Bimodal Cavities for RF Breakdown Studies

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Research supported in part by US DoE –Office of High Energy Physics

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References:

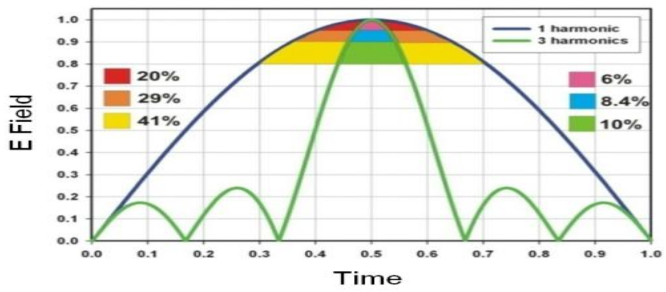
- "Asymmetric bimodal accelerator cavity for raising RF breakdown thresholds," by S.V. Kuzikov, S.Yu. Kazakov, Y. Jiang, and J.L. Hirshfield, *Phys. Rev. Lett.* **104**, 214801 (2010).
- "High-gradient two-beam accelerator structure," by S.Yu. Kazakov, S.V. Kuzikov, Y. Jiang, and J.L. Hirshfield, submitted to *Phys. Rev. ST – Accel. & Beams* (2010).

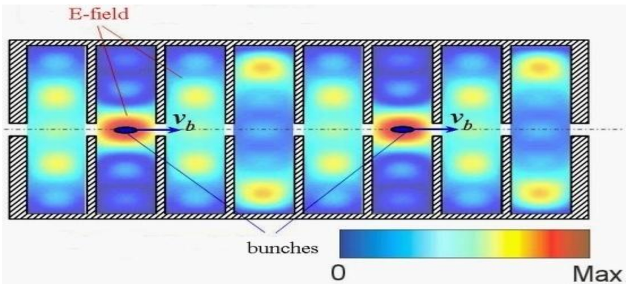
Multi-Harmonic Cavities to Increase Breakdown Threshold

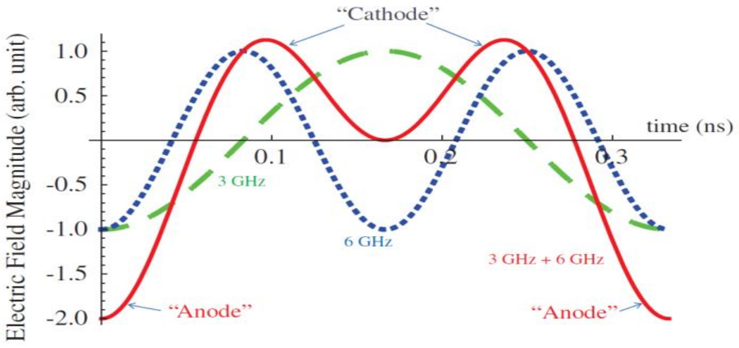
Hypotheses of the onset of RF breakdown

- Initiated by electron emission driven by the RF electric field directing towards the wall, where electrons can be accelerated to escape from the wall, and stimulate a breakdown event;

- Promoted at surface irregularities which are accentuated by stresses induced by pulsed heating due to surface RF magnetic fields.







Superimposing harmonically-related modes

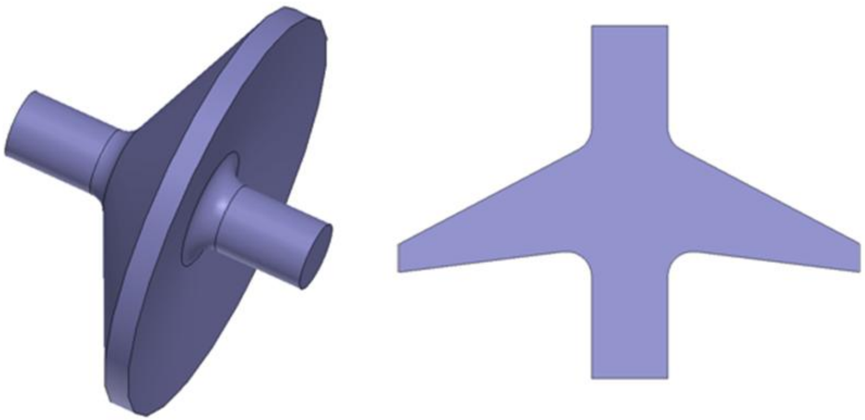
- shorten the exposure times on metallic cavity surfaces to the peak RF electric fields during each RF cycle;

- yield RF electric fields that point into metallic cavity surfaces to be always smaller than fields that point away from the surfaces; and

- cause the exposed areas on the cavity surface where RF magnetic fields have peak values to shrink and sweep around the surface during each RF cycle.

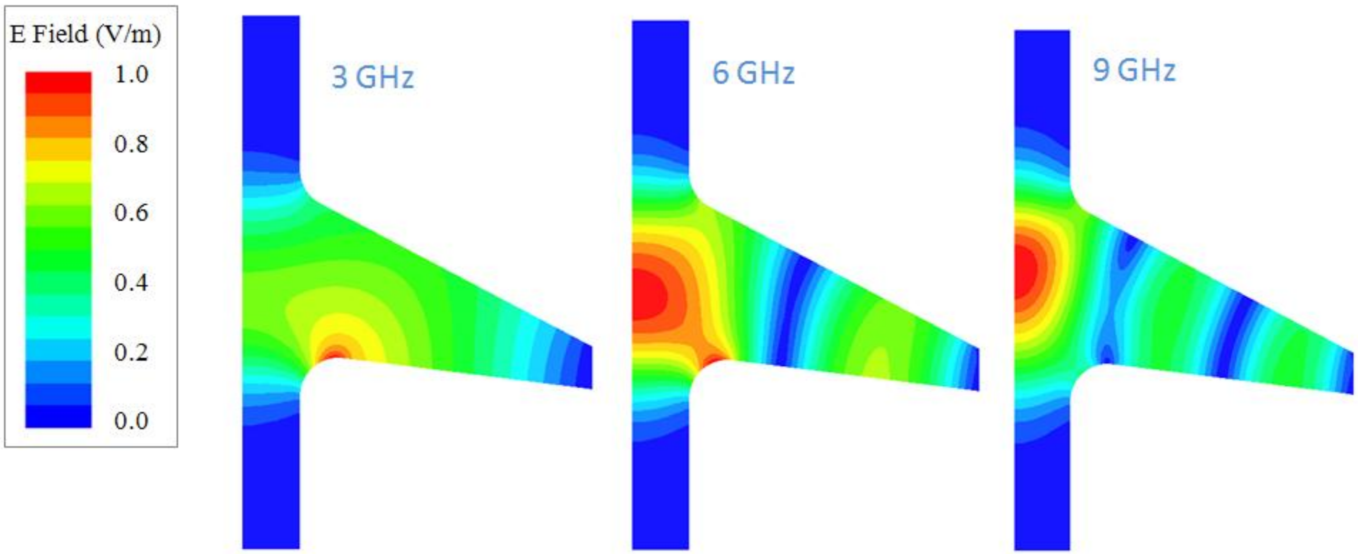
These interconnected mechanisms may occur together

Example of Multi-Harmonic Mode Cavity (3 Modes)

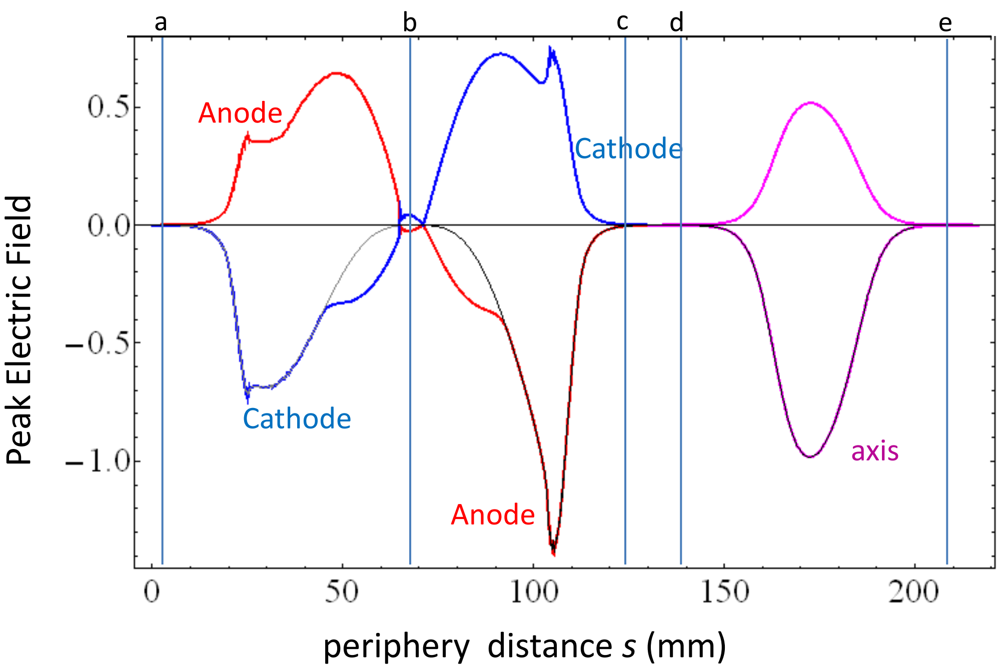


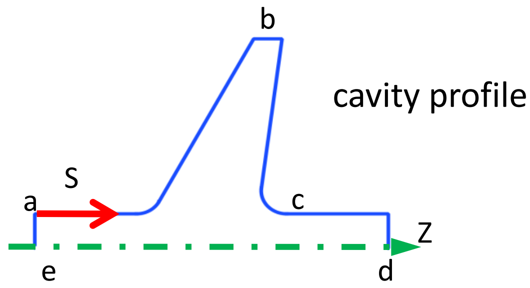
Tri-modal cavity supports three modes at harmonically-related frequencies. Cavity fields are symmetric around the cavity axis, but asymmetric along the axis.

Eigenmodes	TM_{010}	TM_{020}	TM_{030}
Freq (GHz)	2.99998	5.99995	8.99993
Q (Cu walls)	7041.63	10789.1	14077.5



Anode-Cathode Effect in Multi-Harmonic Cavity





Peak electric field envelope around the cavity periphery as coordinate *s* advances along the cavity perimeter and along the cavity axis. Red segments are anodelike, while blue segments are cathodelike. Magenta segments are fields along the cavity axis.

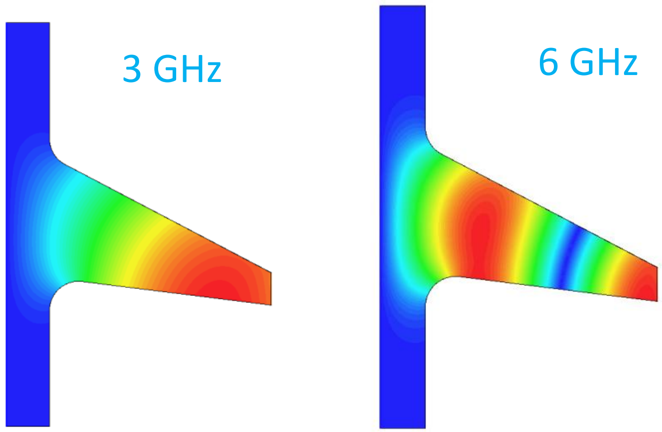
We define a "benefit ratio" *R*, as

$$R = \frac{(G/E_c)_{\text{multi-mode}}}{(G/E_c)_{\text{PillboxCavity}}}$$

E_c is peak magnitude of electric field pointing towards a cavity surface (cathodelike), and *G* is the acceleration gradient. For the cavity profile shown, *R* = 1.55 with field amplitude ratio E_1:E_2=1 : 0.4.

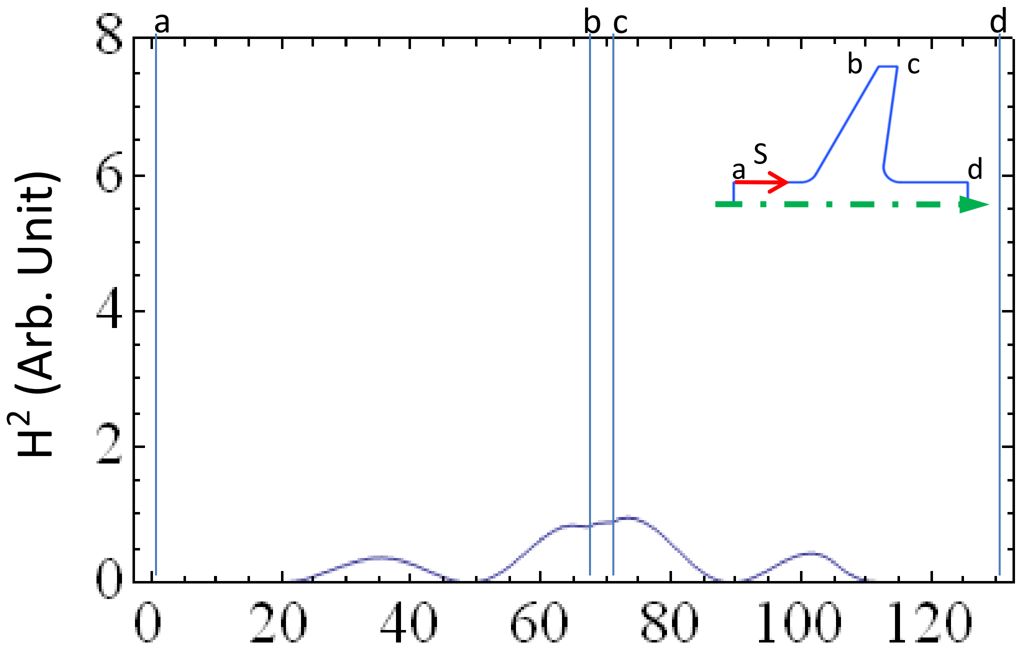
Thus, a structure using such multimode cavities might support an acceleration gradient about 55% greater than that for a structure using similar single-mode cavities, without an increase in breakdown probability.

RF Pulse Heating in Multi-Harmonic Cavity



Magnetic field pattern

Temperature rise ΔT proportional to H^2



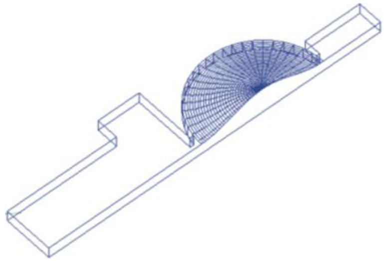
periphery distance *s* (mm)

It has been estimated by the coauthor S. Kuzikov that the total temperature rise from two mode excitation in similar multi-harmonic cavities driven by CTF3 beam is ~50 ° C. Such temperature level suggests that the multi-harmonic cavity is suitable to accumulate necessary statistical information about breakdown rate.

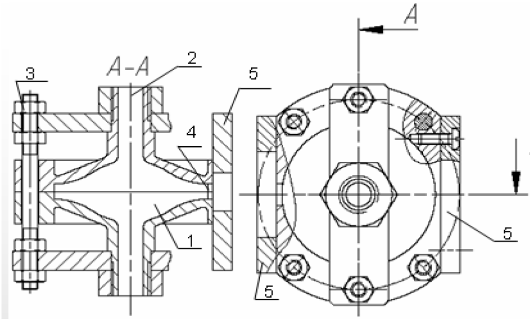
RF Breakdown Experiment using Bimodal Cavity

Experimental efforts are being carried out with

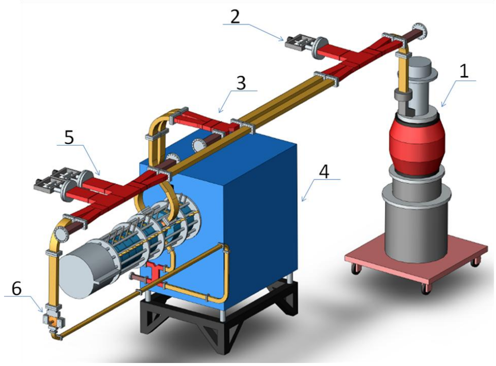
(a) Development of bimodal asymmetric demountable cavities to incorporate practical couplers and diagnostics;



(b) Implementation of low-power cavities for cold tests to confirm the designs; and

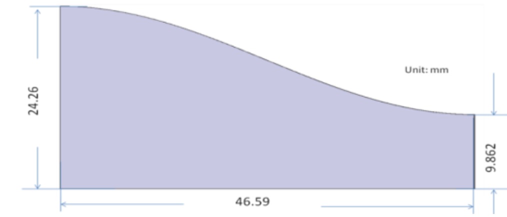


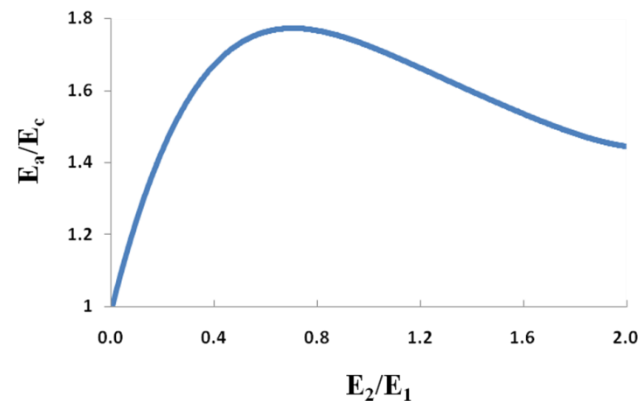
(c) Preparation of a dual-frequency multi-MW mutually-phase coherent RF source for high-power dual-frequency tests to follow.



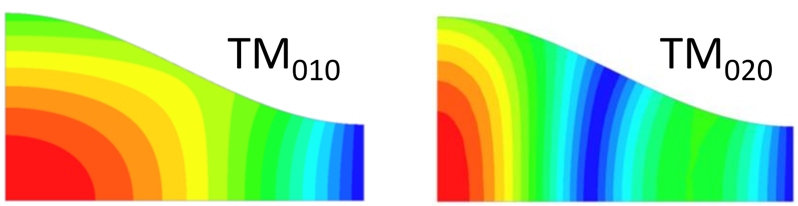
Bimodal Asymmetric Cavity

Frequency (GHz)	2.85599	5.71196
Q	8229.97	12856.8
R (M Ω/m)	41.30	48.26
R/Q (Ω/m)	5018.34	3753.43
P_w(MW) @100MV/m $E_{surface}$	3.492	1.976

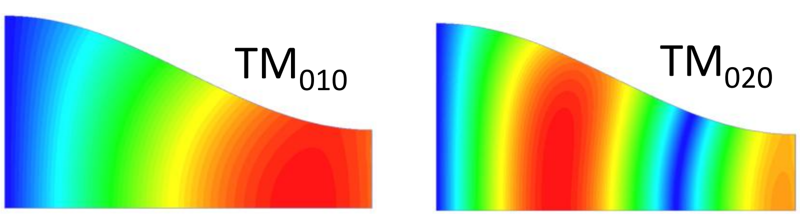




Electric Field Map



Magnetic Field Map

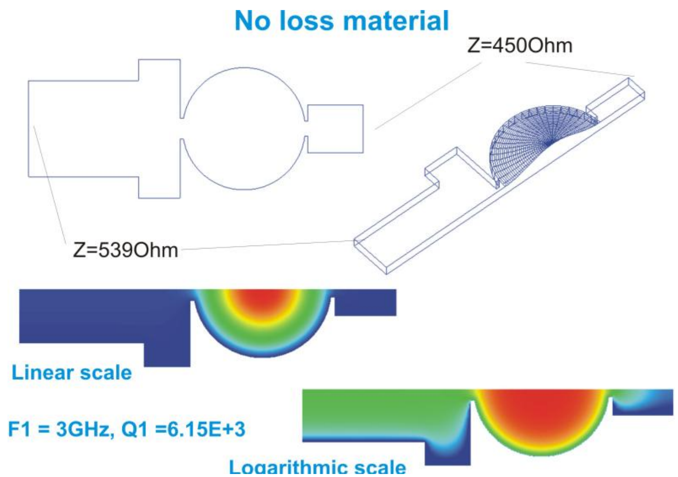


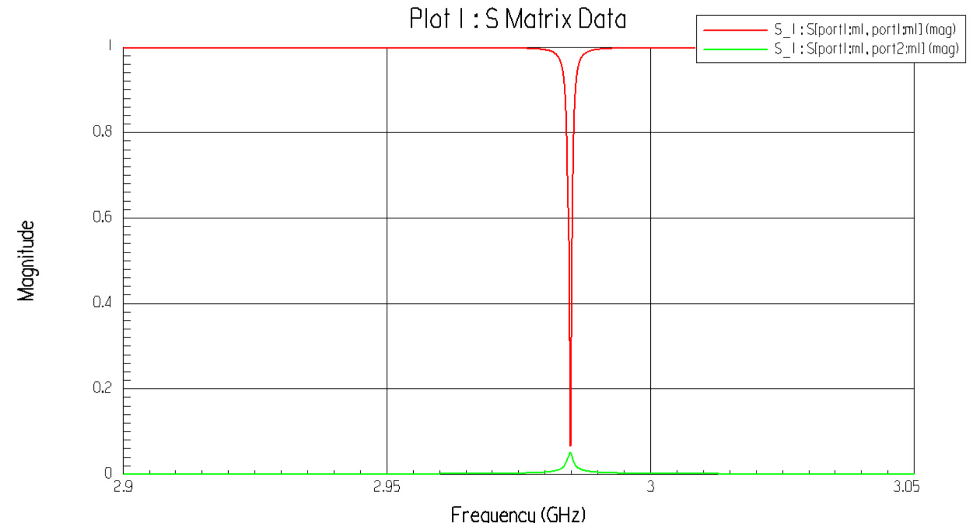
RF power requirements for 2.856 GHz and 5.712 GHz coherent sources needed to sustain the listed peak surface fields with $E_2 = 0.5812E_1$, assuming that breakdown would not intervene.

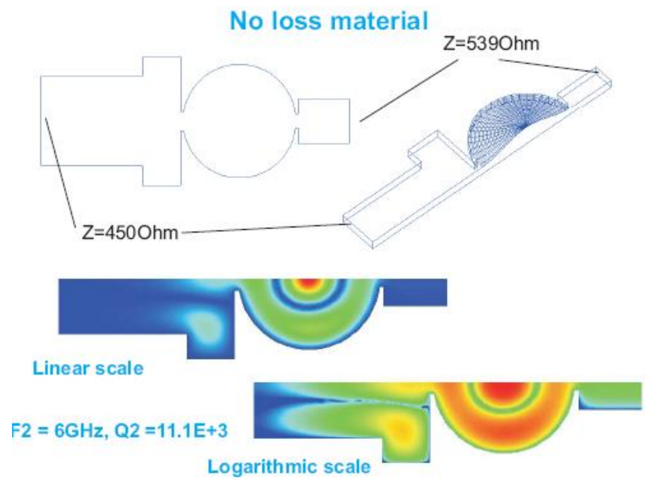
$E_{surface}$ (MV/m)	P_1 (MW)	P_2(MW)	P_{total} (MW)
100	1.397	0.267	1.700
200	5.587	1.068	6.800
300	12.57	2.403	15.301

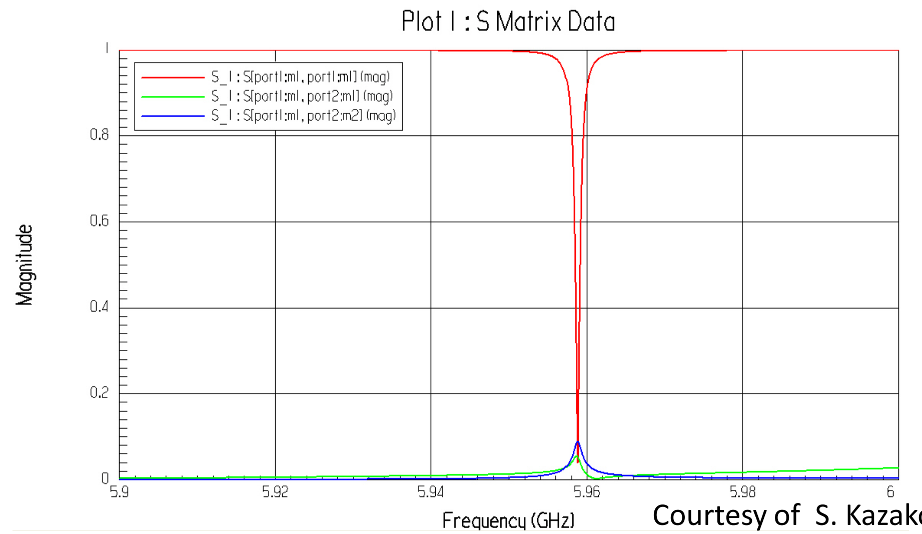
Coupling Design for Bimodal Cavity

A coupling design is used to couple power from two phase-locked high-power RF sources into the bimodal cavity. Amplitude and phase of RF can be adjusted to study various scenarios with certain effect dominant.









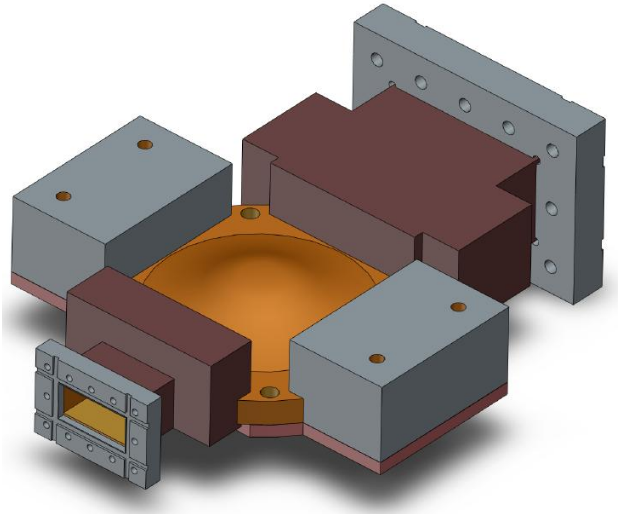
Courtesy of S. Kazakov

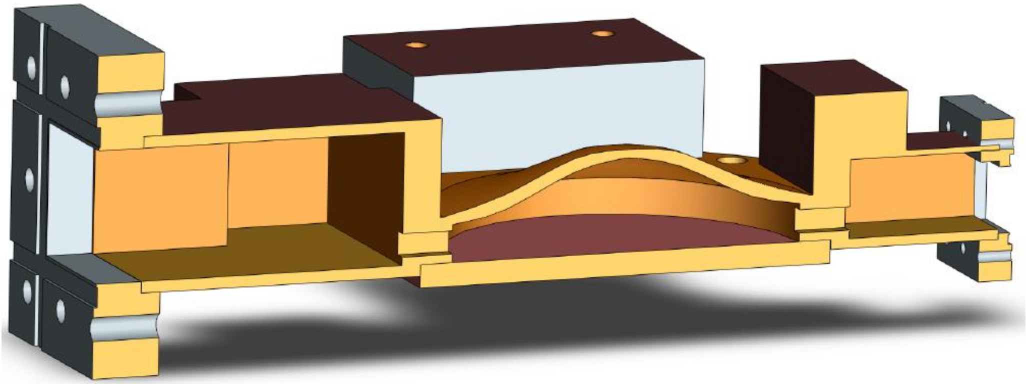
Conceptual Design of Demountable Bimodal Cavity

A bimodal asymmetric cavity design in a clamped structure with demountable bottom flat surface allows convenient replacement of test plates for inspection and reassembling without disconnecting or changing the dual-frequency RF coupling and power feeding systems.

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

- The two input waveguides and the top portion of the cavity are to be reused for a series of tests with varying power levels and phases for the two RF sources, to gauge the validity of the anode-cathode imbalance conjecture.

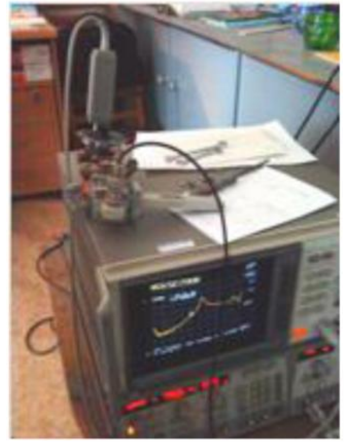


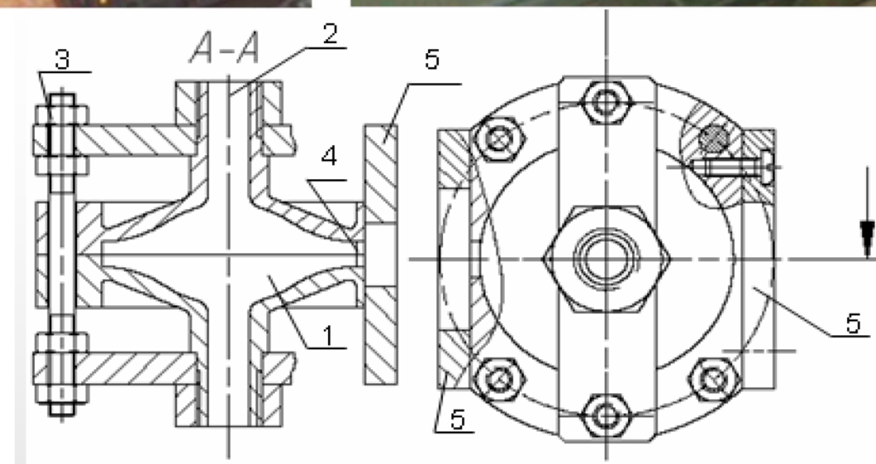


Cold Test of Tunable Bimodal Cavity

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.





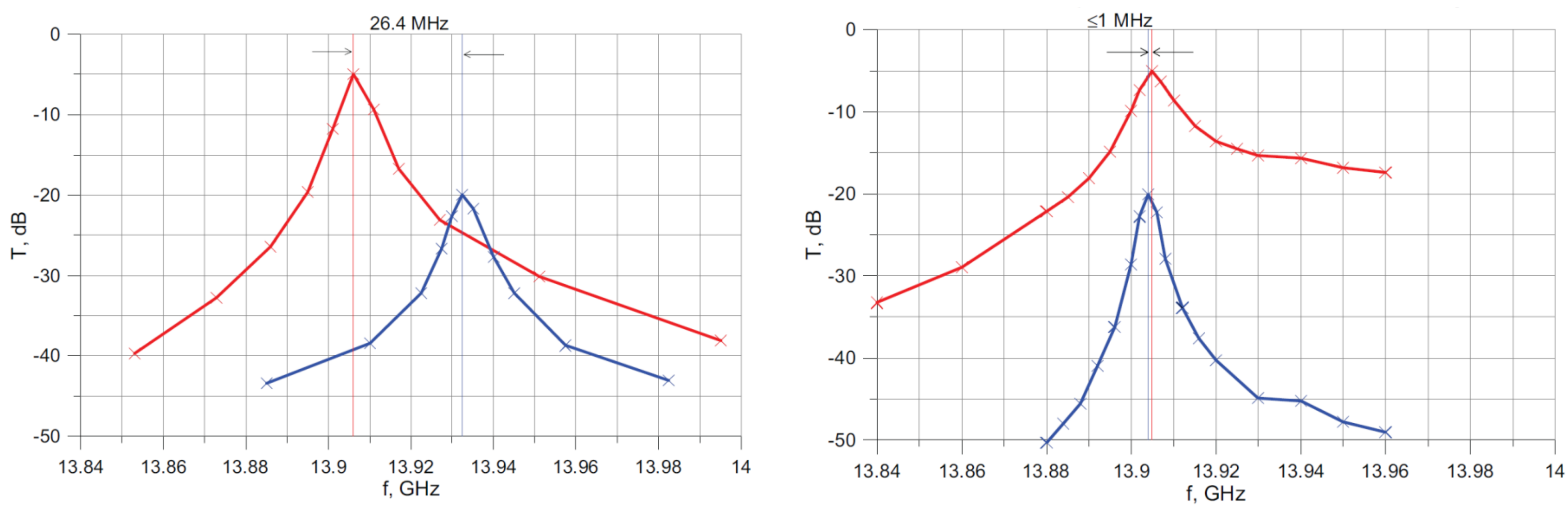
Drawing of the test cavity with a flexible wall: ***1*** – cavity body; ***2*** – simulated beam tunnel; ***3*** – tuning screw, ***4*** – coupling holes; ***5*** – waveguide flanges.

Courtesy of S. Kuzikov

Tuning of Bimodal Cavity

The difference between the doubled frequency of the first mode and the frequency of the second mode, i.e., $\Delta f = 2f_1 - f_2$, characterizes a measure of mode harmonicity.

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



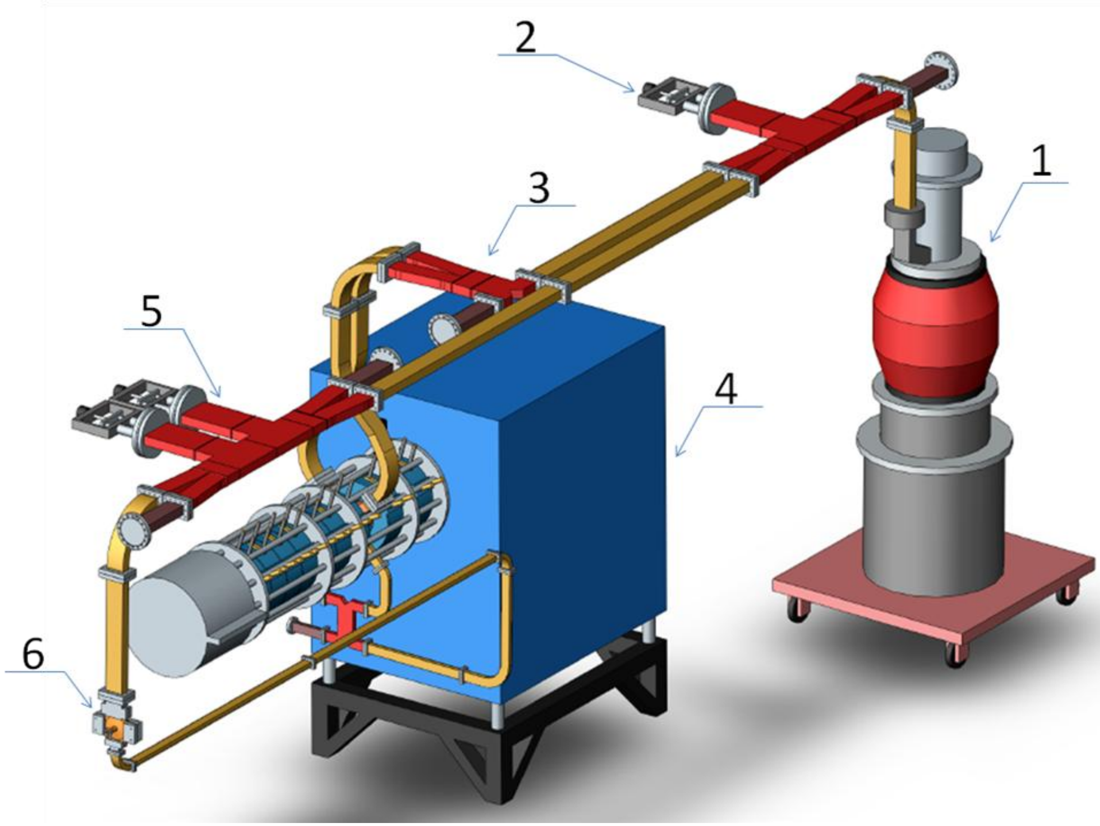
(a) (b)

Measured transmission vs frequency: (a) before cavity deformation, (b) after cavity deformation. Red curve corresponds to 14 GHz mode, blue curve corresponds to 7 GHz mode, whose transmission is plotted as function of $2 \times f$.

Dual-Frequency Test Facility

This dual-frequency source is based on an XK-5 24-MW S-band klystron, an S-band waveguide transmission line with provision for power splitting into two portions with adjustable amplitude and phase, and a second-harmonic frequency multiplier to produce the C-band power.

Thus, the two sources would be automatically phase-locked, and no new modulator or C-band driver would be needed.



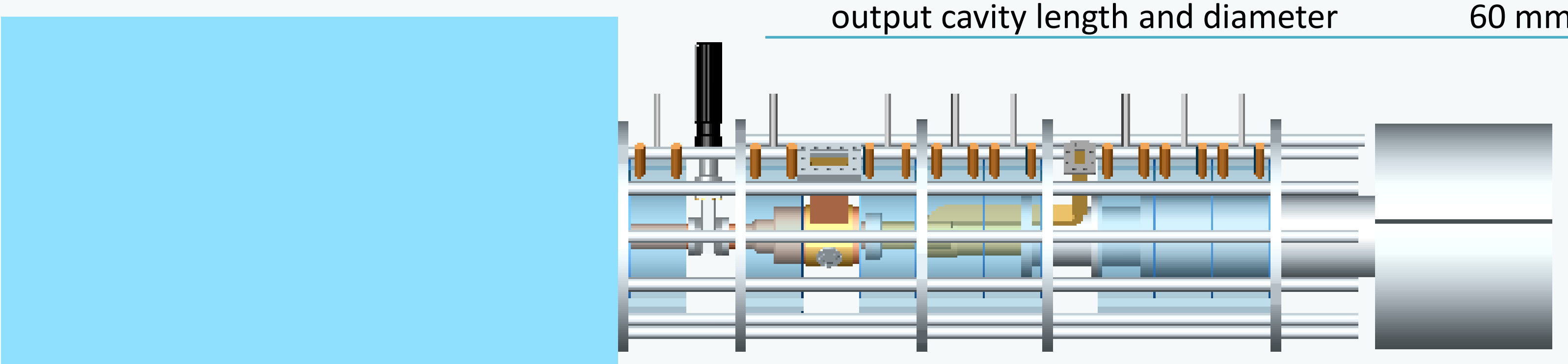
Layout of dual-frequency RF source, shown feeding a bimodal test cavity.

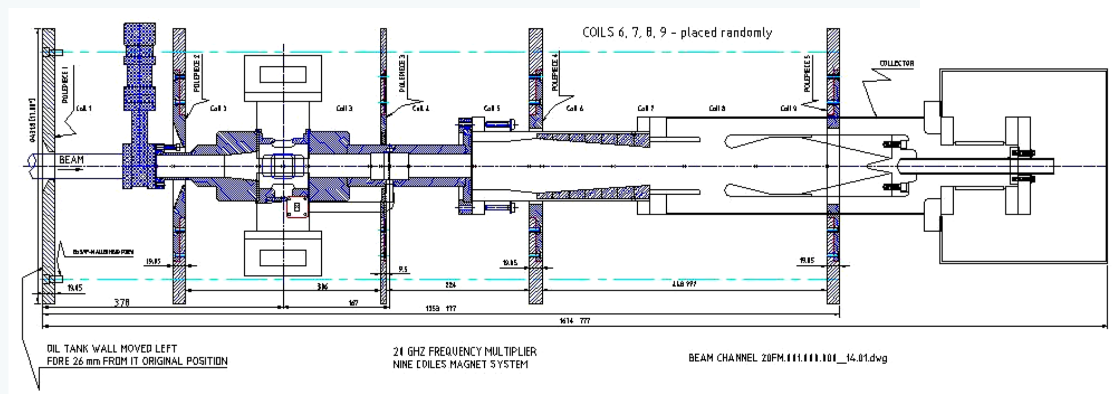
1 – S-band klystron; **2** – variable power splitter; **3** – 3-dB hybrid splitter; **4** – 250-kV gun tank; **5** – variable power splitter and phase shifter; **6** - bimodal test cavity.

Second-Harmonic Frequency Multiplier

The 2nd harmonic source uses the 250 kV, 20 A gun, modulator, magnetic system, and beam collector. 6 MW Power from the klystron is going to the input to yield 5.712 GHz output power of about 5.3 MW.

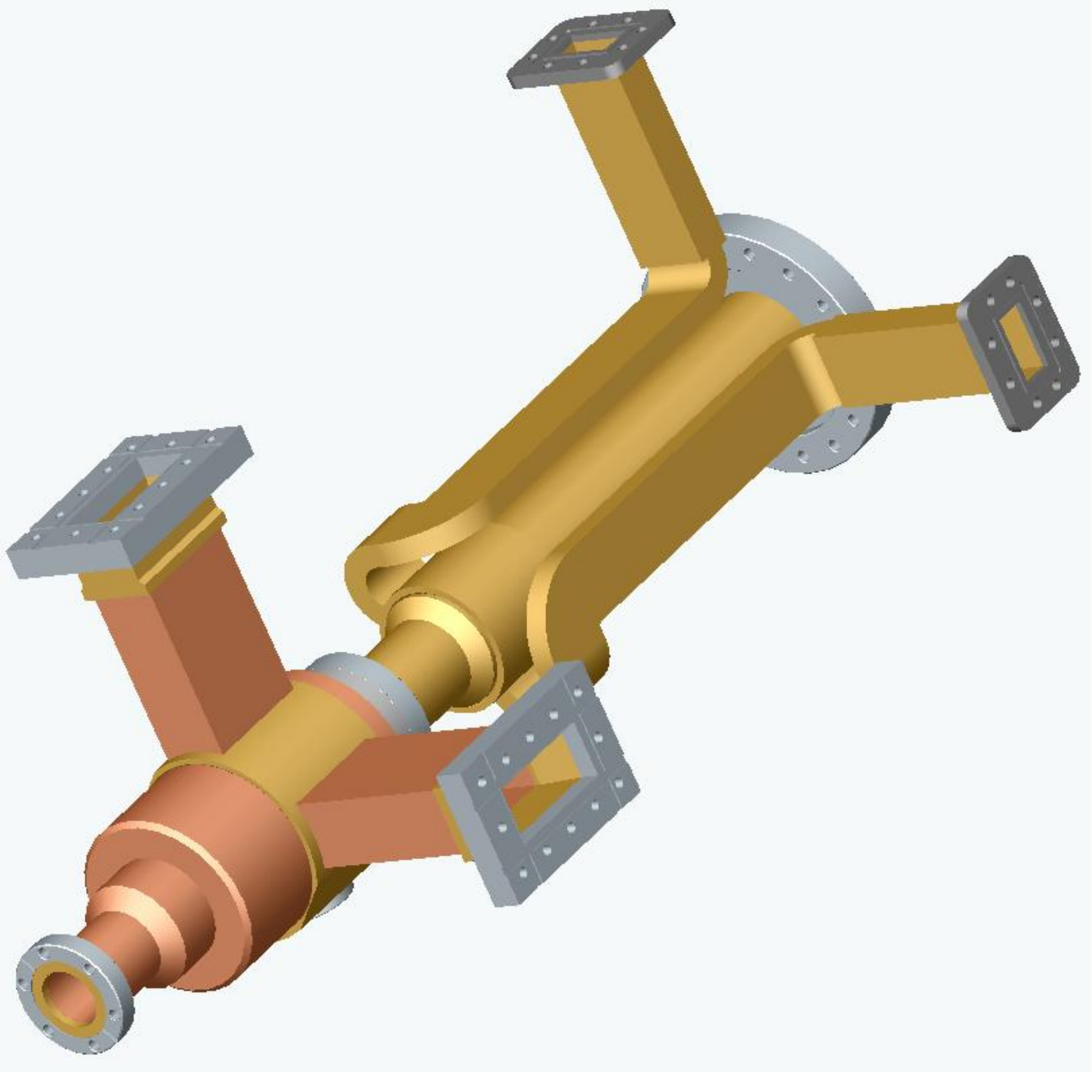
input power at 2856 MHz	6.0 MW
output power at 5712 MHz	~5.3 MW
RF-to-RF conversion efficiency	~88 %
operating mode in drive cavity	TE_{111}
maximum surface field in drive cavity	46 kV/cm
loaded Q of drive cavity	150
operating mode in output cavity	TE_{211}
maximum surface field in output cavity	113 kV/cm
loaded Q of output cavity	400
output cavity length and diameter	60 mm, 55.7 mm



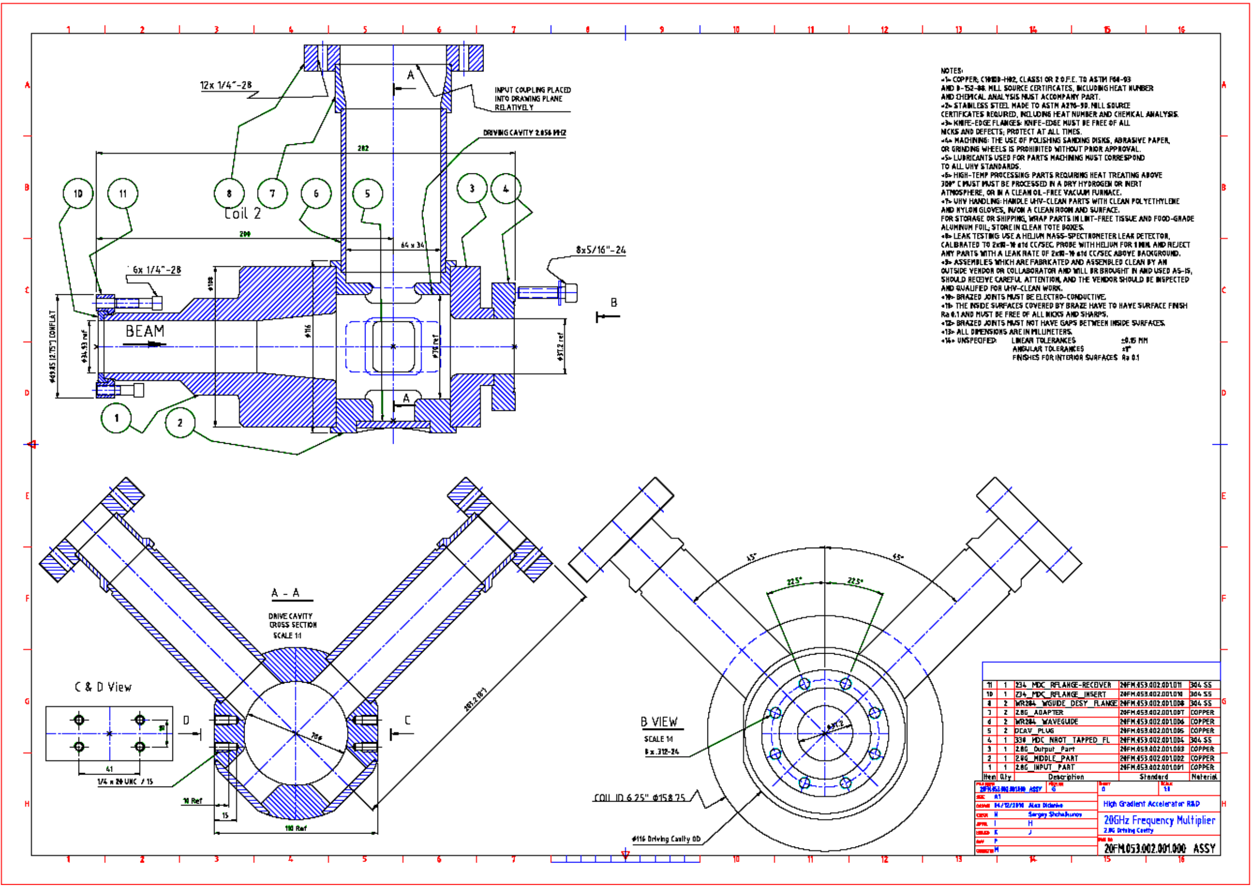


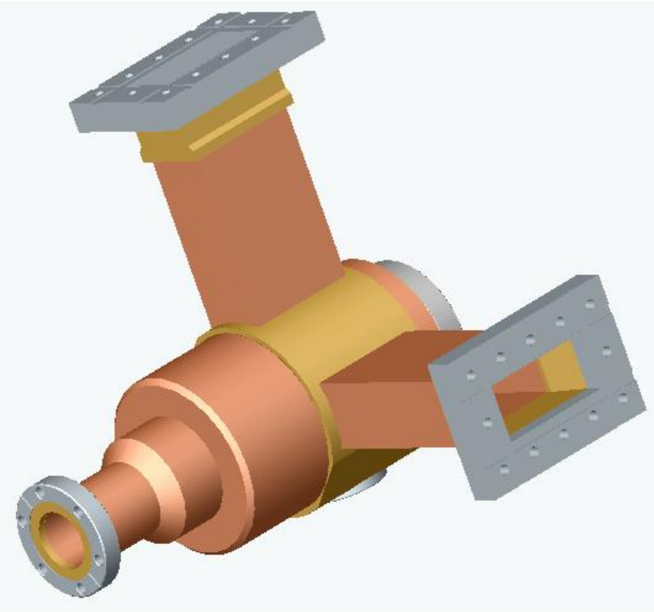
Cavities for Second-Harmonic Frequency Multiplier

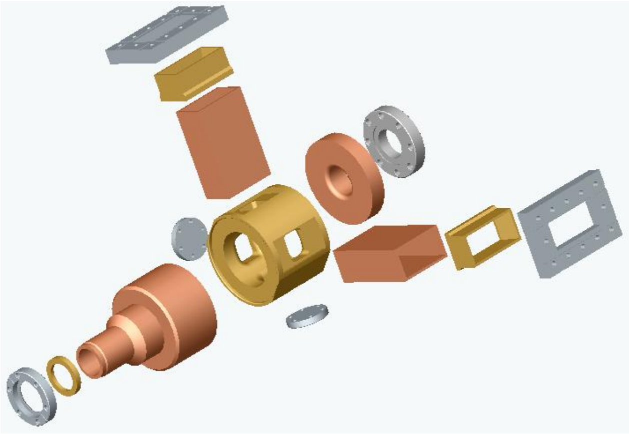
The frequency multiplier is built with a demountable output cavity, to allow substitution of different output cavities to operate at different harmonics.



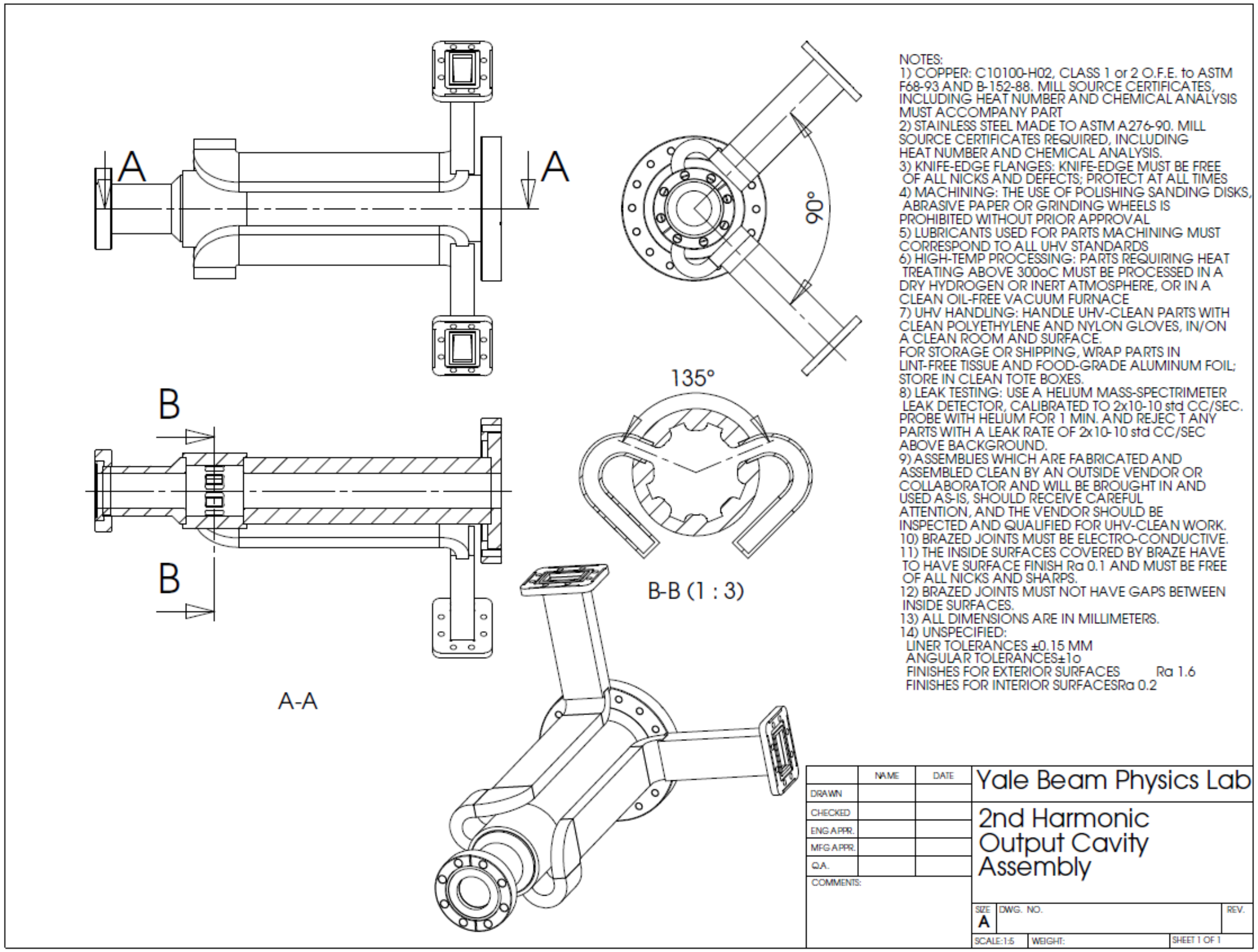
Drive Cavity for Second-Harmonic Frequency Multiplier

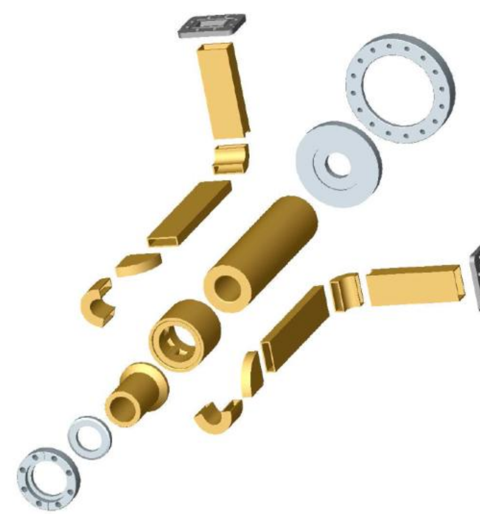






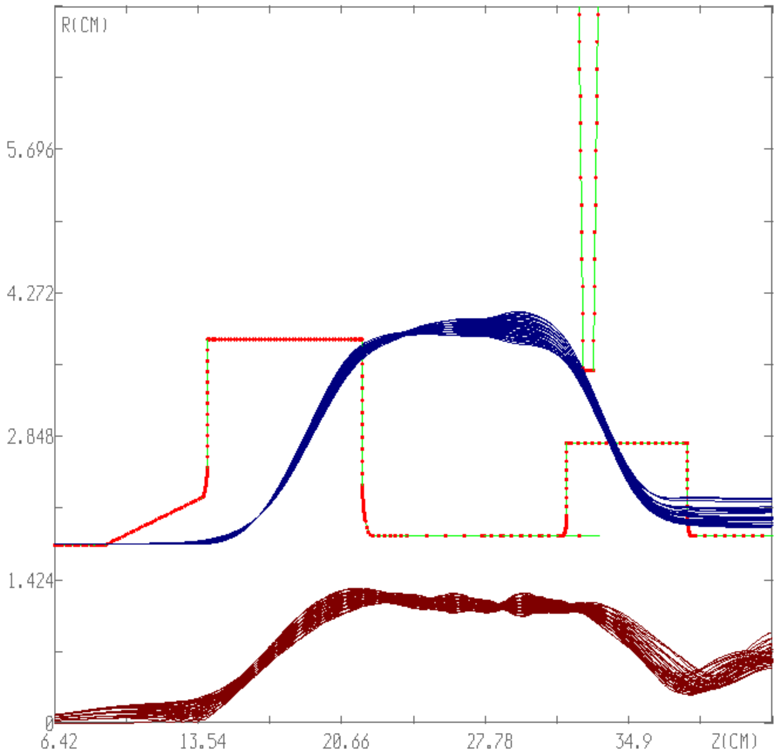
Output Cavity for Second-Harmonic Frequency Multiplier



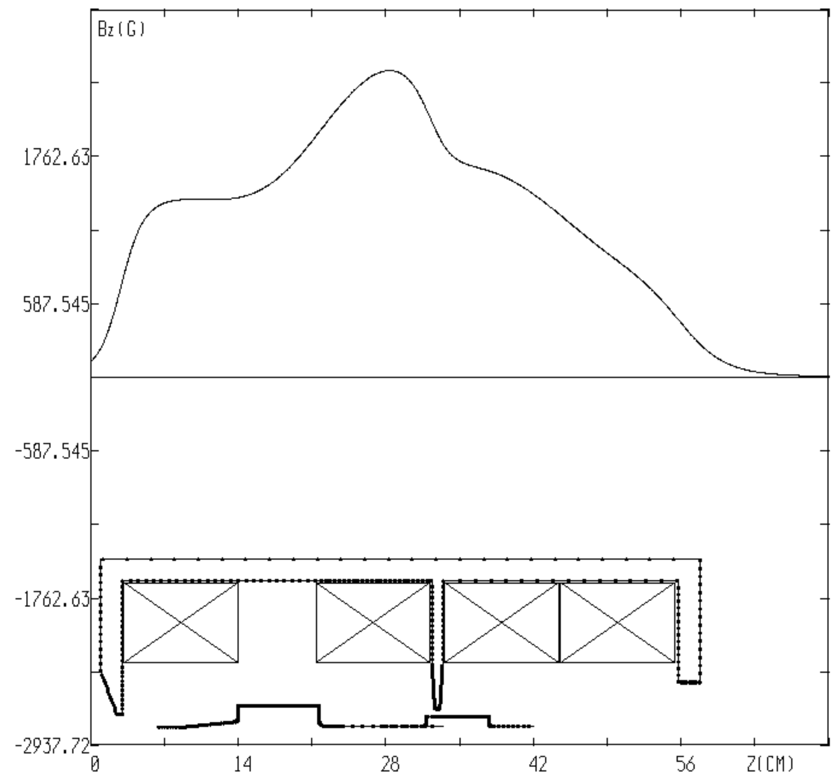


Computational Predictions for Second-Harmonic Frequency Multiplier

The 2nd harmonic frequency multiplier is to be built using a TE_{111} rotating mode input cavity with a TE_{211} rotating mode output cavity.



Computations of beam particle energies (blue) and orbit radii (red) for the 5.7 GHz 2nd harmonic frequency multiplier. Cavity and pole piece outlines are shown.



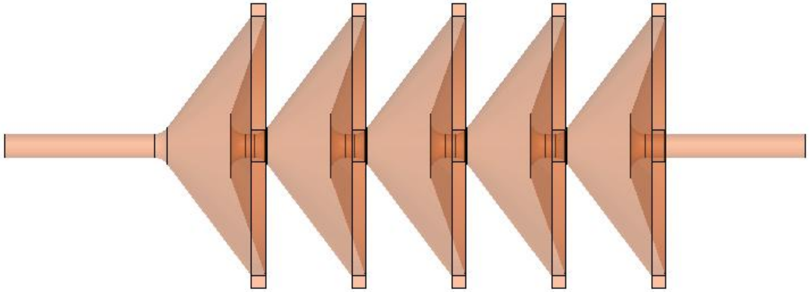
Magnetic field profile in the 5.7 GHz, 2nd harmonic frequency multiplier. Shown at bottom are the coil system and iron circuit, plus the cavity outlines.

Multi-Harmonic Cavity Acceleration Structure with Helical Waveguide

Usual way of feeding rf through the cavity beam channel may not work for multi-frequencies as they will have different dispersion property.

Double helical waveguide structure is introduced to couple individual cavities with correct synchronization for each frequency:

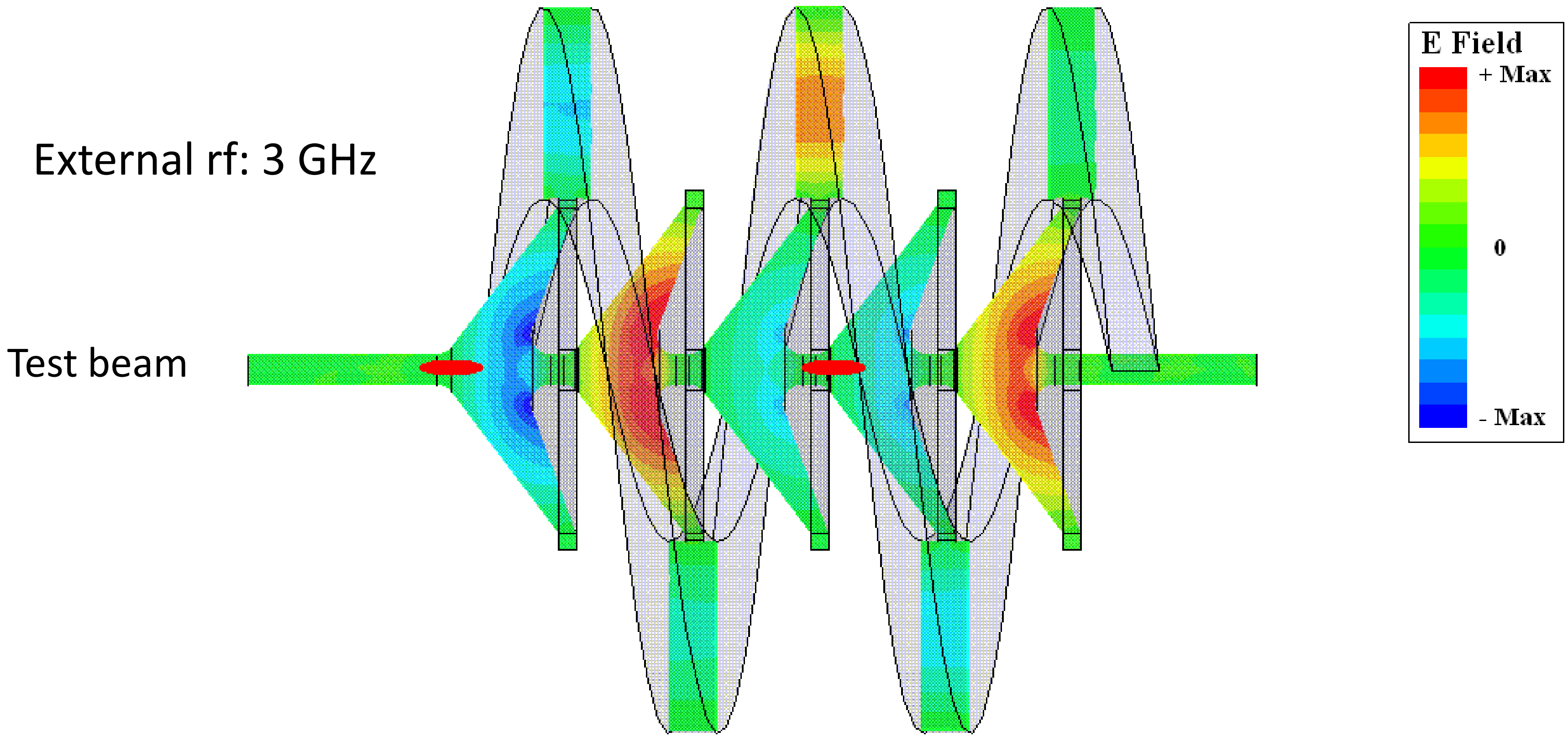
Fast wave in waveguide propagates longer helical path to match the phase of the test beam passing the cavity axis.



* Simplified model: uniform coupling without choke

Multi-Harmonic Excitation and Synchronization via Double Helical Waveguide

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



Multi-Harmonic Excitation and Synchronization via Double Helical Waveguide

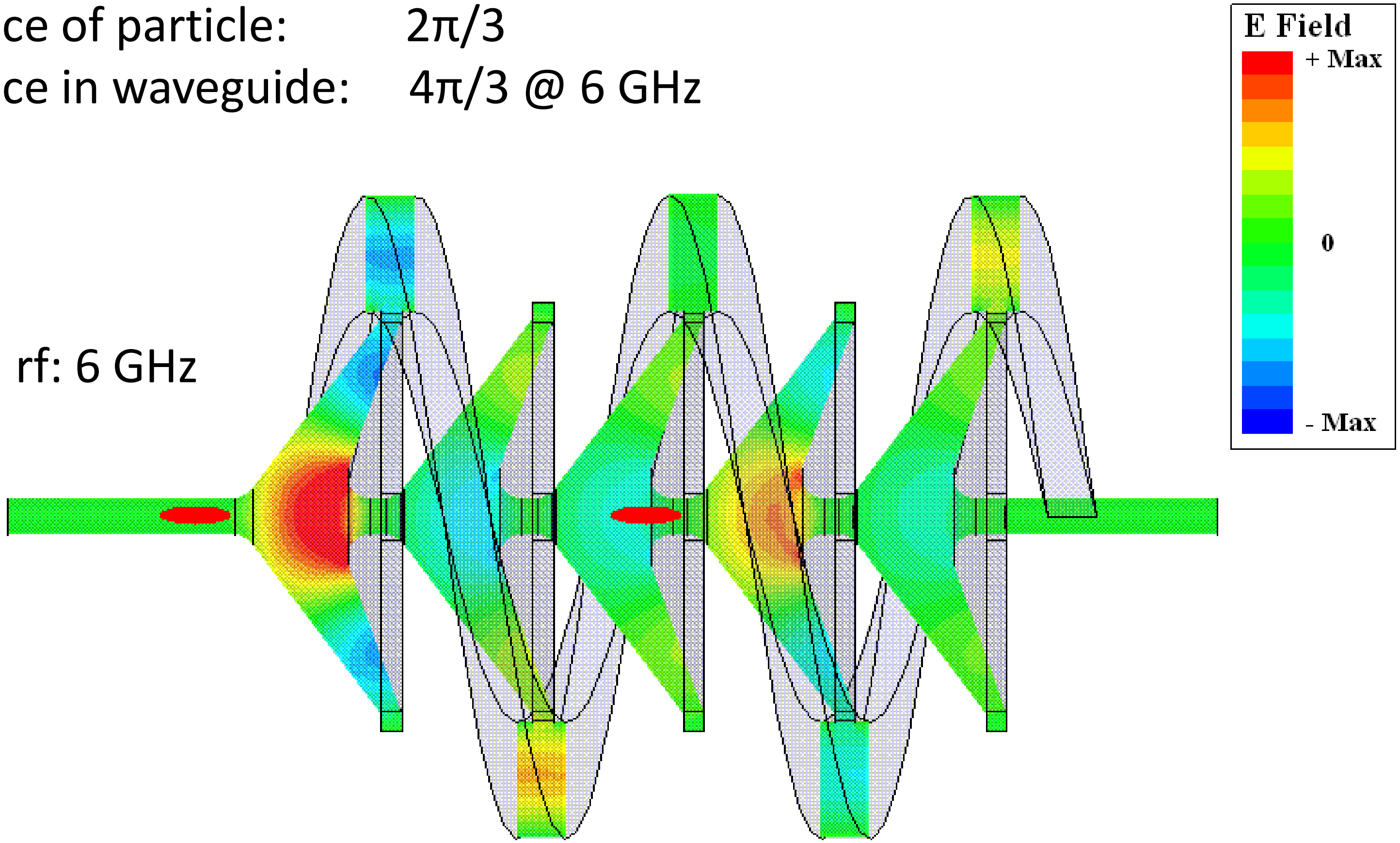
Bunch frequency: 3 GHz

Phase advance of particle: 2π/3

Phase advance in waveguide: 4π/3 @ 6 GHz

External rf: 6 GHz

test beam



Summary

- Use of bimodal cavities may allow an increase in RF breakdown threshold, due to:
  a. Reduced exposure times to high fields;
  b. Cathode-like fields being weaker than anode-like fields;
  c. Migration of field patterns around cavity periphery.

- A two-frequency synchronous multi-MW RF source and a demountable test cavity are being built at Yale for breakdown studies of bimodal cavities, at 2.85 and 5.7 GHz.

- When/if bimodal cavities are proven to allow an increase in RF breakdown thresholds, inventive coupling schemes will be needed; a double-helix scheme has been illustrated.