Simulations of Electrical Arcs: Algorithms, Physical Scales, and Coupling

IET INSTITUTE FOR ENERGY TECHNOLOGY

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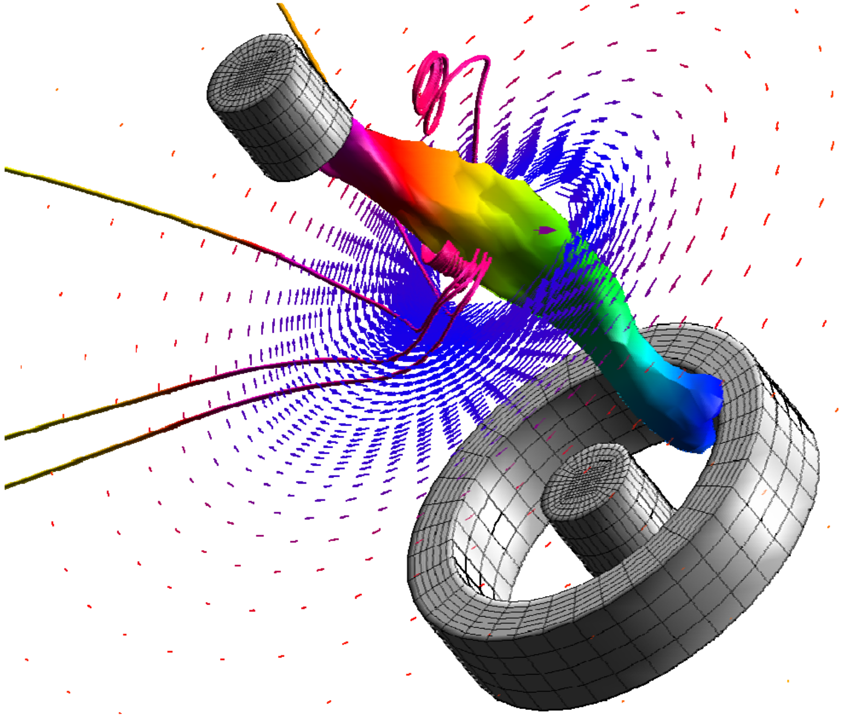

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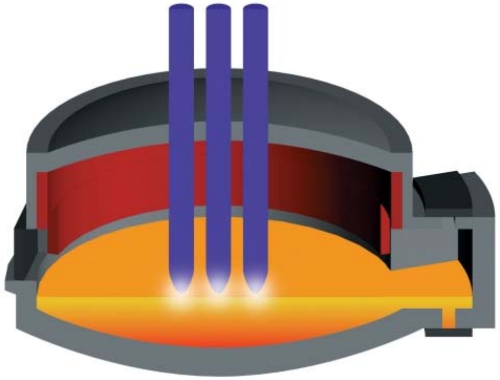
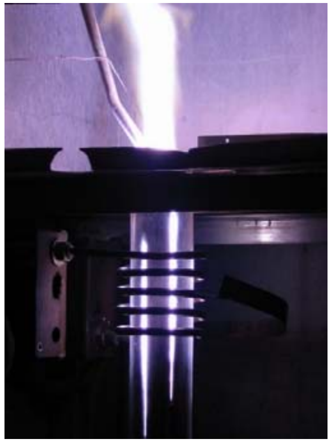
What is an electrical arc?

Technical applications of arcs and industrial plasmas

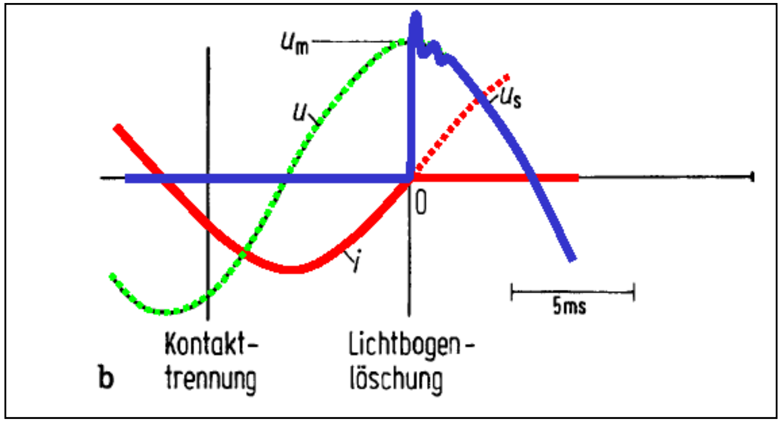
- **Generation of heat**
    - Welding, arc furnaces
- **Decomposition of material**
    - Waste incinerator
- **Electrochemical processes**
    - Plasma deposition
    - Surface coating
    - Plasma surgery
- **Generation of light**
    - Gas discharge lamps
- **Interruption of currents**
    - Circuit breakers





The perfect circuit breaker (AC)

$$U_{arc}(I) = \begin{cases} 0 & \text{before CZ} \\ \infty & \text{after CZ} \end{cases}$$

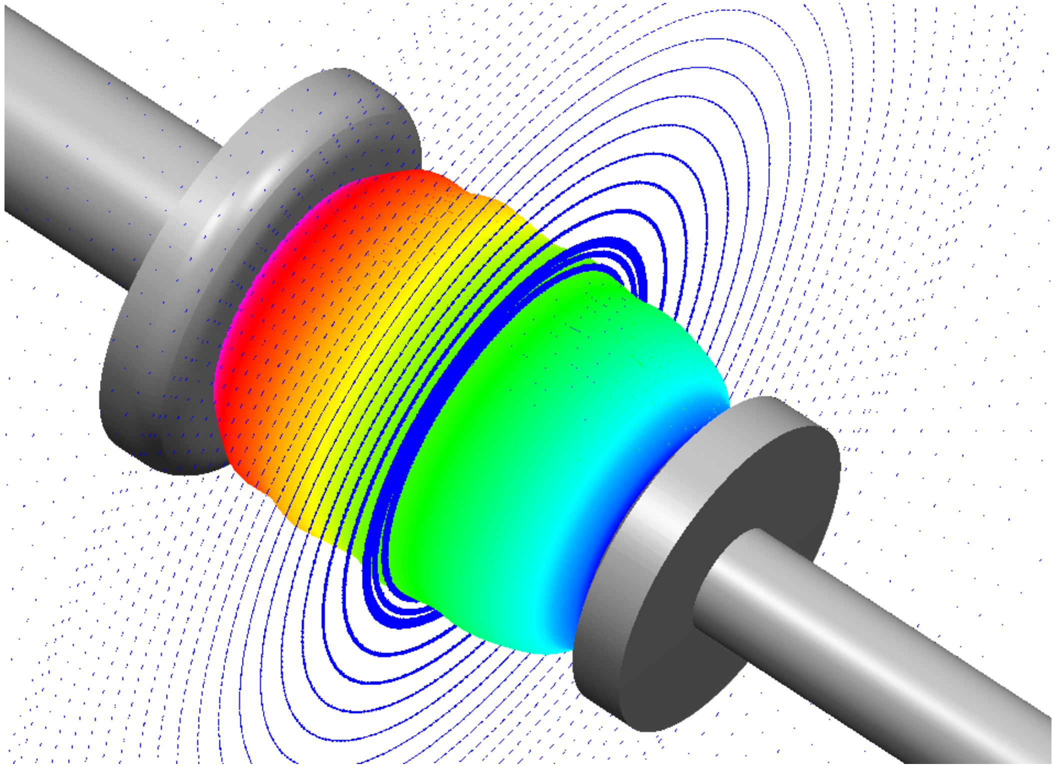


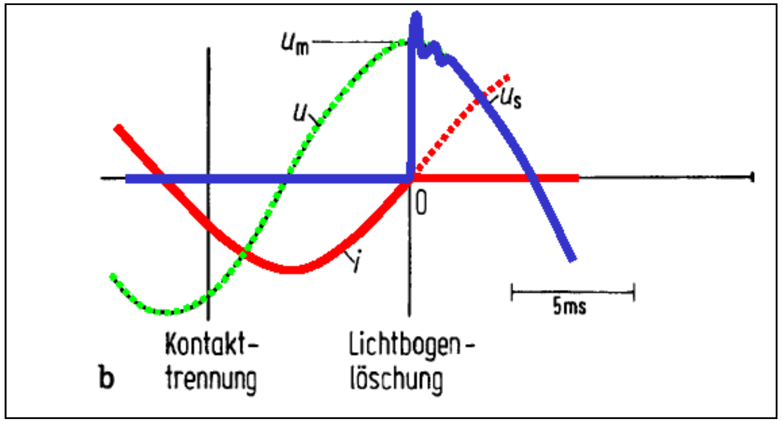
Problems:

- **Time scales (20 A / µs)**
- **Phase shift: current and voltage out of phase**
- **Large currents and energies (before CZ)**
- **Large electric fields (after CZ)**

Why arcs are useful

Before Current Zero: The gas is heated by the current and is highly conducting





At Current Zero:
Resistance increases rapidly as the gas cools off

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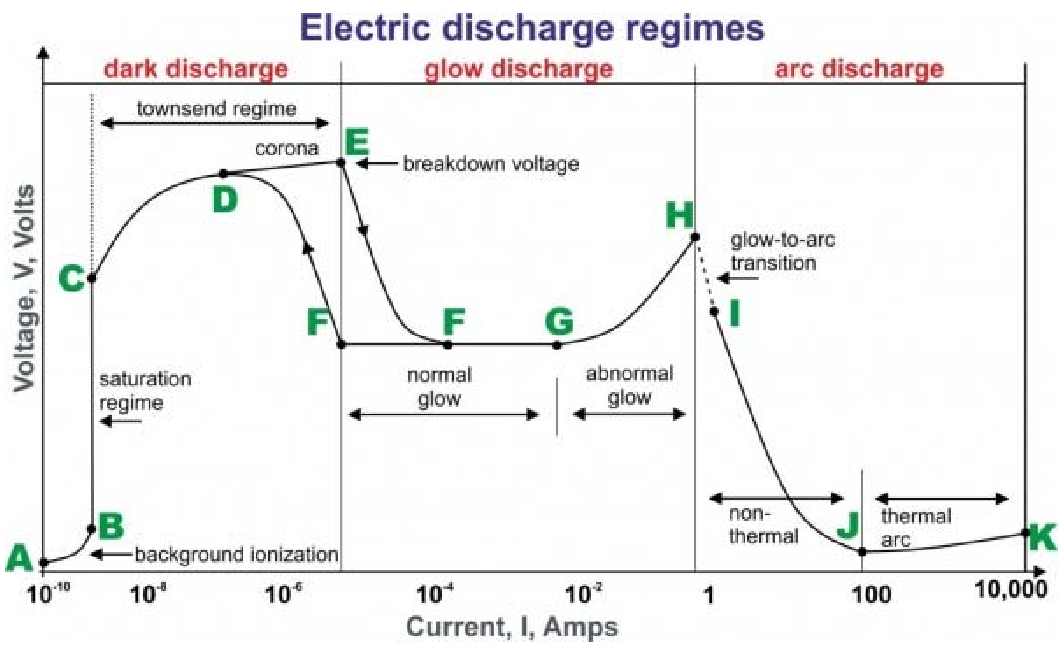
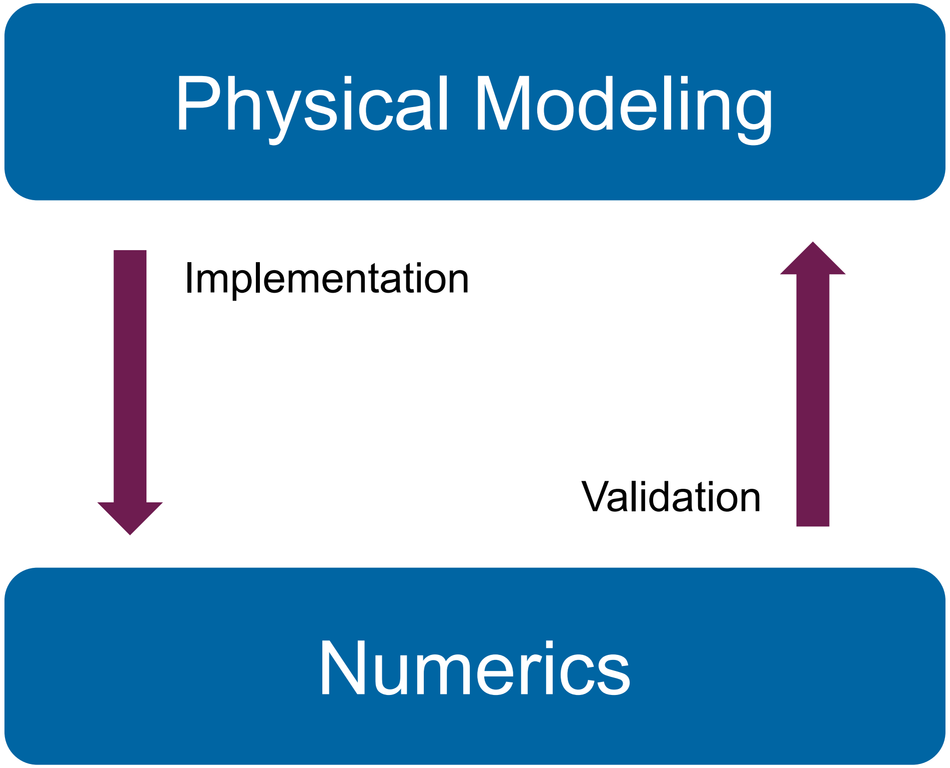
Overview of gas discharges and arcs

- **Gas Discharge**
  - Electric current passes through a gas from an anode to a cathode
- **Glow discharge**
  - Large electric fields
  - Electron temperature much larger than the gas temperature $T_e > T$.
- **Electric arc**
  - High current and lower electric field
  - Thermal plasma with $T_e = T$



The challenge of arc simulations



- **The problem is too complex for the model to be implemented from first principles**
- **All effects are strongly coupled and cannot be validated separately**
- **Most of the models are numerically challenging – simple implementations do not work**
- **We need an efficient implementation of the models before we know if the models are correct**

Magnetohydrodynamics: The simplest possible arc model

CFD

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla \cdot \{\rho \mathbf{u}\} = 0 \\ \dfrac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \{\rho\, \mathbf{u} \otimes \mathbf{u}\} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \mathbf{j} \times \mathbf{B} \\ \dfrac{\partial (\rho e)}{\partial t} + \nabla \cdot \{\rho e \mathbf{u} - \lambda \nabla T + p \mathbf{u}\} = \nabla \cdot (\boldsymbol{\tau} \cdot \mathbf{u}) + \mathbf{j} \cdot \mathbf{E} - \nabla \cdot \mathbf{F} \end{cases}$$

Lorentz force

Ohmic heating

Radiation

Material properties

$\rho = \rho(p, T)$

$e = e(p, T)$

$\sigma = \sigma(p, T)$

EMAG

$$\begin{cases} \dfrac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = 0 \qquad \nabla \cdot \boldsymbol{B} = 0 \\ \dfrac{1}{c^2} \dfrac{\partial \boldsymbol{E}}{\partial_t} - \nabla \times \boldsymbol{B} = -\mu_0 \boldsymbol{j} \qquad \nabla \cdot \boldsymbol{E} = \rho_e / \varepsilon_0 \end{cases}$$

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{U} \times \boldsymbol{B})$$

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Simplifying assumptions

- **Atmospheric high-pressure plasma**
  - Mean free path is short = high collision frequency
- **Local Thermal Equilibrium (LTE)**
  - Reaction dynamics is very fast
  - Material properties can be computed from thermodynamics
- **Thermal plasma**
  - Only one temperature. $T_e = T$
  - The electric field is small
- **Quasi-neutral plasma**
  - Debye length is small. No macroscopic charge accumulation

The approximations are valid for a burning arc but cannot not be used to describe the ignition of the arc.

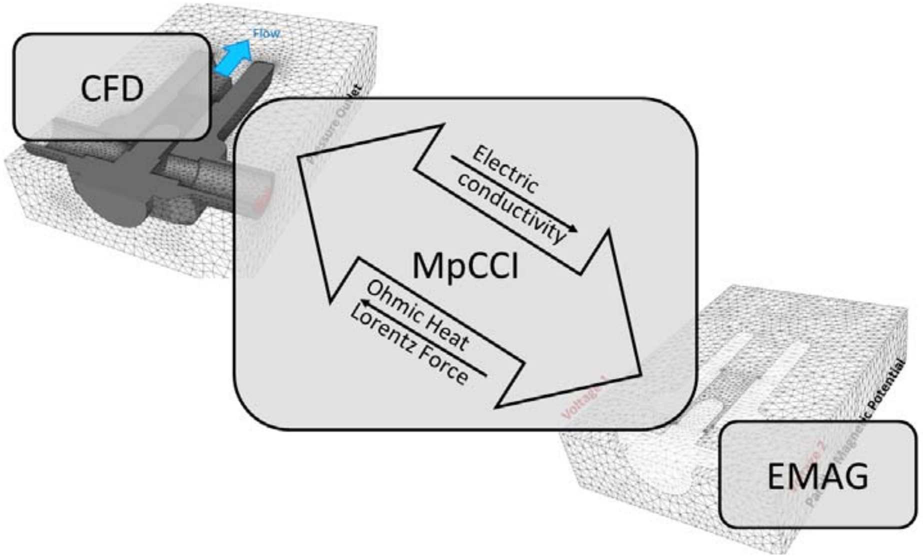
The arc roots at the electrodes need to be treated differently.

Challenges

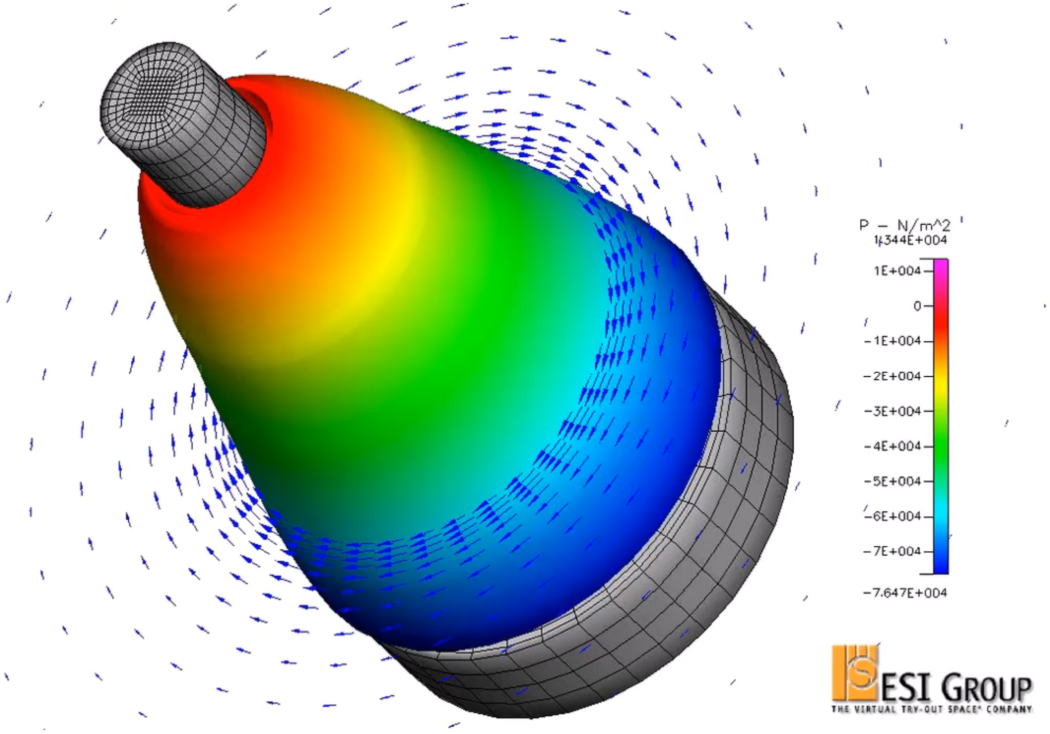
- **We need a state-of-the-art industrial-grade solution**
  - Import of CAD models
  - Easy meshing
- **We need support for moving geometries (contact opening)**
- **We need a scalable solution**
  - It will never be possible to simulate an arc on one core
  - Massively parallel computing required
- **We need interfaces for new physical models**
  - Arc roots
  - Multi-phase flow (gas mixtures)
  - Absorption of radiation

Current state of arc simulations

- **No good arc simulation tool available on the market**
- **Industrial researchers typically couple different tools**
  - Fluent + electromagnetic solver
  - Example: Fluent + MpCCI + ANSYS EMAG
- **Problems**
  - Only weak (iterative) coupling
  - Implementation between two meshes
  - Coupling of finite volumes (FVM) with finite elements (FEI
  - The coupling destroys scalability
  - Implementation of moving contacts in two tools
  - Electromagnetic solvers are not suitable for arcs



The Quest for the Perfect Algorithm



CFD — challenge

- **Very strong heating (hundreds of MW)**
- **High temperatures**
  - Temperatures up to 30000 K
- **High velocities**
  - Mach 2-3
- **Dissociation and ionization of molecules**
  - Real gas properties
  - Chemical reactions
- **Radiation is very important**
  - Radiation transport in an absorbing medium
- **Turbulence?**
- **Moving mesh**

Essentially all the problems found in the simulation of combustion + coupling to the field

$$1\ eV \sim 1.1 \times 10^4 K$$

CFD solutions are available

- **We need a solver for highly compressible flows**
  - Density-based solver?
- **Implicit time stepping required**
  - The high temperature leads to high velocities in the arc
  - We would need very small time steps to satisfy the CFL condition everywhere.
- **Motion of electrodes**
  - Mesh morphing + remeshing
  - Chimera boundaries probably do not work the electromagnetic part

A flow solver which can handle combustion and supersonic flow should be able to handle these problems

Electromagnetic challenge

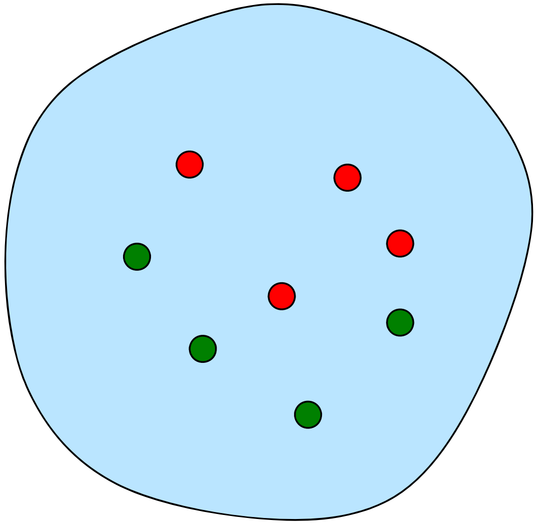
- **Electromagnetic simulations typically use a coarser mesh than CFD**
  - Linear equations – higher order methods
  - Homogeneous material properties
  - What if $\sigma(T)$ varies on a short length scale?
- **Current electromagnetic solvers have poor scalability**
  - CFD simulations use 100 Mio. elements and 100s of processors
  - EMAG simulations are typically 2 orders of magnitude smaller
- **They are not suitable electrical arcs**
  - They divide the simulation domain into insulators and conductors
  - Unfortunately, the arc does not have a sharp boundary; the conductivity vanishes continuously towards the edge
  - Solutions
    - Make the cold gas conducting
    - Solve the full Maxwell equations

Conservation of charge

Charge neutral

$$|n_e - n_i| \ll n_e$$

The Debye length should be small



Debye length

$$\lambda_D = \left(\frac{\varepsilon_0 T}{n_e e^2} \right)^{\frac{1}{2}}$$

Fast charge relaxation

$$\partial_t \rho + \nabla \cdot \mathbf{j} = 0 \Rightarrow \nabla \cdot \left[\left(\varepsilon_0 \partial_t + \sigma \right) \mathbf{E} \right] = 0 \Rightarrow \tau = \frac{\varepsilon_0}{\sigma}$$

τ should be small

We can use the approximation $\nabla \cdot \boldsymbol{j} = 0$

Eddy current approximation

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = 0 \qquad \nabla \cdot \boldsymbol{B} = 0 \qquad \boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B})$$

$$\frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial_t} - \nabla \times \boldsymbol{B} = -\mu_0 \boldsymbol{j} \qquad \nabla \cdot \boldsymbol{E} = \rho/\varepsilon_0$$

$$c^2 = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \qquad \varepsilon_0 \to 0 \Rightarrow c \to \infty$$

There is no wave propagation in the eddy current approximation

B-formulation

$$\nabla \times \left(\frac{1}{\mu_0}\mathbf{B}\right) = \mathbf{j}$$

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \Rightarrow$$

$$\mathbf{E} = \frac{1}{\sigma}\mathbf{j} - \mathbf{v} \times \mathbf{B} = \frac{1}{\sigma}\nabla \times \left(\frac{1}{\mu_0}\mathbf{B}\right) - \mathbf{v} \times \mathbf{B}$$

We can obtain a dynamic equation for the magnetic induction

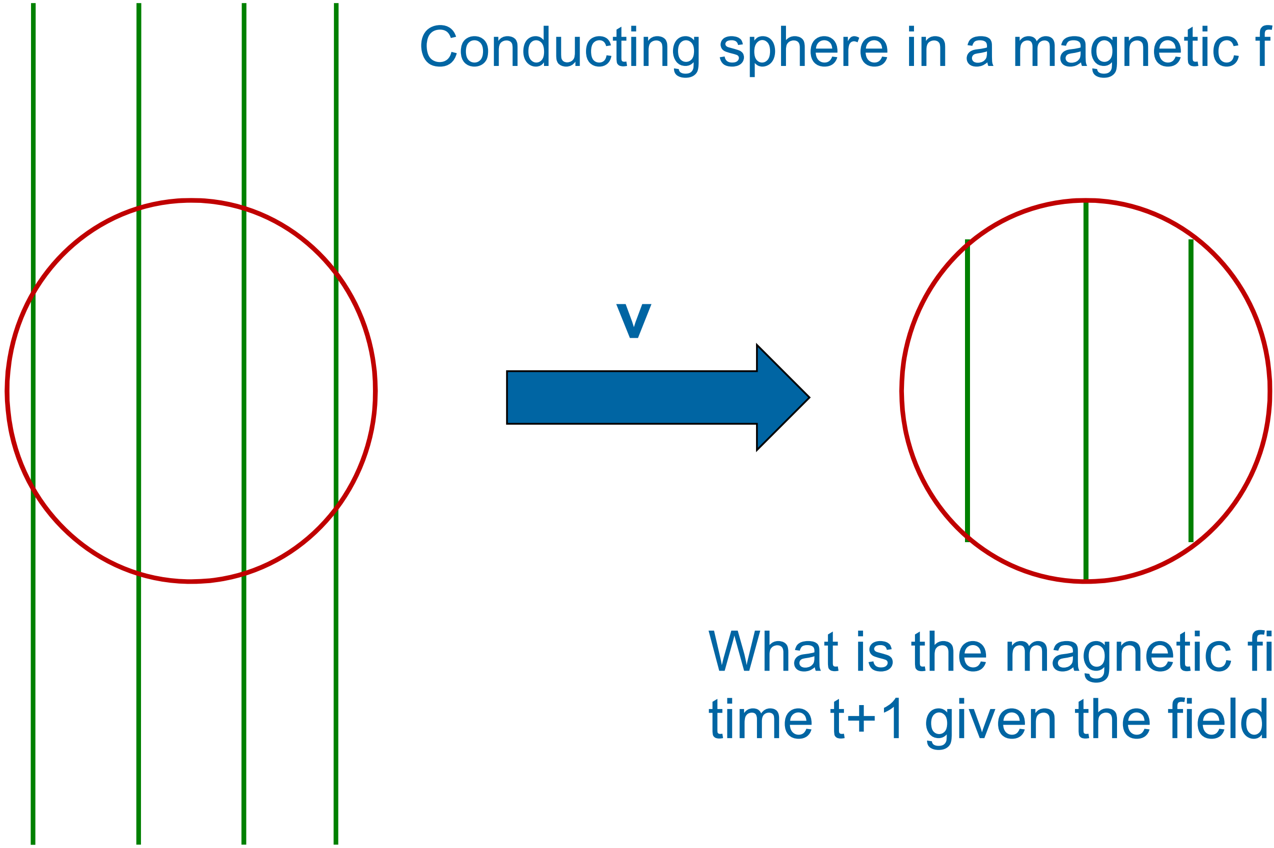
$$\partial_t\mathbf{B} + \nabla \times \mathbf{E} = \partial_t\mathbf{B} + \nabla \times \left[\frac{1}{\sigma}\nabla \times \left(\frac{1}{\mu_0}\mathbf{B}\right) - \mathbf{v} \times \mathbf{B}\right] = 0$$

$$\partial_t\mathbf{B} - \underbrace{\nabla \times \mathbf{v} \times \mathbf{B}}_{Convection} = \underbrace{\frac{1}{\sigma\mu_0}\Delta\mathbf{B}}_{Diffusion}$$

Diffusion constant $D = \frac{1}{\sigma\mu_0}$

Magnetic convection – physical interpretation

Conducting sphere in a magnetic field



What is the magnetic field at time t+1 given the field at t

Fully hyperbolic MHD formulation

It is possible to solve the MHD equation using a fully hyperbolic system of equations

$$X = \begin{bmatrix} \rho \\ \rho\,\boldsymbol{u} \\ \rho\,e \\ \boldsymbol{B} \end{bmatrix} \qquad \frac{\partial X}{\partial t} = \nabla \cdot F(X)$$

Problems:

- Only works well with highly conducting plasmas
- The diffusion term explodes when the conductivity vanishes
- The boundary conditions are difficult to implement

A-ϕ formulation

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \qquad \boldsymbol{E} = -\nabla\phi - \partial_t \boldsymbol{A}$$

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B}) = \sigma[-\nabla\phi - \partial_t \boldsymbol{A} + \boldsymbol{u} \times (\nabla \times \boldsymbol{A})]$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{j} \Rightarrow \nabla \times \left(\frac{1}{\mu_0} \nabla \times \boldsymbol{A}\right) = \boldsymbol{j}$$

$$\nabla \cdot \boldsymbol{j} = 0$$

An elliptic set of equations for A and ϕ

Has to be solved using FEM (edge elements)

Numerically ill-conditioned problem

A better algorithm is needed

Widely differing values of σ

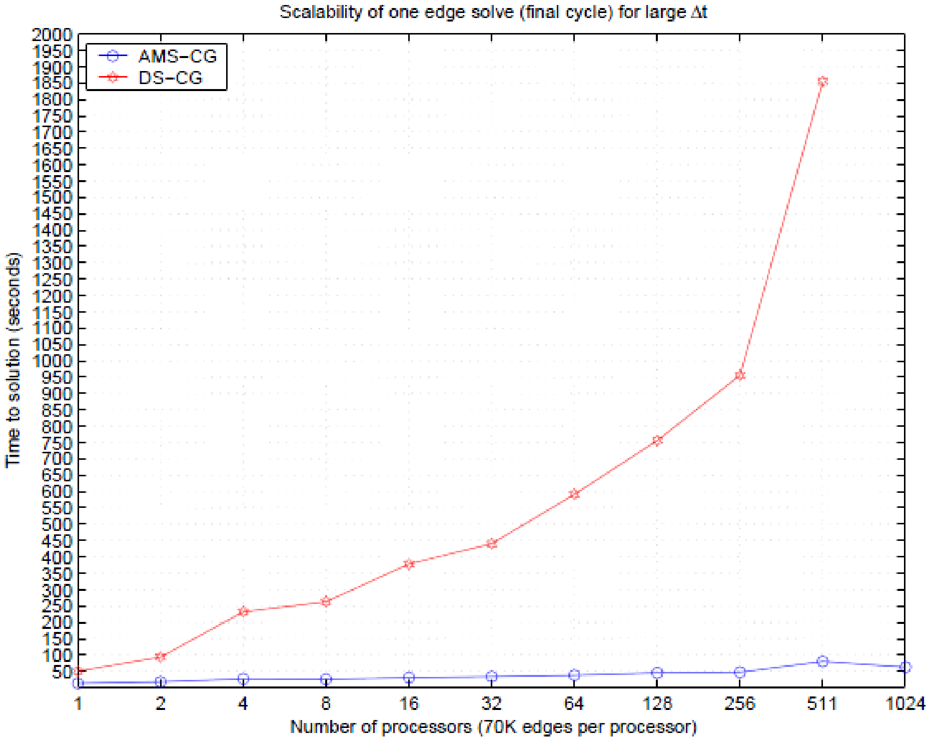
$$\nabla \cdot (\sigma \nabla \phi) \approx 0$$

Curl-curl is a nasty operator

$$\nabla \times (\nabla \times \boldsymbol{A}) \approx \mu_0 \boldsymbol{j}$$

Scalability of eddy current simulation: Ralf Hiptmair 2008

REPORT OF
The Panel on Recent Significant Advancements in Computational Science
BREAKTHROUGHS 2008



Algorithm by R. Hiptmair and J. Xu.
Will be implemented in ANSYS and tested (Spring 2009)
Standard parallel AMG solver can be used for solving EMAG

Magnetostatic approximation

Debye length $\lambda_D = \left(\frac{\varepsilon_0 T}{n_e e^2}\right)^{\frac{1}{2}}$ needs to be small for charge neutrality

Time scale has to be longer than $\tau = \frac{\varepsilon_0}{\sigma}$ in order to ignore the displacement current

Time scale has to be longer than $L^2\,\mu_0\sigma$ in order to ignore the transient magnetic field

$$\nabla \cdot (\sigma \nabla \phi) = 0$$

$$\nabla \times (\nabla \times \boldsymbol{A}) = -\mu_0 \sigma \nabla \phi$$

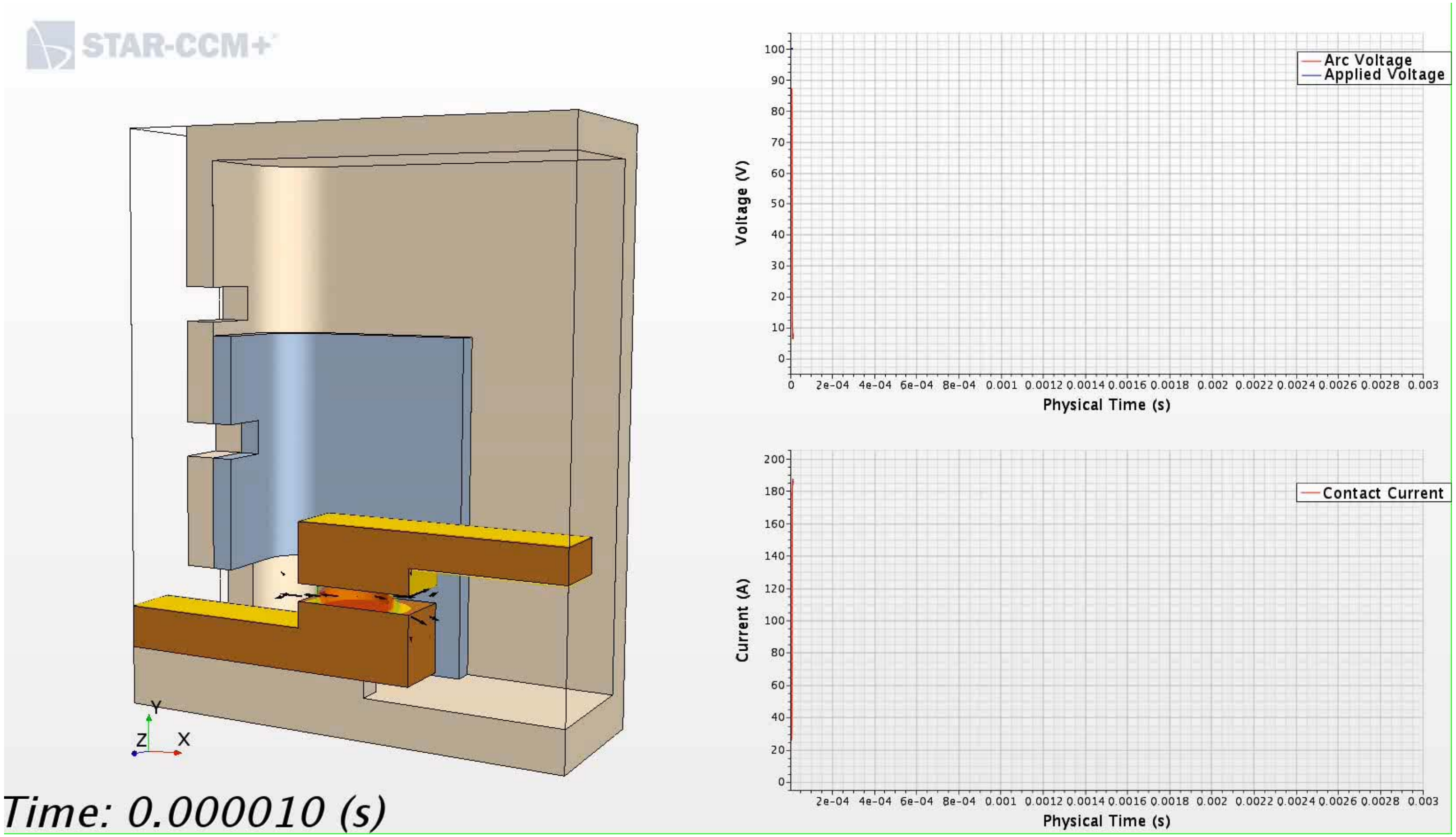
Magnetostatic approximation:

The electromagnetic fields have no memory

Coupled solver – current status

- **Collaboration with CD-Adapco**
- **STAR CCM+ is a very robust flow solver**
- **CD-Adapco has an edge-based EMAG solver**
- **Coupling implemented within one tool**
- **Some improvements are still necessary**
  - Performance of EMAG solver
  - Coupling to an external circuit
- **Currently with two different meshes**
  - Automatic remeshing on both meshes
  - We would like to get to one mesh

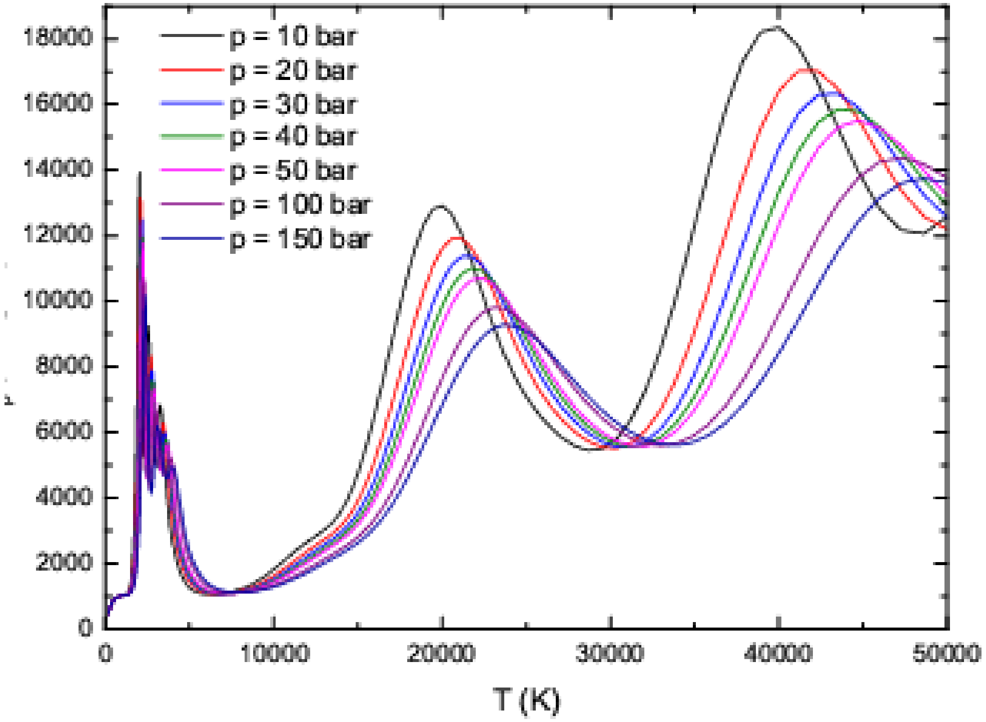
Simple Model Breaker



What about material models?

The thermodynamic properties are strongly temperature dependent

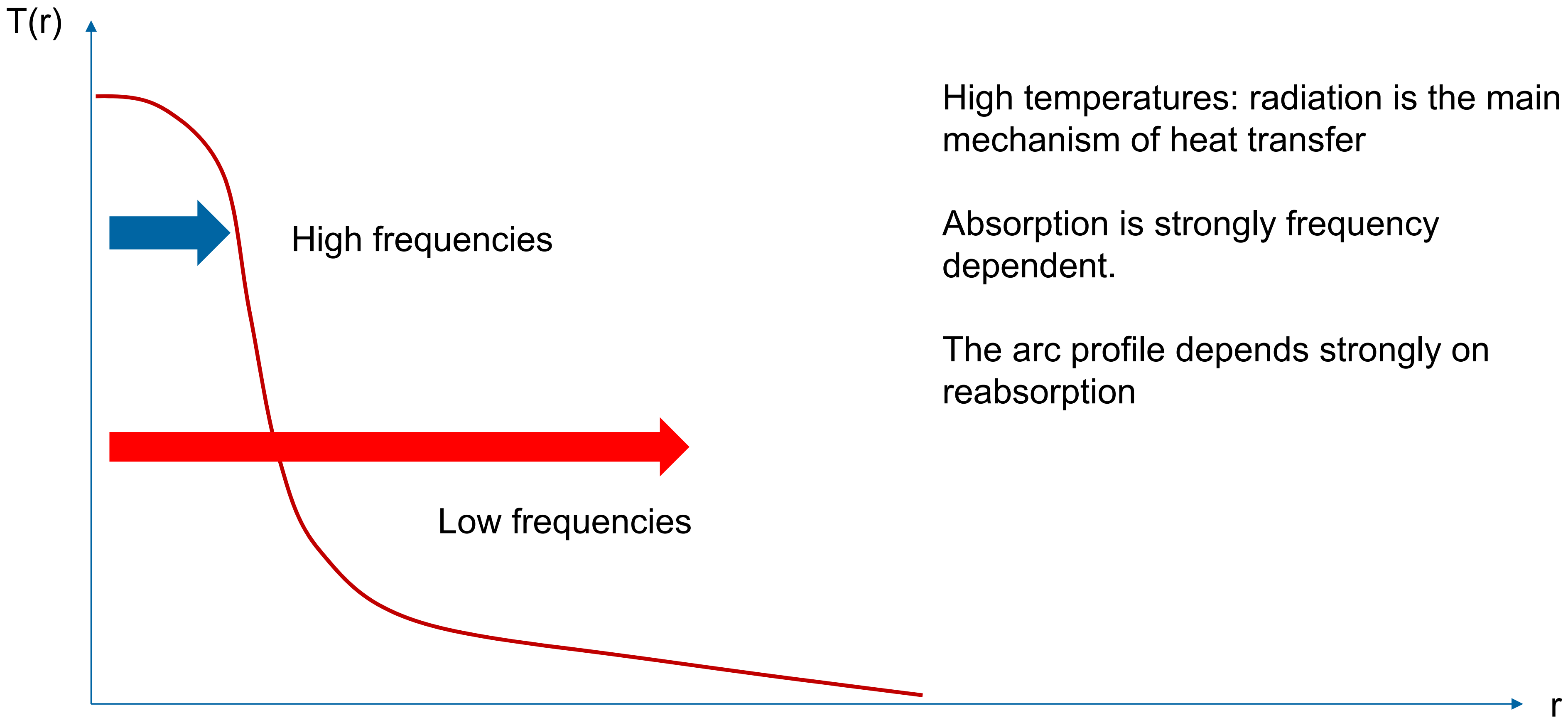
Specific heat of SF6



Pre-calculated in the LTE approximation.

What to do when the composition changes?

Radiation



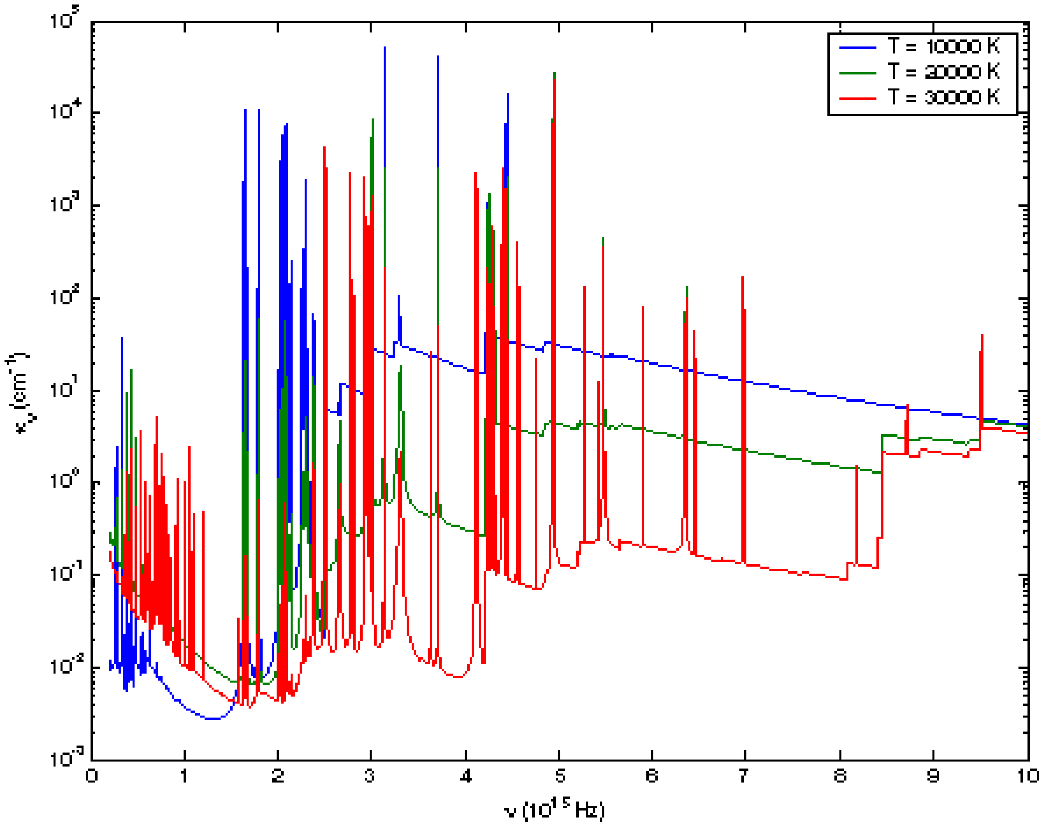
High temperatures: radiation is the main mechanism of heat transfer

Absorption is strongly frequency dependent.

The arc profile depends strongly on reabsorption

Absorption spectrum of SF6

□



Is this spectrum correct?

What is the average absorption coefficient?

Summary & Outlook

- **Simulation of electrical arcs is a challenging problem**
  - Physical modelling
  - Numerical implementation
- **A perfect algorithm is still far away**
  - Lots of interesting problems to be solved
- **We have a reasonable tool with STAR CCM+**
- **Validation is a real challenge**
  - Arc root modeling
  - Material properties (including radiation)
  - Turbulence modeling
- **A large number experiments will be necessary**

Thank you for your attention!

Questions?