

Accurate Field and Harmonic
Calculations for Accelerator magnets
(*Using OPERA*)

John Simkin

Vector Fields Limited

Overview

- **Accurate Fields**
 - Total and reduced Potentials
 - Integral Fields
 - Existing procedures & Developments
- **Material Models**
 - Anisotropic magnetic properties
 - Models for superconductor hysteresis and loss
 - Existing procedures & Developments
- **Developments**



Accurate Fields

Total and Reduced Potentials

$$H_{\text{TOTAL}}$$

$$H_{\text{coil}} + H_{\text{iron}}$$

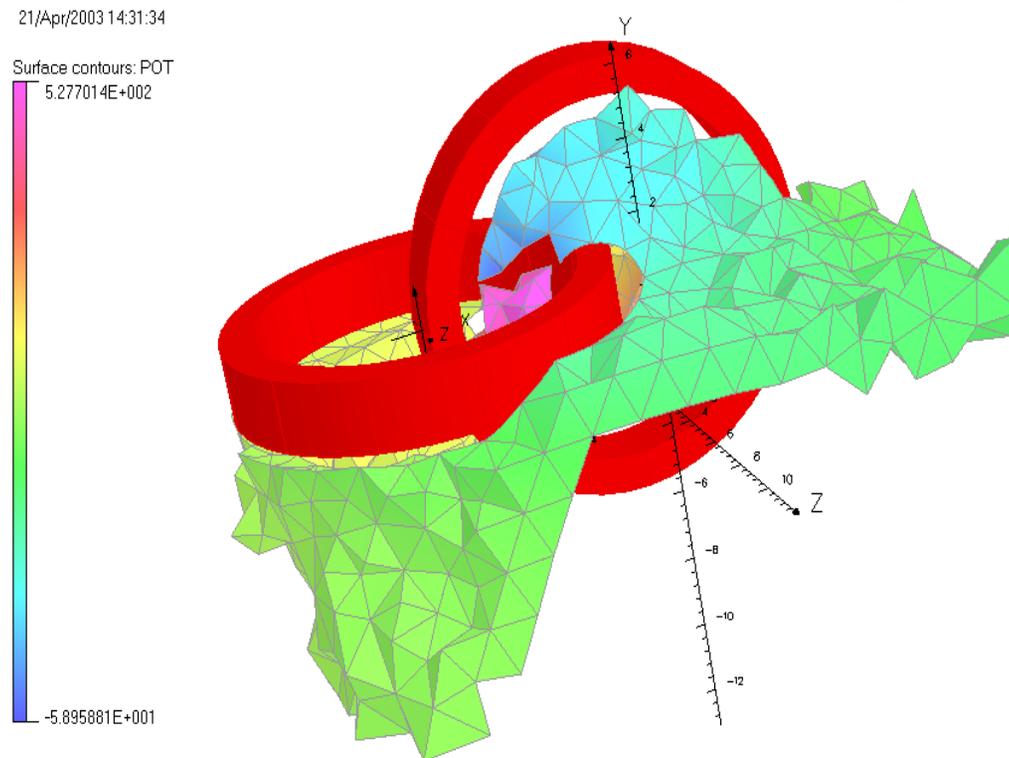
- Gives the best results for a given mesh
 - Providing it is used intelligently
 - Simple rules

Inside Coil	- REDUCED
Coil fields dominate	- REDUCED
Iron & Coil fields cancel	- TOTAL
- However, the cost \propto volume of reduced potential



Multiple Connectivity and cuts

- Cuts required to make scalar potentials single valued are calculated completely automatically



V VECTOR FIELDS



Accurate fields in the working Volume

- **Fields direct from the FE solution**
 - Model should use high order elements (locally)
 - Post processing: Switch to coil fields by integration
(otherwise interpolated using the FE mesh)
 - Check the error in the solution (errB)

- **Fields by Integration**

$$\vec{H}_{iron} = \nabla \left(\iiint \vec{M} \cdot \nabla \left(\frac{1}{R} \right) dv \right)$$

- Available in OPERA-2d and OPERA-3d
 - Impressive improvement in accuracy (not too close to the iron)
 - But it's expensive (do as many points as possible at one time)
- Low order numerical integration for speed \propto even worse answers close to iron



Developments

- **Fields by Surface Integration**

Use Green's theorem to evaluate the field at any point inside a volume given the fields on its surface eg.

$$\phi = \oiint_{\gamma} \phi \nabla \left(\frac{1}{R} \right) \cdot \hat{n} + \frac{1}{R} \nabla \phi \cdot \hat{n} ds$$

- Advantages:
 - Speed – compare number of surface and volume ‘elements’ (and accuracy because we can afford better integration methods)
 - Flexibility – Could be done in a selected volume



Should there be :

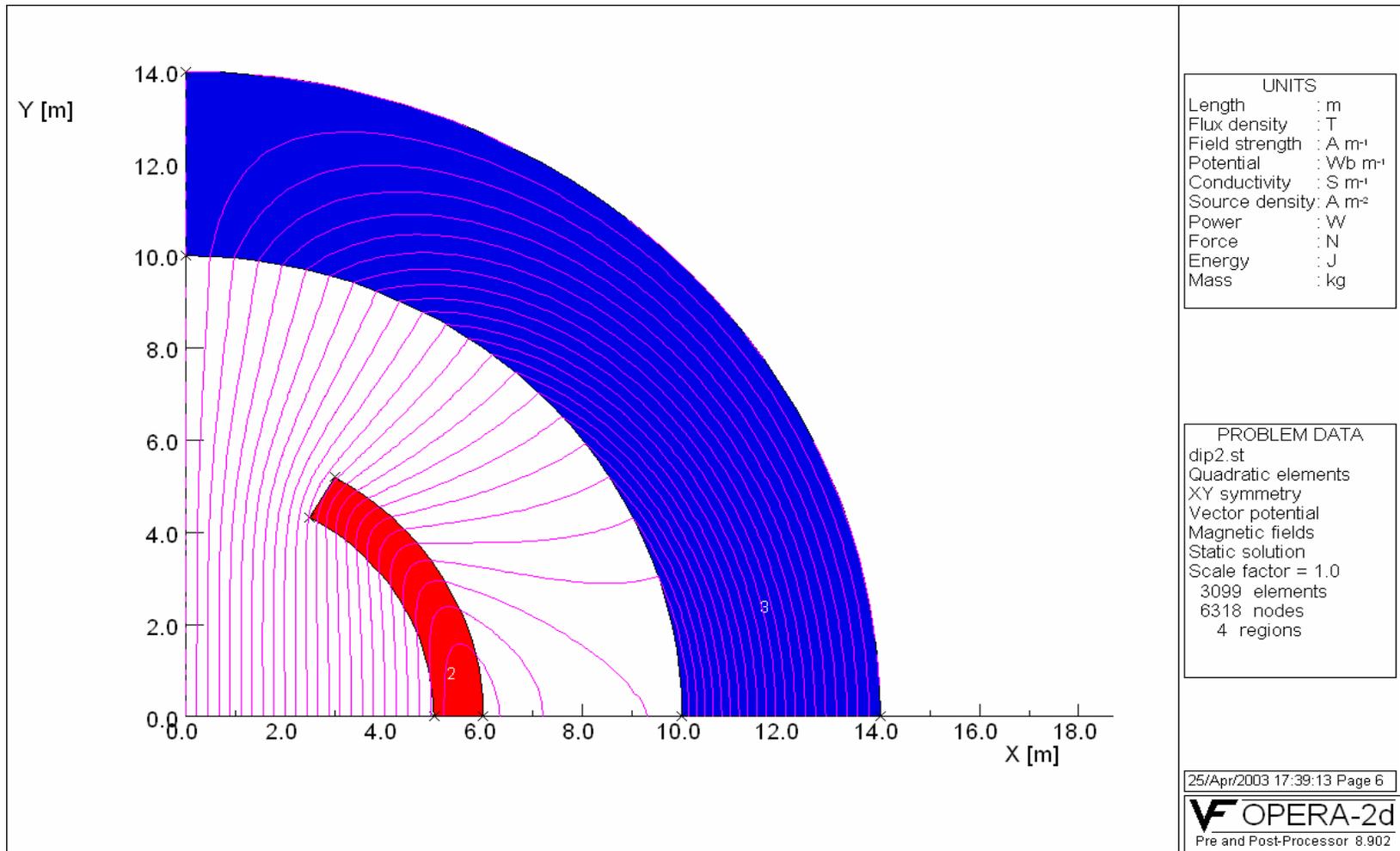
- Direct access to Field integrals

$$\vec{F} = \int_{-\infty}^{+\infty} \left[\nabla \left(\iiint \vec{M} \cdot \nabla \left(\frac{1}{R} \right) dv \right) + \iiint J \times R / |R^3| dv \right] dz$$

- Would it be good enough to only integrate wrt Z



Fitting to Fields or Potentials



Fitting to Fields or Potentials

- For best accuracy should you fit to the calculated potentials or fields
 - Comparison of the RMS errors in the first 5 non-zero harmonics for a dipole magnet

		% RMS Error in harmonics	
	Element size	Fitting to A_z	Fitting to B_r
FE Interpolate	0.5	0.017	0.077
FE Interpolate	0.25	0.004	0.016
FE Integral	0.25	N/A	0.001



Modelling Superconducting windings

Multi-turn coil with filamentary conductor

- Calculate maximum magnetisation as a function of B (for the given J), and use this to specify the magnetic characteristics of the material.
 - Approximation, not accurate near transition (up-down)
 - Assuming field change has caused saturation
 - Isotropic property $M(|B|)$
 - Easier to solve with + magnetisation



GSI/BNL/Martin Wilson

- Requirement to model both hysteresis and rate dependent eddy currents in cable wound coil
 - Anisotropic Magnetisation
 - Different transverse and parallel rate dependence
 - Isotropic hysteresis components
 - Terms depend on

$$B \quad dB/dt \quad B_p \quad B_t \quad dB_p/dt \quad \text{and} \quad dB_t/dt$$
- Not possible to define magnetic characteristics with this this vector dependence

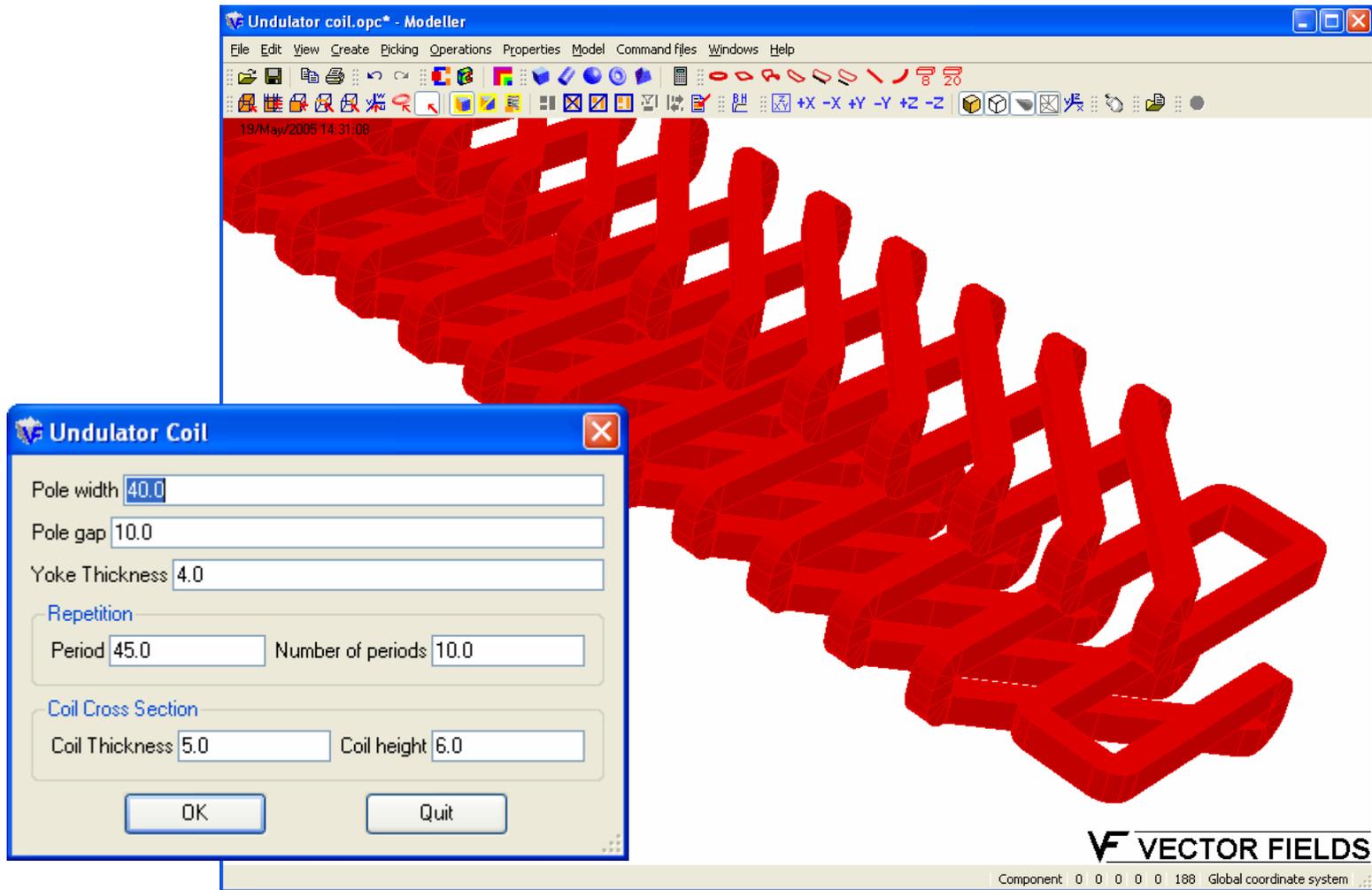


Development

- User defined permeability tensor function has been added to OPERA-2d
 - But its not very easy to use
- Is this useful to other people?
 - Should we put in the effort to make it easy

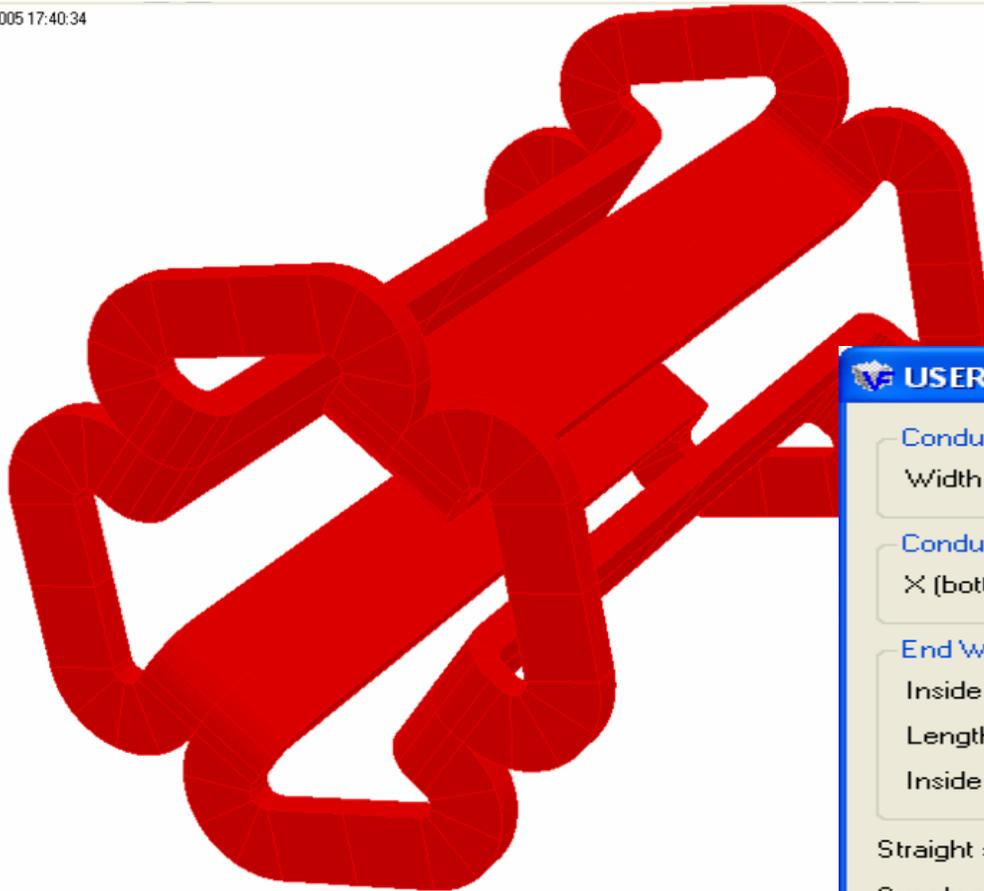


Making it easy - User Dialogs



Another example

19/May/2005 17:40:34



USER DEFINED - Quadrupole Bedstead Winding

Conductor Cross section dimensions
Width Height

Conductor position
X (bottom left) Y (bottom left)

End Winding dimensions
Inside radius of first arc
Length of straight between arcs
Inside radius of second arc

Straight section Half length

Supply current (Amps)



Constructed using the Command file editor

The screenshot shows the 'Command File Editor' window for '[Sc-Undulator.comi *]'. The main editor contains the following script:

```

VARIABLE OPTION=CONSTANT NAME=#t VALUE=4
VARIABLE OPTION=CONSTANT NAME=#theta VALUE=45
VARIABLE OPTION=CONSTANT NAME=#Number VALUE=10

$DIALOG START 'Undulator Coil'
  $ASK #w 'Pole width'
  $ASK #g 'Pole gap'
  $ASK #t 'Yoke Thickness'
  $GROUPBOX START 'Repetition'
    $ASK #theta 'Period'
    $ASK #number 'Number of periods'
  $GROUPBOX STOP
  $GROUPBOX START 'Coil Cross Section'
    $ASK #a 'Coil Thickness'
    $ASK #b 'Coil height'
  $GROUPBOX STOP
$Dialog STOP

/ Place coils in slots in Pole face - adjust gap parameter
  
```

The status bar at the bottom left indicates 'Ln 25, Col 15'. On the right side, there is a 'Command list' panel with the following table:

Commands	Description
VOLUME	Set the volume properties
WCS	Set or unset the working coordinate system
WINDOW	Enable or disable parts of the display
\$ABORTCOMI	Abort execution of a command file
\$ASK	Request a constant value from user
NAME	Name of constant user variable to be set
PROMPT	Prompt message
HISTORY	If history is required in a GUI i.e. a ComboBox()
EDIT	If a Combobox is editable
\$ASKPARAMETER	Request an expression from user
\$ASSIGN	Assign format types to the data fields
\$BACKSPACE	Backspace a file
\$BREAKERROR	Break out of the current block (loop etc)
\$CD	Change current working directory
\$CLOSE	Close file



Make the optimiser easy to use

