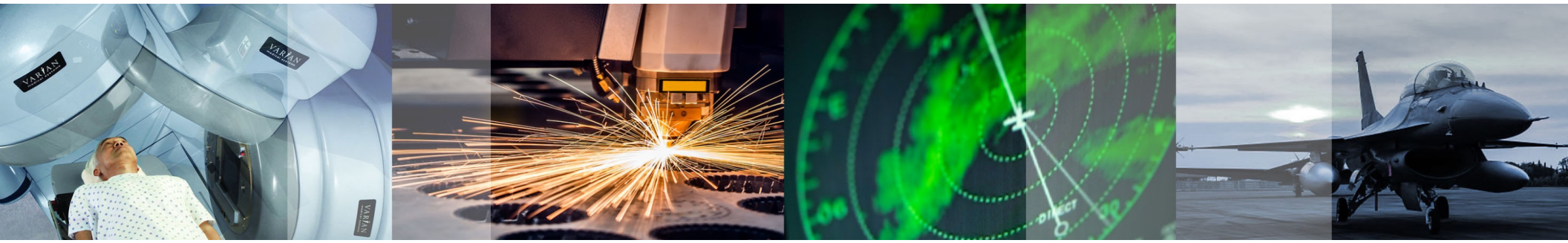
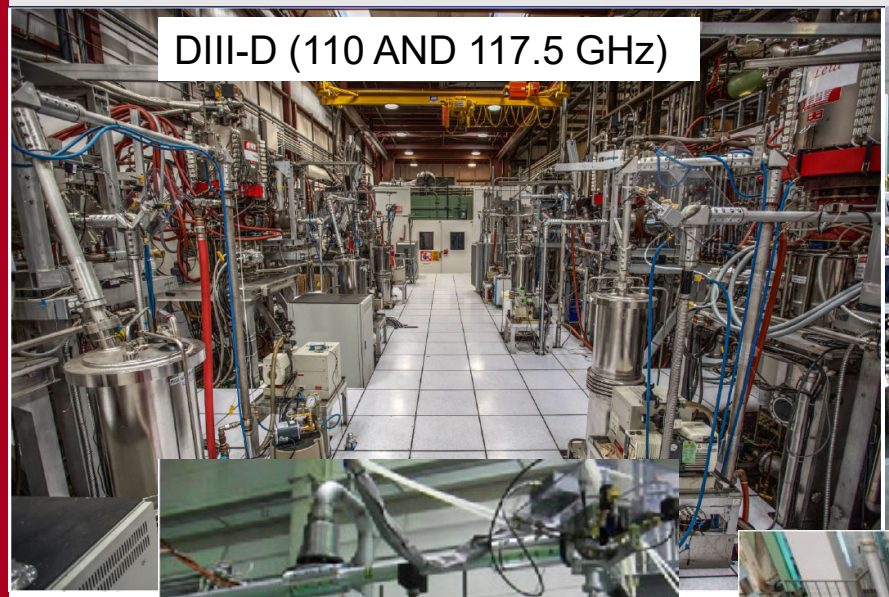
Communications & Power Industries

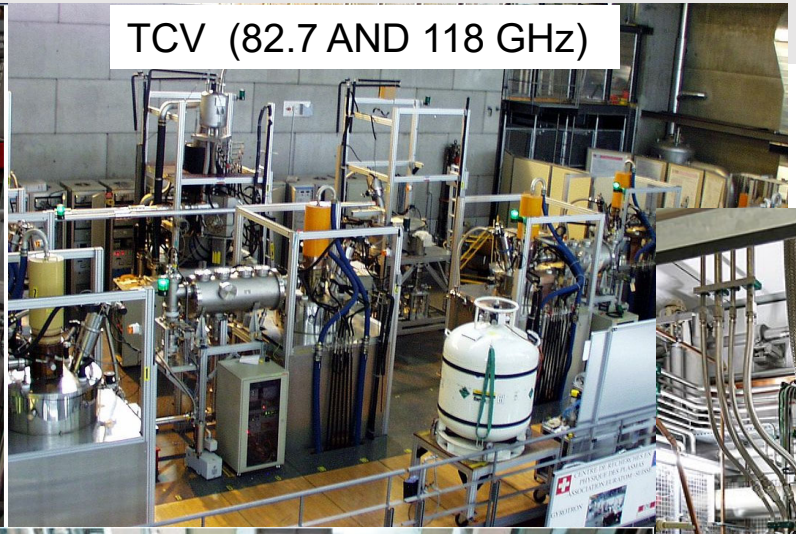


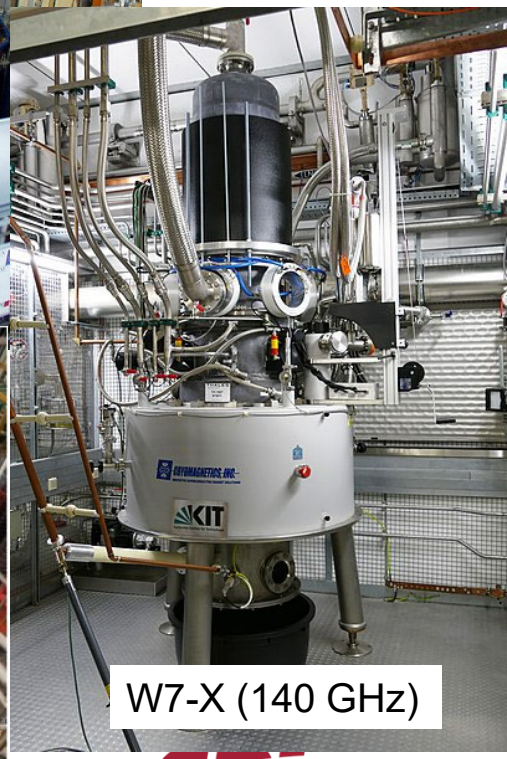
NEXT GENERATION GYROTRON SOURCES FOR ECH

M. Blank, S. Cauffman, K. Felch, P. Borchard, CPI, Palo Alto, CA

ECH SYSTEMS AROUND THE WORLD

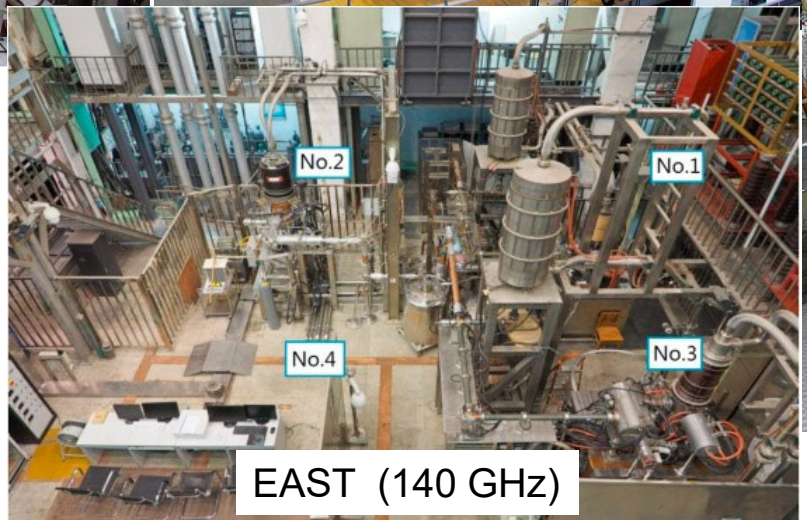

DIII-D (110 AND 117.5 GHz)


TCV (82.7 AND 118 GHz)



W7-X (140 GHz)

KSTAR (110 AND 170 GHz)



EAST (140 GHz)

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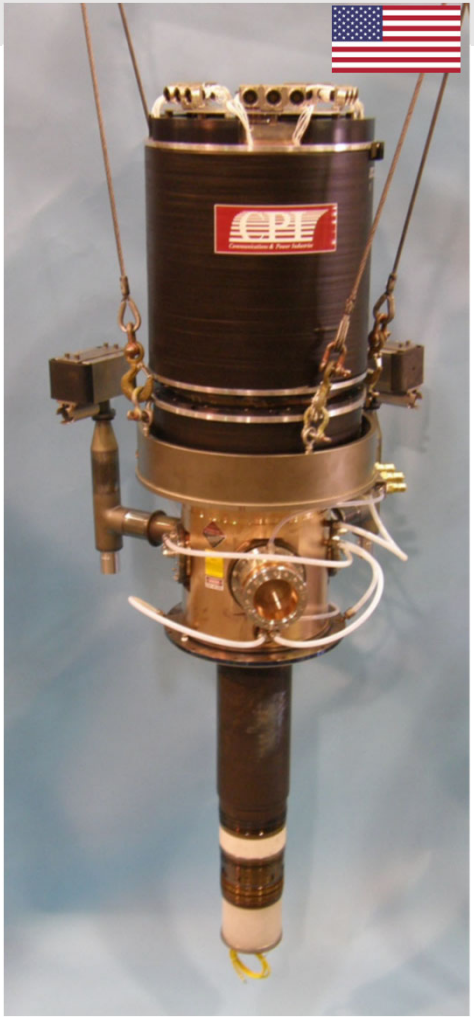
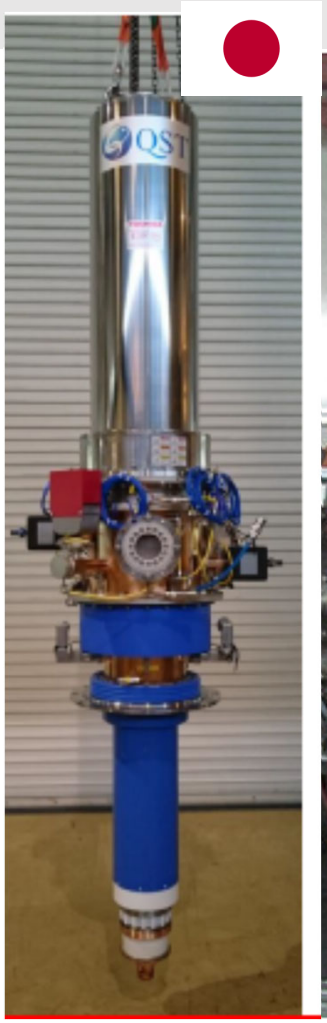
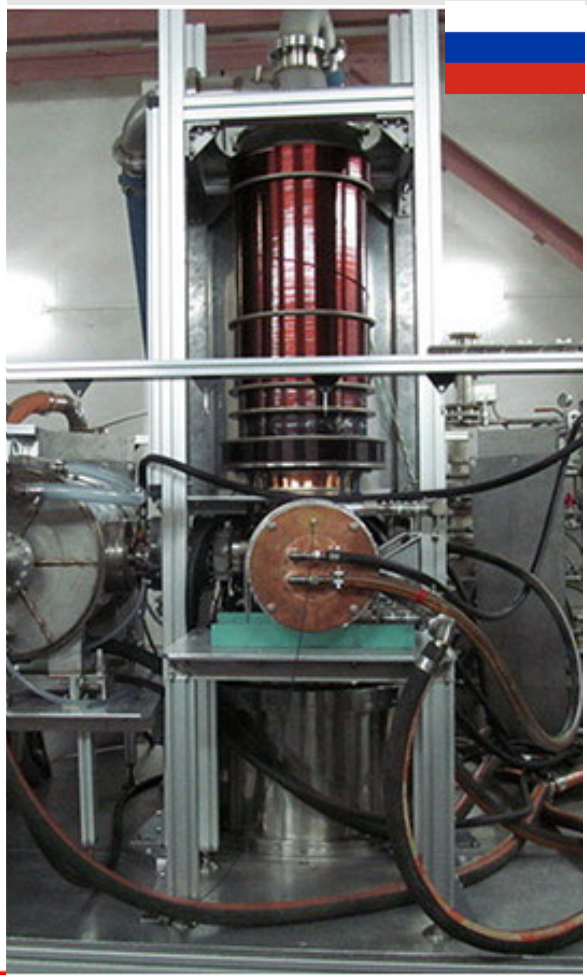
OUTLINE

- CURRENT CAPABILITIES
- ENABLING TECHNOLOGIES
- CHALLENGES FOR NEXT GEN GYROTRONS
- SUMMARY AND OUTLOOK

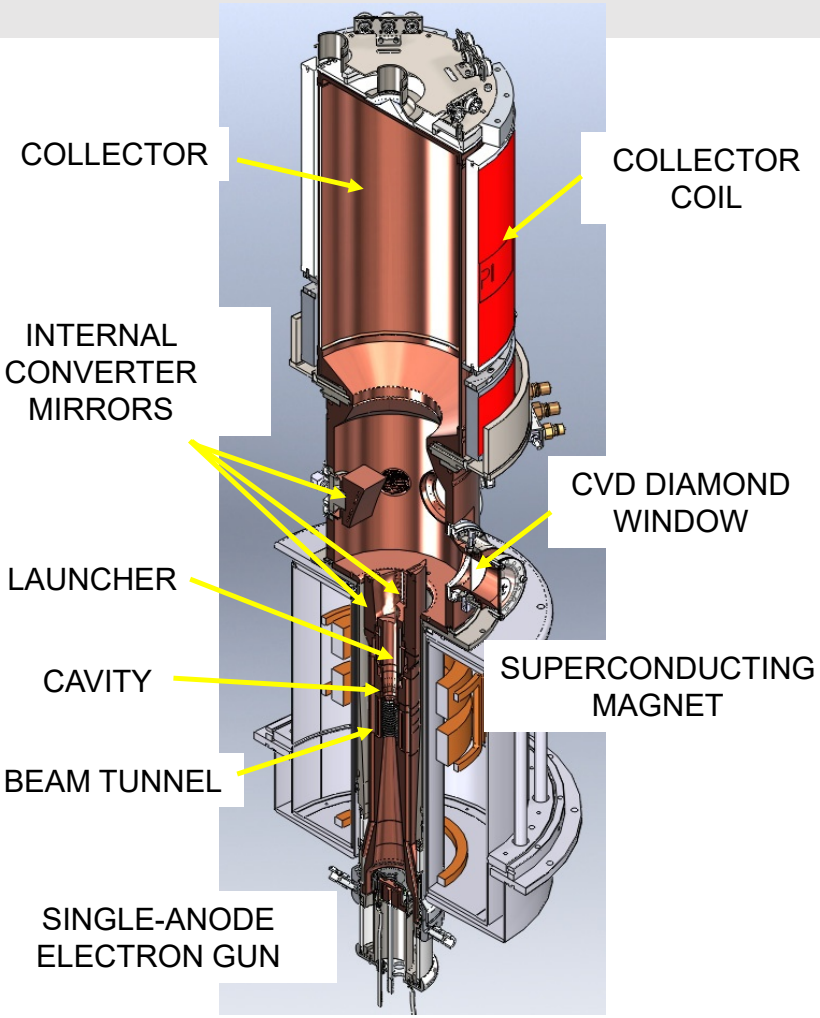
COMMERCIAL GYROTRON CAPABILITIES:140 – 170 GHz, 1 MW CW







CPI 140 GHz , 900 kW, 1800 SEC



FREQUENCY	140 GHz
OUTPUT POWER	0.9 MW
PULSE DURATION	1800 SEC
MAX CATH-BODY VOLTAGE	85 kV
MAX BODY-COLL VOLTAGE	30 kV
MAXIMUM CATH-COLL VOLTAGE	60 kV
MAXIMUM BEAM CURRENT	45 A
MAX BODY CURRENT	40 mA
INTERACTION MODE	$TE_{28,7}$
OUTPUT MODE	TEM_{00}
MODE PURITY	97%

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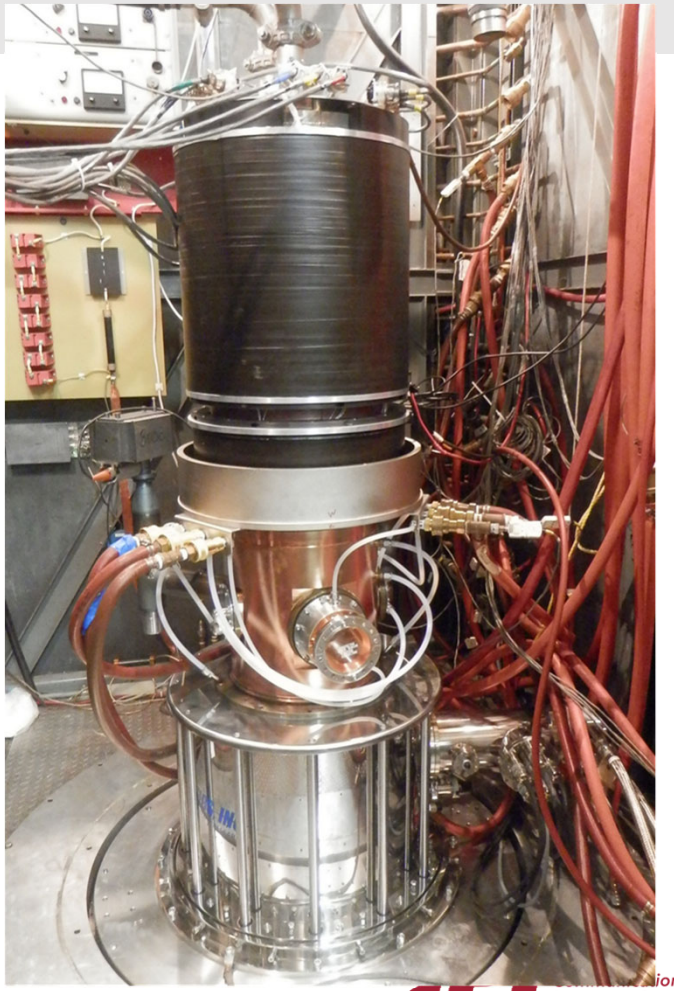
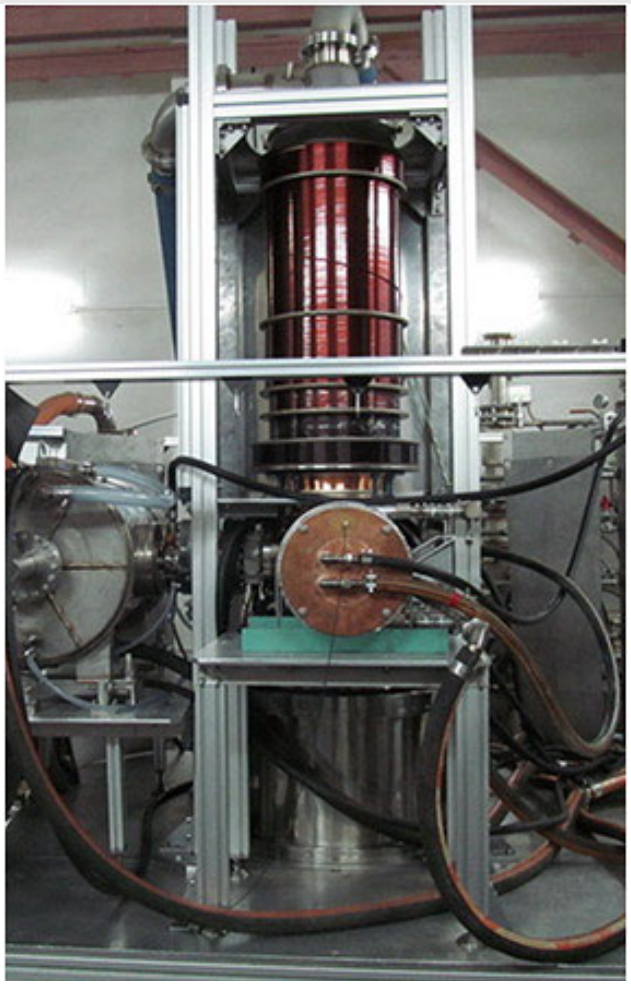
CPI 140 GHz , 900 kW, 1800 SEC



GYCOM 170 GHz, 1 MW, 1000 SEC



FREQUENCY	170 GHz
OUTPUT POWER	0.96 MW
PULSE DURATION	1000 SEC
MAXIMUM CATH-COLL VOLTAGE	50 kV
MAXIMUM BEAM CURRENT	45 A
INTERACTION MODE	$TE_{25,10}$
OUTPUT MODE	TEM_{00}
MODE PURITY	97%

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OUTLINE

- CURRENT CAPABILITIES
- ENABLING TECHNOLOGIES
  - LARGE BORE HIGH FIELD SUPERCONDUCTING MAGNETS
  - CVD DIAMOND WINDOWS
  - HIGH-EFFICIENCY INTERNAL MODE CONVERTERS
  - ADVANCED MODELING AND DESIGN TOOLS
- CHALLENGES FOR NEXT GEN GYROTRONS
- SUMMARY AND OUTLOOK

ENABLING TECHNOLOGY: SUPERCONDUCTING MAGNET

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ENABLING TECHNOLOGY: CVD DIAMOND WINDOWS

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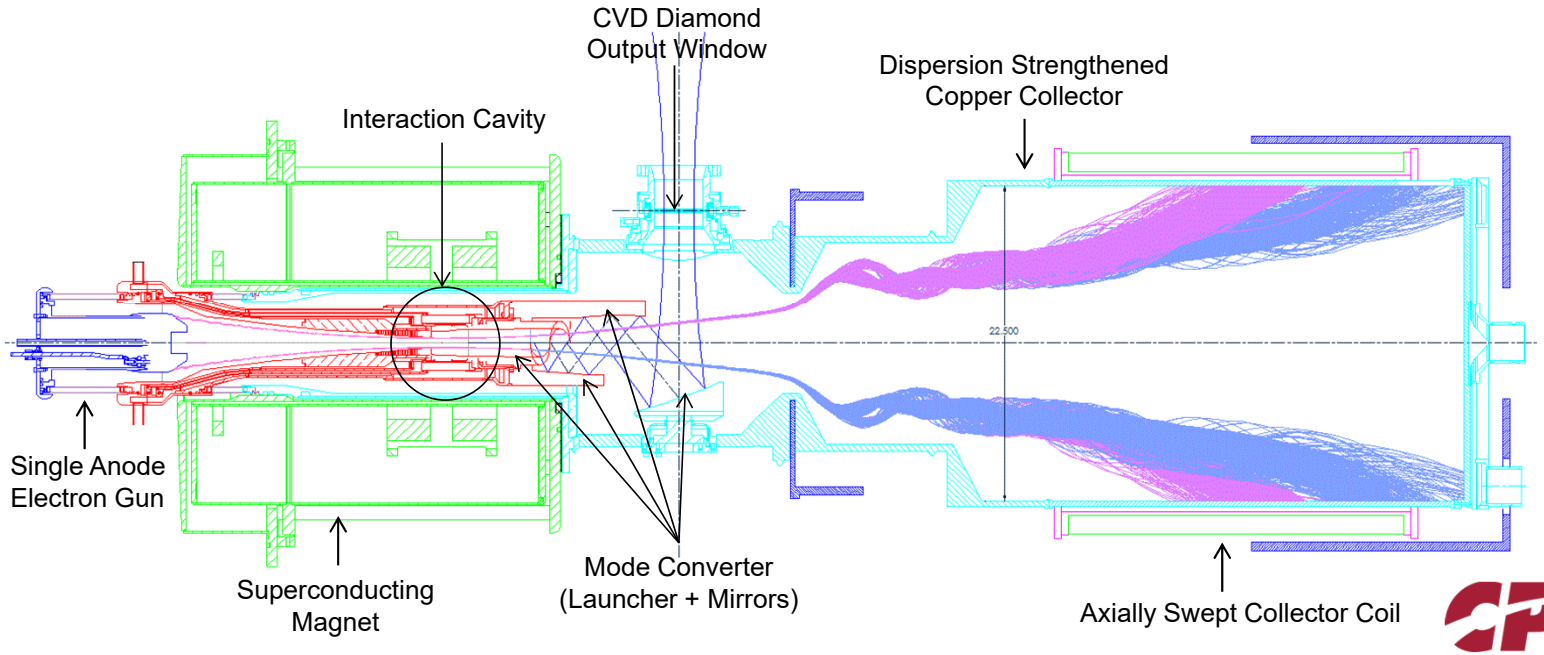
ENABLING TECHNOLOGY: CVD DIAMOND WINDOWS

- BY THE MID-1990s, GYROTRONS COULD GENERATE MORE POWER THAN VACUUM WINDOWS COULD HANDLE
- TYPICAL 1990s GYROTRON WINDOW MATERIALS
  - SAPPHIRE
  - AL_20_3
  - BeO
  - BN
  - MAXIMUM CW POWER-HANDLING CAPABILITY WAS < 500 kW
- DE BEERS PERFECTED LARGE DIAMETER CVD DIAMOND WINDOW PRODUCTION
- “MAGIC” MATERIAL
  - STRONG
  - 4 TIMES THE THERMAL CONDUCTIVITY OF COPPER
  - LOW-LOSS IN MILLIMETER WAVE REGIME (30 – 300 GHz)

ENABLING TECHNOLOGY: HIGH EFFICIENCY INTERNAL MODE CONVERTERS

- IN THE EARLY 1990s, NEW IDEAS FOR CONVERTERS TO TRANSFORM HIGH-ORDER GYROTRON MODES TO GAUSSIAN BEAMS WERE COMING INTO FASHION
- INTERNAL CONVERTERS ALLOWED THE USE OF LARGE DIAMETER AND DEPRESSED COLLECTORS



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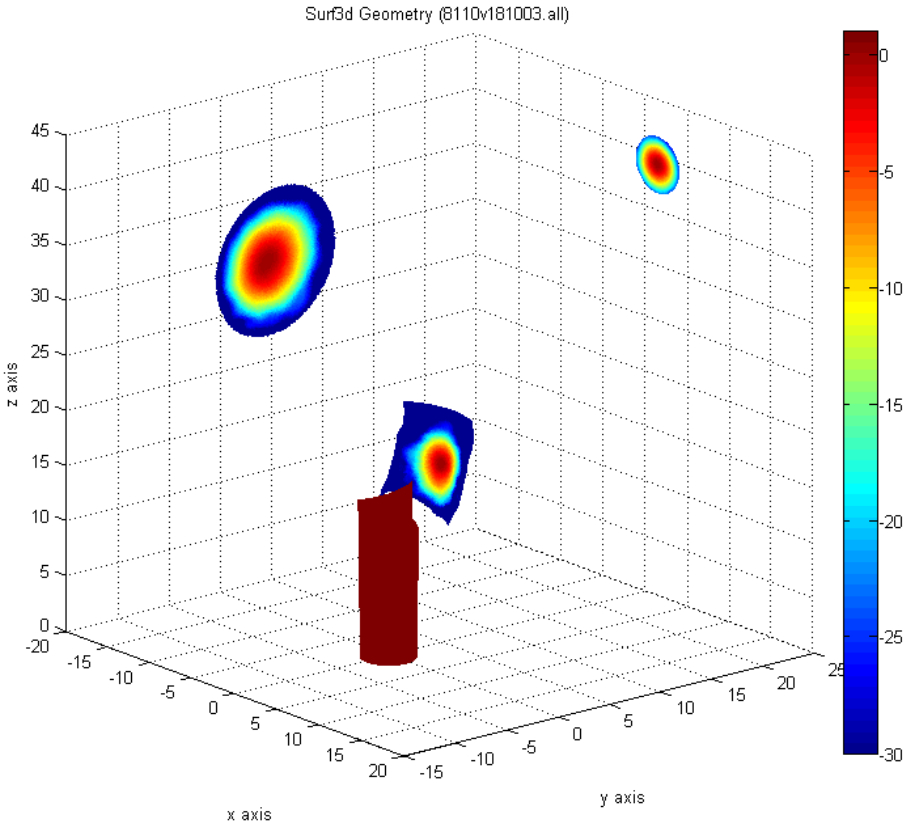
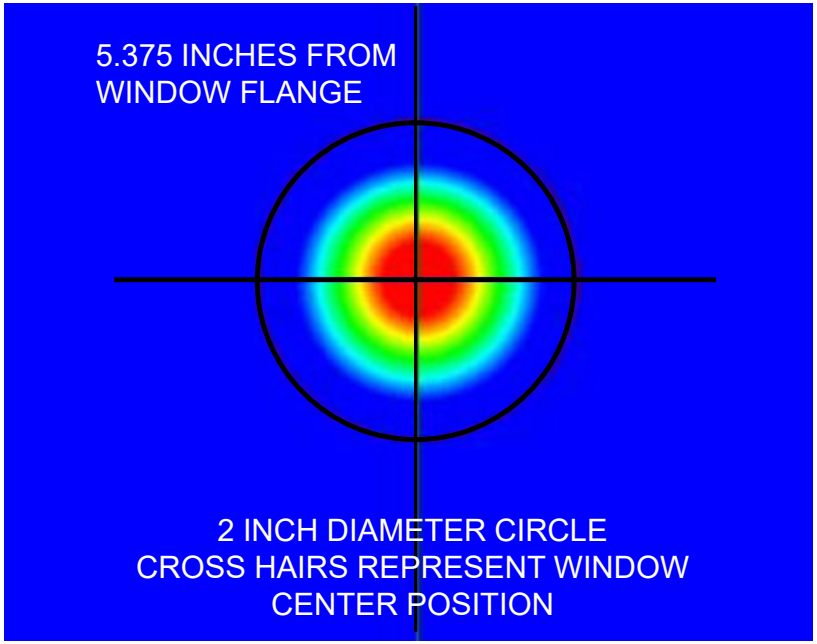
ENABLING TECHNOLOGY: HIGH EFFICIENCY INTERNAL MODE CONVERTERS

- EARLY VERSIONS OF INTERNAL CONVERTERS SUFFERED FROM LOW EFFICIENCY AND STRAY RF IN GYROTRON
  - TYPICAL STRAY RF 5 – 7% OF GENERATED POWER
  - REDUCED OUTPUT POWERS
  - DETRIMENTAL HEATING IN GYROTRON, ESPECIALLY AT LONG PULSE WIDTHS
- IN THE LAST 30 YEARS EFFICIENCY OF CONVERTERS HAS VASTLY IMPROVED
  - DESIGN TOOLS
  - FABRICATION AND MECHANICAL VERIFICATION
- INTERNAL STRAY RF LOSSES NOW VERY LOW, 2 – 3%
- OUTPUT BEAMS NEARLY PERFECT, 98 - 99% GAUSSIAN

ENABLING TECHNOLOGY:
HIGH EFFICIENCY INTERNAL MODE CONVERTERS



DESIGN



MEASUREMENT

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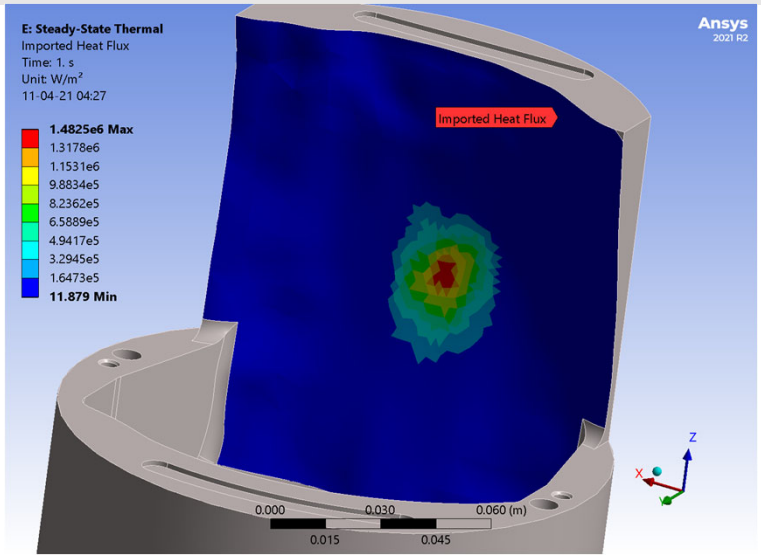
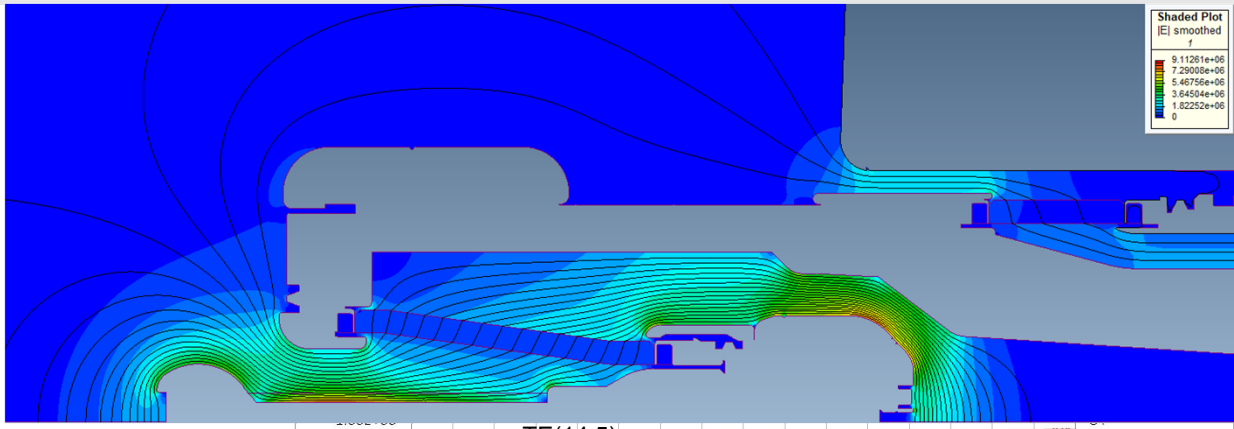
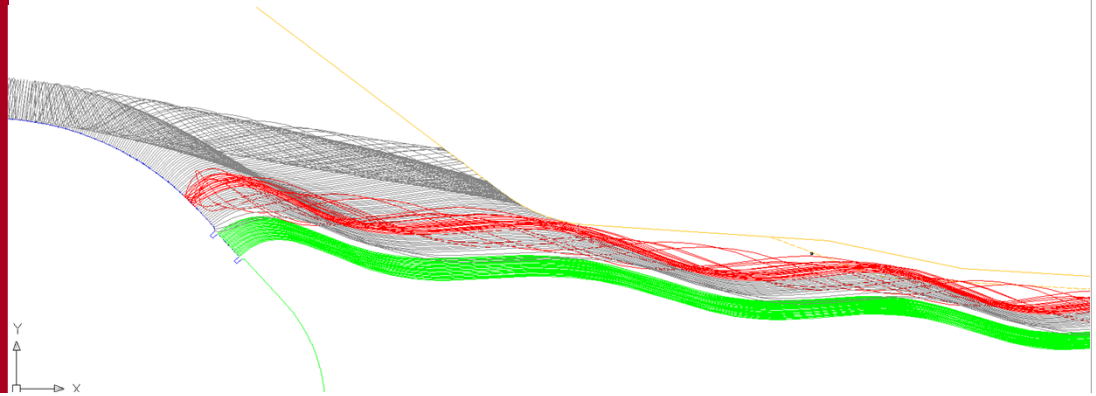
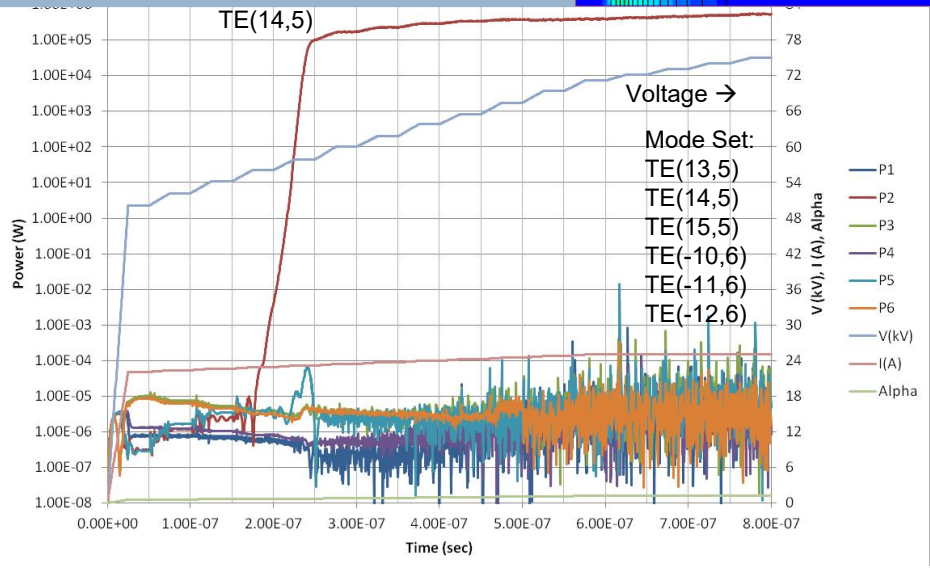
ENABLING TECHNOLOGY: ADVANCED MODELING AND DESIGN TOOLS









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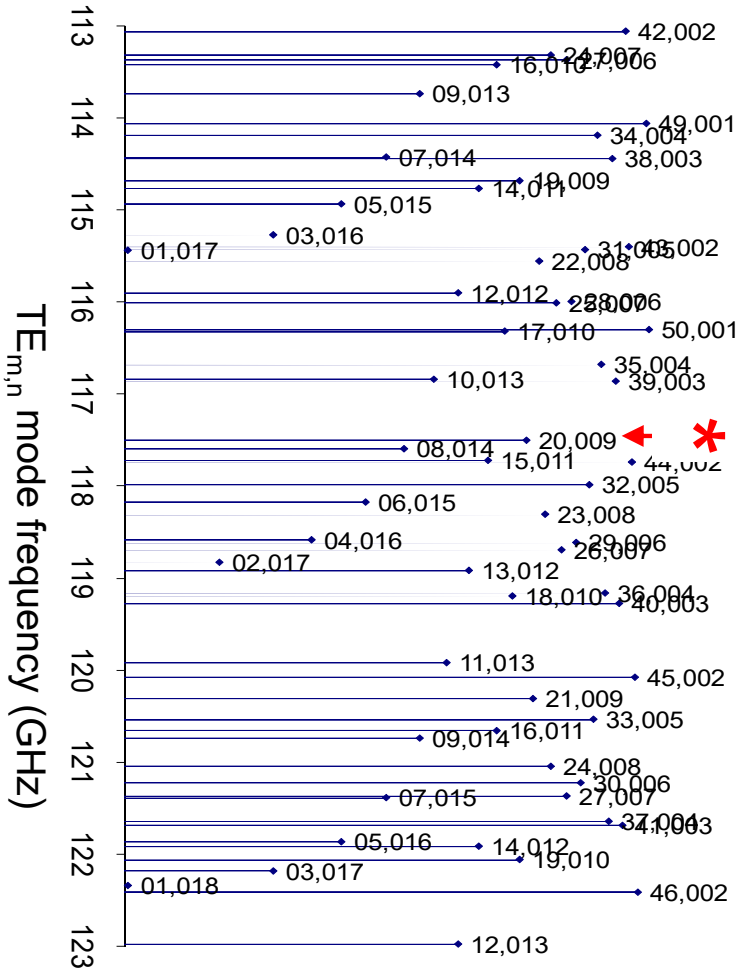
CHALLENGES FOR NEXT GEN GYROTRONS

- HIGHER FREQUENCY
  - DEMO AIMING AT > 200 GHz
  - CFETR 170/230 GHz
  - HIGHER ORDER MODES REQUIRED FOR 200 GHz AND ABOVE
  - IDEAS TO TAME MODE COMPETITION INCLUDE EXTERNAL MODE LOCKING, COAXIAL CAVITIES



CHALLENGES FOR NEXT GEN GYROTRONS

- HIGHER OUTPUT POWER PER GYROTRON
  - 1.5 – 2 MW GYROTRONS PLANNED FOR MANY MAJOR ECH SYSTEMS
  - MODE COMPETITION, COLLECTOR POWER DENSITIES MUST BE ADDRESSED

CHALLENGES FOR NEXT GEN GYROTRONS

- GYROTRON EFFICIENCIES > 60%
  - REDUCE MODE COMPETITION
  - MORE EFFICIENT DEPRESSED COLLECTORS
  - MULTI-STAGE DEPRESSED COLLECTORS
    - MUCH MORE DIFFICULT TO ENVISION EFFECTIVE MULTI-STAGE DC FOR A GYROTRON BEAM THAN FOR A LINEAR BEAM DEVICE
  - EFFICIENCIES > 70% BUMPING UP AGAINST BASIC DEVICE PHYSICS LIMITS, DIFFICULT TO ENVISION

CHALLENGES FOR NEXT GEN GYROTRONS

- PRICE PER WATT
  - PRESENT COST FOR A 1 MW CW GYROTRON WITH TURNKEY SUPERCONDUCTING MAGNET SYSTEM IS $2 -$3 /WATT
    - THAT PRICE DOES NOT INCLUDE POWER SUPPLY/CONTROL OR WATER-COOLING SYSTEMS
  - COST OF A 2 MW GYROTRON AND MAGNET WILL BE JUST 10 OR 15% MORE THAN A 1 MW UNIT
    - $1 - $2/WATT
  - BEST WAY TO REDUCE COST/WATT IS MORE POWER FROM EACH GYROTRON

CHALLENGES FOR NEXT GEN GYROTRONS

- RELIABILITY
  - ECH SYSTEM RELIABILITY IMPROVING OVER PAST DECADES
  - FUTURE ECH SYSTEMS WILL NEED > 95%
  - BEST WAY TO ACHIEVE 100% RELIABILITY IS TO OVER SPECIFY AND BACK OFF
  - 1 MW CW GYROTRONS WOULD MISS FEW PULSES AND LAST LONGER IF OPERATED AT 500 kW

HOW TO ADDRESS CHALLENGES

- FOCUSED AND SUSTAINED DEVELOPMENT PROGRAMS
  - ADVANCING STATE-OF-THE-ART UNDER FIXED-PRICE CONTRACTS WITH FIRM SPECIFICATIONS VERY LIMITING
  - DEVELOPMENT PROGRAMS AND PROTOTYPES FOR INDUSTRIAL GYROTRON MAKERS FOSTER PROGRESS
  - COMMERCIAL GYROTRON MAKERS IN OTHER COUNTRIES BENEFIT FROM STRONG GOVERNMENT INVESTMENT

OUTLINE

- CURRENT CAPABILITIES
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SUMMARY AND OUTLOOK

- FOUR WORLD-WIDE GYROTRON MANUFACTURERS CURRENTLY ABLE TO ACHIEVE 1 MW LONG-PULSE OPERATION AT FREQUENCIES UP TO 170 GHz
- FUTURE ECH SYSTEMS WILL NEED
  - HIGHER FREQUENCIES (200 – 300 GHz)
  - HIGHER OUTPUT POWER PER GYROTRON (1.5 – 2 MW)
  - IMPROVED EFFICIENCIES (> 60%)
  - LOWER COST/WATT
  - HIGH RELIABILITY (> 95%)
- ACTIVE RESEARCH AND DEVELOPMENT PROGRAM NEEDED TO CONTINUE ADVANCEMENT OF STATE-OF-THE-ART