Studies of High-Power Microwave Structures that Employ Bimodal Cavities*

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Yale University

Omega-P R&D, Inc.

Outline

MOTIVATION: ***Trying to avert RF breakdown at high gradients.***

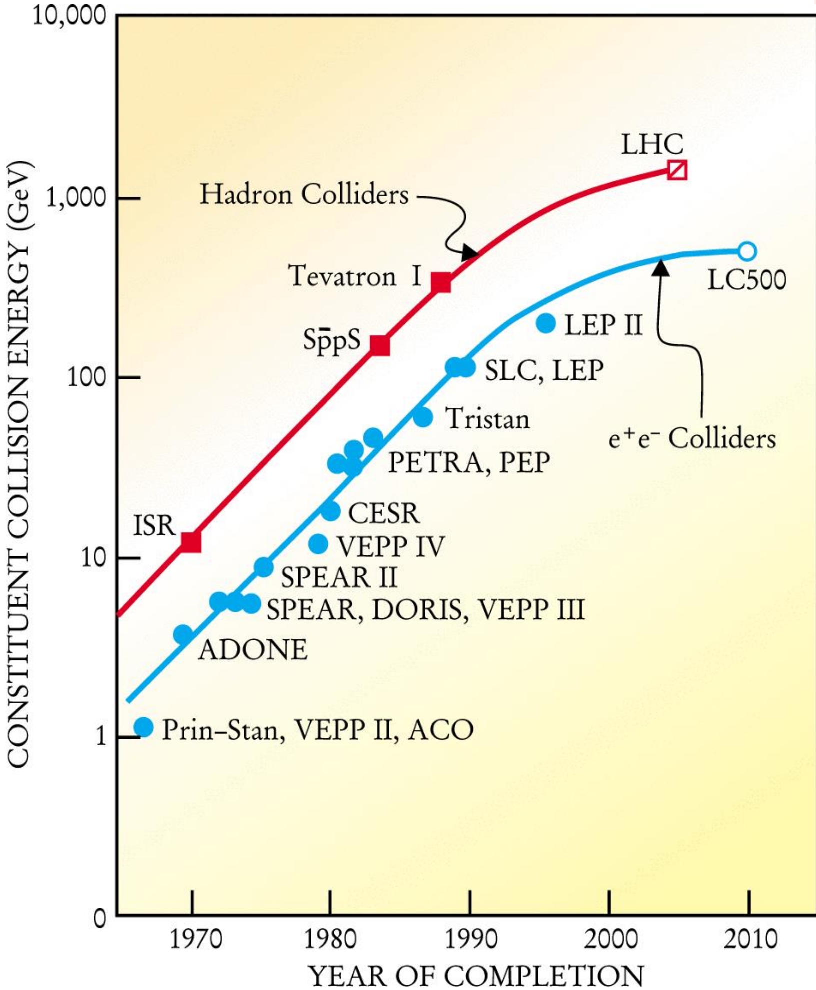
- **Bimodal RF-driven cavity structures**
  (possibly leading to a bimodal linac)

- **Bimodal beam-driven detuned cavity structures**
  (possibly leading to a bimodal two-beam accelerator)

- **Bimodal RF electron gun**
  (a near-term application of a bimodal cavity structure)

Accelerator Moore's Law

RF BREAKDOWN is a fundamental limitation in the practical realization of high-energy accelerators/



FCC (100 TeV, ?)

SPPC (70 TeV, 2042)

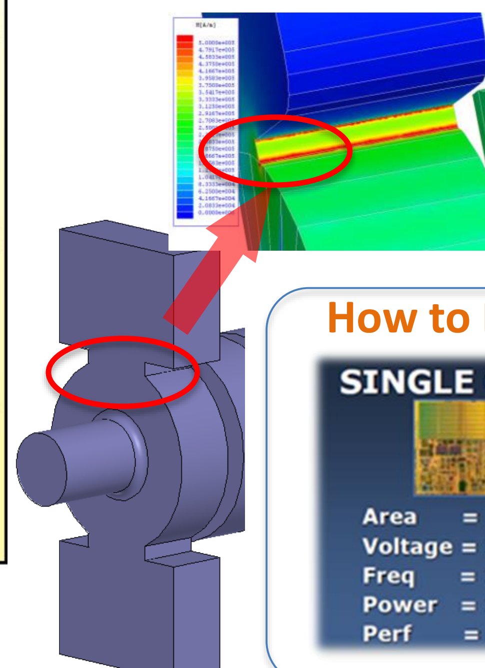
LHC Run II (13 TeV)

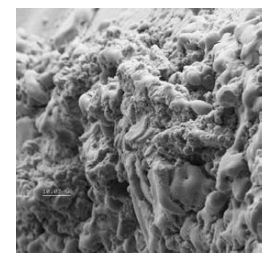
CLIC (linac, 3 TeV, ?)

ILC (linac, 500 GeV, ?)

FCC-ee (ring, 350 GeV, ?)

CEPC (ring, 240 GeV, 2028)





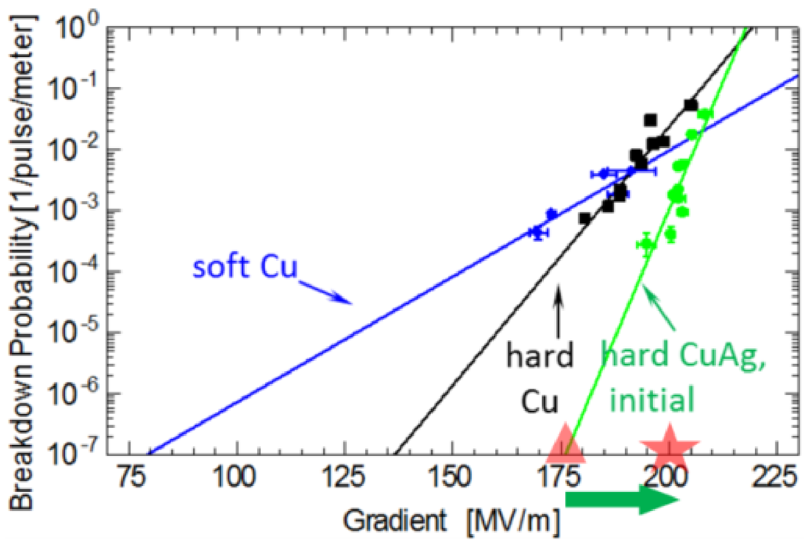
How to Beat CPU Moore's Law

Multi-Mode Accelerator Structures

❑ Scaling laws: higher frequency operation could allow higher gradients w/o an increase in breakdown probability.

❑ But development of suitable high frequency high power RF sources has lagged behind.

SLAC 1C-SW-A2.75-T2.0-structures



Our Objective:

To push room-temperature metallic structures towards 200 MV/m with a breakdown rate less than 10^{-7}/pulse/meter !

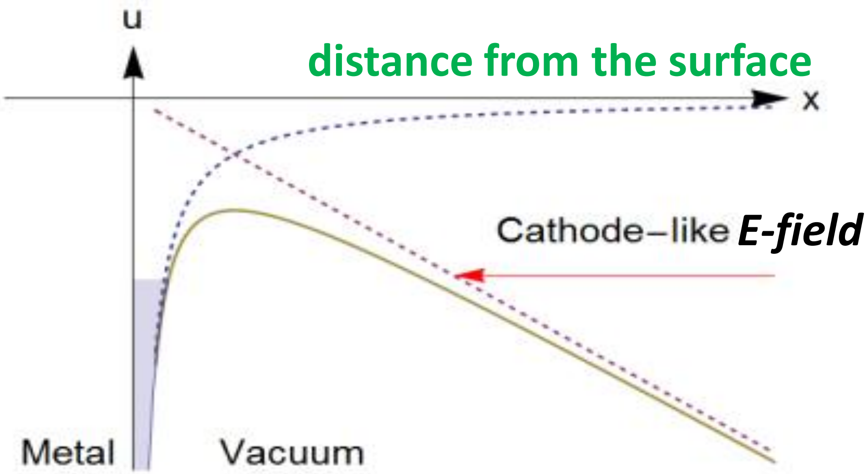
❑ Our alternate approach: using cavities with a mode at a harmonic frequency operating together with the fundamental mode to reduce RF power requirements.

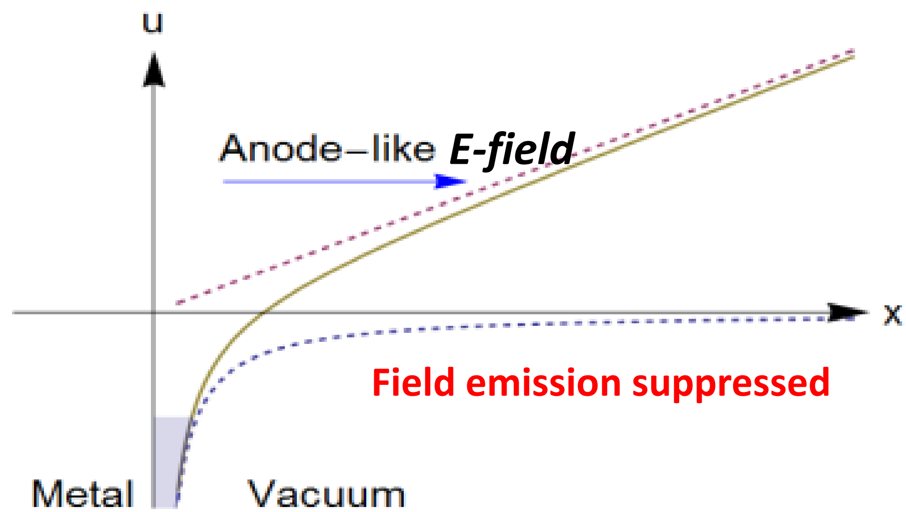
❑ Multimode operation could suppress RF breakdown via (a) "anode-cathode" effect; and/or (b) "quadratic dependence" effect.

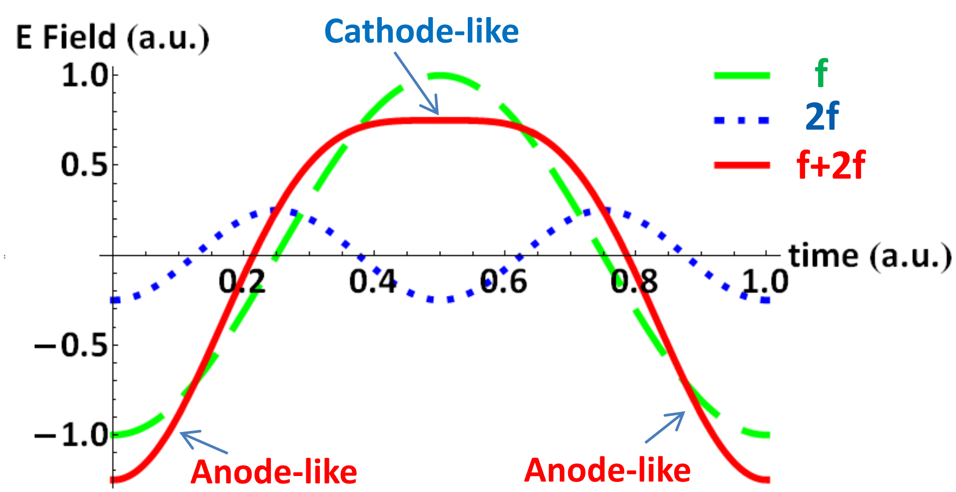
❑ Another approach is a 2-beam accelerator scheme, possibly with multi-mode cavities.

Motivation I: Field Emission

potential energy of an electron near metal surface



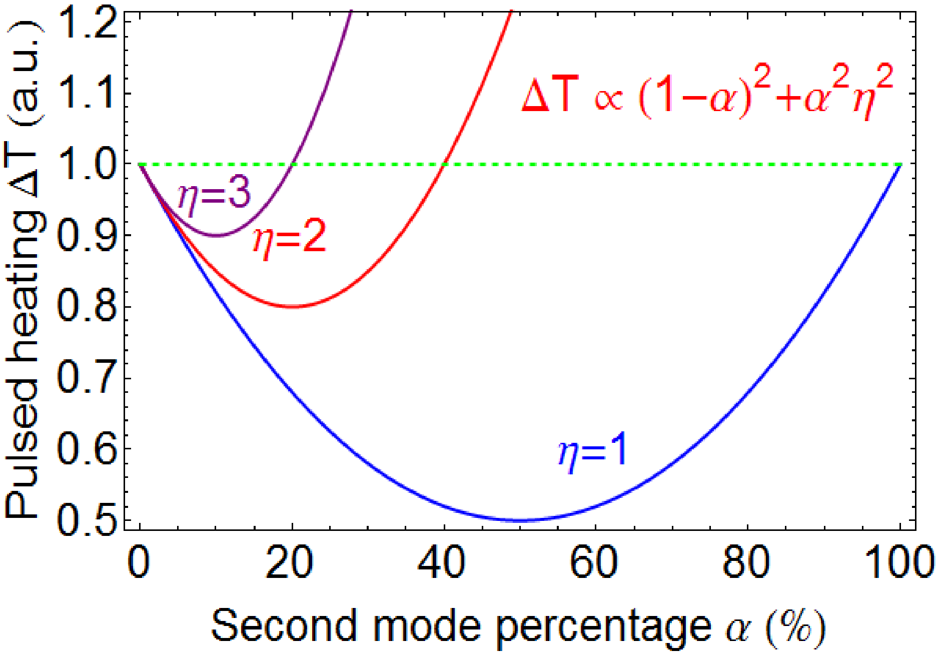




<u>"Anode – Cathode" Effect</u>

two harmonic mode superposition should suppress field emission

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

<u>"Quadratic Dependence" Effect</u>

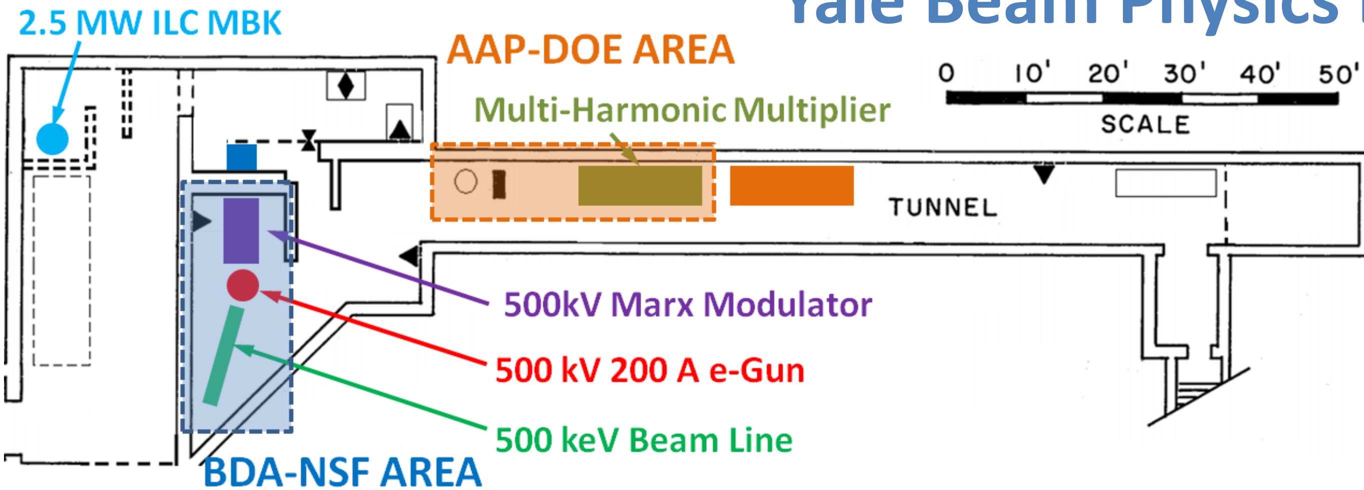
$$\exists\alpha \quad (1-\alpha)^2 + \alpha^2\eta^2 < 1$$

Similarly for modified Poynting vector S_c and total required RF power P_{total}

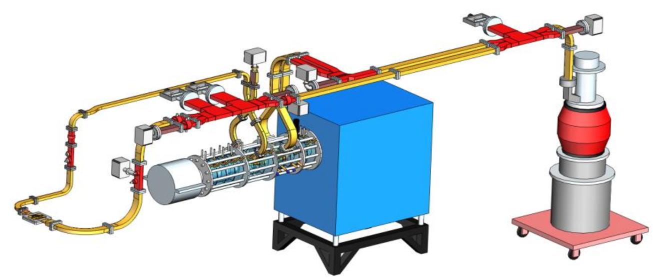
So two harmonic mode superposition could suppress pulsed heating.

Two Research Projects at Yale

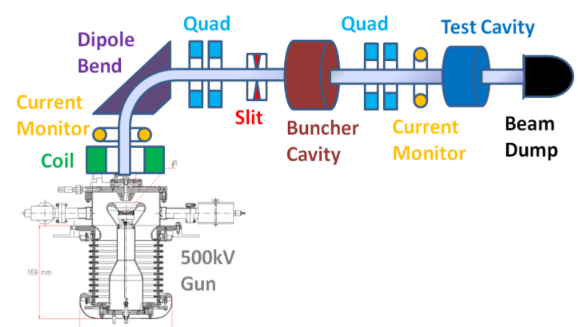
Yale Beam Physics Lab



RF Driven Bimodal Cavity Experiment



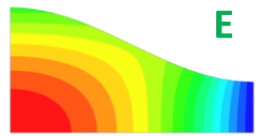
Beam Driven Bimodal Cavity Experiment



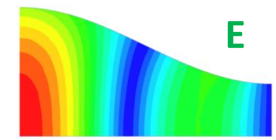
RF Properties of Anode-Cathode Cavity

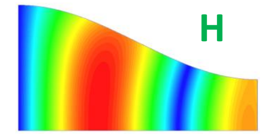
TM_{010}+TM_{020} Cavity

TM_{010} 2.856 GHz



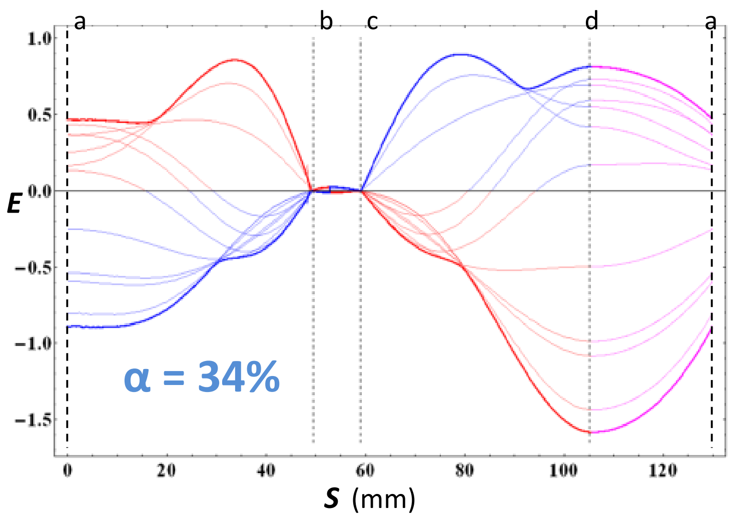
TM_{020} 5.712 GHz



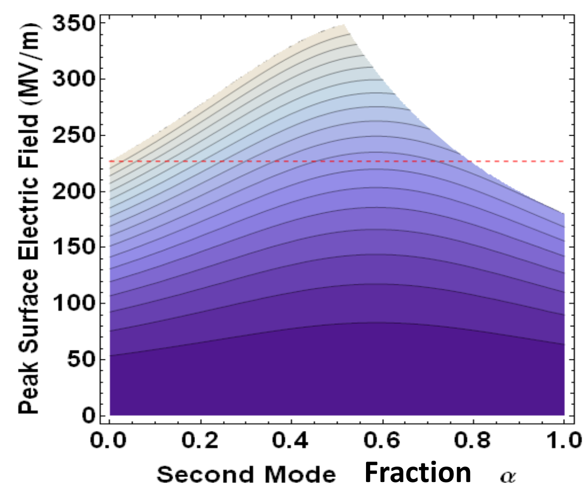


required RF power	1st harmonic alone	2nd harmonic alone	both modes
frequency (GHz)	2.856	5.712	66% f_1 and 34% f_2
P (MW) for E_{surf}= 100 MV/m	3.49	1.98	1.75
P (MW) for E_{surf}= 200 MV/m	13.97	7.92	7.21
P (MW) for E_{surf}= 300 MV/m	31.43	17.82	16.23

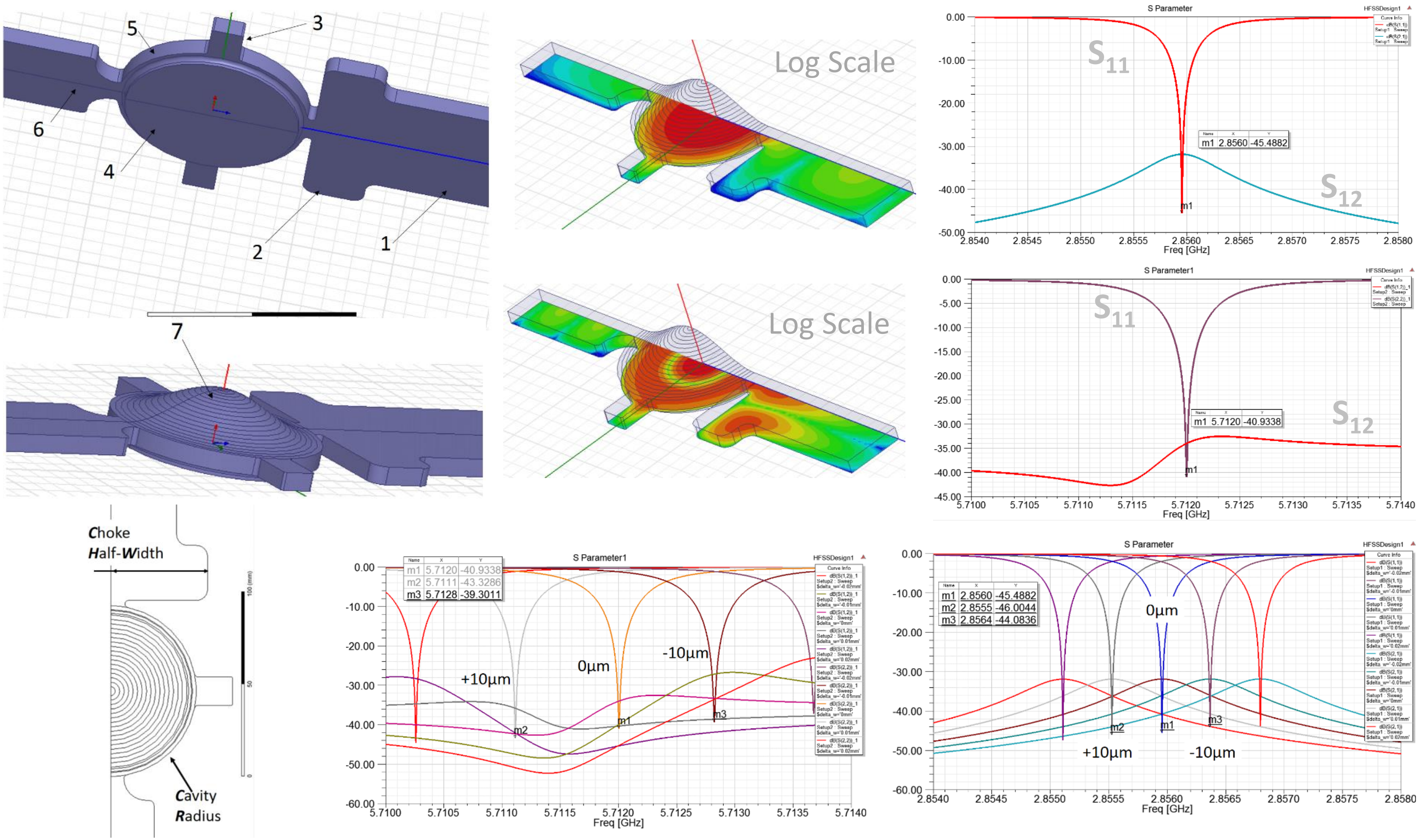
E-field distribution along cavity periphery *S*



peak surface E-field with 18 MW klystron power

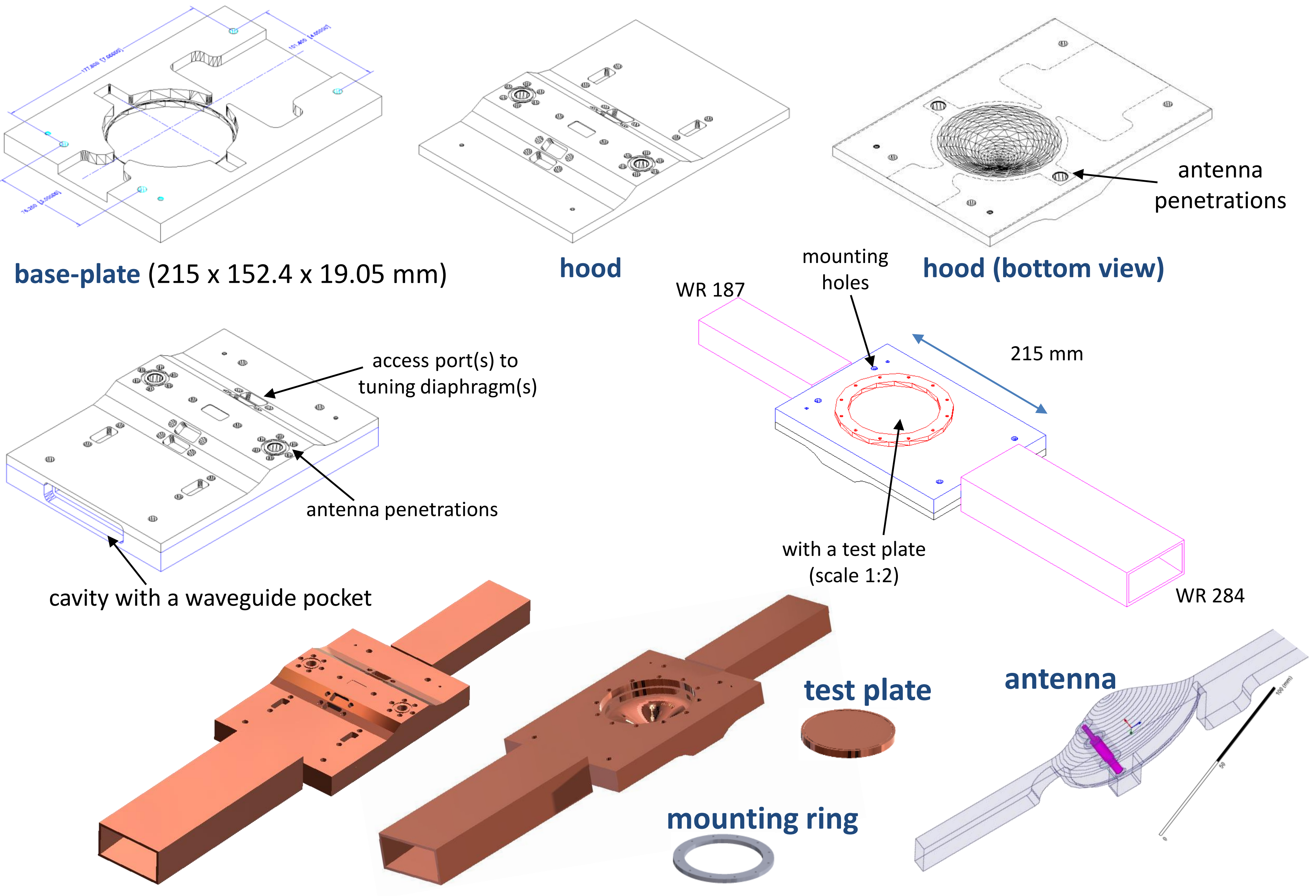


RF Design of Anode-Cathode Cavity



The tolerances are reasonable: (a) Cavity Radius 5µm; (b) Cavity Height 10µm; and (c) The other typical tolerances on other sizes vary from 15µm~100µm.

Engineering Design of Anode-Cathode Cavity

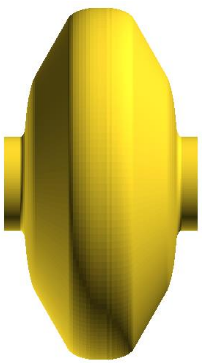


MHC : Pulsed Heating Suppression I

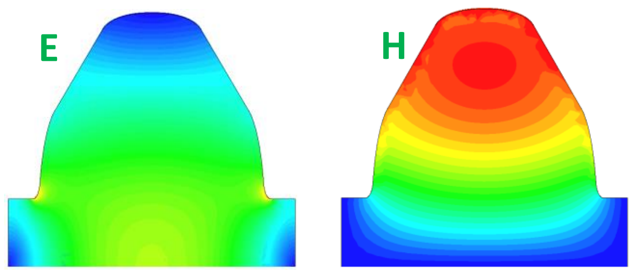
Symmetric Bimodal Cavity

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

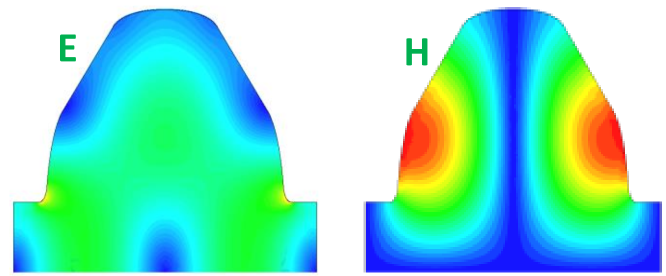
Quadratic Dependence Effect



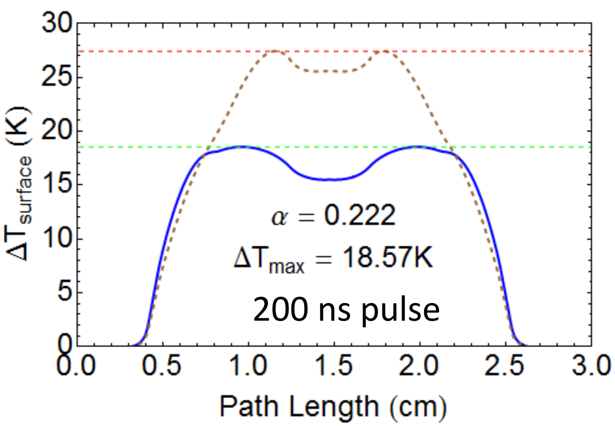
TM_{010} 12 GHz



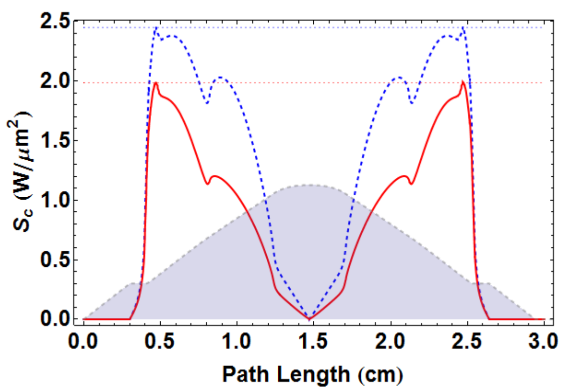
TM_{011} 24 GHz



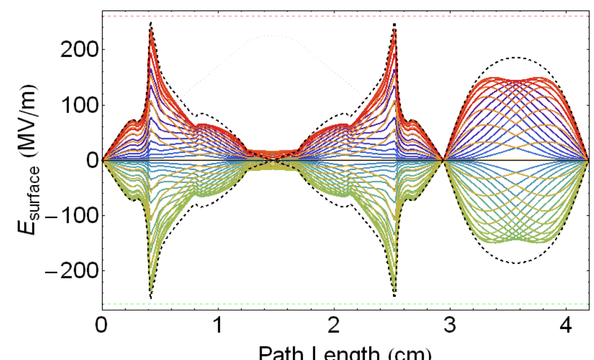
Pulsed temperature rise



modified Poynting vector S_c



surface E-field along periphery



Effective acceleration gradient 100 MV/m

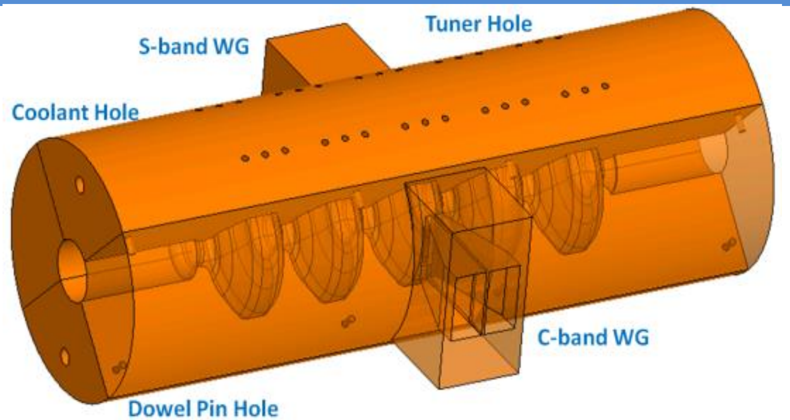
TM_{010}+TM_{011} Cavity

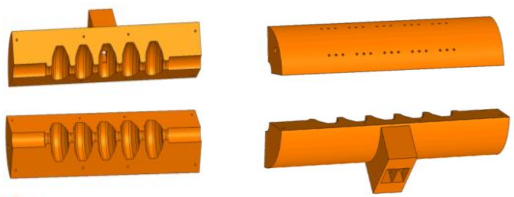
a/λ=0.12 π mode standing wave effective gradient E_{acc}=100MV/m	 TM_{010} + TM_{011} Bimodal Cavity			 Pillbox A	 Pillbox B	 Nose-cone
	1^{st} harmonic alone	2^{nd} harmonic alone	78% 1^{st} +22% 2^{nd}	1^{st} harmonic only	1^{st} harmonic only	1^{st} harmonic only
frequency (GHz)	11.9942	23.9884		11.9942	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

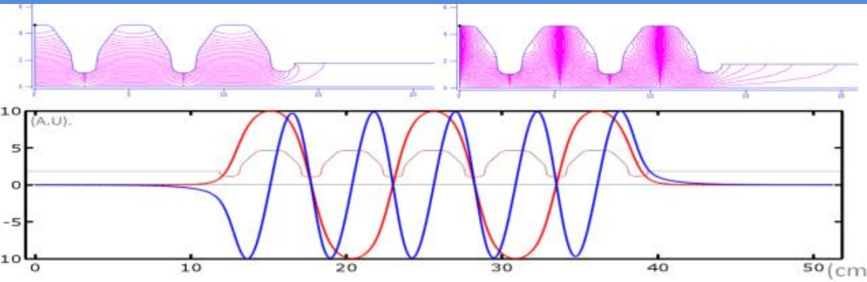
2-mode superposition compared to fundamental mode alone in the same MHC :

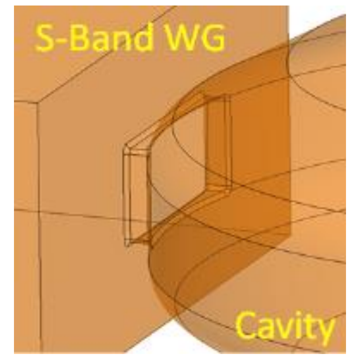
- □ pulsed heating temperature ↓32%
- □ total required RF power ↓ 27%
- □ maximum modified Poynting vector S_c ↓ 20%
- □ effective shunt impedance ↑ 37%

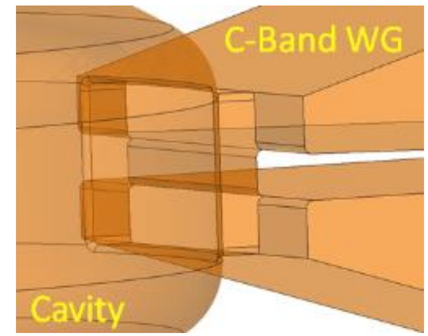
Symmetric Bimodal Cavity Structure

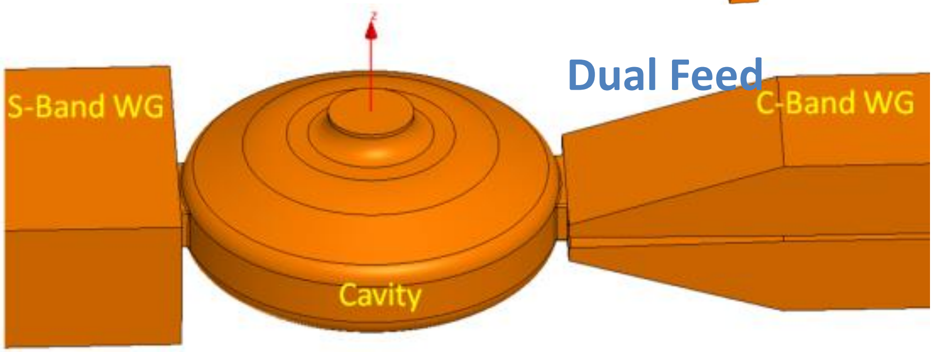




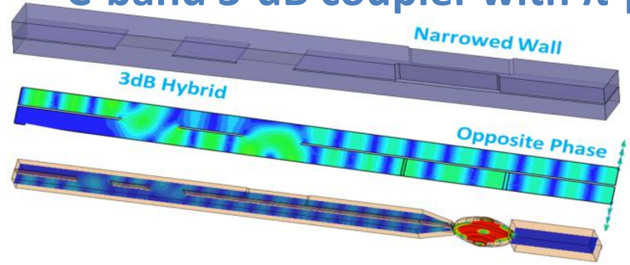


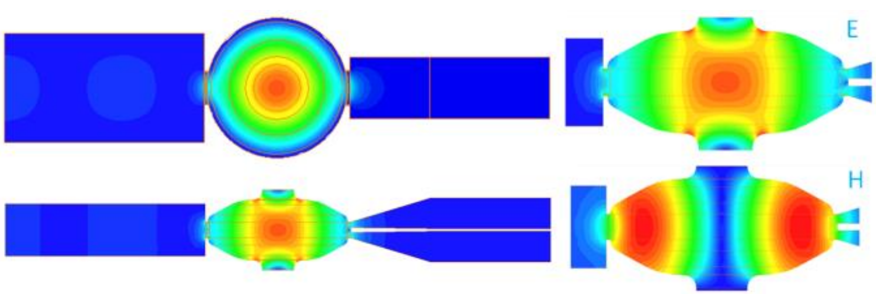


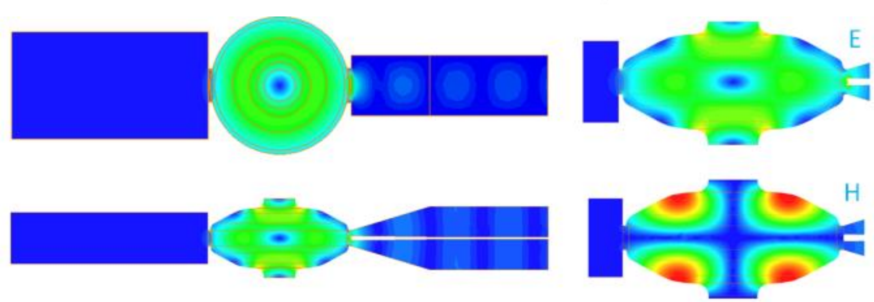




C-band 3-dB coupler with π-phase shift

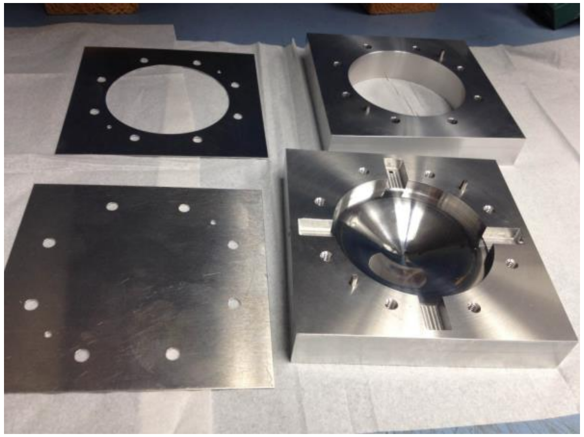


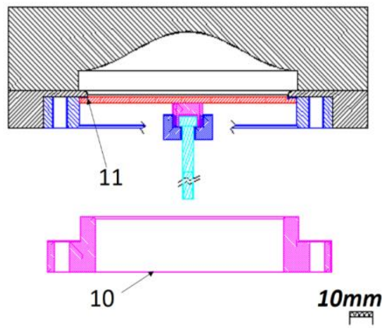


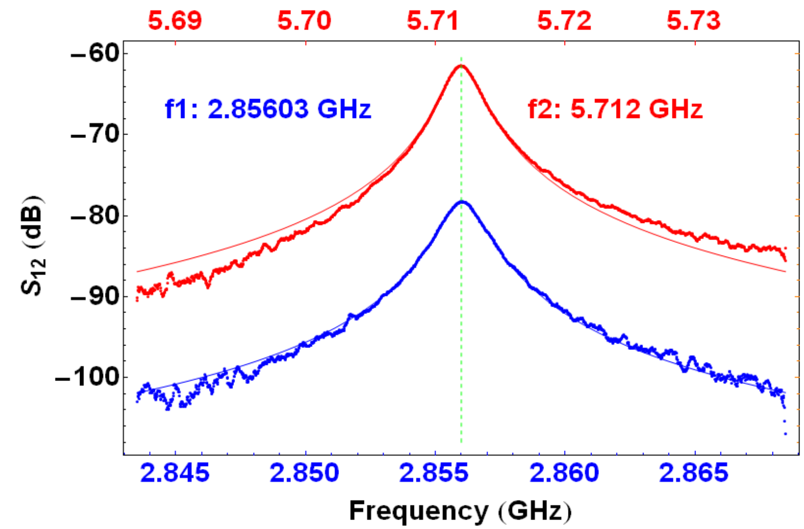


Two Frequency Tuning of Bimodal Cavity

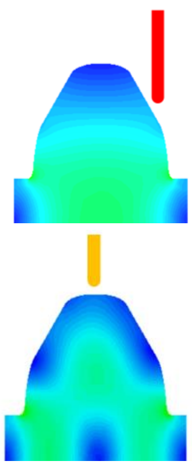
Anode-Cathode Cavity

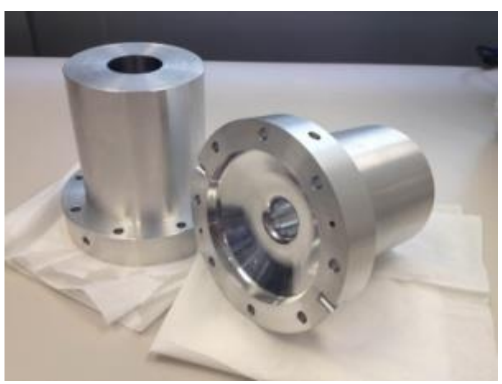


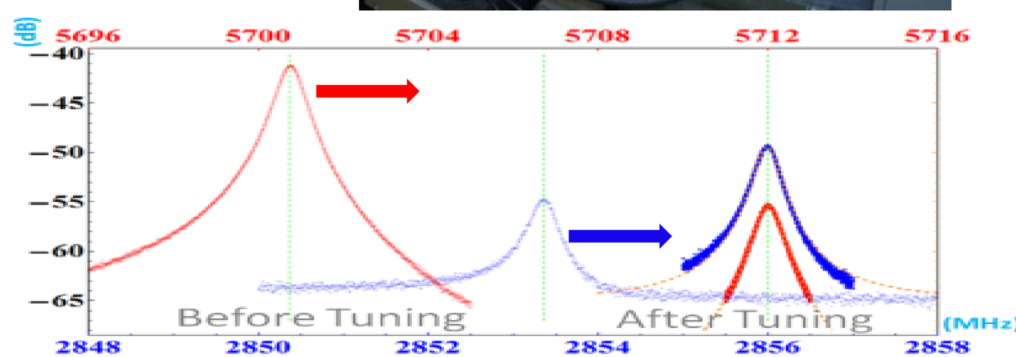




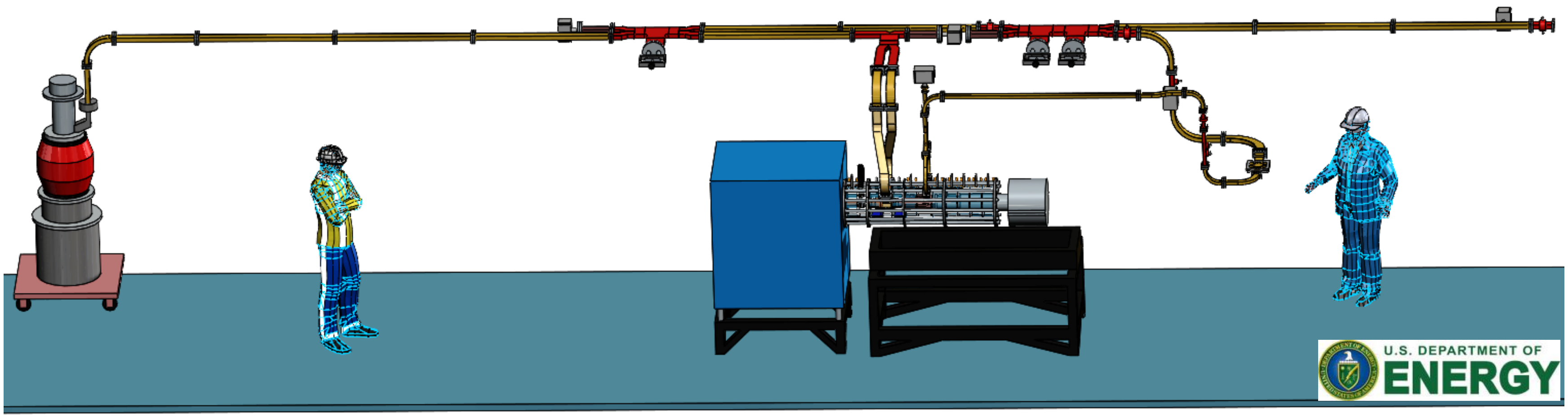
Symmetric Bimodal Cavity

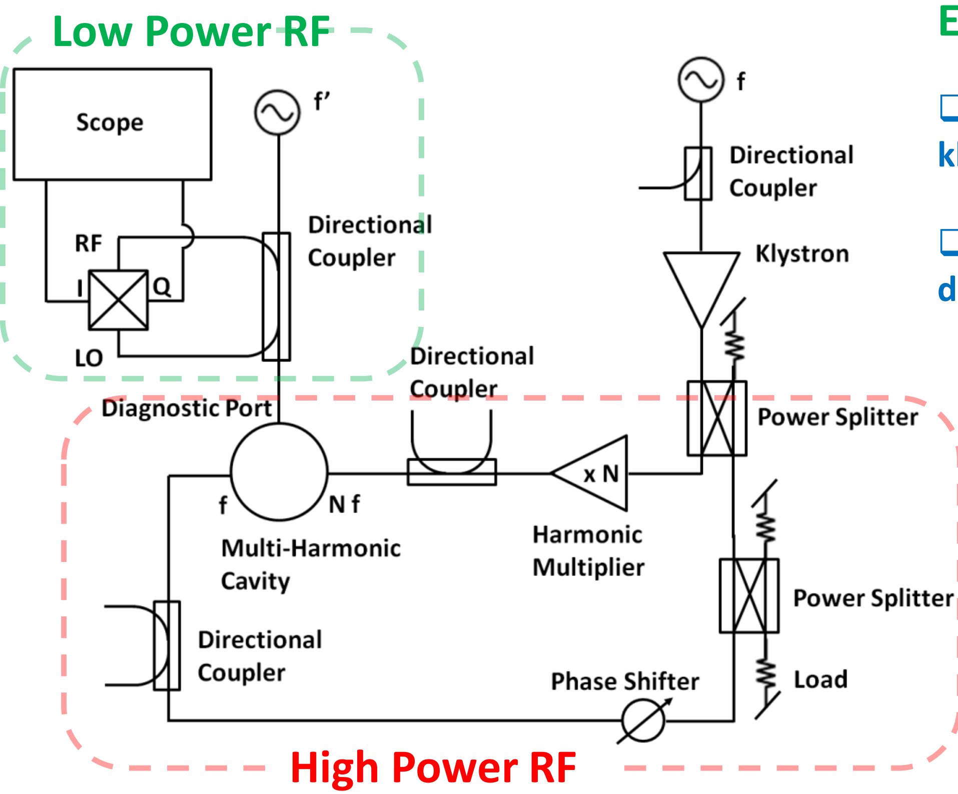






RF Breakdown and Pulsed Heating Experiment

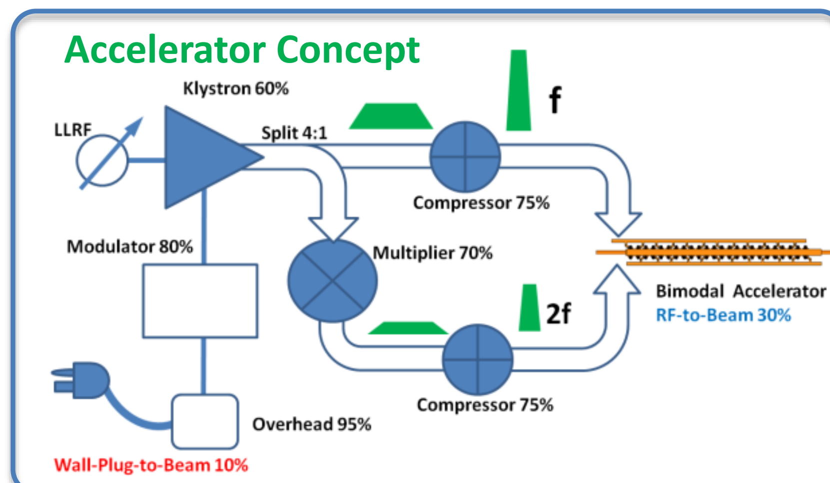




Experimental Schematic

❑ High power RFs at frequencies *f* and N*f* generated by the klystron and harmonic multiplier

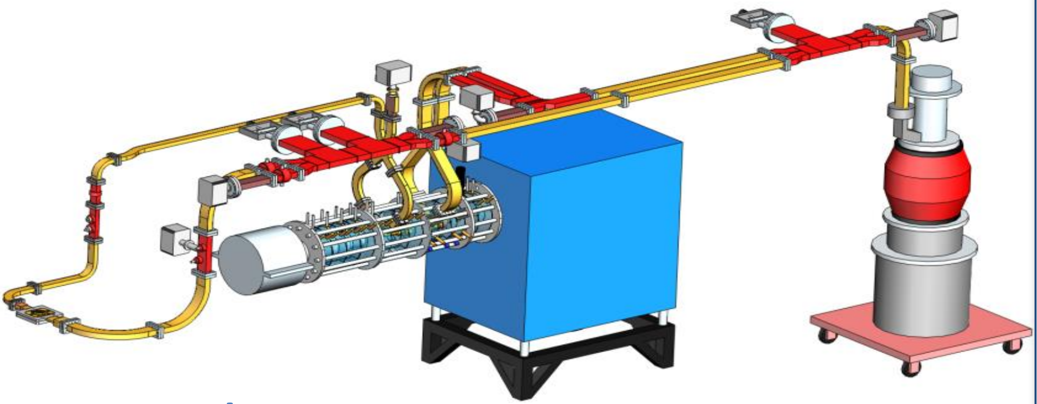
❑ Low power RF at a different frequency *f'* to excite the diagnostic mode and measure cavity *Q*



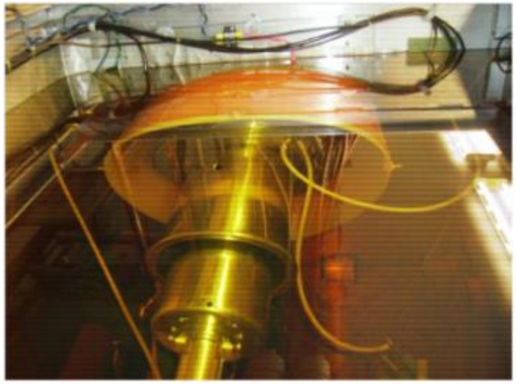
Progress of Harmonic Multiplier

Nominal operating parameters

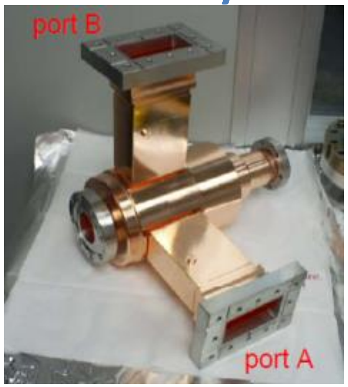
Output frequency	5.712 GHz
RF input power at 2.856 GHz	6.0 MW
Beam voltage and power at 20 A	250 kV, 5.0 MW
RF output power	5.3 MW
Harmonic power multiplication factor	0.88
Overall efficiency	48%



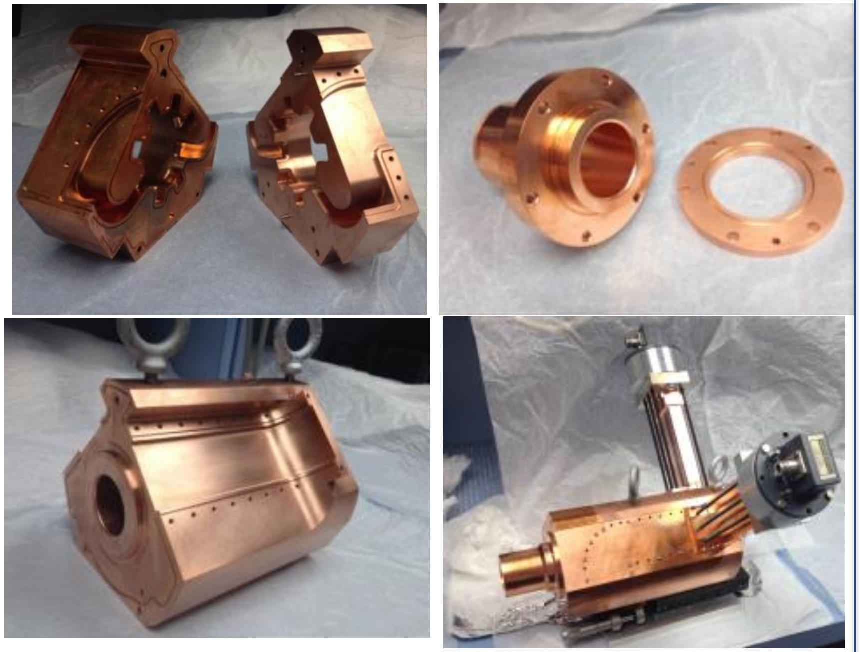
Gun Tank



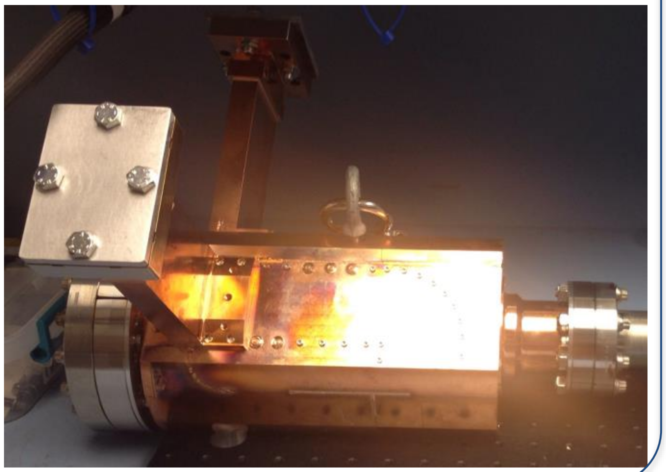
Drive Cavity



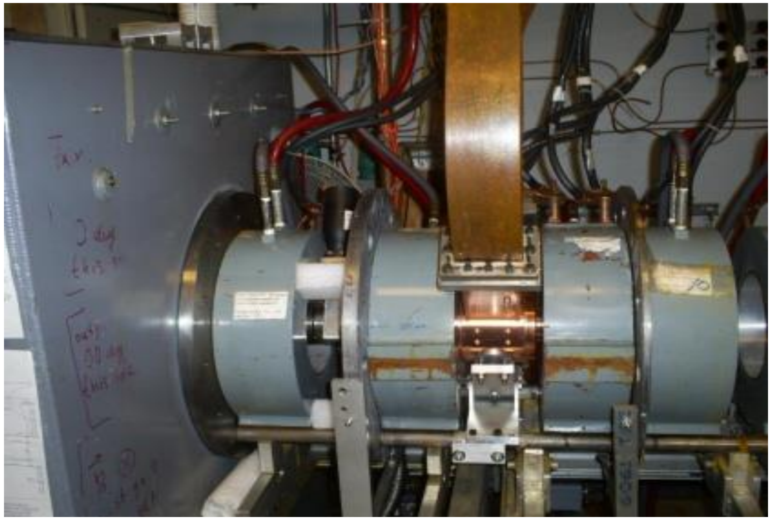
Output Cavity

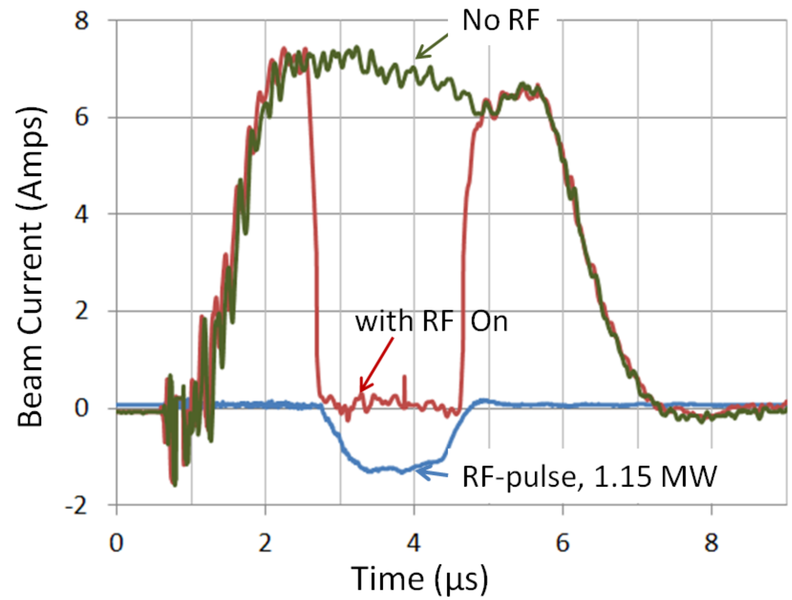


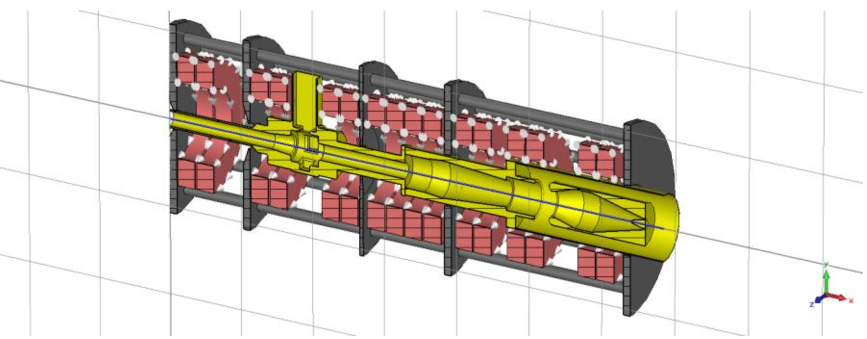
finally

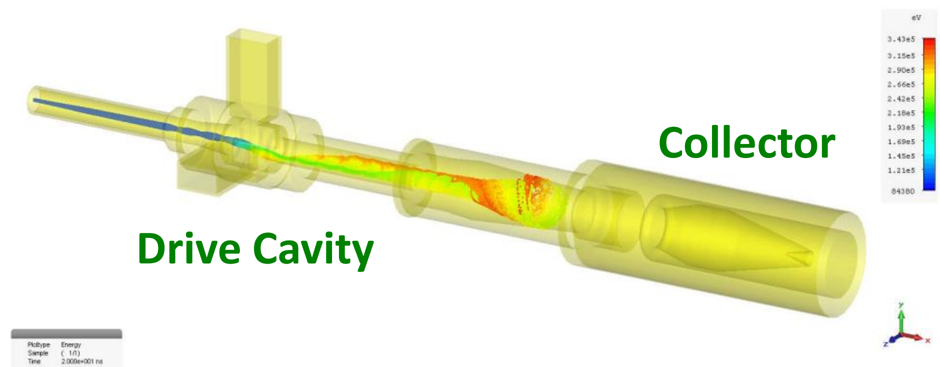


Harmonic Multiplier Drive Cavity Test





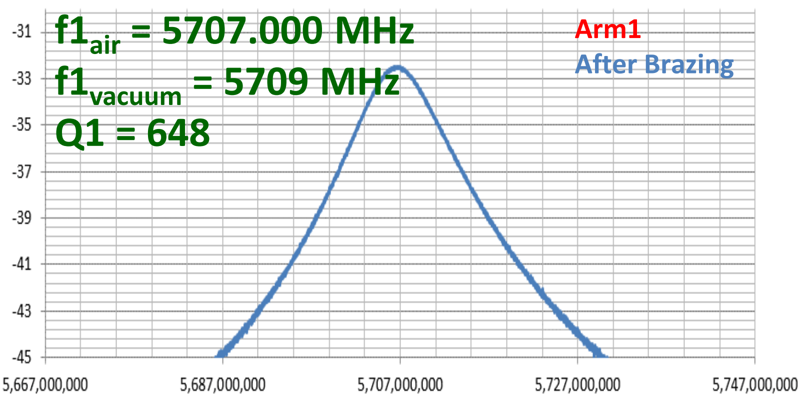


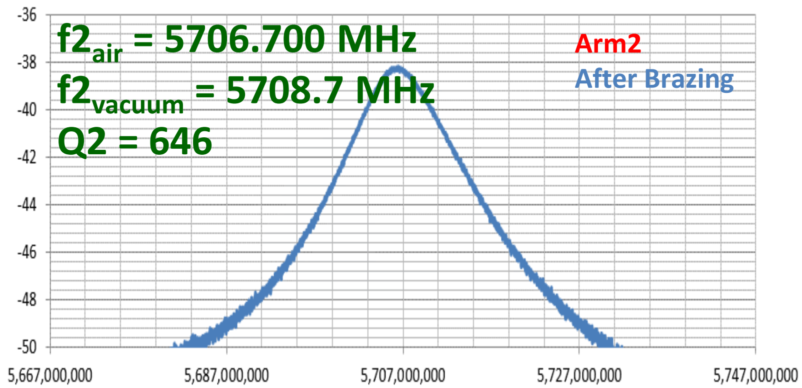


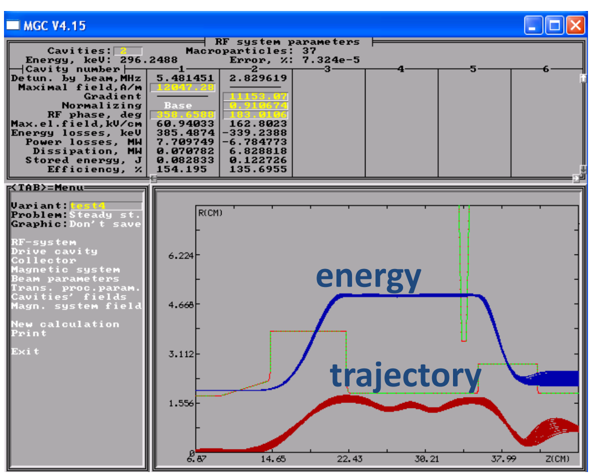
Drive cavity of second harmonic multiplier installed and tested.

CST Simulation to understand the beam transmission to the collector

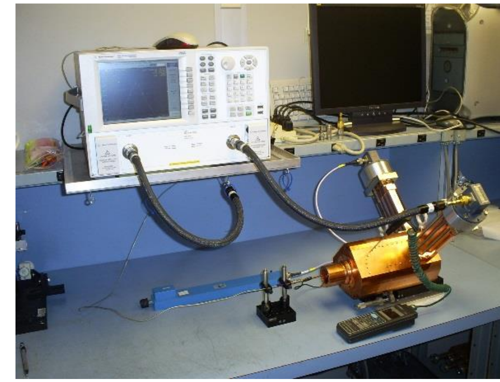
Cold Test of Harmonic Multiplier Output Cavity



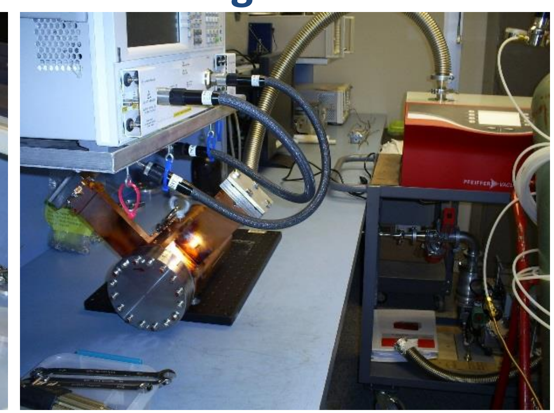


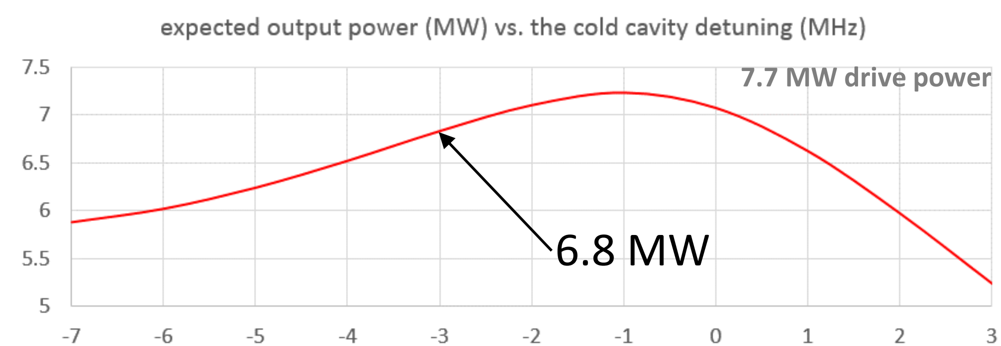


Cold Test Before Brazing



Cold Test and Leak Check After Brazing





MHC : Pulsed Heating Suppression II

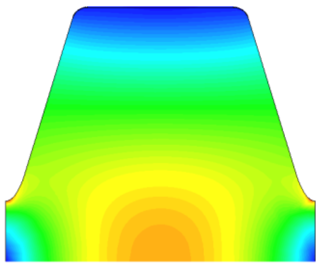
TM_{010}+TM_{012} (f + 3f)

elliptical cavity

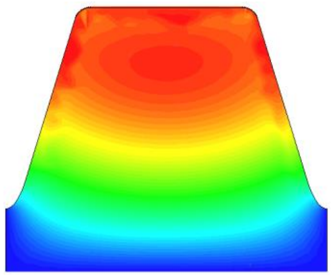
a/λ=0.1

TM_{010} 12 GHz

E

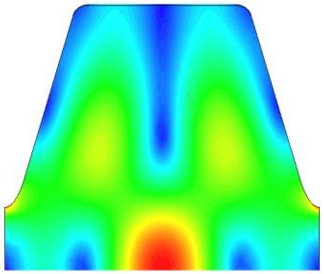


H



TM_{012} 36 GHz

E



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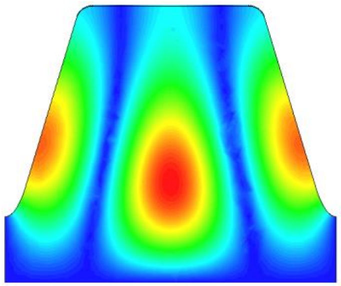
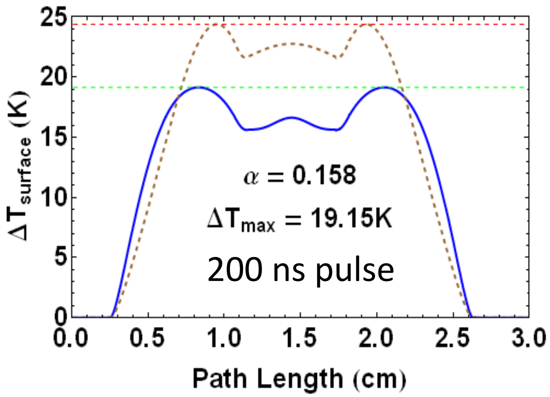
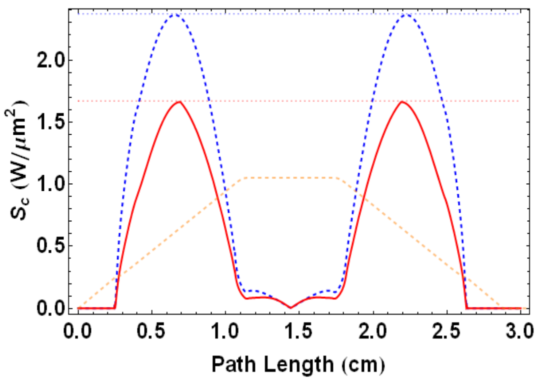


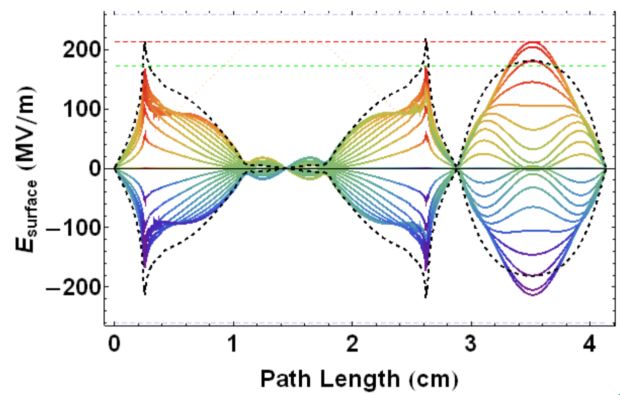
pulsed heating temperature



modified Poynting vector S_c



surface E-field along periphery



Effective acceleration gradient 100 MV/m

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

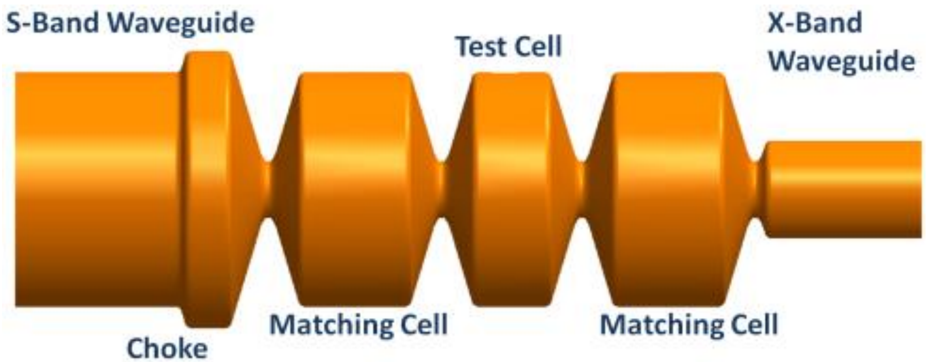
2-mode superposition compared to fundamental mode alone in the same MHC :

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

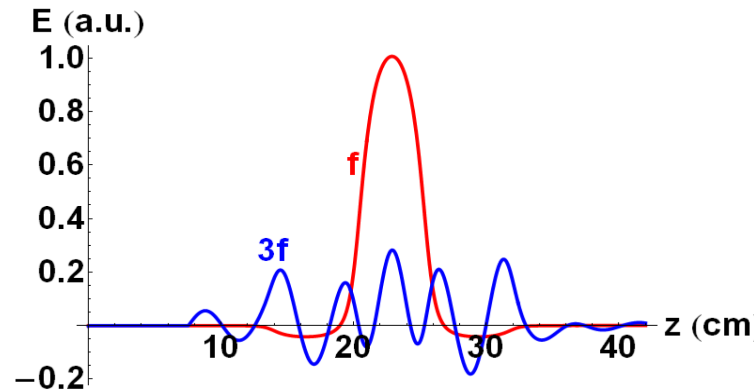
- ◊ pulsed heating temperature ↓22%
- ◊ effect shunt impedance ↑23%
- ◊ peak surface E-field ↓19.4%
- ◊ modified Poynting vector ↓30%
- ◊ total RF power ↓ 19%

Bimodal Cavity to Suppress Pulsed Heating

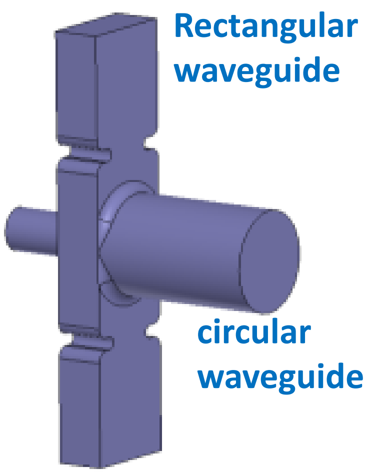
TM_{010} + TM_{012} Test Structure

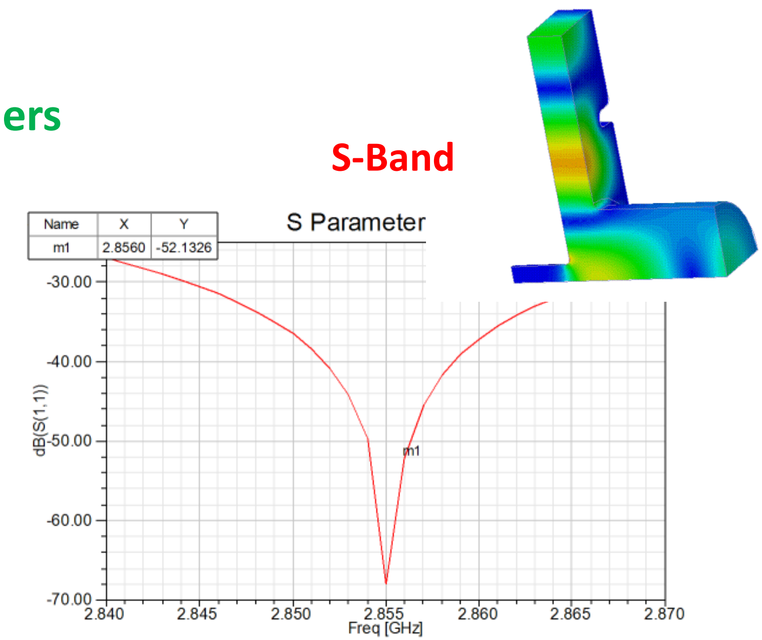


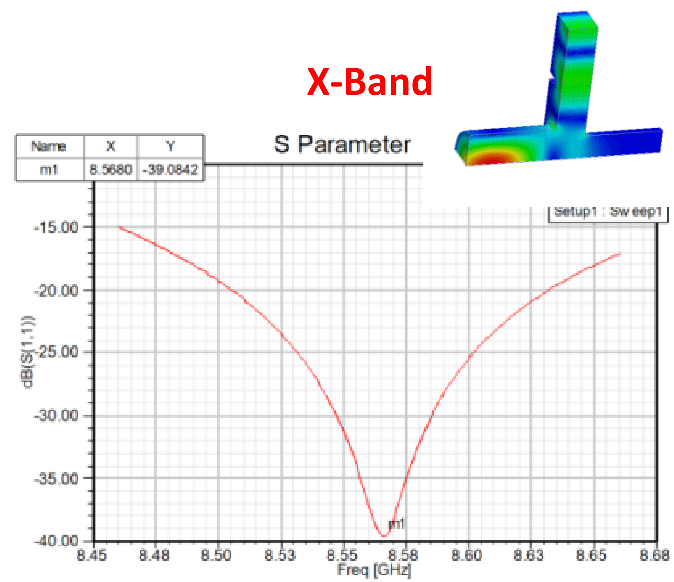
Axial E fields of TM_{010} and TM_{012}



TM_{01} mode launchers



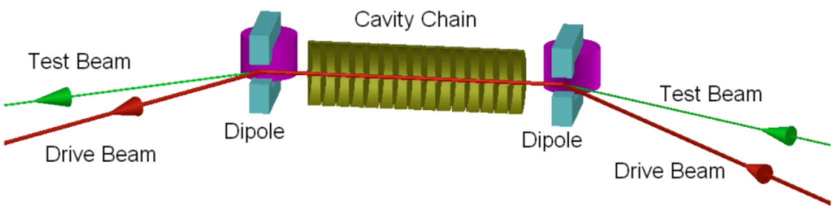


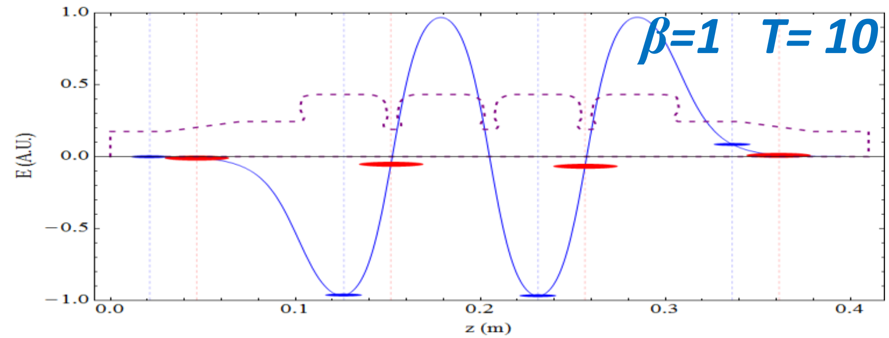


Detuned-Cavity Two-Beam Accelerator

Fixed Detuning

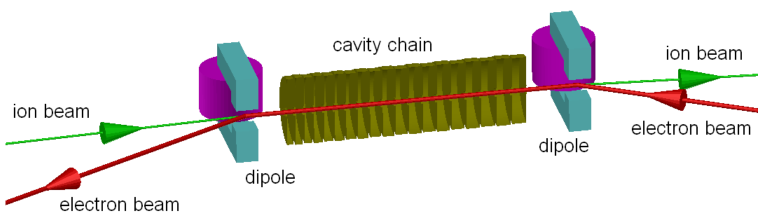
Co-propagate

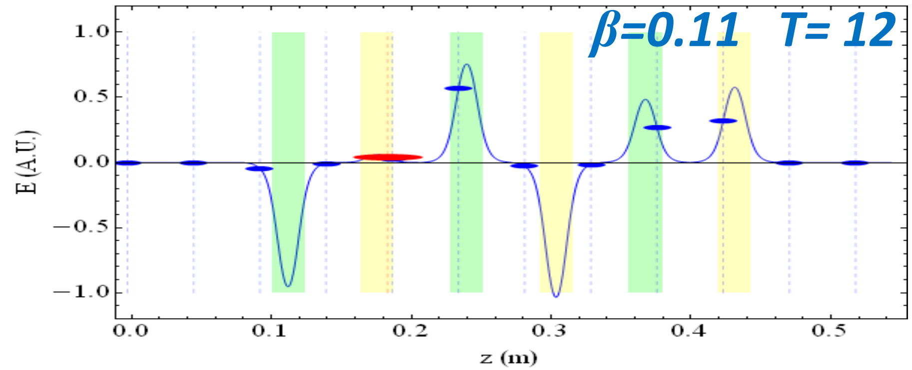


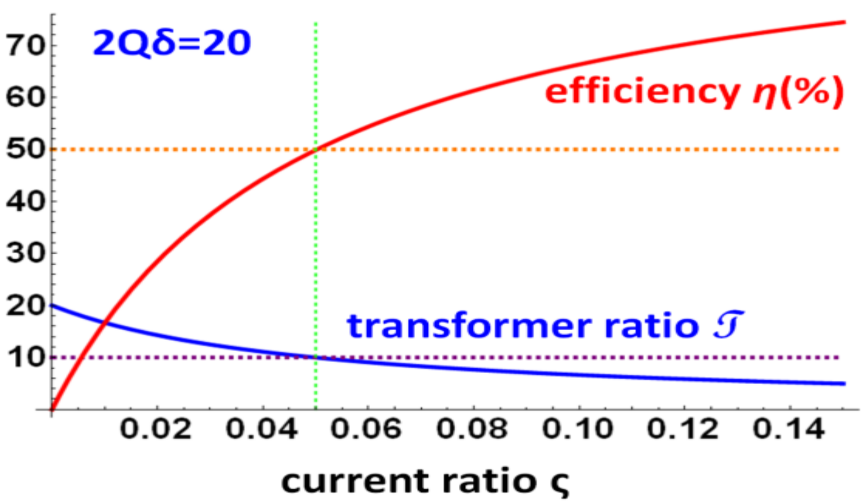


Alternative Detuning

Counter-propagate







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

Circuit Model for Collinear Two Beam Accelerator

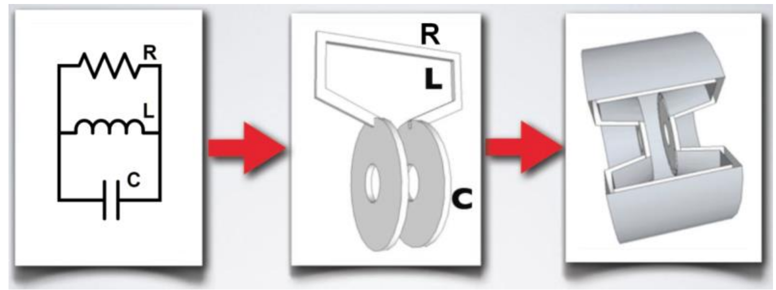
RLC Circuit Model

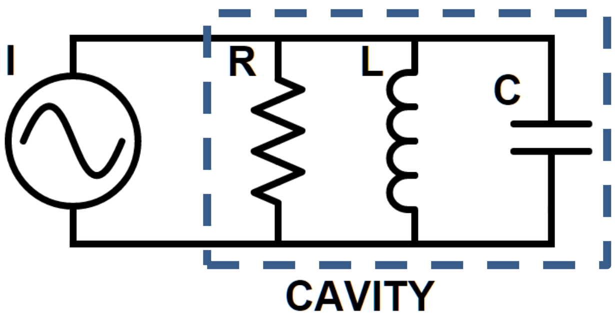
↓

Accelerating Cavity

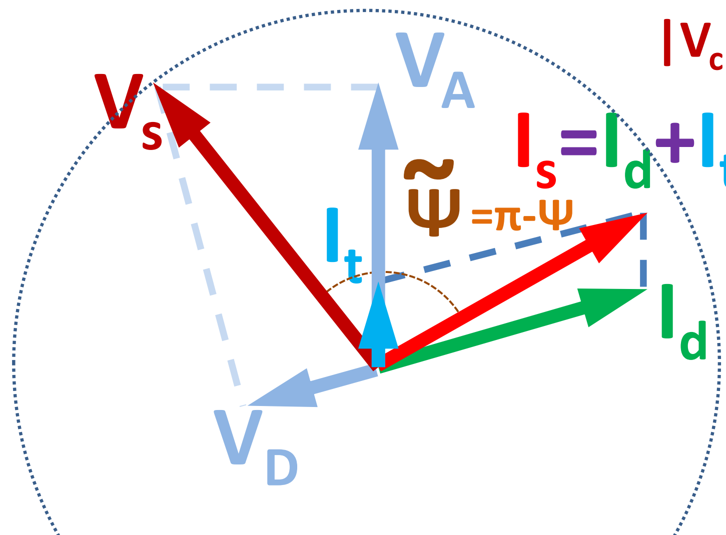
↓

Beam Cavity Interaction





$$V = \frac{IRe^{i\omega t}}{1 + i2Q\Delta\omega/\omega}$$

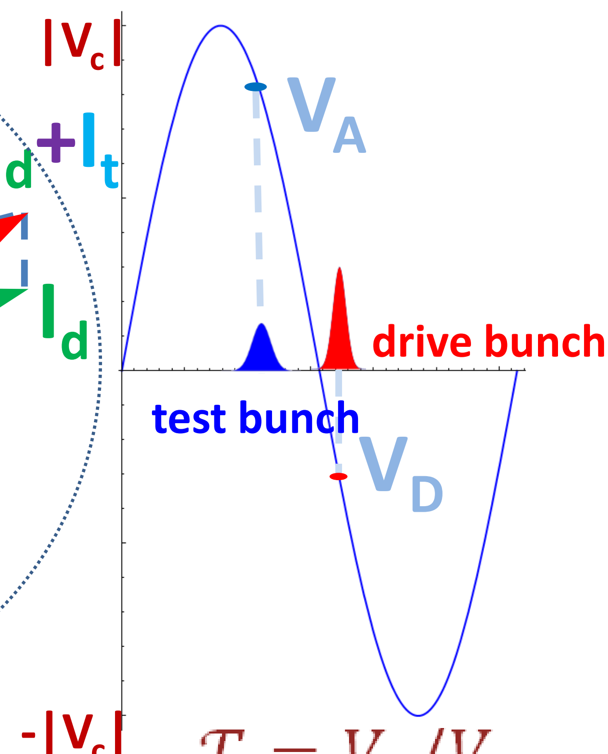


$$V_s = -(I_d + I_t)R\cos\Psi\, e^{i\Psi}$$

$$\Psi = -\arctan(2Q\Delta\omega/\omega)$$

$$V_A = I_t \Re(V_s/I_t)$$

$$V_D = I_d \Re(V_s/I_d)$$

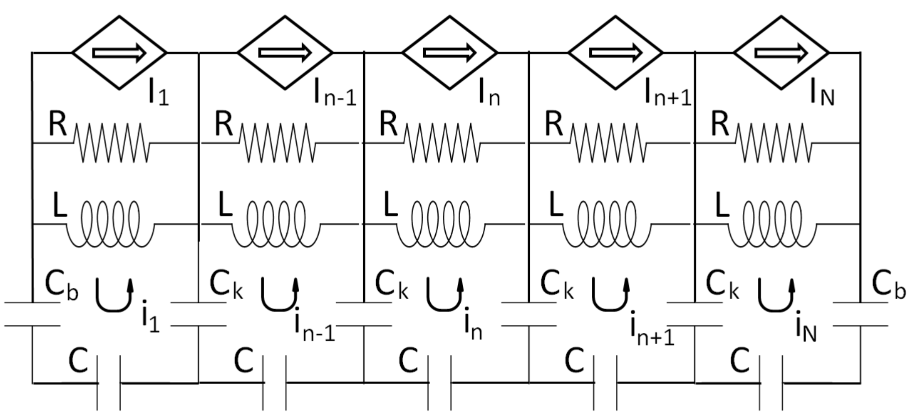


$$\mathcal{T} = V_A/V_D$$

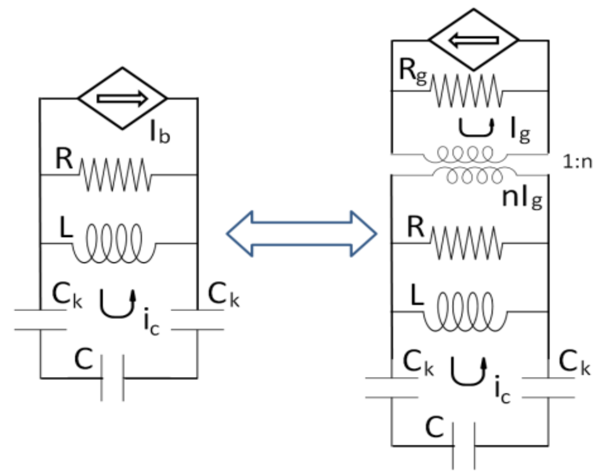
Circuit Model for Beam-Driven Structure

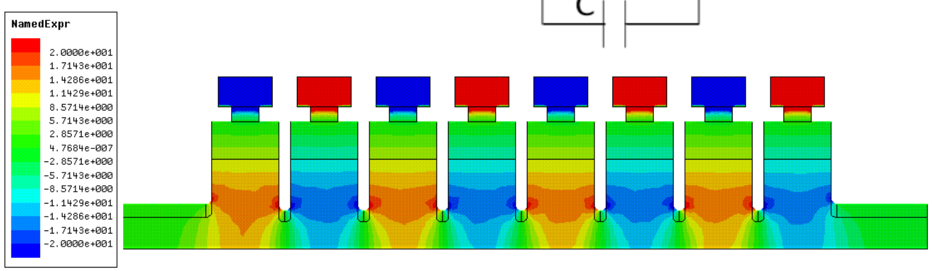
Modified Current Ratio	$\varsigma = I_T\Theta_T / I_D\Theta_D$
Transformer Ratio	$\mathcal{T} = \dfrac{\varsigma - 2\Delta}{2\Delta\varsigma + 1}$
Power Transfer Efficiency	$\eta = \dfrac{2\Delta\varsigma - \varsigma^2}{2\Delta\varsigma + 1}$
Normalized Electric Field	$\varepsilon = \dfrac{4\Delta - 2\varsigma}{1 + 4\Delta^2}$
Normalized Detuning Factor	$\Delta = Q(\Delta\omega / \omega)$
Transit Time Factor	Θ_T Θ_D

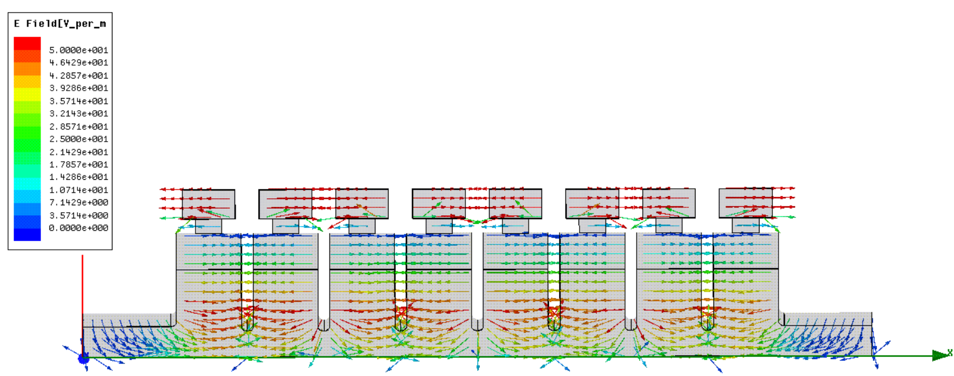
$\{\varsigma, \varepsilon, \mathcal{T}, \Delta, \eta\}$ these parameters are interrelated and only two are free parameters, the rest can be represented by any two parameters.



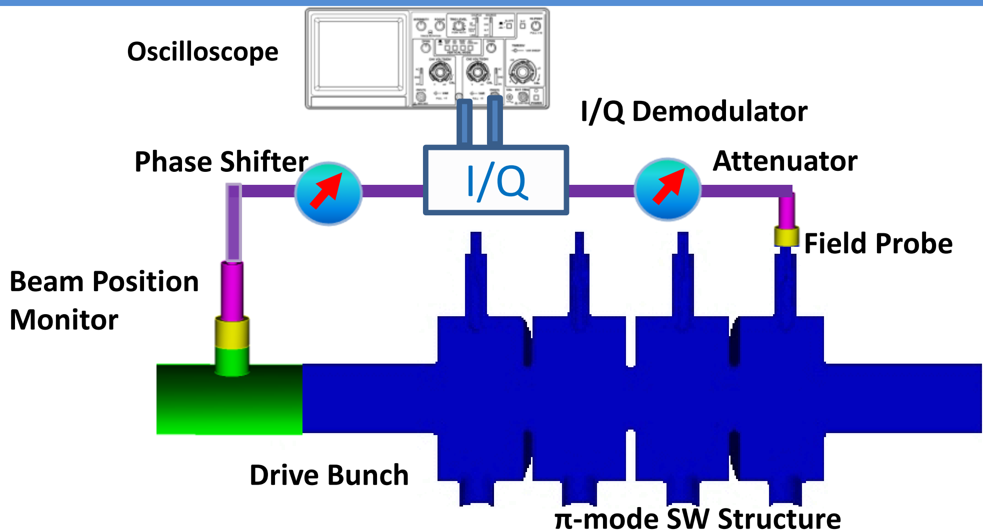
Use external rf source to mimic the drive beam to demonstrate the operating mode's field amplitude uniformity and correct synchronization phase



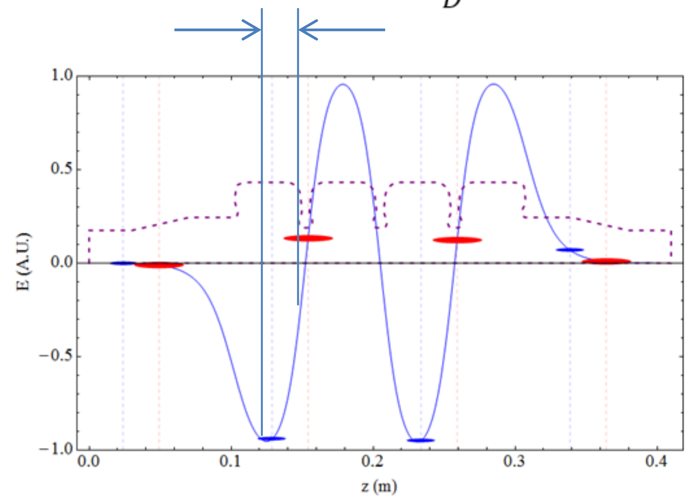




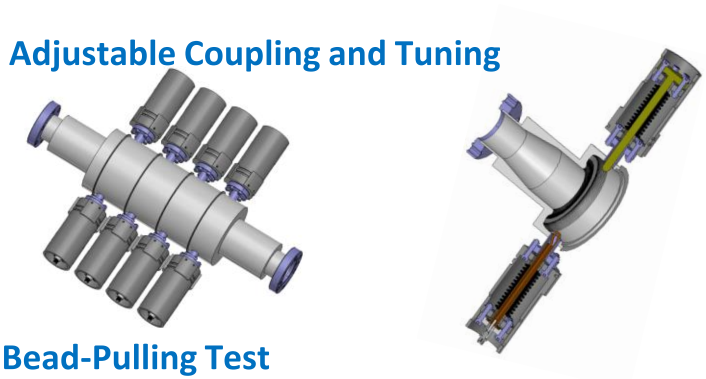
Single Mode TBA Experiment



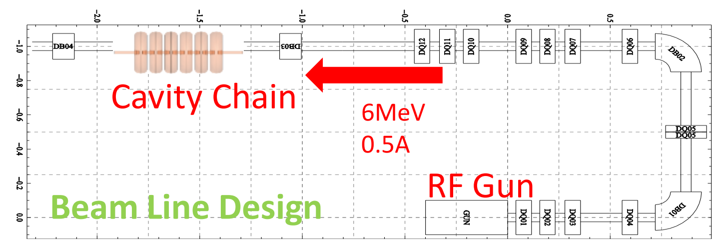
Detuning angle Δθ=ϕ $T = \frac{A}{D} = -\tan\phi = 2Q\delta$



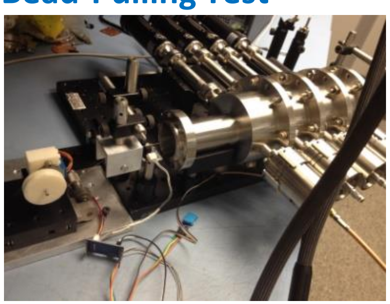
Adjustable Coupling and Tuning

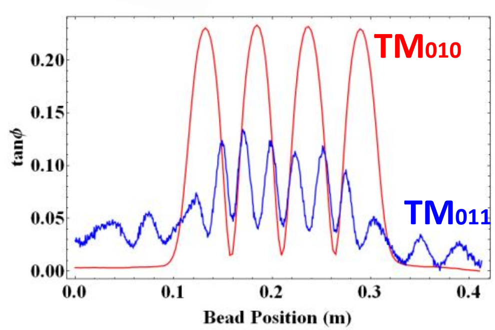


Transformer Ratio Measurement

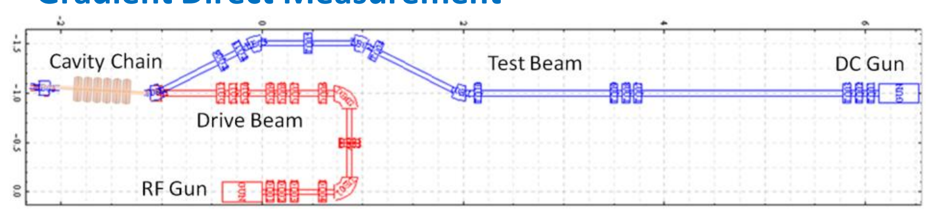


Bead-Pulling Test





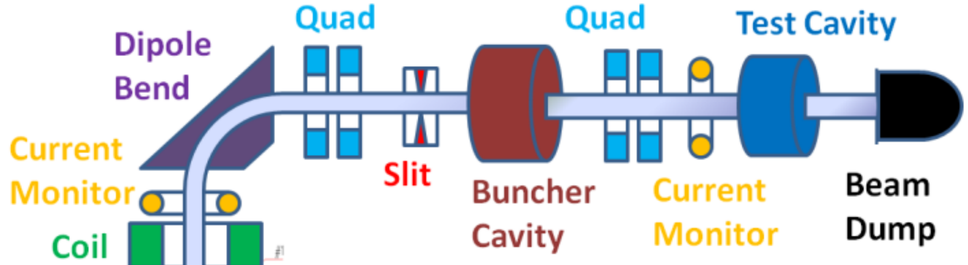
Gradient Direct Measurement

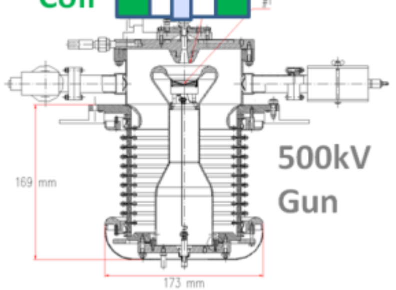


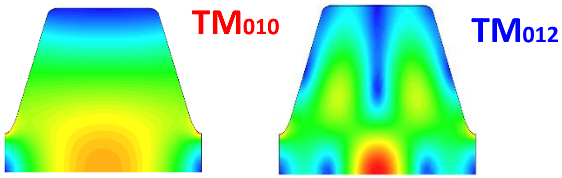
Bimodal TBA Experiment

Beam-Driven RF Breakdown Test of Bimodal Cavity

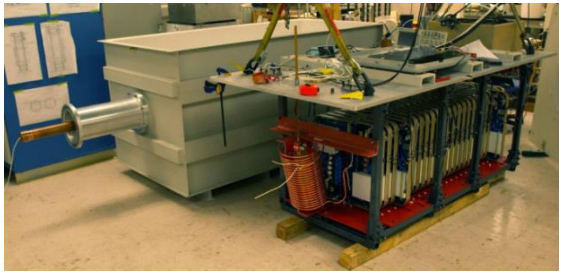
Supported by US NSF





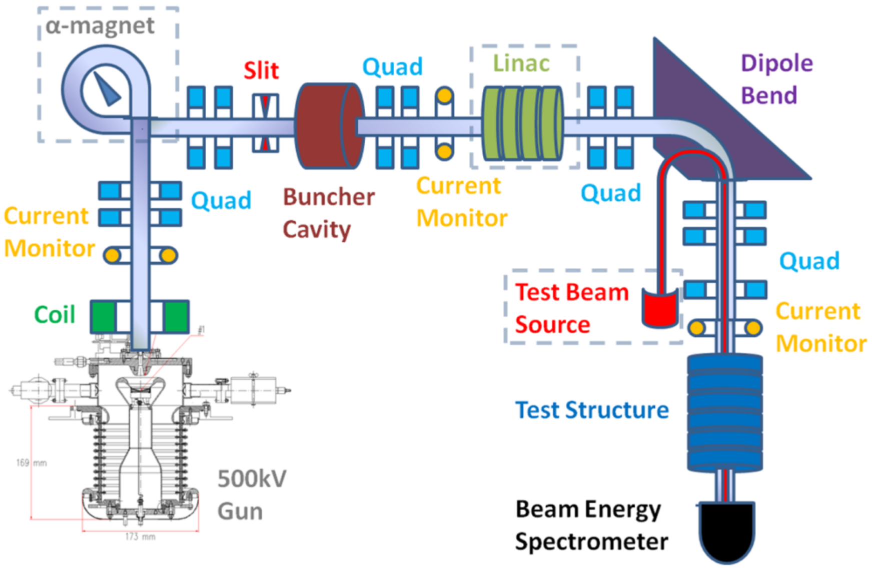


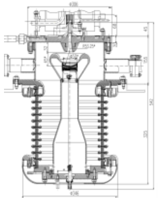
Electron Gun
500kV
220 A

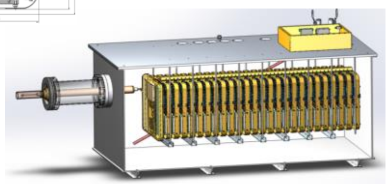


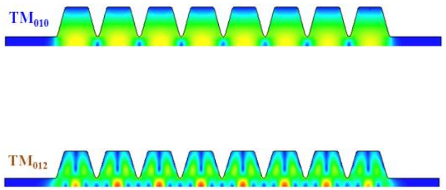
Solid State Marx Modulator
500kV
250 A
1.8 μs
20 Hz

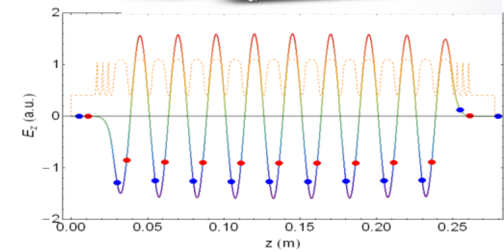
Bimodal TBA Structure Test





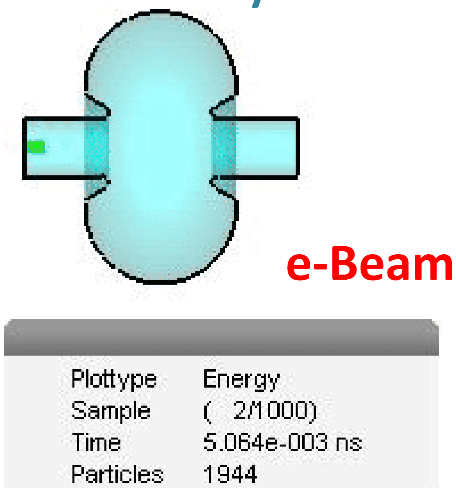




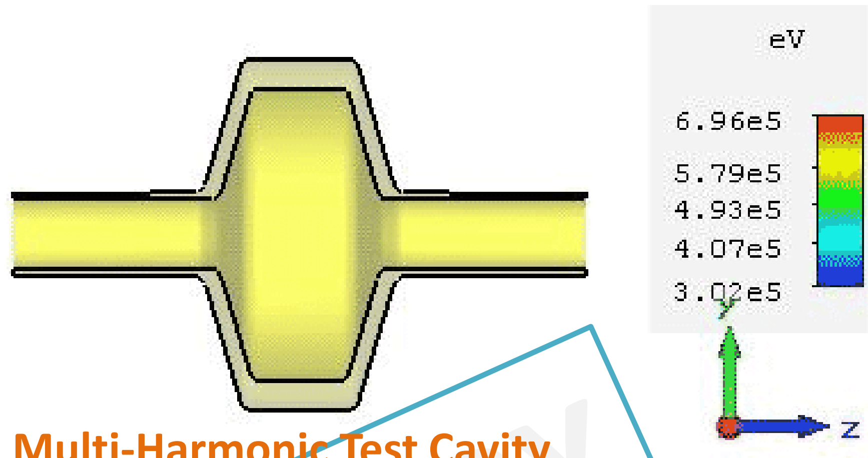


Simulation of Beam Bunching and Excitation

Buncher Cavity

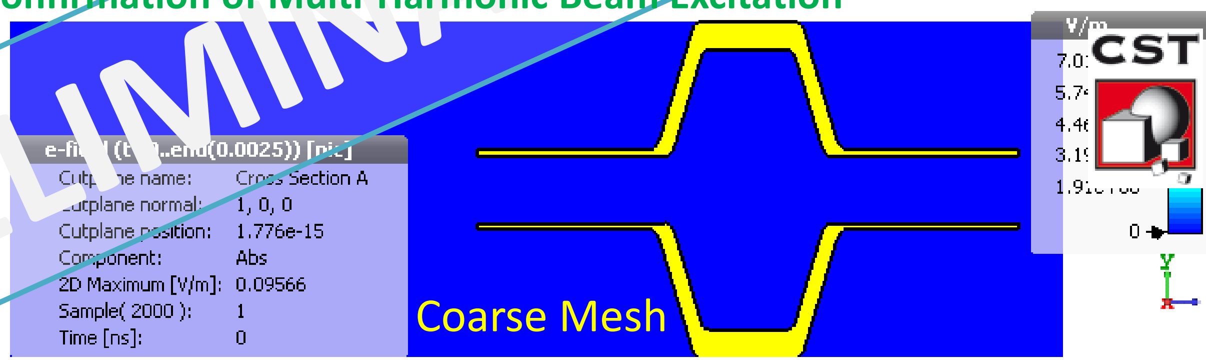


e-Beam

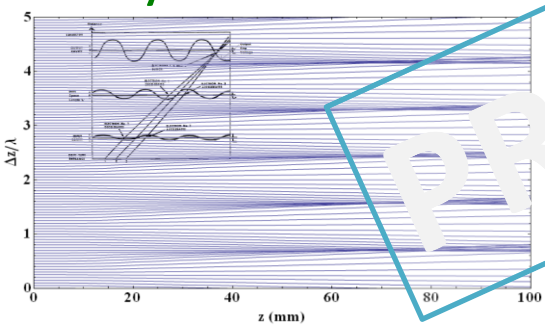


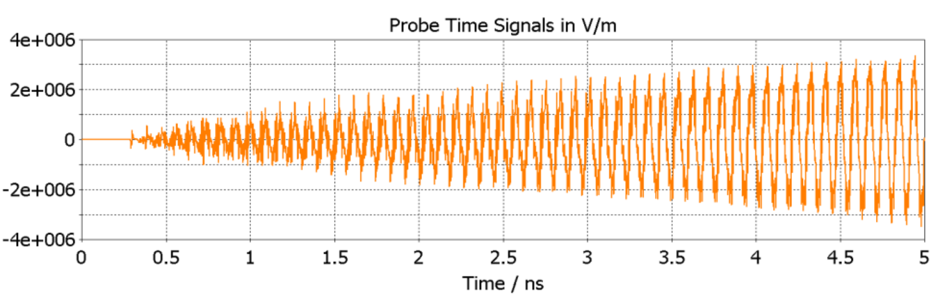
Multi-Harmonic Test Cavity

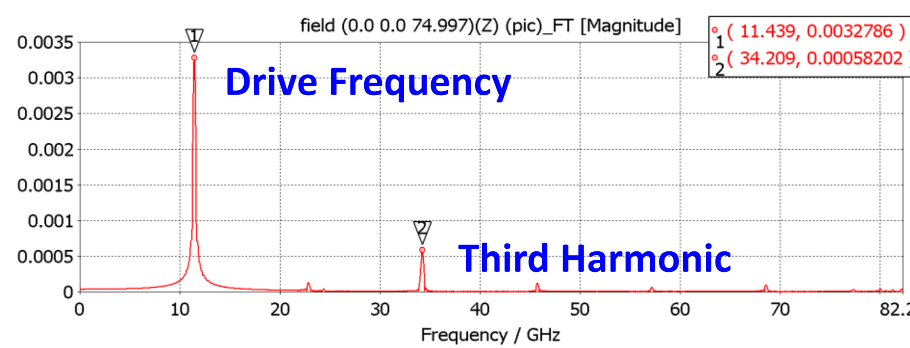
Confirmation of Multi-Harmonic Beam Excitation



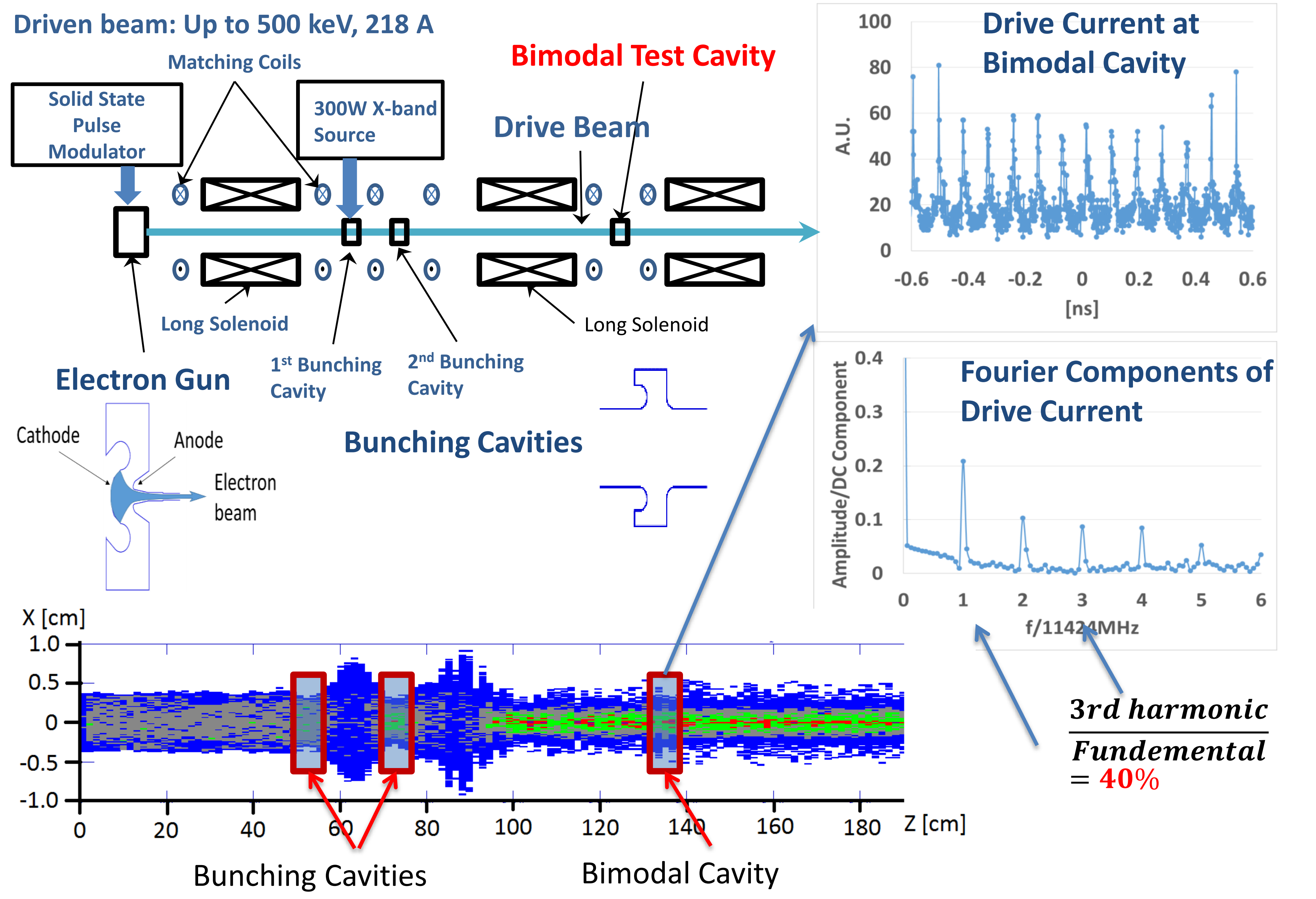
Velocity Modulation





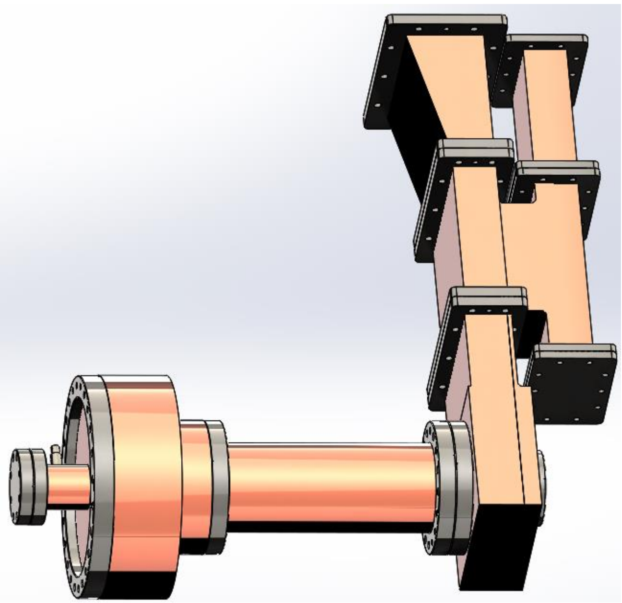


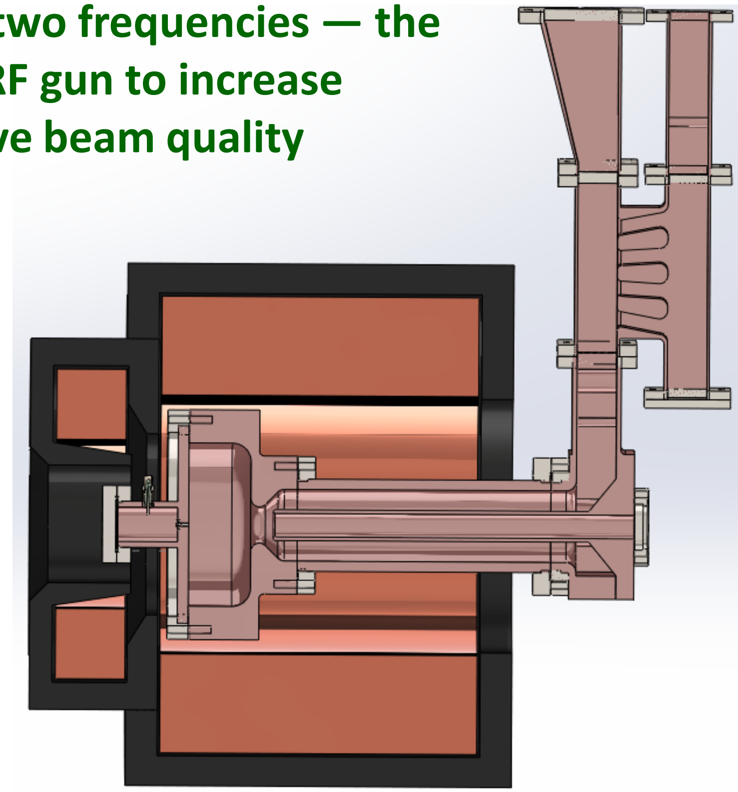
PARMELA Simulation of Beam Driven Bimodal Cavity

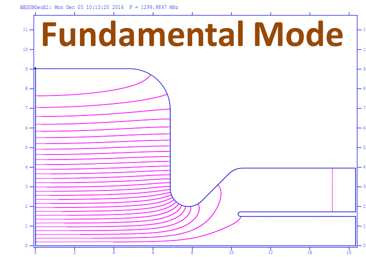


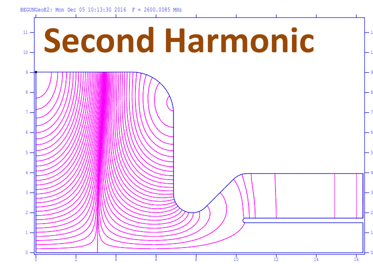
BIMODAL ELECTRON GUN

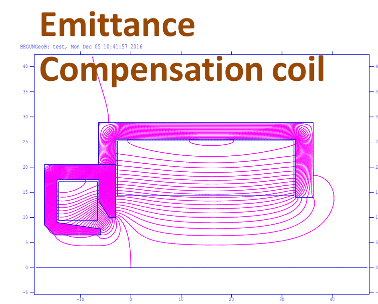
Superposition of microwaves at two frequencies — the first and second harmonic — in RF gun to increase acceleration gradient and improve beam quality



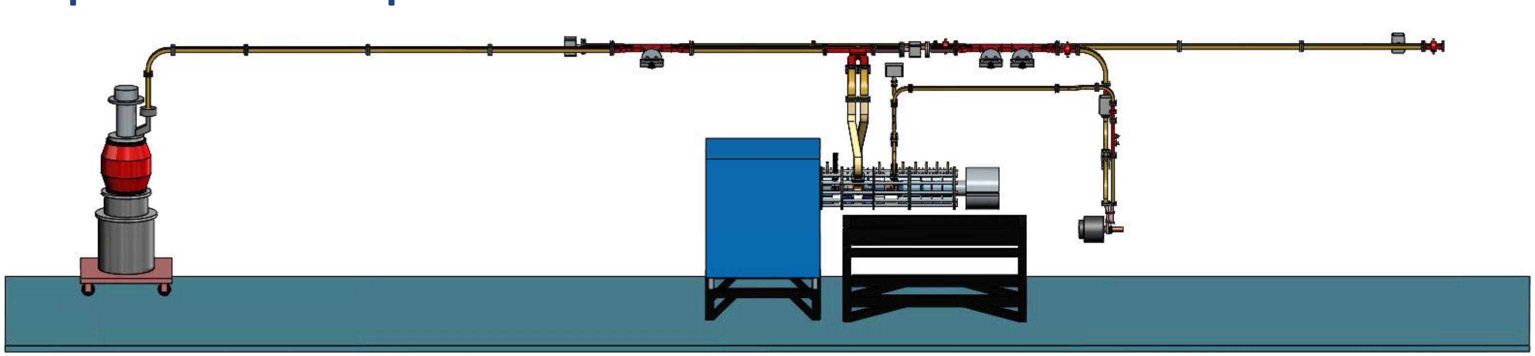


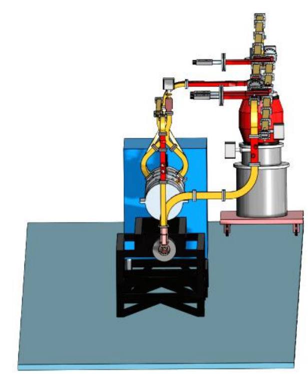




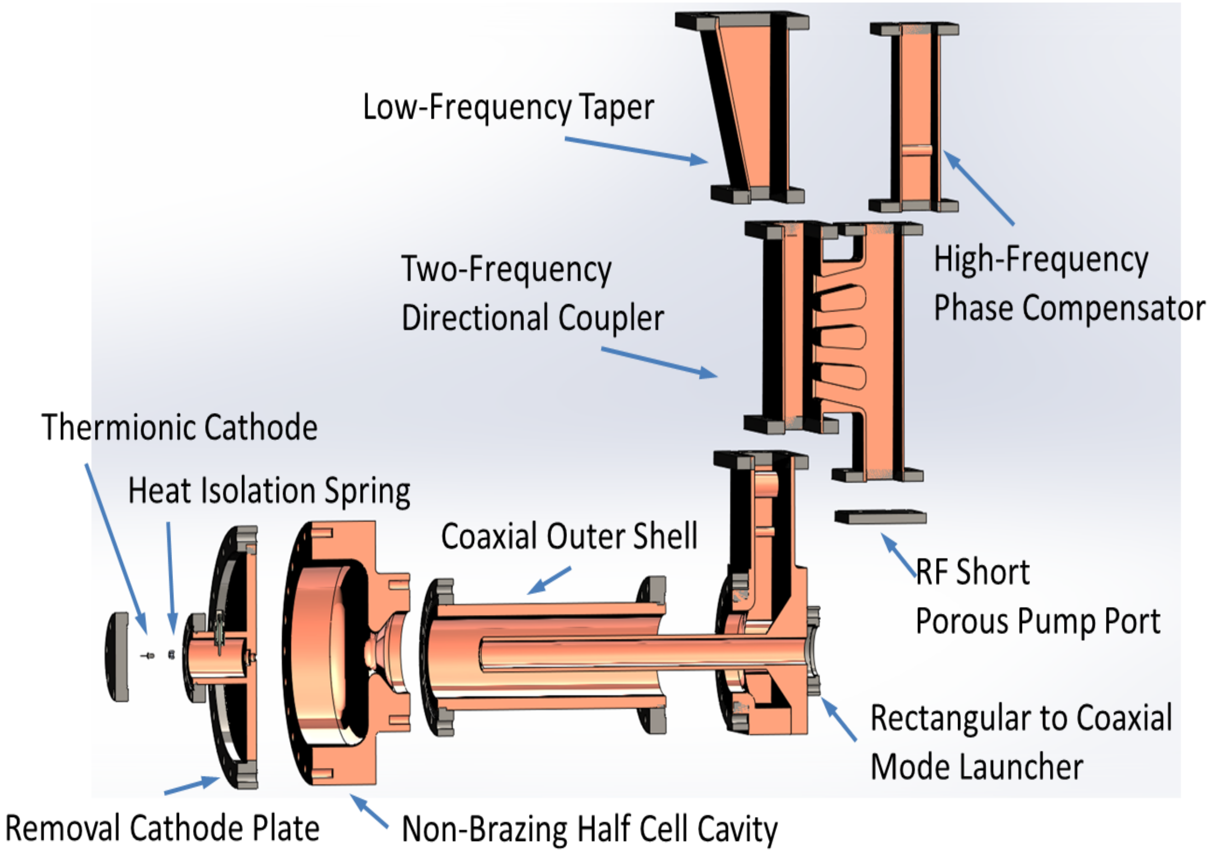


Experimental Setup at Yale BPL

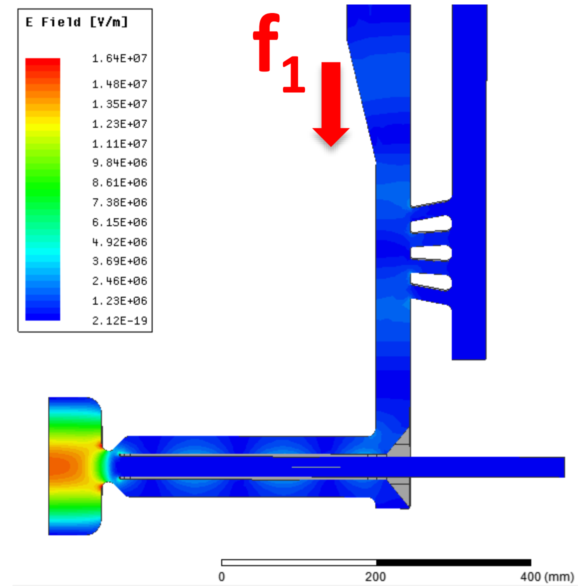


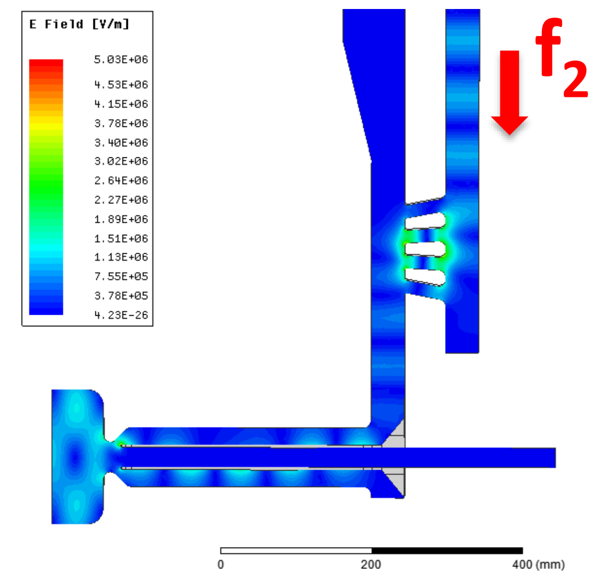


Design of Bimodal Electron Gun

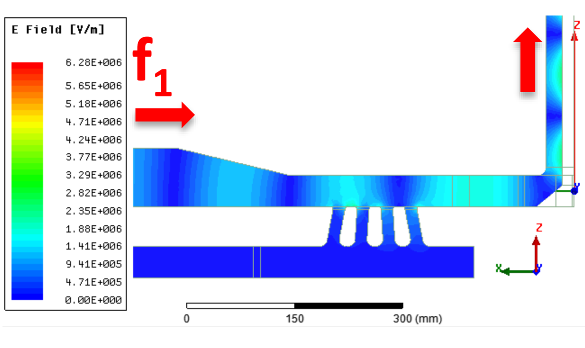


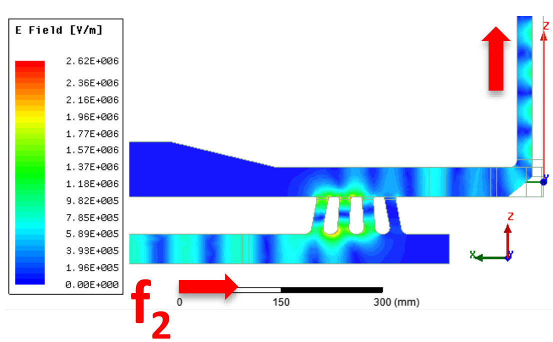
Two-Frequency Excitation





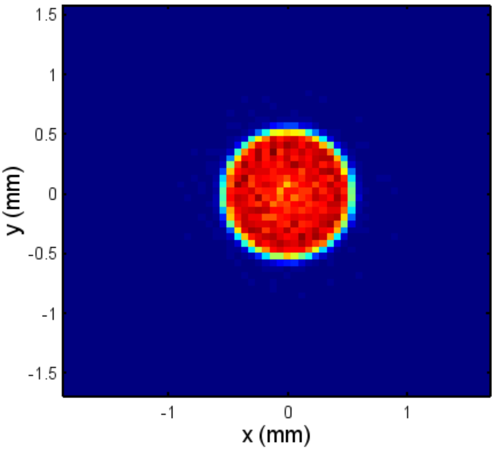
Two-Frequency Directional Coupler

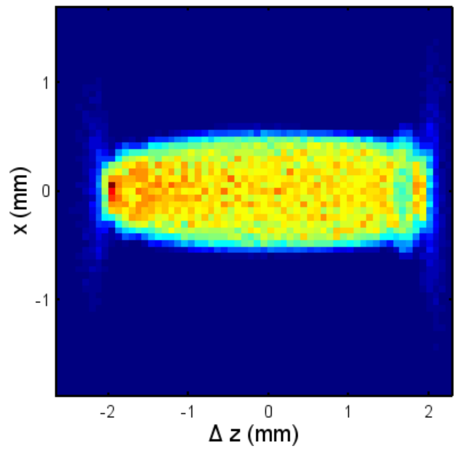


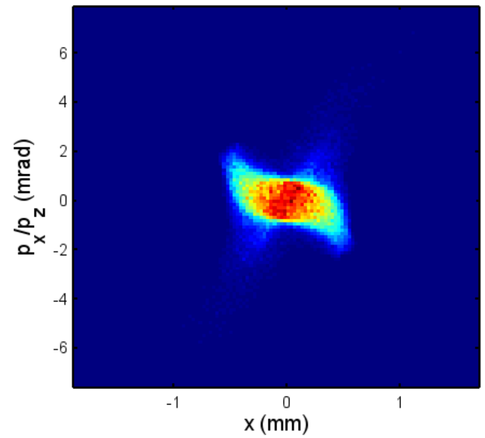


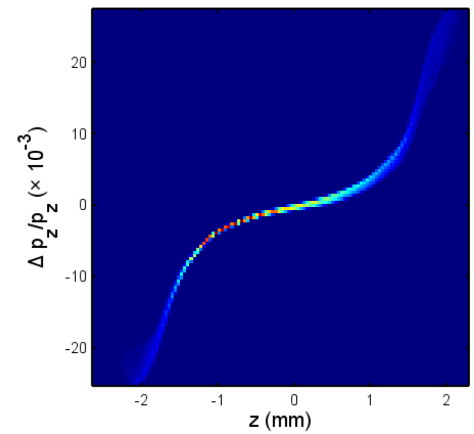
Simulation of Bimodal Electron Gun

1.3 GHz + 2.6 GHz initial: charge 1 nC, beam size σ_x=1mm, pulse length L_t=20 ps, rise time rt=2 ps, intrinsic emittance ε_{therm} = 1.23 π μm

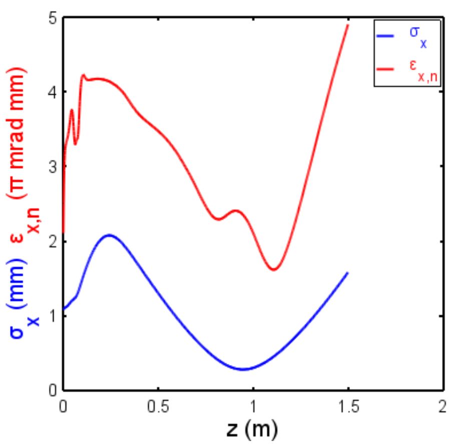


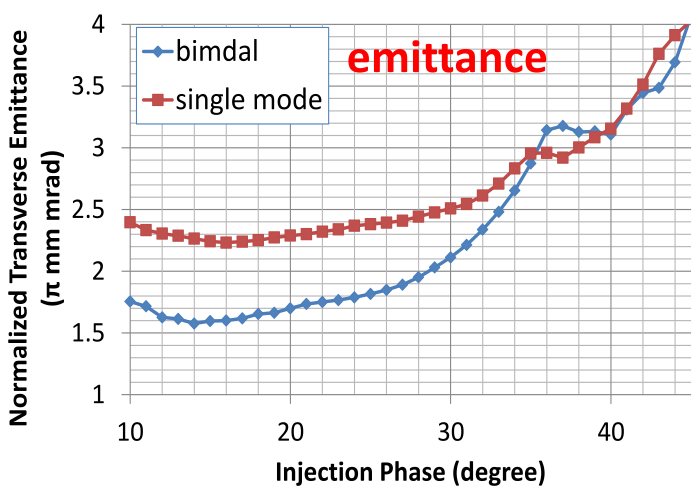


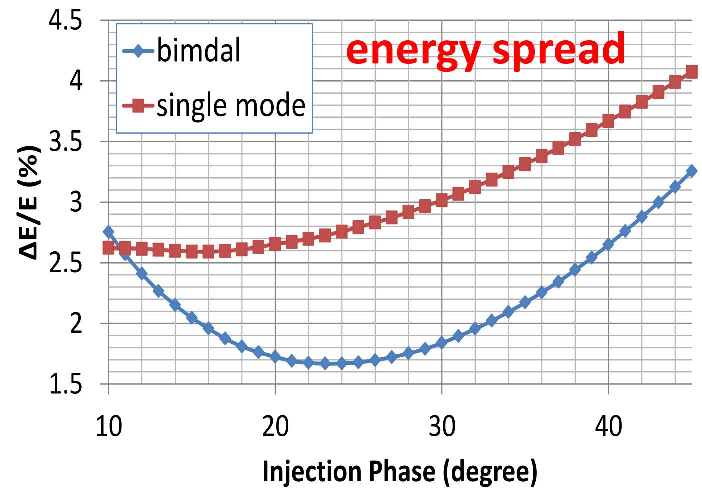




Simulation Results: Beam energy 3.74 MeV, beam size $\sigma_{x,min}$=0.28mm, normalized emittance $\varepsilon_{x,min}$ = 1.62 π mm mrad, energy spread ΔE/E = 1.9%, P_1=2.2 MW, P_2 =1.7 MW, $B_{z,max}$=0.16 T.

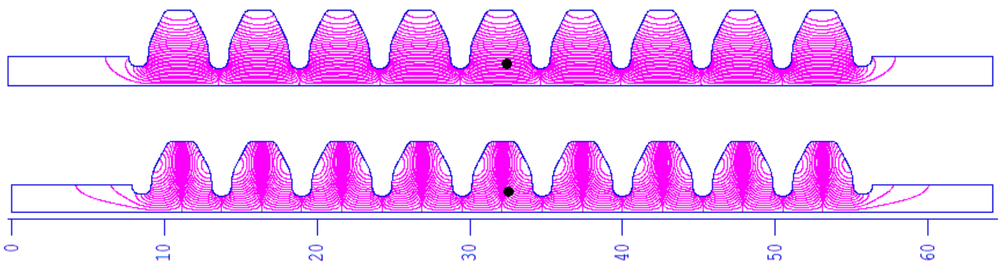




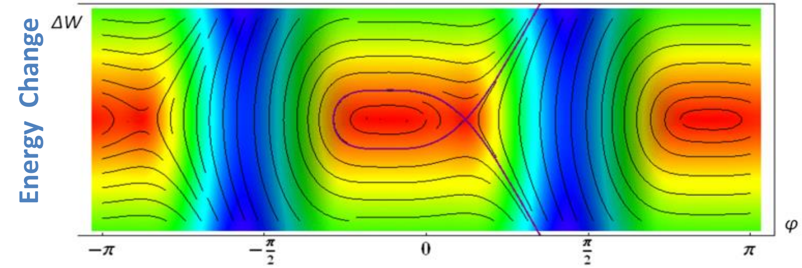


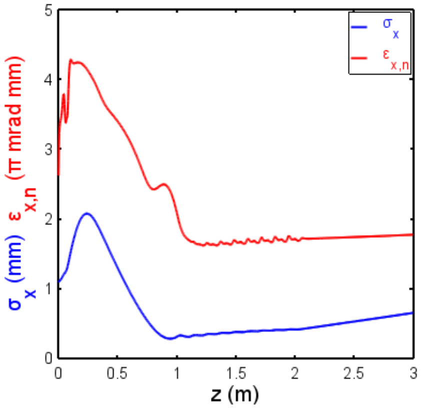
BIMODAL ELECTRON GUN with Boost Linac

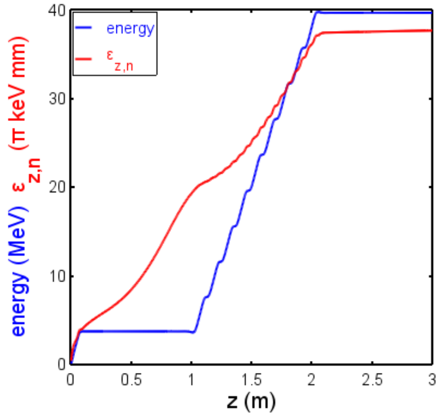
Two Frequency Boost Linac



Two Frequency Fish Plot







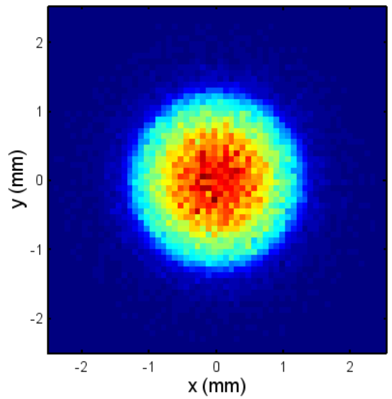
Simulation Results:

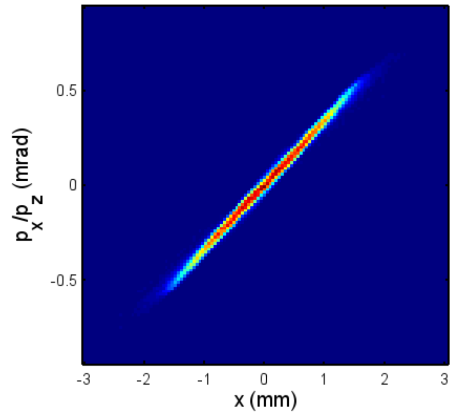
Beam energy 39.6 MeV

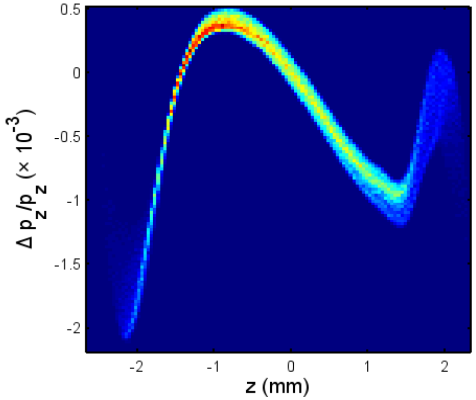
Norm. emit. $\varepsilon_x = 1.8\,\pi$ mm mrad

Norm. emit. $\varepsilon_z = 37.6\,\pi$ keV mrad

Energy spread ΔE/E = 0.082%







Summary

- **USE OF BIMODAL CAVITIES IS PREDICTED TO REDUCE BREAKDOWN PROBABILITY, FOR A GIVEN ACCELERATION GRADIENT, *via***

  ANODE-CATHODE EFFECT (*f* + 2n*f*), to suppress field emission; and/or

  QUADRATIC EFFECT (*f* + n*f*), to also suppress pulsed heating.

- **CONCEPT CAN APPLY TO A LINAC COMPRISING BIMODAL CAVITIES, WITH EXTERNAL TWO-FREQUENCY RF DRIVE; or**
- **CONCEPT CAN APPLY TO A BEAM-DRIVEN TWO-BEAM ACCELERATOR ARRANGEMENT, USING DETUNED BIMODAL CAVITIES.**
- **VIRTUES INCLUDE INCREASED SHUNT IMPEDANCE, REDUCED RF POWER, REDUCED EFFECTIVE POYNTING VECTOR, REDUCED PEAK SURFACE FIELDS, AND HIGH TRANSFORMER RATIO (FOR DETUNED CAVITIES).**
- **EXPERIMENTS TO CONFIRM RF-DRIVEN AND BEAM-DRIVEN APPROACHES TO SUPPRESS BEAKDOWN ARE PROGRESSING, *ALL BE IT SLOWLY*.**
- **A HALF-CELL RF GUN DESIGN USING A BIMODAL CAVITY HAS EVOLVED WITH PREDICTED PERFORMANCE THAT IS COMPETITIVE TO A CONVENTIONAL 1-1/2 CELL GUN.**
- ***LOTS OF WORK REMAINS!!***

Acknowledgements

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NSF

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LUX ET VERITAS

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http://bpl.yale.edu

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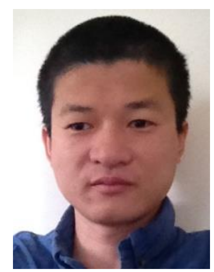

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