SRF technology for proton and ion accelerators

G. Devanz CEA-Saclay

IPAC 2011 – San Sebastian
Quarter and half wave resonators

Found on ion linacs with continuous beams. Started with ATLAS, ALPI, PIAVE

Historically, low beam intensity and narrow resonator bandwidth: technology development was focussed more on microphonics control (mechanical vibration dampers, feedback, fast tuning)

The trend is to use them for higher beam currents (from several mA to 125 mA) and at higher gradients: more emphasis is put on RF optimization for lower peak surface fields preparation and power couplers. Bulk niobium is also widely used.

When aiming at higher voltage per cavity, elliptical cavity preparation procedure are being adopted. Cryomodule vacuum and cavity vacuum separation is needed in order to be consistent with the cleanliness which is sought after.

For QWRs two types of designs exist: some are fully welded, some use a removable end plate in the low magnetic field region to give access to the inside for surface treatments and inspection. In many cases this end plate region is where RF couplers or tuners are installed, is not directly cooled by He: at lot of technology is concentrated here.
One 72 MHz $\beta = 0.077$ QWR (x7) module will replace three split ring modules as part of the intensity (x10) upgrade: **17.5 MV in 5.2 m**

- Optimized surface fields
- Minimized pressure sensitivity
- Separate vacuum
- Welded cavity
- Tuning by cavity deformation in the beam tube region

Courtesy M. Kelly
ANL-ATLAS upgrade

Long tradition of EP at Argonne on individual parts of QWR which were then welded together. 2008: switch to open cavity and removable plate separate Eps. 2011: New horizontal low $\beta$ EP tool able to polish a fully dressed cavity with a complex shape in a single operation.

- Cooled by chilled water in the He vessel
- 4 cathodes
- Rotating system

Courtesy M. Kelly, S. Gerbick
ANL-ATLAS upgrade

Test Results for Prototype 72 MHz QWR

\[ R_S = 1 \, \text{n}\Omega \]

150 μm removal 
(12hrs EP)
$\beta = 0.07$ at CEA-Saclay (12 single cavity modules)
$\beta = 0.12$ at IPN Orsay (7 dual cavity modules)

Common technologies:
- bulk Nb
- BCP
- separate vacuum
- 20 kW CW power couplers (LPSC – Grenoble)

5 mA Deuteron beam
20 Mev/u for RIB production
88 MHz SC linac
Room temperature focusing elements

Status: cryomodule construction phase: 2 low beta CMs and 4 high beta CMs tested
# GANIL – SPIRAL 2

<table>
<thead>
<tr>
<th>beta</th>
<th>0.07</th>
<th>0.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity</td>
<td>Copper removable end plate</td>
<td>Fully welded</td>
</tr>
<tr>
<td>He vessel</td>
<td>Stainless steel</td>
<td>titanium</td>
</tr>
<tr>
<td>Cold tuning system</td>
<td>Mechanical squeezing beam region</td>
<td>SC plunger</td>
</tr>
<tr>
<td>Magnetic shield</td>
<td>Room temperature</td>
<td>Actively pre-cooled cryo-specific alloy</td>
</tr>
</tbody>
</table>

**Tuner options**

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$\beta = 0.07$ vertical tests with copper end plate

$Q_0$ vs. $E_{acc} (MV/m)$

GANIL – SPIRAL 2
TRIUMF – ISAC II

• simple cylindrical resonator design adopted from ALPI-PIAVE from INFN-Legnaro
• cavity and cryomodule share the same vacuum
• tuning is achieved by flexible Nb end plate at cavity bottom
• narrow bandwidth : microphonics must be minimized
  • reduce the pressure sensitivity Df/DP
  • run the cavities overcoupled with respect to matched coupling
  • damp mechanical vibrations (Legnaro friction damper installed in the stem)

106 MHz

2001 : $\beta = 0.072$
prototype

$\beta = 0.072$

$\beta = 0.057$

$\beta = 0.11$

ISAC II phase 2 : 141 MHz
3 added CMs
Specs 7W 6 MV/m

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β=0.11 top assembly insertion in CM tank

Phase I : $8 \times \beta=0.057 + 12 \times \beta=0.072$
Phase II : $20 \times \beta=0.11$ added

Operating experience:
Problems mainly due to interruptions in He delivery to the CMs. Observed consequences are:
• trapped flux
• the necessary warm up is followed by multipacting activity which has to be processed before beam operation

Phase II cavity performance

Courtesy D. Longuevergne
Rare isotope beam formed from stable ions (He to U) with a minimum energy of 200 MeV/u 400 kW maximum beam power

112 QWRs and 229 HWR cavities at 2 K
ReA - FRIB

ReA is re accelerator for rare isotope beams produced by MSU Coupled Cyclotron Facility
ReA3 is the first stage of ReA
ReA also serves as a prototype for FRIB linac

First module 0.041 1 rebuncher cavity + 2 solenoids
Module 2 : 6 QWR $\beta = 0.041 + 3$ solenoids -> commissioned with beam
Module 3 : 8 QWR $\beta = 0.085 + 3$ solenoids - > testing cavities

Critical part for removable endplate QWR (thermal stability problems and gasket heating or leaks occurred on many projects):

- slotted flexible plate (initiated by ISAC - II design) combined with separate vacuum design
- RF ports moved to the cavity side (reduction of thermal flux on the plate)

$\beta=0.085$ Cavity test:
$E_p=58$ MV/m $B_p = 130$ mT

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Courtesy A. Facco
SOREQ - SARAF

2 mA, 40 MeV Deuteron
First HWR cryomodule in operation with beam ($\beta = 0.09$)

Early problems of field emission in the cryomodule situation
Helium processing used for reduction of F.E.
Cavities operate at $V_{acc} = 0.84$ MV ($E_p=25$ MV/m) (total cryo losses 62 W)
Instabilities: high PHe sensitivity (60 Hz/mbar) and Lorentz force detuning 11 Hz/(MV/m)$^2$
The hysteresis of the tuner RF prevents the regulation of the cavity voltage: more RF power will be installed (2 -> 4 kW)

Phase 2 designs:
Beta 0.13 cavity

176 MHz $\beta = 0.09$ cryomodule

Phase 2 designs:
Beta 0.13 cavity

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Courtesy A. Perry
CEA – IFMIF EVEDA SRF Linac

For fusion material irradiation

Two 125 mA 40 MeV Deuteron beams on Li Target (10^{17} neutron/s)

HWR cryomodule

β=0.094 175 MHz HWR

Max. 200 kW power coupler
IFMIF

First tests on prototype HWRs:
• strong MP at in the tuner port before installation of the plunger prevented the HWR qualification
• Tests done with NbTi membrane supporting the plunger with quench at low field.
• A modified version of the tuner is being designed

Vertical test setup at IPN Orsay

HWR equipped with Ti He vessel and SC plunger
High power H+/H- SRF accelerators

- Machines and projects:
  - Operating and pioneer: SNS
  - LHC
  - Projects with on going R&D and prototypes: ESS, SPL, MYRRHA
  - Planned SRF linacs CSNS, CIADS,
  - R&D demonstrators: MSU, J-PARC, EUROTRANS

- Recurring questions:
  - HOM couplers or not?
  - Cryomodule architecture (cryo-losses vs maintenance and availability)
  - Should the transition between RT and SC sections be lowered using low beta structures, e.g. spokes?
<table>
<thead>
<tr>
<th>Lab</th>
<th>Type</th>
<th>Frequency</th>
<th>Opt beta</th>
<th>Eacc,max</th>
<th>Vmax</th>
<th>Epk/Eacc</th>
<th>Bpk/Eacc</th>
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<td>21</td>
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</table>

Data normalized with $L_{acc} = \beta \lambda / 2$ per gap

Many spoke resonators reach $E_{acc} \approx 8$ MV/m

Courtesy G. Olry
FNAL - Project X

3 GeV, 1 mA CW proton linac followed by a 3-8 GeV pulsed linac

SSR0 with improved He vessel
- Lowering the Df/dP + ASME pressure vessel code compliant
- Tuning on one side only
- Temperature 2K

Updated designs for CW mode

SSR1 horizontal test

Updated designs for CW mode

HINS Jacketed SSR1-01 - $Q_0$ vs $E_{acc}$

Q-Disease Test at 4.8 K

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LFD compensation

Courtesy L. Ristori
**FNAL - Project X**

**Elliptical cavities**

650 MHz 5 cell cavities

Maximum load at 2K is 250 W per module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>JLab</th>
<th>FNAL</th>
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<tr>
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<td>650</td>
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<td>$E_{\text{peak}}/E_{\text{acc}}$</td>
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<td>$B_{\text{peak}}/E_{\text{acc}}$</td>
<td>mT/(MV/m)</td>
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<tr>
<td>R/Q</td>
<td>Ω</td>
<td>297</td>
<td>378</td>
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<tr>
<td>G</td>
<td>Ω</td>
<td>190</td>
<td>191</td>
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<tr>
<td>R/Q·G</td>
<td>Ω²</td>
<td>56430</td>
<td>72198</td>
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</table>

Single cell $\beta=0.6$ results

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Courtesy C. Ginsburg, F. Marhauser
### CERN - SPL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
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<tbody>
<tr>
<td>$\beta$</td>
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<tr>
<td>$f$ (MHz)</td>
<td>704.4</td>
<td>704.4</td>
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<tr>
<td>$E_{pk}/E_{acc}$</td>
<td>2.63</td>
<td>2</td>
</tr>
<tr>
<td>$B_{pk}/E_{acc}$</td>
<td>5.12</td>
<td>4.2</td>
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<tr>
<td>$K$ (%)</td>
<td>1.45</td>
<td>1.9</td>
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<tr>
<td>$r/Q$ (Ohm)</td>
<td>275</td>
<td>566</td>
</tr>
<tr>
<td>$G$ (Ohm)</td>
<td>197</td>
<td>270</td>
</tr>
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</table>

- Cern stainless steel He vessel
- $\beta=1$ 5-cell cavity
- IPNO $\beta=0.65$

**Short cryomodule prototype concept**

**Intercavity supports**

**RF coupler double-walled tube flange fixed to vacuum vessel**

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CERN – SPL R&D

CEA-Saclay coupler tested up to 1.2 MW 50Hz 2ms
Design derived from KEK-SNS style coupler

Saclay-V type piezo tuner for SPL cavities

Integrated test in Cryholab of power coupler and tuner on a $\beta=0.5$ 5cell cavity. LDF compensation with piezo

Amplitude excursion reduced to 1.4% and phase shift within $\pm 8$ deg.
SNS has demonstrated:

- The suitability of SRF technology for a high power pulsed H-linac
- Operational flexibility of independently phased cavities

Problems:

Field emitted electrons propagating from cavity to cavity.
Multipactor in HOM couplers ultimately detuning the notch filter and damaging the coupler

Cures:

- Remove HOM probes
- Re-process the cavities, with enhanced surface treatments, electropolishing

81 6-cell elliptical cavities
ONRL – SNS – Power upgrade

SNS Second Target Station
Optimized for intense beams of cold neutrons
20 Hz long pulse at ~1 MW
20 instrument beamlines

Accelerator
Beam energy: 1 GeV → 1.3 GeV
Beam current: 26 mA → 42 mA
Beam power: 1.4 MW → 2.4~3 MW
40 Hz→FTS (short pulse), 20 Hz→STS (long pulse)
Preliminary design of $\beta=0.57$ 352 MHz double spoke cavity (IPN Orsay)

Prototypes of spokes and high beta elliptical cavities tests planned in 2012

G. Olry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Frequency (MHz)</td>
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<tr>
<td>Number of cells</td>
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<td>Operating temperature (K)</td>
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<tr>
<td>Maximum surface field in operation (MV/m)</td>
<td>40</td>
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<tr>
<td>Nominal Accelerating gradient (MV/m)</td>
<td>&lt; 18</td>
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<tr>
<td>$Q_0$ at nominal gradient</td>
<td>&gt; 6e9</td>
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<tr>
<td>Repetition rate (Hz)</td>
<td>14</td>
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<tr>
<td>Beam pulse length (ms)</td>
<td>2.86</td>
</tr>
<tr>
<td>Nominal peak power transmitted by power couplers (kW)</td>
<td>&lt; 900</td>
</tr>
</tbody>
</table>

Geometrical beta | 0.86 |
Iris diameter (mm) | 120 |
Cell to cell coupling $\kappa$ (%) | 1.8 |
$\pi$ and $4\pi/5$ mode separation (MHz) | 1.2 |
$E_{pk}/E_{acc}$ | 4.3 |
Maximum. $r/Q$ (Ω) | 477 |
Optimum beta | 0.92 |
G (Ω) | 241 |
ADS - MYRRHA

600 MeV 4 mA CW proton linac

<table>
<thead>
<tr>
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<th>#1</th>
<th>#2</th>
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<td>$E_{\text{input}}$ (MeV)</td>
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<td>88.4</td>
<td>188.2</td>
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<tr>
<td>$E_{\text{output}}$ (MeV)</td>
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<td>186.2</td>
<td>605.3</td>
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<td>Cav. technology</td>
<td>Spoke</td>
<td>Elliptical</td>
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<td>0.47</td>
<td>0.65</td>
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<tr>
<td>Nb of cells / cav.</td>
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<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Focusing type</td>
<td>NC quadrupole doublets</td>
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<tr>
<td>Nb cav / cryom</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Total nb of cav.</td>
<td>63</td>
<td>30</td>
<td>64</td>
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<tr>
<td>Nominal $E_{\text{sec}}$ (MV/m)</td>
<td>5.3</td>
<td>8.5</td>
<td>10.3</td>
</tr>
<tr>
<td>Synch. phase (deg)</td>
<td>-40 to -18</td>
<td>-36 to -15</td>
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</tr>
<tr>
<td>5mA beam load / cav (kW)</td>
<td>1 to 8</td>
<td>3 to 22</td>
<td>17 to 38</td>
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<tr>
<td>Section length (m)</td>
<td>63.2</td>
<td>52.5</td>
<td>100.8</td>
</tr>
</tbody>
</table>

$E_{\text{sec}}$ is normalized to $L_{\text{sec}}=N_{\text{cell}}\beta_{\text{opt}}/2$, & given at $\beta_{\text{opt}}$

17 MeV Injector : dual injector for fault tolerance

IAP- Frankfurt
CH structure

Eurotrans test cryomodule at IPN Orsay with INFN-Milano $\beta=0.5$ 5-cell cavity equipped with the blade tuner

Courtesy J.-L. Biarrotte
Medium beta related R&D

- BARC: 325 MHz spoke resonators and 650 MHz elliptical cavities
- RRCAT 650 MHz $\beta=0.9$ single cell prototype in 2011
- PEFP in Korea 700 MHz $\beta=0.42$
- PKU 450 MHz $\beta=0.2$ single spoke

- Chinese ADS: CIADS spoke & HWR R&D
- Full cavity testing of 352 MHz spoke at IPN Orsay

Single spoke equipped with power coupler and tuner
Conclusion

• very wide and active field due to the many cavity types available

• ion and proton cavities benefit from the preparation techniques developed on electron cavities, and their performance has been greatly improved during the last decade

• Spoke resonators are now included in several machine baseline. Beam testing of a spoke based system has not been carried out yet, but huge progress has been achieved recently in spoke technology
Thanks to

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P. Bosland, P-E Bernaudin
E. Montesinos
A. Perry
D. Longuevergne

Thank you for your attention