MICROWAVE POWER PRODUCTS

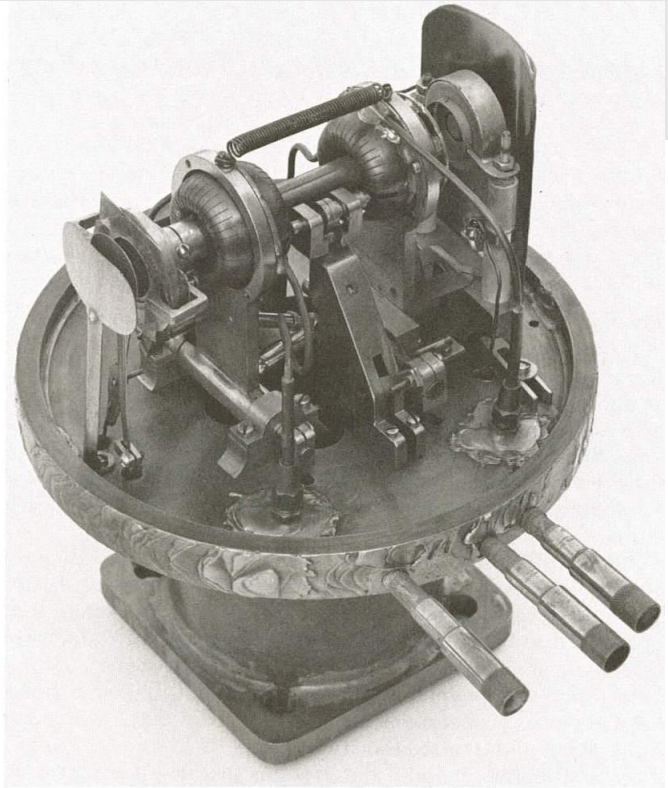
Development of High Efficiency Klystrons at MPP

2nd Workshop on Efficient RF Sources

23-25 September 2024 – Toledo, Spain

Presentation Outline

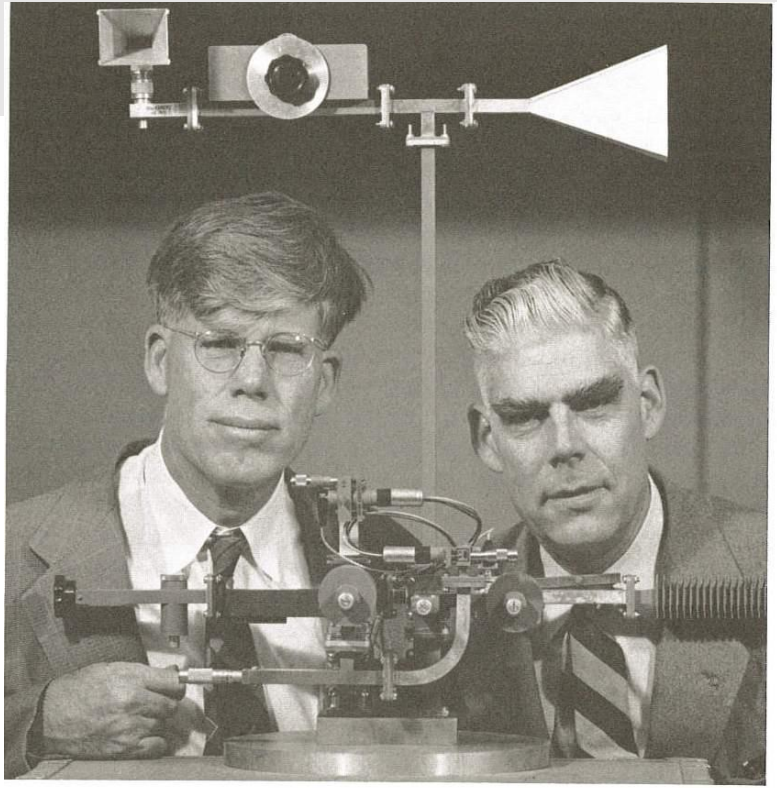
- MPP History
- Markets Served
- Recent Developments
  - High Power X Band Klystrons
  - High Efficiency Efforts
- Summary



Evolution of the klystron tube, Stanford University, 1937. Model B was designed to be operated under a bell jar. Its parts were readily accessible, so that improvements could be made and experiments conducted without having to rebuild the tube each time. (Stanford University photo)

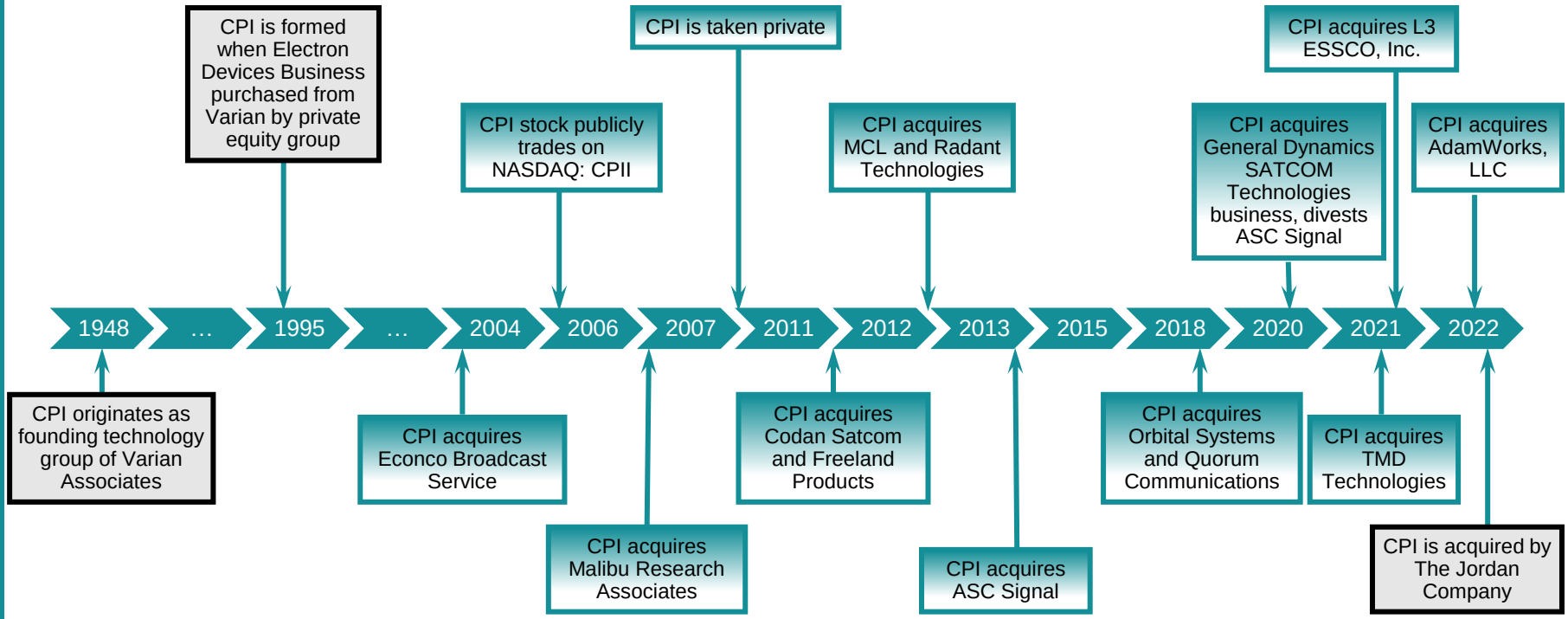
MPP History

- Founded in 1948, original business of Varian Associates
  - Spun out of Varian Associates in 1995
  - Acquired by the TransDigm Group in 2024

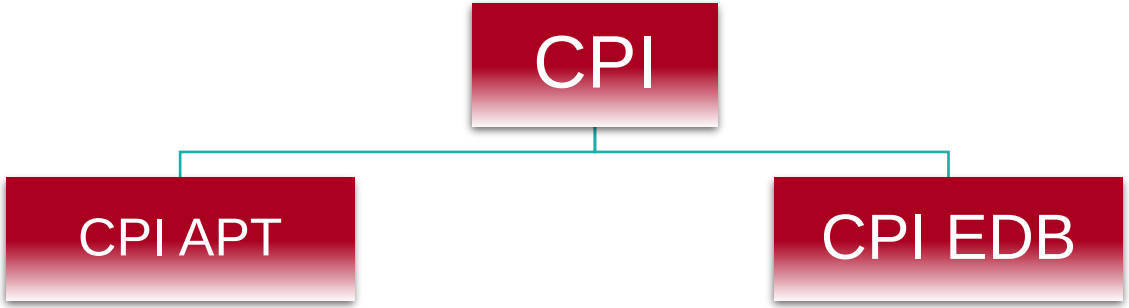


Life Magazine's January 4, 1954, issue featured Russell and Sig surrounded by wave guide apparatus used with klystrons. (Ansel Adams photo)

Historical Timeline



Structure at The Jordan Group



Antenna & Power Technologies

- Former GD Satcom
- CPI Satcom (Amplifier)
- CPI Radome
  - Radant, ESSCO, Adam Works

Electron Device Business

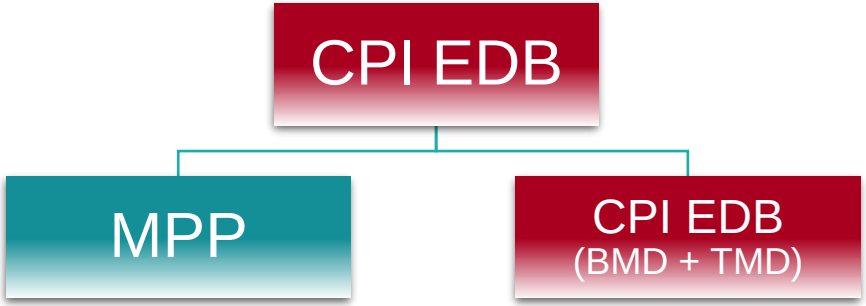
- CPI MPP Division
  - CPI Econco
- CPI BMD Division
- CPI TMD Division

Communications & Power Industries LLC

mpp Microwave Power Products

Recent History

- In September 2023, The Jordan Group and the TransDigm Group came to a definite Agreement for the transfer of the CPI Electron Device Business to TransDigm
- This agreement, after sorting out all legal and administrative tasks, was executed in June 2024
- After the transition, TransDigm decided to operate the former CPI MPP division as a separate company, allowing it to do a stronger focus on its products and markets.



Microwave Power Products, Inc

- Helix TWT
- CCTWT
- Klystrons
- Gyrotrons

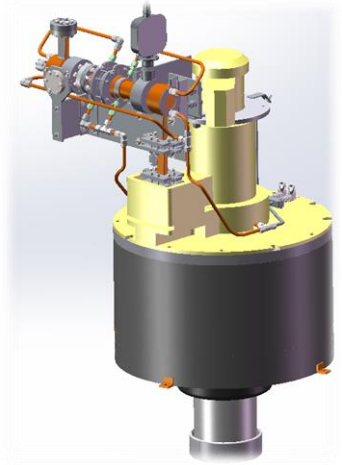
CPI International, Inc

- Magnetrons
- Control Components (Incl. Coupler)
- Transmitter
- Transponder
- CPI TMD

Medical Market

- MPP Products:
  - Klystrons
  - Power Grid Devices

VKS8252 5 MW S Band Klystron



VKX-8255A 25 MW X Band Klystron

Industrial Market

- Irradiation Market for sterilization, Klystrons
  - 2.856 & 2.998 GHz
  - 5, 7, 10 MW output power
- Industrial Heating
  - Klystron & Power Grid
- Dynamic Nuclear Polarization
  - Gyrotron & EIK

Science Market Products Developed

2021 – 3 MW 402.5 MHz
Klystron, SNS ORNL

2003 – 700 kW
805 MHz Klystron, ORNL

2007 – 10 MW 1.3 GHz
Klystron, DESY

2010 – 2 MW 500 MHz
Klystron, CAS

2010 – 3 MW 352 MHz
Klystron, CERN/ESS

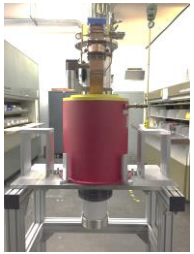
2016 – 5 MW 201 MHz
Klystron, PIP

2012 – 3 MW cw
324 MHz Klystron, IHEP

2011 – 300 kW
CW 1.3 GHz Klystron,
HZB, TRIUMF

2011 – 50 MW
12 GHz Klystron, CERN

2011 – 3 MW
325 MHz Klystron, CAS



2017 – 20 MW 3 GHz
Klystron, CLARA

2016 – 1.2 MW
704 MHz Klystron, ESS

2014 – 1.2 MW
704 MHz MBIOT, ESS

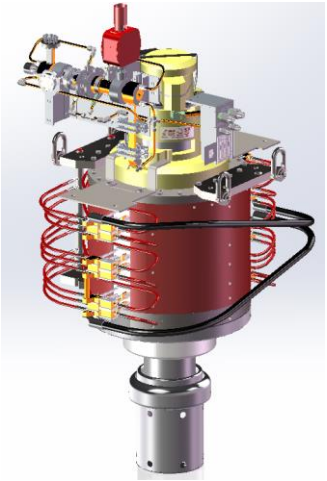
cpii.com

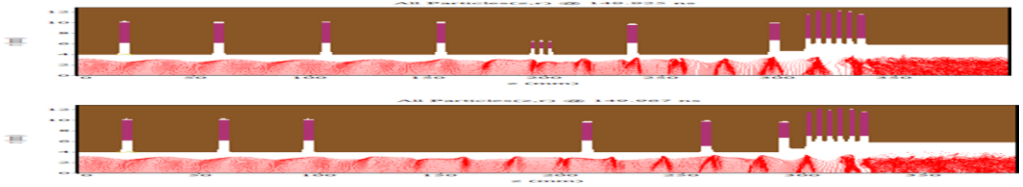
BMD - Power Couplers

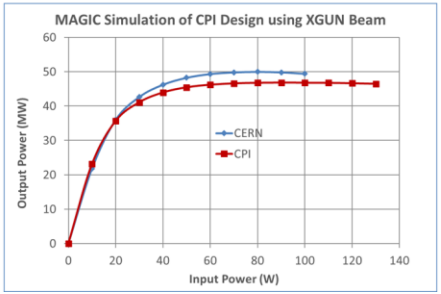
CPI Model Number	Accelerator Application	Freq. (MHz)	Peak Power (kW)	Avg. Power (kW)
VWP3097	IFMIF Prototype (CEA Saclay)	175	200	200
VWP3098	FRIB Prototype (MSU)	322	14	14
VWP3124	RFQ (ORNL)	402	14	14
VWP3107	NSLSII (AES, BNL)	500	500	500
VWP3070	FEL Injector (AES, BNL)	704	1000	1000
VWP1185/86	FEL Injector (AES, JLAB)	748	350	350
VWP1133	SNS Prototype (JLAB)	805	1000	60
VWP1162	RIA Prototype (MSU)	805	1000	10
VWP1137	Tesla Test Facility (CNRS Orsay, DESY)	1300	1100	7.2
VWP3049	ILC Test Area (Fermi, SLAC and Triumf)	1300	1100	7.2
VWP3126	XFEL (EuXFEL)	1300	1100	7.2
VWP3135	SLAC (LCLS-II)	1300	7	7
VWP3032	ERL Injector (Cornell and Triumf)	1300	75	75
VWP3069	ERL Injector (Daresbury)	1300	75	75
VWP3113	SRF (Peking University)	1300	50	50
VWP3108	ERL (Cornell)	1300	5	5
VWP3088	XFEL Third Harmonic Cavity (Fermi, DESY)	3900	45	12.5

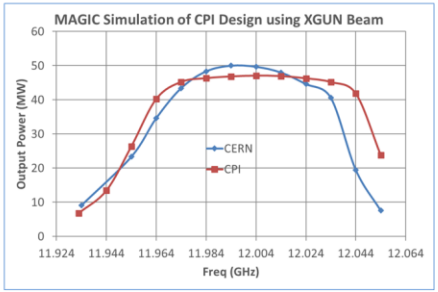
VKX-8311A3
11.994 GHz, 50 MW Peak
High Efficiency
Pulse Klystron

Development of VKX-8311A3,11.994 GHz, 50 MW High Efficiency Klystron



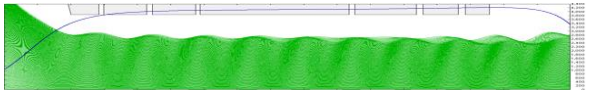




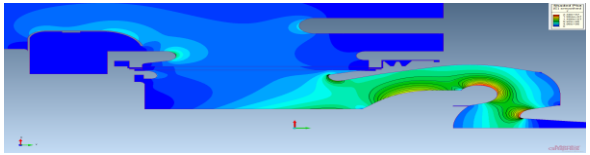


- CERN & MPP collaboration to develop a 50 MW 12 GHz High Efficiency Klystron
- Two stable designs with predicted RF efficiency of over 60%
- Received contract from INFN in March 2023 for design, fabrication, testing, and delivery of one proto-type unit

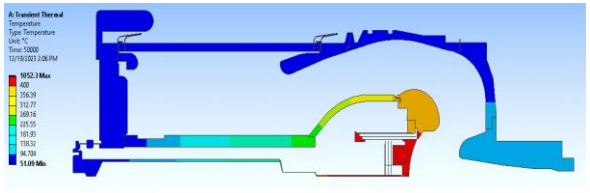
Final Design & Analysis of VKX-8311A3 Klystron



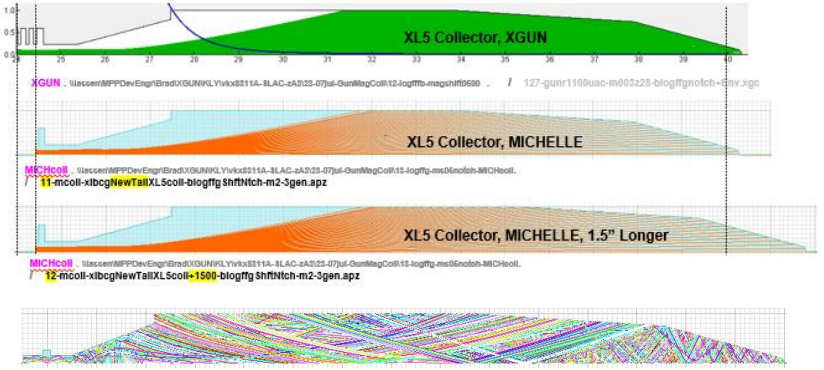
Beam optics & Magnetics



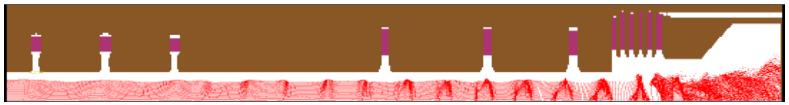
DC Electric Field Gradient Analysis



Gun Thermal Analysis with ANSYS

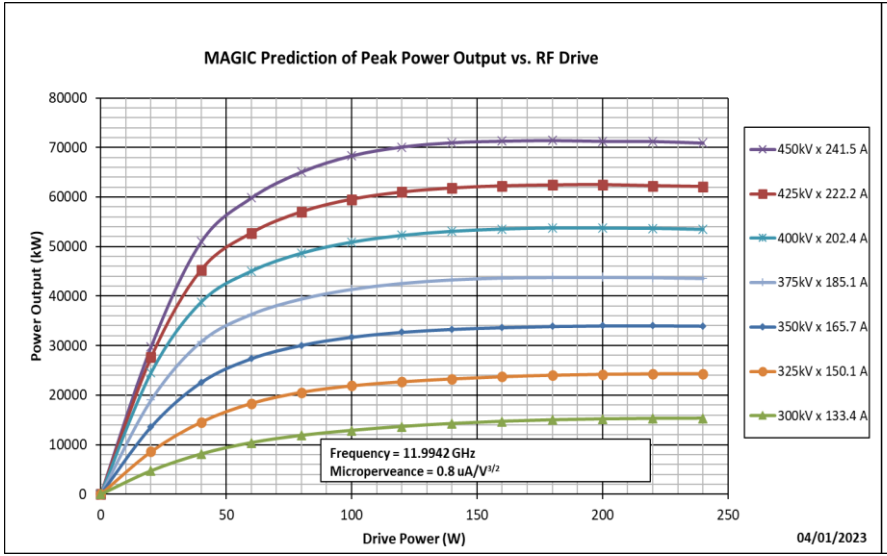


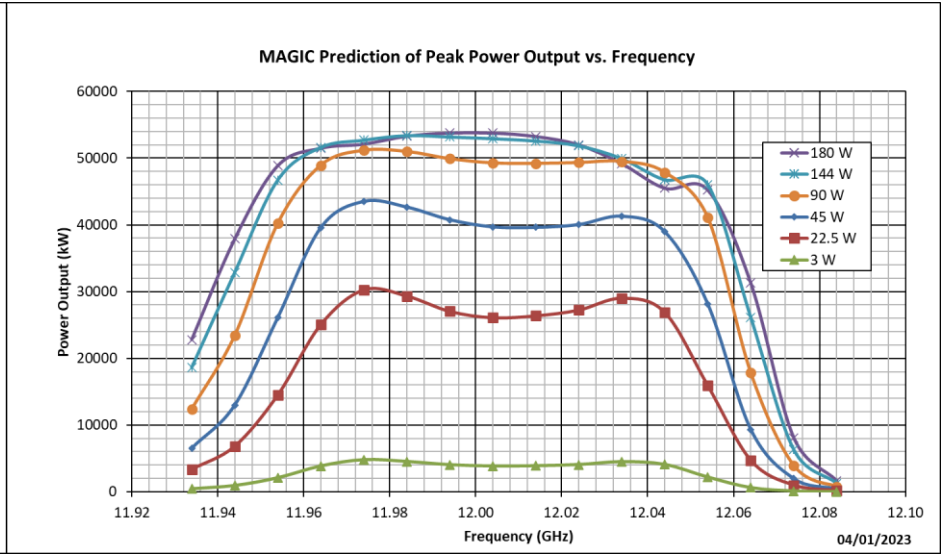
Collector Analysis



RF Circuit Analysis with MAGIC PIC code

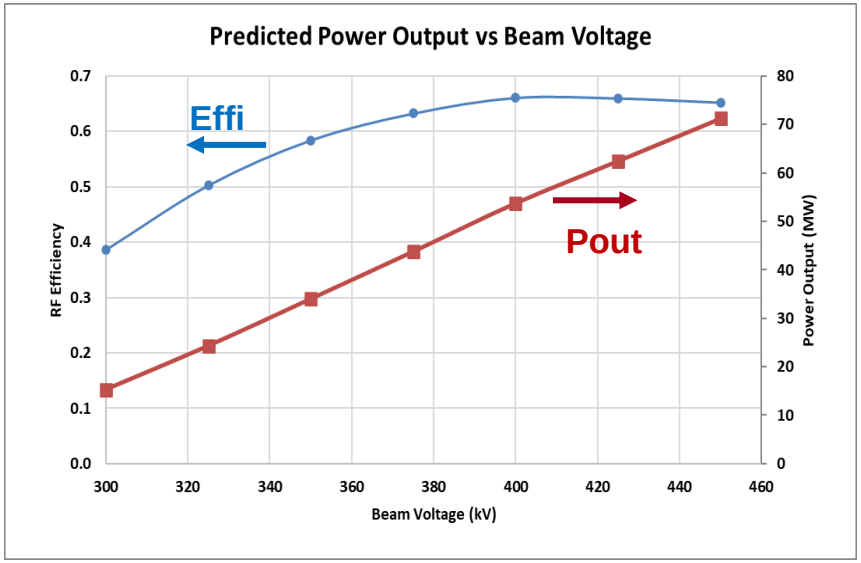
Predicted Pout vs Pd & Pout vs Frequency Curves

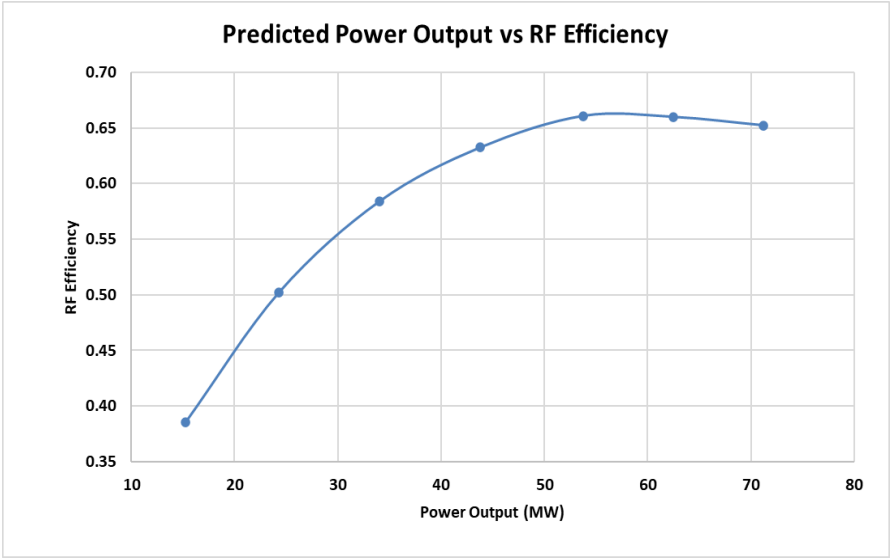




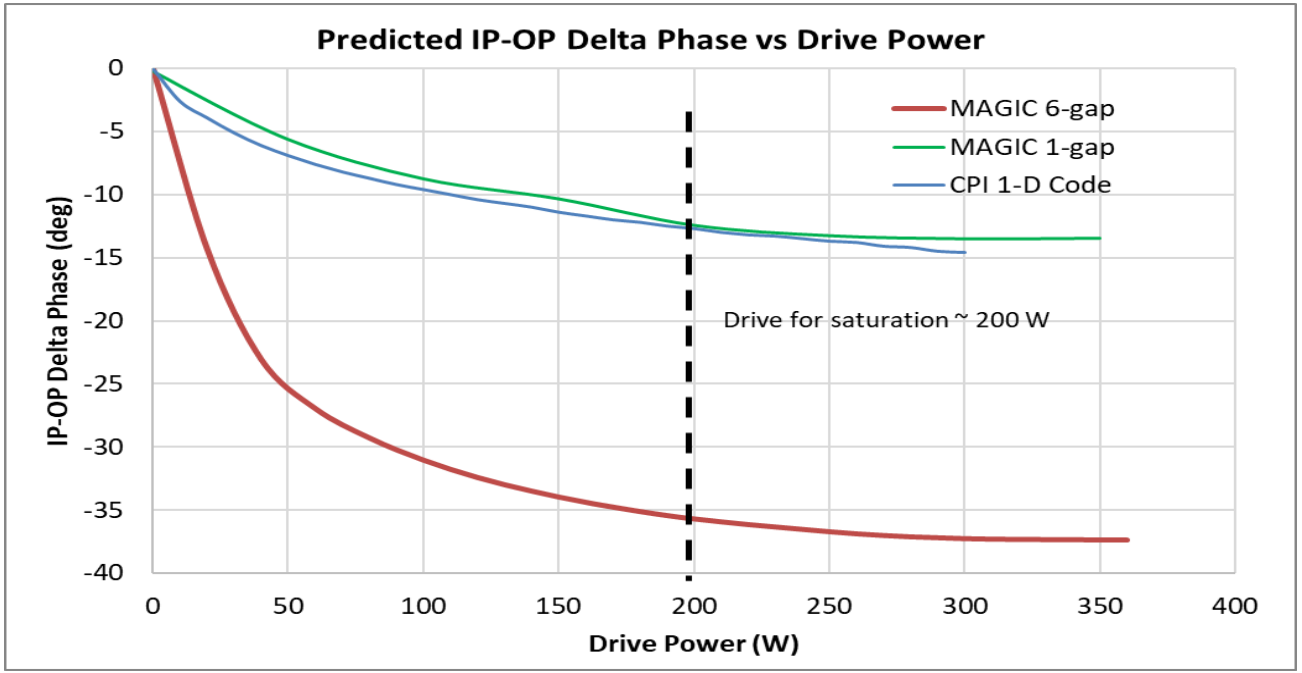
- 54 MW output is predicted with 400 kV x 202.4 A beam for 66.7% rf efficiency

Predicted Pout & RF Efficiency vs Beam Voltage





Predicted IP-OP Delta Phase vs Drive Power



Status of VKX-8311A3 Proto-type Fabrication

- Completed final design, drafting, and parts procurement
- Parts for proto-type unit have been issued to production (expect cathode due end September 2024!!!)
- Fabrication of proto-type unit is underway
- Seal-in scheduled in November 2024
- Test in February 2025

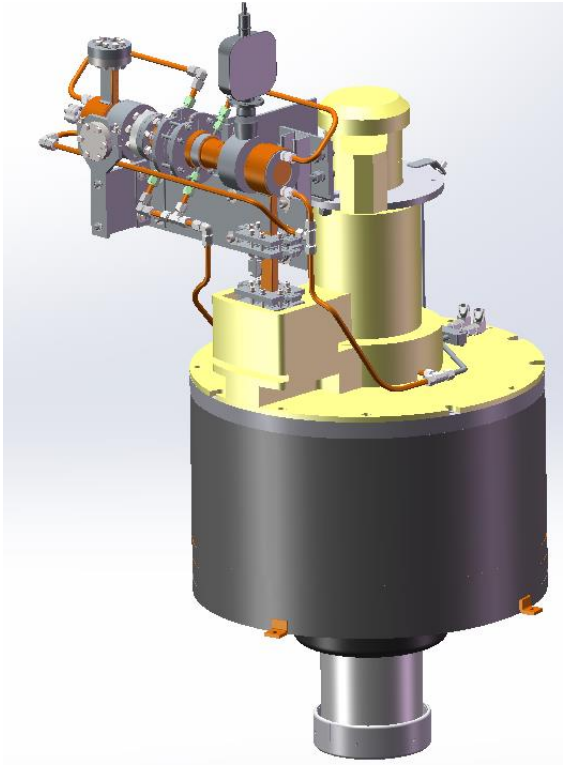
Specification of VKX-8311A3

Parameter	Spec	Design Analysis	Proto-Type Target	Units
RF Operating Frequency	11.994	11.994	11.994	GHz
Peak Power Output	≥ 50	52	52	MW
Average Power Output	≥ 7.5	7.8	7.8	kW
DC to RF Efficiency	≥ 46	65	55	%
Beam Voltage	≤ 450	400	430	kV
Beam Current	≤ 240	204	225	A
Beam Perveance	≥ 0.67	0.81	0.81	$uA/V^{3/2}$
Average Beam Power	≤ 37.8	28.6	33.8	kW
RF Power Gain	≥ 47	54	51	dB
RF Input Drive Power	≤ 1000	100	200	W
HV Video Pulse Width (FWHM)	3.5	3.5	3.5	μsec
RF Pulse Width (at -3dB)	1.5	1.5	1.5	μsec
Pulse Repetition Frequency	100	100	100	Hz
Video Duty Factor	0.035	0.035	0.035	%
RF Duty Factor	0.015	0.015	0.015	%
-3dB Bandwidth	----	> 80	---	MHz
VSWR Tolerance	1.2:1	----	1.2:1	----
X-ray	≤ 1		≤ 1	μSv / h @ 1 m
Arc Rate at Full Power	≤ 1		≤ 1	per 24 hours

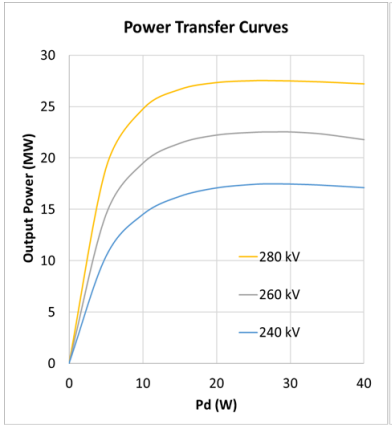
Based on the analysis results, considering the manufacturing tolerances of the prototype, and particularly the six-gap output structure, the final efficiency is projected be greater than 55%.

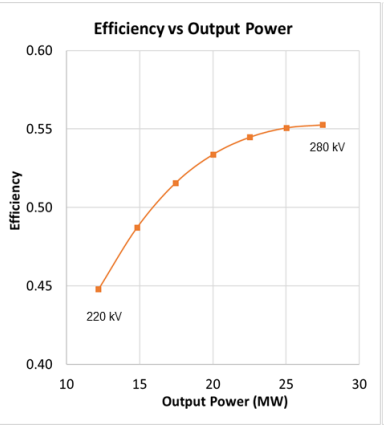
VKX-8255A
11.994 GHz, 25 MW Peak
High Efficinecy
Pulse Klystron

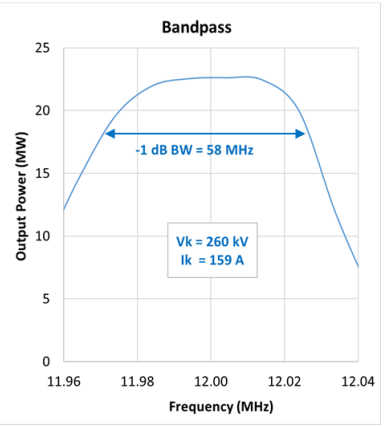
Development of VKX-8255A,11.994 GHz, 25 MW Klystron



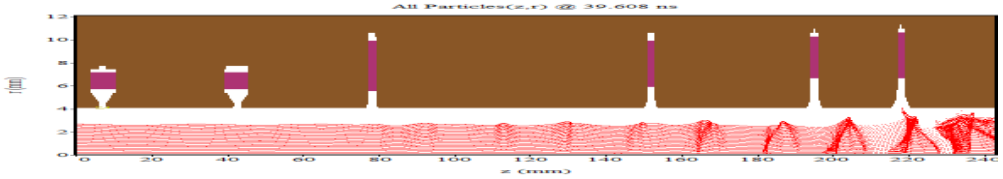
MAGIC-2D Simulation Results for VKX-8255A 25 MW, 11.994 GHz Klystron



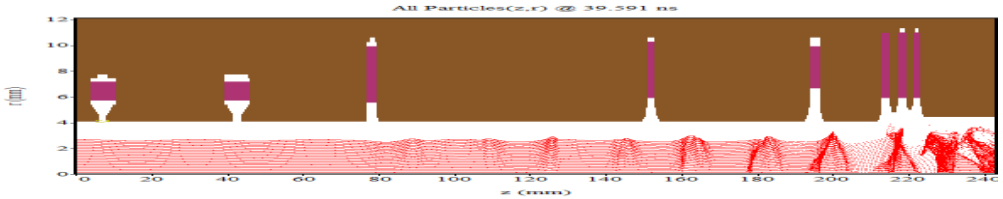




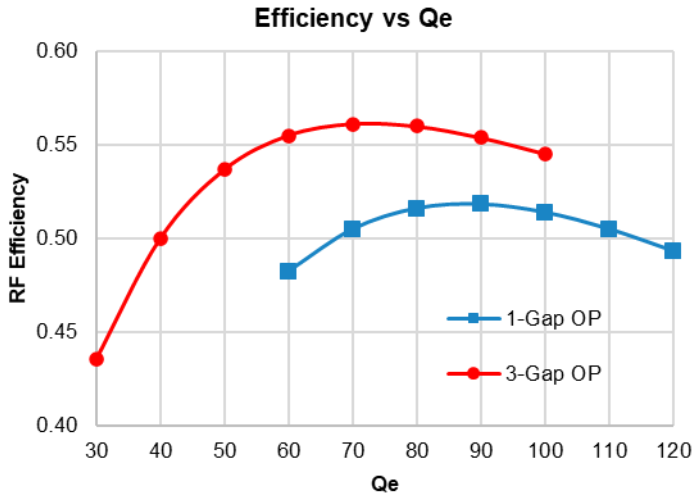
High Efficiency with 3-Gap Output



1-Gap OP



3-Gap OP

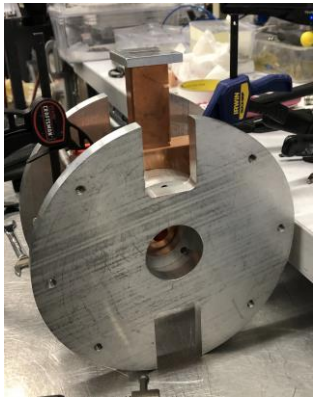


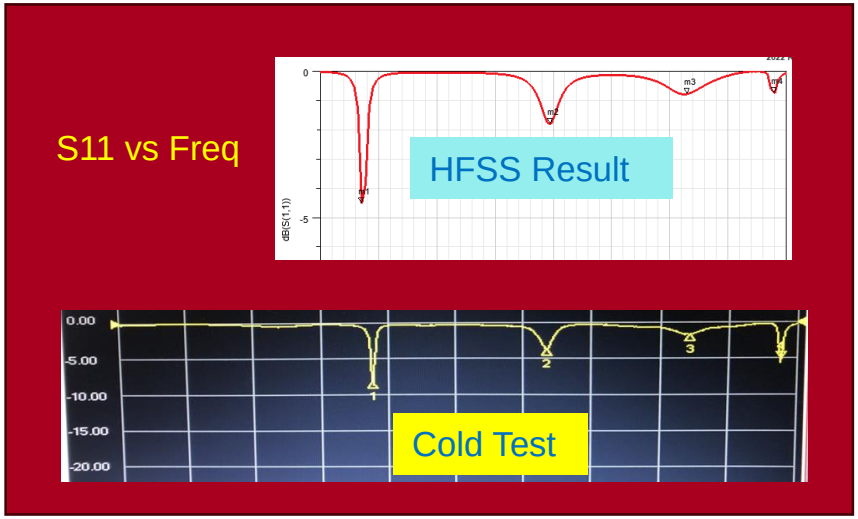
- **Studied the effect of efficiency improvement with 3-gap output using ideal beam**
- **RF efficiency improved from 52% with 1-gap output to 56% with 3-gap output**

Status of VKX-8255A Proto-type Fabrication

- Completed critical design review
- Completed final design, drafting, and parts procurement
- Parts for proto-type unit have been issued (except cathode)
- Fabrication of proto-type unit is underway
- Seal-in Jan 2025
- Test schedule TBD (late 2025)

Cold Test of 3-Gap Output of VKX-8255A (25 MW X-band)





- Initial Cold test of 3-gap output
- Good agreement with HFSS prediction
- Tuning in progress to understand the effect of minor geometry change
- Bead pull test under preparation

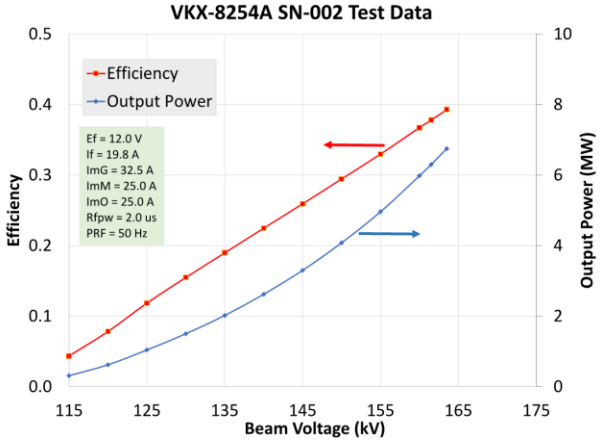
Specification of VKX-8255A

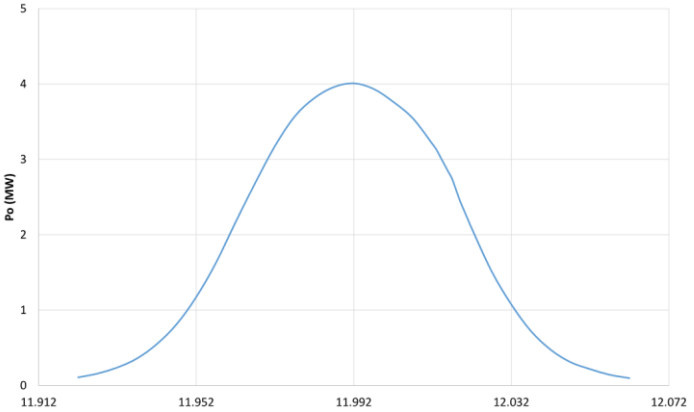
Parameter	Minimum	Nominal	Maximum	Units
RF Operating Frequency	----	11.994	----	GHz
Peak Power Output	25	26	27	MW
Average Power Output	15.0	15.6	16.2	kW
DC to RF Efficiency	40	46	50	%
Beam Voltage	----	290	320	kV
Beam Current	----	187.4	212	A
Beam Perveance	1.1	1.2	1.25	$uA/V^{3/2}$
Average Beam Power		76	95	kW
RF Power Gain	51	54	----	dB
RF Input Drive Power	----	100	200	W
Pulse Width (video)	3.5	3.5	3.5	μsec
Pulse Width (RF)	1.5	1.5	1.5	μsec
Pulse Repetition Frequency	50	400	400	Hz
Video Duty Factor	0.0175	0.14	0.14	%
RF Duty Factor	0.0075	0.06	0.06	%
Instantaneous Saturated Bandwidth < 0.2dB Power Variation	20	25	----	MHz
VSWR Tolerance	----	----	1.2:1	----
X-ray			20	μSv / h
Arc Rate at Full Power			2	per hour

VKX-8254A
11.992 GHz, 6 MW Peak Pulse Klystron

VKX8254A - 11.992 GHz, 6 MW Klystron

- SN-02 achieved 6.2 MW at 161.6 kV, 106 A, 50 Hz PRR, 1.8 us RF pulse and 37% RF efficiency
- SN-01 was retuned and achieved a higher efficiency of 42%





Summary

- Three X-band klystrons are available / under development at MPP
- VKX-8311A3 High Efficiency 11.994 GHz, 12 MW Klystron for INFN
  - Design complete
  - Fabrication underway for proto-type unit
  - Delivery to INFN in July 2025
  - VKX-8255A proto-type under fabrication
- VKX-8255A 11.994 GHz, 25 MW Klystron
  - Fabrication underway for proto-type unit
- VKX-8254A 11.992 GHz, 6 MW Klystron
  - SN-001 & SN-002 built and tested

Questions