Status of (some) Spoke cavity developments worldwide

Guillaume OLRY
olry@ipno.in2p3.fr
Proofs of inflation in Spoke cavity use...

From Big Bang to 1992

1 cavity

From 1992 to 2004

+6 cavities

From 2004 to nowadays

+ >30 cavities
Nowadays...
Developments for **low and medium velocity** ($\beta \leq 0.5$) proton and ion Linacs

Developments **for electron** ($\beta = 1$) and **high velocity** ($\beta \geq 0.5$) proton and ion Linacs
IPN involvements

“in-house” R&D
1999-2004
Prototyping (done): 2 Single-Spoke cavities

RIB
2005-2009: EURISOL Design Study
Prototyping (done): 1 Triple-Spoke Cavity

ADS
From 2005: IP-EUROTRANS, CDT, MAX, (MYRTE)
Prototyping (on-going): 2 Single-Spoke cavities

Spallation Source
From 2009: ESS
Prototyping phase (on-going): 3 Double-Spoke cavities
Construction phase (in 2016): 26 Double-Spoke cavities
1 prototype built (2011)

@300K
- tested with several tuning systems

@2K
- 1st RF test showed strong multipacting barriers
- Recent RF test failed because of cracks (weld seam)
Design of Single-Spoke cavities at 352 MHz with $\beta=0.37$

24 cryomodules, 48 spoke cavities

Bare cavity

1. Cavity body
2. Beam tube connection (x2)
3. Spoke bar rib (x2)
4. Internal ring (x2)
5. External ring (x2)
6. Titanium disc (x2)
7. CF63 Flange (x4)
8. Coupler port
9. Pick-up port

Same stiffeners as the ESS Spoke cavity = cost reduction ("standardisation")

2 fully jacketed Single-Spoke in fabrication (2015)

Stiffeners for vacuum load compensation

Titanium vessel

4 ports on cavity end - wall for High Pressure Rinsing

Ø100 Coupler port

Mechanical optimisation

SRF 2013

Double-Spoke cavities being delivered in 2014

MP calculations (after final design, no optimisation)

7–13 MV/m

0.3–0.6 MV/m

Design of a double-spoke cavities at 352 MHz with $\beta = 0.50$

13 cryomodules

26 spokes

FIRST CAVITY RECEIVED (October 13, 2014)
IHEP/IMP: C-ADS

- Design of a *Single-spoke cavities at 325 MHz with 3 different betas (0.12, 0.21 & 0.40)*, more than 100 cavities
- R&D on other betas and Spoke type

IHEP and IMP co-work on the accelerator. Final project has two identical injectors. Two designs of injector is due to technical uncertainty at very low energy segment.
Injector I: Two Single-Spoke 0.12, 325 MHz already built, tested in VT and HT.

Mass production has started
→ 4/11 cavities already produced and received!

6.5 MV/m
Limitation: Heavy MP
Main linac: Vertical test of one (over 5) Single-Spoke 0.21, 325 MHz

From design to fab.

Recipes of Post-Treatment

- Finish Fabri.
- CBP (100 hours)
- Heavy BCP (100um)
- UPR (50° & 3 hours)
- Annealing (650° & 10 hours)
- Light BCP (20um)
- HPR (60bar, 5 hours)
- Assembly
- LowT Baking (150° & 24 hours)

VT in Jan 2014 @ 4 K

- $Q_0 = 5 \times 10^8$
- $B_{peak} = 65$ mT
- Designed $Q_0 = 5 \times 10^8$
- $E_{peak} = 11.4$ MV/m

Quench (?)

Jacked with adjustable antenna

ECOS-EURISOL Joint Town Meeting – 28-31/10/2014 - Orsay
Main Linac: design of a **Single-Spoke 0.40, 325 MHz**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>556</td>
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<tr>
<td>length</td>
<td>386.5</td>
<td>mm</td>
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<tr>
<td>Beam aperture</td>
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<td>mm</td>
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<tr>
<td>R/Q</td>
<td>250</td>
<td>Ω</td>
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<tr>
<td>G</td>
<td>104</td>
<td>Ω</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>8.2</td>
<td>mT/(MV/m)</td>
</tr>
</tbody>
</table>
Main Linac: Single-Spoke 0.21, 325 MHz: 3 cavities built and tested in vertical cryostat

Max. $B_{\text{peak}} = 107$ mT @ $Q_0 = 4.0 \times 10^8$
On-going R&D activities on cavity design

Design of Single-Spoke 0.32, 325 MHz
- Magnetic field distribution
- Electric field distribution

Design of Double-Spoke 0.37, 325 MHz (as an alternative to Spoke 0.40)
- Y. He, private communication

Design of Double-Spoke 0.52, 325 MHz
- Without Stiffeners
- With Stiffeners

Design of CH-type 0.067, 162.5 MHz
- Vertical Test Sept 2014

Y. He, private communication
For PXIE, 25 MeV, 1 mA (=Injector of Project X)

**SSR1** Single-Spoke Resonator at 325 MHz with $\beta=0.22$

**SSR2** Single-Spoke Resonator at 325 MHz with $\beta=0.51$
2 SSR1 prototypes and 10 SSR1 series cavities

Prototype: jacketed cavity

Series: bare cavity

Spoke with collars

Finished end-wall

largest series of Spoke cavities in the world
Vertical tests @ 2K of the 9 received SSR1: **all validated**

No severe degradation from bare cavity tested in VC (black dots) to jacketed cavity tested in HC (red dots)

Highest Eacc (22 MV/m) and Epk (84 MV/m) ever reached in Spoke cavity in CW mode
2 SC Linacs (SCL1 and SCL2) for ions acceleration: proton (600 MeV) to Uranium (200 MeV/u)

1 SC Linac for RIB acceleration (18.5 MeV/u)

RAON (Driver Linac SCL1 and SCL2)

- 23 SSR1 Single-Spoke Resonators at 325 MHz with $\beta=0.30$
- 23 SSR2 Single-Spoke Resonators at 325 MHz with $\beta=0.51$
Rebuncher for intense heavy ions

Triple-Spoke Resonator at 219 MHz with $\beta=0.303$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Frequency</td>
<td>219 MHz</td>
</tr>
<tr>
<td>$\beta (= v/c)$</td>
<td>0.303</td>
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<tr>
<td>Voltage ($V_{total}$)</td>
<td>3 MV</td>
</tr>
<tr>
<td>Cavity Length</td>
<td>829 mm</td>
</tr>
<tr>
<td>Effective Length ($L_{eff}$)</td>
<td>829 mm</td>
</tr>
<tr>
<td>Cavity Diameter</td>
<td>580 mm</td>
</tr>
<tr>
<td>Beam Bore Diameter</td>
<td>30 mm</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>665 $\Omega$</td>
</tr>
<tr>
<td>$G (=QR_s)$</td>
<td>74.0 $\Omega$</td>
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<tr>
<td>$E_{acc}$</td>
<td>3.62 MV/m</td>
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<tr>
<td>$E_{pk}/E_{acc}$</td>
<td>4.42</td>
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<tr>
<td>$B_{pk}/E_{acc}$</td>
<td>11.01 mT/(MV/m)</td>
</tr>
<tr>
<td>$R_s$ @ 4.5 K</td>
<td>48 n$\Omega$</td>
</tr>
<tr>
<td>$Q$</td>
<td>$1.54 \times 10^9$</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>8.8 W</td>
</tr>
</tbody>
</table>

Low frequency for better phase acceptance

First Single-Spoke model in Copper under fabrication
Developments for low and medium velocity ($\beta \leq 0.5$) proton and ion Linacs

Developments for electron ($\beta = 1$) and high velocity ($\beta \geq 0.5$) proton and ion Linacs
Old Dominion University

- **325 MHz, β= 0.82 and 1, single and double**
  - Collaboration with JLab

- **352 MHz, β= 0.82 and 1, single and double**
  - Collaboration with JLab

- **500 MHz, β= 1, double**
  - Collaboration with Niowave
  - Collaboration with JLab

- **700 MHz, β= 1, single, double, and triple**
  - Collaboration with Niowave, Los Alamos and NPS
Generic studies for high velocity protons and ions linac

- Design and optimization of double-spoke cavities at 325 and 352 MHz with $\beta_0 = 0.82$ and 1

<table>
<thead>
<tr>
<th>RF properties</th>
<th>325 MHz, $\beta_0 = 0.82$</th>
<th>325 MHz, $\beta_0 = 1.0$</th>
<th>352 MHz, $\beta_0 = 0.82$</th>
<th>352 MHz, $\beta_0 = 1.0$</th>
<th>Units</th>
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<tbody>
<tr>
<td>Energy gain at $\beta_0$</td>
<td>757</td>
<td>922</td>
<td>699</td>
<td>852</td>
<td>kV</td>
</tr>
<tr>
<td>R/Q</td>
<td>625</td>
<td>744</td>
<td>630</td>
<td>754</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>QRs</td>
<td>168</td>
<td>195</td>
<td>169</td>
<td>193</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>(R/Q)*QRs</td>
<td>1.05x10^5</td>
<td>1.45x10^5</td>
<td>1.07x10^5</td>
<td>1.46x10^5</td>
<td>$\Omega^2$</td>
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<tr>
<td>Ep/Eacc</td>
<td>2.6</td>
<td>2.8</td>
<td>2.7</td>
<td>2.75</td>
<td>-</td>
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<tr>
<td>Bp/Eacc</td>
<td>4.97</td>
<td>5.6</td>
<td>4.9</td>
<td>5.82</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>Bp/Ep</td>
<td>1.9</td>
<td>2.0</td>
<td>1.8</td>
<td>2.12</td>
<td>mT/(MV/m)</td>
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<tr>
<td>Energy Content</td>
<td>0.45</td>
<td>0.56</td>
<td>0.35</td>
<td>0.43</td>
<td>-</td>
</tr>
<tr>
<td>Power Dissipation*</td>
<td>0.37*</td>
<td>0.43*</td>
<td>0.33**</td>
<td>0.36**</td>
<td>W</td>
</tr>
</tbody>
</table>

At Eacc = 1 MV/m and reference length $\beta_0 \lambda$

*Rs = 68 n$\Omega$

**Rs = 73 n$\Omega$

First prototype under fabrication: 325 MHz, $\beta_0 = 0.82$ Single-Spoke cavity
For Compact Light Source (CLS)

- Goal: energy gain > 25MeV with 4 double-spoke cavities at 500 MHz with $\beta_0 = 1$

Interesting point: cavity in 2 pieces and final welding in the centre

Leak on cavity's flange
For ERL

- Design of a 5-gap spoke cavities at 650 MHz with $\beta_0=1$

→ Compactness and easier HOM extraction compared to 9-cell elliptical cavity

First Aluminum cavity model for RF and HOM studies
For compact **industrial-use** X-ray source

- Design of a **2-gap spoke cavity** at 325 MHz with $\beta_0 = 1$

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>325</td>
<td>MHz</td>
</tr>
<tr>
<td>Cavity diameter</td>
<td>609.5</td>
<td>mm</td>
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<td>Cell length</td>
<td>461.2</td>
<td>mm</td>
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<tr>
<td>Cavity length</td>
<td>1383.6</td>
<td>mm</td>
</tr>
<tr>
<td>$E_{\text{peak}}/E_{\text{acc}}$</td>
<td>3.7</td>
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<tr>
<td>$B_{\text{peak}}/E_{\text{acc}}$</td>
<td>7.5</td>
<td>mT/(MV/m)</td>
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<tr>
<td>$R/Q$</td>
<td>691</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Transit time factor</td>
<td>0.81</td>
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**Fabrication has just started**
Thank you for your attention
Balloon geometry motivation

- suppresses multipacting for single spoke resonators
- may find a useful application for proton and ion accelerator projects
- TRIUMF has completed initial RF, mechanical studies on this special geometry for both low ($\beta=0.12$) and medium ($\beta=0.3$) $\beta$ geometries
- The RF properties are comparable with that of traditional spoke cavities but with improved RF efficiency in addition to the reduced multipacting
- The balloon geometry supplies a better mechanical strength than the traditional bare spoke cavity. Good mechanical parameters are obtained by a compact stiffeners design based on the electro-magnetic and deformation compensation
- The mechanical study on the $\beta=0.3$ balloon resonator is still ongoing. Fully study of balloon variant spoke cavity on the low and medium $\beta$ region will make an in-depth understand of this new kind of spoke geometry

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>CADS Spoke012</th>
<th>Balloon 0.12</th>
<th>RISP SSR1</th>
<th>Balloon 0.3</th>
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<tbody>
<tr>
<td>$E_p/E_{acc}$</td>
<td>1</td>
<td>4.5</td>
<td>4.8</td>
<td>4.7</td>
<td>4.4</td>
</tr>
<tr>
<td>$B_p/E_{acc}$</td>
<td>mT/(MV/m)</td>
<td>6.4</td>
<td>7.5</td>
<td>6.4</td>
<td>6.8</td>
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<tr>
<td>$R/Q$</td>
<td>$\Omega$</td>
<td>142</td>
<td>161</td>
<td>234</td>
<td>272</td>
</tr>
<tr>
<td>$G$</td>
<td>$\Omega$</td>
<td>61</td>
<td>63</td>
<td>94</td>
<td>98</td>
</tr>
<tr>
<td>$E_{acc}$</td>
<td>MV/m</td>
<td>7.1</td>
<td>7.1</td>
<td>7.5</td>
<td>8.0</td>
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<tr>
<td>$E_p$</td>
<td>MV/m</td>
<td>32</td>
<td>34</td>
<td>35</td>
<td>35</td>
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<tr>
<td>$B_p$</td>
<td>mT</td>
<td>44</td>
<td>53</td>
<td>48</td>
<td>54</td>
</tr>
</tbody>
</table>
Intensive MultiPacting calculations and cavity shape optimizations to reduce MP barriers

Original geometry

Surviving MP after 20 RF periods

Optimised geometry

Suppress MP > 4.6 MV/m and reduce the impact energy of the 2 points, order=1

order = 1
order = 2
order = 4
order = 6
For Compact Light Source (CLS)

- CW Linac at 4 K for 1 mA electron, 4 MeV in, 22 MeV out (20 MeV minimum). Linac length <= 4m
- Two double-spoke cavities at 352 MHz with $\beta_0=1$ in one cryomodule

Specification: $V_{acc/cavity} = 9$ MV, $E_p < 30$ MV/m, $B_p < 80$ mT

Single-Spoke cavity as a first prototype.