

30MeV 사이클로트론 RF 기술현황과 앞으로의 방향

한국원자력의학원
RI생산기기사업팀

- 고주파시스템 설계
- 고주파시스템 제작
- 고주파시스템 개선사항
- 향후 계획

■ 고주파시스템 설계 변수

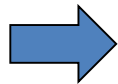
Resonant Frequency	63.96MHz
Harmonic Number	4 th
Dee Voltage	50kV
Resonant Mode	$\lambda/2$ mode
Characteristic Impedance	50 Ω
Hill / Valley Gap	0.03 / 0.62m
Hill / Valley Angle	48 / 42 degree
Q Value	5269
No. of Sector / Dee	4 / 2
Coupling Type	Capacitive

■ 공진주파수

$$B_0 = 1.047 [T]$$

Harmonic Number : $h = 4$

$$\omega = \frac{qB}{M} = \frac{qB_0}{M_0} = \frac{qB_{ext}}{\gamma M_{ext}} = const.$$



$$f_{ion} = \frac{\omega}{2\pi} = \frac{qB_0}{2\pi M_0} = \frac{1 \times 1.047}{2\pi \times 1.0425 \times 10^{-8}} = 15.99 \times 10^6 [Hz]$$

$$f_{rf} = hf_{ion} = 63.96 [MHz]$$

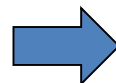
■ 인출반경

• 상대론적 요소

$$E_p = 30 [\text{MeV}]$$

$$\begin{aligned}\gamma &= \frac{E}{E_0} = \frac{E_0 + E_p}{E_0} = 1 + \frac{E_p}{E_0} \\ &= 1 + \frac{30}{938.271} = 1.032\end{aligned}$$

$$\beta = \frac{\sqrt{(\gamma+1)(\gamma-1)}}{\gamma} = 0.2471$$



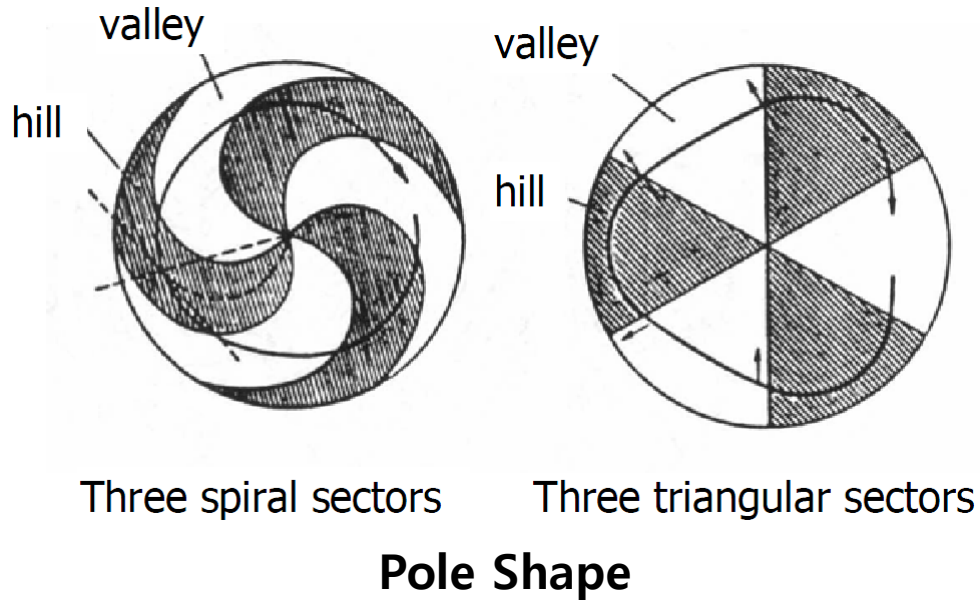
$$B_0 R_0 = B_{ext} R_{ext},$$

$$R_0 = \frac{B_{ext} R_{ext}}{B_0} = 0.7612$$

• 자기 강도 (Magnetic Rigidity)

$$BR = \frac{p}{q} = \frac{Mv}{q} = \frac{M_0 c \beta \gamma}{q} = 0.797$$

■ Dee, Stem & Liner 구조



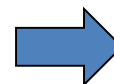
• Sector (Hill-Valley) 구조

- Dee, Stem & Liner 형상 결정
- Q Value에 영향

■ Stem 형상 : 무손실 전송선로 모델

• Stem 길이

$$Z(L) = Z_0 \frac{1 - Z_0 \omega C_{dee} \tan\left(\frac{L\omega}{c}\right)}{j \left[\tan\left(\frac{L\omega}{c}\right) + Z_0 \omega C_{dee} \right]} = 0$$



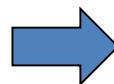
$$L = 664 [\text{m}]$$

$$\tan\left(\frac{L\omega}{c}\right) = \frac{1}{Z_0 \omega C_{dee}} \Rightarrow L = \frac{c}{\omega} \tan^{-1}\left(\frac{1}{Z_0 \omega C_{dee}}\right)$$

$$C_{dee} = N \times \epsilon_0 \frac{A_{dee}}{d} = 20 [\text{pF}], \quad c = 3 \times 10^8 [\text{m/s}], \quad \omega = 2\pi f_{rf}$$

• Stem 지름

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \frac{1}{2\pi} \ln\left(\frac{b}{a}\right)$$



$$\text{Stem diameter, } a = 90 [\text{mm}]$$

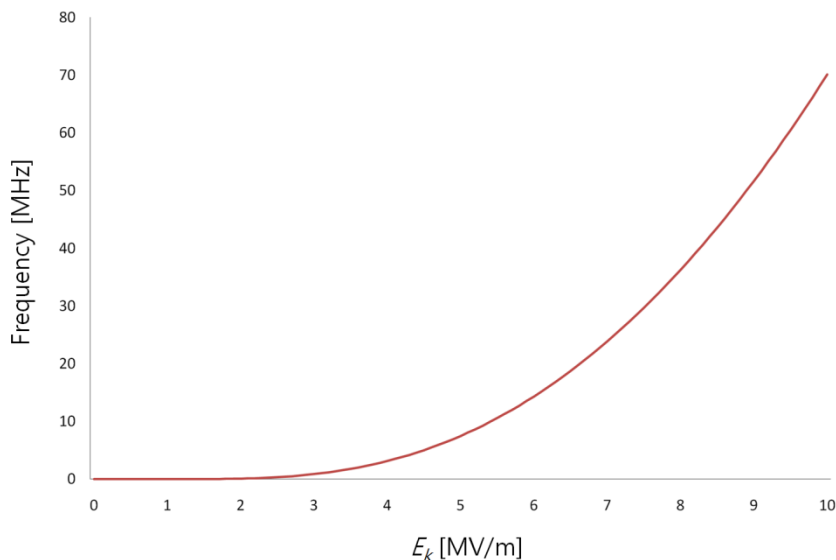
$$\text{Liner diameter, } b = 276 [\text{mm}]$$

■ 고주파 방전

• Kilpatrick Limit

$$f_{rf} = 1.64 E_k^2 e^{-8.5/E_k}$$

$$E_k = 9.685 \text{ [MV/m]}$$



▶ 최대 표면전기장

$$E_s = b E_k = 12.59 \text{ [MV/m]}$$

$$b = 1.3$$

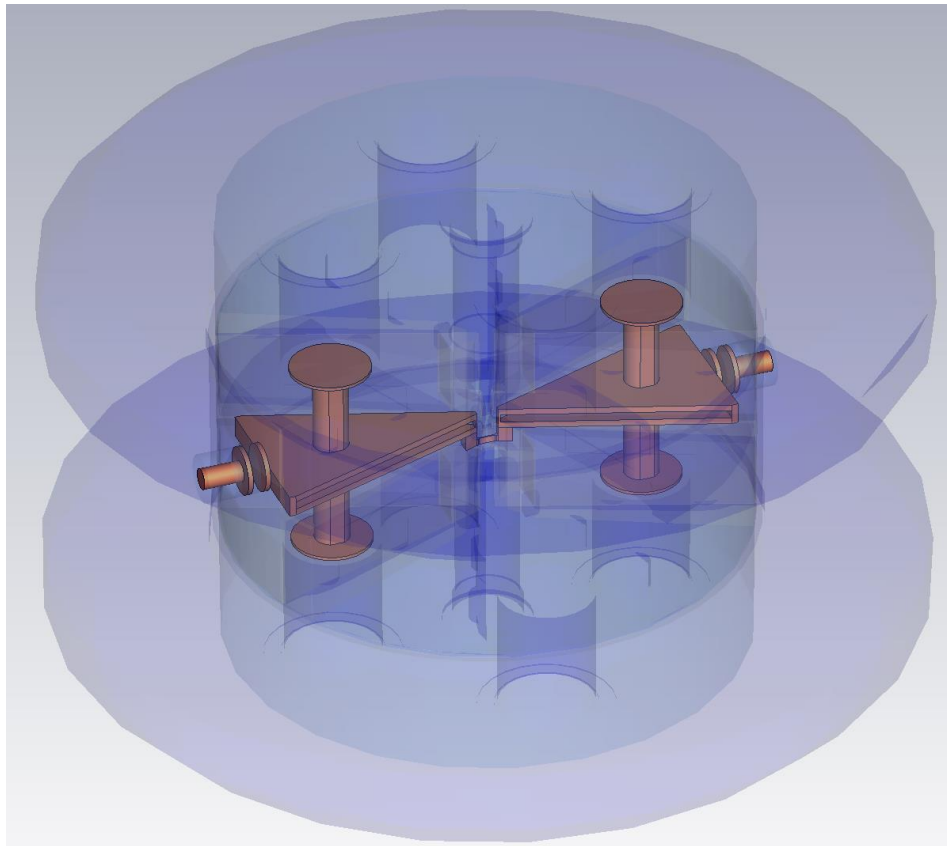
▶ 고주파 방전 예방을 위한 최소 거리

- Dee 전압 50kV

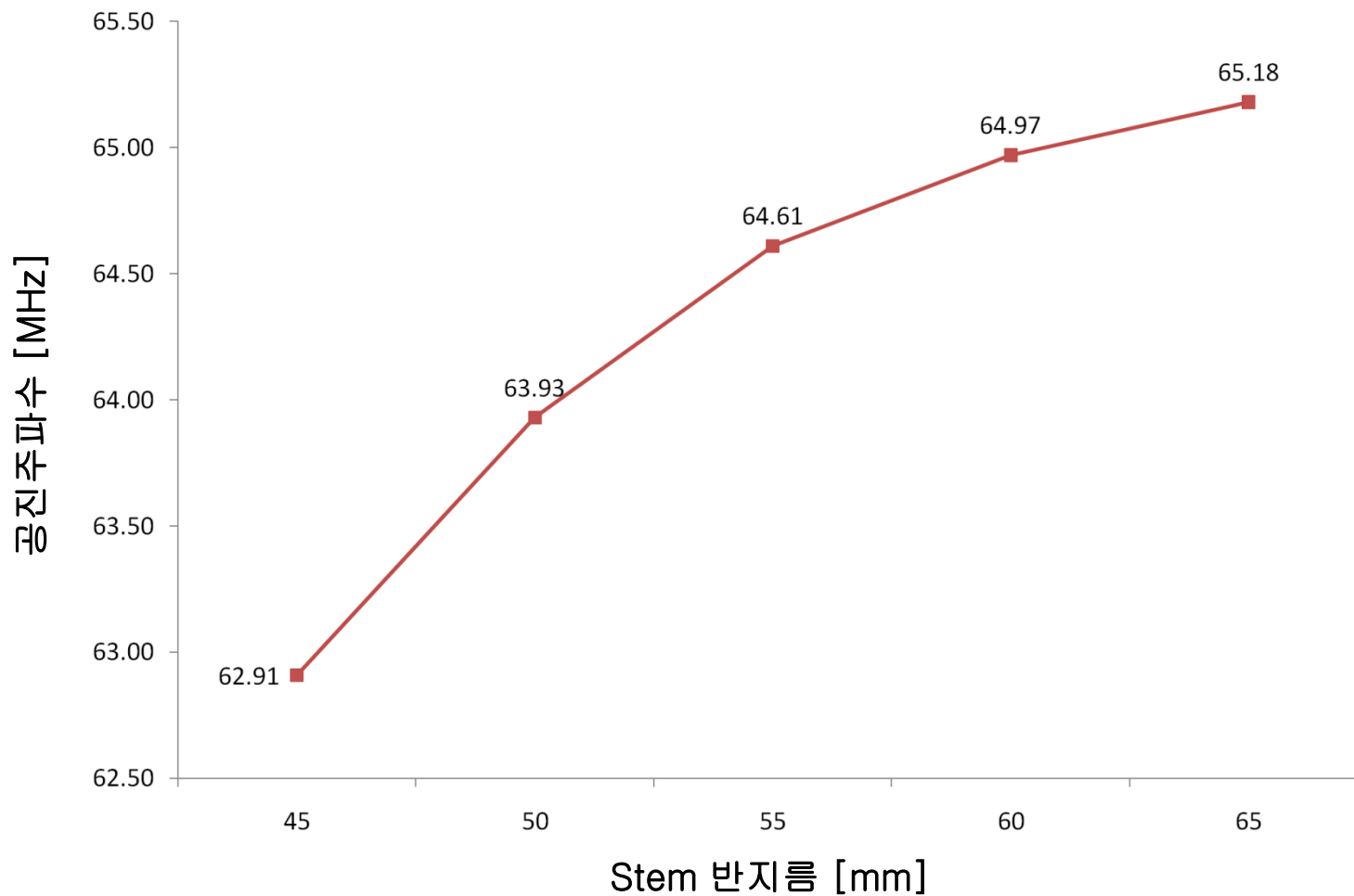
$$d_{\min} = 3.9 \text{ [mm]}$$

■ 시뮬레이션 모델링

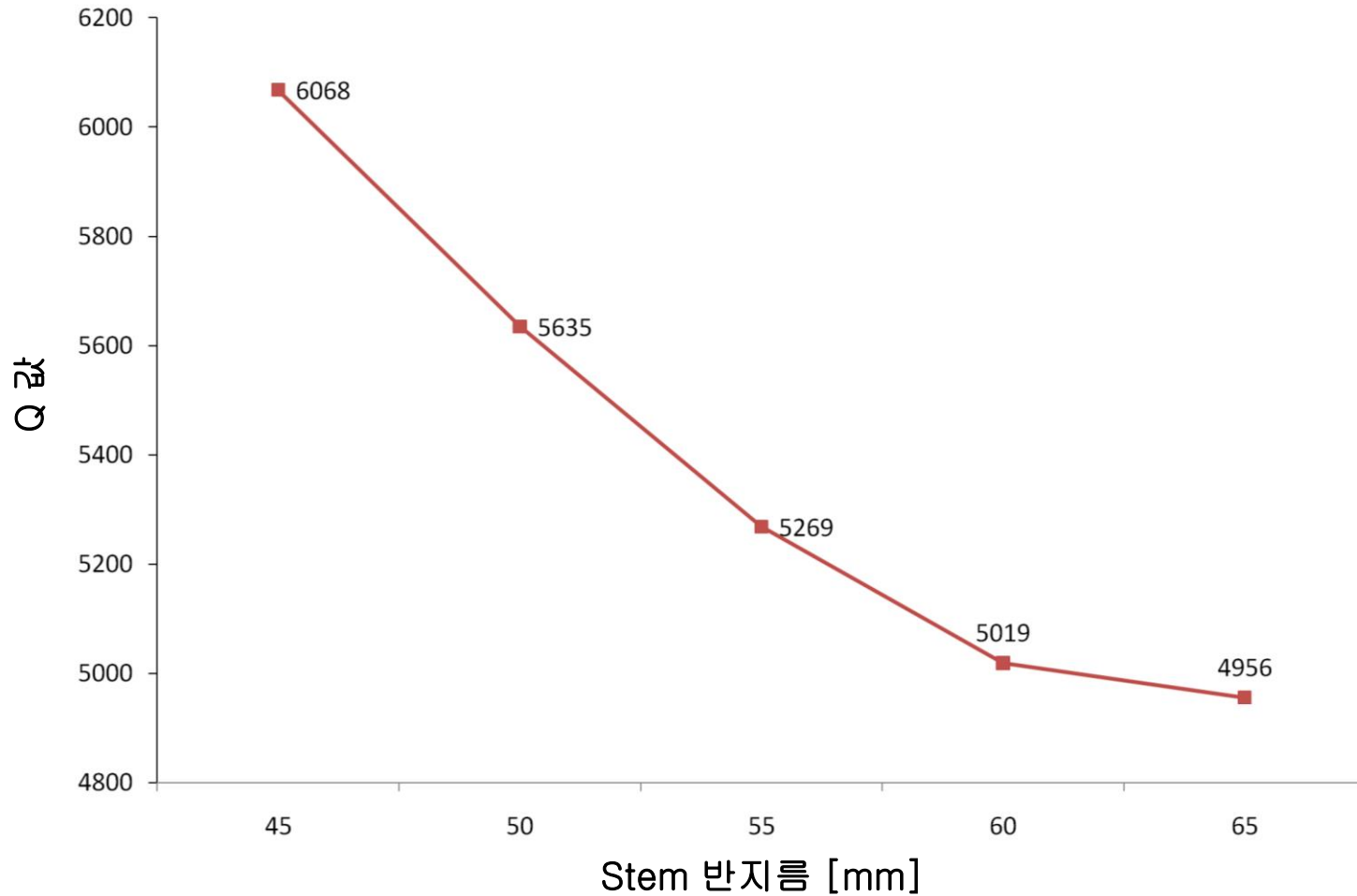
- CST MWS 이용 : 3차원 전자기장 해석툴



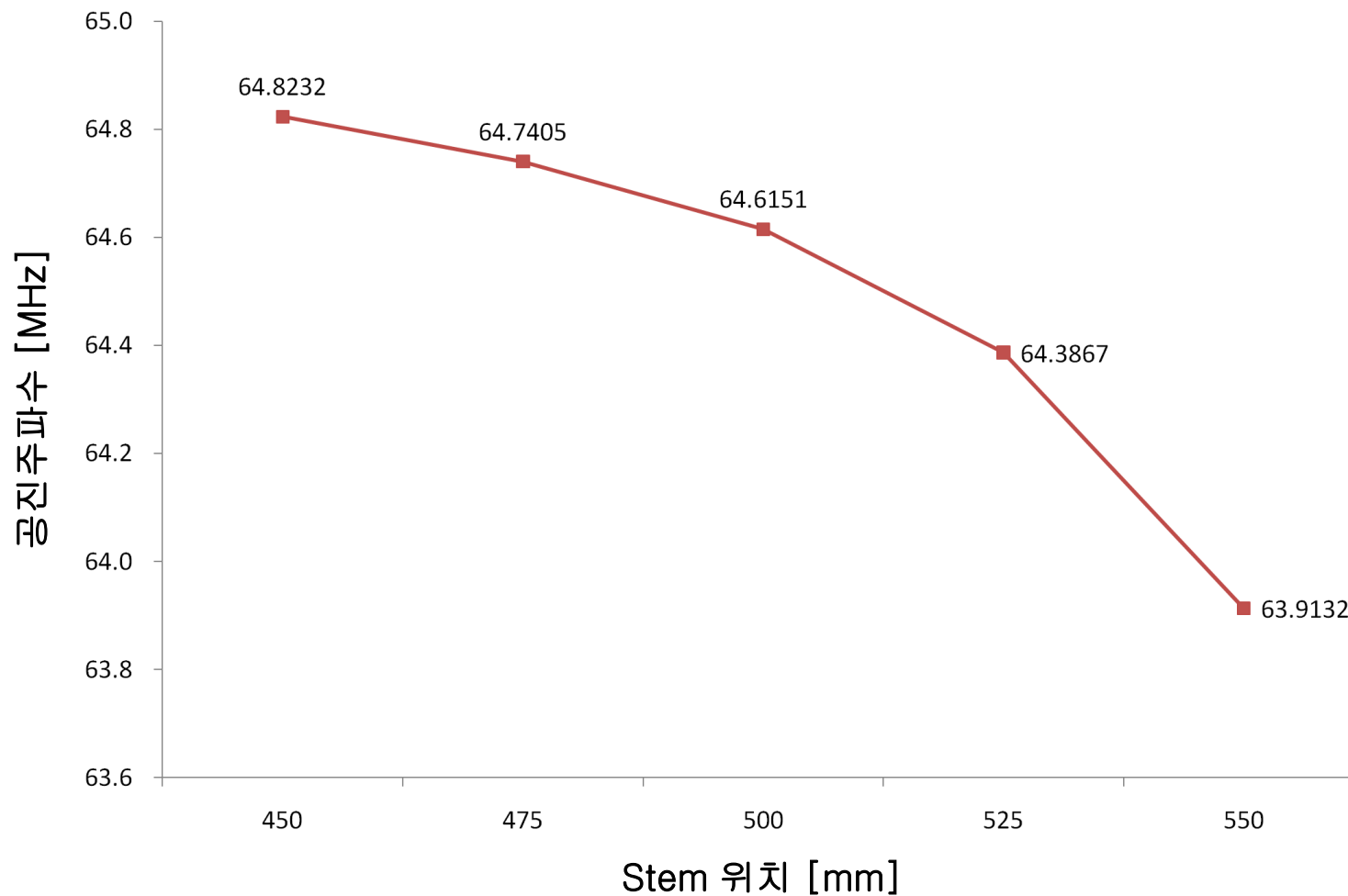
■ Stem 반경에 따른 공진주파수 변화



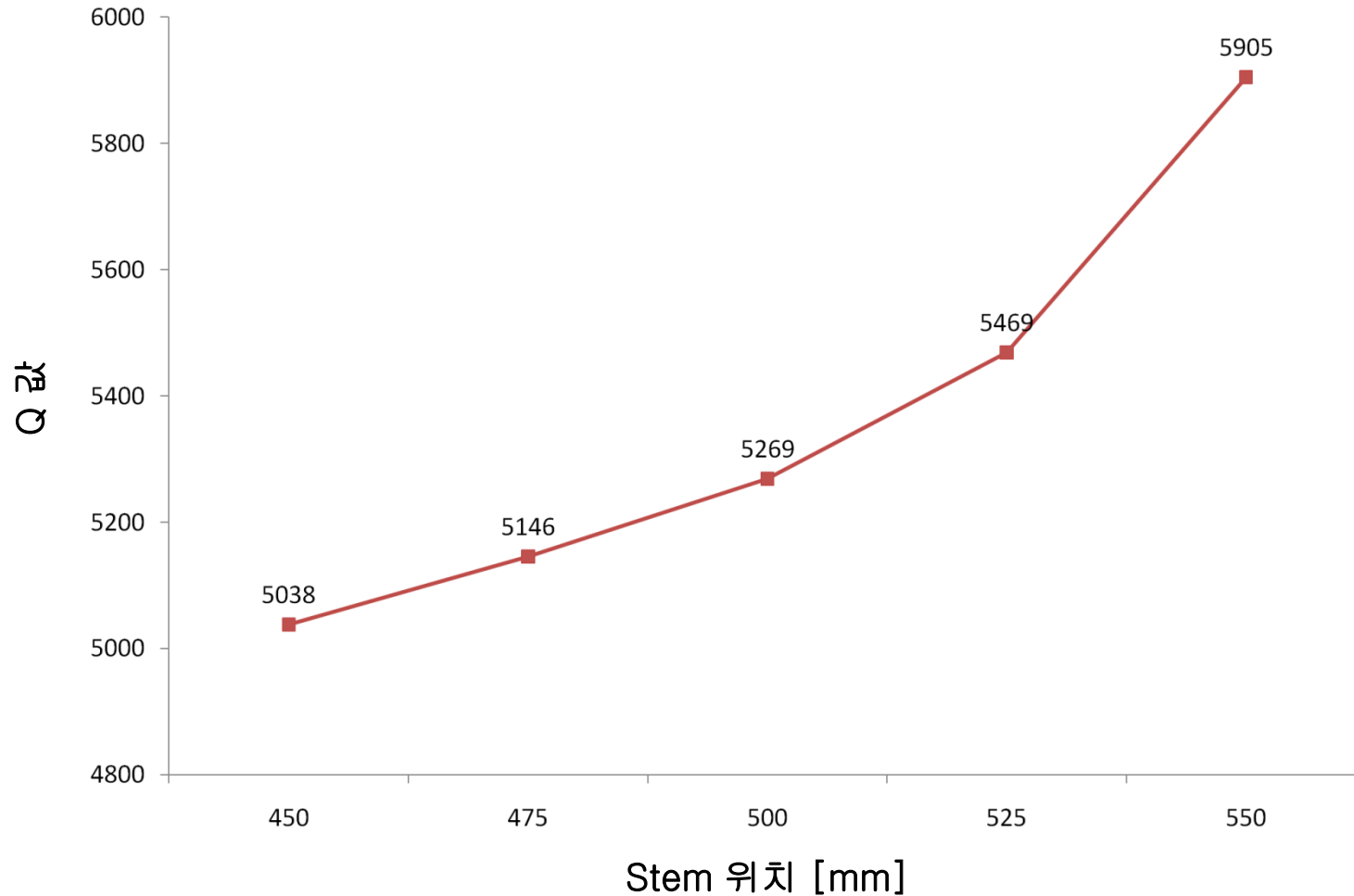
■ Stem 반경에 따른 Q 값 변화



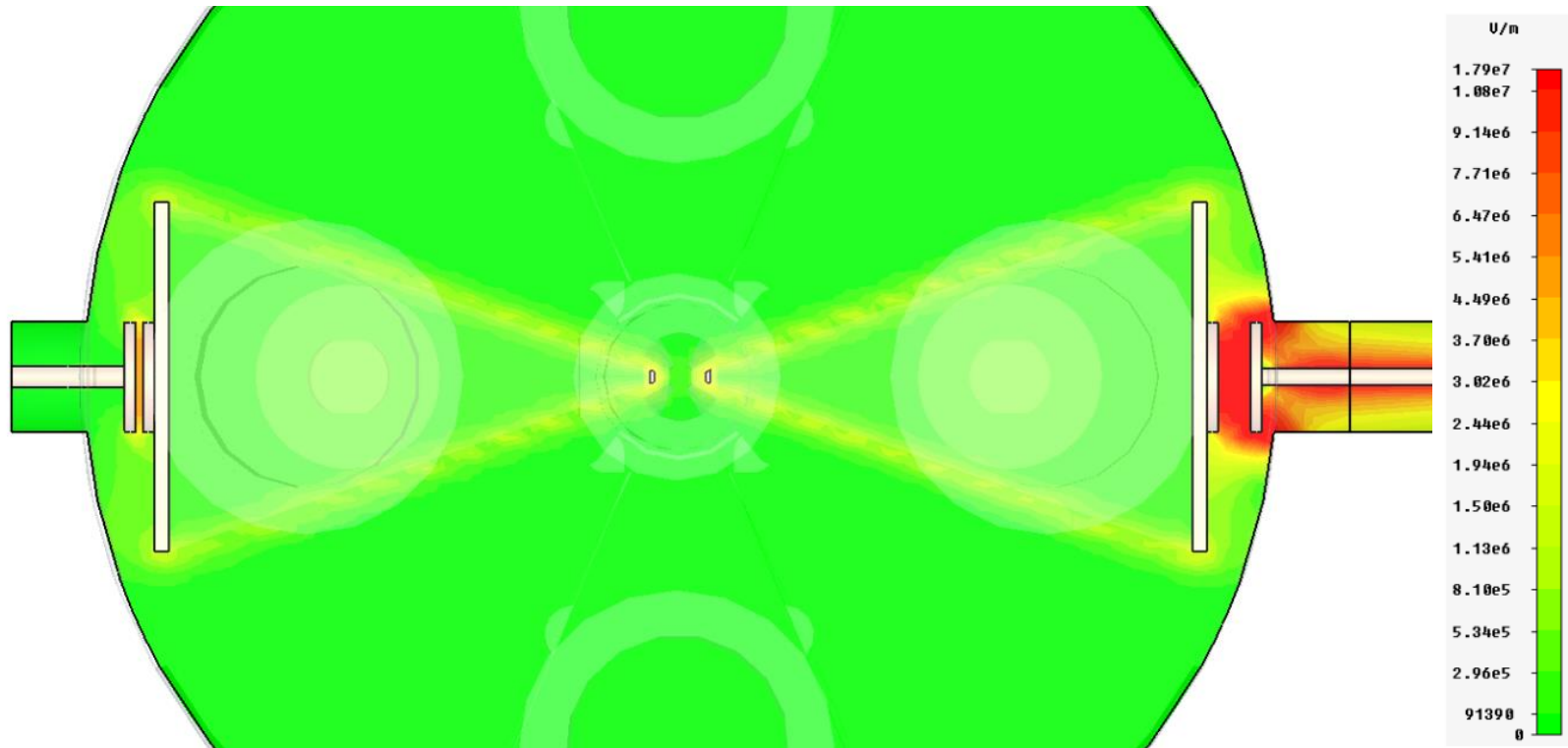
■ Stem 위치에 따른 공진주파수 변화



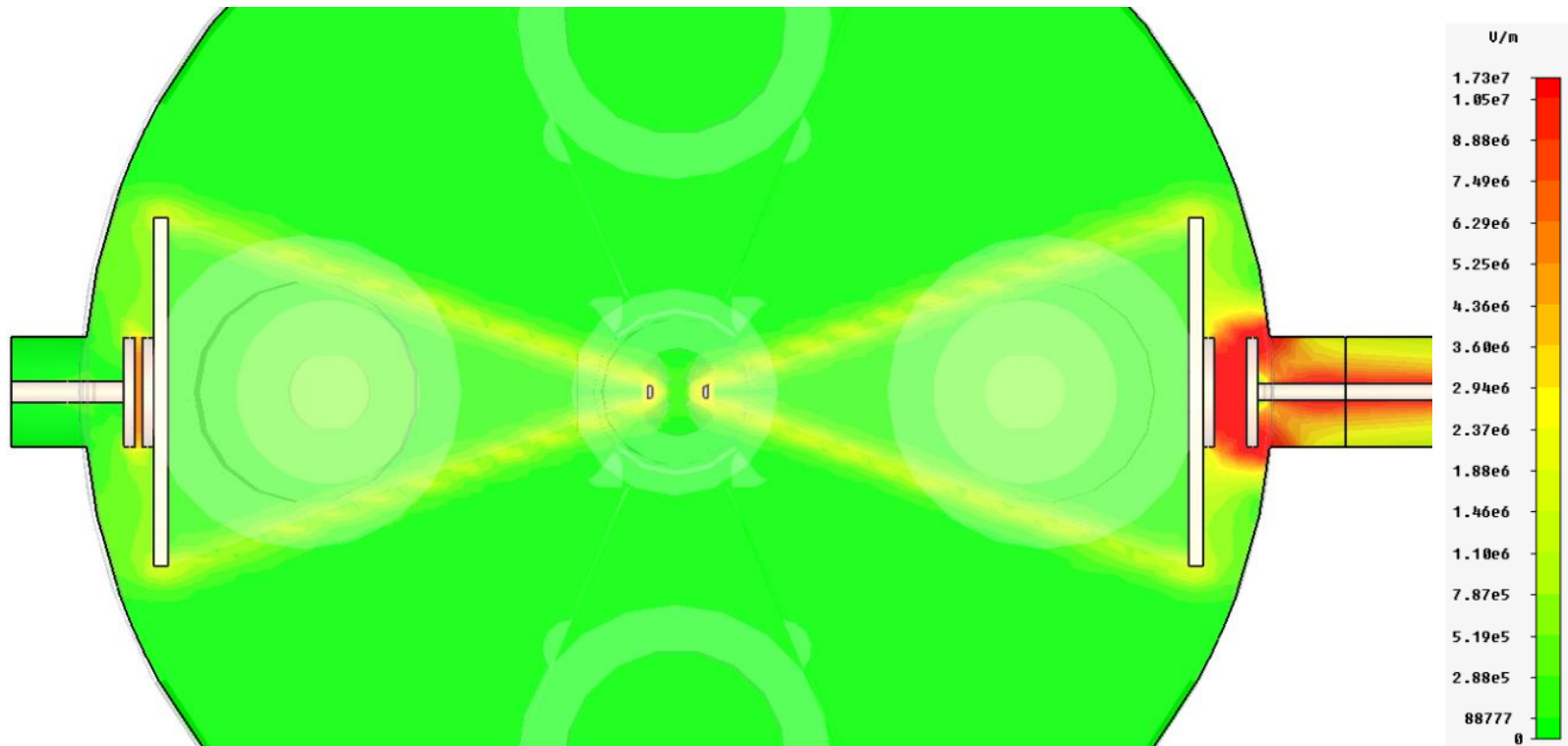
■ Stem 위치에 따른 Q 값 변화



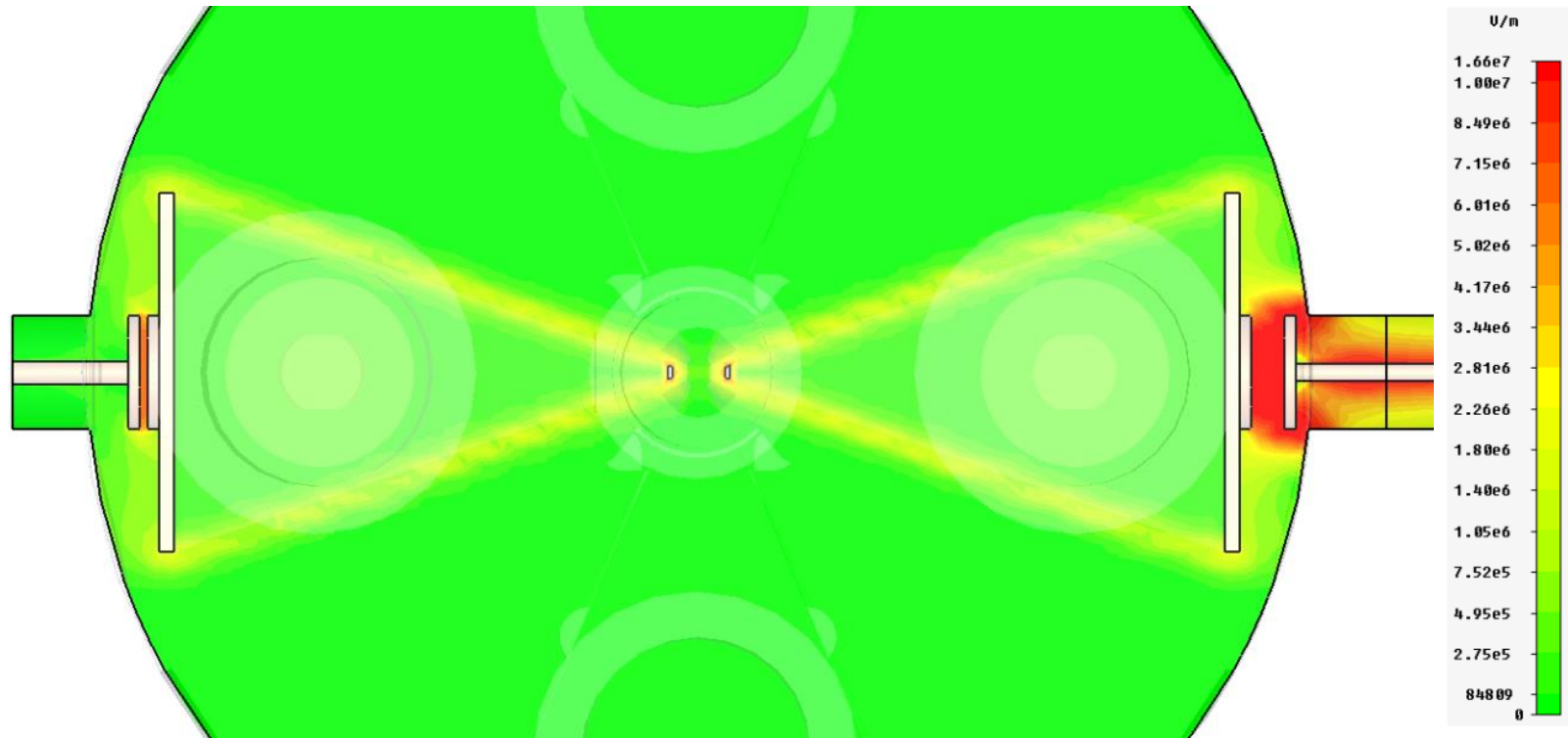
- Stem 위치에 따른 전기장 분포
 - Stem Position = 450 [mm]



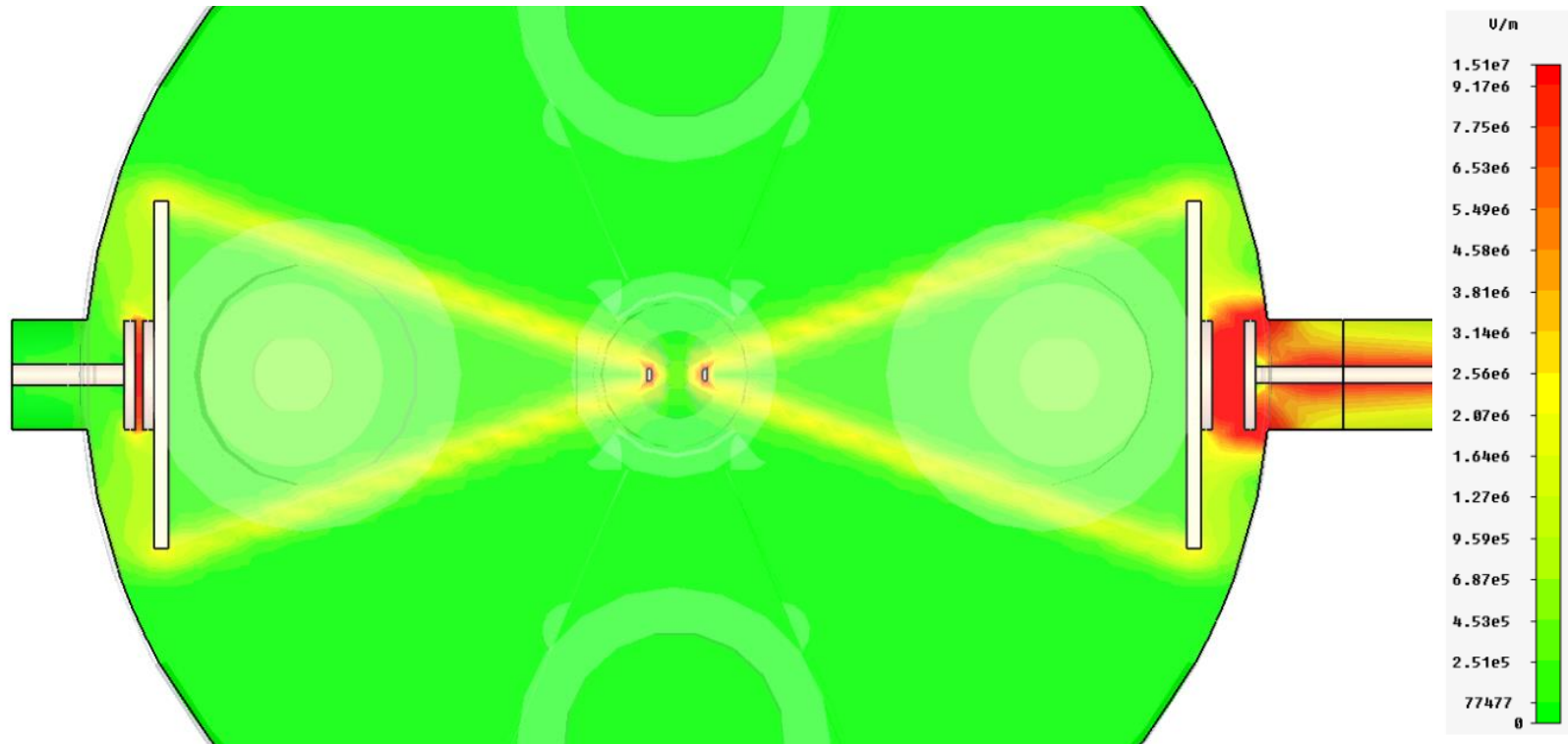
- Stem 위치에 따른 전기장 분포
 - Stem Position = 475 [mm]



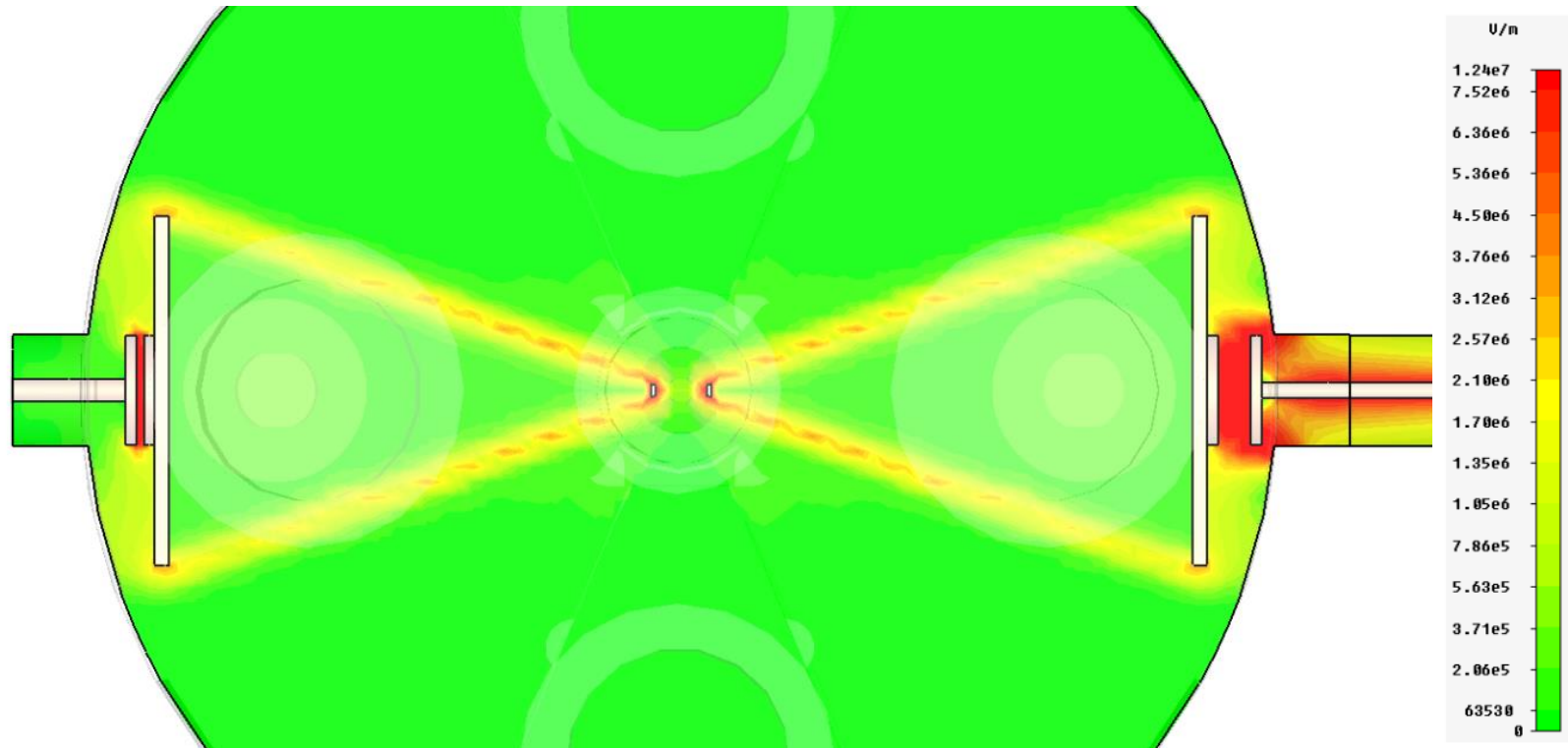
- Stem 위치에 따른 전기장 분포
 - Stem Position = 500 [mm]



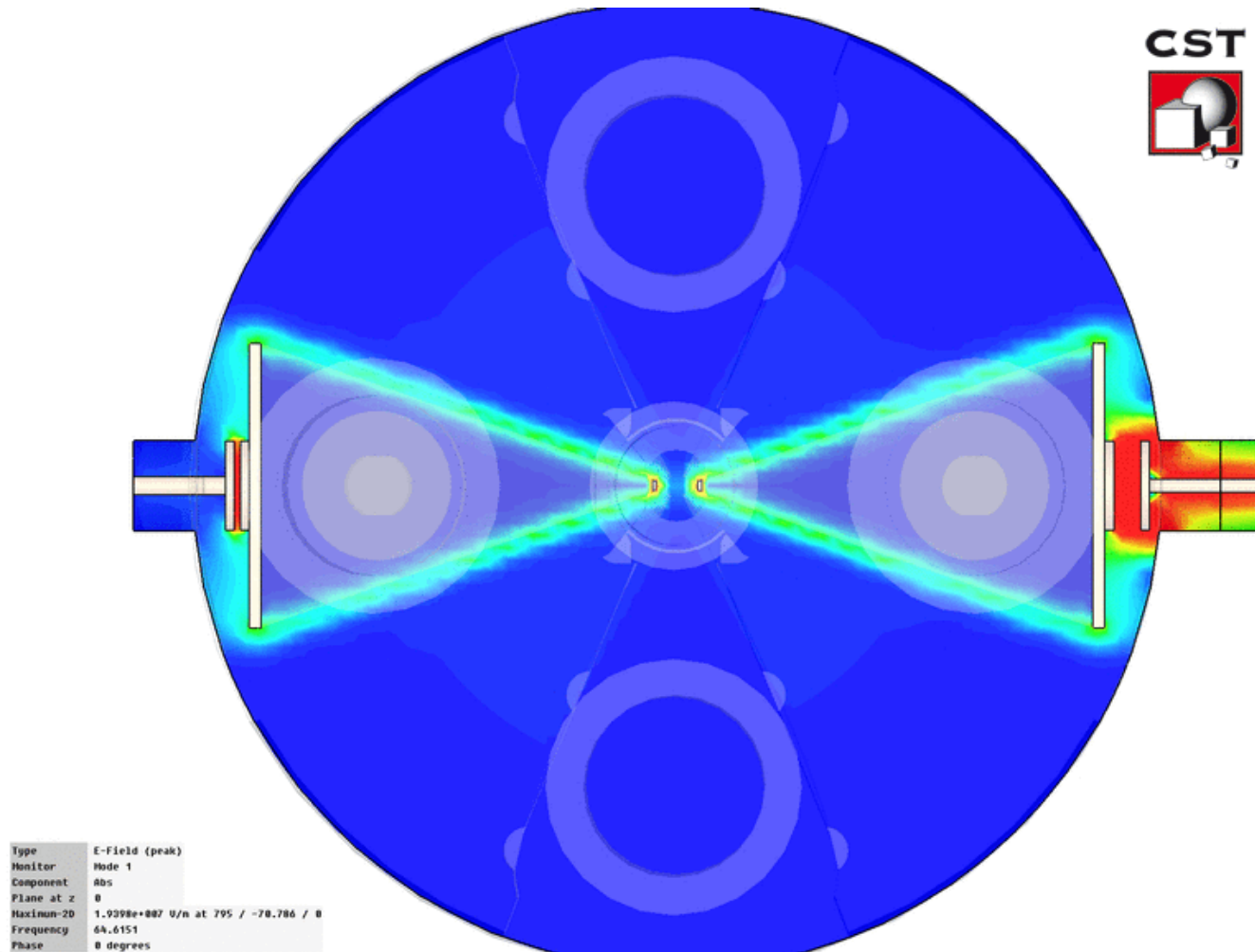
- Stem 위치에 따른 전기장 분포
 - Stem Position = 525 [mm]



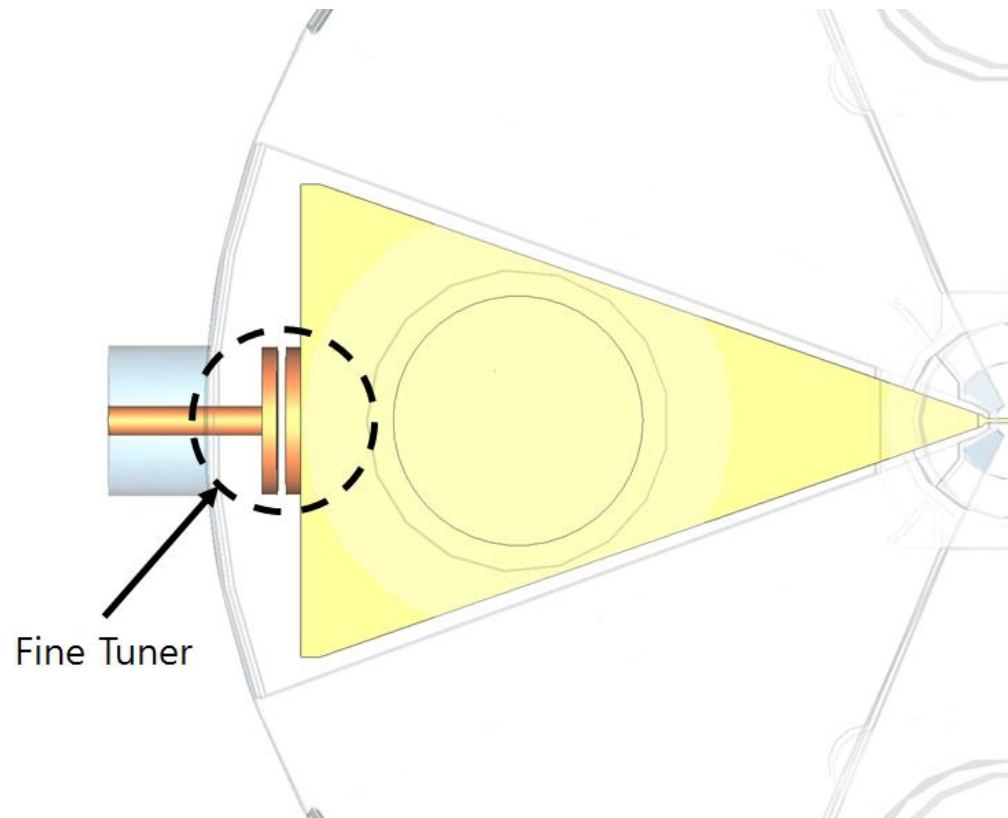
- Stem 위치에 따른 전기장 분포
 - Stem Position = 550 [mm]



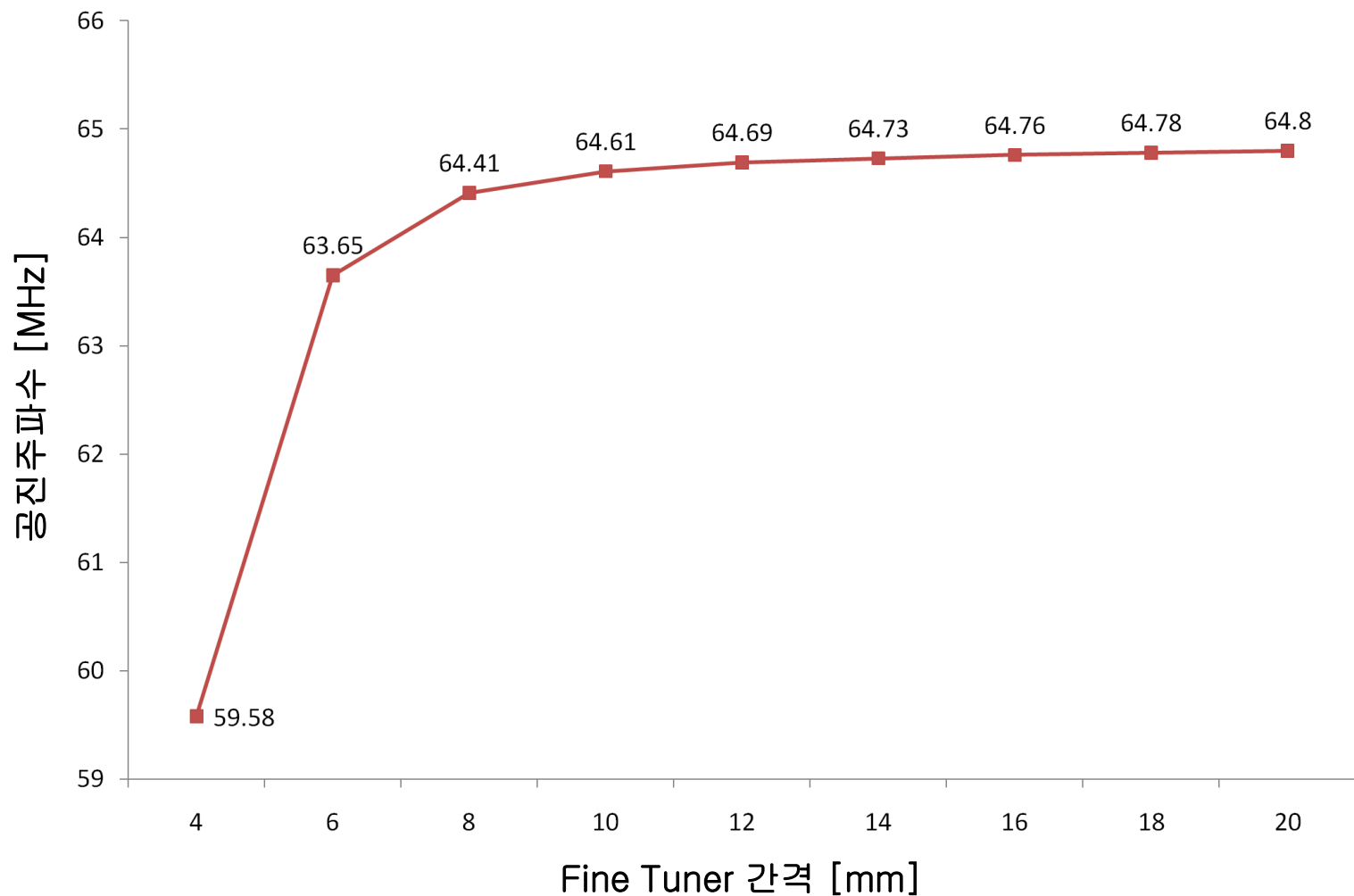
■ Electric Field Distribution



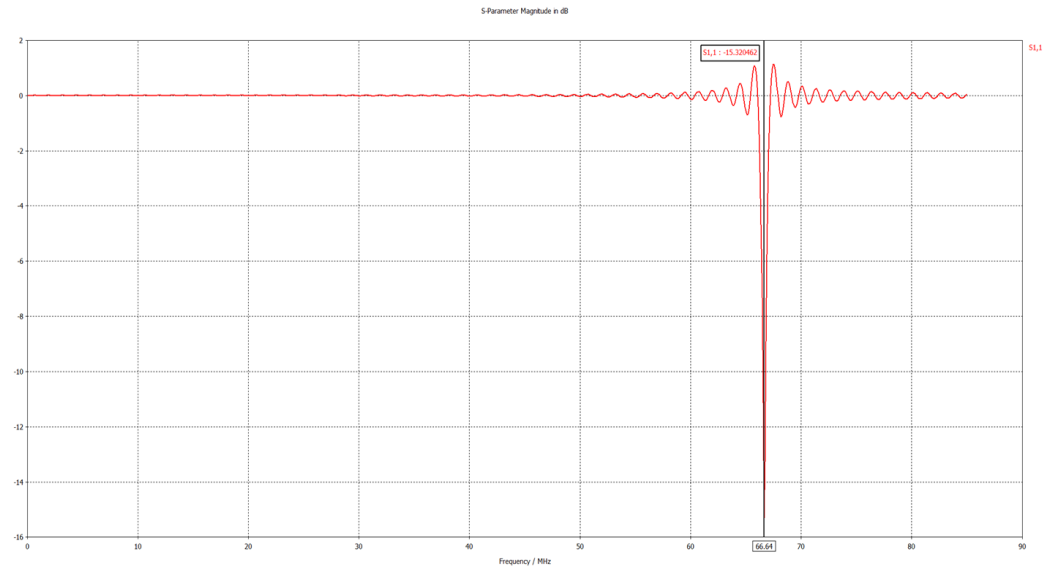
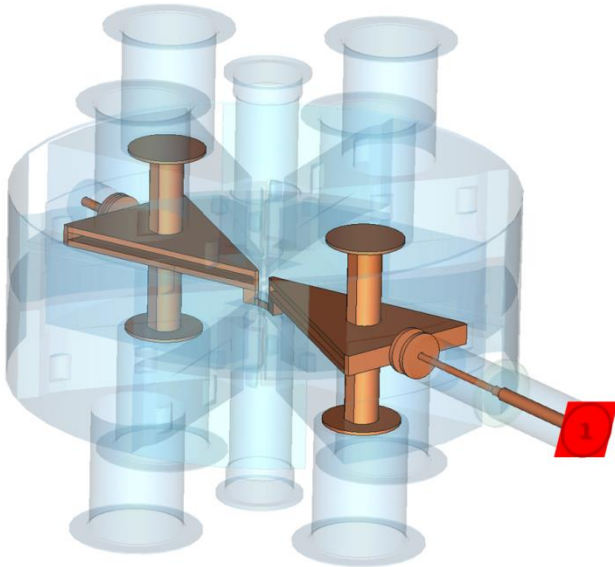
- Fine Tuner 구조
 - 공진주파수 유지



■ Fine Tuner 간격 변화에 따른 공진주파수 변화

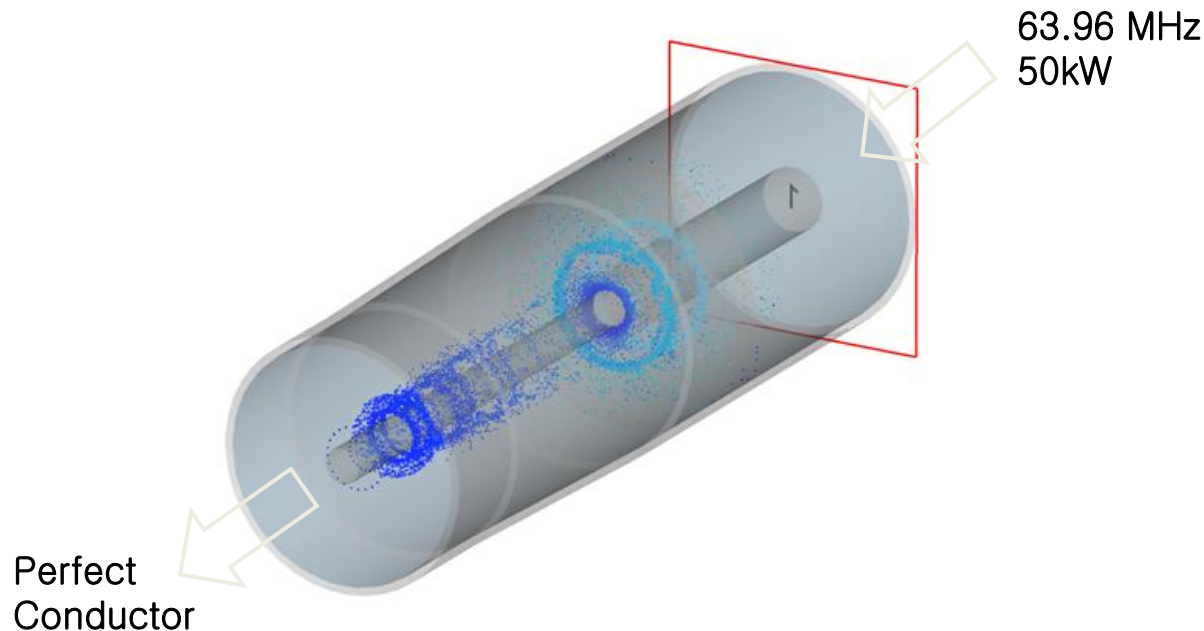


- Power Coupler 전력 전달 해석
 - CST MWS 사용

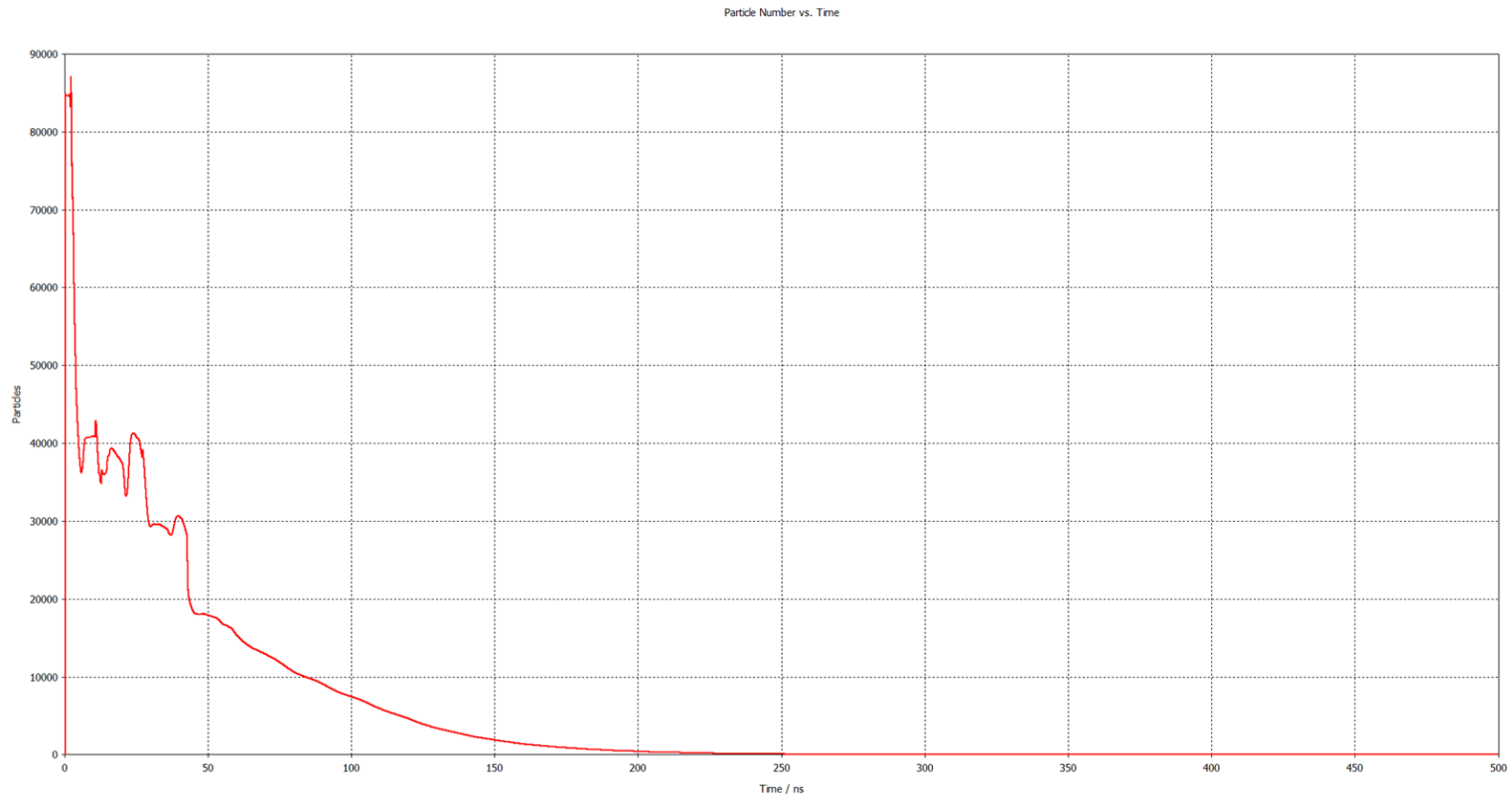


■ Power Coupler의 Multipacting 현상 해석

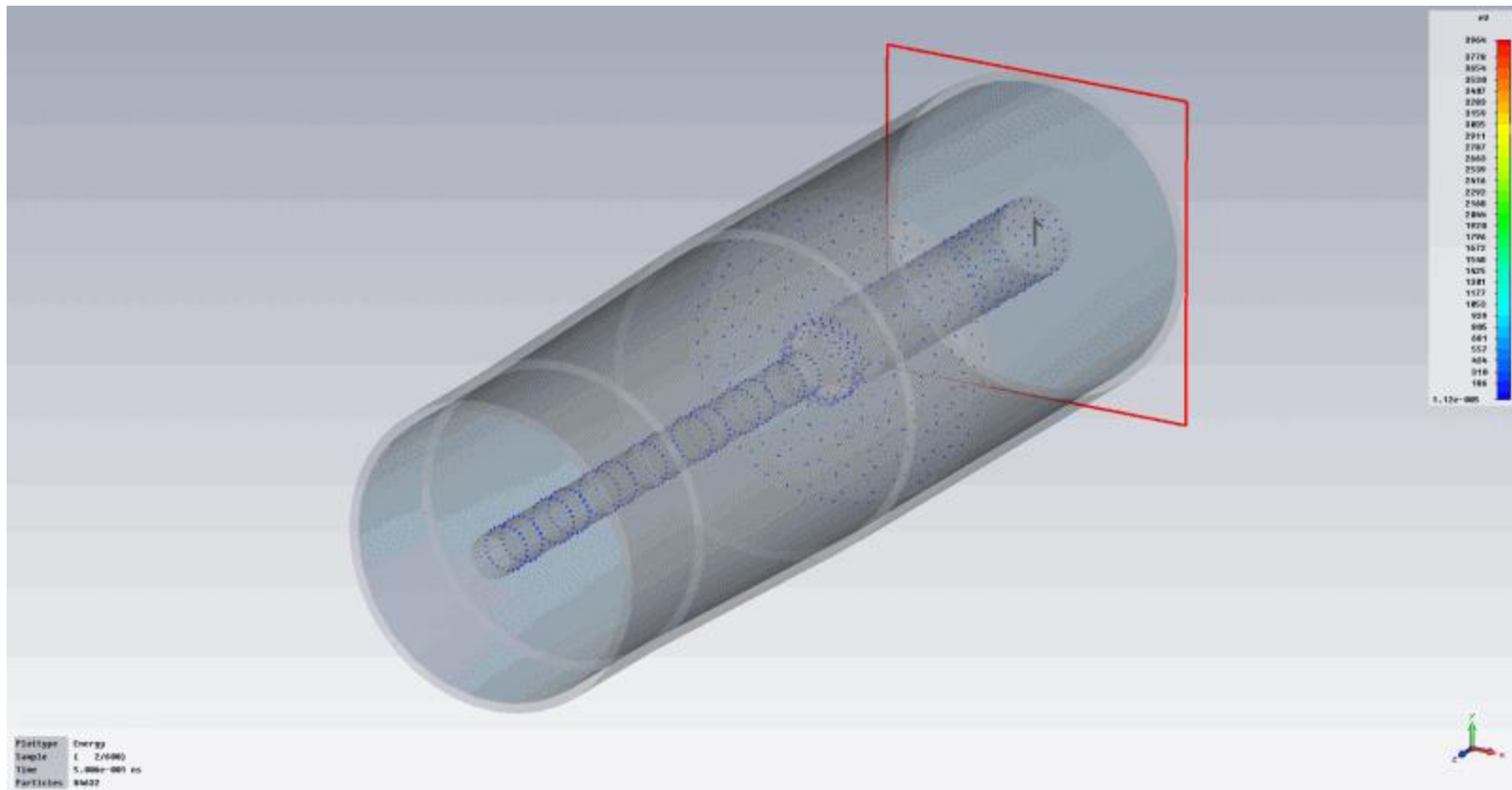
- 내외부 도파관 재질 : Copper (SEY : 1.2)
- 진공 윈도우 재질 : SiO_2 (SEY : 3.5)
- 입력 신호 : 63.96MHz, 50kW
- 도파관 내부도체 및 진공 윈도우 표면에서 전자방출 : 초기 에너지 10eV



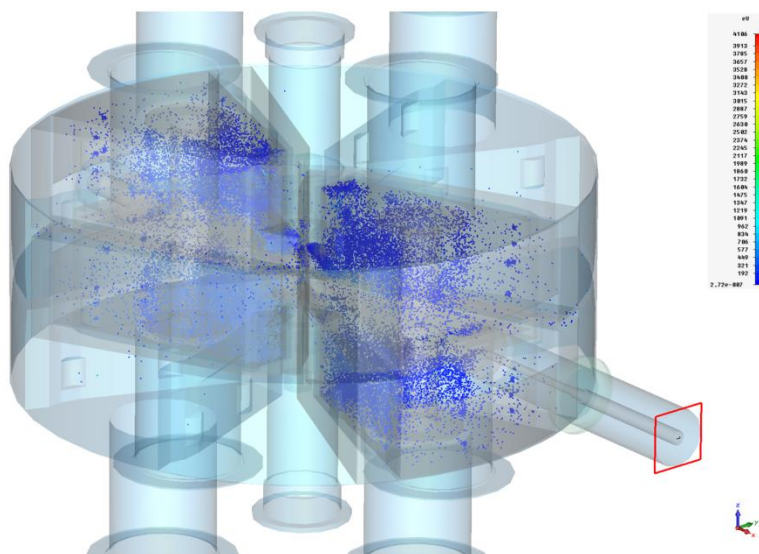
- Power Coupler의 Multipacting 현상 해석
 - 시간에 따른 전자 수



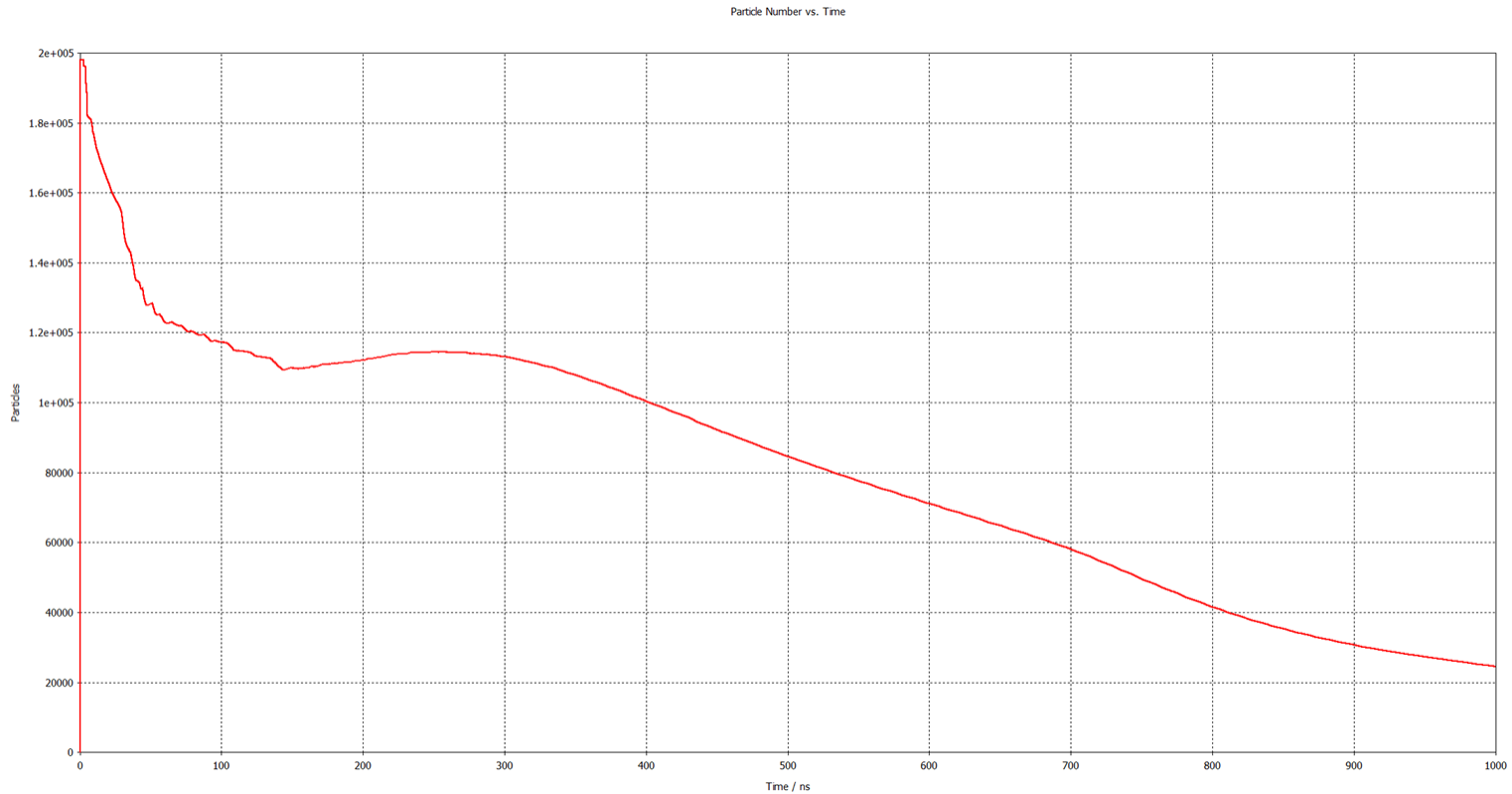
- Power Coupler의 Multipacting 현상 해석
 - 전자 궤적



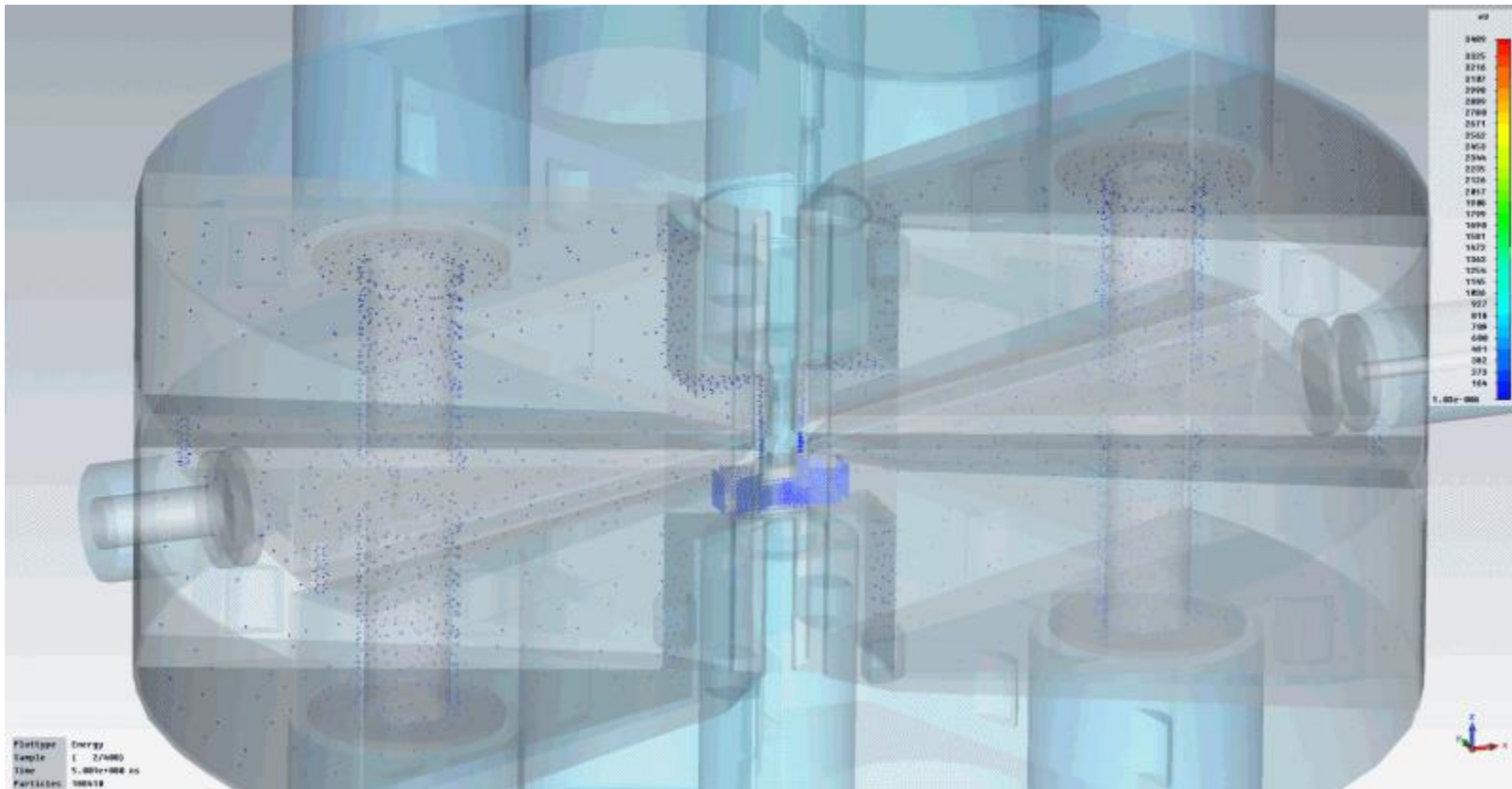
- 사이클로트론 내부의 Multipacting 현상 해석
 - 고주파시스템 재질 : Copper (SEY : 1.2)
 - 진공 챔버 재질 : Aluminum (SEY : 3.5)
 - 전자석 재질 : Iron (SEY : 3.5)
 - 입력신호 : 63.96MHz, 50kW
 - Dee, Stem & Liner 표면에서 전자방출 : 초기 에너지 10eV



- 사이클로트론 내부의 Multipacting 현상 해석
 - 시간에 따른 전자 수

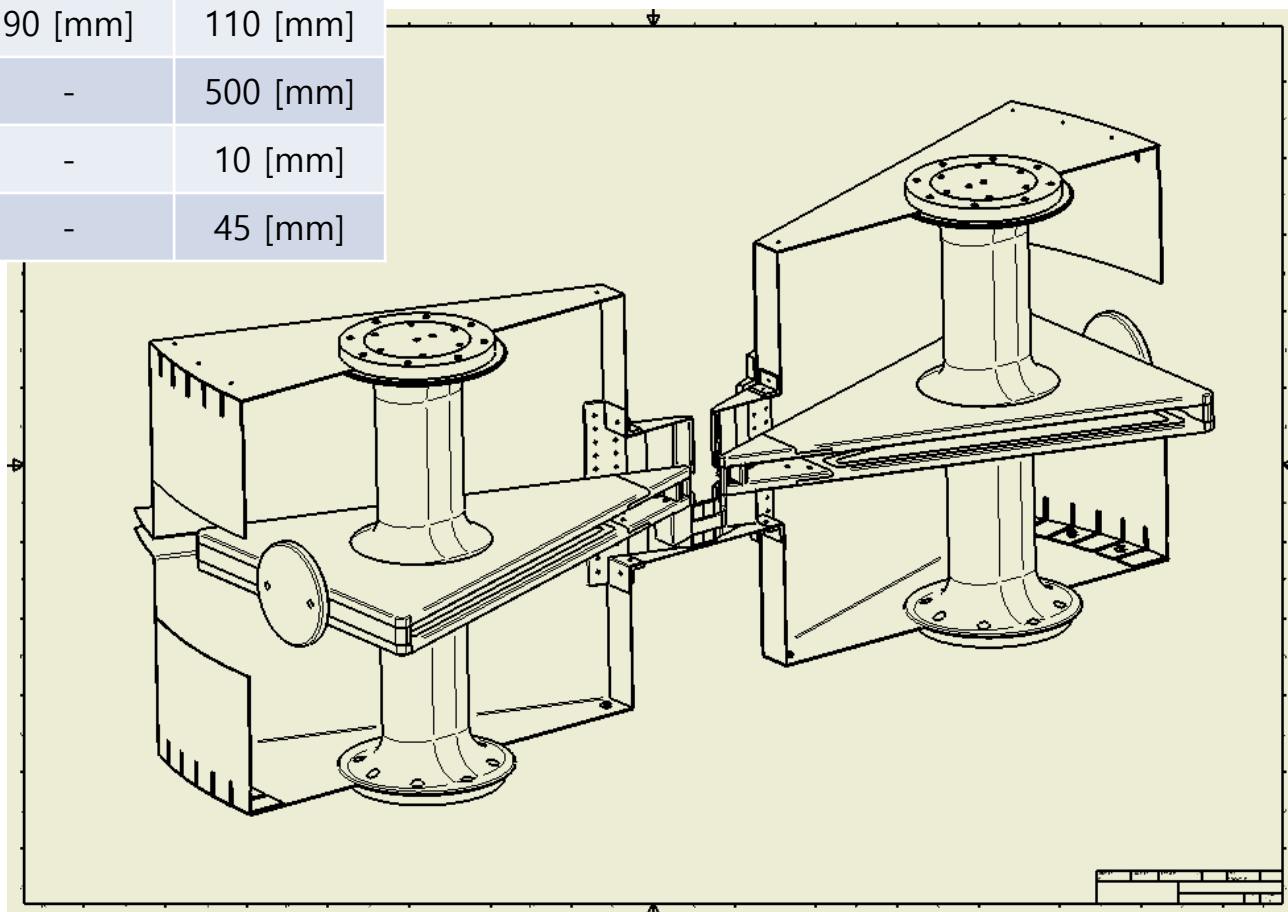


- 사이클로트론 내부의 Multipacting 현상 해석
 - 전자 궤적



■ 최종 설계안

	초기안	설계안
Stem 길이	664 [mm]	616 [mm]
Stem 지름	90 [mm]	110 [mm]
Stem 위치	-	500 [mm]
Fine Tuner 간격	-	10 [mm]
Power Coupler 간격	-	45 [mm]



■ 제작시 고려 사항

- 기계적 안정성 및 가공성
- 고주파 전력 전달로 인한 열 발생 및 냉각시스템
- 유지보수의 간편성
- 제작단가

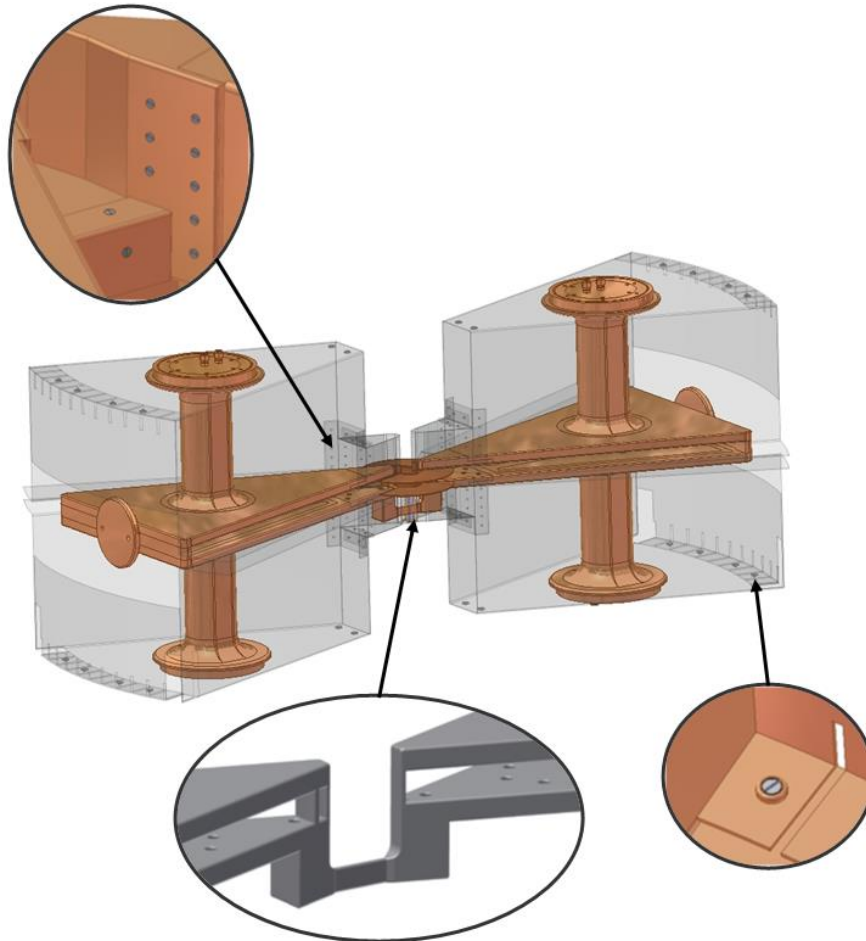
■ 재질에 따른 물리적 특성

	Electrical Conductivity	Thermal Conductivity	Mechanical Stiffness	Secondary Emission Yield
OFHC COPPER	$5.8 \times 10^9 (\Omega\text{m})^{-1}$	400 W/m/K	1.2×10^{10} daN/m ²	Good
COPPER on STEEL	$5.0 \times 10^9 (\Omega\text{m})^{-1}$	20 W/m/K	2.1×10^{10} daN/m ²	Good
PURE ALUMINUM	$3.7 \times 10^9 (\Omega\text{m})^{-1}$	220 W/m/K	0.7×10^{10} daN/m ²	Bad

■ 재질에 따른 공학적 특성

	Availability Cost	Machinability Formability	Weldability Brazability	Vacuum Outgassing Rate
OFHC COPPER	Expensive 40 EUR/kg	Good	Good	1.5×10^{-11}
COPPER on STEEL	Cheep 4 EUR/kg	Good	Very Good	1.5×10^{-10}
PURE ALUMINUM	Rather cheap 10 EUR/kg	Good	Bad	1.5×10^{-11}

■ 고주파 방전

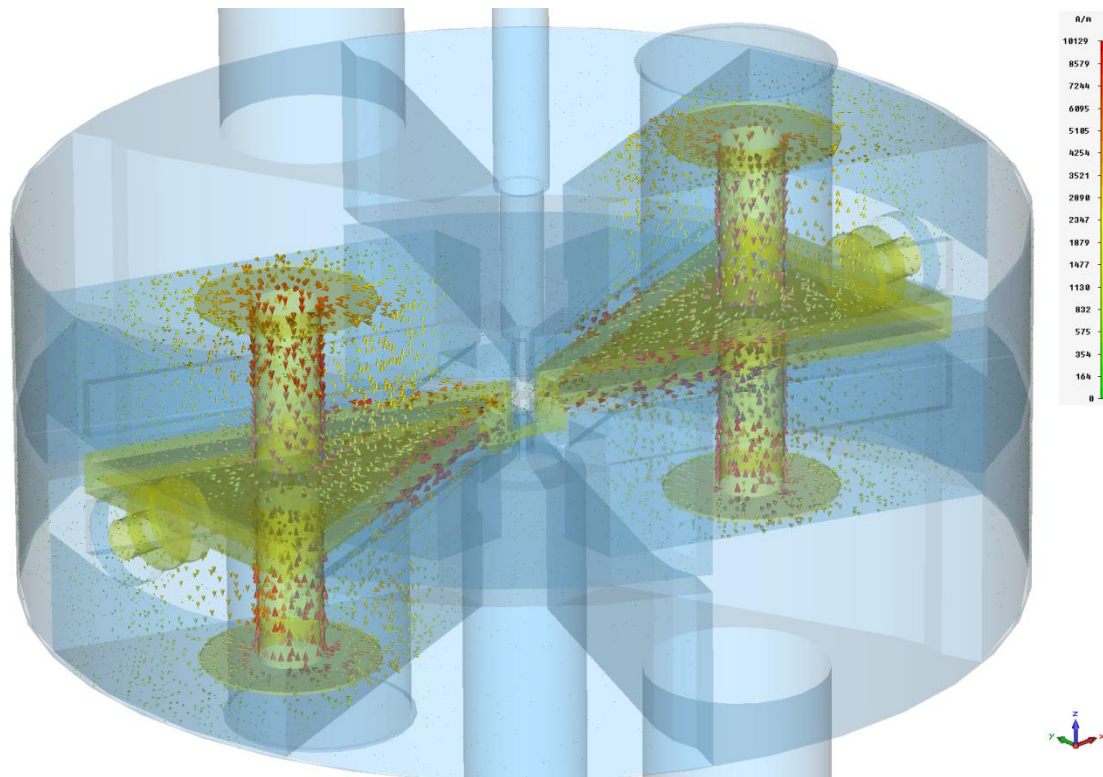


■ Multipacting

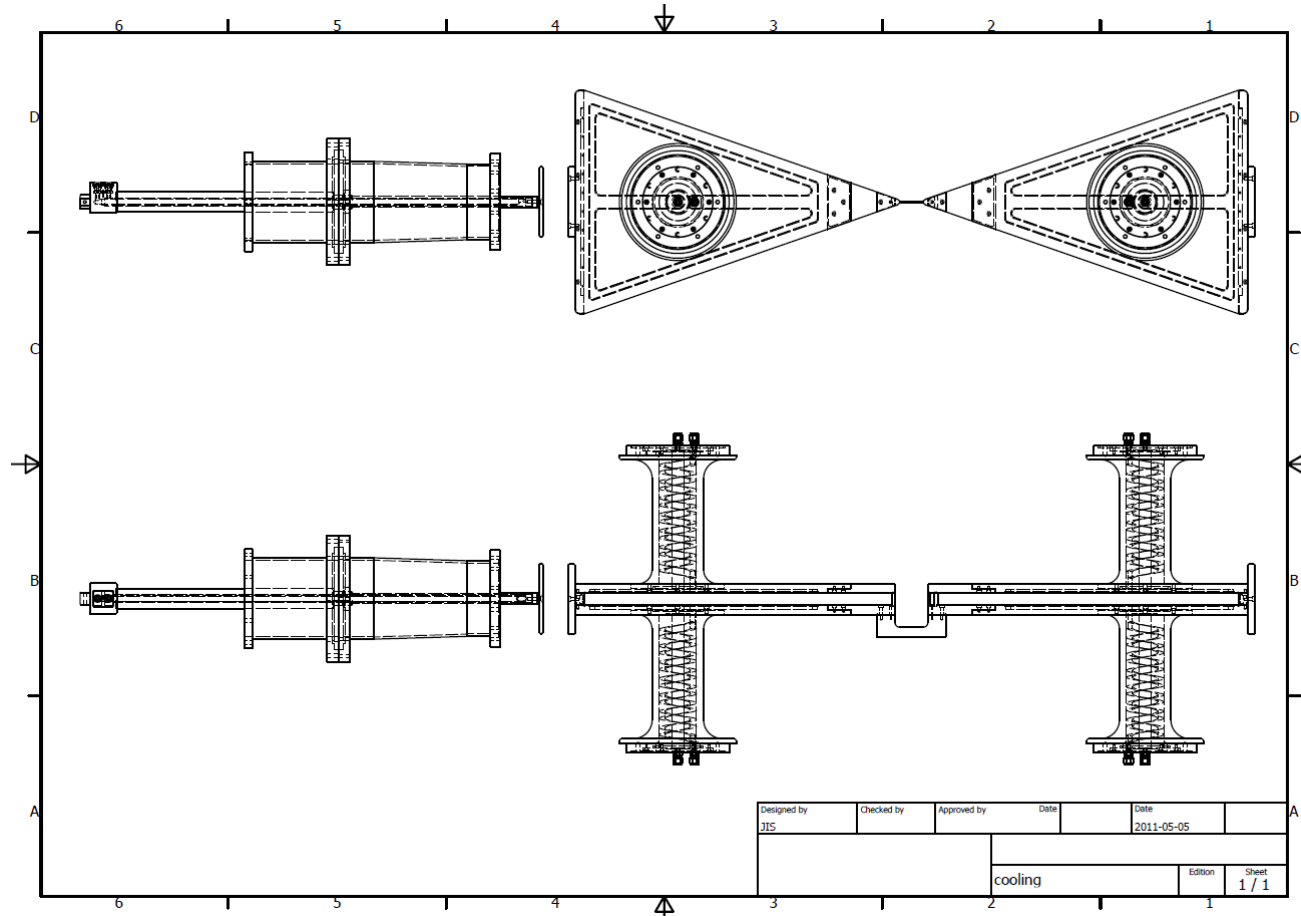
- ▶ 표면 정밀 가공
- ▶ 기계 래핑 공정 추가

■ 열 발생 및 냉각시스템

- 고주파 공진구조내 표면전류 분포

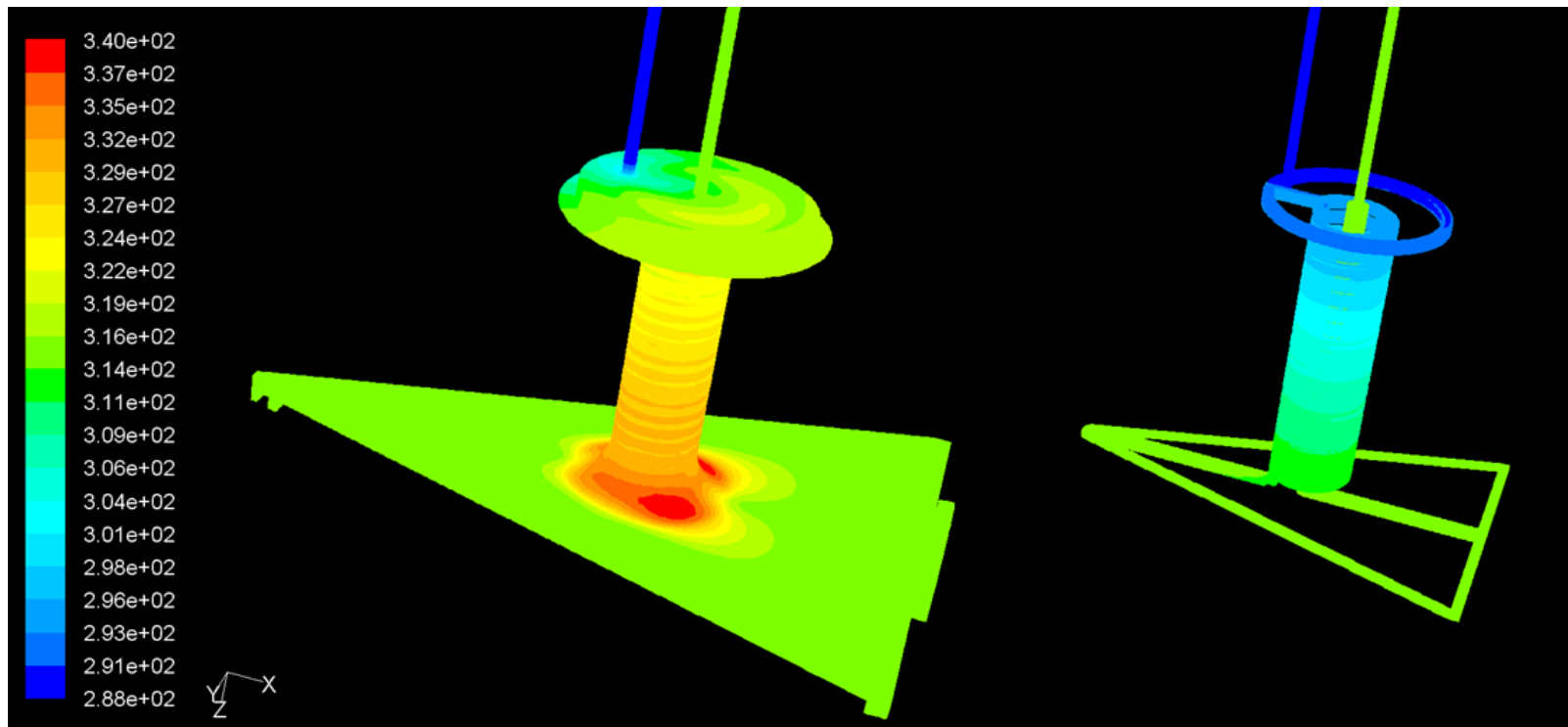


■ 냉각라인 설계

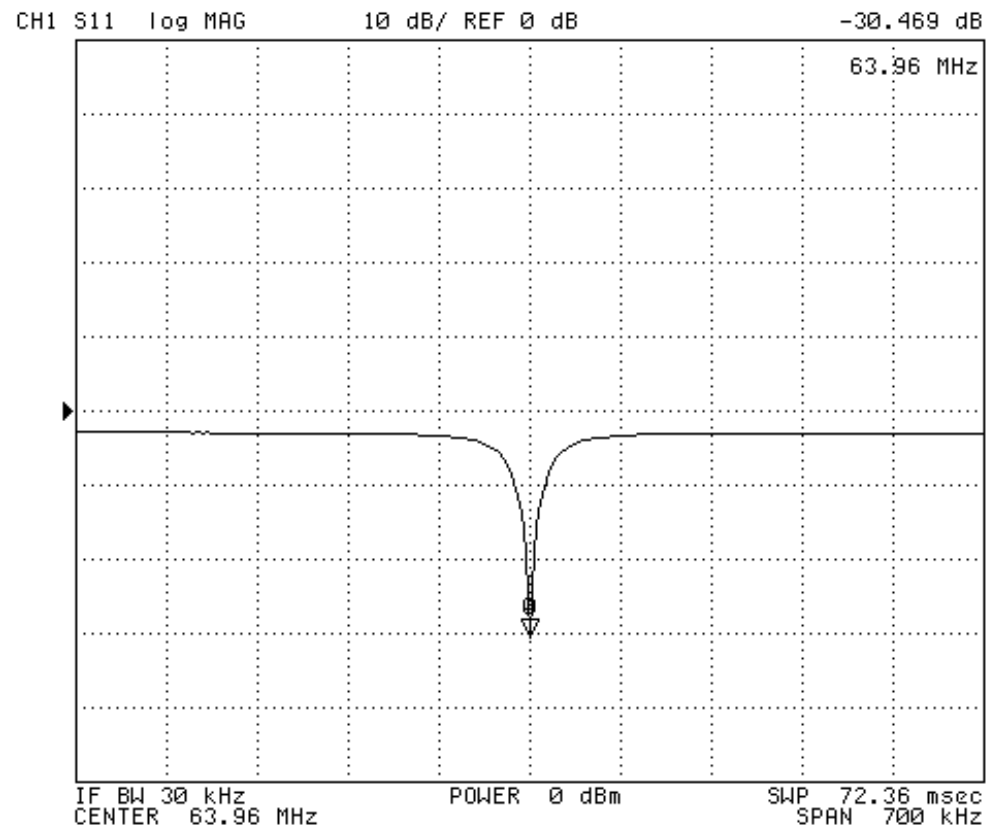


■ 열해석

- ANSYS Fluent
- 도체 표면 열량 : 50kW
- 입력 냉각수 온도 : 15 degree



■ 고주파 주파수



SELECT
LETTER

SPACE

BACK
SPACE

ERASE
TITLE

DONE

STOR DEV
[DISK]

CANCEL

■ 특성 임피던스

CH1 S11 FScI 1 U 50.196 Ω 3.6595 Ω 9.1061 nH
63.96 MHz

SELECT
LETTER

SPACE

BACK
SPACE

ERASE
TITLE

DONE

STOR DEV
[DISK]

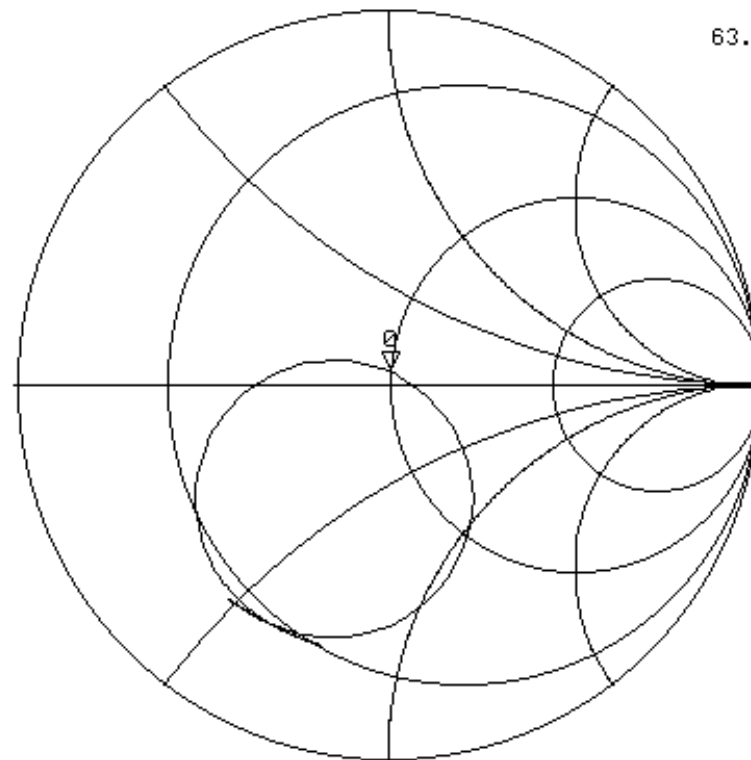
CANCEL

↑

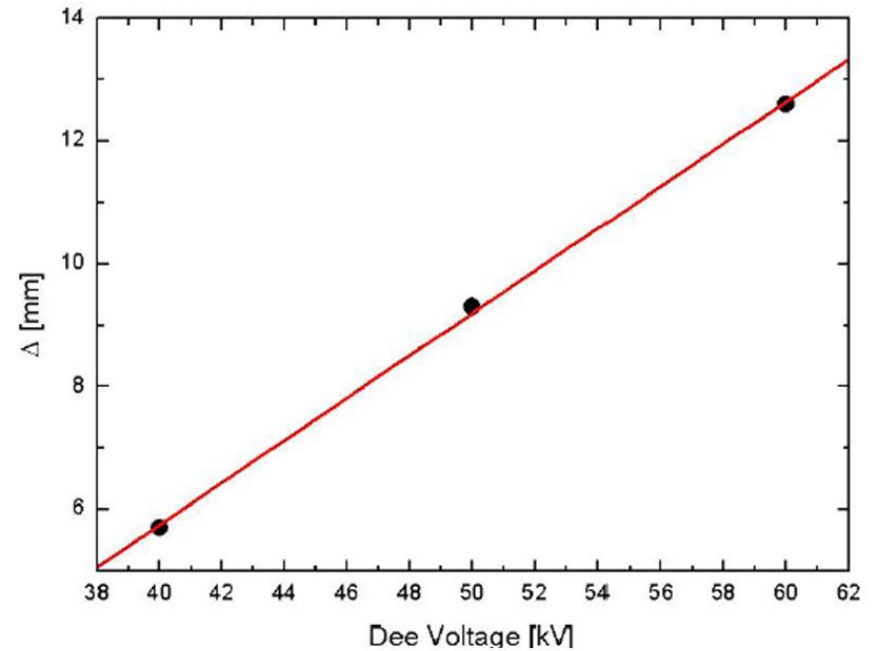
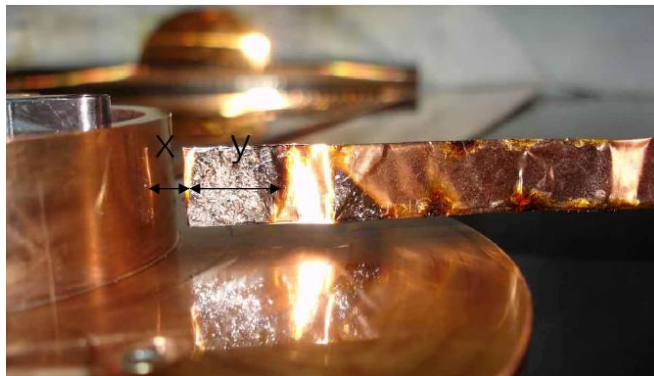
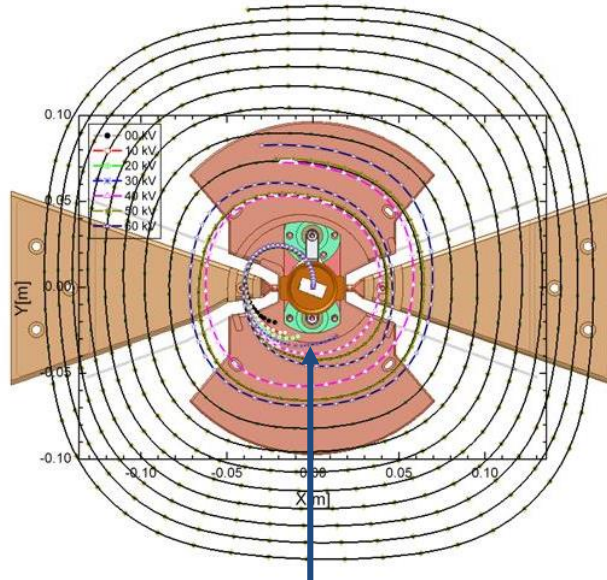
IF BW 30 kHz
CENTER 63.96 MHz

POWER 0 dBm

SWP 72.36 msec
SPAN 700 kHz

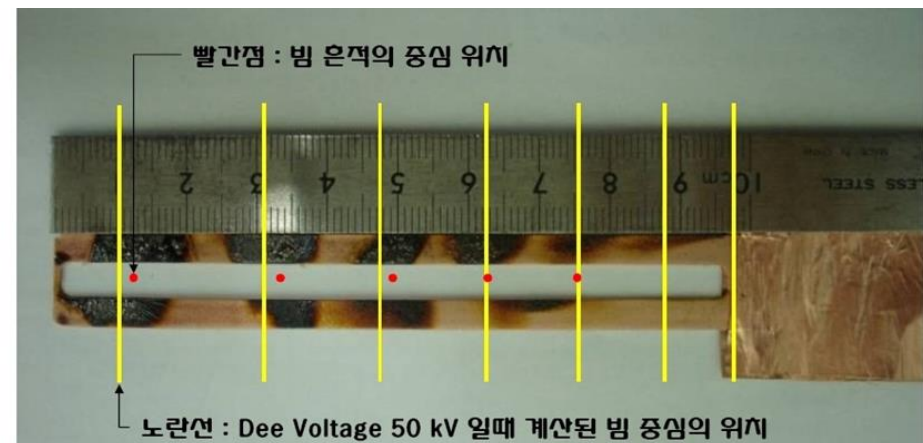
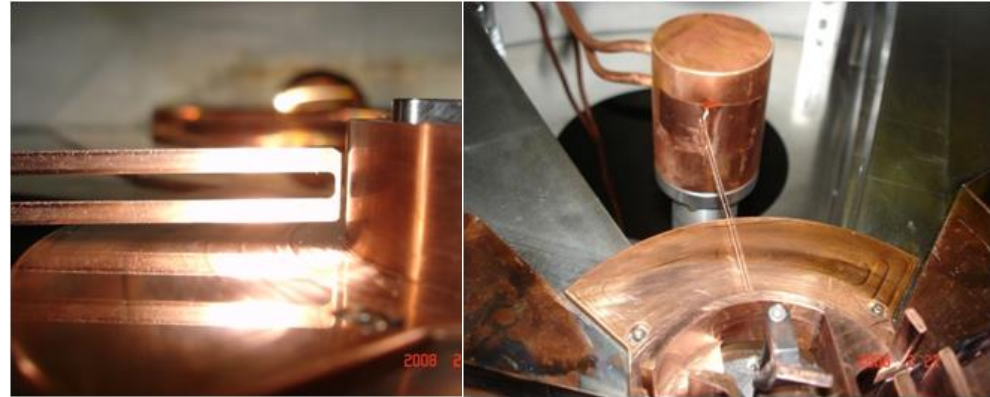
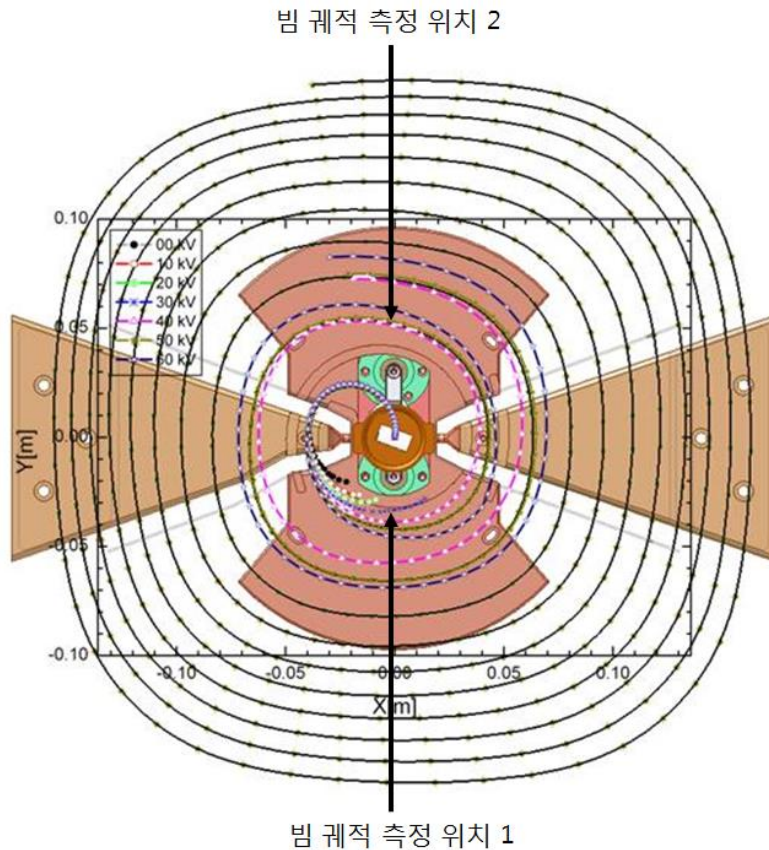


Dee 전압 측정

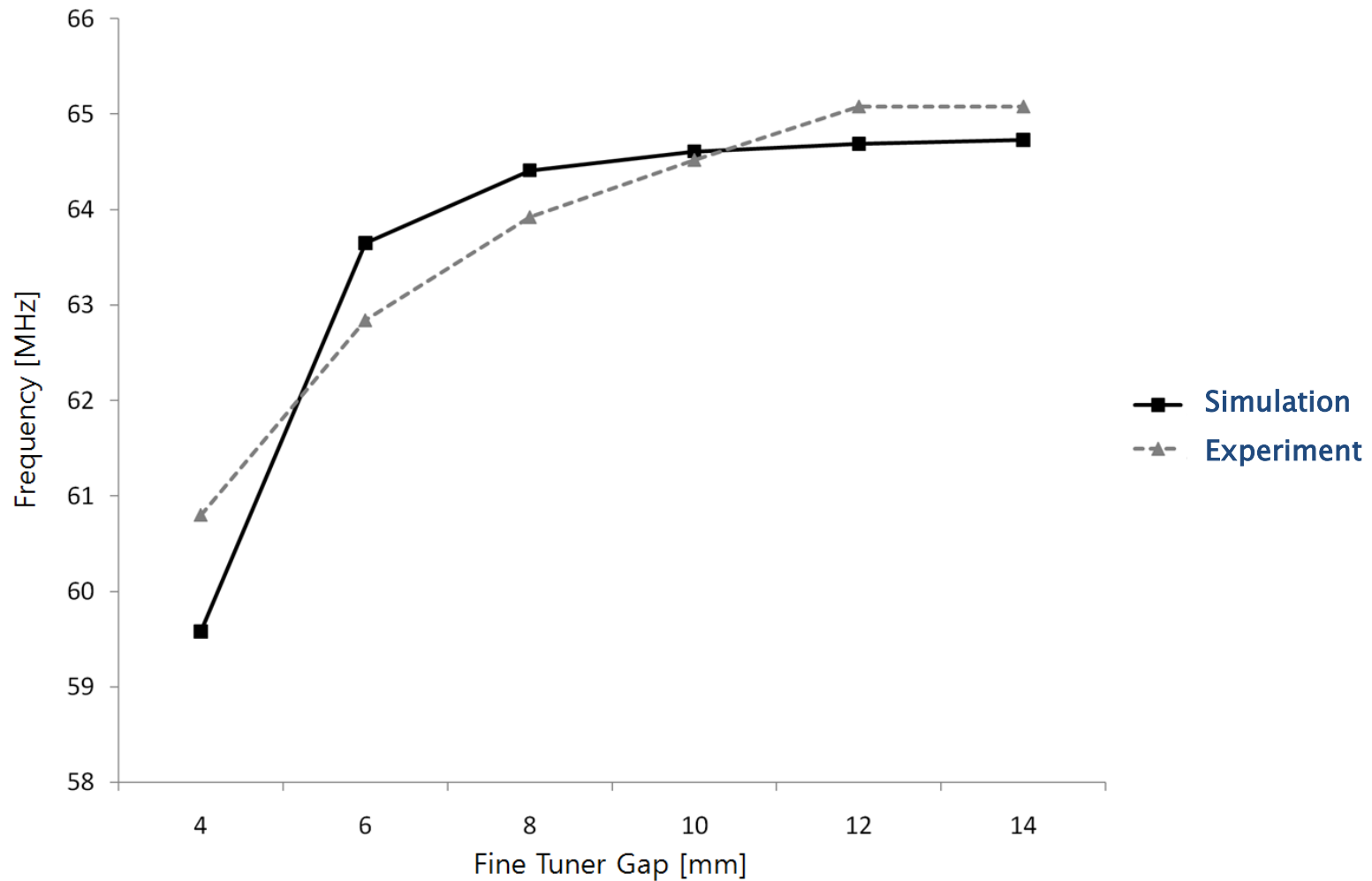


Dee Voltage = 58 [kV]

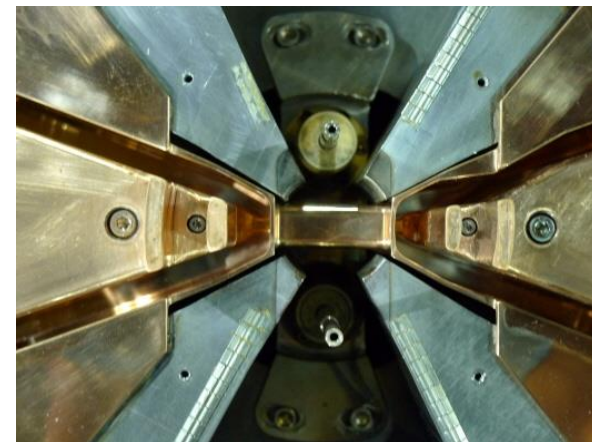
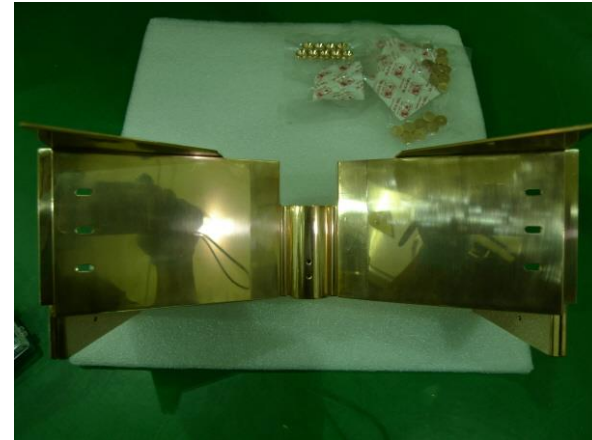
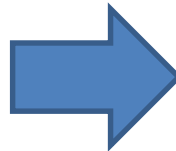
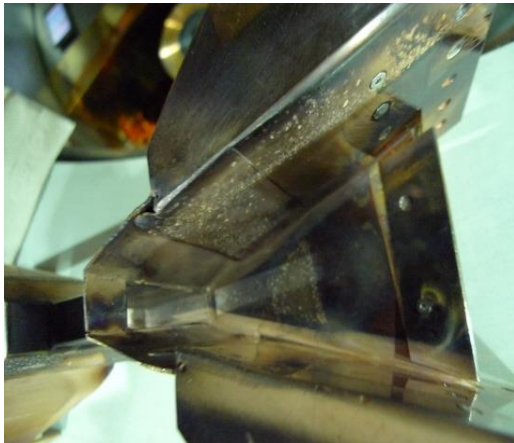
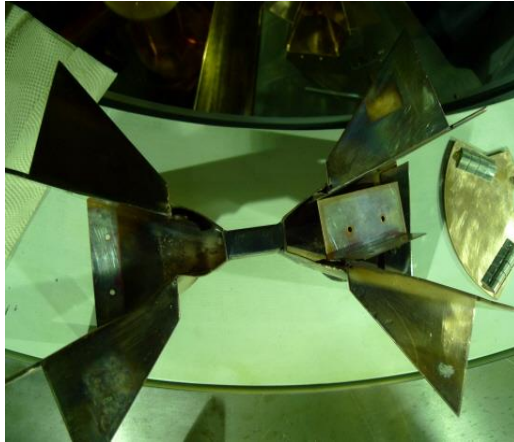
■ 중심부 Beam Test 결과



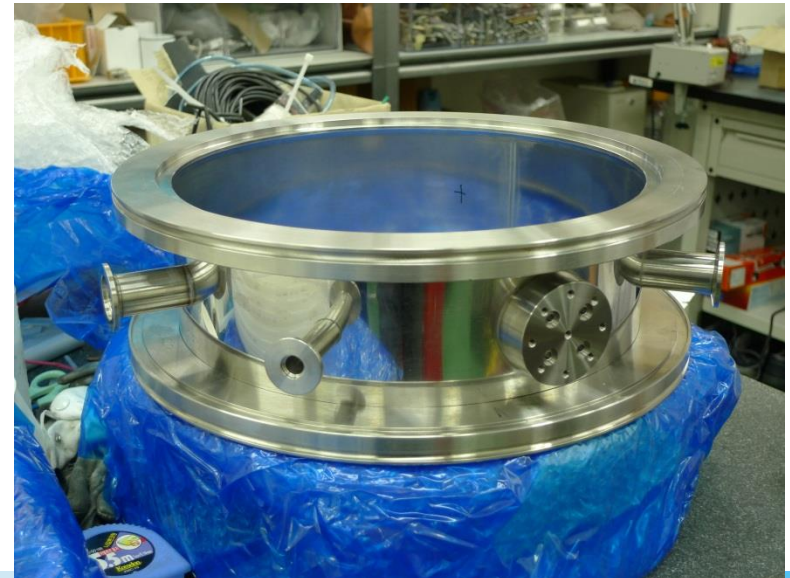
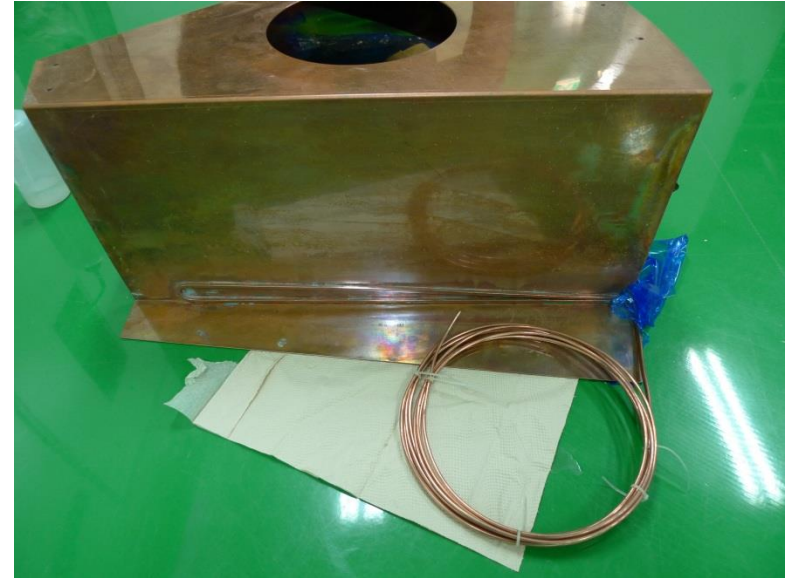
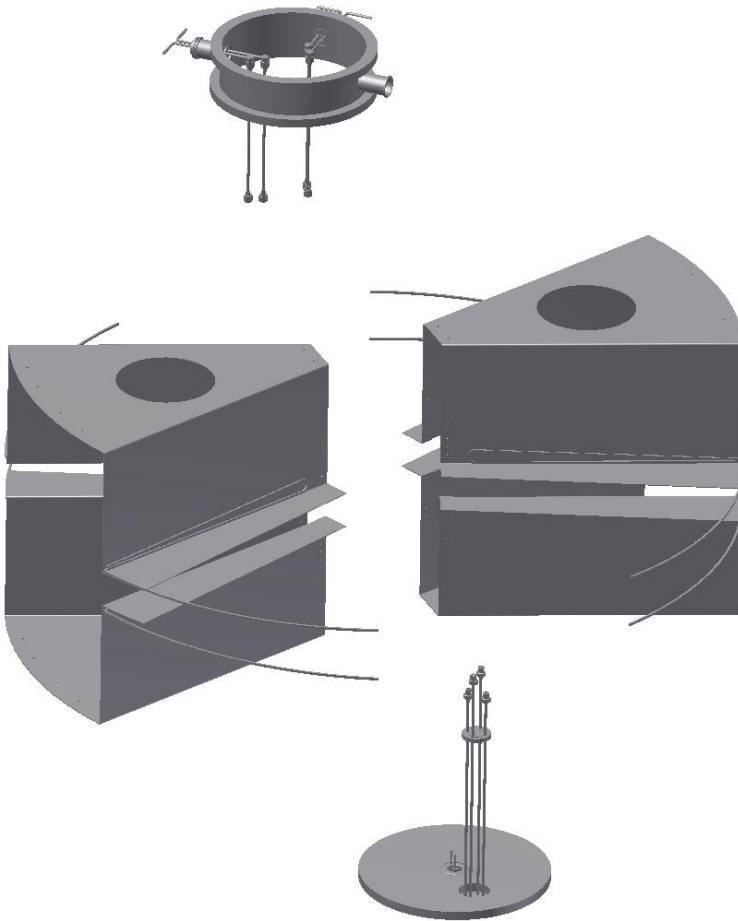
■ Fine Tuner Tuning Range



■ 중심부 설계 변경

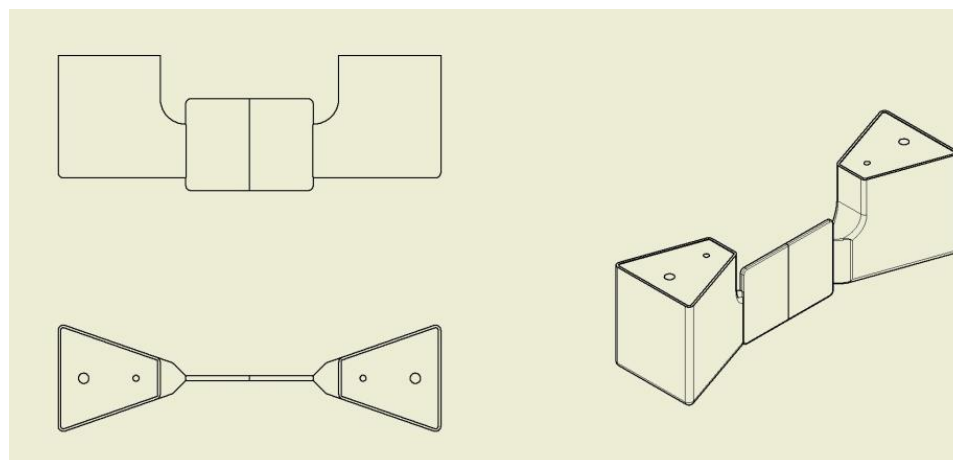
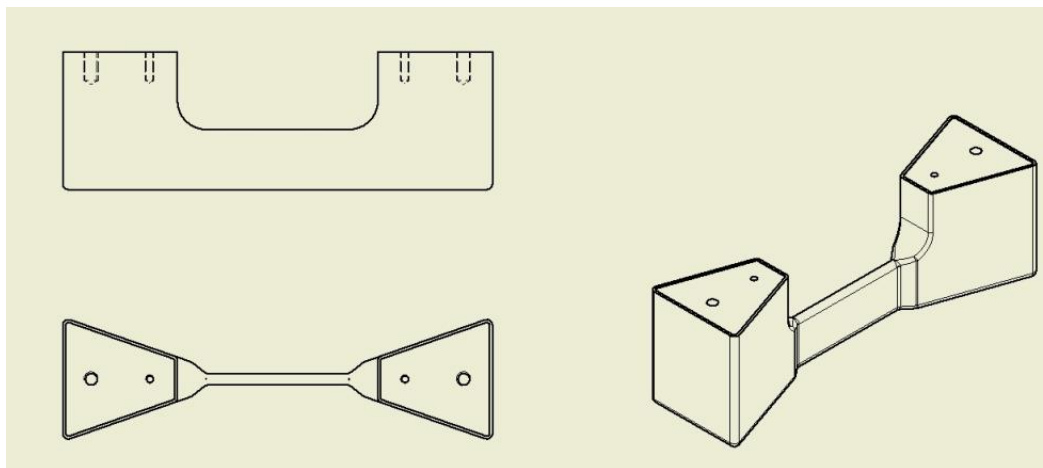


■ Liner Cooling Line 추가



■ Dee Connector 수정

- Dee Connector 형상 변경을 통해 간격 확대 (4mm → 5mm)



■ 고주파 안정성 향상

- 고주파 방전 발생 최소화 구조 설계
- Low Level RF (LLRF) controller 설계 & 제작
- Reflection Power 발생시 문제점 해결 방안 모색

■ RF Amp 국산화 방안 모색

- RF Amp 제작 업체 파산 이후 국내 수급 및 유지보수 문제 발생

➡ 산업화를 위한 사용자 편의성 향상