Theory and Experiment of a 95 GHz Gyrotron Traveling Wave Amplifier

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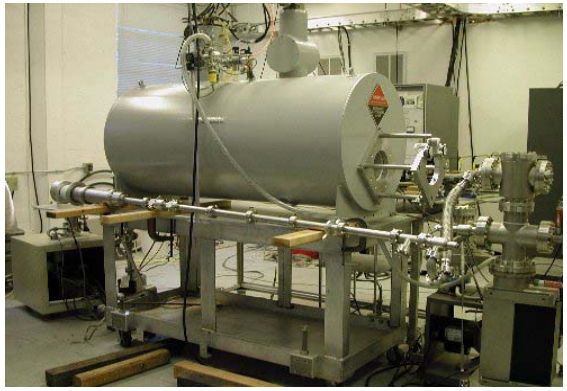
MURI
Microwave Vacuum Electronics

UCD Heavily Loaded W-band TE_{01} Gyro-TWT Amplifier

Objectives

- Develop wide bandwidth millimeter wave amplifier technology
- Develop stable W-band 100 kW Gyro-TWT amplifier

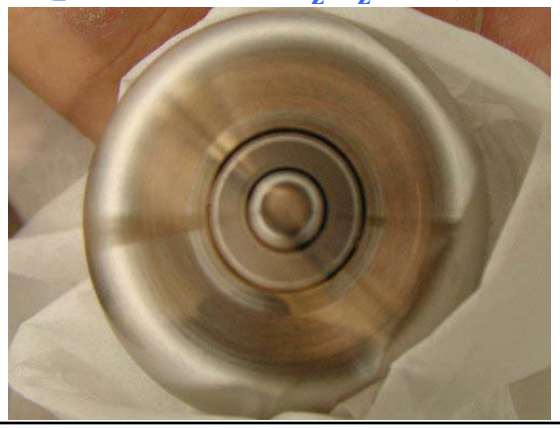
50 kG Superconducting Magnet with assembled Gyro-TWT circuit



Approach

- Gyro-TWT's offer wide bandwidth
- TE_{01} mode transmits high power
- Loss stabilizes amplifier
- Lossy circuit gives 90 dB loss at 93GHz

New cathode assembly (predicted $\Delta v_z/v_z$=2%)

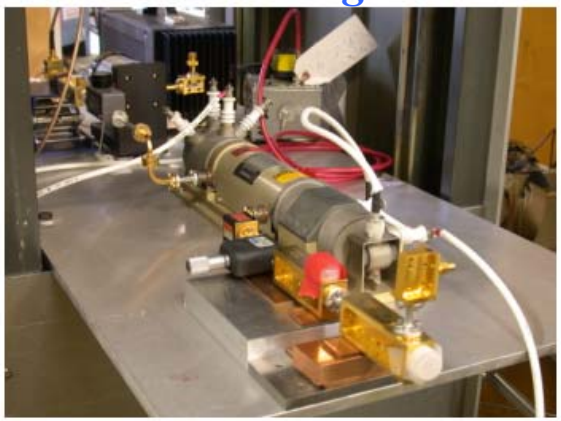


UCD Heavily Loaded W-band TE_{01} Gyro-TWT Amplifier

Significant Accomplishments

- Large-signal code predicts $\eta = 30\%$
- TE_{01} couplers, MIG have been optimized, measured
- Stability code determines required loss
- 94 GHz, 140 kW, 5 % BW gyro-TWT designed and fabricated

Input driver – Hughes 94 GHz, 100W Folded Waveguide TWT



- SLAC-UCDavis W-Band Input driver has been completed
- The circuit has been reassembled employing optimized MIG (predicted $\Delta v_z/v_z = 2\%$)
- Gyro-TWT under hot test with 45 dB gain, 60 kW, 26.6 % efficiency, zero drive stable in initial experiments at 60 kV (unoptimized)

SLAC-UC Davis W-Band Modulator

Eras in Gyro-TWT Research and Development

- First Era

  The potential for high gain and wideband millimeter wave amplification generated considerable interest in the gyro-TWT

  NRL (1979) $TE^{(1)}_{01}$ 35 GHz,16.6 kW,20 dB gain, η =7.8 %,1.5 % BW
  First demonstration of gyro-TWT

  NRL(1980) $TE^{(1)}_{01}$ 35 GHz, 3.2 kW, 42 dB gain, η = 1.5 %, 2 % BW
  Gain enhancement with distributed wall losses

  Varian(1979) $TE^{(1)}_{11}$ 5 GHz,120 kW,18 dB gain, η = 26 %,6 % BW
  Distributed wall losses, AM/PM sensitivity, noise characterization

- Second Era

  Long (nearly decade long) hiatus in gyro-TWT research due to stability issues

Eras in Gyro-TWT Research and Development

- Third Era

Improved physics understanding and experimental verifications

NTHU(1989) $TE^{(1)}_{11}$ 35 GHz, 18.4 kW, 18 dB gain, η = 18.6 %, 10 % BW
Systematic characterization of mode competition

NTHU(1990) $TE^{(1)}_{11}$ 35 GHz, 27 kW, 35 dB gain, η = 16 %,7.5 % BW
Improved stability with a sever

NTHU(1995) $TE^{(1)}_{11}$ 35 GHz, 62 kW, 33 dB gain, η = 21%, 12 % BW
Study of oscillation suppression with distributed wall losses

NTHU(1998) TE(1)11 35 GHz, 93 kW, 70 dB gain, η = 26.5%, 8.6 % BW
Demonstration of an ultra high gain scheme employing distributed wall losses

UCLA/UC Davis(1995) $TE^{(2)}_{2}$ 15.7 GHz, 207 kW, 16 dB gain, η = 13 %, 2.1% BW
Demonstration of stability and high power with harmonic interaction

IAP/U Strathclyde(1998)$(TE_{11} + TE_{21})^{(2)}$ 9.4 GHz,1.1MW,37 dB gain, η = 29 %, 21 % BW
Demonstration of broadband and highly efficient corrugated circuit

Eras in Gyro-TWT Research and Development

- Fourth (Current) Era

Focus on higher frequencies as well as devices which would be compatible with eventual applications

NRL (2002) $TE^{(1)}$, 34 GHz, 137 kW, 47 dB gain, η = 17 %, 3.3 % BW

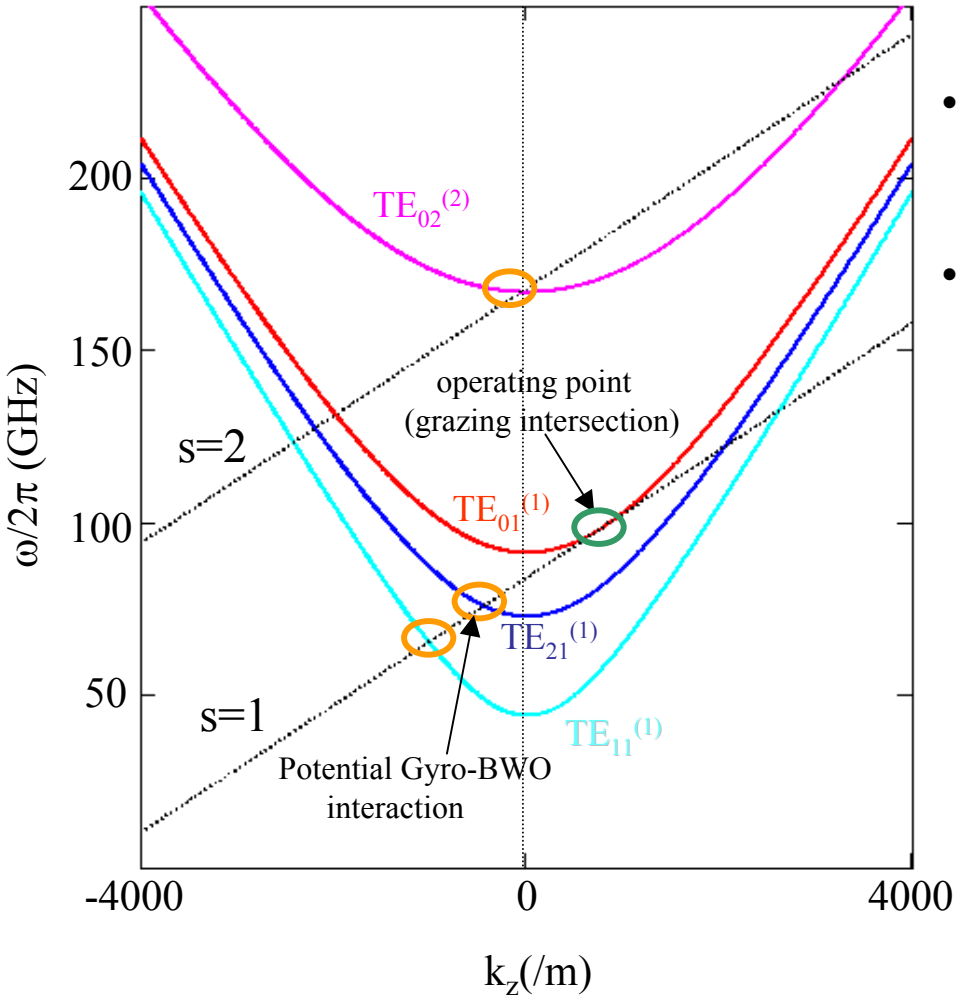
MIT (2002/3) 140 GHz, 30 kW, 29 dB gain, η = 25 %, > 1.1 % BW

IAP (2002) 35 GHz, 180 kW, 25 dB gain, 10 % BW

UCD (2003)* 94 GHz, 60 kW, 45 dB gain, η = 26.6 %,1.3 % BW

* Unoptimized- operating at reduced voltage and current from design values.

Dispersion Diagram of TE_{01} Gyro-TWT



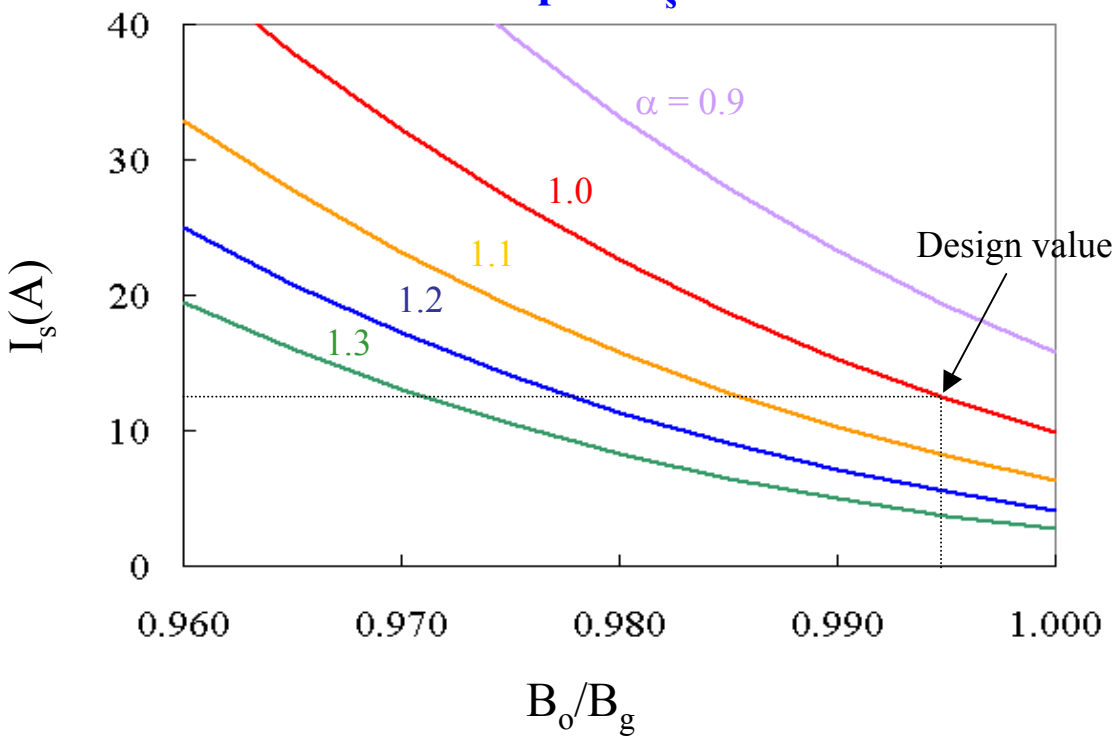
- Beam mode dispersion: $\omega = s\Omega_c + k_z v_z$
  Wave mode dispersion: $\omega^2 = \omega_c^2 + c^2 k_z^2$

- Competing modes must be suppressed
  : $TE_{21}^{(1)}$, $TE_{02}^{(2)}$ Gyro-BWO interactions

Stable Beam Current

- Gyro-TWT exhibits absolute instability near cutoff at sufficiently high beam current
- Unloaded TE_{01} circuit is stable for beam current = 5 A for design value α =1.0 and B_o/B_g= 0.995
- Beam current can be higher for lower α (=$v_\perp/v_z$) and lower B_o/B_g

Stability from TE_{01} Cutoff Oscillation
Keep $I < I_s$



Simulation results using 'Absolute Instability' code

Gyro-BWO Stability

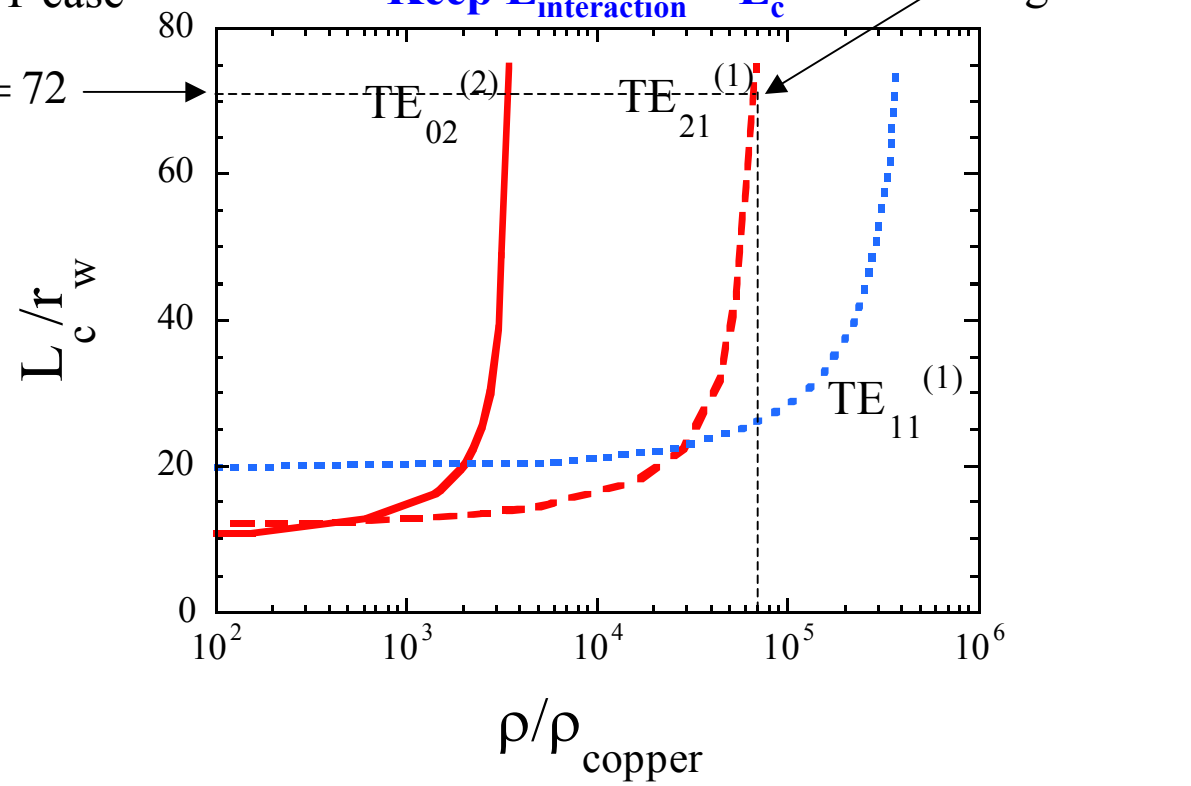
- Loss has been applied to suppress potential Gyro-BWO interactions
- ρ/ρ_{Cu} = 70,000 suppress potential $TE_{02}^{(2)}$ and $TE_{21}^{(1)}$ Gyro-BWO

Stability from Gyro-BWO

Keep $L_{interaction} < L_c$

TE_{01} Gyro-TWT case

$$\frac{L}{r_w} = \frac{14.5}{0.201} = 72$$



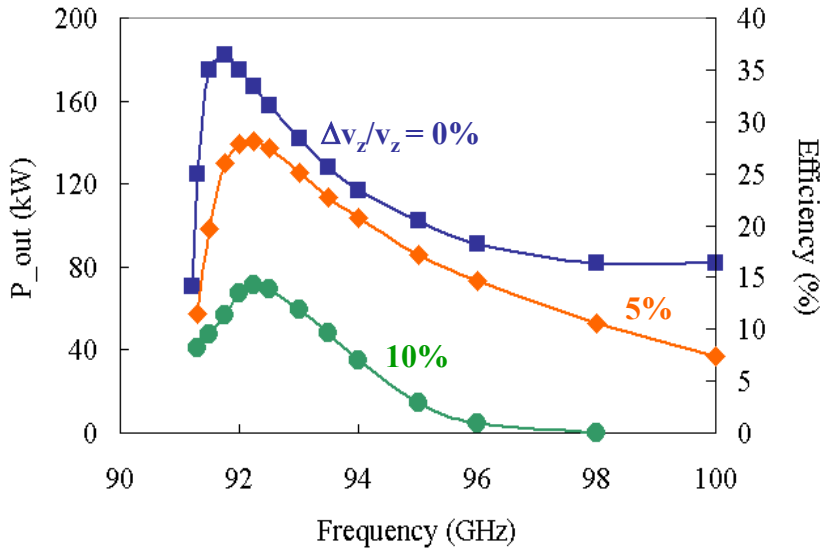
Simulation results using 'Gyro-BWO' code

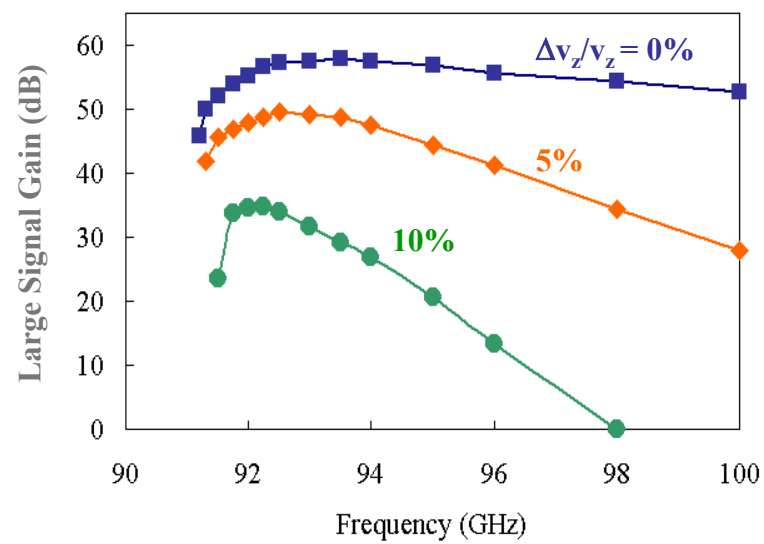
Device Parameters

Voltage	100 kV
Current	5 A
$\alpha = v_\perp / v_z$	1.0
$\Delta v_z / v_z$	5 %
Magnetic Field(B_o)	35.6 kG
B_o/B_g	0.995
Cutoff Frequency	90.97 GHz
Wall Resistivity	70,000 ρ_{Cu}
Circuit Radius, r_w	0.201 cm
Guiding Center Radius, r_c	0.45 r_w
Circuit Length	14.5 cm

Predicted Gyro-TWT Performance

- Nonlinear large signal code predicts output power, efficiency and gain





For predicted velocity spread $\Delta v_z/v_z = 5\%$

-Bandwidth $\Delta\omega/\omega = 5\%$

- $P_{out} = 140$ kW

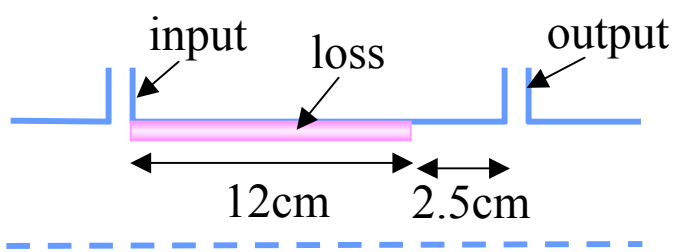
- $\eta = 28\%$

- Large signal gain = 50 dB

Application of Loss

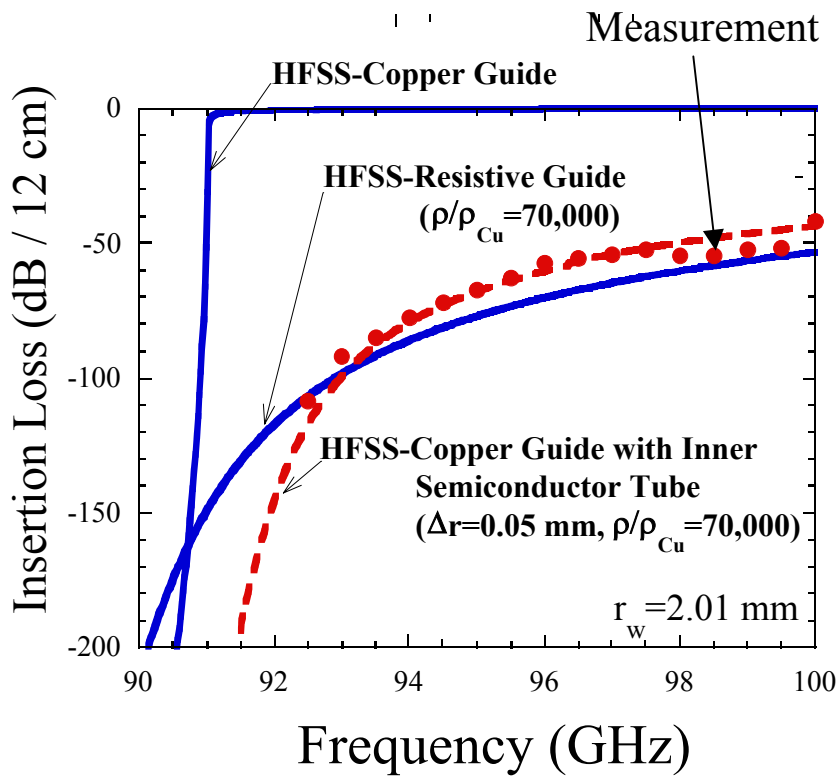
- Loss has been added to circuit to suppress Gyro-BWO
  Theory $\Rightarrow \rho/\rho_{Cu} = 70{,}000$ is needed
- 'Aquadag' (a Carbon colloid) has the desired loss of $\rho/\rho_{Cu} \cong 70{,}000$

Axial view of TE_{01} Gyro-TWT circuit



- Initial 12 cm is coated. Final 2.5 cm is uncoated to prevent wave damping
- 90 dB loss is measured at 93 GHz
- Loss lowers the gain but this can be compensated by increasing the circuit length to just below the critical length

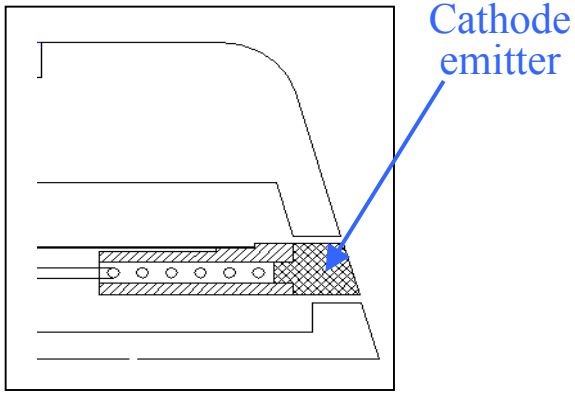
Measurement versus HFSS simulation



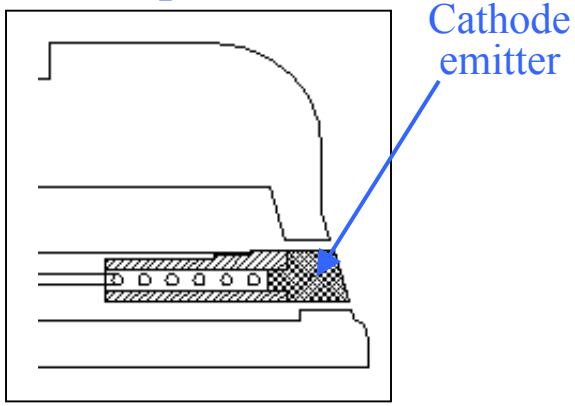
Optimized MIG

- MIG has been optimized using EGUN code
  - MIG velocity spread has been reduced to 2.17%
  - Peak Electric field near emitter has been reduced

Old MIG



Current optimized MIG



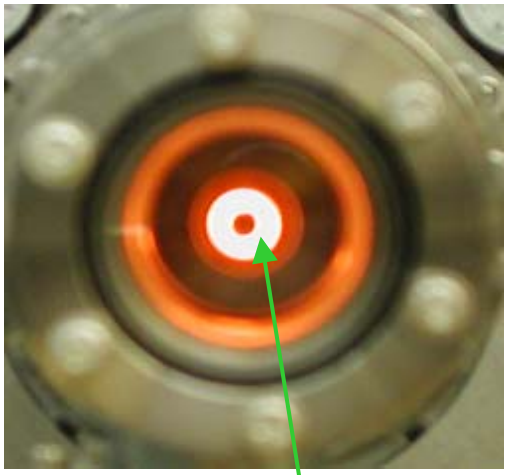
Comparison of old and current optimized MIG

	Old MIG	Current optimized MIG
α ($v_\perp$ / v_z) Velocity ratio	0.93	0.96
$\Delta v_z / v_z$ Velocity spread	5.96	2.17
Maximum Electric Field	169 kV/cm	**115 kV/cm**
Compression Ratio	32.99	33.64

Optimized Single Anode MIG

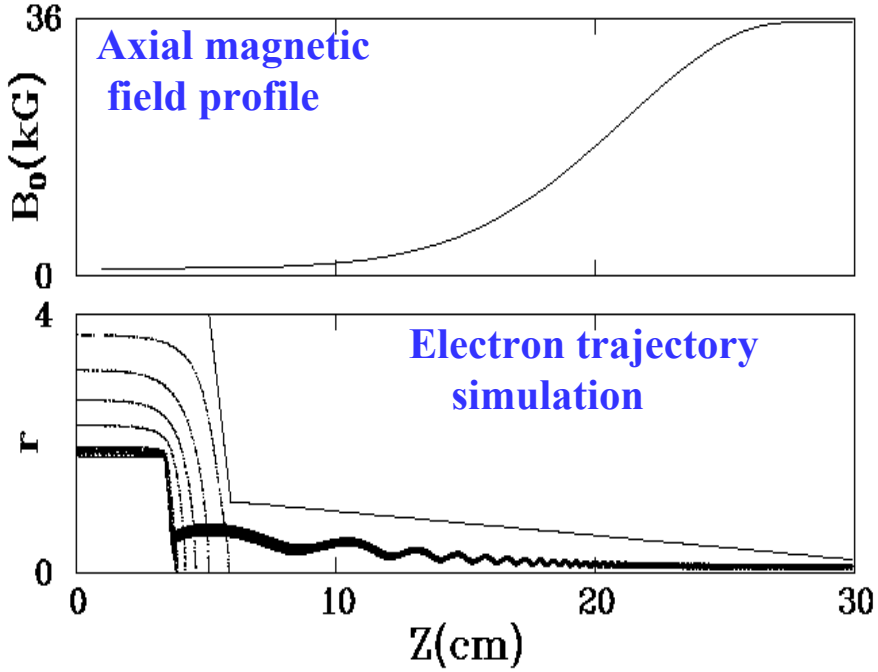
Assembled MIG

Activated MIG



- Designed MIG beam parameters

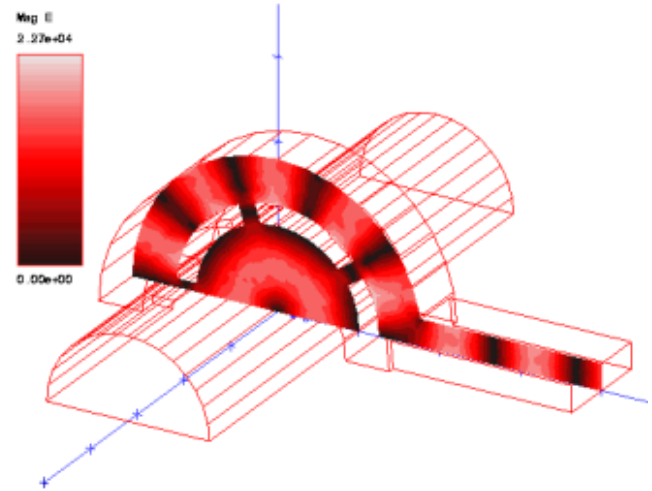
Beam voltage	100 kV
Beam current	5 A
Velocity ratio ($v_\perp / v_z$)	1.0
Velocity spread	2%
Cathode radius	5.1 mm
Guiding center radius	0.9 mm



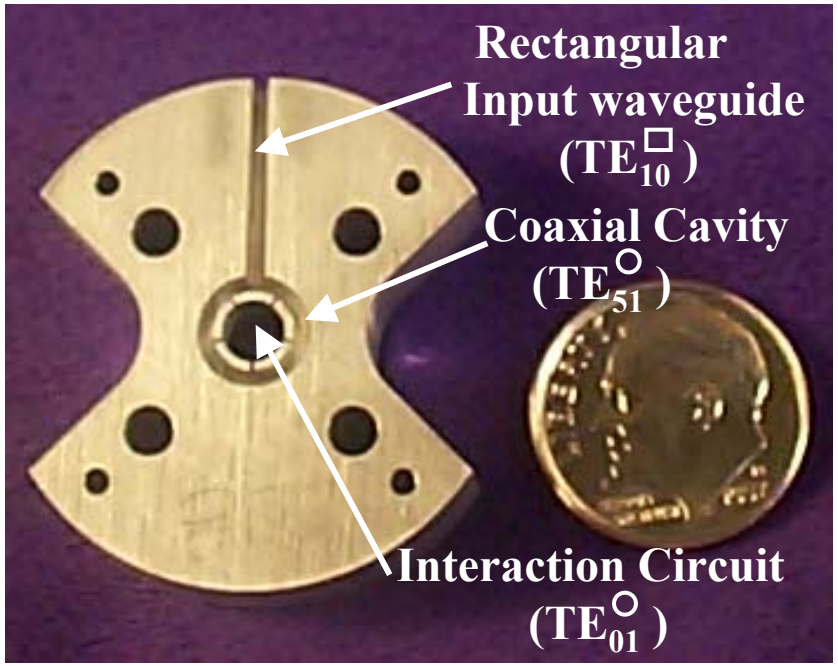
RF Couplers

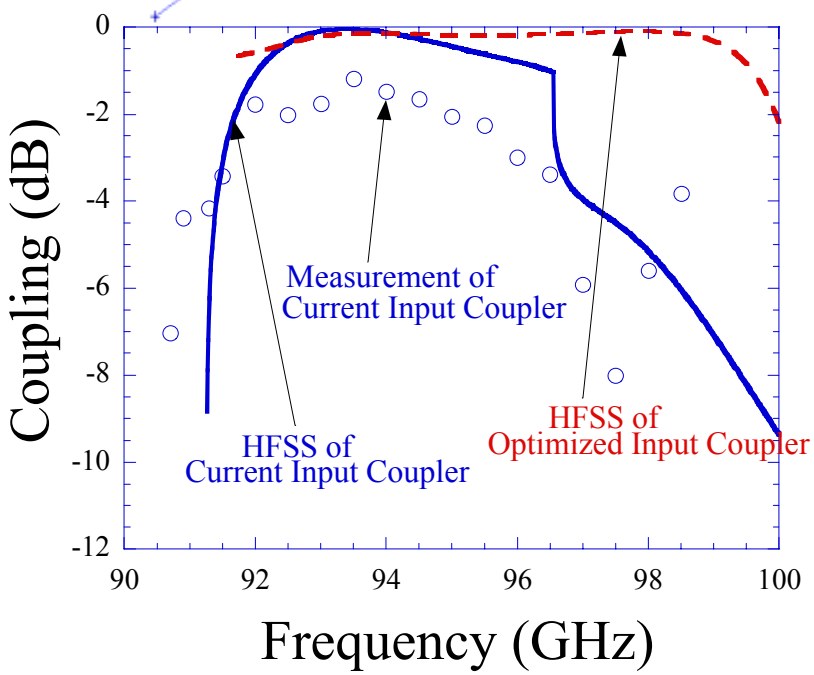
- 0 dB input coupler and 10 dB output coupler are employed

$TE_{10}^{\square} \rightarrow TE_{51}^{\bigcirc} \rightarrow TE_{01}^{\bigcirc}$ Coax Coupler
Designed with HFSS
All Modes are Matched



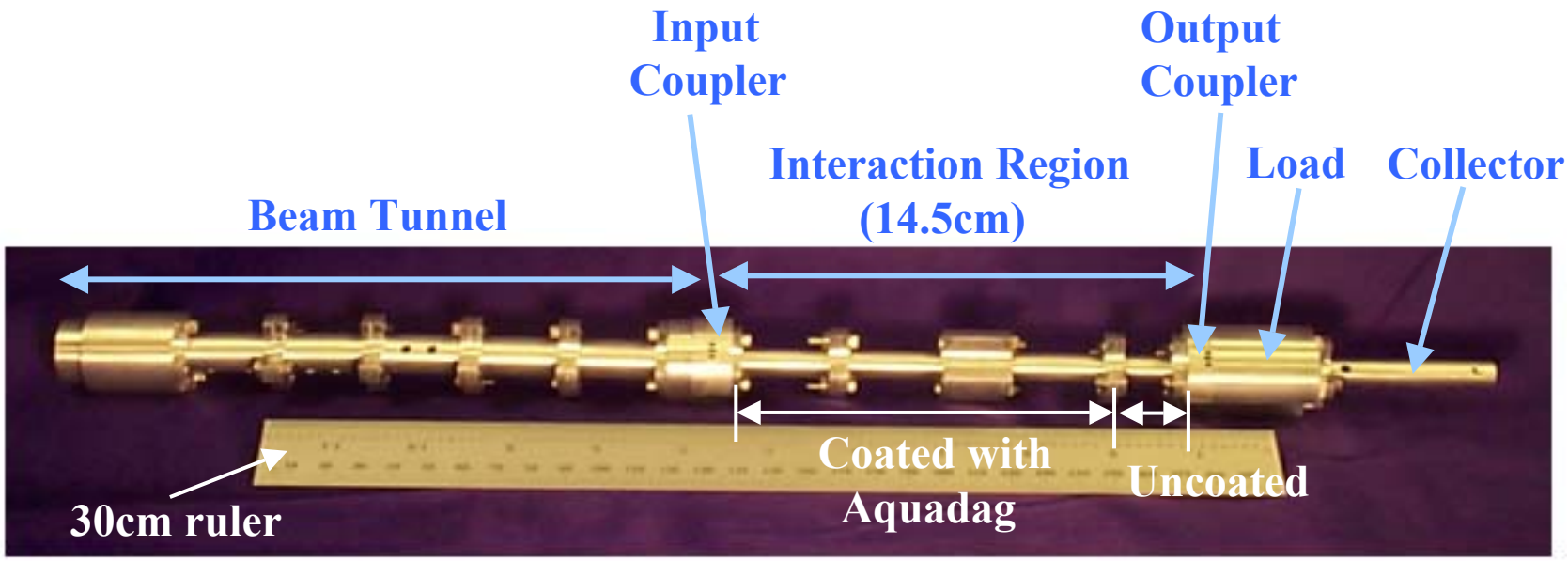
Cross section of the Fabricated Coax Coupler





Interaction Circuit

- Interaction region is heavily loaded with 'Aquadag'
  'Aquadag' is a carbon colloid with $\rho/\rho_{cu} = 70{,}000$
- Final 2.5 cm of interaction region is unloaded to avoid damping of high power wave



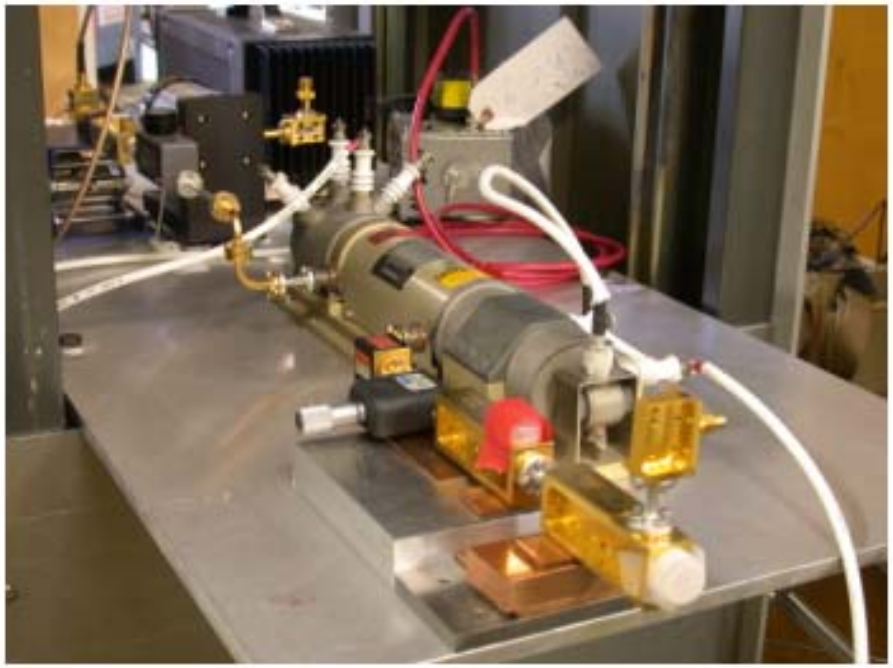
Axial View of Fabricated TE_{01} interaction circuit

RF Input Driver

- W-Band input driver is capable of driving either Hughes Folded Waveguide TWT (94 GHz, 100W, BW=5%) or CPI EIO (93 GHz, 1 kW, BW=5%)

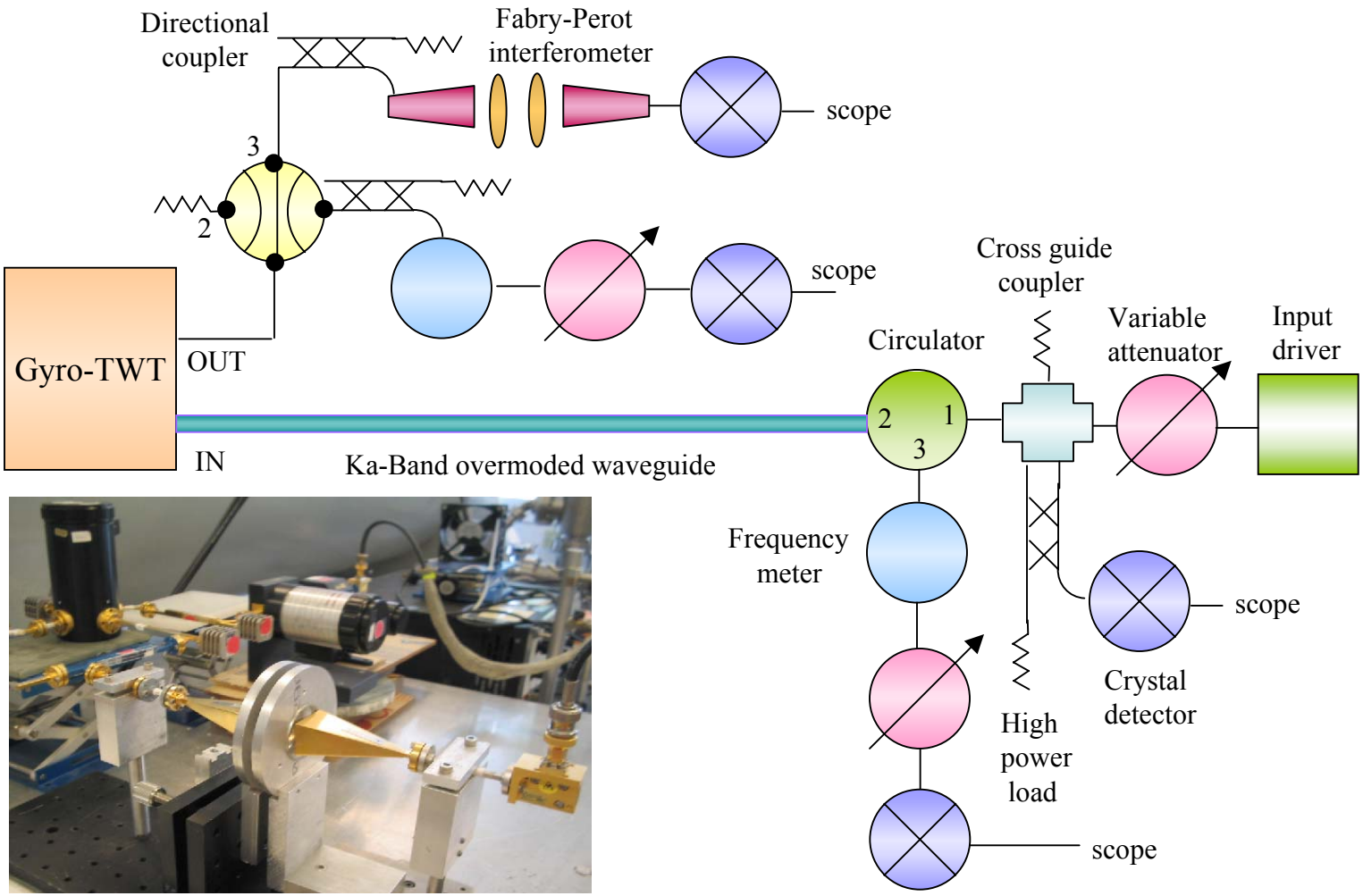
SLAC-UC Davis
W-Band Modulator

Hughes 94 GHz, 100 W Folded Waveguide TWT



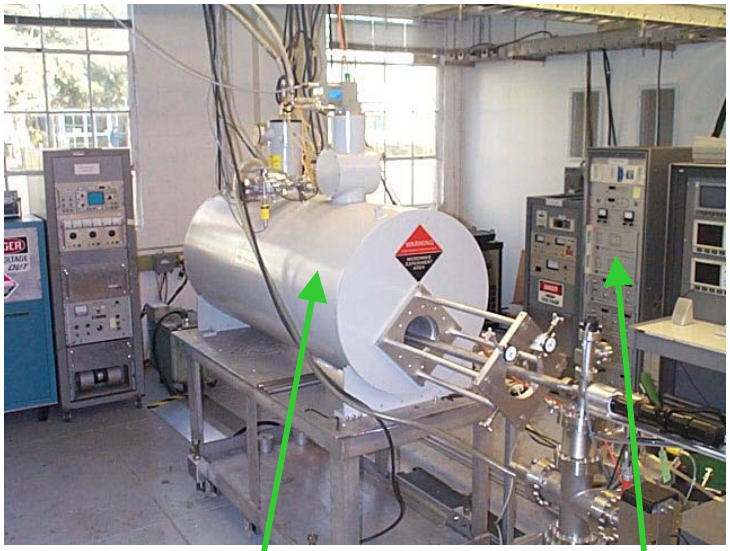
RF Diagnostics

- RF diagnostics are setup to monitor the output power w/ and w/o input drive
- Various modes are measured simultaniously using waveguide switch, cavity filter, waveguide cutoff sections, and Fabry-Perot interferometer



Magnet System

- Refrigerated Superconducting Magnet

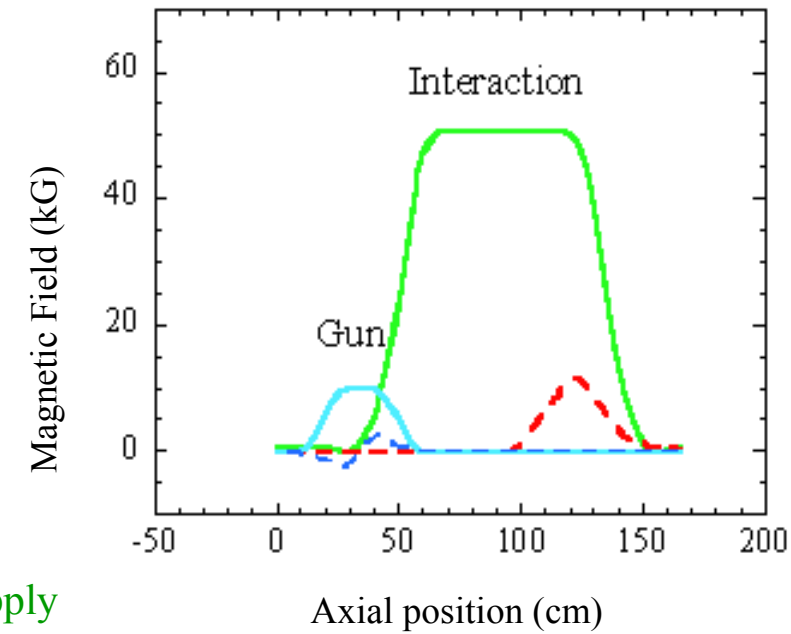


Superconducting magnet

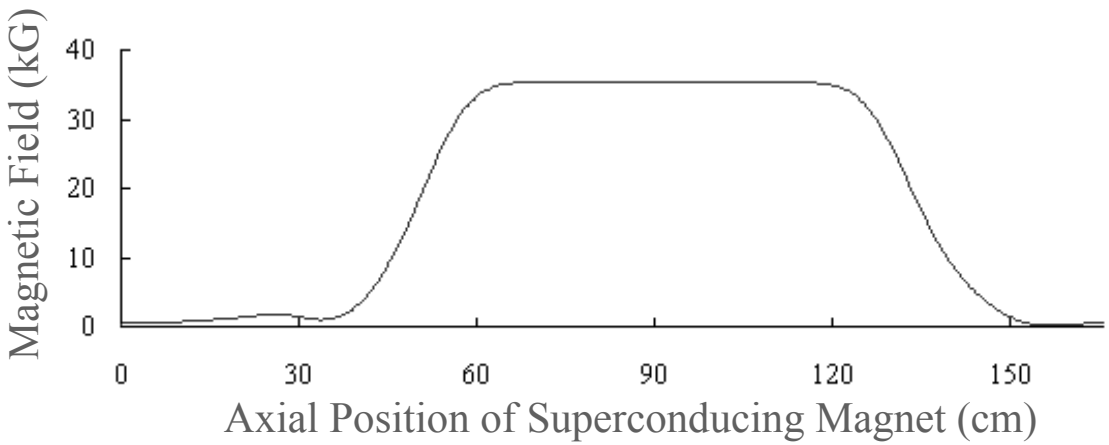
Coil power supply

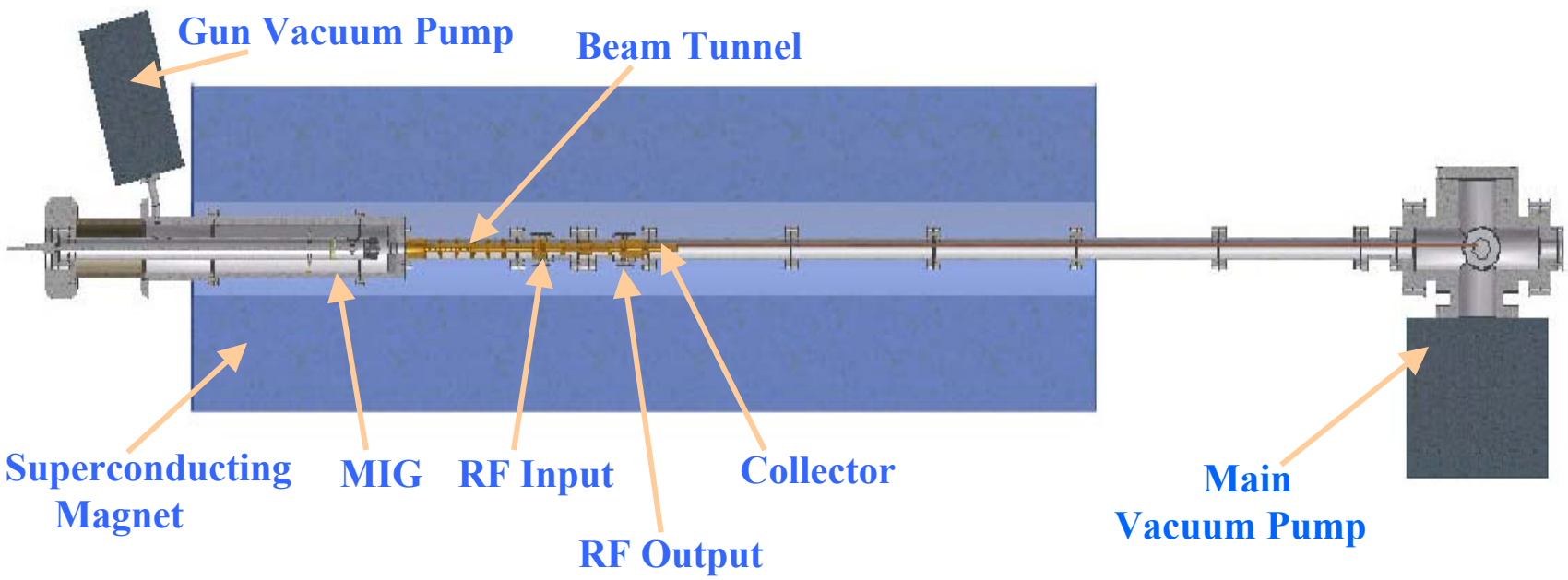
- 50 kG ± 0.1% over 50 cm
- 4 compensated independent coils
- 6” large bore

- Magnetic field profile for 4 coils



Integrated Gyro-TWT System





Overall system setup for hot test of the heavily loaded W-Band TE_{01} gyro-TWT

Experimental Progress Flowchart

1st version Gyro-TWT

- MIG design $\Delta v_z/v_z = 5\%$
- Small signal gain = 34 dB
- Bandwidth = 2%

MIG misaligned
($\Delta v_z/v_z = 10\%$ inferred from Gyro-TWT code)

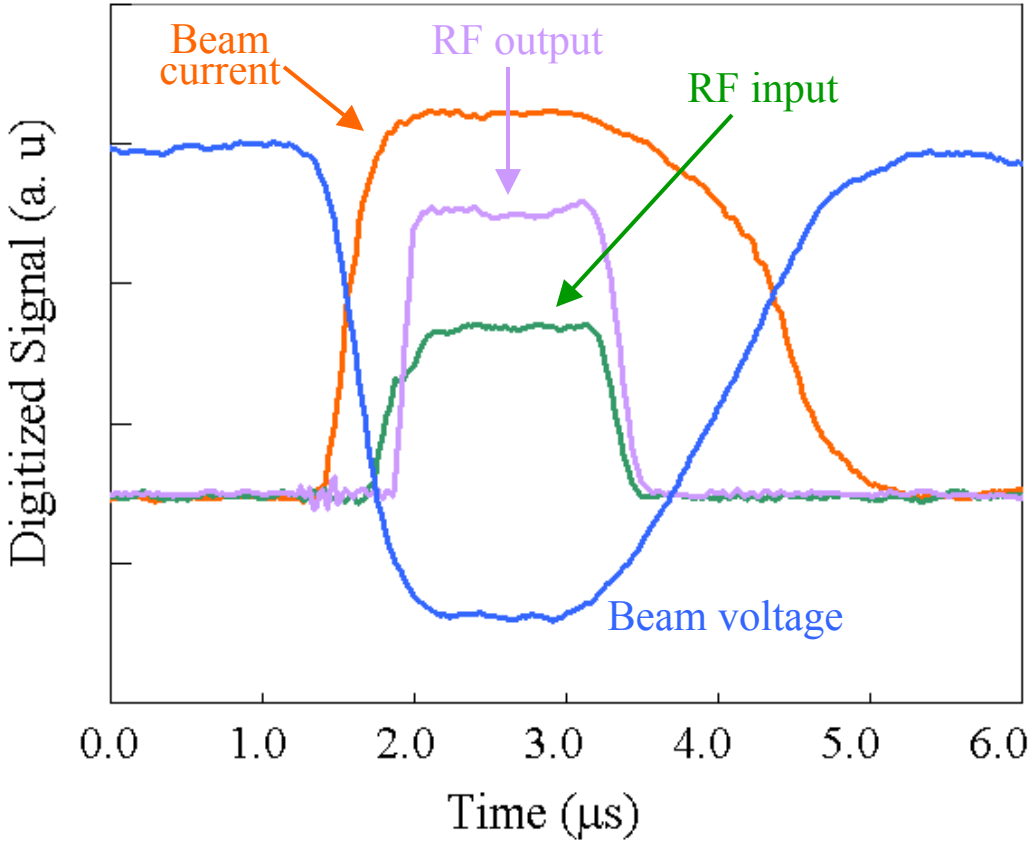
MIG disassembled and replaced with optimized new MIG

- Verified MIG misalignment and roughened cathode surface

2nd version Gyro-TWT

- Employed optimized MIG design $\Delta v_z/v_z = 2\%$
- Preliminary, unoptimized performance:
  60 kW 45 dB gain, $\eta = 26.6\ \%$, 1.3 % BW

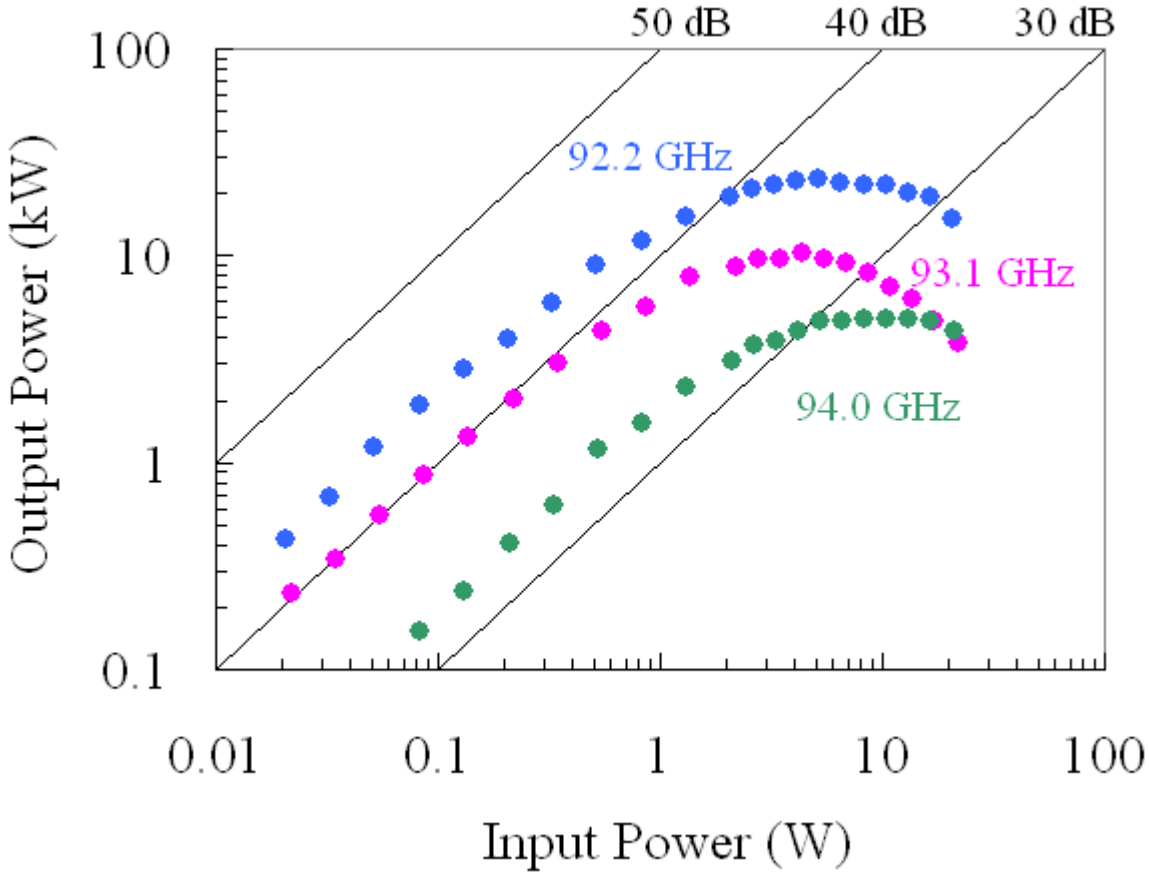
Temporal history of beam voltage, beam current, RF drive, and RF output



Measured Transfer Characteristics

- Gyro-TWT shows good linearity at lower voltages (< 70 kV)

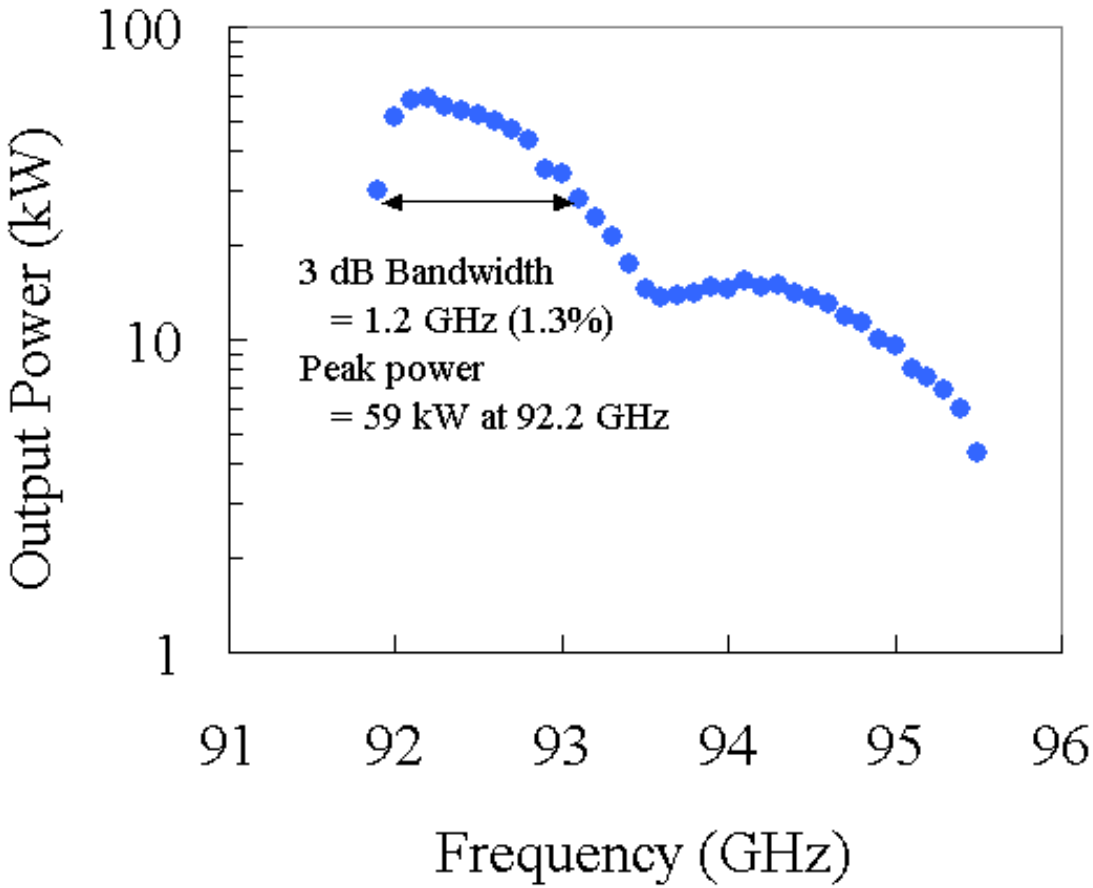
• V_b=56 kV, I_b=3.7 A and B_o=34.1 kG



Measured Bandwidth

- 1.2 GHz 3 dB bandwidth has been measured

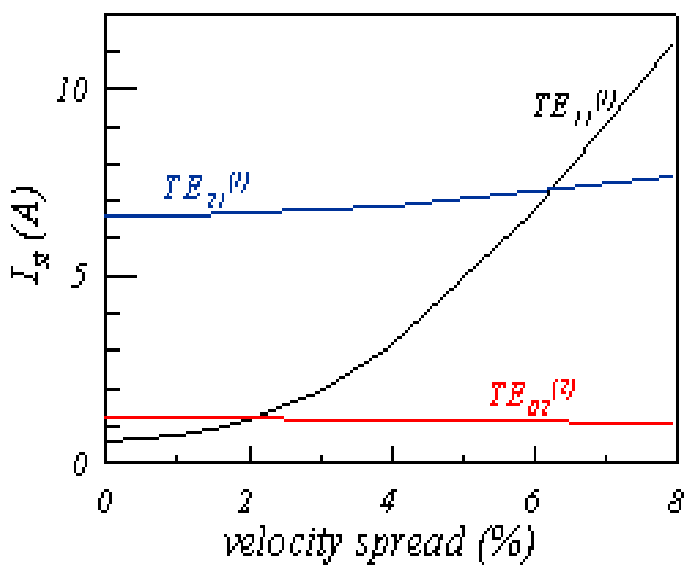
• V_b=60 kV, I_b=3.7 A and B_o=34.0 kG



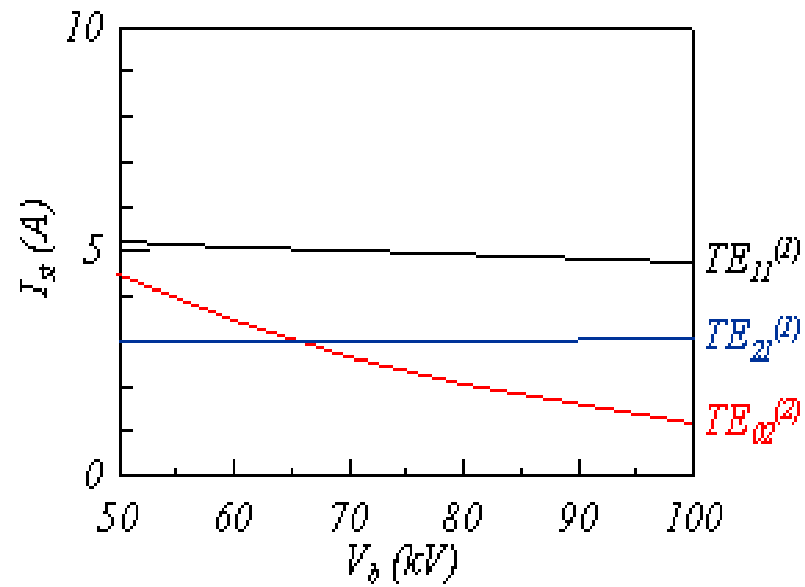
Predicted Competing Modes

- Competing modes have been predicted using self-consistent nonlinear code
- TE_{02} mode at 167 GHz, TE_{11} mode at 66 GHz, and TE_{21} at 75 GHz are predicted to be most probable competing modes

• Start oscillation current vs. velocity spread for V_b=100 kV, B_o / B_g=0.995, α=1.0, and ρ/ρ_{cu}=70,000

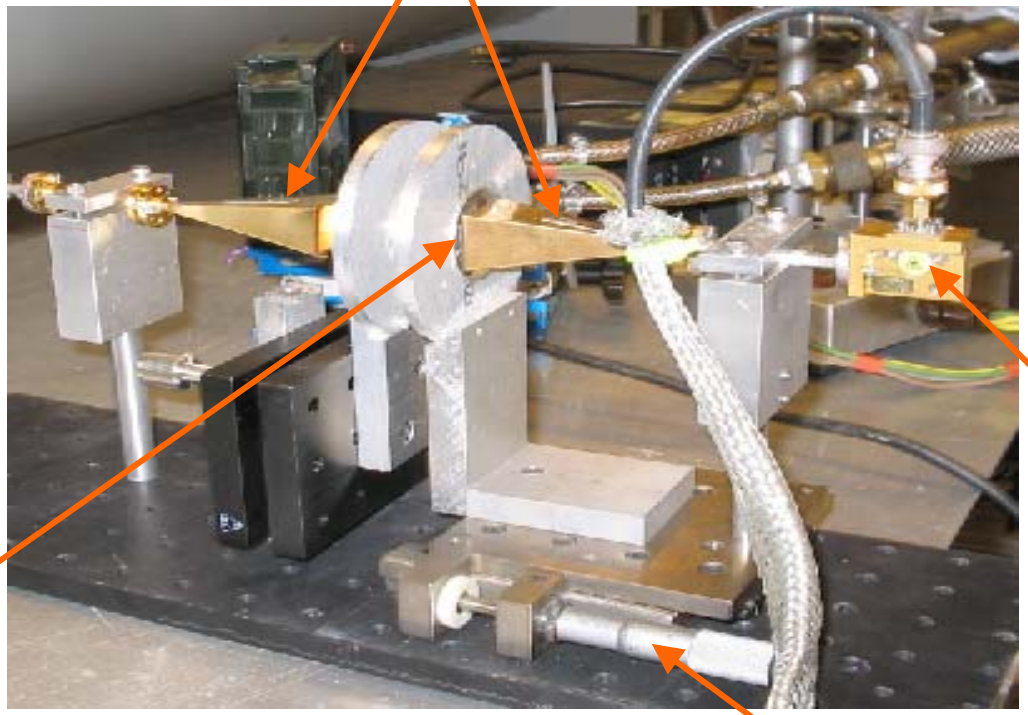


• Start oscillation current vs. beam voltage for B_o / B_g=0.995, α=1.0, ρ/ρ_{cu}=70,000, and $\Delta v_z/v_z$=5%



Frequency Identification using Fabry-Perot Interferometer

- Fabry-Perot interferometer using two horn antennas, metal mesh, and translational stage employed to identify competing modes



Mode Competition Identification

- TE_{02} :170 GHz

  Has not appeared to be serious at current operating voltages,but we will increase the threshold current by increasing the loading and reducing the length of the unloaded section

- TE_{01} Input Drift Tube Oscillation: 85 GHz

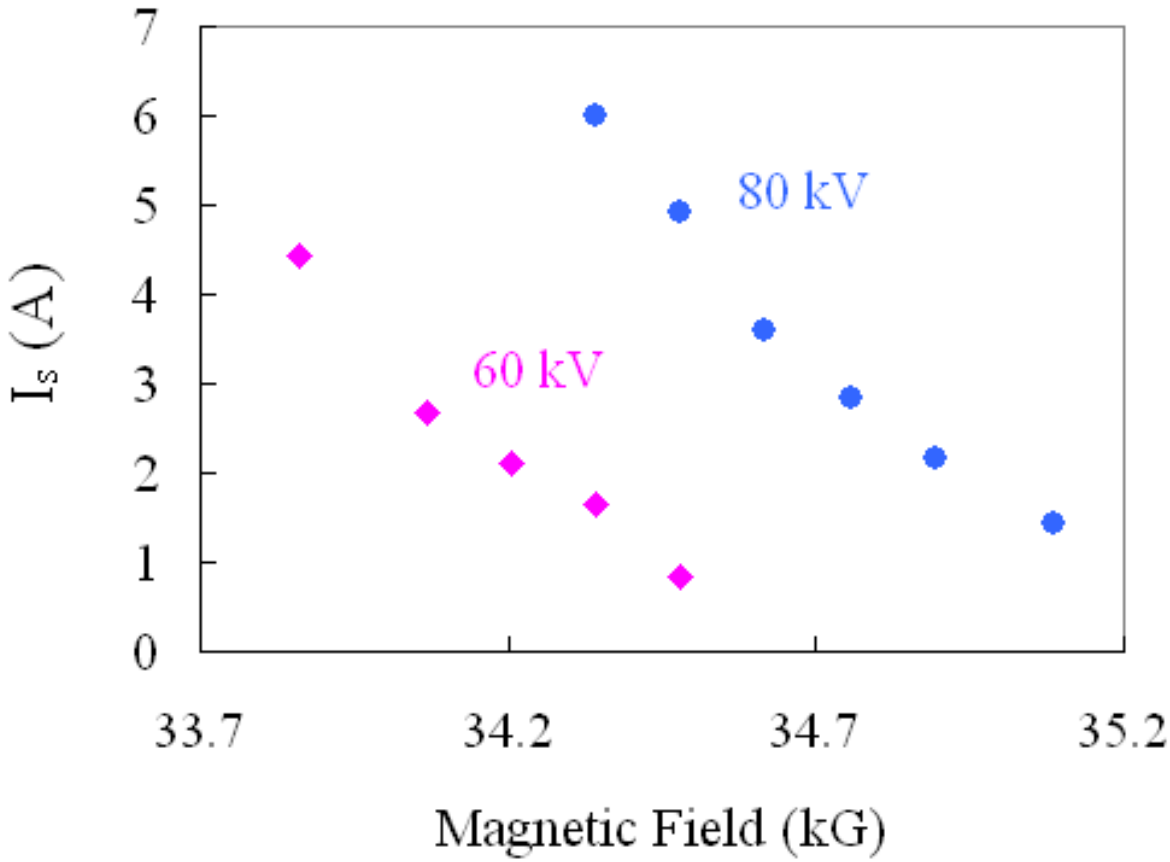
  Obviously harmful to the beam- will eliminate by reducing beam tunnel diameter and altering magnetic field profile

- TE_{01} Cutoff Oscillation: 91 GHz

  Lower start current than predicted-thought to be due to coupler and loaded-unloaded boundary reflections

Measured Start Oscillation Current

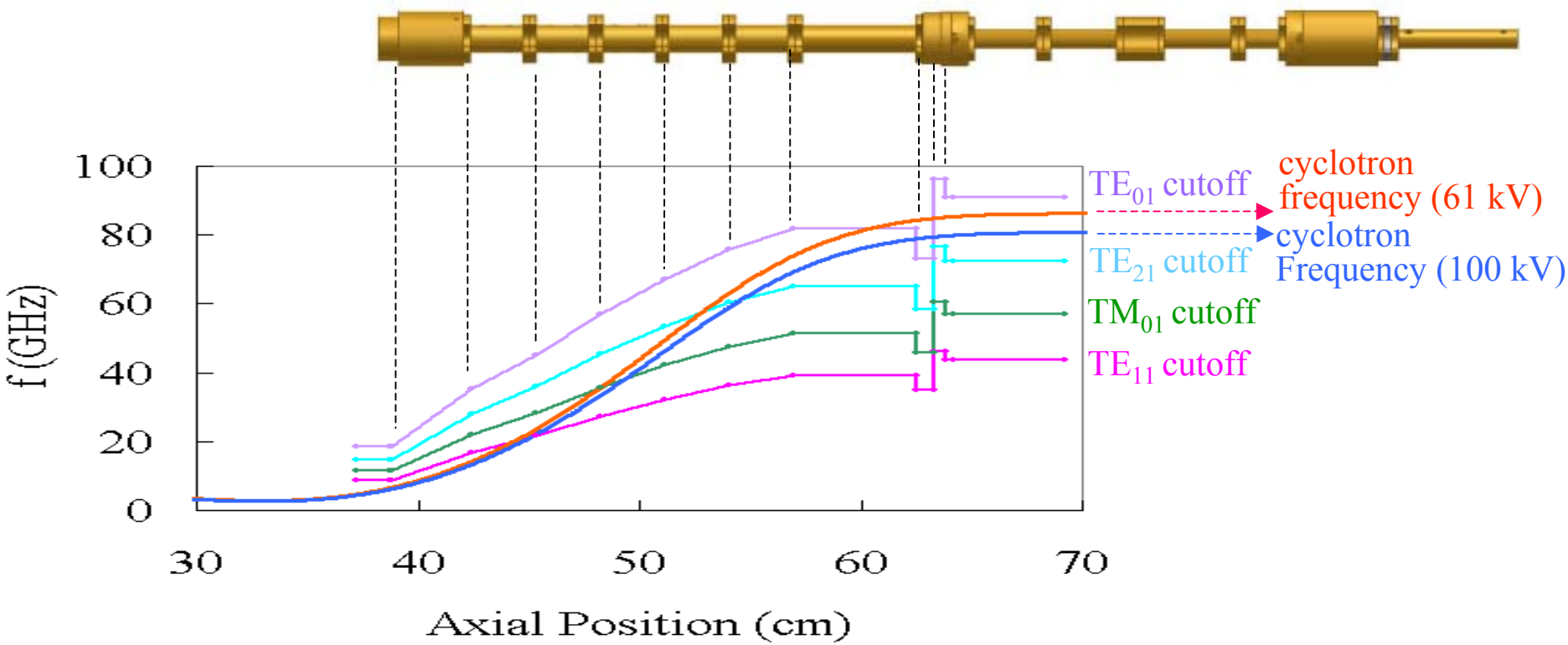
- Start oscillation current for TE_{01} cutoff oscillation were measured
- Oscillation threshold decreases for increasing magnetic field



Drift Tube Oscillation

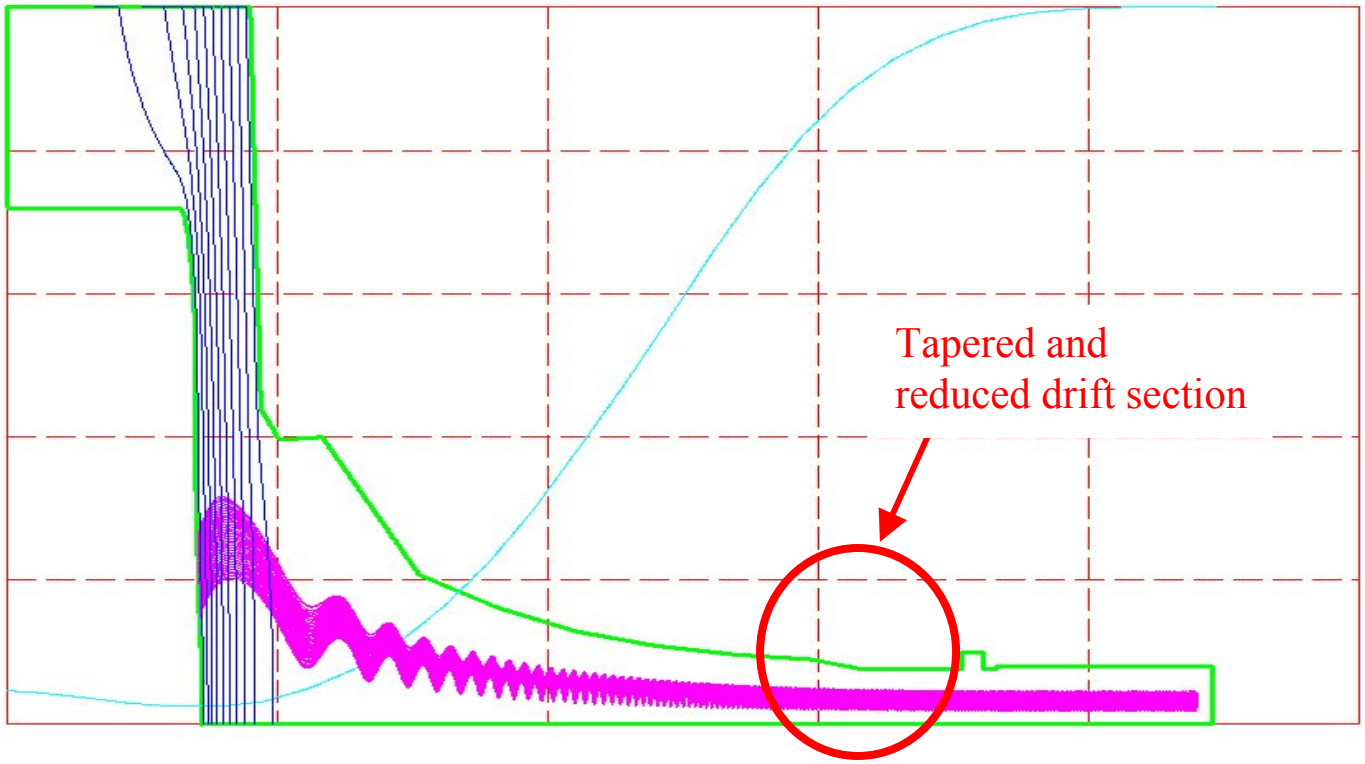
- Oscillation has been measured at 85 GHz at the drift tube using Fabry-Perot interferometer
- TE_{01} mode at the drift tube has been identified to be the source of oscillation
  → drift tube radius needs to be reduced

• Cyclotron and cutoff frequency vs. axial position of beam tunnel region



Electron Beam Propagation in the Drift Tube

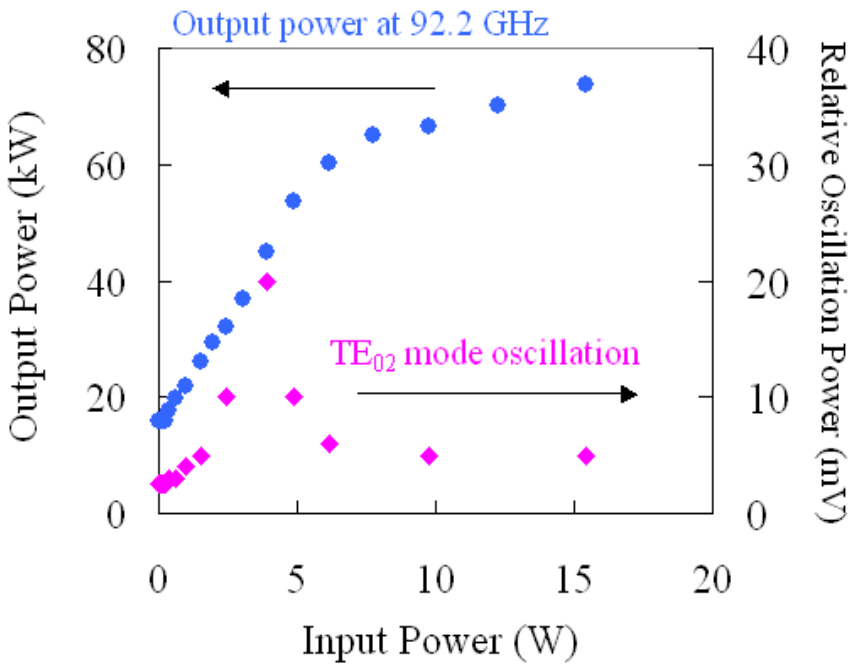
Proposed Configuration: taper and reduce drift



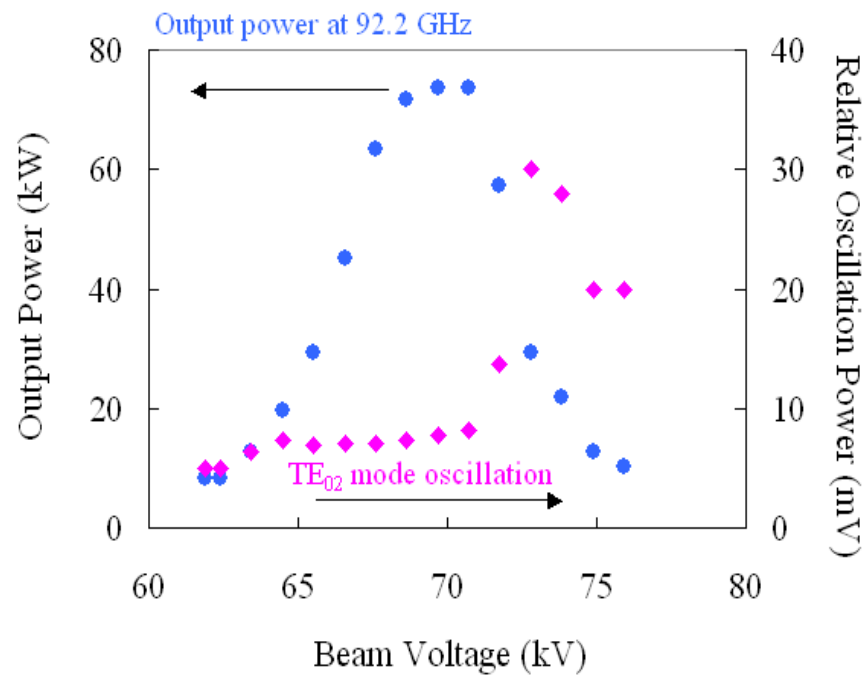
Mode Competition

- Gyro-TWT performance limited to lower voltage due to mode competition
- Competing mode are identified to be TE_{02} mode measured at 170 GHz using Fabry-Perot interferometer-

• V_b=70 kV, I_b=5.3 A, Bo=34.3 kG



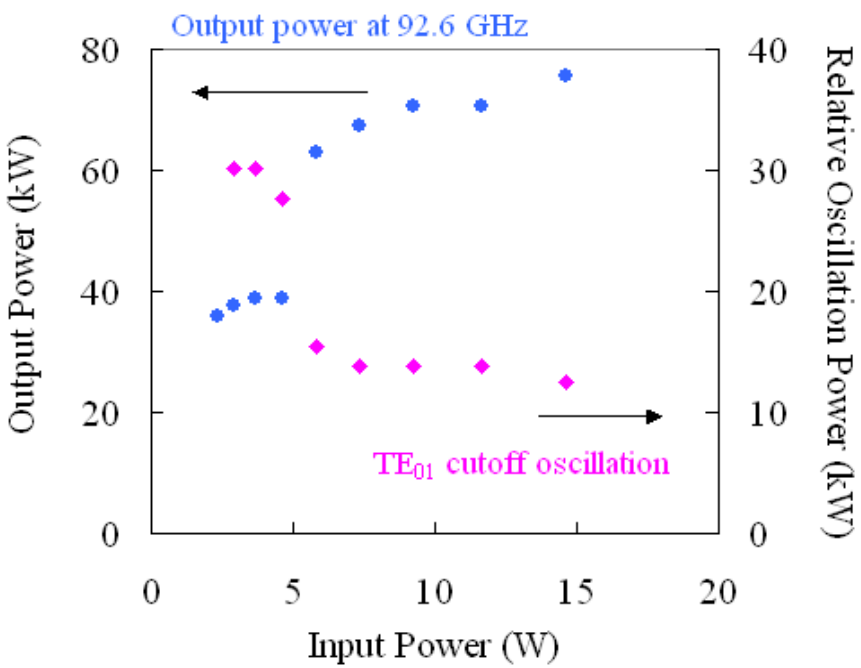
• I_b=5.4 A, B_o=34.3 kG



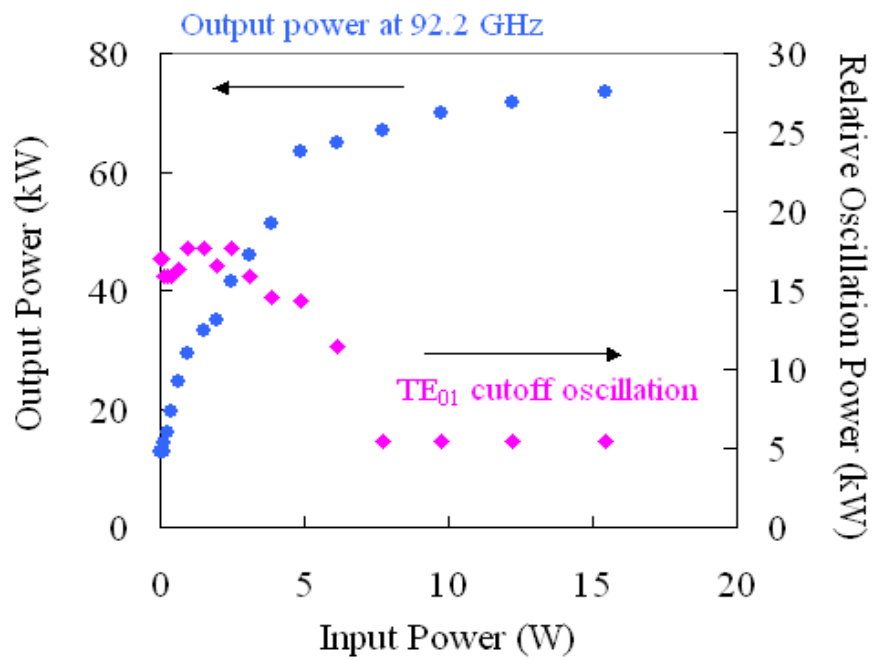
Measured Absolute Instability

- Oscillations near cutoff frequency (~91 GHz) have been observed at higher voltages than > 70 kV
- The cutoff oscillation degrades the amplified signal

•V_b=80 kV, I_b=5.1 A, B_o=34.8 kG

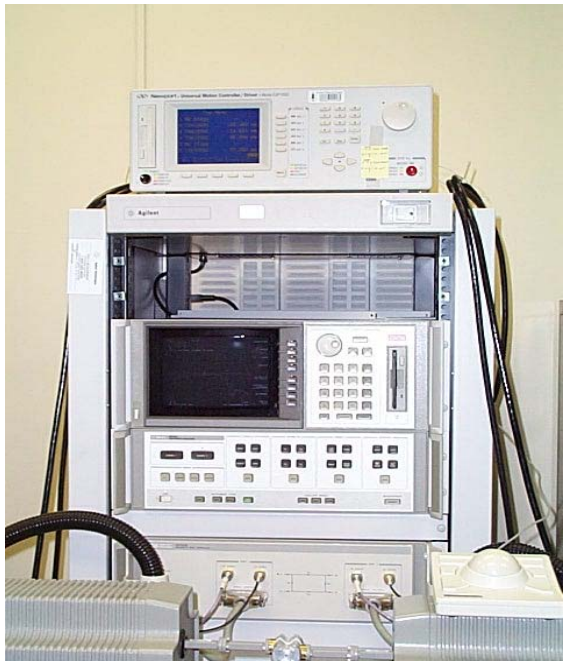


• V_b=72 kV, I_b=5.3 A, B_o=34.1 kG



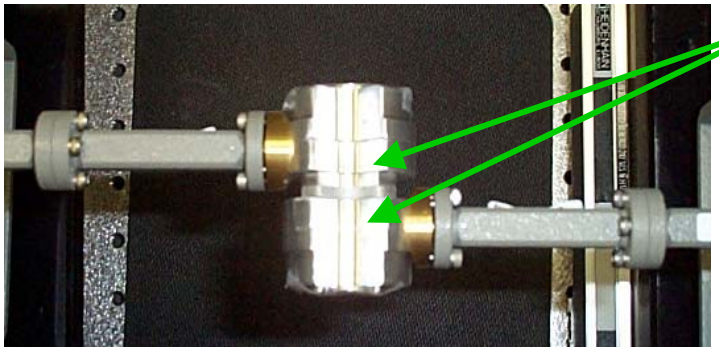
Optimized Input Coupler

- An optimized coax coupler has been designed, fabricated and measured in collaboration with NTHU (National Tsing Hua Univ., Taiwan); will be employed in the next experimental campaign
- Optimized input coupler measurement gives > -2 dB throughout the band

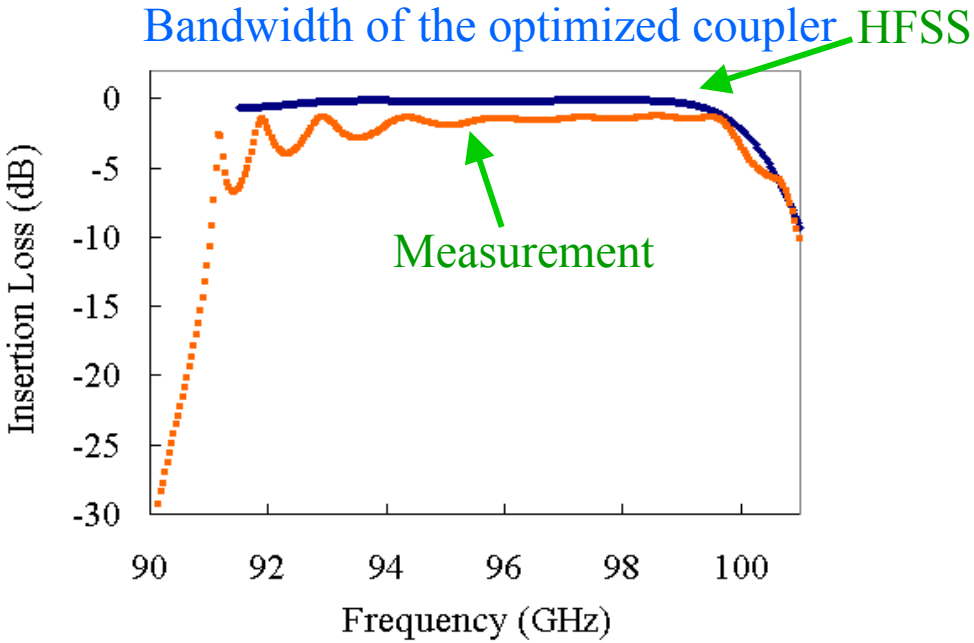


W-band network Analyzer used in coupler measurement

Coupler back-to-back measurement



Bandwidth of the optimized coupler



W-Band Gyro-amplifier Performance Comparisons

Year	Institution	Device	V_b (kV)	3dB Bandwidth (MHz)	Peak Power (kW)	Average Power (kW)	Saturated Gain (dB)	η (%)
1982	Varian	Gyro-TWT	50	1880	20	-	30	8
2003	CPI	Gyro-Klystron	55	700	100	10	35	30
2003	CPI	Gyro-Twystron	65	1600	60	0.3*	34	15
2003	UC Davis (Designed)	Gyro-TWT	100	4625	140	14 **	50	28
2003	UC Davis (Measured)	Gyro-TWT	60	1200	60	-	45	26.6

*Limits of current testing-9 kW predicted

** Potential with high power absorber and collector

Summary

- UCD 94 GHz TE_{01} Gyro-TWT has been constructed with predicted capability of 140 kW with $\Delta\omega/\omega$=5% and η=28%
- Circuit has been heavily loaded to suppress Gyro-BWO with 90 dB loss measured at 93 GHz
- Initial measurements indicated velocity spread problems-Gyro-TWT was reassembled employing optimized MIG with predicted velocity spread of 2%
- Gyro-TWT employing new optimized MIG hot tested with 60 kW saturated output power, 45 dB gain, 26.6% efficiency, and 1.2 GHz bandwidth (1.3 % BW)
- Operation has been limited to low voltages (< 70 kV) due to oscillations: competing modes have been identified to be $TE^{(2)}_{02}$ mode at 170 GHz, TE_{01} cutoff oscillation at 91 GHz, and drift tube oscillation at 85 GHz
- To suppress competing mode oscillations, reduced length unloaded section with compensating increase in loaded section length, reduced radius input drift section, and optimized input coupler will be employed for the next version of the UCD TE_{01} Gyro-TWT