SUPERCONDUCTING SPOKE CAVITIES FOR ELECTRON AND HIGH-VELOCITY PROTON LINACS

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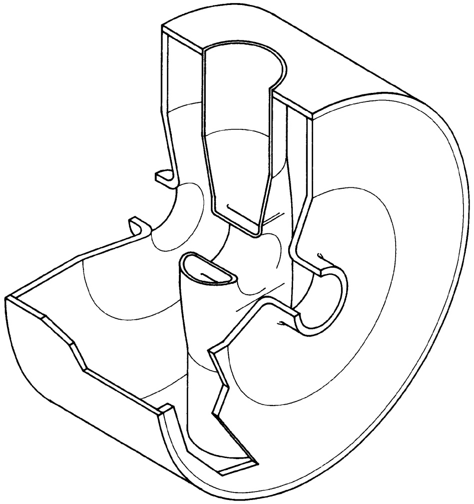
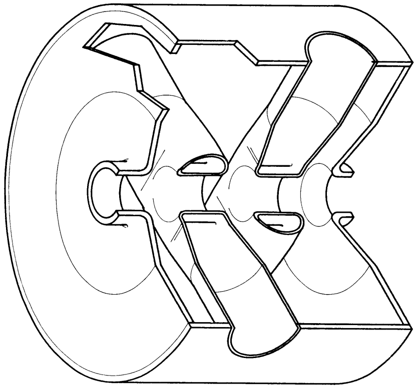
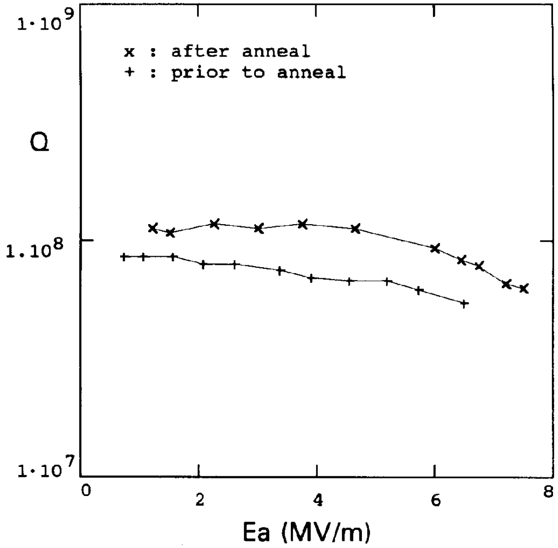
History

- 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)

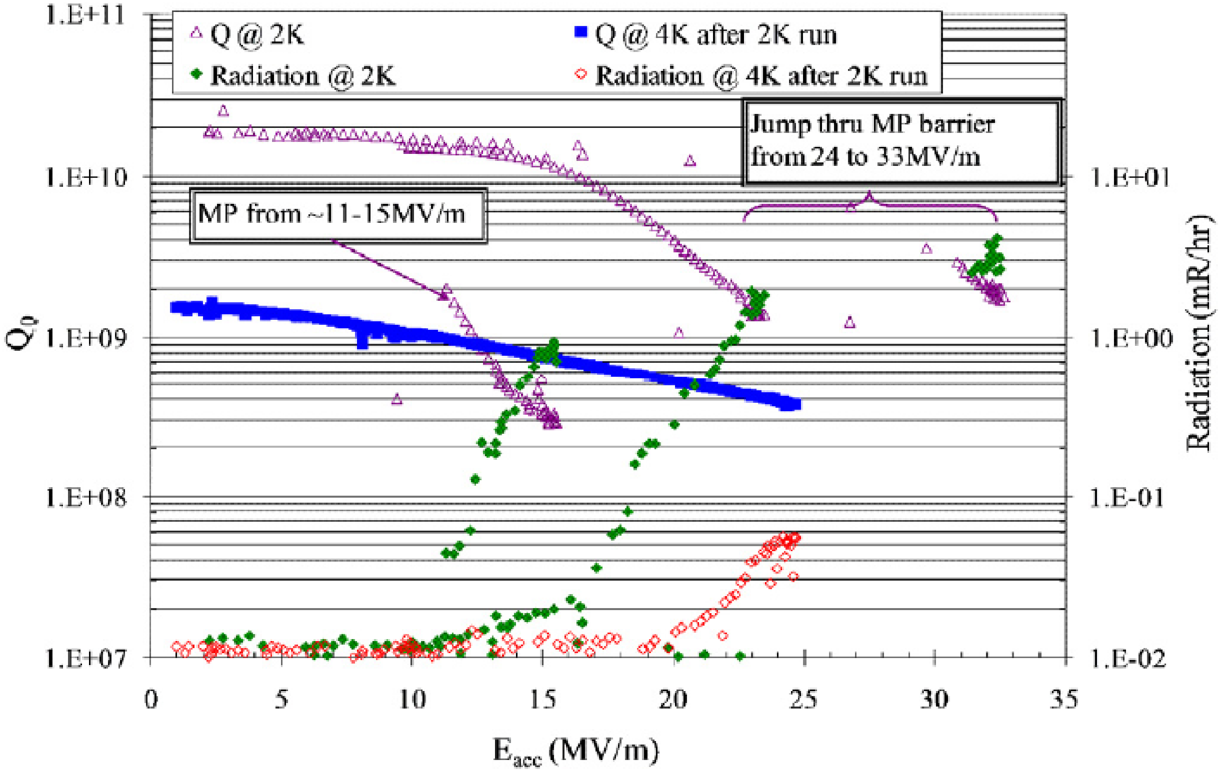


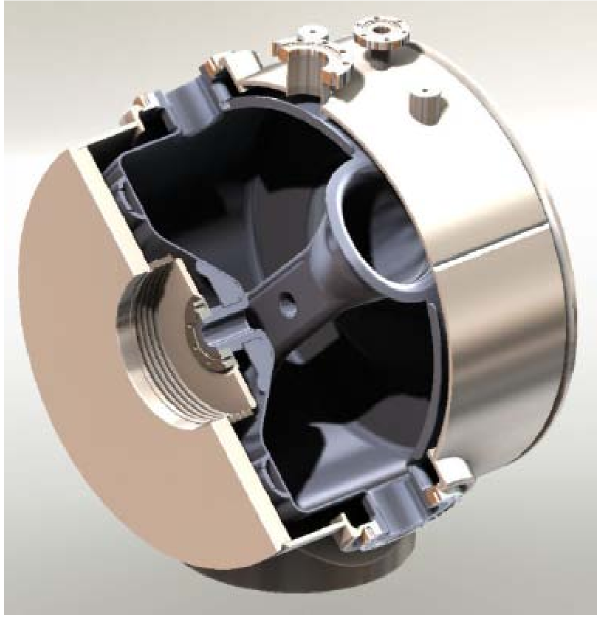




ANL

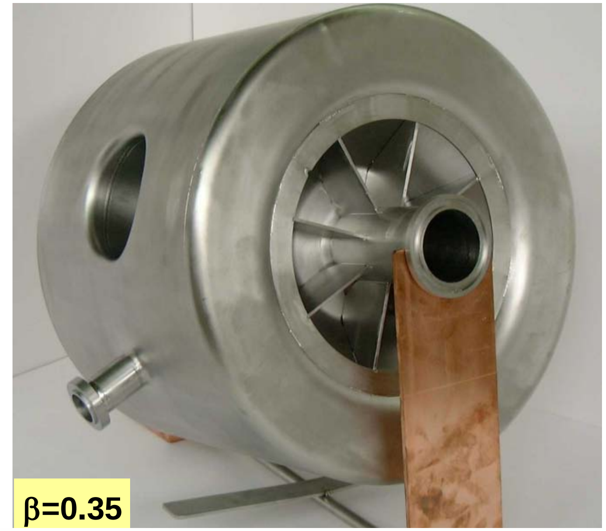
Fermilab Project X

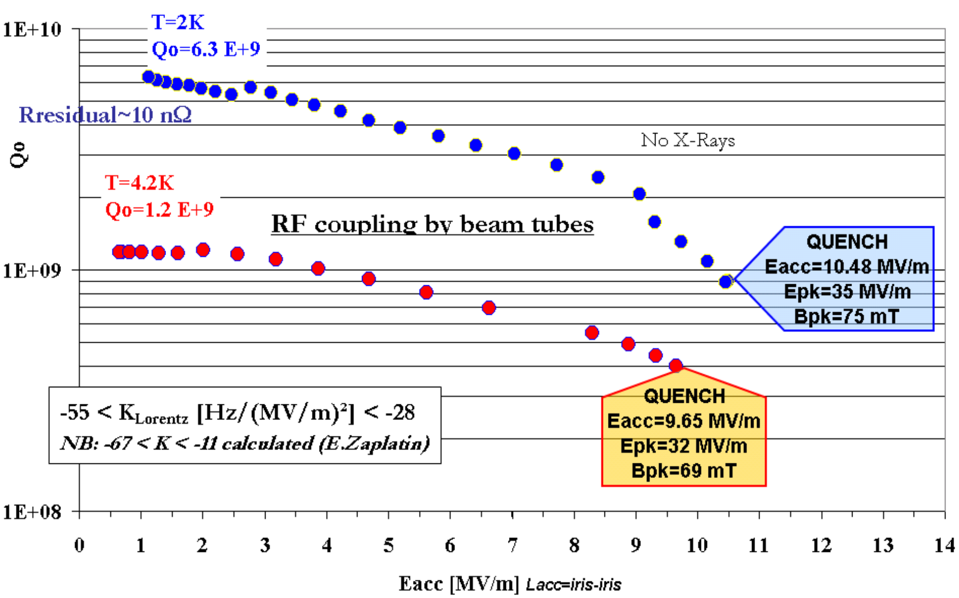


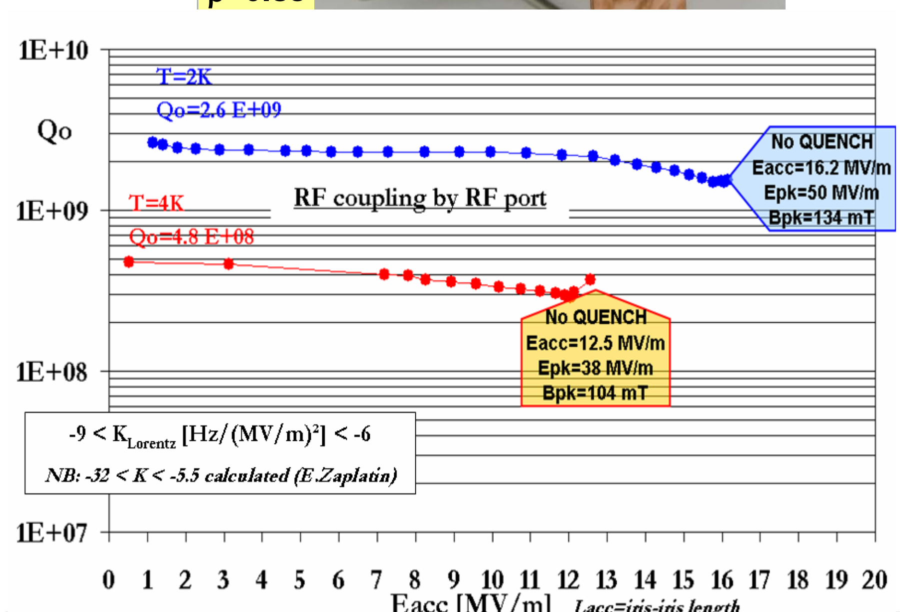


325 MHz, β=0.22

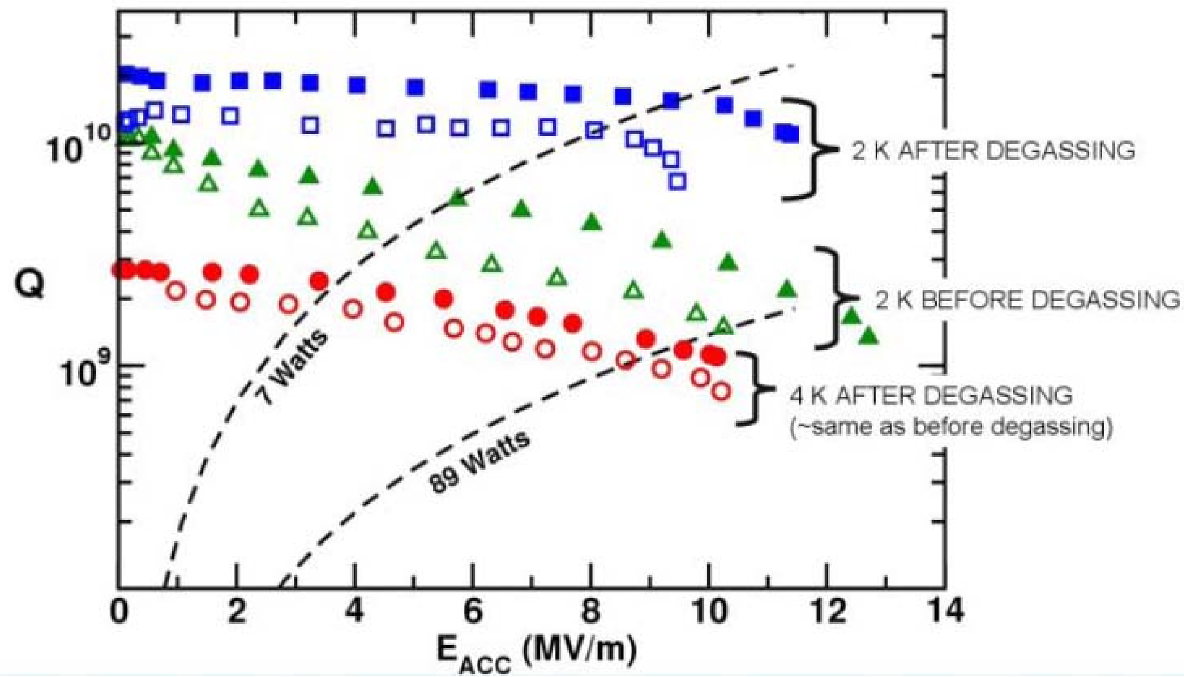
ORSAY - EURISOL



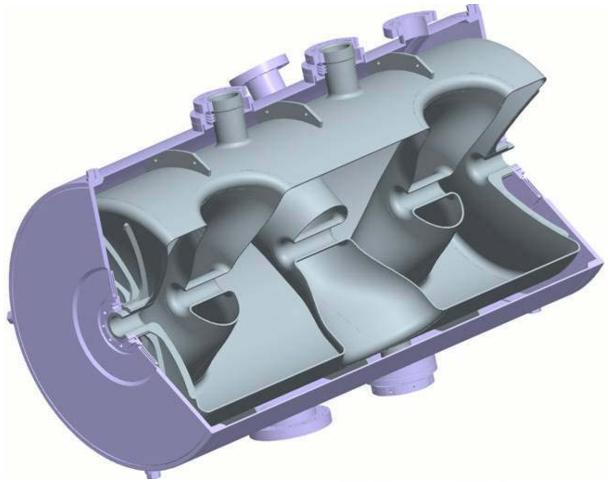


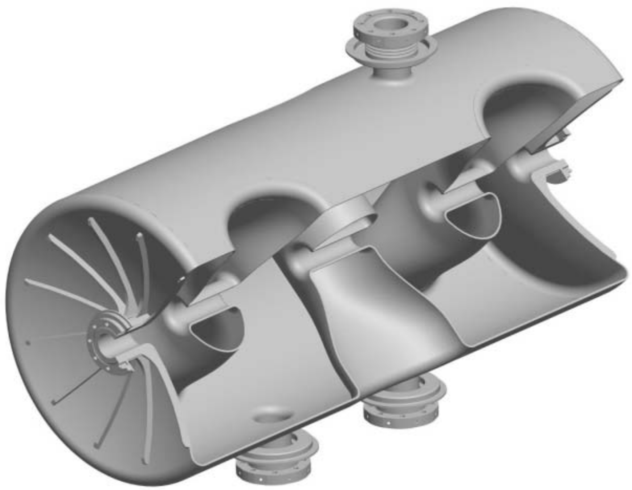


Argonne National Lab



Open symbols: 345 MHz, β=0.5)





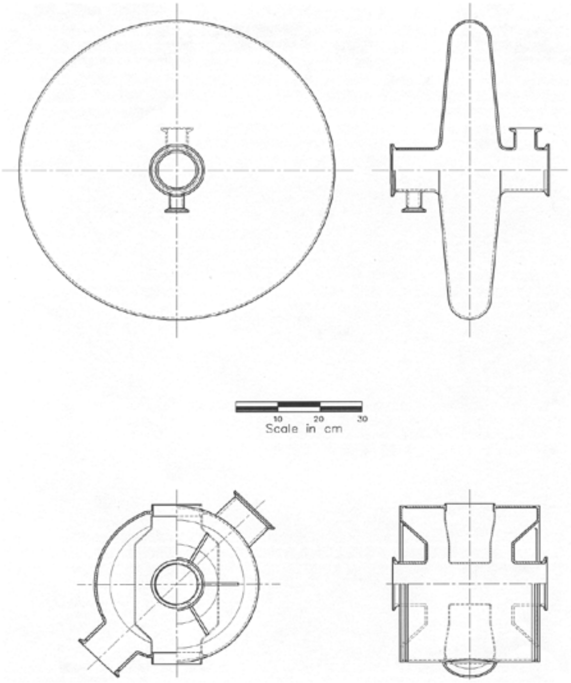
Closed symbols: 345 MHz, β=0.63

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

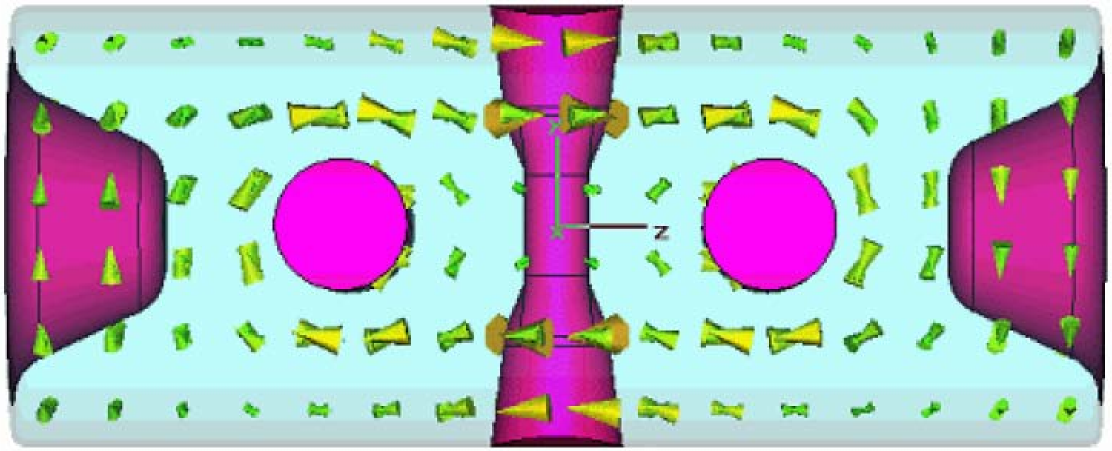
- Fewer number of cells
  - Wider velocity acceptance



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

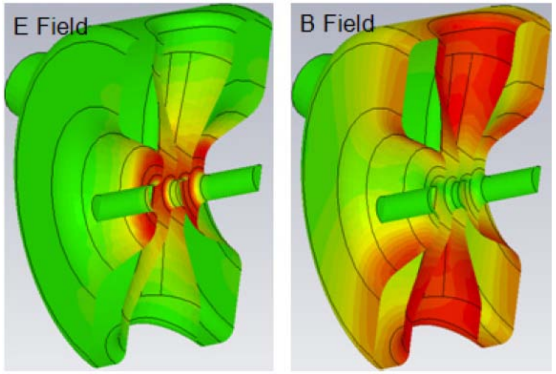
- **Accelerating mode has lowest frequency**
  - No lower-order mode
  - Easier HOM damping

	3-spoke		9-cell (TESLA)	
Mode #	Freq. (MHz)	$\Delta f/f$ % of f_{ACC}	Freq. (MHz)	$\Delta f/f$ % 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		

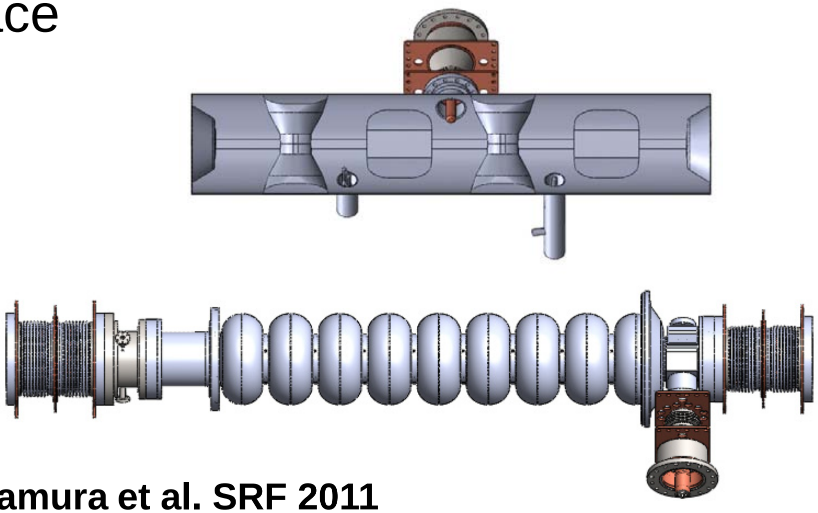
M. Kelly (ANL)

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



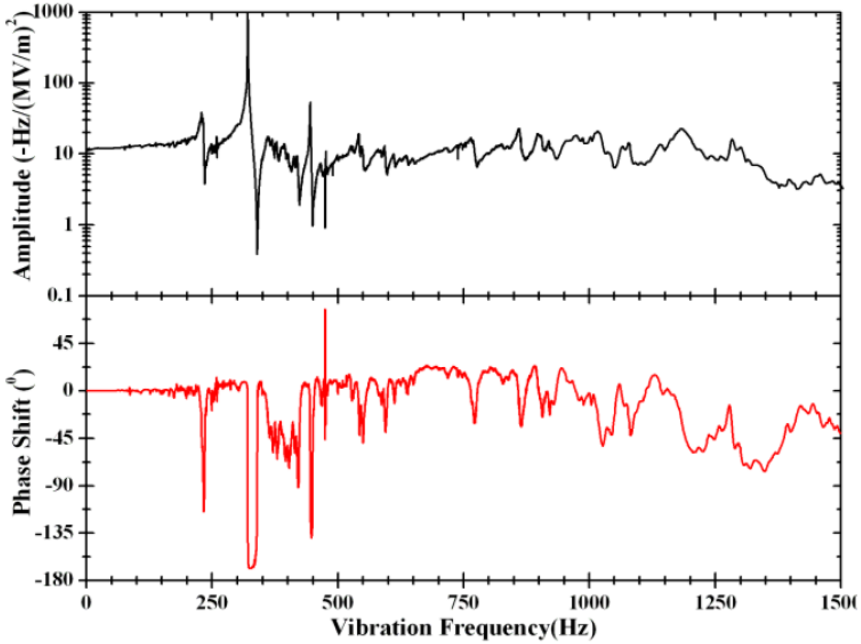
325 MHz, β=0.17 (FNAL)



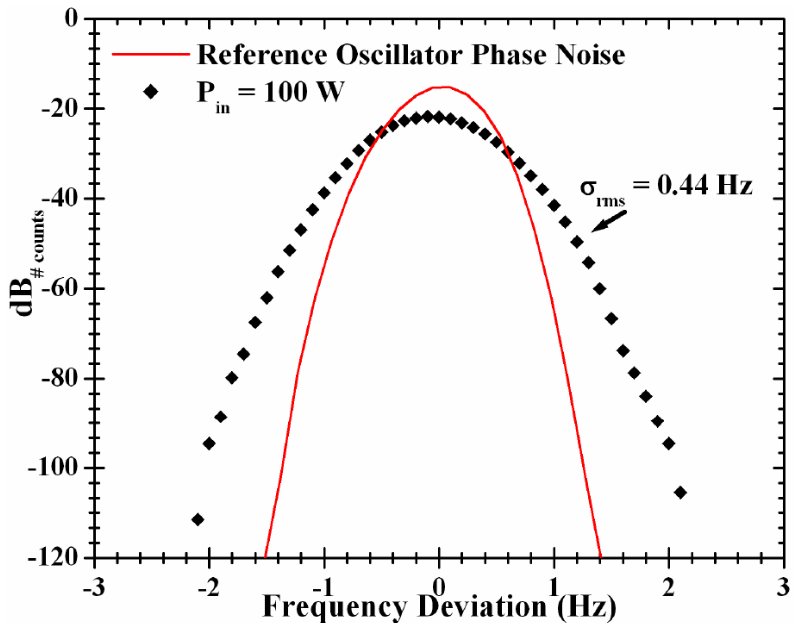
M. Sawamura et al. SRF 2011

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

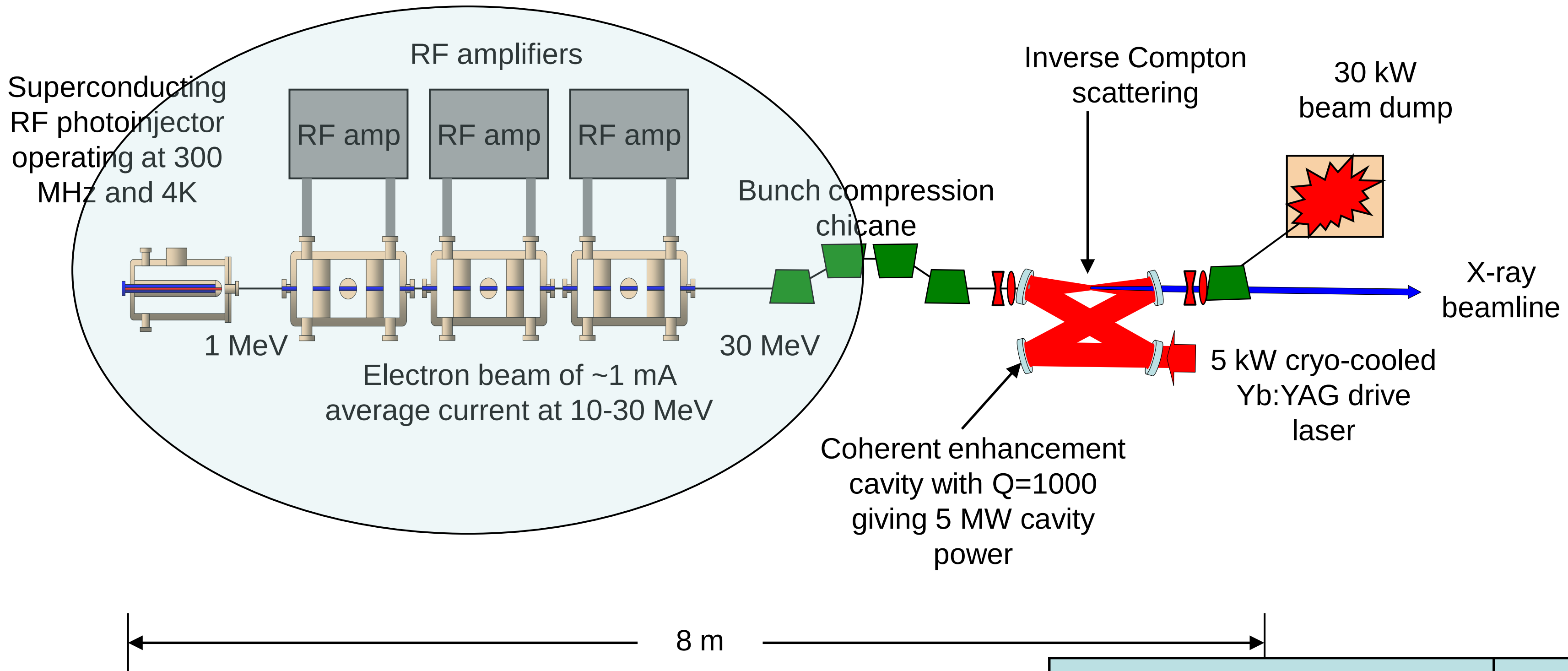
Compact Light Sources

- 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

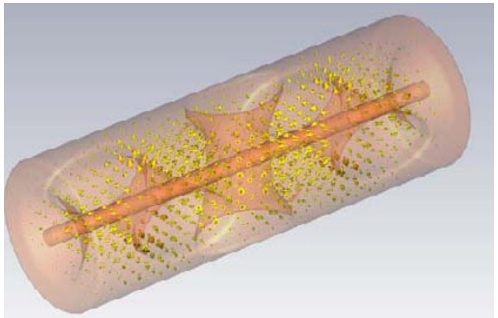
Compact Light Sources



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



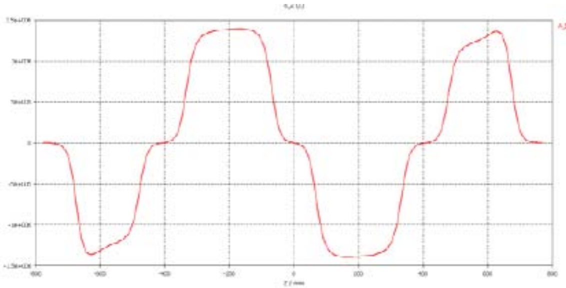
2.5 GeV Superconducting Single-Frequency Linac, pulsed current is 100 mA, f=325 MHz

- 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

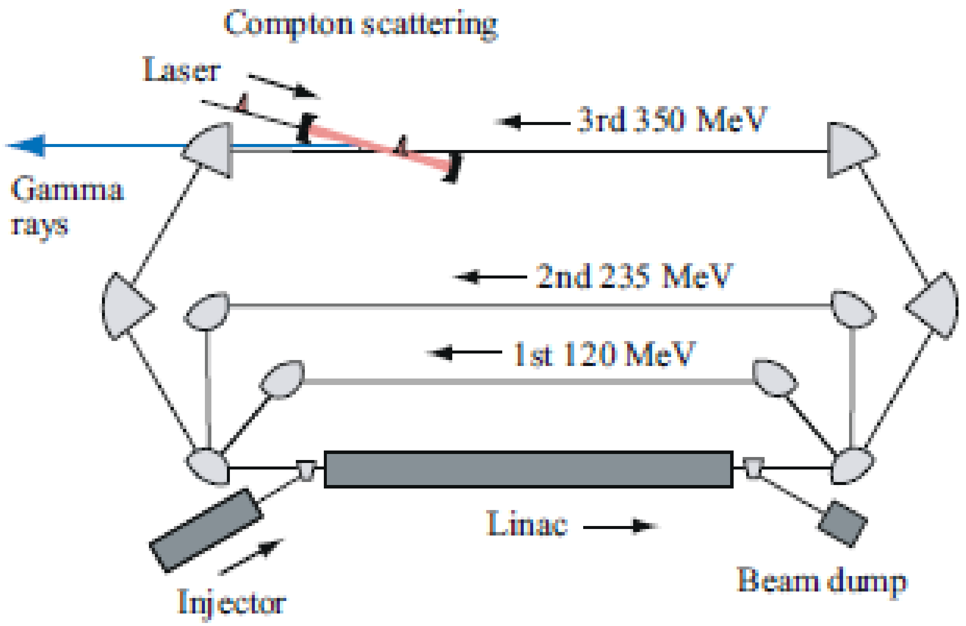


- Focusing with SC solenoids, eff. length = 20 cm, B=from 4T to 10.4T

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

Compact ERL (JAEA)

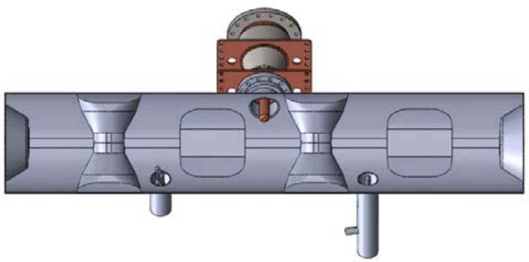
- ERL combined with laser Compton scattering for non-destructive assay system for nuclear materials in spent fuel

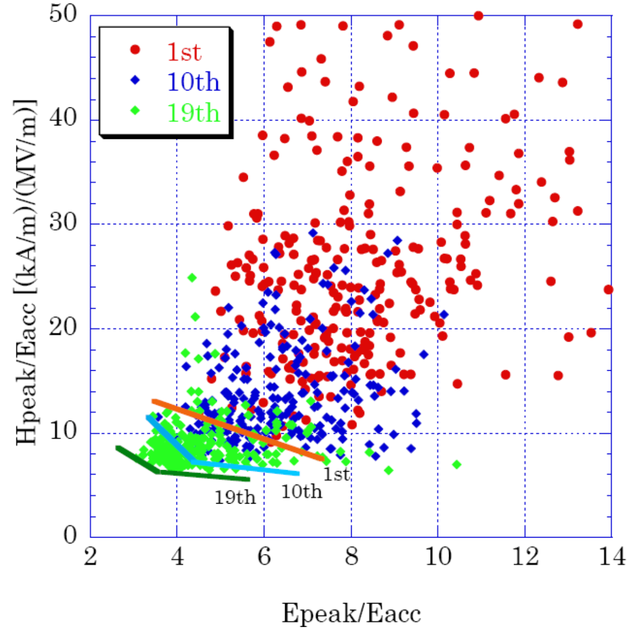


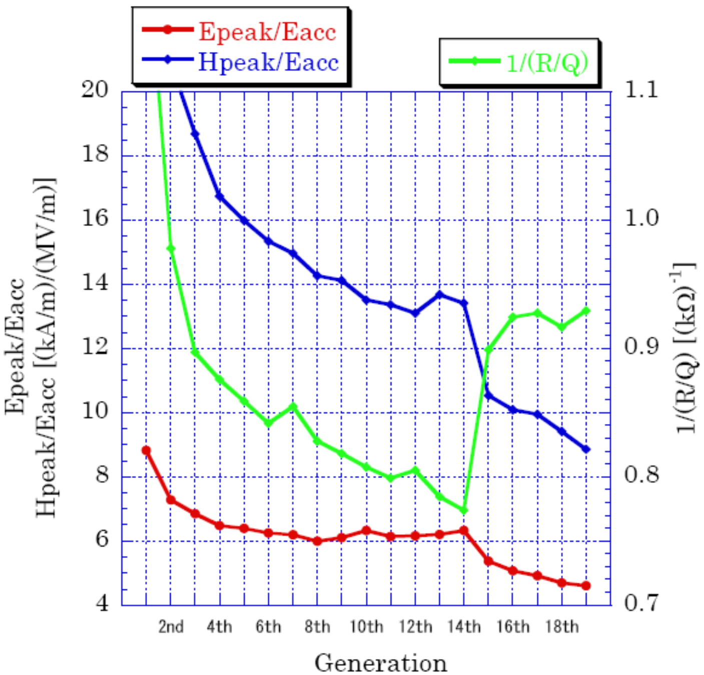
Nondestructive assay of plutonium and minor actinide in spent fuel using nuclear resonance fluorescence with laser Compton scattering γ−rays

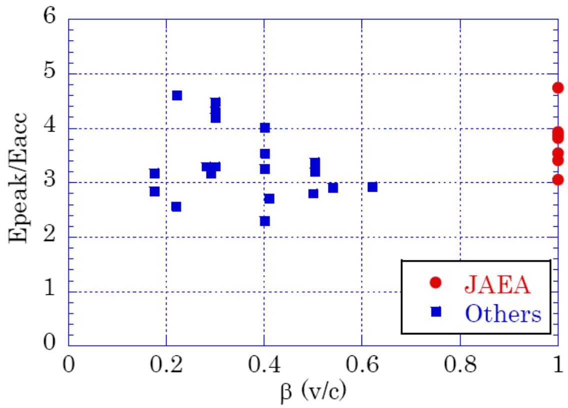
Takehito Hayakawa [a,*], Nobuhiro Kikuzawa [b,c], Ryoichi Hajima [c], Toshiyuki Shizuma [a], Nobuyuki Nishimori [c], Mamoru Fujiwara [a,d], Michio Seya [e]

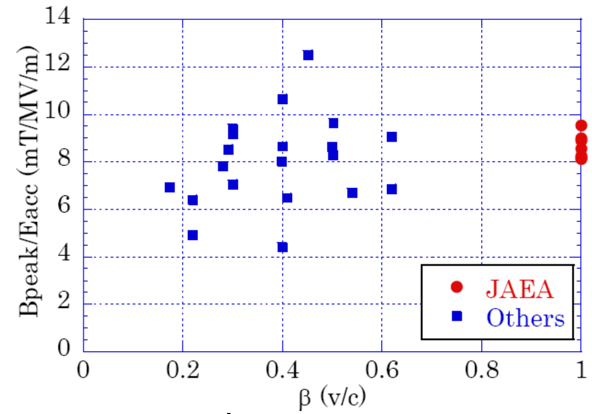
JAEA Tokai (650 MHz)





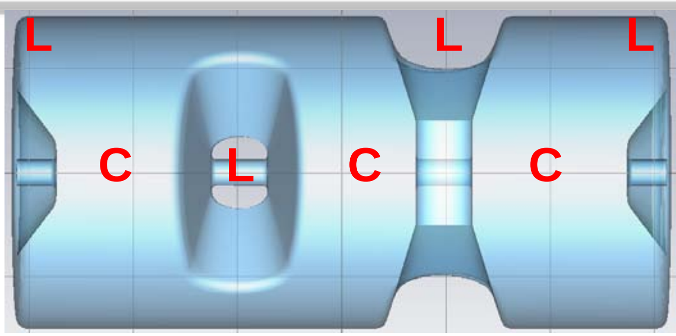




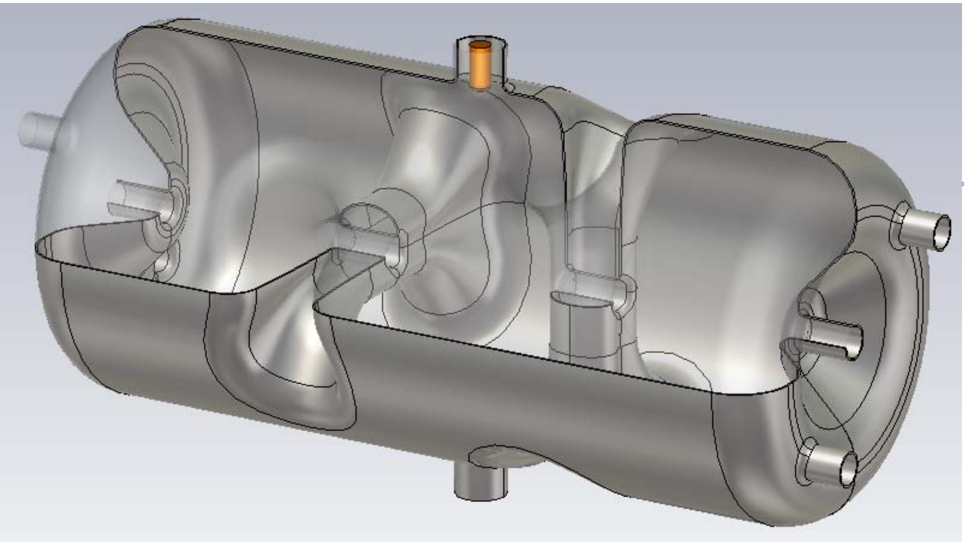


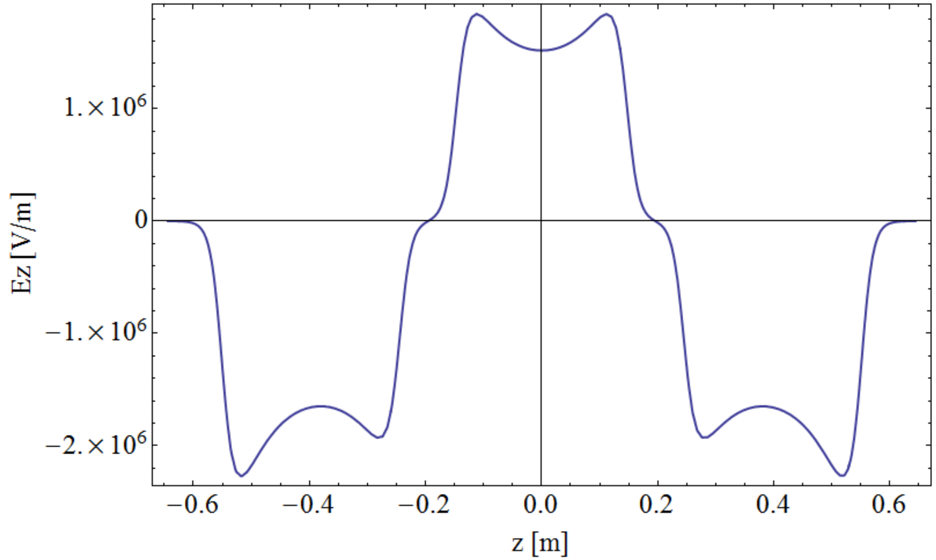
Masaru Sawamura et al.

Jlab: Double spoke cavity RF design



- Goal is to maximize G*R/Q:
  - C↓; L↑; 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)

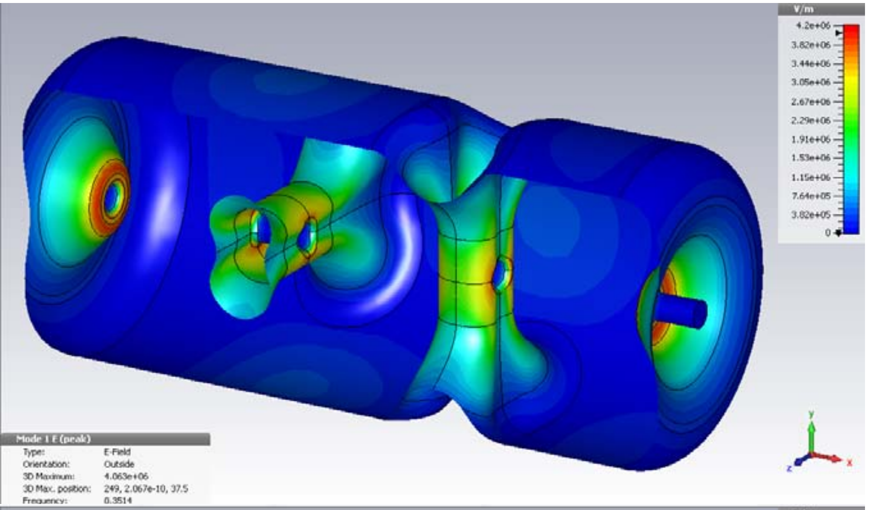


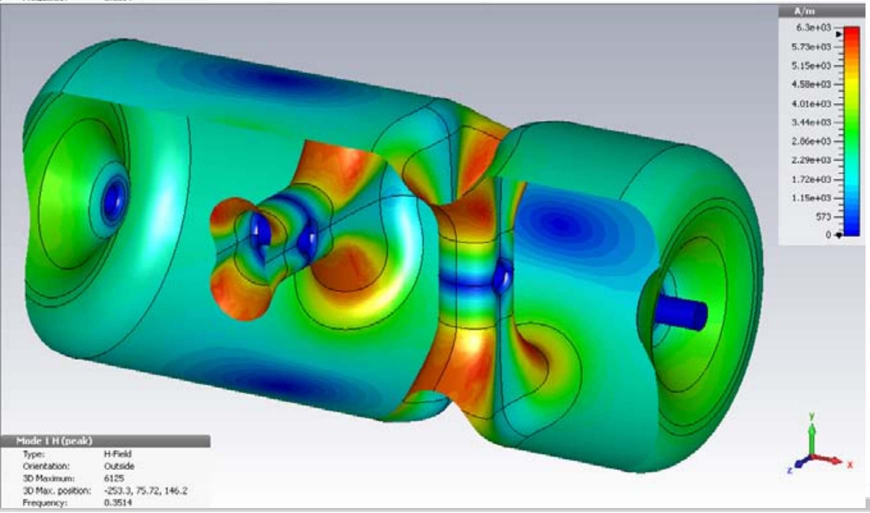


Feisi He, JLab

Jlab: Cavity RF design (2)

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





JLAB 352 MHz Cavity Design		Spoke	Elliptical
Frequency [MHz]		352	352
Aperture diameter[mm]		50	170
Lcavity (end-to-end) [mm]		1289 + 140	1277 + 300
Cavity inner diameter [mm]		578	730
Cavity weight (3mm wall) [kg]		111	99
Ep/Ea		4.3 ± 0.1	2.26 ± 0.1
Bp/Ea [mT/(MV/m)]		7.6 ± 0.2	3.42 ± 0.1
Geometry factor [Ω]		179	283
Ra/Q [Ω]		781	458
Ra*Rs (=G*Ra/Q) [Ω^2]		1.40 x 10^5	1.29 x 10^5
At Vacc = 8.5 MV and 4.5K. So Rbcs=48nΩ, and assume Rres=20nΩ	Ep [MV/m]	28.6 ± 0.9	15.0 ± 0.5
	Bp [mT]	50.3 ± 1.5	22.8 ± 0.7
	Max heat flux [mW/cm^2]	4.6	1.4
	Q_0	2.6 x 10^9	4.2 x 10^9
	Power loss [W]	35	42.6
	Leff=1.5*β_0*λ [m]	1.2768	1.2768

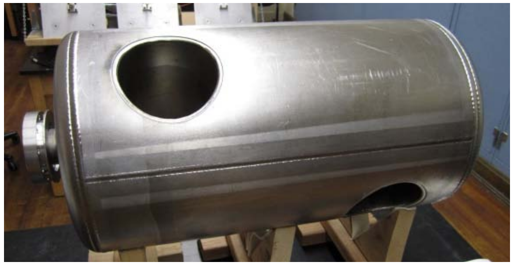
Old Dominion University

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

Designs by:
Chris Hopper
Suba De Silva
Rocio Olave

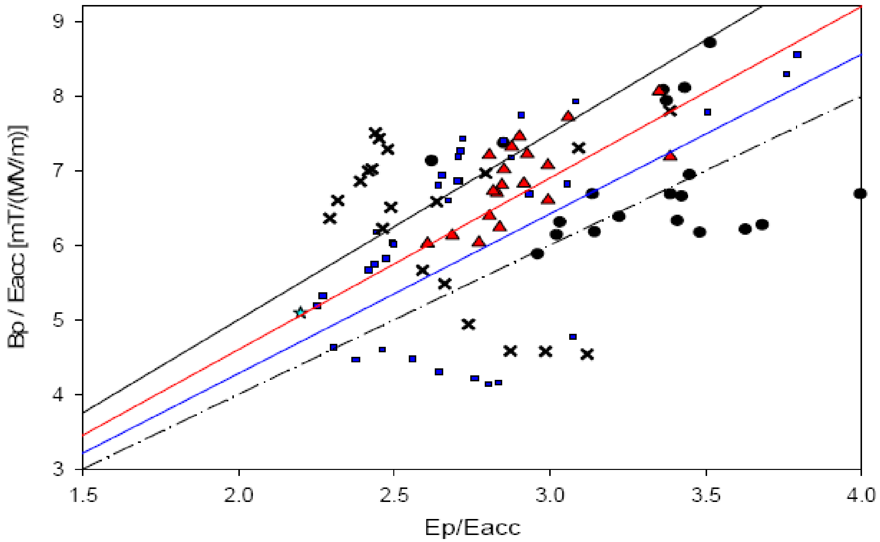
- 352 MHz, β= 0.82 and 1, single and double
  - Collaboration with JLab

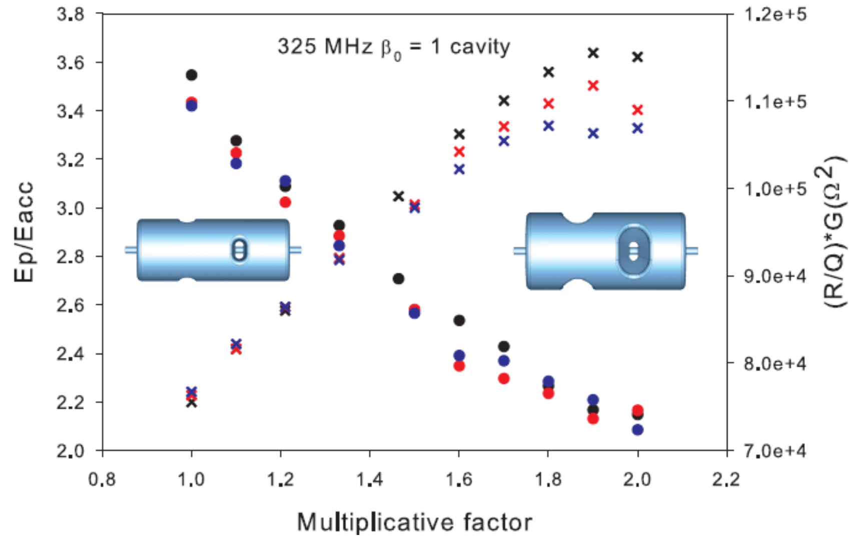
- 500 MHz, β= 1, double
  - Collaboration with Niowave
  - Collaboration with JLab

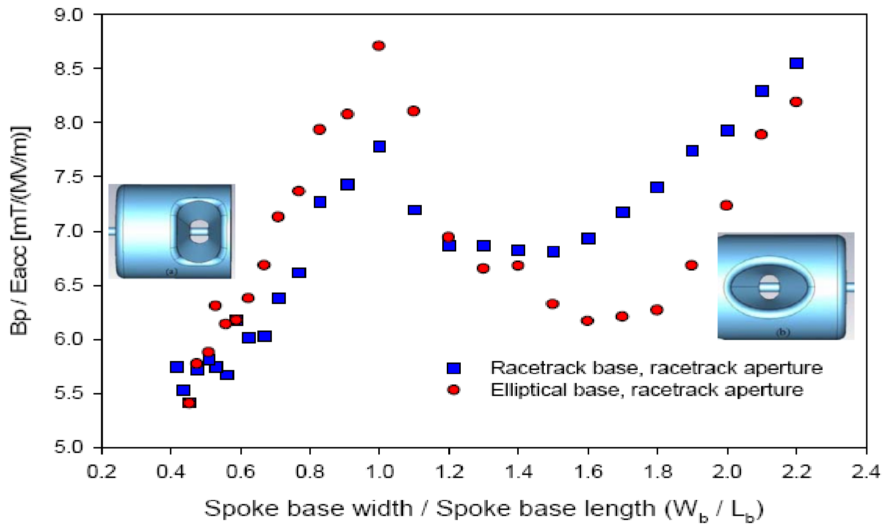


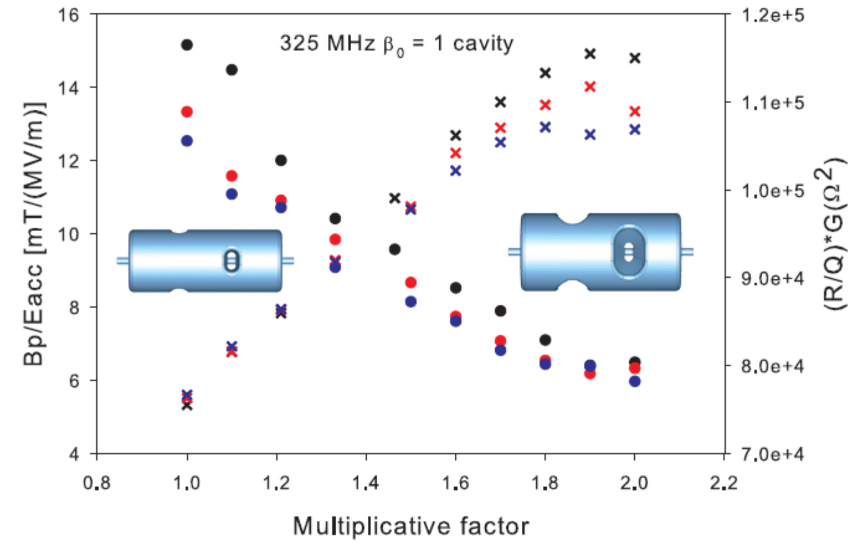
- 700 MHz, β= 1, single, double, and triple
  - Collaboration with Niowave, Los Alamos and NPS

Design Optimization (a small sample)

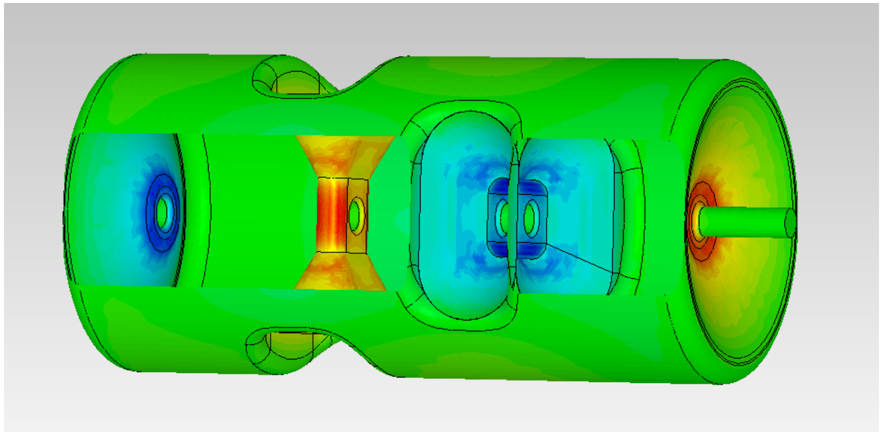




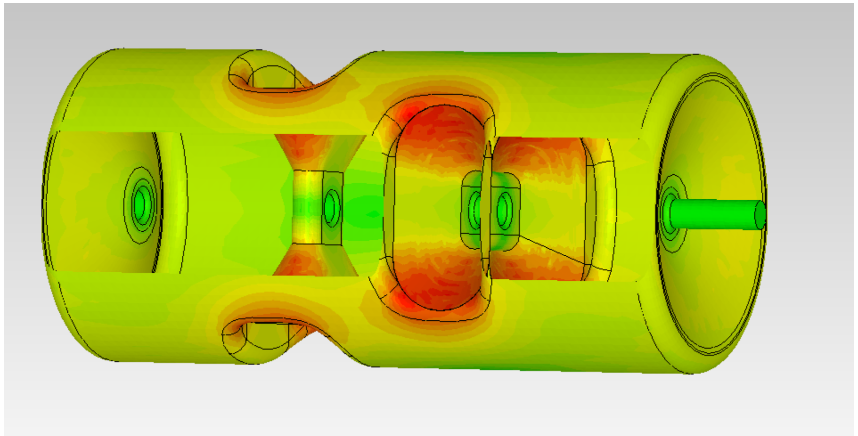




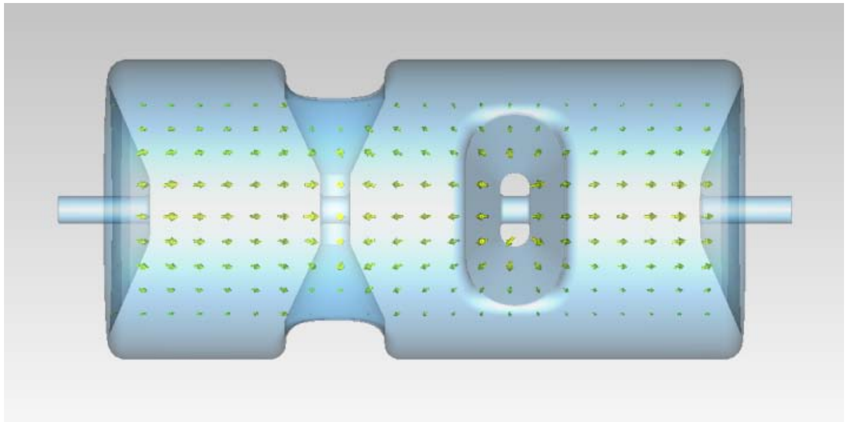
Double Spoke



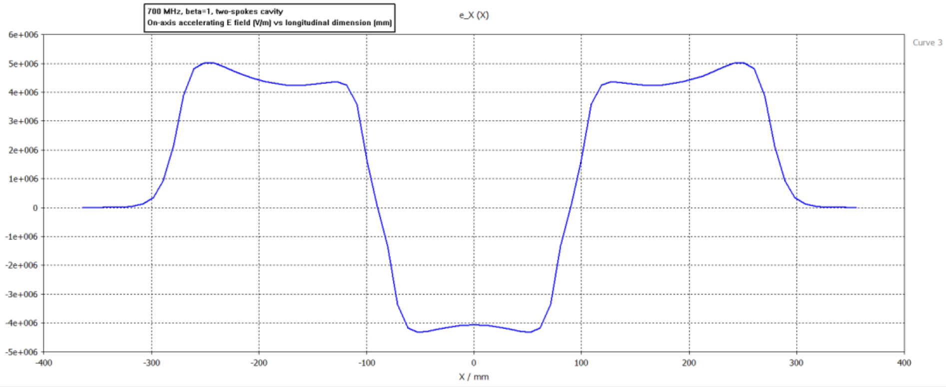
Surface Electric Field



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

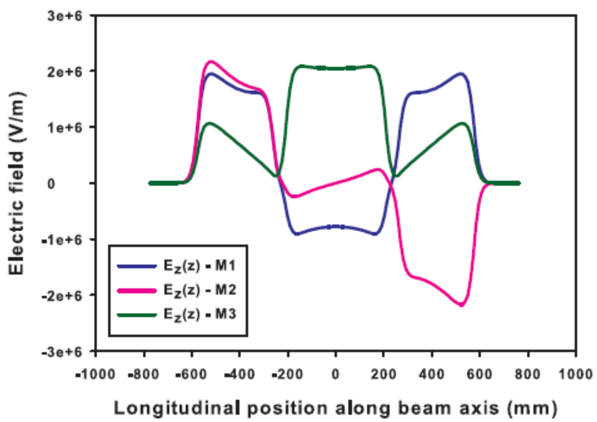
Cavity properties

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

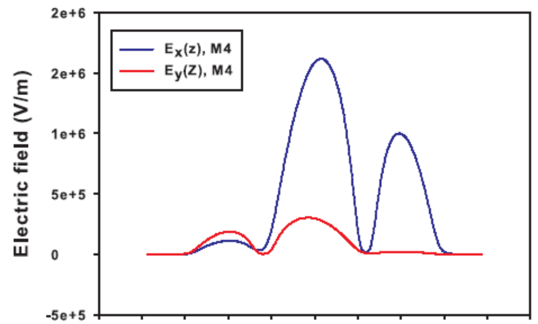
At Eacc = 1 MV/m and reference length $\beta_0\lambda$
***Rs = 68 nΩ**
****Rs = 73 nΩ**

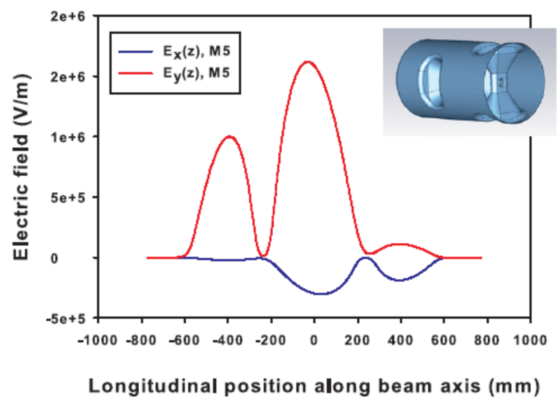
Mode types in two-spoke cavities

Accelerating modes

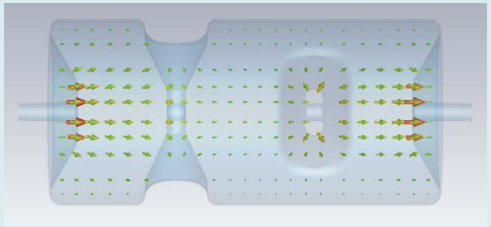


Deflecting (degenerate) modes

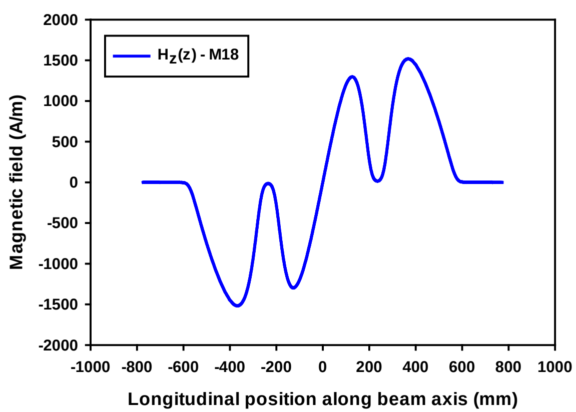




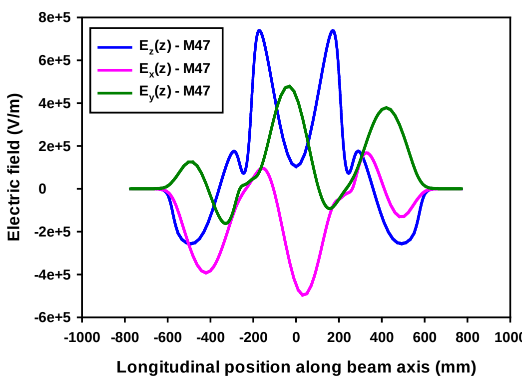
Examples of modes for the 325 MHz cavity, β=1



TE-type modes



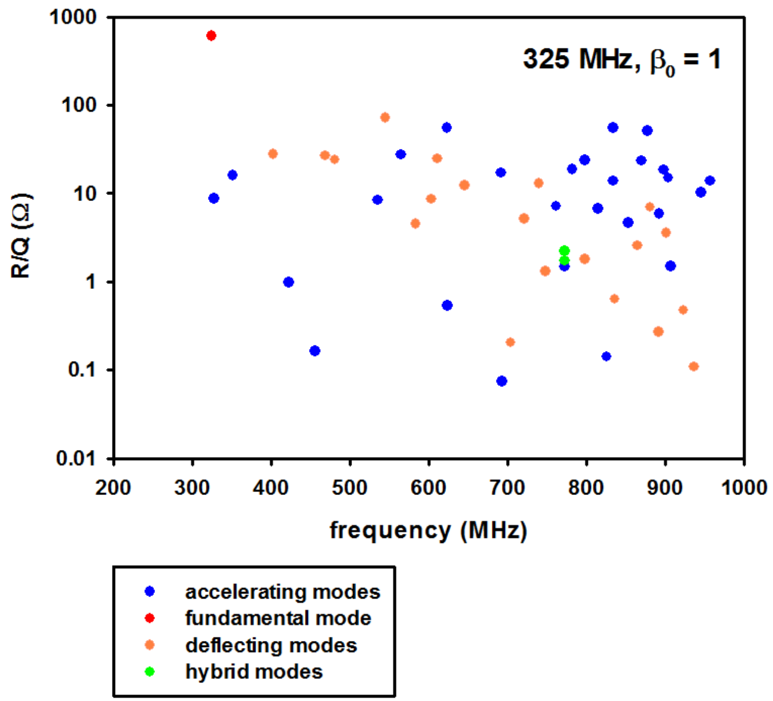
Hybrid modes

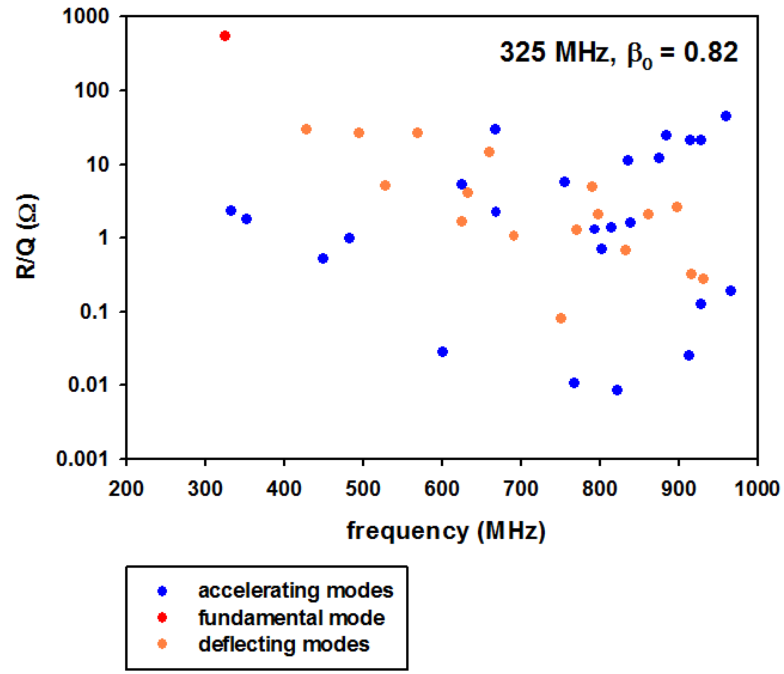


C. Hopper, R. Olave, ODU

R/Q values of HOMs

(*R/Q*) values for particles at design velocities
β_0=1 and β_0=0.82 for the 325 MHz two-spoke cavity



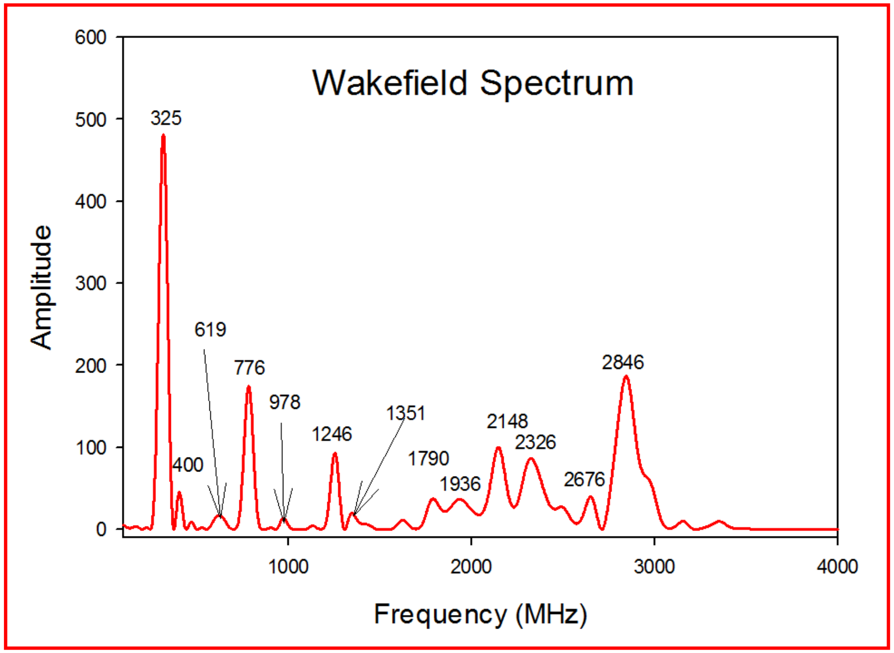


C. Hopper, R. Olave, ODU

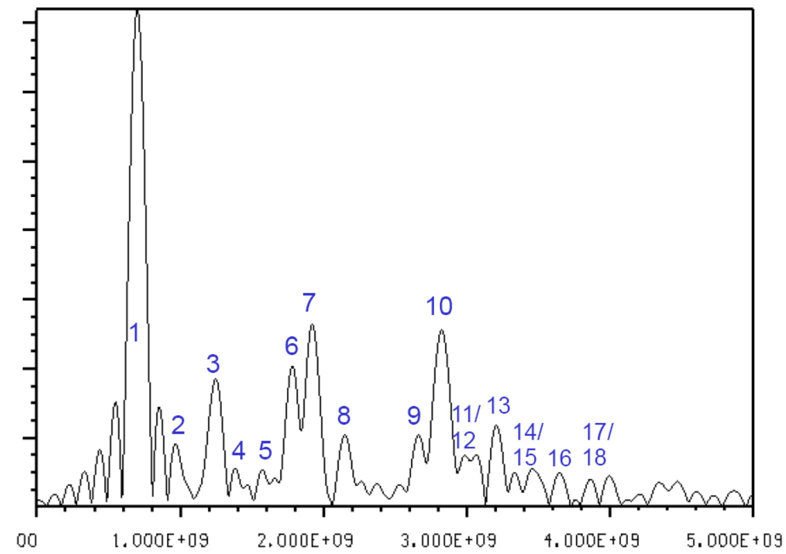
All HOMs have (*R/Q*)s significantly smaller values than the fundamental mode

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

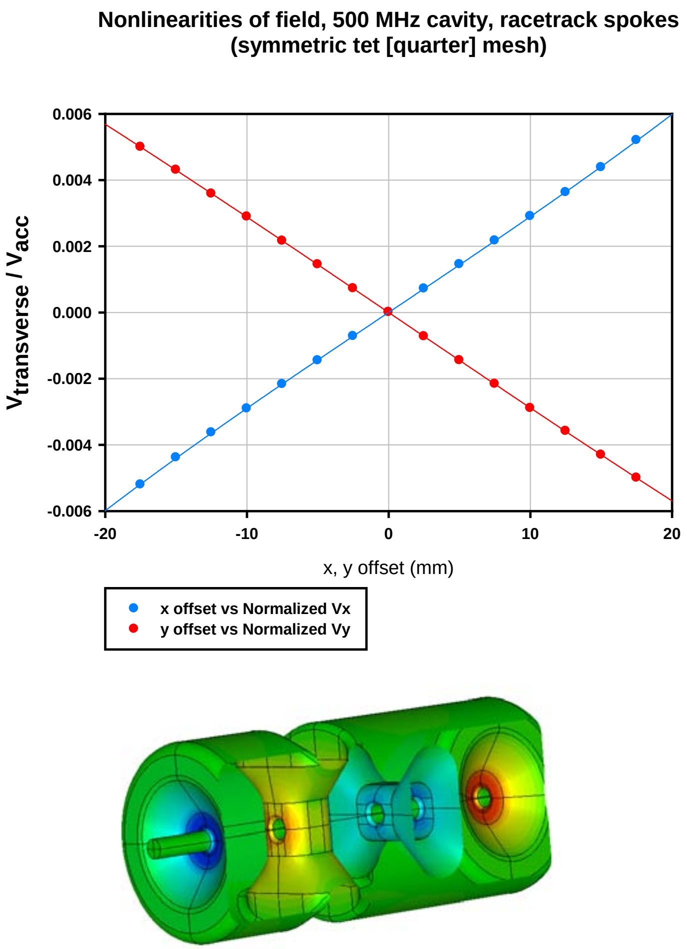


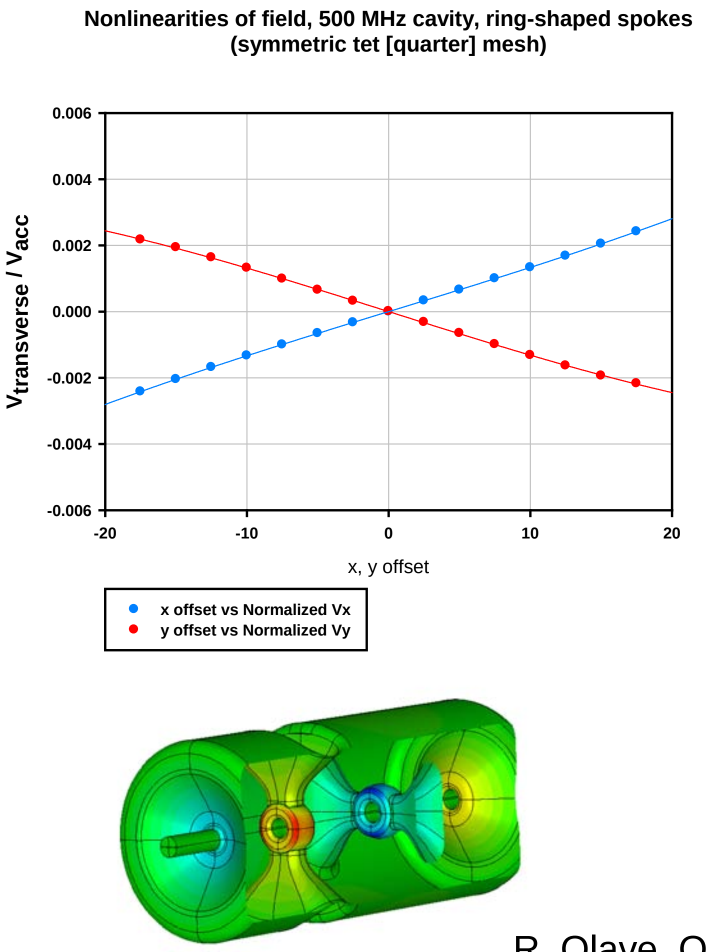
C. Hopper, ODU
ACE3P

F. Krawczyk, LANL
MAFIA

Multipoles

500 MHz, β = 1



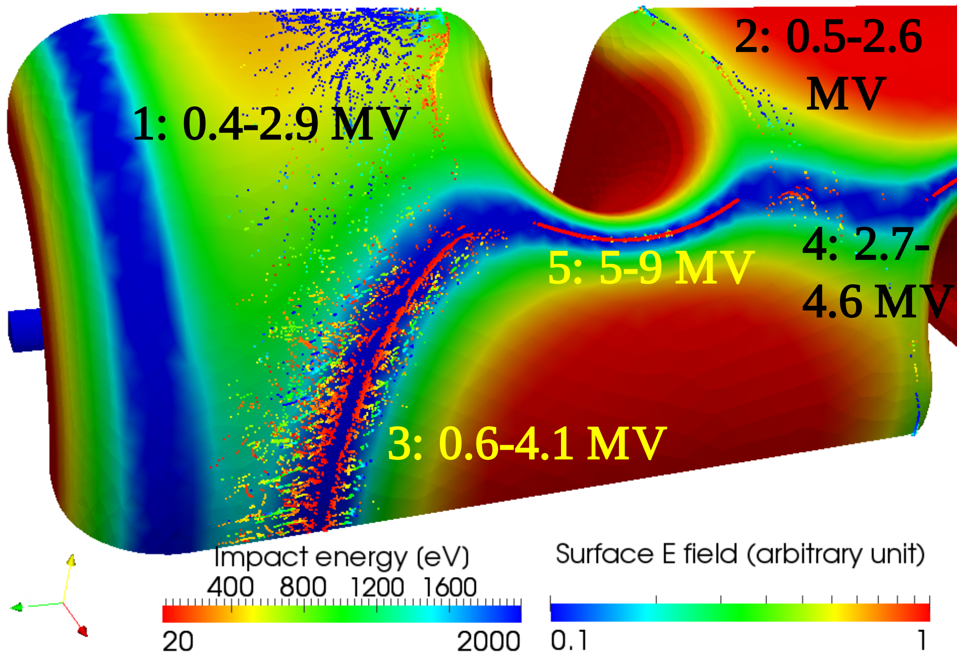


R. Olave, ODU

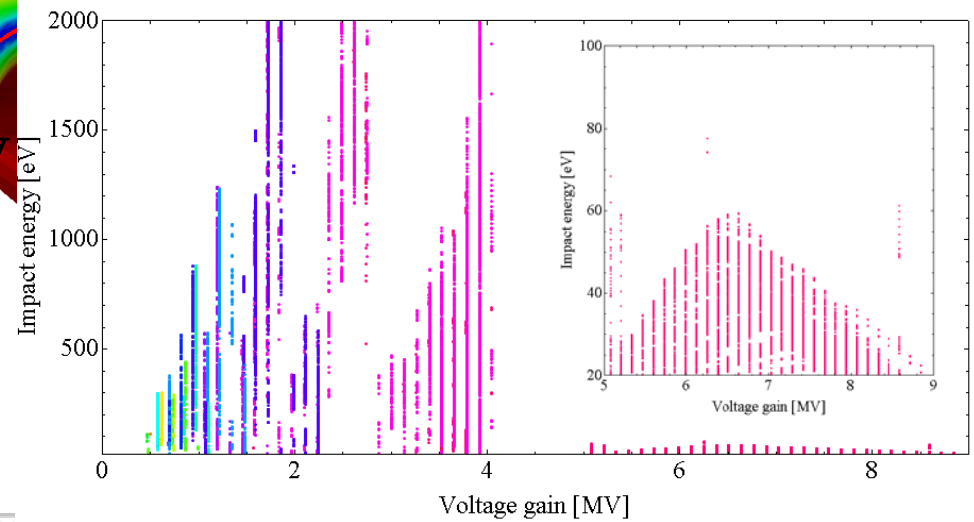
Prediction of multipacting (MP) level

- 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

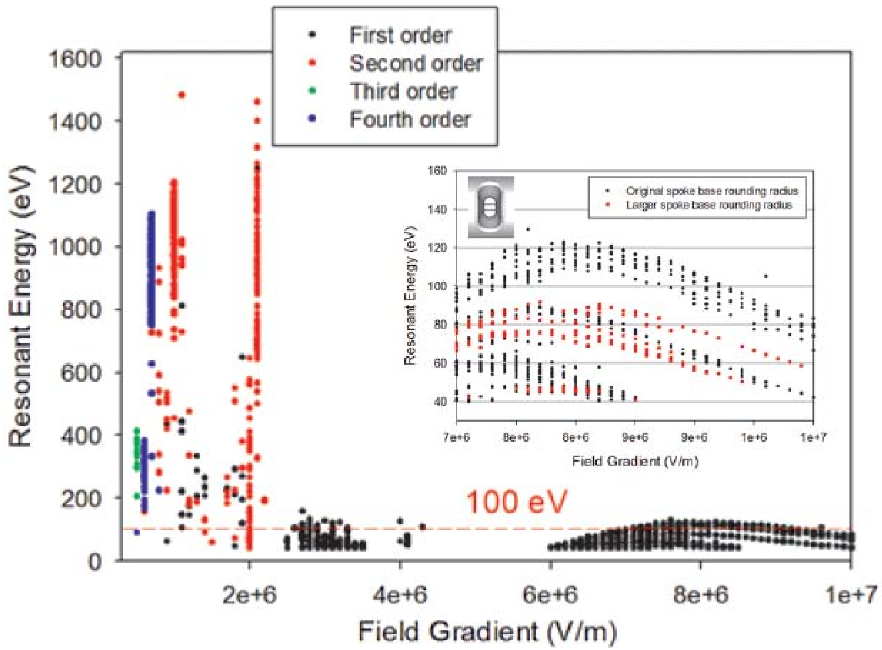
352 MHz, β=1
Feisi He, JLab

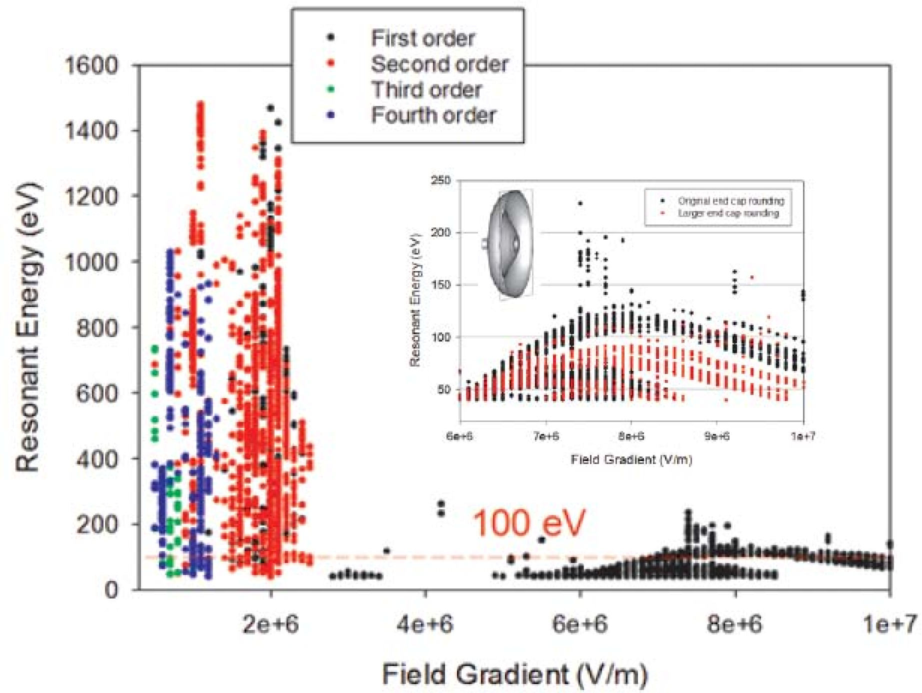


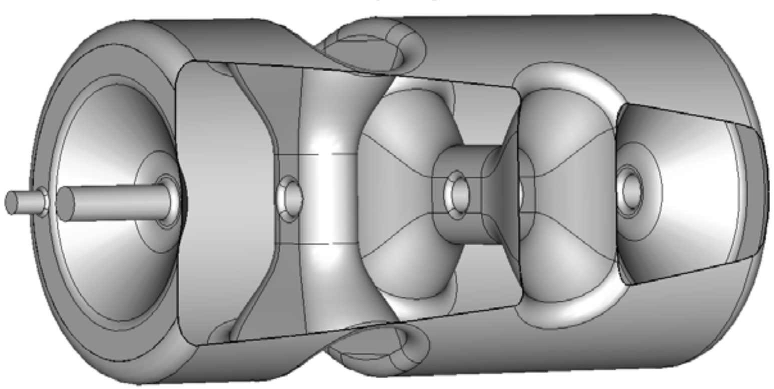
Surviving MP after 40 RF periods



Multipacting

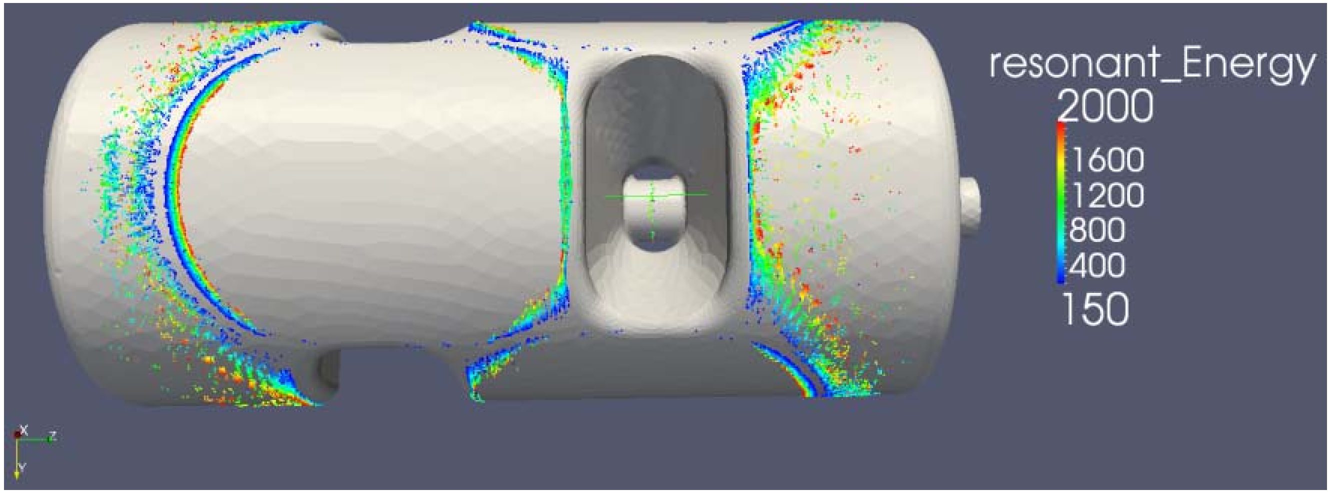




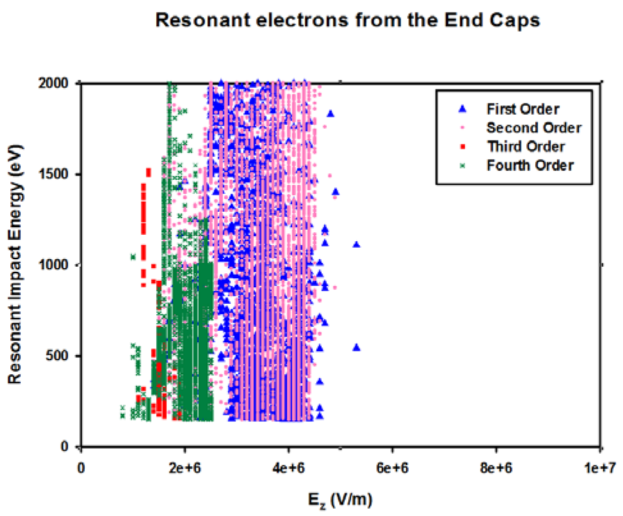


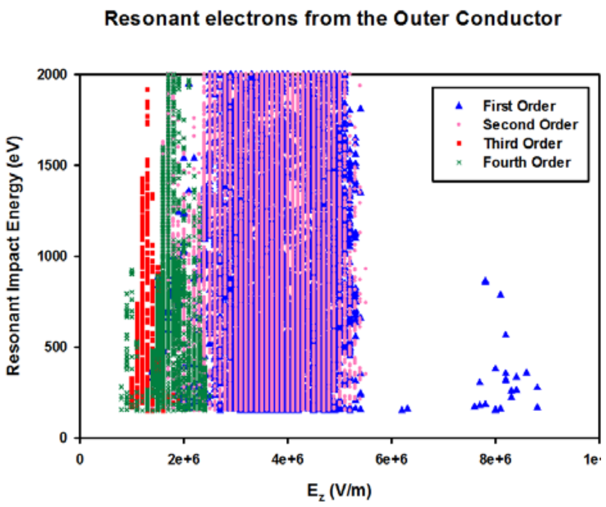
325 MHz, β=0.82
ACE3P
C. Hopper, ODU

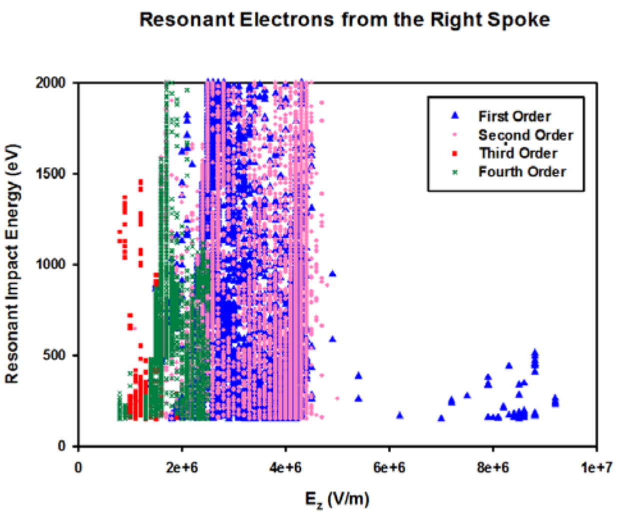
Multipacting



700 MHz, β=1
ACE3P
R. Olave, ODU

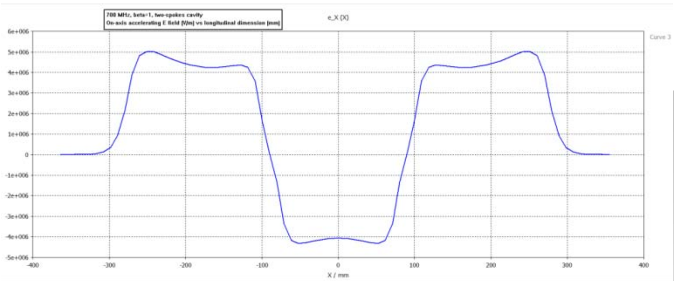


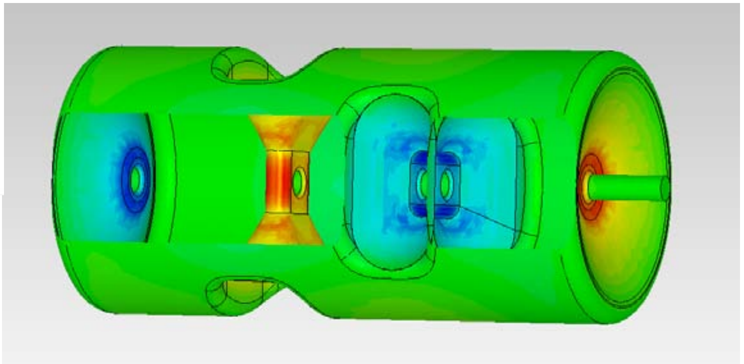


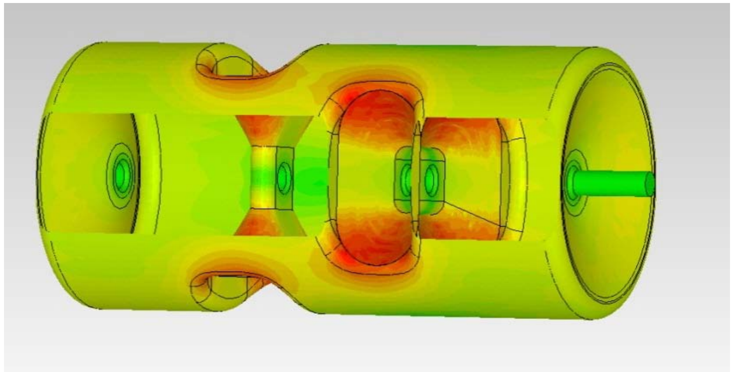


700 MHz, β=1, double-spoke

Collaboration between Niowave, ODU, Los Alamos, NPS
Designed By ODU
Fabricated by Niowave







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 may be the first ones to accelerate beam
  - The first particle to be accelerated by a spoke cavity will probably be an electron

Acknowledgements

- ODU
  - Subashini de Silva
  - Christopher Hopper
  - Rocio Olave
- Jefferson Lab
  - Feisi He
- JAEA, Tokai
  - Masaru Sawumara
- Los Alamos
  - Frank Krawczyk
- Niowave
  - Chase Boulware
  - Dmitry Gorelov
  - Terry Grimm