TEM-CLASS CAVITY DESIGN

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Introduction

- There have been increased needs for reduced-beta ($\beta<1$) SRF cavity especially in CW machine (or high duty pulsed machine; duty $>10\%$)

  - Accelerator driven system (ADS)
    Nuclear transmutation of long-lived radio active waste
    Energy amplifier
    Intense spallation neutron source

  - Nuclear physics
    Radioactive ion acceleration
    Muon/neutrino production

- Defense applications

- SRF technology $\rightarrow$ Critical path !!
Introduction

• SRF cavity for CW application or long pulse application
  • efforts for expanding their application regions down to $\beta \sim 0.1$,

• Reduced beta Elliptical multi-cell SRF cavity
  • for CW, prototyping by several R&D groups have demonstrated as low as $\beta = 0.47$
  • for pulsed, SNS $\beta = 0.61, 0.81$ cavities & ESS

• Elliptical cavity has intrinsic problem as $\beta$ goes down
  • mechanical problem, multipacting, low RF efficiency

• Spoke cavity; supposed to cover ranges $\beta = 0.1 \sim 0.5(6), f = 300 \sim 900$ MHz
  • design & prototype efforts in RIA, AAA, EURISOL, XADS, ESS, etc.
  For proton $\beta = 0.12$ corresponds $\sim 7$ MeV $\rightarrow$ all the accelerating structures (except RFQ)
# Low and Medium $\beta$ Superconducting Accelerators

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High-current cw accelerators

- Beam: p, H⁻, d
- Technical issues and challenges
  - Beam losses (~ 1 W/m)
  - Activation
  - High cw rf power
  - Higher order modes
  - Cryogenics losses
- Implications for SRF technology
  - Cavities with high acceptance
  - Development of high cw power couplers
  - Extraction of HOM power
  - Cavities with high shunt impedance
High-current pulsed accelerators

- Beam: p, H⁻
- Technical issues and challenges
  - Beam losses (~ 1 W/m)
  - Activation
  - Higher order modes
  - High peak rf power
  - Dynamic Lorentz detuning
- Implications for SRF technology
  - Cavities with high acceptance
  - Development of high peak power couplers
  - Extraction of HOM power
  - Development of active compensation of dynamic Lorentz detuning
Medium to low current cw accelerators

- Beam; p to U
- Technical issues and challenges
  - Microphonics, frequency control
  - Cryogenic losses
  - Wide charge to mass ratio
  - Multicharged state acceleration
  - Activation
- Implications for SRF technology
  - Cavities with low sensitivity to vibration
  - Development of microphonics compensation
  - Cavities with high shunt impedance
  - Cavities with large velocity acceptance (few cells)
  - Cavities with large beam acceptance (low frequency, small frequency transitions)
Common considerations (I)

- Intermediate velocity applications usually do not require (or cannot afford) very high gradients.

- Operational and practical gradients are limited by:
  - Cryogenics losses (cw applications)
  - Rf power to control microphonics (low current applications)
  - Rf power couplers (high-current applications)

- High shunt impedance is often more important.

- To various degrees, beam losses and activation are a consideration.
Common considerations (II)

- Superconducting accelerators in the medium velocity range are mostly used for the production of secondary species
  - Neutrons (spallation sources)
  - Exotic ions (radioactive beam facilities)
- Medium power (100s kW) to high power (~MW) primary impinging on a target
- Thermal properties and dynamics of the target are important considerations in the design of the accelerator (frequency, duration, recovery from beam trips)
- Some implications:
  - Operate cavities sufficiently far from the edge
  - Provide an ample frequency control window
Design considerations

- Low cryogenics losses
  - High $\text{QR}_s \times R_{sh}/Q$
  - Low frequency
- High gradient
  - Low $E_p/E_{\text{acc}}$
  - Low $B_p/E_{\text{acc}}$
- Large velocity acceptance
  - Small number of cells
  - Low frequency
- Frequency control
  - Low sensitivity to microphonics
  - Low energy content
  - Low Lorentz coefficient
- Large beam acceptance
  - Large aperture (transverse acceptance)
  - Low frequency (longitudinal acceptance)
A Few Obvious Statements

Low and medium $\beta$

$\beta < 1$

Particle velocity will change

The lower the velocity of the particle or cavity $\beta$

The faster the velocity of the particle will change

The narrower the velocity range of a particular cavity

The smaller the number of cavities of that $\beta$

The more important it is that the particle achieve design velocity

Be conservative at lower $\beta$

Be more aggressive at higher $\beta$
Two main types of structure geometries
   TEM class (QW, HW, Spoke)
   TM class (elliptical)

Design criteria for elliptical cavities

Challenges and the future of reduced beta srf cavity design
Sang-ho Kim, LINAC 2002.

Low and intermediate $\beta$ cavity design
Jean Delayen, SRF 2003

High-energy ion linacs based on superconducting spoke cavities
Superconducting Structures – Circa 1987
$\beta < 1$ Superconducting Structures – Circa 1989

\[ \frac{\beta}{\beta_{\text{crit}}} \text{ vs. Frequency, MHz} \]

- + NIOBIUM
- ○ LEAD

- A : ALVAREZ
- CH : COAXIAL HALF-WAVE
- H : HELIX
- HW : HALF-WAVE
- I : INTER DIGITAL QW
- QW : QUARTER-WAVE
- R : REENTRANT
- S : SPIRAL
- SP : SPOKE
- SI : SLOTTED IRIS
- SR : SPLIT RING

\[ \frac{\beta}{\beta_{\text{crit}}} \text{ vs. Frequency, MHz} \]
$\beta < 1$ Superconducting Structures – 2002..
Basic Structure Geometries

Resonant Transmission Lines

- $\lambda/4$
  - Quarter-wave
  - Split-ring
  - Twin quarter-wave
  - Lollipop

- $\lambda/2$
  - Coaxial half-wave
  - Spoke
  - H-types

- TM
  - Elliptical
  - Reentrant

- Other
  - Alvarez
  - Slotted-iris
A Word on Design Tools

TEM-class cavities are essentially 3D geometries

3D electromagnetic software is available
MAFIA, Microwave Studio, HFSS, etc.

3D software is usually very good at calculating frequencies
Not quite as good at calculating surface fields
Use caution, vary mesh size
Remember Electromagnetism 101
Design Tradeoffs

Number of cells
  Voltage gain
  Velocity acceptance

Frequency
  Size
  Voltage gain
  Rf losses
  Energy content, microphonics, rf control
  Acceptance, beam quality and losses
Energy Gain
Transit Time Factor - Velocity Acceptance

\[ \Delta W = q \int_{-\infty}^{+\infty} E(z) \cos(\omega t + \phi) \, dz \]

Assumption: constant velocity

\[ \Delta W = q \cos \phi \Delta W_0 \, T(\beta) \]

\[ \Delta W_0 = \Theta \int_{-\infty}^{+\infty} |E(z)| \, dz \]

\[ \Theta = \frac{\text{Max} \int_{-\infty}^{+\infty} E(z) \cos \left( \frac{\omega z}{\beta c} \right) \, dz}{\int_{-\infty}^{+\infty} |E(z)| \, dz} \]

Transit Time Factor

\[ T(\beta) = \frac{\text{Max} \int_{-\infty}^{+\infty} E(z) \cos \left( \frac{\omega z}{\beta c} \right) \, dz}{\text{Max} \int_{-\infty}^{+\infty} E(z) \cos \left( \frac{\omega z}{\beta c} \right) \, dz} \]

Velocity Acceptance
Transit Time Factor

(a) 

(b) 

Graph showing the relationship between transit time and factor.
Velocity Acceptance for 2-Gap Structures

\[
T(\beta) = \frac{\beta}{\beta_0} \frac{\sin\left(\frac{\pi \alpha \beta_0}{2x_0 \beta}\right) \sin\left(\frac{\pi}{2x_0 \beta}\right)}{\sin\left(\frac{\pi \alpha}{2x_0}\right) \sin\left(\frac{\pi}{2x_0}\right)}
\]

\[
x_0 = \frac{\beta_0 \lambda}{2l}
\]
Velocity Acceptance for 3-Gap Structures

\[ T(\beta) = \frac{\beta}{\beta_0} \frac{\sin \left( \frac{\pi \alpha \beta_0}{3x_0 \beta} \right)}{\sin \left( \frac{\pi \alpha}{3x_0} \right)} \left[ \cos \left( \frac{\pi \alpha \beta_0}{3x_0 \beta} \right) - \cos \left( \frac{\pi}{x_0} \right) \right] \]

\[ x_0 = \frac{\beta_0 \lambda}{2l} \]
Higher-Order Effects

\[ \Delta W = q \cos \phi \Delta W_0 \, T(\beta) + \left( \frac{q \Delta W_0}{W} \right)^2 \left[ T^{(2)}(\beta) + \sin 2\phi \, T_s^{(2)}(\beta) \right] \]

\[ T^{(2)}(k) = -\frac{k}{4} T(k) \frac{d}{dk} T(k) \quad k = \omega / \beta c \]

\[ T_s^{(2)}(k) = -\frac{k}{4\pi} \int_0^\infty \frac{T(k+k')T(k-k') - T(k)T(k)}{k'^2} \, dk' \]
If characteristic length $\ll \lambda$ ($\beta < 0.5$), separate the problem in two parts:

- Electrostatic model of high voltage region
- Transmission line

![Diagram of loaded quarter-wavelength resonant line]
Basic Electrostatics

a: concentric spheres
b: sphere in cylinder
c: sphere between 2 planes
d: coaxial cylinders
e: cylinder between 2 planes

\[ V_p : \text{Voltage on center conductor} \]
\[ \text{Outer conductor at ground} \]
\[ E_p : \text{Peak field on center conductor} \]
Loaded Quarter-wavelength Resonant Line

Capacitance per unit length

\[ C = \frac{2\pi \varepsilon_0}{\ln\left(\frac{b}{r_0}\right)} = \frac{2\pi \varepsilon_0}{\ln\left(\frac{1}{\rho_0}\right)} \]

Inductance per unit length

\[ L = \frac{\mu_0}{2\pi} \ln\left(\frac{b}{r_0}\right) = \frac{\mu_0}{2\pi} \ln\left(\frac{1}{\rho_0}\right) \]
Loaded Quarter-wavelength Resonant Line

Center conductor voltage

\[ V(z) = V_0 \sin \left( \frac{2\pi}{\lambda} z \right) \]

Center conductor current

\[ I(z) = I_0 \cos \left( \frac{2\pi}{\lambda} z \right) \]

Line impedance

\[ Z_0 = \frac{V_0}{I_0} = \frac{\eta}{2\pi} \ln \left( \frac{1}{\rho_0} \right), \quad \eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377 \Omega \]
Loading capacitance

\[ \Gamma(z) = \lambda \varepsilon \frac{\cotan\left(\frac{2\pi}{\lambda} z\right)}{\ln\left(\frac{1}{r_0}\right)} = \lambda \varepsilon \frac{\cotan\left(\frac{\pi}{2} \frac{\zeta}{\lambda}\right)}{\ln\left(\frac{1}{\rho_0}\right)} \]

\[ l = \frac{\lambda}{2\pi} \text{Arctan} \left[ \frac{\lambda \varepsilon}{\Gamma \ln\left(\frac{1}{\rho_0}\right)} \right] \]
Loaded Quarter-wavelength Resonant Line

Peak magnetic field

\[ \frac{V_p}{b} = \left\{ \frac{\eta H}{c B} \right\} \rho_0 \ln \left( \frac{1}{\rho_0} \right) \sin \left( \frac{\pi}{2} \zeta \right) \]

\[ V_p : \text{Voltage across loading capacitance} \]

\[ B \approx 9 \text{ mT at 1 MV/m} \]
Power dissipation (ignore losses in the shorting plate)

\[ P = V_p^2 \frac{\pi R_s}{8} \frac{\lambda}{b} \frac{1+1/\rho_0}{\ln^2 \rho_0} \frac{\zeta + \frac{1}{\pi} \sin \pi \zeta}{\sin^2 \frac{\pi}{2} \zeta} \]

\[ P \propto \frac{R_s}{\eta^2} E^2 \beta \lambda^2 \]
Energy content

\[ U = V_p^2 \frac{\pi \varepsilon_0}{8} \lambda \frac{1}{\ln(1/\rho_0)} \left( \frac{\zeta + \frac{1}{\pi} \sin \pi \zeta}{\sin^2 \frac{\pi}{2} \zeta} \right) \]

\[ U \propto \varepsilon_0 E^2 \beta^2 \lambda^3 \]
Geometrical factor

\[ G = QR_s = 2\pi\,\eta\, b\,\frac{\ln(1/\rho_0)}{\lambda} \frac{1}{1+1/\rho_0} \]

\[ G \propto \eta \beta \]
Loaded Quarter-wavelength Resonant Line

Shunt impedance \((4V_p^2 / P)\)

\[
R_{sh} = \frac{\eta^2}{R_s} \frac{32}{\pi} \frac{b}{\lambda} \ln^2 \frac{\rho_0}{\rho_0 + 1 + \rho_0} \frac{\sin^2 \frac{\pi}{2} \zeta}{2} = \frac{1}{\sin \pi \zeta} + \frac{1}{\pi}
\]

\[
R_{sh} \approx R_s \cdot \eta^2 \beta
\]
Loaded Quarter-wavelength Resonant Line

\[ \frac{R_{sh}}{Q} = \frac{16}{\pi^2} \eta \ln \left( \frac{1}{\rho_0} \right) \frac{\sin^2 \frac{\pi}{2} \zeta}{\zeta + \frac{1}{\pi} \sin \pi \zeta} \]

\[ \frac{R_{sh}}{Q} \propto \eta \]
Loaded Quarter-wavelength Resonant Line

\[
\rho_0 = \frac{r_0}{b}
\]

- loading capacitance: \( \frac{\Gamma}{\lambda \epsilon} \)
- end voltage: \( 10^{-8} \frac{V}{Bb} \)
- shunt impedance: \( 10^{-6}R_{Sh}R_S \frac{\lambda}{b} \)

\[
\zeta = \frac{4z}{\lambda}
\]
Loaded Quarter-wavelength Resonant Line

MKS units, lines of constant normalized loading capacitance \( \Gamma/\lambda \varepsilon_0 \)
More Complicated Center Conductor Geometries

\[ \frac{d^2 v}{d\zeta^2} - \frac{1}{\rho \ln \rho} \frac{d \rho}{d \zeta} \frac{dv}{d \zeta} + \frac{\pi^2}{4} v = 0 \]

\[ \frac{d^2 i}{d\zeta^2} + \frac{1}{\rho \ln \rho} \frac{d \rho}{d \zeta} \frac{di}{d \zeta} + \frac{\pi^2}{4} i = 0 \]

\[ \Gamma(z) = -C(z) \frac{i(z)}{di/dz} \]
Constant logarithmic derivative of line capacitance
Good model for linear taper

\[
\frac{1}{C} \frac{dC}{dz} = -\frac{1}{d} \quad r(z) = b \left( \frac{r_0}{b} \right)^{\exp(z/d)}
\]

Constant surface magnetic field

\[
i(z) \propto r(z)
\]

\[
\frac{d^2 r}{dz^2} - \frac{1}{r \ln(b/r)} \left( \frac{dr}{dz} \right)^2 + \frac{4\pi^2}{\lambda^2} r = 0
\]
Profile of Constant Surface Magnetic Field

MKS units, lines of constant normalized loading capacitance $\Gamma/\lambda\varepsilon_0$
Another Simple Model: Coaxial Half-wave Resonator
Coaxial Half-wave Resonator

Capacitance per unit length

\[ C = \frac{2\pi\varepsilon_0}{\ln \left( \frac{b}{a} \right)} = \frac{2\pi\varepsilon_0}{\ln \left( \frac{1}{\rho_0} \right)} \]

Inductance per unit length

\[ L = \frac{\mu_0}{2\pi} \ln \left( \frac{b}{r_0} \right) = \frac{\mu_0}{2\pi} \ln \left( \frac{1}{\rho_0} \right) \]
Coaxial Half-wave Resonator

Center conductor voltage

\[ V(z) = V_0 \cos \left( \frac{2\pi}{\lambda} z \right) \]

Center conductor current

\[ I(z) = I_0 \sin \left( \frac{2\pi}{\lambda} z \right) \]

Line impedance

\[ Z_0 = \frac{V_0}{I_0} = \frac{\eta}{2\pi} \ln \left( \frac{1}{\rho_0} \right), \quad \eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377\Omega \]
d: coaxial cylinders

$V_p$: Voltage on center conductor
Outer conductor at ground
$E_p$: Peak field on center conductor

(a), (b), (d)
Coaxial Half-wave Resonator

Peak magnetic field

\[
\frac{V_p}{b} = \left\{ \begin{array}{c} \eta \\ c \\ 300 \end{array} \right\} \frac{H}{B} \rho_0 \ln \left( \frac{1}{\rho_0} \right) \left\{ \begin{array}{c} \text{m, A/m} \\ \text{m, T} \\ \text{cm, G} \end{array} \right\}
\]

\[V_p: \text{ Voltage across loading capacitance}\]
\[B \approx 9 \text{ mT at 1 MV/m}\]
Coaxial Half-wave Resonator

Power dissipation (ignore losses in the shorting plate)

\[ P = \frac{V_p^2 \pi R_s \lambda}{4 \eta^2 b} \frac{1 + 1/ \rho_0}{\ln^2 \rho_0} \]

\[ P \propto \frac{R_s}{\eta^2} E^2 \beta \lambda^2 \]
Coaxial Half-wave Resonator

Energy content

\[
U = V_p^2 \frac{\pi \varepsilon_0 \lambda}{4} \frac{1}{\ln(1/\rho_0)}
\]

\[
U \propto \varepsilon_0 E^2 \beta^2 \lambda^3
\]
Geometrical factor

\[ G = Q R_s = 2\pi \eta \frac{b \ln\left(1/ \rho_0\right)}{\lambda} \frac{1}{1 + 1/ \rho_0} \]

\[ G \propto \eta \beta \]
Coaxial Half-wave Resonator

Shunt impedance \( \left( \frac{4V_p^2}{P} \right) \)

\[
R_{sh} = \frac{\eta^2}{R_s} \frac{16}{\pi} \frac{b}{\lambda} \frac{\ln^2 \rho_0}{1 + 1/\rho_0}
\]

\( R_{sh} R_s \propto \eta^2 \beta \)
Coaxial Half-wave Resonator

\[
\frac{R_{sh}}{Q} = \frac{8}{\pi^2} \eta \ln \left( \frac{1}{\rho_0} \right)
\]

\[
\frac{R_{sh}}{Q} \propto \eta
\]
Some Real Geometries ($\lambda/4$)
Some Real Geometries ($\lambda/4$)
$\lambda/4$ Resonant Lines
\( \lambda/2 \) Resonant Lines
$\lambda/2$ Resonant Lines – Single-Spoke
\(\lambda/2\) Resonant Lines – Double and Triple-Spoke
\( \lambda/2 \) Resonant Lines – Multi-Spoke
TM Modes
Design Considerations

• Minimize the peak surface fields $B_p$; approaches to theoretical limit (190 mT) $\leftarrow$ high RRR, defect control, better surface treatment ($\sim$170 mT) $E_p$; fields exceed 80 MV/m $\leftarrow$ improved surface cleaning tech.
• Reasonable **Inter-cell coupling** between cells in Elliptical cavity
• Spoke cavity intrinsically has big coupling constant
• Provide required **external Q**
• In CW, **higher shunt impedance** (mainly determined by the cavity type)
• Reasonable **mechanical stiffness**
  common; reasonable tuning force, mechanical stability under vacuum pressure (test~2 atm), stable against microphonics pulsed; affordable dynamic Lorentz force detuning
• Safe from **Multipacting**
• Verify **HOM** and related issues
• **Coupled field problems** are common between RF, mechanical, thermal..
  $\rightarrow$ **strong interfaces are needed**
RF Geometry Optimization (elliptical cavity)

Elliptical cell geometry and dependencies of RF parameters on the ellipse aspect ratio \( (a/b) \) at the fixed slope angle, dome radius and bore radius.

\[ \text{Ex. } \beta = 0.61, \ 805 \text{ MHz} \]

For fixed \( \alpha \), \( R_c \), \( R_i \)

Now, \( a/b \) is dependent parameter

\[ k \]
\[ B_{p/T}(\beta_g) \]
\[ R_s Q \]
\[ Z_{TT} \]

For circular dome
(Elliptical dome cases are same)

\( R_c, R_i, \alpha \), one of \( (a/b, a, b) \)
4 controllable parameters
\( R_{eq} \) (for tuning)
RF Geometry Optimization (Spoke Cavity)

• There have been extensive efforts for design optimization especially to reduce the ratios of \( \frac{E_p}{E_{acc}} \) and \( \frac{B_p}{E_{acc}} \).
  • Controlling A/B (\( \frac{E_p}{E_{acc}} \)) and C/D (\( \frac{B_p}{E_{acc}} \)) → **Shape optimization**
  • Flat contacting surface at spoke base will help in another minimization of \( \frac{B_p}{E_{acc}} \)
  • For these cavities:
    Calculations agree well → \( \frac{E_p}{E_{acc}} \sim 3, \frac{B_p}{E_{acc}} \sim (7\sim8) \text{ mT/(MV/m)} \),
    though it is tricky to obtain precise surface field information from the 3D simulation.

Intrinsically have very strong RF coupling in multi-gap cavity.
Have rigid nature against static and dynamic vibrations.
Beta dependency is quite small.
Diameter~half of elliptical cavity.
Velocity Acceptance

• Energy gain

\[ \Delta W = q \ V \ T(x) \ \Phi(x) \ \cos \phi \]

\[ x = \frac{\beta \lambda}{2l} \]

- \( T(x) \) Transit time factor for single cell
  Depends on field profile in cell

- \( \Phi(x) \) Phasing factor in multicell cavities
  Depends on cell spacing and field amplitude in cells
  Does not depend on field profile in cells (assumed to be identical)
Velocity Acceptance for Sinusoidal Field Profile

\[
\frac{\beta}{\beta_g}
\]

Velocity Acceptance

\[
\begin{array}{cccccccccccccc}
0.5 & 0.6 & 0.7 & 0.8 & 0.9 & 1.0 & 1.1 & 1.2 & 1.3 & 1.4 & 1.5 & 1.6 & 1.7 & 1.8 & 1.9 & 2.0 \\
\end{array}
\]
Voltage in Cells

Voltage in $j^{th}$ cell

$$ V_j^M = \sin \left( \pi M \frac{(2j-1)}{2N} \right) $$

N: Number of cells,  M: Mode number

6 Cell, Mode 6

6 Cell, Mode 5

6 Cell, Mode 4

6 Cell, Mode 3

6 Cell, Mode 2

6 Cell, Mode 1
Phasing Factor

For fundamental $(\pi)$ mode: $$\Phi(x) = \frac{1}{\cos\left(\frac{\pi}{2x}\right)} \left\{ (-1)^{n+1} \sin\left(\frac{N\pi}{2x}\right), \quad N = 2n \right\}
\left\{ (-1)^n \cos\left(\frac{N\pi}{2x}\right), \quad N = 2n + 1 \right\}
$$

For all modes:
$$\Phi(x) = \frac{1}{2} \left\{ \sin\left[ \frac{N\pi}{2} \left( \frac{M}{N} - \frac{1}{x} \right) \right] \right\} + (-1)^{M+1} \left\{ \sin\left[ \frac{N\pi}{2} \left( \frac{M}{N} + \frac{1}{x} \right) \right] \right\}
$$

If $M=N$, recover previous formula

If $x=1$
$$\Phi(x) = N\delta_{MN}$$
Phasing Factor

6 Cells, Mode 6

\[ \Phi(x) = \frac{\beta \lambda}{2l} \]

x = \frac{\beta \lambda}{2l}
Phasing Factor

6 Cells, Mode 5

\[ x = \frac{\beta \lambda}{2I} \]

\[ \Phi(x) \]

-4 -3 -2 -1 0 1 2 3 4 5 6

-4 -3 -2 -1 0 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5

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Phasing Factor

6 Cells, Mode 4

\[ x = \beta \lambda / 2 \lambda \]

\[ \Phi(x) \]

\[ \begin{align*}
-1 & & -0.8 & & -0.6 & & -0.4 & & -0.2 & & 0 & & 0.2 & & 0.4 & & 0.6 & & 0.8 & & 1 \\
1 & & 2 & & 3 & & 4 & & 5 & & 6
\end{align*} \]
Surface Electric Field

- **$\text{TM}_{010}$ elliptical structures**
  - $E_p/E_a \sim 2$ for $\beta = 1$
  - Increases slowly as $\beta$ decreases

- **$\lambda/2$ structures:**
  - Sensitive to geometrical design
  - Electrostatic model of an “shaped geometry” gives $E_p/E_a \sim 3.3$, independent of $\beta$
Surface Electric Field

- Lines: Elliptical
- Squares: Spoke
Surface Magnetic Field

- **$\text{TM}_{010}$ elliptical cavities:**
  - $B/E_a \sim 4 \text{ mT}/(\text{MV/m})$ for $\beta=1$
  - Increases slowly as $\beta$ decreases

- **$\lambda/2$ structures:**
  - Sensitive to geometrical design
  - Transmission line model gives $B/E_a \sim 8 \text{ mT}/(\text{MV/m})$, independent of $\beta$
Surface Magnetic Field

- **Lines: Elliptical**
- **Squares: Spoke**

**Graph:**
- $B_p/E_a$ (mT/(MV/m))
- Beta

- Data points and trend lines represent the relationship between $B_p/E_a$ and Beta.

---

**Note:**
- 

---
Geometrical Factor ($QR_s$)

- **$TM_{010}$ elliptical cavities:**
  - Simple scaling: $QR_s \sim 275 \beta (\Omega)$

- $\lambda/2$ structures:
  - Transmission line model: $QR_s \sim 200 \beta (\Omega)$
Geometrical Factor ($QR_s$)

- Lines: Elliptical
- Squares: Spoke
$R_{sh}/Q$ per Cell or Loading Element

- $R_{sh} = V^2/P$
- $\text{TM}_{010}$ elliptical cavities:
  - Simple-minded argument, ignoring effect of beam line aperture, gives: $R_{sh}/Q \propto \beta$
  - When cavity length becomes comparable to beam line aperture: $R_{sh}/Q \propto \beta^2$
  - $R_{sl}/Q \sim 120 \beta^2$ (Ω)

- $\lambda/2$ structures:
  - Transmission line model gives: $R_{sh}/Q \sim 205$ Ω
  - Independent of $\beta$
$R_{sh}/Q$ per Cell or Loading Element

Lines: Elliptical
Squares: Spoke

$R_{sh}$ per cell ($\Omega$)

Beta

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Shunt Impedance $R_{sh}$
($R_{sh}/Q\ Q R_s$ per Cell or Loading Element)

- TM$_{010}$ elliptical cavities:
  - $R_{sh} R_s \sim 33000 \beta^3 (\Omega^2)$

- $\lambda/2$ structures:
  - $R_{sh} R_s \sim 40000 \beta (\Omega^2)$
Shunt Impedance $R_{sh}$

($R_{sh}/Q$, $QR_s$ per cell or loading element)

- Lines: Elliptical
- Squares: Spoke

![Graph showing $R_{sh}R_s$ per cell versus Beta.](image)

**Beta**
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

*Values on the x-axis range from 0 to 1.*

*Values on the y-axis range from 0 to 35,000.*
Energy Content per Cell or Loading Element

Proportional to $E^2 \lambda^3$

At 1 MV/m, normalized to 500 MHz:

- **TM$_{010}$ elliptical cavities:**
  - Simple-minded model gives $U/E^2 \propto \beta$
  - In practice: $U/E^2 \sim 200$-$250$ mJ
  - Independent of $\beta$ (seems to increase when $\beta < 0.5 - 0.6$)

- **$\lambda/2$ structures:**
  - Sensitive to geometrical design
  - Transmission line model gives $U/E^2 \sim 200 \beta^2$ (mJ)
Energy Content per Cell or Loading Element

@ 1 MV/m, 500 MHz
Size & Cell-to-Cell Coupling

$\text{TM}_{010} \text{ Structures}$

Dia $\sim 0.88 \text{ – } 0.92 \lambda$

Coupling $\sim 2\%$

$\lambda/2 \text{ Structures}$

Dia $\sim 0.46 \text{ – } 0.51 \lambda$

Coupling $\sim 20 \text{ - } 30\%$

Example: $350 \text{ MHz, } \beta = 0.45$
Multipacting

- $\text{TM}_{010}$ elliptical structures
  - Can reasonably be modeled and predicted/avoided
  - Modeling tools exist

- $\lambda/2$ Structures
  - Much more difficult to model
  - Reliable modeling tools do not exist
  - Multipacting “always” occurs
  - “Never” a show stopper
TM Structures – Positive Features

- Geometrically simple
- Familiar
- Large knowledge base
- Good modeling tools
- Low surface fields at high $\beta$
- Small number of degrees of freedom
\[ \lambda/2 \] Structures – Positive Features

- Compact, small size
- High shunt impedance
- Robust, stable field profile (high cell-to-cell coupling)
- Mechanically stable, rigid (low Lorentz coefficient, microphonics)
- Small energy content
- Low surface fields at low \( \beta \)
- Large number of degrees of freedom
How Low Can We Go with $\beta_g$ in TM Cavities?

- Static Lorentz force detuning (LFD) at EoT($\beta_g$)=10 MV/m, 805 MHz (Magnification; 50,000)
- In CW application LFD is not an issue, but static LFD coeff. provides some indication of mechanical stability of structure.

$\beta_g$ values:
- $\beta_g=0.35$
- $\beta_g=0.48$
- $\beta_g=0.61$
- $\beta_g=0.81$

RF efficiency; x Mechanical Stability; x Multipacting; Strong possibility

Will work in CW Pessimistic in Pulsed application Would be a competing Region with spoke cavity

Suitable for all CW & pulsed applications Recent test results of SNS prototype cryomodule, $\beta_g=0.61$; quite positive; piezo compensation will work
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
Layout of the AEBL at ANL – 200 MeV/u, 400 kW

Color code:
Black = existing facility
Blue+ green = AEBL baseline
Red = Low-cost upgrade

Courtesy P. Ostroumov and K. Shepard
Driver linac

Layout for the AEBL driver linac

Q = 77+, 78+, 79+, 80+, 81+

Q = 33+, 34+

HWR 172.5 MHz
Double-Spoke 345 MHz
Triplet-Spoke 345 MHz

400 kW @200 MeV/u (for $^{238}$U)

$\beta = 0.26$ $\beta = 0.39$ $\beta = 0.50, 0.62$

Stripper

17 MeV/u

QWR 57.5, 115 MHz

RFQ 57.5 MHz

MHB

ECR Ion Sources
(H$^+$ to $^{238}$U)

14 keV/u

300 keV/u

Courtesy P. Ostroumov and K. Shepard

Advanced Exotic Beam Laboratory
### AEBL Driver Linac - SC Resonator Configuration

- **Input of uranium 33+ and 34+ at beta = 0.0254**

<table>
<thead>
<tr>
<th>Beta</th>
<th>Type</th>
<th>Freq</th>
<th>Length</th>
<th>Esurf</th>
<th>Eacc</th>
<th># Cav</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.031</td>
<td>FORK</td>
<td>57.5</td>
<td>25</td>
<td>22.4</td>
<td>5.60</td>
<td>3</td>
</tr>
<tr>
<td>0.061</td>
<td>QWR</td>
<td>57.5</td>
<td>20</td>
<td>27.5</td>
<td>9.29</td>
<td>21</td>
</tr>
<tr>
<td>0.151</td>
<td>QWR</td>
<td>115.0</td>
<td>25</td>
<td>27.5</td>
<td>8.68</td>
<td>48</td>
</tr>
</tbody>
</table>

**STRIPPER**

<table>
<thead>
<tr>
<th>Beta</th>
<th>Type</th>
<th>Freq</th>
<th>Length</th>
<th>Esurf</th>
<th>Eacc</th>
<th># Cav</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.263</td>
<td>HWR</td>
<td>172.5</td>
<td>30</td>
<td>27.5</td>
<td>9.45</td>
<td>40</td>
</tr>
<tr>
<td>0.393</td>
<td>2SPOKE</td>
<td>345.0</td>
<td>38.1</td>
<td>27.5</td>
<td>9.17</td>
<td>16</td>
</tr>
<tr>
<td>0.500</td>
<td>3SPOKE</td>
<td>345.0</td>
<td>65.2</td>
<td>27.5</td>
<td>9.55</td>
<td>54</td>
</tr>
<tr>
<td>0.620</td>
<td>3SPOKE</td>
<td>345.0</td>
<td>80.9</td>
<td>27.5</td>
<td>9.26</td>
<td>24</td>
</tr>
</tbody>
</table>

**Subtotal** 134

**Total Cavity Count = 206**

*Courtesy P. Ostroumov and K. Shepard*
SC cavities covering the velocity range $0.12 < \beta < 0.8$ developed for the RIA driver linac and will be used in AEBL

- 115 MHz $\beta=0.15$
  - Steering-corrected QWR

- 172.5 MHz $\beta=0.28$ HWR

- 345 MHz $\beta=0.5$
  - Triple-spoke

- 345 MHz $\beta=0.62$
  - Triple-spoke

- 345 MHz $\beta=0.4$
  - Double-spoke

See publications by K.W. Shepard, et al.

Courtesy P. Ostroumov and K. Shepard
Cavity Walk – Voltage Gain per Cavity for Uranium Beam

Courtesy P. Ostroumov and K. Shepard

\[ \beta = \frac{v}{c} \]
ANL extended to TEM-class SC cavities the very high-performance techniques pioneered by TESLA

Courtesy P. Ostroumov and K. Shepard
Effects of interstitial hydrogen on triple-spoke cavity performance

![Graph showing cavity Q vs. Eacc - MV/m for different temperatures and bake conditions.]

- At 1.9K
- At 1.9K after 600C bake
- At 4.2K
- At 4.2K after 600C bake

Courtesy P. Ostroumov and K. Shepard
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>3-spoke</th>
<th>9-cell (TESLA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. (MHz)</td>
<td>( \Delta f/f ) % of ( f_{\text{ACC}} )</td>
</tr>
<tr>
<td>1</td>
<td>345</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>365</td>
<td>5.7</td>
</tr>
<tr>
<td>3</td>
<td>401</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>442</td>
<td>28</td>
</tr>
<tr>
<td>5</td>
<td>482</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>519.7</td>
<td>51</td>
</tr>
<tr>
<td>7</td>
<td>520.2</td>
<td>51</td>
</tr>
<tr>
<td>8</td>
<td>534</td>
<td>55</td>
</tr>
<tr>
<td>9</td>
<td>619</td>
<td>79</td>
</tr>
<tr>
<td>10</td>
<td>679</td>
<td>97</td>
</tr>
</tbody>
</table>

M. Kelly (ANL)
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

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

• Low microphonics and sensitivity to helium pressure

$\frac{df}{dp} = -0.4 \text{ Hz/mbar}$

$\sigma_{\text{rms}} = 0.44 \text{ Hz}$
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

1 MeV

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

30 MeV

Bunch compression chicane

Inverse Compton scattering

30 kW beam dump

5 kW cryo-cooled Yb:YAG drive laser

X-ray beamline

8 m

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

**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>
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, β=0.6

TSR, β=0.87

- Focusing with SC solenoids, eff. length = 20 cm, B=from 4T to 10.4T
- f = 325 MHz
- β = 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
Jlab: Double spoke cavity RF design

- Goal is to maximize $G*R/Q$:
  - $C \downarrow; \ L \uparrow; \ B$ field broad distributed
  - Longer and thinner spoke central part
  - Smaller end-cone radius
  - Larger spoke base in beam transverse direction
  - Make field stronger in the end-gap (by making the re-entrant part deeper)

Feisi He, JLab
**Jlab: Cavity RF design (2)**

- Key is to maximize $G*Ra/Q$ to minimize dynamic heat load

### JLAB 352 MHz Cavity Design

<table>
<thead>
<tr>
<th></th>
<th>Spoke</th>
<th>Elliptical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [MHz]</td>
<td>352</td>
<td>352</td>
</tr>
<tr>
<td>Aperture diameter [mm]</td>
<td>50</td>
<td>170</td>
</tr>
<tr>
<td>Lcavity (end-to-end) [mm]</td>
<td>1289 + 140</td>
<td>1277 + 300</td>
</tr>
<tr>
<td>Cavity inner diameter [mm]</td>
<td>578</td>
<td>730</td>
</tr>
<tr>
<td>Cavity weight (3mm wall) [kg]</td>
<td>111</td>
<td>99</td>
</tr>
<tr>
<td>Ep/Ea</td>
<td>$4.3 \pm 0.1$</td>
<td>$2.26 \pm 0.1$</td>
</tr>
<tr>
<td>Bp/Ea [mT/(MV/m)]</td>
<td>$7.6 \pm 0.2$</td>
<td>$3.42 \pm 0.1$</td>
</tr>
<tr>
<td>Geometry factor [$\Omega$]</td>
<td>179</td>
<td>283</td>
</tr>
<tr>
<td>Ra/Q [$\Omega$]</td>
<td>781</td>
<td>458</td>
</tr>
<tr>
<td>Ra<em>Rs ($=G</em>Ra/Q$) [$\Omega^2$]</td>
<td>$1.40 \times 10^5$</td>
<td>$1.29 \times 10^5$</td>
</tr>
</tbody>
</table>

At Vacc = 8.5 MV and 4.5K. So $R_{bcs}=48\Omega$, and assume $R_{res}=20n\Omega$.

<table>
<thead>
<tr>
<th></th>
<th>Spoke</th>
<th>Elliptical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ep [MV/m]</td>
<td>$28.6 \pm 0.9$</td>
<td>$15.0 \pm 0.5$</td>
</tr>
<tr>
<td>Bp [mT]</td>
<td>$50.3 \pm 1.5$</td>
<td>$22.8 \pm 0.7$</td>
</tr>
<tr>
<td>Max heat flux [mW/cm^2]</td>
<td>4.6</td>
<td>1.4</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$2.6 \times 10^9$</td>
<td>$4.2 \times 10^9$</td>
</tr>
<tr>
<td>Power loss [W]</td>
<td>35</td>
<td>42.6</td>
</tr>
<tr>
<td>$Leff=1.5*\beta_0*\lambda$ [m]</td>
<td>1.2768</td>
<td>1.2768</td>
</tr>
</tbody>
</table>

Feisi He, JLab
- 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
Design Optimization (a small sample)

C. Hopper, ODU
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>
</tr>
</thead>
<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>
</tr>
<tr>
<td>Cavity diameter</td>
<td>627</td>
<td>640</td>
<td>mm</td>
</tr>
<tr>
<td>Iris-to-iris length</td>
<td>949</td>
<td>1148</td>
<td>mm</td>
</tr>
<tr>
<td>Cavity length</td>
<td>1149</td>
<td>1328</td>
<td>mm</td>
</tr>
<tr>
<td>Reference length</td>
<td>757</td>
<td>922</td>
<td>mm</td>
</tr>
<tr>
<td>Aperture diameter at spoke</td>
<td>60</td>
<td>60</td>
<td>mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cavity Parameters</th>
<th>$\beta_0 = 0.82$</th>
<th>$\beta_0 = 1.0$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of accelerating mode</td>
<td>352</td>
<td>352</td>
<td>MHz</td>
</tr>
<tr>
<td>Frequency of nearest mode</td>
<td>361</td>
<td>357</td>
<td>MHz</td>
</tr>
<tr>
<td>Cavity diameter</td>
<td>563</td>
<td>595</td>
<td>mm</td>
</tr>
<tr>
<td>Iris-to-iris length</td>
<td>869</td>
<td>1059</td>
<td>mm</td>
</tr>
<tr>
<td>Cavity length</td>
<td>1052</td>
<td>1224</td>
<td>mm</td>
</tr>
<tr>
<td>Reference length</td>
<td>699</td>
<td>852</td>
<td>mm</td>
</tr>
<tr>
<td>Aperture diameter at spoke</td>
<td>50</td>
<td>50</td>
<td>mm</td>
</tr>
</tbody>
</table>
Cavity properties

| RF properties          | 325 MHz,  
|                      | $\beta_0 = 0.82$  
|                      | 325 MHz,  
|                      | $\beta_0 = 1.0$  
|                      | 352 MHz,  
|                      | $\beta_0 = 0.82$  
|                      | 352 MHz,  
|                      | $\beta_0 = 1.0$  
|                   | Low $E_p,B_p$ | High $R$ | Low $E_p,B_p$ | High $R$ | Units |
| Energy gain at $\beta_0$ | 757       | 922      | 699         | 852          | kV    |
| R/Q                   | 625       | 744      | 630         | 754          | $\Omega$ |
| QRs                   | 168       | 195      | 169         | 193          | $\Omega$ |
| $(R/Q)*QRs$           | 1.05x10^5 | 1.45x10^5 | 1.07x10^5 | 1.46x10^5  | $\Omega^2$ |
| $E_p/E_{acc}$         | 2.6       | 2.8      | 2.7         | 2.75         | -     |
| $B_p/E_{acc}$         | 4.97      | 5.6      | 4.9         | 5.82         | mT/(MV/m) |
| $B_p/E_p$             | 1.9       | 2.0      | 1.8         | 2.12         | mT/(MV/m) |
| Energy Content        | 0.45      | 0.56     | 0.35        | 0.43         | J     |
| Power Dissipation*    | 0.37*     | 0.43*    | 0.33**      | 0.36**       | W     |

At $E_{acc} = 1$ MV/m and reference length $\beta_0\lambda$

*Rs = 68 n$\Omega$
**Rs = 73 n$\Omega$
Mode types in two-spoke cavities

Accelerating modes

Deflecting (degenerate) modes

TE-type modes

Hybrid modes

Examples of modes for the 325 MHz cavity, $\beta=1$

C. Hopper, R. Olave, ODU
$R/Q$ values for particles at design velocities
$\beta_0=1$ and $\beta_0=0.82$ for the 325 MHz two-spoke cavity

All HOMs have $(R/Q)$s significantly smaller values than the fundamental mode

C. Hopper, R. Olave, ODU
Excitation of modes by a single bunch

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

Wakefield Spectrum

- Amplitude vs. Frequency (MHz)
  - Peaks at:
    - 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
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
Prediction of multipacting (MP) level

- No stable MP with impact energy between 60 to 1000 eV
- 0.5 – 4 MV and 5 – 9 MV is likely to have MP in the first high power RF test
- Some field levels are especially dangerous when the surface is not clean:
  - 1.4 – 1.7 MV and 2.3 – 2.9 MV in zone 1
  - 1.5 MV, and 2.4 – 2.6 MV in zone 2
  - 1.4 – 2.2 MV and 2.8 – 4.1 MV in zone 3
  - 6 – 7 MV in zone 4
- Plasma cleaning may be used to process away the MP
Multipacting

325 MHz, $\beta=0.82$
ACE3P
C. Hopper, ODU
Multipacting

700 MHz, $\beta=1$
ACE3P
R. Olave, ODU
700 MHz, $\beta=1$, double-spoke

Collaboration between Niowave, ODU, Los Alamos, NPS
Designed By ODU
Fabricated by Niowave
In the last 30+ years, the development of low and medium $\beta$ superconducting cavities has been one of the richest and most imaginative area of srf

The field has been in perpetual evolution and progress
New geometries are constantly being developed
The final word has not been said

The parameter, tradeoff, and option space available to the designer is large
The design process is not, and probably will never be, reduced to a few simple rules or recipes
There will always be ample opportunities for imagination, originality, and common sense