SRF TECHNOLOGY FOR PARTICLE ACCELERATORS: PROGRESS REPORT

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Old Dominion University
and
Thomas Jefferson National Accelerator Facility
SRF Technology

• The SRF technology is increasingly becoming the technology of choice for an increasing number of accelerator applications
  – High energy physics (ILC, Project X)
  – Nuclear Physics (Jlab, FRIB)
  – Spallation Neutron Sources (SNS, ESS, CSNS)
  – Accelerator Driven Systems (EUROTRANS, MYRRAH)
  – Light Sources (X-FEL)
Global Plan for ILC Gradient R&D

<table>
<thead>
<tr>
<th>Year</th>
<th>07</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>TDP-1</td>
<td></td>
<td></td>
<td></td>
<td>TDP-2</td>
<td></td>
</tr>
<tr>
<td>Cavity Gradient in v. test to reach 35 MV/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>→ Yield 50%</td>
</tr>
<tr>
<td>Cavity-string to reach 31.5 MV/m, with one-cryomodule</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Global effort for string assembly and test (DESY, FNAL, INFN, KEK)</td>
</tr>
<tr>
<td>System Test with beam acceleration</td>
<td></td>
<td></td>
<td>flash (DESY), NML (FNAL)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preparation for Industrialization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Production Technology R&amp;D</td>
</tr>
</tbody>
</table>

**New baseline gradient:**
- Vertical acceptance: 35 MV/m average, allowing ±20% spread (28-42 MV/m)
- Operational: 31.5 MV/m average, allowing ±20% spread (25-38 MV/m)

A. Yamamoto, SRF-110725

Advances in ILC-SRF
Global ILC Cavity Gradient Yield
Updated, March, 2011

Electropolished 9-cell cavities
JLab/DESY/KEK (combined) up-to-second successful test of

|-----------------|------------------|----------------|--------------------------|-----------------------|-------------------|

- **TDP-2 Goal**: 35 MV/m usable
- **TDP-1 Goal**: Achieved > 50 %

Plot courtesy Camille Ginsburg of FNAL

Advances in ILC-SRF

A. Yamamoto, SRF-110725
Fermilab Project X

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq</th>
<th>Energy (MeV)</th>
<th>Cav/mag/CM</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSR0 ($\beta_G=0.11$)</td>
<td>325 MHz</td>
<td>2.5-10 MeV</td>
<td>26 /26/1</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR1 ($\beta_G=0.22$)</td>
<td>325 MHz</td>
<td>10-32 MeV</td>
<td>18 /18/ 2</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR2 ($\beta_G=0.4$)</td>
<td>325 MHz</td>
<td>32-160 MeV</td>
<td>44 /24/ 4</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>LB 650 ($\beta_G=0.61$)</td>
<td>650 MHz</td>
<td>160-520 MeV</td>
<td>42 /21/ 7</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>HB 650 ($\beta_G=0.9$)</td>
<td>650 MHz</td>
<td>520-2000 MeV</td>
<td>96 /12/12</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>ILC 1.3 ($\beta_G=1.0$)</td>
<td>1.3 GHz</td>
<td>2-3 GeV</td>
<td>64 / 8/ 8</td>
<td>9-cell elliptical, quad</td>
</tr>
</tbody>
</table>
CEBAF 12 GeV Upgrade

First **two** cryomodules - installation 2011

Eight more CMs in 2012-2013

≥108 MV avg.

300 W @ 2.07K

Add 5 cryomodules

20 cryomodules

Upgrade magnets and power supplies

Add arc

20 cryomodules

Add 5 cryomodules

Cavity: 0.7 m, “Low loss” cell shape, 1.497 GHz

8 cavities/cryomodule
JLab : State-of-the-art Production Cavities

$Q_0$ at 2.07K, 1.497 GHz, fine-grain bulk niobium
Acid etch + 38 μm electropolish + 24 hr 120 C bake

(Q is BCS-limited)
Project objectives: Produce RIB using a 400 kW CW heavy ion driver linac (p to U) up to 200 MeV/u.

Cavity type: Quarter-wave resonators (80.5 MHz) and half-wave resonators (322 MHz), bulk niobium for a total of 344 cavities and 52 cryomodules.

<table>
<thead>
<tr>
<th>Type</th>
<th>λ/4</th>
<th>λ/4</th>
<th>λ/2</th>
<th>λ/2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>β_{opt}</td>
<td>0.041</td>
<td>0.085</td>
<td>0.29</td>
<td>0.53</td>
<td>144</td>
</tr>
<tr>
<td>Cavities</td>
<td>[0]</td>
<td>[2]</td>
<td>[4]</td>
<td>[4]</td>
<td>344</td>
</tr>
<tr>
<td>Solenoids</td>
<td>[0]</td>
<td>[0]</td>
<td>[2]</td>
<td>[2]</td>
<td>87</td>
</tr>
<tr>
<td>Cryomodules</td>
<td>[0]</td>
<td>[1]</td>
<td>[2]</td>
<td>[2]</td>
<td>52</td>
</tr>
</tbody>
</table>

Courtesy Q. Zhao, R. York

in [J]: matching cryomodule
Project objectives: Produce RIB using a 400 kW CW heavy ion driver linac (p to U) up to 200 MeV/u.

Cavity type: Quarter-wave resonators (80.5 MHz) and half-wave resonators (322 MHz), bulk niobium for a total of 344 cavities and 52 cryomodules

<table>
<thead>
<tr>
<th>Type</th>
<th>λ/4</th>
<th>λ/4</th>
<th>λ/2</th>
<th>λ/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>β_opt</td>
<td>0.041</td>
<td>0.085</td>
<td>0.29</td>
<td>0.530</td>
</tr>
<tr>
<td>f(MHz)</td>
<td>80.5</td>
<td>80.5</td>
<td>322</td>
<td>322</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>V_a (MV)</td>
<td>0.81</td>
<td>1.62</td>
<td>1.90</td>
<td>3.70</td>
</tr>
<tr>
<td>E_p (MV/m)</td>
<td>30.0</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>B_p (mT)</td>
<td>53</td>
<td>71</td>
<td>75</td>
<td>77</td>
</tr>
<tr>
<td>T(K)</td>
<td>4.5</td>
<td>4.5</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

4 cavity types and 2 frequencies
Project objectives: construction of a 40 MeV deuton accelerator (which can also accelerate q/A = 1/3 and 1/6) as a driver for RIB production

<table>
<thead>
<tr>
<th>Cryomodule</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve-to-valve length [mm]</td>
<td>610</td>
<td>1360</td>
</tr>
<tr>
<td># cavities</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>f [MHz]</td>
<td>88.05</td>
<td>88.05</td>
</tr>
<tr>
<td>(\beta_{opt})</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>Epk/Eacc</td>
<td>5.36</td>
<td>4.76</td>
</tr>
<tr>
<td>Bpk/Eacc [mT/MV/m]</td>
<td>8.70</td>
<td>9.35</td>
</tr>
<tr>
<td>r/Q [(\Omega)]</td>
<td>599</td>
<td>515</td>
</tr>
<tr>
<td>Vacc @ 6.5 MV/m &amp; (\beta_{opt})</td>
<td>1.55</td>
<td>2.66</td>
</tr>
<tr>
<td>Lacc [m]</td>
<td>0.24</td>
<td>0.41</td>
</tr>
<tr>
<td>Beam tube (\varnothing) [mm]</td>
<td>38</td>
<td>44</td>
</tr>
</tbody>
</table>
Low beta cavities ("A" type): developed by CEA Saclay: QWR with dismountable copper bottom flange

Zanon and SDMS cavities
12 over 13 cavities received – 1 under repair

Courtesy P. Bosland
High beta cavities ("B" type): developed by IPN Orsay: QWR with welded Nb bottom flange, Titanium He tank (4 mm), SS cavity flanges.

Total produced:
- R1D phase: 1 prototype + 2 pre-series
- Series production: 16 (made by Research Instruments)
ESS **accelerator** high-level technical objectives:

- 5 MW long pulse source
  - 2.86 ms pulses
  - 14 Hz
  - Protons (H+)
  - Low losses
  - High reliability, >95%
  - Continuous cryostats for minimum energy consumption
  - Flexible design for a future power upgrade

Mats Lindross SRF 2011
## European Spallation Source

### Table of Properties

<table>
<thead>
<tr>
<th>Component</th>
<th>Length (m)</th>
<th>Input Energy (MeV)</th>
<th>Frequency (MHz)</th>
<th>Geometric $\beta$</th>
<th># of Sections</th>
<th>Temp (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ</td>
<td>4.7</td>
<td>$75 \times 10^{-3}$</td>
<td>352.2</td>
<td>--</td>
<td>1</td>
<td>$\approx 300$</td>
</tr>
<tr>
<td>DTL</td>
<td>19</td>
<td>3</td>
<td>352.2</td>
<td>--</td>
<td>3</td>
<td>$\approx 300$</td>
</tr>
<tr>
<td>Spoke</td>
<td>58</td>
<td>50</td>
<td>352.2</td>
<td>0.57</td>
<td>14 (2c)</td>
<td>2</td>
</tr>
<tr>
<td>Low Beta</td>
<td>108</td>
<td>188</td>
<td>704.4</td>
<td>0.70</td>
<td>16 (4c)</td>
<td>2</td>
</tr>
<tr>
<td>High Beta</td>
<td>196</td>
<td>606</td>
<td>704.4</td>
<td>0.90</td>
<td>15 (8c)</td>
<td>2</td>
</tr>
<tr>
<td>HEBT</td>
<td>100</td>
<td>2500</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Mats Lindross SRF 2011
European Spallation Source

IPHI RFQ at CEA-Saclay

LINAC 4

SC single spoke cavity, IPNO (CNRS)

SC 5 cell cavity for 704 MHz, CEA and CNRS

Mats Lindross SRF 2011
A possible schematic layout for a EURISOL facility

EURISOL

H- RFO 176 MHz
HWRs 176 MHz
3-spoke ISCL 325 MHz
Elliptical ISCL 704 MHz
Elliptical ISCL 704 MHz

n-generator

UC_x target

One of several target stations

1+ ion source

Low-resolution mass-selector

High-resolution mass-selector

Secondary fragmentation target

Spoke ISCL 264 MHz
8 HWRs ISCL 176 MHz
3 0WRs ISCL 88 MHz
OWR ISCL 88 MHz

Bunching RFO

Charge selector

Charge breeder

To high-energy experimental areas

20-150 MeV/u (for 131Sn)

To medium-energy experimental areas

9.3-62.5 MeV/u

2.1-19.9 MeV/u

To low-energy areas

H+, D+, 3He++

ion sources

100 keV

1.5 MeV/u

60 MeV/q

140 MeV/q

β = 0.09, β = 0.15

β = 0.3

β = 0.47

β = 0.65

β = 0.78

>200 MeV/q

D+, A/q=2

1 GeV/q H+, H++,

3He++
**EURISOL**

**IPN Orsay**

\[ \beta = 0.15 \]

\[ \beta = 0.35 \]

\[ T = 2K \]
\[ Q_0 = 6.3 \times 10^9 \]

\[ T = 4.2K \]
\[ Q_0 = 1.2 \times 10^9 \]

- \[ -55 < K_{\text{Lorentz}} [\text{Hz/(MV/m)^2}] < -28 \]
- \[ 67 < K = -H \text{ calculated (E.Zaplatin)} \]

**RF coupling by beam tubes**

**QUENCH**

\[ E_{\text{acc}} = 10.45 \text{ MV/m} \]
\[ E_{\text{pk}} = 35 \text{ MV/m} \]
\[ B_{\text{pk}} = 75 \text{ mT} \]

\[ -9 < K_{\text{Lorentz}} [\text{Hz/(MV/m)^2}] < -6 \]
\[ NB: -32 < K < -5.5 \text{ calculated (E.Zaplatin)} \]

\[ T = 4 \text{K} \]
\[ Q_0 = 2.6 \times 10^9 \]

**RF coupling by RF port**

**QUENCH**

\[ E_{\text{acc}} = 12.5 \text{ MV/m} \]
\[ E_{\text{pk}} = 38 \text{ MV/m} \]
\[ B_{\text{pk}} = 104 \text{ mT} \]

\[ T = 2 \text{K} \]
\[ Q_0 = 2.6 \times 10^9 \]
IFMIF Project
(International Fusion Materials Irradiation Facility)

Objective of the IFMIF project: characterization of materials with intense neutrons flux \((10^{17} \text{ n/s})\) for the future Fusion Reactor DEMO (~150 dpa)

In the framework of an agreement between EURATOM & Government of Japan, the program IFMIF/EVEDA has been launched in June 2007
Cryomodule under construction for the accelerator prototype
The first one of the IFMIF SRF Linac~5 m Long
4.5 MV/m, reliability, limits the coupler power
Large beam aperture 40-48 mm
Qex=6.3e4

2 accelerators, 2 x 125 mA, 2 x 5MW

Deuteron source
140 mA, 100 keV

RFQ 5 MeV

SRF Linac 40 MeV
(Half Wave Resonators)

Lithium Target
25 mm thick, 15 m/s

Beam shape
200 x 50 mm²

Typical reactions

\(^7\text{Li}(d,2n)^7\text{Be}\)
\(^6\text{Li}(d,n)^7\text{Be}\)
\(^8\text{Li}(n,T)^4\text{He}\)

Test Cell

High >20 dpa/an, 0.5 L
Medium > 1 dpa/an, 6 L
Low < 1 dpa/an, > 8 L

(Courtesy of Alban Mosnier, CEA)
IFMIF Cryomodule general layout

- HWR equipped with Tuning System on top
- Solenoid Package equipped with VCCL
- Vacuum Vessel
- Magnetic shielding Thermal screen
- He phase separator
- Vacuum valve
- LHe manifolds
- RF couplers
- Tee Transition
- Vacuum manifold and valve
- Main support
Accelerator Driven Systems

EU-ADS

(Courtesy of Jean-Luc Biarrotte, IPN, Orsay)

- (EU) ETWG report on ADS, 2001
- (EU-FP5) PDS-XADS project (2001-2004)
- (EU-FP6) EUROTRANS programme (2005-2010)
- MYRRHA Project (Multi-purpose hYbrid Research Reactor for High-tech Applications at Mol (Belgium): ADS demonstrator to be operational in 2023, 2.5 mA 600 MeV CW
- Industrial transmuter (EFIT): ~20 mA, 800 MeV
ADS : MYRRAH

Main features of the ADS demo
~70 MWth power
k\textsubscript{eff} around 0.95
600 MeV, 4 mA proton beam
Highly-enriched MOX fuel
Pb-Bi Eutectic coolant & target

Indepedently-phased SC linac
- 352 MHz spoke & 704MHz elliptical
- low gradients, fast fault-tolerance capabilities expected

<table>
<thead>
<tr>
<th>Section number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input energy (MeV)</td>
<td>17.0</td>
<td>86.4</td>
<td>165.2</td>
</tr>
<tr>
<td>Output energy (MeV)</td>
<td>86.2</td>
<td>86.2</td>
<td>605.3</td>
</tr>
<tr>
<td>Cavity technology</td>
<td>Spoke 352.2 MHz</td>
<td>Elliptical 704 MHz</td>
<td></td>
</tr>
<tr>
<td>Cavity geometrical β</td>
<td>0.35</td>
<td>0.47</td>
<td>0.66</td>
</tr>
<tr>
<td>Cavity optimal β</td>
<td>0.37</td>
<td>0.51</td>
<td>0.70</td>
</tr>
<tr>
<td>Nb of cells / cavity</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Focusing type</td>
<td>NC quadrupole doublets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb of cavities / cryomodule</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Total nb of cavities</td>
<td>63</td>
<td>30</td>
<td>64</td>
</tr>
<tr>
<td>Acc. field (MV/m at opt. β)</td>
<td>5.5</td>
<td>8.5</td>
<td>10.3</td>
</tr>
<tr>
<td>Synchronous phase (deg)</td>
<td>-40 to -18</td>
<td>-26 to -15</td>
<td></td>
</tr>
<tr>
<td>5mA beam loading / cav (kW)</td>
<td>1 to 8</td>
<td>3 to 22</td>
<td>17 to 38</td>
</tr>
<tr>
<td>Section length (m)</td>
<td>63.2</td>
<td>52.5</td>
<td>100.8</td>
</tr>
</tbody>
</table>
ADS: Chinese Road Map

C-ADS is being developed by CAS. IHEP and IMP are in charge of proton accelerator. The facility is dedicated for transmutation and subcritical reactor. The project will be three stages. It is for technology R&D in the first 5~7 years.
100 accelerator modules

800 cavities + power couplers
1.3 GHz / 23.6 MV/m

25 RF stations
5.2 MW each
XFEL Collaboration

Injector
Bunch Compressor
Main Linac
Collimation
Beam Distribution
Undulators

SRF Conference, Chicago, July 24-29, 2011
Detlef Reschke, DESY
XFEL String and Module
String assembly is crucial for the cavity performance
String + power coupler assembly for all modules will take place at CEA Saclay site
Commissioning of infrastructure and training of CEA staff with prototype modules ongoing
Knowledge transfer to executing company to be done after placing of order
Compact Light Sources

Superconducting RF photoinjector operating at 300 MHz and 4K

RF amplifiers

1 MeV

Electron beam of ~1 mA average current at 10-30 MeV

Bunch compression chicane

Inverse Compton scattering

30 kW beam dump

X-ray beamline

Coherent enhancement cavity with Q=1000 giving 5 MW cavity power

30 MeV

5 kW cryo-cooled Yb:YAG drive laser

Inverse Compton scattering

SRF Linac Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy gain [MeV]</td>
<td>25</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>352</td>
</tr>
<tr>
<td>Average current [mA]</td>
<td>1</td>
</tr>
<tr>
<td>Operating temperature [K]</td>
<td>4.2</td>
</tr>
<tr>
<td>RF power [kW]</td>
<td>30</td>
</tr>
</tbody>
</table>
Crabbing/Deflecting Systems

- Use of the magnetic field of a $TM_{110}$ horizontal dipole mode
- The field gives a phase-dependent transverse momentum kick to the beam
Crabbing/Deflecting Systems

Installation of Crab Cavities
for HER  Jan. 8, 2007,
for LER  Jan. 11, 2007

Carrying the Crab cavity using crane track

Crab Cavity for HER

Cool-down of Crab Cavities
Jan. 29, 2007

Beam Operation Start
Feb. 13

Crab Cavity for LER
# LHC Upgrade Crabbing System

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Unit</th>
<th>LHC</th>
<th>KEK-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>400 (800)</td>
<td>509</td>
</tr>
<tr>
<td>Deflecting Voltage</td>
<td>MV/Cav</td>
<td>5</td>
<td>2.0 (0.9-1.5)</td>
</tr>
<tr>
<td>Peak E-field</td>
<td>MV/m</td>
<td>&lt; 45</td>
<td>28</td>
</tr>
<tr>
<td>Peak B-field</td>
<td>mT</td>
<td>&lt; 80 mT</td>
<td>82 mT</td>
</tr>
<tr>
<td>Aperture (diameter)</td>
<td>mm</td>
<td>84</td>
<td>130</td>
</tr>
<tr>
<td>Cav Outer Envelope</td>
<td>mm</td>
<td>&lt; 150</td>
<td>866/483</td>
</tr>
<tr>
<td>Module length</td>
<td>m</td>
<td>~ 1m</td>
<td>1.5 m</td>
</tr>
<tr>
<td>HV crossing</td>
<td>-</td>
<td>Desirable</td>
<td>N/A</td>
</tr>
<tr>
<td>$\beta^*$ (IR1/IR5)</td>
<td>cm</td>
<td>15-25</td>
<td>63/0.7</td>
</tr>
<tr>
<td>$\beta$ crab</td>
<td>km</td>
<td>~ 5</td>
<td>0.2/0.04</td>
</tr>
<tr>
<td>Non-linear harmonics</td>
<td>Units $[10^{-4}]$</td>
<td>2-3</td>
<td>N/A</td>
</tr>
<tr>
<td>Impedance Budget</td>
<td>Longitudinal, Transverse</td>
<td>60kΩ, 2.5MΩ/m</td>
<td>-</td>
</tr>
</tbody>
</table>
## Properties of 400 MHz Crabbing Cavities for LHC

<table>
<thead>
<tr>
<th>Reel</th>
<th>4-rod</th>
<th>Half-wave</th>
<th>Par-bar/Ridged</th>
<th>Quarter-wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK</td>
<td>U. Lancaster</td>
<td>SLAC</td>
<td>ODU</td>
<td>BNL</td>
</tr>
<tr>
<td>$E_p/E_t$</td>
<td>10.9</td>
<td>4</td>
<td>3.9</td>
<td>3.8</td>
</tr>
<tr>
<td>$B_p/E_t$ (mT/(MV/m))</td>
<td>18.7</td>
<td>7.6</td>
<td>7.3</td>
<td>7.1</td>
</tr>
<tr>
<td>$R/Q$ (Ω)</td>
<td>765</td>
<td>215</td>
<td>312</td>
<td>132</td>
</tr>
</tbody>
</table>

Aperture: 84 mm

$E_t = 2V_t/\lambda$, $V_t = 375$ kV at $E_t = 1$ MV/m
SRF Technology

- The SRF technology is increasingly becoming the technology of choice for an increasing number of accelerator applications

- Steady progress has been made

- We are beginning to bump into the fundamental limits of the niobium-based technology
  - Still struggling with repeatability and consistency
  - Process and procedure control

- The next frontier is new materials
  - Niobium alloys
  - High Tc materials