SRF Linac Technology Development at Fermilab:
New requirements, challenges and perspectives

Vyacheslav Yakovlev (FNAL)
XXVI Linear Accelerator Conference
September 9, 2012
Outlook

The application of SRF technology to electron and hadron linacs has a long and successful history;

50 –years anniversary, 1962-2012

1961: The first suggestion to apply SC principles to proton accelerator design, A. P. Banford and G. H. Stafford


Lead-plated S-band 2856 MHz muffin tin cavities $Q_o \sim 1e8-1e9$, $B_{\text{peak}} \sim 10 \text{ mT}$

Recently SRF is a well-established technology.
Recent applications of SRF linacs (operating facilities and projects):

- High Energy Physics,
  - high-energy frontier (SPL***, ILC***),
  - high-intensity frontier (Project-X***);
- X-Ray Light Sources (XFEL**, NGLS***, ERLs***);
- Neutron spallation sources (SNS*, ESS***);
- Nuclear Physics, Neutrino physics, Rare Isotope Accelerators (ATLAS*, CBEAF*, FRIB**, SARAF**, ISAC-II*, Spiral-II**, HIE-ISOLDE****, JPARC****, KoRIA***, etc);
- ADS (MYRRHA***, India***, China***).

* in operation;
** under construction;
*** project;
**** facility upgrade using SRF technology.
Progress in SRF technology is caused in high degree by the development of the ILC project:

- Pulse regime with low duty factor (0.5%):
  - considerably low RF load – $Q_0$ is not a main issue.
  - Lorentz detuning is an issue.
- Pulse current $\sim 9$ mA:
  - microphonics are not a big problem.
- High acceleration gradient is a primary concern ($E_{\text{acc}} = 35$ MeV/m):
  - quench;
  - field emission;
  - manufacturing yield.
ILC – quest to high gradients.

~16000 cavities!

2007 ILC reference design

TESLA-type cavity:
- 1.3 GHz;
- 9 cells;
- 35 MeV/m.

ILC: breakthrough to high gradients:
- electro-polishing;
- 120° C baking.
ILC Cavity Processing Basic Recipe:

1. Inspection – RF & Optical
2. Bulk Electro-Polishing (EP)
3. High Pressure Rinse (HPR)
4. 800°C Bake 2 hrs
5. RF Tuning
6. Light EP
7. HPR
8. Assemble
9. HPR
10. Evacuate
11. 120°C Vacuum Bake 48 hrs
12. Vertical Test
13. Dress
14. HPR
15. Assemble
16. HPR
17. Evacuate
18. Horizontal Test
FNAL 1.3 GHz EP Tool.

FNAL HPR Tool with 1.3 GHz 9-cell
ILC Cryo-module assembly (FNAL):
ILC gradient yield.
ILC cavities reach 35 MV/m more than half the time after one or two processing cycles

Good progress, good achievements!
New projects of CW SC accelerators:

Project X: Multi-experimental accelerator facility:

- 1-2 mA H-
- 2.1 MeV-160 MeV: 162.5 MHz Half – Wave and 325 MHz spoke resonators;
- 160 MeV -3GeV: 650 MHz elliptical cavities ($\beta=0.61$ and $\beta=0.9$);
- 3-8 GeV: 1.3 GHz ILC-type cavity, pulsed (up to 30 msec).
Project X multi-experiment facility:

- 3-GeV, 1-mA CW linac provides beam for rare processes program ~3 MW;
- flexible provision for beam requirements supporting multiple users;
- <5% of beam is sent to the Main Injector.

3 MW @ 3 GeV
200 kW @ 8 GeV
2 MW @ 120 GeV
## Concepts of SC CW 3GeV and Pulsed 3-8 GeV Linac

### Diagram

- **H^+ gun**
- **RFQ**
- **MEBT**
- **HWR**
- **SSR1**
- **SSR2**
- **β=0.6**
- **β=0.9**
- **1.3GHz ILC**

### Table

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq, MHz</th>
<th>Energy (MeV)</th>
<th>Cav/mag/CM</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWR (β_G=0.11)</td>
<td>162.5</td>
<td>2.1-10</td>
<td>8 /8/1</td>
<td>HWR, solenoid, 5.26m</td>
</tr>
<tr>
<td>SSR1 (β_G=0.22)</td>
<td>325</td>
<td>10-32</td>
<td>16 /8/ 2</td>
<td>SSR, solenoid, 4.76m</td>
</tr>
<tr>
<td>SSR2 (β_G=0.47)</td>
<td>325</td>
<td>32-160</td>
<td>36 /20/ 4</td>
<td>SSR, solenoid, 7.77m</td>
</tr>
<tr>
<td>LB 650 (β_G=0.61)</td>
<td>650</td>
<td>160-520</td>
<td>42 /14/ 7</td>
<td>5-cell ellip, doublet, 7.1m</td>
</tr>
<tr>
<td>HB 650 (β_G=0.9)</td>
<td>650</td>
<td>520-3000</td>
<td>152 /19 /19</td>
<td>5-cell ellipt, doubl, 11.2m</td>
</tr>
<tr>
<td>ILC 1.3 (β_G=1.0)</td>
<td>1300</td>
<td>3000-8000</td>
<td>224 / 28 /28</td>
<td>9-cell ellipt., quad, 12.6m</td>
</tr>
</tbody>
</table>
RF Cavities of the Project-X linac:

HWR model, 162.5 MHz (ANL)  
SSR1 photos, 325 MHz (FNAL)  
SSR2 model, 325 MHz (FNAL)

<table>
<thead>
<tr>
<th>cavity type</th>
<th>$\beta_{\text{geom}}$</th>
<th>Freq MHz</th>
<th>Beam pipe $\phi$, mm</th>
<th>$V_{\text{acc, max}}$, MeV</th>
<th>$E_{\text{peak}}$, MV/m</th>
<th>$B_{\text{peak}}$, mT</th>
<th>R/Q, $\Omega$</th>
<th>G, $\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWR</td>
<td>$\beta=0.113$</td>
<td>162.5</td>
<td>33</td>
<td>1.8</td>
<td>40</td>
<td>62</td>
<td>225</td>
<td>47.7</td>
</tr>
<tr>
<td>SSR1</td>
<td>$\beta=0.215$</td>
<td>325</td>
<td>30</td>
<td>1.95</td>
<td>28</td>
<td>70</td>
<td>242</td>
<td>84</td>
</tr>
<tr>
<td>SSR2</td>
<td>$\beta=0.47$</td>
<td>325</td>
<td>40</td>
<td>3.34</td>
<td>32</td>
<td>60</td>
<td>292</td>
<td>109</td>
</tr>
</tbody>
</table>

HWR and spoke cavities of the Project X front end
Elliptical cavities of the high-energy part of CW linac

Single-cell prototypes (photos):
- LE 650 MHz (JLAB version)
- HE 650 MHz (FNAL)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LE650 (FNAL)</th>
<th>HE650(FNAL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{\text{geom}}$</td>
<td>0.61</td>
<td>0.9</td>
</tr>
<tr>
<td>Cavity Length = $n_{\text{cell}} \cdot \beta_{\text{geom}} \cdot \lambda/2$</td>
<td>mm</td>
<td>703</td>
</tr>
<tr>
<td>R/Q</td>
<td>Ohm</td>
<td>378</td>
</tr>
<tr>
<td>G-factor</td>
<td>Ohm</td>
<td>191</td>
</tr>
<tr>
<td>Max. Gain/cavity (on crest)</td>
<td>MeV</td>
<td>11.7</td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>MV/m</td>
<td>16.6</td>
</tr>
<tr>
<td>Max surf. electric field</td>
<td>MV/m</td>
<td>37.5</td>
</tr>
<tr>
<td>Max surf. magnetic field,</td>
<td>mT</td>
<td>70</td>
</tr>
<tr>
<td>$Q_0$ @ 2K</td>
<td>$\times 10^{10}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$P_{2K}$ max</td>
<td>[W]</td>
<td>24</td>
</tr>
</tbody>
</table>
JLAB version of the 650 MHz, beta=0.61 cavity for the Project X*

For the cavity #2
$Q_0 > 2 \times 10^{10} @ 17 \text{MeV/m}$

*F. Marhauser, et al, IPAC 2011
CM designs for Project X CW linac:

HWR (ANL)

SSR1 (FNAL)

HE650 (FNAL)
CW Operation

RF load:
• ILC: <5 W/cryo-module (0.5 % duty cycle, $E_{\text{acc}} = 35$ MeV/m);
• Project X: ~200 W/cryo-module (100% duty cycle, $E_{\text{acc}} = 17$ MeV/m).
• For CW operation very high gradient is not an issue.
• The issue for CW is high RF load.

High $Q_0$ is necessary!
RF load at CW regime determines the power consumption of a cryogenic system and thus:

- Capital cost of the cryogenic system, and thus, project;
  - Cost of a cryogenic system \( \sim (RF \text{ load})^{0.6} \sim Q_0^{-0.6} \) (for fixed gradient – for big projects, LHC experience);
  - Cost of the cryogenic system is a significant part of the project cost, \( \sim 10\% \).

- Operational cost \( \sim RF \text{ load} \sim Q_0^{-1} \).

- High \( Q_0 \) allows higher gradient at CW and, thus, allows lower capital cost of the linac.

- Increase of \( Q_0 \) two times may save many tens of M\$ for a billion-scale project.
Cryogenic Plant of the Project X

- $Q_0 \Rightarrow R_{\text{surface}} \Rightarrow R_{\text{res}}$ (residual resistance)
- Medium field $Q$-slope (described by $\gamma$, J. Halbritter’s model)
- Cryogenic efficiency, a.k.a. coefficient of performance (COP)

A. Klebaner
Annual Operating Cost for the Project X

\[ \gamma = 1 \]

Normalized Annual Cryogenic Power Cost vs. Temperature, [K]

- \( \gamma = 1 \)
- \( R_{\text{res}} = 10 \) [nOhm]
- \( R_{\text{res}} = 5 \) [nOhm]

A. Klebaner
Different approaches to improve $Q_0$:

NbN (A. Grassellino, Fermilab)

- NbN: superconductor with higher $T_c$ (~16K, compared to 9.2K for Nb);
- Potential for lower surface resistance than Nb;
- Material made via bulk diffusion: simple and inexpensive modification to standard Nb treatments. Large grain Nb is used;
- First result at FNAL: world record $Q \sim 7.5 \times 10^{10}$ at 2K and 10MV/m for a 1.3GHz single cell $E_{acc}$ for a 1.3GHz single cell, residual resistance <0.5 nOhm!
HF rinse for high Q: Simple higher $Q_0$ recipe

- Single HF rinse (5 min) followed by water rinse is beneficial for the medium field $Q$ value – gains of up to 35% measured at 70 mT
- $f=1.3$ GHz;
- $B_{\text{peak}}/E_{\text{acc}}=4.26$ mT/MeV/m

A. Romanenko, Fermilab APT Seminar, 2012, also TTC Meeting'2011
Jlab 1400C RF Test

- $f = 1.3\, \text{GHz}$;
- $B_{\text{peak}}/E_{\text{acc}} = 4.26\, \text{mT}/\text{MeV/m}$

Dhakal et al, IPAC 12, WEPPC091

CEBAF upgrade standard process average $Q_0(2K, 70\, \text{mT}) = 1.2 \pm 0.7 \times 10^{10}$
New projects of CW linacs:

- Next Generation Light Source (NGLS)*:

```
Exit of Injector  70 MeV
High brightness, high repetition rate electron gun
Injector

Laser heater 160 MeV
Exit of Linac 0 160 MeV
Exit of Linac 0 160 MeV
Exit of Linac 1 350 MeV
Exit of Harmonic Linearizer 350 MeV
Bunch compressor 350 MeV

Bunch spreader
Beam spreader
Array of configurable FELs
X-ray beamlines

Endstations

Exit of Linac 2 ~2 GeV
```

Energy, GeV        ~2
Operation mode    CW
Average current, mA 0.3-1
Bunch rep. rate, MHz 1
Bunch population, nC 0.3-1

*J.N. Corlett, LINAC 2012
SRF Accelerator for Indian ADS
Scheme for 200 MeV High Intensity Proton Accelerator
(a front end of the 1 GeV Linac)

- Frequency: 325 and 650 MHz
- Current: 30 mA

P. Singh, SRF -2011
ADS Roadmap in China

CW 162.5MHz/ 325MHz / 650MHz

Phase I
R&D Facility

Phase II
Experiment Facility

Phase III
DEMO. Facility

RFQ+HWR

RFQ+Spoke

10 MeV

5~10 MW_t

100 MW_t

≥1 GW_t

2013
~5 MeV

2017
25~50 MeV

201X
50/150 MeV

~2022
0.6~1 GeV

~2032
1.2~1.5 GeV

Verification of
two ways

Integration

Integral test

Phase II target

Phase III target

Shinian Fu, SRF 2011
Narrow bandwidth of the PX cavities caused by low beam loading:

- Lorentz detuning;
- Microphonics.

\[ Q_{\text{load}} = \frac{U}{(R/Q)/I_{\text{beam}}} \] - very high for small beam current <1 mA, \( Q_{\text{load}} \sim 1e7-1e8 \);

- Cavity bandwidth: \( f/ Q_{\text{load}} \sim \) tens of Hz.

- Lorentz detuning – cavity detuning caused by the cavity wall deformation by ponderomotive forces of RF field (M.M. Karliner, 1968)
  \[ \Delta f_{\text{Lorentz}} = k_L E_{\text{acc}}^2, \quad k_L \text{- Lorentz coefficient, } E_{\text{acc}} \text{- acceleration gradient.} \]
  For ILC cavity \( k_L \sim -1 \text{ Hz/(MeV/m)}^2 \). For CW Lorenz detuning is not a problem.

- Microphonics – cavity resonance frequency changes caused by the cavity wall vibration. Main source of vibration – He pressure fluctuations \( \delta P^* \).
  \[ \Delta f_m = \frac{df}{dP} \times \delta P, \quad \delta P \sim 0.05-0.1 \text{ mbar at 2 K. } \frac{df}{dP} = 30-130 \text{ Hz/mbar (ILC)} \]

*Matthias Liepe, Project X Collaboration meeting, Fermilab, 2011*
Power overhead caused by microphonics:

- **Loaded Q:**
  \[ Q_{\text{load}} = \frac{U}{(R/Q)/I_{\text{beam}}} \]
  \[ Q_{\text{load}}(\text{PX HE 650MHz}) = 2.8 \times 10^7 \]

- **Bandwidth \( \Delta f \):**
  \[ \Delta f = \frac{f}{Q} \]
  \[ \Delta f(\text{PX 650 MHz}) = 23 \text{ Hz} \]

- **Required power from RF source \( P_g \) for optimal coupling at r.m.s microphonic amplitude \( \delta f \) and the energy gain per cavity \( V \):**

\[
P_g = \frac{V^2 (1+\beta)^2}{4\beta Q_0 (r/Q)} \left[ 1 + \frac{I_{\text{Re}} (r/Q) Q_0}{V (1+\beta)} \right]^2 + \left( \frac{Q_0}{1+\beta} \frac{2\delta f}{f} \right)^2
\]

\[
\beta_{\text{opt}} = \left[ 1 + \frac{I_{\text{Re}} (r/Q) Q_0}{V} \right]^2 + \left( \frac{2\delta Q_0}{f} \right)^2 \right]^{1/2}
\]

\( I_{\text{Re}} \) and \( I_{\text{Im}} \) are real and imaginary part of the current,
\( I_{\text{Re}} = I_{\text{beam}} \cdot \cos(\phi) \), \( \phi \) - acceleration phase.
Example: for Project X HE 650 MHz section, I=1 mA, V=17.7 MeV (G=17 MeV/m), (r/Q)=638 Ohm, acceleration phase of -15°:

<table>
<thead>
<tr>
<th>( \sigma_f ) [Hz]</th>
<th>6( \sigma_f ) [Hz]</th>
<th>Power overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>1.07</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td><strong>1.23</strong></td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td><strong>1.44</strong></td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td><strong>1.67</strong></td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td><strong>1.92</strong></td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td><strong>2.17</strong></td>
</tr>
</tbody>
</table>

\( \sigma_f \) must be less than \(~ 2\) Hz for <20% power overhead!

How much detuning can we expect in realistic modules?

<table>
<thead>
<tr>
<th>Machine</th>
<th>( \sigma ) [Hz]</th>
<th>6( \sigma ) [Hz]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEBAF</td>
<td>2.5 (average)</td>
<td>15 (average)</td>
<td>significant fluctuation between cavities</td>
</tr>
<tr>
<td>ELBE</td>
<td>1 (average)</td>
<td>6 (average)</td>
<td></td>
</tr>
<tr>
<td>SNS</td>
<td>1 to 6</td>
<td>6 to 36</td>
<td>significant fluctuation between cavities</td>
</tr>
<tr>
<td>TJNAF FEL</td>
<td>0.6 to 1.3</td>
<td>3.6 to 7.8</td>
<td>center cavities more quiet</td>
</tr>
<tr>
<td>TTF</td>
<td>2 to 7 (pulsed)</td>
<td>12 to 42 (pulsed)</td>
<td>significant fluctuation between cavities</td>
</tr>
</tbody>
</table>

Special efforts to reduce microphonics are necessary!
Microphonics Control Strategies

Microphonics can be mitigated by taking some combination of any or all of the following measures:

• Providing sufficient reserve RF power to compensate for the expected peak detuning levels.

• Improving the regulation of the bath pressure to minimize the magnitude of cyclic variations and transients (option: operation at 2K).

• Reducing the sensitivity of the cavity resonant frequency to variations in the helium bath pressure (df/dP).

• Minimizing the acoustic energy transmitted to the cavity by external vibration sources.

• Actively damping cavity vibrations using a fast mechanical or electromagnetic tuner driven by feedback from measurements of the cavity resonant frequency.

The optimal combination of measures may differ for different cavity types.
Reducing the sensitivity of the cavity resonant frequency to variations in the helium bath pressure (df/dP):

1. Mechanical coupling of a cavity and a He vessel (L. Ristori, et al)

2. “Self-compensated cavity” (Z. Conway, P. Ostroumov, et al)

\[ \Delta f \propto -\frac{1}{4} \int \left[ \mu_0 |\vec{H}_{0}(\vec{x})|^2 - \varepsilon_0 |\vec{E}_{0}(\vec{x})|^2 \right] u(\vec{x},t) \, da \]
\[ \int \left[ \mu_0 |\vec{H}_{0}(\vec{x})|^2 \right] u(\vec{x},t) \, da \approx \int \left[ \mu_0 |\vec{E}_{0}(\vec{x})|^2 \right] u(\vec{x},t) \, da \]

3. “Self-tuning cavity” (E. Zaplatin)
Active Microphonics Compensation in the ERL Injector

Piezo Feedback on Cavity Frequency: ⇒ Reduces rms microphonics by up to 70%!

Matthias Liepe, Cornell University, PAC2005
SSR1 Active Microphonics Control (Fermilab)

- Narrower peak
- No evidence of large tails
  - HoBiCaT @2K
  - SSR1 @4K
Slow and Fast Tuner Development (FNAL)
Conclusions

- SRF for linear accelerators has a long and successful history;
- SRF for ILC is well-developed, and international team has made good progress in achieving high accelerating gradient;
- New CW projects for large linacs - Project X, NGLS, ADS projects, ERL's, etc. - need not high gradient, but high $Q_0$ at modest gradient. New SC material research concentrates on the achievement of high $Q_0$.
- Another critical issue for new CW projects is microphonics. Dedicated research is ongoing to develop both passive and active means for microphonics compensation suitable for large SC linacs with low beam loading.
Many thanks to colleagues, from whom I have obtained the information for this presentation – Tug Arkan (FNAL), Zachary Conway (ANL), Anna Grassellino, Camille Ginsburg, Arkadiy Klebaner (FNAL), Matthias Liepe (Cornell), Peter Ostroumov (ANL), Yury Pischalnikov, Allan Rowe, Warren Schappert, Nikolai Solyak, Timergali Khabiboulline (FNAL), and Evgeny Zaplatin (Jülich).

Thanks for the many publications, from which I got the material used in the presentation.