
CFD-ACE+ Plasma Tutorial

Plasma – 2D ICP Model

Base Case

Flow/Heat/Chem/Plasma/Magnet

(주)경원이앤씨

❖ ICP 해석 설정 및 실행

- 압력, 반응 메커니즘 및 혼합물 지정
- Coil Excitation을 위한 모델 선택방법 확인
- 재료 및 물성 지정
- 경계 조건의 수정
- 초기 조건의 설정
- Numerical solution parameters 확인
- 해석 실행 및 결과 검토

※ 이 예제를 기반으로 아래와 같은 추가적인 해석 진행이 가능합니다.

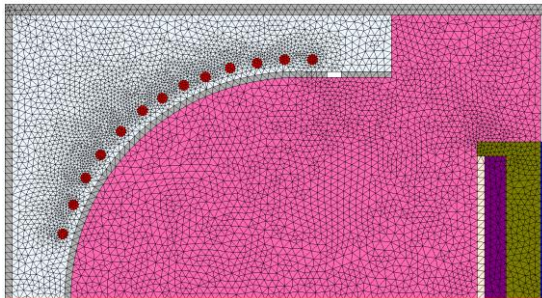
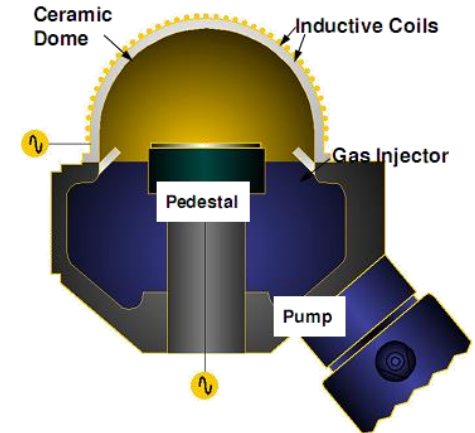
- ① Add Surface Deposition Mechanism
- ② Specifying ICP Power
- ③ Non-Maxwellian EEDF (LUT)
- ④ Sheath Model for IED, IAD
- ⑤ Ion Momentum Equation, Improving Convergence
- ⑥ Pulsed ICP

❖ 해석 적용

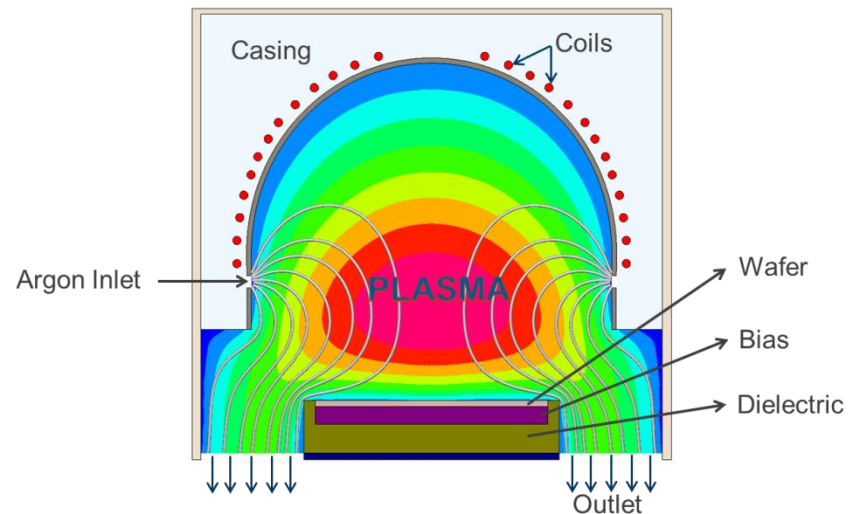
- 2D Axisymmetric Domain (X축은 ACE+에서 원통형 대칭의 축)
- 단순 아르곤
 - 관련된 화학 종은 Ar, Ar⁺, Ar^{*} 및 전자
 - 4 step gas phase kinetics는 운동량 전달, 여기(excitation) 및 단계적 이온화로 구성
 - 2 step gas phase kinetics는 이온의 재결합과 여기(excitation) 상태의 탈여기(de-excitation)로 구성
- Quasi-neutral plasma : 전자 밀도는 이온 밀도의 합으로 설정
- 양극성 전기장
- 순수 유도 방전 : 코일 또는 웨이퍼 바이어스에서 정전 용량 결합 없음

❖ 해석 형상 및 경계 조건

- 곡선 모양의 200mm 반응기
- 챔버의 압력은 10mTorr
- Coil current = 10A, 0.4 MHz
("Why Low Frequency?" – 5page 참고)
- Fixed mass inlet : Ar at 9.474×10^{-7} kg/s (35 sccm)



축대칭 형상 및 비정렬 격자 생성



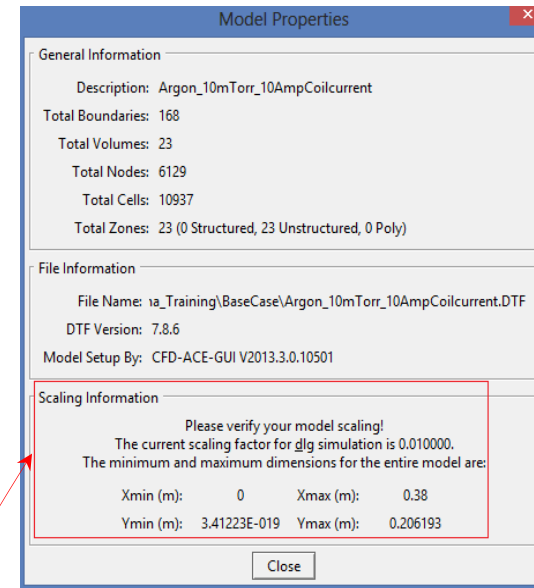
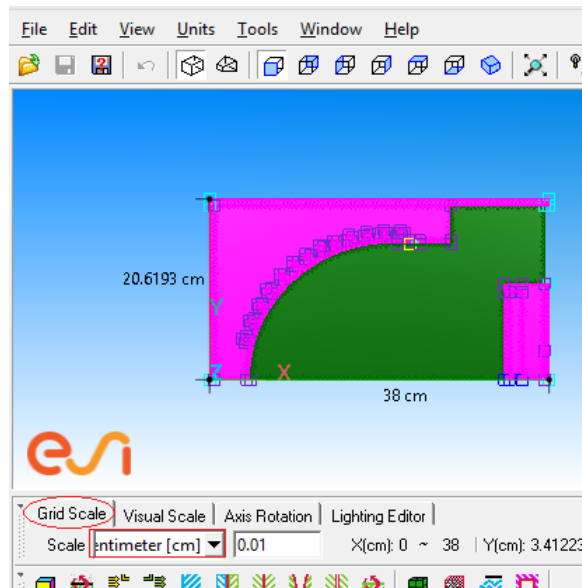
❖ Why Low Frequency?

- Electron collision frequency with background gas, ν (units = 1/s or Hz)
- rf driving frequency, $f = \omega/2\pi$ (units of 1/s or Hz)
- Consider 2 different electron heating regimes – collisional and collisionless depending on whether electron collisions with the background gas are numerous on the rf time scale.
- Compare ν and f : if $\nu \gg f$, collisional heating occurs. For collisionless heating to be significant, $\nu \ll f$ should hold true and additionally electrons have to pass through strong electric fields, not undergo collisions with neutrals and dissipate the gained energy elsewhere.
- In our reactor, in much of the dome $\nu \ll 6$ MHz. So efficient collisional heating cannot occur in higher frequencies (like 13.56 MHz excitation). Further there are no strong electric fields for collisionless heating. Therefore, the coil excitation was chosen to be low at 400 kHz, so $\nu \gg f$ in much of the dome and collisional heating can occur.
- ν is a function of gas pressure. As pressure increases, ν increases.

❖ Import Grid System into CFD-GUI

File → Open → [Argon_10mTorr_10AmpCoilcurrent.DTF](#)

Scale을 Centimeter[cm] 단위로 설정



CFD-ACE-GUI에서 DTF 파일을 Open하거나, CFD-GUI의 좌측 상단의 File → Properties를 통해 Model Properties → scaling information 확인 가능

❖ Choose Physics Modules

PT(Problem Type)

➤ Flow, Heat, Chem, Plasma, Magnet 모듈 선택

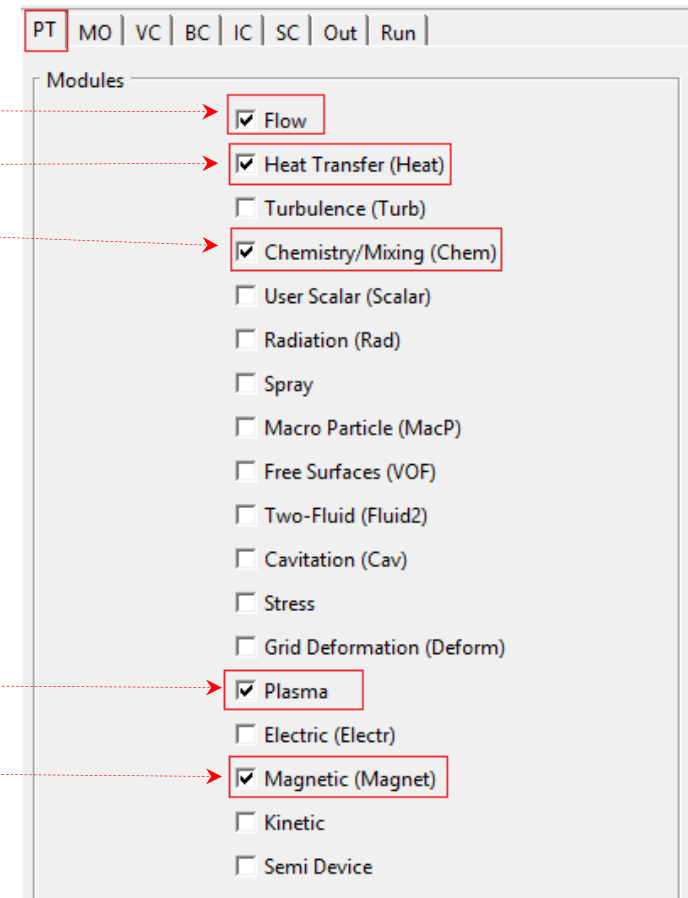
Mass and momentum, pressure correction

Gas Temperature

Heavy species mass fractions, reaction rates

Electron Density and Temperature

Magnetic Fields, Coil Currents, ICP Power



❖ Setup - Model Options

MO(Model Options)

➤ Share(모든 module에서 공통으로 사용)

- ◆ Title : ICP Ar plasma
- ◆ Polar : Axisymmetric
- ◆ Time Dependence : Steady

➤ Flow

- ◆ Reference Pressure = 1.33 N/m^2
(Units conversion $10 \text{ mTorr} = 1.33 \text{ N/m}^2$)

➤ Plasma

- ◆ Plasma Model : ICP
- ◆ Power control: Coil Current

Recall that electron density is obtained from quasi-neutrality and the sheath is not mesh resolved.

➤ Magnet

- ◆ Magnetic Option : AC Single Freq.
- ◆ AC Freq. : 0.4 MHz

The magnetic vector potential is solved in the frequency domain

PT **MO** VC BC IC SC Out Run

Shared

Simulation Description

Title ICP Ar Plasma

Polar (Axisymmetric about X-axis)

→ Axisymmetric

Transient Conditions

Time Dependence → Steady

PT **MO** VC BC IC SC Out Run

Flow

Pressure

Reference Pressure 1.33 N/m^2

PT **MO** VC BC IC SC Out Run

Magnet

Magnetic Field Options → AC Single Frequency

Displacement Current

AC Single Frequency

Field Frequency 400000 Hz

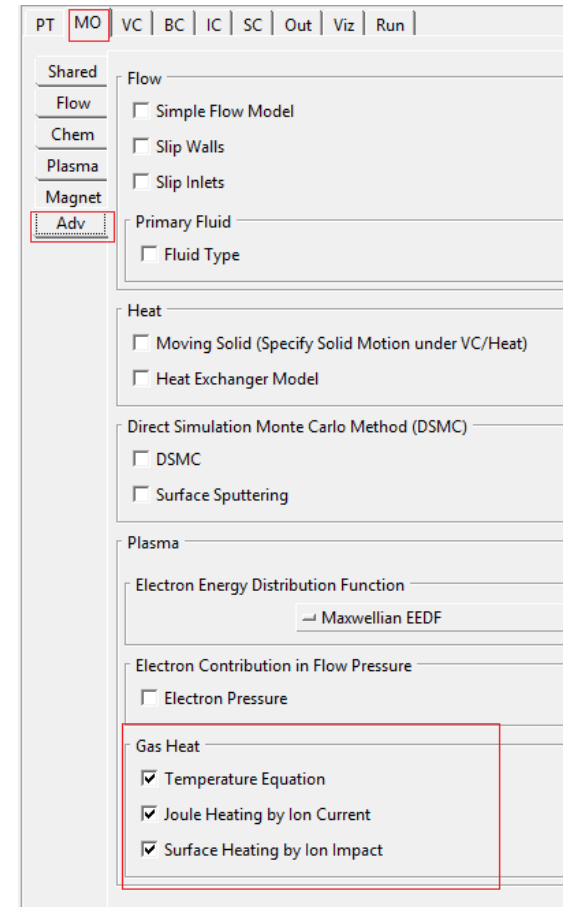
❖ Setup - Model Options

MO(Model Options)

➤ Advanced

- ◆ Gas Heat options are relevant
- ◆ Check Temperature Equation
- ◆ Check Ion Joule Heating
- ◆ Check Surface Heating (Ion Impact)

Heat of recombination of ions and de-excitation of excited species at surfaces are always included by default as source terms for the solution of temperature in the gas and in solids

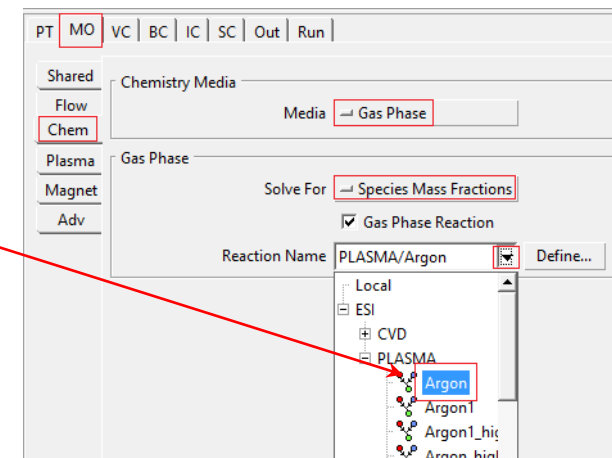
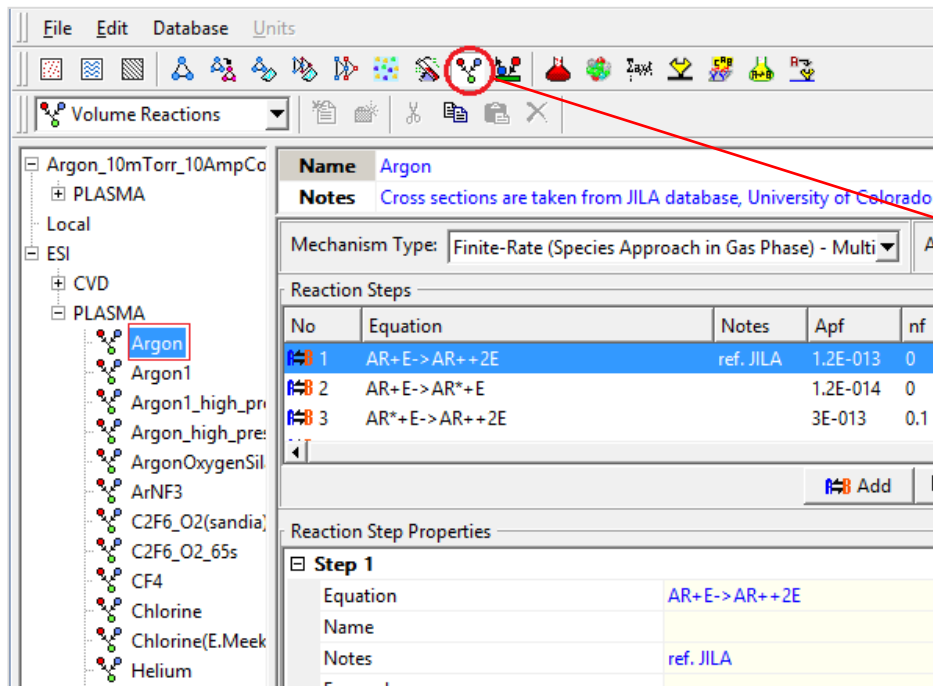


❖ Setup - Model Options

MO(Model Options)

➤ Chem

- ◆ Chemistry Media : Gas Phase
- ◆ Solve For : Species Mass Fractions
- ◆ Reaction Name : Argon



❖ Setup - Volume Conditions

VC(Volume Conditions) – Fluid 영역(Plasma) 물성 설정

VC 패널에서는 Volume 기준에서 유체/재료 물성이나 Source term을 설정할 수 있습니다.

➤ Properties (VC Setting Mode)

- ◆ Phys : Density → Ideal Gas Law

We are not interested in modeling any discharge in the Air outside the Dielectric, so Air is treated as a Solid

Volume Name	VC Type	Blanked	Properties	Zone	Key
Ground	Solid		Ground		
Dielectric	Solid			3	761
Bias	Solid			4	764
Wafer	Solid			5	767
Plasma	Fluid			7	844
Air	Solid			10	856

- ◆ Fluid : Viscosity → Mix Sutherland's Law

$$\mu = \sum_i x_i \frac{A_i T^{3/2}}{B_i + T}$$

Accurate if A & B are known

- ◆ Therm

Specific Heat : Mix JANAF Method

Mix Kinetic Theory : Mix Kinetic Theory

PT | MO | **VC** | BC | IC | SC | Out | Run |

VC Setting Mode

Properties → Properties

Properties → Fluid

Material

Property Sources → User Input

Phys

Density → Ideal Gas Law

Fluid

Therm

Chem

E/M

Plasma

Phys

Fluid

Viscosity → Mix Sutherland's Law

Therm

Chem

E/M

Plasma

Phys

Fluid

Therm

Specific Heat → Mix JANAF Method

Chem

E/M

Plasma

Thermal Conductivity → Mix Kinetic Theory

❖ Setup - Volume Conditions

VC(Volume Conditions)

➤ Properties (VC Setting Mode)

- ◆ Chem : Mass Diffusivity = Multi-Component Diffusion
Thermo Diffusion, Conservation of Species 선택
Species Conservation = Stefan Maxwell
Mobility = blanc Law

- ◆ E/M : Relative Pereability
Plasma에서는 Electric Conductivity가 의미 없음.
전자 충동 주파수, Coil Current angular frequency와 Plasma 주파수를 계산하여 Plasma Conductivity를 계산함

$$\tilde{\sigma} = \frac{\epsilon_0 \omega_p^2}{\nu_m + \sqrt{-1}\omega}$$

↓ Electron colli-freq ↓ coil current angular freq

Electron plasma-freq: $\omega_p = \sqrt{e^2 n_e / \epsilon_0 m_e}$

❖ Setup - Volume Conditions

VC(Volume Conditions)

➤ Properties (VC Setting Mode)

- ◆ Plasma : Electron Collision Frequency = Function of Te

"Function of Te" (X-sec 데이터가 있는 운동량 전달 반응 필요)

→ 동역학이 풀릴 때 전자 속성에 대해 정확도를 높일 수 있음

Electron Diffusion Coefficient = Einstein's Equation

Ion Diffusion = From mobility (Einstein Eq.)

Phys	Electron Collision Frequency	<input type="text" value="Function of Te"/>
Fluid		
Therm		
Chem	Electron Diffusion Coefficient	<input type="text" value="Einstein's Equation"/>
E/M		
Plasma	Ion Diffusion	<input type="text" value="From mobility (Einstein Eq.)"/>

Electron mobility : $\mu_e = e/m_e \vartheta_m$

Electron diffusivity : $D_e = T_e \mu_e$

❖ Setup - Volume Conditions

VC(Volume Conditions) – Coils 물성 설정

➤ Properties (VC Setting Mode)

- ◆ Coils 볼륨 선택 후 Solid 물성으로 변경
활성화 창에서 Pure Metals/Copper 선택
- ◆ Phys : Density = 8960 kg/m^3
- ◆ Therm : Specific Heat = 385 J/kg-K
Thermal Conductivity → 385 W/m-K
- ◆ E/M : Electric Conductivity = 0 [$1/\text{ohm-m}$]
Relative Permittivity = 1
Permeability = 1

Zero electrical conductivity is specified for the coil VCs to avoid numerical difficulties related to skin effects

Coil current is specified in VC Setting Mode Magnet later.

Name	VC Type	Blanked	Zone	Key
Ground	Solid			
Chamber_wall	Solid			
Coils	Solid			
Dielectric	Solid		3	761
Bias	Solid		4	764
Wafer	Solid		5	767
Plasma	Fluid		7	844
Air	Solid		10	856

PT | MO | **VC** | BC | IC | SC | Out | Viz | Run |

VC Setting Mode

→ Properties

Properties → Solid

Material

Property Sources → Import From Database

Solid Material Name: Pure_Metals/Copper Define...

Phys

Density

→ Constant

Rho: 8960 kg/m^3

Therm

Specific Heat

→ Constant

Cp: 385 J/kg-K

Thermal Conductivity

→ Constant

K: 385 W/m-K

E/M

Electrical Conductivity

→ Isotropic

Electrical Conductivity (Resistivity)

→ Const Conductivity

Sigma: 0 $1/\text{ohm-m}$

Relative Permittivity

→ Constant

Value: 1

Relative Permeability

→ Constant

Value: 1

❖ Setup - Volume Conditions

VC(Volume Conditions) – **Wafer** 물성 설정

➤ Properties (VC Setting Mode)

- ◆ Phys : Density = 2650 kg/m³
- ◆ Therm : Specific Heat → Constant and Cp = 840 J/Kg-K
Thermal conductivity → Constant and K = 1 W/m-k
- ◆ E/M : Electrical Conductivity → Isotropic and Sigma = 0 1/ohm-m
Relative Permittivity → Constant = 4
Relative Permeability → Constant = 1

Name	VC Type	Blanked	Zone	Key
Ground	Solid			
Chamber_wall	Solid			
Coils	Solid			
Dielectric	Solid		3	761
Bias	Solid		4	764
Wafer	Solid		5	767
Plasma	Fluid		7	844
Air	Solid		10	856

VC(Volume Conditions) – **Air** 물성 설정

➤ Properties (VC Setting Mode)

- ◆ Phys : Density = 1 kg/m³
- ◆ Therm : Specific Heat → Constant and Cp = 1000 J/Kg-K
Thermal conductivity → Constant and K = 0.023 W/m-k
- ◆ E/M : Electrical Conductivity → Isotropic and Sigma = 0 1/ohm-m
Relative Permittivity → Constant = 1
Relative Permeability → Constant = 1

Name	VC Type	Blanked	Zone	Key
Ground	Solid			
Chamber_wall	Solid			
Coils	Solid			
Dielectric	Solid		3	761
Bias	Solid		4	764
Wafer	Solid		5	767
Plasma	Fluid		7	844
Air	Solid		10	856

❖ Setup - Volume Conditions

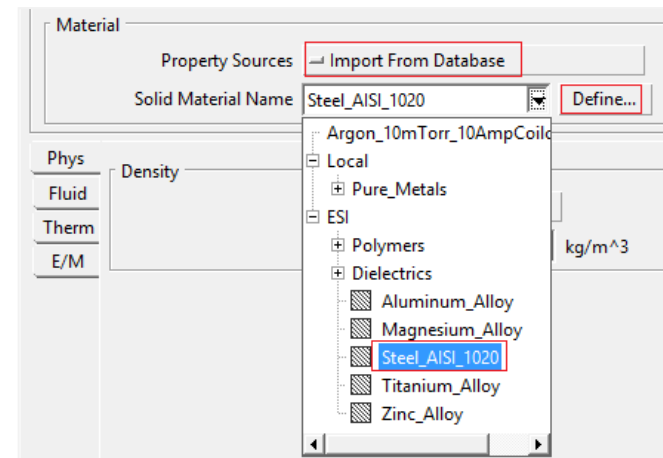
VC(Volume Conditions) – Bias 물성 설정

➤ Properties

- ◆ Property Sources → Import from Data Base → ESI → Steel_AISI_1020 선택

※ 오류 메시지가 표시되면 '확인'을 클릭하고 상대 유전율과 투자율을 모두 1로 설정(E/M 탭)

Name	VC Type	Blanked	Zone	Key
Ground	Solid			
Chamber_wall	Solid			
Coils	Solid			
Dielectric	Solid		3	761
Bias	Solid		4	764
Wafer	Solid		5	767
Plasma	Fluid		7	844
Air	Solid		10	856



VC(Volume Conditions) – Ground 물성 설정

➤ Properties

- ◆ Bias 물성 설정 과정과 동일하게 진행

※ Conductivity를 0로 설정

Name	VC Type	Blanked	Zone	Key
Ground	Solid			
Chamber_wall	Solid			
Coils	Solid			
Dielectric	Solid		3	761
Bias	Solid		4	764
Wafer	Solid		5	767
Plasma	Fluid		7	844
Air	Solid		10	856

❖ Setup - Volume Conditions

VC(Volume Conditions) – Dielectric 물성 설정

➤ Properties (VC Setting Mode)

- ◆ Phys : Density = 1000 kg/m³
- ◆ Therm : Specific Heat → Constant and Cp = 1000 J/Kg-K
Thermal conductivity → Constant and K = 1 W/m-k
- ◆ E/M : Electrical Conductivity → Isotropic: Sigma = 0 (1/ohm-m)
Relative Permittivity → Constant = 1
Relative Permeability → Constant = 1

Name	VC Type	Blanked	Zone	Key
Ground	Solid			
Chamber_wall	Solid			
Coils	Solid			
Dielectric	Solid		3	761
Bias	Solid		4	764
Wafer	Solid		5	767
Plasma	Fluid		7	844
Air	Solid		10	856

VC(Volume Conditions) – Chamber_Wall 물성 설정

➤ Properties (VC Setting Mode)

- ◆ Phys : Density = 2650 kg/m³
- ◆ Therm : Specific Heat → Constant and Cp = 840 J/Kg-K
Thermal conductivity → Constant and K = 1.3 W/m-k
- ◆ E/M : Electrical Conductivity → Isotropic: Sigma = 0 (1/ohm-m)
Relative Permittivity → Constant = 4
Relative Permeability → Constant = 1

Name	VC Type	Blanked	Zone	Key
Ground	Solid			
Chamber_wall	Solid			
Coils	Solid			
Dielectric	Solid		3	761
Bias	Solid		4	764
Wafer	Solid		5	767
Plasma	Fluid		7	844
Air	Solid		10	856

❖ Setup - Volume Conditions

VC(Volume Conditions) – **Coils Current 설정**

➤ Magnet (VC Setting Mode)

VC Setting Mode에서 Properties를 Magnet으로 변경

→ Magnetic Field Source 체크

◆ Magnet : Electric Current → AC Source → Current (Real) = 10 A

Name	VC Type	Blanked	Zone	Key
Ground	Solid			
Chamber_wall	Solid			
Coils	Solid			
Dielectric	Solid		3	761
Bias	Solid		4	764
Wafer	Solid		5	767
Plasma	Fluid		7	844
Air	Solid		10	856

PT | MO | **VC** | BC | IC | SC | Out | Run |

VC Setting Mode

→ Magnet

☒ Magnetic Field Source

Magnet

Electro Magnetic Source

Electric Current

→ AC Source

☐ Specify Current Density

Field Frequency 400000 Hz

Current(Real) 10 A

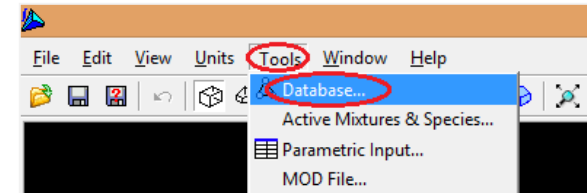
Current(Imaginary) 0 A

❖ Setup - Mixtures in Database

Database – **Mixture 설정**

➤ Tool – Database...

※ Mixture는 경계조건 및 초기조건에서 사용됩니다.

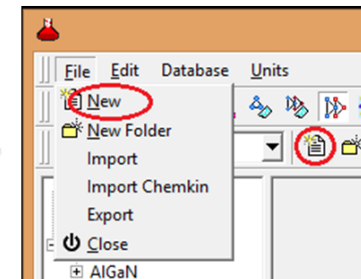
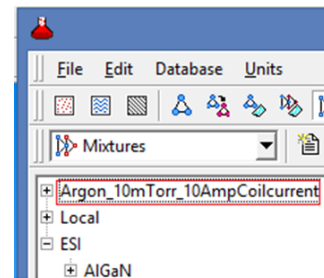
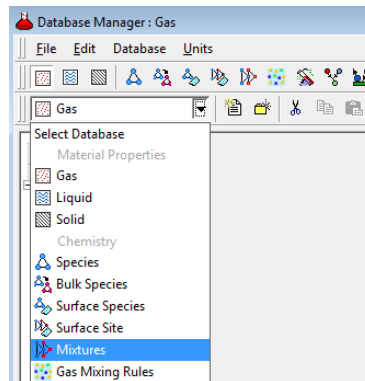


CFD-GUI 좌측상단 Tool → Database... 선택

(Database Manager에서 Chemical species, mixtures, surface reactions, volume reactions 등이 정의 됨)

◆ Database Manager → Mixtures 아이콘 클릭

(Mixture 정의를 위한 Mixture 레이아웃으로 Database 창이 변경됨)



① Argon_10mTorr_10AmpCoilcurrent 선택

② File 메뉴에서 New 선택 or New 아이콘 선택

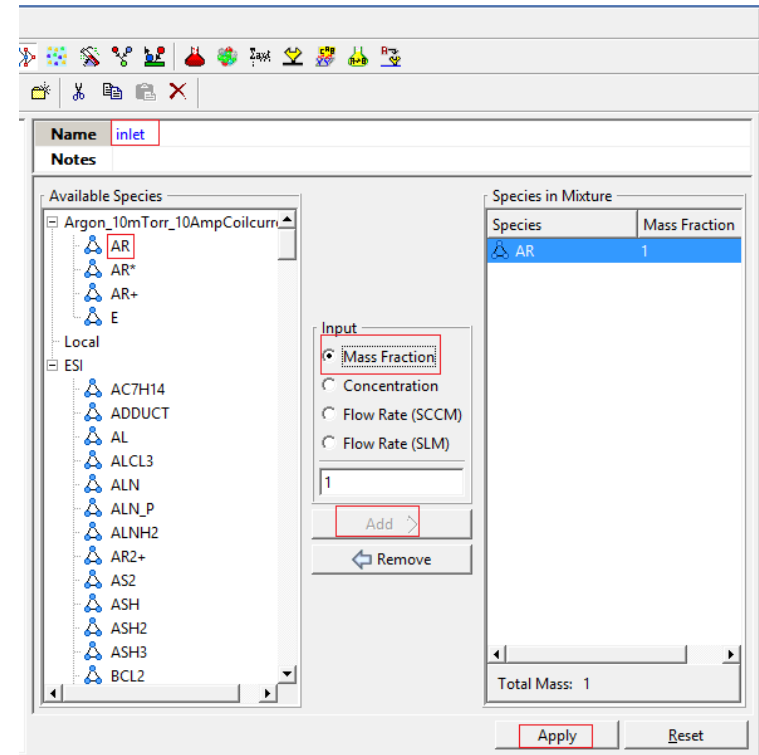
(새로운 mixture를 편집할 수 있도록 Database창이 변경됩니다.)

❖ Setup - Mixtures in Database

Database – **Inlet Mixture** 설정

➤ Tool – Database Manager → Mixtures

- ① Name 란에 Inlet 입력
(추후 Boundary Condition 설정 시 구분)
- ② Available Species에서 AR을 선택
Mass Fraction : 1 설정 후 Add 버튼 클릭
- ③ Apply

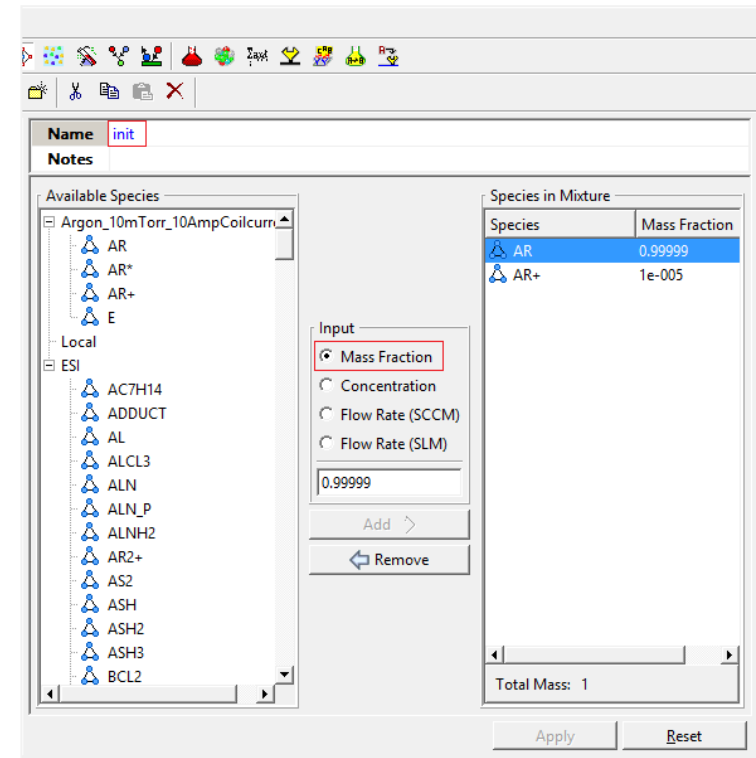


❖ Setup - Mixtures in Database

Database – **Initial Condition Mixture** 설정

➤ Tool – Database Manager → Mixtures

- ① Name 란에 init 입력
- ② Available Species에서 AR을 선택
Mass Fraction : 0.99999 설정 후 Add 버튼 클릭
- ③ Available Species에서 AR+을 선택
Mass Fraction : 1e-05 설정 후 Add 버튼 클릭
- ④ Apply 클릭



❖ Setup – Boundary Condition

BC(Boundary Conditions) – Inlet 설정

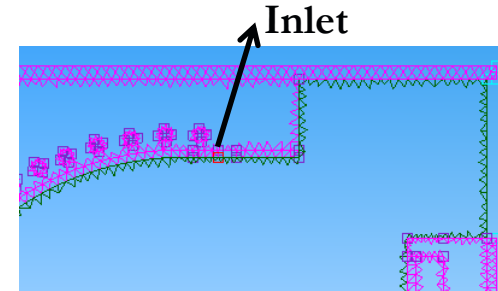
➤ General (BC Setting Mode)

	Boundary Name	BC Type	BC SubType	Blanked	General	Zone	Key
	Ground-External	Wall	No Sheath Model		Ground-Ex...		
	Ground-Solid	Interface			Ground-So...		
	Inlet	Inlet				7	745
	Outlet	Outlet				7	718
	Solid-Plasma	Interface			Solid-Plas...		
	Symmetry	Symmetry			Symmetry		

Boundary 항목에서 inlet 선택

◆ Flow : Temperature = 300 K

Mass-Flow Rate per Patch → $\dot{M} = 9.474\text{E-}007$



PT | MO | VC | **BC** | IC | SC | Out | Run |

BC Setting Mode
General

BC Type
Inlet
(External Face on Fluid Volume)

Flow
Chem
Plasma
Magnet

SubType
Fix Mass. (Normal)

Pressure
Constant
P 0
Reference Pressure 1.33

Temperature
Constant
T 300

Mass-Flow Rate per Patch
Constant (Inflow: +v)
Mdot (per radian) 9.474E-007

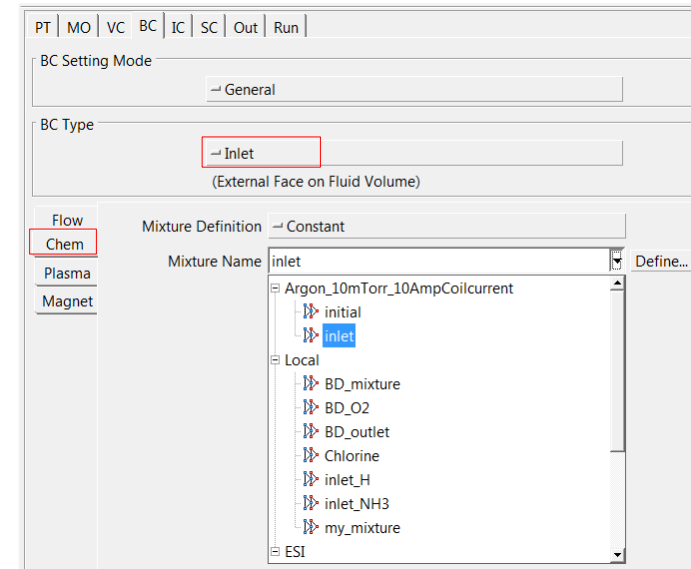
❖ Setup – Boundary Condition

BC(Boundary Conditions) – **Inlet** 설정

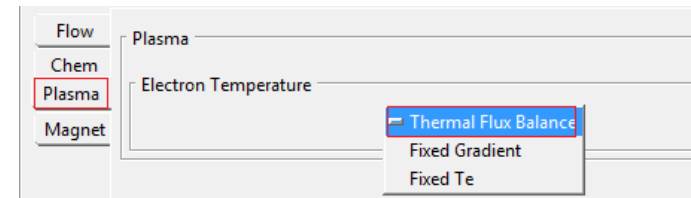
➤ General (BC Setting Mode)

Boundary 항목에서 inlet 선택

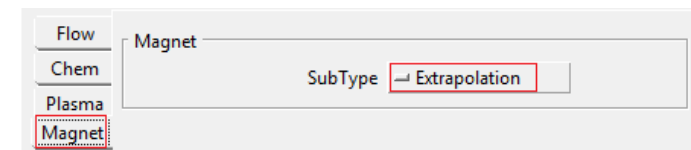
◆ Chem : Mixtures 항목에서 inlet 선택



◆ Plasma : Thermal Flux Balance



◆ Magnet : Extrapolation



❖ Setup – Boundary Condition

BC(Boundary Conditions) – **Outlet 설정**

➤ General (BC Setting Mode)

	Boundary Name	BC Type	BC SubType	Blank
	Ground-Solid	Interface		
	Inlet	Inlet		
	Outlet	Outlet		
	Solid-Plasma	Interface		
	Symmetry	Symmetry		
	Wafer-Bias	Interface		

Boundary 항목에서 Outlet 선택

- ◆ Flow : Temperature = 300 K
Pressure = 0
- ◆ Chem : Initial
- ◆ Plasma : Thermal Flux Balance
- ◆ Magnet : Extrapolation

PT | MO | VC | **BC** | VR | IC | SC | Out | Viz | Run |

BC Setting Mode
→ General

BC Type
→ Outlet
(External Face on Fluid Volume)

Flow
Chem
Plasma
Magnet

SubType → Fixed Pressure

Pressure
→ Constant
P 0 N/m²
Reference Pressure 1.33 N/m²

Backflow Temperature
→ Constant
T 300 K

Flow
Chem
Plasma
Magnet

Mixture Definition → Constant
Mixture Name initial

Flow
Chem
Plasma
Magnet

Plasma
Electron Temperature
→ Thermal Flux Balance

Flow
Chem
Plasma
Magnet

SubType → Extrapolation

❖ Setup – Boundary Condition

BC(Boundary Conditions) – **Air-Block** 설정

➤ General (BC Setting Mode)

Boundary Name	BC Type	BC SubType	Blanked
Air-Block	Wall	No Sheath Model	
ChamberWall-Air	Interface		
ChamberWall-Bl...	Wall	No Sheath Model	
Coils	Interface		
Dielectric-Bias	Interface		
Ground-External	Wall	No Sheath Model	

Boundary 항목에서 Air-Block 선택
→ BC Type Wall 설정 확인

◆ Heat : Isothermal Temperature = 300 K

◆ Magnet : Fixed Potential

$$A_z (\text{Real}) = 0$$

$$A_z (\text{imaginary}) = 0$$

PT | MO | VC | **BC** | IC | SC | Out | Run |

BC Setting Mode
→ General

BC Type
→ Wall
(External Face on Solid Volume)

Heat
Magnet

SubType → Isothermal

Temperature
→ Constant
T 300 K

Heat
Magnet

SubType → Fixed Pot. (Cart)

Z-Direction Magnetic Potential(Real)
→ Constant
Az(Real) 0 V-s/m

Z-Direction Magnetic Potential(Imaginary)
→ Constant
Az(Imaginary) 0 V-s/m

❖ Setup – Boundary Condition

BC(Boundary Conditions) – **ChamberWall-Block** 설정

➤ General (BC Setting Mode)

	Boundary Name	BC Type	BC SubType	Bla
	Air-Block	Wall	No Sheath Model	
	ChamberWall-Air	Interface		
	ChamberWall-Block	Wall	No Sheath Model	
	Coils	Interface		
	Dielectric-Bias	Interface		
	Ground-External	Wall	No Sheath Model	

Boundary 항목에서 ChamberWall-Block 선택
→ BC Type Wall 설정 확인

◆ Heat : Isothermal Temperature = 300 K

◆ Magnet : Fixed Potential

$A_z(\text{Real}) = 0$

$A_z(\text{imaginary}) = 0$

PT | MO | VC | **BC** | IC | SC | Out | Run |

BC Setting Mode
→ General

BC Type
→ Wall
(External Face on Solid Volume)

Heat
Magnet

SubType → Isothermal

Temperature
→ Constant
T 300 K

Heat
Magnet

SubType → Fixed Pot. (Cart)

Z-Direction Magnetic Potential(Real)
→ Constant
Az(Real) 0 V-s/m

Z-Direction Magnetic Potential(Imaginary)
→ Constant
Az(Imaginary) 0 V-s/m

❖ Setup – Boundary Condition

BC(Boundary Conditions) – **Wafer-Plasma** 설정

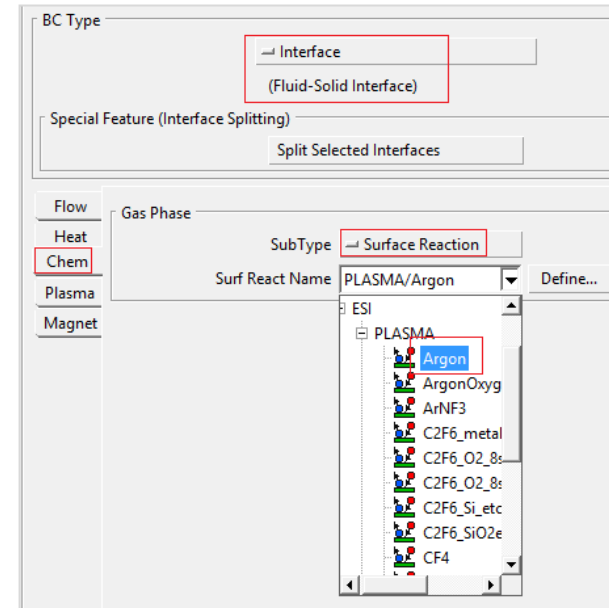
➤ General (BC Setting Mode)

Name	BC Type	BC SubType	Blan
Ground-Solid	Interface	No Sheath Model	
Ground-External	Wall	No Sheath Model	
Symmetry	Symmetry		
Solid-Plasma	Interface	No Sheath Model	
Dielectric-Bias	Interface	No Sheath Model	
ChamberWall-Air	Interface	No Sheath Model	
ChamberWall-Block	Wall	No Sheath Model	
Coils	Interface	No Sheath Model	
Wafer-Dielectric	Interface	No Sheath Model	
Wafer-Bias	Interface	No Sheath Model	
Wafer-Plasma	Interface	No Sheath Model	
Outlet	Outlet		
Inlet	Inlet		
Air-Block	Wall	No Sheath Model	

Boundary 항목에서 Wafer-Plasma선택

→ BC Type에서 interface(fluid-solid) 설정 확인

◆ Flow : No Slip



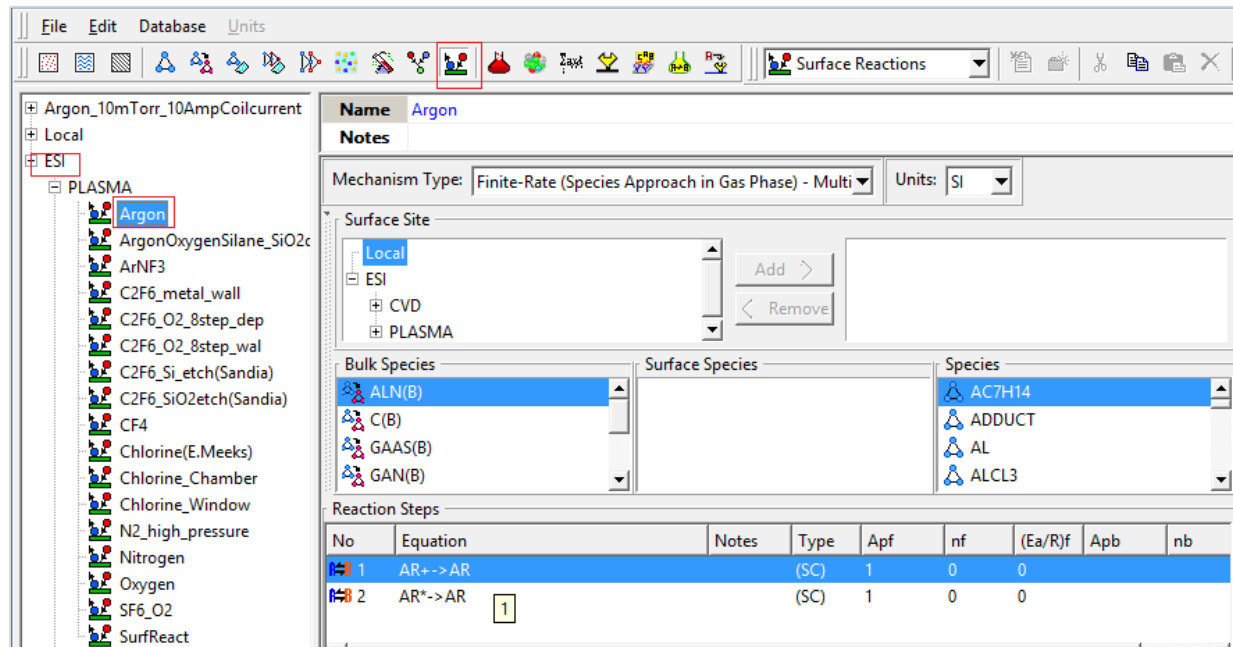
❖ Setup – Boundary Condition

BC(Boundary Conditions) – **Wafer-Plasma** 설정

➤ General (BC Setting Mode)

◆ Chem : Surface Reaction → ESI → Plasma = Argon

(메커니즘 확인을 위해서 Tools → Database → Surface Reactions → Argon 확인)



◆ Plasma : Sub Type = No Sheath Model

Electron Temperature = Thermal Flux Balance

◆ Magnet : Extrapolation

❖ Setup – Boundary Condition

BC(Boundary Conditions) – **Solid-Plasma 설정**

➤ General (BC Setting Mode)

Name	BC Type	BC SubType	Bla
Ground-Solid	Interface	No Sheath Model	
Ground-External	Wall	No Sheath Model	
Symmetry	Symmetry		
Solid-Plasma	Interface	No Sheath Model	
Dielectric-Bias	Interface	No Sheath Model	
ChamberWall-Air	Interface	No Sheath Model	
ChamberWall-Block	Wall	No Sheath Model	
Coils	Interface	No Sheath Model	

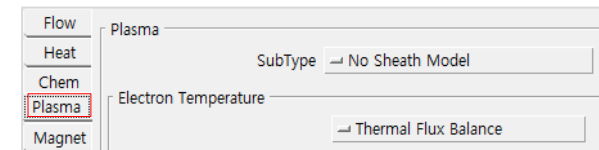
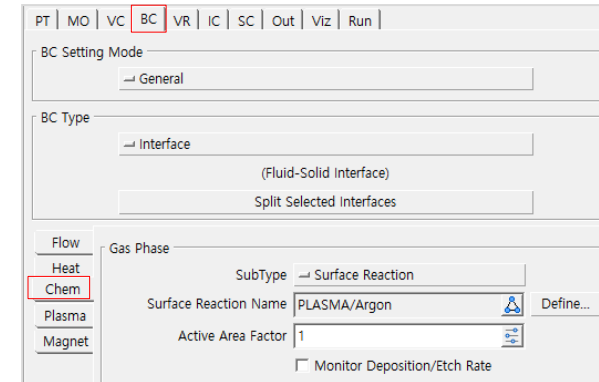
Boundary 항목에서 Solid-Plasma 선택

→ BC Type에서 interface(fluid-solid) 설정 확인

- ◆ Flow : No Slip
- ◆ Chem : Surface Reaction → ESI → Plasma = Argon

- ◆ Plasma : Sub Type = No Sheath Model
Electron Temperature = Thermal Flux Balance

- ◆ Magnet : Extrapolation



※ 플라스마 반응의 모든 표면에서 Surface Reaction 메커니즘을 지정해 주어야 합니다.

❖ Setup – Boundary Condition

BC(Boundary Conditions) – **Ground-external 설정**

➤ General (BC Setting Mode)

Name	BC Type	BC SubType	Blar
Ground-Solid	Interface	No Sheath Model	
Ground-External	Wall	No Sheath Model	
Symmetry	Symmetry		
Solid-Plasma	Interface	No Sheath Model	
Dielectric-Bias	Interface	No Sheath Model	
ChamberWall-Air	Interface	No Sheath Model	
ChamberWall-Block	Wall	No Sheath Model	
Coils	Interface	No Sheath Model	

Boundary 항목에서 Ground-external 선택

→ BC Type에서 Wall 설정 확인

- ◆ Heat : Isothermal → Temperature $T = 300$ K
- ◆ Magnet : Extrapolation

PT | MO | VC | **BC** | VR | IC | SC | Out | Viz | Run |

BC Setting Mode
→ General

BC Type
→ Wall
(External Face on Solid Volume)

Heat SubType → Isothermal
Magnet

Temperature
→ Constant
T 300 K

Solid Cell
☐ Solid Cell at Wall

Wall Heat Source
☐ Wall Heat Source

Heat SubType → Extrapolation
Magnet

❖ Setup – Initial Condition

➤ IC Option

Initial Condition : User Specified

IC Applied : For All Volumes

- ◆ Shared : Temperature $T = 300$ K
- ◆ Flow : $U = V = P = 0$
- ◆ Chem : Mixture Name = initial
- ◆ Plasma : Electron Temperature $T_e = 1$ eV
- ◆ Magnet : Vector Potential $\rightarrow A_z$ (Real) = 0
 A_z (imaginary) = 0

The screenshot displays the 'IC Option' and 'Initial Condition' settings for a simulation. The 'IC' tab is selected in the top navigation bar. The 'Initial Condition' is set to 'User Specified' and 'IC Applied' is set to 'For All Volumes'. The 'Shared' tab is selected in the left sidebar, and the 'Temperature' section is active, showing a constant value of 300 K. The 'Flow' tab is also selected, showing constant values of 0 m/s for X-Direction Velocity (U) and Y-Direction Velocity (V). The 'Pressure' section shows a constant value of 0 N/m², with a reference pressure of 1.33 N/m². The 'Chem' tab is selected, showing the 'Mixture Specification' section with 'initial' as the mixture name. The 'Plasma' tab is selected, showing the 'Electron Temperature' section with a constant value of 1 eV.

PT | MO | VC | BC | **IC** | SC | Out | Run |

IC Option (For whole simulation, Apply button not applicable)

Initial Condition

IC Applied

Shared

Temperature

T K

Flow

X-Direction Velocity

U m/s

Y-Direction Velocity

V m/s

Pressure

P N/m²

Reference Pressure N/m²

Chem

Mixture Specification

Mixture Name Define...

Argon_10mTorr_10AmpCoilcurrent

initial

inlet

Local

BD_mixture

Plasma

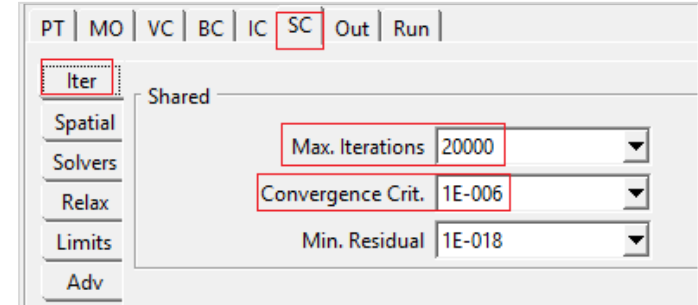
Electron Temperature

Te eV

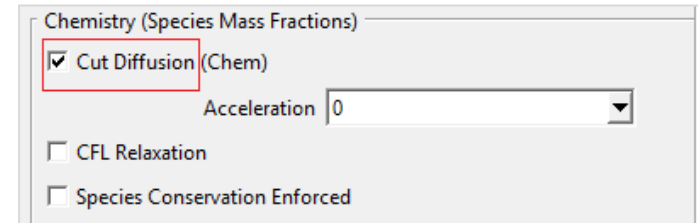
❖ Setup – Solver Controls

➤ SC Option

- ◆ Iter → Shared → Max. iterations = 20000
Convergence Crit. = 1E-06



- ◆ Adv → Cut Diffusion(Chem) 선택 = 0
Cut Diffusion at inlet to ensure the incoming species flux



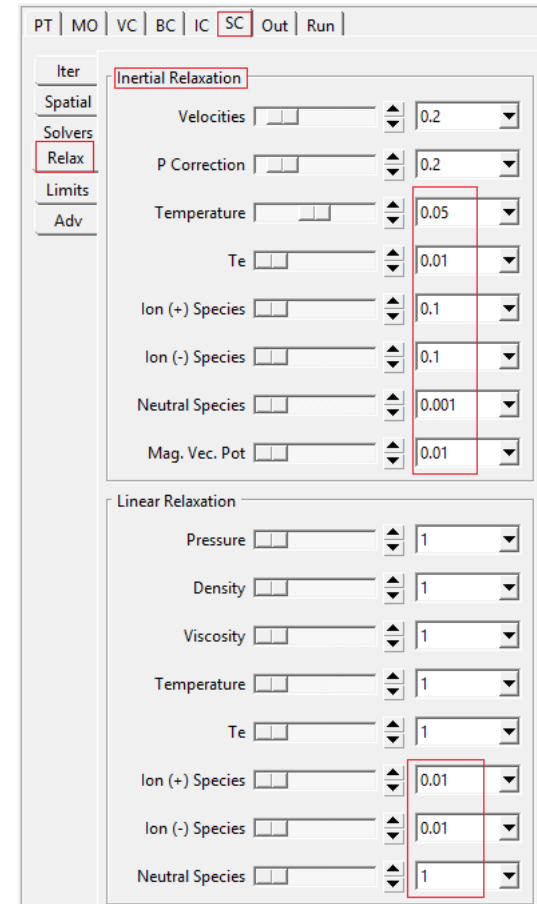
❖ Setup – Solver Controls

➤ SC Option

◆ Relax

Inertial: Generally light except flow

Linear: very heavy on Ions (0.001-0.01)



Section	Parameter	Value
Inertial Relaxation	Velocities	0.2
	P Correction	0.2
	Temperature	0.05
	Te	0.01
	Ion (+) Species	0.1
	Ion (-) Species	0.1
	Neutral Species	0.001
	Mag. Vec. Pot	0.01
Linear Relaxation	Pressure	1
	Density	1
	Viscosity	1
	Temperature	1
	Te	1
	Ion (+) Species	0.01
	Ion (-) Species	0.01
	Neutral Species	1

- ※ Ions transport rate (due to drift) is much faster than neutrals.
- ※ Electron density is from quasi-neutrality (depending on ion solution).
- ※ Numerically, this requires the linear relaxation on ions very heavy

❖ Setup – Request Outputs

➤ Out Option

◆ Out → Graphic

The screenshot displays the ICP software interface with the 'Out' tab selected in the top menu bar. The left sidebar contains a tree view with 'Graphic' highlighted. The main panel is divided into several sections:

- General**
 - Restart
 - Graphic** (highlighted)
 - Summaries
 - Monitor Point
 - Monitor Plane
 - User Access Control
 - Adv
- Output Controls**
 - Write Graphic Output To: DTF
 - ☐ Override General Output Controls
 - Output By: Iteration
 - Interval Options: End of Simulation
- Shared**
 - ☒ Density
 - ☒ Static Temperature
 - ☒ Total Temperature
 - ☒ Electrical Conductivity
 - ☐ Relative Permeability
 - ☐ Relative Permittivity
- Flow**
 - ☒ Velocity Vector
 - ☒ Velocity Magnitude
 - ☐ Static Pressure
 - ☒ Total Pressure
 - ☐ Laminar Viscosity
 - ☐ Mach Number
 - ☐ Vorticity
 - ☒ Stream Function
- Gas-Chemistry**
 - ☒ Species Mass Fractions
 - ☒ Species Mole Fractions
 - ☐ Reaction Rate
 - ☐ Species Flux
 - ☒ Species Diffusivity
 - ☐ Species Therm Diff
 - ☐ Deposition Rate
 - ☒ Number Density
 - ☒ Ion Mobility
 - ☐ Species Residual
- Plasma**
 - ☒ Electron Density
 - ☒ Electron Temperature
 - ☒ Electron Mobility
 - ☒ Ambipolar Field
- Magnetic**
 - ☒ Magnetic Vector Potential (A)
 - ☒ Magnetic Field Vector (B)
 - ☒ Induced Electric Field Vector (E_tot)
 - ☒ Total Electric Field
 - ☒ Induction Power
 - ☒ Eddy Current (J_eddy)

❖ Setup – Request Outputs

➤ Out Option

◆ Out → Summaries

The screenshot shows the 'Out' tab selected in the top menu bar. The left sidebar contains the following tabs: General, Restart, Graphic, Summaries (selected), Monitor Point, Monitor Plane, User Access Control, and Adv. The main panel displays the 'Output Controls' section with the following options:

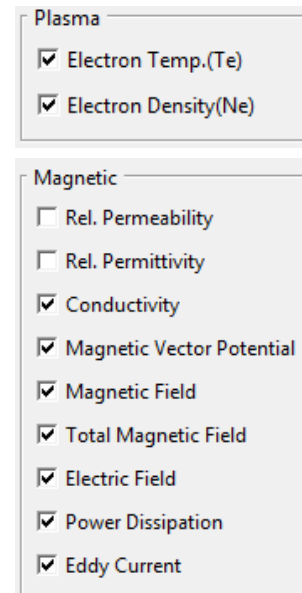
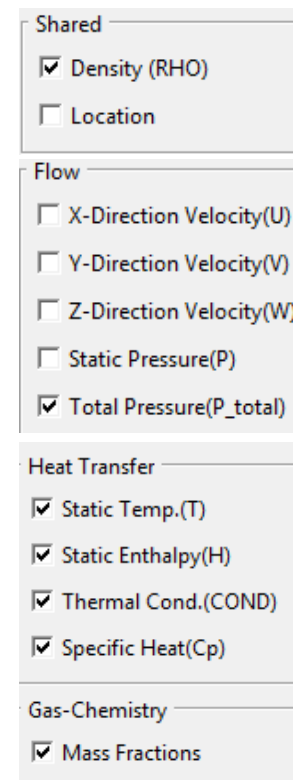
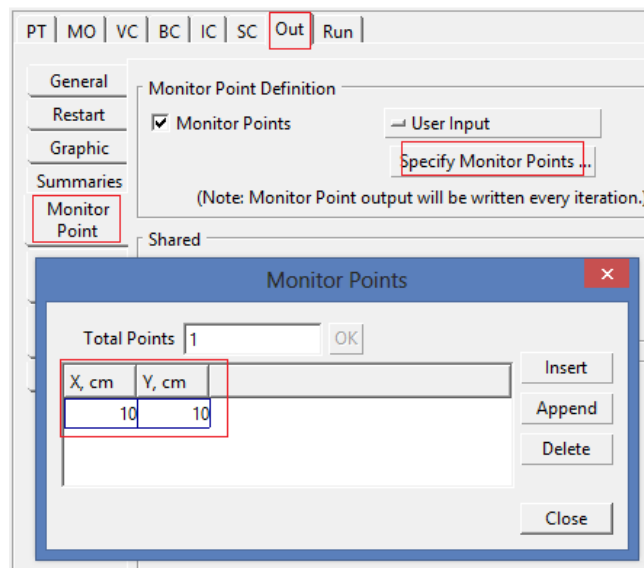
- ☐ Override General Output Controls
- Output By: Iteration
- Interval Options: End of Simulation
- ☐ Write ID-Key Maps
- ☐ Force and Moment Summary (Flow)
- ☐ Mass Balance Summary (Flow)
- ☒ Energy Balance Summary (Heat)
 - ☒ Energy Balance Summary
 - ☐ Monitor Energy Imbalance
 - Grouping: Individual
- ☐ Species Summary
- ☐ Surface Reaction Summary

❖ Setup – Request Outputs

➤ Out Option

- ◆ Out → Monitor Point(수렴 판단에 유용)

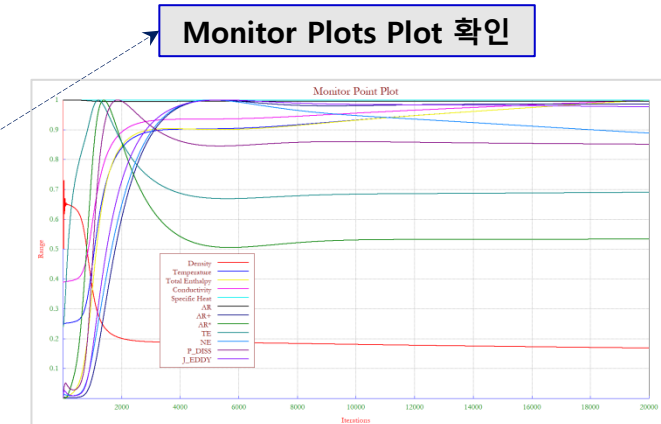
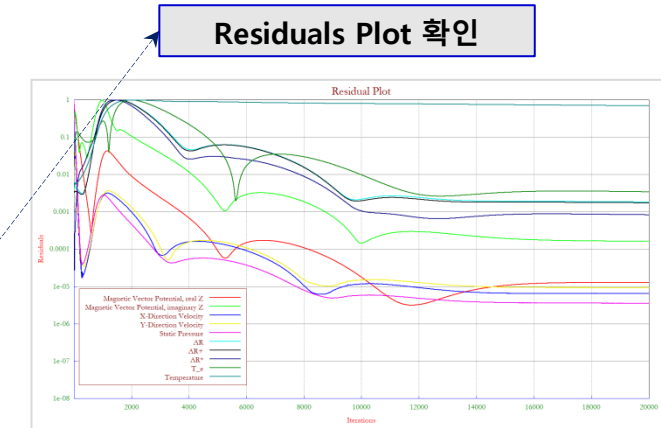
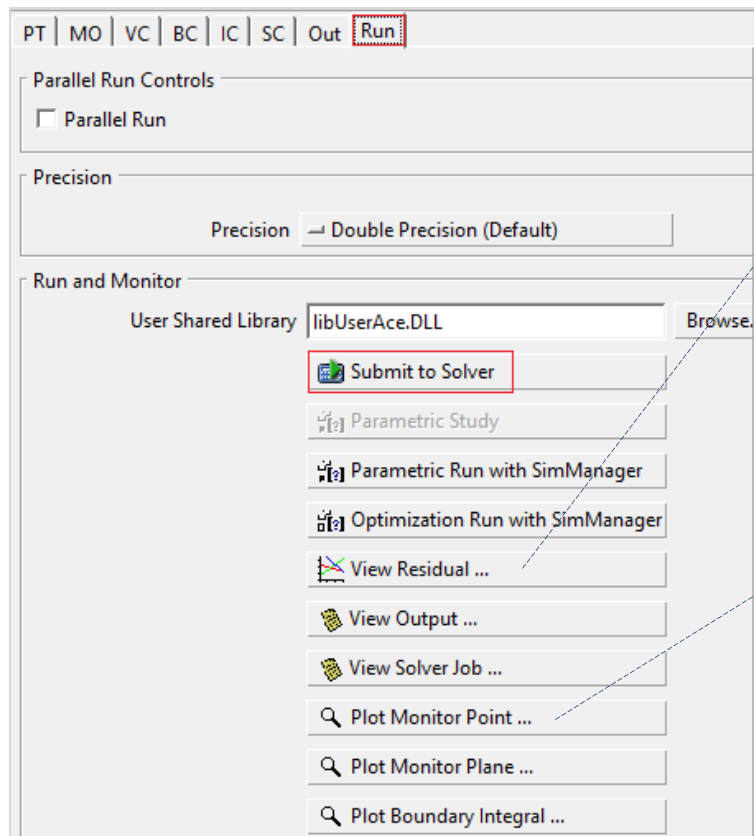
모니터 포인트 위치 설정 후 확인하고자 하는 모니터 변수 선택



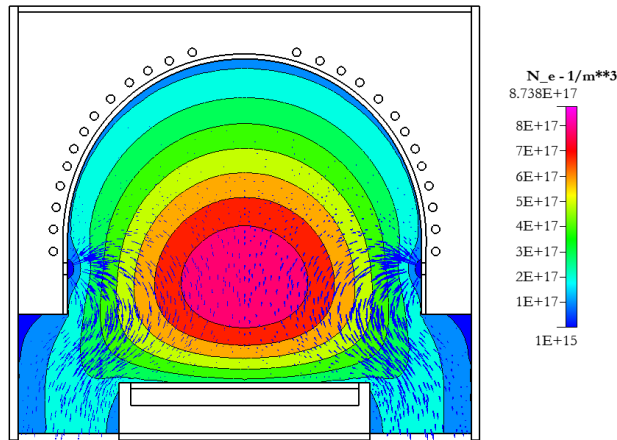
❖ Setup – Run the Simulation

➤ Run Option

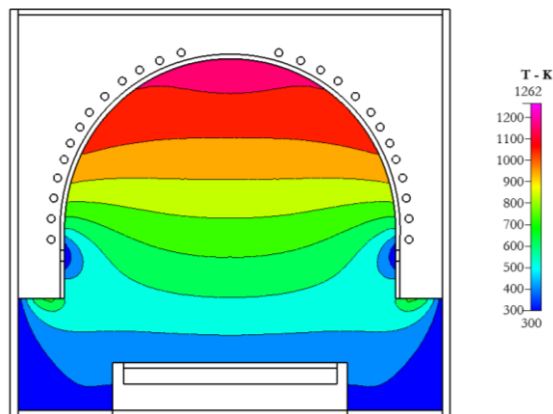
◆ Run → Submit to Solver



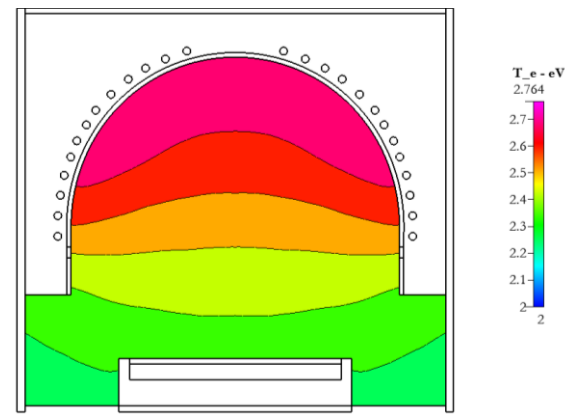
❖ Results – Plasma Density & Gas and Electron Temperature



Electron density와 속도 벡터
(돔 근처에서 $n_e \sim 10^{11} \text{ cm}^{-3}$ 를 고려한다고 가정)



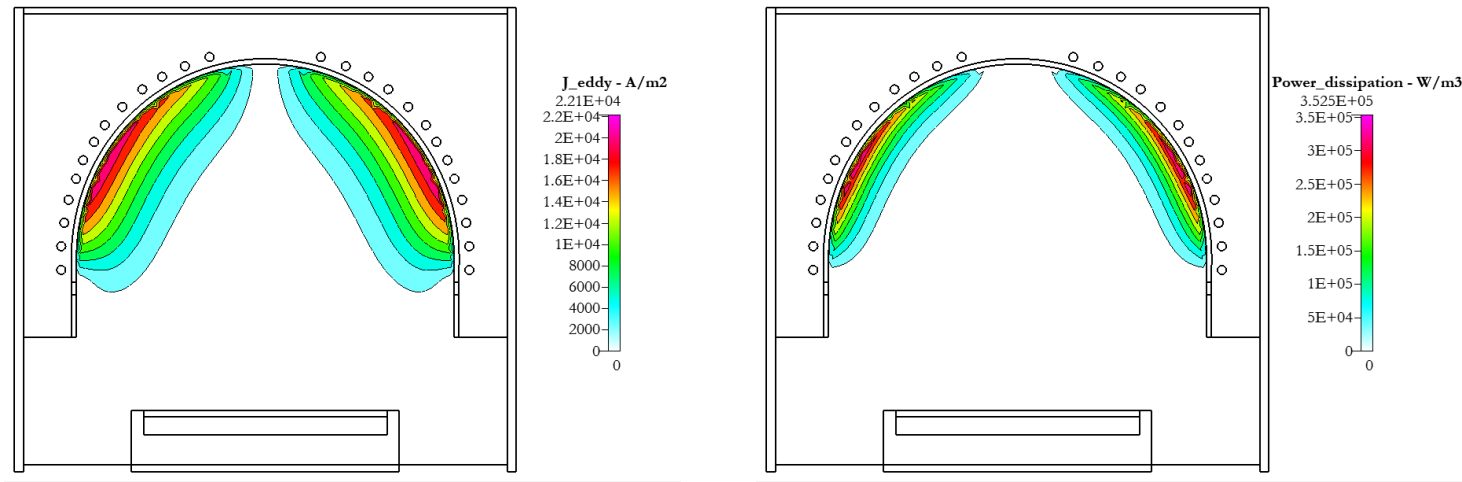
가스 온도 분포



전자 온도 분포

(챔버 중앙에서 정점을 이루는 전자 밀도와 달리 가스 및 전자 온도는 모두 돔 상단 부근에서 정점을 이룸)

❖ Results – Power Density



- ◆ 코일 근처의 챔버 돔에 가까운 영역에서 와전류 및 전자로의 전력 증착 발생
- ◆ Peak power density ~ 0.35 W/cc
- ◆ Plasma skin depth = $5.31 \times 10^5 \cdot n_e^{-0.5} = 1.7$ cm (using $n_e = 10^{11} \text{ cm}^{-3}$)

❖ Results – Summaries

```
=====
Electron Energy Loss (Volumetric Reaction) [Watt]
=====
```

```
VC      7  Plasma      0.51680E+03
-----
```

```
Total E-Energy Loss (W):      0.51680E+03
=====
```

Electron energy loss = 517 Watt

```
=====
ICP Power Absorbed by Electrons [Watt]
=====
```

```
VC      7  Plasma      0.70793E+03
-----
```

```
Total ICP Power (Watts):      0.70793E+03
=====
```

ICP power absorbed = 708 Watt

```
=====
Heat Release (Volumetric Reaction) to Gas [Watt]
=====
```

```
VC      7  Plasma      0.26623E+01
-----
```

```
Total Gas Heating P (W):      0.26623E+01
=====
```

Heat generation in gas
= 3 Watt – just through chemical reaction

※ 유용한 정보가 출력되어 저장되는 text file – modelname.OUT



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