SUPERCONDUCTING SPOKE CAVITIES FOR ELECTRON AND HIGH-VELOCITY PROTON LINACS

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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

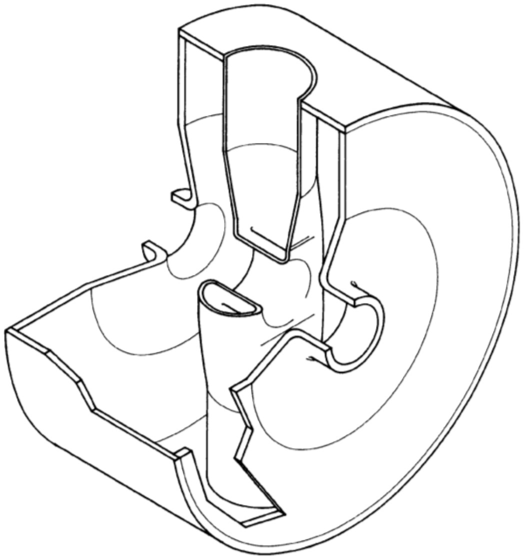
- Support from DoD stopped in 1992, and in 1994 for IFMIF and ADS.

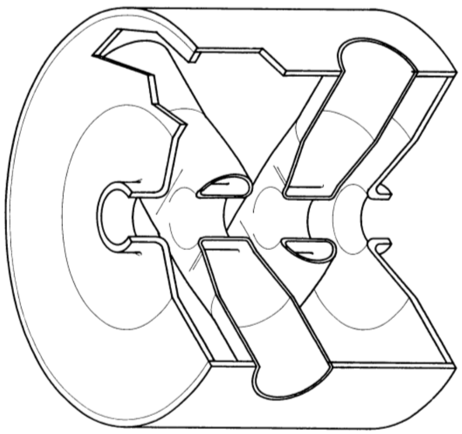
- Interest was revived in the late 1990s at ANL for RIA, and at other laboratories for other high-current ion accelerators

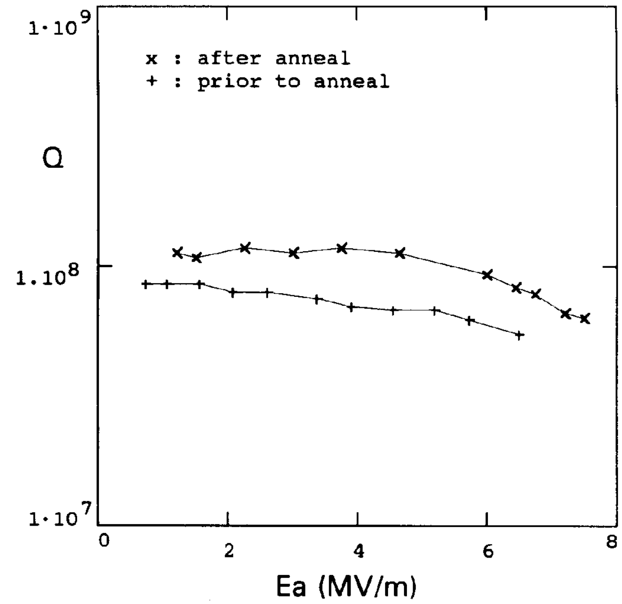
- The spoke geometry is now the geometry of choice in the medium velocity region and is being developed in many laboratories worldwide

- It is now under development for the acceleration of particles going at close to the velocity-of-light

850 MHz, β=0.3 Spoke (1990)

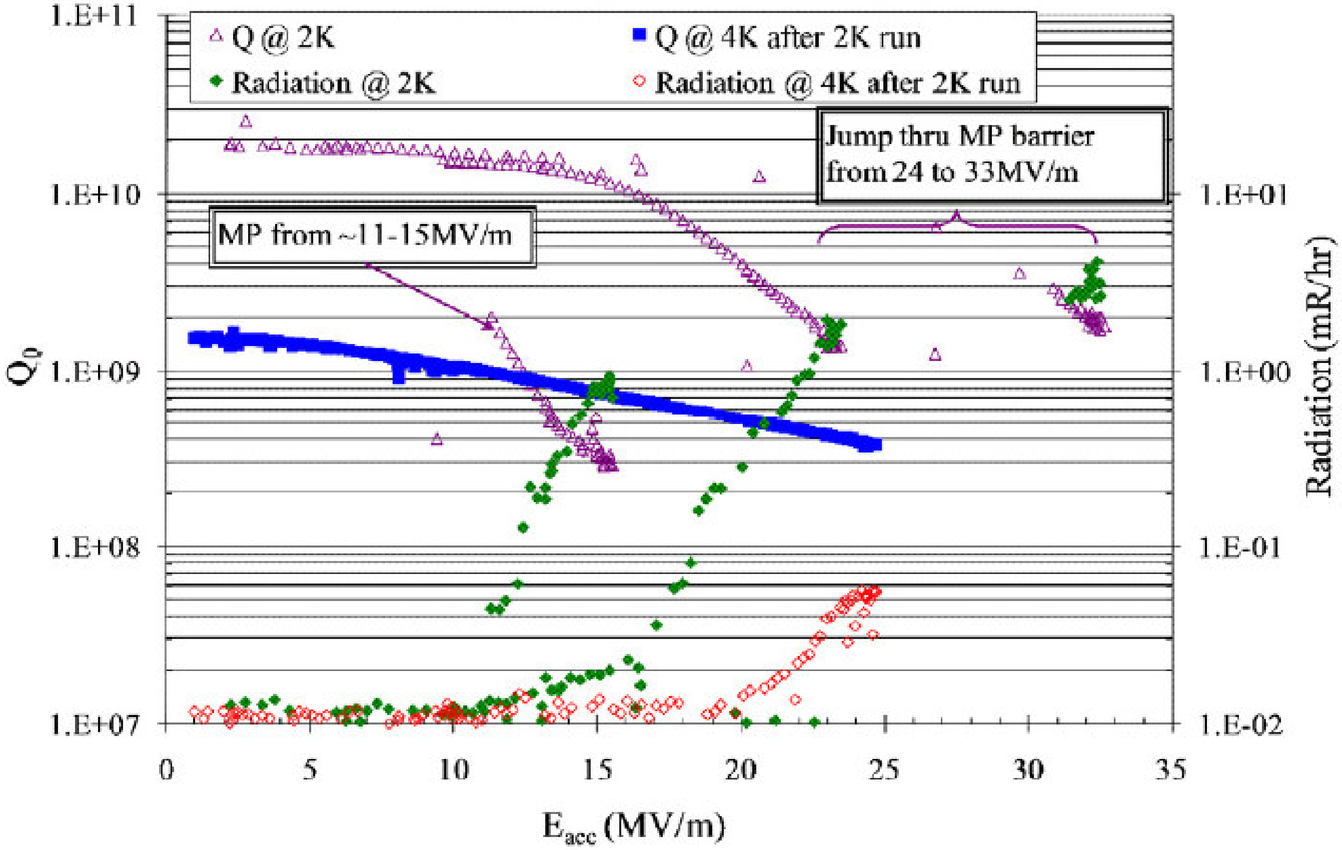




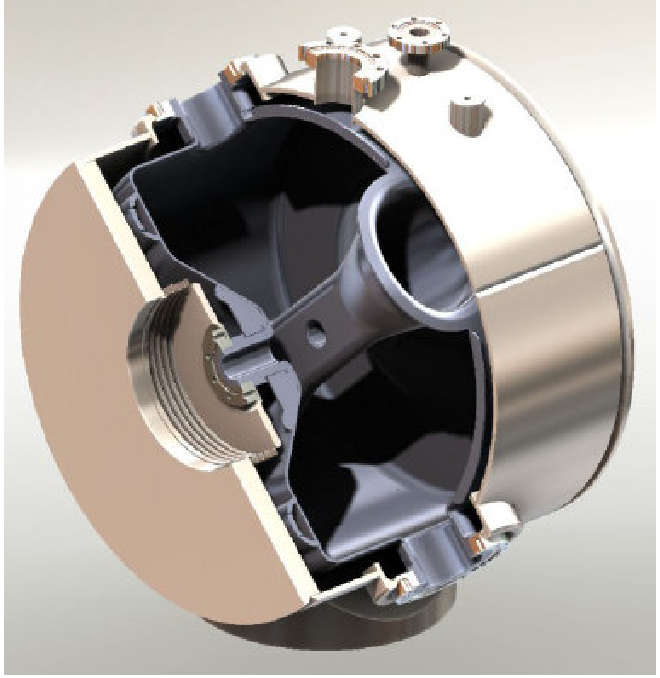


ANL

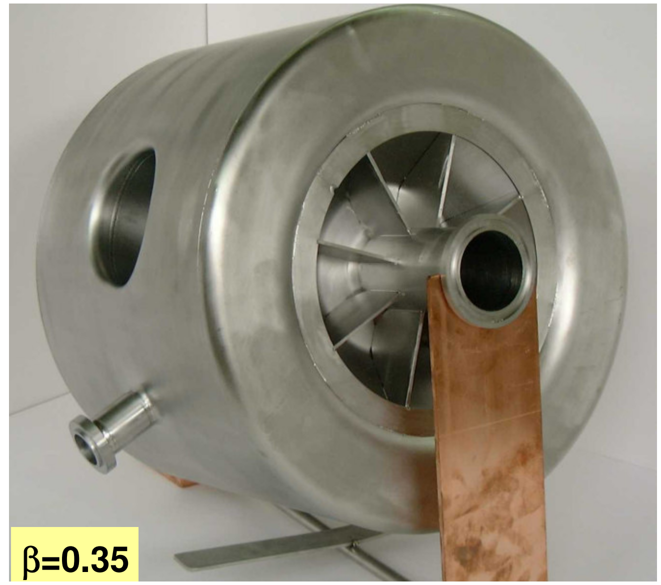
Fermilab Project X

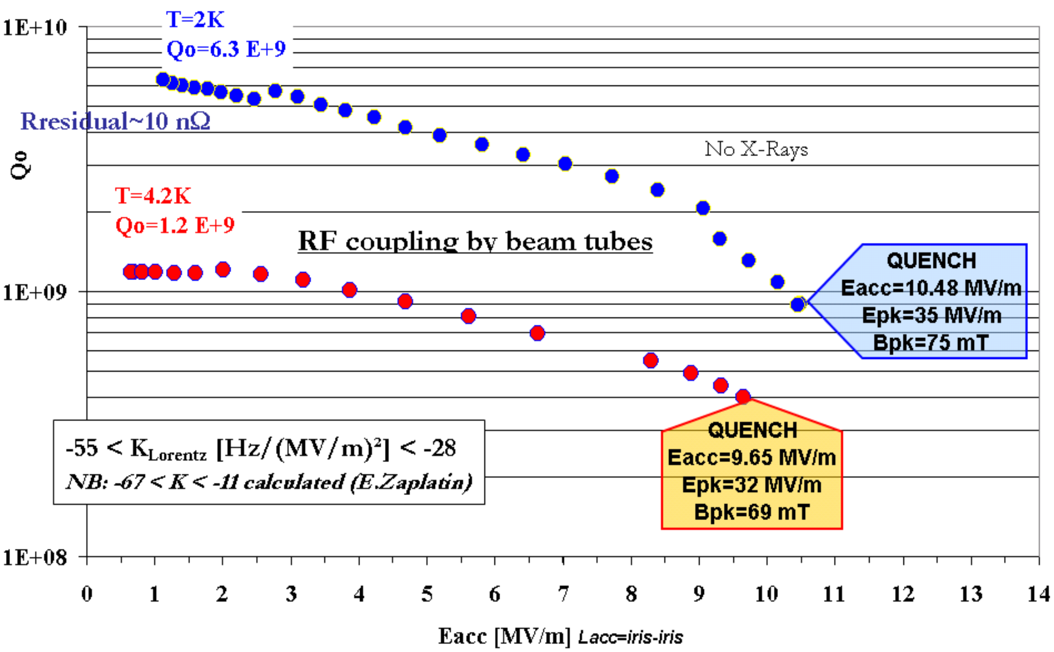


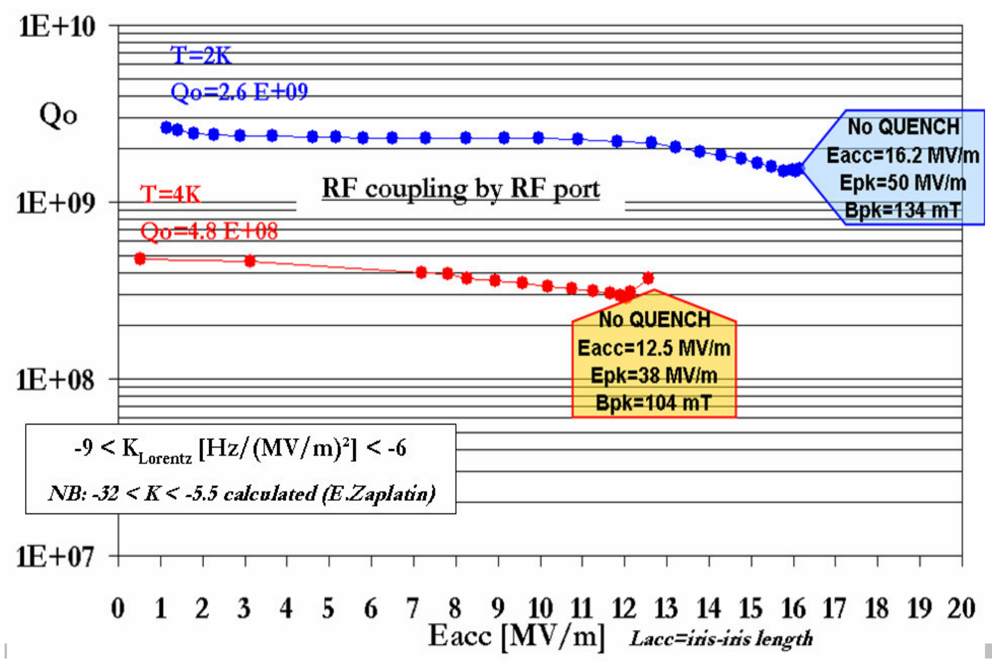
325 MHz, β=0.22



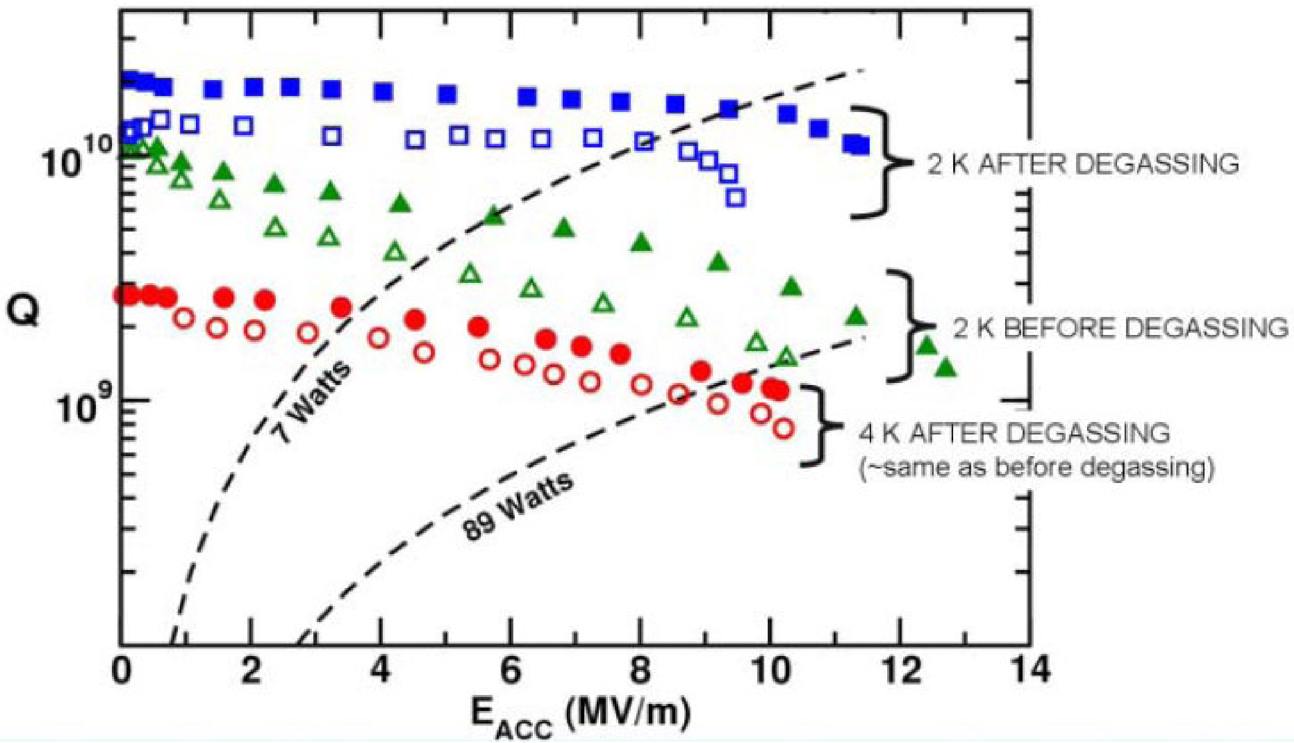
ORSAY - EURISOL



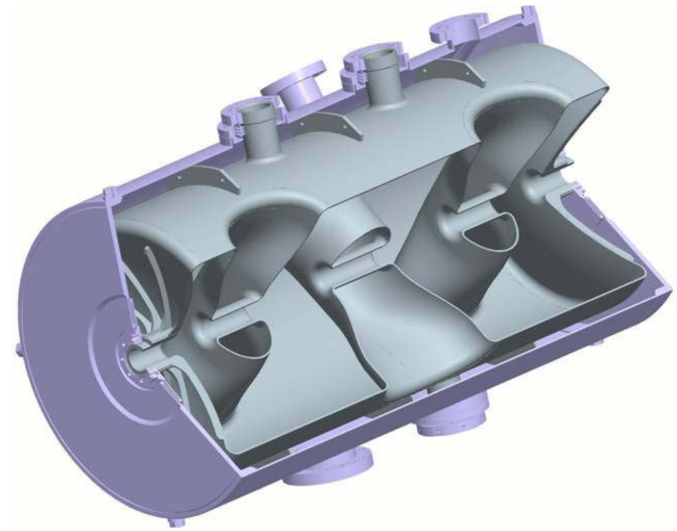


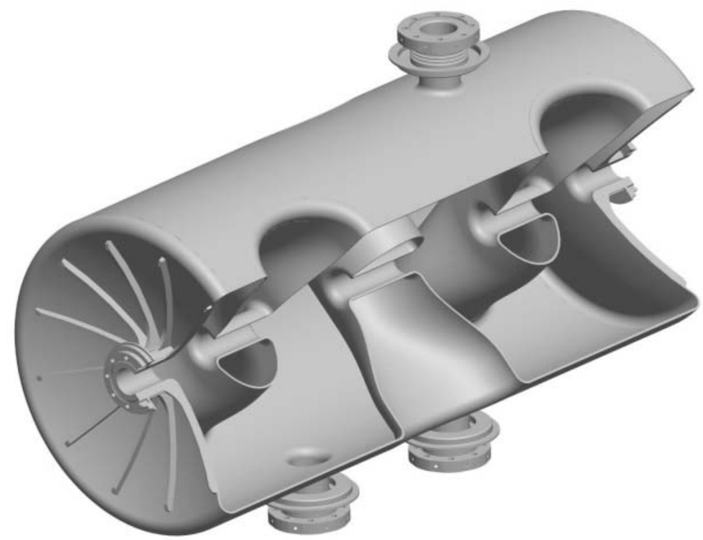


Argonne National Lab



Open symbols: 345 MHz, β=0.5)





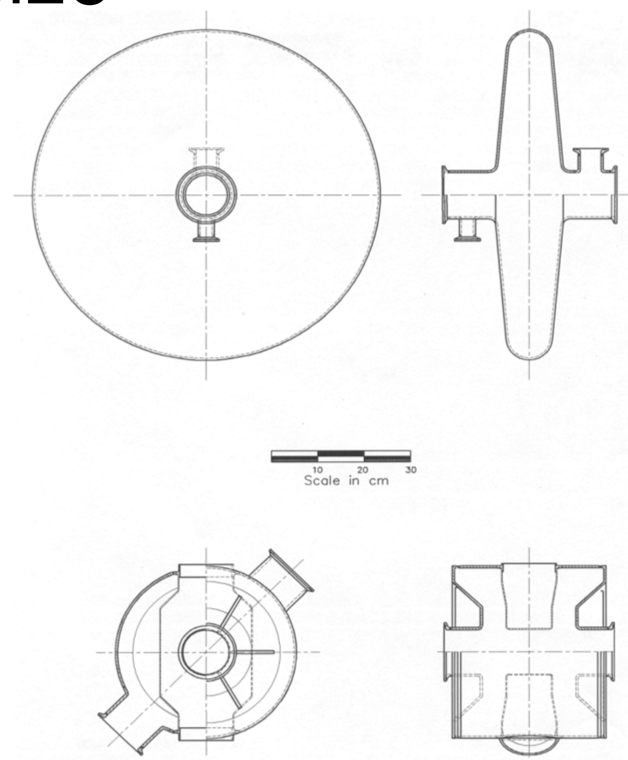
Closed symbols: 345 MHz, β=0.63

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

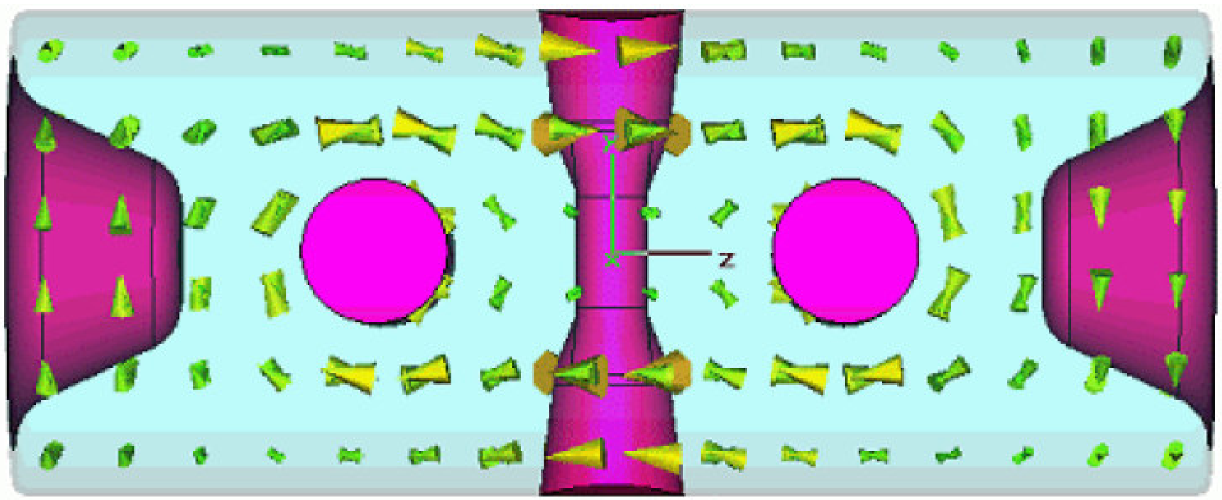
- Fewer number of cells
  - Wider velocity acceptance



350 MHz, β= 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, β=0.48 (FZJ)

Features of Spoke Cavities

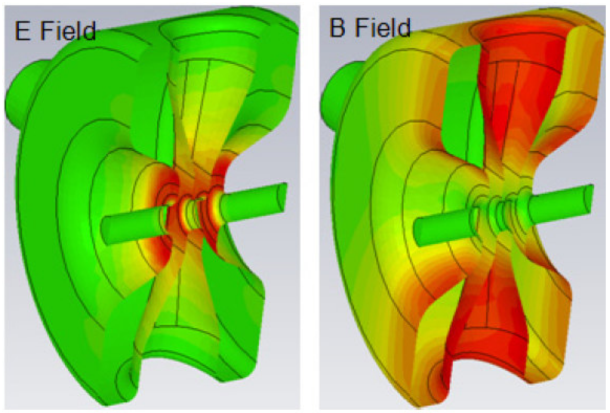
- **Accelerating mode has lowest frequency**
  - No lower-order mode
  - Easier HOM damping

	3-spoke		9-cell (TESLA)	
Mode #	Freq. (MHz)	Δf/f % of f_{ACC}	Freq. (MHz)	Δf/f % of f_{ACC}
1	345		1275.6	1.7
2	365	5.7	1277.6	1.6
3	401	14	1280.7	1.4
4	442	28	1284.5	1.1
5	482	40	1288.5	0.8
6	519.7	51	1292.4	0.5
7	520.2	51	1295.5	0.2
8	534	55	1297.6	0.05
9	619	79	1298.3	
10	679	97		

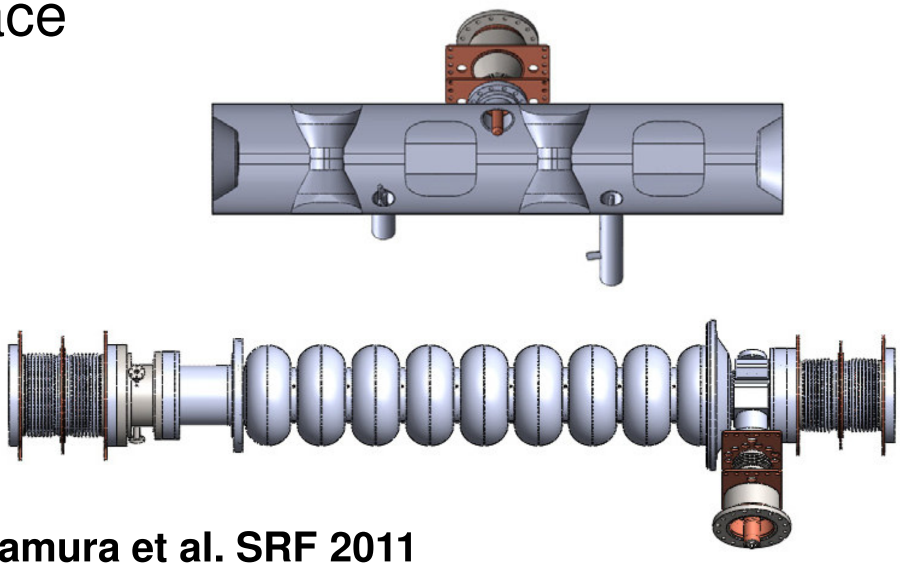
M. Kelly (ANL)

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



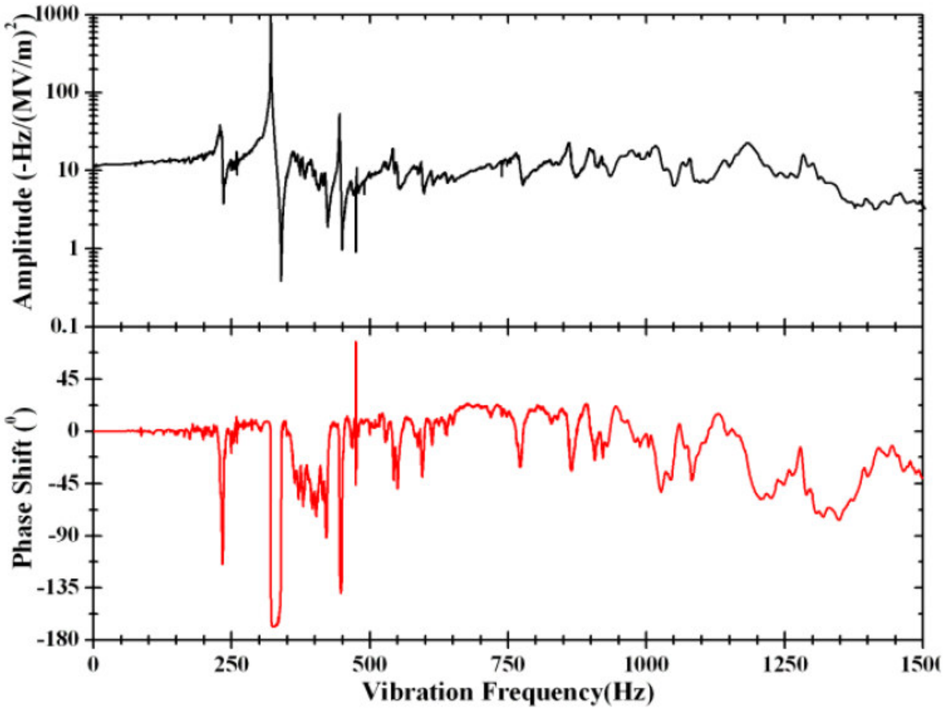
325 MHz, β=0.17 (FNAL)



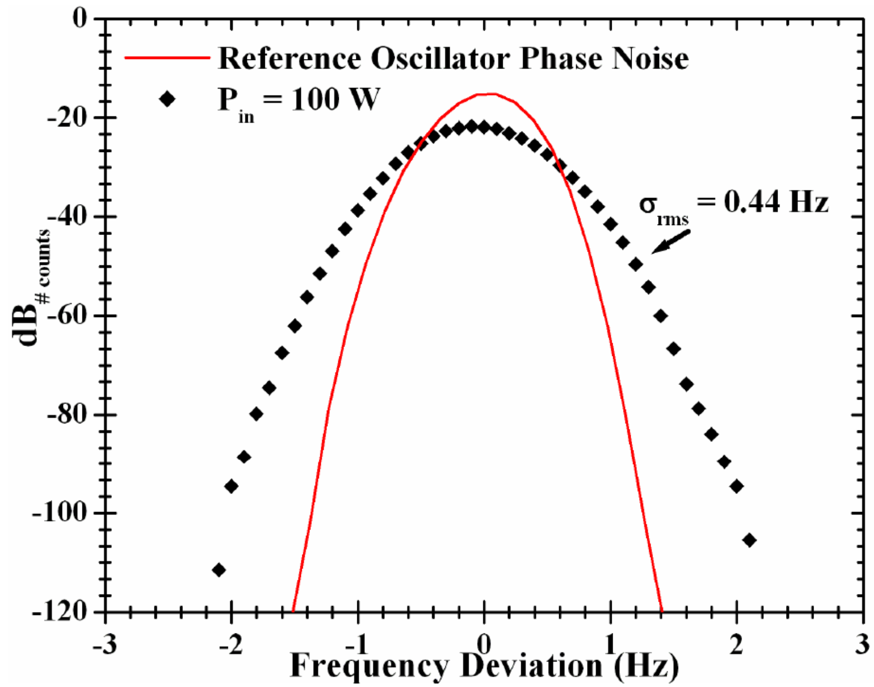
M. Sawamura et al. SRF 2011

Features of Spoke Cavities

- **Few mechanical modes, none at low frequency**



345 MHz, β=0.5, triple-spoke (Z. Conway, ANL)



- **Low microphonics and sensitivity to helium pressure**

df/dp= -0.4 Hz/mbar

How High Can We Go with β_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-β high-current applications?
  - FELs, ERLs
  - Higher order modes extraction

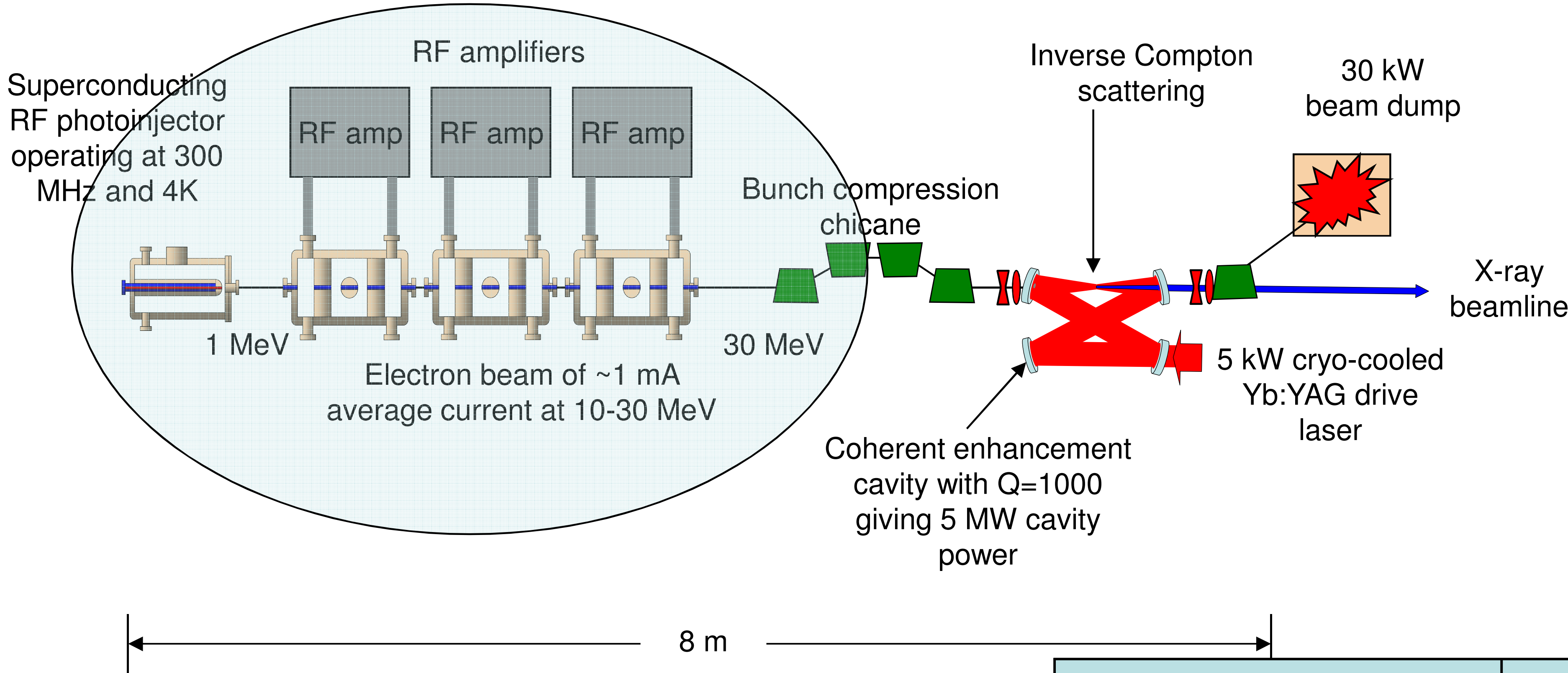
Compact Light Sources

- 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

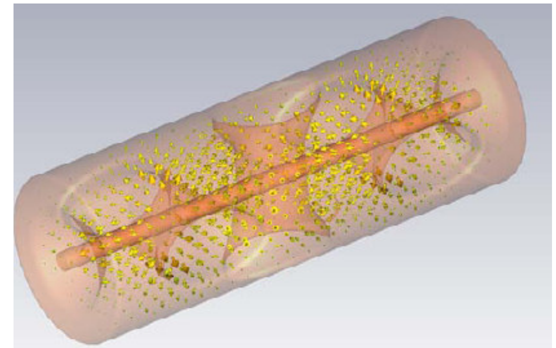


MIT proposal

SRF Linac Parameters	
Energy gain [MeV]	25
RF frequency [MHz]	352
Average current [mA]	1
Operating temperature [K]	4.2
RF power [kW]	30

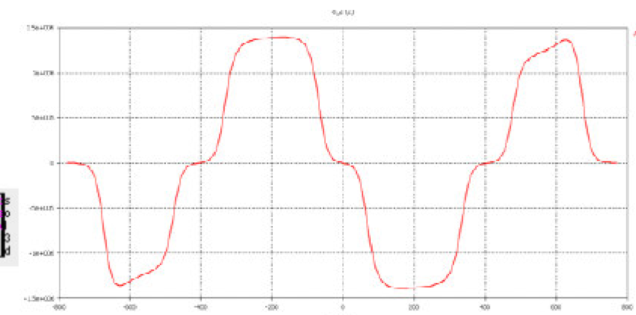
GeV-scale Proton LINAC

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

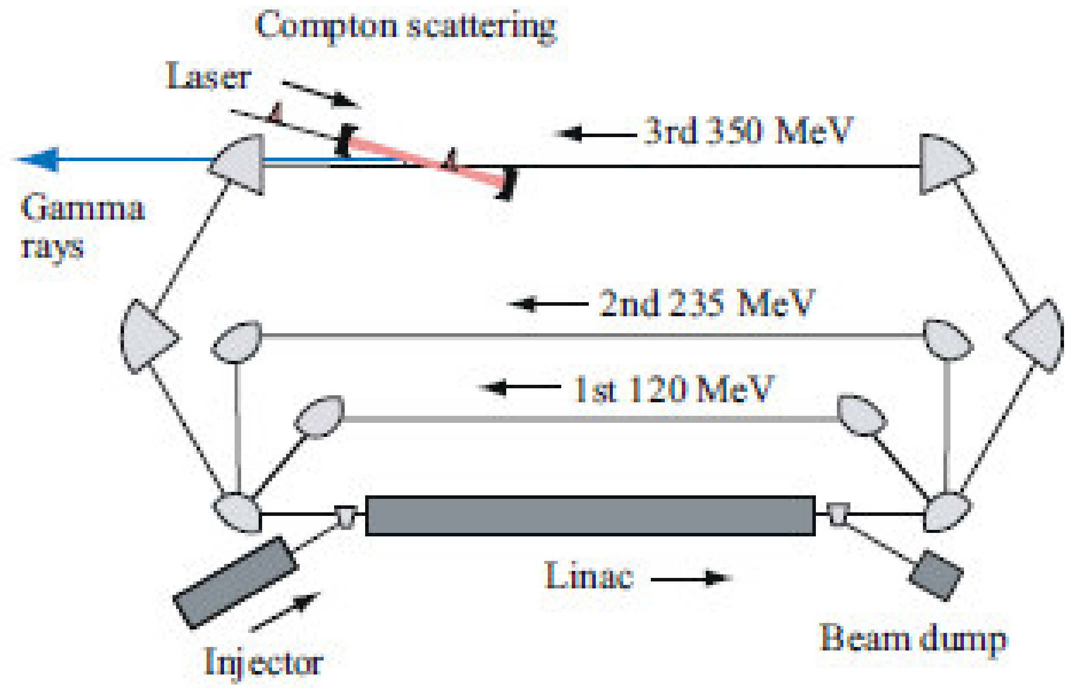
- Focusing with SC solenoids, eff. length = 20 cm, B=from 4T to 10.4T

- f = 325 MHz
- β = 0.87
- Length = 1.55 m
- Aperture diameter – 60 mm

Argonne NATIONAL LABORATORY P.N. Ostroumov Fourth meeting of ESSS linac reference group October 9, 2009 17

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]

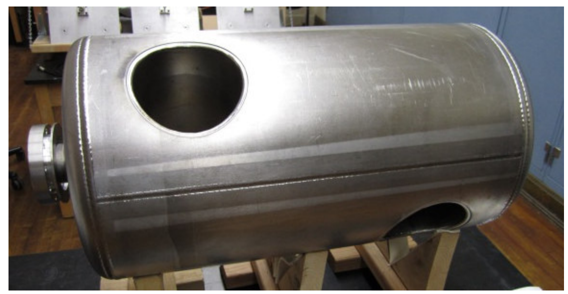
Old Dominion University

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

Designs by:
Chris Hopper
Suba De Silva
Rocio Olave

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

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

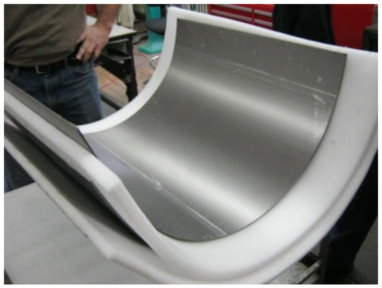


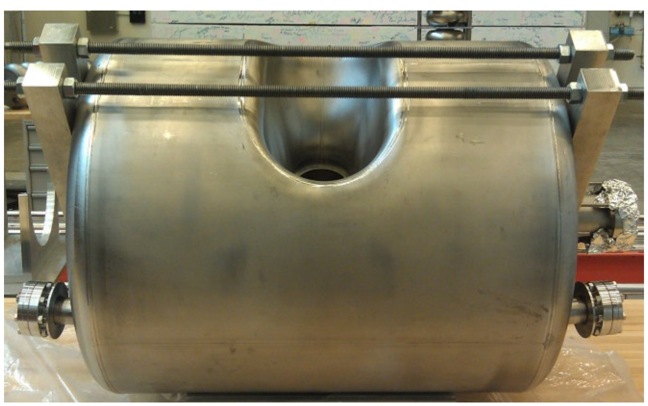
- 700 MHz, β= 1, single, double, and triple
  - Collaboration with Niowave, Los Alamos and NPS

Old Dominion University

325 MHz Single-Spoke

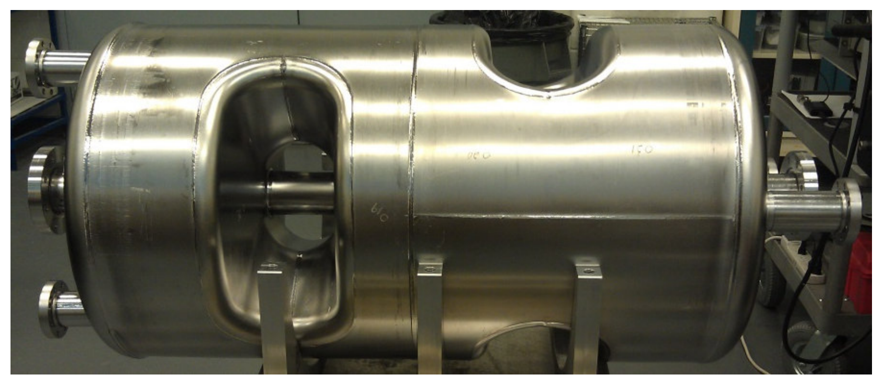
Fabricated at Niowave Inc.



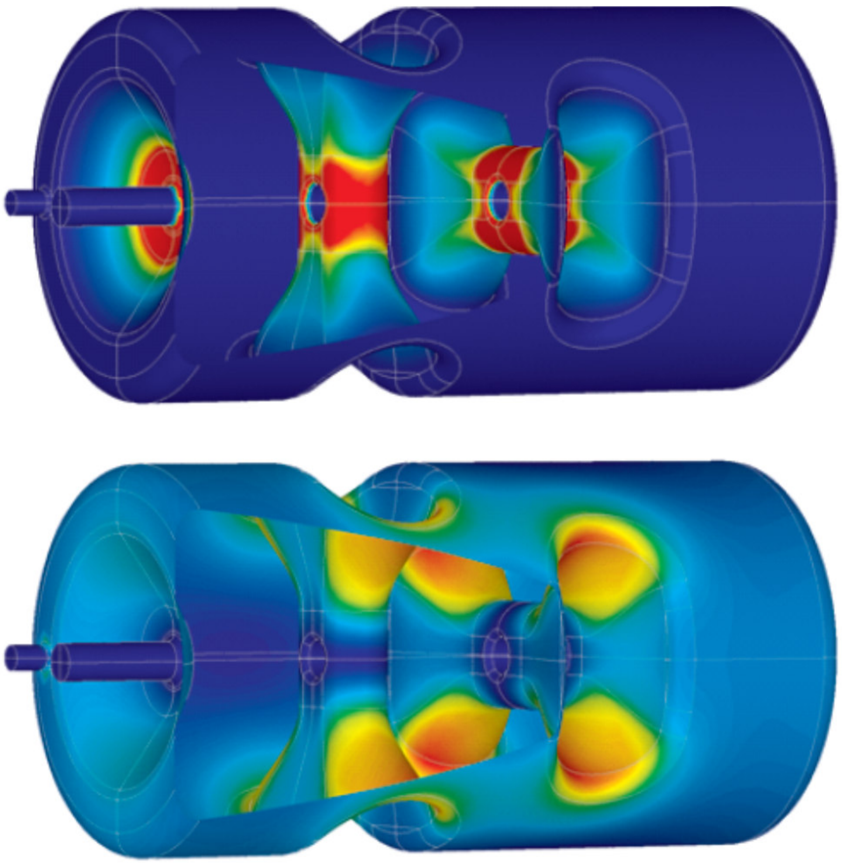


500 MHz Double-Spoke

Fabricated at Jefferson Lab
(HyeKyoung Park)



ELECTROMAGNETIC DESIGN GOALS



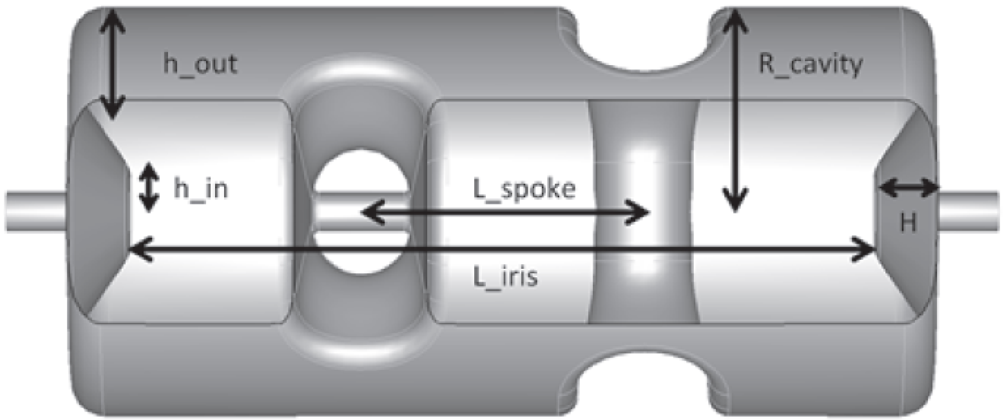
- Minimize the peak surface fields
  - High electric field can lead to field emission (Reliable operation: E_p ~ 50 MV/m)
  - High magnetic field can cause quenching (Theoretical limit: B_p ~ 170 mT)

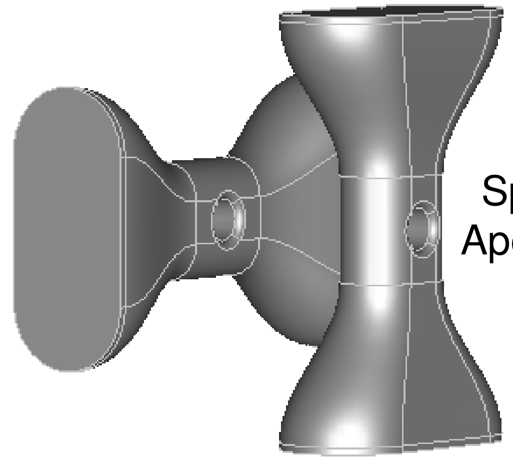
$$\frac{E_p}{E_{acc}} \qquad \frac{B_p}{E_{acc}}$$

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

- Balanced peak fields (Bp/Ep)
  - Achieve the reliable limits simultaneously

Parameters of Optimization



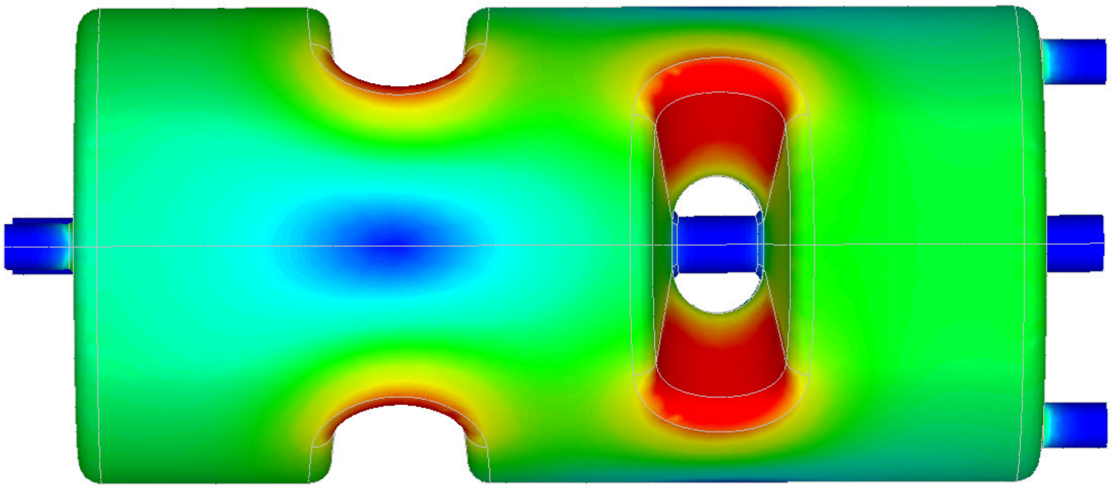


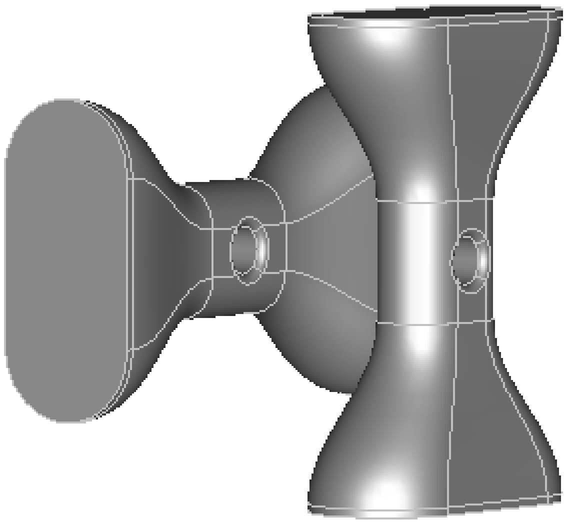
- Fixed Quantities
  - Design velocity (β_0), operating frequency (f_0), and beam aperture

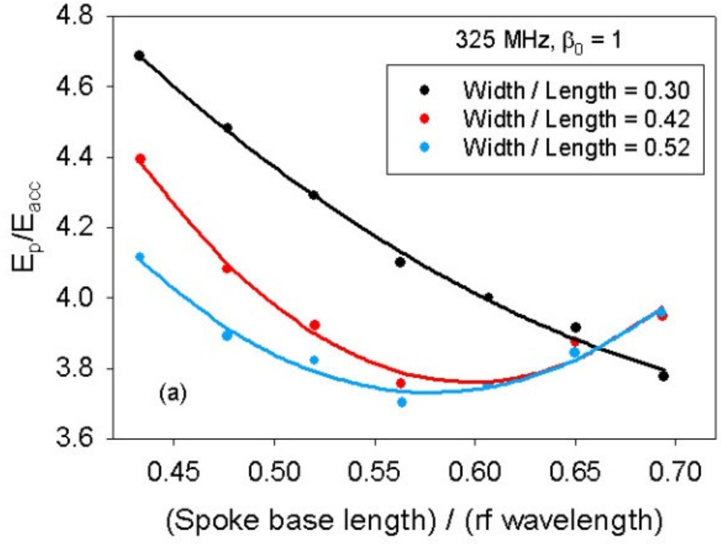
- Geometric parameters
  - No single parameter can be used to minimize surface fields or maximize shunt impedance
  - Very generally speaking, the spoke base and separation (L_spoke) are the most influential for minimizing B_p while the spoke aperture and separation are used for minimizing E_p
  - Several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

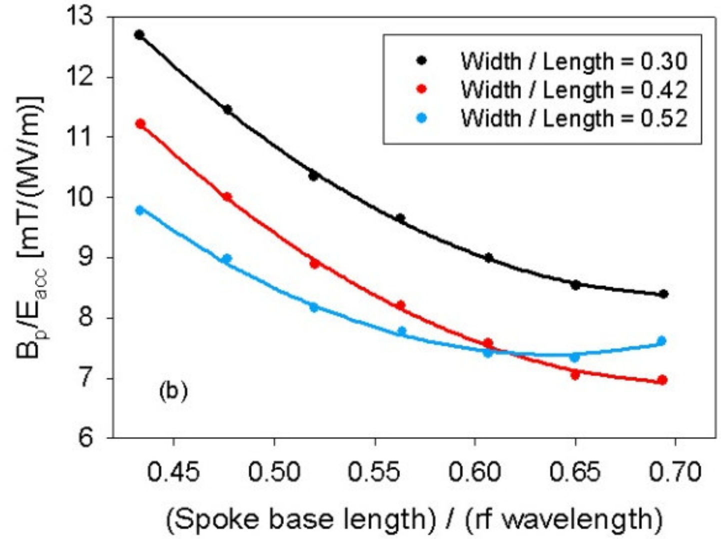
SPOKE BASE PROPERTIES

Peak Surface Magnetic field is at the spoke base



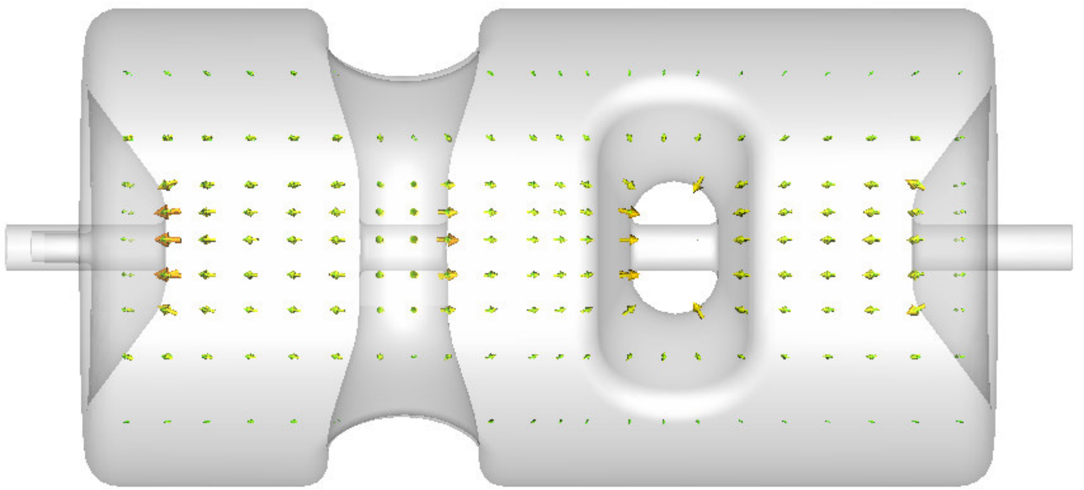


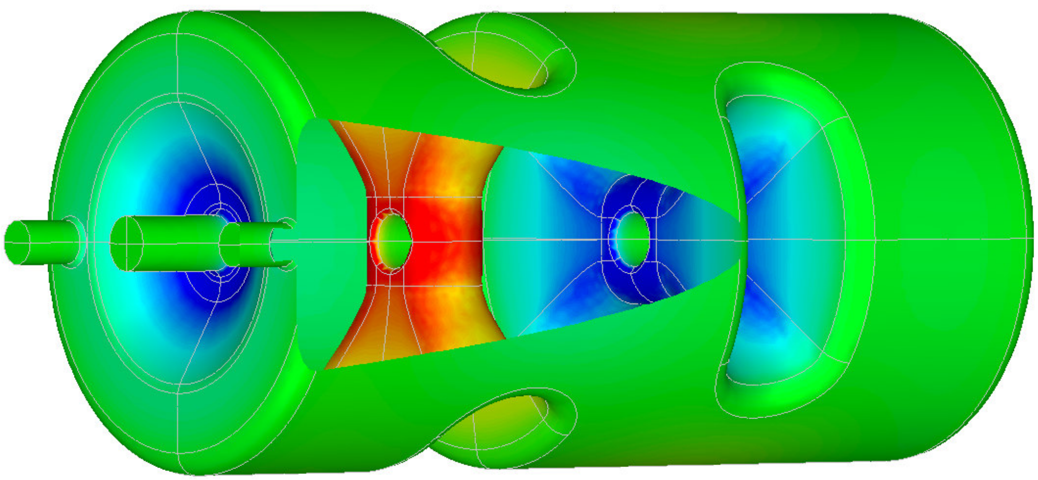


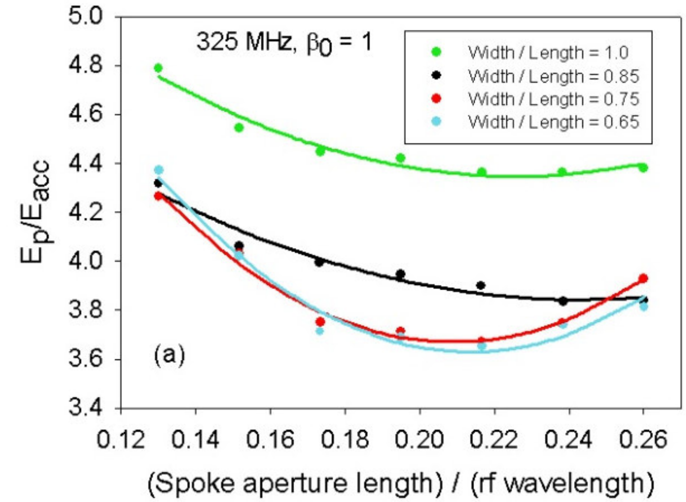


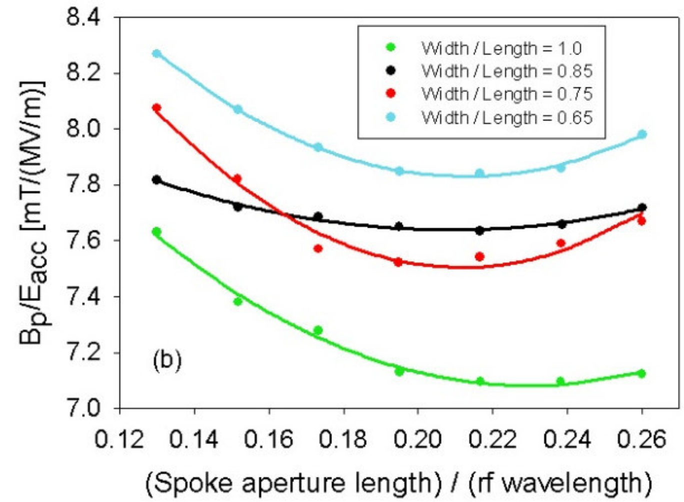
Spoke Aperture Properties

Peak Surface Field field is at the spoke aperture

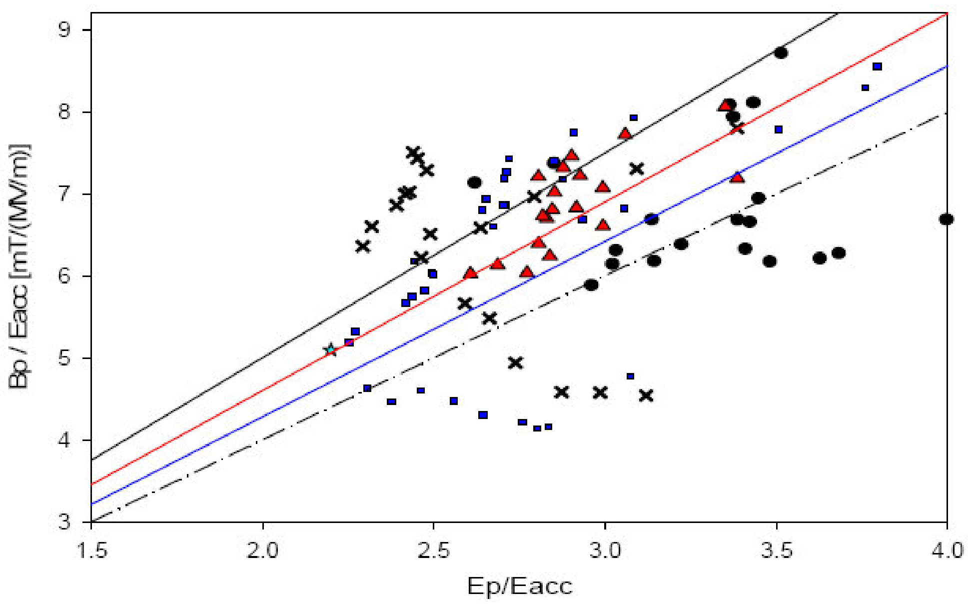


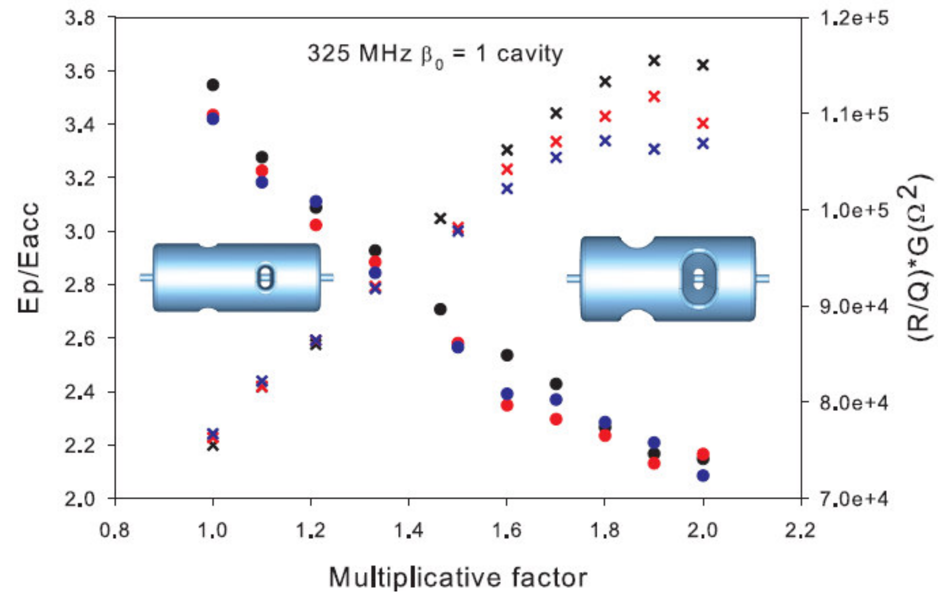


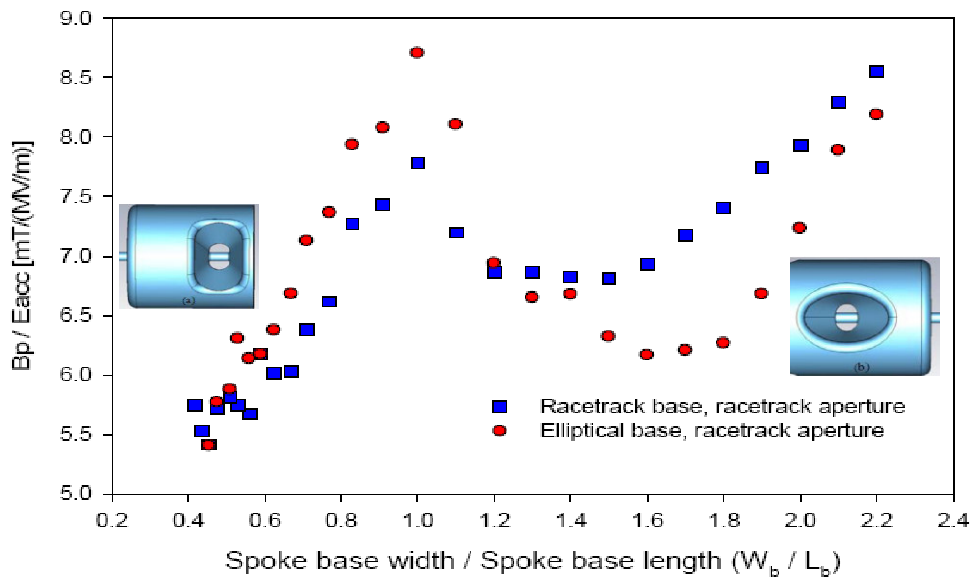


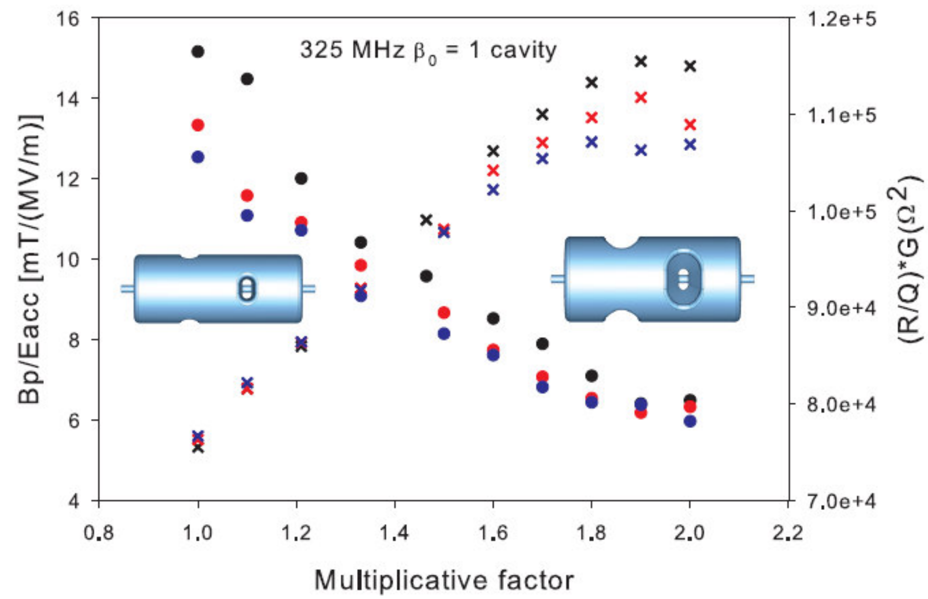


Design Optimization (a small sample)

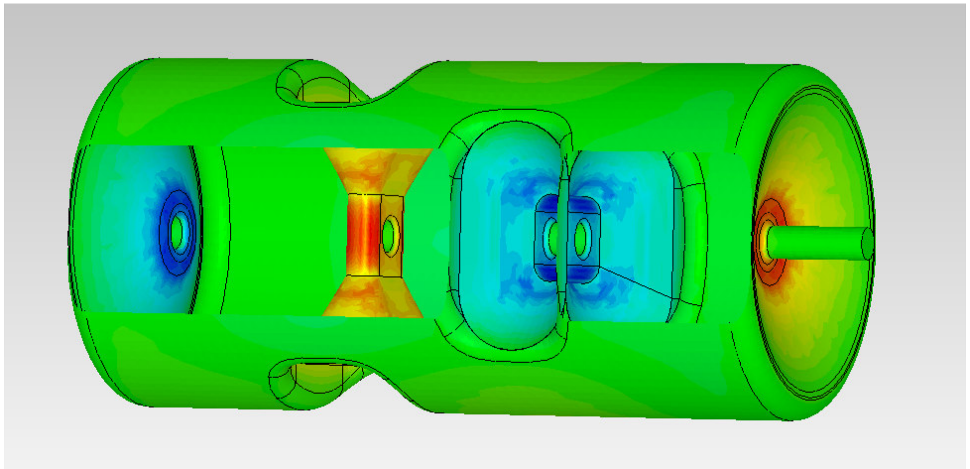




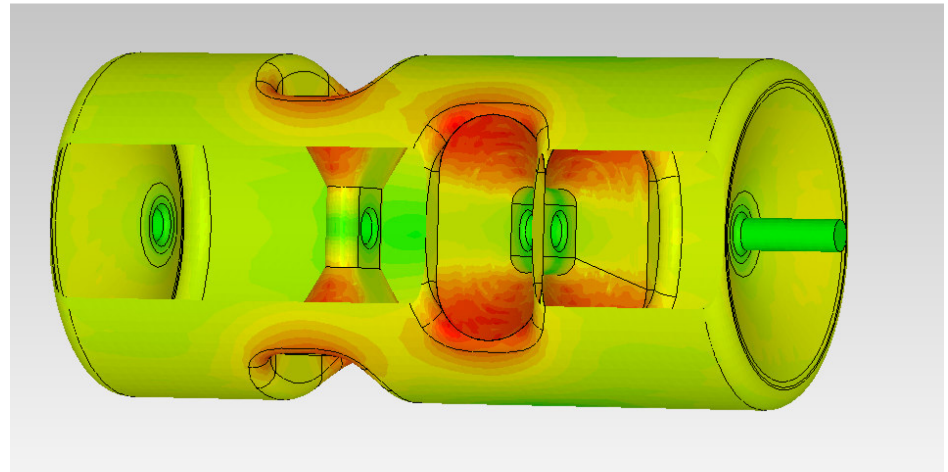




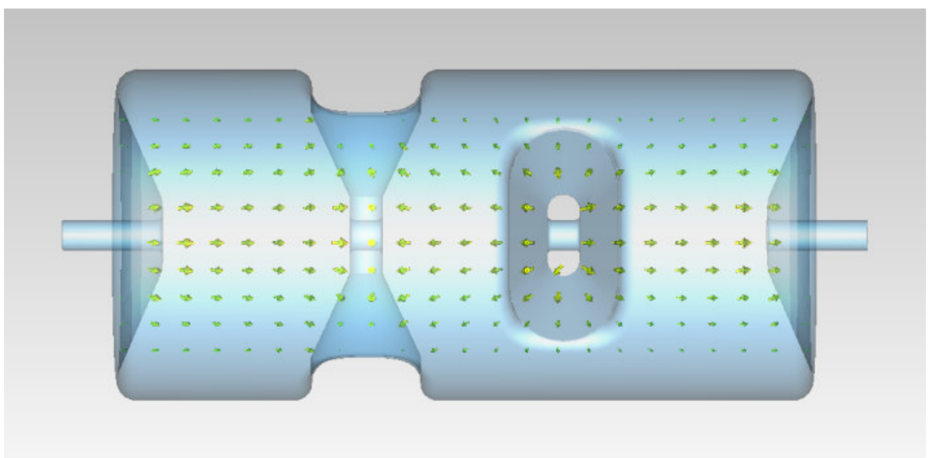
Double Spoke



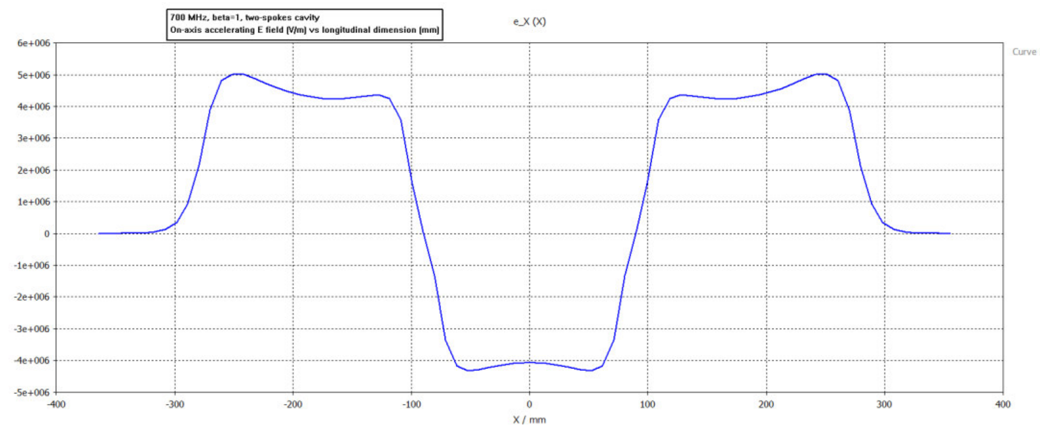
Surface Electric Field



Surface Magnetic Field



Electric Field



On Axis Electric Field

Cavity properties

Cavity Parameters	$\beta_0 = 0.82$	$\beta_0 = 1.0$	Units
Frequency of accelerating mode	325	325	MHz
Frequency of nearest mode	333	329	MHz
Cavity diameter	627	640	mm
Iris-to-iris length	949	1148	mm
Cavity length	1149	1328	mm
Reference length	757	922	mm
Aperture diameter at spoke	60	60	mm

Cavity Parameters	$\beta_0 = 0.82$	$\beta_0 = 1.0$	Units
Frequency of accelerating mode	352	352	MHz
Frequency of nearest mode	361	357	MHz
Cavity diameter	563	595	mm
Iris-to-iris length	869	1059	mm
Cavity length	1052	1224	mm
Reference length	699	852	mm
Aperture diameter at spoke	50	50	mm

Cavity properties

RF properties	325 MHz, $\beta_0 = 0.82$ *Low Ep,Bp*	325 MHz, $\beta_0 = 1.0$ *High R*	352MHz, $\beta_0 = 0.82$ *Low Ep,Bp*	352 MHz, $\beta_0 = 1.0$ *High R*	Units
Energy gain at β_0	757	922	699	852	kV
R/Q	625	744	630	754	Ω
QRs	168	195	169	193	Ω
(R/Q)*QRs	1.05×10^5	1.45×10^5	1.07×10^5	1.46×10^5	Ω^2
Ep/Eacc	2.6	2.8	2.7	2.75	-
Bp/Eacc	4.97	5.6	4.9	5.82	mT/(MV/m)
Bp/Ep	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 Eacc = 1 MV/m and reference length $\beta_0\lambda$
***Rs = 68 nΩ**
****Rs = 73 nΩ**

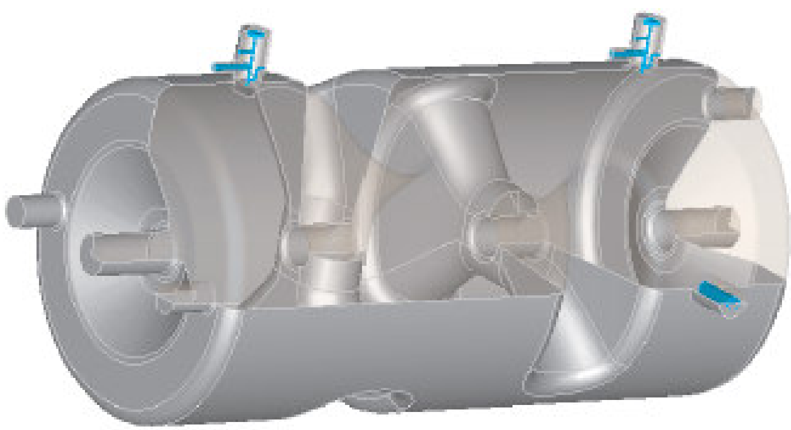
HIGHER ORDER MODE TERMINOLOGY

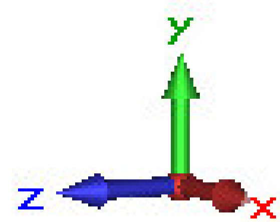
- The beam travels along the *z*-axis. The electrical *z*-axis is taken to be the geometric *z*-axis. Transverse directions are *x* and *y*, which run parallel to the spoke(s).

- 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 $E_z(z)$.

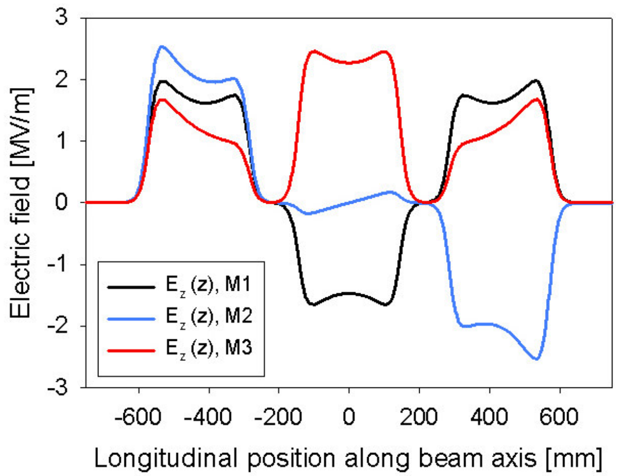
- φ is the phase between the particle and the rf fields. When considered in a calculation of [R/Q], $[R/Q]_T$, the value φ of is that which maximizes the voltage.



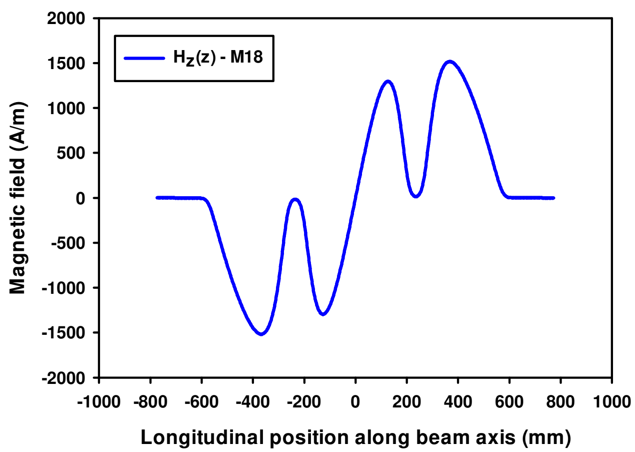


Higher Order Modes (Double-Spoke)

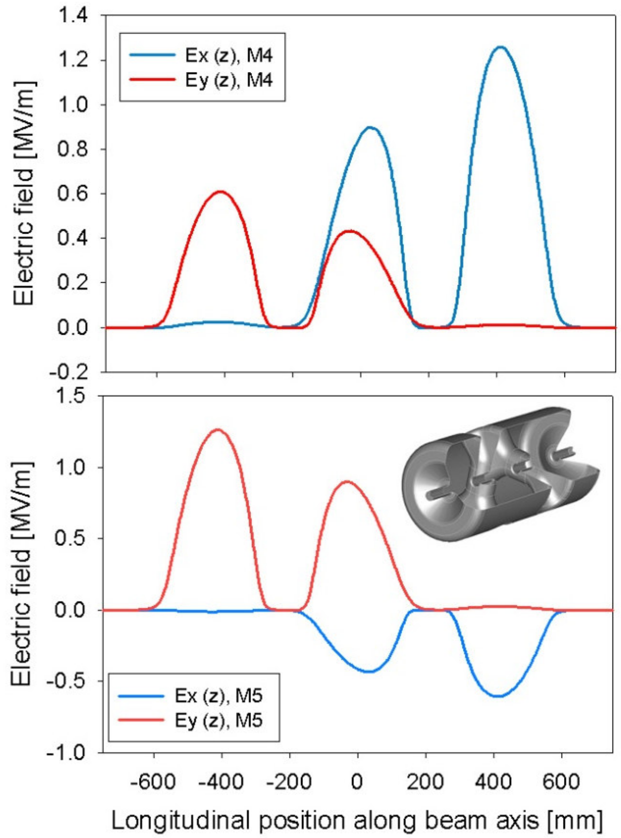
Accelerating modes



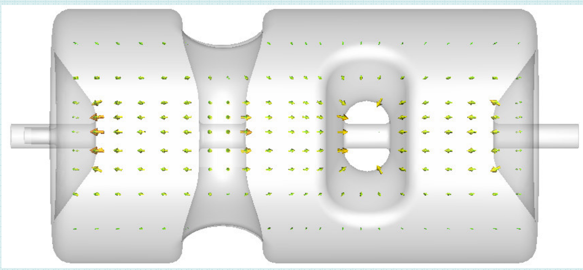
TE-type modes



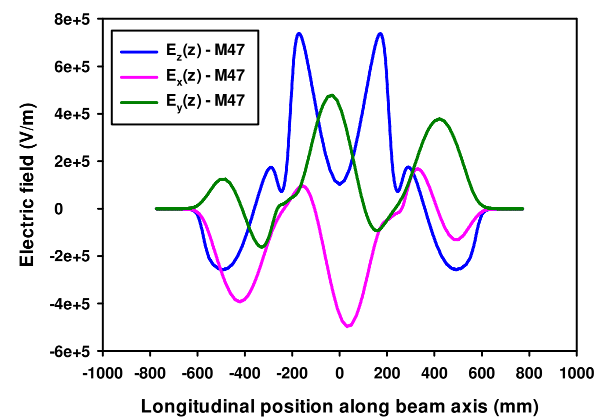
Deflecting Modes (degenerate modes)



Examples of modes for the 325 MHz cavity, β_0 =1

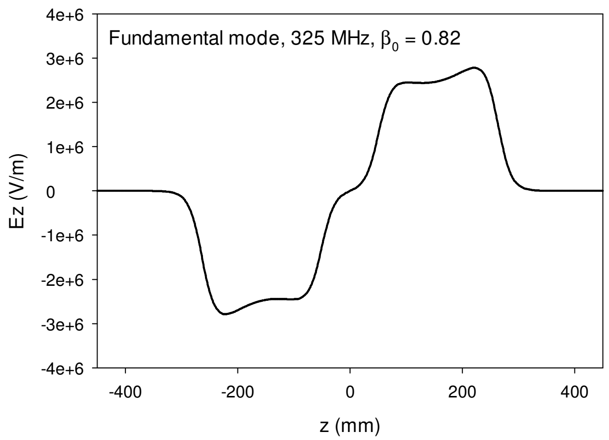


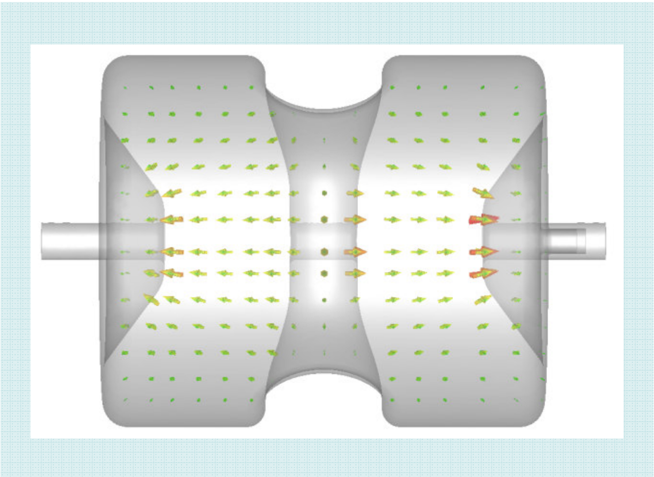
Hybrid modes



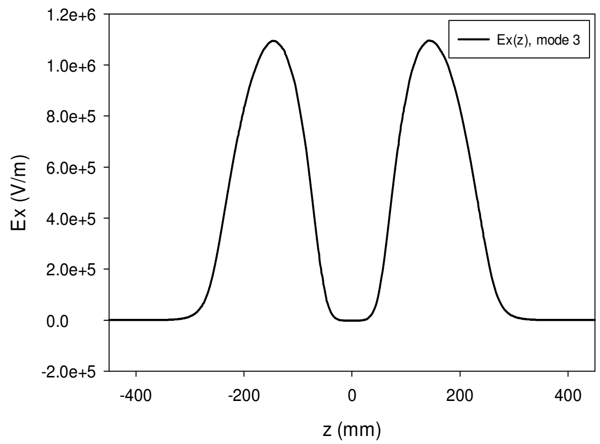
HIGHER ORDER MODES (SINGLE-SPOKE)

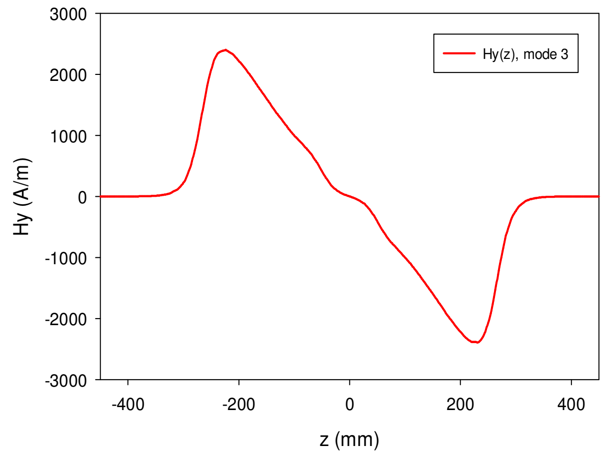
Accelerating modes



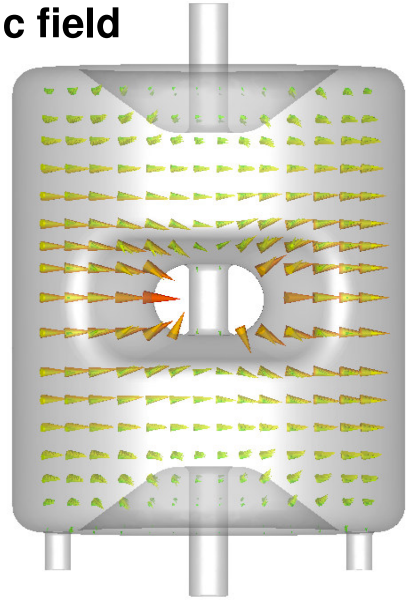


Deflecting modes

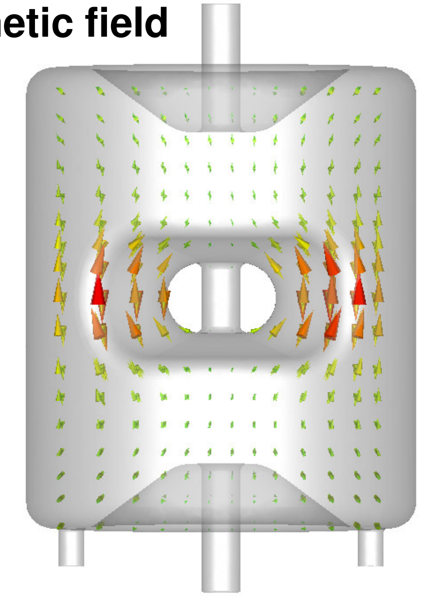




Electric field



Magnetic field



CALCULATING [R/Q], [R/Q]$_T$

Accelerating Modes

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

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

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

Deflecting Modes

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

$$\left(\frac{\boldsymbol{R}}{\boldsymbol{Q}}\right)_{\boldsymbol{T}} = \frac{\boldsymbol{V_T^2}}{\boldsymbol{\omega_n U}}$$

Verify with PWT

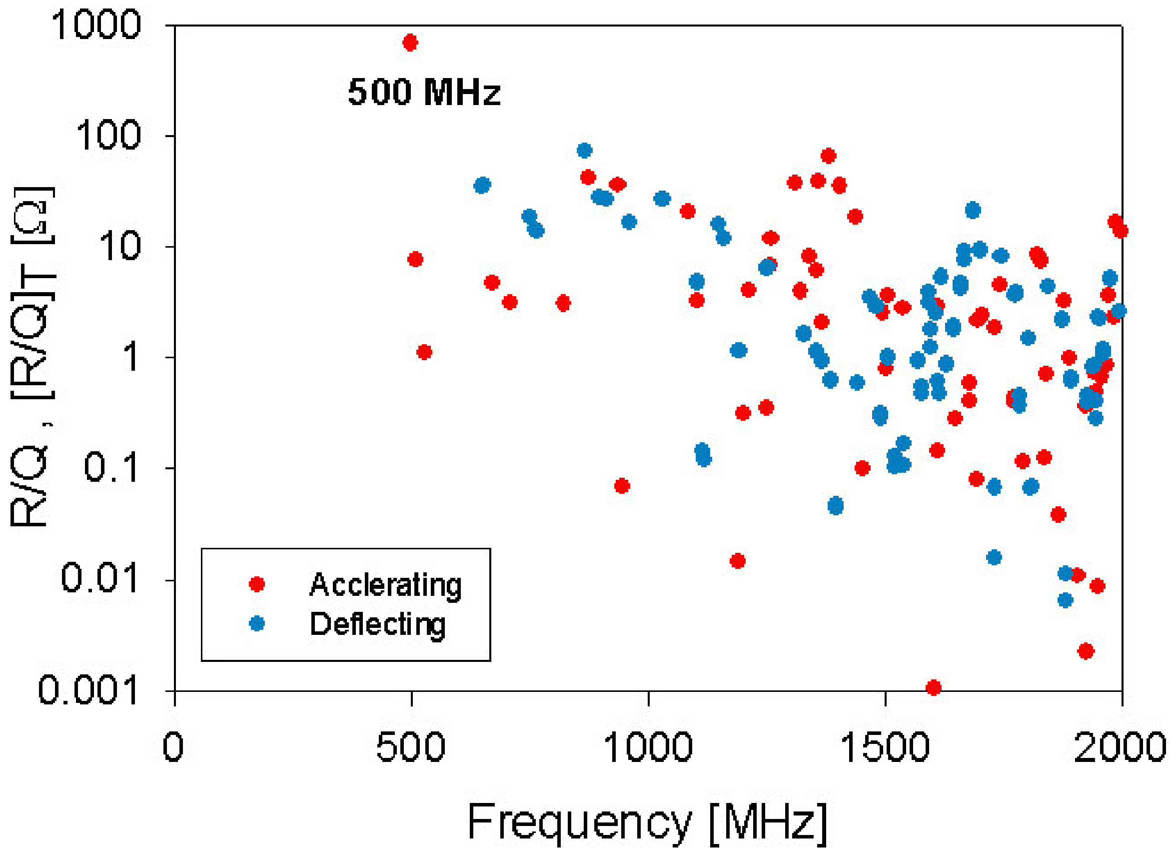
$$\Delta p_T = \left(\frac{e}{\omega_n}\right) \int_0^L (-i) \nabla_\perp E_z dz$$

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

GEOMETRIC SHUNT IMPEDANCE (DOUBLE-SPOKE)

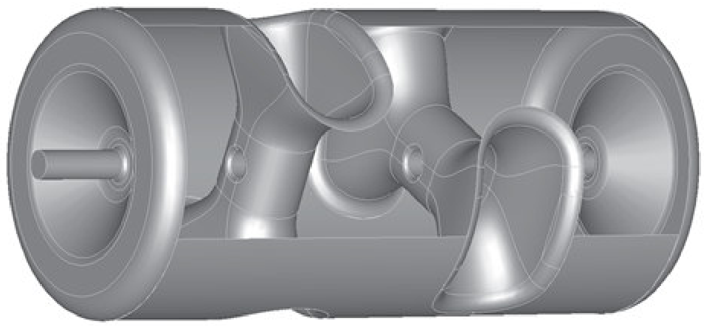
[R/Q] values for particles at design velocity

β_0 = 1 for the 500 MHz double-spoke cavity



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

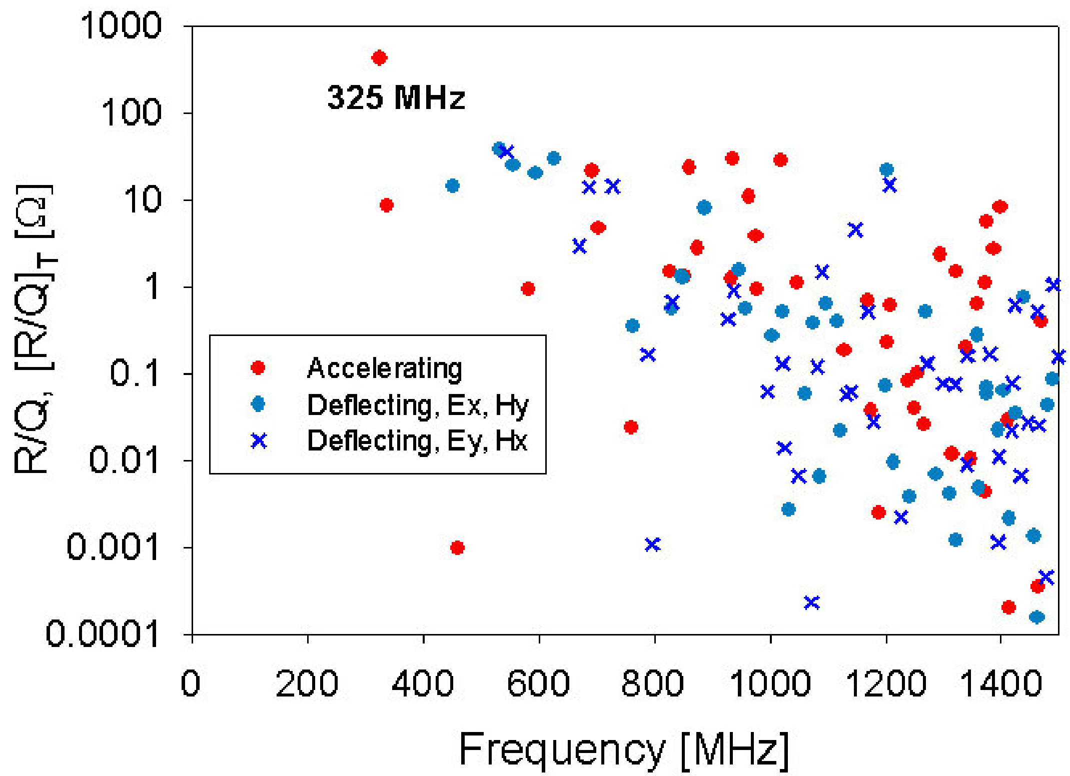
$$f_c = \frac{1.841 * c}{2\pi a} = 3.52 \text{ GHz}$$



Geometric Shunt Impedance (Single-Spoke)

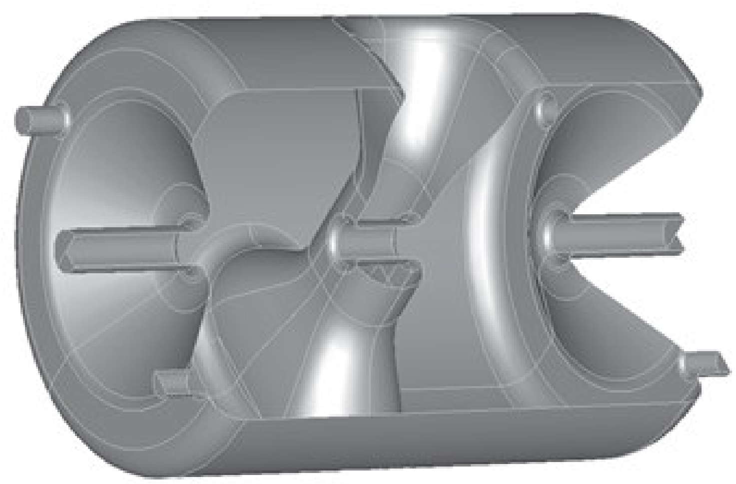
[R/Q] values for particles at design velocity

β_0 = 0.82 for the 325 MHz single-spoke cavity



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

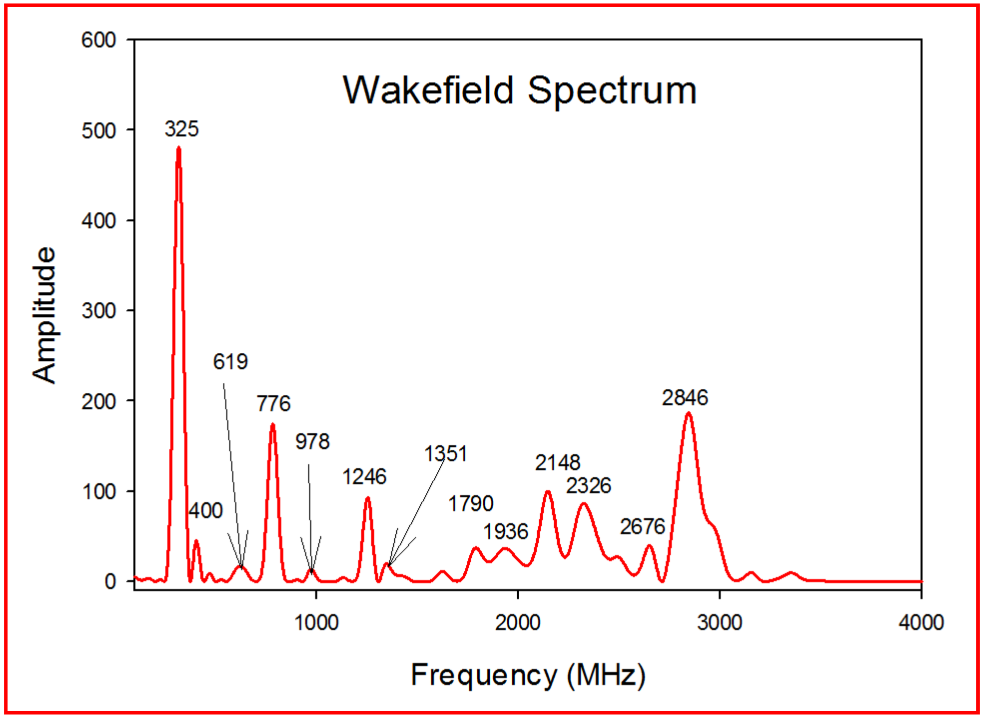
$$f_c = \frac{1.841 * c}{2\pi a} = 2.93 \text{ GHz}$$



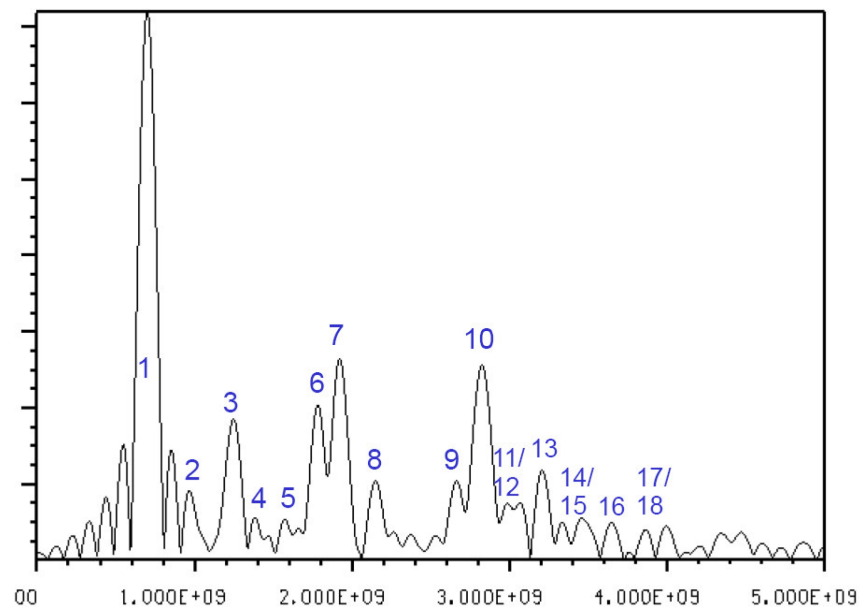
325 MHz, β_0 = 0.82 single-spoke cavity

Excitation of modes by a single bunch

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



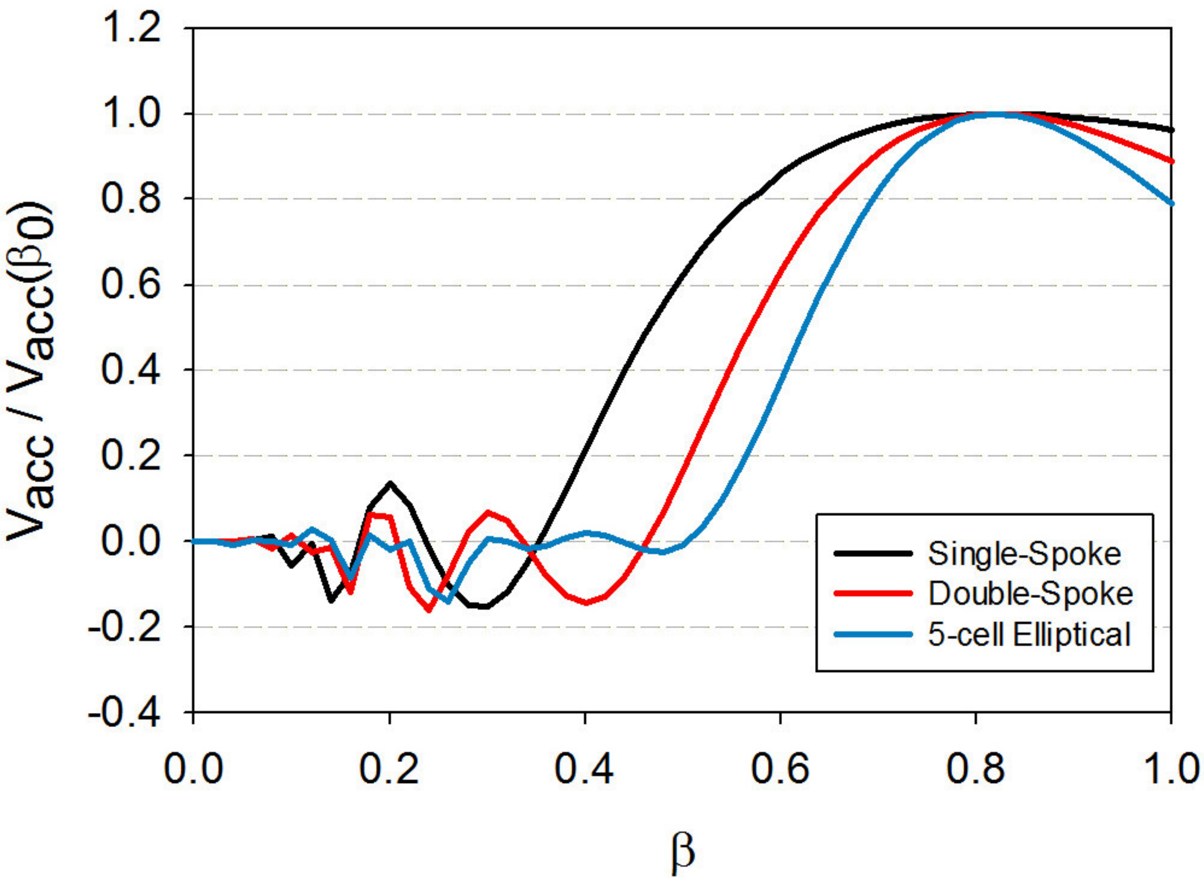
1: 700.6 MHz
2: 965.9 MHz
3: 1247.5 MHz
4: 1383.2 MHz
5: 1571.4 MHz
6: 1782.3 MHz
7: 1921.0 MHz
8: 2148.9 MHz
9: 2663.3 MHz
10: 2825.2 MHz
11: 2986.0 MHz
12: 3067.5 MHz
13: 3207.8 MHz
14: 3336.4 MHz
15: 3461.1 MHz
16: 3647.8 MHz
17: 3864.2 MHz
18: 3992.9 MHz



C. Hopper, ODU
ACE3P

F. Krawczyk, LANL
MAFIA

VELOCITY ACCEPTANCE



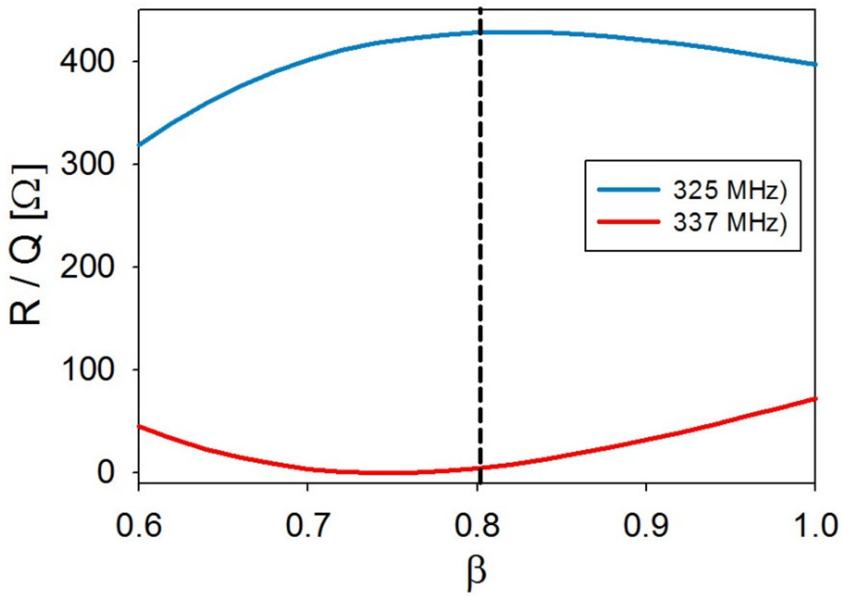
Large velocity acceptance which is important for protons and ions

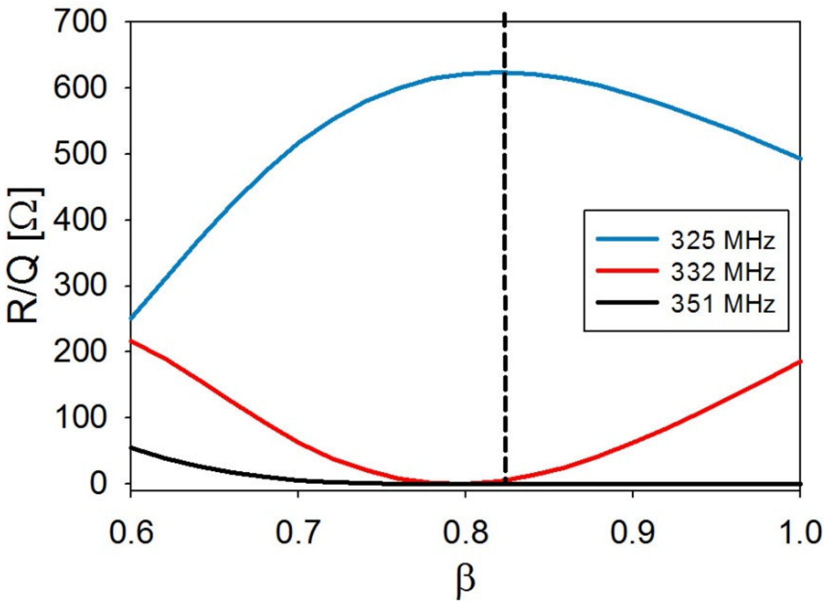
- Single-spoke cavity: Greater than 96% efficiency between 0.7 ≤ β ≤ 1.
- Double-spoke cavity: Greater than 96% efficiency between 0.74 ≤ β ≤ 0.92.

$$E = K + m_0c^2 - \gamma m_0 c^2$$

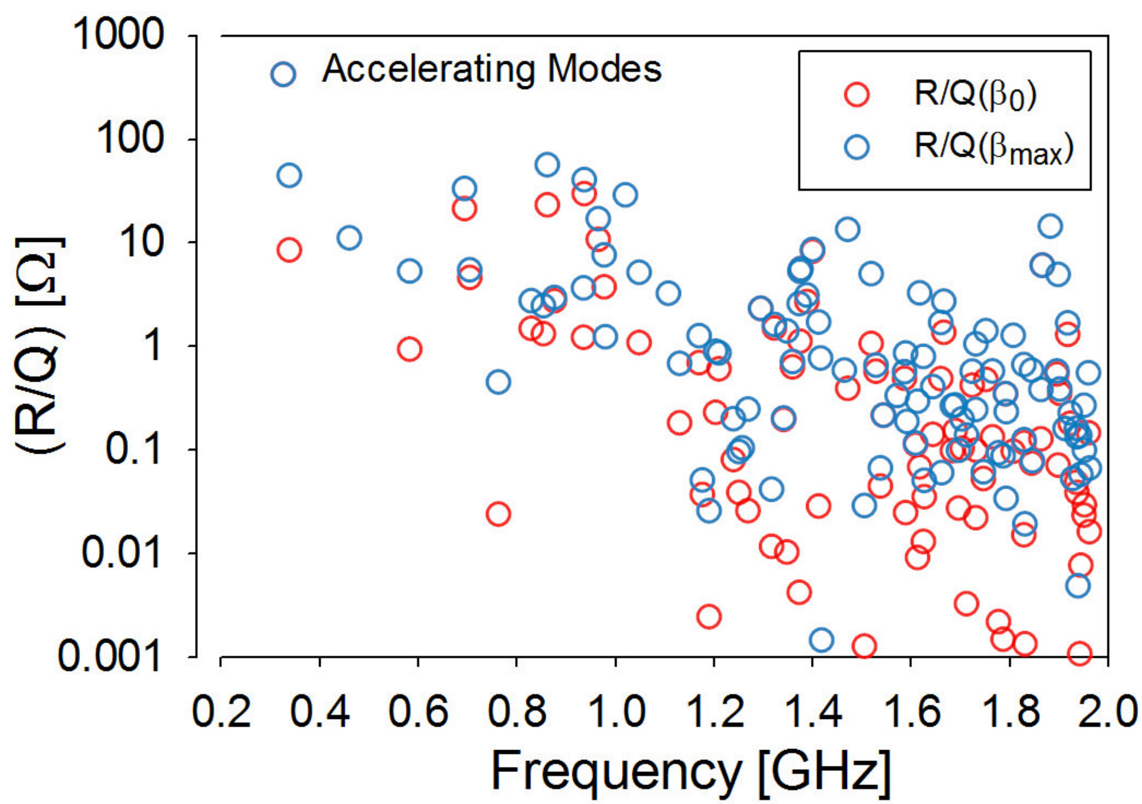
$$v = \sqrt{1 - \frac{1}{\gamma^2}} \cdot c$$

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



MULITPOLE COMPONENTS

Higher order multipole components can have effects on beam dynamics. Starting with the general description of the time dependent multipole fields:

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

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

Fourier series expansion

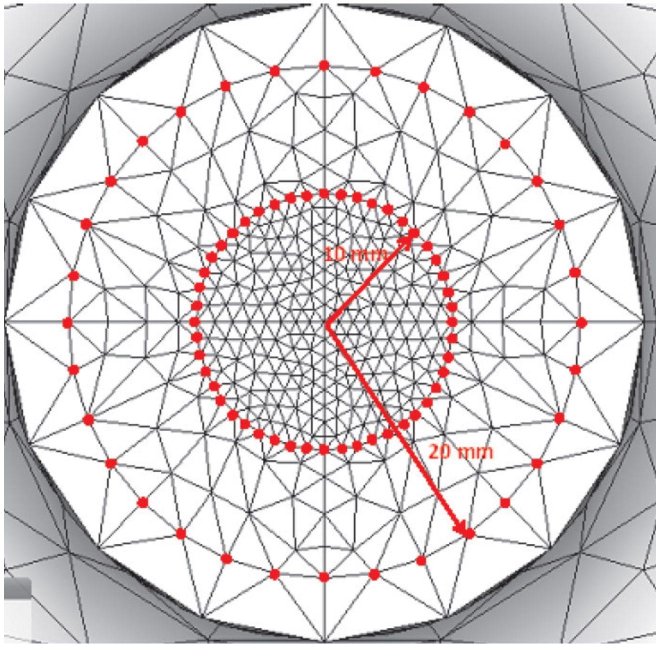
$$E_{acc}^{(n)}(z,t) = E_z^{(n)}(z)e^{i\omega t} = \frac{1}{r^n}\int_0^{2\pi} E_z(r,\varphi,z)\ [\cos(n\varphi) + i\sin(n\varphi)]e^{i\omega t}\, d\varphi$$

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

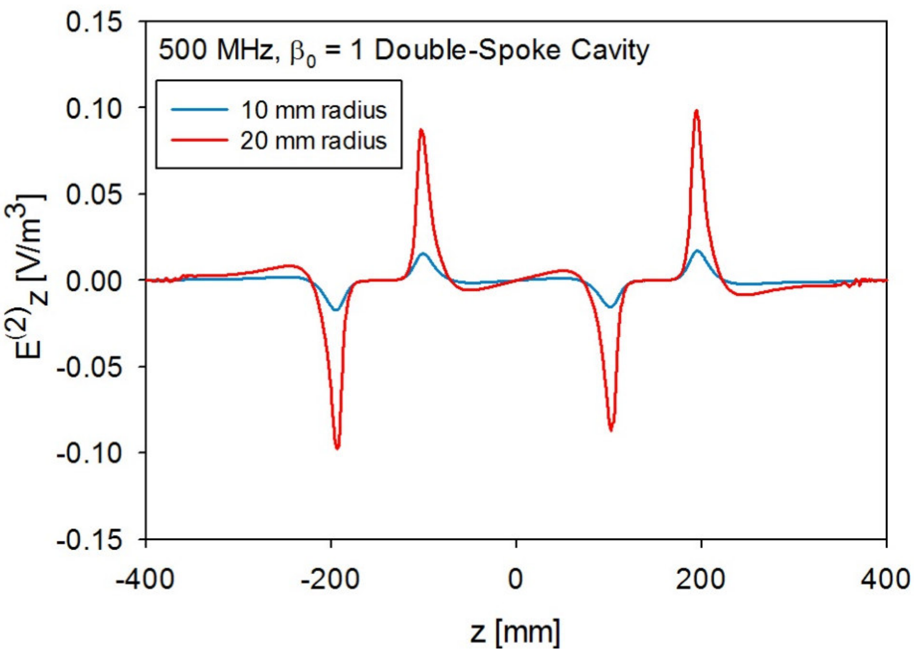
Magnet definition

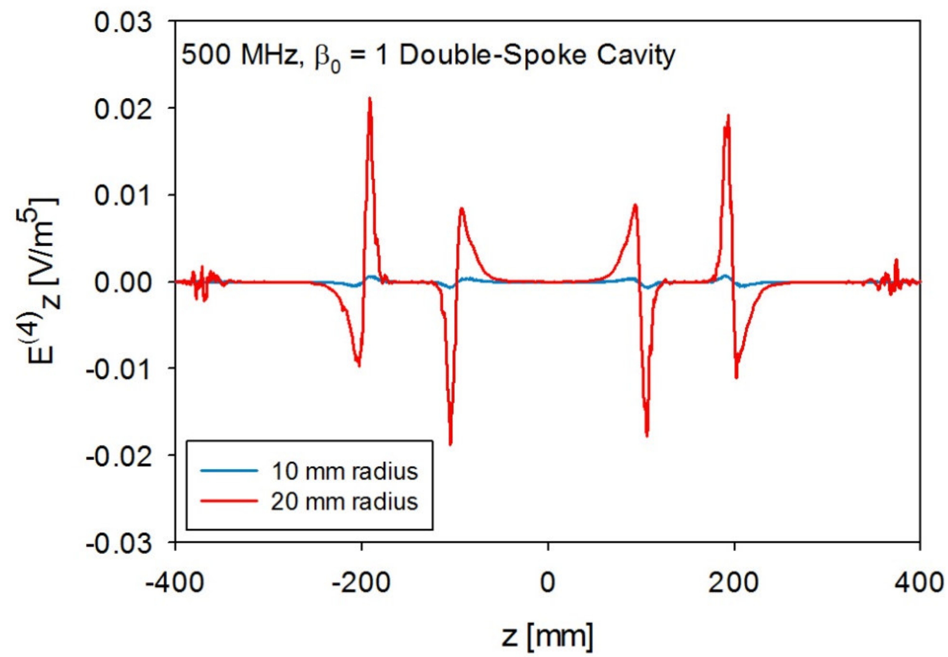
$$b_n = \int_{-\infty}^{\infty} B^{(n)}(z)\, dz \quad [\mathrm{T/m^{n-2}}]$$

Multipole components



MULITPOLE COMPONENTS





Components have been identified, beam dynamics simulated, and methods for reduction explored*

Net focusing in one direction and defocusing in perpendicular direction

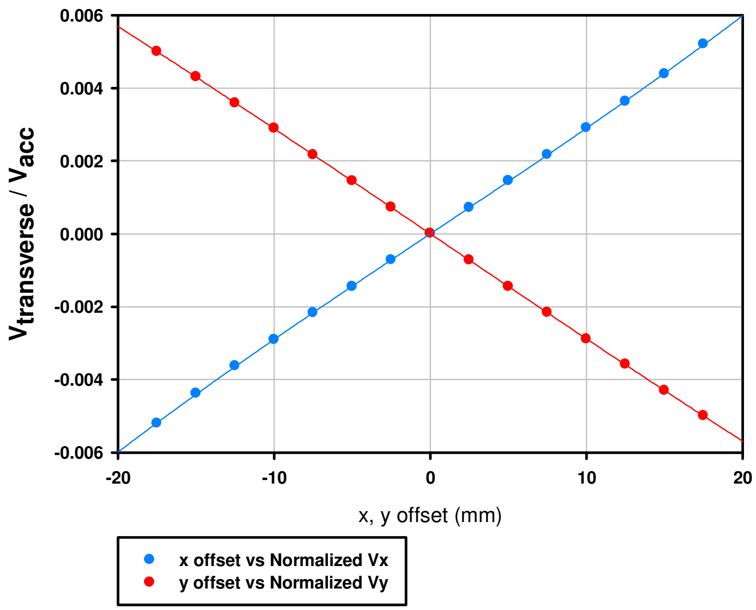
Can be reduced through modifications to the geometry immediately around the beam path or using an even number of cavities oriented 90° from nearest neighbor

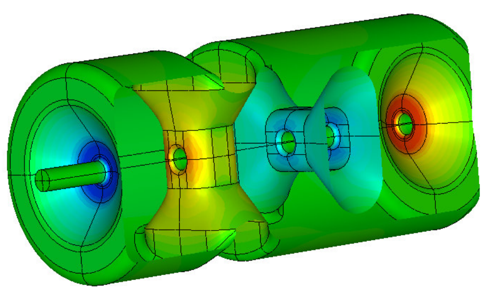
C.S. Hopper, K. Deitrick, and J.R. Delayen, “Geometry Effects on Multipole Components and Beam Optics in High-Velocity Multi-Spoke Cavities,” PAC 2013, WEPAC42, 2013

Multipoles

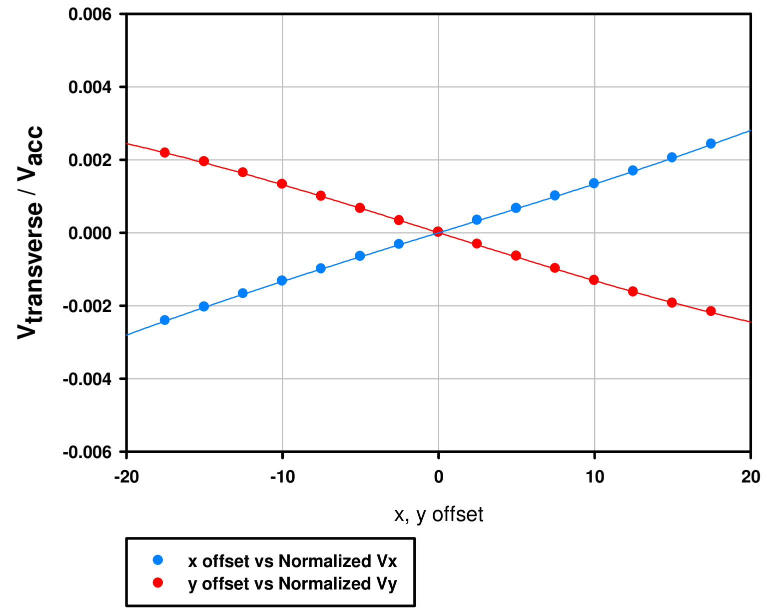
500 MHz, β = 1

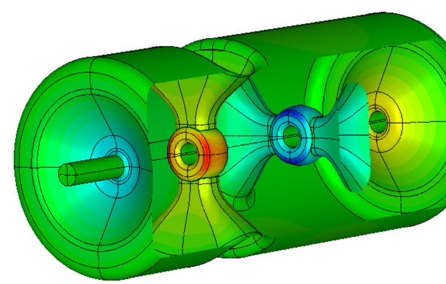
Nonlinearities of field, 500 MHz cavity, racetrack spokes (symmetric tet [quarter] mesh)





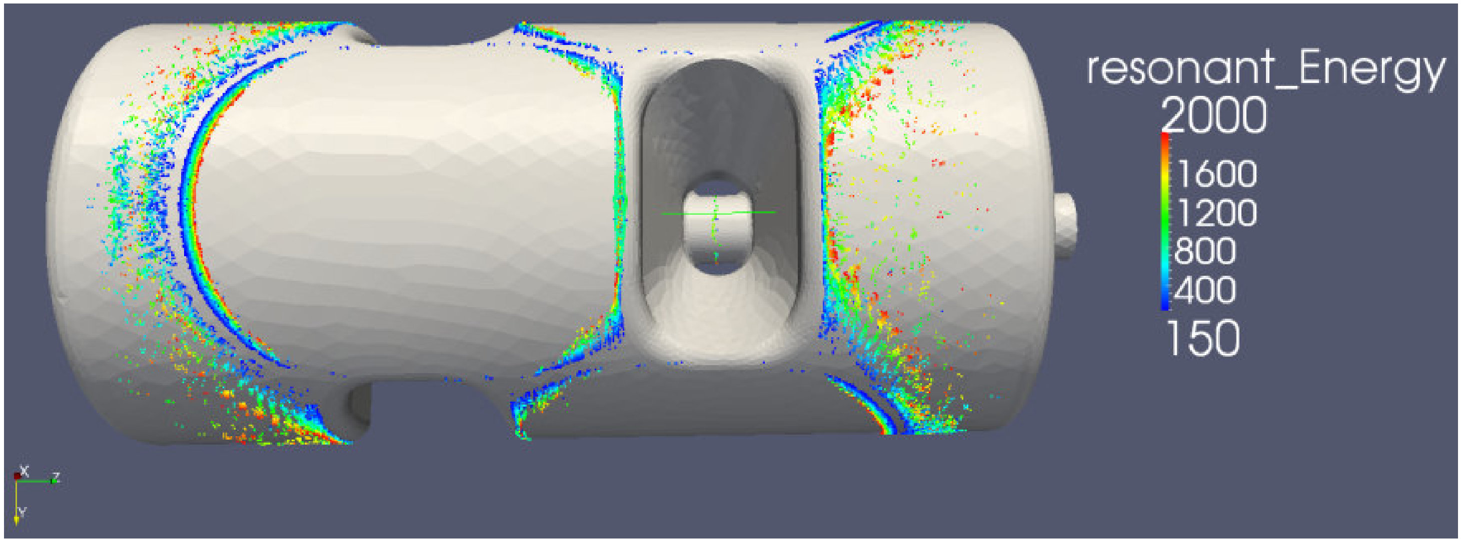
Nonlinearities of field, 500 MHz cavity, ring-shaped spokes (symmetric tet [quarter] mesh)



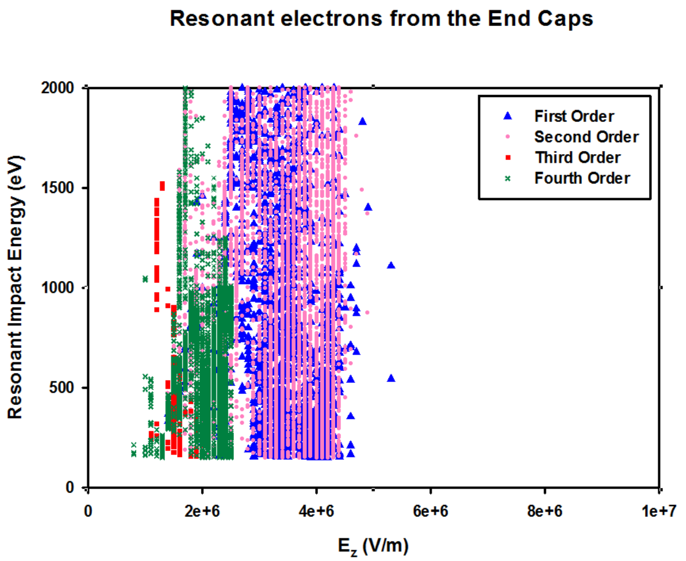


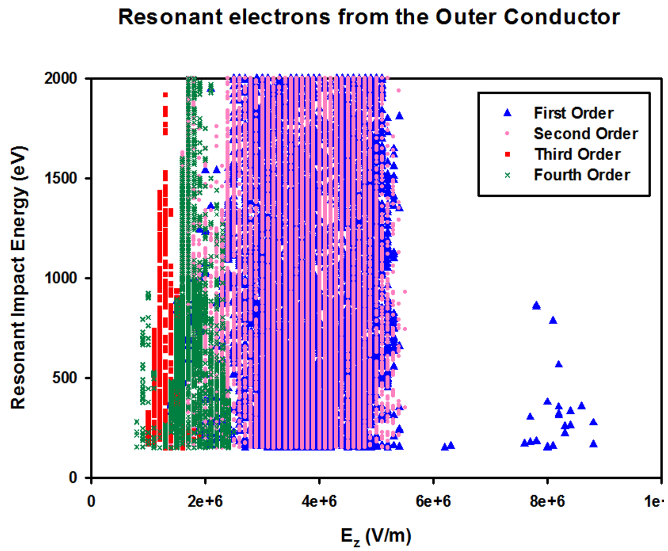
R. Olave, ODU

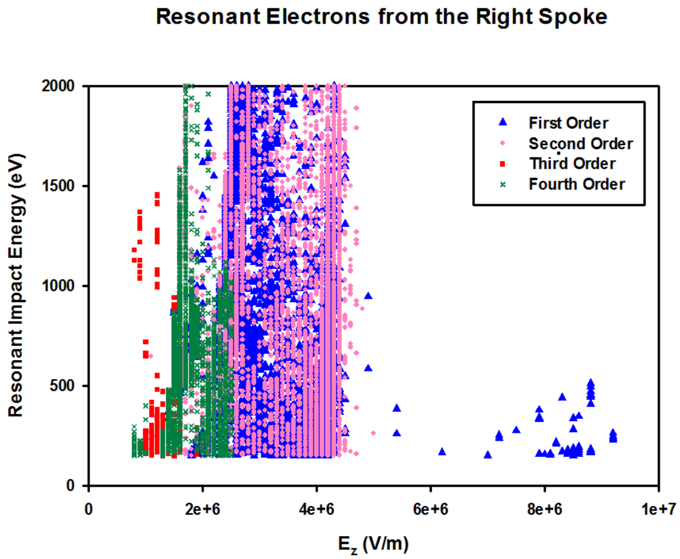
Multipacting



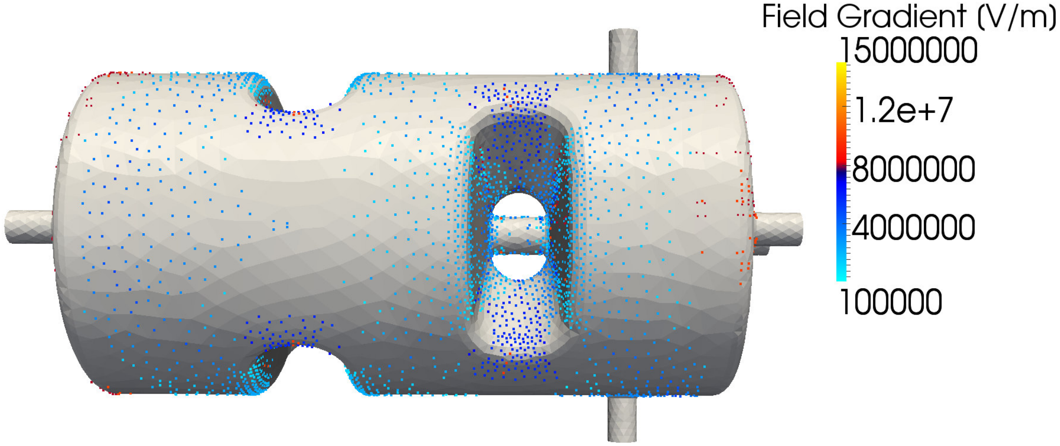
700 MHz, β=1
ACE3P
R. Olave, ODU

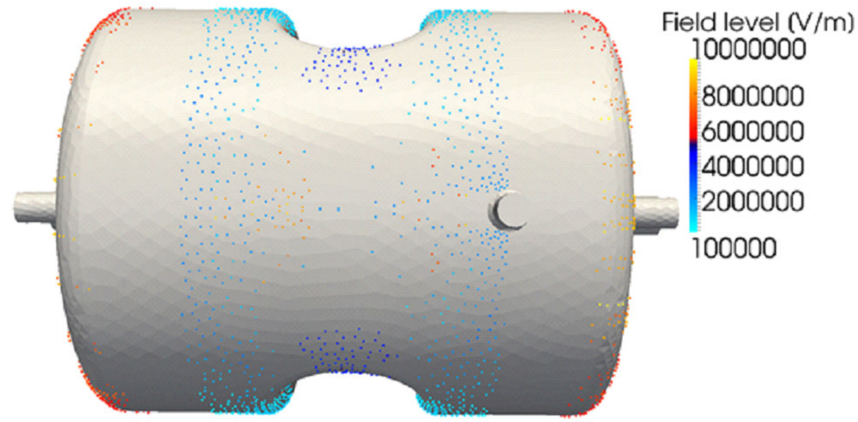


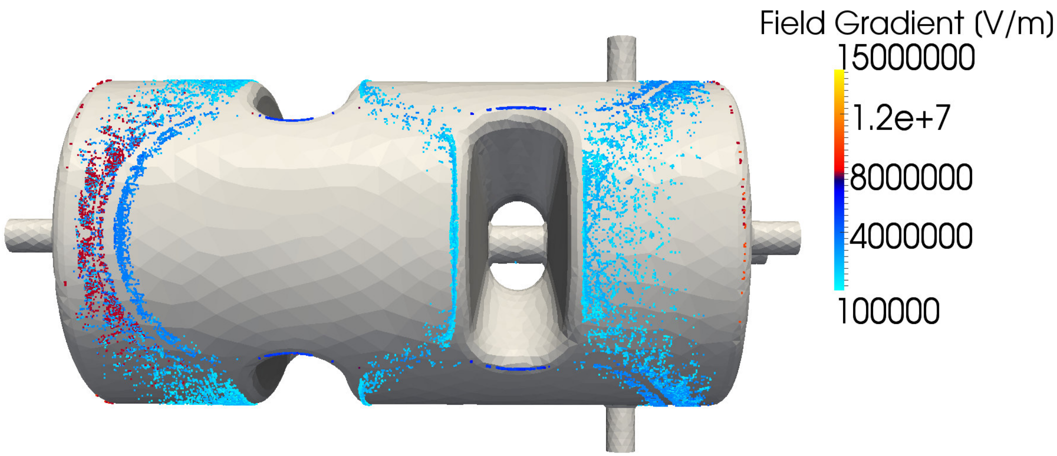


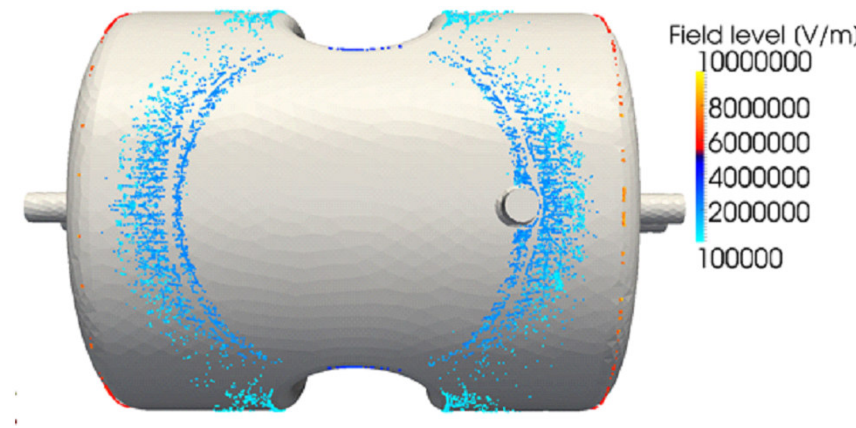


Emitting and Resonant Locations







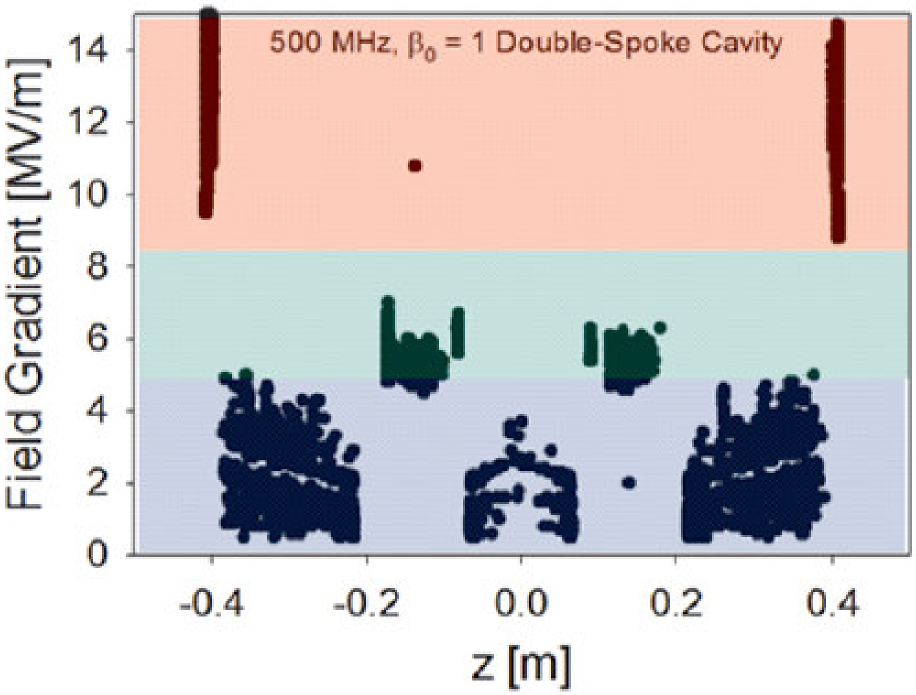


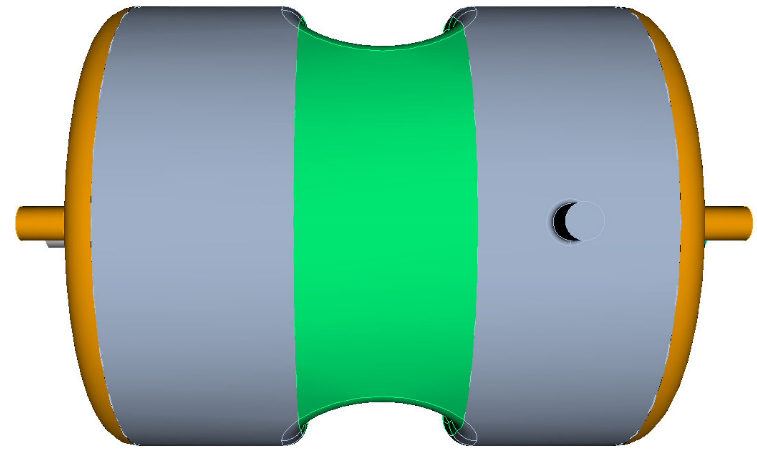
500 MHz double-spoke

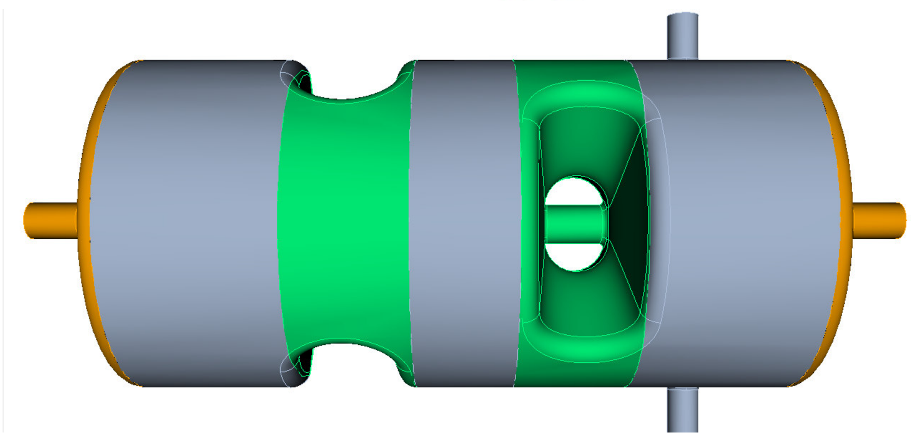
325 MHz single-spoke

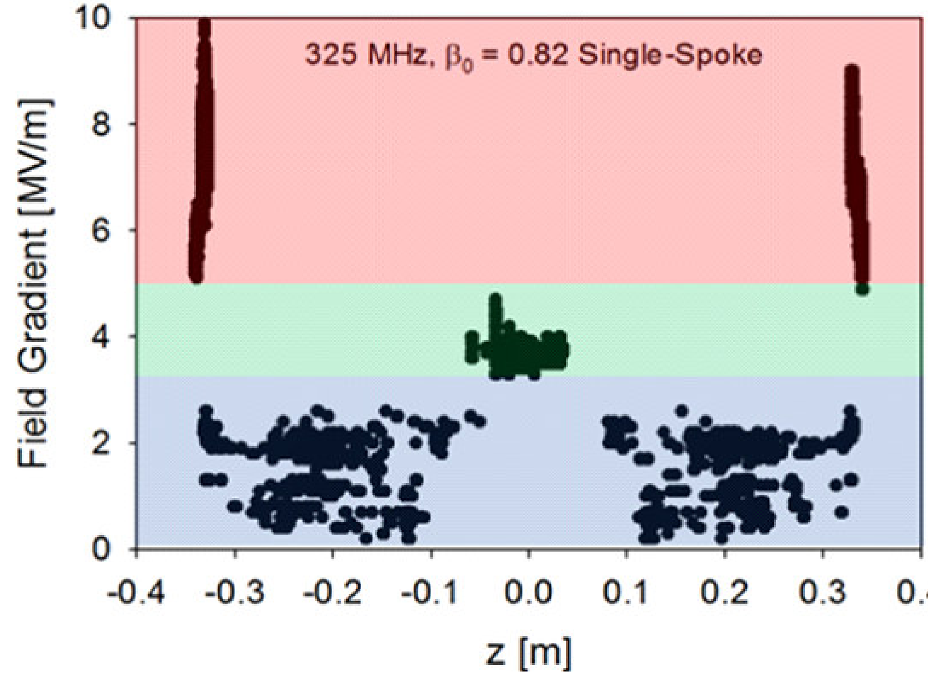
Initial and resonant locations by accelerating field gradient.

Emitting and Resonant Locations



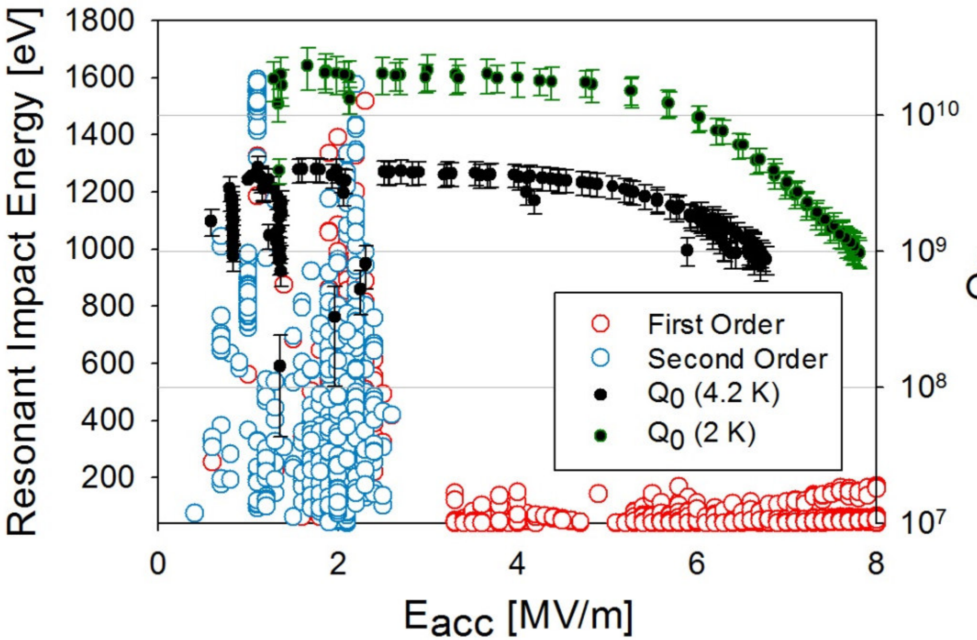


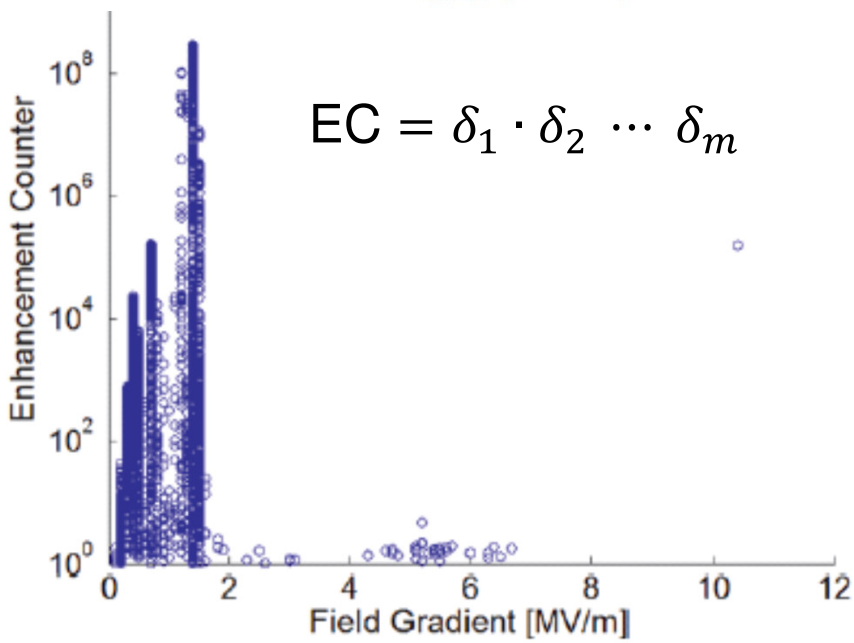




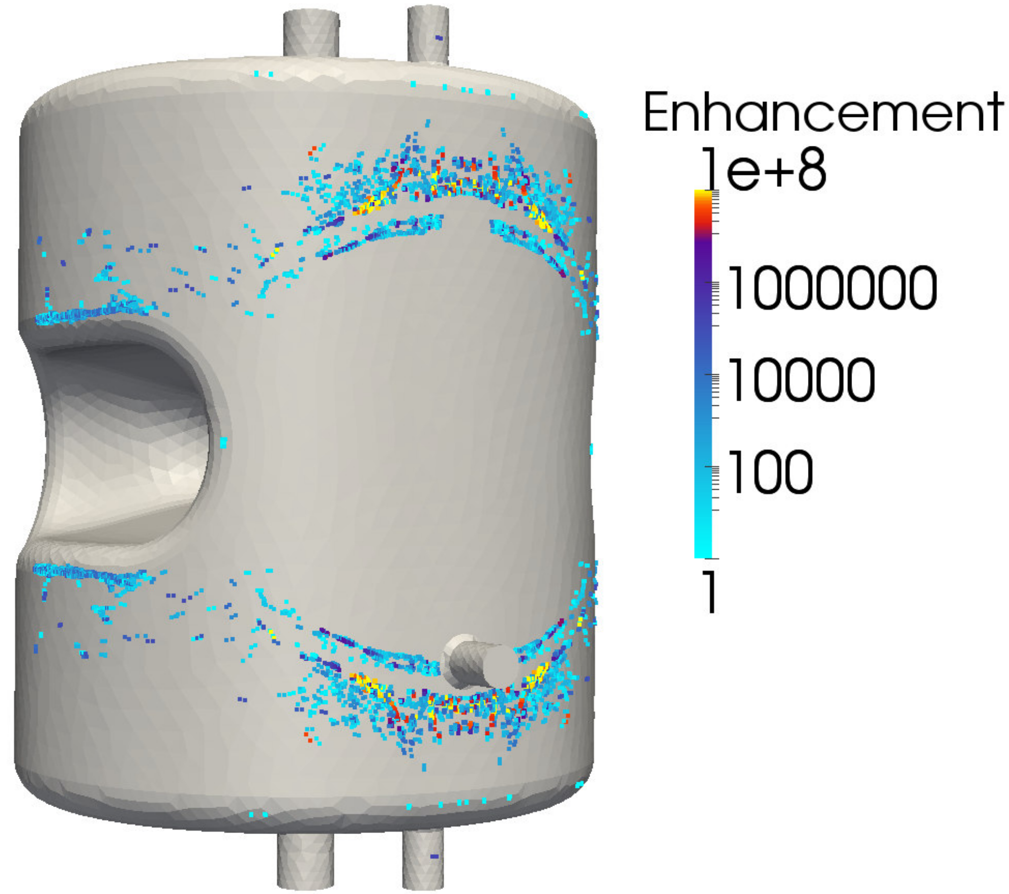
Distinct gradient levels where multipacting occurs in different locations of the cavity

MULTIPACTING (325 MHz)



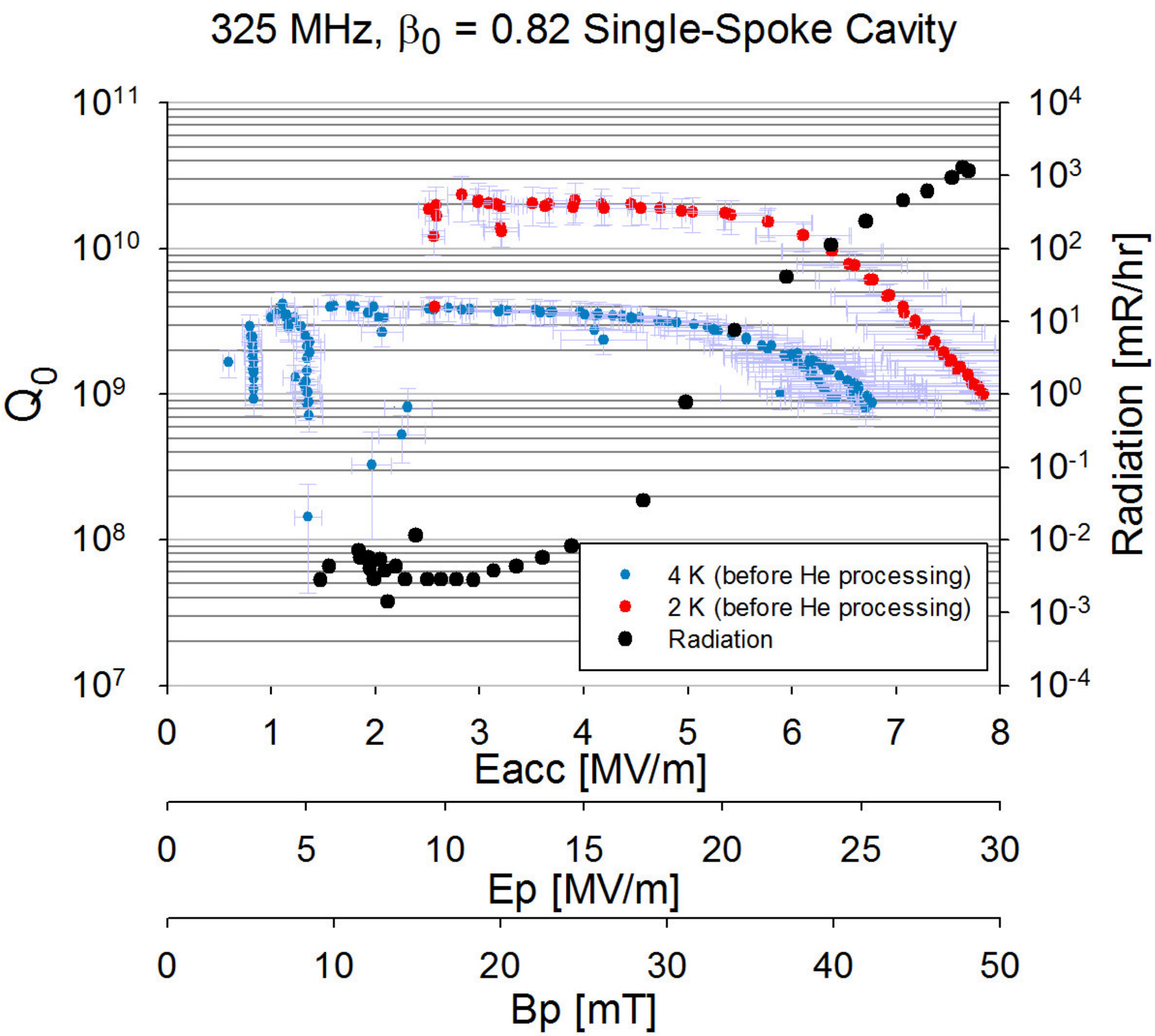


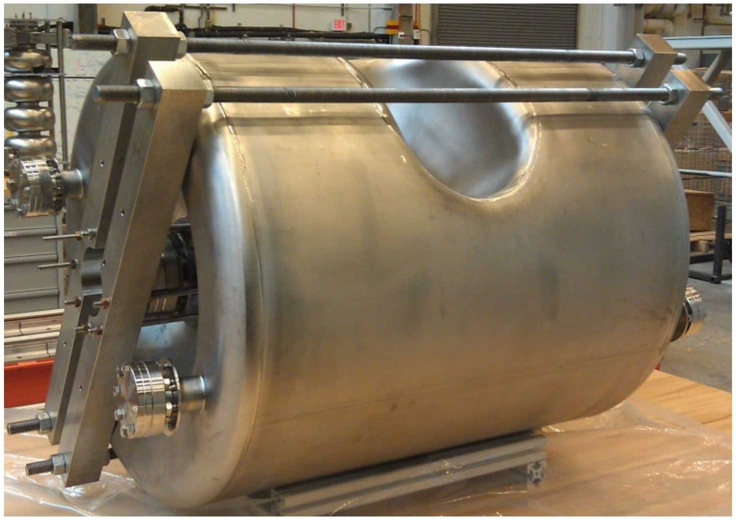
$$\mathrm{EC} = \delta_1 \cdot \delta_2 \cdots \delta_m$$

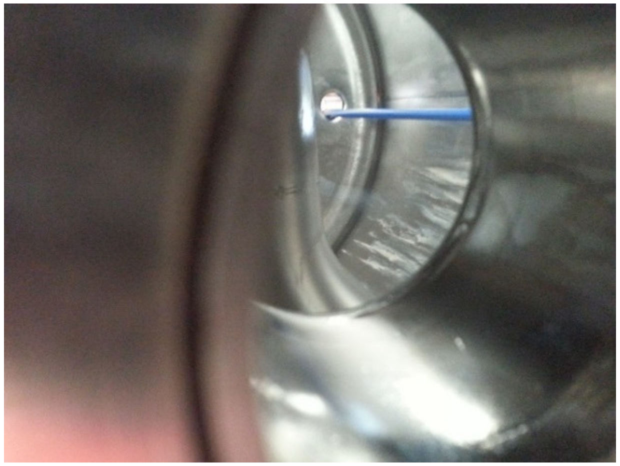


Multipacting experienced up to 2.1 MV/m

Gradient Measurements (325 MHz)

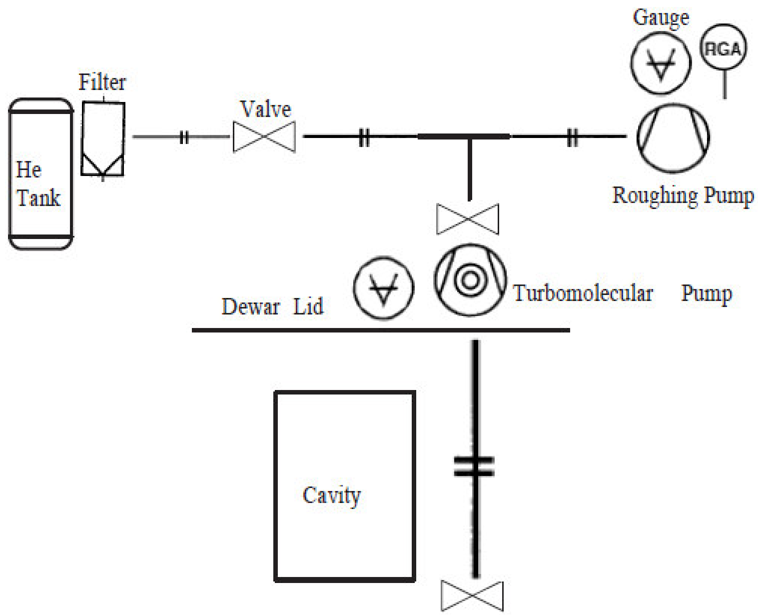


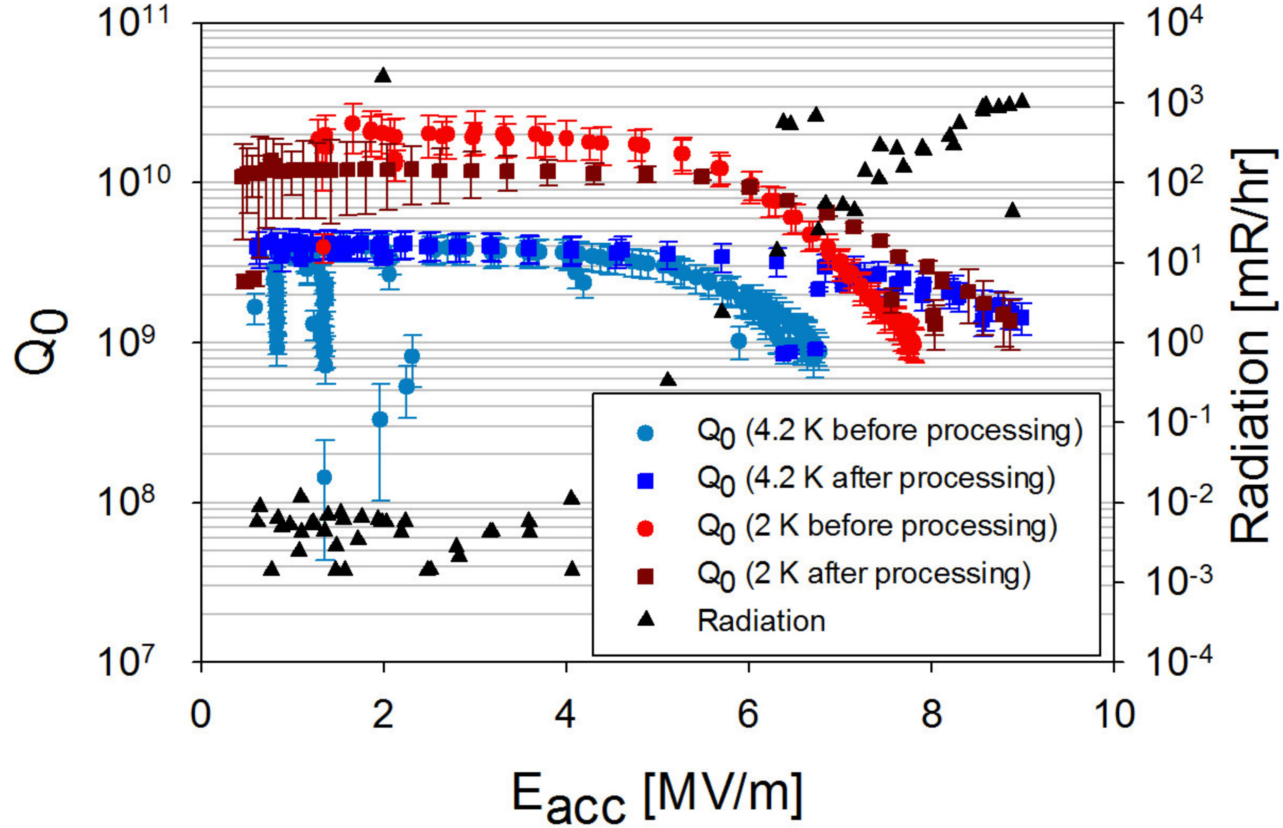




High levels of radiation from field emission

HELIUM PROCESSING (325 MHz)

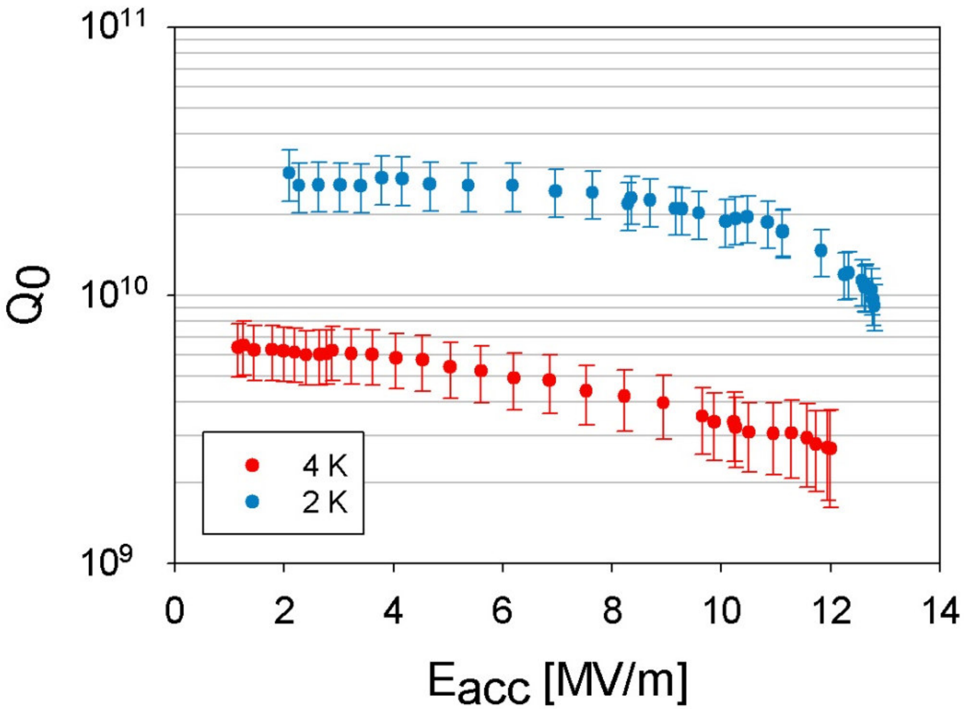




- Inject clean helium gas into the cavity while in the dewar, under vacuum
- Apply high power rf in cw and/or pulsed mode

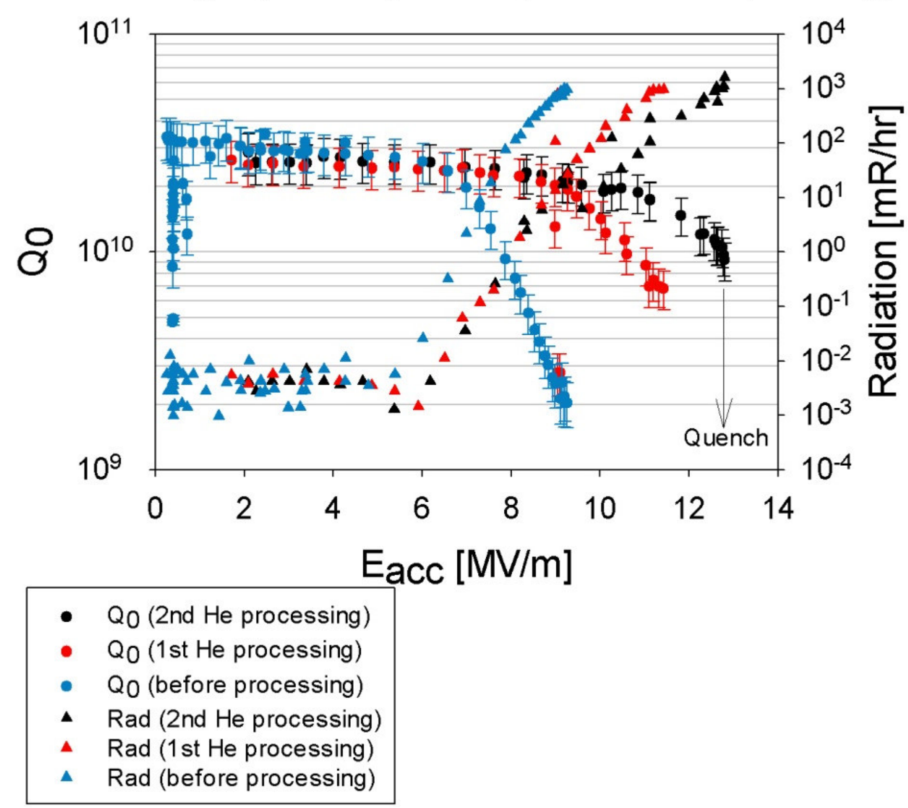
SECOND PROCESSING (325 MHz)

325 MHz Single-Spoke Cavity 4K and 2 K Tests (after He processing)



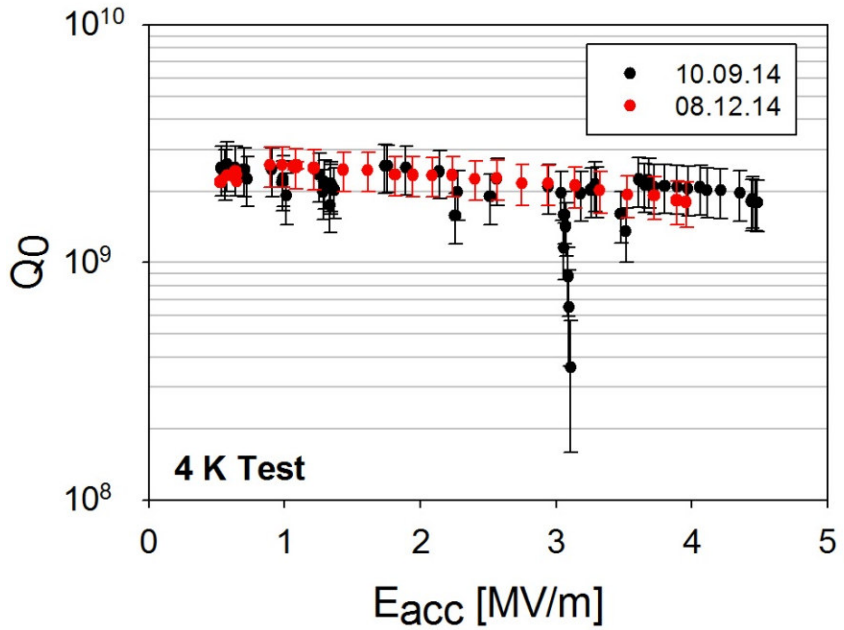
- Similar to previous test, but higher Q_0.
- Onset of field emission at 6 MV/m

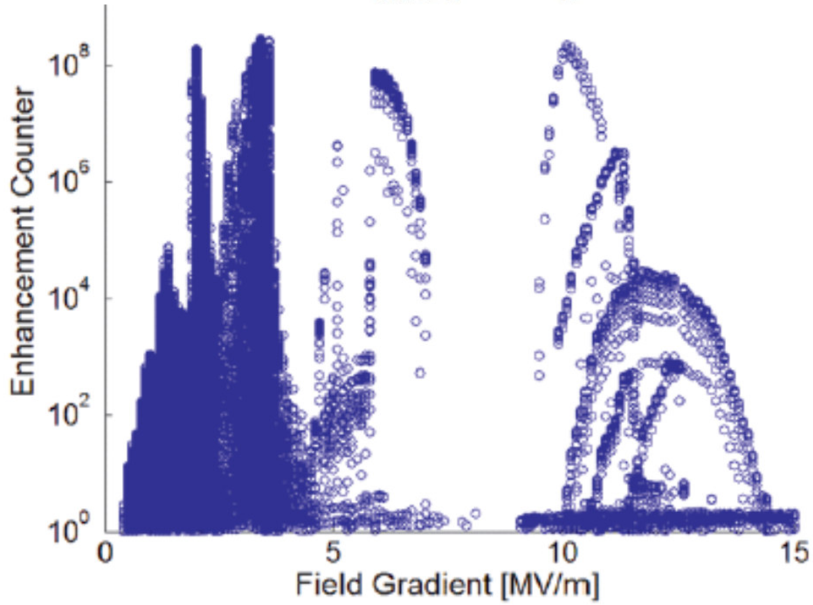
325 MHz Single-Spoke Cavity 2 K Test (before & after He processing)

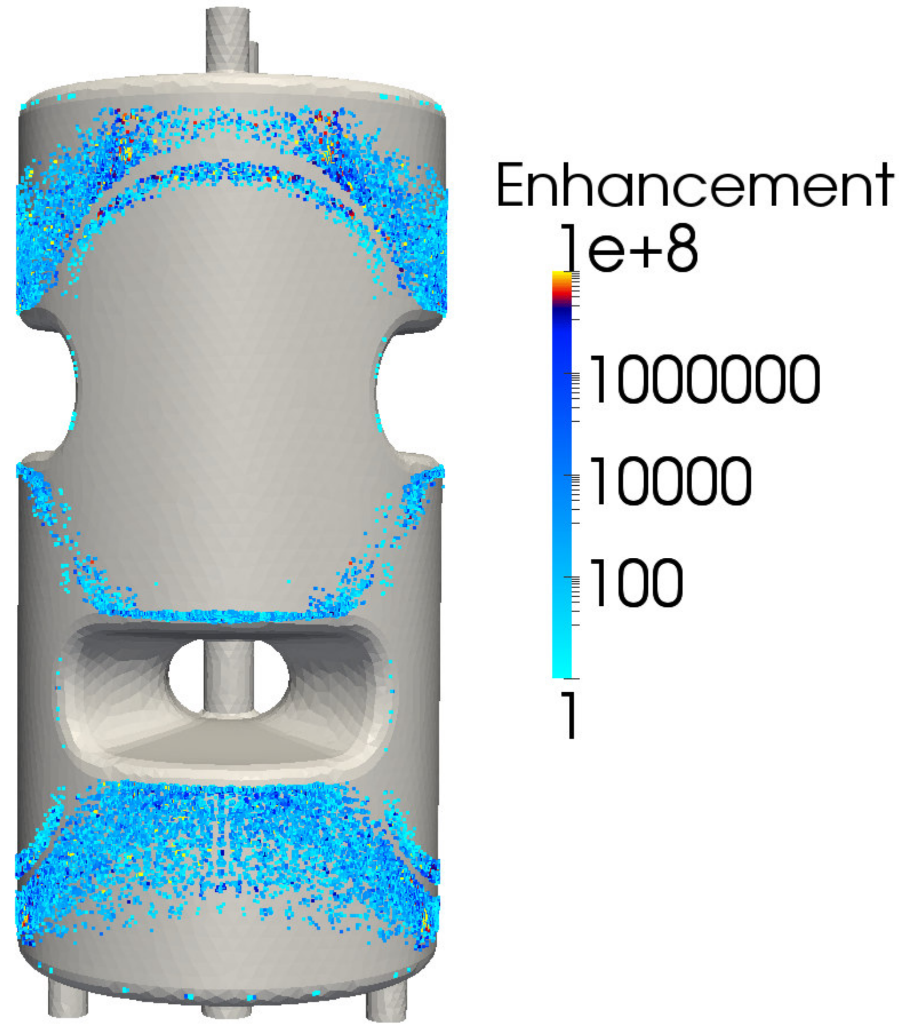


- High low-field Q_0
- After 2 rounds of He processing, achieved ~13 MV/m before quenching

Multipacting (500 MHz)

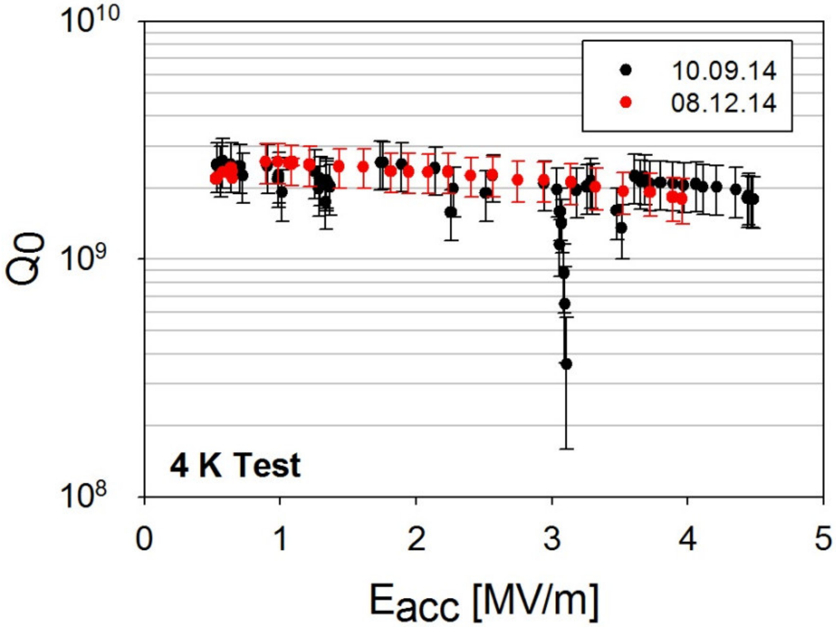


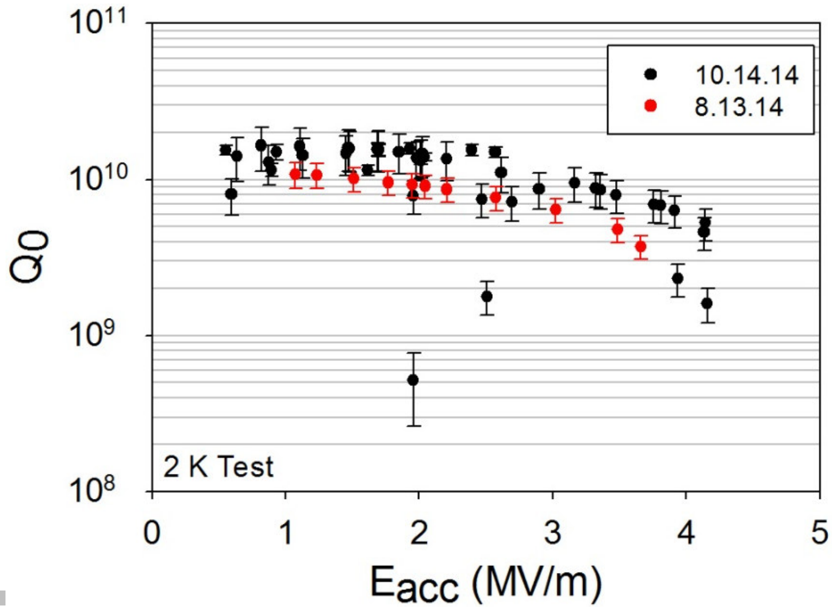


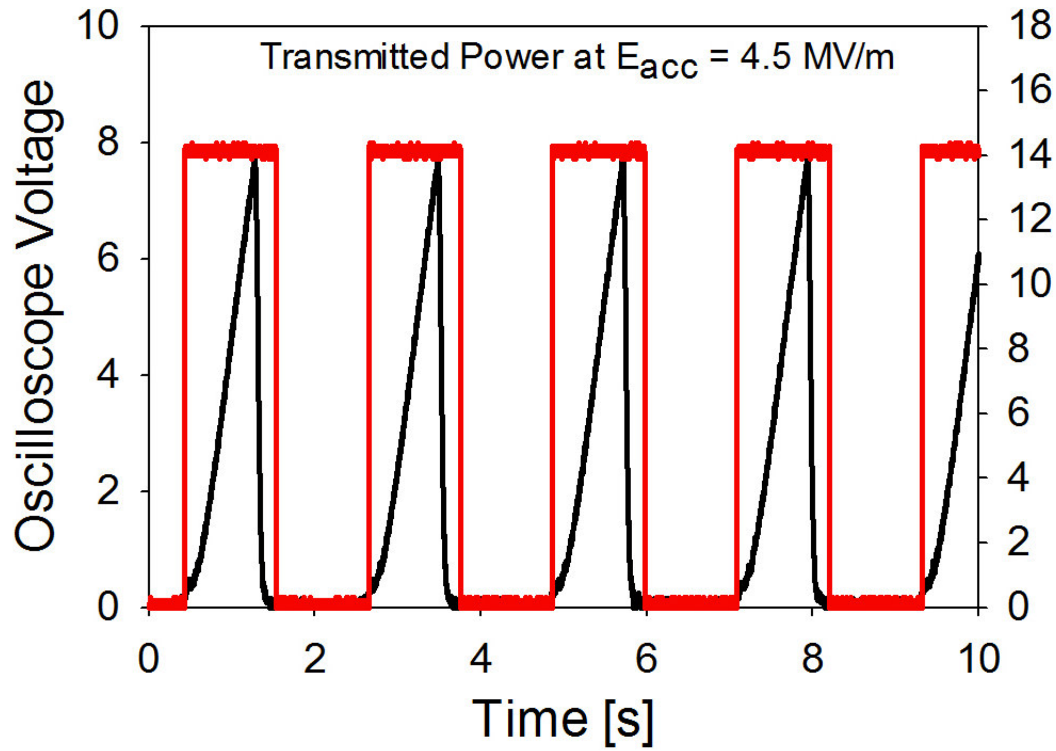


Strong multipacting up to 4.5 MV/m

GRADIENT MEASUREMENTS (500 MHz)

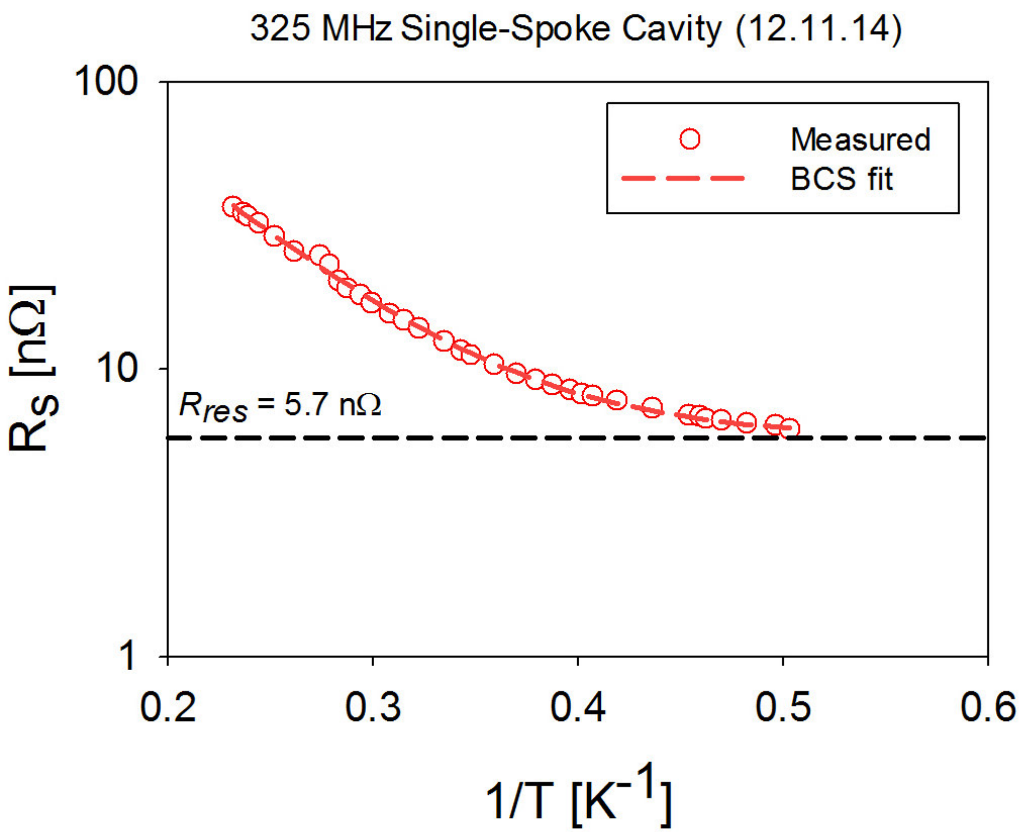


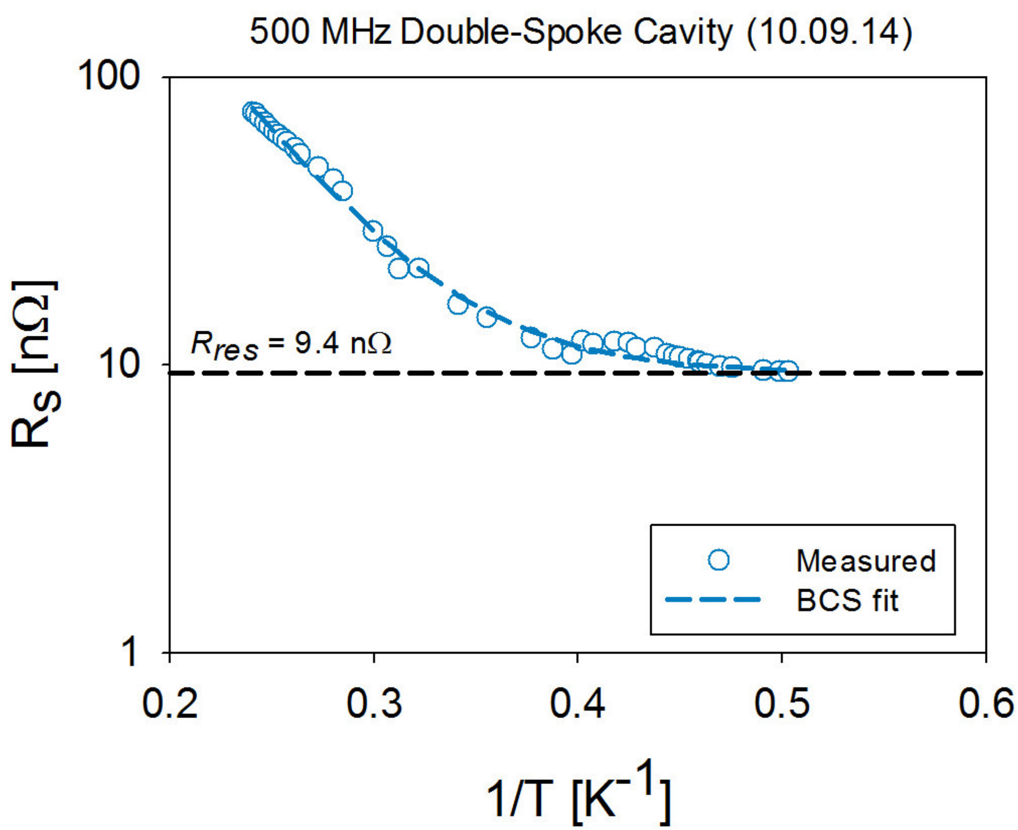




Thermal event at 4 MV/m

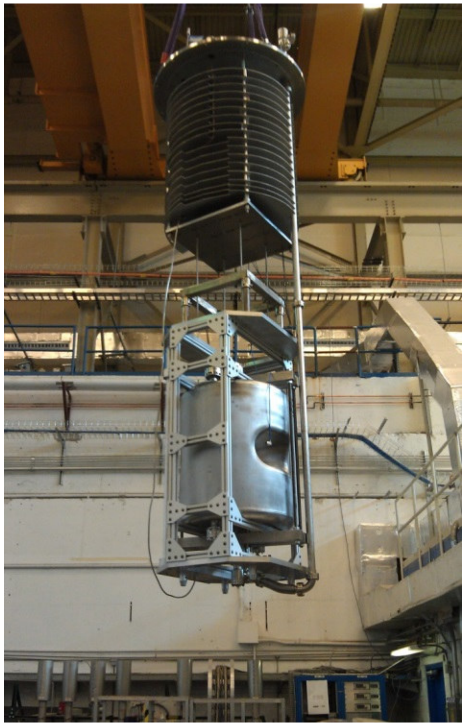
SURFACE RESISTANCE MEASUREMENTS





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

CAVITY PERFORMANCE



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

Frequency	500	325	MHz
4 K			
V_{acc}	2.7	9.1	MV
E_{acc}	4.5	12	MV/m
E_p	16.7	43.2	MV/m
B_p	34.2	72	mT
Q_0	2.5×10^{9}	5.6×10^{9}	-
2 K			
V_{acc}	2.7	9.7	MV
E_{acc}	4.1	12.8	MV/m
E_p	15.2	46	MV/m
B_p	31.2	77	mT
Q_0	1.5×10^{10}	2.5×10^{10}	-

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, β 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
- β~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

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