71st Annual Gaseous Electronics Conference
& 60th Annual meeting of the APS Division of Plasma Physic

3D unsteady model of arc heater plasma flow using the ARC Heater Simulator (ARCHeS)

Abstract

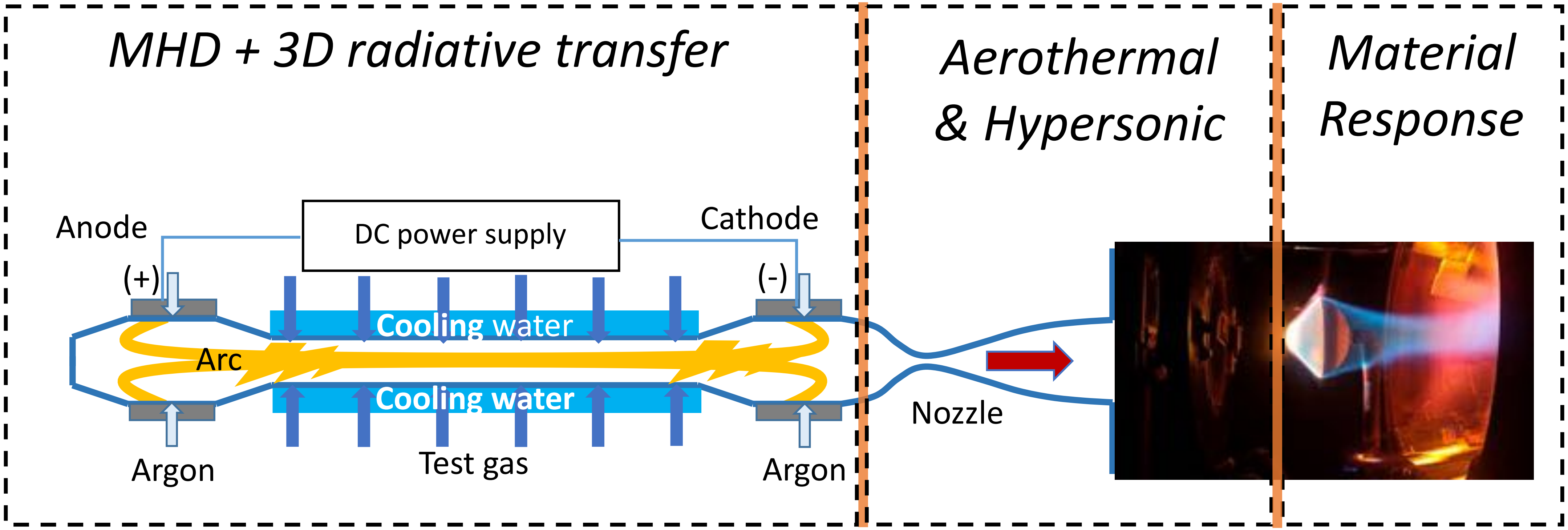
GEC18-2018-000221

November 5th – 9th, 2018

Jeremie B. E. Meurisse, Sander J. Visser, Sergio Fraile Izquierdo,
Magnus Haw and Nagi N. Mansour

TECHNOLOGY DRIVES EXPLORATION

Arc jet facility



ARCHeS is a platform being developed to…

- provide inlet conditions needed by aerothermal models that yield flow properties and conditions at the test article,
- provide understanding of facility operation,
- guide setting up test conditions,
- tailor conditions to improve uniformity,
- inform electrode maintenance schedule,
- inform (V&V) upgrade designs,
- optimize current operational capability…

Plasma fields

FLOW CONDITION	$U_{avg} \approx 400\ m/s$	$P_{avg} \approx 13\ atm$	$T_{avg} \approx 8000\ K$
ELECTROMAG.	$I_{avg} \approx 1200\ A$	$B_{avg} \approx 0.2\ T$	$\sigma_{avg} \approx 0.1\ S/m$

$$S = \frac{L\,v_A}{\eta} = \frac{L\frac{B}{\sqrt{\rho\mu_0}}}{\eta} = 10^{-5}$$

High Lundquist numbers indicate **highly conducting** plasmas.
Low Lundquist numbers indicate **more resistive** plasmas.

Lundquist number scale

- 10^{-5} — *Arc jet facility*
- 10^{1} — *Highly resistive plasma*
- $10^{2} - 10^{8}$ — *Laboratory plasma experiments*
- 10^{20} — *Astrophysical situations*

Assumptions

$S = \frac{L\, v_A}{\eta} = 10^{-5}$ ⟶ The magnetic convection is negligible

$\mathbf{J} = \sigma \mathbf{E}$ ⟶ The Ohm's law is simplified

$\boldsymbol{\partial}_{\mathbf{x}} \times \mathbf{B} = \mu_0 \mathbf{J}$ ⟶ The displacement current is ignored (V_0 << c)

$\mathbf{B} = \boldsymbol{\partial}_{\mathbf{x}} \times \mathbf{A}$ ⟶ The vector potential formulation ensures zero divergence of the **B** field

$\boldsymbol{\partial}_{\mathbf{x}} . \mathbf{J} = 0$ ⟶ Diverge of Ampere's law gives the continuity of current

$-\boldsymbol{\partial}_{\mathbf{x}}^{2} \mathbf{A} = \mu_0 \mathbf{J}$ ⟶ Rotational of Ampere's law simplifies the equation

$$\begin{cases} \boldsymbol{\partial}_{\mathbf{x}} . (-\sigma \boldsymbol{\partial}_{\mathbf{x}} \phi_i) = 0 \\ \boldsymbol{\partial}_{\mathbf{x}}^{2} \mathbf{A}_{\mathbf{i}} - \mu_0 \sigma \boldsymbol{\partial}_{\mathbf{x}} \phi_i = 0 \end{cases}$$

⟶ System of electromagnetic equations solved in ARCHeS

Physical model

MASS	$\partial_t \rho + \boldsymbol{\partial}_\mathbf{x} . (\rho \mathbf{u}) = 0$
MOMENTUM	$\partial_t(\rho \mathbf{u}) + \boldsymbol{\partial}_\mathbf{x} . (\rho \mathbf{u}\mathbf{u}) = - \boldsymbol{\partial}_\mathbf{x} p + \boldsymbol{\partial}_\mathbf{x} . \overline{\overline{\boldsymbol{\tau}}}$
ENERGY	$\partial_t(\rho E_0) + \boldsymbol{\partial}_\mathbf{x} . (\rho H_0 \mathbf{u}) = \boldsymbol{\partial}_\mathbf{x} . (\overline{\overline{\boldsymbol{\tau}}} . \mathbf{u} + \mathbf{q}^{cond})$

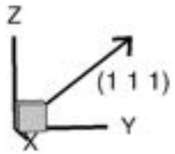
Physical model

MASS	$\partial_t \rho + \boldsymbol{\partial}_{\mathbf{x}} . (\rho \mathbf{u}) = 0$
MOMENTUM	$\partial_t (\rho \mathbf{u}) + \boldsymbol{\partial}_{\mathbf{x}} . (\rho \mathbf{u}\mathbf{u}) = - \boldsymbol{\partial}_{\mathbf{x}} p + \boldsymbol{\partial}_{\mathbf{x}} . \bar{\bar{\boldsymbol{\tau}}} + \mathbf{J} \times \mathbf{B}$
ENERGY	$\partial_t (\rho E_0) + \boldsymbol{\partial}_{\mathbf{x}} . (\rho H_0 \mathbf{u}) = \boldsymbol{\partial}_{\mathbf{x}} . (\bar{\bar{\boldsymbol{\tau}}} . \mathbf{u} + \mathbf{q}^{\mathbf{cond}}) + \sigma \lvert \mathbf{E} \rvert^2 + \mathbf{u} . (\mathbf{J} \times \mathbf{B})$
IMPOSED CURRENT	$\boldsymbol{\partial}_{\mathbf{x}} . (-\sigma \boldsymbol{\partial}_{\mathbf{x}} \phi_i) = 0$ $\quad \mathbf{E}_i = - \boldsymbol{\partial}_{\mathbf{x}} \phi_i$ $\quad \mathbf{J}_i = \sigma \mathbf{E}_i$
IMPOSED MAGNETIC	$\boldsymbol{\partial}_{\mathbf{x}}^2 \mathbf{A}_i - \mu_0 \sigma \boldsymbol{\partial}_{\mathbf{x}} \phi_i = 0$ $\quad \mathbf{B}_i = \boldsymbol{\partial}_{\mathbf{x}} \times \mathbf{Ai}$
EXTERNAL MAGNETIC	$\mathbf{A}_e = \frac{\mu_0 I_e}{4\pi} \oint \frac{\boldsymbol{dl}}{\lvert \boldsymbol{r} - \boldsymbol{r}' \rvert}$ $\quad \mathbf{B}_e = \boldsymbol{\partial}_{\mathbf{x}} \times \mathbf{A}_e$
TOTAL FIELD	$\mathbf{B} = \mathbf{B}_i + \mathbf{B}_e$ $\quad \mathbf{E} = \mathbf{E}_i$ $\quad \mathbf{J} = \mathbf{J}_i$

Physical model

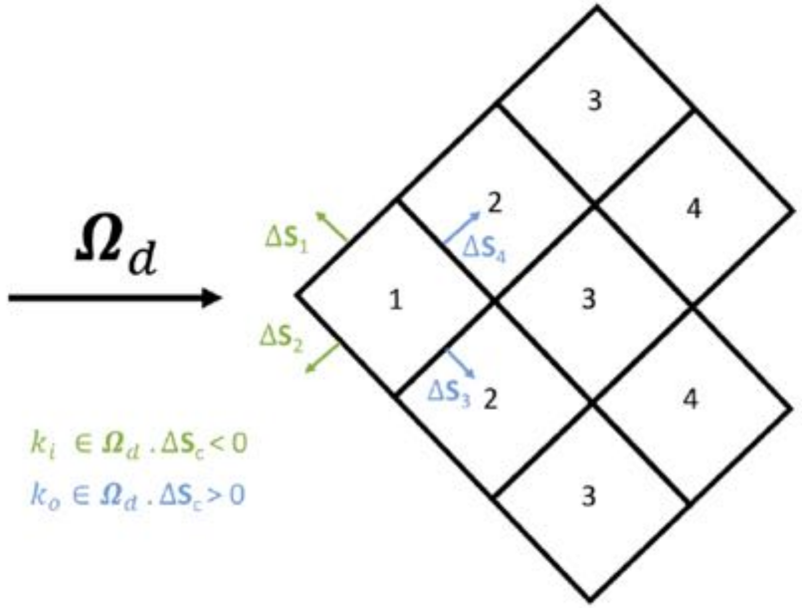
MASS	$\partial_t \rho + \boldsymbol{\partial}_\mathbf{x} . (\rho \mathbf{u}) = 0$
MOMENTUM	$\partial_t(\rho \mathbf{u}) + \boldsymbol{\partial}_\mathbf{x} . (\rho \mathbf{u}\mathbf{u}) = - \boldsymbol{\partial}_\mathbf{x} p + \boldsymbol{\partial}_\mathbf{x} . \bar{\bar{\boldsymbol{\tau}}} + \mathbf{J} \times \mathbf{B}$
ENERGY	$\partial_t(\rho E_0) + \boldsymbol{\partial}_\mathbf{x} . (\rho H_0 \mathbf{u}) = \boldsymbol{\partial}_\mathbf{x} . (\bar{\bar{\boldsymbol{\tau}}} . \mathbf{u} + \mathbf{q}^{cond}) + \sigma \lvert \mathbf{E} \rvert^2 + \mathbf{u} . (\mathbf{J} \times \mathbf{B}) - \boldsymbol{\partial}_\mathbf{x} . \mathbf{q}^{rad}$
IMPOSED CURRENT	$\boldsymbol{\partial}_\mathbf{x} . (-\sigma \boldsymbol{\partial}_\mathbf{x} \phi_i) = 0$ $\quad \mathbf{E}_i = - \boldsymbol{\partial}_\mathbf{x} \phi_i$ $\quad \mathbf{J}_i = \sigma \mathbf{E}_i$
IMPOSED MAGNETIC	$\boldsymbol{\partial}_\mathbf{x}^2 \mathbf{A}_i - \mu_0 \sigma \boldsymbol{\partial}_\mathbf{x} \phi_i = 0$ $\quad \mathbf{B}_i = \boldsymbol{\partial}_\mathbf{x} \times \mathbf{Ai}$
EXTERNAL MAGNETIC	$\mathbf{A}_e = \frac{\mu_0 I_e}{4\pi} \oint \frac{\boldsymbol{dl}}{\lvert \boldsymbol{r} - \boldsymbol{r}' \rvert}$ $\quad \mathbf{B}_e = \boldsymbol{\partial}_\mathbf{x} \times \mathbf{A}_e$
TOTAL FIELD	$\mathbf{B} = \mathbf{B}_i + \mathbf{B}_e$ $\quad \mathbf{E} = \mathbf{E}_i$ $\quad \mathbf{J} = \mathbf{J}_i$

Physical model



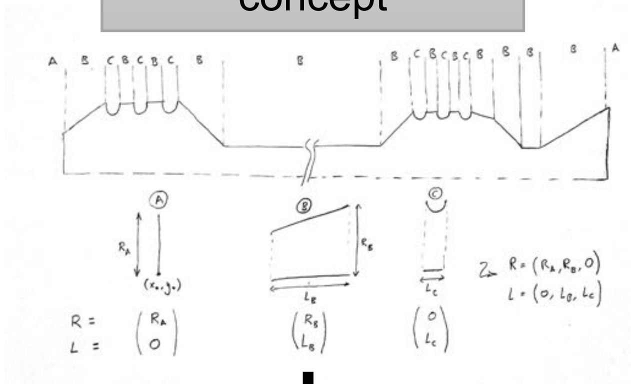
$$I^{d}_{\upsilon,c} = \frac{\sum_{k_i}^{N_{k_i}} I^{d}_{\upsilon,k_i}\,\Omega_d \,.\, \Delta S_c . + \kappa_{\upsilon,c}\; B_{\upsilon,c}\, V_c}{\sum_{k_o}^{N_{k_o}} I^{d}_{\upsilon,k_o}\,\Omega_d \,.\, \Delta S_c . + \kappa_{\upsilon,c}\; V_c}$$

$$\partial_x \,.\, q^{rad} = \sum_{\upsilon}^{N_b} \sum_{d}^{N_d} \frac{a_d\, I^{d}_{\upsilon,c}\, \Omega_d \,.\, \Delta S_c}{V_c}$$

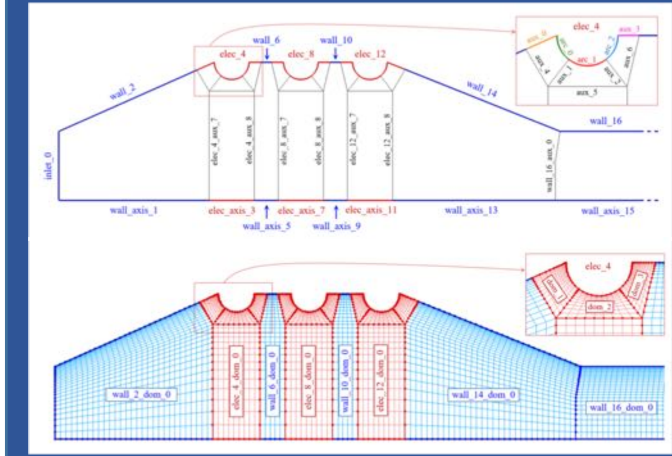


ARC Heater Simulator

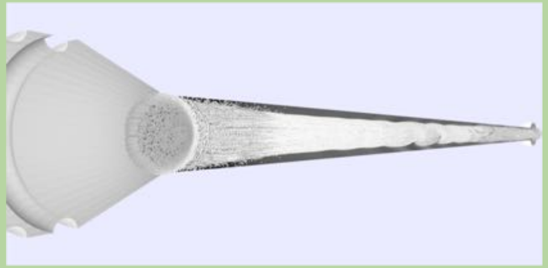
Geometry concept



Automatic mesh inputs



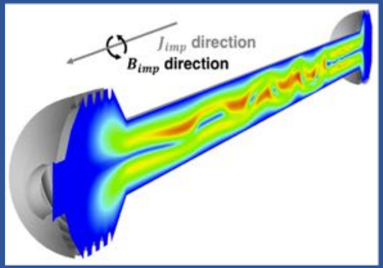
OpenFOAM



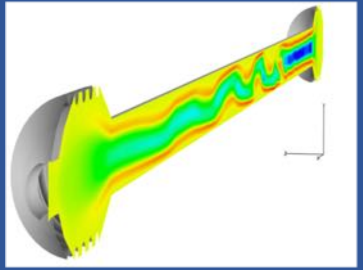
- Finite Volume
- I/O management
- Massive MPI
- Mixture tables
- Turbulence
- Moving geometry
- Chemistry
- Compressible flow
- Basic mesh gen.
- Thermo/Transp.
- Radiation

ARCHeS

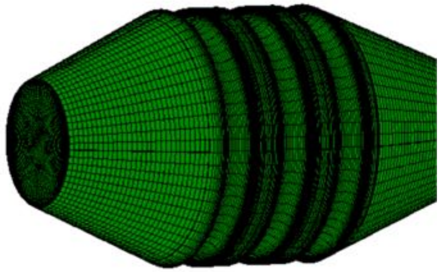
MHD + ballast BC



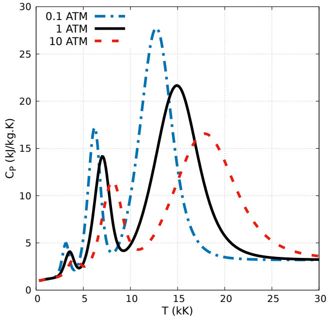
3D radiative transfer



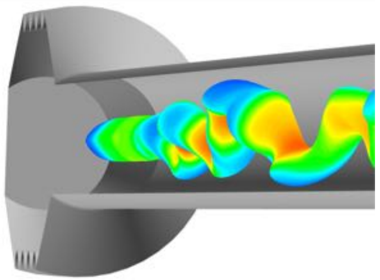
Complex mesh generation



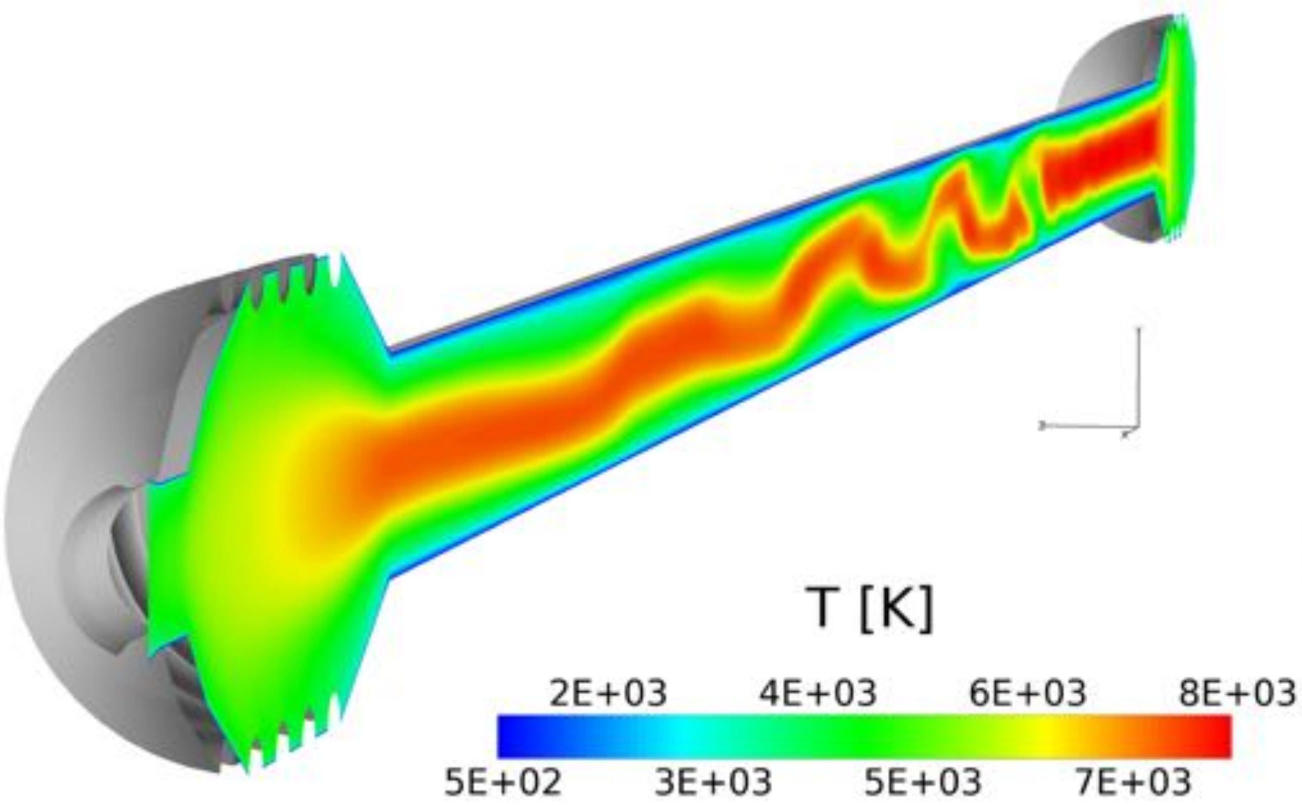
Thermo/Transport/ Chemistry

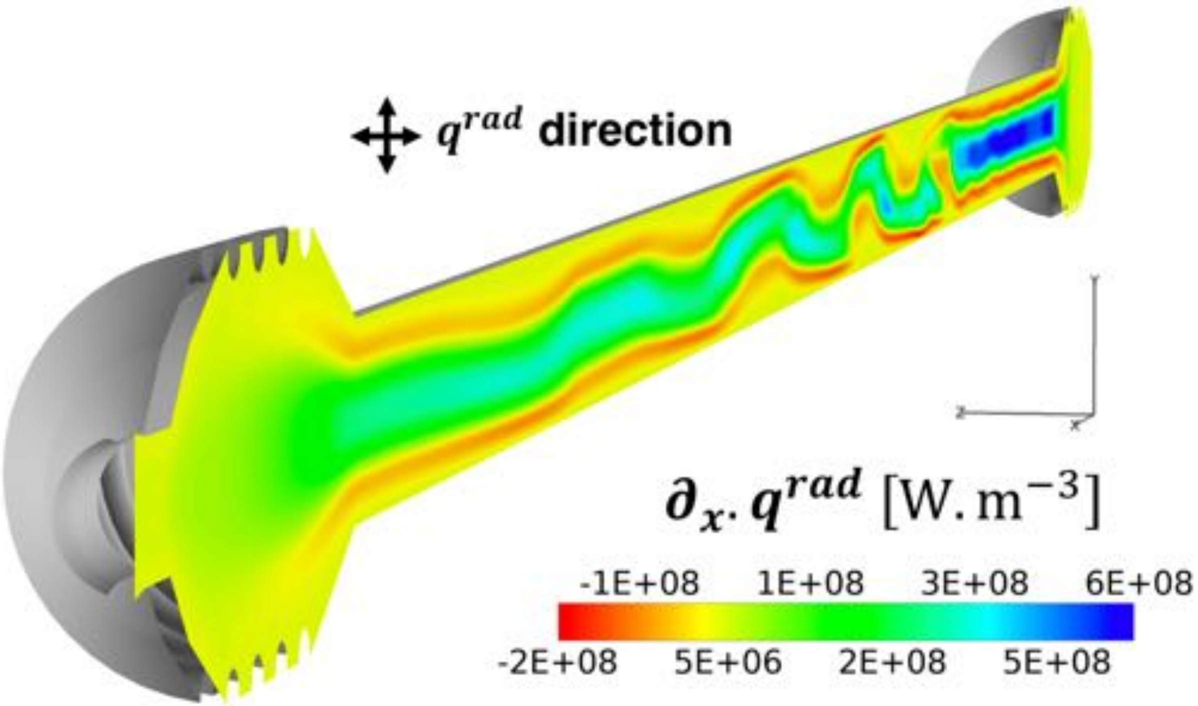


Post-processing 1D/2D/3D



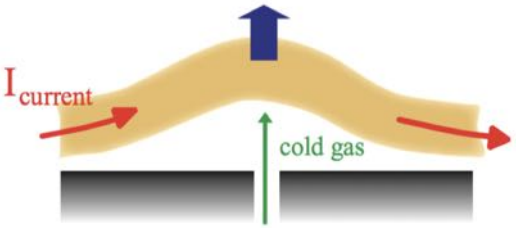
Cutting plane



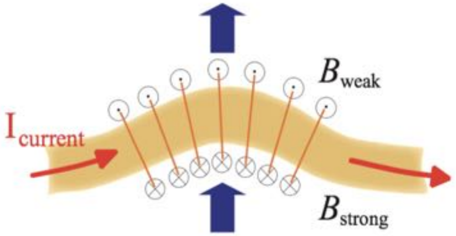


Hot electric arc core cools down and the surroundings warm up.
Importance of the 3D radiative transfer.

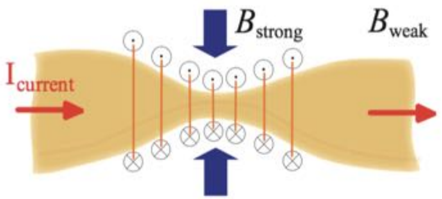
Electric arc instabilities



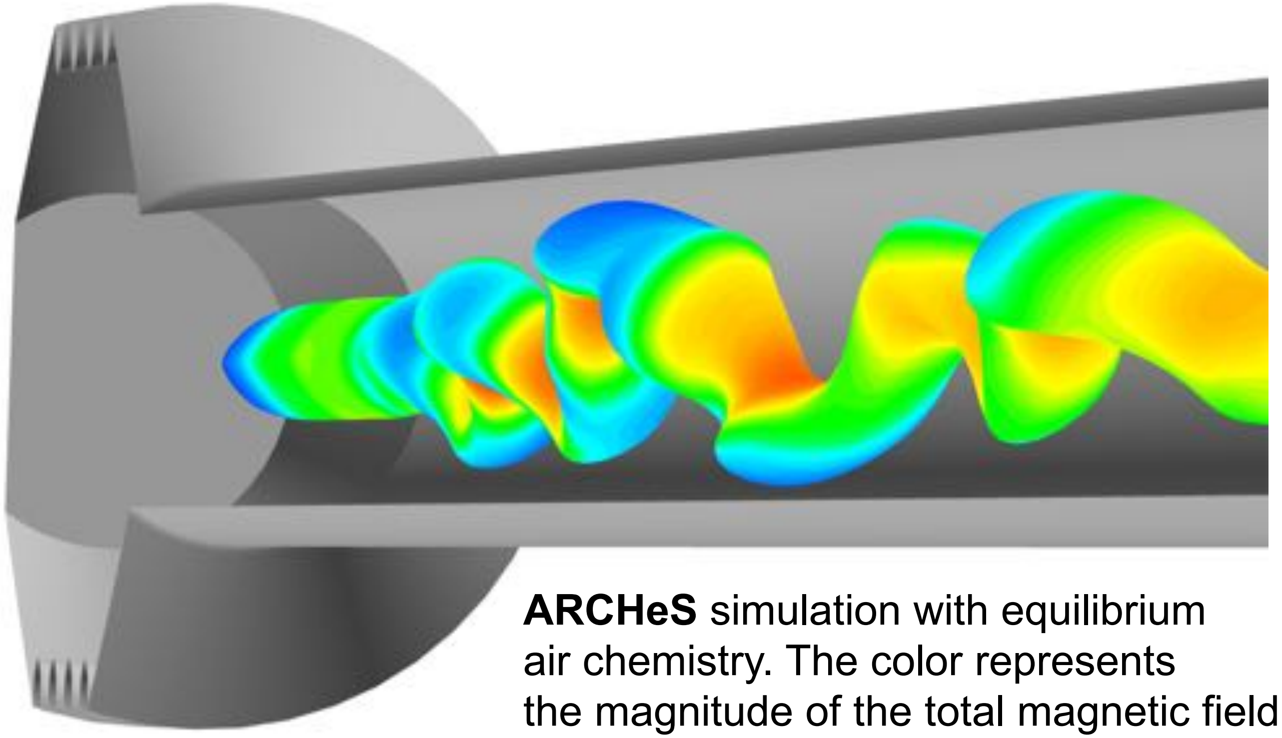
Thermal instability



Kink instability



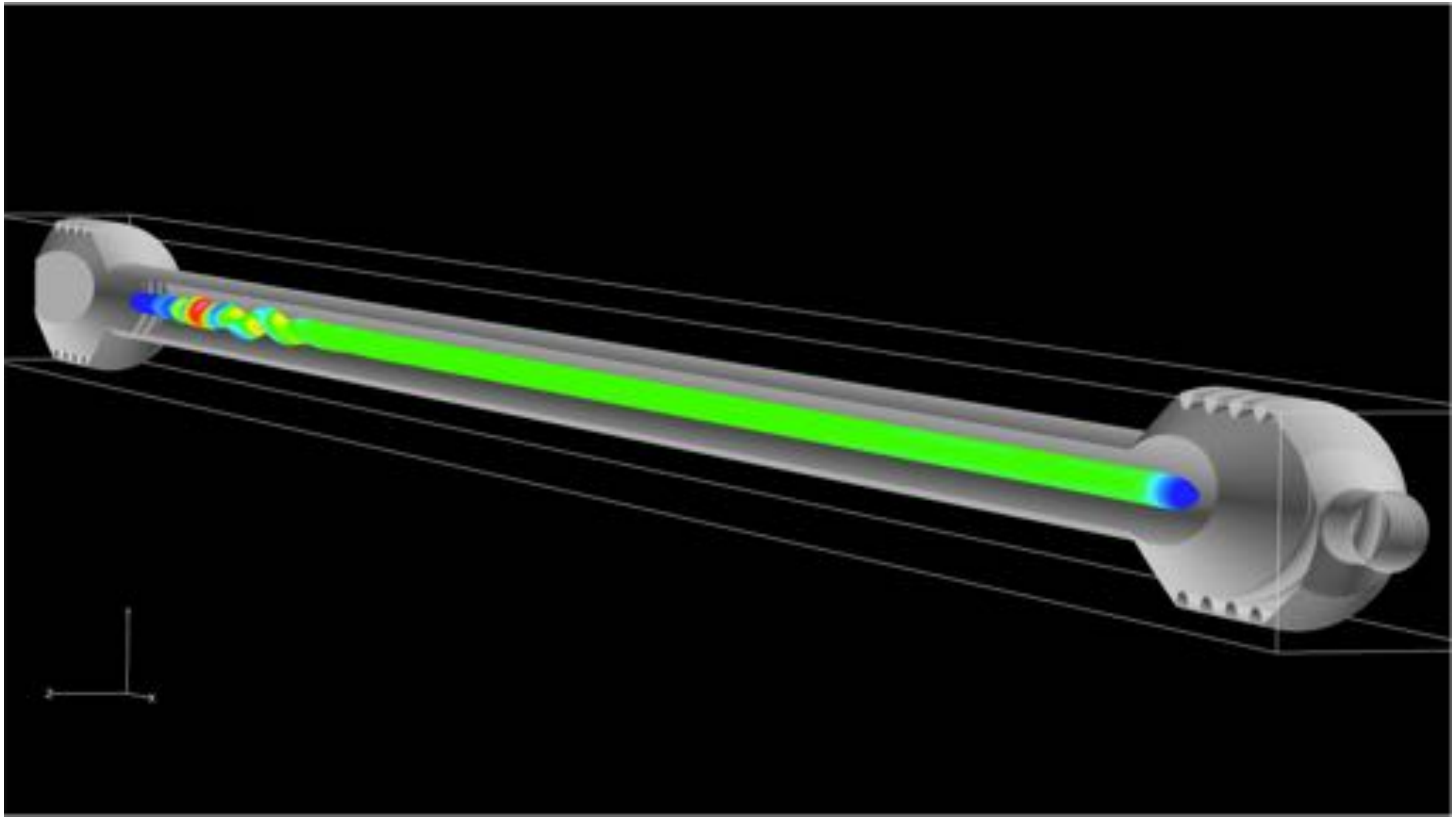
Sausage instability



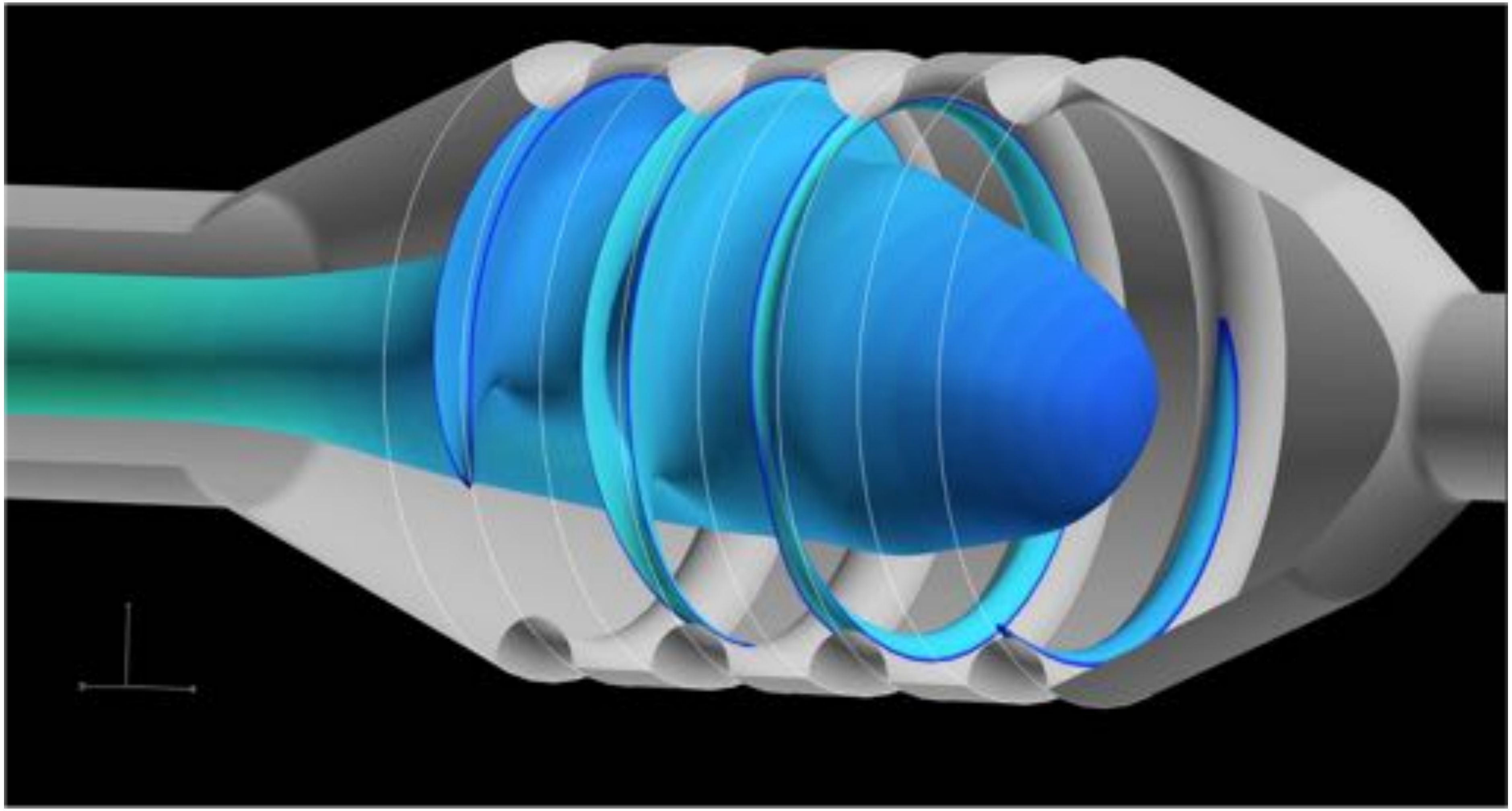
ARCHeS simulation with equilibrium air chemistry. The color represents the magnitude of the total magnetic field. Iso-surface of the current density of 1 MA/m^2.

Stable arc next to the electrode chambers.
Instablilities arise in the constrictor.

Air mixture



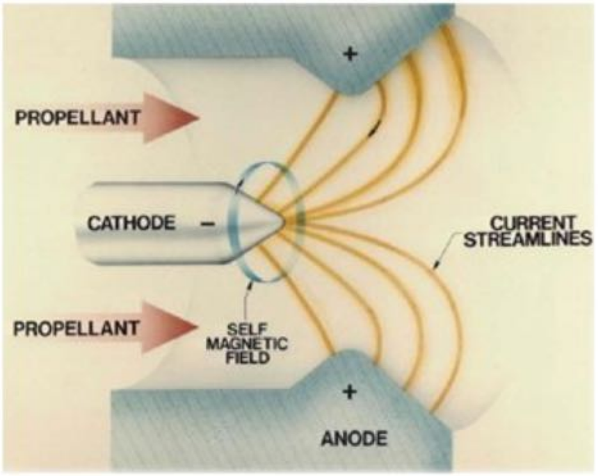
Electric arc attachment



Cross technology impact

ARCHeS

- Aerothermodynamics Plasmadynamics
- Electromagnetism
- Radiative transfer



Magnetohydrodynamic Thruster
https://www.nasa.gov/centers/glenn/about/fs22grc.html, 08/10/2018

With **minimal investment** the toolkit can provide modern simulation toolkit for optimizing **in-space electric propulsion systems** such as:

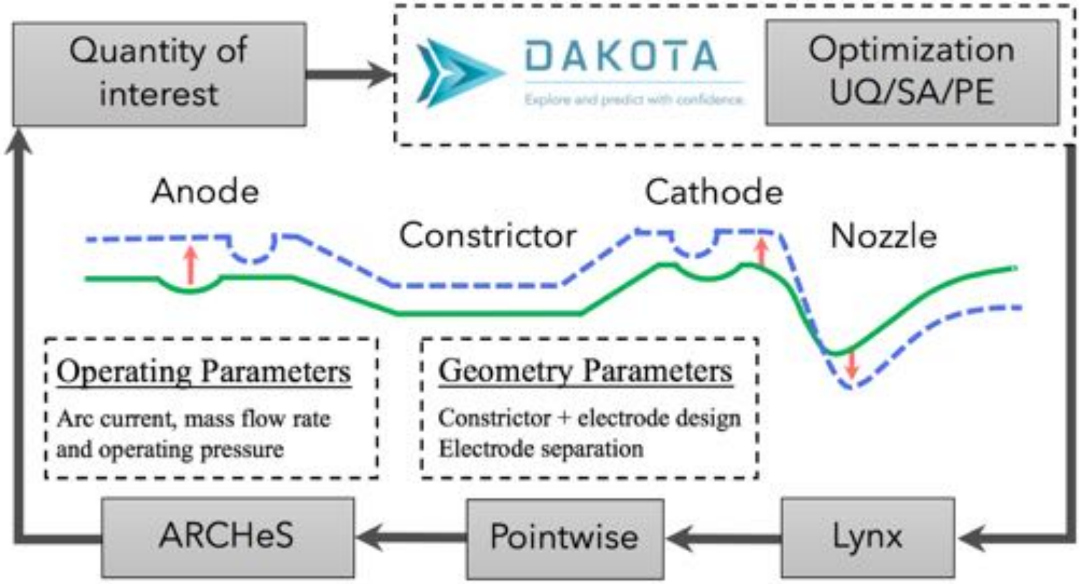
- Magnetohydrodynamic Thruster
- Pulsed Plasma Thruster
- Hall Effect Thruster
- Helicon Double Layer Thruster
- Variable Specific Impulse Magnetoplasma Rocket

Future work

ARCHeS improvement

- **MHD physical models**
  Magnetic flux equations with regions of zero conductivity
- **2 temperature formulation**
  Very thin layer where the electron temperature and heavy separate due to strong magnetic field
- **Thermo/Transport/Chemistry**
  Elemental conservation and finite-rate
- **Radiation**
  Opacity tables with variable elemental composition
- **Electrodes surface response**
  Melt & evaporation of copper formulation
  Coupling to PATO
- **Validation experiments**

Coupling to optimization library



ARCHeS will be coupled to DAKOTA to enable optimization of operating parameters to achieve quantity of interest

Experimental validation plan

- **Electrode arc detachment events**
  - High frequency electrode current probe
  - High frequency electrode voltage probe

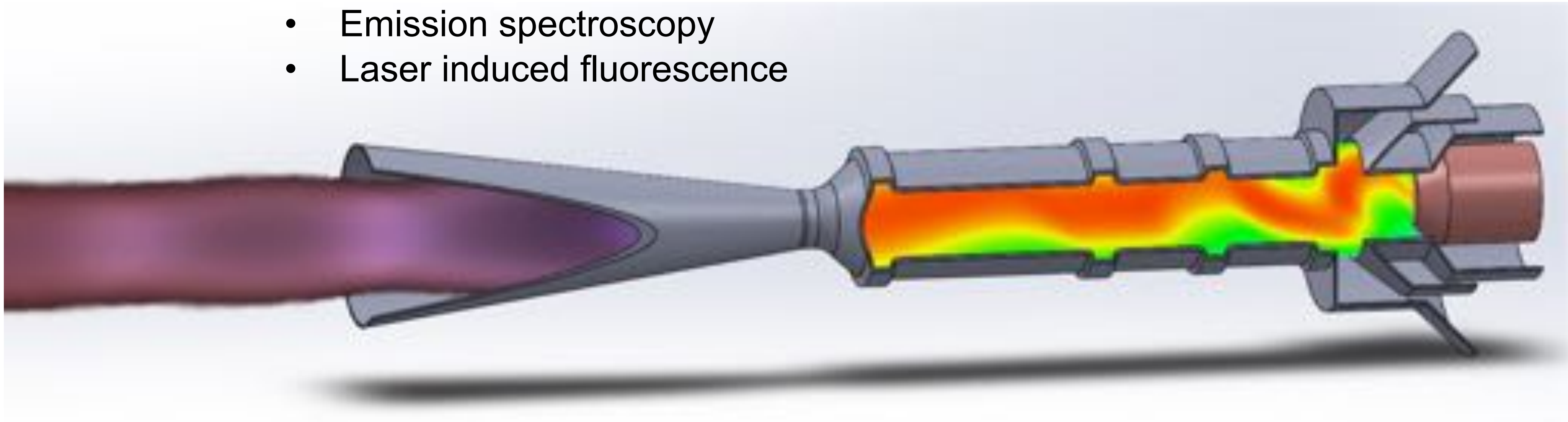
- **Thermal and electromagnetic boundary conditions**
  - Electrostatic (Langmuir) probes
  - External magnetic probes
  - Laser induced fluorescence

- **Internal temperature, flow profiles**
  - Emission spectroscopy
  - Laser induced fluorescence

mARC 2.0

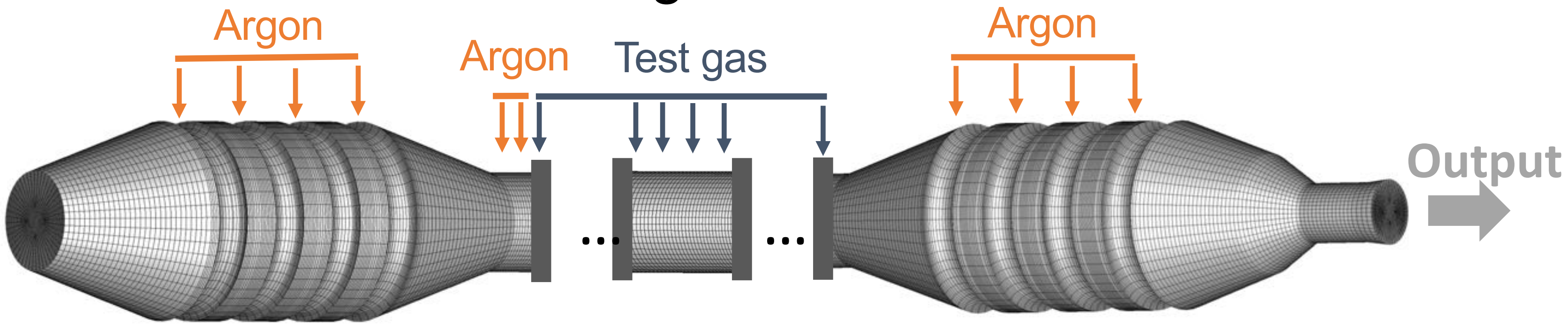
TS division

NASA Ames Research Center

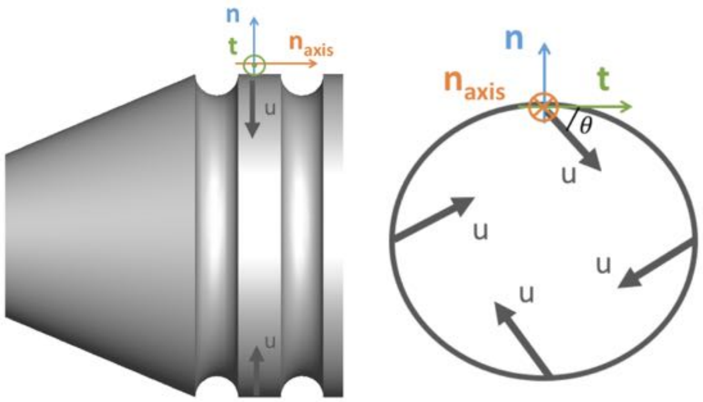


Important features

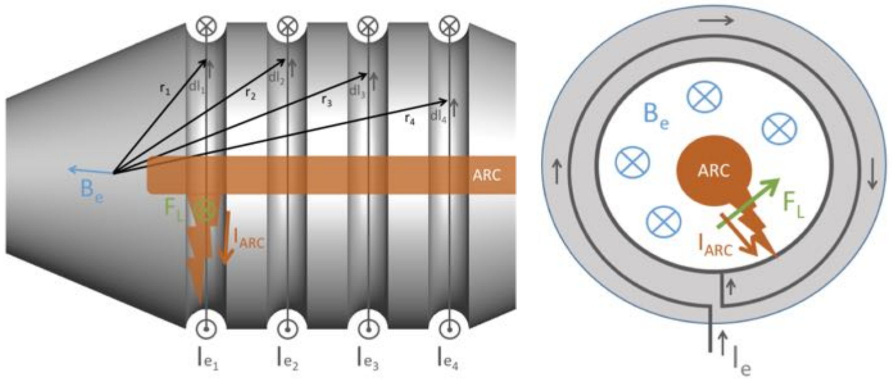
Variable gas mixture



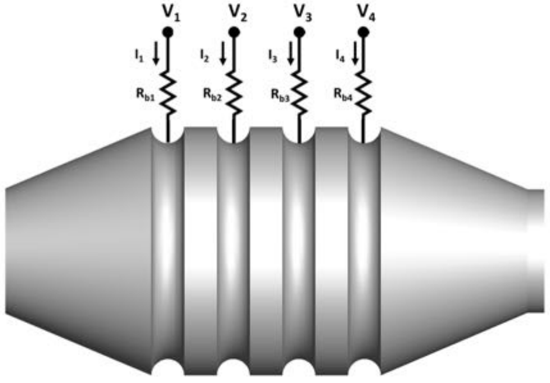
Swirl



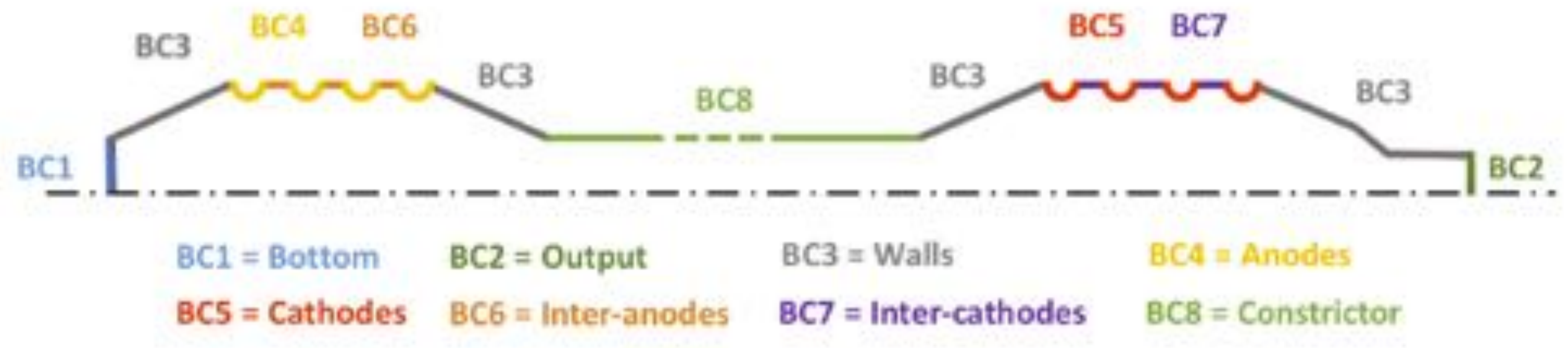
Internal magnetic drive



Electrical ballast



Boundary conditions



	p [Pa]	T [K]	$\boldsymbol{u}$ [m/s]
$BC1$	$\partial_{\boldsymbol{x}} p \cdot \boldsymbol{n} = 0$	T_w	$\boldsymbol{u} = \boldsymbol{0}$
$BC2$	$\partial_{\boldsymbol{x}} p \cdot \boldsymbol{n} = 0$	$\partial_{\boldsymbol{x}} T \cdot \boldsymbol{n} = 0$	$\partial_{\boldsymbol{x}} \boldsymbol{u} \cdot \boldsymbol{n} = \boldsymbol{0}$
$BC3$	$\partial_{\boldsymbol{x}} p \cdot \boldsymbol{n} = 0$	T_w	$\boldsymbol{u} = \boldsymbol{0}$
$BC4$	$\partial_{\boldsymbol{x}} p \cdot \boldsymbol{n} = 0$	$\partial_{\boldsymbol{x}} T \cdot \boldsymbol{n} = 0$	$\boldsymbol{u} = \boldsymbol{0}$
$BC5$	$\partial_{\boldsymbol{x}} p \cdot \boldsymbol{n} = 0$	$\partial_{\boldsymbol{x}} T \cdot \boldsymbol{n} = 0$	$\boldsymbol{u} = \boldsymbol{0}$
$BC6$	$\partial_{\boldsymbol{x}} p \cdot \boldsymbol{n} = 0$	T_w	$\dot{m}_{BC6}$
$BC7$	$\partial_{\boldsymbol{x}} p \cdot \boldsymbol{n} = 0$	T_w	$\boldsymbol{u} = \boldsymbol{0}$
$BC8$	$\partial_{\boldsymbol{x}} p \cdot \boldsymbol{n} = 0$	T_w	$\dot{m}_{BC8}$

BC of the Navier-Stokes equations

	ϕ_{imp} [V]	$\boldsymbol{A}_{imp}$ [T · m]	$\boldsymbol{A}_e$ [T · m]
$BC1$	$\partial_{\boldsymbol{x}} \phi_{imp} \cdot \boldsymbol{n} = 0$	$\boldsymbol{A}_{imp} = \boldsymbol{0}$	$\boldsymbol{A}_e = \boldsymbol{0}$
$BC2$	$\partial_{\boldsymbol{x}} \phi_{imp} \cdot \boldsymbol{n} = 0$	$\boldsymbol{A}_{imp} = \boldsymbol{0}$	$\boldsymbol{A}_e = \boldsymbol{0}$
$BC3$	$\partial_{\boldsymbol{x}} \phi_{imp} \cdot \boldsymbol{n} = 0$	$\boldsymbol{A}_{imp} = \boldsymbol{0}$	$\boldsymbol{A}_e = \boldsymbol{0}$
$BC4$	$I_{imp,tot}$	$\boldsymbol{A}_{imp} = \boldsymbol{0}$	$\boldsymbol{A}_e = \boldsymbol{0}$
$BC5$	$\phi^n_{imp,c_i} = \phi_G - R_b I^{n-1}_{imp,c_i}$	$\boldsymbol{A}_{imp} = \boldsymbol{0}$	$\boldsymbol{A}_e = \boldsymbol{0}$
$BC6$	$\partial_{\boldsymbol{x}} \phi_{imp} \cdot \boldsymbol{n} = 0$	$\boldsymbol{A}_{imp} = \boldsymbol{0}$	$\boldsymbol{A}_e = \boldsymbol{0}$
$BC7$	$\partial_{\boldsymbol{x}} \phi_{imp} \cdot \boldsymbol{n} = 0$	$\boldsymbol{A}_{imp} = \boldsymbol{0}$	$\boldsymbol{A}_e = \boldsymbol{0}$
$BC8$	$\partial_{\boldsymbol{x}} \phi_{imp} \cdot \boldsymbol{n} = 0$	$\boldsymbol{A}_{imp} = \boldsymbol{0}$	$\boldsymbol{A}_e = \boldsymbol{0}$

BC of the Maxwell equations