
</tr>
<tr>
<td>SRF cavity number</td>
<td>33+48</td>
<td>33+80 (+4 reserve)</td>
</tr>
<tr>
<td>Peak surface gradient (b=0.61 cavity) [MV/m]</td>
<td>27.5 (+/- 2.5)</td>
<td>27.5 (+/- 2.5)</td>
</tr>
<tr>
<td>Peak surface gradient (b=0.81 cavity) [MV/m]</td>
<td>35 (+2.5/-7.5)</td>
<td>31</td>
</tr>
<tr>
<td>Ring injection time [ms] / turns</td>
<td>1.0 / 1060</td>
<td>1.0 / 1100</td>
</tr>
<tr>
<td>Ring rf frequency [MHz]</td>
<td>1.058</td>
<td>1.098</td>
</tr>
<tr>
<td>Ring bunch intensity [$10^{14}$]</td>
<td>1.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Ring space-charge tune spread, DQ&lt;sub&gt;sc&lt;/sub&gt;</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Pulse length on target [ns]</td>
<td>695</td>
<td>691</td>
</tr>
</tbody>
</table>
SCL Scope and Improvement for PUP

Scope
- Beam energy; 1 GeV → 1.3 GeV (PUP)
  - 9 additional high beta cryomodules (36 high beta cavities)
  - With all supporting systems (RF, HVCM, Cryogenics)
- Beam current; 26 mA → 42 mA (AIP, R&D)

Outline
- Cavity performance (better control of surface cleanness for less radiation at the operating gradients)
- Fundamental power coupler (about same or less thermal radiation at the higher average RF power)
- HOM coupler (remove feedthrough for existing cavities or remove HOM couplers for new cavities)
- Thermal improvements at the end of cryomodule (put intermediate temperature region away from the cavities)

9 additional cryomodules to fill the empty spaces at the end of the linac tunnel
Summary

- The first fully operational pulsed superconducting RF linac has been running with beam for two years, reaching full design energy

- Behavior peculiar to pulse operation is being studied, understood and the problems associated with are being corrected
  - Down time due to SRF linac is now almost nil (the most reliable among subsystems)

- Full power ramp up to 1.4 MW is being planned and facilities are being prepared to support full power operation by improving existing CMs/supporting systems and procuring spares

- Power Upgrade Project (PUP) has been initiated, waiting for CD-1 improvement
supplementary
Quenching

- Rs (BCS, Rres, etc. limits; intrinsic SC limits)
- Material defect (end group has more margin; low B)
  - Cell (covered with He vessel)
  - End group (indirect conduction cooled)
- External thermal load (cell region has more margin)
  - Wide range heating
  - Much smaller thermal power density
  - Thermal radiation from FPC
  - Radiation (FE, MP, cavity-coupler interaction)
Lorentz force detuning

Most cavities show dynamic detuning as expected

$K_{LD} \rightarrow 3-4$: medium, 1-2: high

But, a few cavities show bigger resonance phenomena as higher repetition rate

The 2 kHz components shows resonances at higher repetition rate in one medium beta cavities.

In this example the accelerating gradient is 12.7 MV/m.

High beta cavity

Victoria Canada
For 1-ms beam

The max. width of HVCM; 1350us

Beam length 950us → 1000us

HVCM pulse width 1350 us at 60 Hz

HPRF settling time; 70 us

FB settling time; 30 us

Filling time 300us → 250us

Cavity parameter Qex, Ea, Δf,

Available RF power

RF/Klystron performances

HVCN voltage