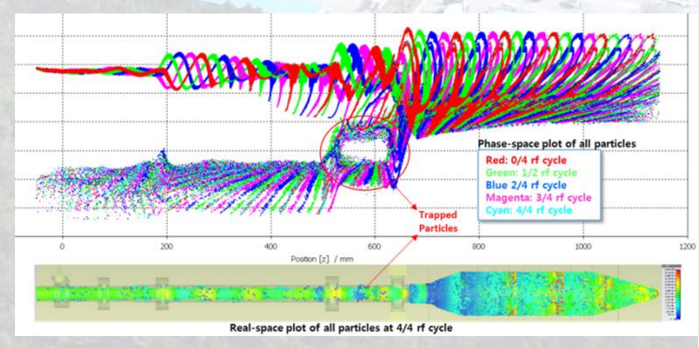
The 7th Asian School on Superconductivity and Cryogenics for Accelerators
February 1-9, 2026, Korea University Sejong Campus, Sejong, Korea

RF Source Development in Pohang Accelerator Laboratory

2026. 2. 6

Sung-Ju Park

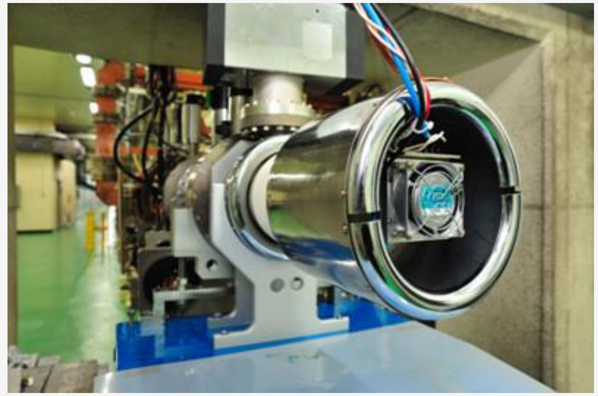
Pohang Accelerator Laboratory

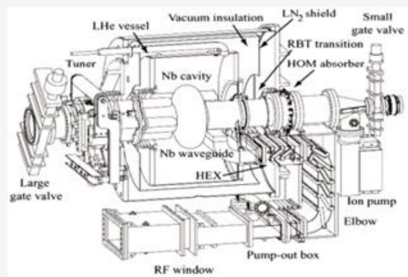


Pohang Accelerator Laboratory

Brief Tour to the PAL-XFEL

Brief Tour to the PLS-II





Energy Conversions in Synchrotron Light Source

SUN
(Fusion Energy)
→ **Power Plants in Earth**
(Fossil Energy)
→ **High Voltage Power Supply**

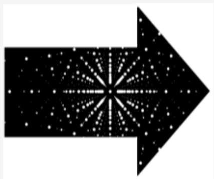
Supernova Explosions
Neutron Star Mergers
(Nuclear Binding Energy)
→ **Nuclear Power Plants**
($E = mc^2$)

High Voltage Power Supply ↓

Klystron
(Electron Kinetic Energy → Electromagnetic Energy
←
Accelerating Structure
(Electromagnetic Energy → Electron Kinetic Energy)
←
Undulator
(Electron Kinetic Energy → X-ray Energy)

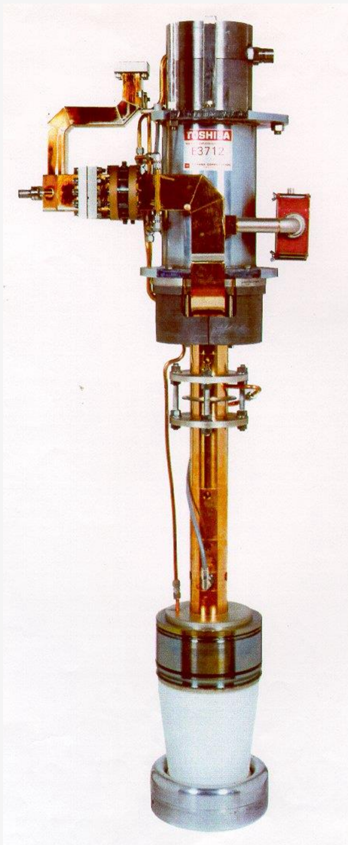
↓

Experimental Stations



SCIENCE

Klystrons in Pohang Accelerator Laboratory

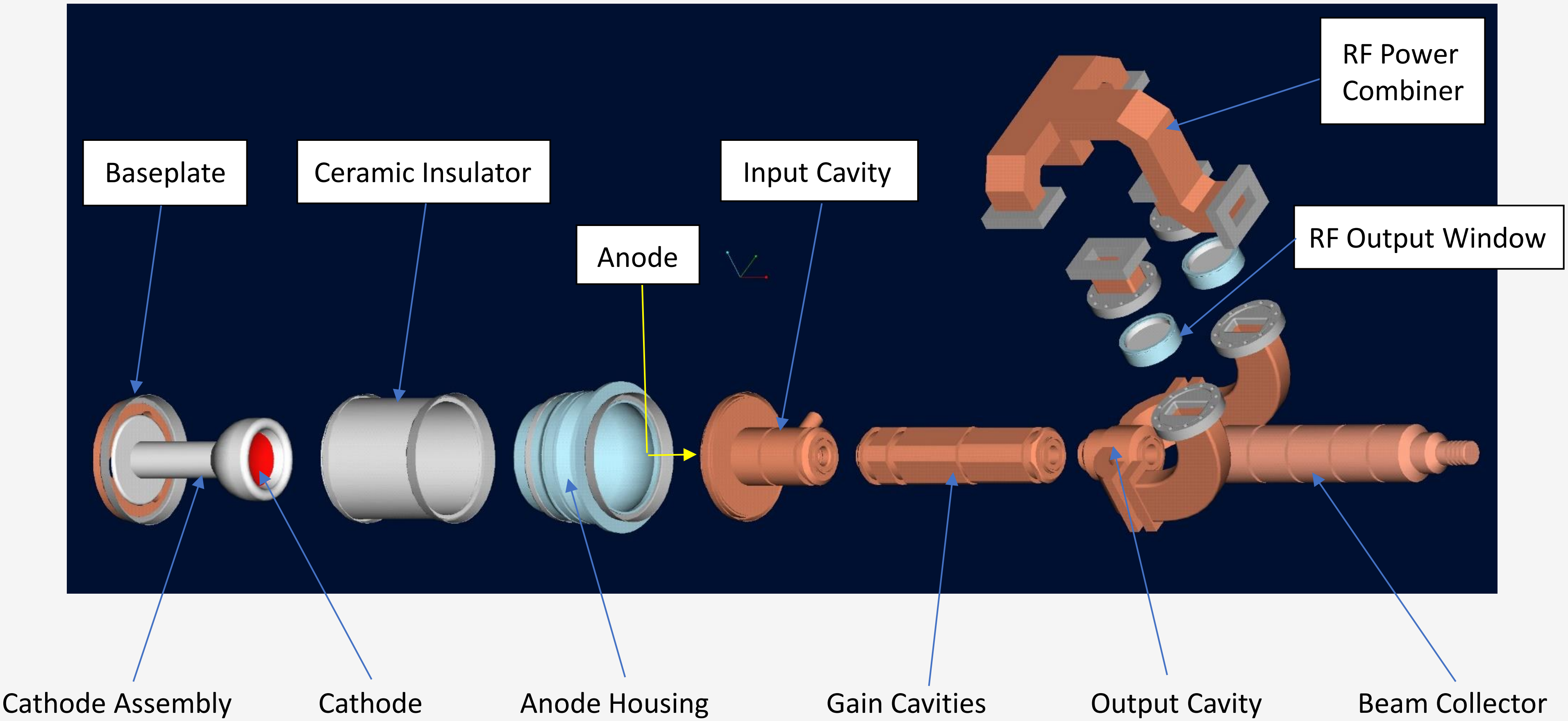


Toshiba E3712/E37320		cf) SLAC5045
2,856	Frequency (MHz)	2,856
80	Peak Output Power (MW)	65
400	Beam Voltage (kV)	350
2	Microperveance	2
4	Pulse Width (μs)	3.5
55	Gain (dB)	50
19	Average Output Power (kW)	45
42	Efficiency	45

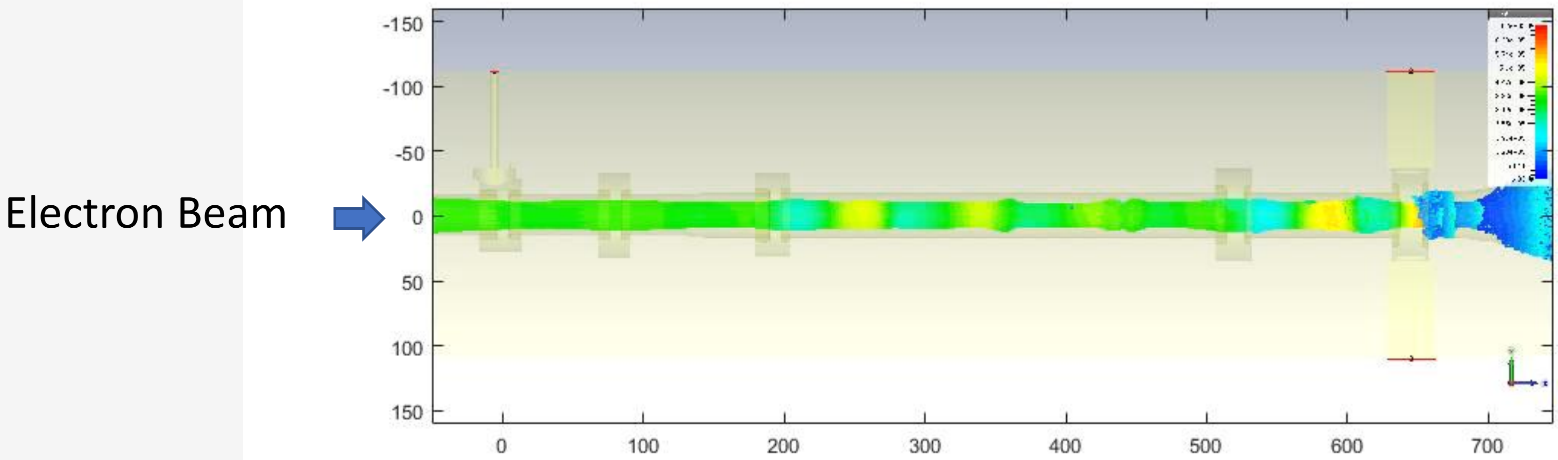
3D View of Klystron

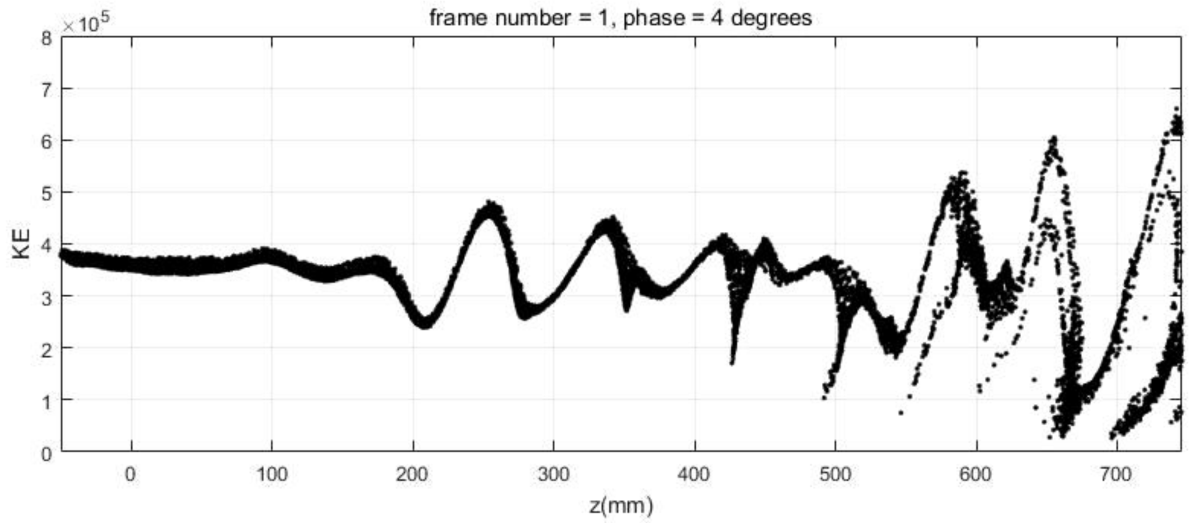
Exploded View of Klystron in PAL

- Focusing Electromagnet not Shown -



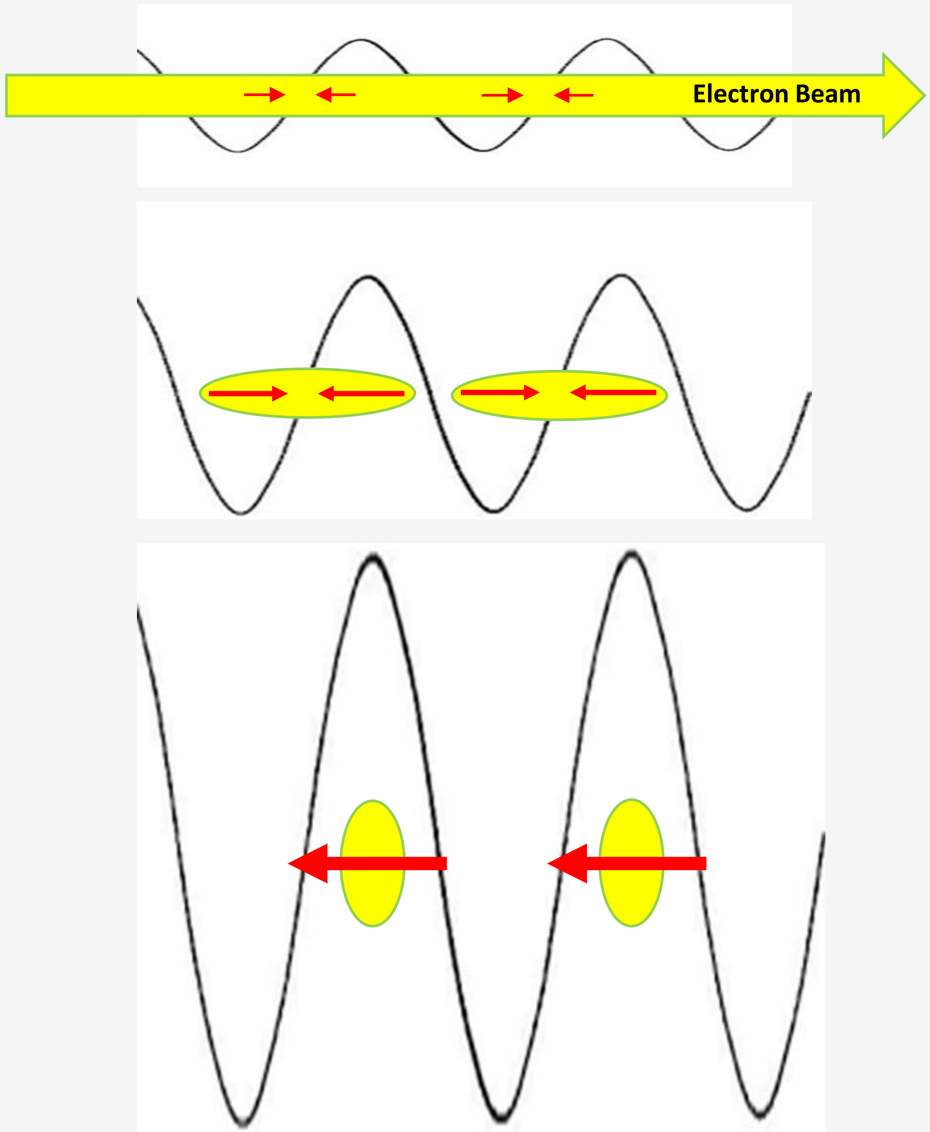
Space-Charge Wave in Klystron





Beam-Field Interaction in a Klystron

Input Cavity → Velocity Modulation



Density Modulation

Gain Cavities → Bunching

Density Modulation

Output Cavity → Partcle Kinetic Energy
→ Wave Energy

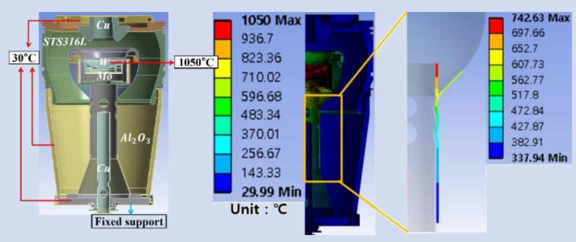
Cavity Tuning and Impedances

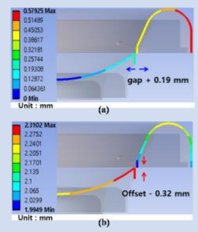
Cav. No.		1	2	3	4	5
f (MHz)		2,856	2,862	2,871	2,951	2,856
R/Q		64.5	65.6	70.6	86.9	111.2
Q_L		175	2,000	2,000	2,000	17
β		10				120
Z_{cav} (ohms)	amplitude	11,288	15,503	6,714	1,306	1,835
	angle	0.00	1.45	1.52	1.56	0.00
i_{cav} (A)*		0.2	1.7	27	270	296
V_{cav} (V)	amplitude	2,258	26,356	181,265	352,676	543,101
	angle	0.00	1.45	1.52	1.56	0.00
P_w (W)		226	2,647	116,349	357,826	663,126
P_e (W)						80,378,918
Avg. P_w (W)	4 μs, 60 Hz	0.05	1	28	86	159
Avg. P_e (W)						19,291

- 1st harmonic of the induced beam current to each cavity.

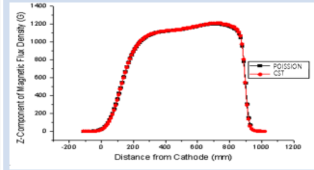
Electron Gun Design

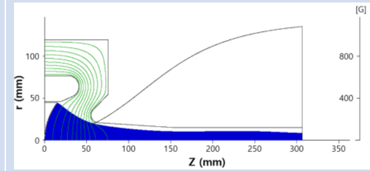
Modelling	Thermal Analysis	Structural Analysis

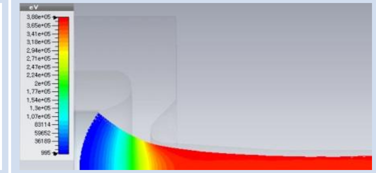




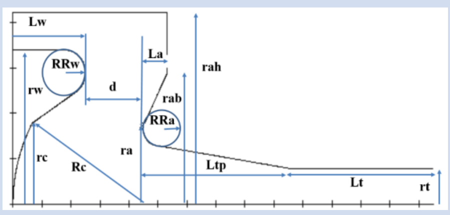
B-Field Profile	EGUN Simulation	CST-TRK Tracking Simulation







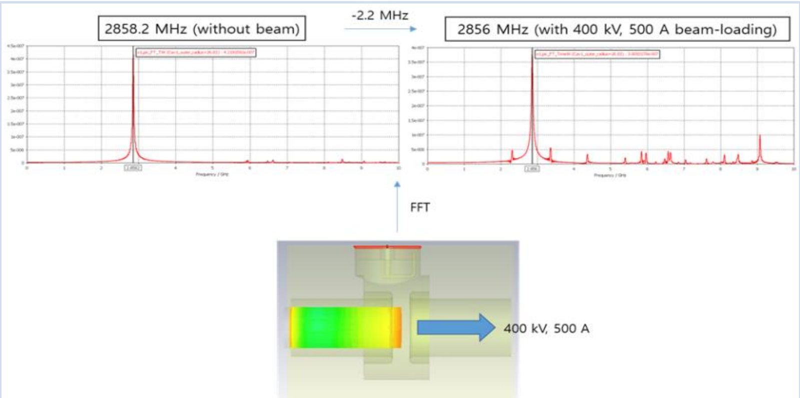
Design Parameters



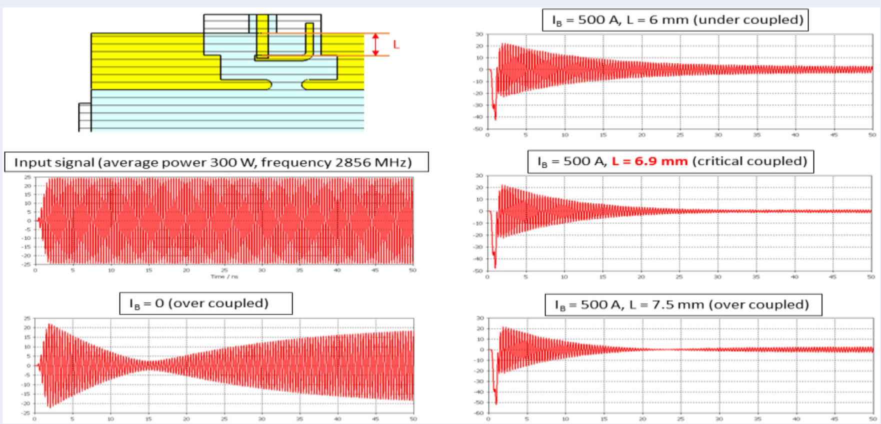
	Cold [mm]	Hot [mm]
r_c	44.57	44.77(+0.2)
R_c	73.69	74.03(+0.34)
r_w	76.5	77.08(+0.58)
L_w	40.91	40.83(-0.08)
RR_w	13	13.05(+0.05)
d	16.58	14.42(-2.16)

Input Cavity Design

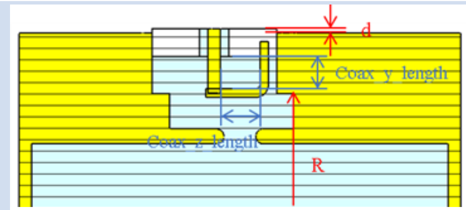
Beam Loading Effect



- Coupler insertion depth vs. RF Reflection Waveform



Q_e with various Coupler parameters



R	d	PIC solver: Freq. (beam-loading)	PIC solver: Freq. (no beam-loading)	F solver: Freq. (no beam-loading)	Q_e
26.81	0.5	2857	2859.4	2858.8	175.35
26.82	0.5	2855.7	2858.2	2857.6	175.9
26.83	0.5	2854.5	2857	2856.4	176.27
26.82	0.6	2855.7	2858	2857.2	180.55
26.82	0.7	2855.4	2857.8	2856.8	184.63

Cavity Design

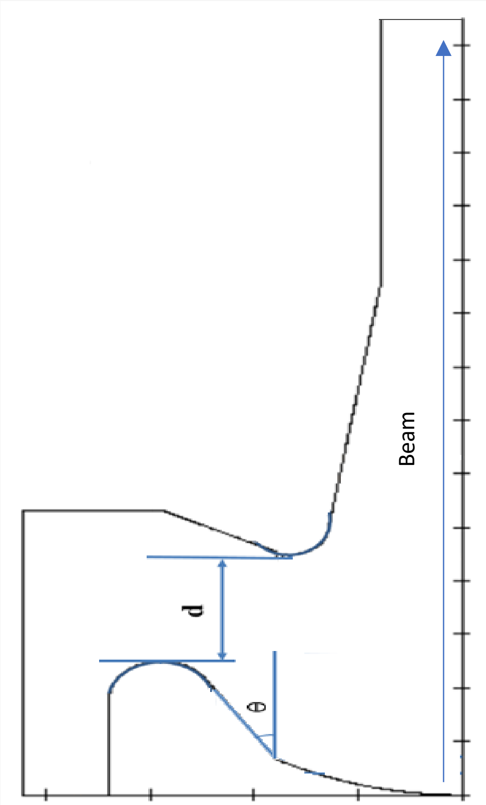
Cavity HOM Frequencies

Cavity		R [mm]	L [mm]	Aspect ratio (2*R/L)	f1 [MHz]	f2 [MHz]	f3 [MHz]	Qe
Input	Initial	26.40	29.70	1.778	2910	4299.2	5943.8	159.08
	Opt.	26.84	29.70	1.807	**2855.5**	4268	5943.8	176.73
2nd	Initial	31.00	22.20	2.793	2855.2	4371.2	-	
	Opt.	30.95	22.20	2.788	**2860.4**	4375.6	-	
3rd	Initial	31.00	24.85	2.495	2855.6	4208.4	5453.2	
	Opt.	30.88	24.85	2.485	**2868.8**	4219.2	5452.8	
4th	Initial	33.70	25.45	2.648	2954.8	4280.4	-	
	Opt.	33.76	25.45	2.653	**2948.6**	4274.8	-	
Output	Initial	35.00	25.00	2.8	2877.4	3879.2	5850	20.23
	Opt.	35.26	25.00	2.821	**2854.6**	3860.3	5843.8	20.69

Cavity Fabrication Dimensions

Cavity		Initial	Optimized	
			Before Tuning	After Tuning
Input	R [mm]	26.40	**26.84**	-
	L [mm]	29.70	**29.70**	-
2nd	Res. Freq. [MHz]	2910	**2855.5**	**2858**
	R [mm]	31.00	**30.95**	-
	L [mm]	22.20	**22.20**	-
	Res. Freq. [MHz]	2855.2	**2860.4**	**2862**
3rd	R [mm]	31.00	**30.88**	-
	L [mm]	24.85	**24.85**	-
	Res. Freq. [MHz]	2855.6	**2868.8**	**2871**
4th	R [mm]	33.70	**33.76**	-
	L [mm]	25.45	**25.45**	-
	Res. Freq. [MHz]	2954.8	**2948.6**	**2951**
Output	R [mm]	35.00	**35.26**	-
	L [mm]	25.00	**25.00**	-
	Res. Freq. [MHz]	2877.4	**2854.6**	**2856**

Tolerances for E-Gun Dimensions



Parameters	Sensitivity	Nominal value	Tolerance (Including safety margin)
Perveance(μP)		2.0 μpervs	± 0.1 μpervs
d → μP	-0.107 μpervs/mm		± 0.1 mm
θ → μP	0.048 μpervs/deg		± 0.1 deg
Beam radius(r_b)		11 mm	± 0.3 mm
d → r_b	-0.58 mm/mm		± 0.1 mm
θ → r_b	0.6 mm/deg		± 0.1 deg
Waist position(Z_w)		160 mm	± 1.0 mm
d → z_w	2.3 mm/mm		± 0.1 mm
θ → z_w	1.08 mm/deg 0.6 mm/deg		± 0.1 deg

Tolerances for Cavity Dimensions

Output Power Sensitivities (%), Nominal Operating Condition : 400 kV, 500 A, 84 MW, 42%

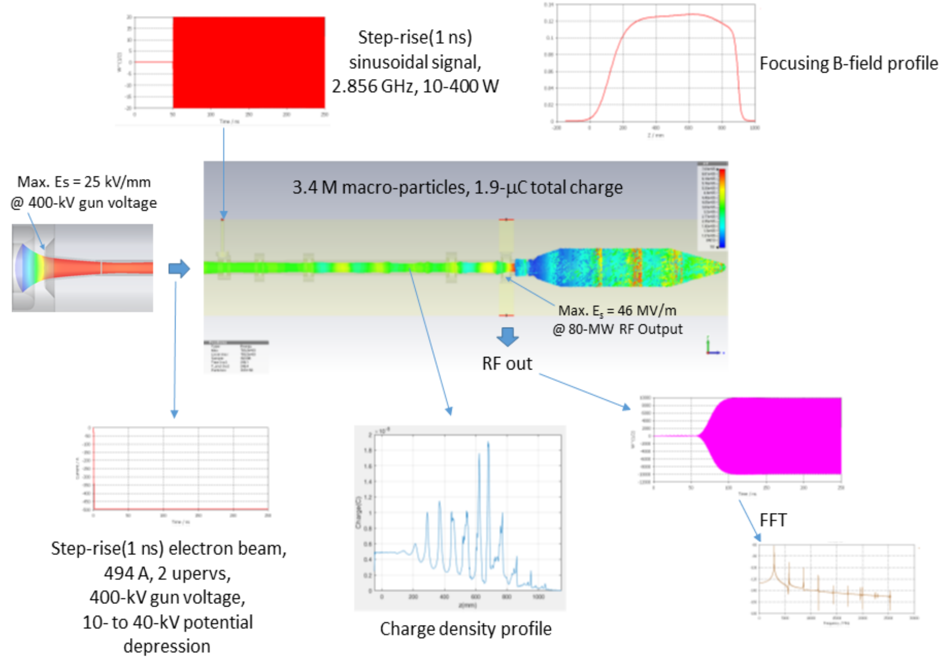
Cavity No.	Frequency Change by -2~+2 MHz	Position Change by -2~+2 mm	Q_L Change by ±35 (input) or ±3.5 (output)
1	-1.28 ~ -0.12	+0.23 ~ +0.47	+10.5 ~ +10.97
2	+3.73 ~ -6.3	-1.87 ~ +1.28	
3	+3.97 ~ -5.72	-1.05 ~ +0.93	
4	+1.52 ~ -1.75	+0.7 ~ -0.7	
5	+0.12 ~ -0.12	-0.47 ~ +0.47	+1.98 ~ +13.65

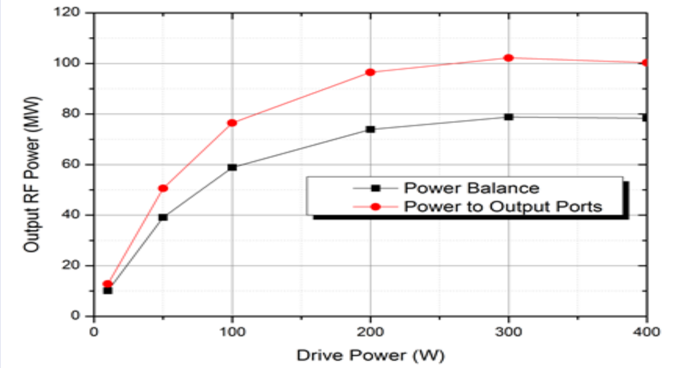
Beam-Loss (on Output Cavity Wall) Sensitivities (%), Nominal Loss : 0.573%

Cavity No.	Frequency Change by -2~+2 MHz	Position Change by -2~+2 mm	Q_L Change by ±35 (input) or ±3.5 (output)
1	-10.65 ~ -6.28	-7.33 ~ +22.69	+508.03 ~ +513.96
2	+153.75 ~ -16.93	-26 ~ +9.08	
3	+217.28 ~ -23.39	-31.59 ~ +15.36	
4	+26 ~ -24.08	-8.03 ~ +16.06	
5	-7.5 ~ -2.62	-25.3 ~ +34.2	+27.57 ~ +1106.81

PIC Simulations (1/3)

Simulation Setup (CST-PIC)	Transfer Characteristic

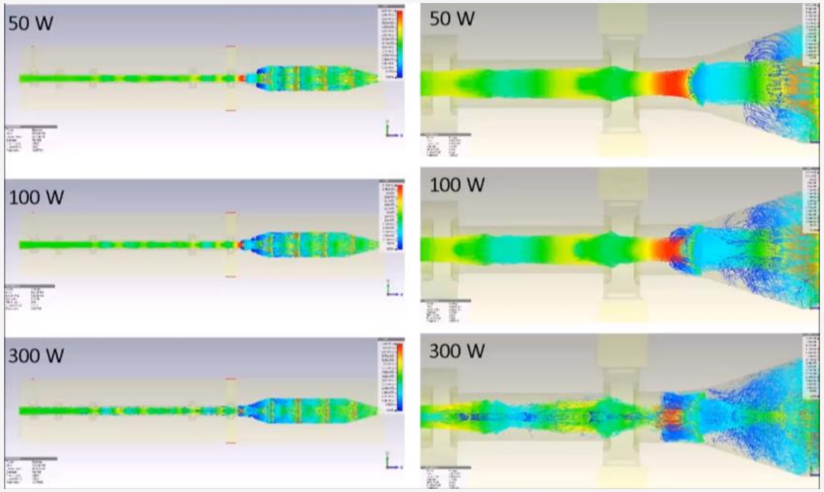




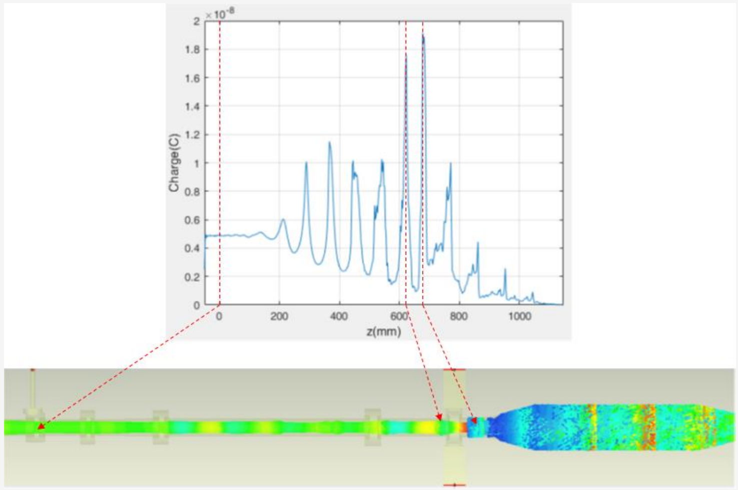
Drive RF Power (W)	RF Output Power (MW)	
	Power Balance	Wave Power to Output Ports
10	10.1	12.8
50	39.1	50.6
100	58.9	76.5
200	73.9	96.5
300	78.8	102.2
400	78.3	100.3

- Power balance method : RF Output Power = Injected Beam Power – Kinetic Power Deposited to model boundaries

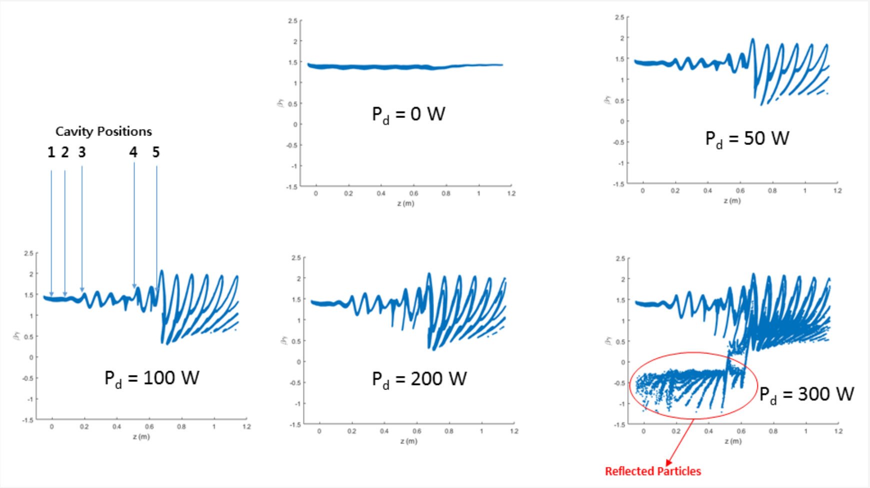
PIC Simulations (2/3)



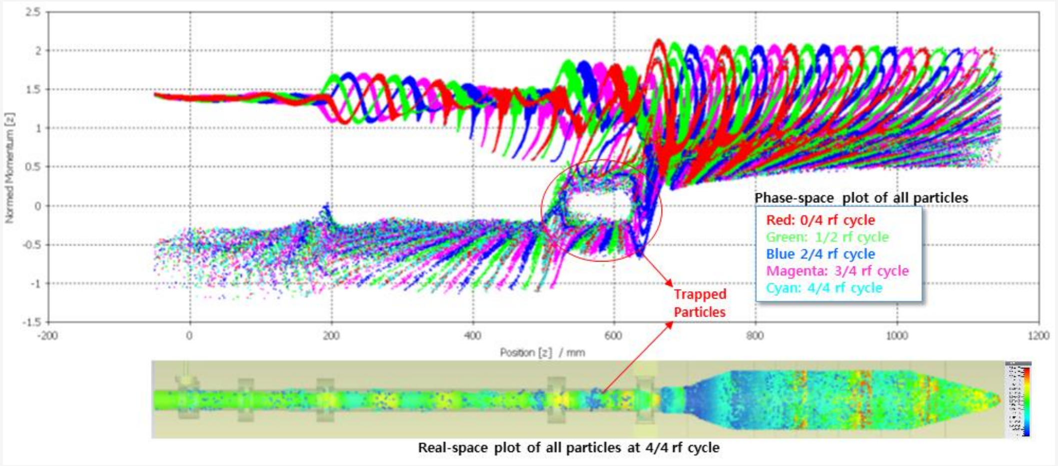
Distributions of Particle Positions and Energies vs. Drive Power
Color represents particle energy : 680 keV (Red) – 350 keV (Green) – 2 keV (Blue)



Longitudinal Distribution of Charge Density



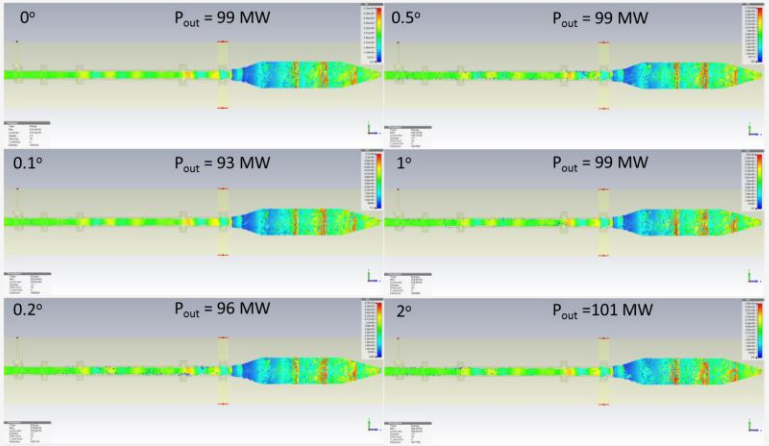
Particle Distribution in Longitudinal Phase Space



PIC Simulations (3/3)

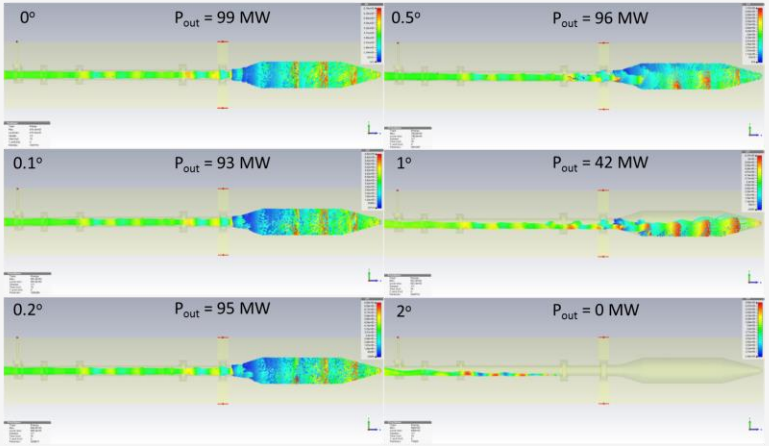
Effect of Focusing-Field Mis-alignment on Output RF Power

Klystron Beam Profiles with Different Cathode Tilt Angles



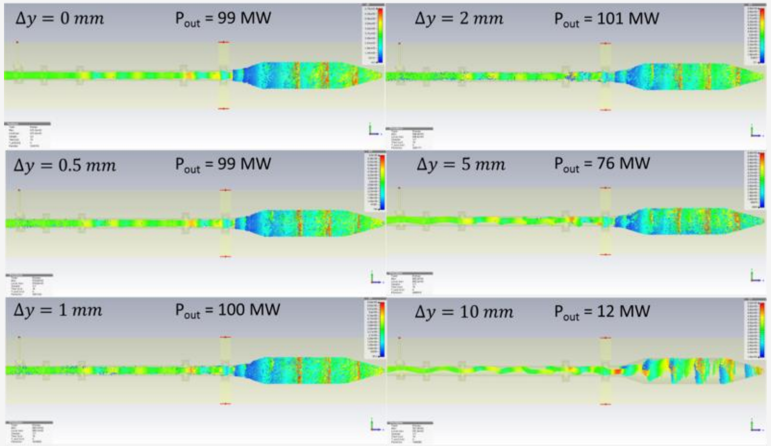
Cathode tilt alone does not have significant impact on klystron performance

Klystron Beam Profiles with Different Magnet Tilt Angles



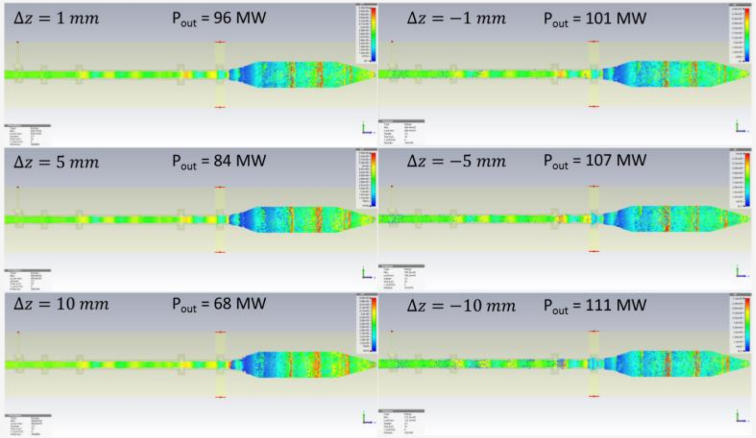
Magnet tilt should be < 0.1 deg.

Klystron Beam Profiles with Different Magnet Offsets(y)



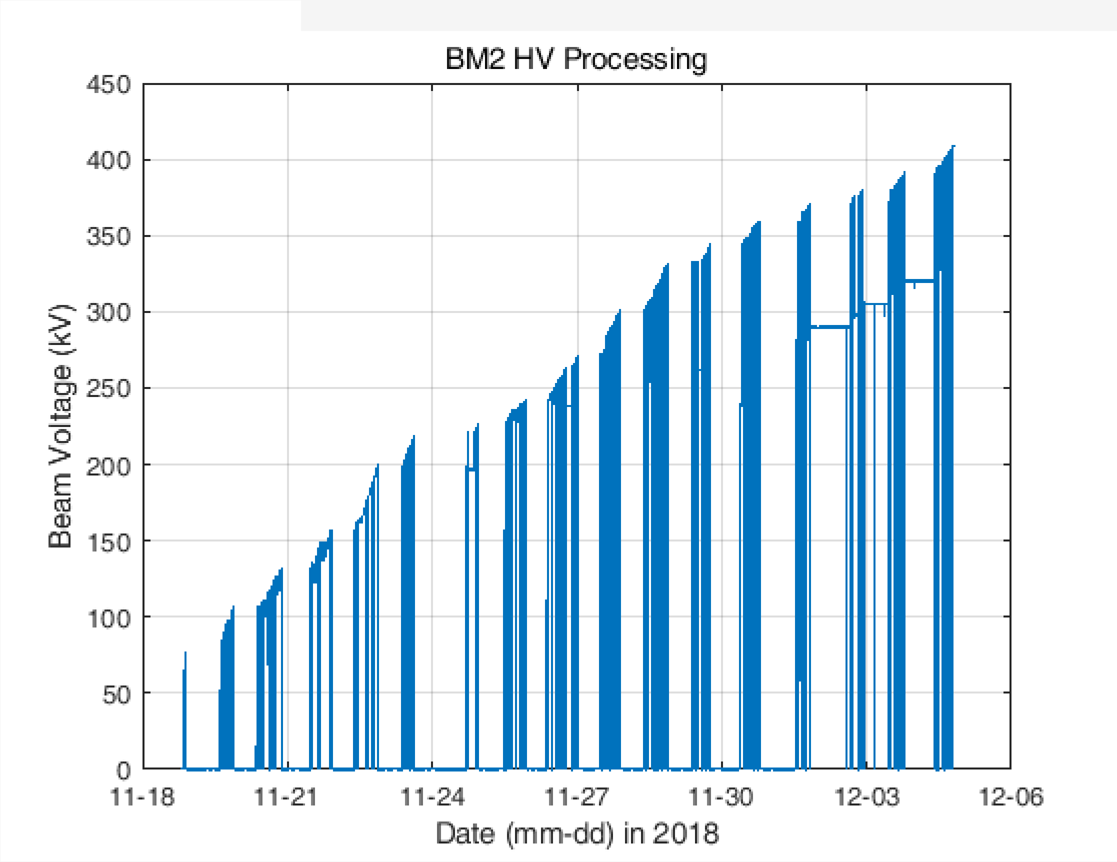
Slight P_{out} increase is observed with 1~2 mm offsets. But it accompanies increased electron reflection at the output cavity (due to asymmetric beam-cavity coupling). Magnet offset should be < 0.5 mm.

Klystron Beam Profiles with Different Magnet Offsets(z)



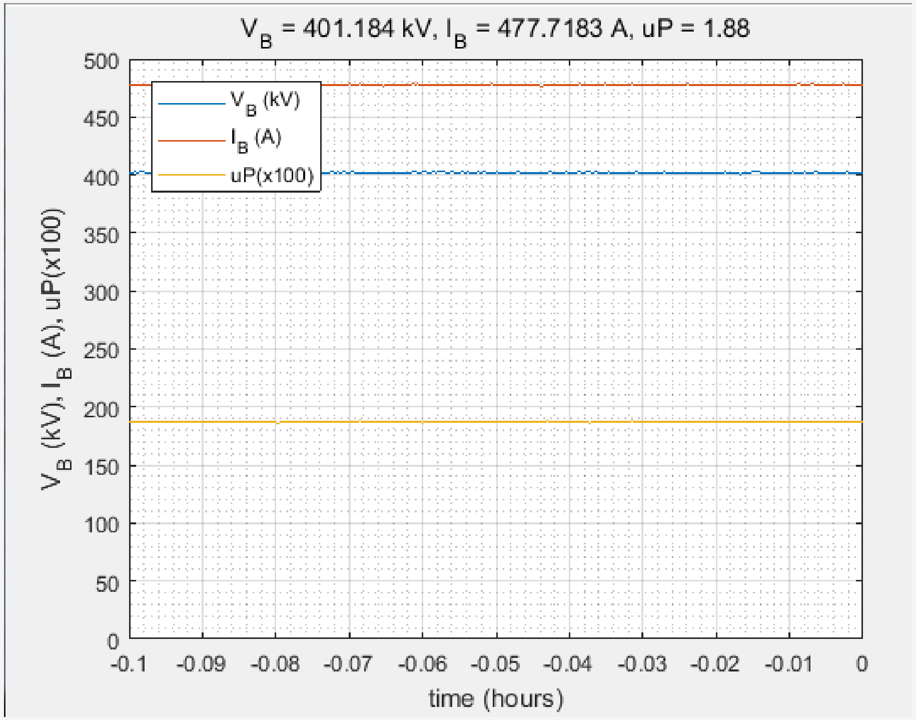
Longitudinal offset, if no transverse offsets are accompanied, would be useful for controlling beam size.

Arrival of Klystron to PAL
(2018.11.1)



60 Hz operation of BM2 gun

($V_{inverter}$ = 45 kV)



Collector cooling status:

- inlet temp. = 30.2 ^{o}C
- outlet temp. = 48.9 ^{o}C
- water flow ≅ 50 l/m

Arcing Spots in Cathode Assembly

1 spot on maximum E-field position

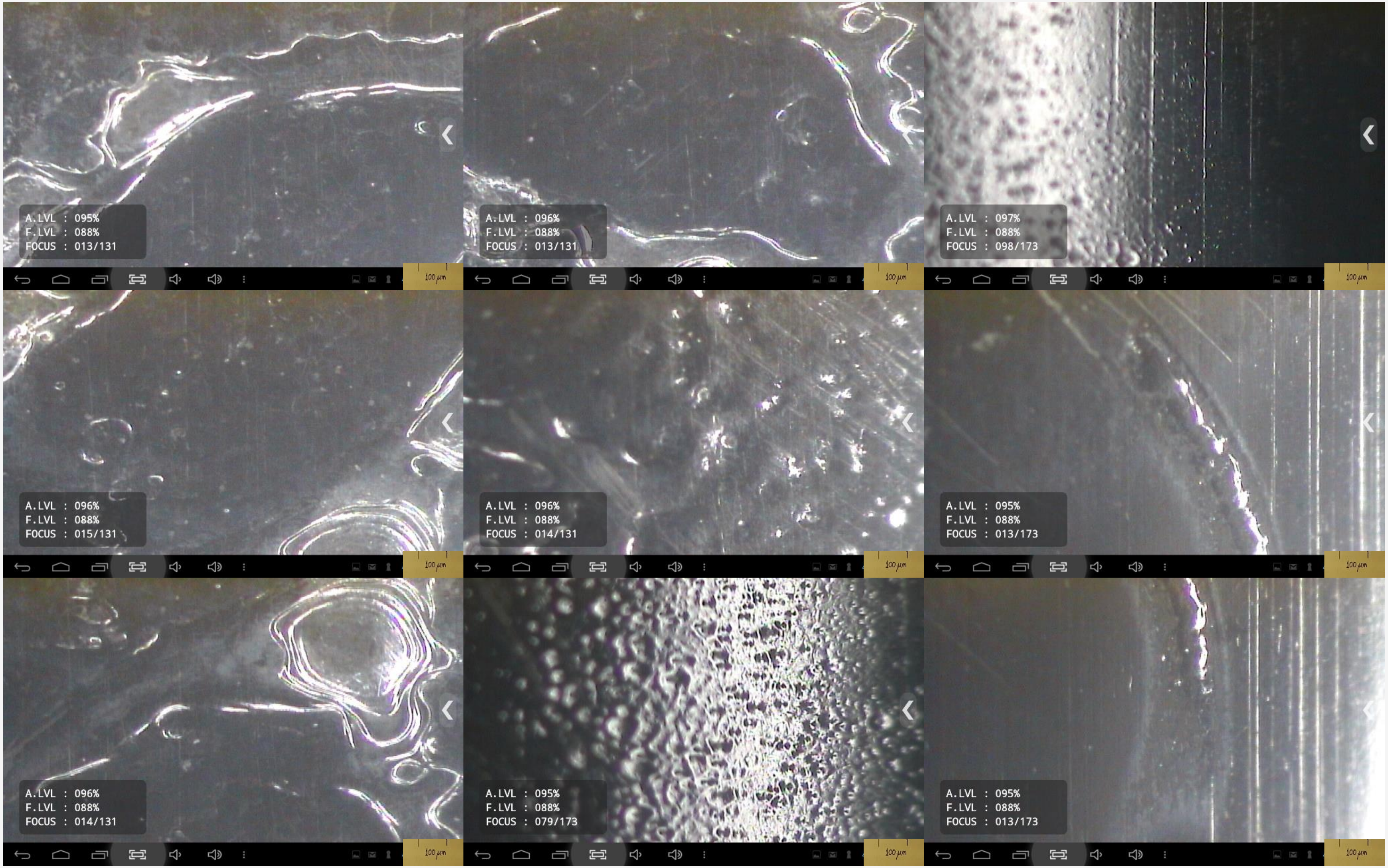
1 spot on inner surface

12 spots on outer surface

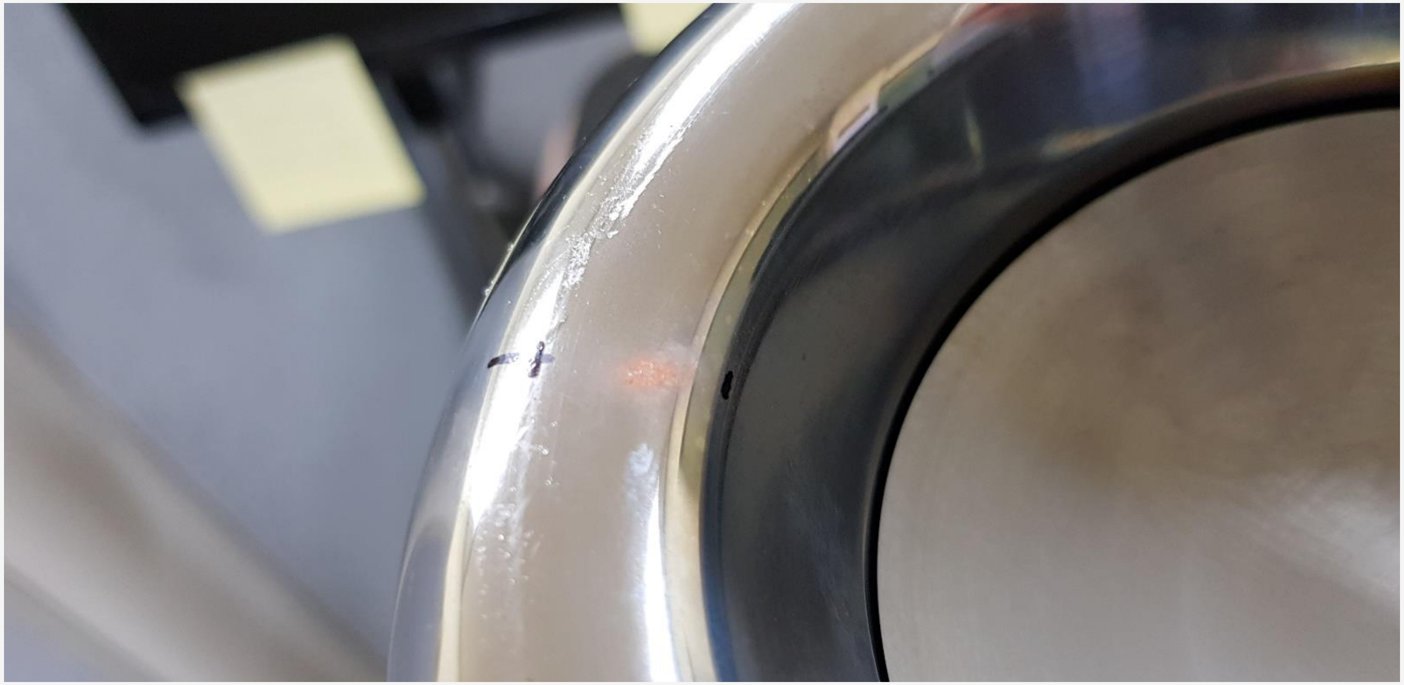
Arcing Spots in Cathode Assembly

Arcing Spot #2

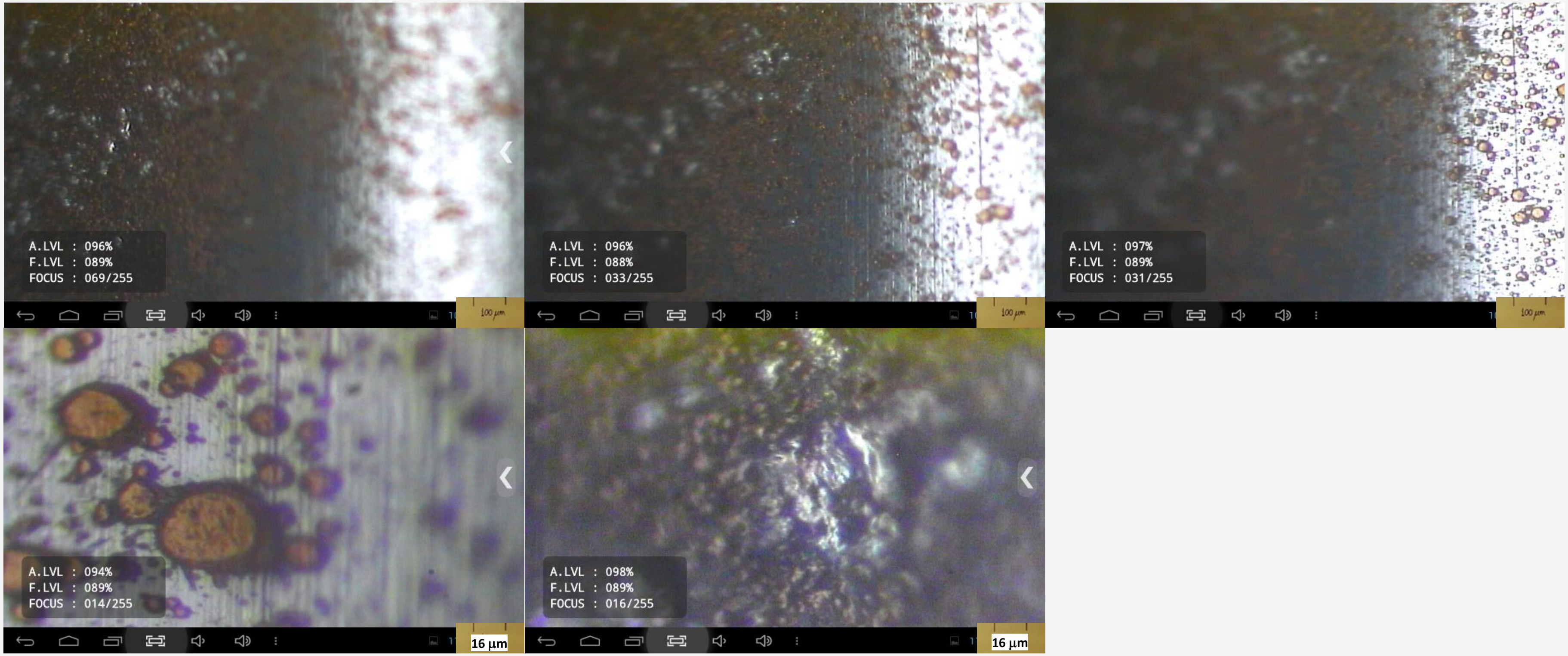
Close-Up View of Arcing Spot #2



Arcing Spot #13

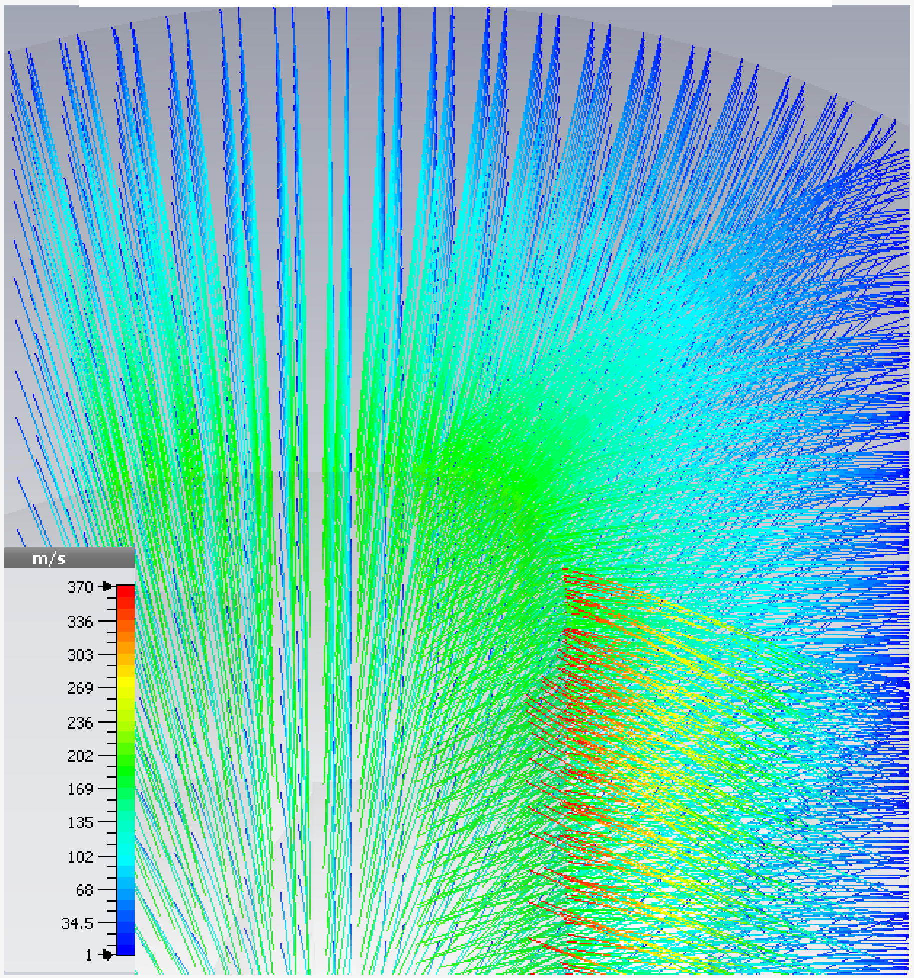


Close-Up View of Arcing Spot #13

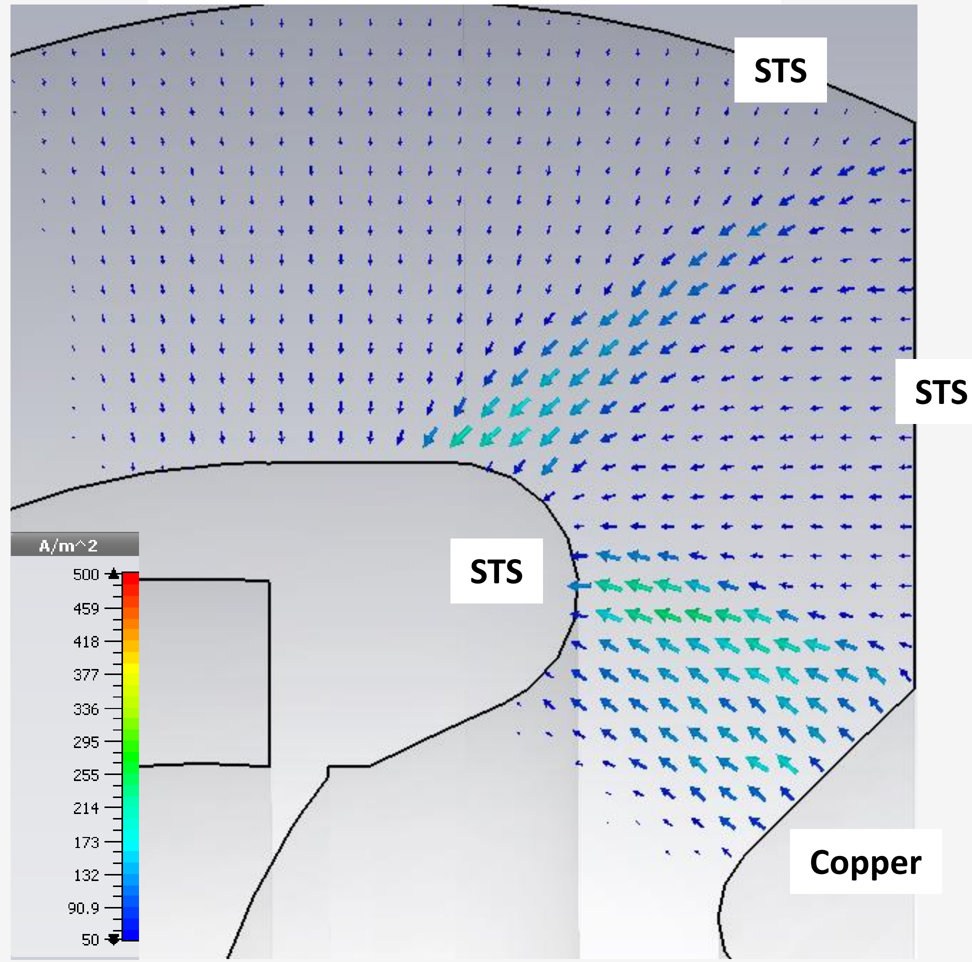


Arcing Mechanism of Spot #1 to 12 (1/2)

Microparticle Trajectories (Velocity)

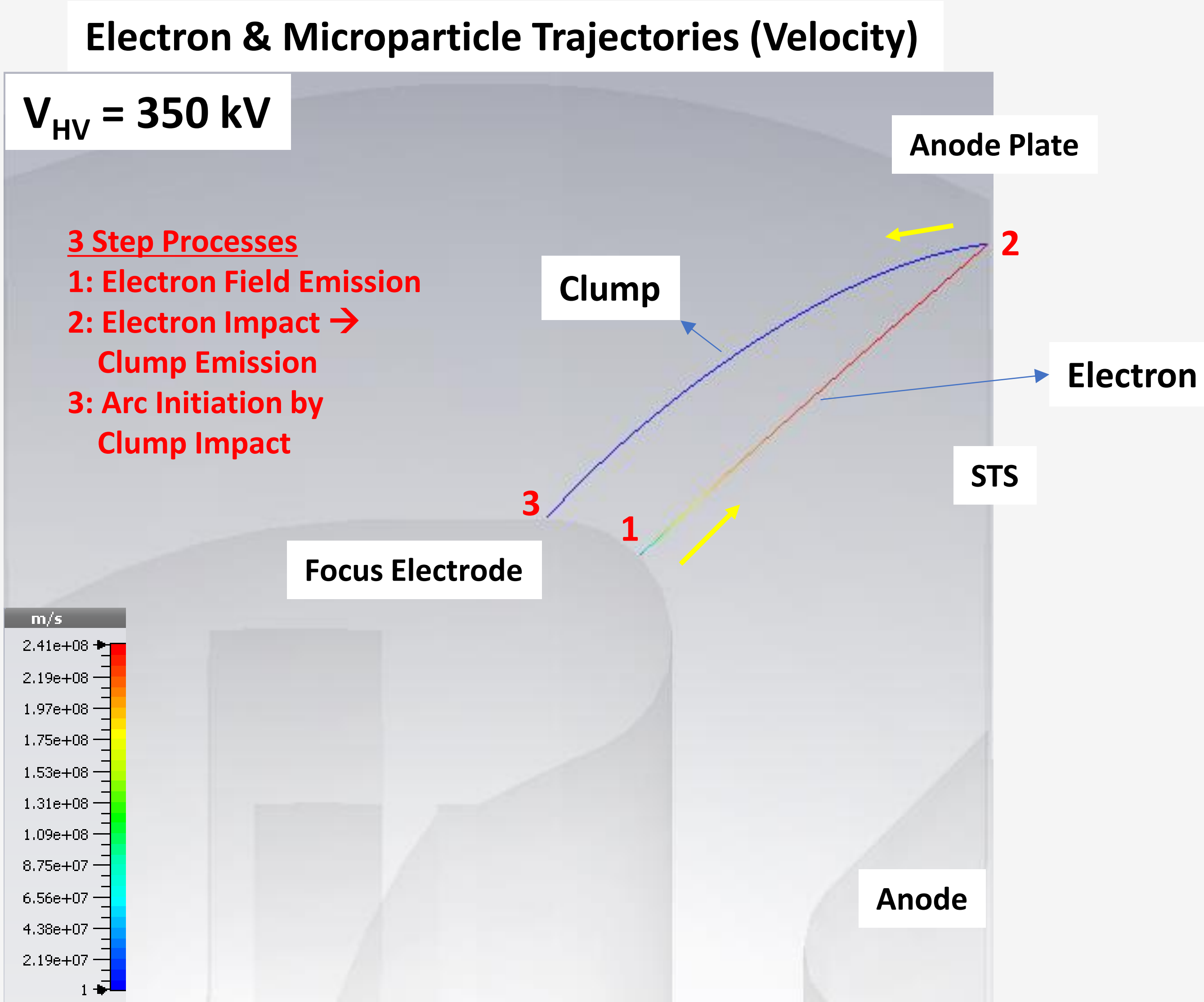


Microparticle Current Density

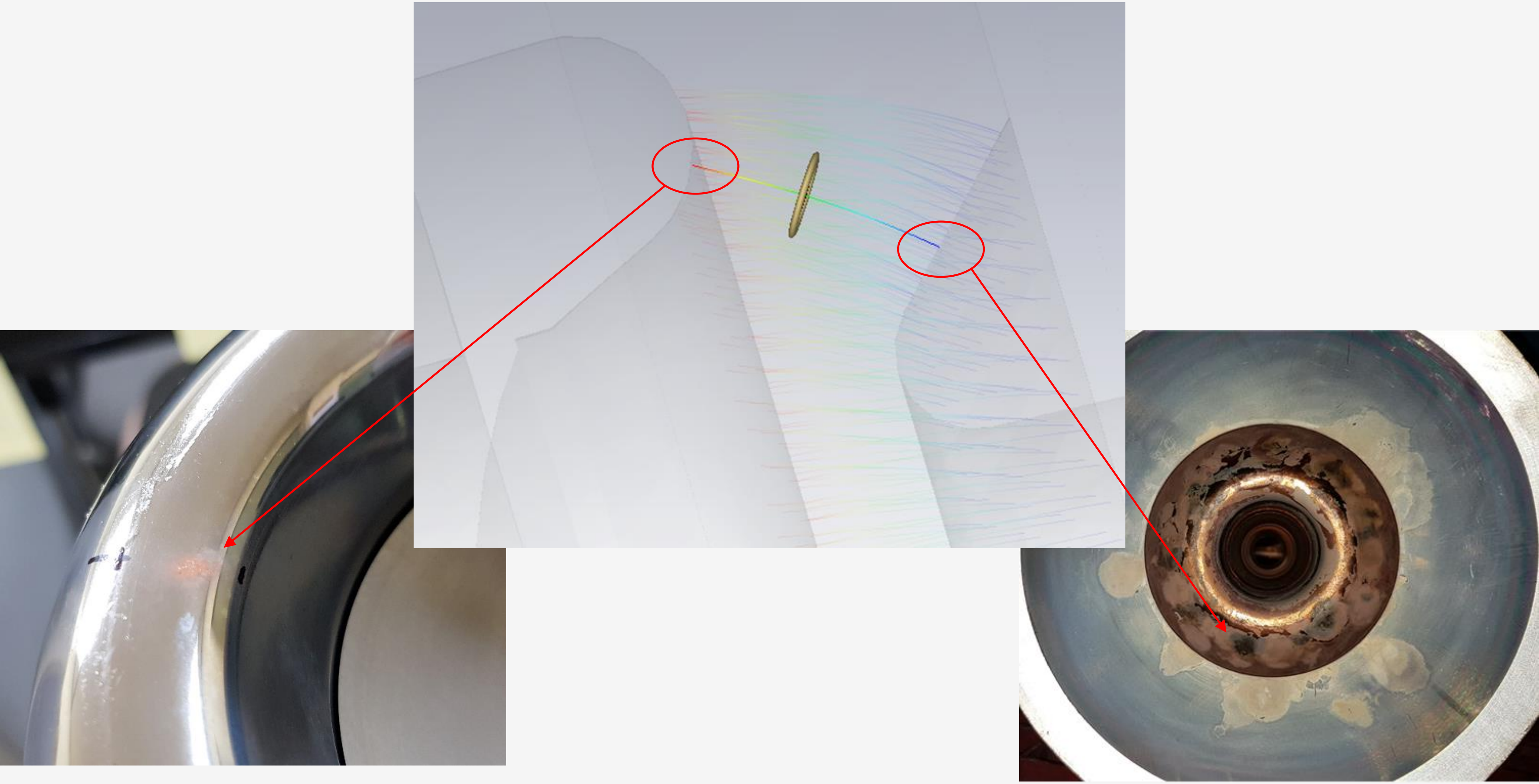


V_b = 350 kV

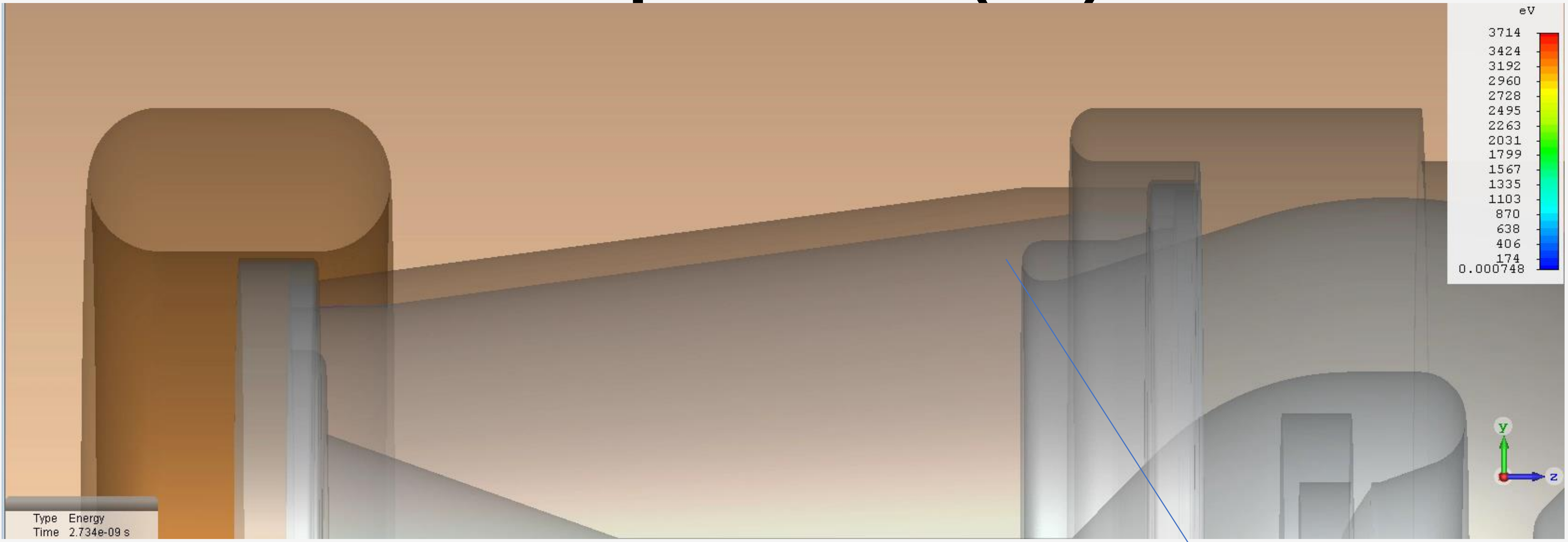
Arcing Mechanism of Spot #1 to 12 (2/2)

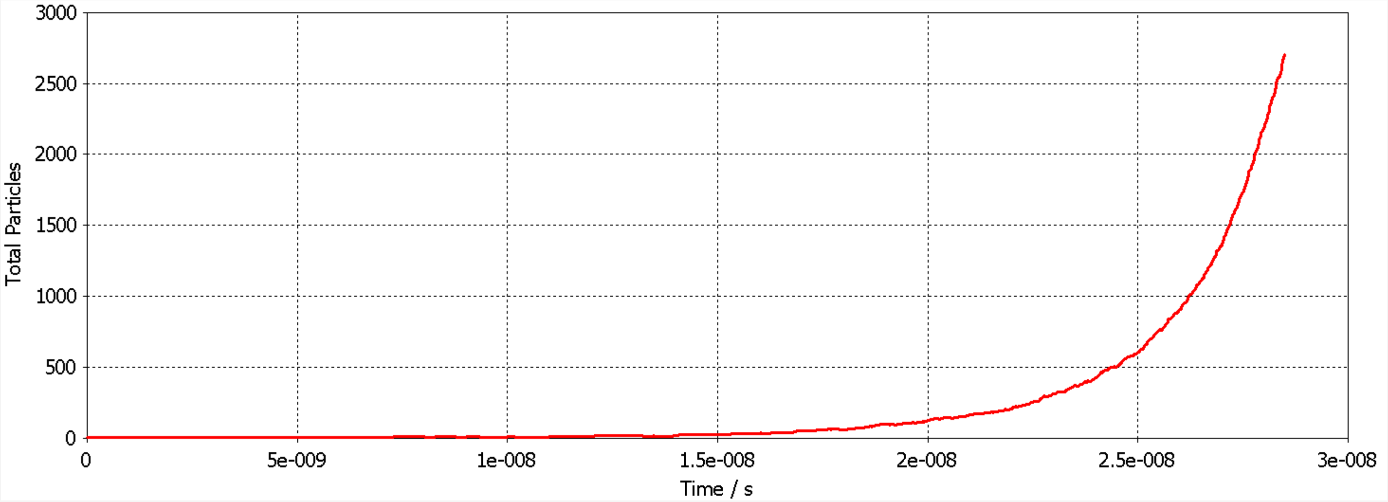


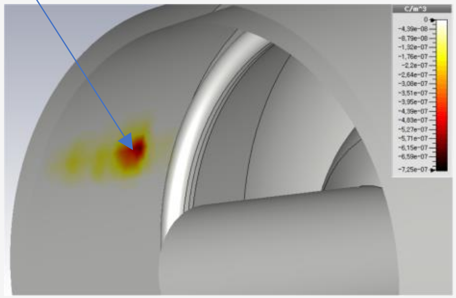
Arcing Mechanism of Spot #13



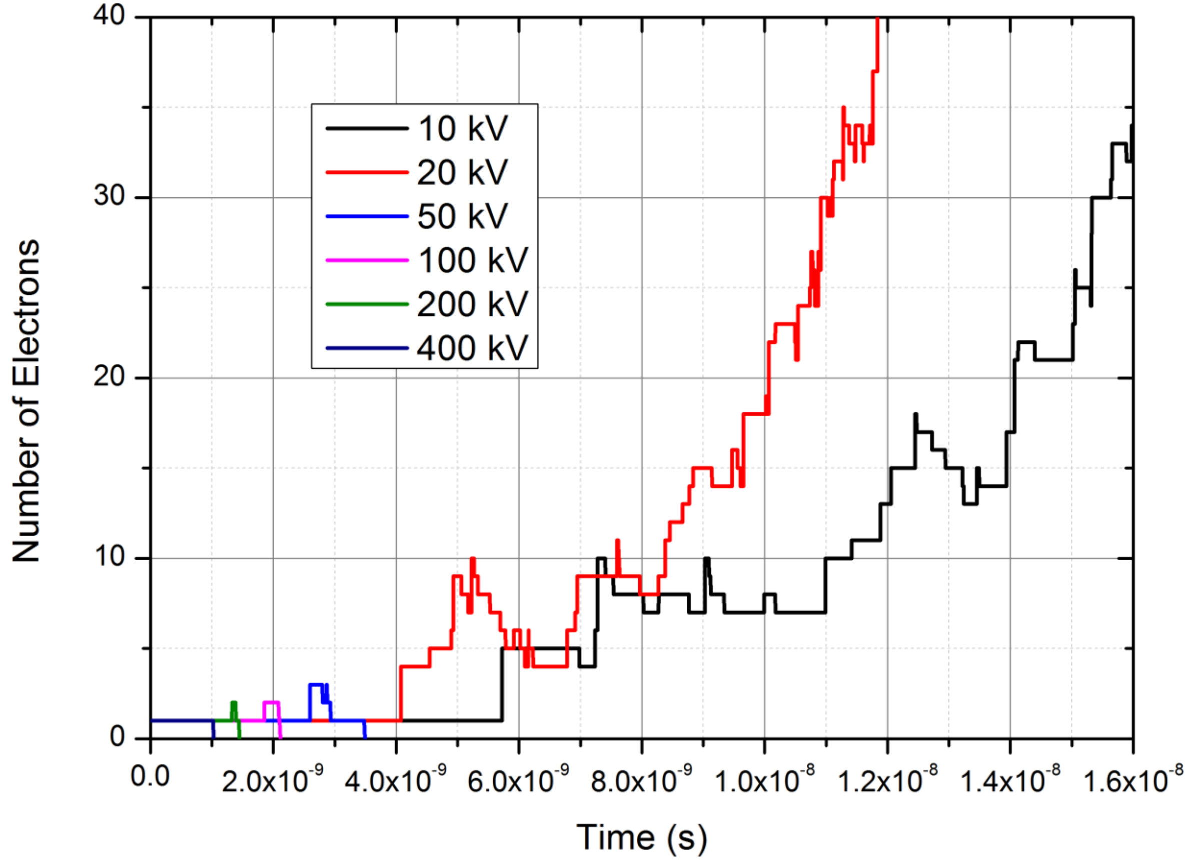
Multipacting of Electrons Emitted from the Triple Point (TP)



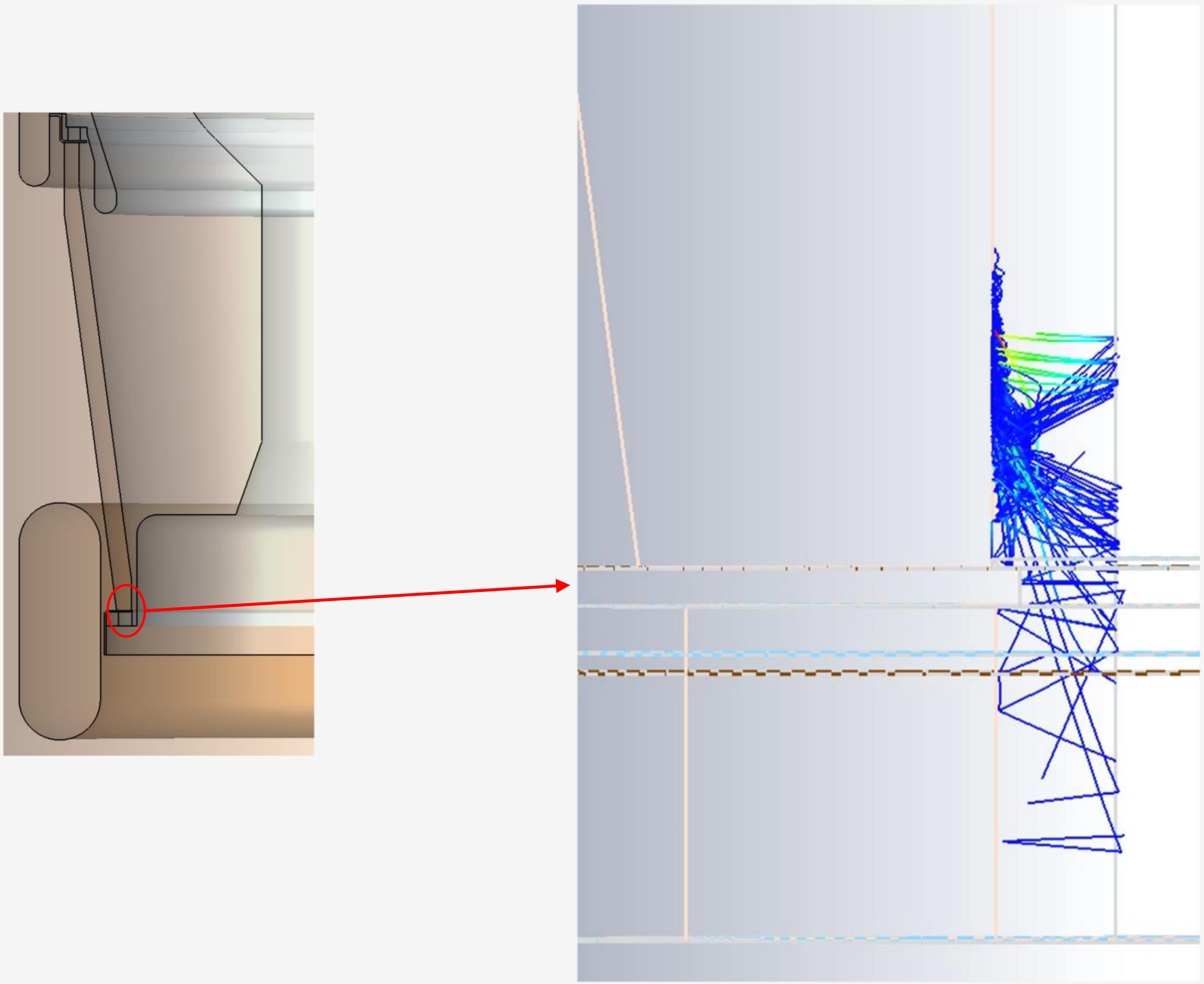




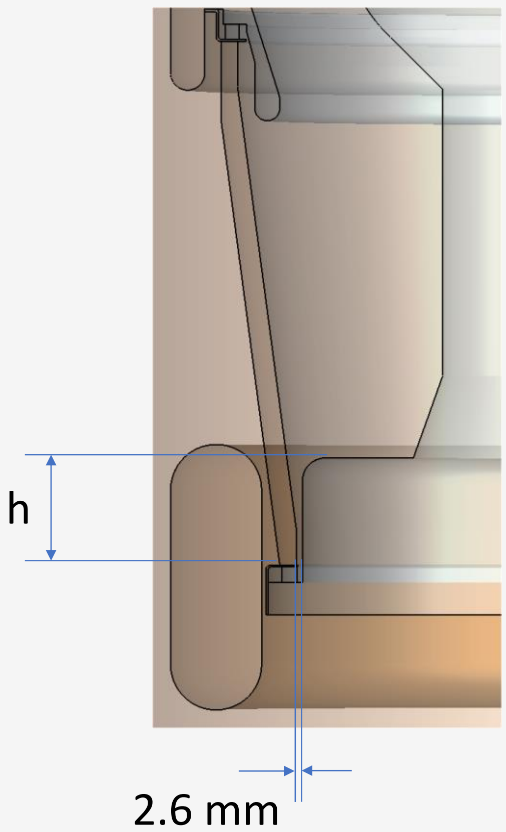
Beam-Voltage Dependence of Electron Multipacting

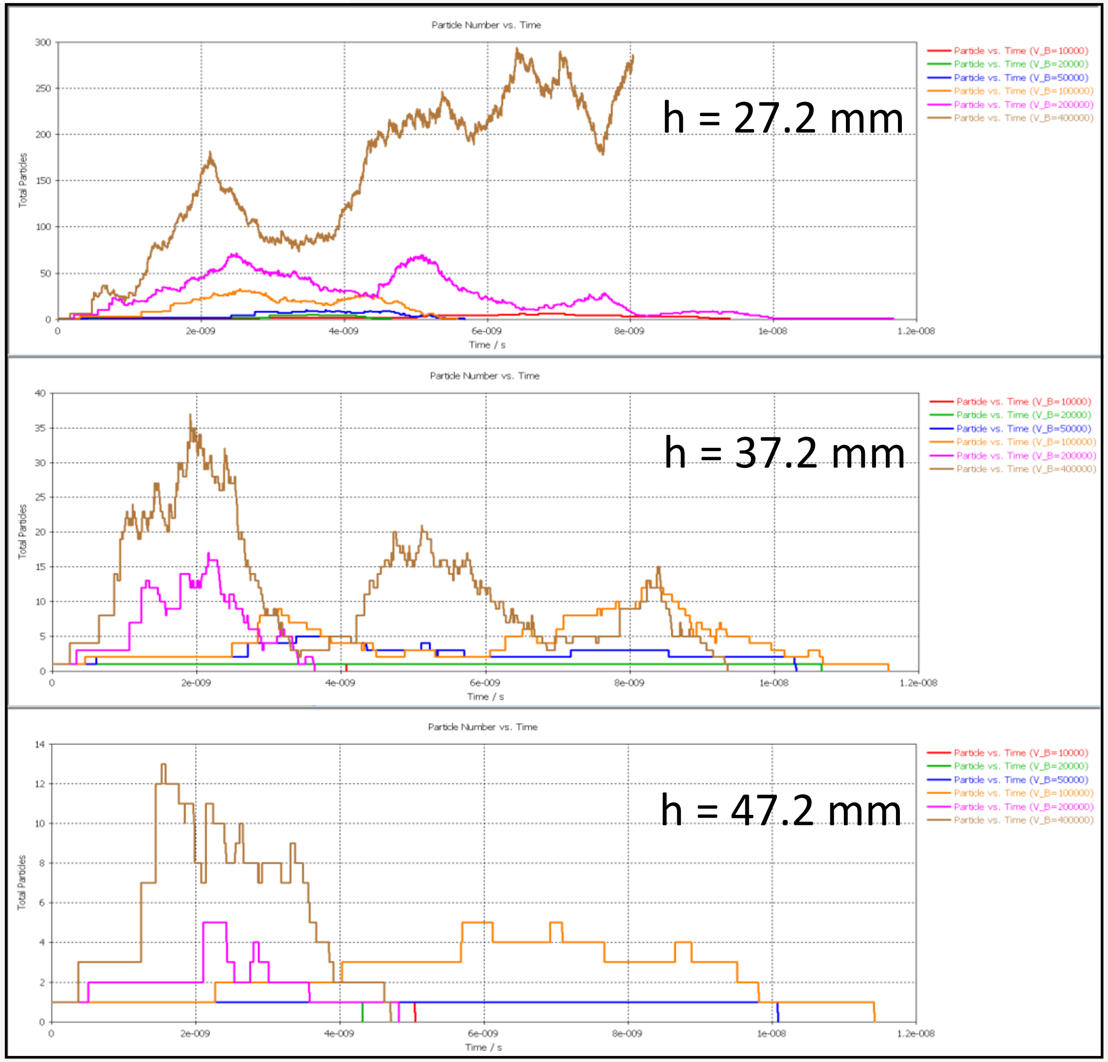


Suppression of Electron Multipacting (1/2)

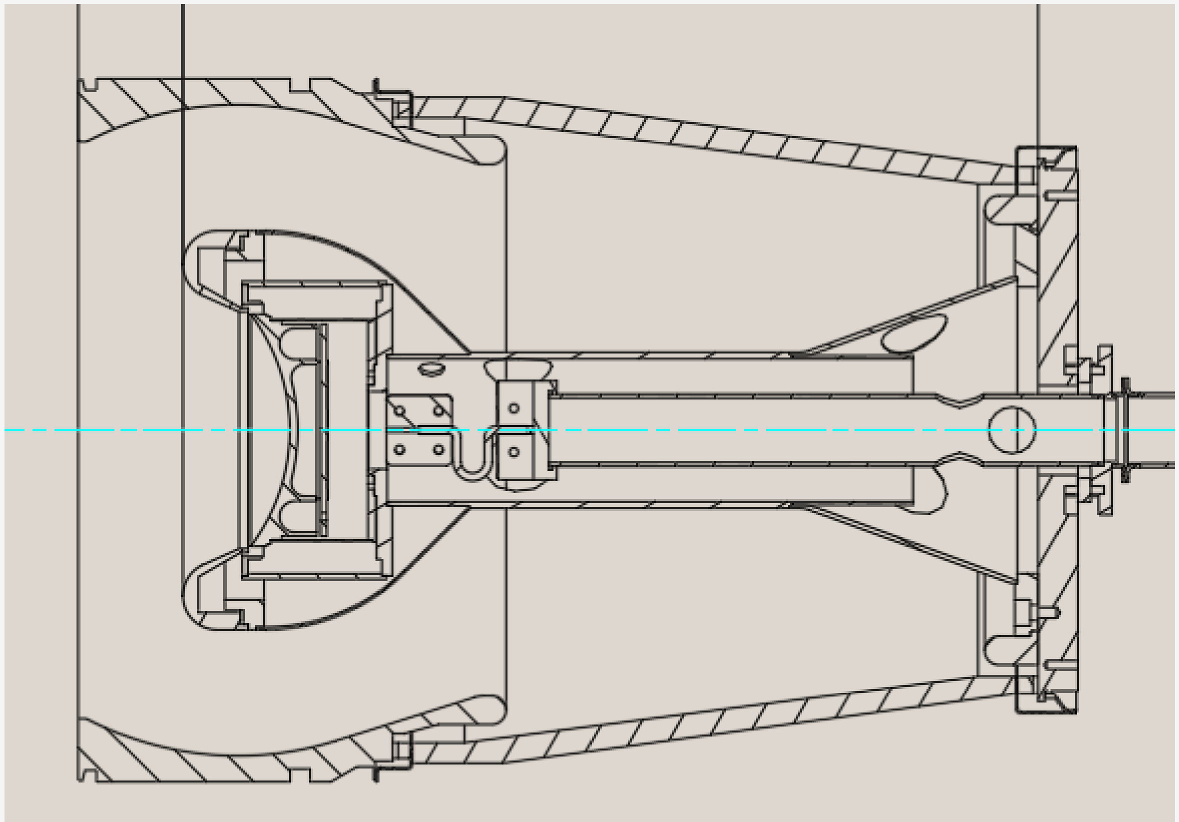


Suppression of Electron Multipacting (2/2)





Improvement of Gun Design to Suppress Electron Emission from Triple Point



Journal of the Korean Physical Society (2025) 87:860–867
https://doi.org/10.1007/s40042-025-01338-1

Online ISSN 1976-8524
Print ISSN 0374-4884

RESEARCH - PARTICLES AND NUCLEI

Design improvements of electron gun for PAL klystron

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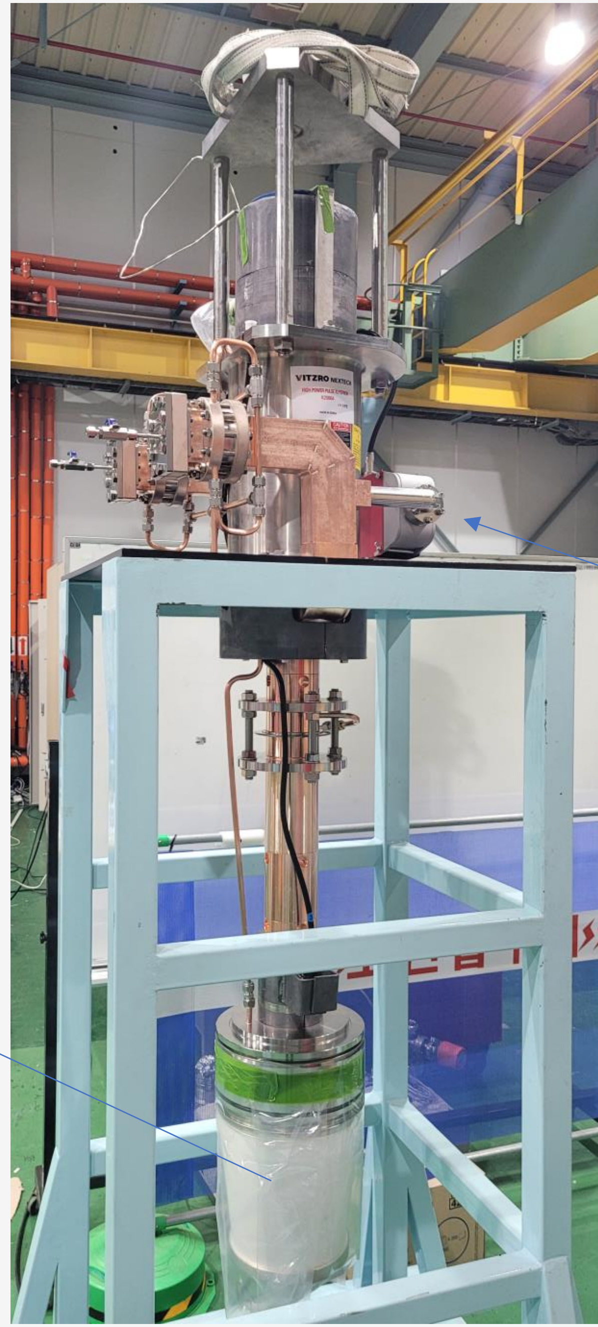
Received: 24 January 2025 / Revised: 26 February 2025 / Accepted: 1 March 2025 / Published online: 10 March 2025

Abstract

Several prototype S-band pulsed klystrons for use at the Pohang Accelerator Laboratory (PAL) have been developed by a domestic company in collaboration with PAL. These klystrons successfully achieved the required RF output power at a low repetition rate (< 30 Hz) but suffered from gun arcing when operated at 60 Hz, which is the repetition rate required for the PAL-XFEL. Post-mortem inspection revealed that the arcing spots on the focusing electrode (Wehnelt) were not located at the regions of maximum electric field. Particle trajectory simulations in the electron gun region suggest that the initial arcing is triggered by electron emission and followed by clump-induced breakdown processes. In addition, vacuum breakdown can be initiated from the so-called triple point (TP) at the lower end of the ceramic insulator, where a negative potential is applied during high-voltage (HV) operation. Further numerical simulations confirmed that electrons emitted from this TP can travel along the ceramic surface, undergo multiplication, and eventually cause breakdown near the anode housing. Based on these findings, we propose design improvements—most notably enhanced cleaning and polishing procedures as well as an added electric field shield near the TP—to suppress vacuum breakdown at higher repetition rates (e.g., 60 Hz). Initial high-voltage (HV) processing data show that the improved gun design significantly reduces arcing events, enabling stable klystron operation.

Keywords Klystron · Electron gun · Vacuum breakdown · Triple point · Field emission · Clump

Latest Fabrication of PAL Klystron In 2024

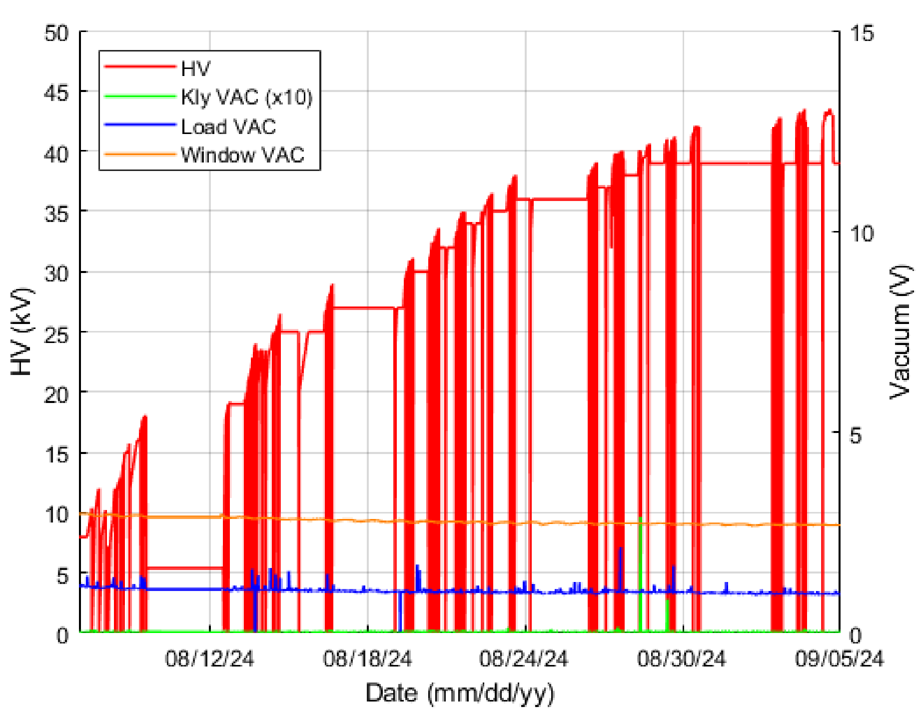


Comparison of VK4 and VK5

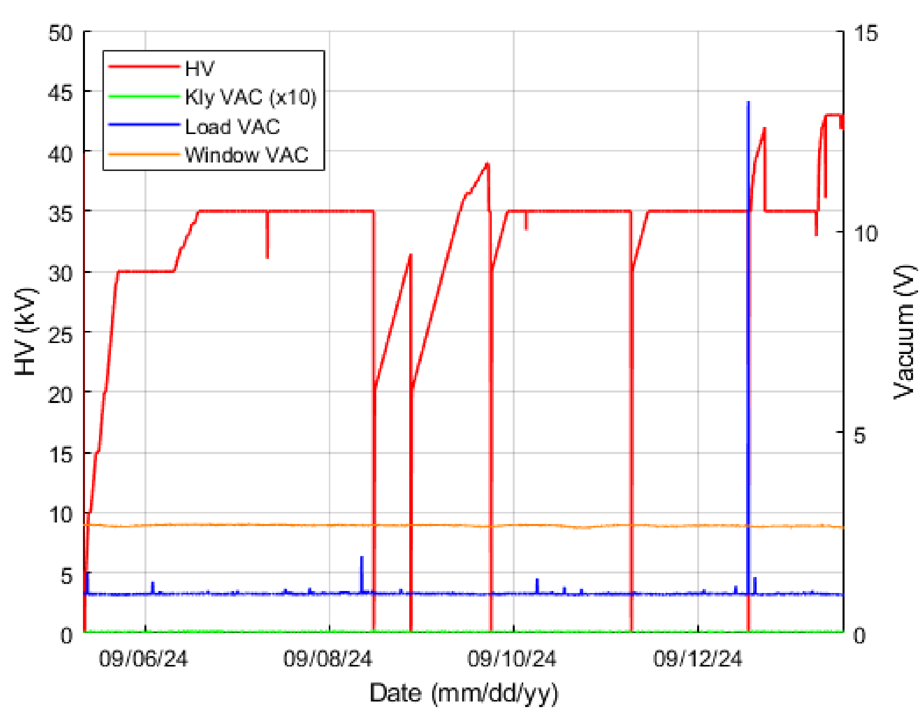
	VK4	VK5
Electrode Polishing	Mechanical Polishing + Standard Cleaning	Mechanical Polishing + ECB + Standard Cleaning
Cathode Assy Firing	Standard	Standard
TP Shield	Yes	Yes
Thickness of TiN Coatings on Output Windows	5 nm	10 nm

HV Processing of VK4

10Hz

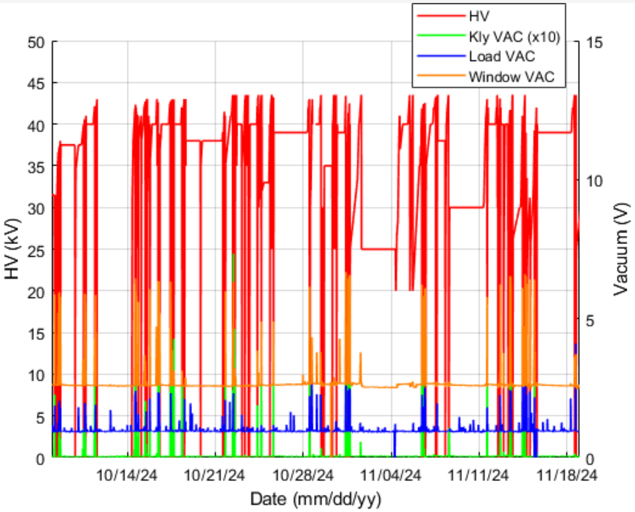


30Hz

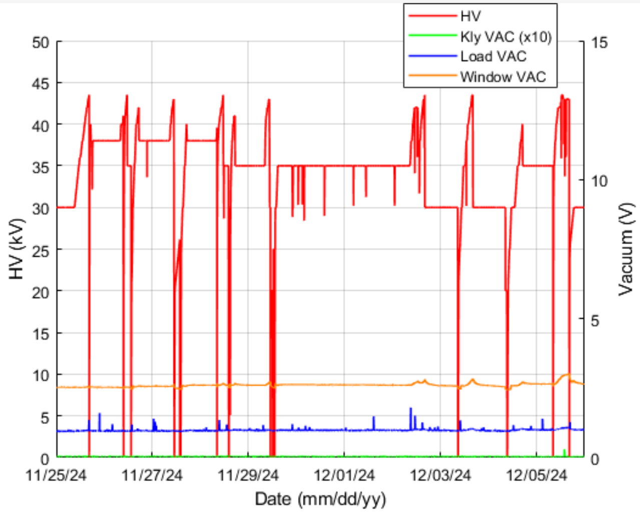


RF Processing of VK4

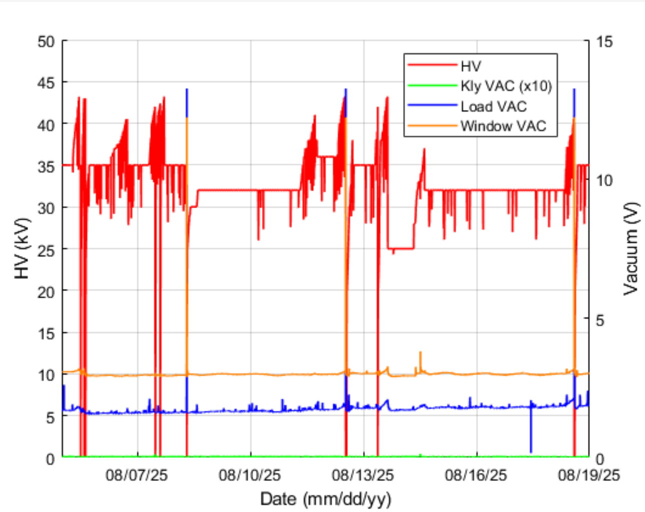
10Hz



30Hz

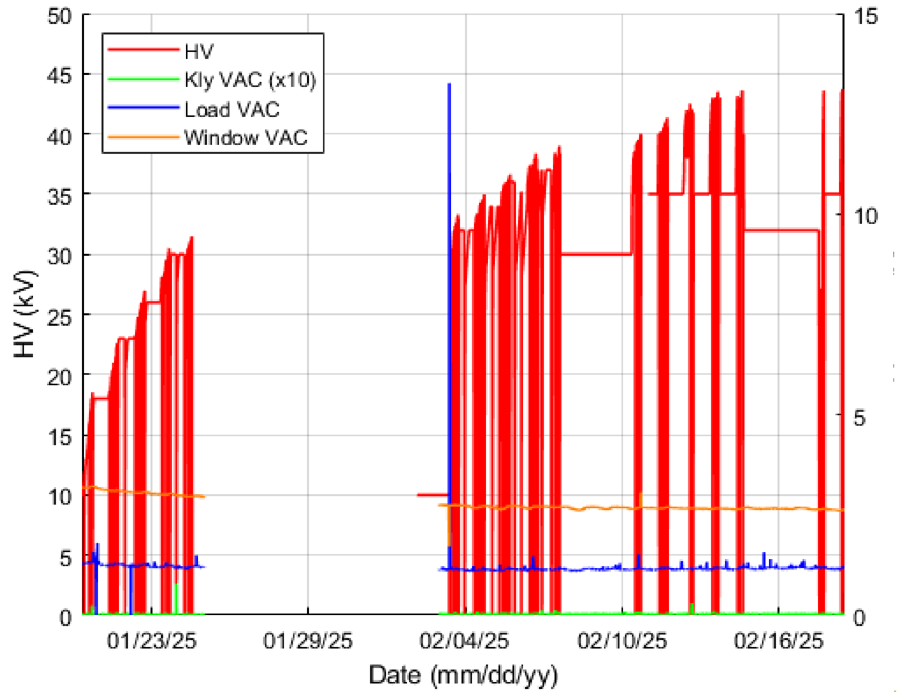


60Hz

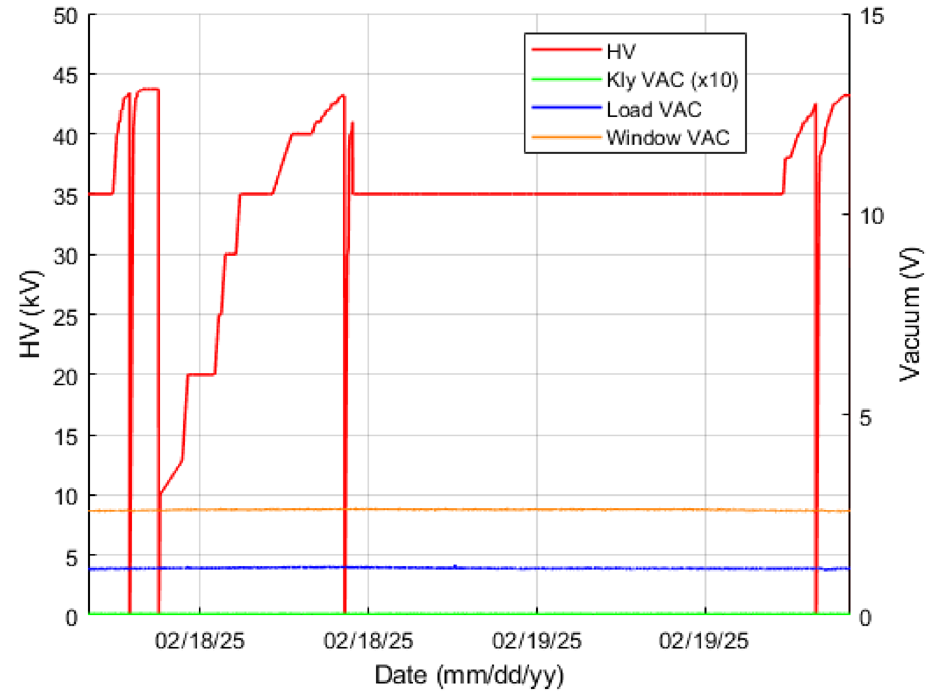


HV Processing of VK5

10Hz

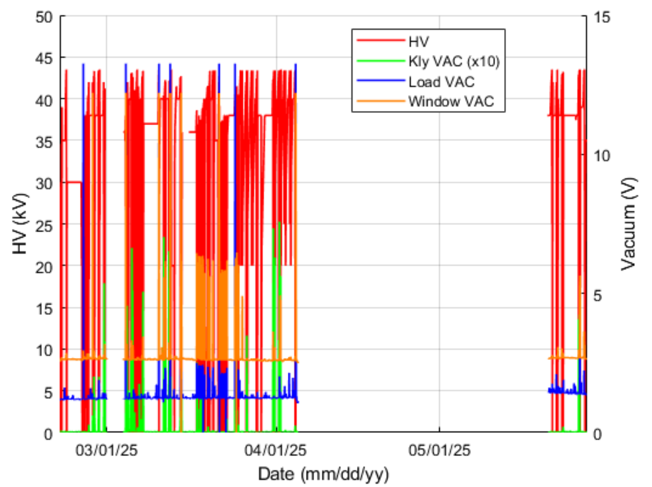


30Hz

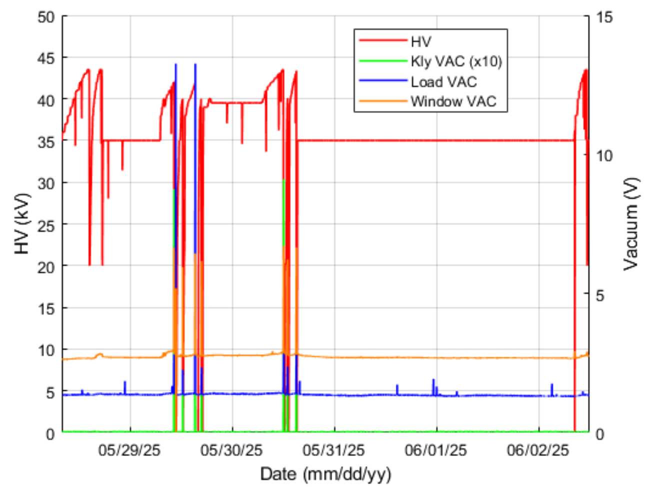


RF Processing of VK5

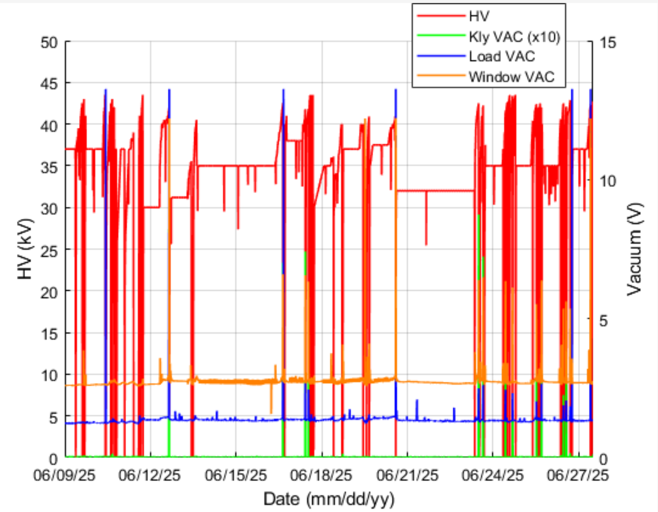
10Hz



30Hz



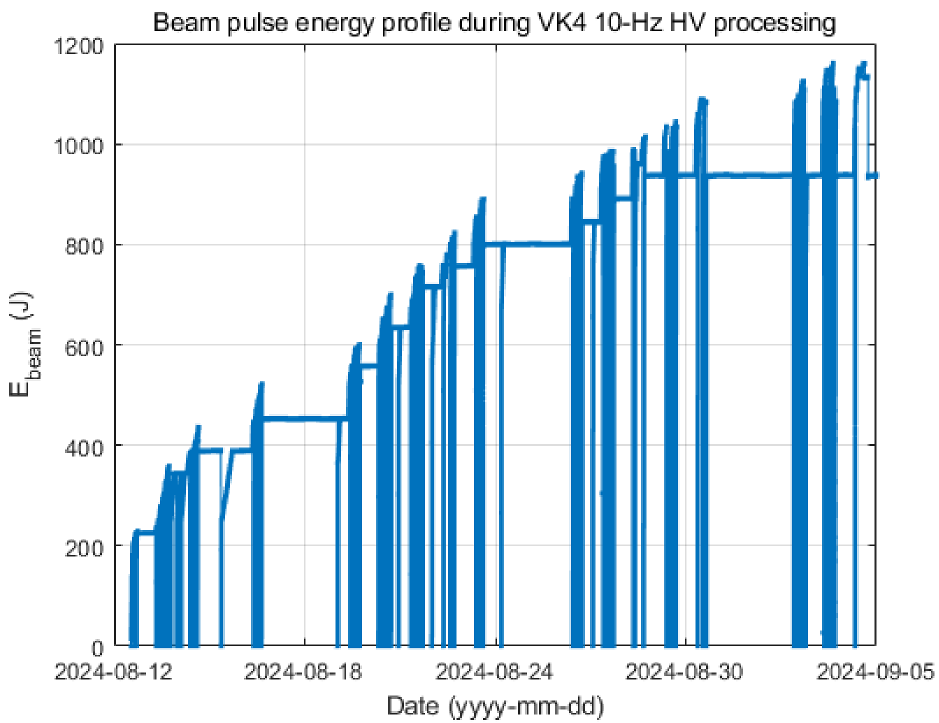
60Hz

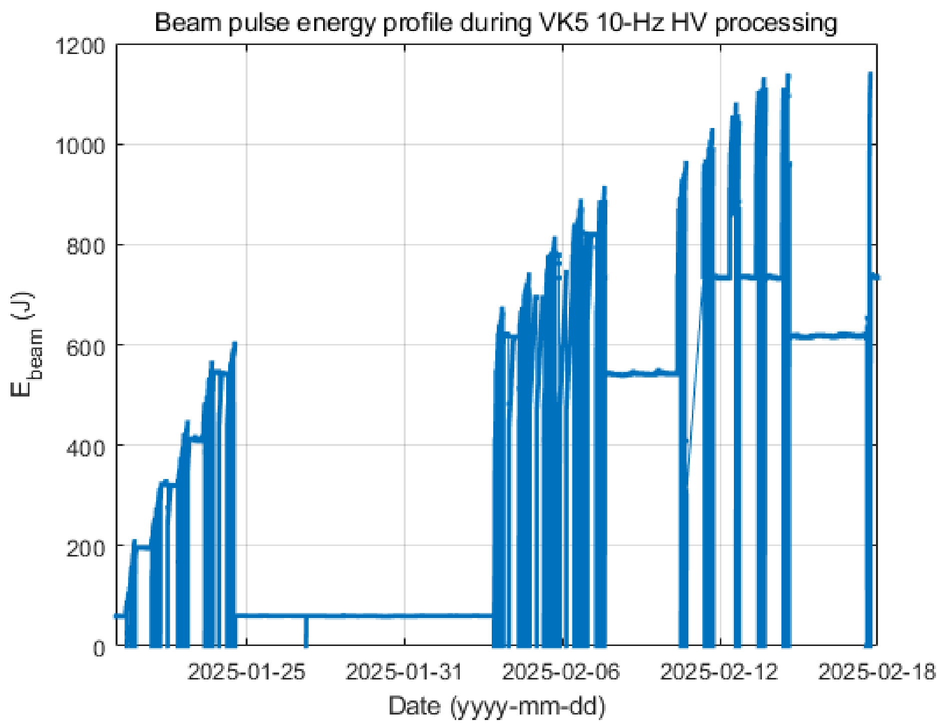


Summary of Processing Results

KLYSTRON TUBE TYPE		VK4					VK5				
Processing Type		HV		RF			HV		RF		
Pulse Repetition Rate (Hz)		10	30	10	30	60	10	30	10	30	60
period		24.8.7 - 9.5	24.9.6 - 9.13	24.10.8 - 11.19	24.11.25 - 12.5	25.8.5 - 8.19	25.1.20 - 2.18	25.2.18 - 2.19	25.2.19 - 4.4, 25.5.20 - 5.27	25.5.27 - 6.2	25.6.9 - 6.27
number of days		30	8	43	13	15	30	2	53	7	19
number of fast arcs (excluding rf arcs)		142	5	No Data	No Data	7	38	2	23	No Data	18
Total/Avg. arc energy (J)		~ 5000/35					~ 1600/40				
number of slow arcs (excluding rf arcs)		0	0	No Data	No Data	0	0	0	0	No Data	0
Processing Result	Beam Voltage (kV)	411	402	402	403	400	403.5	400.61	401	401.3	391
	Beam Current (A)	372	461	472	472	465.5	476.1	469.16	473	473.4	452
	Microperveance	1.81	1.81	1.85	1.85	1.84	1.86	1.85	1.86	1.86	1.85
	Output Power (MW)			80	83	81.2			80.7	80.9	76.2
	RF Pulse Length (us)			4	4	4			4	4	4

Beam Pulse Energy Profile during HV Processing



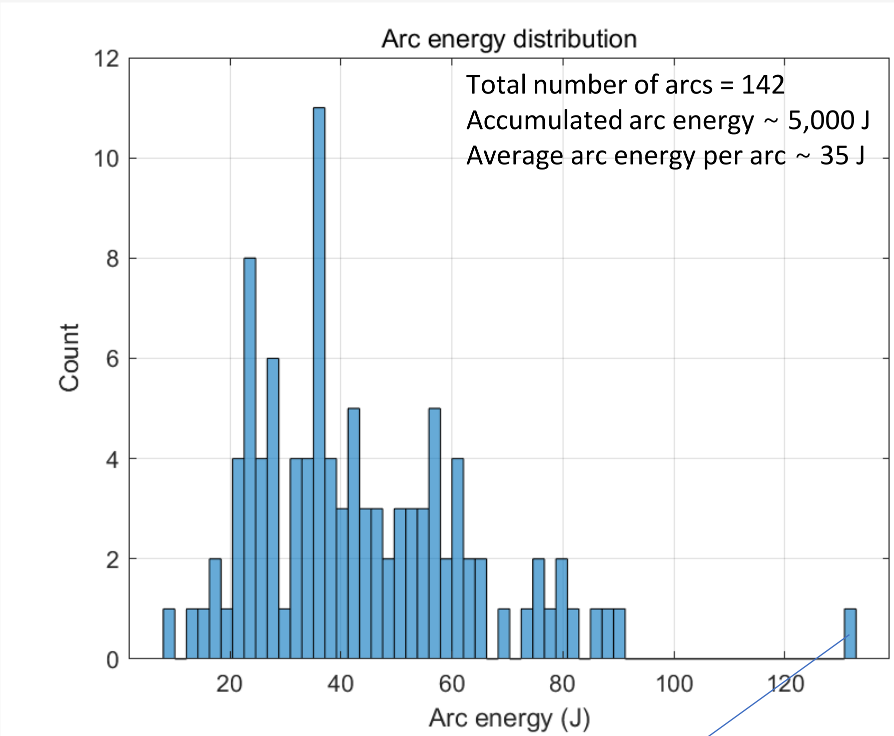


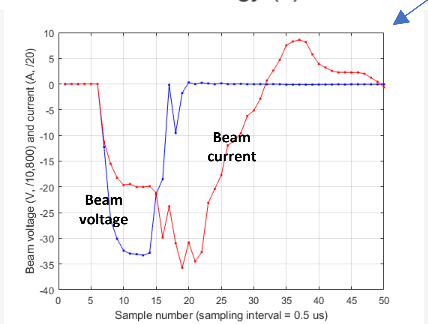
Total beam pulse energy deposited to klystron beam collector = 1.4×10^{10} J

Total beam pulse energy deposited to klystron beam collector = 1.0×10^{10} J

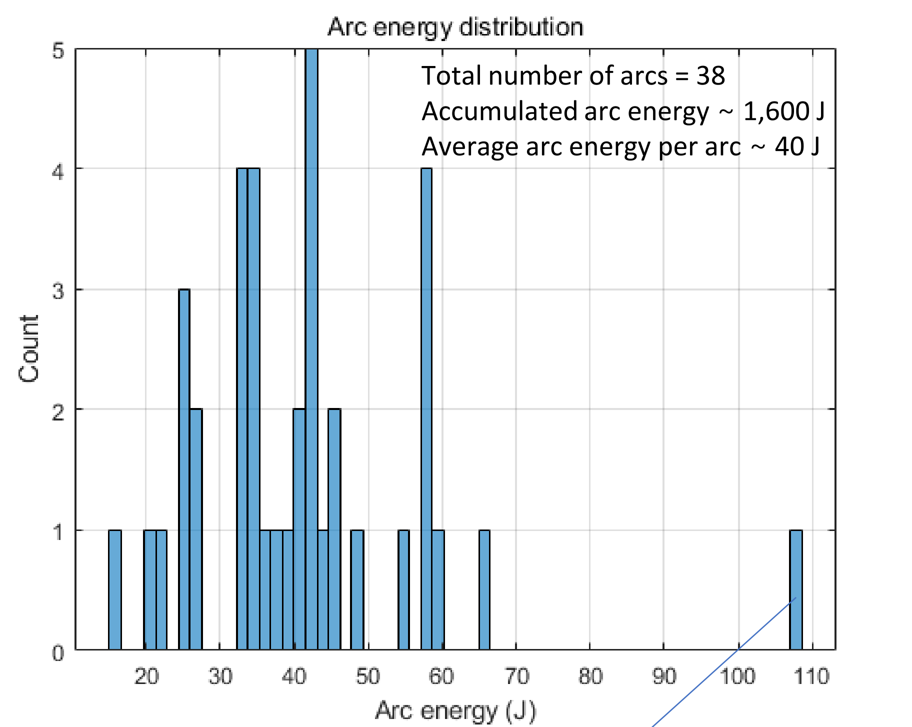
Arc Energy Distributions

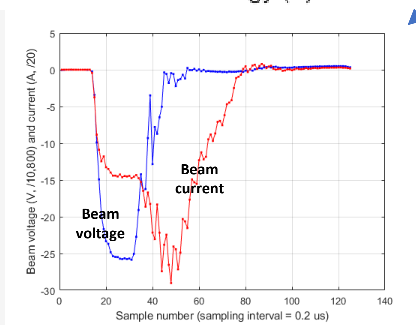
VK4_HV_10Hz



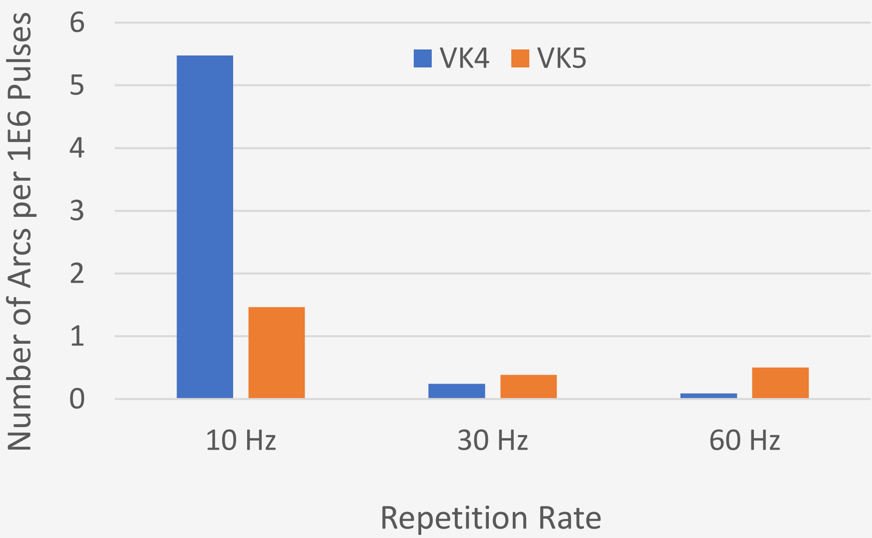


VK5_HV_10Hz





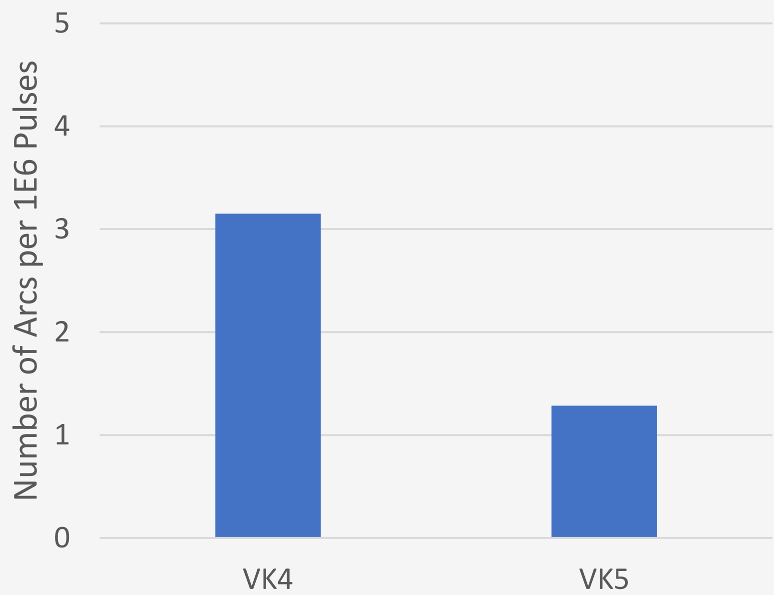
HV Fast-Arc Rate vs. Repetition Frequency



Key Observation

- VK5 exhibits a dramatically lower fast-arc rate at 10 Hz (≈1.47 vs 5.48 per 10^6 pulses).
- At 30 Hz the rates converge (≈0.39 vs 0.24 per 10^6 pulses).
- At 60 Hz VK5 exhibits higher rate (≈0.183 vs 0.090 per 10^6 pulses). This would be because 60-Hz processing were done with RF (for saving the processing times). And output window performance for VK4 was superior to VK5 (gas outgassing and/or X-ray emission from the window seems to have a certain effects on gun arcing).

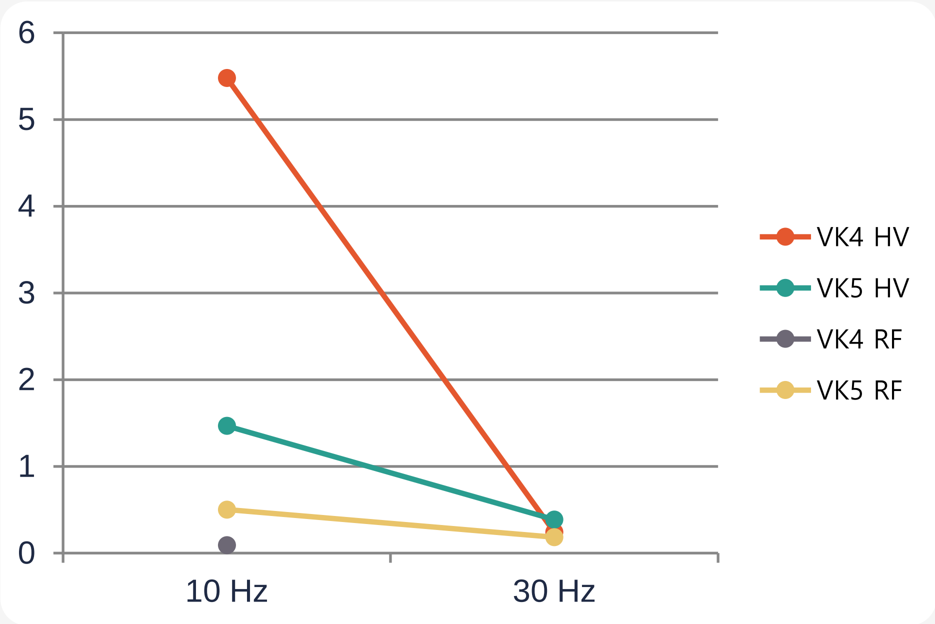
Cumulative HV Fast-Arc Rate



Aggregated HV data

- VK4: 3.151 arcs/10^6 pulses
- VK5: 1.286 arcs/10^6 pulses
- Rate Ratio VK5/VK4 = 0.408 (≈59% reduction)

Arc Rate vs. Repetition Frequency



Trend Summary

• HV rates drop dramatically as repetition frequency increases from 10 to 30 Hz.

Conditioning Effects

• Fast-arc rates decline with increased repetition rate (10 → 30 Hz) as surfaces are conditioned.
• HV processing typically completes before RF processing, leaving fewer arcs during the RF phase.
• Arc rate per hour: VK4 HV 10 Hz ≈ 5 h/arc vs VK5 HV 10 Hz ≈ 19 h/arc (improved duty cycle).

Comparative Timeline (2024 → 2025)

Findings as of 2024

• Early prototypes limited to 30 Hz due to gun arcing.
• Identified clump & triple-point breakdown as root causes.
• Proposed polishing, cleaning & TP shield solutions.

Results as of 2025

• Implemented improvements yield reliable operation at 60 Hz.
• HV arc rate reduced dramatically; slow arcs eliminated entirely.
• RF arc seems depend on TiN coatings on output windows

Test of Full-Performance Operation (80 MW, 4 μs, 60 Hz) of the Latest S-band Klystron at PAL

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(Received December 15, 2025)

Abstract

We report high-voltage (HV) and RF processing results of the latest domestically manufactured S-band pulse klystrons developed for the Pohang Accelerator Laboratory (PAL). Previous prototypes of the 80 MW-class tube suffered from frequent gun arcing at 60 Hz repetition rate, which limited routine operation to 30 Hz. Earlier studies identified clump-assisted breakdown in the diode region and electron multiplication at the ceramic triple point as the dominant mechanisms, and proposed mitigation via improved electrode surface preparation and a triple-point electrostatic shield. These measures were incorporated into the latest units (serial numbers VK4 and VK5), which were fabricated in 2024 and conditioned in the PAL klystron and modulator test laboratory. VK4 reached 80 MW peak RF output with a 4 μs pulse width at 60 Hz repetition rate and exhibited stable operation. From detailed analysis of HV and RF processing data, we show that enhanced electrode polishing reduces the total HV arc rate by $\approx 60\%$ and that slow breakdown events are eliminated by the triple-point shield so that only fast arcs remain. We further observe that RF breakdowns depend sensitively on the TiN coating of the output window, with an excessively thick coating leading to increased RF arc activity, likely by ohmic heating. The successful demonstration of 80-MW, 4-μs, 60-Hz operation with a domestically produced tube validates the maturity of the klystron design and supports readiness for series production and routine accelerator service.

Keywords: PAL klystron, 60-Hz operation, HV and RF processing, gun arcing, triple-point shielding, accelerator service

Submitted to the JKPS

Conclusions

- Enhanced surface preparation and triple-point shielding substantially reduce HV fast-arc rates.

- Slow breakdowns are eliminated by the TP shield; only fast arcs remain.

- RF arc seems depend on TiN coatings on output windows

- Successful demonstration of 80-MW, 4-μs, 60-Hz operations validates design & fabrication maturity for routine accelerator service.

Suggestion of Future Improvements

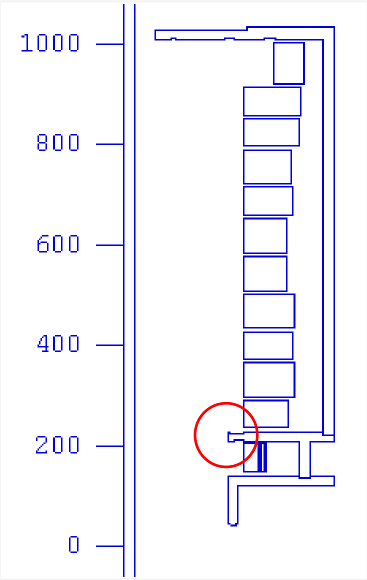
- Improvement of gun-solenoid optics matching
- Efficiency improvement

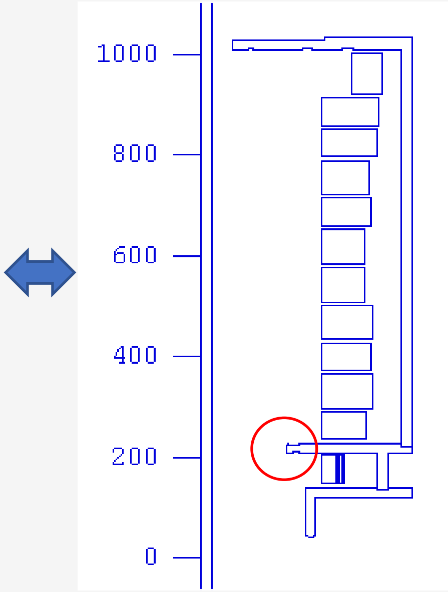
Method of Beam Matching to an arbitrary beam sizes Given a gun design

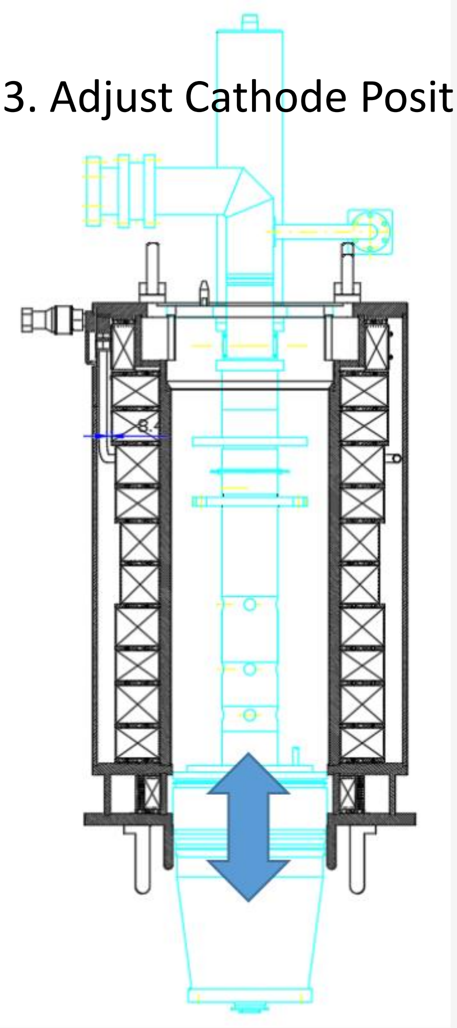
1. Adjust B_c (i.e., Bucking Coil Current)

3. Adjust Cathode Position

2. Adjust Shield Aperture

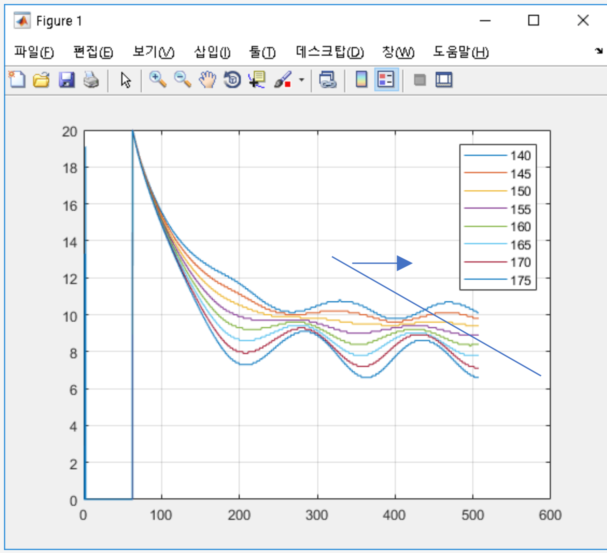




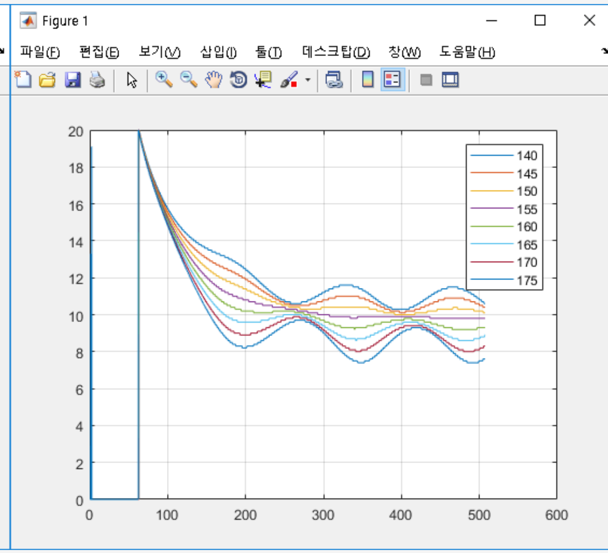


Beam-Trajectory Families Generated from Bucking-Strength Scan for Mismatched and Matched Cases

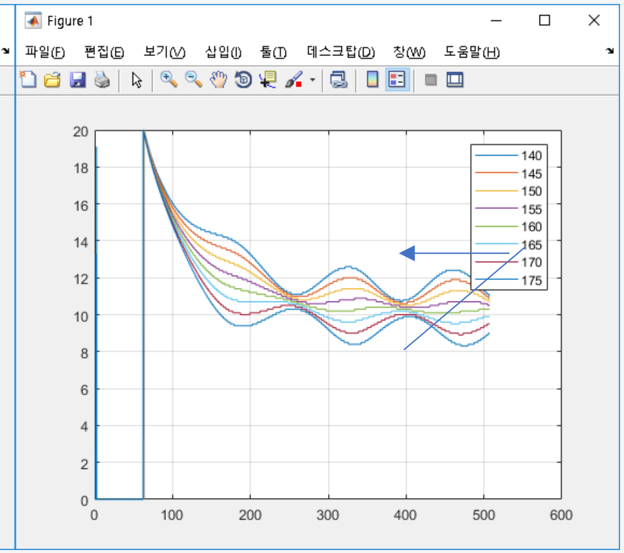
z-trans = 0 mm



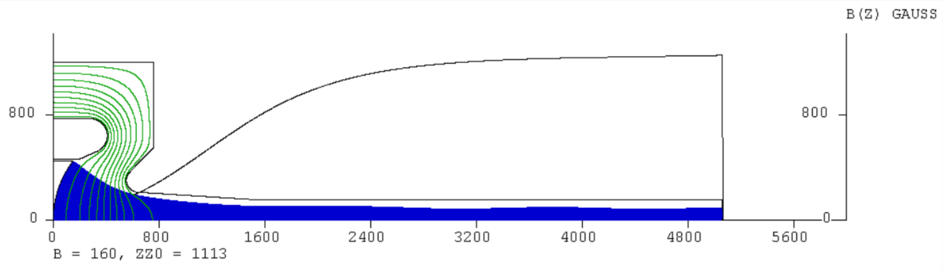
z-trans = 5 mm

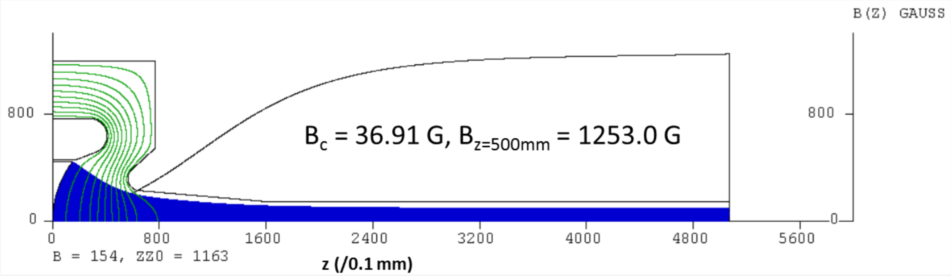


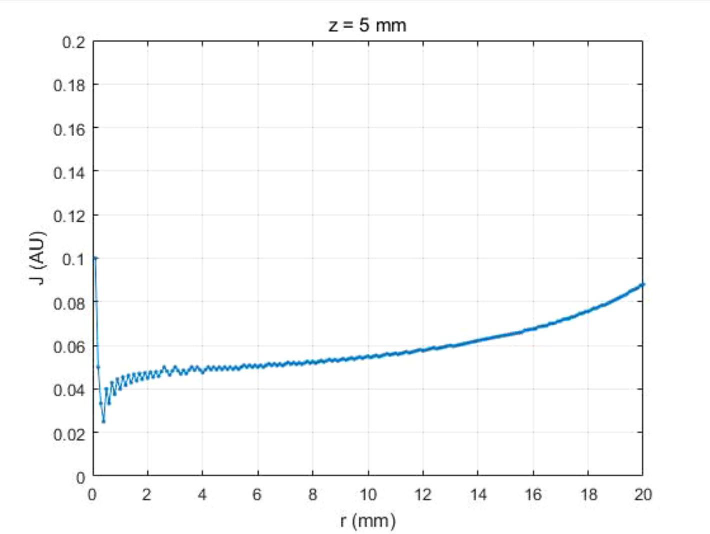
z-trans = 10 mm

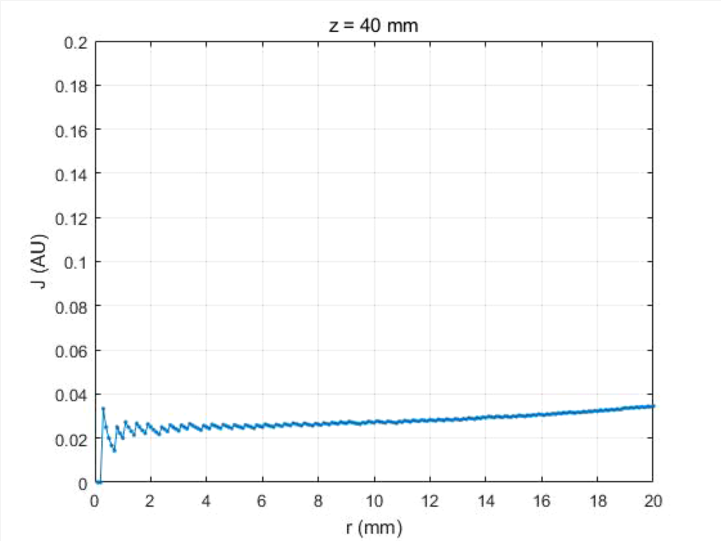


Beam Profile Comparison
Between Mis-matched and Matched Beams





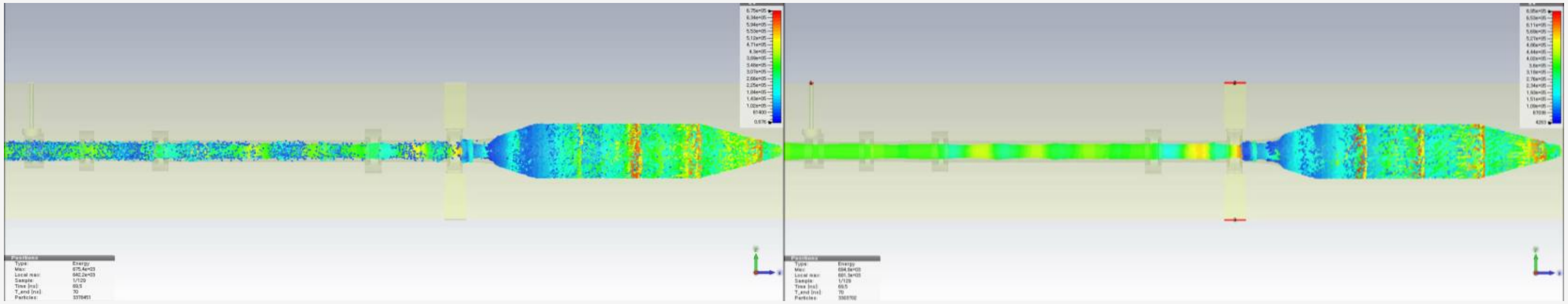




Beam Loss Comparison for Present & Improved Beams

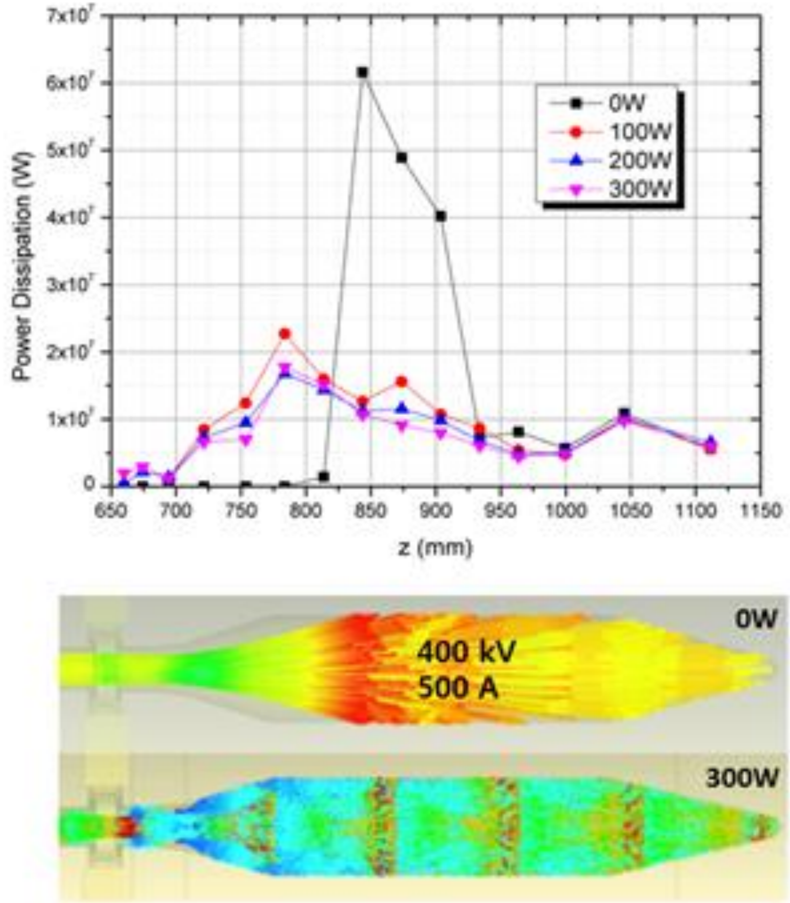
	Present Beam	Improved Beam
P_{out} (MW)	74.9	77.4
P_{drive} (W)	300	140
P_{loss} @ OPC (kW)	64	0
$P_{reflection}$ (kW)	98	0
$r_{avg,95\%}$ (mm)	9.0	~ 9.5
Scallop (%) $(r_{max}-r_{min})/r_{avg}$	22	< 5
I_{focus} (A)	18	18

Real-Space Beam Profile
(Colors indicate Particle Energy)



Power Dissipation Distribution in Collector

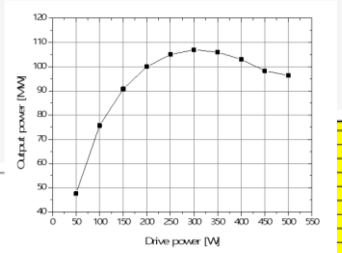
- A clue to the 120-Hz klystron-

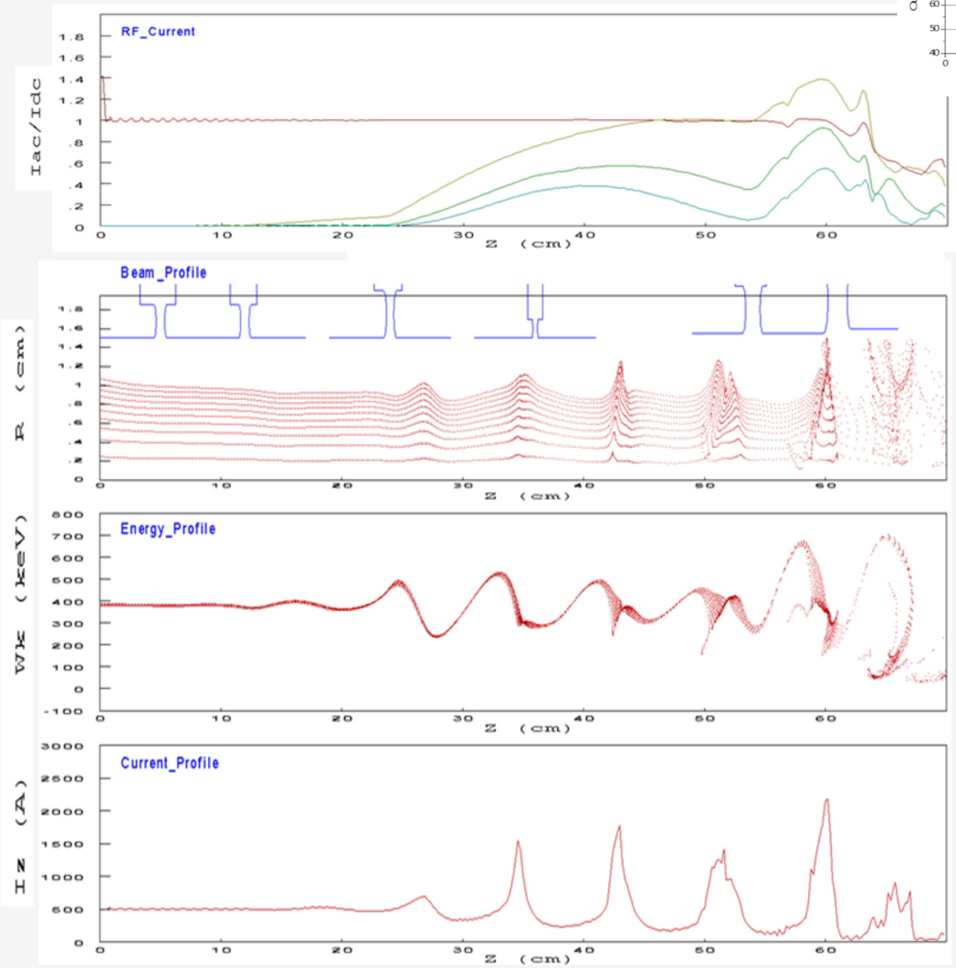


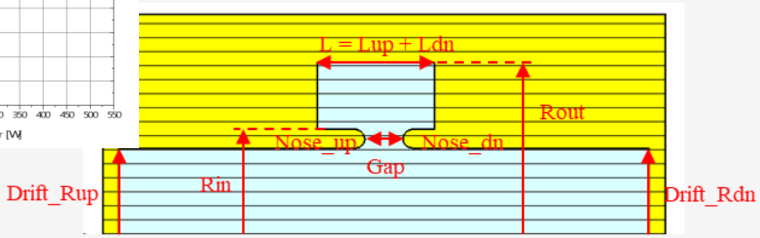
120-Hz Klystron seems feasible by changing beam-trajectories in collector, i. e., no major changes in the collector itself are required. But we would need a stronger Solenoid magnet.

High-efficiency Design with 2nd Harmonic Cavity

Pout = 107 MW, η = 53.4%



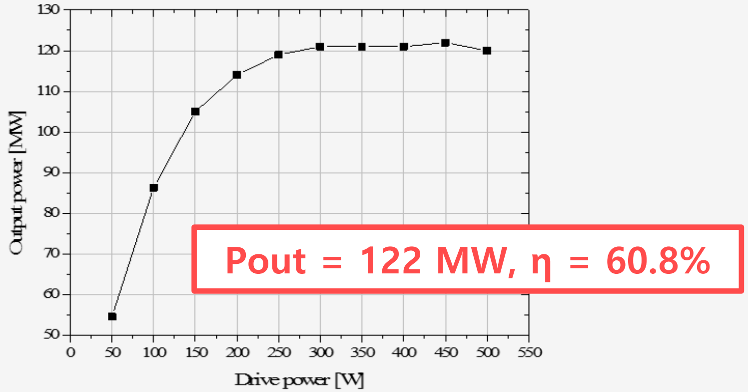


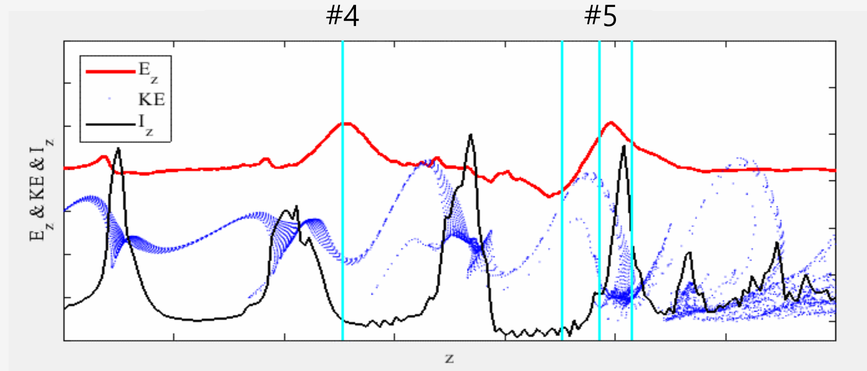


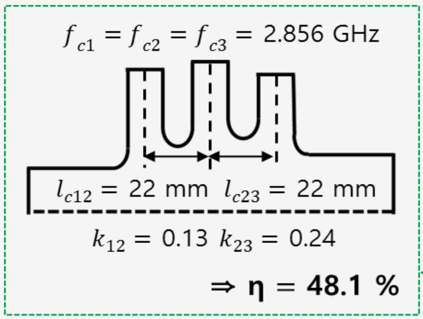
Cav. No.	1	2	3	4	5	6
f (MHz)	2,856	2,860	2,870	5,320	2,970	2,856
Position (cm)	5	12	24	36	54	61
R/Q	64.33	65.57	56.05	140.19	85.77	106.37
QL	175	2,000	2,000	2,000	2,000	16.5
β	10					121
$E_{s,max}$ (MV/m)	0.15	1.35	9.53	5.63	19.48	28.76
Drift_Rup	15	15	15	15	15.5	15.5
Drift_Rdn	15	15	15	15	15.5	16
Rout	26.4	30.95	29.95	24.79	33.02	34.2
Rin	18.5	18.5	18.5	17	20.5	22.5
L	29.7	22.2	24.85	14	25.45	25
Nose_up	1.75	1.75	1.75	1	2.5	3.5
Nose_dn	1.75	1.75	1.75	1	2.5	3.5
Gap	7.7	7.2	7.85	4	12	15.5

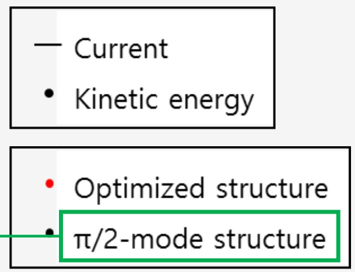
unit: mm

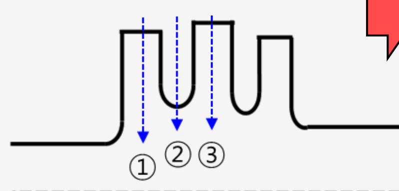
High-efficiency Design with Multi-cell OP Cavity
EMSYS Simulation



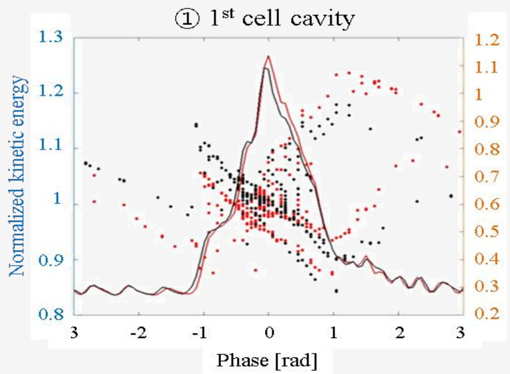


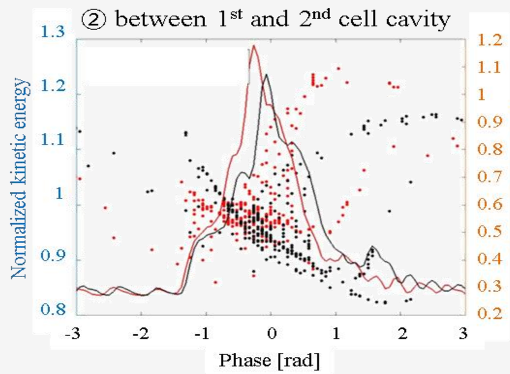


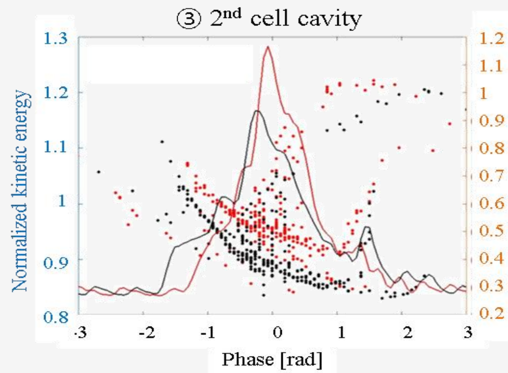




- **Optimum field strength**
- **Right phasing**
- **Low energy spread**

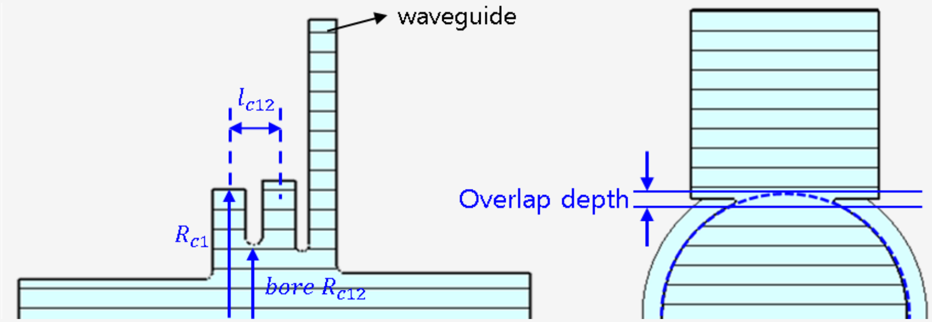


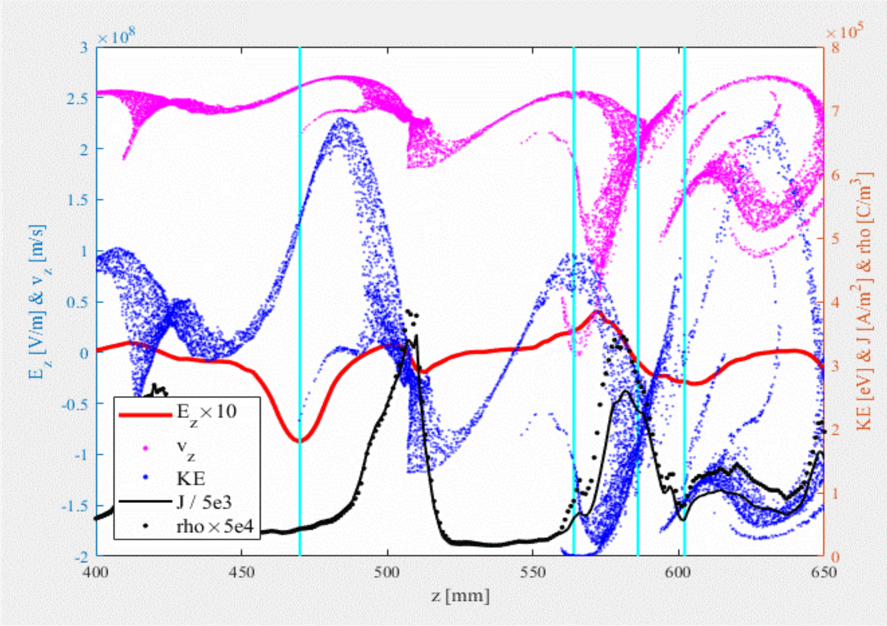




High-efficiency Design with Multi-cell OP Cavity
CST-PIC Simulation

Pout = 113 MW, η = 56.5%





- $R_{c1} = 51.28$ mm, $R_{c2} = 54.834$ mm & $R_{c3} = 47.184$ mm
- $l_{c12} = 22$ mm, $l_{c23} = 16$ mm
- $bore\ R_{c12} = 30$ mm, $bore\ R_{c23} = 27.53$ mm
- Overlap depth = 2.32 mm

Three-cell

Max. E_s = 31.5 MV/m
at 113-MW RF output

Single-cell

Max. E_s = 46 MV/m
at 80-MW RF output

High-Efficiency Klystron Design

How about combining high-quality bunching and efficient power extraction?

Y. Okubo et al., IPAC2018

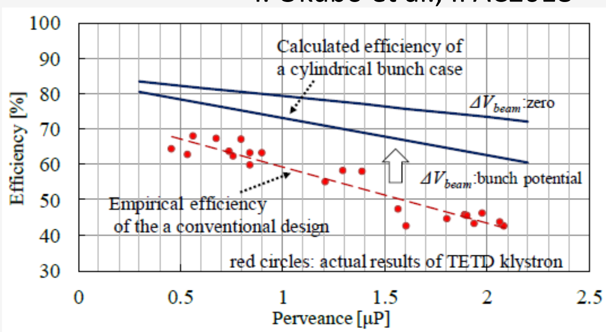
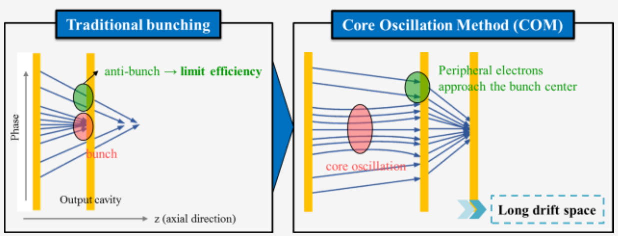


Figure 1: Relation between the perveance and the expectable efficiency of a cylindrical bunch shape.



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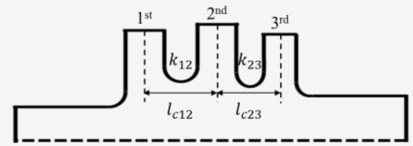

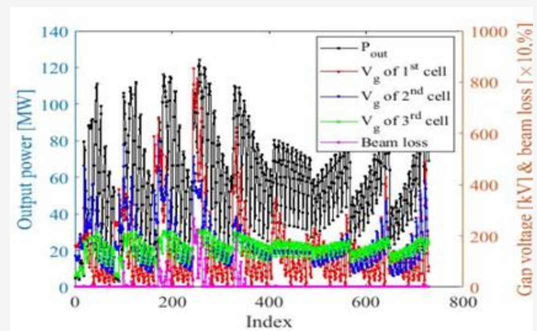

J. Hwang, Ph. D. Thesis

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