325 MHz Superconducting Spoke Resonator Development at Fermilab

Bob Webber
TTC Meeting
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Fermilab efforts on superconducting spoke resonator (SSR) accelerating cavities began about five years ago.

Development of SC spoke cavities at 325 MHz was an enterprise of the Fermilab HINS program apart from the larger 1.3/3.9 GHz efforts.

The context was for a pulsed, high-intensity proton/H- linac:
- Up to 3 msec pulse length and 1% duty factor
- 4 °K operation
- 27 mA pulsed beam current

The frequency was chosen to be 325 MHz:
- 4 th subharmonic of ILC 1.3 GHz
- JPARC klystron is available at 324 MHz
Spoke Cavities in Present Context of Project X

- Within the past year Project X concept has morphed
  - Linac operating CW
  - 2°K operation to reduce cryo load
  - 1 mA continuous accelerated beam current
- Threshold energy for application of SSR cavities has been lowered from 10 MeV to 2.5 MeV requiring design of a $\beta=0.11$ structure
- Triple-spoke cavities in the earlier machine design are replaced in favor of more efficient $\beta=0.6$ 650 MHz elliptical cavities
- Now there are plans to tightly integrate the whole Fermilab SRF program to include Project X, ILC, and 3rd harmonic (3.9 GHz) activities
Project X 3 GeV CW Linac

- **Low-energy SRF 325 MHZ linac (2.5-160 MeV)**
  - 3 families of single-spoke cavities ($\beta=0.11, \beta=0.22, \beta=0.4$)
  - 1 mA CW accelerated beam current
Technical Progress on Cavities

- Two $\beta = 0.22$ spoke cavities are fabricated and processed
- Both have tested successfully (bare) in the Fermilab VTS to beyond design accelerating gradient:
  - Pre-CW design requirement was $10 \text{ MV/m} @ Q_0 > 5E8$ at 4°K
  - $>30 \text{ MV/m}$ has been achieved in one HINS cavity at 2°K
- The first cavity manifested symptoms of Q-disease and has since undergone a 600°C bake at TJNL
  - That cavity is now welded into helium vessel
  - First post-bake test will be in the new horizontal test cryostat by this summer
- The second cavity was cooled down and tested only one time
- Cavity end-wall spring constant (~20 N/micron) and tuning sensitivity (~550 Hz/micron) have been measured to set cavity tuner design parameters
- Cavity resonant frequency has been successfully tuned by in-elastically deforming the end-walls
**Project X**  
325 MHz Testing Facilities

- **Fermilab VTS**
  - Design and construction of a 1300 ↔ 325 MHz frequency convertor and procurement of a 200W 325 MHz amplifier has allowed spoke cavity testing using the full complement of facilities and software at VTS developed for 1300 MHz elliptical cavities

- **325 MHz Superconducting Spoke Cavity Test Facility**
  - Pulsed RF power from 2.5 MW 325MHz J-PARC type klystron
  - Horizontal test cryostat for dressed spoke cavities at 4°K operation
  - Cryostat without cavity will begin first test cool down in Meson Detector Building within days
  - Allows low power, full-gradient CW VTS-like testing for cavities with high-$Q_{\text{ext}}$ drive antenna
  - Allows full pulsed-power testing with 400kW 325 MHz RF source for cavities with ‘real’ power input coupler installed
  - Modifications of the cryostat for 2°K operation are being designed
### HINS 325 MHz Single Spoke Design Parameters

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>4.4 K</td>
</tr>
<tr>
<td>HINS accelerating gradient, $E_{acc}$ *</td>
<td>10 MV/m</td>
</tr>
<tr>
<td>$Q_0$ at accelerating gradient</td>
<td>$&gt; 0.5 \times 10^9$</td>
</tr>
<tr>
<td>Beam pipe, Shell ID</td>
<td>30 mm, 492 mm</td>
</tr>
<tr>
<td>Lorentz force detuning coefficient</td>
<td>$3.8 \text{ Hz}/(\text{MV/m})^2$ (with He vessel)</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$ *</td>
<td>2.56</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$ *</td>
<td>3.87 mT/(MV/m)</td>
</tr>
<tr>
<td>$G$</td>
<td>84 Ω</td>
</tr>
<tr>
<td>$R/Q_0$</td>
<td>242 Ω</td>
</tr>
<tr>
<td>Geometrical Beta, $\beta_g$</td>
<td>0.21</td>
</tr>
</tbody>
</table>

* $E_{acc}$ is the total accelerating voltage divided by $L_{eff}$, where $L_{eff} = (2/3)\beta \lambda = 135$ mm, the distance between the edges of the accelerating gaps at the two endwalls.

SSR1-02, the 2nd SSR1 prototype. Fabricated by Roark.
SSR1 Cavity – Bare and with Helium Vessel and Tuner
BCP and HPR Infrastructure at the ANL G150 Facility

BCP Set-up

Spoke Cavity in HPR Set-up
SSR cavity tuning fixture with cavity SSR1-01.

4 Position Sensors and 2 Dynamometers. Cavity can be hold on coupler and vacuum port flanges or by 2 rings on equator near C-shape stiffening rings.

<table>
<thead>
<tr>
<th>MHz/mm</th>
<th>lb/mm</th>
<th>N/mm</th>
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<tbody>
<tr>
<td>566</td>
<td>4507</td>
<td>20053</td>
</tr>
</tbody>
</table>
SSR Cavity Testing

• **SSR1-1**
  - Four VTS tests between March 2008 and March 2009
  - Vacuum problems in first two tests
  - Active pumping added to VTS before 4\textsuperscript{th} test
  - 4\textsuperscript{th} test included cool-down dwell at 100°K in attempt to induce Q-disease
  - Cavity subsequently baked at 600°C at JLAB, welded into He jacket and dressed with tuner
  - Will next be tested in new test cryostat in coming months

• **SSR1-2**
  - One VTS test in 2009
  - Reached very high gradient – 33MV/m
Project X

Spoke Cavity Prepared for VTS
SSR1-01 Vertical Test
Q vs. E

Dressed Cavity
Operating Goal @ 4K

This test ended when multipacting due to poor cavity vacuum became unacceptable.

Accelerating Gradient MV/m

Cold test results, 2K and 4.4K.
SSR1-1 Final Test Results

HINS SSR1-01 - $Q_0$ vs $E$

Test results for 4.4K and 2K

- $Q @ 4K$
- $Q @ 2K$
- Radiation @ 4K
- Radiation @ 2K

Additional "soft" barriers

Final 2K run after processing

Strong MP barrier from 7-8 MV/m remained at both 4.4K and 2K

Final 4K run after processing thru MP barriers

Limited by RF power

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SSR1-1 Final VTS Test
Inducing Q-disease

Cavity gradient was limited by RF power in all cases.

After 100K hold for ~7hrs, effects of Q-disease evident, along with reappearance of strong MP barriers.
HINS SSR-01 - $R_s$ vs $T$

$R_0 = 5.1 \pm 0.1 \, \Omega$ from WinSuperfit (G. Ciovati, JLab)

Tested 2/27/08
SSR1-2 First Cool-down
VTS Test Results

- Q @ 2K
- Q @ 4K after 2K run
- Radiation @ 2K
- Radiation @ 4K after 2K run

Jump thru MP barrier from 24 to 33MV/m

MP from ~11-15MV/m

60 mT
Parts for 2 helium vessels are in-house, one of which is welded. One prototype tuner has been tested warm.
Three Fermilab-designed couplers and one SBIR-produced coupler are in-house. First full-power tests have been successfully completed.
Spoke Cavity Horizontal Test Cryostat in MDB

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Project X

3-Cavity Cryomodule Concept
Assemble using the same or similar tooling to that used for ILC final assembly.
• Present conception of SSR1 Cryomodules
  – Contain 9 SSR1 cavities and 9 solenoids
  – Project X expects that these designs could be extended to SSR0 and SSR2 requirements
What’s Next?

- First tests of SSR1 with tuners in new cryostat with full pulsed power
- Two SSR1 cavities are being fabricated in India at IUAC
- Ten SSR1 cavities are being fabricated by Niowave/Roarke
- Make plans to process these cavities
- Address issues relevant to 2°C K CW operation
- Design of SSR0 is beginning
- Cryomodule design work continues
- First beam acceleration through spoke cavities??? – 2012-13-??
Project X

Very early Tests

2008.03.13. 4 hours of work at 2K. Maximum of accelerating gradient reached 13.5MV/m limited by field amplifier power 200 W and field emission.
3rd test history of the cavity SSR1-1 on July 14-17 and 21, 2008.

July 14. Vacuum vessel cooling down started.

July 15. RF test started. Cavity power processed a little at 4K and then cooled down to 2K. Power processing finished at 2K. Results very similar to results of March test.

July 16. “Multipacting/breakdown” in the cavity. About 5 hours in this regime, about 20-50 kV/m

July 17 cavity warmed up.

July 21 cavity cooled to 4.4K and tested. After about 3 hours processing cavity reached 18MV/m. Limited by “Multipacting/breakdown” due to bad vacuum in the cavity. may be caused by leak.