Advanced Study of Multilayer Films: A Proposed Research at LANL

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THIN FILMS AND NEW IDEAS FOR PUSHING THE LIMITS OF RF SUPERCONDUCTIVITY

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Motivation

- Cavities for accelerators are mostly made of Cu (NC) or Nb (SC).
- Performance of superconductors whose T_c is higher than that of Nb (9.2 K) still to be determined.
- Cu and Nb based technology have reached almost their theoretical limit. As to Nb cavities, the reproducibility of high-quality cavities remains to be an issue.
- Multi-layer films with HTS might be able to enhance the capability of SRF cavities

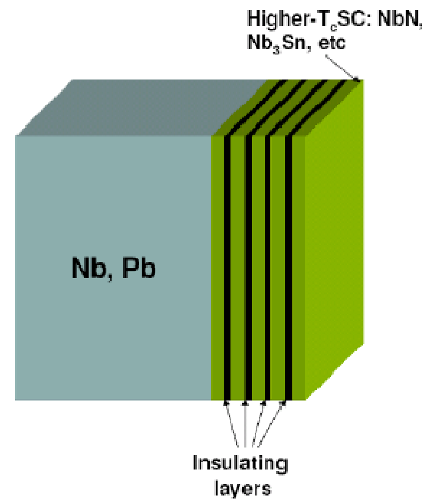
Goals

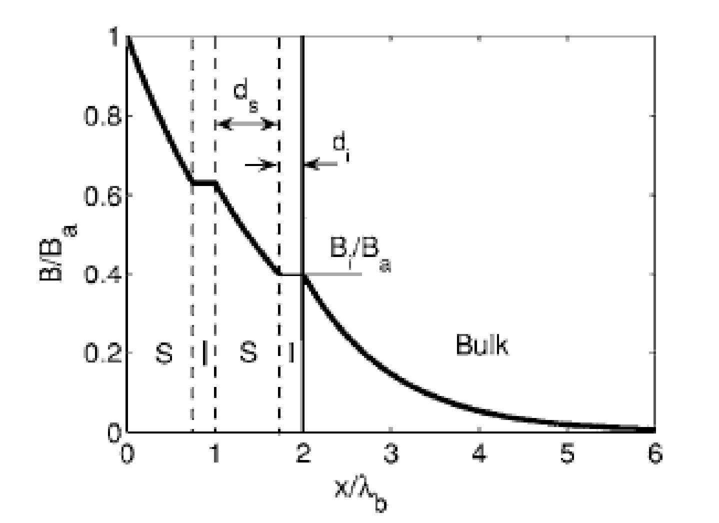
- Improve the performance of RF cavities (NC & SC) by using multilayer-coated normal or superconductors of different type and thicknesses.
- Achieve **overall** values of δ, λ_L, R_s, **k**, etc. better than with a single material.
- Solve the different scenarios (NC & SC) with both local and non-local electromagnetics for arbitrary orientation of the incident fields and including He and SF He.
- Development of a thermal-electromagnetic coupled 2D FDTD code and optimization of parameters.
- Predict Q vs E_{acc} graphs.

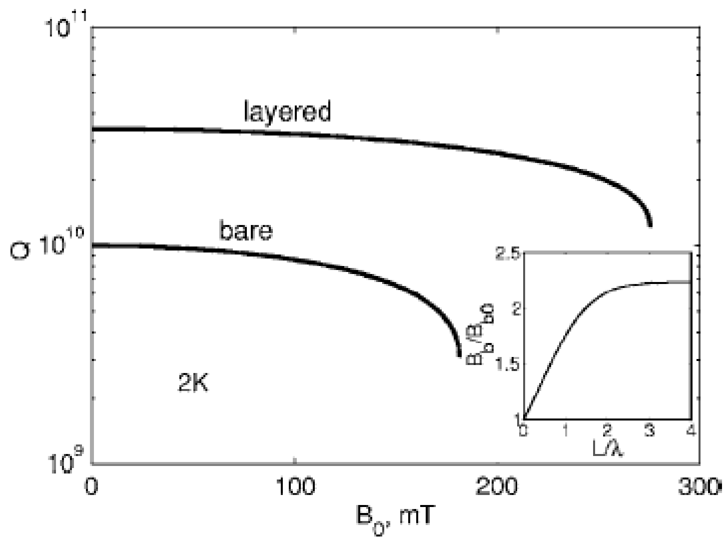
Goals

Background

- A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006)

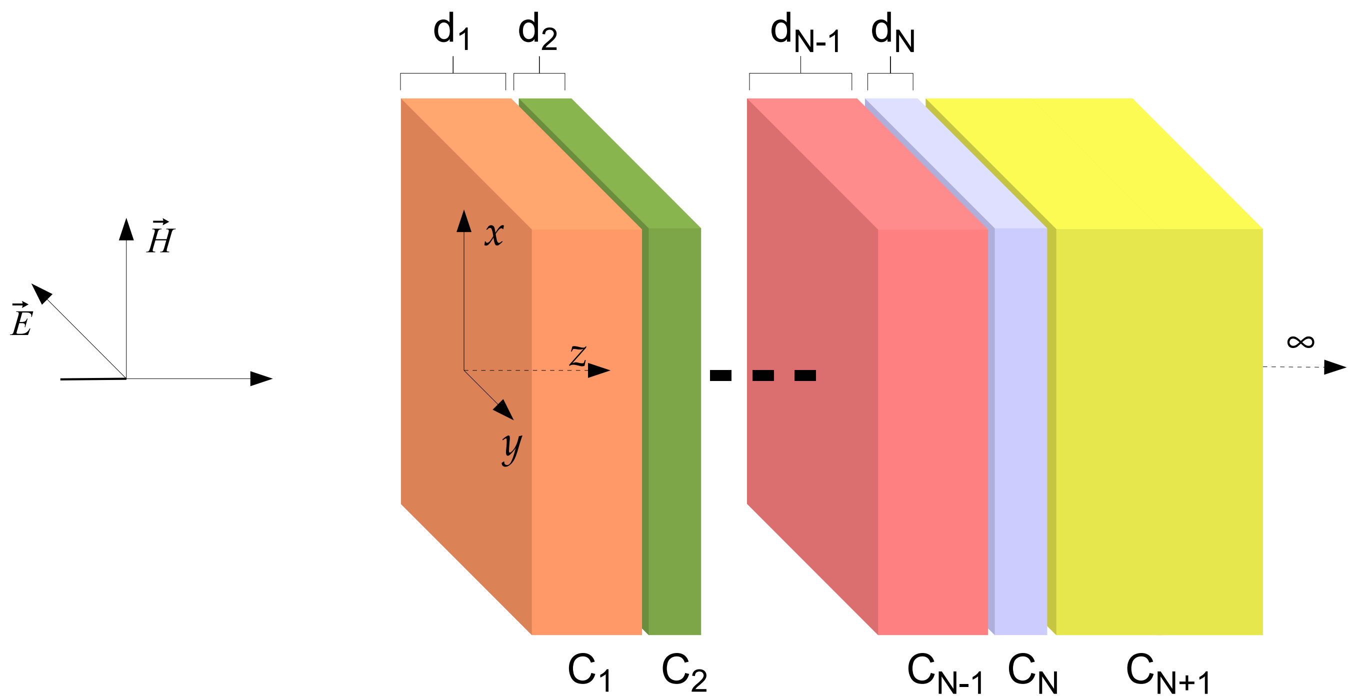






Goals

- Big picture…



Normal Conductors

- local electromagnetics

$$\nabla \times \vec{E} = -\vec{M} - j\omega\vec{B}$$
$$\nabla \times \vec{H} = \vec{J}_i + \vec{J}_c + j\omega\vec{D}$$
$$\nabla \cdot \vec{D} = \rho_{ev}$$
$$\nabla \cdot \vec{B} = \rho_{mv}$$

$$\vec{D} = \varepsilon\vec{E}$$
$$\vec{B} = \mu\vec{H}$$

ε, μ are tensors in general

Local relation: $\vec{J}_c = \sigma\vec{E}$

$$\boxed{\nabla \times \vec{H} = \sigma\vec{E} + j\omega\varepsilon\vec{E} \Rightarrow \nabla \times \nabla \times \vec{H} = (\sigma + j\omega\varepsilon)\nabla \times \vec{E}}$$

Given $\nabla \times \nabla \times \vec{A} = \nabla(\nabla \cdot \vec{A}) - \nabla^2\vec{A}$ and that $\nabla \cdot \vec{H} = 0$

$$\boxed{\nabla^2\vec{H} = (\sigma + j\omega\varepsilon)\, j\omega\mu\vec{H}}$$

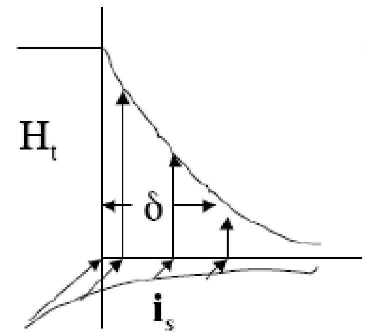
Normal Conductors

- local electromagnetics

	Exact	$\left(\frac{\sigma}{\omega\varepsilon}\right)^2 << 1$	$\left(\frac{\sigma}{\omega\varepsilon}\right)^2 >> 1$
α	$=\omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]\right\}^{1/2}$	$\approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}}$	$\approx \sqrt{\frac{\omega\mu\sigma}{2}}$
β	$=\omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right]\right\}^{1/2}$	$\approx \omega\sqrt{\mu\varepsilon}$	$\approx \sqrt{\frac{\omega\mu\sigma}{2}}$
Z_w	$=\sqrt{\frac{j\omega\mu}{\sigma+j\omega\varepsilon}}$	$\approx \sqrt{\frac{\mu}{\varepsilon}}$	$\approx \sqrt{\frac{\omega\mu}{2\sigma}}(1+j)$
λ	$=\frac{2\pi}{\beta}$	$\approx \frac{2\pi}{\omega\sqrt{\mu\varepsilon}}$	$\approx 2\pi\sqrt{\frac{2}{\omega\mu\sigma}}$
v	$=\frac{\omega}{\beta}$	$\approx \frac{1}{\sqrt{\mu\varepsilon}}$	$\approx \sqrt{\frac{2\omega}{\mu\sigma}}$
δ	$=\frac{1}{\alpha}$	$\approx \frac{2}{\sigma}\sqrt{\frac{\varepsilon}{\mu}}$	$\approx \sqrt{\frac{2}{\omega\mu\sigma}}$

$$\boxed{\vec{H} = e^{\pm(\alpha+j\beta)\cdot z} = e^{\pm\alpha\cdot z}\cdot e^{\pm j\beta\cdot z}}$$

Local relation: $\vec{J}_c = \sigma\vec{E}$

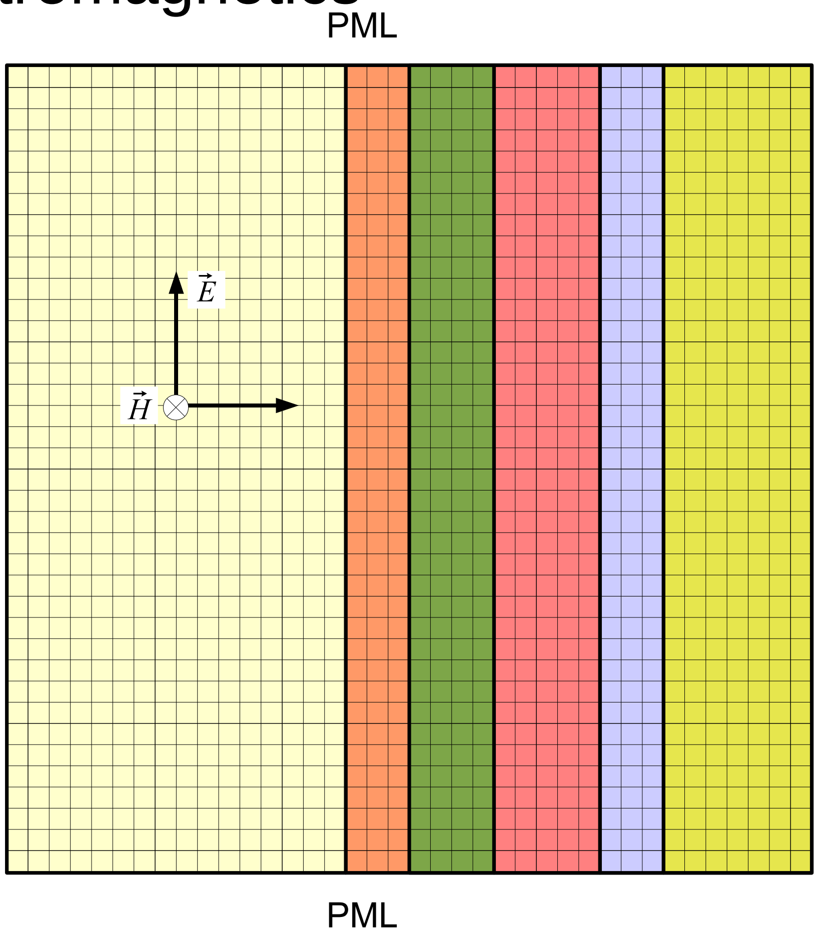


$$\boxed{Z = \frac{E_y(0)}{\int_0^\infty J_y(z)dz}}$$

UNCLASSIFIED

Normal Conductors

- local electromagnetics



$$\nabla^2 \vec{E} = \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}$$

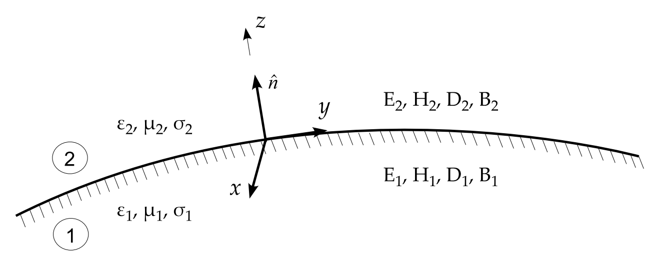
$$\nabla^2 \vec{E}_i = \mu_i \sigma_i \frac{\partial}{\partial t}\vec{E}_i + \frac{1}{c_i^{\,2}}\frac{\partial^2}{\partial t^2}\vec{E}_i$$

$$\hat{n} \times (\vec{E}_2 - \vec{E}_1) = -\vec{M}_s$$

$$\hat{n} \times (\vec{H}_2 - \vec{H}_1) = \vec{J}_s$$

$$\hat{n} \cdot (\vec{D}_2 - \vec{D}_1) = \rho_{es}$$

$$\hat{n} \cdot (\vec{B}_2 - \vec{B}_1) = \rho_{ms}$$



Normal Conductors

- non-local electromagnetics $\vec{J}(z) \neq \sigma\vec{E}(z)$

$$\vec{J}(\vec{r},t) = \frac{3\sigma}{4\pi l}\int_V \frac{\vec{R}\left[\vec{R}\cdot\vec{E}(\vec{r}\,',t-\vec{R}/v_F)\right]\cdot e^{-R/l}}{R^4}d\vec{r}\,' \quad \text{with } \vec{R} = \vec{r}-\vec{r}\,'$$

Wave equation in terms of …

H

$$\nabla^2\vec{H} = \omega^2\mu\varepsilon\vec{H} - \frac{3\sigma}{4\pi l}\int_V \frac{\nabla\times\left\{\vec{R}\left[\vec{R}\cdot\vec{E}(\vec{r}\,',t-\vec{R}/v_F)\right]\right\}\cdot e^{-R/l}}{R^4}d\vec{r}\,'$$

E

$$\nabla^2\vec{E} = \frac{3\mu\sigma}{4\pi l}\int_V \frac{\vec{R}\left[\vec{R}\cdot\frac{\partial}{\partial t}\vec{E}(\vec{r}\,',t-\vec{R}/v_F)\right]\cdot e^{-R/l}}{R^4}d\vec{r}\,' + \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}$$

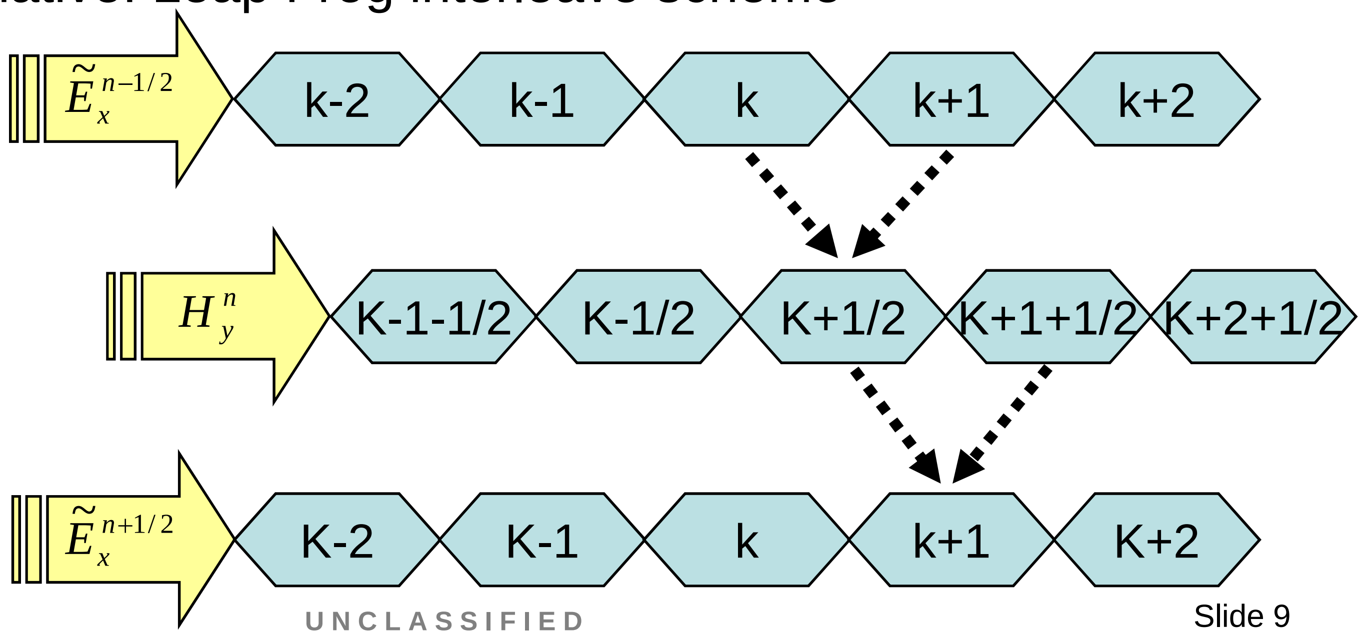
Simpler!

Normal Conductors

- non-local electromagnetics
  – Issues
    – Still a rather complicated expression
    – Need only to keep track of E but at the end H needs to be calculated through a **numerical curl**, adding unnecessary errors
  – Better alternative: Leap Frog interleave scheme

$$\varepsilon \frac{\partial}{\partial t}\vec{E} = \nabla \times \vec{H} - \vec{J}_c$$

$$\frac{\partial}{\partial t}\vec{H} = -\frac{1}{\mu}\nabla \times \vec{E}$$



Normal Conductors

- non-local electromagnetics

$$\varepsilon \frac{\partial}{\partial t}\vec{E} = \nabla \times \vec{H} - \frac{3\sigma}{4\pi l}\int_V \frac{\vec{R}\left[\vec{R}\cdot\vec{E}(\vec{r}\,',t-\vec{R}/v_F)\right]\cdot e^{-R/l}}{R^4}\,d\vec{r}\,'$$

$$\frac{\partial}{\partial t}\vec{H} = -\frac{1}{\mu}\nabla \times \vec{E}$$

where $\vec{r} = \hat{x}\cdot x + \hat{z}\cdot z$ $\quad \vec{R} = \vec{r} - \vec{r}\,' = \hat{x}\cdot(x-x') + \hat{z}\cdot(z-z')$

$\vec{r}\,' = \hat{x}\cdot x' + \hat{z}\cdot z'$ $\quad R = \left|\vec{r} - \vec{r}\,'\right| = \sqrt{(x-x')^2 + (z-z')^2}$

- Only first order derivatives in both time and space!

$$f'(x_0) \cong \frac{f_1 - f_{-1}}{2h}$$

Superconductors

- local electromagnetics

London equation $\boxed{\nabla^2 \vec{B} - \frac{\mu n_s e^2}{m}\vec{B} = 0}$ $\nabla \times \vec{B} = \mu \vec{J}_s$

Rewrite London equation $\lambda_L^2 \nabla \times \vec{J}_s = -\frac{\vec{B}}{\mu} = -\vec{H}$

$\nabla \times \vec{A} = \vec{H}$ vector potential

choose $\nabla \cdot \vec{A} = 0$ London gauge

$\boxed{\vec{J}_s = -\frac{1}{\lambda_L^2}\vec{A}}$ Local relation

Superconductors

- non-local electromagnetics

$$\vec{J}_S(\vec{r}) = \frac{3n_s e^2}{4\pi\xi_0 mc}\int_V \frac{\vec{R}\left[\vec{R}\cdot\vec{A}(\vec{r}\,')\right]\cdot e^{-R/\xi}}{R^4}\,d\vec{r}\,' \quad \text{with} \quad \vec{R} = \vec{r} - \vec{r}\,'$$

$$\frac{1}{\xi} = \frac{1}{\xi_0} + \frac{1}{l}$$

In BCS theory

$$\xi_0 = \frac{\hbar v_F}{\pi\Delta(0)}$$

Summary

- **Normal Conductors**
  - Local

$$\vec{J}_c = \sigma\vec{E}$$

  - Non-local

$$\vec{J}(\vec{r},t) = \frac{3\sigma}{4\pi l}\int_V \frac{\vec{R}\left[\vec{R}\cdot\vec{E}(\vec{r}\,',t-\vec{R}/v_F)\right]\cdot e^{-R/l}}{R^4}\,d\vec{r}\,'$$

- **Superconductors**
  - Local

$$\vec{J}_s = -\frac{1}{\lambda_L^2}\vec{A}$$

$$\nabla\times\vec{A} = \vec{H}$$

$$\nabla\cdot\vec{A} = 0$$

  - Non-local

$$\vec{J}_S(\vec{r}) = \frac{3n_s e^2}{4\pi\xi_0 mc}\int_V \frac{\vec{R}\left[\vec{R}\cdot\vec{A}(\vec{r}\,')\right]\cdot e^{-R/\xi}}{R^4}\,d\vec{r}\,'$$

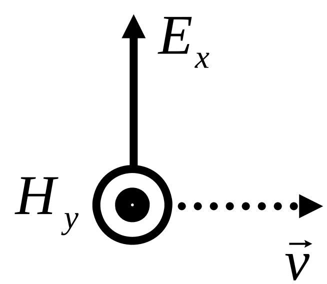
Perfect Matched Layer (PML)

- For 1D not necessary

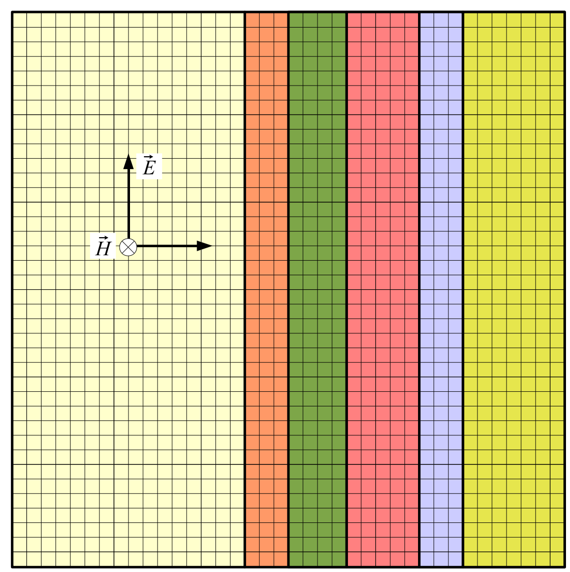
$$\Gamma = \frac{\eta_A - \eta_B}{\eta_A + \eta_B}$$

for local relation

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$



PML



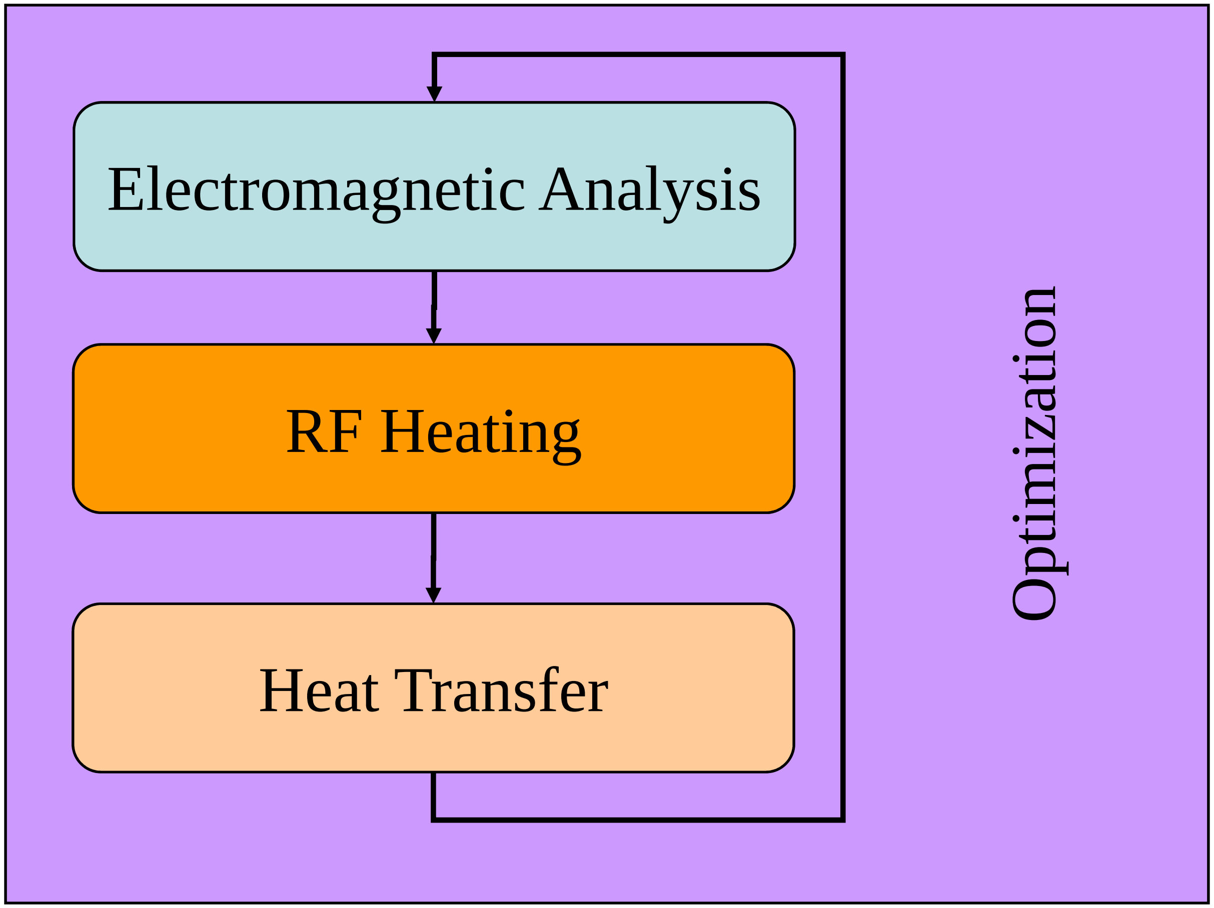
PML

PML

for non-local relation
PML still has to be formulated!

Ultimate goal

- Program flowchart



Backup Slides

- Comments/Suggestions