Research Interests & Plan about Plasma - Beam Applications

MuHyeop Cha (Chacha)

Seoul National University Plasma, Radiation & Ion Sources Laboratory
Department of Nuclear Engineering,
Seoul National University

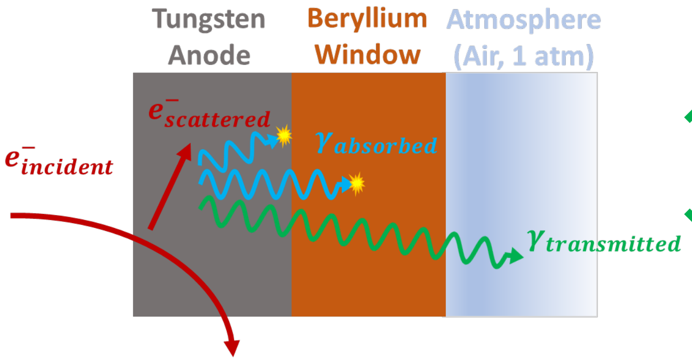
What I look like

SNU
Plasma, Radiation &
Ion Sources Laboratory

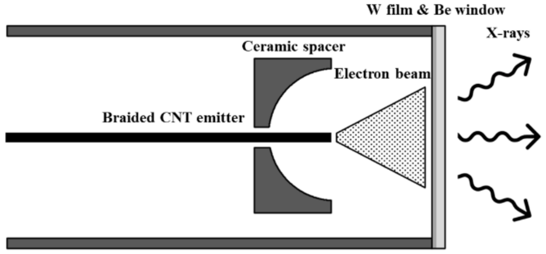
Electron Beam & X-ray Source Design

- Bremsstrahlung & Characteristic X-ray from field-emitted electron

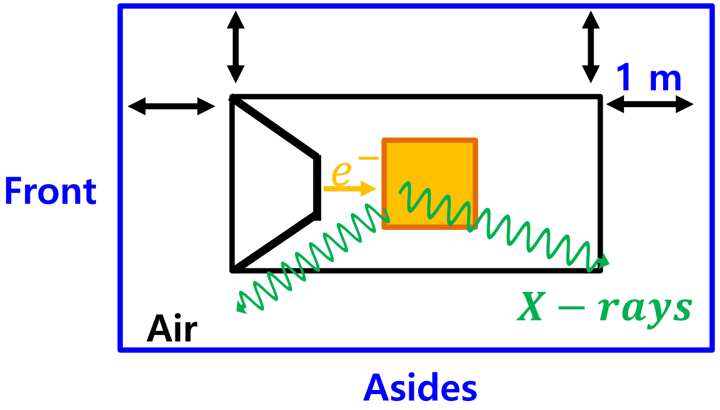
Mechanisms of X-ray conversion



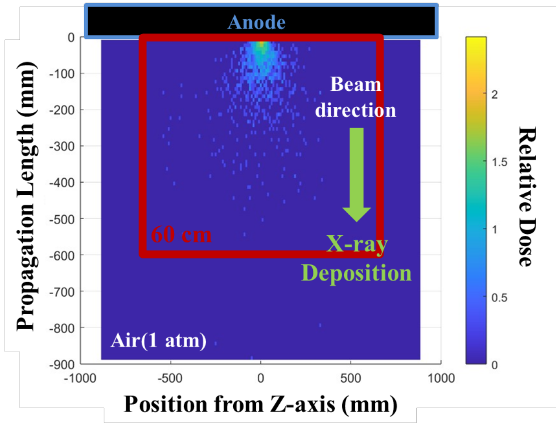
Designed X-ray source



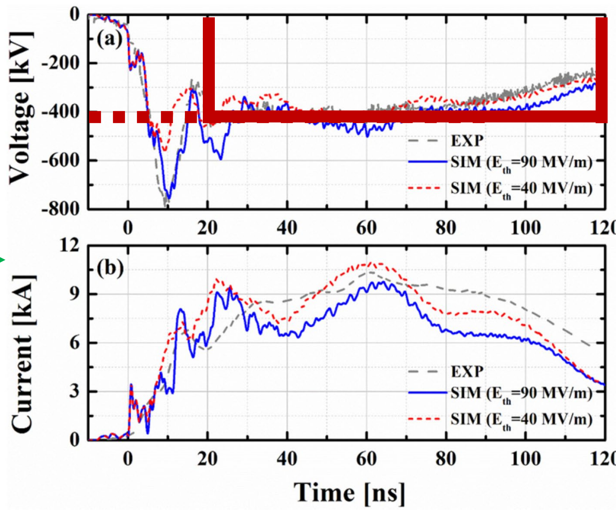
Unexpected X-ray source (from microwave source)



Diagnosis / Purification design



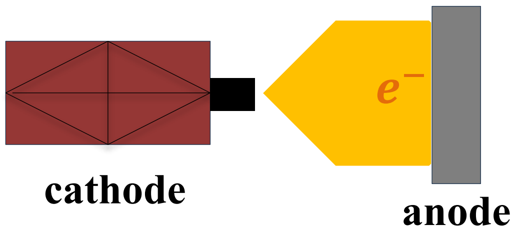
Shielding design



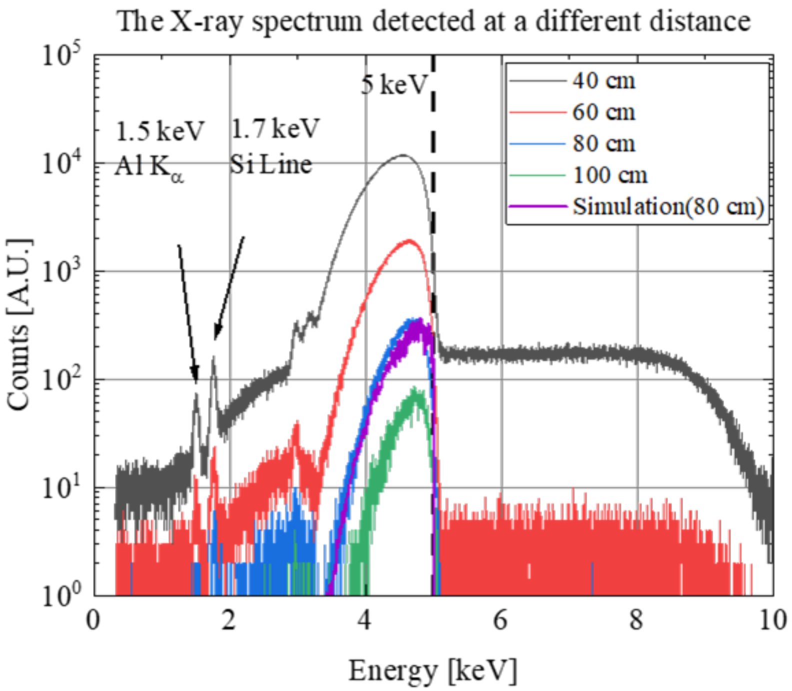
V & I wave form on Marx Generator

Bremsstrahlung Yield Framework Study

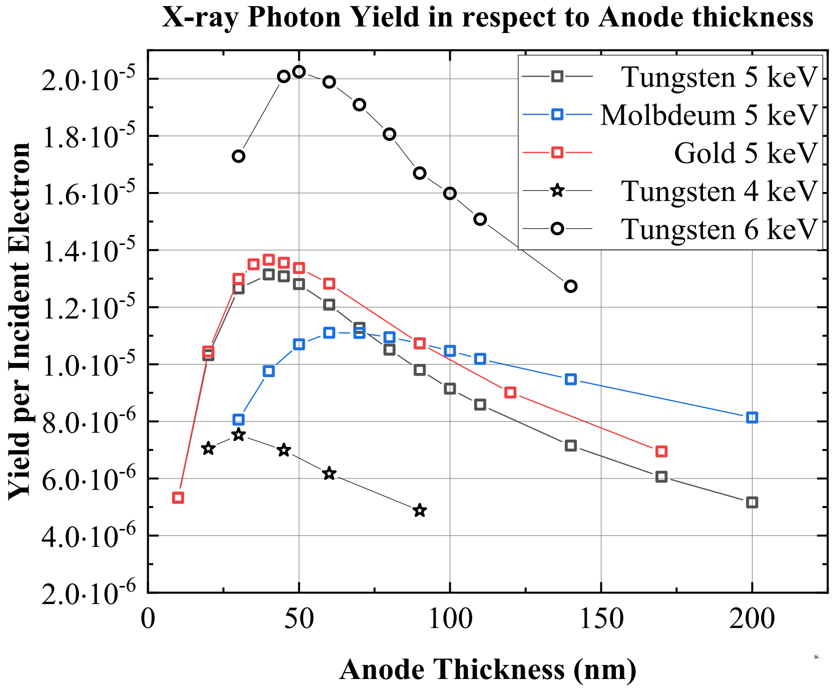
- Soft X-ray source(< ~ 10 keV): Bremsstrahlung >> Characteristic X-ray
- Optimal thickness: balance between **X-ray production** & **attenuation**
- Experimental & Simulational & Theoretical framework



X-ray energy spectrum comparsion



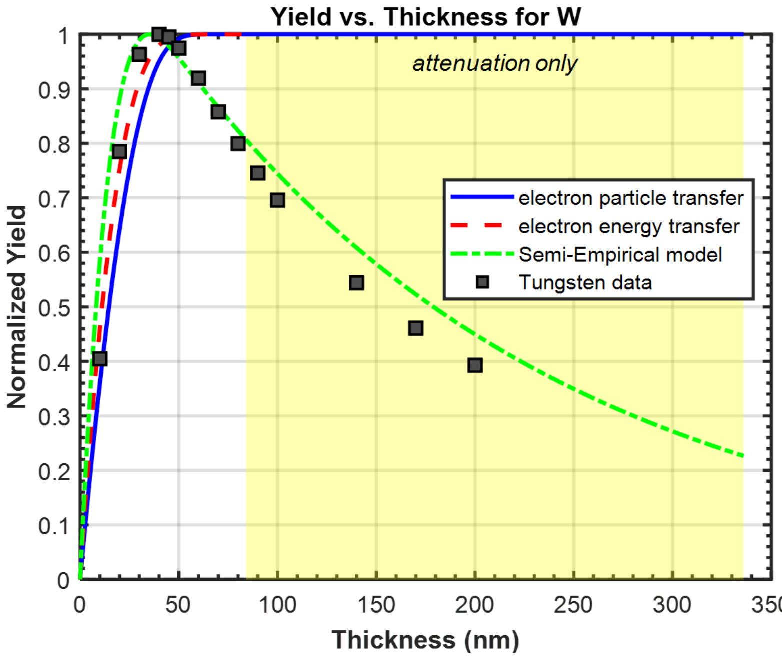
Anode thickness optimization



Optimal thickness for photon yield

$$R \simeq 27.6\, A\, E_0^{1.00} / \rho Z^{0.80}\ [nm]$$

Empirical model suggestion



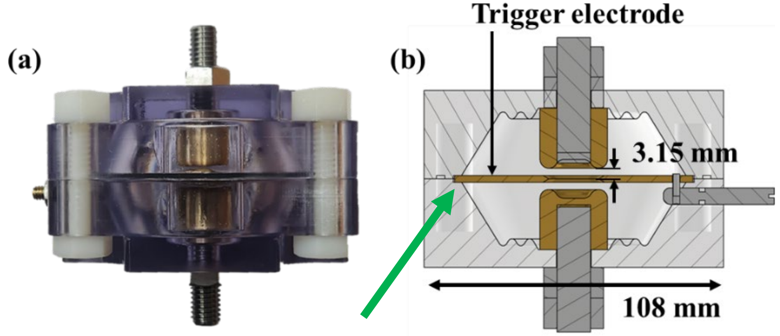
Kanaya-Okayama model for electron depth R

$$R \simeq 27.6\, A\, E_0^{1.67} / \rho Z^{0.89}\ [nm]$$

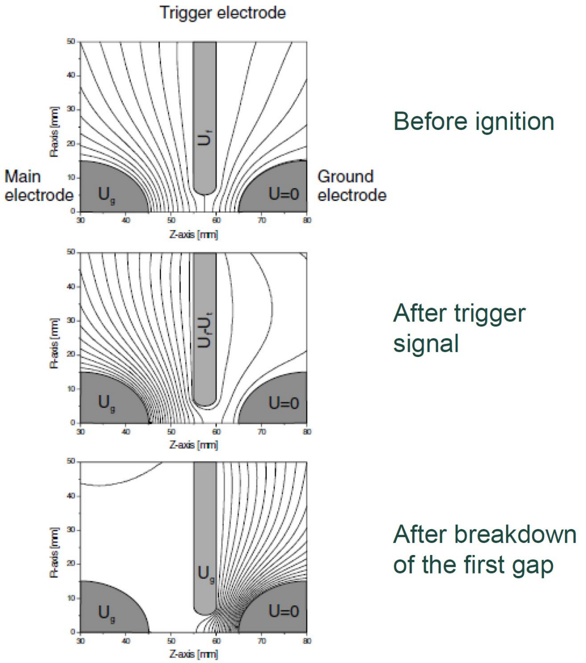
X-pinch to Z-pinch

- **SNU X-pinch**: 100 kA / ~ 500 ns rise with -50 kV charging
- Designed trigger **spark gap switch**
- Plan to upgrade ~ 1MA LTD Z-pinch system till 2028

Spark gap switch design

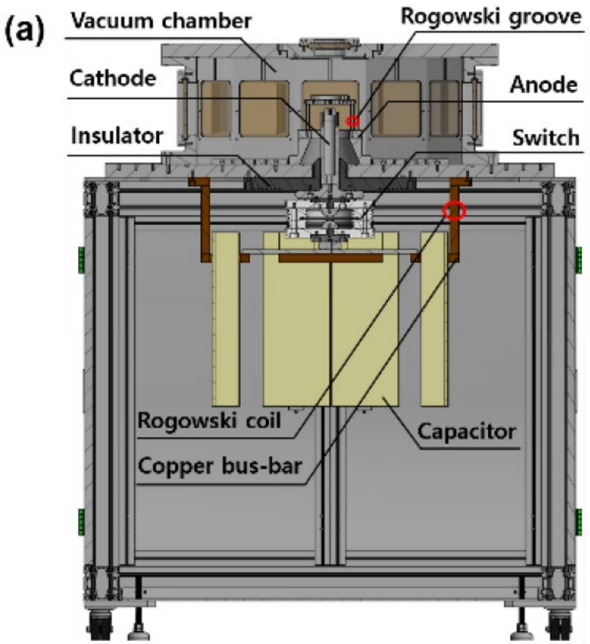


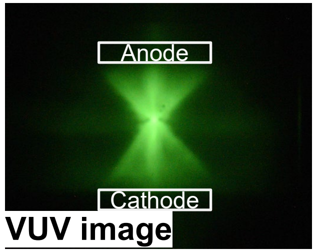
Marx + IGBT + optical trigger(insulation)

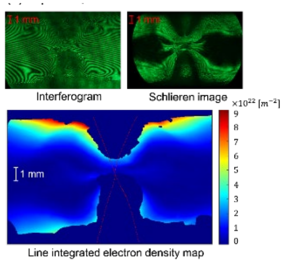


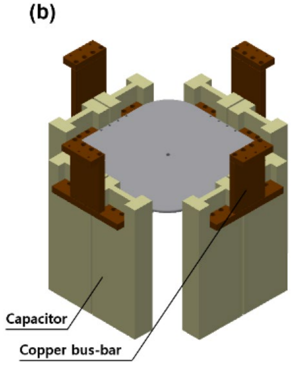
Z-pinch on aluminum can

SNU X-pinch Design









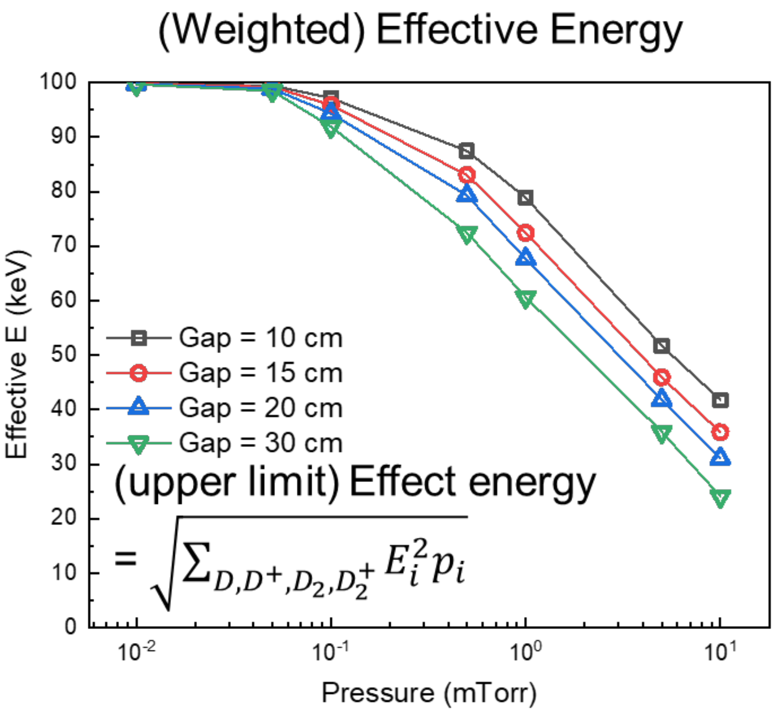
Cylindrical Magnetron Type Test Chamber of IECF

Neutron source using D-D fusion in IECF(Inertial Electrostatic Confined Fusion) chamber

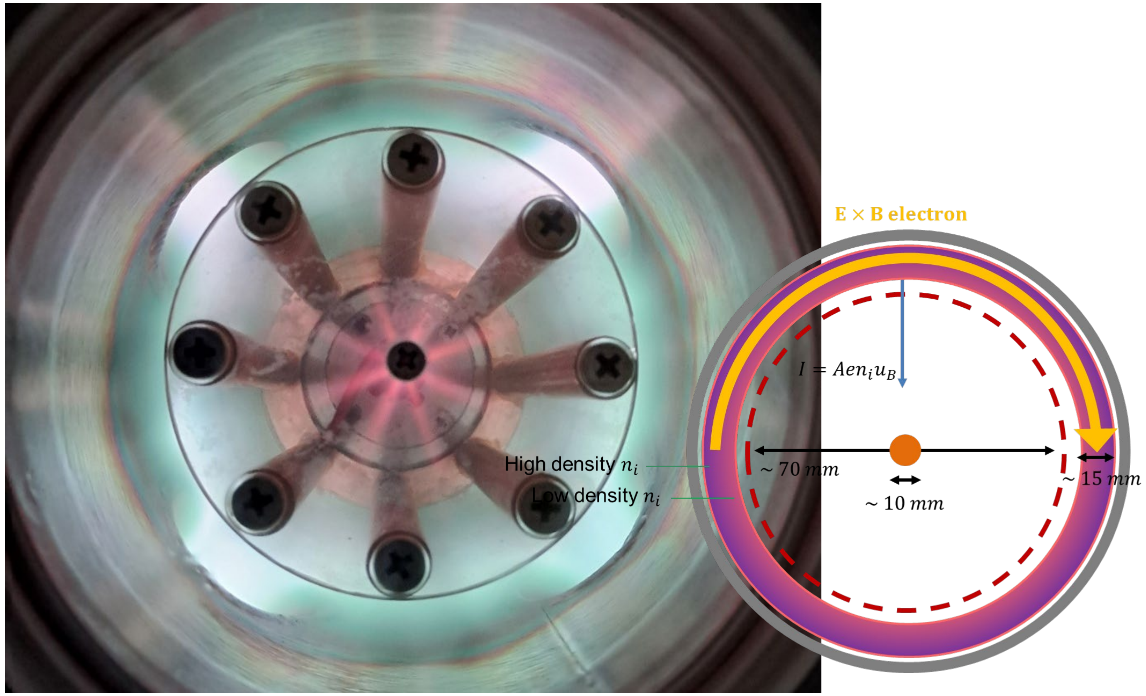
Cylindrical DC magnetron type: **compact, low pressure** operation

Prototype(100ϕ 100T) → Advanced type (600ϕ 600T)

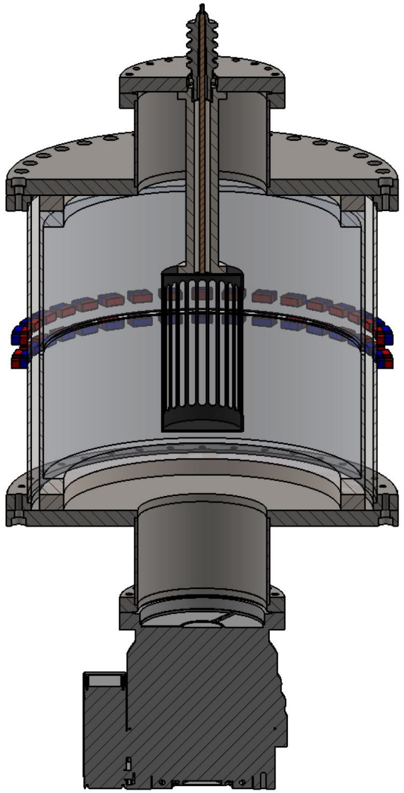
Effective fusion energy after CX reaction energy loss



Cylindrical plasma source & Beam extraction image



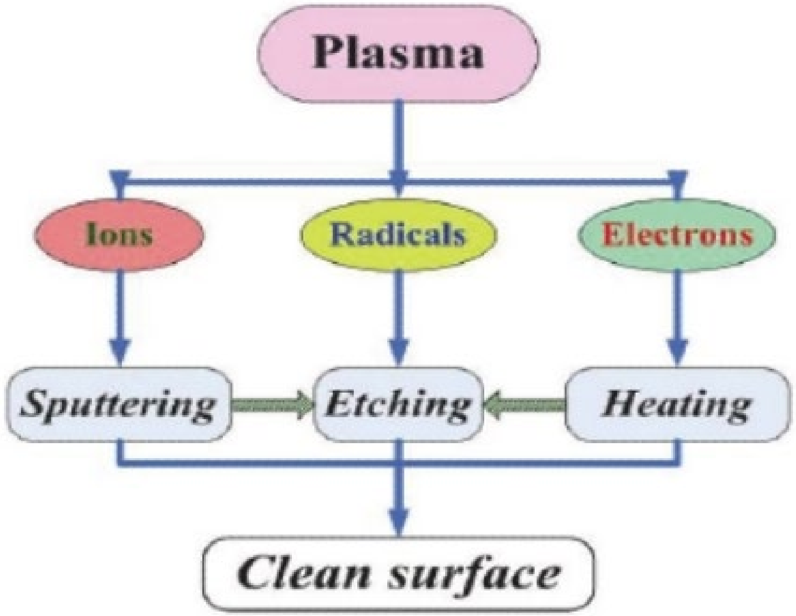
Advanced IECF chamber design

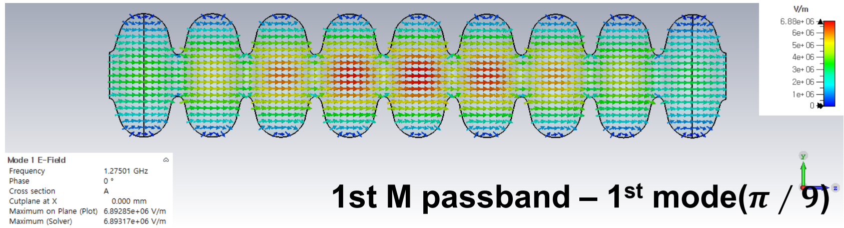


In-situ Cavity Cleaning Research

- **In-situ Cleaning** RAON HWR / SSR cavity using **Ar/Ne + O_2 plasma**
- Checking proper RF eigenmode range of cavities with CST eigenmode solver

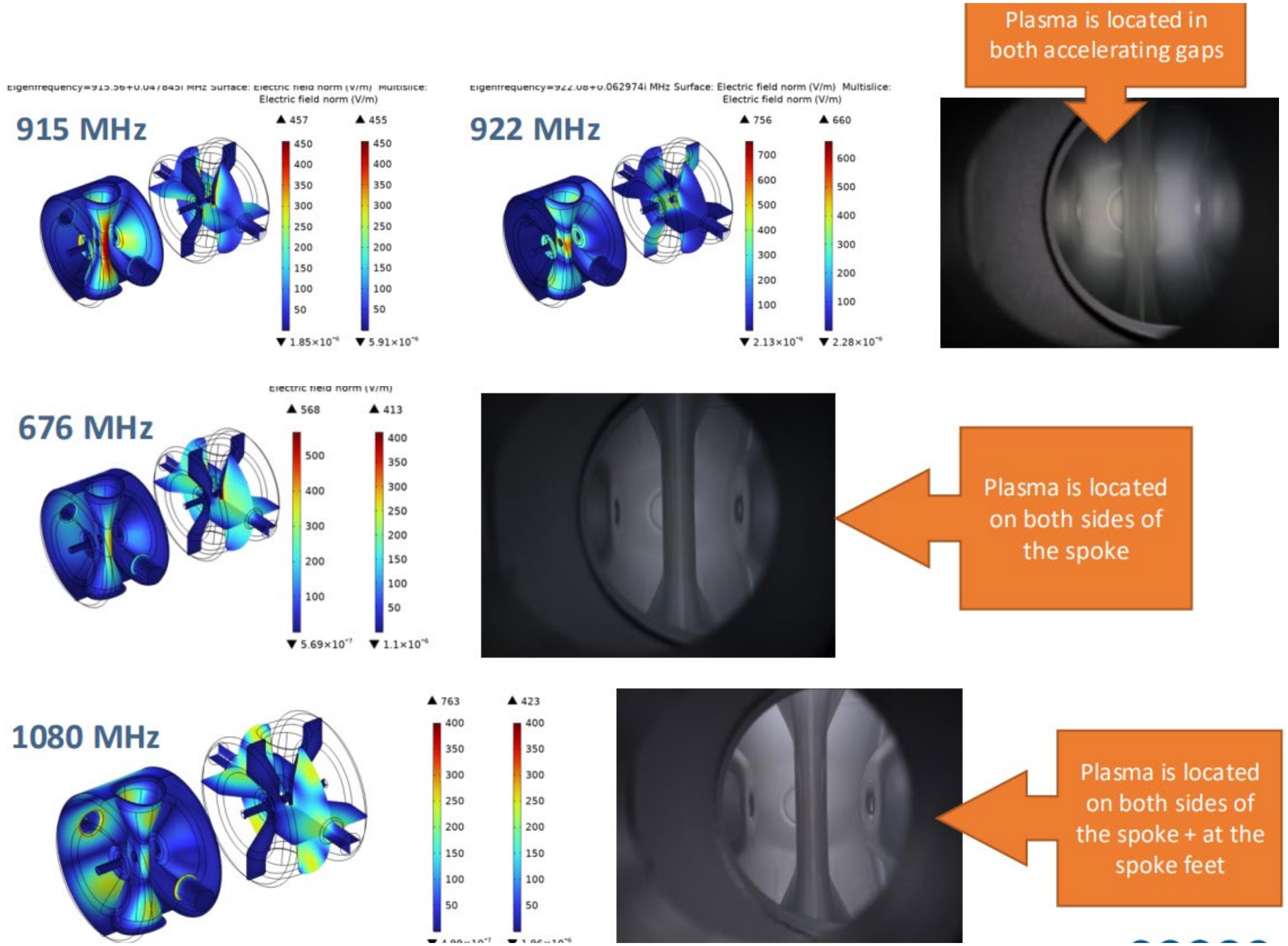
Plasma Cleaning Schematic





1st M passband – 1st mode(π / 9)

Ar + O2 Plasma Ignition in SSR Cavity (PIP-II as reference)



Supplementary materials

ISBA 2025

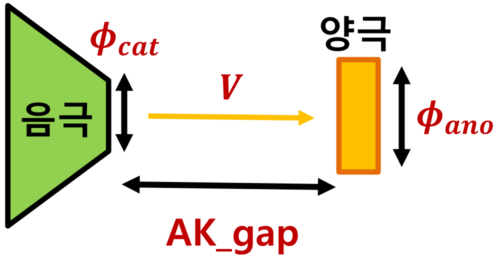
전자 방출량 추산

❖ 전자 방출량 결정 요인

- 보수적 평가를 위하여 공간 전하에 대한 최대 전류(SCL) 고려
- SCL 계산 시 양극 전압, 간격, 방출 면적이 요구 → 통제 변인

❖ 계산 과정

1) 방출 시간 100 ns의 사각 펄스 가정
2) 전류를 단위 전하로 나눠 방출 개수 추산



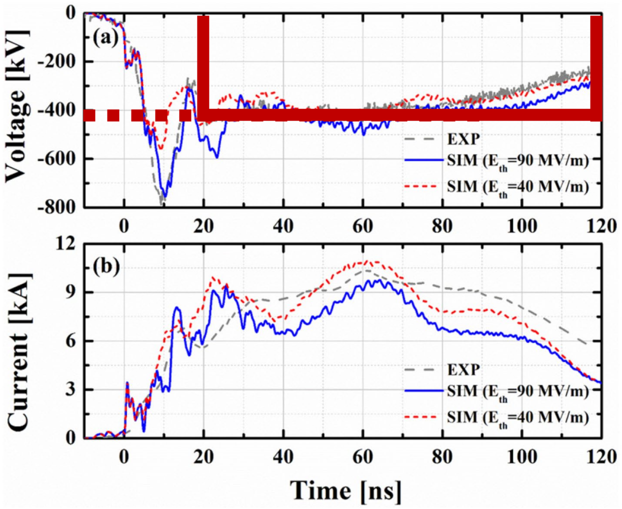
SCL 계산 과정

$$I_{SCL,2D} = kP\phi_{avg}^{3/2}$$

$$P = 2.33 \times 10^{-6} \left(\frac{S_k}{d_{ak}^2}\right)$$

$$k = 1 + 0.315\left(\frac{d_{ak}}{D}\right) - 0.0004\left(\frac{d_{ak}}{D}\right)^2$$

공간 전하 최대 전류 계산 과정



Marx에서의 전압 및 전류 파형

	Case 1	Case 2	Case 3
전압	400 keV	200 keV	200 keV
AK-gap	10 mm	6.7 mm	29 mm
음극/양극 직경	50/60 mm	40/60 mm	150/170 mm
SCL 전류	17.5 kA	6.1 kA	4.6 kA
전자 방출량	7.7E+15	3.8E+15	2.9E+15

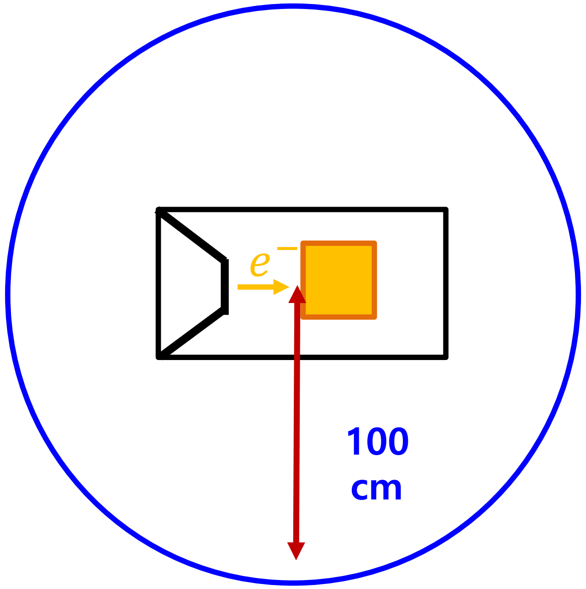
설계 안에서의 상황 별 전자 방출량

시뮬레이션 결과

ISO 방식 평가:

전체 방출량에 구면적을 나눠 계산

Total X-ray number [#] * ISO conversion factor $[pSv \cdot cm^2/\#]$ / Spherical Area

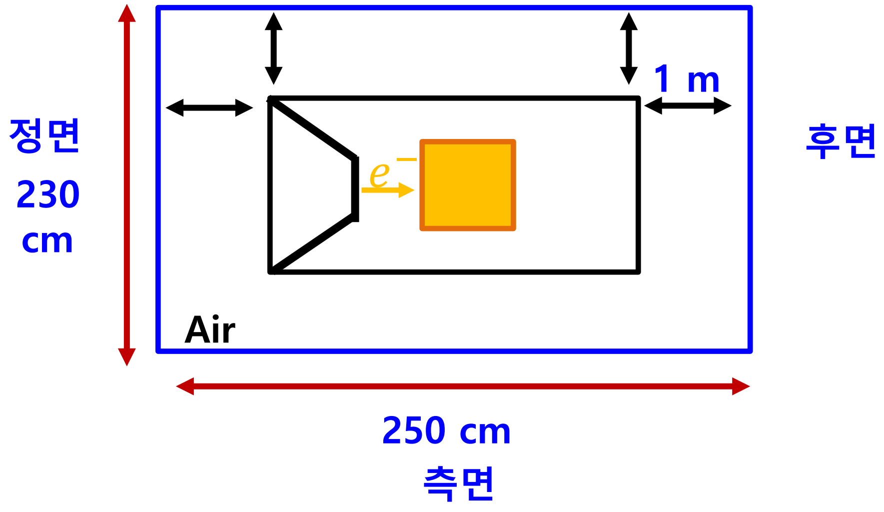


AP 방식 평가:

옆면, 앞면, 뒷면 따로 계산

Ex) 앞면 계산

Front X-ray number [#] * AP conversion factor $[pSv \cdot cm^2/\#]$ / Circle Area



	전압	AK gap	음/양극 직경	ISO 선량	AP선량 (μSv)		
					정면	측면	후면
Case 1	400 keV	10 mm	50/60 mm	67 μSv	-	17	14
Case 2	200 keV	6.7 mm	40/60 mm	≃2 μSv	1.1	1.9	0.2
Case 3	200 keV	29 mm	150/170 mm	≃2 μSv	1.2	1.8	0.2

주간 연간 피폭량 한계

❖ 연간 피폭 선량

- 주당 피폭시간 : 50 펄스 / 주
- 작업자와 방사선원과의 거리 = 2 m

→ 0.6 μSv / $pulse$ (AP 측면) 혹은 **0.5** μSv / $pulse$ (ISO)

- 50 펄스, 연 50 주 사용시

→ ISO 기준 주 0.025 mSv, 연 1.25 mSv 이하 예상

→ AP 측면 기준 주 0.03 mSv, 연 1.5 mSv 이하 예상

→ AP 후면 기준 주 0.001 mSv, 연 0.05 mSv 이하 예상

- 작업자와 방사선원과의 거리 = 1 m 일시 추가 차폐 요구

❖ 사고 상황 예상

- 발생 장치 최소 접근 가능 거리 20 cm에서 발진 사고시
- 피폭 시간: 1펄스/회, 연간 사고 횟수: 1회/년

→ 피폭 시 25*0.6 μSv = 15 μSv

- 방사선 긴급 작업시 선량 제한 한도 500 mSv에 비하면 매우 작은 수치

1. 차폐물의 설계기준
   1) 원자력안전위원회고시 제2019-10호 방사선방호등에 관한 기준 고시 제13조(차폐물의 설계기준) 방사선규칙 제17조제2항제2호, 제19조제1항제3호, 제27조제1항제2호 및 제33조제1항제1호에 따른 차폐벽이나 차폐물에 대한 설계기준은 다음 각 호와 같다.
      1. 사용시설 등의 내부에 사람이 상시 출입하는 장소는 연간 방사선량이 20 mSv를 초과하지 아니 하여야 하고 1주당 방사선량은 1 mSv를 초과하지 아니 하여야 한다.
      2. 사용시설 등의 경계에 인접하여 사람이 거주하는 구역은 연간 방사선량이 1 mSv를 초과하지 아니 하여야 하고 1주당 방사선량은 0.1 mSv를 초과하지 아니하여야 한다.

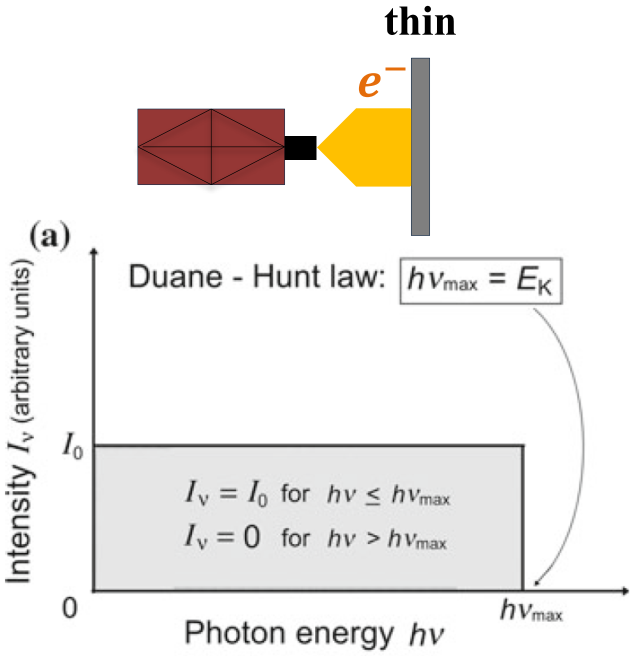
2. 선량한도의 적용
   1) 원자력안전위원회고시 제2019-10호 방사선방호등에 관한 기준 고시 제4조(선량한도의 적용) 영 제2조제4호에 따른 별표 1의 비고 제2호에 따라 선량한도를 다음 각 호와 같이 적용한다.
      2. 방사성동위원소 등을 제한적 또는 일시적으로 사용하는 경우 일반인에 대한 선량은 연간 선량한도를 초과하지 아니하는 범위 내에서 주당 0.1 mSv 및 시간당 20 μSv까지 허용할 수 있다.

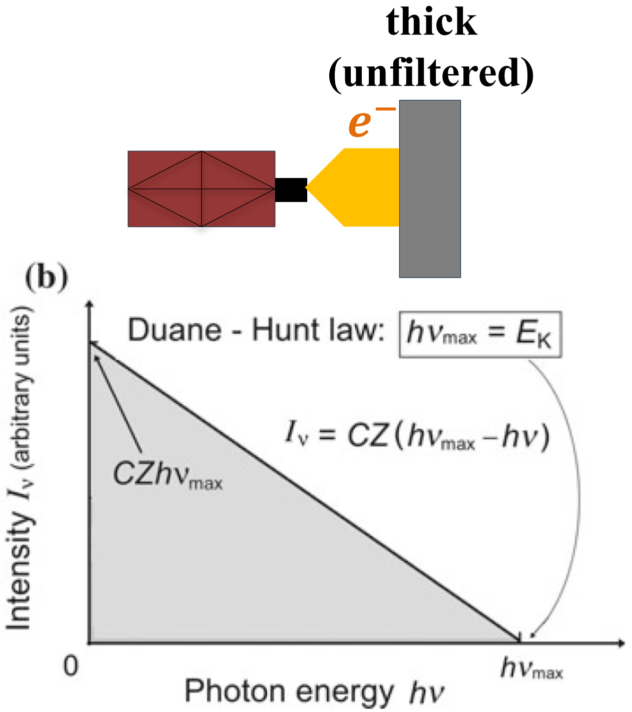
3. 점유도(NCRP Report No.151 Table B-1)

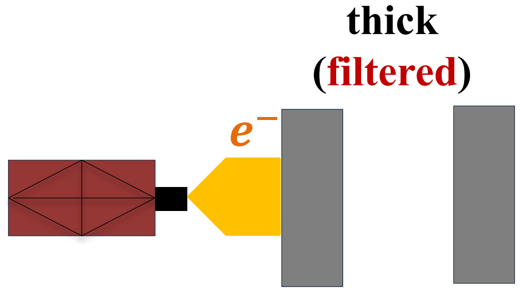
장소	점유율
완전점유구역(치료계획구역, 간호사실, 접수실, 행정사무실 등)	1
인접 치료실	1/2
복도, 직원 라운지, 직원 휴게실	1/5
치료실 도어	1/8
공중화장실, 저장실, 무인 대기실 등	1/20
일시적인 보행자 또는 차량 통행만 있는 옥외 구역, 계단, 무인 주차장	1/40

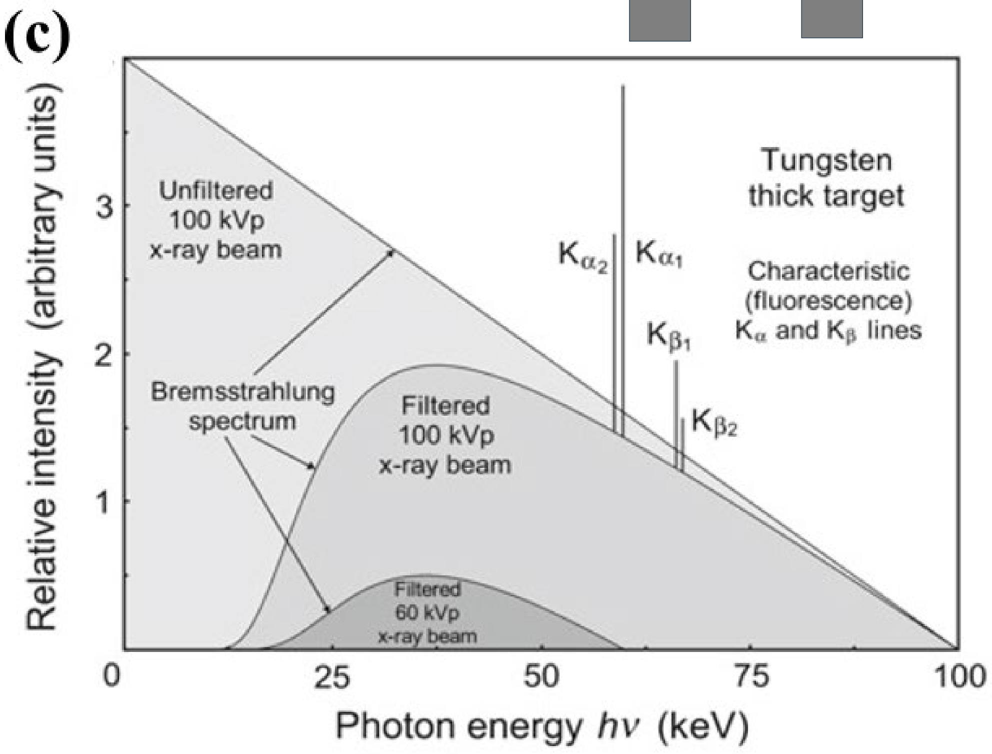
Theory in anode - Bremsstrahlung

- Double differential XS for Bremsstralung: Seltzer-Berger model modified by Tsai
  - → -10% difference in Born approximation under 2 MeV
- **Filtered** thick target spectrum in X-ray tube
  - → Deformed Duane-Hunt law by low energy particle shielding









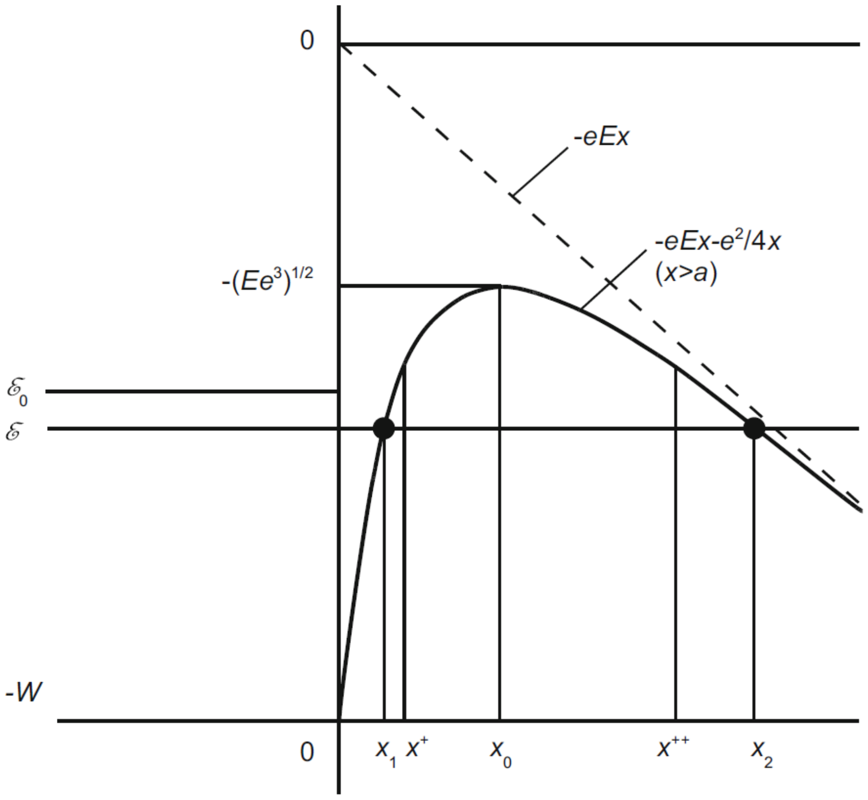
X-ray spectrum after penetrating (a) thin target (b) un-filtered thick target (c) filtered thick target

Theory in cathode – Field Emission

- Fowler-Nordheim model deduced by tunneling transmission rate under Schotty effect

  → relation between (J, E): **unmeasurable**

- Performance: Field enhancement factor $\boldsymbol{\beta}$ & Effective emission area $\boldsymbol{\delta S}$ for new relation (I, V)



Field emission electron principle diagram

Fowler-Nordheim model (FN model)

$$j = A_{FN} \exp\left[-B_{FN}\frac{\phi^{3/2}}{E}\,\theta\left(\frac{\sqrt{e^3E}}{\phi}\right)\right]$$

Fowler-Nordheim plot relation

$$\ln\left(\frac{I}{V^2}\right) = -b\frac{1}{V} + \ln(a)$$

$$b \sim \mathrm{B_{FN}}\frac{\phi^{3/2}d}{\beta}$$

$$a \sim A_{FN}\frac{\beta^2\delta S}{\phi d^2}$$

Empirical effective emission area

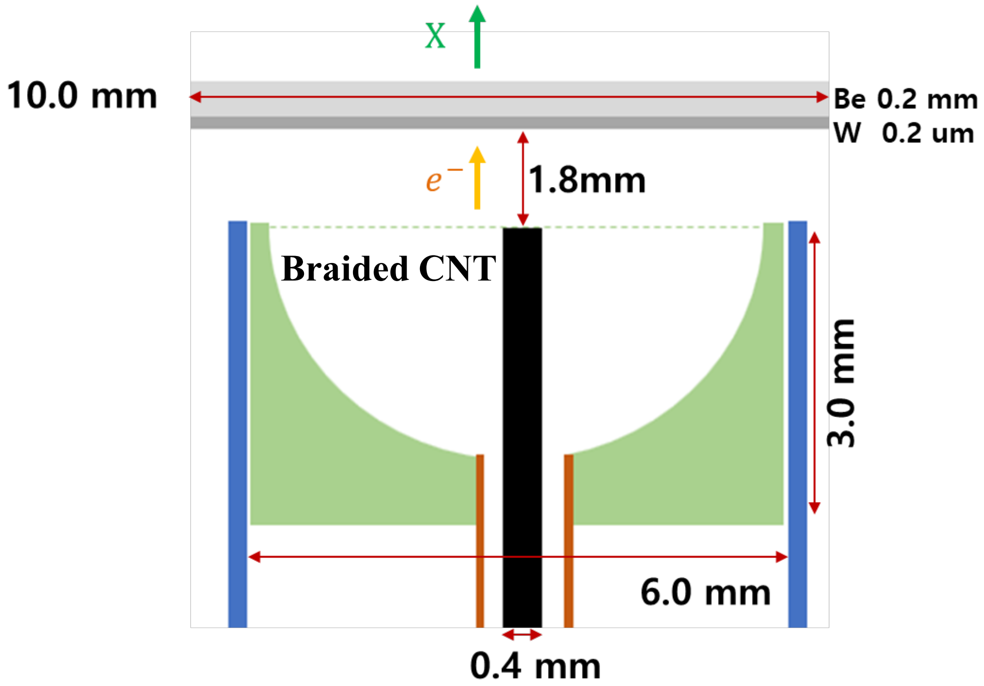
$$\delta S = 4\times10^{-17}b^2(I/V^2)_{1/V=0}$$

Diode Tube Monte Carlo Simulation

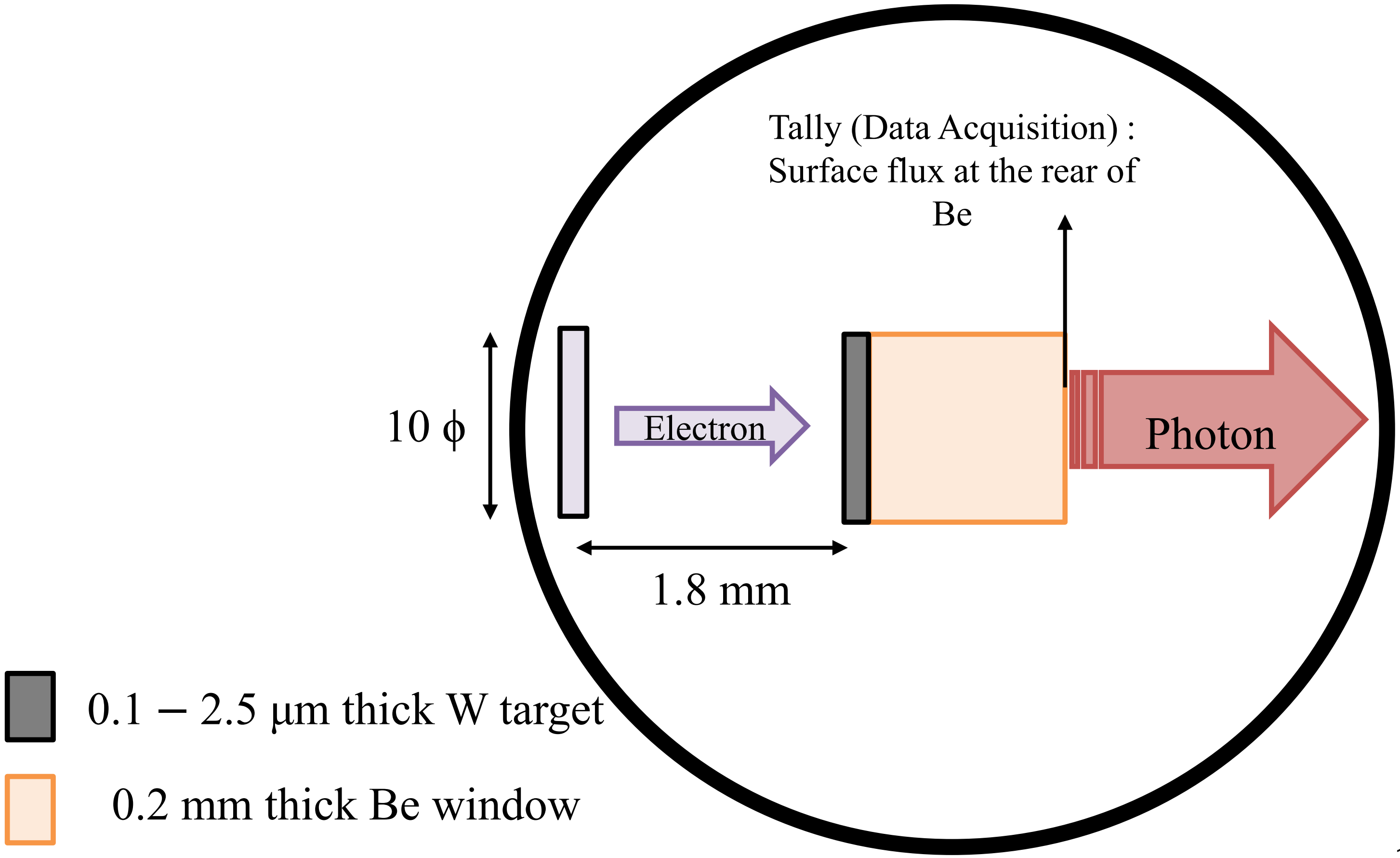
- **Assumption:** 10 ϕ planar beam incident to tungsten target and beryllium window
- **Estimation:** 1) Energy spectrum, angular distribution

  2) Propagation, deposition in the air
- **Key factor:** Anode characteristics

Skematic view commercial diode tube (aweXome Ray)

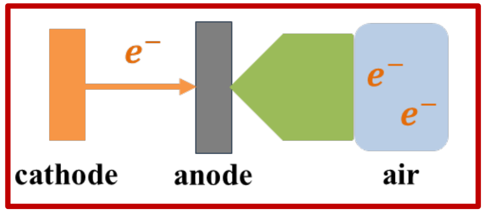


The diode tube simulation diagram

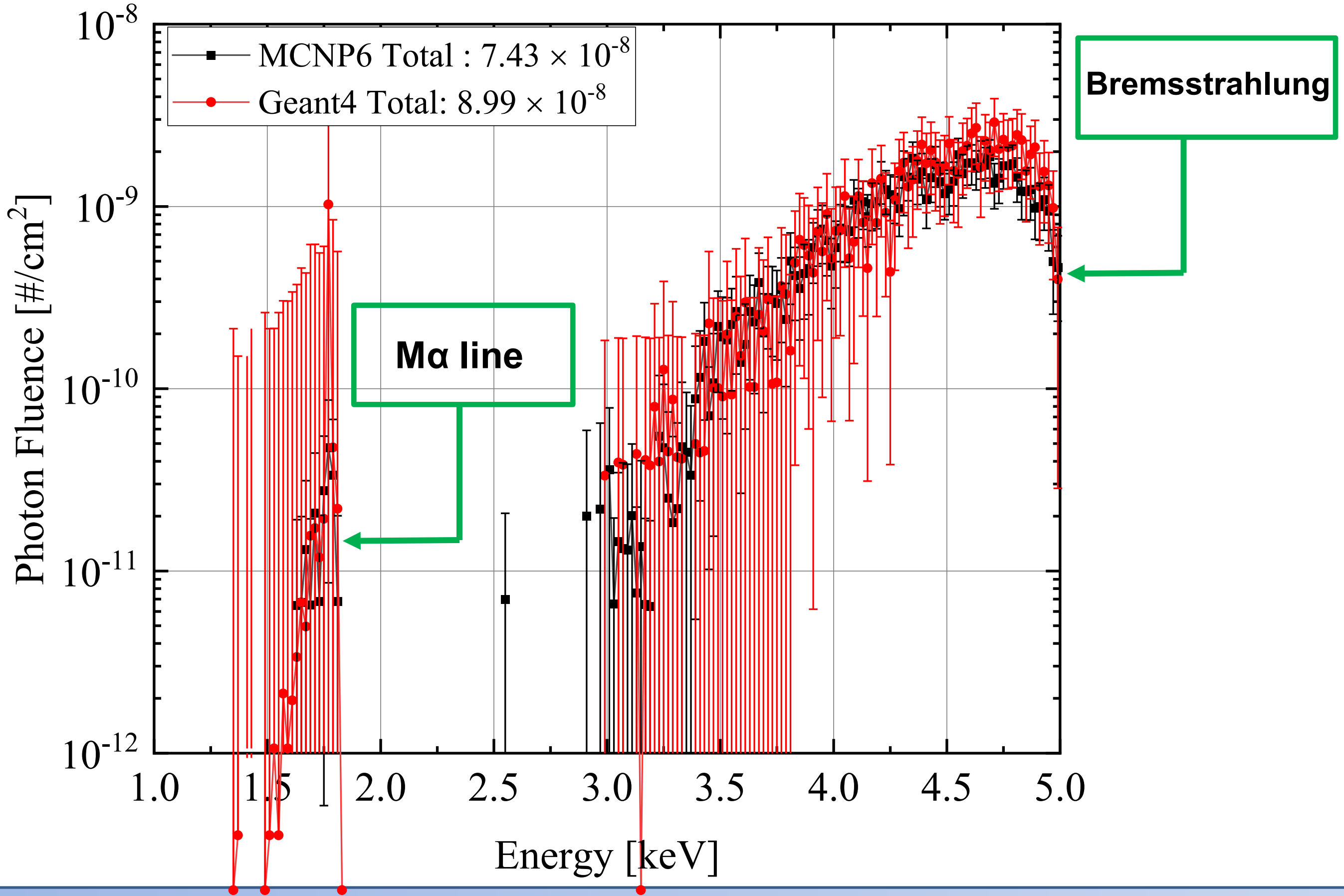


X-ray Energy Spectrum

- Observation of **continuous X-ray** and **characteristic line** produced by tungsten target



X-ray energy spectrum on 2.5 μm W / 0.2 mm Be anode



Characteristic X-ray line of Tungsten

Energy (keV)	Characteristic Spectral Line
1.78	$M\alpha_1$
7.39	LI
8.33	$L\alpha_2$
8.40	$L\alpha_1$
9.67	$L\beta_1$
9.96	$L\beta_2$
11.29	$L\gamma_1$
57.98	$K\alpha_2$
59.32	$K\alpha_1$
66.95	$K\beta_3$
67.24	$K\beta_1$

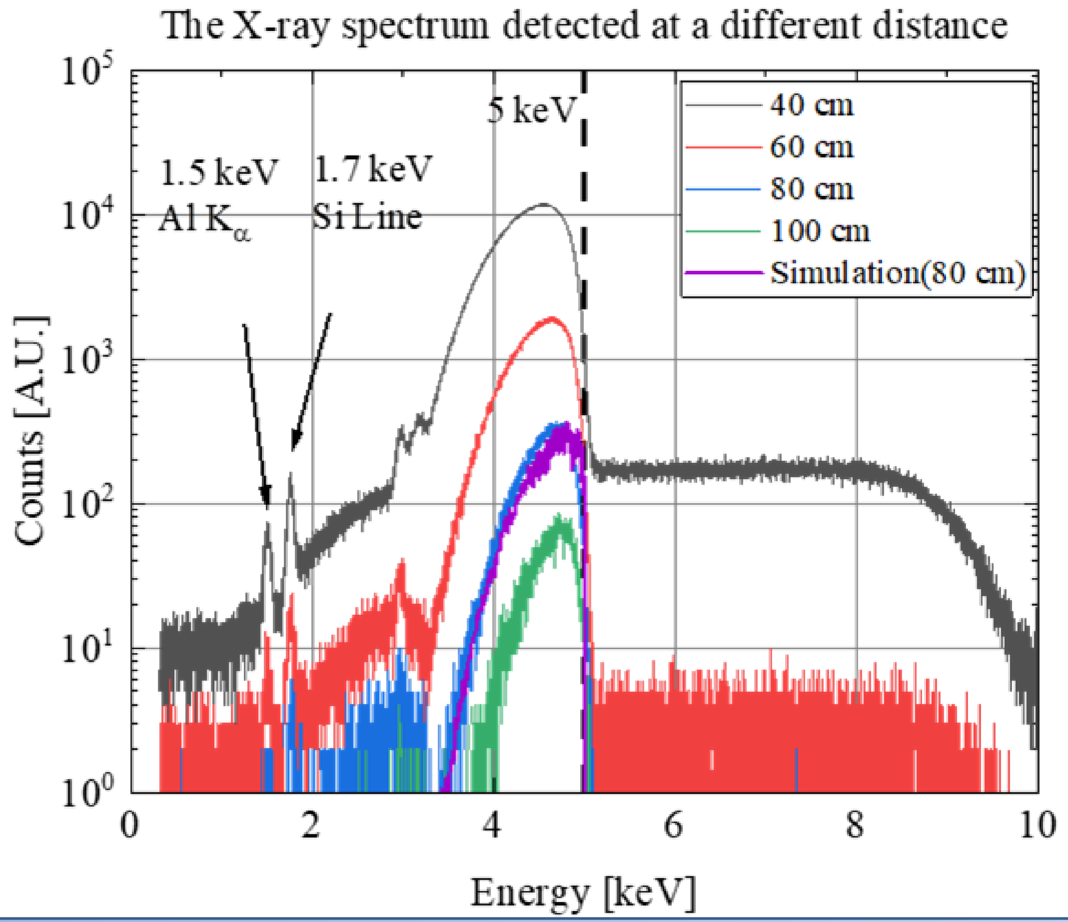
X-ray Energy Spectrum Validation

- **Agreement** between simulation result and experiment
- Average **4 keV** energy – about **60 cm operation regime**

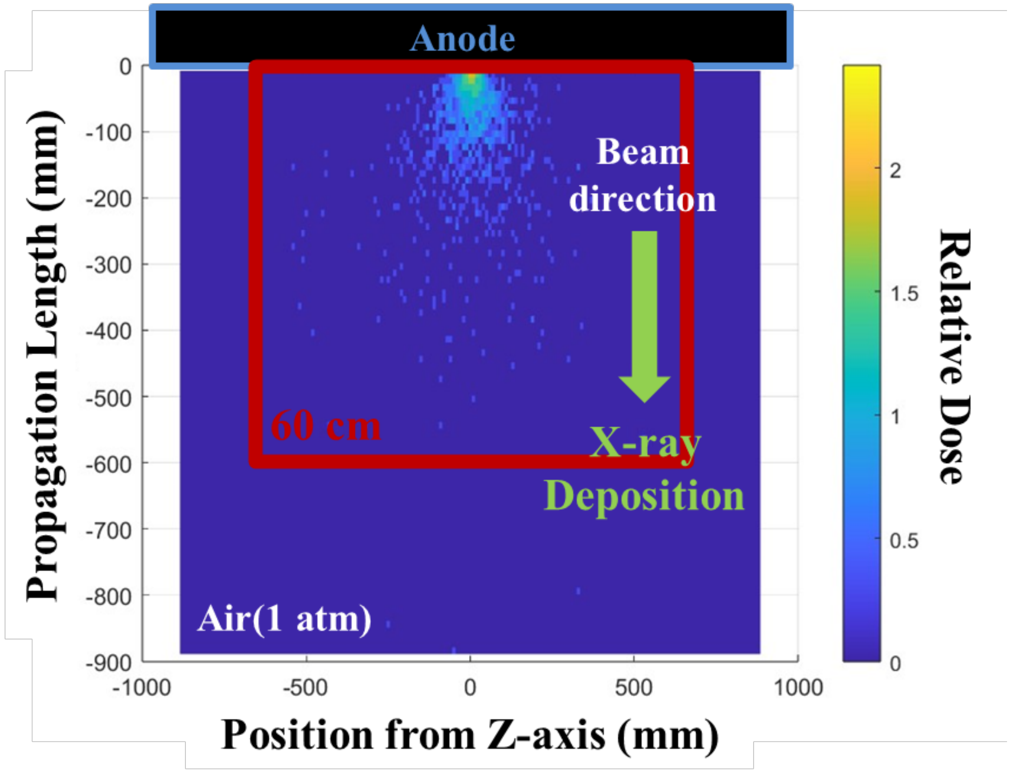
Distance	Counts	Dose (Relative)
40 cm	39,546,113	100 %
60 cm	4,901,768	12.4%
80 cm	734,591	1.86%
100 cm	131,866	0.33%

~ 9.6 cm
~ 10.5 cm
~ 11.6 cm

X-ray e-folding length in air
3 keV: 5 cm
4 keV: 10 cm
5 keV: 20 cm



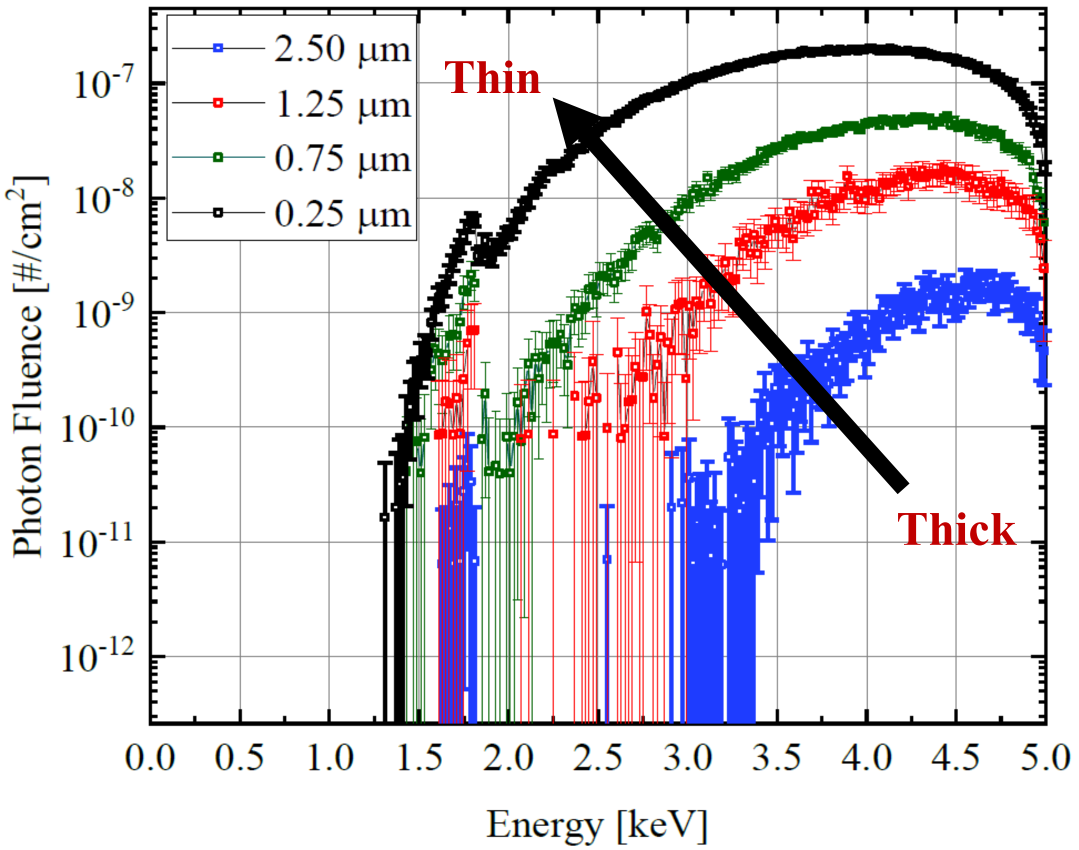
X-ray propagation & deposition in the air



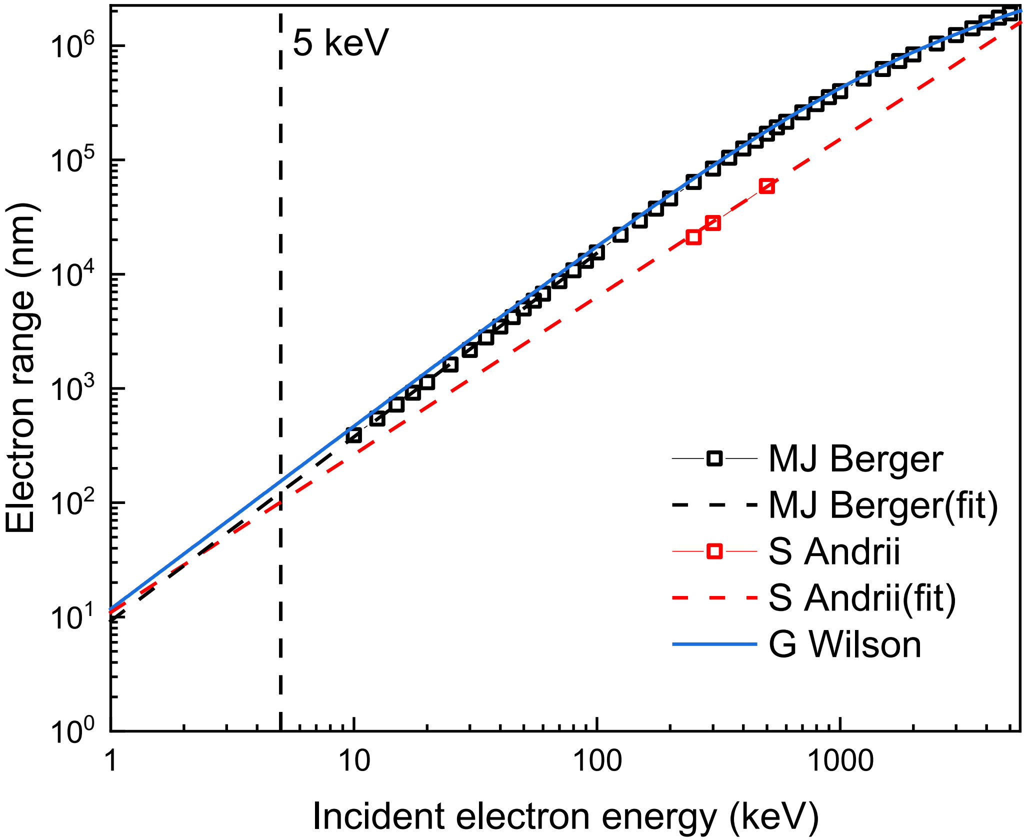
X-ray Characteristic by Tungsten Target

- **Thinner** anode thickness, **higher** emission & **broader** energy spectrum
- Until **unfiltered** anode condition: 1.1 Range (120-150 nm)

X-ray fluence per unit incident electron



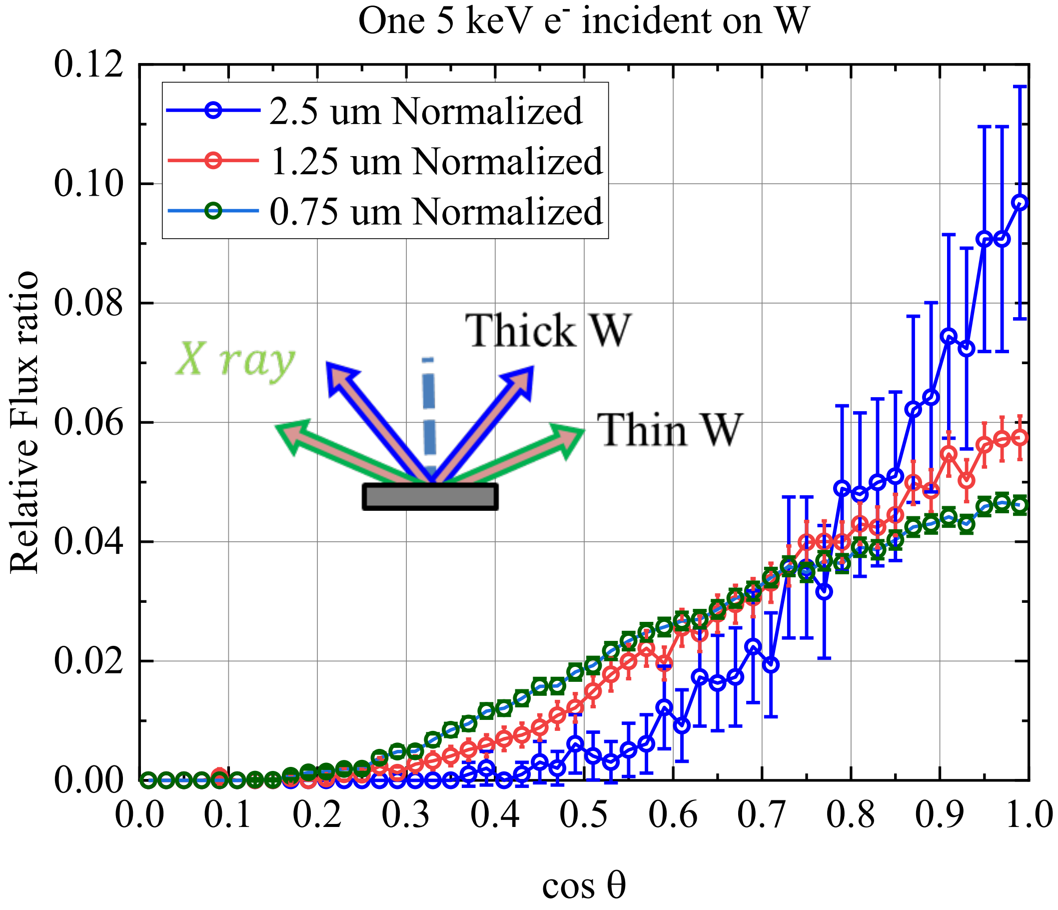
Theoretical electron range in tungsten target



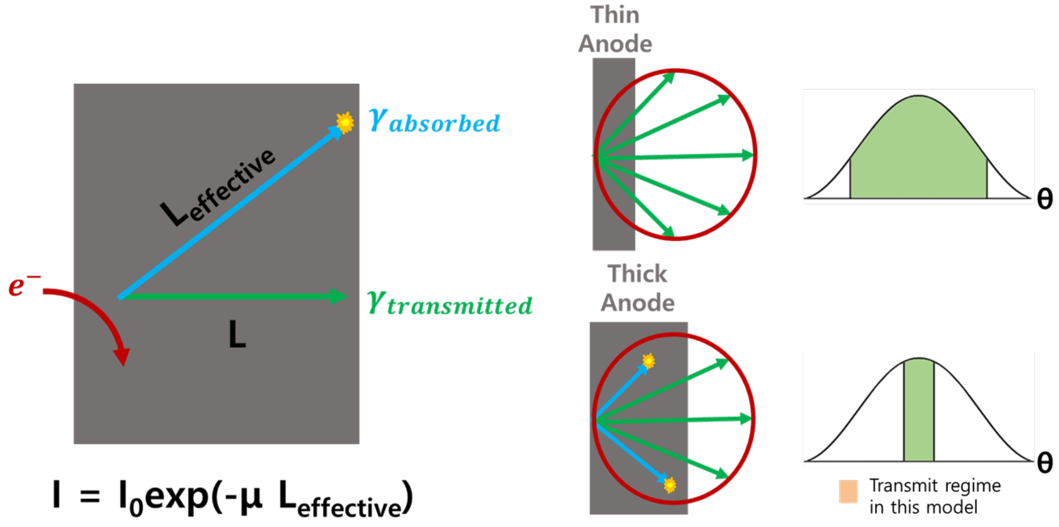
X-ray Heel Effect by Tungsten Target

- **Thinner** anode thickness, **broader** angular distribution
- Explanation using **Heel** effect

W Thickness [μm]	90% Threshold	99% Threshold
2.50	≃45°	≃60°
1.25	≃56°	≃72°
0.75	≃62°	≃74°
0.25	≃72°	≃81°



Skematic view of Heel effect in transmission type anode



$$I = I_0 \exp(-\mu\, L_{effective})$$

Field Emission Characteristic

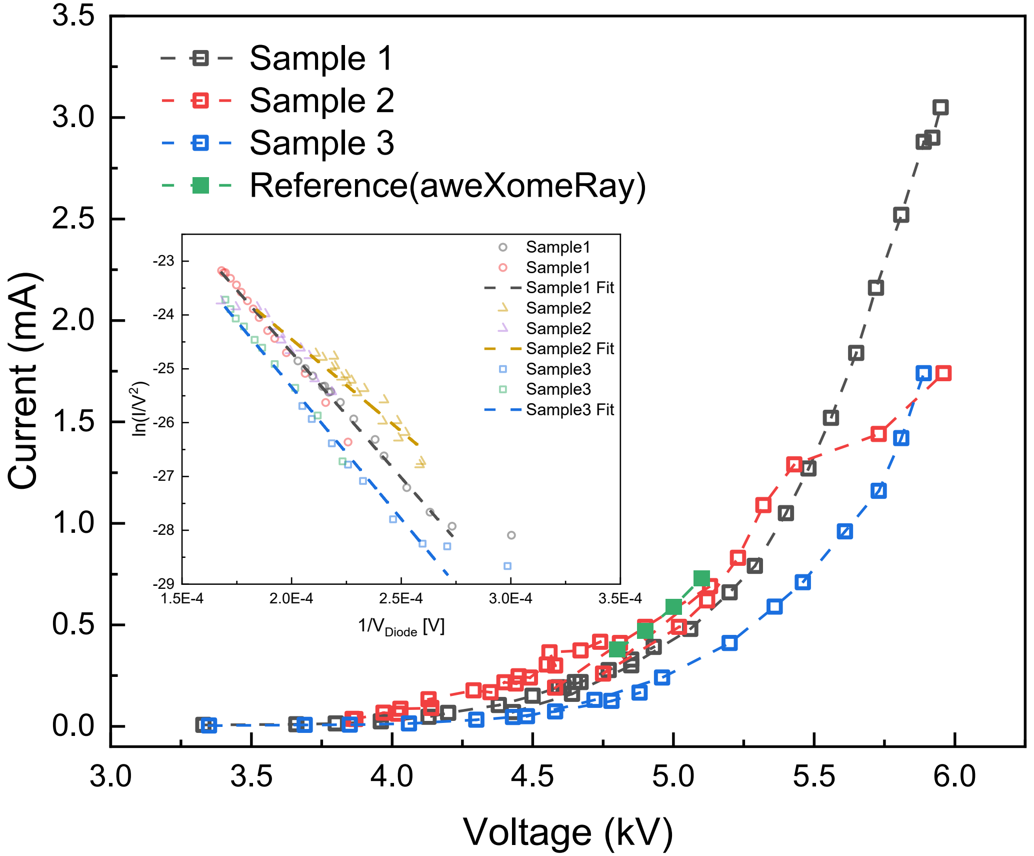
- Exponential current increase along voltage sweep

  → Enhancement factor $\beta \sim 2000$ / Effective emission area $\delta S \sim 0.5\ \mu m^2$

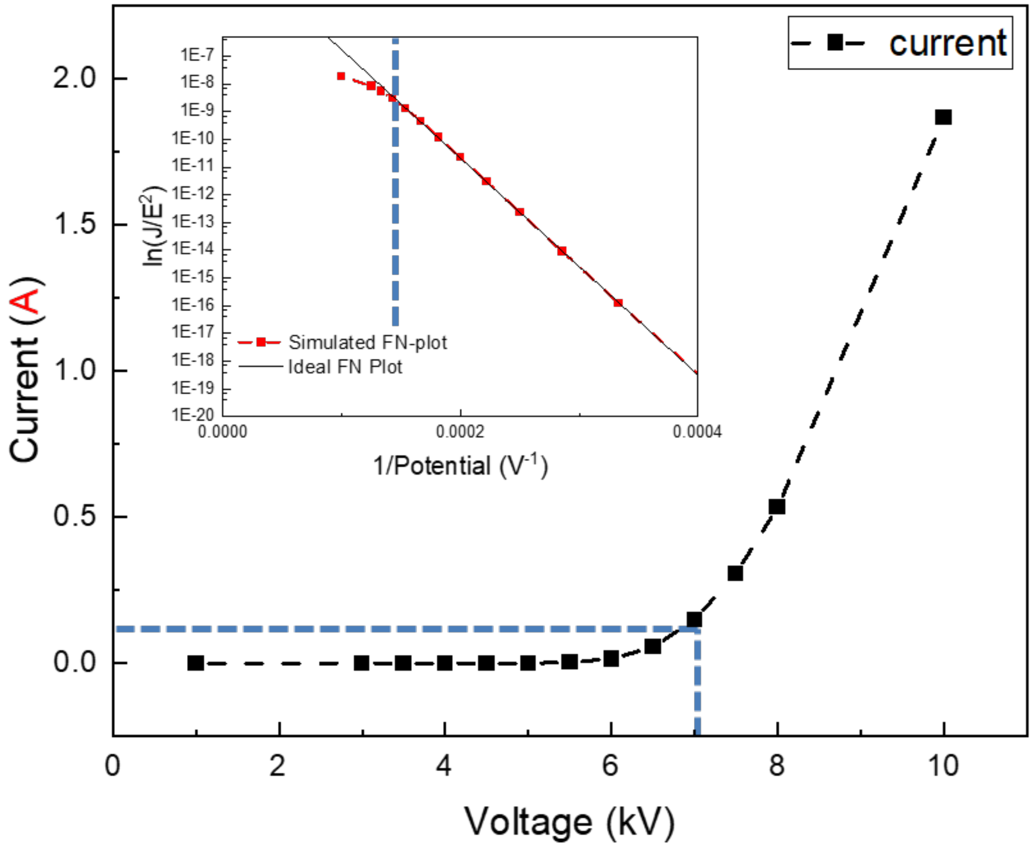
$$J = A_{FN}\phi^{-1}\beta^2E^2\exp\left(-\frac{B_{FN}\phi^{\frac{3}{2}}}{\beta E}\right)$$

- Estimated space charge screening effect over $\simeq 150$ mA

I-V curve & FN Plot on commercial X-ray tube

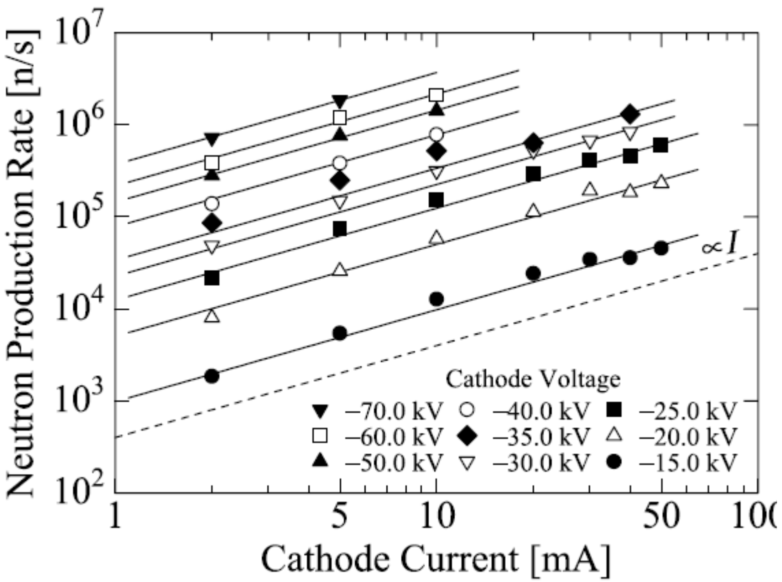


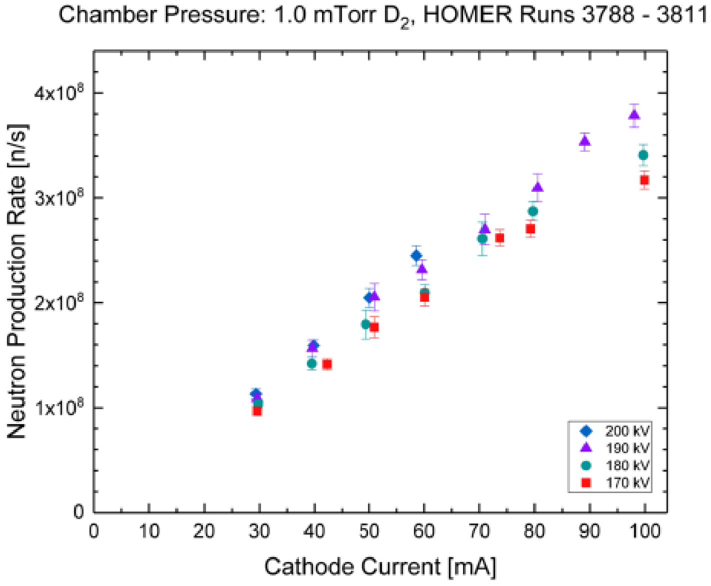
FN Plot deformation in high current region



정전형 핵융합로 장치 수율 동향

- 2024년 기준 TIT 및 UW 기록이 최고
- 빔-타겟에 의한 기여 높음





	TIT (2009)	TIT (2006)	UW (2007)	UW (2018)
Plasma Source (Electron Loss Control)	Cusp B field D-D	Cusp B field D-D	Hot filament electron injection (6 filament)	Hot filament electron injection (6 filament)
Power Source Repetition Rate	Pulsed / -80 kV / 15A 4 Hz / 20 μs (0.008%)	CW / -60 kV / 10mA	CW / -145 kV / 35 mA	CW / -190 kV / 98 mA
Plasma Pressure	0.1 – 10 Pa (1-100 mTorr)	1 – 100 mTorr	0.3 Pa (2 mTorr)	1 mTorr
Neutron Production Rate	$7.4 \cdot 10^9$ n/s (CW: $5.9 \cdot 10^5$ n/s)	$2.1 \cdot 10^6$ n/s	$2.0 \cdot 10^7$ n/s	$3.8 \cdot 10^8$ n/s (~10 s)

운전 압력 목표 설정: 운동 에너지 손실

입자 가속 과정에서의 Loss

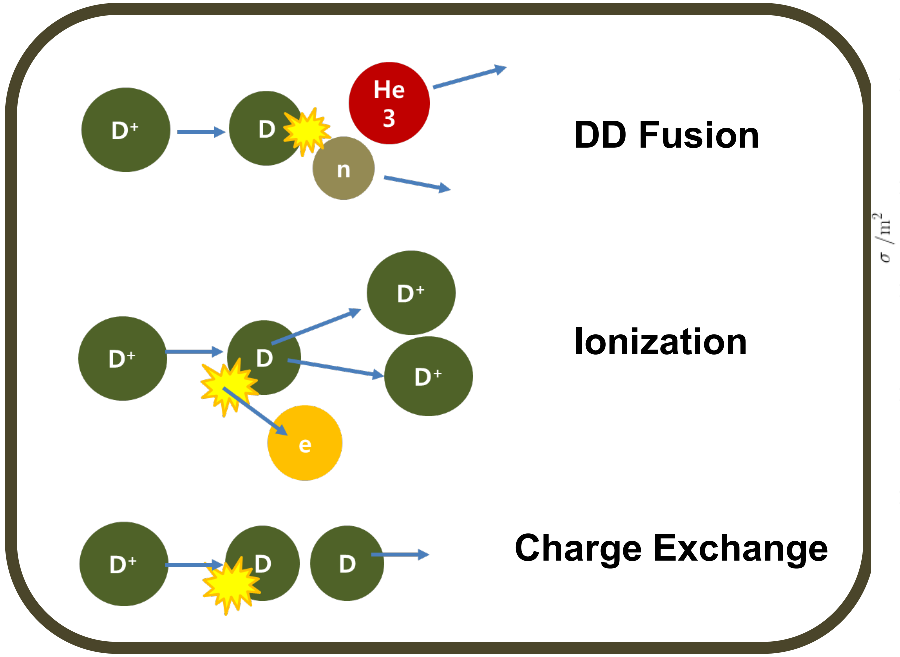
1) Beam - Background DD fusion $\sim O(10^{-25}\ \mathrm{cm}^2)$

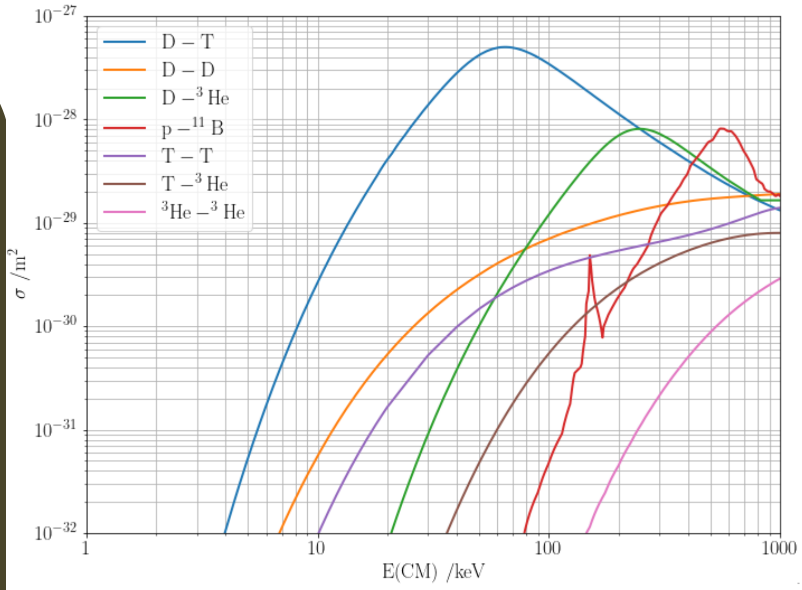
2) Coulomb Scattering , Ionization $\sim O(10^{-16}\ \mathrm{cm}^2)$

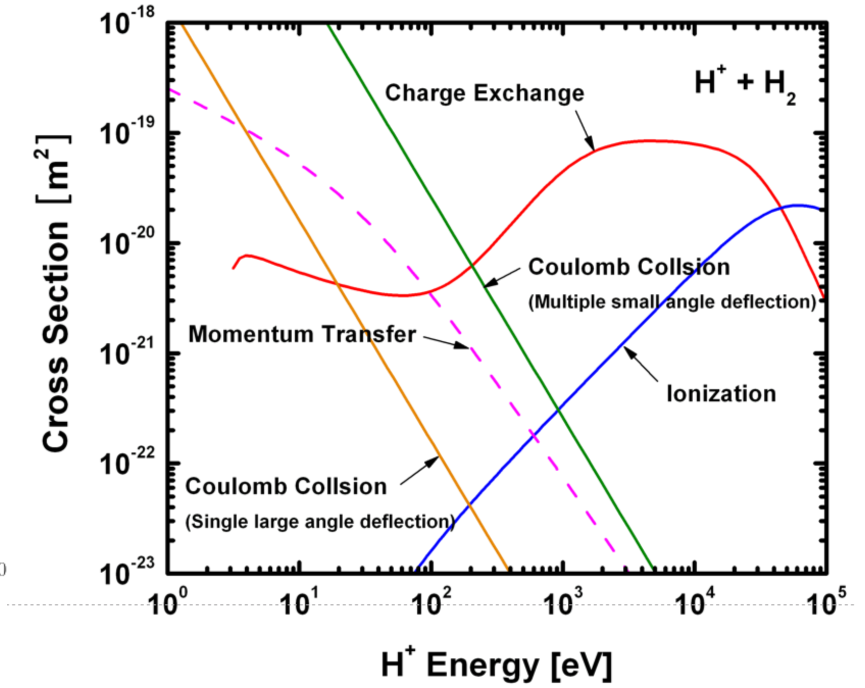
→ Geant4 시뮬레이션을 이용하여 진행, 넓은 범위에서 **에너지 감소 무시 가능 (<<1 %)**

3) **Charge Exchange** $\sim O(10^{-16}\ \mathrm{cm}^2)$

Energy Loss Mechanism







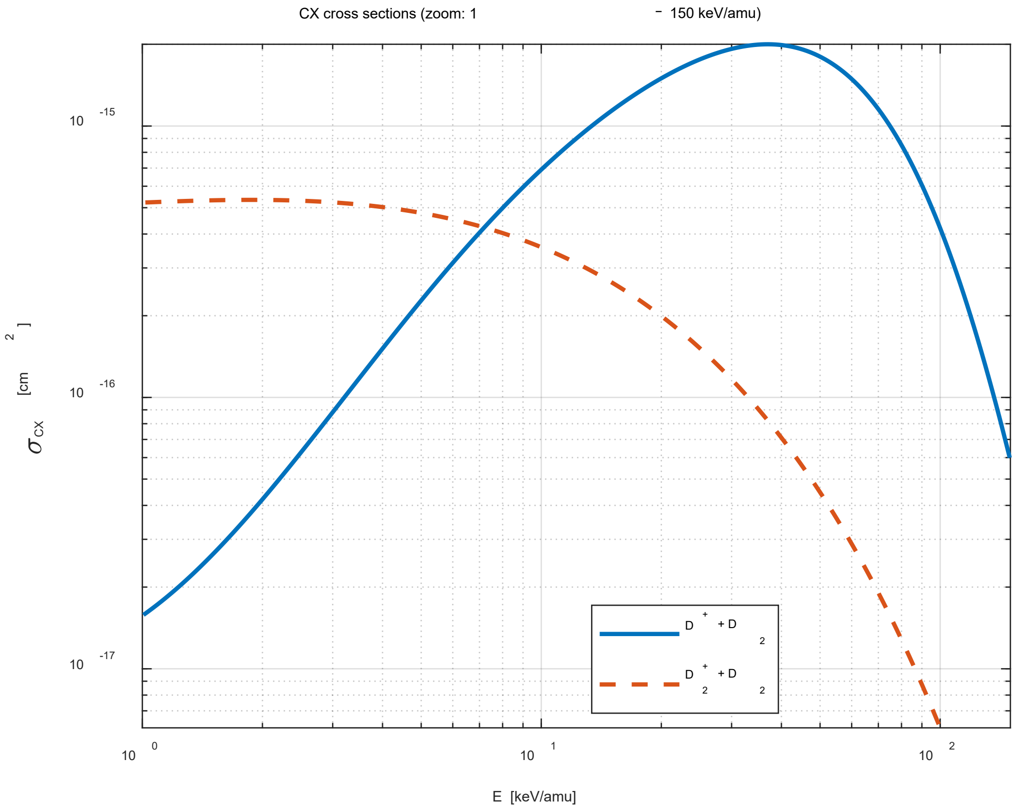
전하 교환 반응 MFP

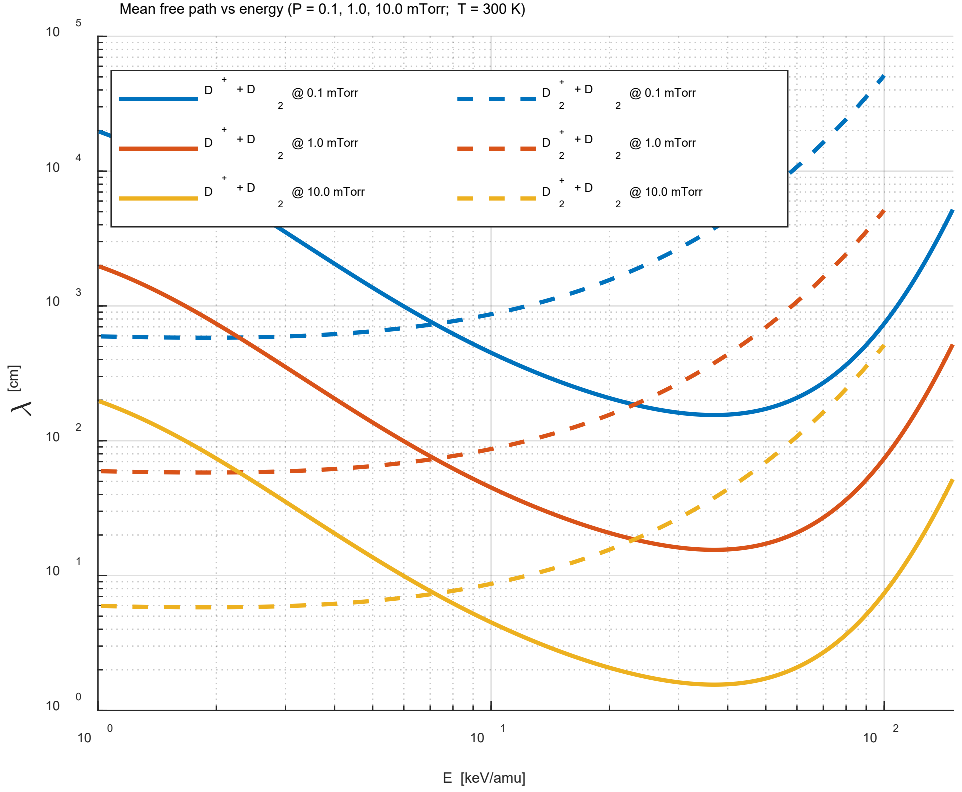
(Resonant) Charge Transfer

$$1)\ D^{+}(fast) + D_2(slow) \rightarrow D(fast) + D_2^{+}(slow)$$

$$2)\ D_2^{+}(fast) + D_2(slow) \rightarrow D_2(fast) + D_2^{+}(slow)$$

20 – 150 keV 영역에서 100 % 오차 내에서 근사

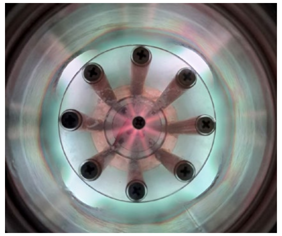




Influence on Charge-Exchange(CX) in IECF

CX distributes kinetic E of incidence particle → **Effective fusion energy loss**

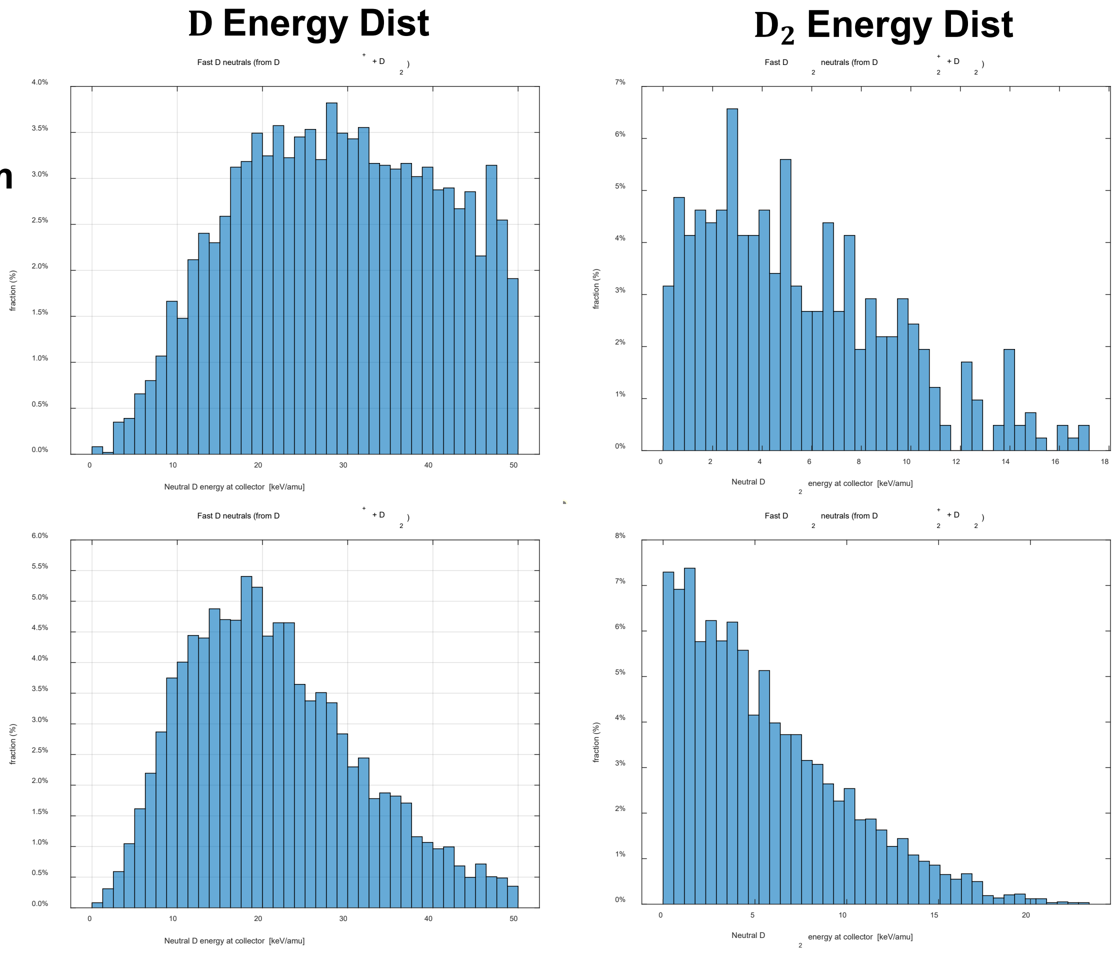
Low pressure(<1 mTorr) operation required



Gap = 15 mm

P = 1 mTorr

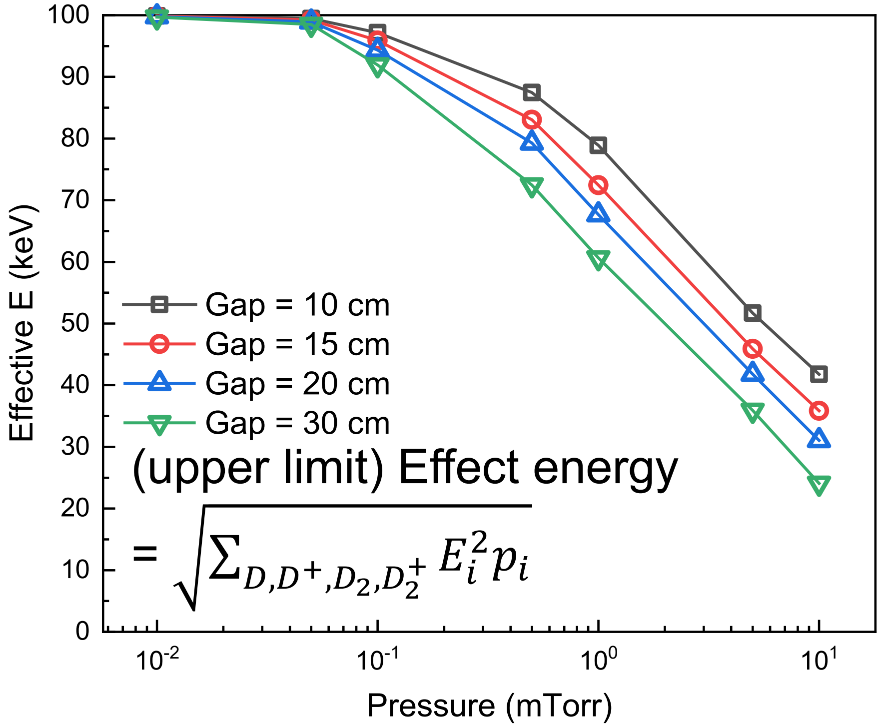
P = 5 mTorr



$$D^+(fast) + D_2(slow) \rightarrow D(fast) + D_2^+(slow)$$

$$D_2^+(fast) + D_2(slow) \rightarrow D_2(fast) + D_2^+(slow)$$

(Weighted) Effective Energy



시뮬레이션 결과: 에너지 분포

고속 중성 D: bell shape distribution

고속 중성 D_2 : right-tailed distribution

$\sigma_{DD} \sim E^2$ 이므로 CX 반응 적을수록 지향

$$\boldsymbol{D^+}(fast) + D_2(slow) \rightarrow \boldsymbol{D}(fast) + \boldsymbol{D_2^+}(slow)$$

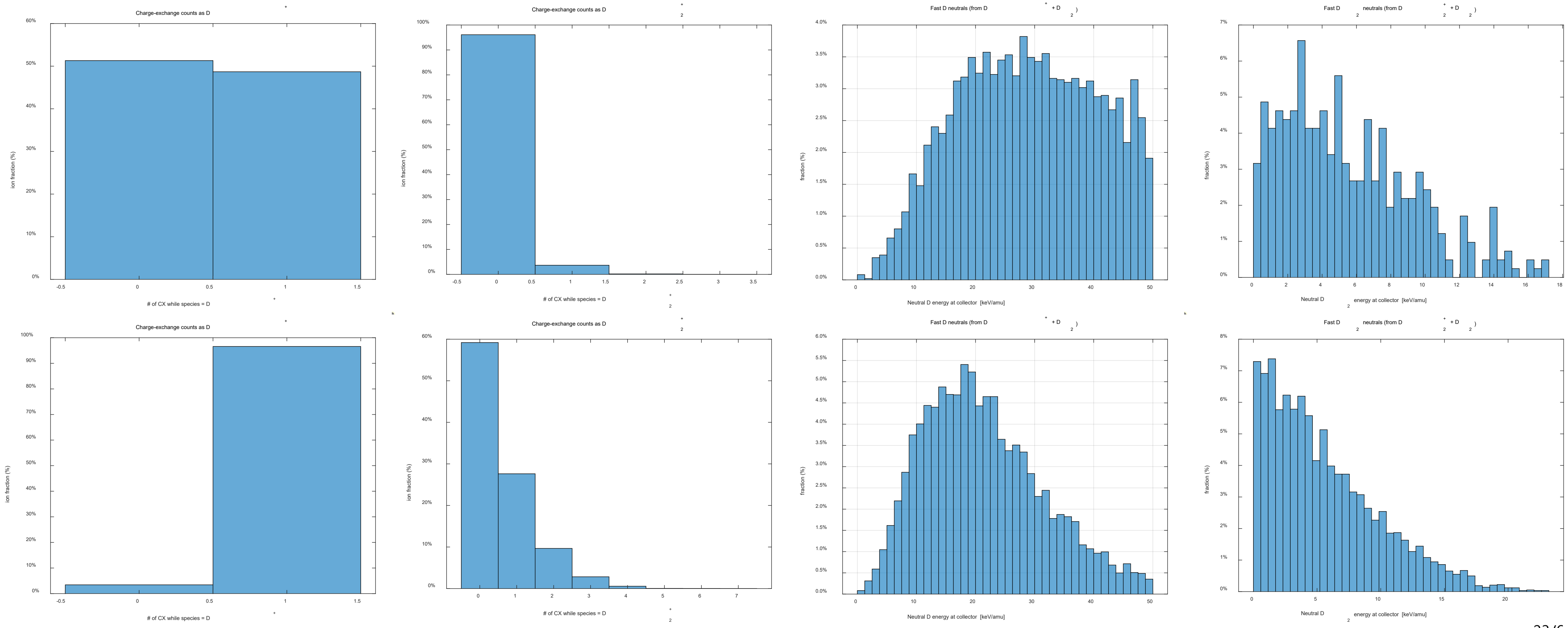
$$\boldsymbol{D_2^+}(fast) + D_2(slow) \rightarrow \boldsymbol{D_2}(fast) + \boldsymbol{D_2^+}(slow)$$

D^+ CX count | **D_2^+ CX count** | **D Energy Dist** | **D_2 Energy Dist**

Gap = 15 mm

P = 1 mTorr

P = 5 mTorr



Effective Energy Calculation

(upper limit) Effect energy = $\sqrt{\sum E_i^2 p_i}$

$$D_2^+(fast) + D_2(slow) \rightarrow D_2(fast) + D_2^+(slow)$$

$$D^+(fast) + D_2(slow) \rightarrow D(fast) + D_2^+(slow)$$

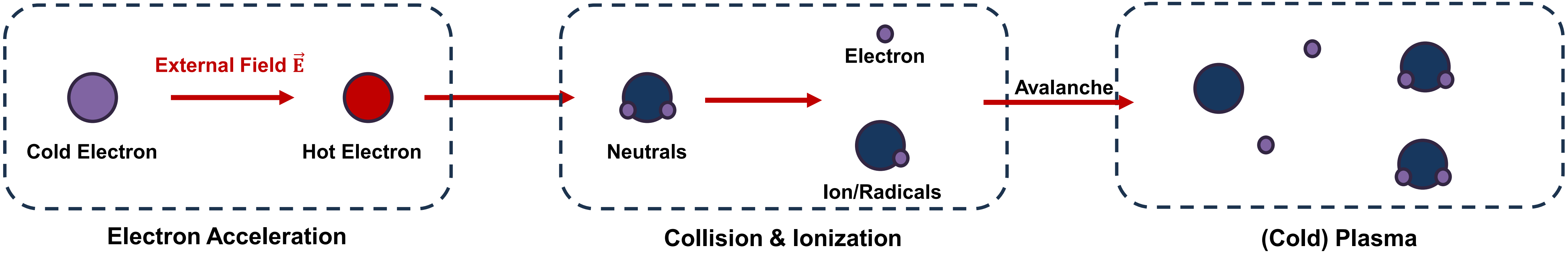
Gap (cm)	Pressure (mTorr)	**Ion** D+ E & Proportion	**Neutral** D E & Proportion	**Ion** D2+ E & Proportion	**Neutral** D2 E & Proportion	**Effective Energy**
15 cm	10	100 keV 0.09%	31.66 keV 99.91%	39.96 keV 99.1 %	19.54 keV 145.26 %	35.86
15 cm	5	100 keV 3.31%	42.35 keV 96.69%	24.04 keV 96.69 %	22.13 keV 58.48 %	45.89
15 cm	1	100 keV 50.66%	57.73 keV 49.34%	40.22 keV 49.34 %	22.83 keV 4.45 %	72.43
15 cm	0.5	100 keV 71.51%	60.23 keV 28.49%	38.88 keV 28.49 %	24.53 keV 1.05 %	83.04
15 *cm*	0.1	100 keV 93.81 %	61.03 keV 6.19%	38.76 keV 6.19 %	-	95.91
15 cm	0.05	100 keV 96.74%	62.19 keV 3.26%	37.59 keV 3.26 %	-	99.24
15 cm	0.01	100 keV 99.40%	60.52 keV 0.60%	39.49 keV 0.60 %	-	99.86

Plasma Generation

- 전체적으로 중성인, 자유 하전 입자 및 중성 입자들의 집합
- 하전 입자의 가속 → 중성 입자의 이온화, 하전 입자 생성 → 2차 하전 입자의 가속 ··

전자 사태(avalanche) 발생으로 플라즈마 방전

- 다른 방식의 플라즈마 방전 존재: 입자, 에너지 balance로 설명

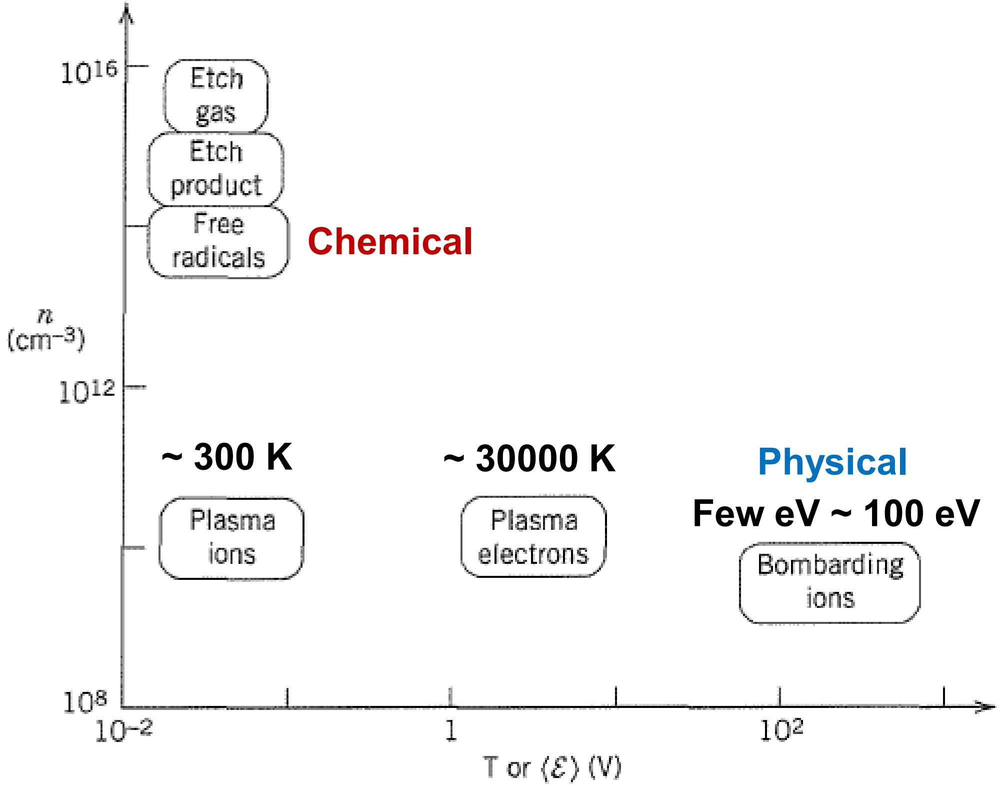


Plasma Reaction on Surface

- 플라즈마 생성 부산물: 전자, 이온, 라디칼
- 처리 대상 표면과의 관계

1) 입자 balance를 위해 플라즈마 전위 형성 → 이온이 표면에 가속하며 bombarding: **Physical process**

2) 라디칼의 높은 활성도로 표면과 반응: **Chemical process**



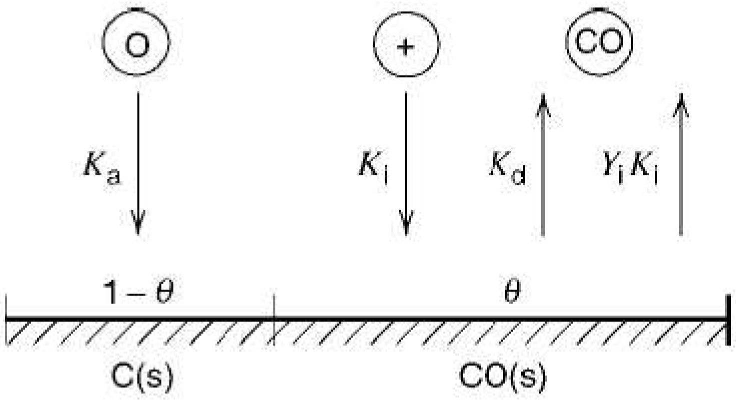
Byproducts & Particle Energy

Reaction Model (Scenario):

$$O(g) + C(s) \xrightarrow[\text{adsorption}]{K_a} C:O$$

$$C:O \xrightarrow[\text{desorption}]{K_d} CO(g)$$

$$ion + C:O \xrightarrow{Y_i K_i} CO(g)$$



Chemical Absorption	Thermal Desorption	Physical Desorption

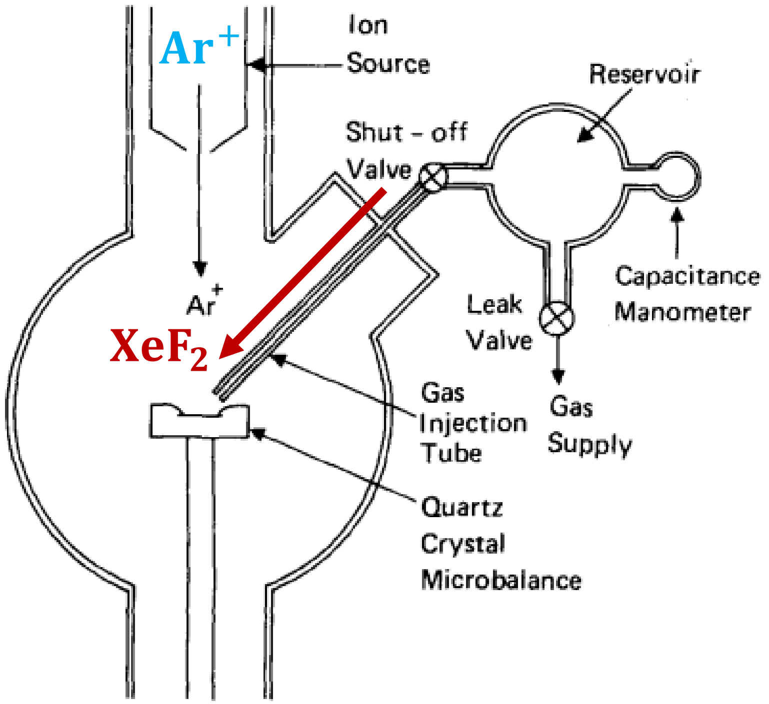
$$\frac{d\theta}{dt} = K_a\, n_{O,s}(1-\theta) - K_d\theta - Y_i K_i n_{i,s}\theta$$

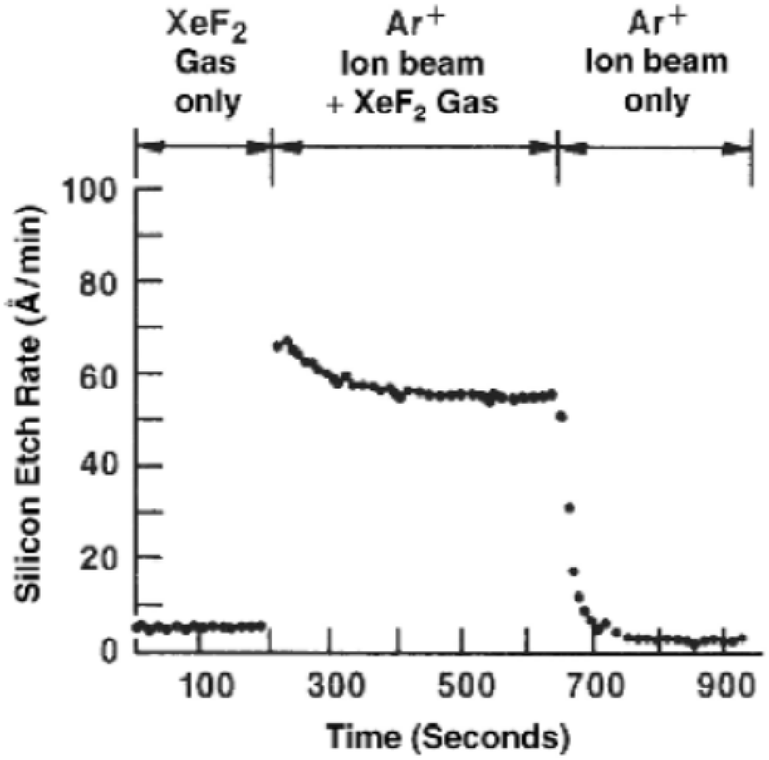
Langmuir Absorption Model

Ion Beam Assisted Chemical Reaction

- Etching gas only: $2XeF_2 + Si(s) \rightarrow SiF_4(g) + 2Xe(g) \rightarrow$ pumping
- 외부 Ar^+ ion beam: Sputtering으로 physical etching
- **플라즈마 방전**으로 빔, 화학적 식각 **병행** + **sample 포괄 영역 세정**

Ion beam + Etchant (RIE)





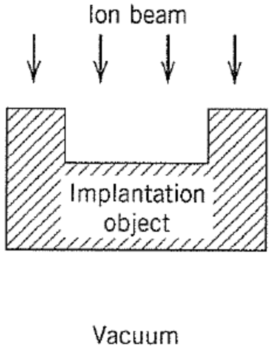
Plasma Itself

$e + CF_4 \rightarrow 2e + CF_3^+ + F$ **To sustain plasma**

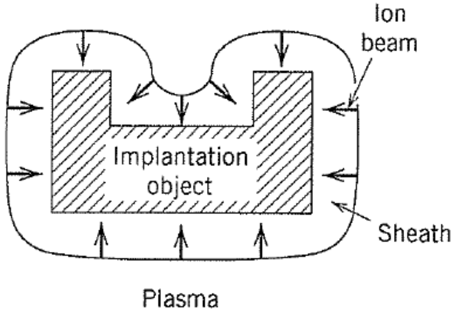
$e + CF_4 \rightarrow e + CF_3 + F$
$e + CF_4 \rightarrow e + CF_2 + 2F$ **To make reactive species**

$Si + 4F \rightarrow SiF_4(g)$ **To etch & pump volatile silicon**

Cleaning directionally



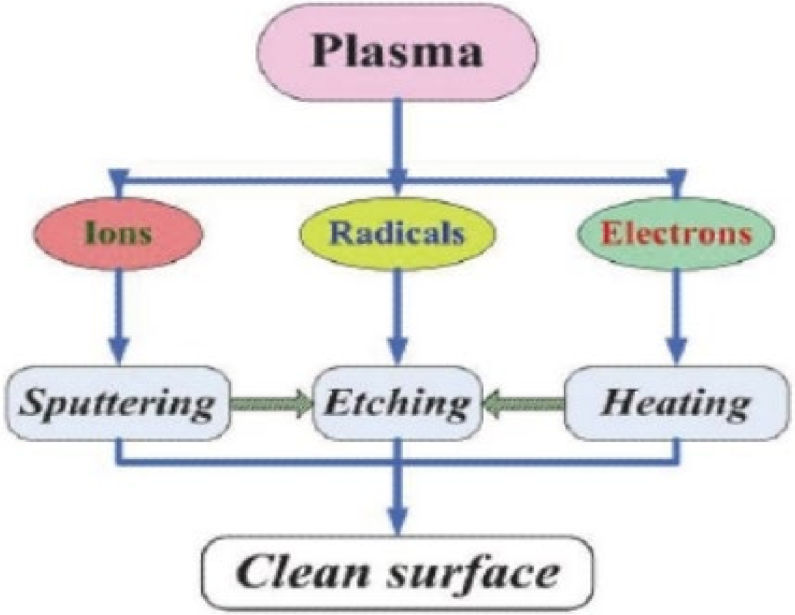
Cleaning all surface over



Plasma Cleaning Mechanism

- Electron / Ion / Radical의 표면 반응을 이용한 표면 세정
- Radical – chemical reaction의 **선택적** · **빠른 반응** → 방전 가스 선정 필요
- 1935 년 첫 Plasma cleaning paper 이후로 방전 방식/가스 발전

Plasma Cleaning Schematic



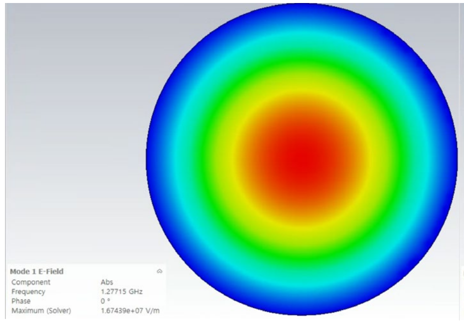
Cleaning Mechanism of Plasma Components

Plasma Components	Cleaning Target	Cleaning method
Electrons	Physiosorbed (~0.2 eV / 600° C) Light Chemisorbed (~ 2 eV)	Heating(Drying)
Ions	All Contaminants (protrusion first)	Sputtering R(nm/s) = YVJ/q Y = sputter yield V = atomic volume J/q = Current density/electron charge
Radicals	Specific Dielectric / Metal → Main plasma gas selection	Reaction with Halogen-, hydride-, methyl- compounds

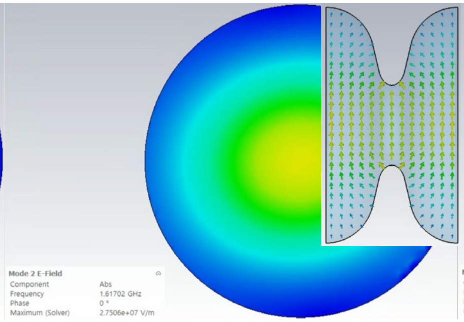
Tesla Cavity Test: Single Cell

- Periodic BC 적용

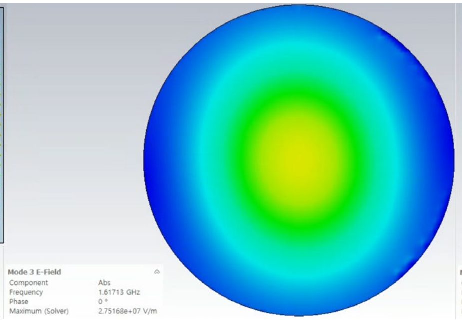
Mode 1(M1)



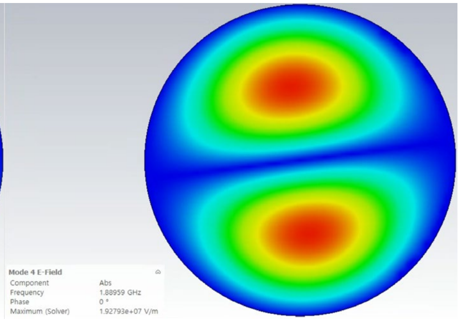
Mode 2(D1)



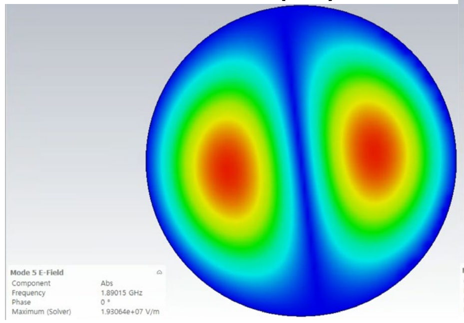
Mode 3(D1)



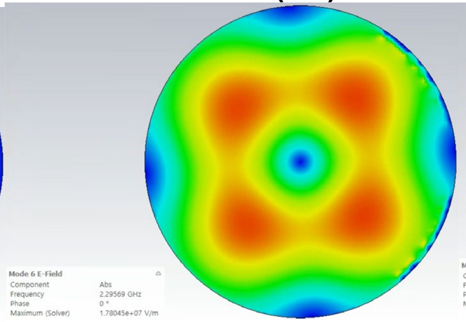
Mode 4(D2)



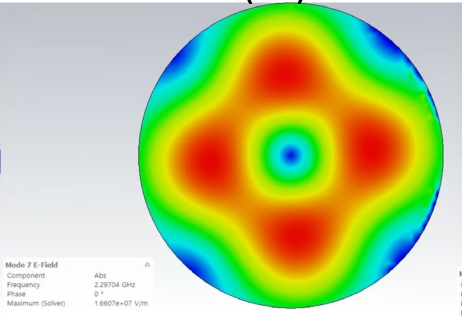
Mode 5(D2)



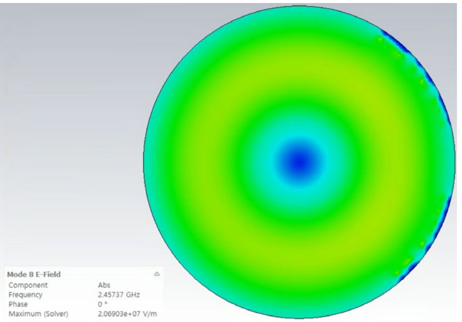
Mode 6(Q1)



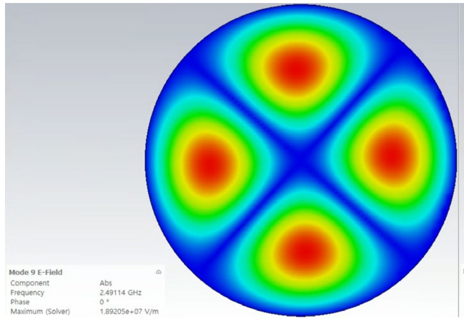
Mode 7(Q1)



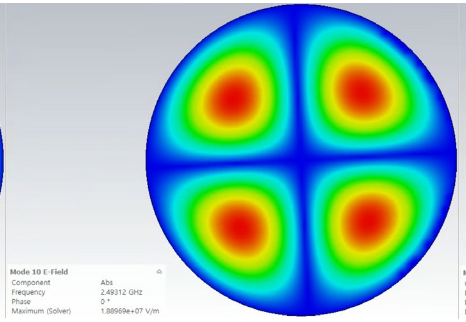
Mode 8(M2)



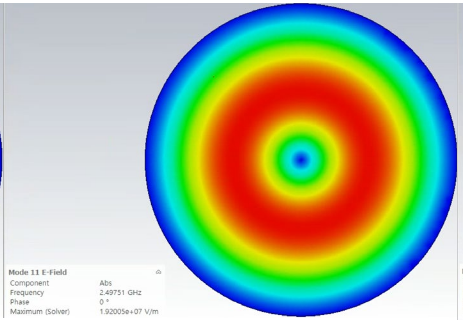
Mode 9(Q2)



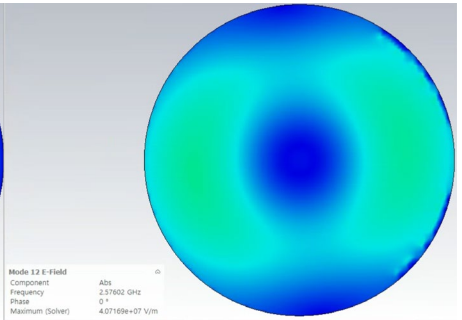
Mode 10(Q2)

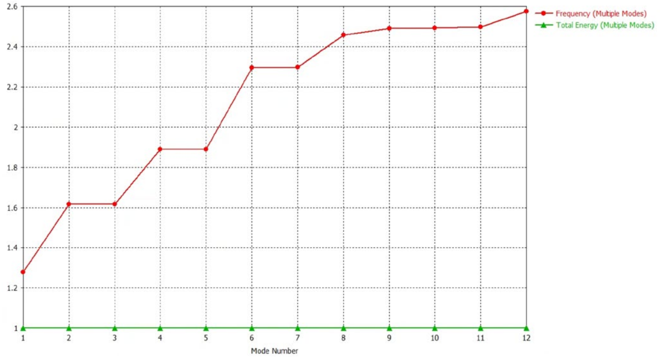


Mode 11(??)



Mode 12(D3)



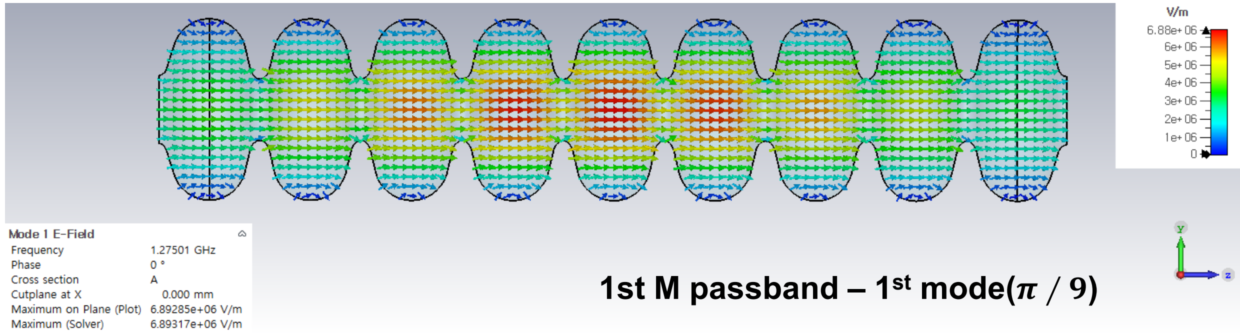


Periodic Single Cell Eigenmodes [DESY]

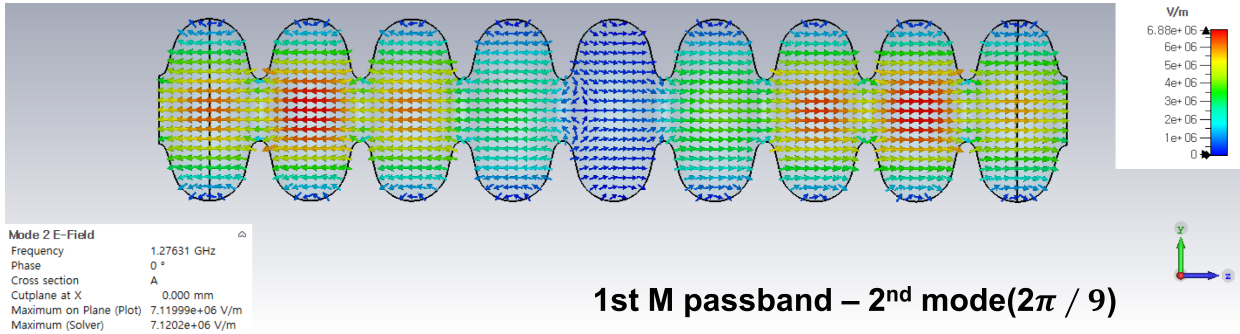
type	band #	f_0 / GHz	f_π / GHz
M	1	1.2755	1.2996
D	1	1.6197	1.7920
D	2	1.8877	1.8261
Q	1	2.2996	2.3223
M	2	2.4576	2.3789
Q	2	2.4903	2.4699
D	3	2.5782	2.4713
M	3	2.6704	2.7730
D	4	3.0333	2.8134
D	5	3.1231	3.0802
Q	3	3.2096	3.3119
D	6	3.3419	3.3595
Q	4	3.6204	3.4443
M	4	3.6603	3.3871

Tesla Cavity Test: 9-cells

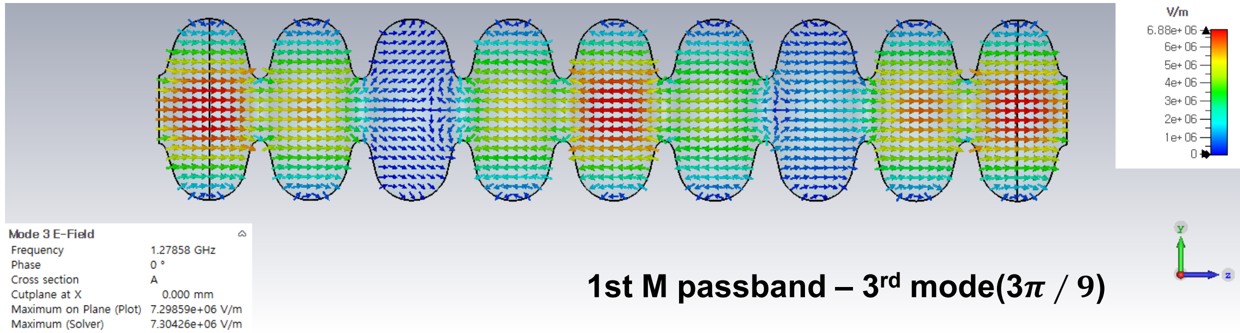
- Monopole(M) passband
- SNS elliptical cavity: 6-cells



1st M passband – 1st mode(π / 9)

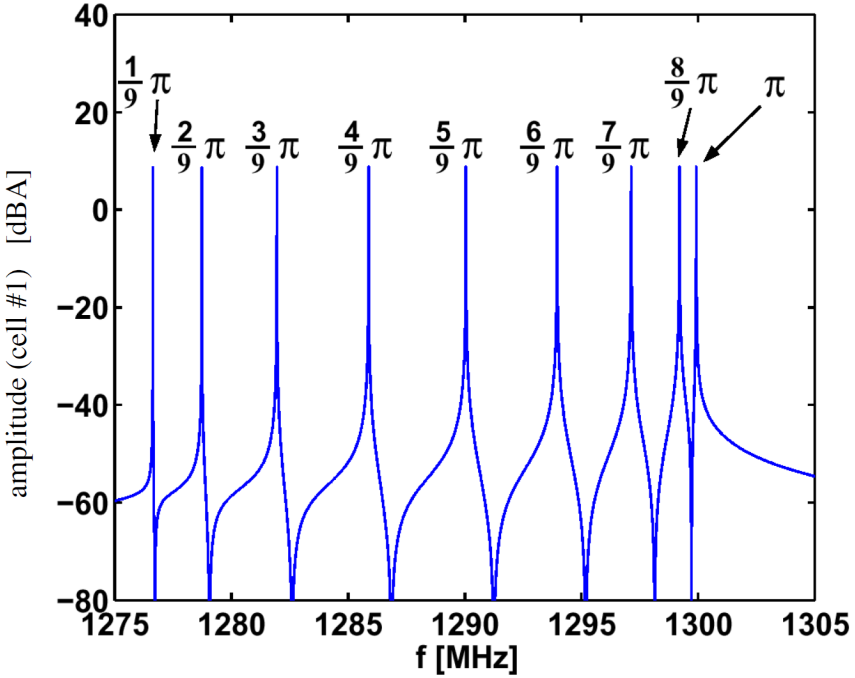


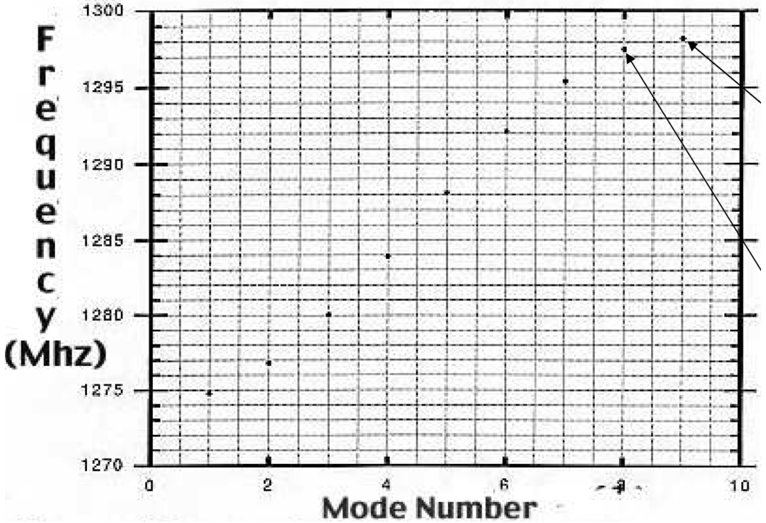
1st M passband – 2nd mode(2π / 9)



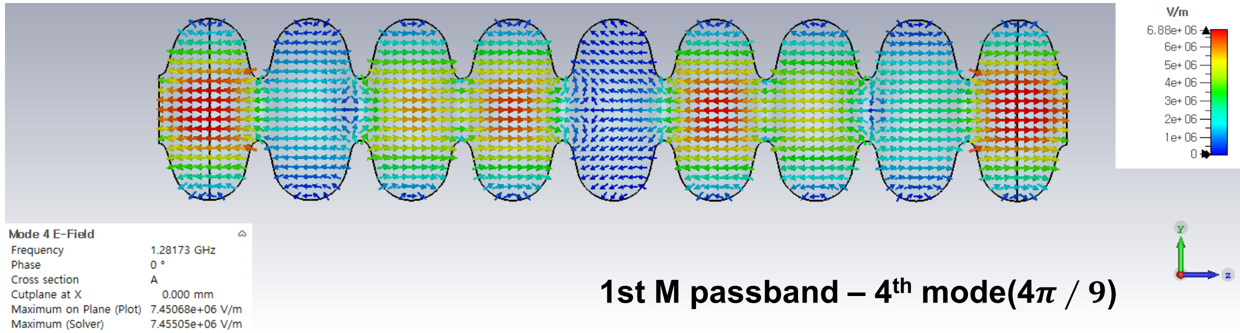
1st M passband – 3rd mode(3π / 9)

TM010 Eigenmode spectrum of 9-cell cavity[cornell]

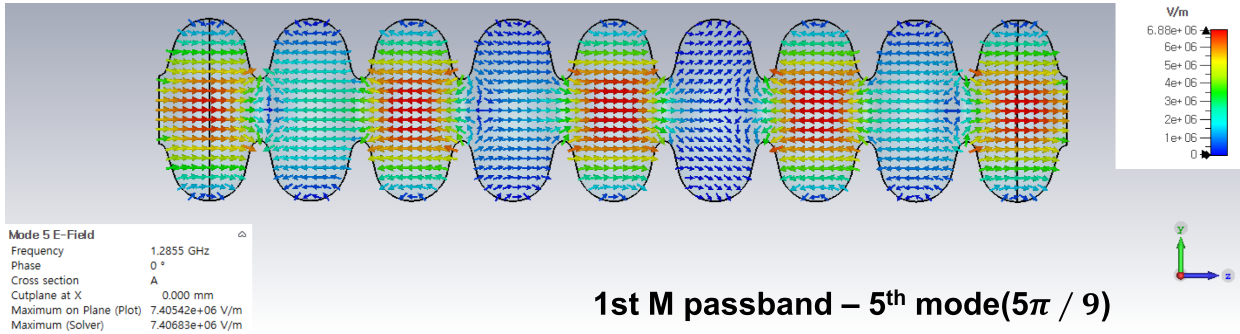




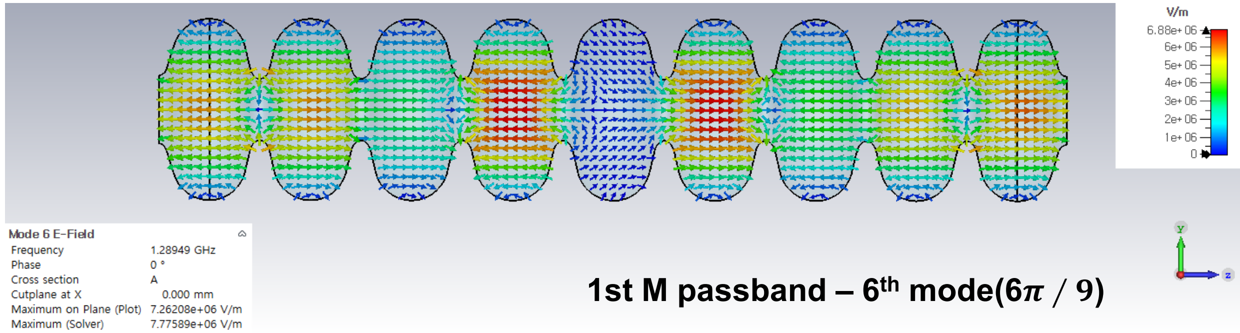
Tesla Cavity Test: 9-cells



1st M passband – 4th mode($4\pi / 9$)

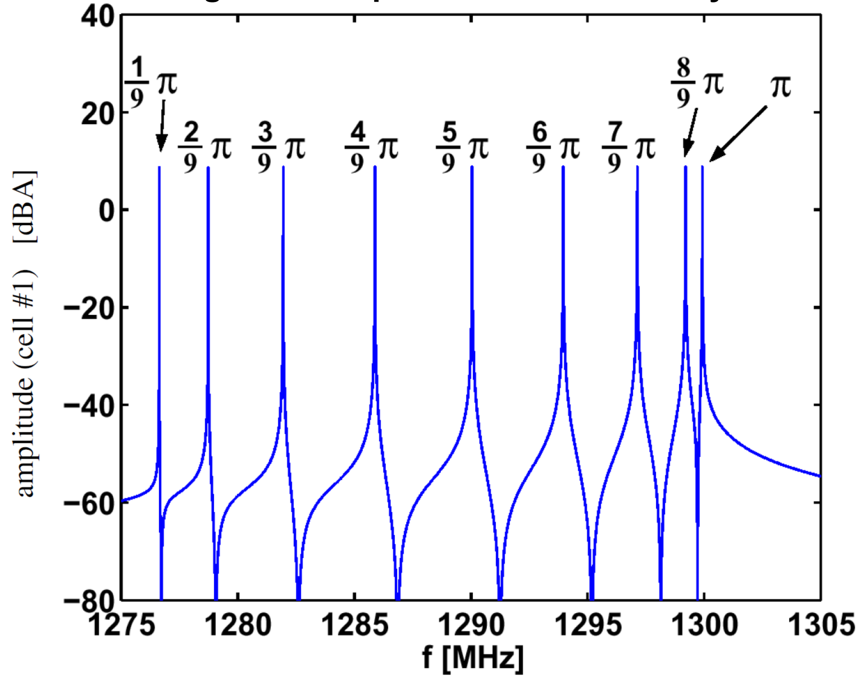


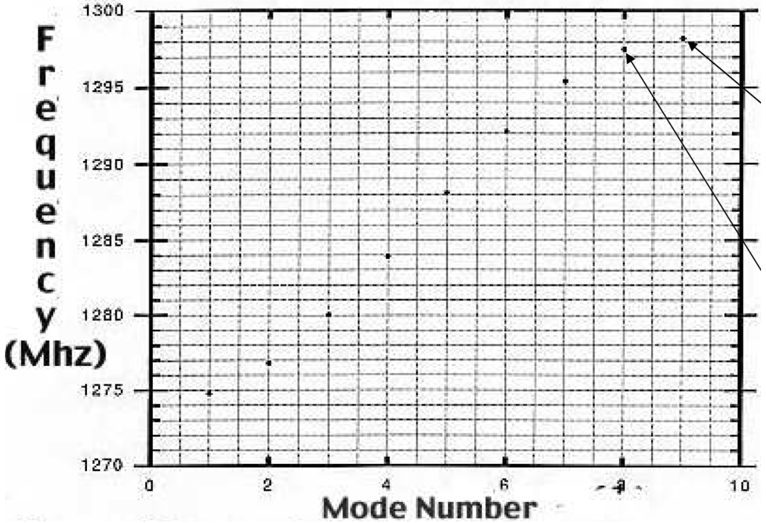
1st M passband – 5th mode($5\pi / 9$)



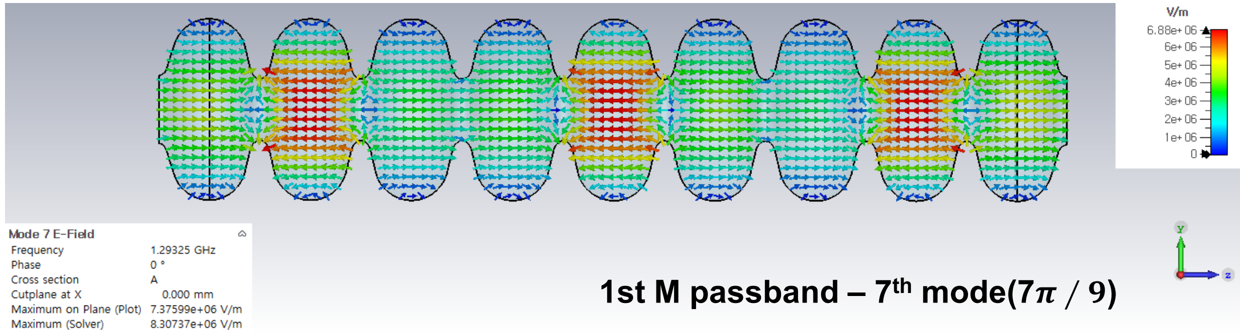
1st M passband – 6th mode($6\pi / 9$)

Eigenmode spectrum of 9-cell cavity

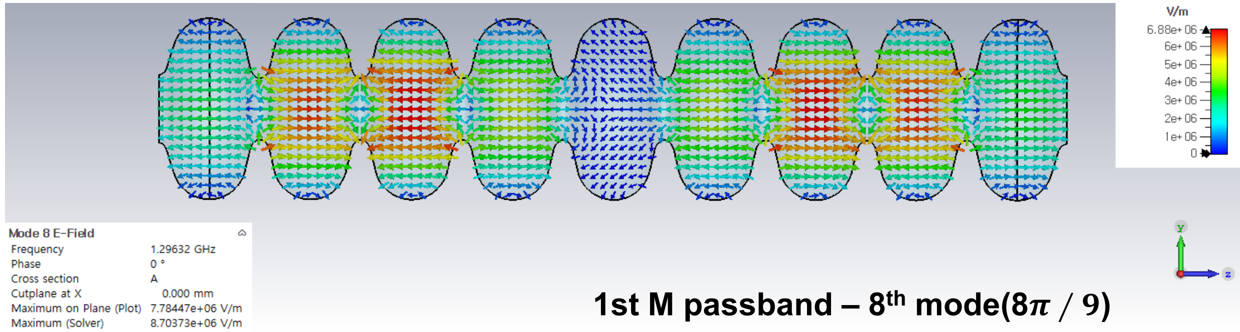




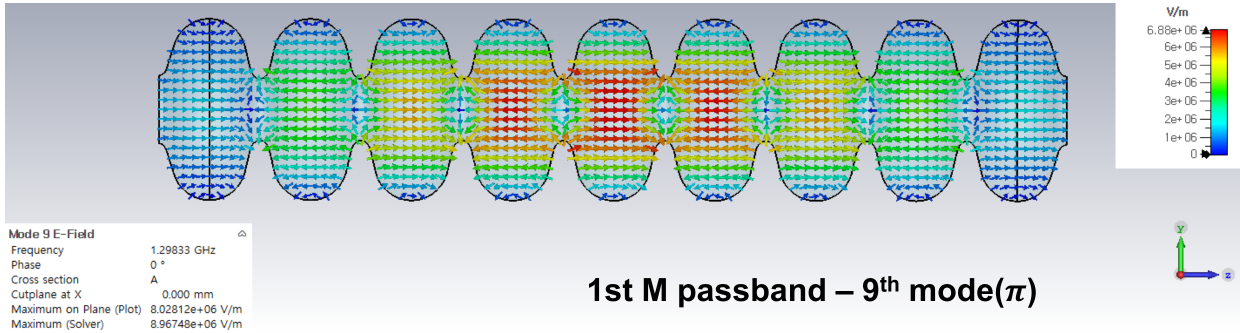
Tesla Cavity Test: 9-cells



1st M passband – 7th mode(7π / 9)

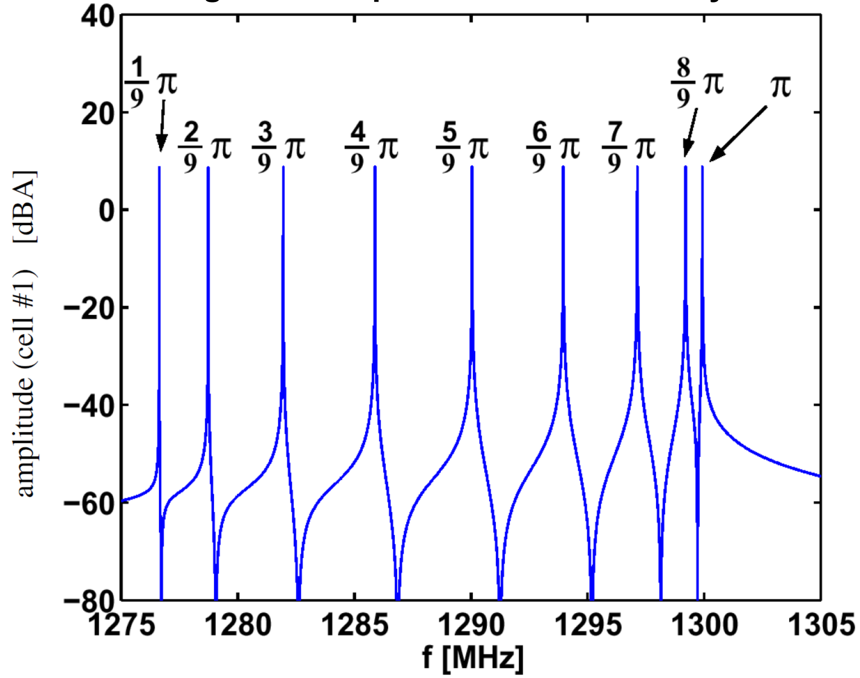


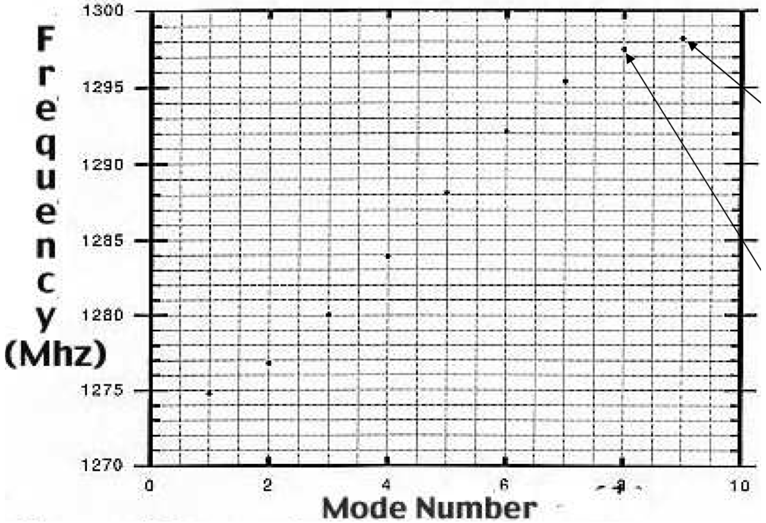
1st M passband – 8th mode(8π / 9)



1st M passband – 9th mode(π)

Eigenmode spectrum of 9-cell cavity

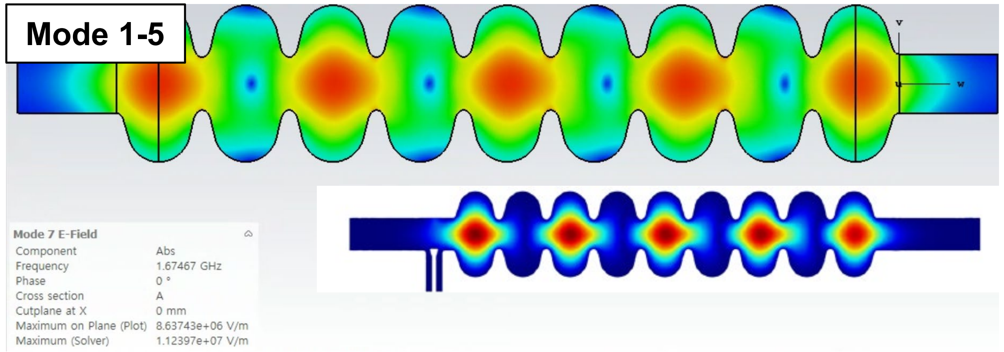


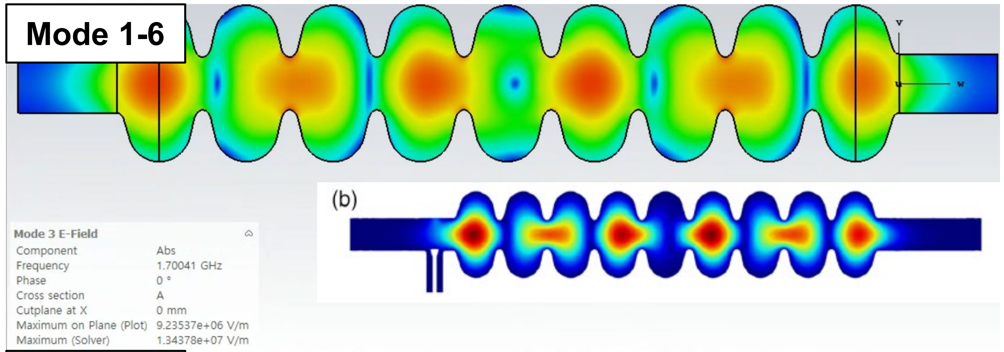


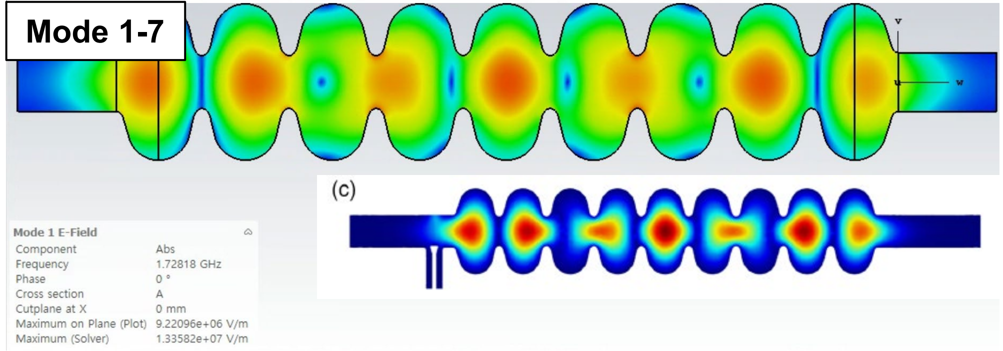
Tesla Cavity Test: 9-cells

- 본 논문 내용(COMSOL)과 CST 시뮬레이션의 HOMs passband 형상 일치

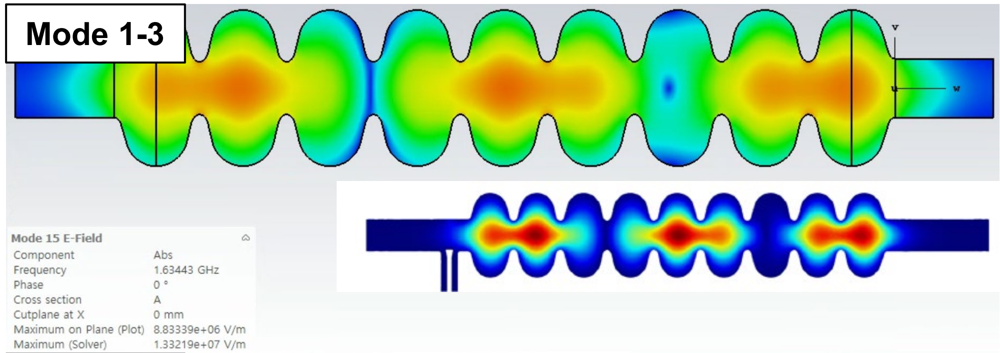
Locking Mode (Mode 3)

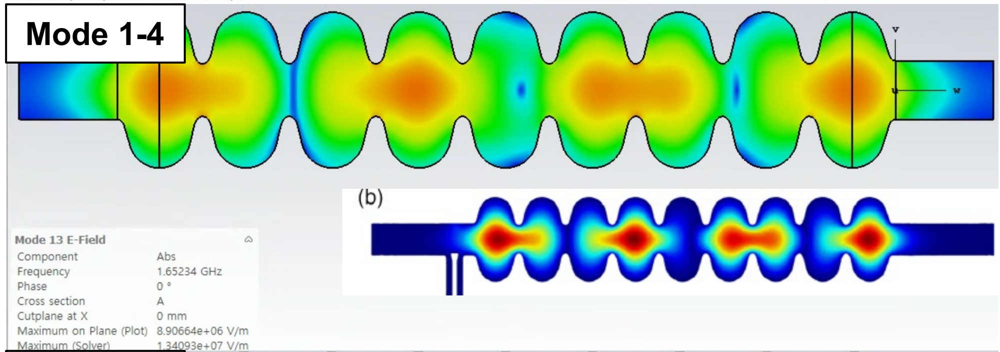


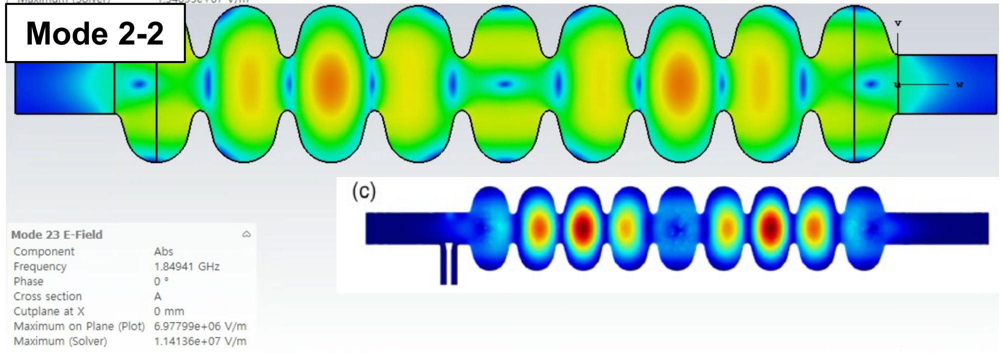




Transfer Mode (Mode 2)







Multipole Dual-Tone Ignition [LCLS 2019]

- SNS 방식: Monopole dual-tone → High coupling 전제
- 두 가지 방법 제시

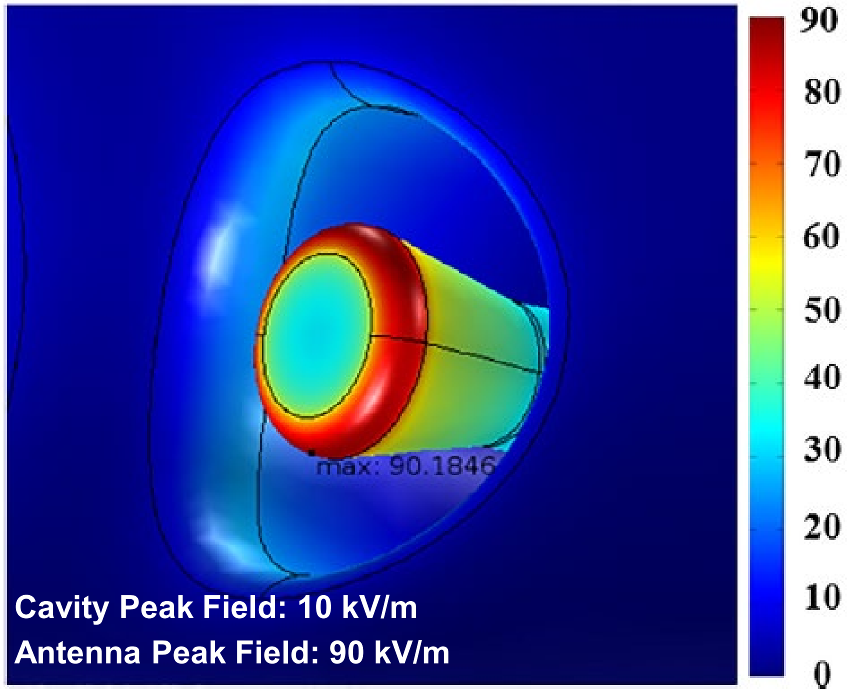
1) HOMs superposition: 선택적 cell ignition

2) Plasma bridging: cell ignition 후 neighbor cell의 ignition 조건으로 환승

- Plasma control: intensity, hosting cell location, plasma detection

	SNS HB Cavity	LCLS-II Cavity
Cavity Q_0	$\approx 1 \cdot 10^4$	$\approx 1 \cdot 10^4$
Power Coupler Q_{ext}	$\approx 7 \cdot 10^5$	$\approx 4 \cdot 10^7$
Coupling Strength	High	Low → P_{FWD} ↑→ $E_{peak,antenna}$ ↑
Wave Mode for Plasma Cleaning	Monopole (π-mode) 1st passband → Dual-tone(fundamental)	Dipole 1st, 2nd passband → Superposition

Peak Electric field in kV/m



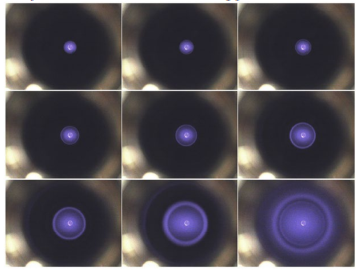
Plasma Bridging with Multipole Dual-Tone [LCLS 2019]

- 중심 셀 점화 → 3개의 모드를 이용하여 이동

1. Stabilize plasma in cell M with MODE1.
2. Superimpose MODE2 to bridge cells M and N.
3. Turn off MODE1.
4. Turn on MODE3 to lock plasma in cell N.

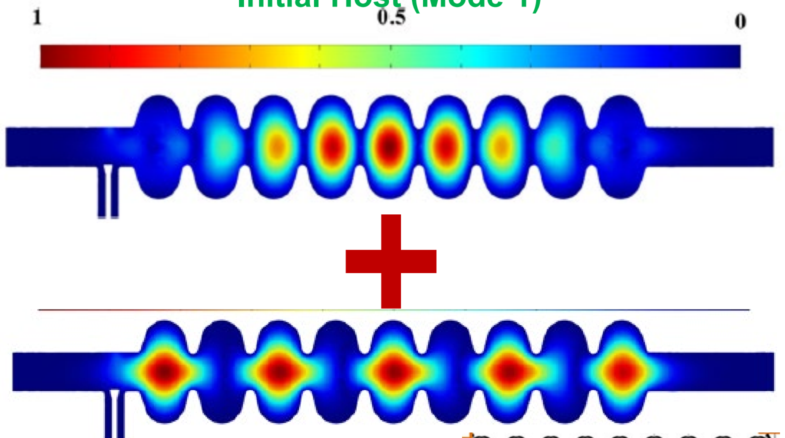
Host(H) Transfer(T) MODE_H MODE_T Locking

Cell M	Cell N	MODE1	MODE2	MODE3
5	5	2-1	. . .	1-5
5	4	1-5	1-4	1-6
4	3	1-6	1-3	1-5
3	2	1-5	2-2	1-7
2	1	1-7	1-3	1-5
1	2	1-5	1-3	1-7
2	3	1-7	2-2	1-5
3	4	1-5	1-4	1-6
4	5	1-6	1-3	1-5
5	6	1-5	1-3	1-6
		1-6	1-4	1-5
		1-5	2-2	1-7
		1-7	1-3	1-5
		1-5	1-3	1-7
		1-7	2-2	1-5
		1-5	1-4	1-6
		1-6	1-3	1-5



Ar discharge using HOMs superposition

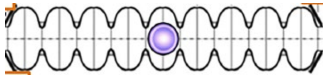
Initial Host (Mode 1)



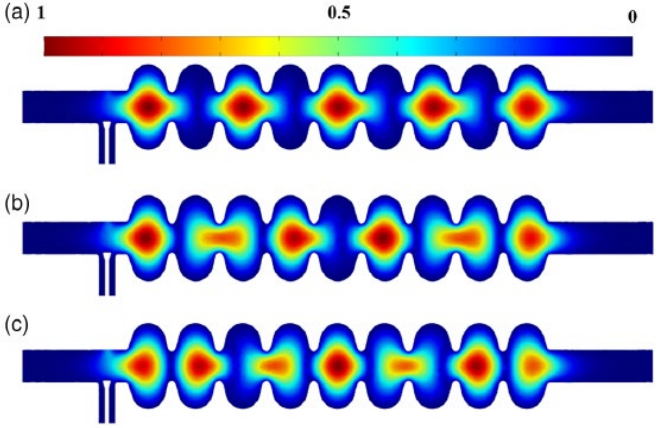
Mode 2-1 (Host)

Mode 1-5 (Locking)

→ Cell 5



Locking Mode (MODE 3)

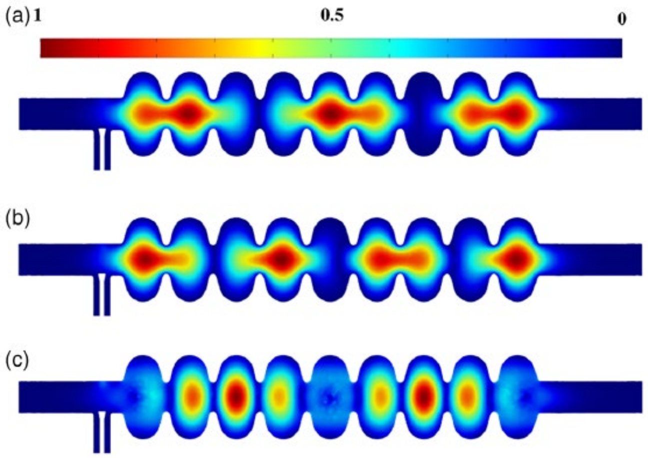


Mode 1-5

Mode 1-6

Mode 1-7

Transfer Mode (MODE 2)



Mode 1-3

Mode 1-4

Mode 2-2