Multi Harmonic Accelerating Cavities for RF Breakdown Studies*

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Outline

I. Harmonic mode superposition for breakdown suppression

– TM_{010} + TM_{020} ("anode-cathode effect" – field emission suppression)
– TM_{010} + TM_{011} or TM_{010} + TM_{012} (pulsed heating suppression)

II. Plan of RF Breakdown Experiments

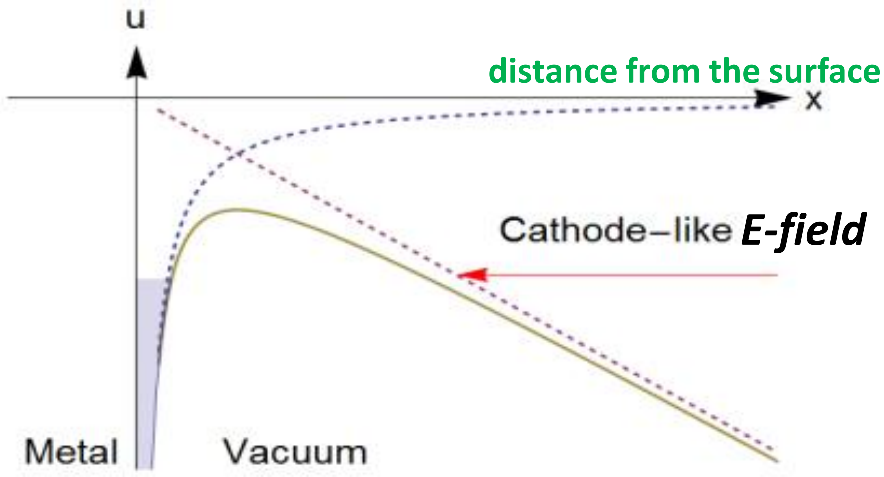
– Two frequency RF Source
– Clamped Test Structures

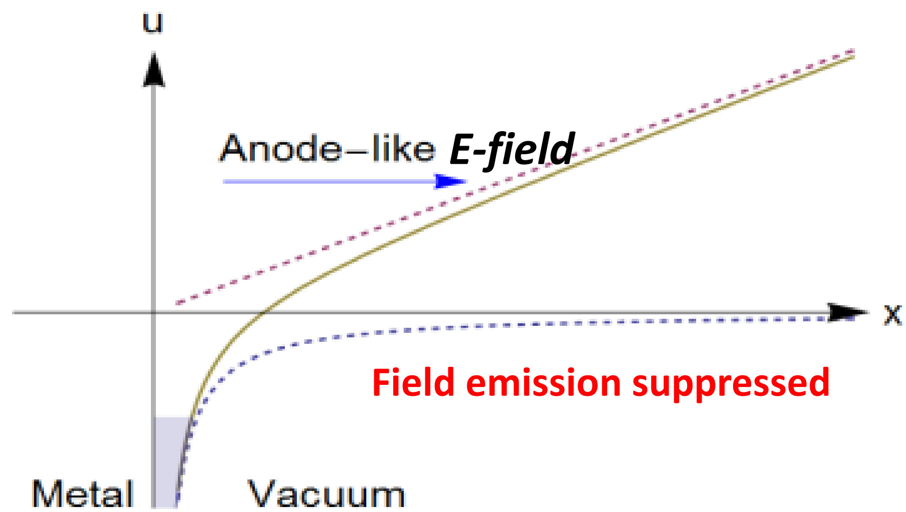
III. Possible application for future accelerators

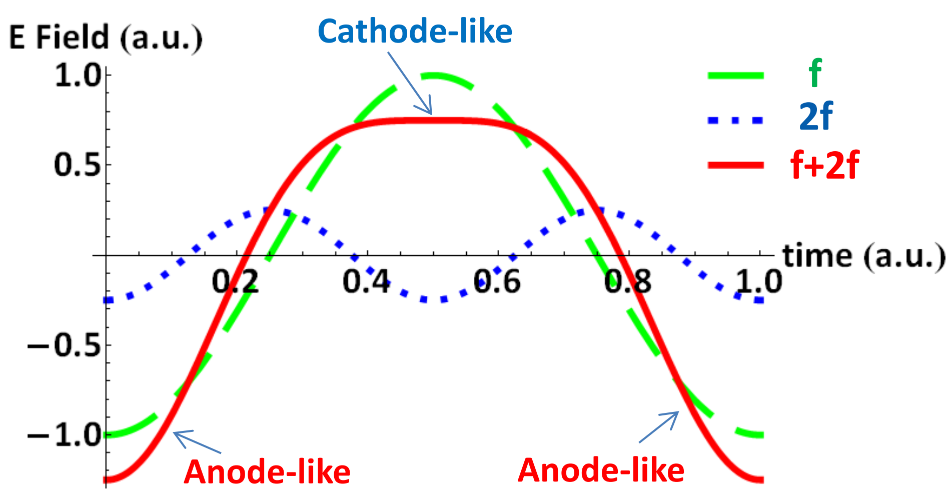
– Externally driven from phase-synchronous RF sources
– Beam driven (detuned cavities in a co-linear TBA configuration)

Motivation I: Field Emission

potential energy of an electron near metal surface







Anode – Cathode Effect

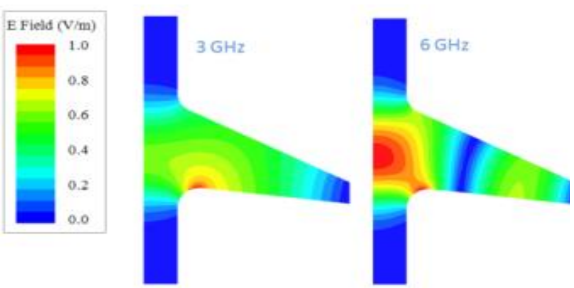
two harmonics-mode superposition to suppress field emission

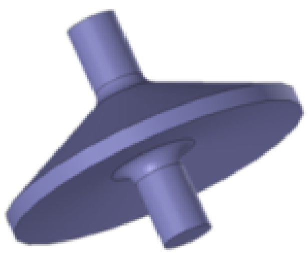
Multi-Harmonic Cavity: Anode-Cathode effect

$TM_{010} + TM_{020}$ (f + 2f) MHC:

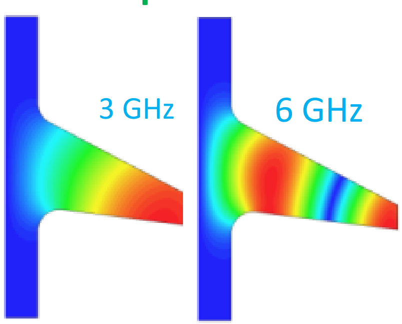
- Superposition of TM_{010} and 2nd -harmonic TM_{020}
- Longitudinal non-symmetric
- Peak accelerating field ≥ breakdown threshold

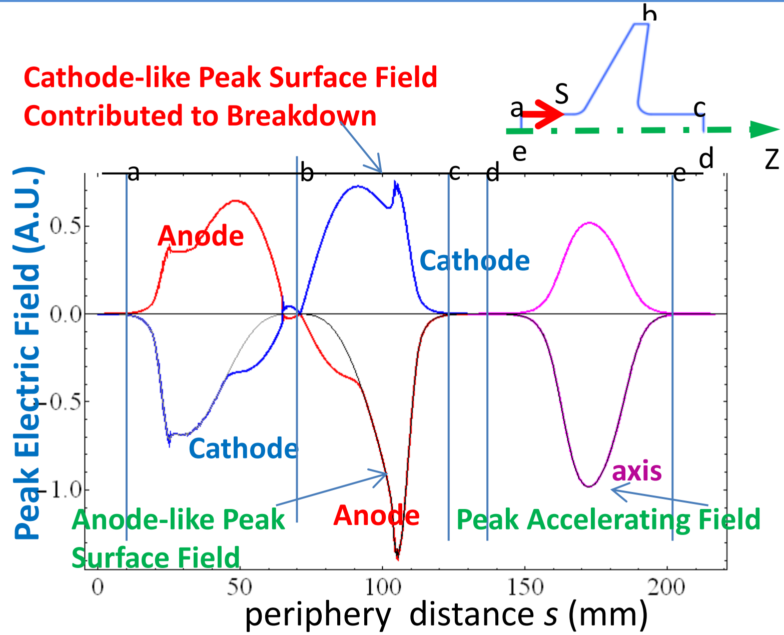
Electric field pattern

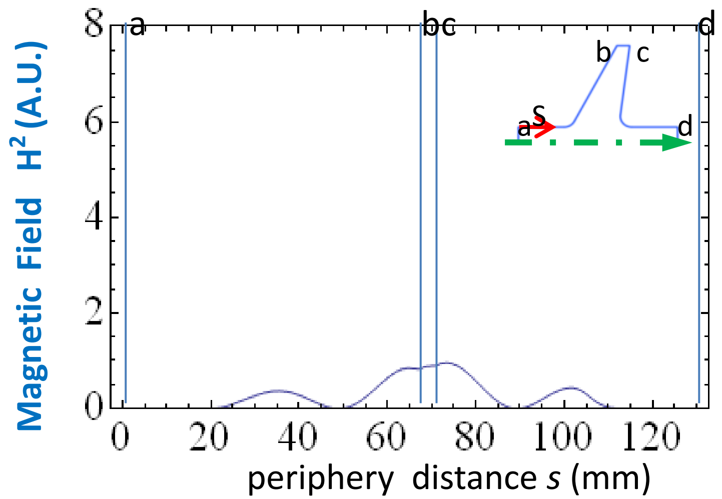




Magnetic field pattern







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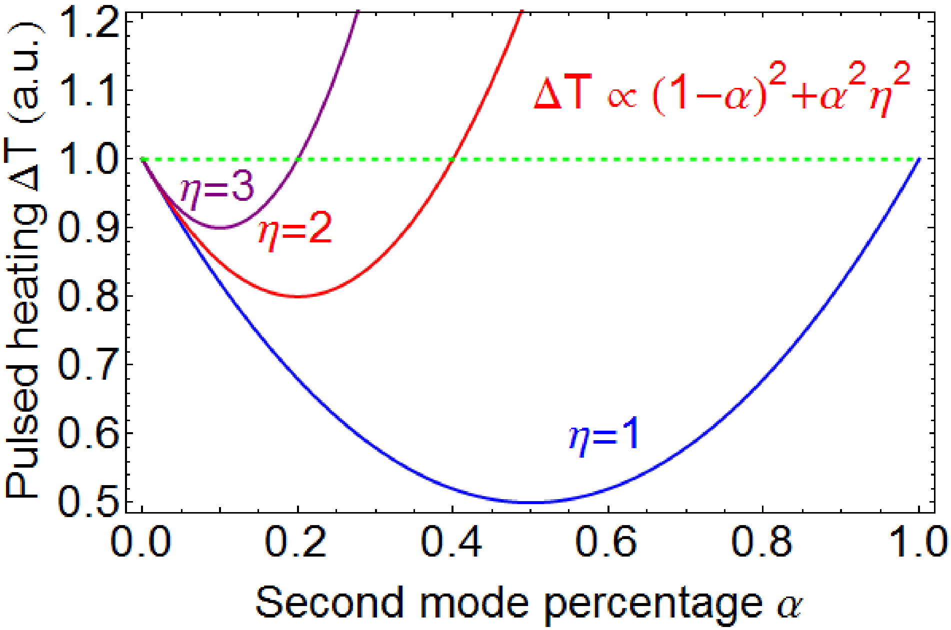
Motivation II: Surface Pulsed Heating



$$E_{total} = (1-\alpha)E_1 + \alpha E_2$$

$$H_{total} = (1-\alpha)H_1 + \alpha H_2$$

E_1 , E_2 normalized to the same acceleration gradient

α is the percentage of the 2nd mode

$$\Delta T \propto (1-\alpha)^2 < H_1^2 > +\alpha^2\sqrt{f_2/f_1} < H_2^2 >$$

$$= < H_1^2 > [(1-\alpha)^2 + \alpha^2\eta^2]$$

where $\eta = \sqrt{(f_2/f_1)^{1/2} < H_2^2 > / < H_1^2 >}$

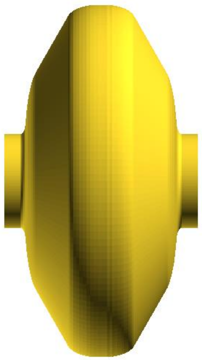
Quadratic dependence: $\exists\alpha \quad (1-\alpha)^2 + \alpha^2\eta^2 < 1$

So are modified Poynting vector S_c and total required RF power P_{total}

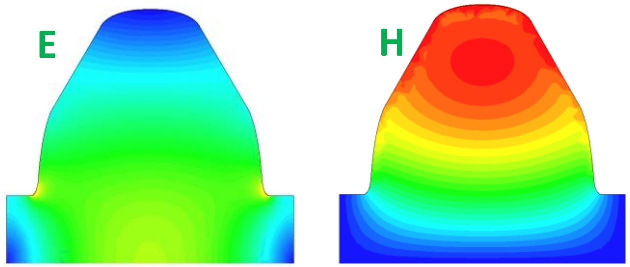
two harmonics-mode superposition to suppress pulsed heating

MHC : Pulsed Heating Suppression I

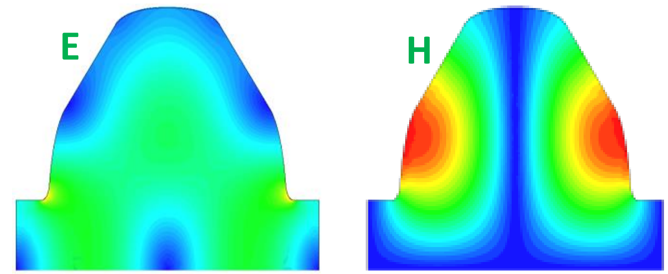
$TM_{010}+TM_{011}$ (f + 2f)



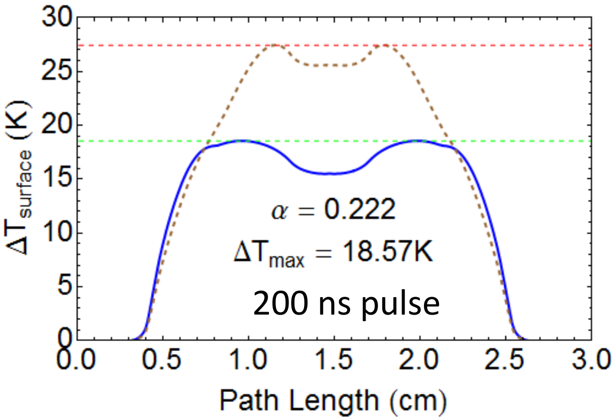
TM_{010} 12 GHz



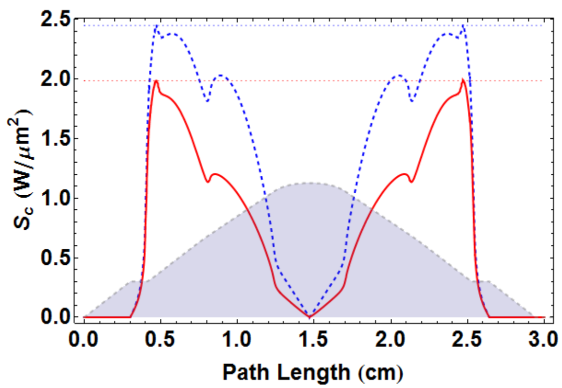
TM_{011} 24 GHz



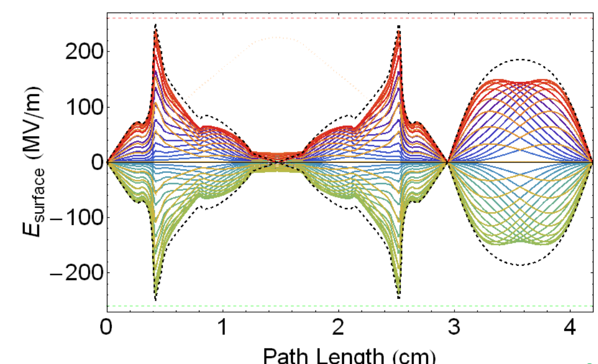
Pulsed temperature rise



modified Poynting vector S_c



surface E-field along periphery

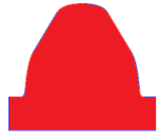


Effective acceleration gradient 100 MV/m

2-mode superposition compared to fundamental mode alone in the same MHC :

- □ pulsed heating temperature ↓32%
- □ total required RF power ↓ 27%
- □ maximum modified Poynting vector S_c ↓ 20%
- effective shunt impedance ↑ 37%

TM_{010}+TM_{011} Cavity

a/λ=0.12 π mode standing wave effective gradient E_{acc}=100MV/m	 TM_{010} + TM_{011} Bimodal Cavity			 Pillbox A	 Pillbox B	 Nose-cone
	1^{st} harmonic alone	2^{nd} harmonic alone	78% 1^{st} +22% 2^{nd}	1^{st} harmonic only	1^{st} harmonic only	1^{st} harmonic only
frequency (GHz)	11.9942	23.9884		11.9942	11.9942	11.9942
effective shunt impedance (MΩ/m)	95.7	38.3	▲131.4	89.7	99.1	113.9
transit time factor	0.765	0.786		0.768	0.753	0.758
max E_{surf} (MV/m)	246.8	367.4	246.8	209.7	246.8	225.0
max H_{surf} (MA/m)	0.327	0.634	0.350	0.327	0.298	0.289
max S_c (W/μm²)	2.45	10.3	▼1.95	3.75	3.02	4.20
max ΔT (K) @ 200ns pulse length	27.5	148.2	▼18.6	27.5	22.87	21.5
wall loss (MW)	1.306	3.263	▼0.95	1.392	1.262	1.097

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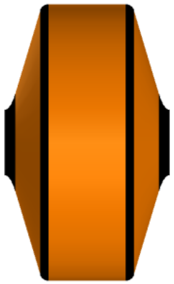
- □ effective shunt impedance ↑ 37%

MHC : Pulsed Heating Suppression II

TM_{010}+TM_{012} (f + 3f)

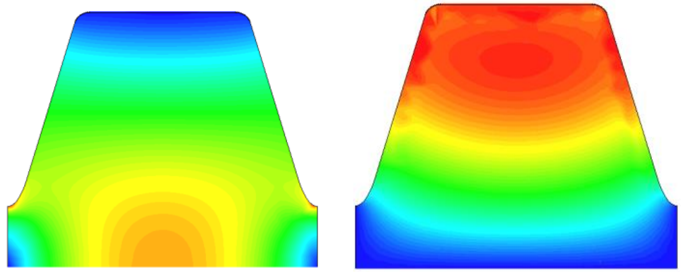
elliptical cavity

$a/\lambda=0.1$



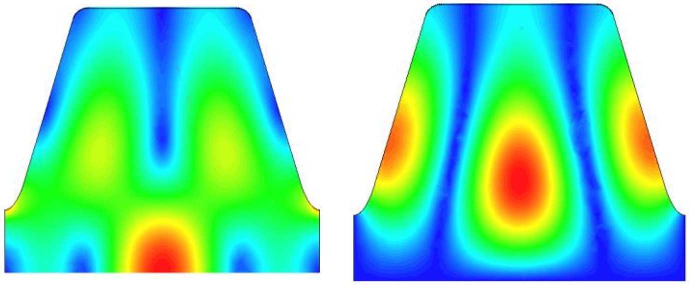
TM_{010} 12 GHz

E H

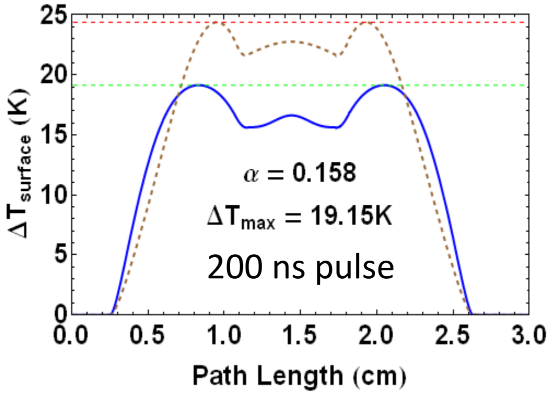


TM_{012} 36 GHz

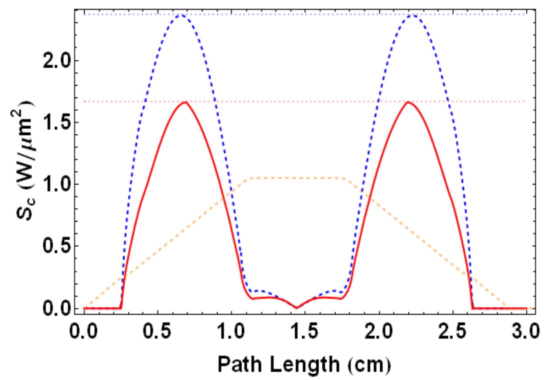
E H



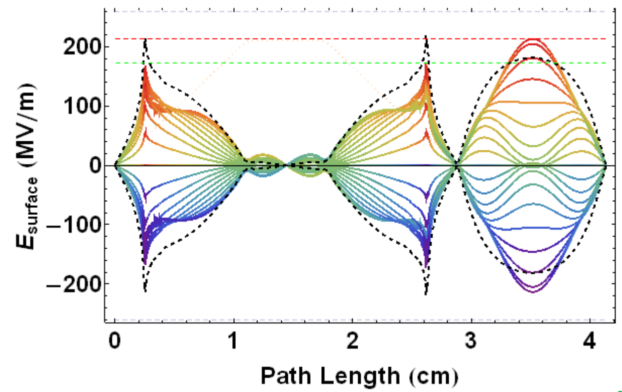
pulsed heating temperature



modified Poynting vector S_c



surface E-field along periphery



Effective acceleration gradient 100 MV/m

- pulsed heating temperature ↓22%
- effect shunt impedance ↑23%
- peak surface E-field ↓19.4%
- modified Poynting vector ↓30%
- total RF power ↓ 19%

TM_{010}+TM_{012} Cavity

a/λ=0.10 π mode standing wave effective gradient E_{acc}=100 MV/m	TM_{010} + TM_{012} Bimodal Cavity			Pillbox A	Pillbox B	Nose-cone
	1st harmonic alone	3rd harmonic alone	84% 1st +16% 3rd	1st harmonic only	1st harmonic only	1st harmonic only
frequency (GHz)	11.9942	35.9826		11.9942	11.9942	11.9942
effective shunt impedance (MΩ/m)	100.73	24.65	▲ 124.19	100.43	99.18	127.7
transit time factor	0.753	0.633		0.762	0.758	0.749
max E_{surf} (MV/m)	209.8	359.2	▼ 178.0	206.7	178.0	218.6
max H_{surf} (MA/m)	0.309	0.776	0.339	0.309	0.309	0.267
max S_c (W/µm²)	2.365	9.700	▼ 1.670	3.190	3.181	3.68
max ΔT (K) @ 200ns pulse length	24.46	261.8	▼ 19.15	24.46	24.46	17.65
wall loss (MW)	1.241	5.069	▼ 1.006	1.244	1.260	0.979

	Bimodal (11%)	Bimodal (16%)	Nose-cone	
effective gradient E_a	150	150	150	MV/m
effective shunt impedance	119.7	124.2	127.7	MΩ/m
max E_{surf}	250.0	267	327.9	MV/m
max H_{surf}	0.488	0.509	0.401	MA/m
max S_c	4.26	3.76	8.28	W/µm²
max ΔT @ 200ns pulse length	45.0	43.1	39.7	K
wall loss	2.35	2.26	2.20	MW

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III. Possible application for future accelerators

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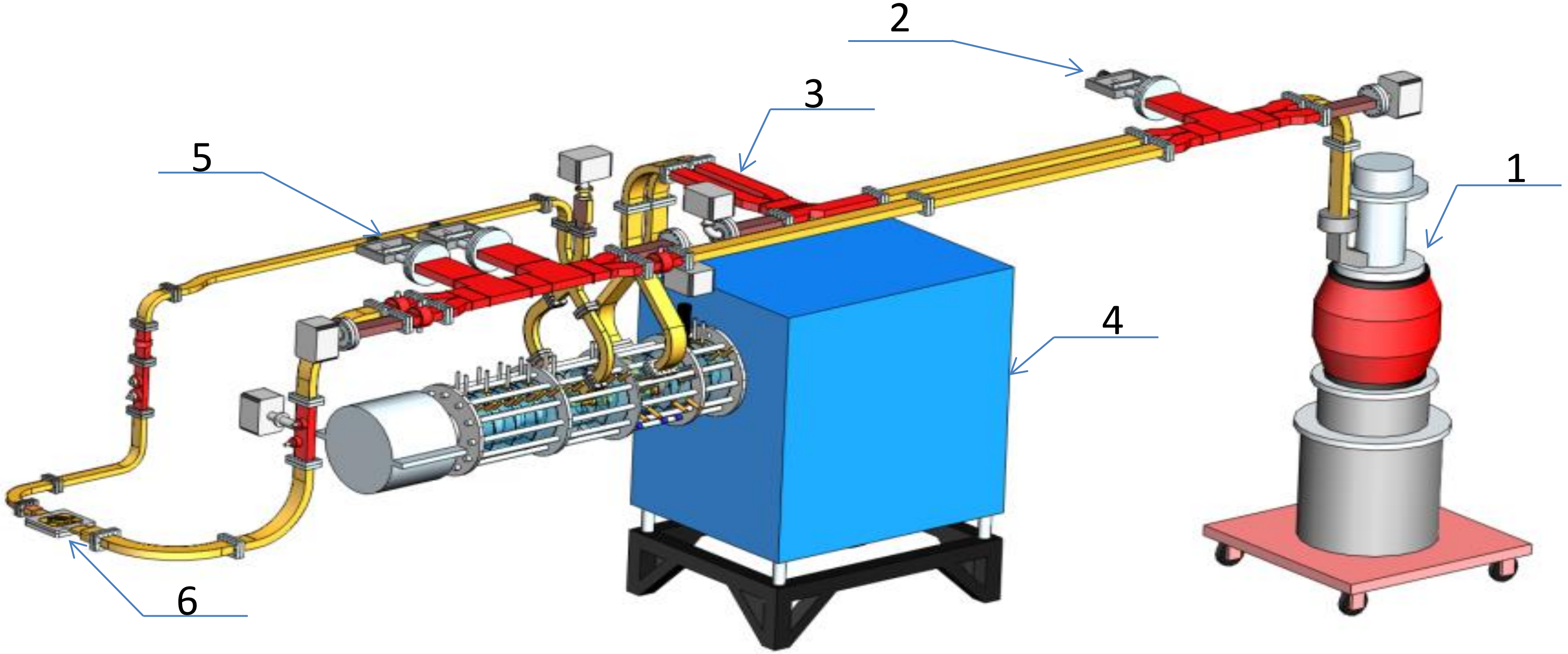
- Beam driven (detuned cavities in a co-linear TBA configuration)

Two-Frequency RF Source at Yale University

- Power splitting into each frequency component with adjustable amplitude and phase
- Two sources automatically phase-locked
- No new modulator, no C-band or X-band driver needed.

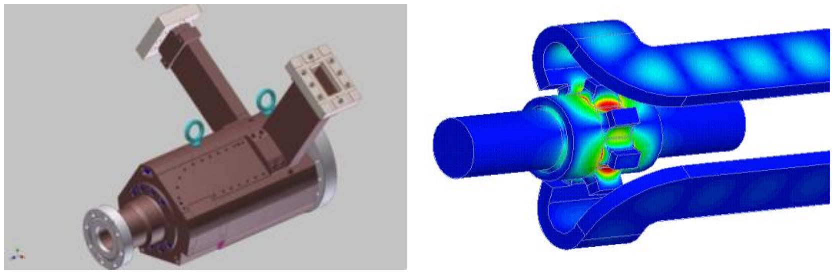


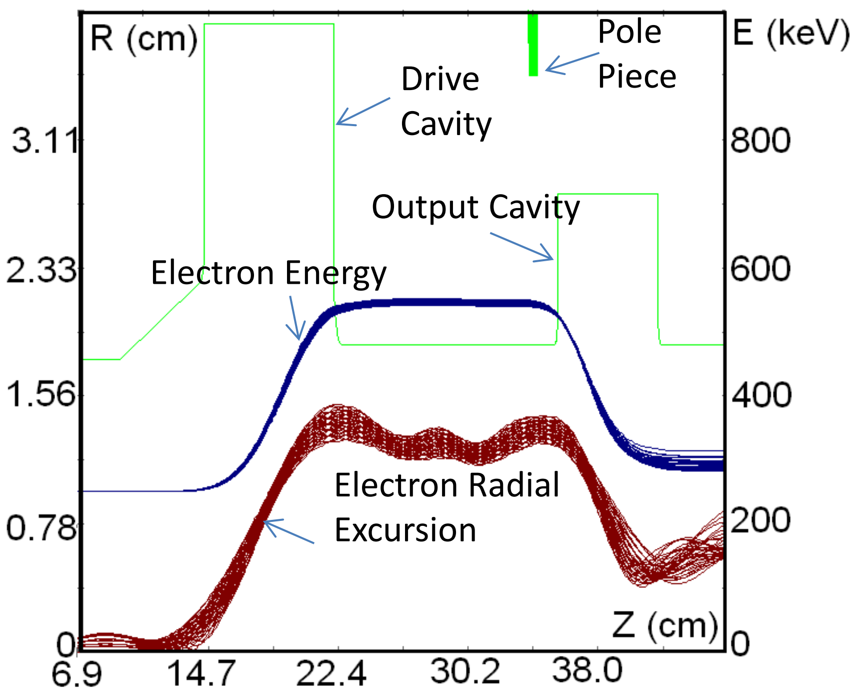
Layout of dual-frequency RF source, shown feeding a bimodal test cavity:

1. S-band klystron
2. variable power splitter
3. 3-dB hybrid splitter
4. 250-kV gun tank
5. variable power splitter and phase shifter
6. bimodal test cavity

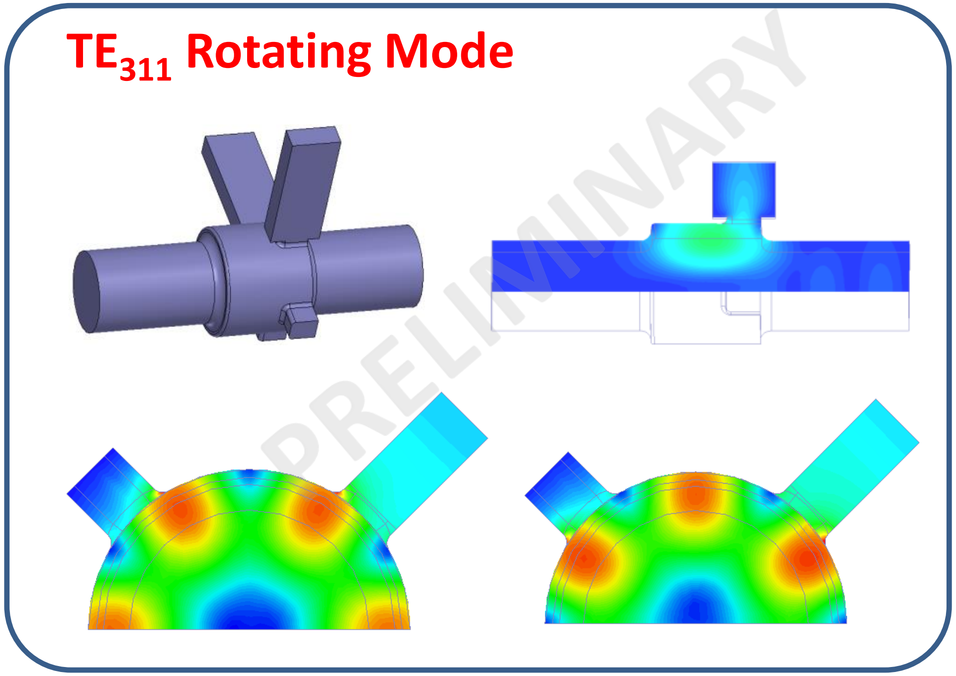
Harmonic Output Cavities

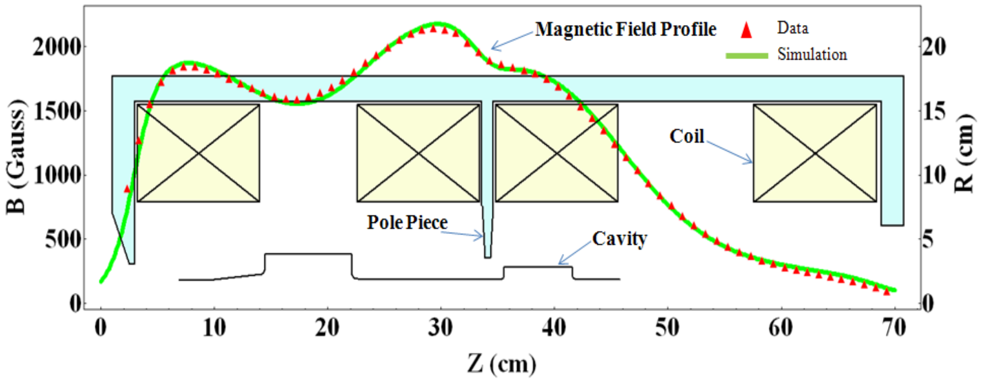
TE_{211} Rotating Mode





TE_{311} Rotating Mode



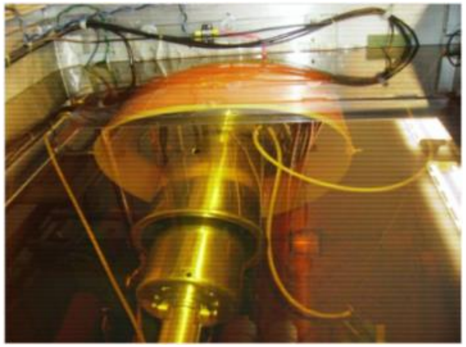


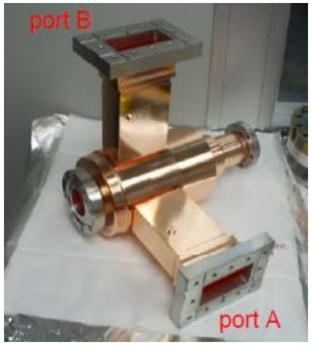
Harmonic Multipliers

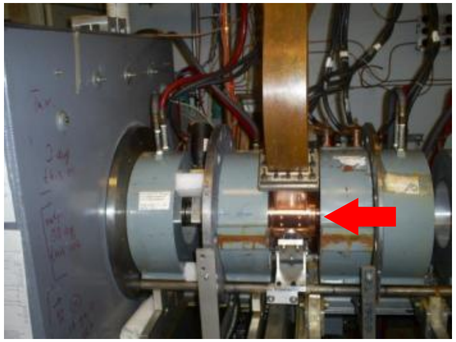
Nominal operating parameters of harmonic multipliers

	2^{nd} harmonic multiplier	3^{rd} harmonic multiplier	7^{th} harmonic multiplier
Output frequency	5.712 GHz	8.568 GHz	19.992 GHz
RF input power at 2.856 GHz	6.0 MW	6.0MW	8.5 MW
Beam voltage and power at 20 A	250 kV, 5.0 MW	200 kV, 4.0 MW	250 kV, 5.0 MW
RF output power	5.3 MW	6.7 MW	4.0 MW
Harmonic power multiplication factor	0.88	1.12	0.47
Overall efficiency	48%	67%	30%

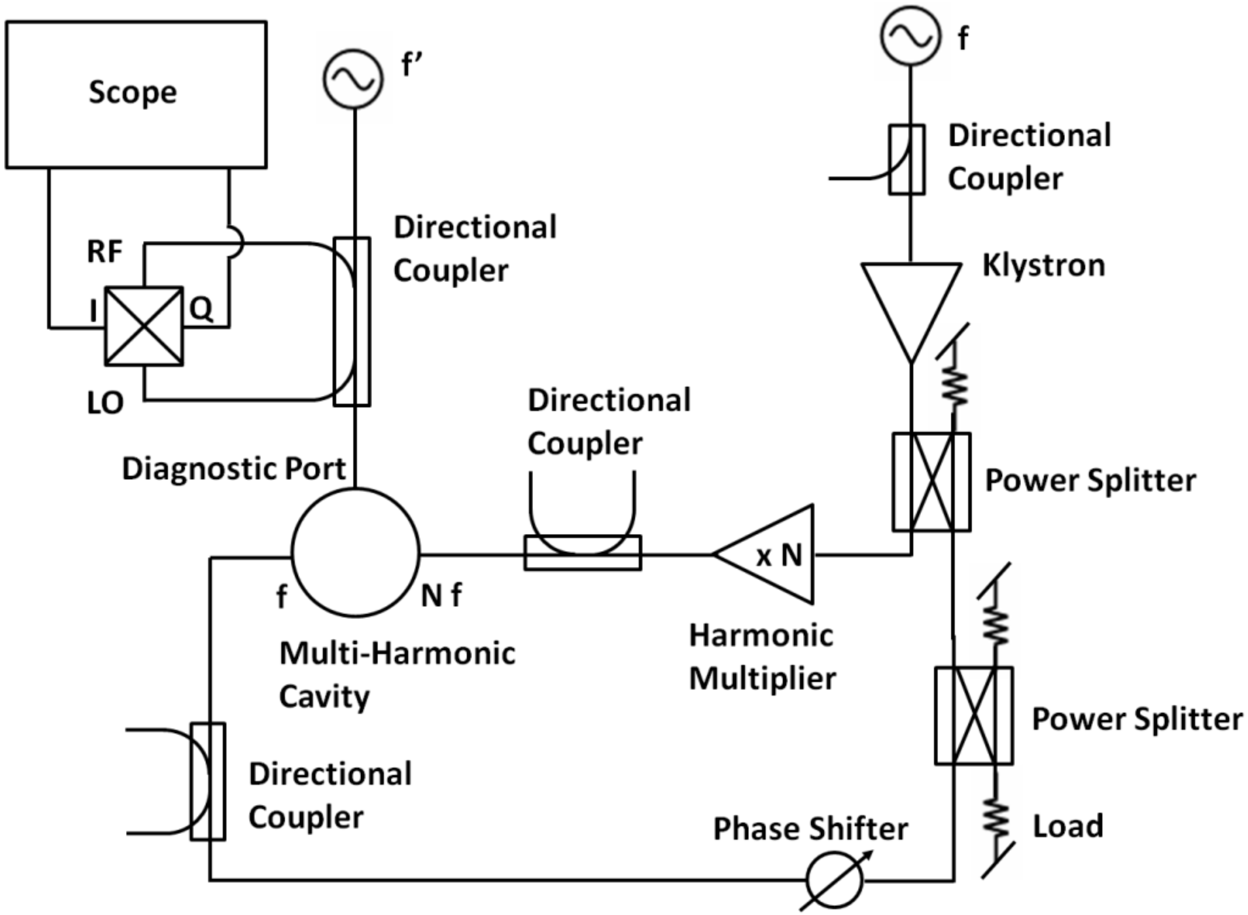
Drive Cavity cold tested and installed







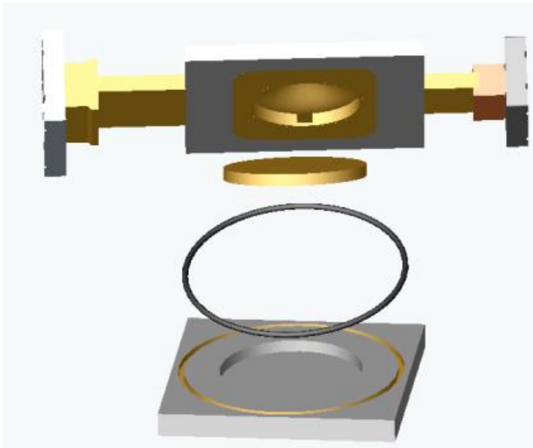
RF Breakdown and Pulsed Heating Experiment

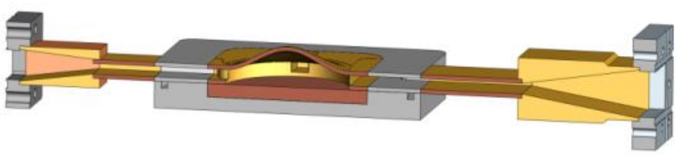


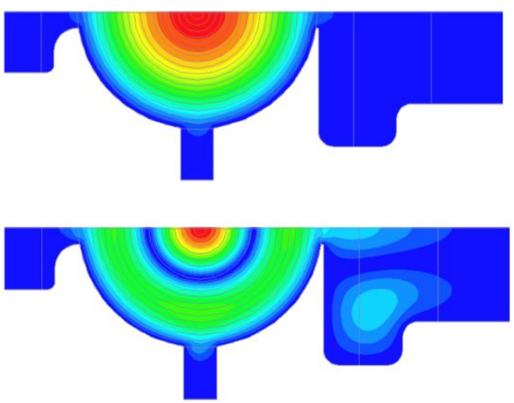
Experimental Schematic

- ❑ High power RFs at frequencies *f* and N*f* generated by the klystron and harmonic multiplier
- ❑ Low power RF at a different frequency *f'* to excite the diagnostic mode and measure cavity *Q*

Clamped Cavity to Test Anode-Cathode Effect







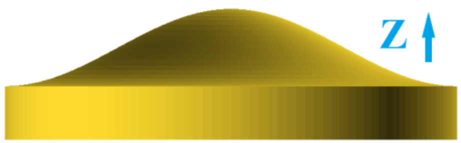
- ❑Clamped structure with demountable bottom flat surface allows convenient replacement of test plates

- ❑The bottom test plate is expected to exhibit the greatest damage from breakdown, due to the anode-cathode field imbalance.

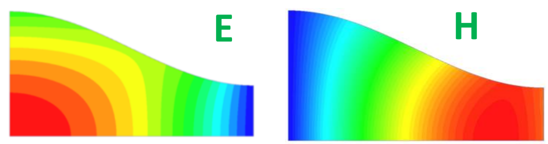
- ❑The top and input wave-guides are to be reused for tests with varying power levels and phases for the two RF sources

RF Properties of Bimodal Test Cavity

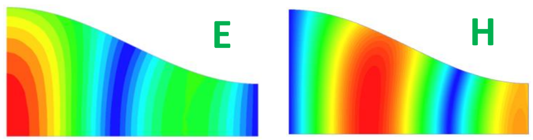
TM_{010}+TM_{020} Cavity



TM_{010} 2.856 GHz

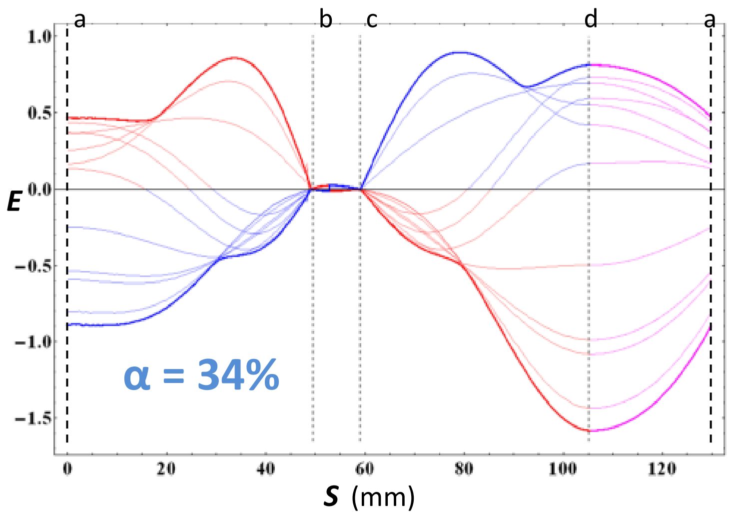


TM_{020} 5.712 GHz

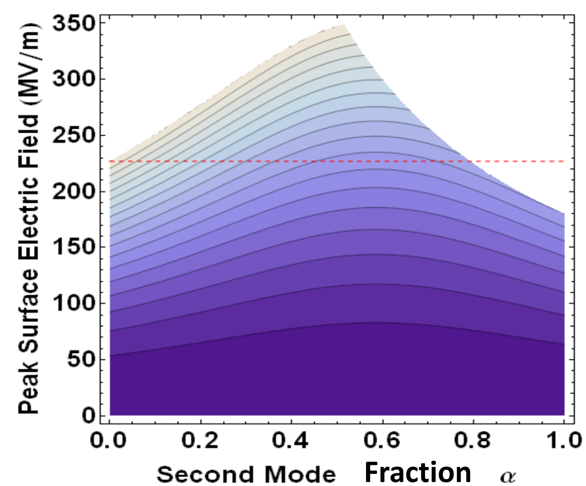


required RF power	1st harmonic alone	2nd harmonic alone	both modes
frequency (GHz)	2.856	5.712	66% f_1 and 34% f_2
P (MW) for E_{surf}= 100 MV/m	3.49	1.98	1.75
P (MW) for E_{surf}= 200 MV/m	13.97	7.92	7.21
P (MW) for E_{surf}= 300 MV/m	31.43	17.82	16.23

E-field distribution along cavity periphery *S*

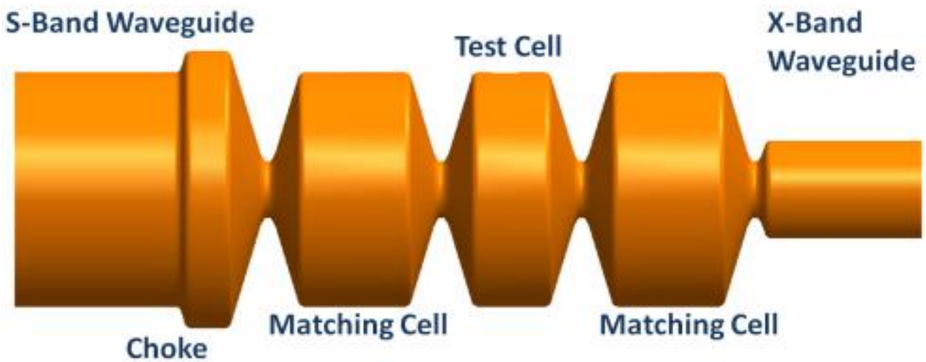


peak surface E-field with 18 MW klystron power

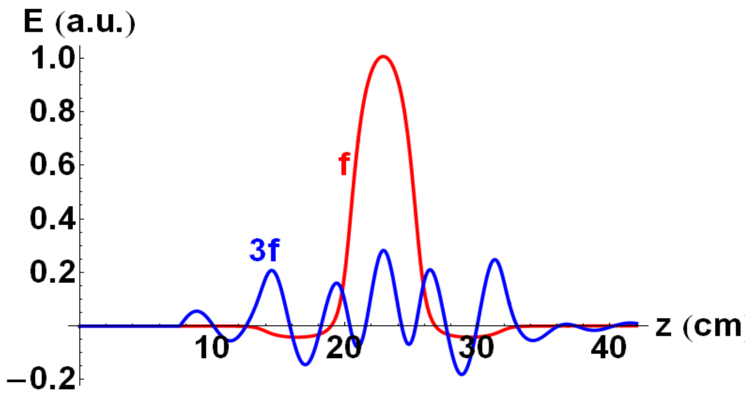


Bimodal Cavity to Suppress Pulsed Heating

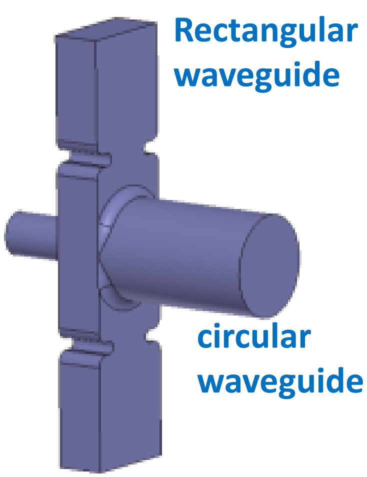
$TM_{010} + TM_{012}$ Test Structure



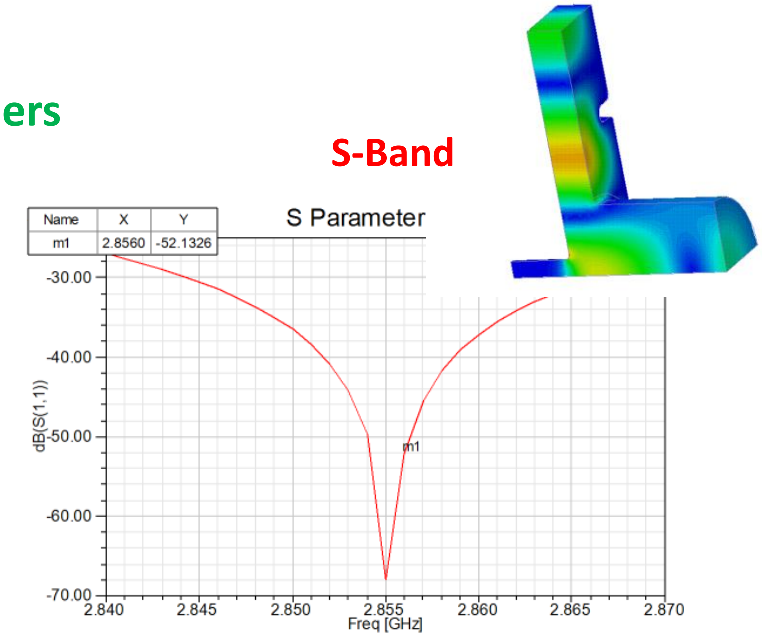
Axial E fields of TM_{010} and TM_{012}



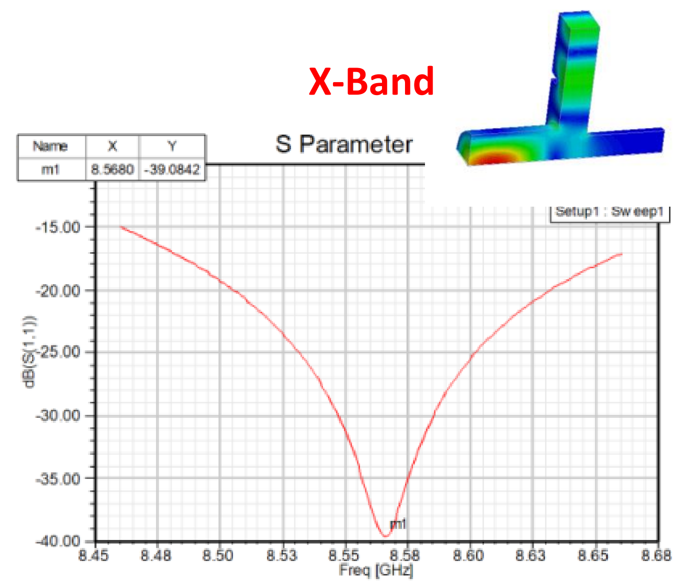
TM_{01} mode launchers



S-Band



X-Band



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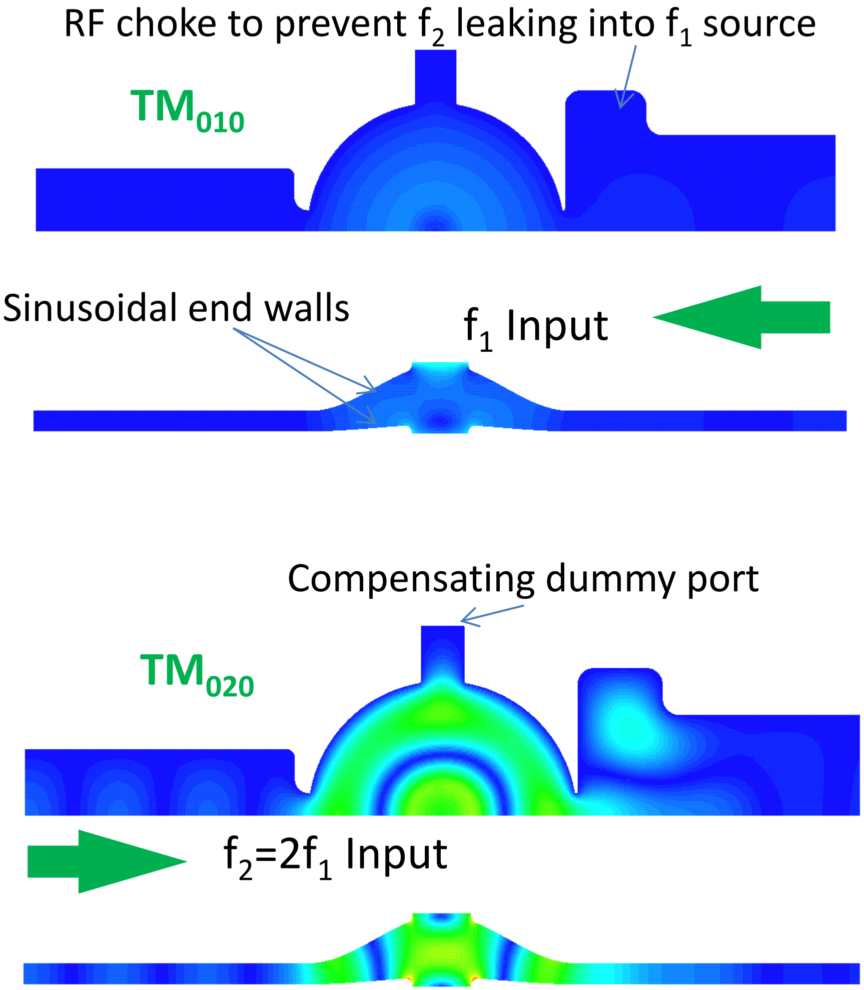
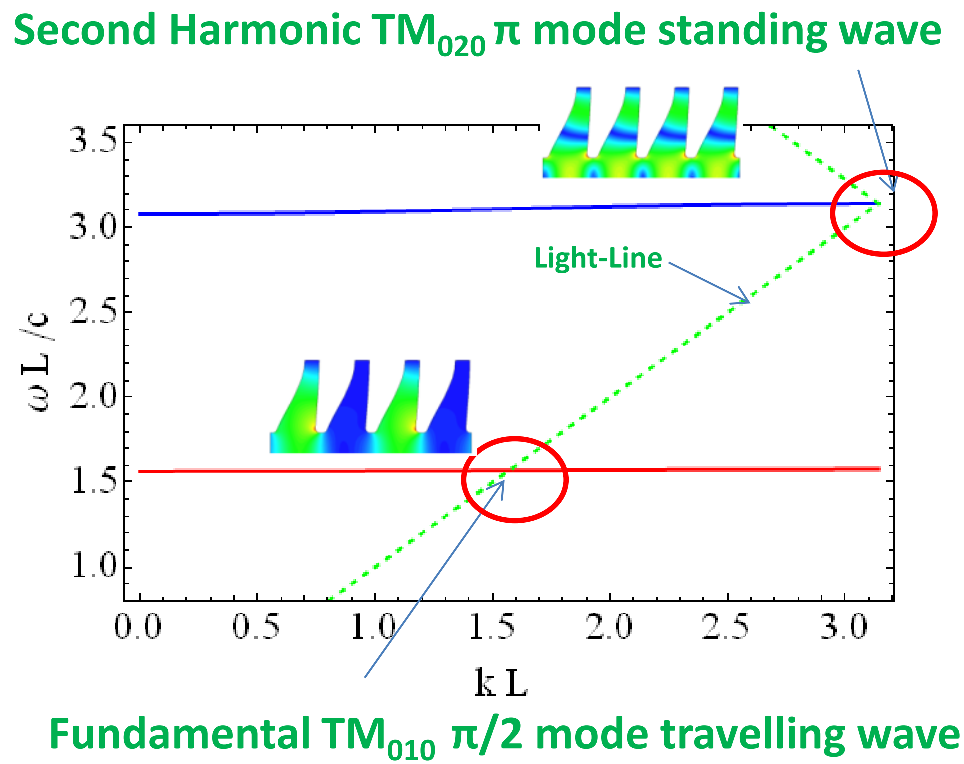
External RF Excitation of MHC Structure

Dual-frequency Coupling

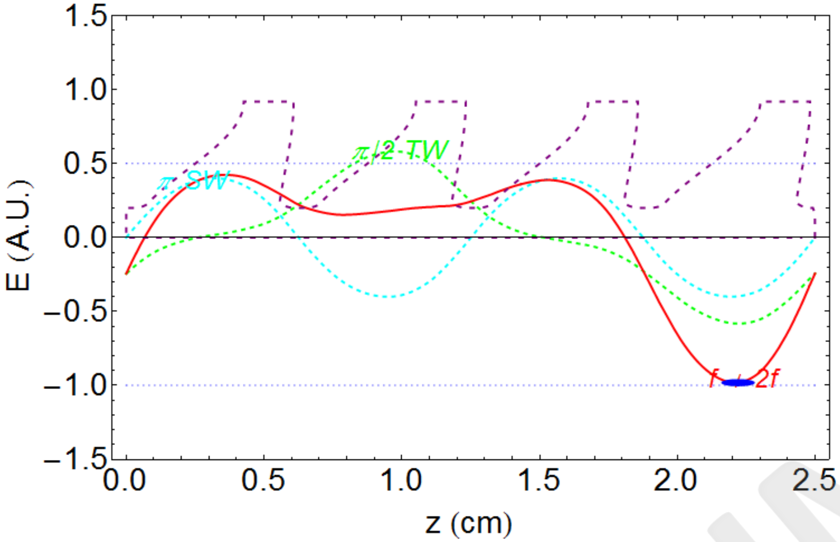


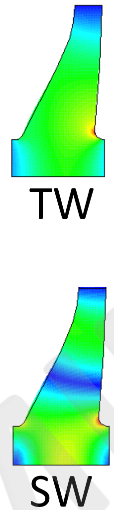
Dispersion Curve and Field Patten

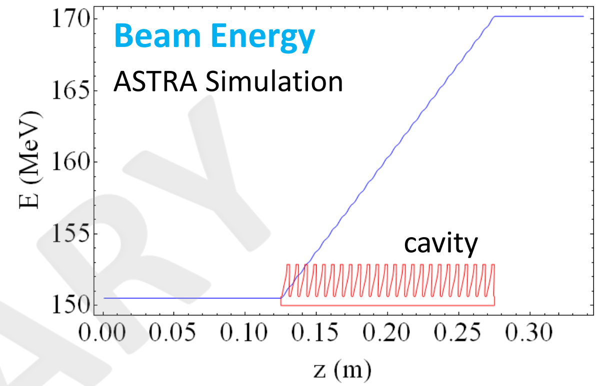


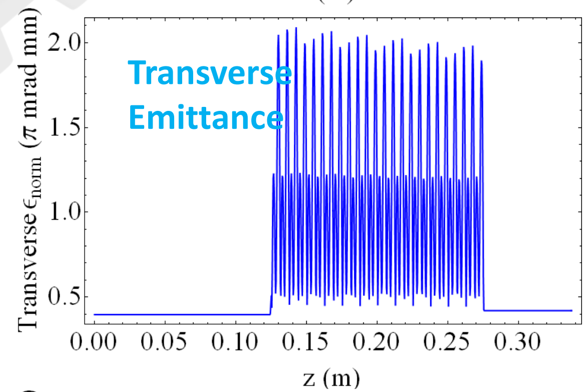
Beam Dynamics in MHC

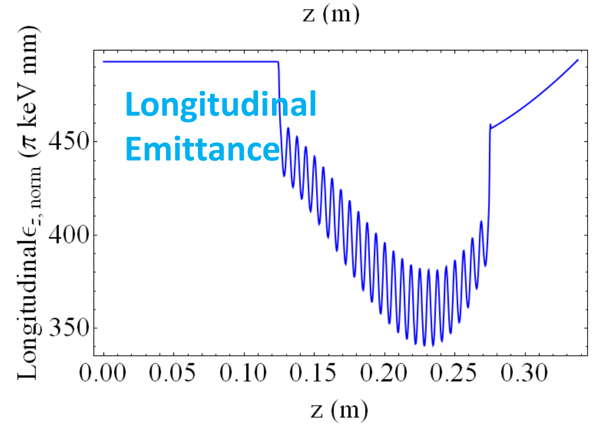
Synchronization of test beam with superposition of TW π/2 and SW π modes in harmonics











- ❑ Peak axial electric field of each mode: E_1=150 MV/m at 12 GHz, E_2=60 MV/m at 24 GHz
- ❑ Peak anode-like surface field 388 MV/m, peak cathode-like surface field 213 MV/m (< breakdown limit)
- ❑ 24 cells, 15 cm, 150 MeV => 170 MeV, Effective Gradient 135 MV/m

Outline

I. Harmonic mode superposition for breakdown suppression

- $TM_{010} + TM_{020}$ ("anode-cathode effect" – field emission suppression)
- $TM_{010} + TM_{011}$ or $TM_{010} + TM_{012}$ (pulsed heating suppression)

II. Plan of RF Breakdown Experiments

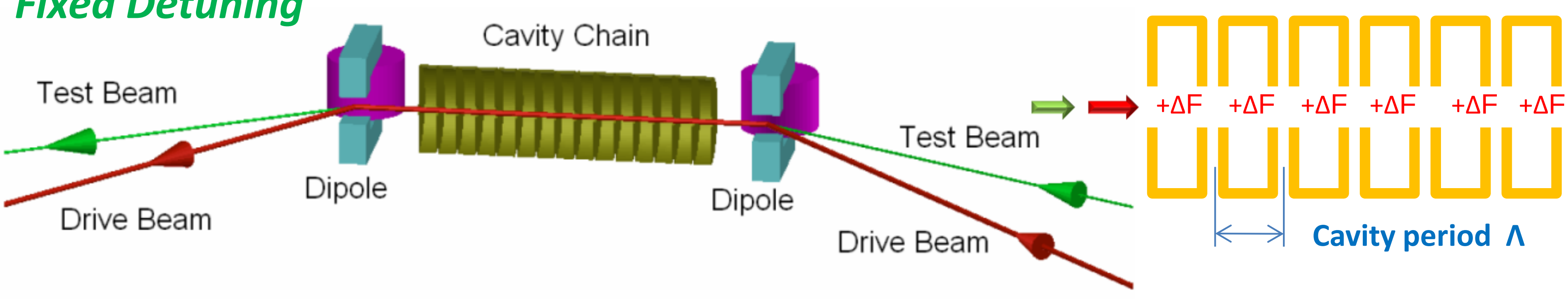
- Two frequency RF Source
- Clamped Test Structures

III. Possible application for future accelerators

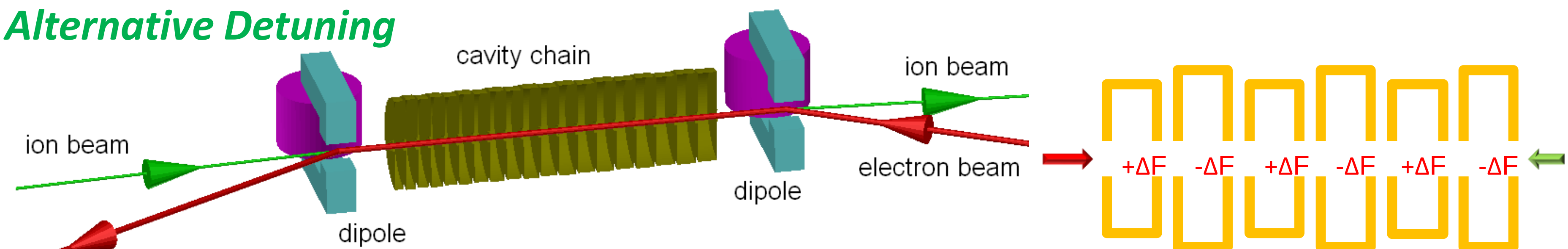
- Externally driven from phase-synchronous RF sources
- **Beam driven (detuned cavities in a co-linear TBA configuration)**

Beam Excitation: Detuned-Cavity TBA

Fixed Detuning



Alternative Detuning



Every other cavities, detuning flips sign

"High-gradient two-beam accelerator structure", S. Yu Kazakov, S.V. Kuzikov, Y. Jiang, and J. L. Hirshfield, PRSTAB 13, 071303 (2010)

Single Mode Detuned Cavity TBA

Estimation for steady state in SW TM_{010} π-mode structure

Steady state E field on axis

$$E(z,t) = -\frac{E(z)}{E_0 T}\frac{I_\omega R}{2}\cos\phi\, e^{i(\omega t+\phi)}$$

Drive beam deceleration

$$D = \frac{1}{\Lambda}\Re\int_{-\Lambda/2}^{\Lambda/2} E(z,t=z/c)dz = -\frac{I_\omega R}{2}\cos^2\phi$$

Test beam acceleration

$$A = \frac{1}{\Lambda}\Re\int_{-\Lambda/2}^{\Lambda/2} E_1(z,t=z/c+\pi/2\omega)dz = \frac{I_\omega R}{4}\sin 2\phi$$

⇒ Transformer ratio

$$T = \frac{A}{D} = -\tan\phi = 2Q\delta$$

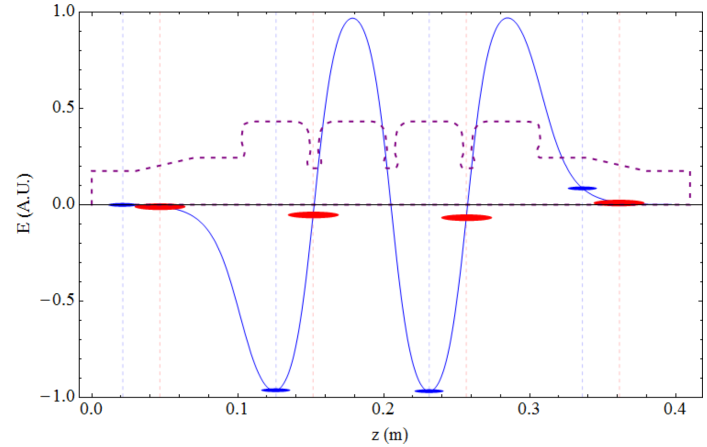
I_ω Fourier component of beam current at ω

R Effective Shunt impedance

ϕ Detuning angle

$\delta = (\omega - \omega_c)/\omega_c$ Detuning

2.856 GHz TM010 π-mode excitation by drive bunches in detuned 4-cell SW structure

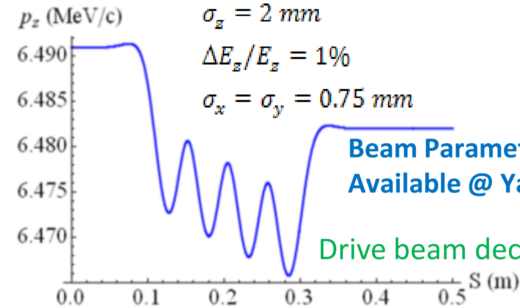


Drive beam
0.5 A , 6 MeV

ΔE_d=9 keV

Test beam
1 mA, 0.3 MeV

ΔE_t=45 keV



$\sigma_z = 2\ mm$

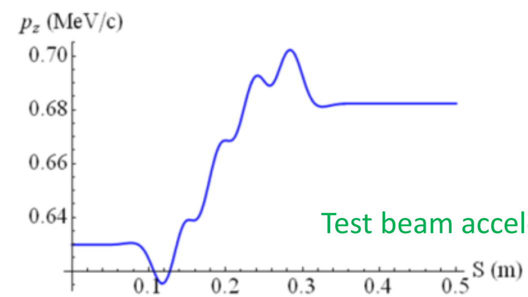
$\Delta E_z/E_z = 1\%$

$\sigma_x = \sigma_y = 0.75\ mm$

Beam Parameters Available @ Yale

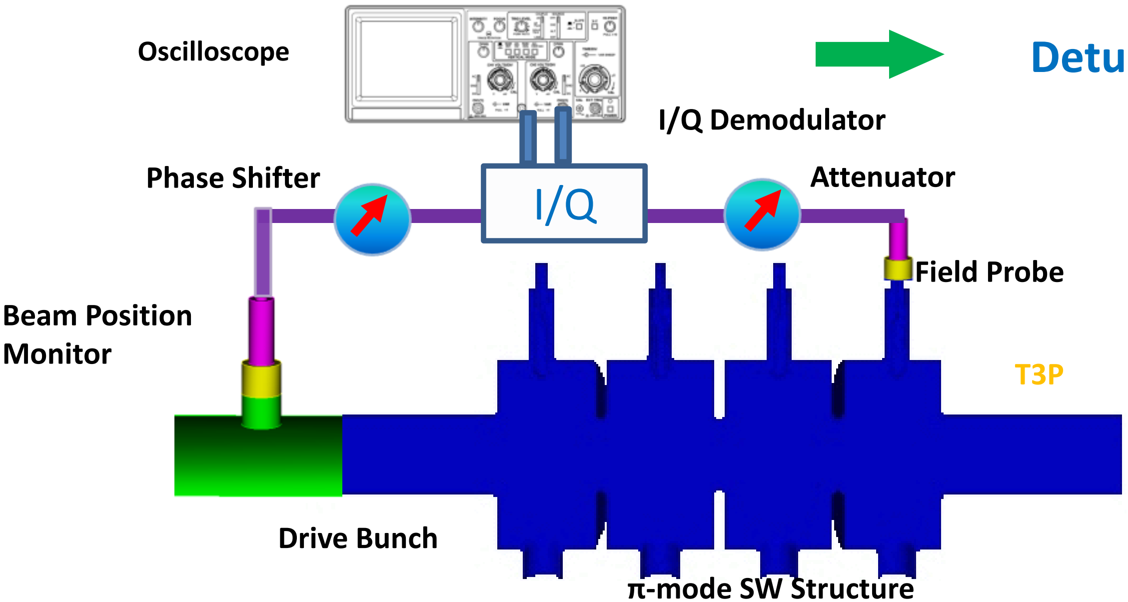
Drive beam deceleration

2Qδ=10, effective Transformer Ratio =5 due to fringe field of end cells in short structure

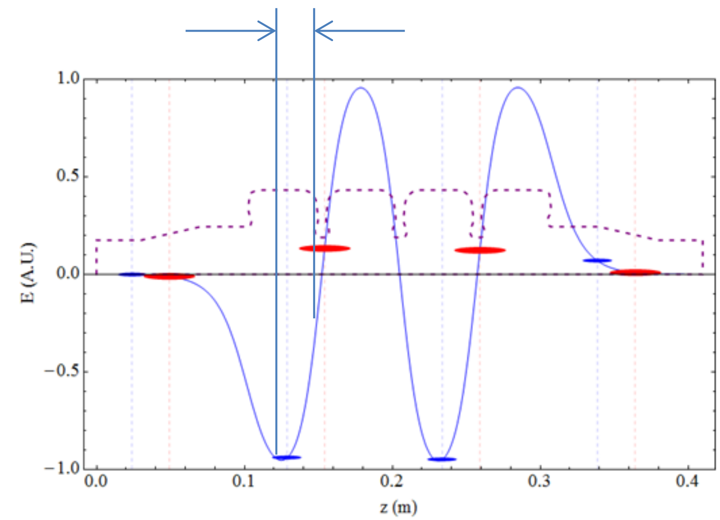


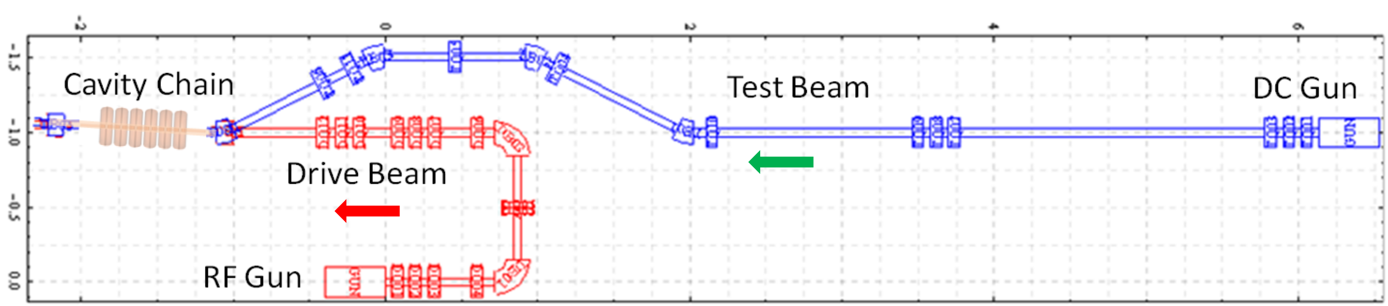
Test beam acceleration

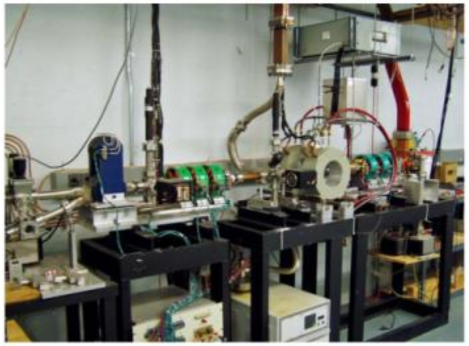
Single Mode TBA Experimental Plan



Detuning angle Δθ=ϕ $T = \frac{A}{D} = -\tan\phi = 2Q\delta$

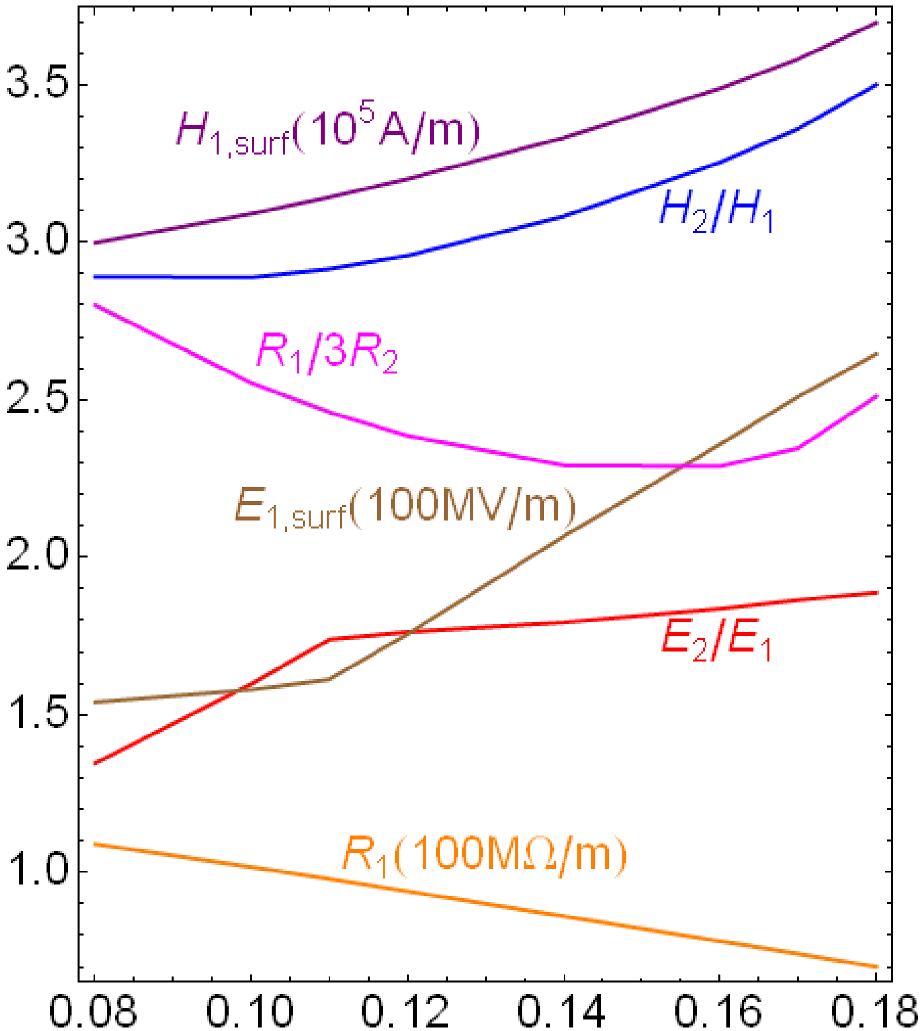




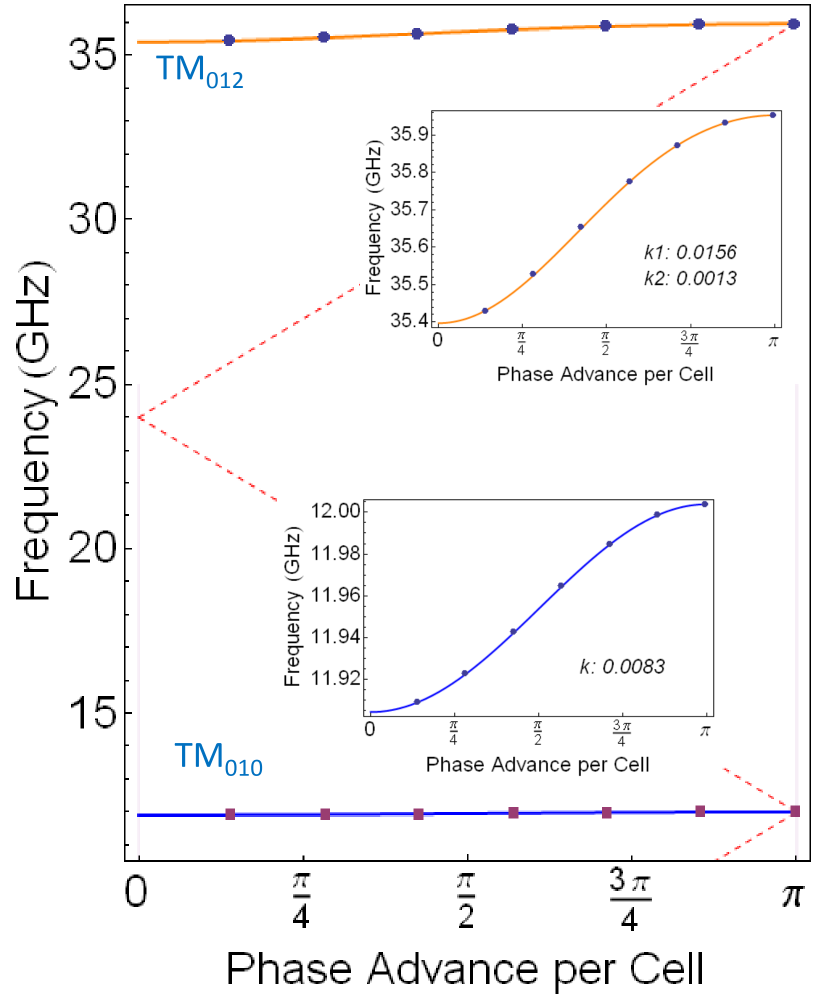


RF Parameters of TM_{012} MHC Structure

Performance with different a/λ



aperture vs wavelength ratio a/λ

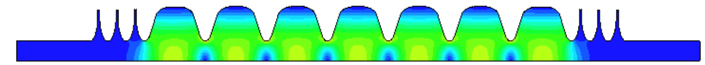


TM_{010} and TM_{012} Monopole Dispersion Curve (intermediate bands omitted)

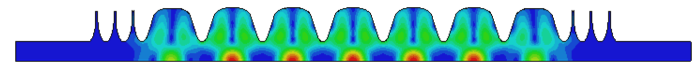
Beam-Driven X-band MHC Structure

- Drive frequency is 11.9942 GHz
- Detuning angle is 85.6 degree and $2Q\delta=13.1$
- Chokes at either end of the structure trap field
- With $a/\lambda=0.12$, the drive current needs to be **13A** to have **100 MV/m** acceleration gradient, or **20A** to have **150 MV/m**. **New TBA paradigm?**

TM010 π-mode 12.0032 GHz



TM012 π-mode 35.9556 GHz



Quick Estimation for steady state:

Acceleration

$$A = -\frac{I_1 R_1}{4}\sin 2\phi_1 + \frac{I_3 R_3}{4}\sin 2\phi_3$$

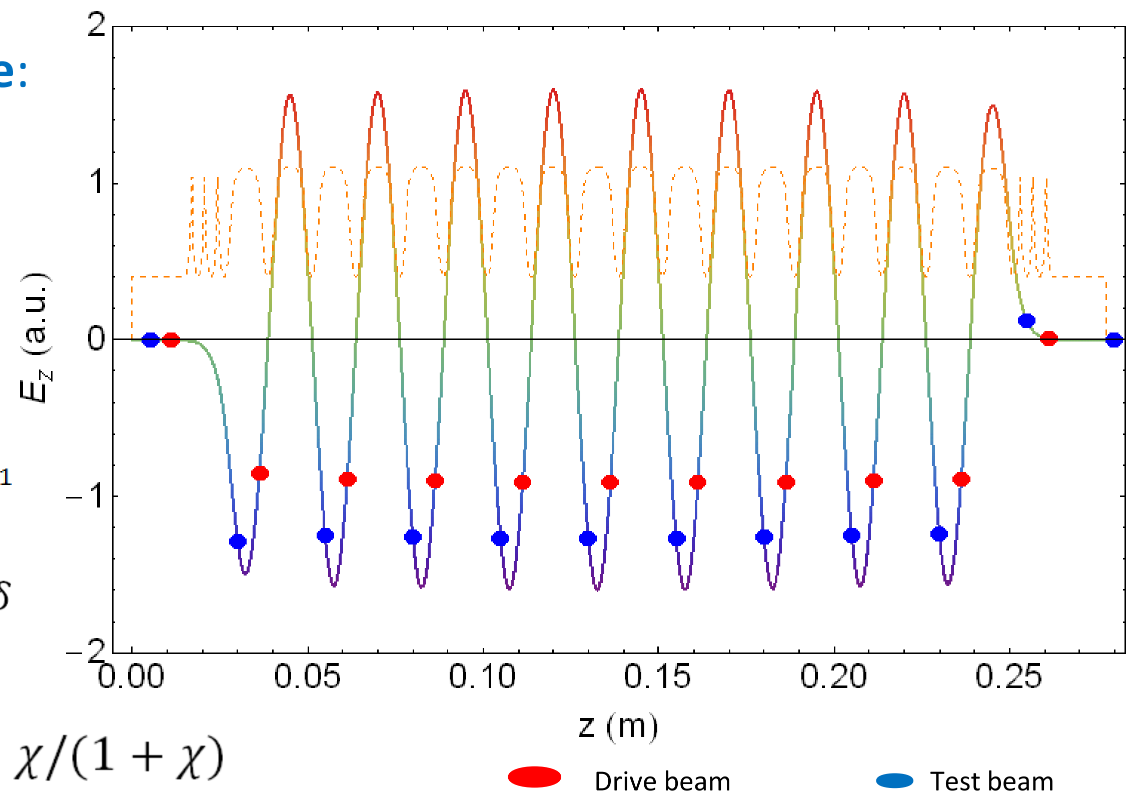
Transformer Ratio

$$T = -\frac{\sin 2\phi_1 - \chi \sin 2\phi_3}{2(\cos^2\phi_1 + \chi\cos^2\phi_3)} \qquad \chi = I_3 R_3 / I_1 R_1$$

if $\phi_1 = -\phi_3 = \phi \qquad T = -\tan\phi = 2Q\delta$

Superposition of two modes

$$E_{total} = (1-\alpha)E_1 + \alpha E_2 \qquad \alpha = \chi/(1+\chi)$$



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University of Manchester
UK

Lee Carver
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UK

Summary

- Multi-harmonic operation of acceleration cavities may allow suppression of RF breakdown and/or pulsed heating, and possible increase in acceleration gradient.

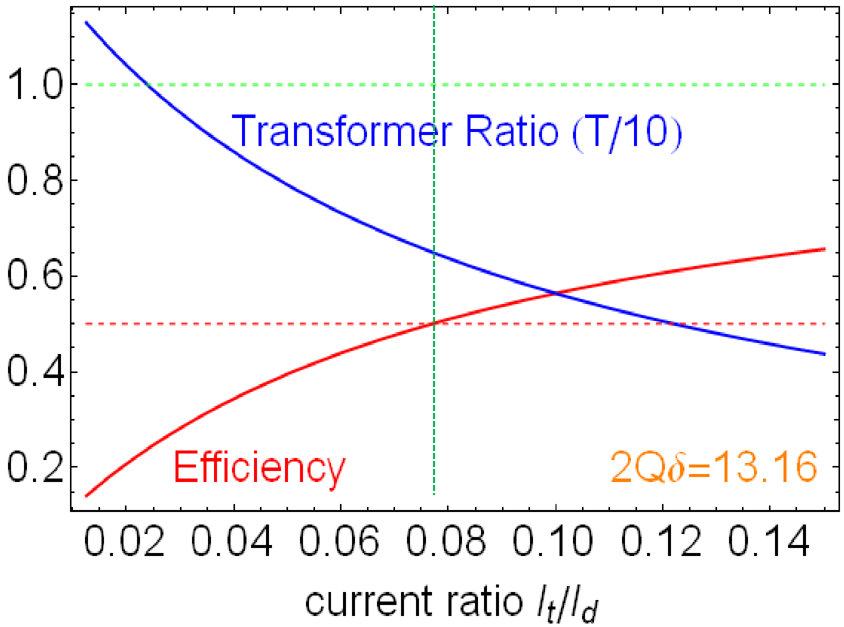
  - TM_{010}+TM_{020}, exhibits anode-cathode effect that could increase acceleration gradient without raising the surface cathode field.
  - TM_{010}+TM_{01m}, exhibits smaller surface pulsed heating than TM_{010} alone.

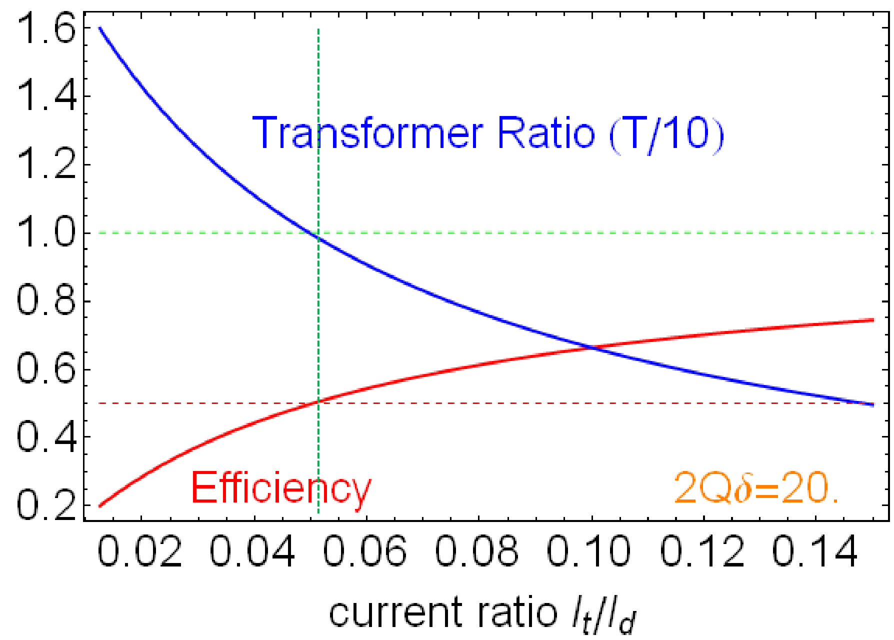
- RF Breakdown tests driven by two-frequency RF source are underway.

- Detuned single-mode cavity two-beam structure shows high transformer ratio, and high beam-to-beam efficiency. Detuned bimodal cavity two-beam structure could have the same virtues with the additional benefit of reduced field emission and/or surface pulsed heating. Beam dynamics and wakefield studies are underway.

Performance of MHC with Beam Loading

Test beam loading with different detuning



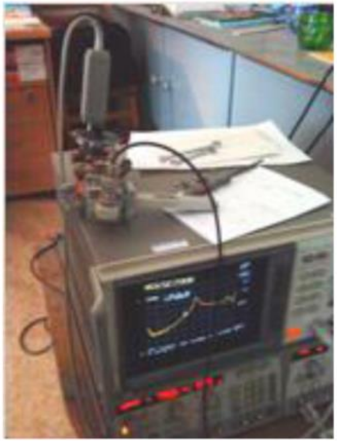


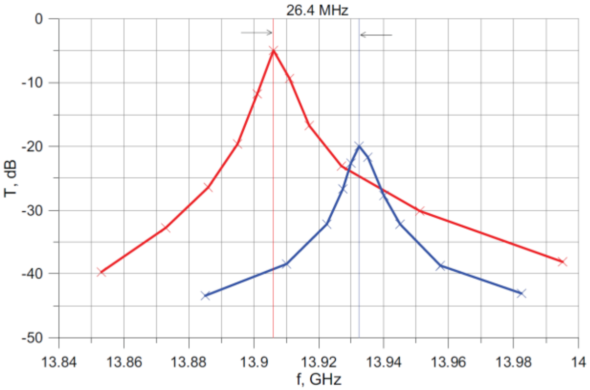
Details in PRSTAB 13, 071303 (2010)

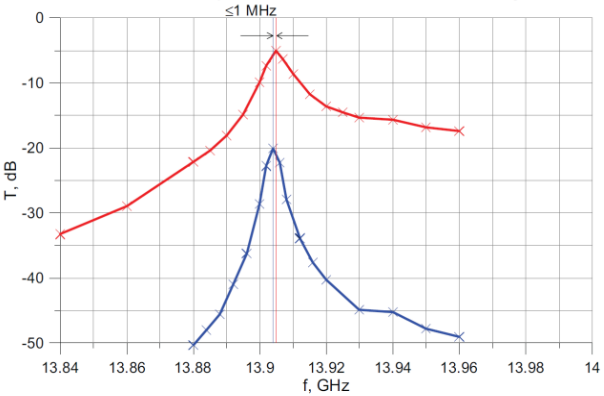
Cold Test of Tunable Bimodal Cavity

Bimodal symmetric cavity was built with its TM_{010}-like mode with f_1 = 7.0 GHz and TM_{020}-like mode with f_2 = 14.0 GHz, with greater sensitivity to fabrication errors.

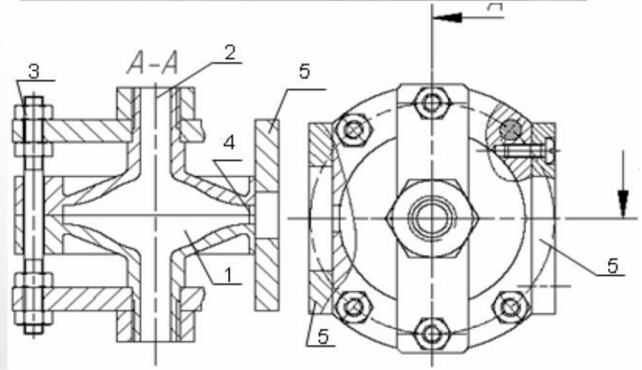
Tuning of frequencies was achieved by slightly squeezing 2-mm thick flexible copper wall which could be easily deformed by ~1 mm without plastic deformation. The first mode is more sensitive to such wall displacement than is the second.







Initial mode equidistance exceeded 26 MHz. Δf ~ 1 MHz can be achieved by squeezing the wall to shift by approximately 0.1 mm.



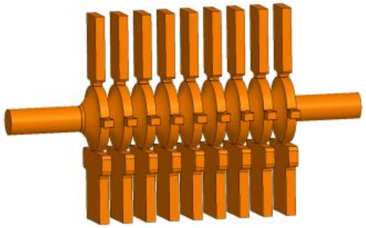
Drawing of the test cavity with a flexible wall: *1* – cavity body; *2* – simulated beam tunnel; *3* – tuning screw, *4* – coupling holes; *5* – waveguide flanges.

Multi-harmonic test setup for RF breakdown studies, Y. Jiang, S.V. Kuzikov, S.Yu. Kazakov, and J. L. Hirshfield, Nuclear Instruments and Methods in Physics Research A, v657, pp 71-77 (2011)

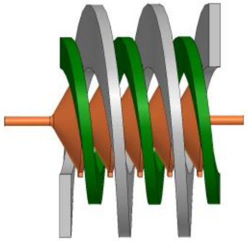
Multi-harmonic excitation and synchronization

Possible Structure Schemes

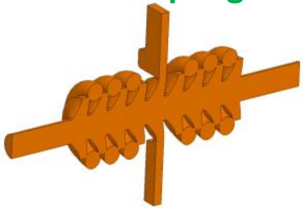
Planar Individual Feed



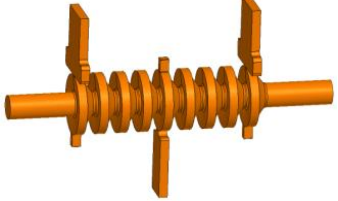
Double Helical



Side Coupling

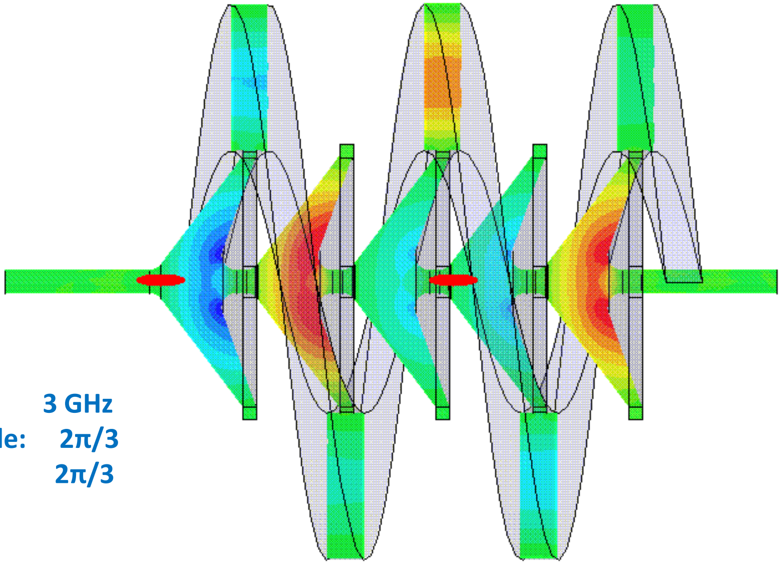


Hybrid Structure



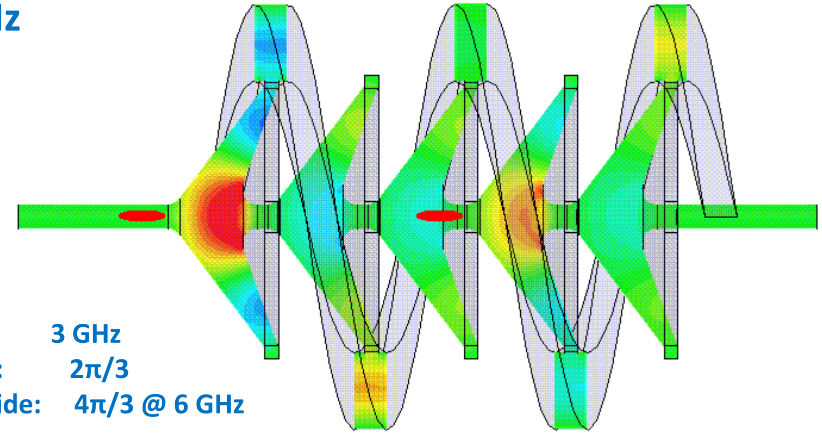
Example: Double Helical

External rf: 3 GHz



Bunch frequency: 3 GHz
Phase advance in waveguide: 2π/3
Phase advance of particle: 2π/3

External rf: 6 GHz



Bunch frequency: 3 GHz
Phase advance of particle: 2π/3
Phase advance in waveguide: 4π/3 @ 6 GHz