Test Stands for Breakdown Studies on RF-Driven and Beam-Driven Structures*

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Yale University

Omega-P R&D, Inc.

Outline

<u>**TWO TEST STANDS**</u>**:** ***One RF-driven and one beam-driven.***

- **Two Frequency Test Stand *f* + 2*f*:**
  S-band + C-band phased -synchronized RF source
- **Beam Driven Accelerator Test Stand:**
  X-band long bunch train source (~10^4 bunches/pulse)

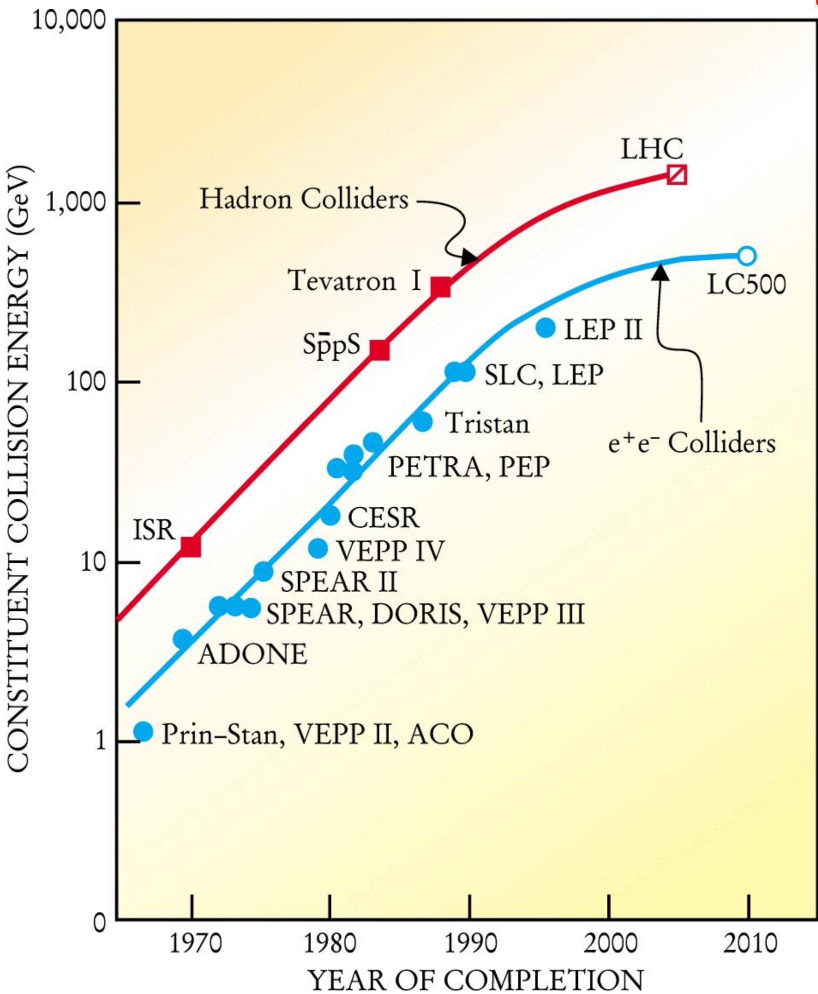
<u>**MOTIVATION**</u>**:** ***Trying to avert RF breakdown at high gradients.***

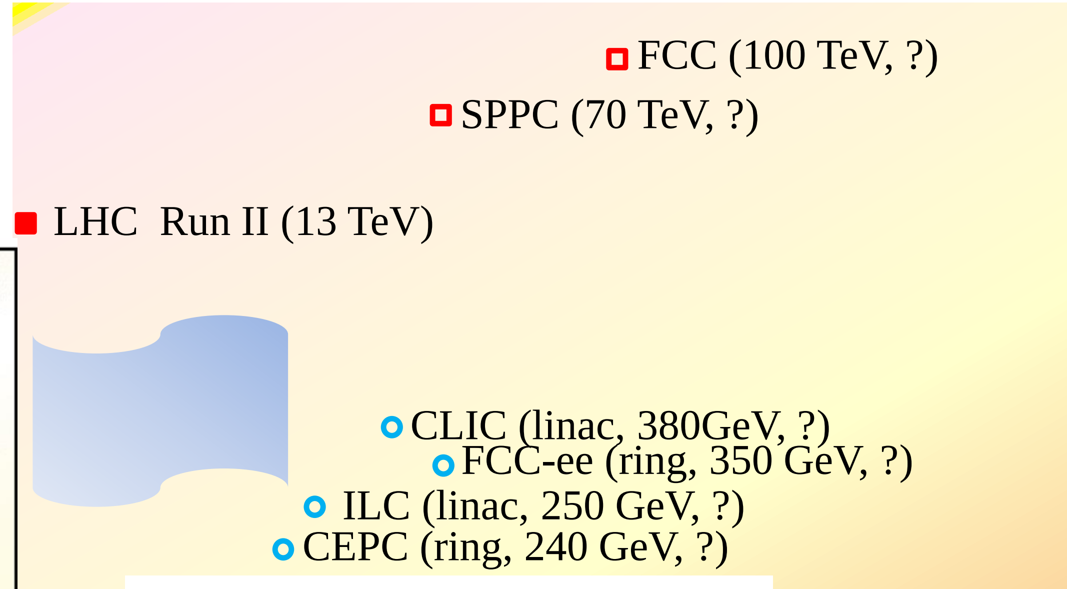
- **Bimodal <u>RF-driven</u> cavity structures**
  (possibly leading to a bimodal linac)
- **Bimodal <u>RF-driven</u> electron gun injector**
  (a near-term application of a bimodal cavity structure)
- **Bimodal <u>beam-driven</u> detuned cavity structures**
  (possibly leading to a bimodal two-beam accelerator)

Two bimodal mechanisms may enable breakdown suppression at high gradients: our planned tests are to confirm this prediction.

Accelerator Moore's Law

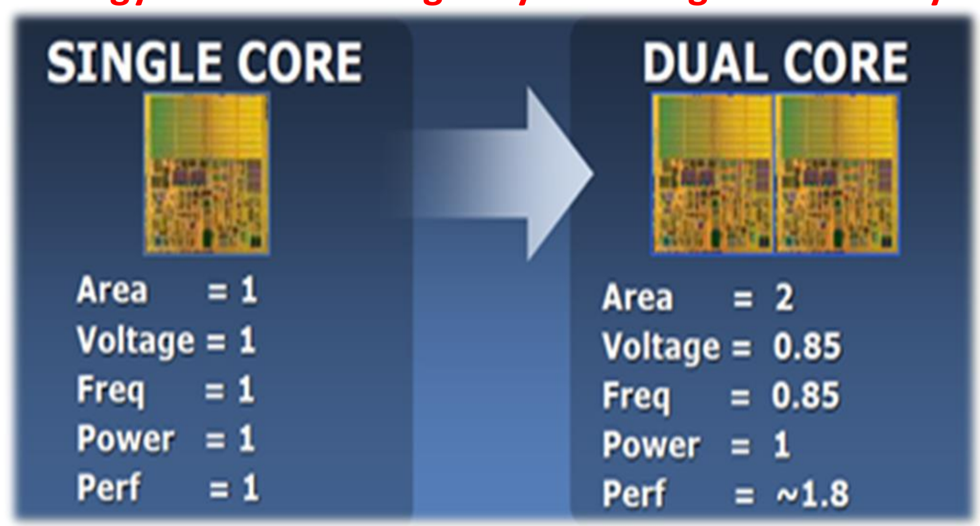
RF BREAKDOWN is a fundamental limitation in the practical realization of high-energy accelerators





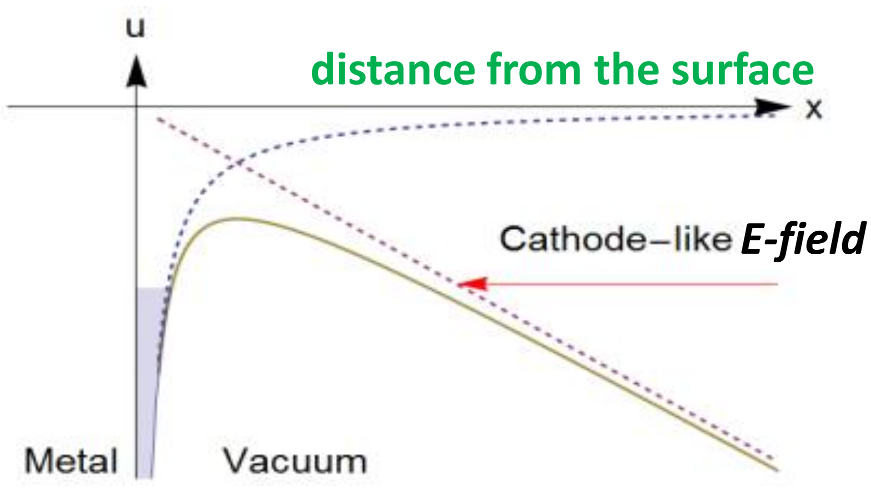
How to Beat CPU Moore's Law

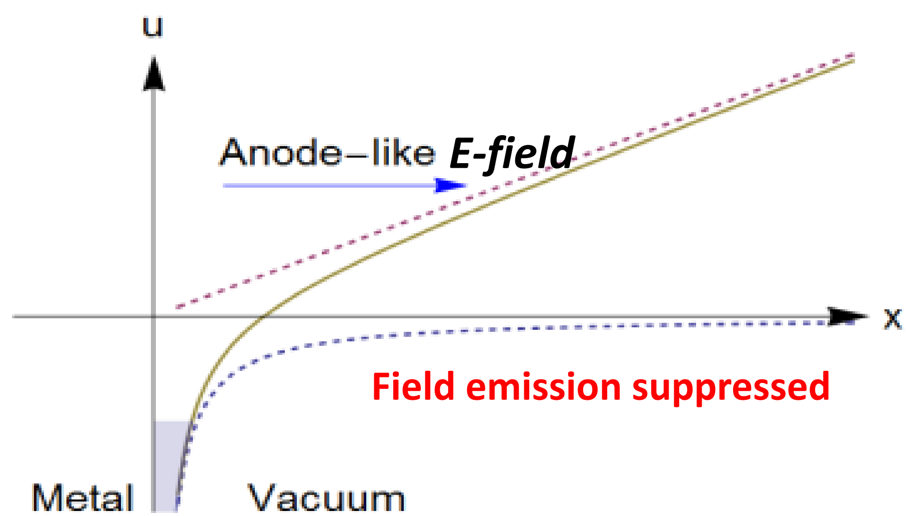
Analogy could be strategically following CPU industry

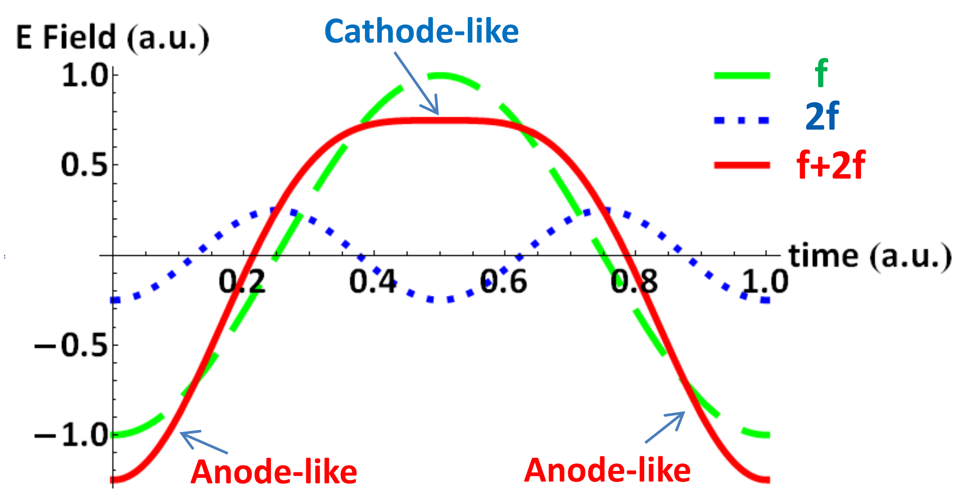


Bimodal Mechanism I: Suppress Field Emission

potential energy of an electron near metal surface



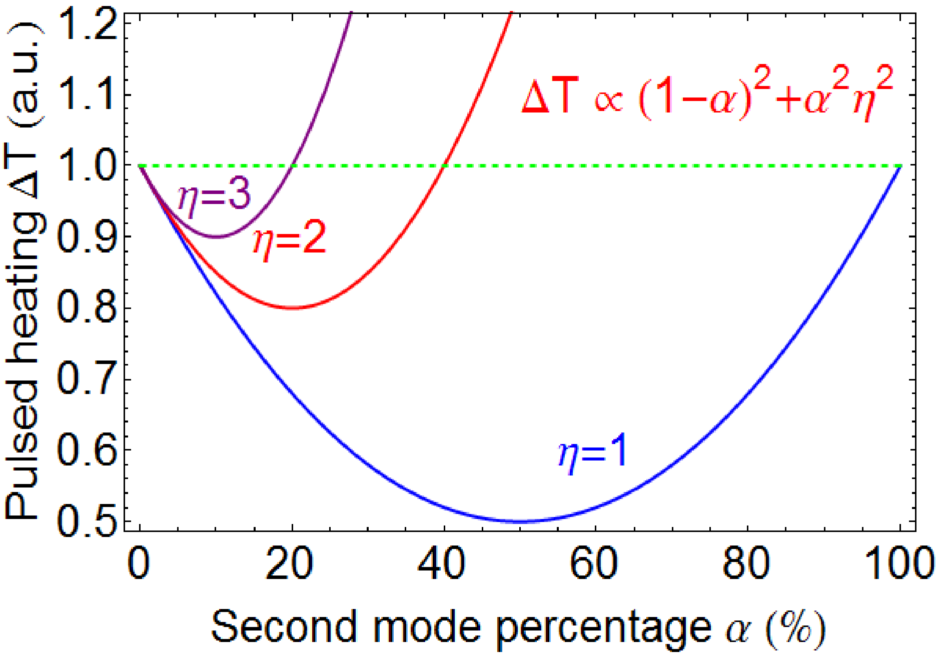




"Anode – Cathode" Effect

Two harmonic mode superposition should suppress field emission, believed to be a precursor to breakdown. Note: requires axial asymmetry.

Bimodal Mechanism II: Suppress 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 $\eta = \sqrt{(f_2/f_1)^{1/2} < H_2^2 >/< H_1^2 >}$

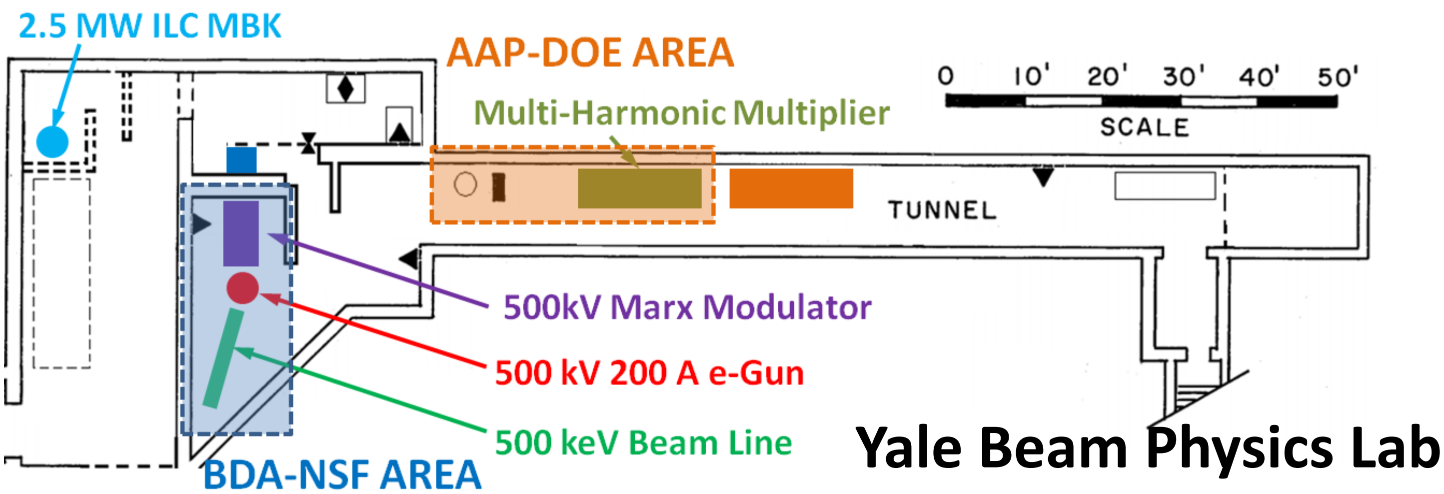
"Quadratic Dependence" Effect

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

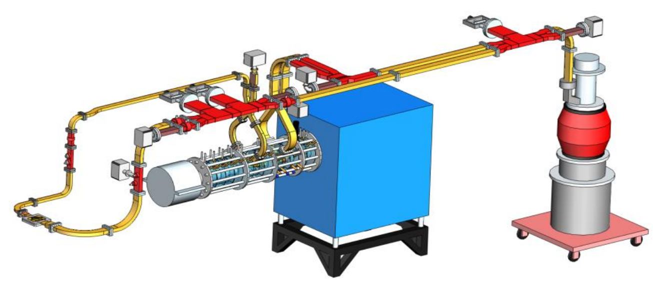
Also, modified Poynting vector S_c and total RF power P_{total} are reduced.

Two harmonic mode superposition could suppress pulsed heating, also believe to be a precursor to breakdown.

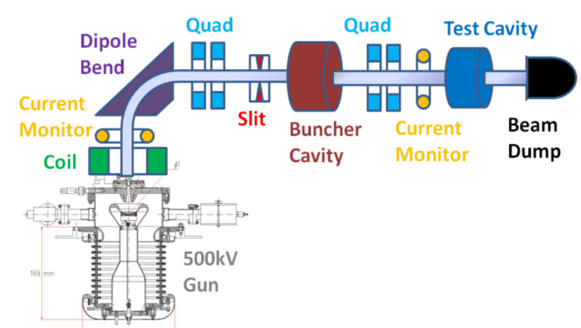
Two Test Stands At Yale Under Construction



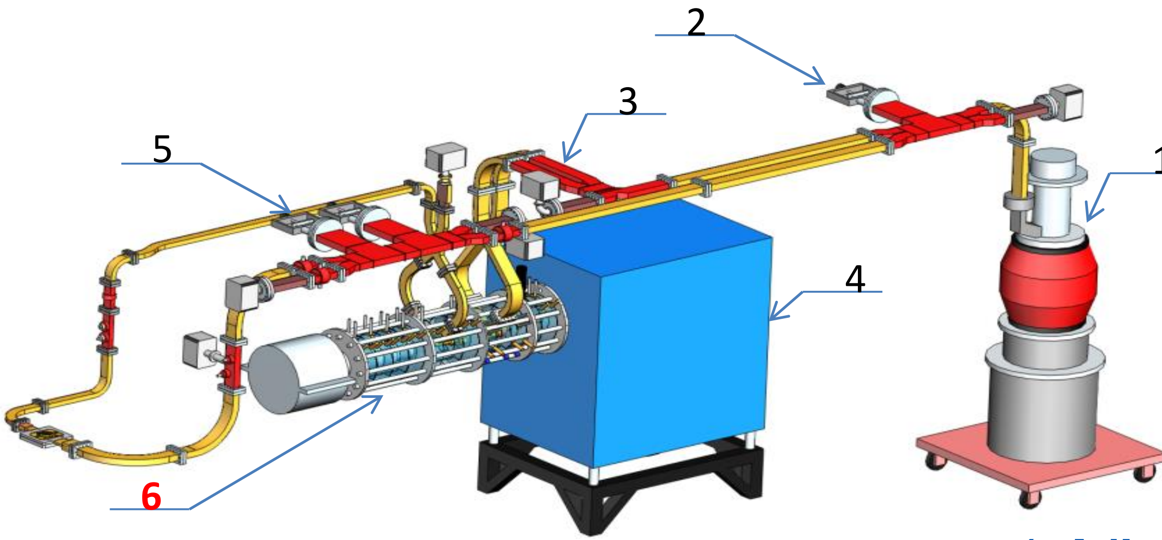
Two Frequency RF Source
for RF Driven Bimodal Structure Experiments



Long Bunch Train Beam Source
for Beam Driven Experiments

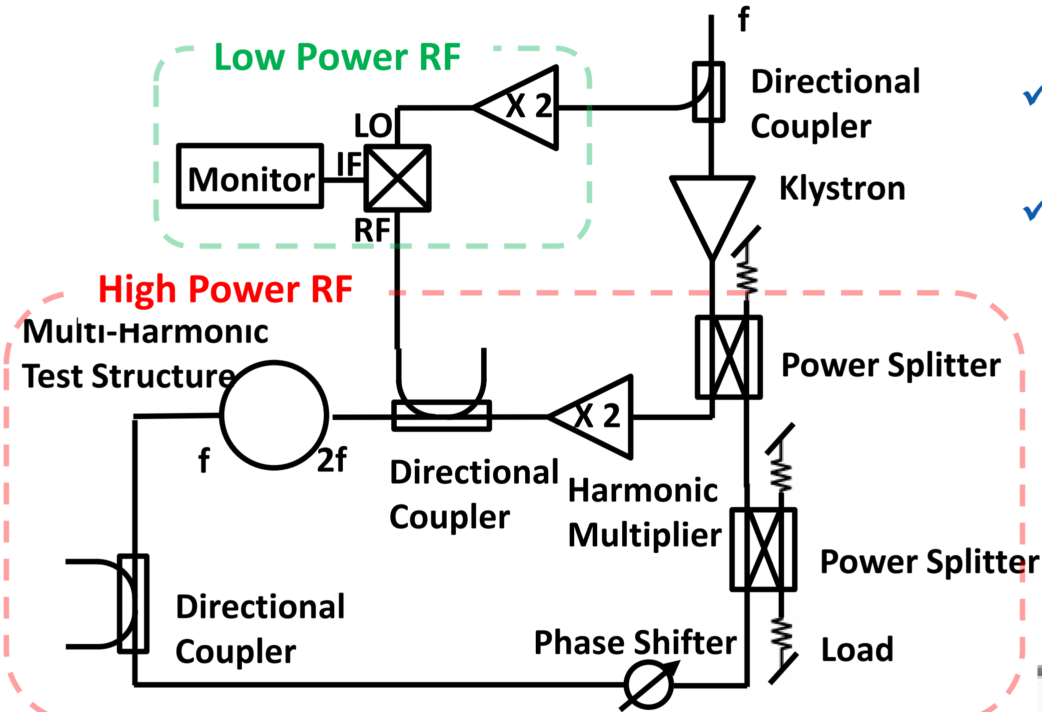


Two Frequency RF Source

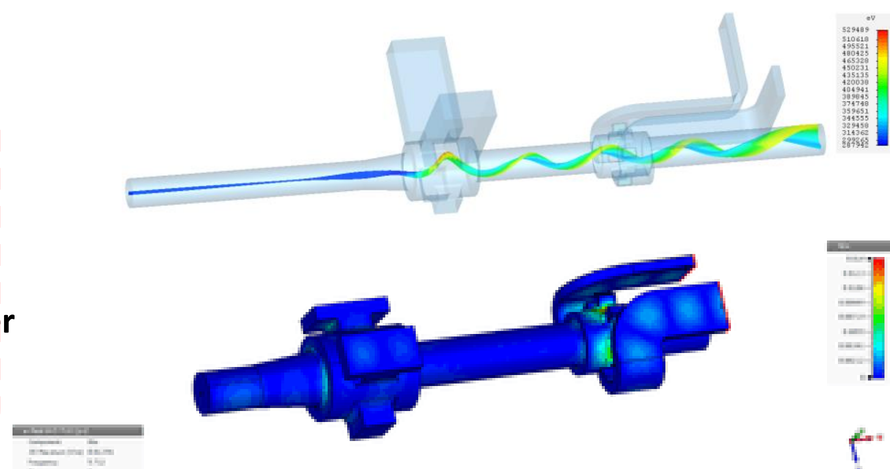


Layout

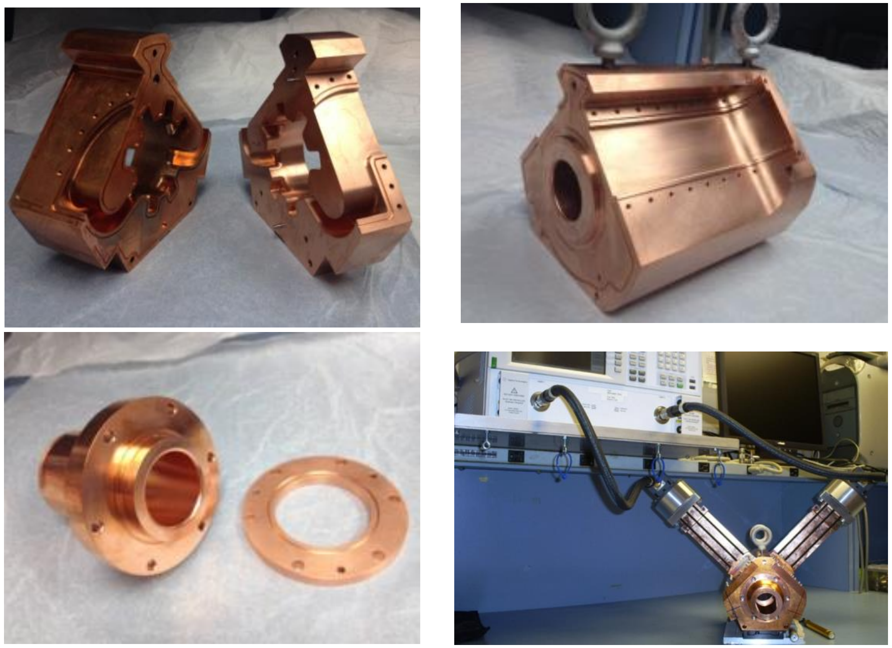
1 – S-band klystron
2 – variable power splitter
3 – 3-dB hybrid splitter
4 – 300-kV gun tank
5 – variable power splitter/phase shifter
6 – harmonic multiplier



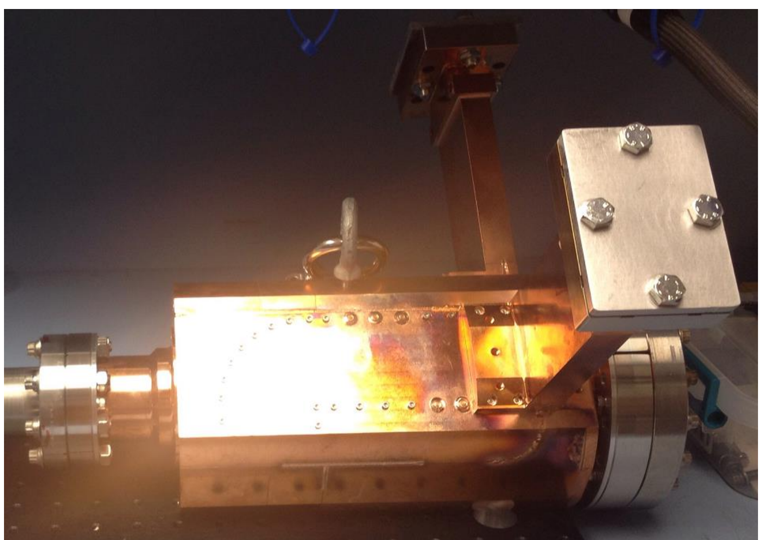
- ✓ Adjustable relative amplitude and phase
- ✓ Two sources automatically phase-locked
- ✓ No new C-band klystron needed

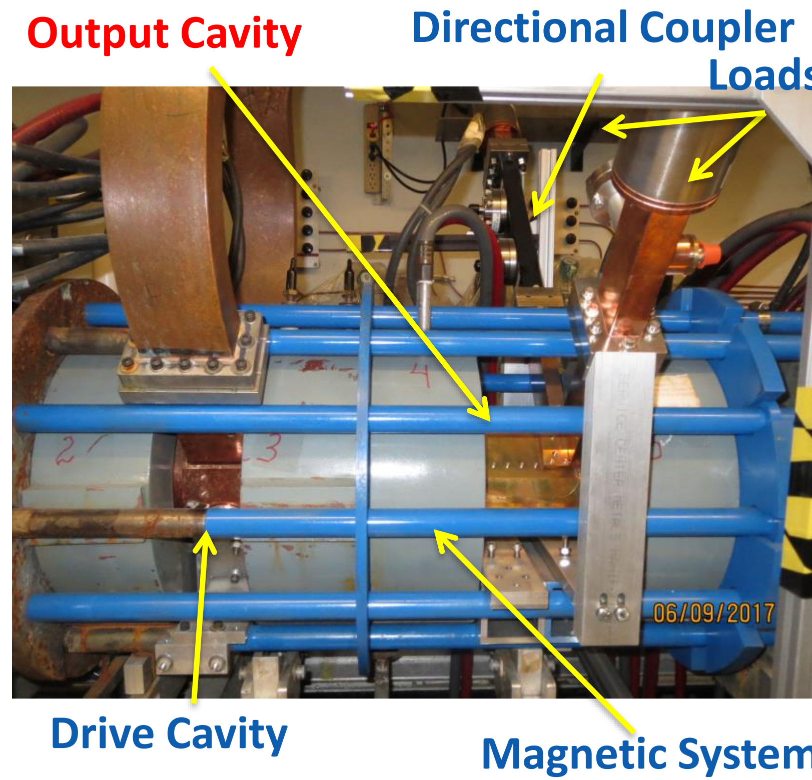


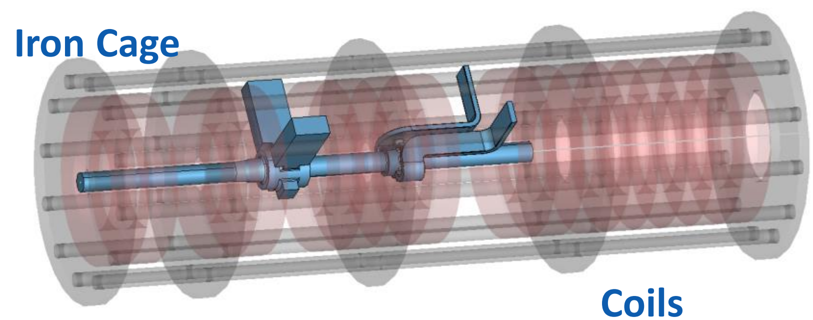
Installation of Output Cavity



After cold tests and brazing

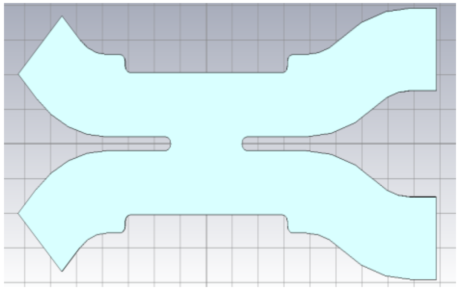


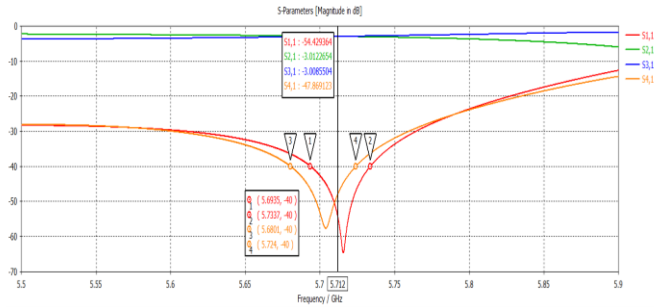




Currently under conditioning

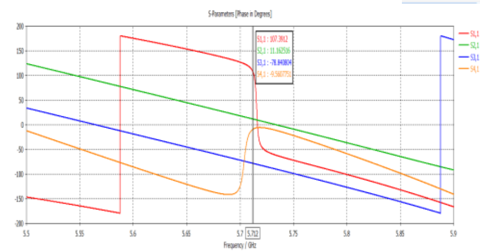
Design & Machining of C-band Hybrid courtesy of SINAP





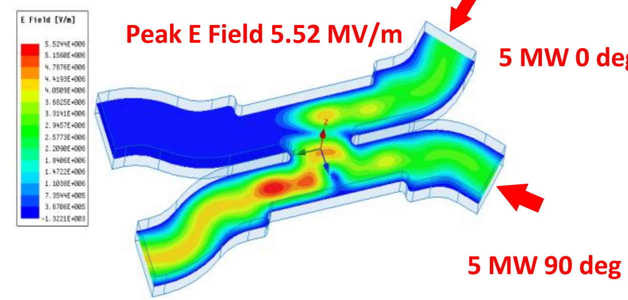
S11	-54.429dB
S21	-3.0123dB
S31	-3.0086dB
S41	-47.869dB

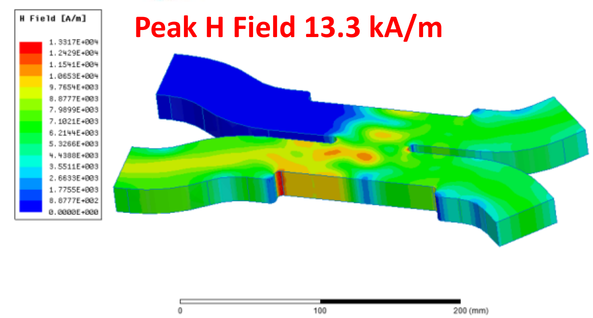
SINAP
中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

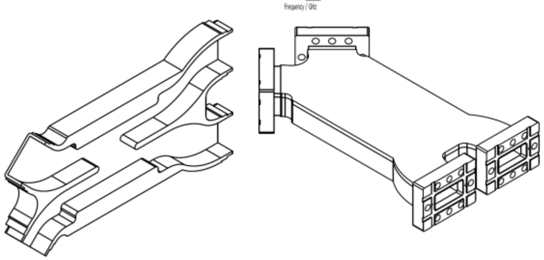


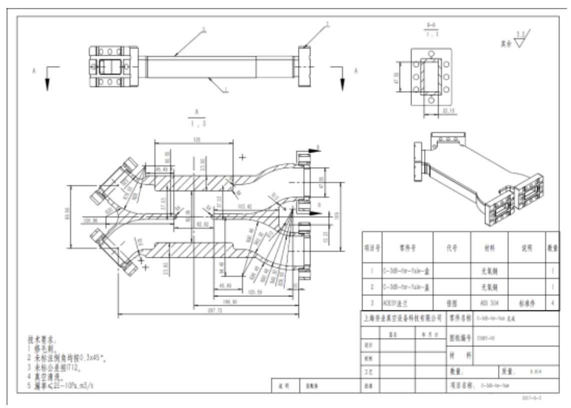
Bandwidth: at least 30MHz

Phase different between Port2 and Port3: 90.003°

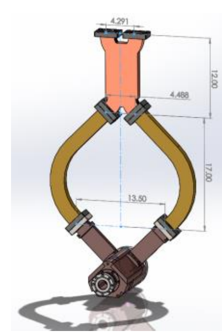


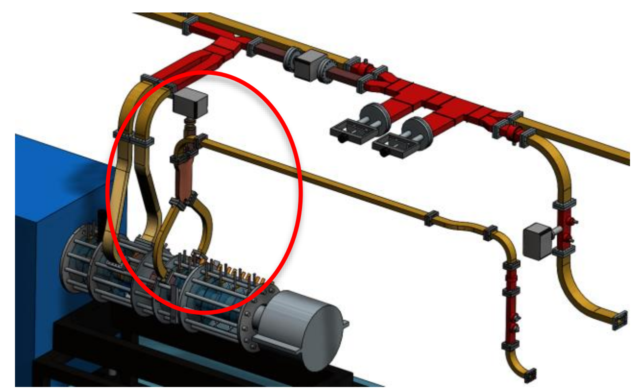






Current Status:
Machined. Cold Test Now

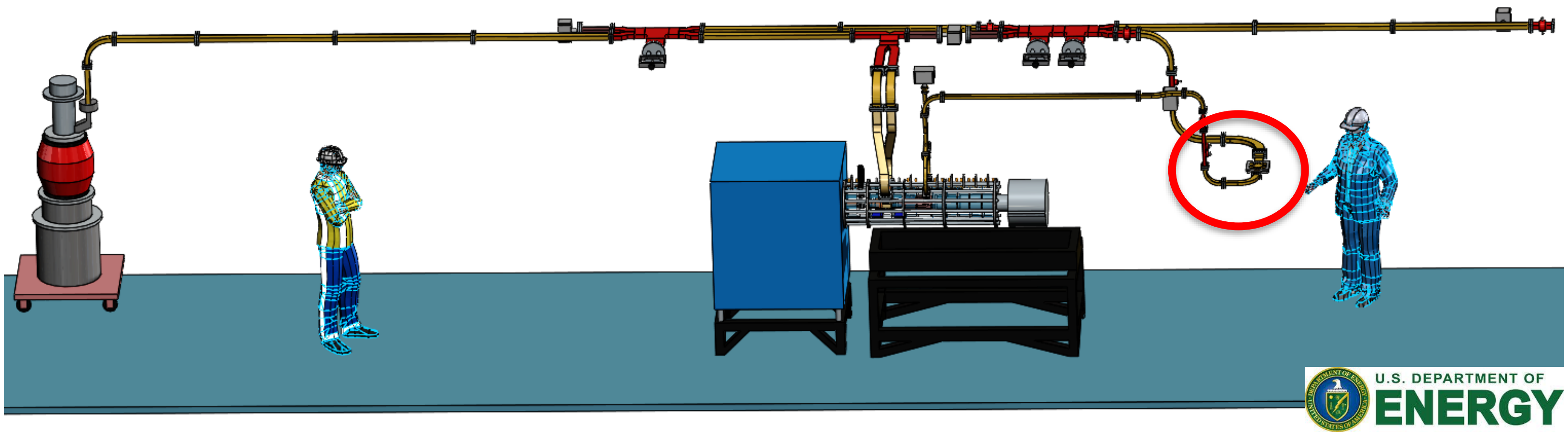




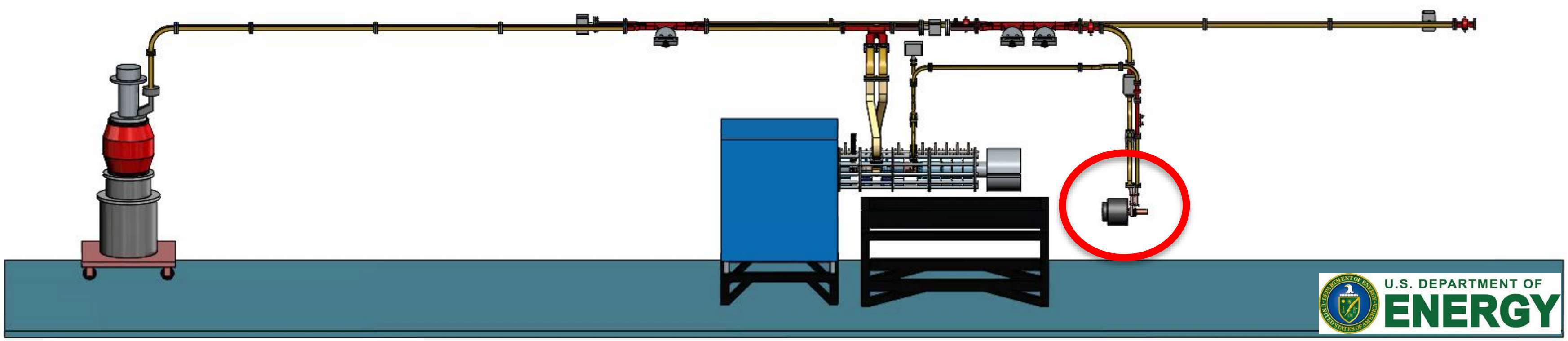
First Planned Experiments on Test Stand

RF Breakdown and Pulsed Heating Experiments (2017-2018)

- *Asymmetric* Bimodal Cavity: Test Anode-Cathode Effect
- *Symmetric* Bimodal Cavity: Test Surface Pulse Heating Effect

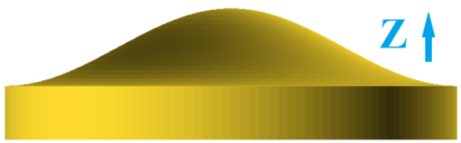


Bimodal Electron Gun Experiments (2018-2019)

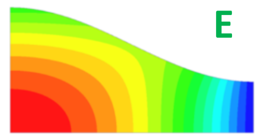


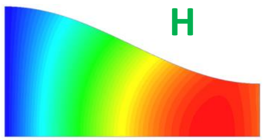
RF Properties of Asymmetric Anode-Cathode Cavity

TM_{010}+TM_{020} Cavity

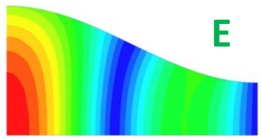


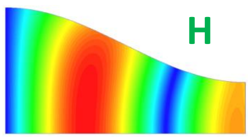
TM_{010} 2.856 GHz





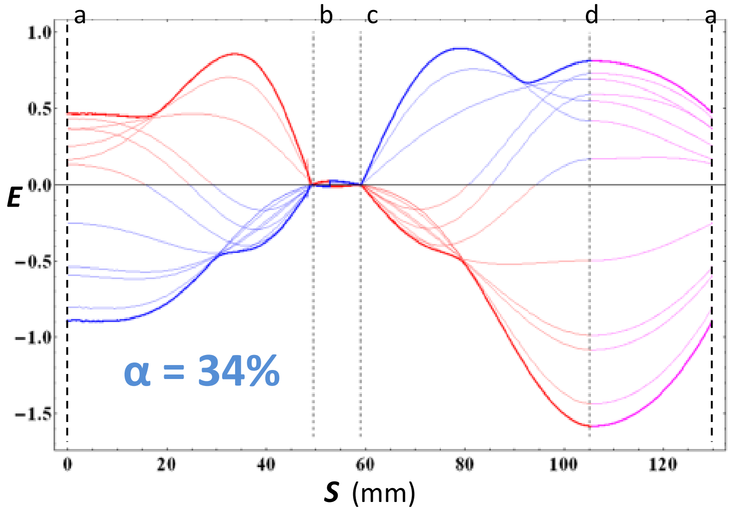
TM_{020} 5.712 GHz



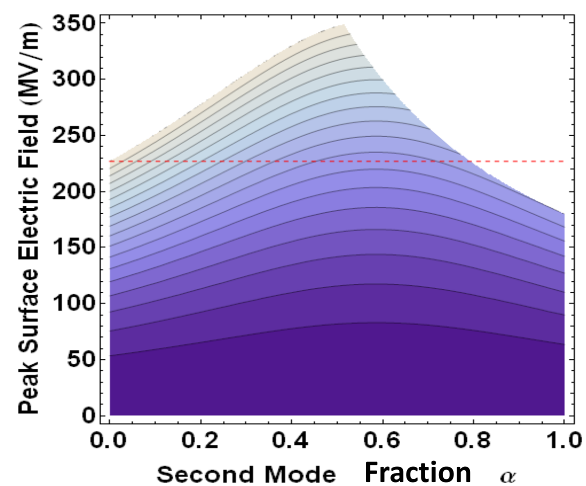


required RF power	1st harmonic alone	2nd harmonic alone	both modes
frequency (GHz)	2.856	5.712	66% f_1 and 34% f_2
P (MW) for E_{surf}= 100 MV/m	3.49	1.98	1.75
P (MW) for E_{surf}= 200 MV/m	13.97	7.92	7.21
P (MW) for E_{surf}= 300 MV/m	31.43	17.82	16.23

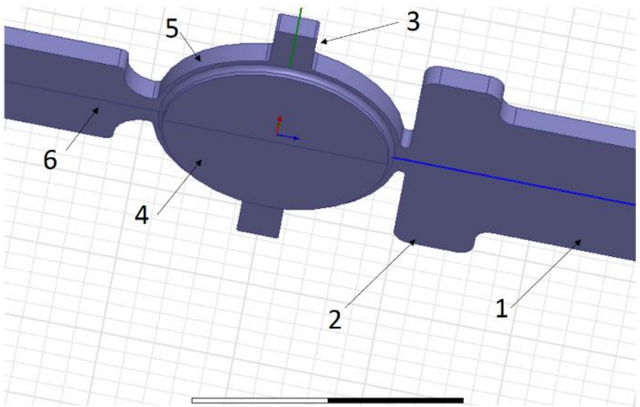
E-field distribution along cavity periphery *S*

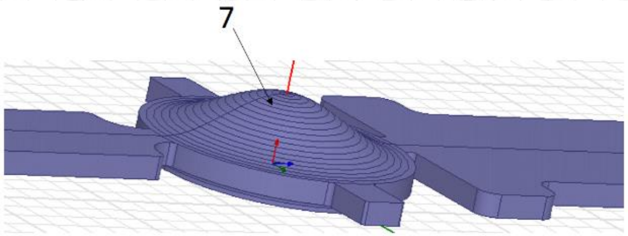


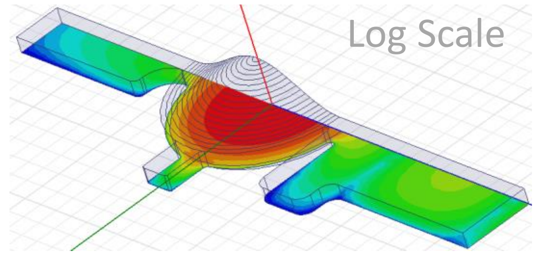
peak surface E-field with 18 MW klystron power

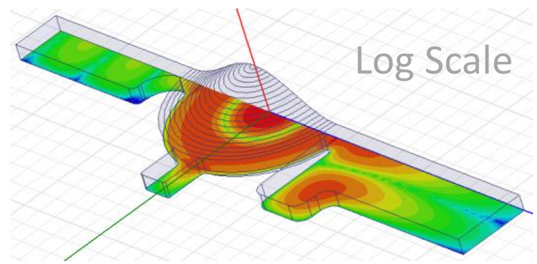


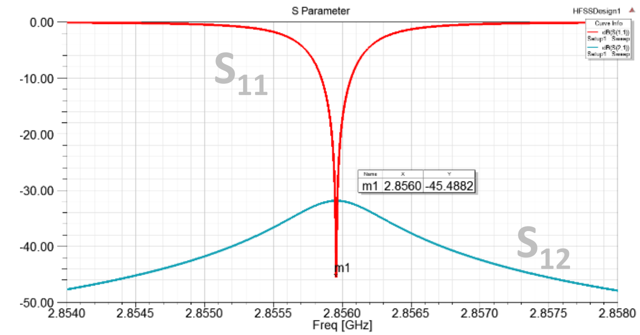
RF/Engineering Design of Anode-Cathode Cavity

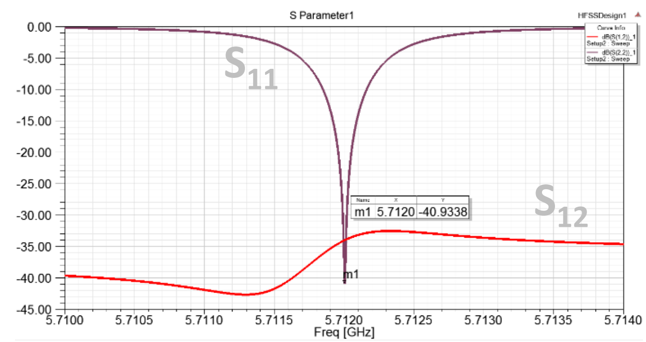


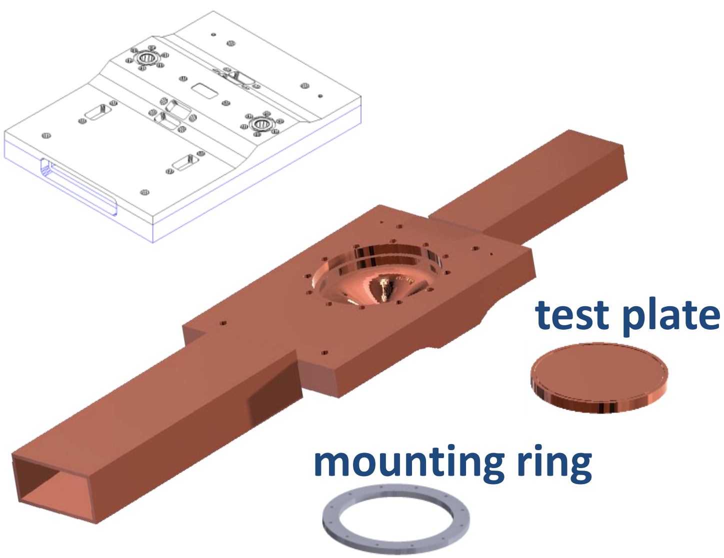


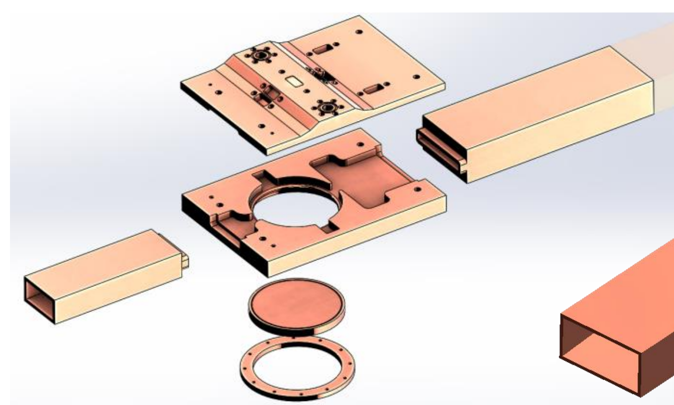


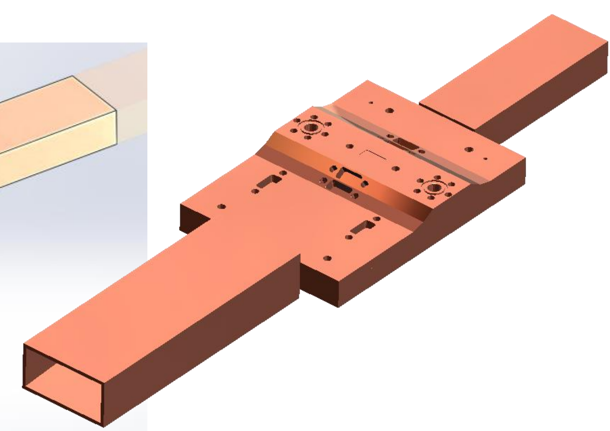








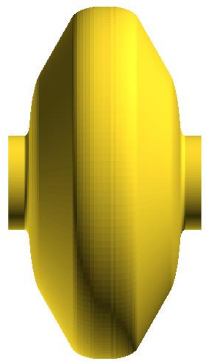




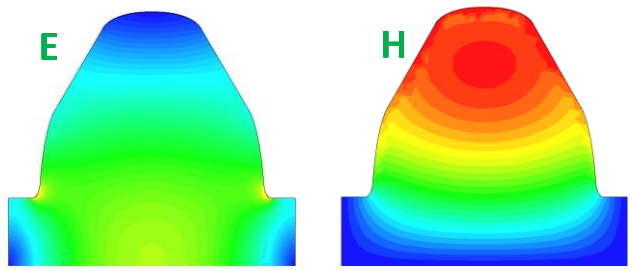
Symmetric Bimodal Cavity for Pulsed Heating Suppression

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

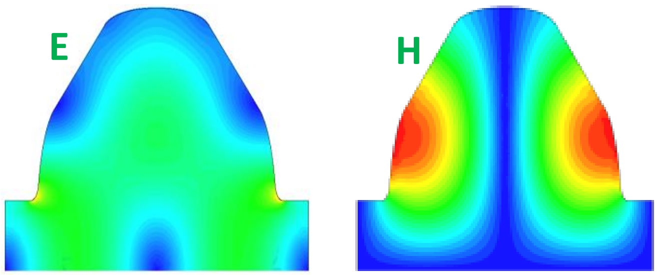
Quadratic Dependence Effect



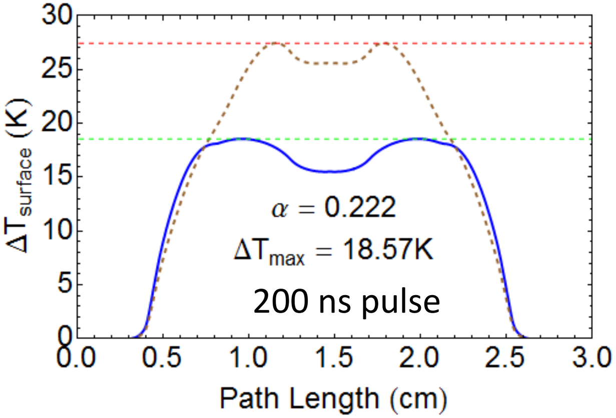
TM_{010} 12 GHz



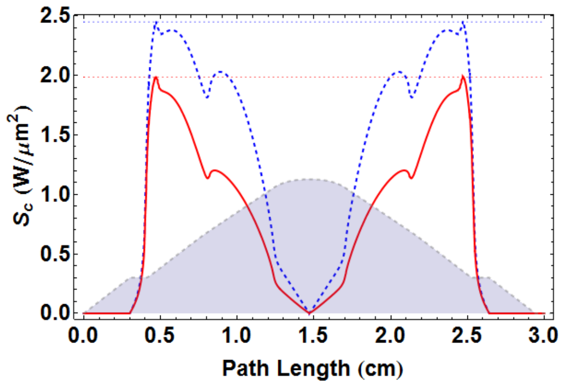
TM_{011} 24 GHz



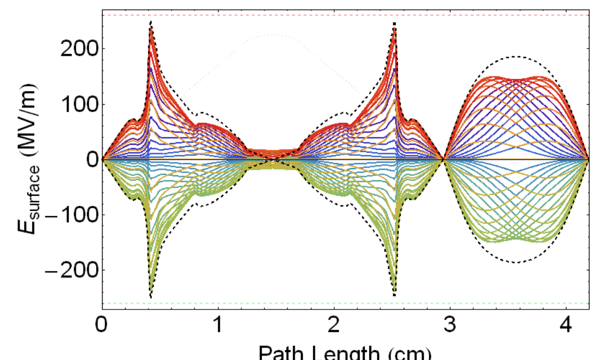
Pulsed temperature rise



modified Poynting vector S_c



surface E-field along periphery

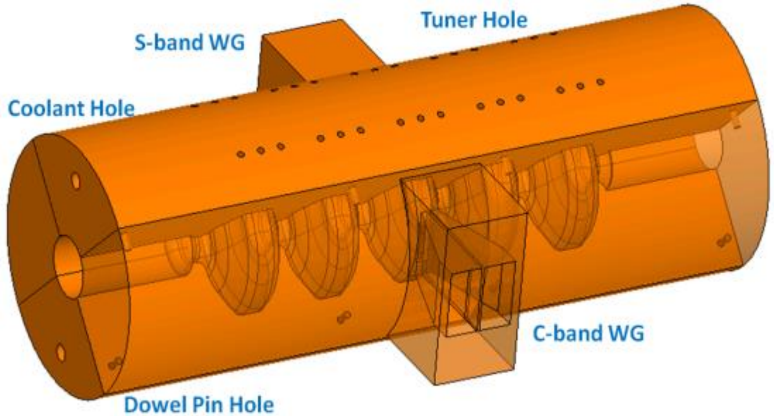


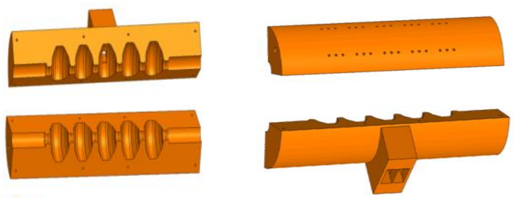
Effective acceleration gradient 100 MV/m

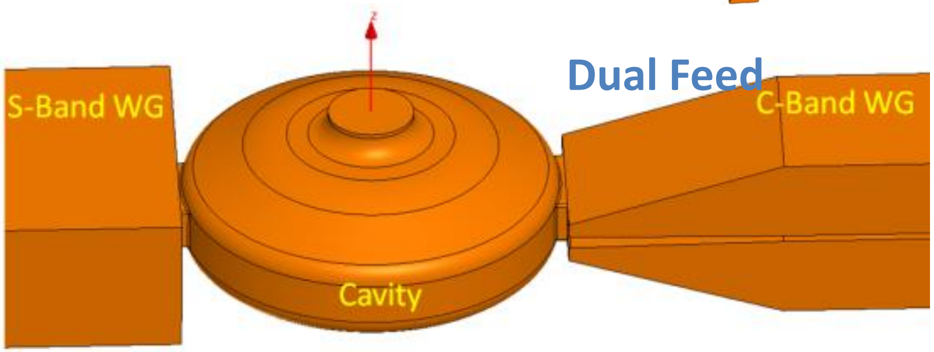
2-mode superposition compared to fundamental mode alone in the same MHC :

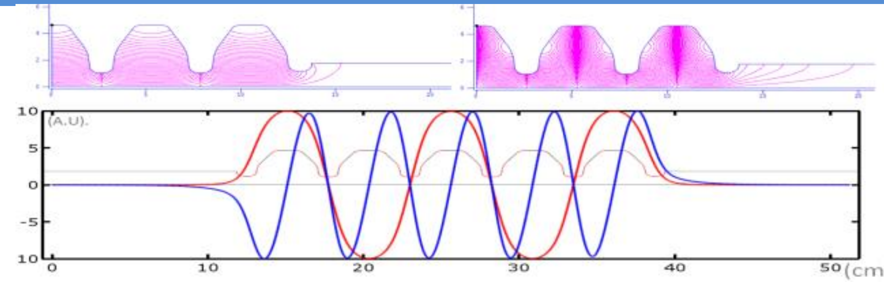
- □ pulsed heating temperature ↓32%
- □ maximum modified Poynting vector S_c ↓ 20%
- □ total required RF power ↓ 27%
- □ effective shunt impedance ↑ 37%

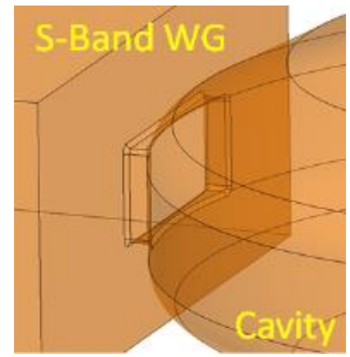
Symmetric Bimodal Cavity Structure

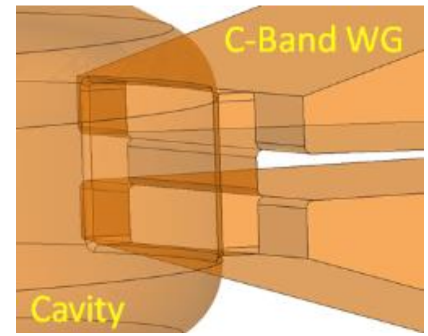




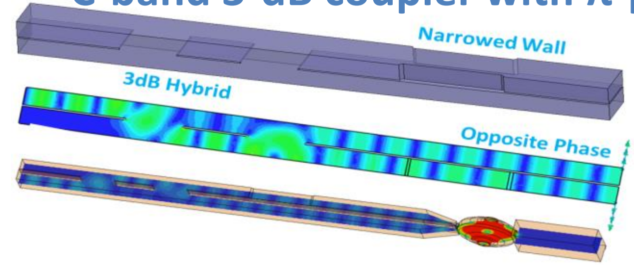


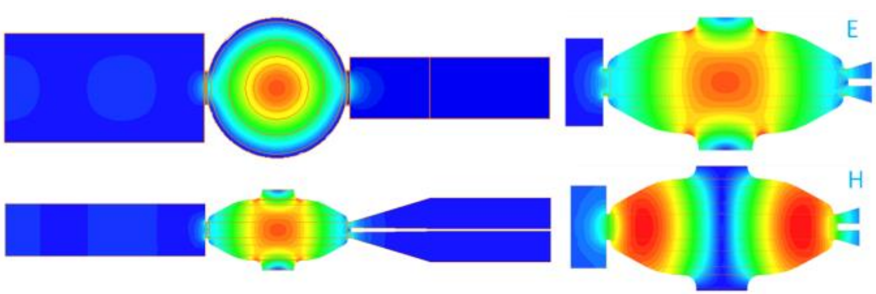


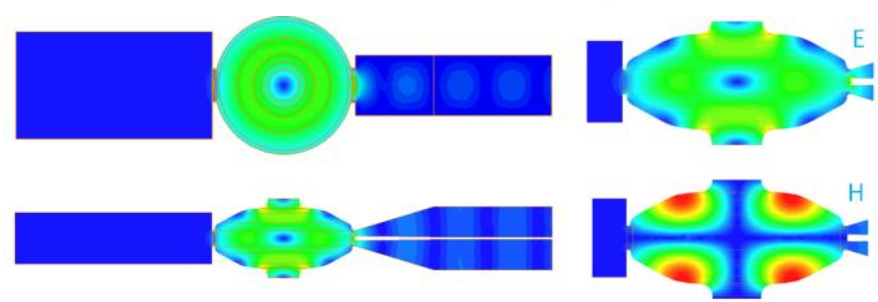




C-band 3-dB coupler with π-phase shift

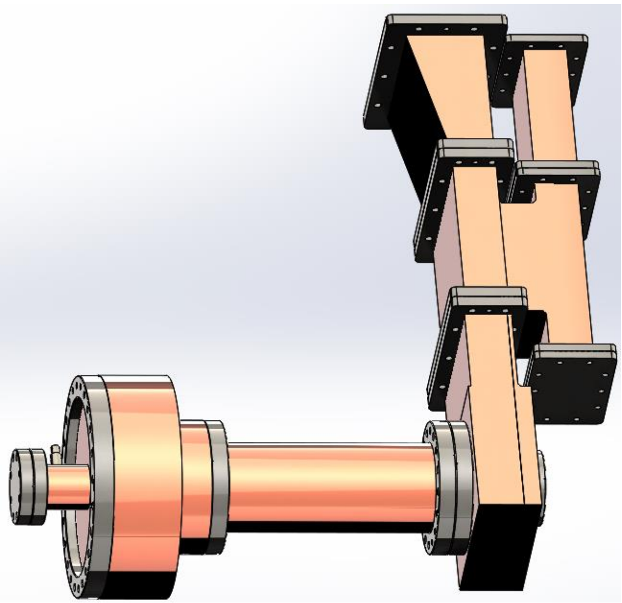


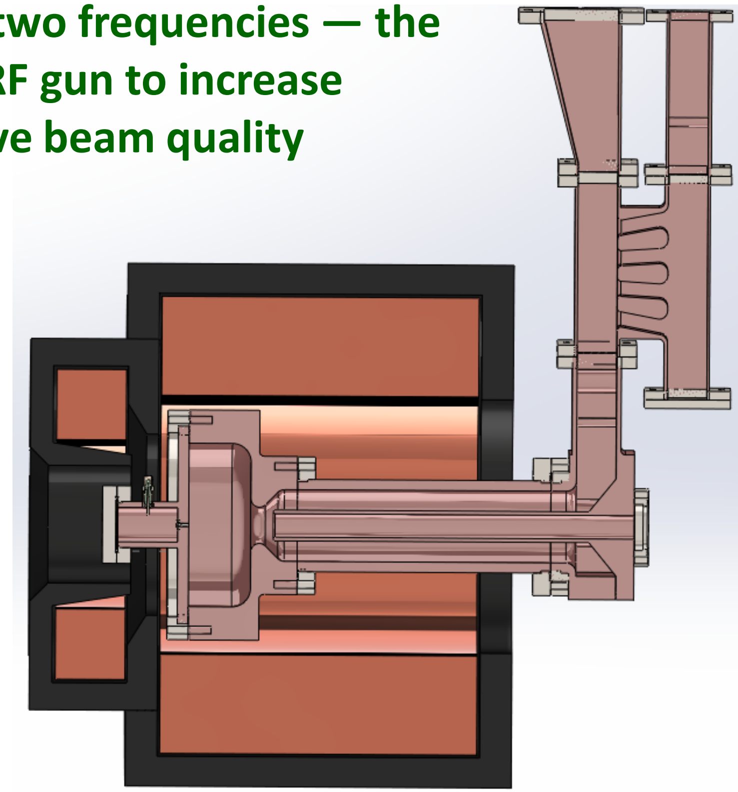


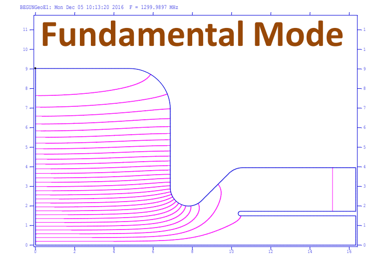


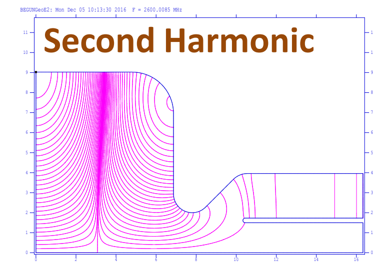
Bimodal Electron Gun Experiment

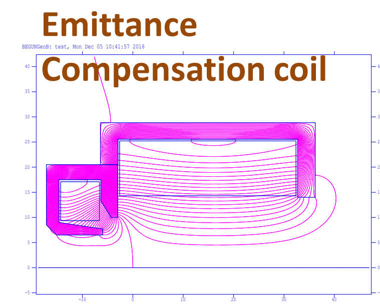
Superposition of microwaves at two frequencies — the first and second harmonic — in RF gun to increase acceleration gradient and improve beam quality



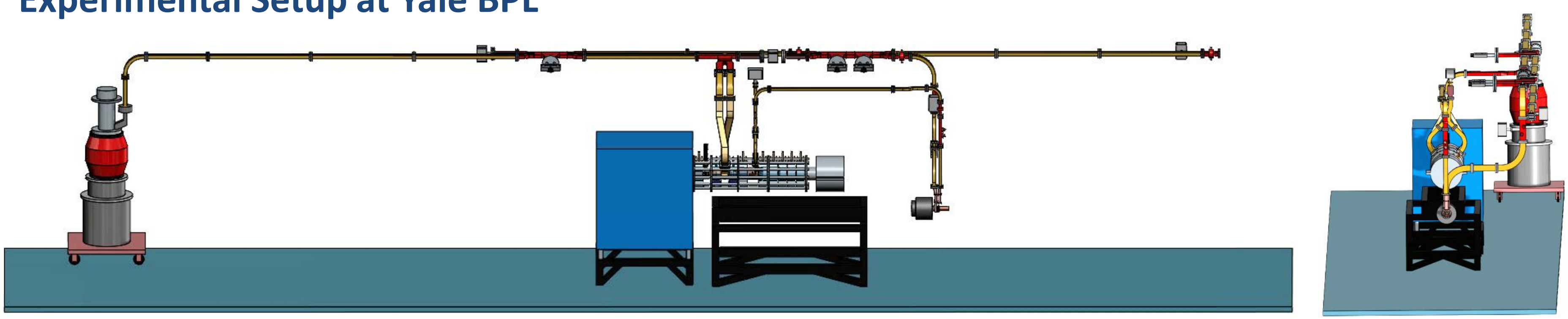




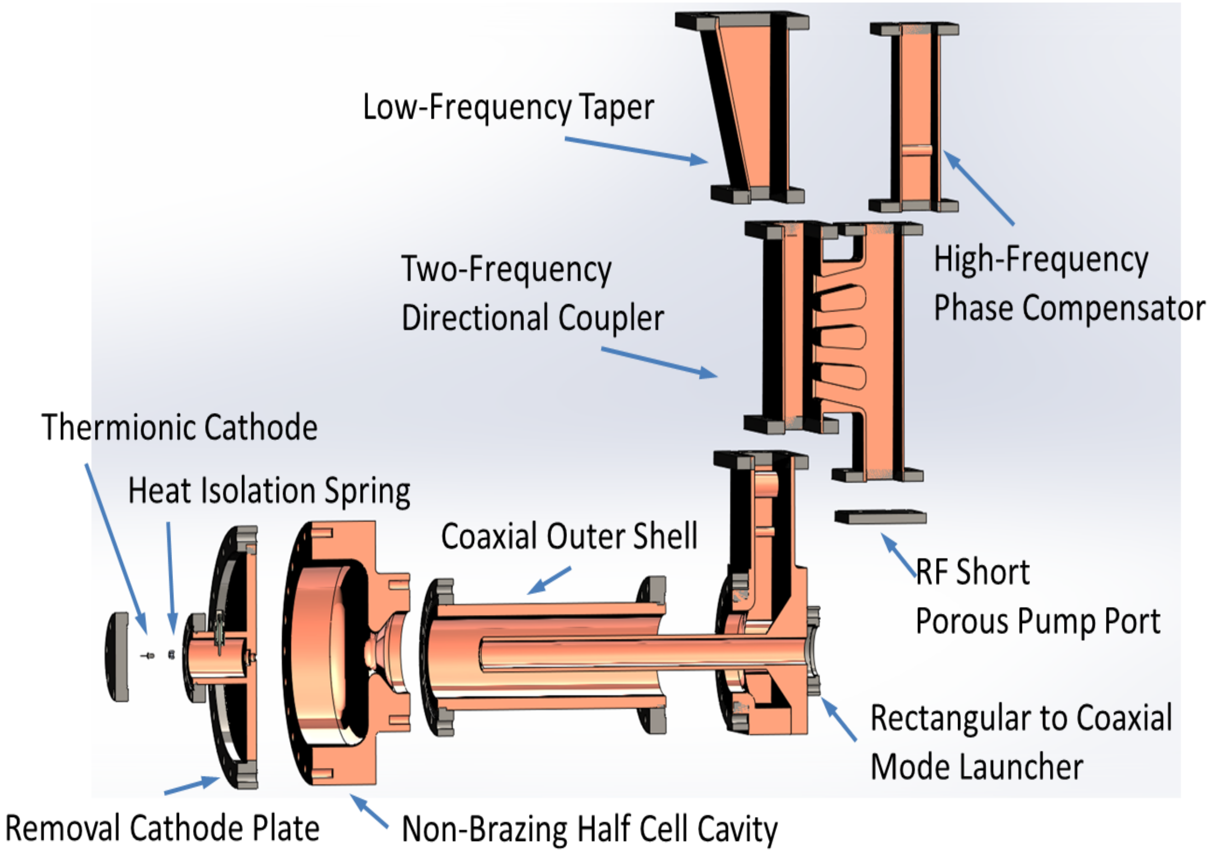




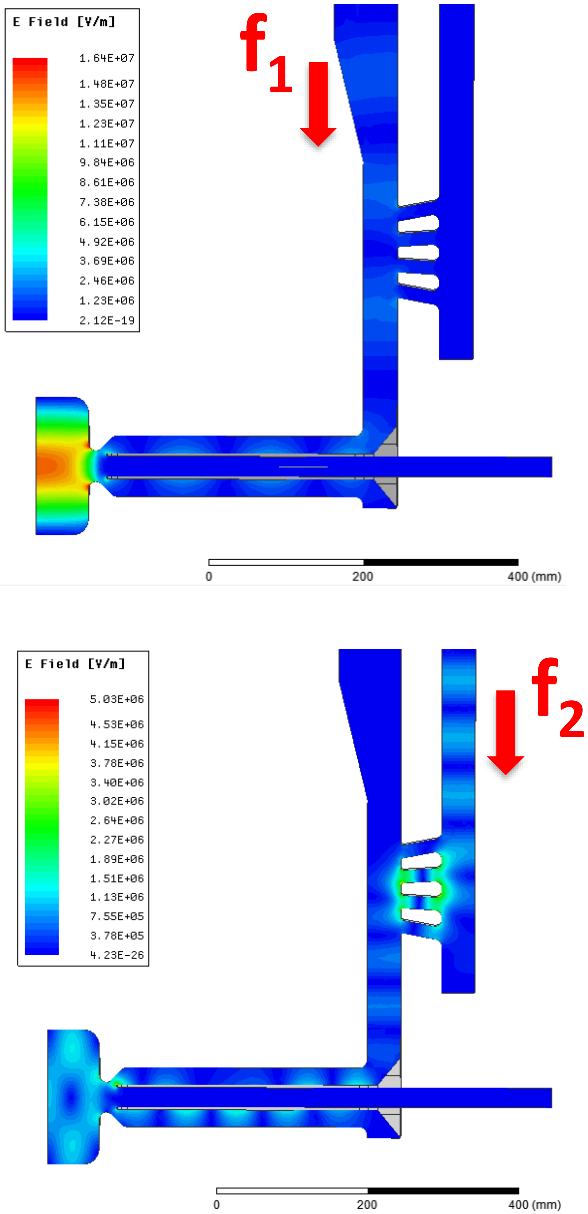
Experimental Setup at Yale BPL



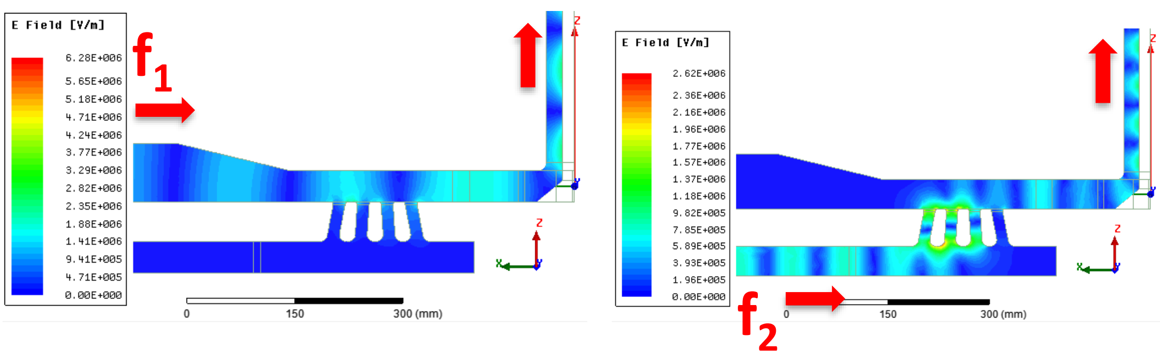
Design of Bimodal Electron Gun



Two-Frequency Excitation

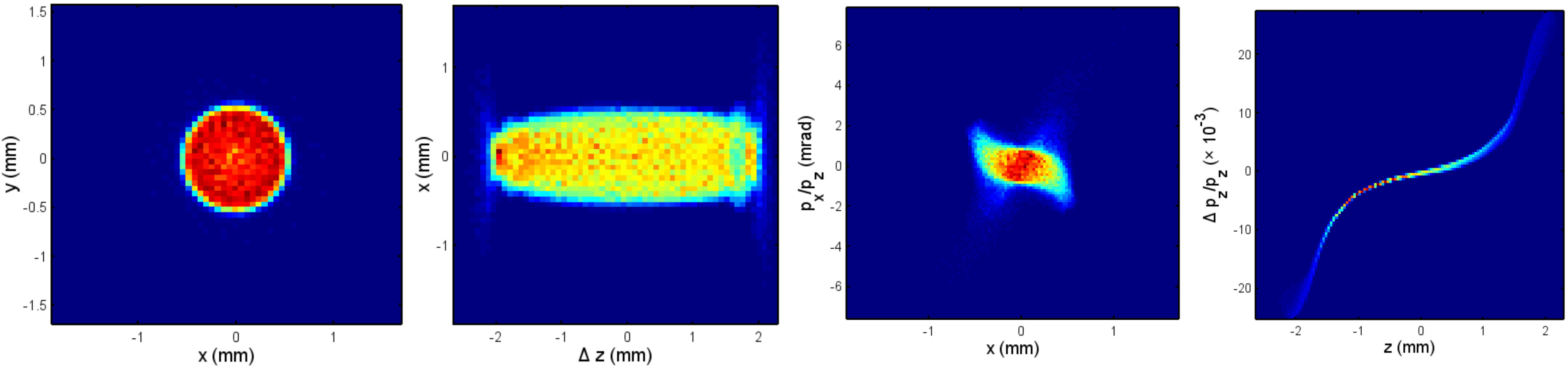


Two-Frequency Directional Coupler

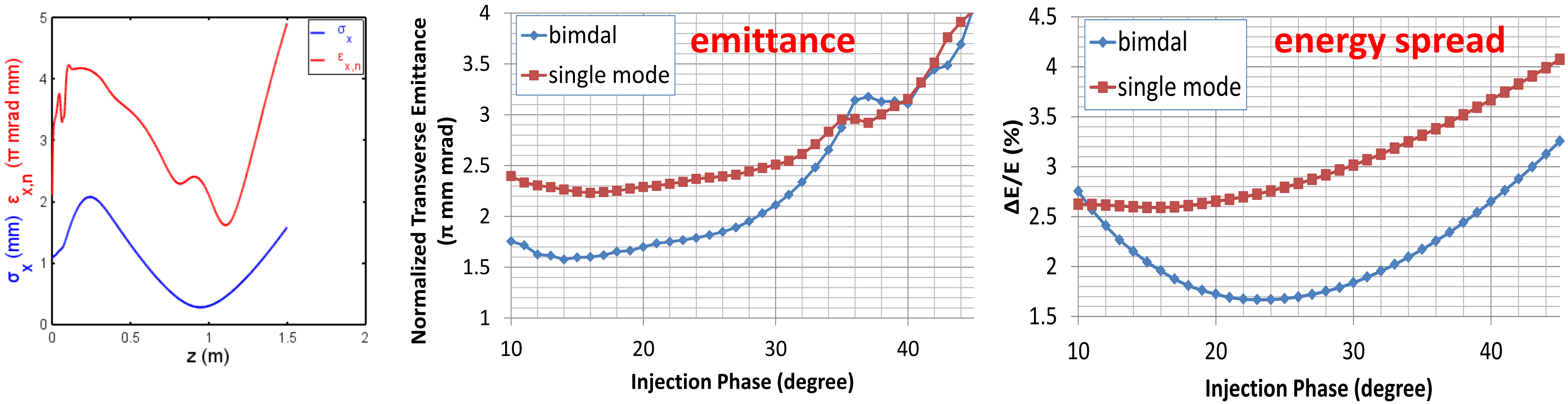


Simulation of Bimodal Electron Gun

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

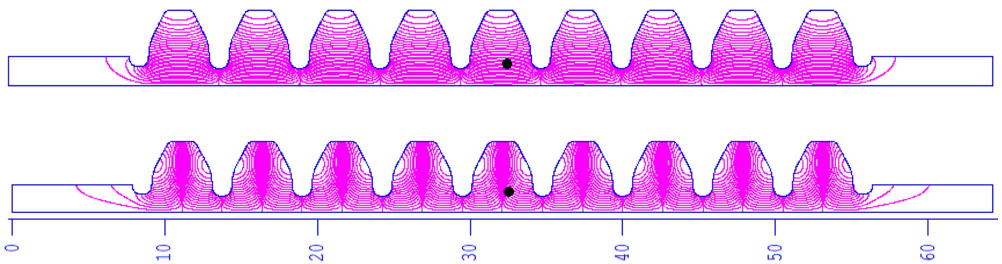


Simulation Results: Beam energy 3.74 MeV, beam size $\sigma_{x,min}$=0.28mm, normalized emittance $\varepsilon_{x,min}$ = 1.62 π mm mrad, energy spread ΔE/E = 1.9%, P_1=2.2 MW, P_2 =1.7 MW, $B_{z,max}$=0.16 T.

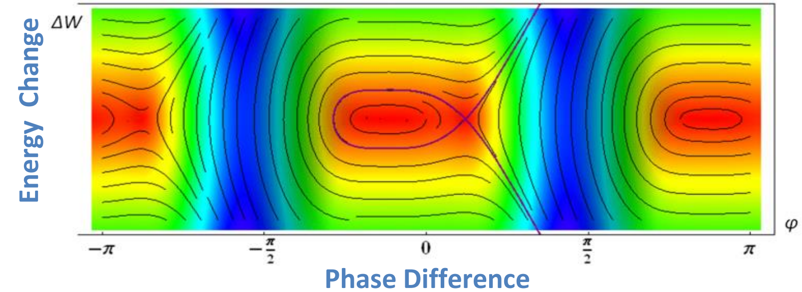


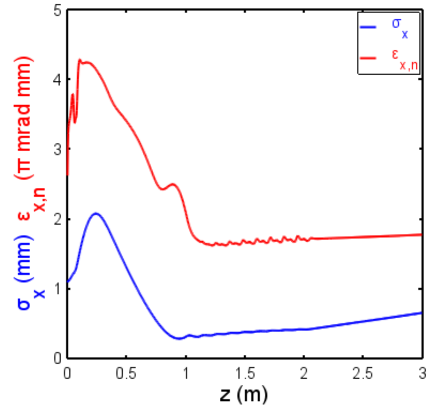
BIMODAL ELECTRON GUN with Boost Linac

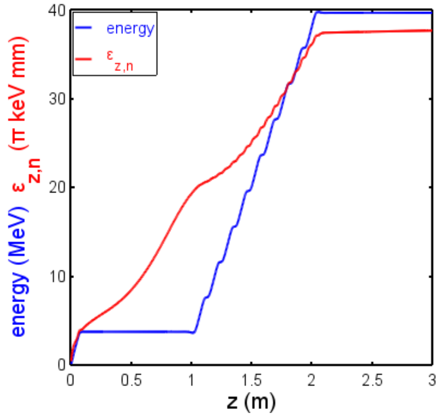
Two Frequency Boost Linac



Two Frequency Fish Plot







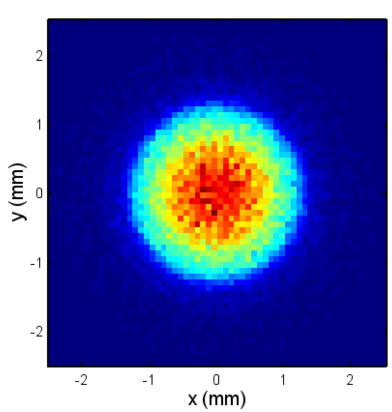
Simulation Results:

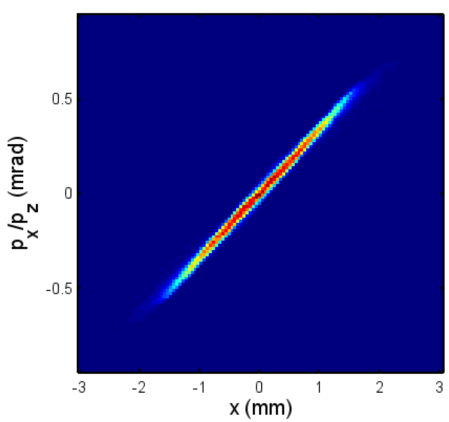
Beam energy 39.6 MeV

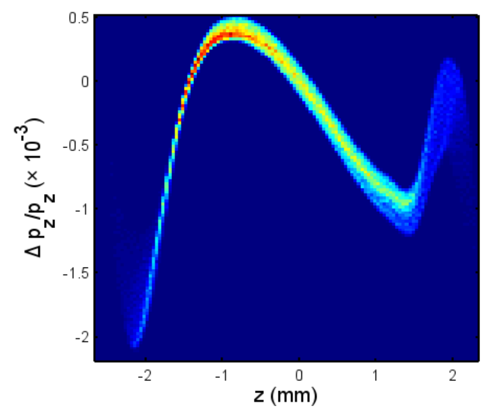
Norm. emit. $\varepsilon_x = 1.8\ \pi$ mm mrad

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

Energy spread $\Delta E/E = 0.082\%$





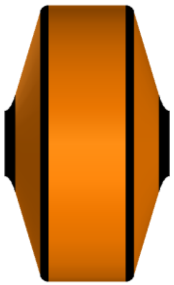


Bimodal Cavity for Pulsed Heating Suppression

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

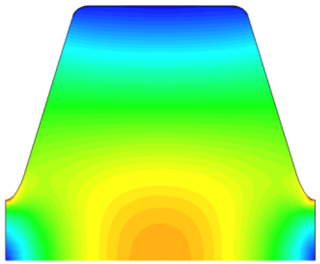
elliptical cavity

$a/\lambda=0.1$

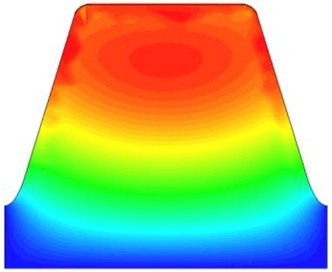


TM_{010} 12 GHz

E

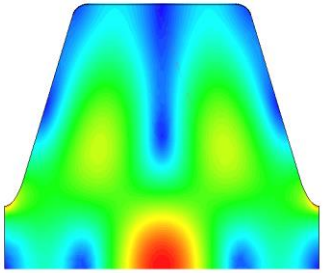


H



TM_{012} 36 GHz

E



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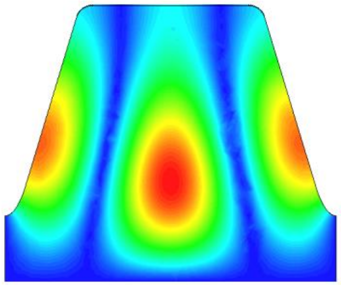
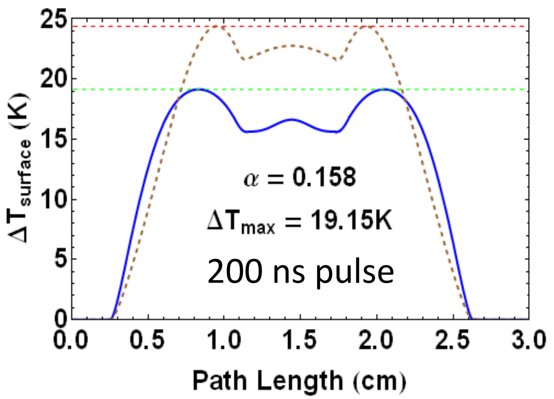
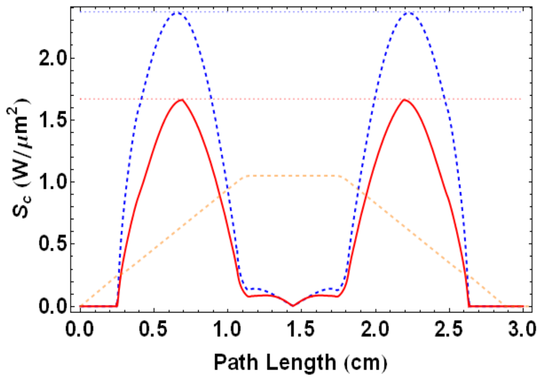


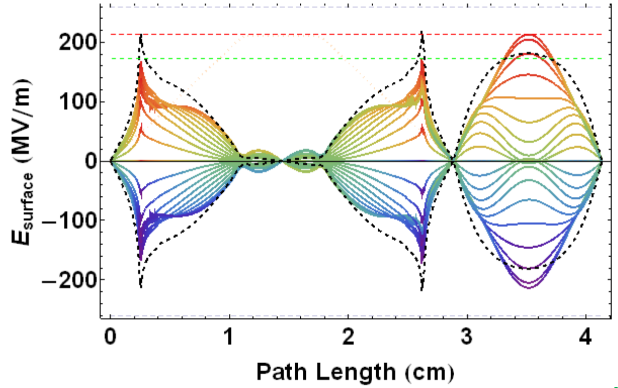
pulsed heating temperature



modified Poynting vector S_c



surface E-field along periphery



Effective acceleration gradient 100 MV/m

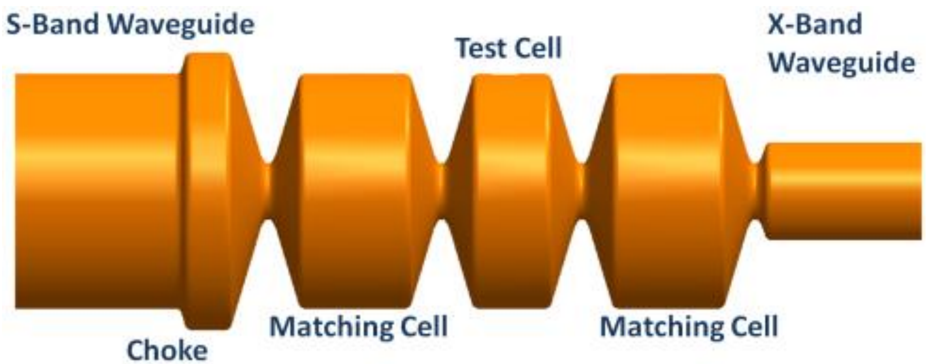
2-mode superposition compared to fundamental mode alone in the same MHC :

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

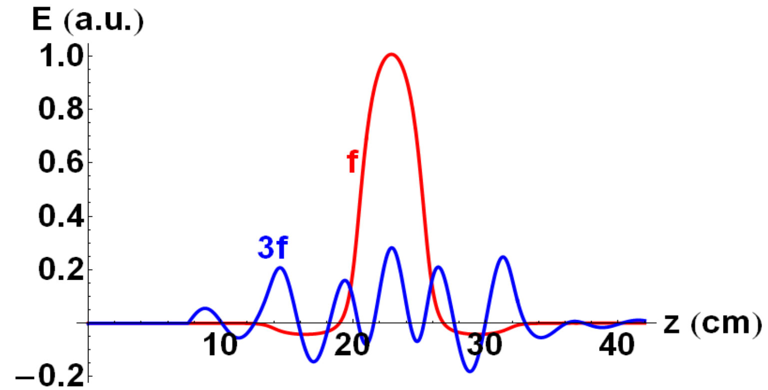
RF Driven Bimodal Cavity with Pulsed Heating Suppressed

RF Driven: Output Cavity of the Two-Frequency RF Source could be changed to third harmonic => *f + 3f – or tested with beam drive.*

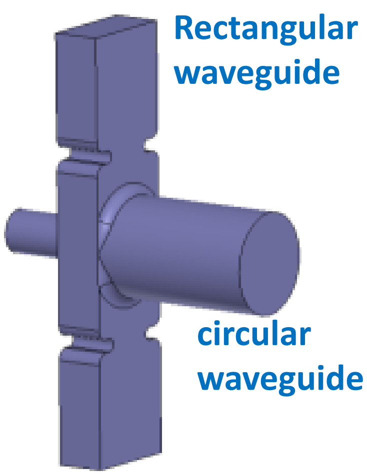
TM_{010} + TM_{012} Test Structure

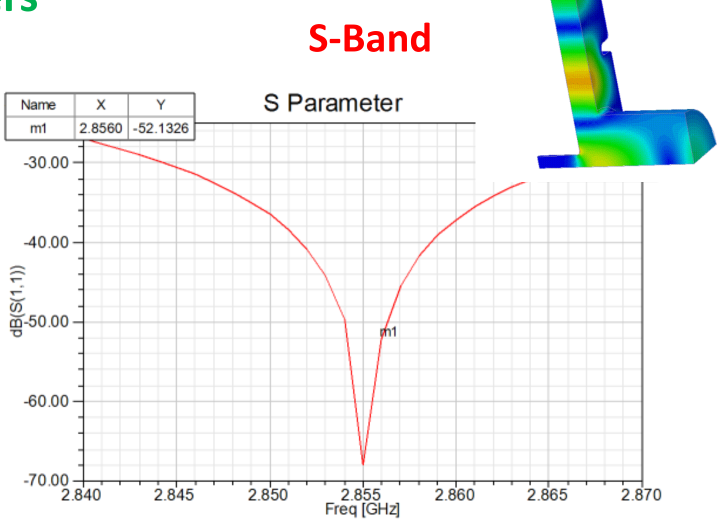


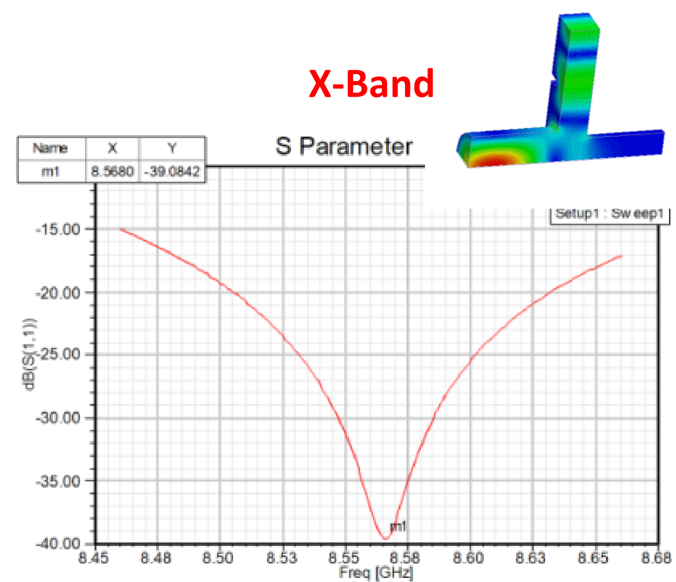
Axial E fields of TM_{010} and TM_{012}



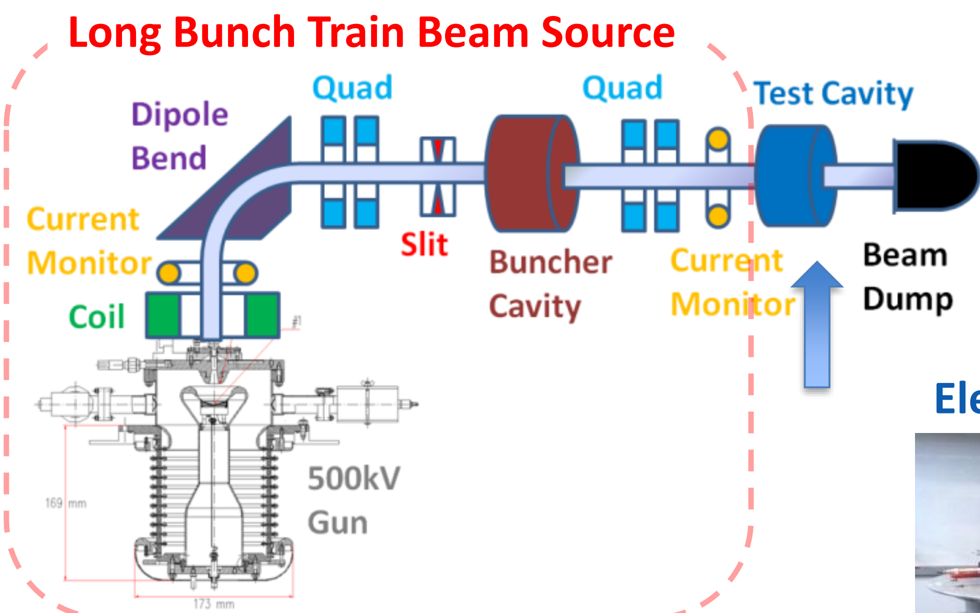
TM_{01} mode launchers

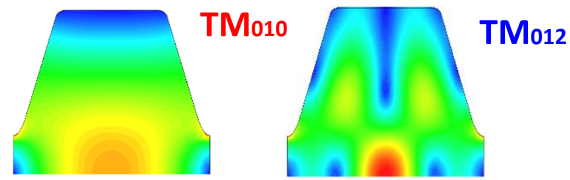






Beam Driven Accelerator Test Stand





Detuned Cavity Two-Beam Acceleration & RF Breakdown Test of Bimodal Cavity

Electron Gun 500kV 220 A

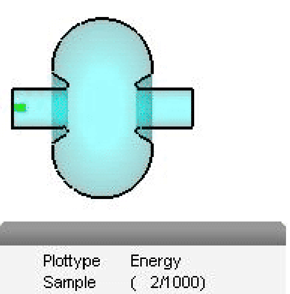
Gun Filament ON

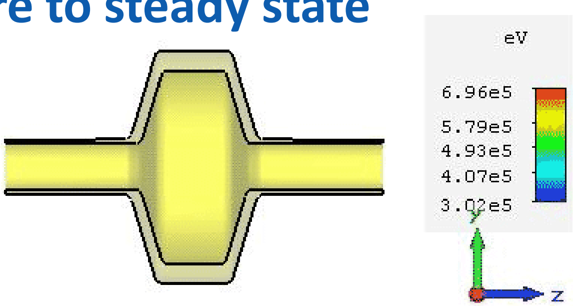
Solid State Marx Modulator 500kV 250 A 1.8 µs 20 Hz

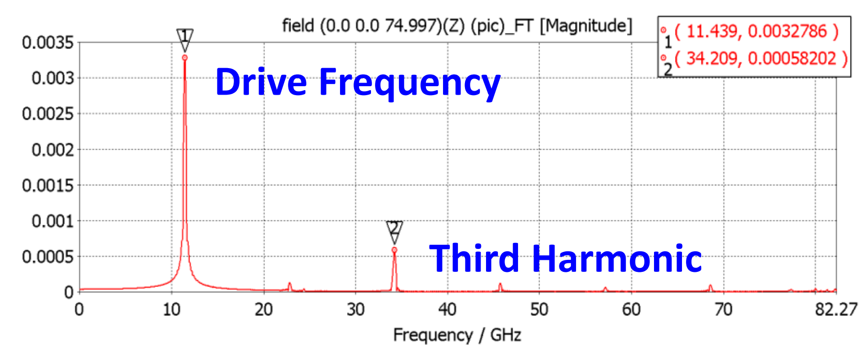
Beam Driven Accelerator Test Stand

- ❑ Long bunch train (1 µs, X-band)
- ❑ High current (up to 220 A DC)
- ❑ High charge per bunch

⇨ **Can provide beam excitation of test structure to steady state**



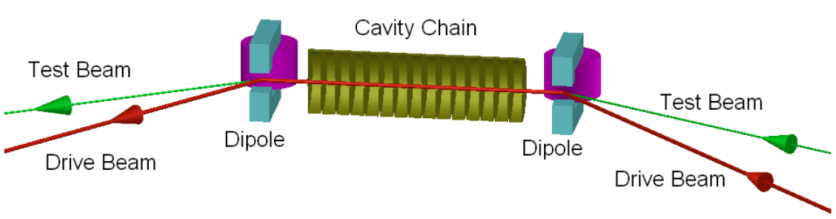


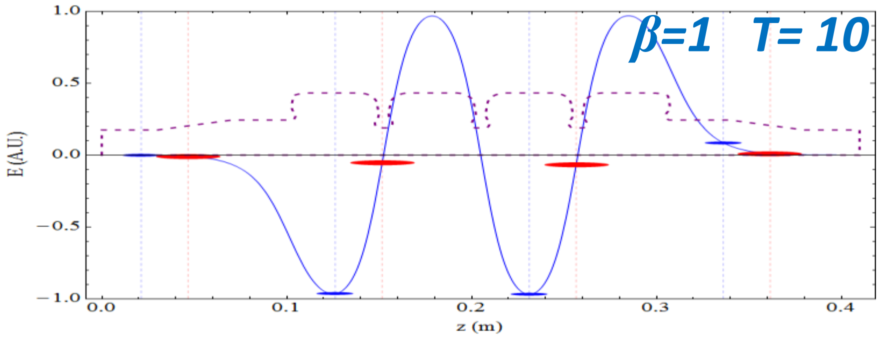


Detuned-Cavity Two-Beam Accelerator

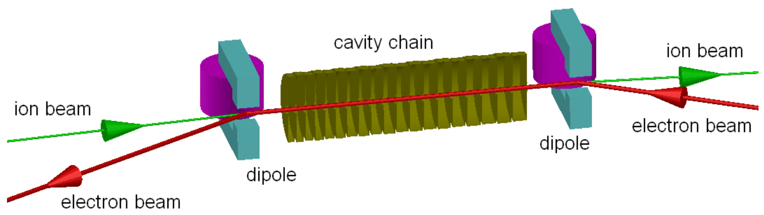
Planned experiment using Beam Driven Accelerator Test Stand: Detuned-Cavity Two-Beam Accelerator

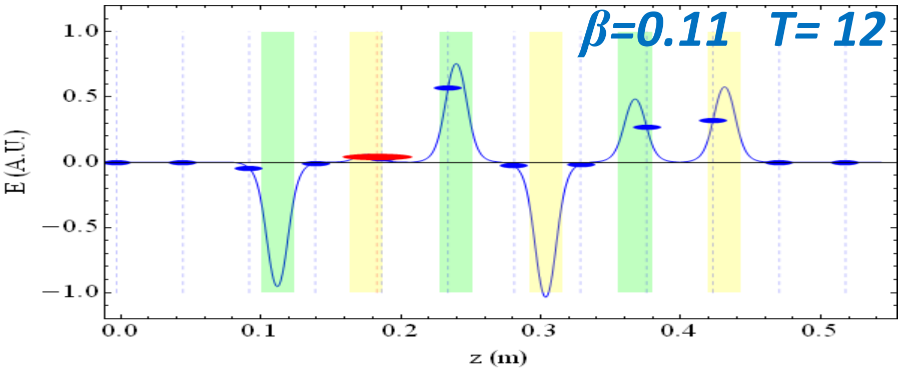
Fixed Detuning Co-propagate

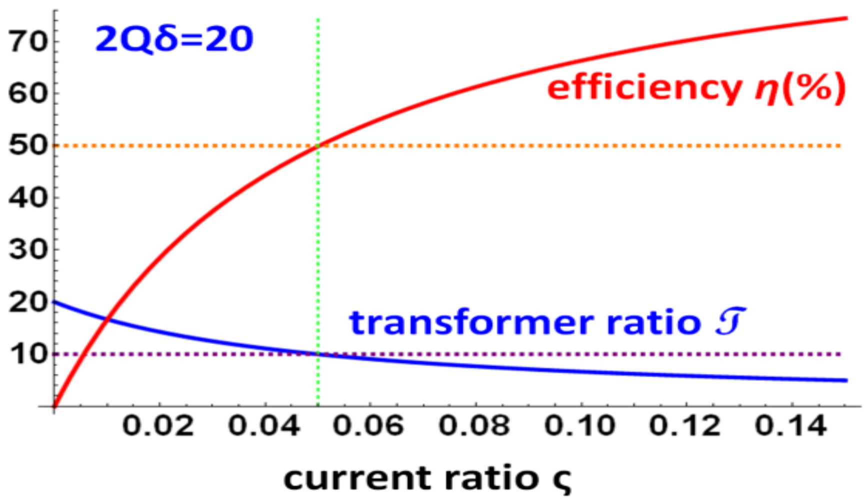




Alternative Detuning Counter-propagate







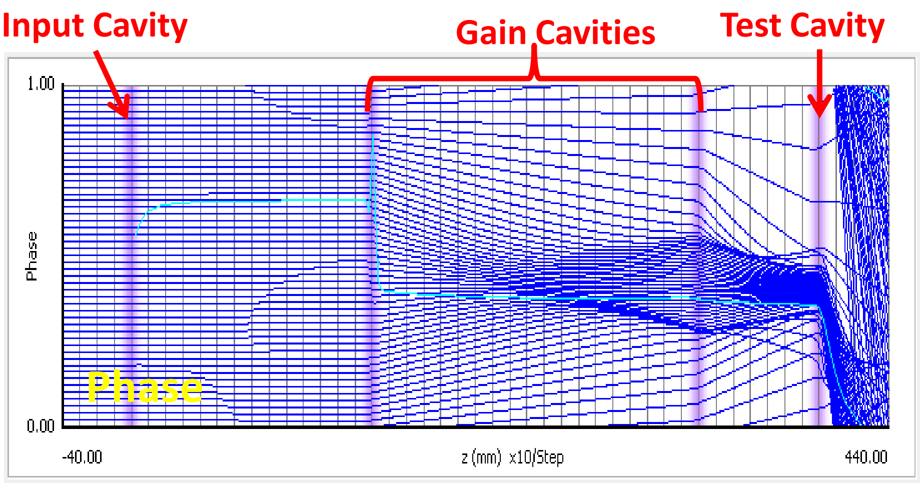
"High-gradient two-beam accelerator structure", S. Yu Kazakov, S.V. Kuzikov, Y. Jiang, and J. L. Hirshfield, PRSTAB 13, 071303 (2010)

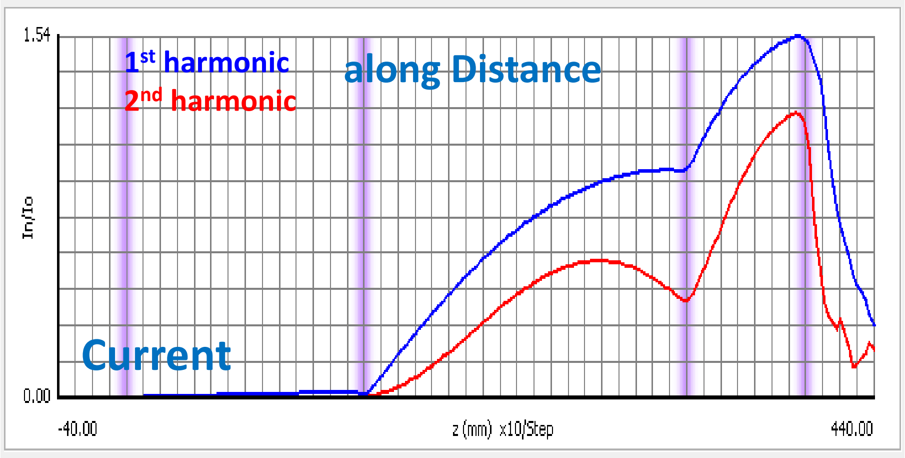
Klystron-like Bunching Scheme

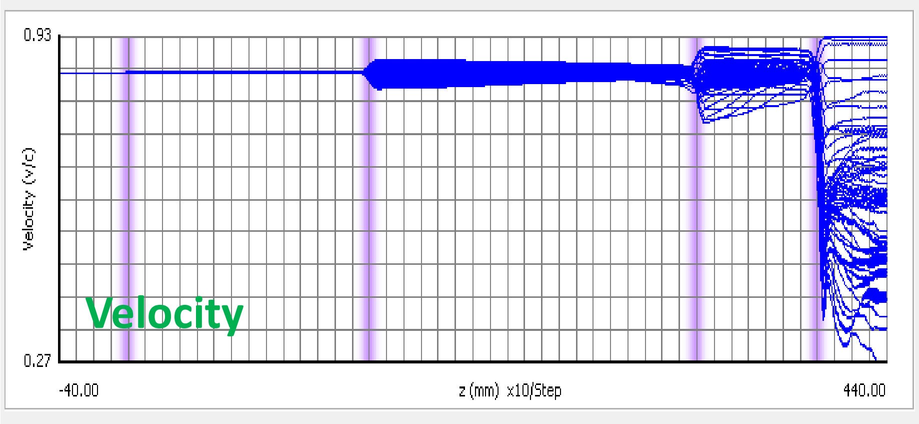
Low Drive Power Requirement, Very High Current, Full Phase Acceptance
=> can use Boost Linac (future) to freeze bunch structure.

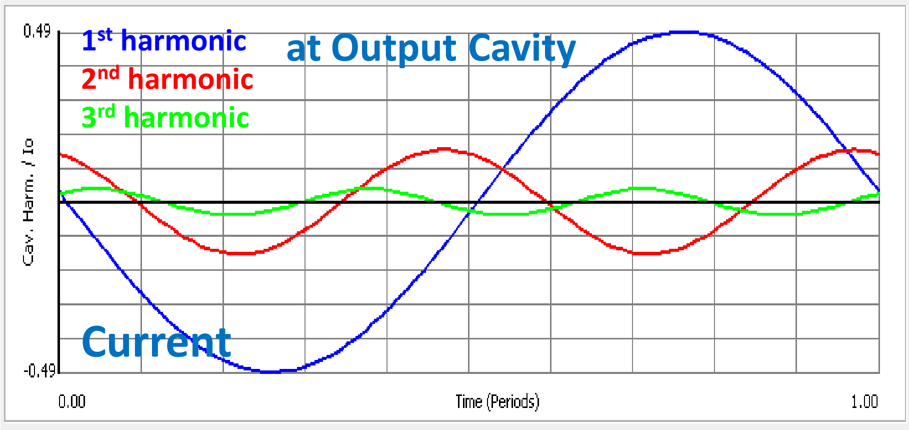
X-band Klystron using Magnicon Gun (AJDisk) - use high efficiency klystron design concept

500 kV, 218 A, Drive 100 W, Output 64 MW, Gain 58 dB, Efficiency 60%, Cavity Chain 40 cm









Bimodal TBA using BDA Test Stand

Issue: Low Energy Drive Beam (without Boost Linac) can be reflected by high field

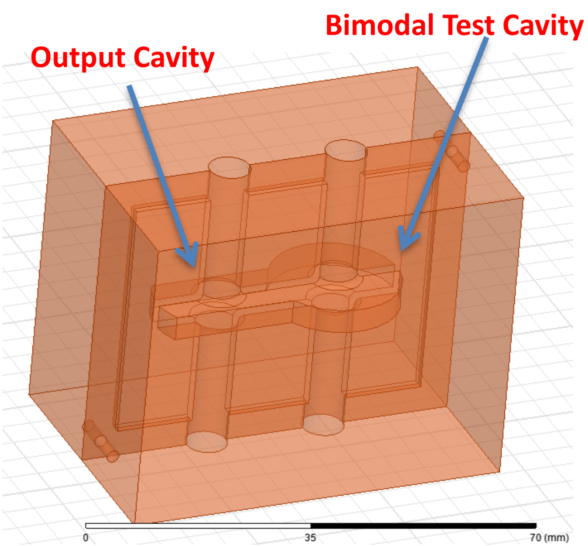
Solution:

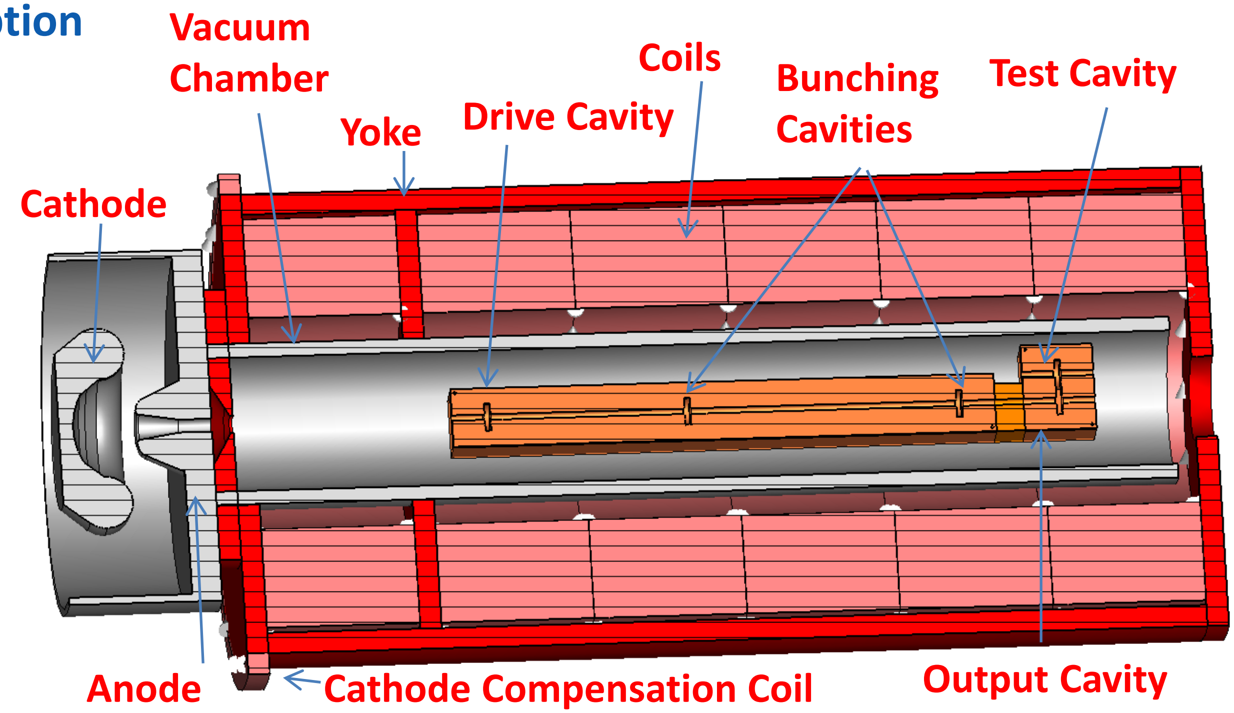
add a two-frequency output cavity and couple to test cavity (until Boost Linac available)

- ✓ Avoid beam reflection
- ✓ Allow large drive beam pipe
  - ➔ lower Brillouin Field (limited by available coils in lab)

Open Half Cavity Design

- ✓ Avoid surface current interruption
- ✓ Good vacuum property
- ✓ Wakefield damping

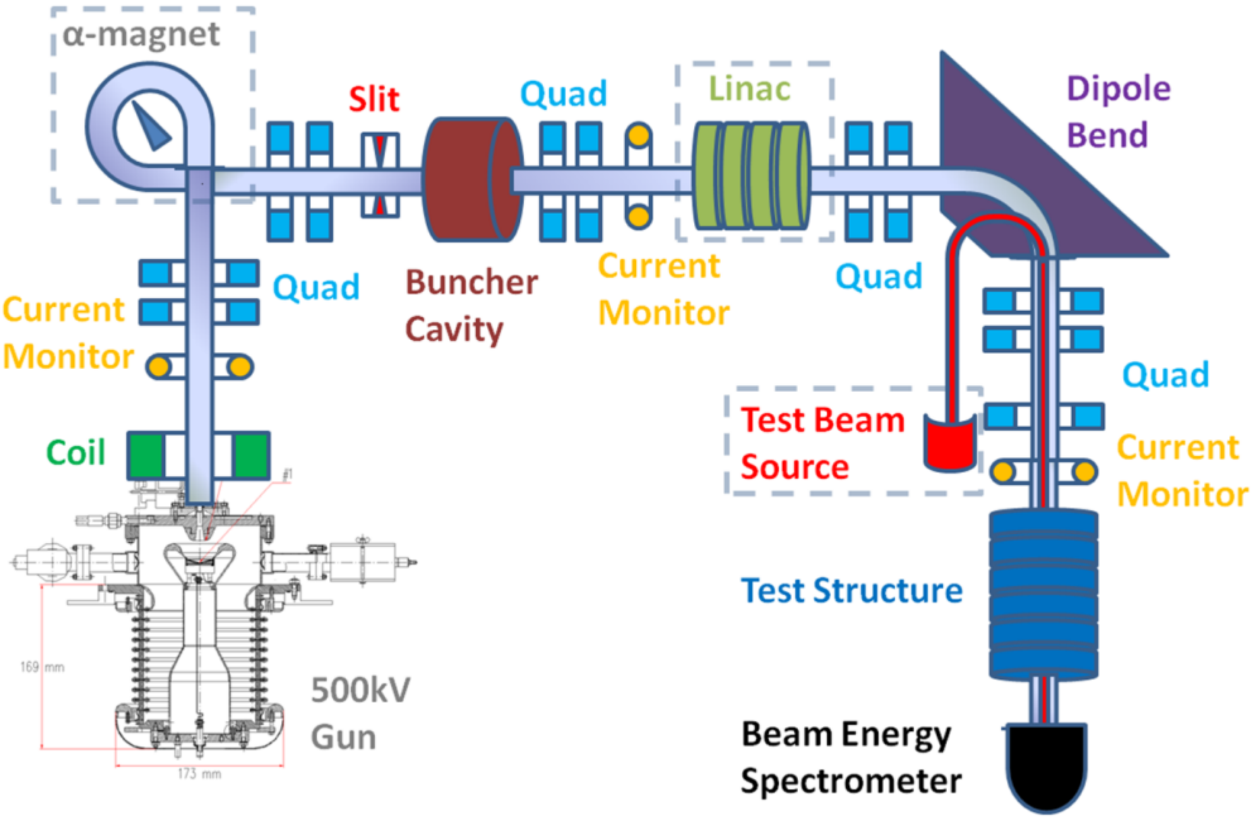




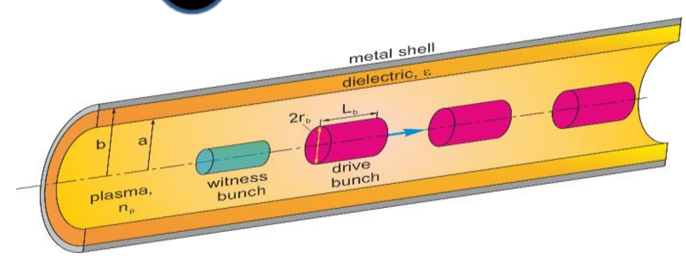
Future BDA Test Stand Upgrade and Tests

Bimodal TBA Structure Test

- Introduce boost linac to freeze bunch structure
- Add test beam source to direct measure transformer ratio and acceleration gradient



Beam Driven Dielectric Wakefield Accelerators



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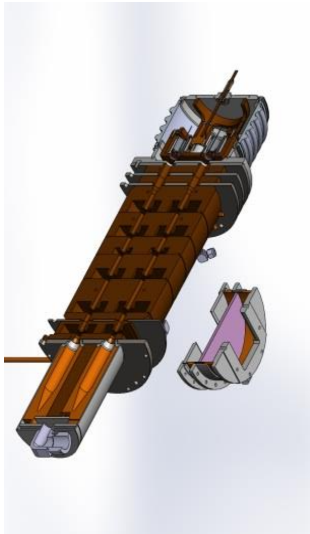
High Efficiency Klystron Development: ILC MBK



Design

Omega-P, Inc.

Assembly

CCR

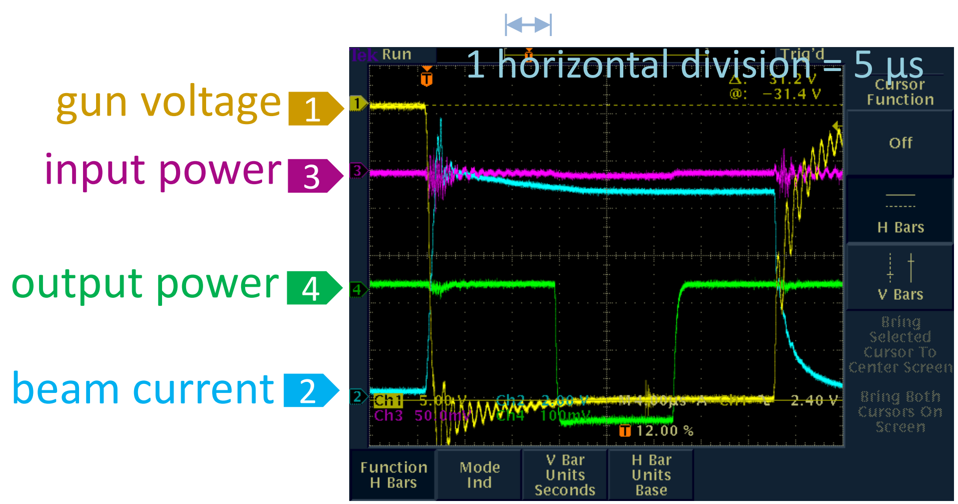
Initial Test

CPI
Communications & Power Industries

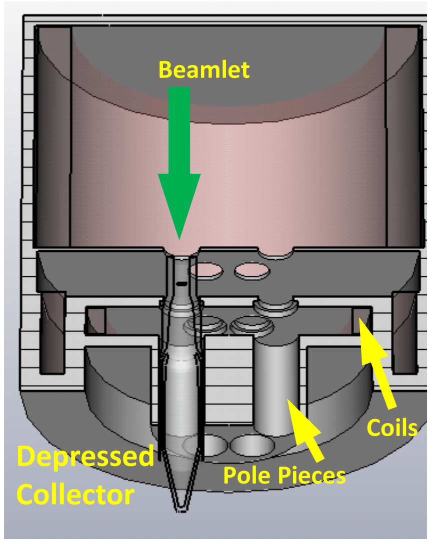
Scheduled to Further Test at SLAC

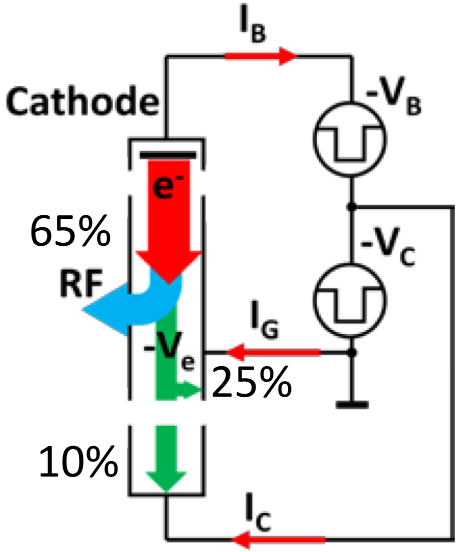
Design Values

COMPACT	**six-beamlet quadrant, 54" high**
LOW-VOLTAGE	**operating voltage of 60 kV**
HIGH-POWER	**2.5 MW, 50 dB gain**
LONG PULSE	**1.5 ms RF pulses**
HIGH EFFICIENCY	**~65%**



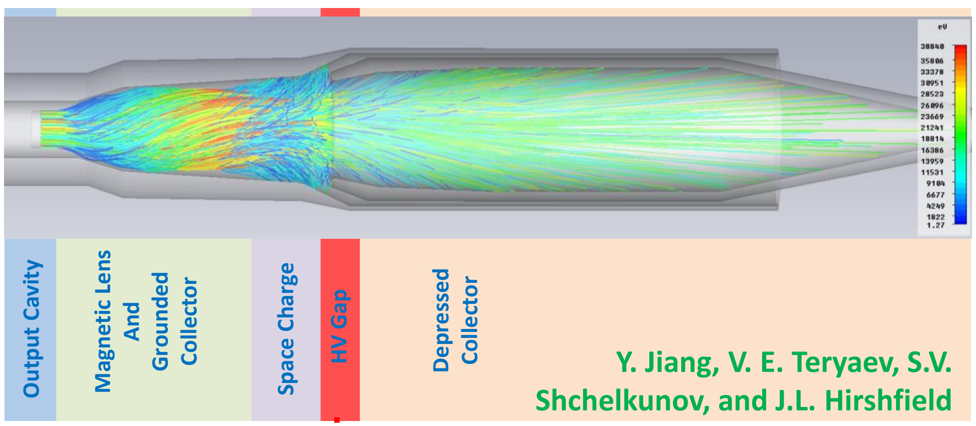
Depressed Collector FOR ILC MBK

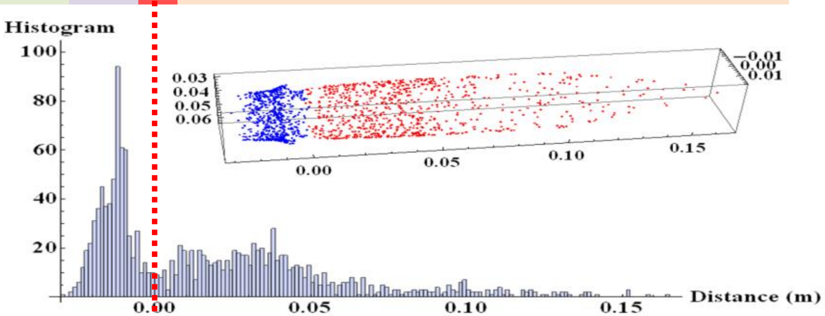


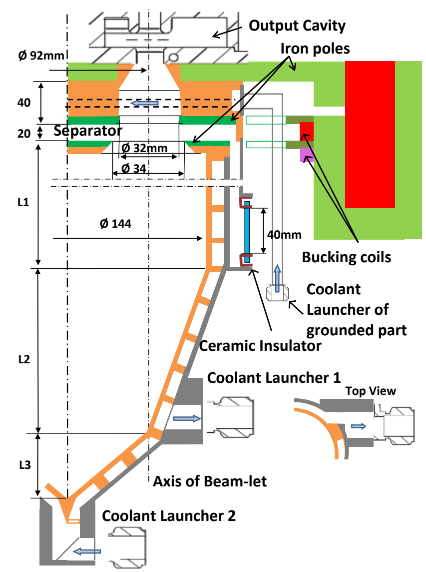


Partially-Grounded Depressed Collector

- ❑Steep B-field gradient and space charge forces →transverse deflection and trapping electrons
- ❑Grounded section absorbing otherwise reflected low-energy electrons
- ❑High energy recovery efficiency :
  Increase from intrinsic tube efficiency 65% towards 75~80%







Collector Rework

Summary

- **Use of bimodal cavities is predicted to reduce breakdown probability, for a given acceleration gradient, *via***

  Anode-cathode effect to suppress field emission; and/or

  Quadratic effect 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, 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.**
- **Parallel efforts in high efficiency klystron development**
- ***LOTS OF WORK REMAINS!!***

Acknowledgements

U.S. DEPARTMENT OF ENERGY

NSF

Yale University

LUX ET VERITAS

Omega-P R&D, Inc.

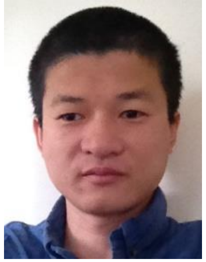
SINAP

中国科学院上海应用物理研究所

Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Beam Physics Lab, Yale University **http://bpl.yale.edu**

Prof. Jay Hirshfield



Dr. Yong Jiang

Dr. Sergey Shchelkunov

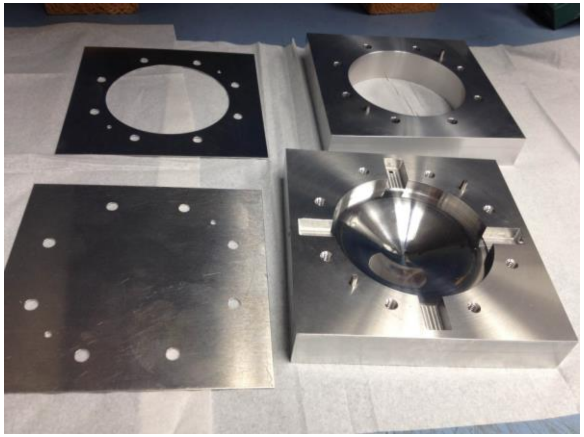
Dr. Xiangyun Chang

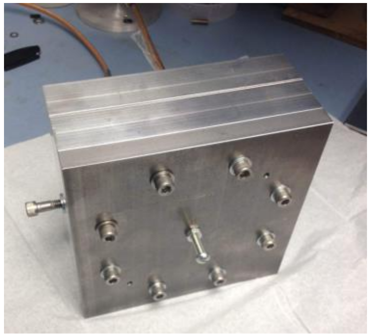
Postdoc Position Open

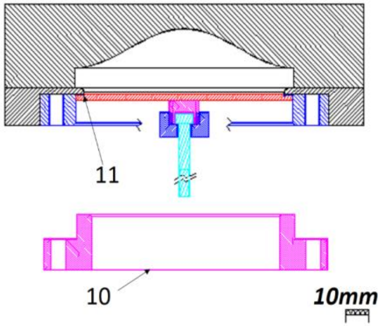
BACKUP SLIDES

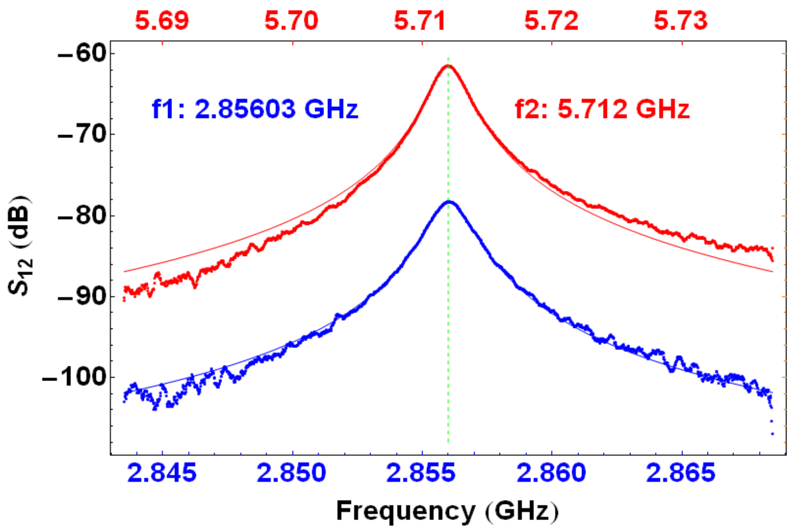
Two Frequency Tuning of Bimodal Cavity

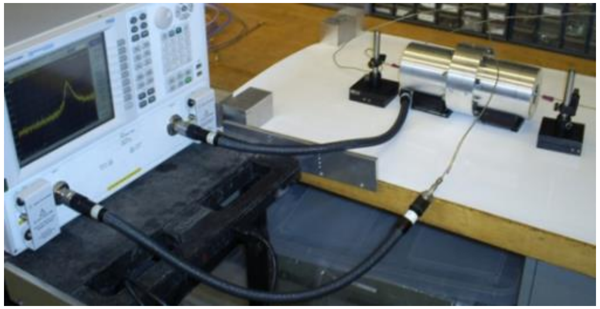
Anode-Cathode Cavity



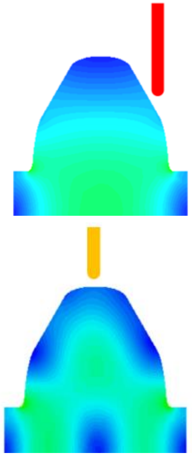


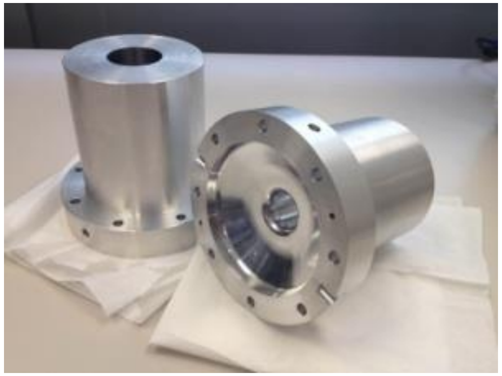


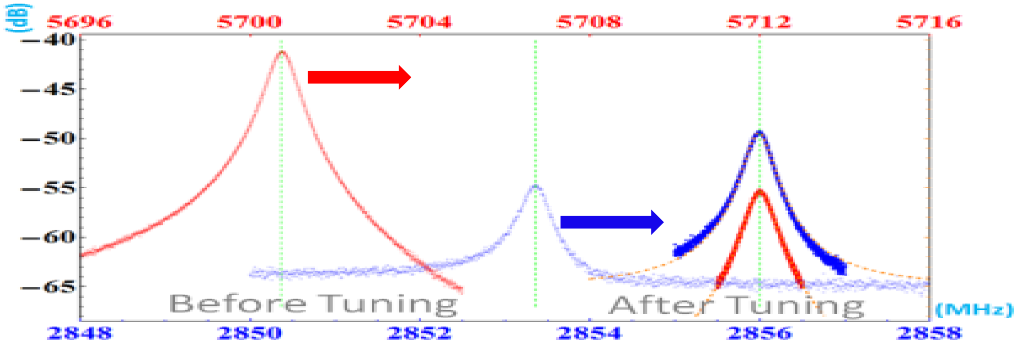




Symmetric Bimodal Cavity







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%

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 :

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

	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

Circuit Model for Collinear Two Beam Accelerator

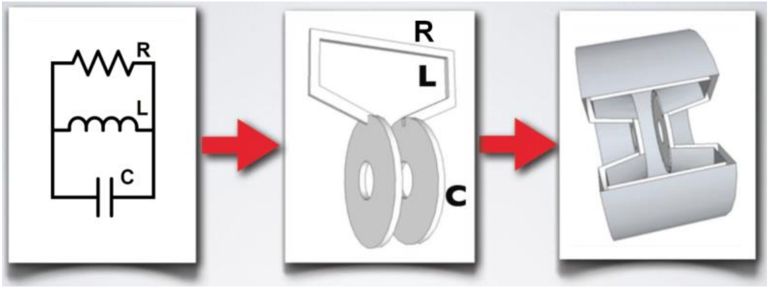
RLC Circuit Model

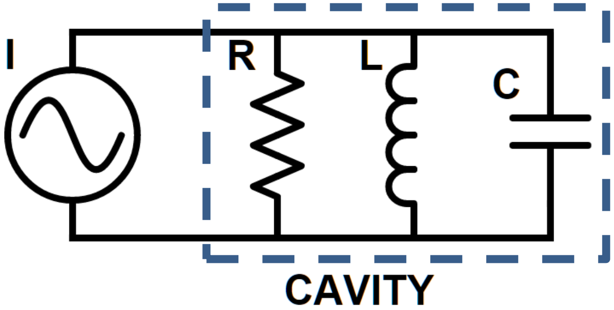
↓

Accelerating Cavity

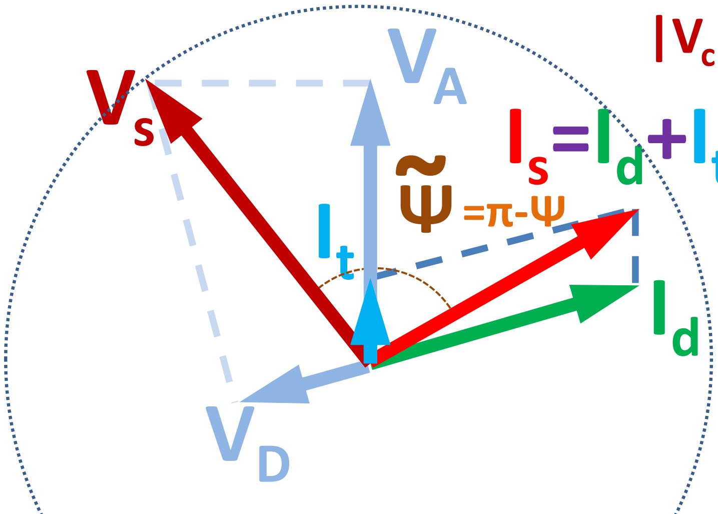
↓

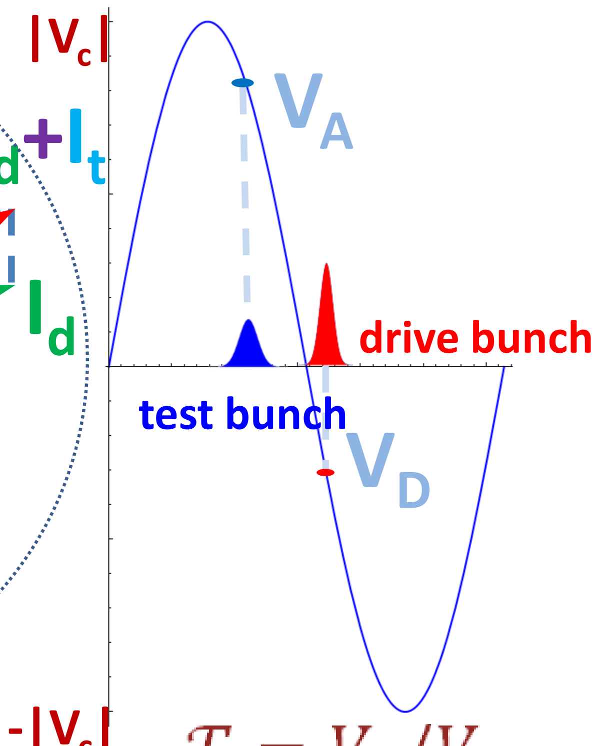
Beam Cavity Interaction





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





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

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

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

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

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