SUPERCONDUCTING SPOKE CAVITIES FOR ELECTRON AND HIGH-VELOCITY PROTON LINACS

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and
Thomas Jefferson National Accelerator Facility
History

• The spoke (and the half-wave) cavity was developed at ANL in the late 1980s for the acceleration of high-current medium velocity particles
  – ~10’s mA, ~100 MeV, p and D, low emittance
  – Proposed for IFMIF
  – Proposed for ADS

• Support from DoD stopped in 1992, and in 1994 for IFMIF and ADS.

• Interest was revived in the late 1990s at ANL for RIA, and at other laboratories for other high-current ion accelerators

• The spoke geometry is now the geometry of choice in the medium velocity region and is being developed in many laboratories worldwide

• It is now under development for the acceleration of particles going at close to the velocity-of-light
850 MHz, $\beta=0.3$ Spoke (1990)
Fermilab Project X

325 MHz, $\beta=0.22$
Open symbols: 345 MHz, $\beta=0.5$

Closed symbols: 345 MHz, $\beta=0.63$
Features of Spoke Cavities

- **Small Size**
  - About half of TM cavity of same frequency

- **Allows low frequency at reasonable size**
  - Possibility of 4.2 K operation
  - High longitudinal acceptance

- **Fewer number of cells**
  - Wider velocity acceptance

350 MHz, $\beta = 0.45$
Features of Spoke Cavities

- **Strong cell-to-cell coupling in multi-spoke**
  - All the cells are linked by the magnetic field
  - Field profile robust with respect to manufacturing inaccuracy
  - No need for field flatness tuning
  - Closest mode well separated

Magnetic Field Profile: 352 MHz, $\beta=0.48$ (FZJ)
Features of Spoke Cavities

- Accelerating mode has lowest frequency
  - No lower-order mode
  - Easier HOM damping

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Freq. (MHz)</th>
<th>$\Delta f/f$ % of $f_{\text{ACC}}$</th>
<th>Freq. (MHz)</th>
<th>$\Delta f/f$ % of $f_{\text{ACC}}$</th>
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<tr>
<td>10</td>
<td>679</td>
<td>97</td>
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</table>
Features of Spoke Cavities

- Electromagnetic energy concentrated near the spokes
  - Low energy content
  - High shunt impedance
  - Low surface field on the outer surfaces
    - Couplers (fundamental and HOM) can be located on outer conductor
    - Couplers do not use beamline space

325 MHz, $\beta=0.17$ (FNAL)  
M. Sawamura et al. SRF 2011
Features of Spoke Cavities

- Few mechanical modes, none at low frequency
- Low microphonics and sensitivity to helium pressure

345 MHz, $\beta=0.5$, triple-spoke (Z. Conway, ANL)

$df/dp = -0.4$ Hz/mbar
How High Can We Go with $\beta_g$ in Spoke Cavities?

- What are their high-order modes properties?
  - Spectrum
  - Impedances
  - Beam stability issues

- Is there a place for spoke cavities in high-$\beta$ high-current applications?
  - FELs, ERLs
  - Higher order modes extraction
Compact Light Sources

• Most existing SRF cavities require or benefit from 2K operation
  – Too complex for a University or small institution-based accelerator
  – Cryogenics is a strong cost driver for compact SRF linacs

• Spoke cavities can operate at lower frequency
  – Lower frequency allows operation at 4K
  – No sub-atmospheric cryogenic system
  – Significant reduction in complexity

• Similar designs for accelerating low-velocity ions are close to desired specifications
Compact Light Sources

Superconducting RF photoinjector operating at 300 MHz and 4K

RF amplifiers

RF amp
RF amp
RF amp

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

1 MeV
30 MeV

Bunch compression chicane

Inverse Compton scattering

30 kW beam dump

X-ray beamline

5 kW cryo-cooled Yb:YAG drive laser

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

8 m

MIT proposal

<table>
<thead>
<tr>
<th>SRF Linac Parameters</th>
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<tbody>
<tr>
<td>Energy gain [MeV]</td>
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<tr>
<td>RF frequency [MHz]</td>
<td>352</td>
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<tr>
<td>Average current [mA]</td>
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<tr>
<td>Operating temperature [K]</td>
<td>4.2</td>
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<tr>
<td>RF power [kW]</td>
<td>30</td>
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</tbody>
</table>
2.5 GeV Superconducting Single-Frequency Linac, pulsed current is 100 mA, f=325 MHz

- Input energy – 7 MeV
- 2 types of spoke cavities, length =48 m, 135 MeV
- 2 types of spoke cavities + 2 types of 3-spoke cavities, total length =480 m, 2.3 GeV (total = 250 SC cavities)
- TSR, $\beta = 0.6$
- TSR, $\beta = 0.87$
- Focusing with SC solenoids, eff. length = 20 cm, B= from 4T to 10.4T
- $f = 325$ MHz
- $\beta = 0.87$
- Length = 1.55 m
- Aperture diameter – 60 mm
Compact ERL (JAEA)

- ERL combined with laser Compton scattering for non-destructive assay system for nuclear materials in spent fuel

Nondestructive assay of plutonium and minor actinide in spent fuel using nuclear resonance fluorescence with laser Compton scattering γ-rays

Takehito Hayakawa a,*, Nobuhiro Kikuzawa b, c, Ryoichi Hajima c, Toshiyuki Shizuma a, Nobuyuki Nishimori c, Mamoru Fujiwara a, d, Michio Seya e
Old Dominion University

- 325 MHz, $\beta = 0.82$ and 1, single and double
  - Collaboration with JLab

- 352 MHz, $\beta = 0.82$ and 1, single and double
  - Collaboration with JLab

- 500 MHz, $\beta = 1$, double
  - Collaboration with Niowave
  - Collaboration with JLab

- 700 MHz, $\beta = 1$, single, double, and triple
  - Collaboration with Niowave, Los Alamos and NPS

Designs by:
Chris Hopper
Suba De Silva
Rocio Olave
Old Dominion University

325 MHz Single-Spoke
Fabricated at Niowave Inc.

500 MHz Double-Spoke
Fabricated at Jefferson Lab
(HyeKyoung Park)
ELECTROMAGNETIC DESIGN GOALS

• Minimize the peak surface fields
  • High electric field can lead to field emission (Reliable operation: $E_p \sim 50$ MV/m)
  • High magnetic field can cause quenching (Theoretical limit: $B_p \sim 170$ mT)

\[
\begin{align*}
\frac{E_p}{E_{acc}} & \quad \frac{B_p}{E_{acc}}
\end{align*}
\]

• Maximize the shunt impedance
  • Decreases dissipation for a given voltage gain

• Balanced peak fields ($B_p/E_p$)
  • Achieve the reliable limits simultaneously
PARAMETERS OF OPTIMIZATION

- Fixed Quantities
  - Design velocity ($\beta_0$), operating frequency ($f_0$), and beam aperture

- Geometric parameters
  - No single parameter can be used to minimize surface fields or maximize shunt impedance
  - Very generally speaking, the spoke base and separation ($L_{\text{spoke}}$) are the most influential for minimizing $B_p$ while the spoke aperture and separation are used for minimizing $E_p$
  - Several parameters can help maximize the shunt impedance, but the spoke base orientation by far has the greatest impact
SPOKE BASE PROPERTIES

Peak Surface Magnetic field is at the spoke base
SPOKE APERTURE PROPERTIES

Peak Surface Field field is at the spoke aperture

(a) 325 MHz, β₀ = 1

(b) E_p / E_acc [mT/(MV/m)]

(Spoke aperture length) / (rf wavelength)
Design Optimization (a small sample)
Double Spoke

Surface Electric Field

Surface Magnetic Field

Electric Field

On Axis Electric Field
## Cavity properties

<table>
<thead>
<tr>
<th>Cavity Parameters</th>
<th>$\beta_0 = 0.82$</th>
<th>$\beta_0 = 1.0$</th>
<th>Units</th>
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<tbody>
<tr>
<td>Frequency of accelerating mode</td>
<td>325</td>
<td>325</td>
<td>MHz</td>
</tr>
<tr>
<td>Frequency of nearest mode</td>
<td>333</td>
<td>329</td>
<td>MHz</td>
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<tr>
<td>Cavity diameter</td>
<td>627</td>
<td>640</td>
<td>mm</td>
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<tr>
<td>Iris-to-iris length</td>
<td>949</td>
<td>1148</td>
<td>mm</td>
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<tr>
<td>Cavity length</td>
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<td>1328</td>
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<tr>
<td>Reference length</td>
<td>757</td>
<td>922</td>
<td>mm</td>
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<tr>
<td>Aperture diameter at spoke</td>
<td>60</td>
<td>60</td>
<td>mm</td>
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<table>
<thead>
<tr>
<th>Cavity Parameters</th>
<th>$\beta_0 = 0.82$</th>
<th>$\beta_0 = 1.0$</th>
<th>Units</th>
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<tbody>
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<td>352</td>
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<td>Frequency of nearest mode</td>
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<td>Cavity diameter</td>
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<td>Reference length</td>
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<td>852</td>
<td>mm</td>
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<tr>
<td>Aperture diameter at spoke</td>
<td>50</td>
<td>50</td>
<td>mm</td>
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# Cavity properties

<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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<tr>
<td><strong>Energy gain at ( \beta_0 )</strong></td>
<td>757</td>
<td>922</td>
<td>699</td>
<td>852</td>
<td>kV</td>
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<tr>
<td><strong>R/Q</strong></td>
<td>625</td>
<td>744</td>
<td>630</td>
<td>754</td>
<td>Ω</td>
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<tr>
<td><strong>QRs</strong></td>
<td>168</td>
<td>195</td>
<td>169</td>
<td>193</td>
<td>Ω</td>
</tr>
<tr>
<td>((R/Q)\times QRs)</td>
<td>(1.05\times10^5)</td>
<td>(1.45\times10^5)</td>
<td>(1.07\times10^5)</td>
<td>(1.46\times10^5)</td>
<td>(Ω^2)</td>
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<td><strong>Ep/Eacc</strong></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><strong>Bp/Eacc</strong></td>
<td>4.97</td>
<td>5.6</td>
<td>4.9</td>
<td>5.82</td>
<td>mT/(MV/m)</td>
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<tr>
<td><strong>Bp/Ep</strong></td>
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<td>2.0</td>
<td>1.8</td>
<td>2.12</td>
<td>mT/(MV/m)</td>
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<tr>
<td><strong>Energy Content</strong></td>
<td>0.45</td>
<td>0.56</td>
<td>0.35</td>
<td>0.43</td>
<td>J</td>
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<tr>
<td><strong>Power Dissipation</strong>&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.37&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.43&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.33&lt;sup&gt;**&lt;/sup&gt;</td>
<td>0.36&lt;sup&gt;**&lt;/sup&gt;</td>
<td>W</td>
</tr>
</tbody>
</table>

At \( E_{acc} = 1 \text{ MV/m} \) and reference length \( \beta_0\Lambda \)

<sup>*</sup>Rs = 68 nΩ  
<sup>**</sup>Rs = 73 nΩ
**Higher Order Mode Terminology**

- The beam travels along the $z$-axis. The electrical $z$-axis is taken to be the geometric $z$-axis. Transverse directions are $x$ and $y$, which run parallel to the spoke(s).

- Accelerating modes are those where $E_z(z)$, along the beam axis, is greater than $E_x(z)$ and $E_y(z)$.

- Deflecting modes are those where either $E_x(z)$ or $E_y(z)$ are greater than $E_z(z)$.

- $\phi$ is the phase between the particle and the rf fields. When considered in a calculation of $[R/Q]$, $[R/Q]_T$, the value $\phi$ of is that which maximizes the voltage.
Higher Order Modes (Double-Spoke)

### Accelerating modes

- Electric field (V/m)
  - $E_z(z)$, M1
  - $E_z(z)$, M2
  - $E_z(z)$, M3

### Deflecting Modes (degenerate modes)

- Electric field (V/m)
  - $E_x(z)$, M4
  - $E_y(z)$, M4

### TE-type modes

- Magnetic field (A/m)
  - $H_z(z)$ - M18

### Hybrid modes

- Electric field (V/m)
  - $E_z(z)$ - M47
  - $E_x(z)$ - M47
  - $E_y(z)$ - M47

Examples of modes for the 325 MHz cavity, $\beta_0 = 1$
**Higher Order Modes (Single-Spoke)**

**Accelerating modes**

Fundamental mode, 325 MHz, $\beta_0 = 0.82$

**Deflecting modes**

**Electric field**

**Magnetic field**
CALCULATING \([R/Q], [R/Q]_T\)

**Accelerating Modes**

\[
\left( \frac{R}{Q} \right) = \frac{V_{\text{acc}}^2}{\omega_n U}
\]

\[
V_{\text{acc}} = \left| \int_{-\infty}^{\infty} E_z(z, r = 0) \cos \left( \frac{\omega z}{\beta c} + \varphi \right) \, dz \right|
\]

\[
\left( \frac{R}{Q} \right) = \left| \int_{-\infty}^{\infty} E_z(z, r = 0) \cos \left( \frac{\omega z}{\beta c} \right) \, dz \right|^2 / \omega_n U
\]

**Deflecting Modes**

\[
V_T = \left| \int_{-\infty}^{\infty} \left[ \vec{E}_\perp (z, r = 0) + i(\vec{v}_z \times \vec{B}_\perp) \right] e^{i\omega z / \beta c} \, dz \right|
\]

\[
\left( \frac{R}{Q} \right)_T = \frac{V_T^2}{\omega_n U}
\]

Verify with PWT

\[
\Delta p_T = \left( \frac{e}{\omega_n} \right) \int_0^L (-i) \vec{v}_z E_z \, dz
\]

\[
\left( \frac{R}{Q} \right) = \left| \int_{-\infty}^{\infty} \left[ \vec{E}_\perp (z, r = a) - \vec{E}_\perp (z, r = 0) \right] e^{i\omega z / \beta c} \, dz \right|^2 / (ka)^2 \omega_n U
\]
GEOMETRIC SHUNT IMPEDANCE (DOUBLE-SPOKE)

[R/Q] values for particles at design velocity \( \beta_0 = 1 \) for the 500 MHz double-spoke cavity

Beam pipe cut-off frequency (50 mm aperture):

\[
f_c = \frac{1.841* c}{2\pi a} = 3.52 \text{ GHz}
\]
[R/Q] values for particles at design velocity $\beta_0 = 0.82$ for the 325 MHz single-spoke cavity

Beam pipe cut-off frequency (60 mm aperture):

$$f_c = \frac{1.841 \times c}{2\pi a} = 2.93 \text{ GHz}$$
Excitation of modes by a single bunch

Single Gaussian bunch, on-axis, $\sigma = 1$ cm
(bunch couples only to accelerating modes)

 Wakefield Spectrum

1: 700.6 MHz
2: 965.9 MHz
3: 1247.5 MHz
4: 1383.2 MHz
5: 1571.4 MHz
6: 1782.3 MHz
7: 1921.0 MHz
8: 2148.9 MHz
9: 2663.3 MHz
10: 2825.2 MHz
11: 2986.0 MHz
12: 3067.5 MHz
13: 3207.8 MHz
14: 3336.4 MHz
15: 3461.1 MHz
16: 3647.8 MHz
17: 3864.2 MHz
18: 3992.9 MHz

C. Hopper, ODU
ACE3P

F. Krawczyk, LANL
MAFIA
Large velocity acceptance which is important for protons and ions

- Single-spoke cavity: Greater than 96% efficiency between $0.7 \leq \beta \leq 1$.
- Double-spoke cavity: Greater than 96% efficiency between $0.74 \leq \beta \leq 0.92$.

$$E = K + m_0 c^2 - \gamma m_0 c^2$$

$$v = \sqrt{1 - \frac{1}{\gamma^2}} \cdot c$$
VELOCITY DEPENDENCE OF [R/Q] (325 MHz DS)

- Single-spoke cavity 96% efficient for protons with energies between 380 MeV and > 1.5 GeV
- Double-spoke cavity 96% efficient for protons with energies between 460 MeV and 1.5 GeV
Higher order multipole components can have effects on beam dynamics. Starting with the general description of the time dependent multipole fields:

\[ E_{\text{acc}}(r, \varphi, z, t) = E_z(r, \varphi, z)e^{i\omega t} = \sum_{n=0}^{\infty} E_z^{(n)}(z) r^n e^{in\varphi} e^{i\omega t} \]

\[ E_z^{(n)}(z) = \frac{1}{r^n} \int_0^{2\pi} E_z(r, \varphi, z) e^{in\varphi} \, d\varphi \]

\[ E_{\text{acc}}^{(n)}(z, t) = E_z^{(n)}(z) e^{i\omega t} = \frac{1}{r^n} \int_0^{2\pi} E_z(r, \varphi, z) [\cos(n\varphi) + i \sin(n\varphi)] e^{i\omega t} \, d\varphi \]

\[ B^{(n)}(z) = \frac{1}{q_c} E_{\text{acc}}^{(n)}(z) \quad [\text{T/m}^{n-1}] \]

\[ b_n = \int_{-\infty}^{\infty} B^{(n)}(z) \, dz \quad [\text{T/m}^{n-2}] \]
Components have been identified, beam dynamics simulated, and methods for reduction explored*

Net focusing in one direction and defocusing in perpendicular direction

Can be reduced through modifications to the geometry immediately around the beam path or using an even number of cavities oriented 90° from nearest neighbor.
Multipoles

500 MHz, $\beta = 1$

Nonlinearities of field, 500 MHz cavity, racetrack spokes
(symmetric tet [quarter] mesh)

Nonlinearities of field, 500 MHz cavity, ring-shaped spokes
(symmetric tet [quarter] mesh)

R. Olave, ODU
Multipacting

700 MHz, $\beta=1$
ACE3P
R. Olave, ODU
EMITTING AND RESONANT LOCATIONS

Initial and resonant locations by accelerating field gradient.

500 MHz double-spoke

325 MHz single-spoke
EMITTING AND RESONANT LOCATIONS

Distinct gradient levels where multipacting occurs in different locations of the cavity.
**MULTIPACTING (325 MHz)**

Multipacting experienced up to 2.1 MV/m

\[ EC = \delta_1 \cdot \delta_2 \cdots \delta_m \]
Gradient Measurements (325 MHz)

High levels of radiation from field emission
HELUM PROCESSING (325 MHz)

- Inject clean helium gas into the cavity while in the dewar, under vacuum
- Apply high power rf in cw and/or pulsed mode
SECOND PROCESSING (325 MHz)

- Similar to previous test, but higher $Q_0$.
- Onset of field emission at 6 MV/m

- High low-field $Q_0$
- After 2 rounds of He processing, achieved ~13 MV/m before quenching
MULTIPACTING (500 MHz)

Strong multipacting up to 4.5 MV/m
GRADIENT MEASUREMENTS (500 MHz)

Thermal event at 4 MV/m
**Surface Resistance Measurements**

### 325 MHz Single-Spoke Cavity (12.11.14)

- **Measured**
- **BCS fit**

- $R_{res} = 5.7 \, \text{n}\Omega$

### 500 MHz Double-Spoke Cavity (10.09.14)

- **Measured**
- **BCS fit**

- $R_{res} = 9.4 \, \text{n}\Omega$

Mathematical equation:

$$R_s \, [n\Omega] = \frac{a}{T[K]} \cdot e^{\left[-\frac{b}{T[K]}\right]} + R_{res}$$
## Cavity Performance

- 500 MHz double-spoke cavity was limited by thermal activity
- 325 MHz single-spoke cavity performed well after helium processing

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<th>Frequency</th>
<th>500</th>
<th>325</th>
<th>MHz</th>
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<tbody>
<tr>
<td>4 K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_{\text{acc}} )</td>
<td>2.7</td>
<td>9.1</td>
<td>MV</td>
</tr>
<tr>
<td>( E_{\text{acc}} )</td>
<td>4.5</td>
<td>12</td>
<td>MV/m</td>
</tr>
<tr>
<td>( E_p )</td>
<td>16.7</td>
<td>43.2</td>
<td>MV/m</td>
</tr>
<tr>
<td>( B_p )</td>
<td>34.2</td>
<td>72</td>
<td>mT</td>
</tr>
<tr>
<td>( Q_0 )</td>
<td>2.5\times10^9</td>
<td>5.6\times10^9</td>
<td>-</td>
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<table>
<thead>
<tr>
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<td>( E_{\text{acc}} )</td>
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<td>( E_p )</td>
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<tr>
<td>( B_p )</td>
<td>31.2</td>
</tr>
<tr>
<td>( Q_0 )</td>
<td>1.5\times10^{10}</td>
</tr>
</tbody>
</table>
Parting Thoughts

- The first spoke cavity was developed more than 20 years ago
- The spoke geometry has a number of attractive features
- Many prototypes have been, or are being, developed in many institutions
  - 300 to 850 MHz, \( \beta \) from <0.2 to 1
- They are not yet in use in any operating machine
  - The main argument against using them seems to be that they are not in use yet
- \( \beta \sim 1 \) spoke cavities have been built and are undergoing test
  - They were the first ones to accelerate beam
  - The first particle to be accelerated by a spoke cavity was an electron
Acknowledgements

• ODU
  – Subashini de Silva
  – Christopher Hopper
  – Rocio Olave

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  – Feisi He

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  – Masaru Sawumara

• Los Alamos
  – Frank Krawczyk

• Niowave
  – Chase Boulware
  – Dmitry Gorelov
  – Terry Grimm