RF Cavity Design with Superfish
- an introduction -

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Overview

• RF Cavity Design
  – Design Criteria
  – Figures of merit
• Introduction to Superfish
• Examples:
  – Pill-box type cavity
  – DTL type cavity
  – Elliptical cavity
  – ACOL Cavity
  – A possible cavity design for LHeC
  – A ferrite loaded cavity
RF Cavity Design

- In most particle accelerators, the energy is delivered to the particle by means of a large variety of devices, normally known as cavity resonators.
- The ideal cavity is defined as a volume of perfect dielectric limited by infinitely conducting walls (the reality is a bit different).
- Hollow cylindrical resonator excited by a radio transmitter -> standing wave -> accelerating fields (the pillbox cavity).
RF Cavity Design
- Design Criteria -

• Define the requirements (intended application), RF frequency, NC/SC, voltage, tuning, etc.

• General design criteria:
  – Power Efficiency & RF Properties
  – Beam Dynamics considerations (control of loss and emittance growth, etc.) – especially true for linacs
  – Technologies and precisions involved
  – Tuning procedures (frequency, field profile, stability against perturbations)
  – Sensitivity to RF errors (phase and amplitude)
  – Etc.
The “Magic Pentagon” of Cavity Design

- The pentagon shows the importance of each design and manufacturing choice
- Technologies are interdependent
RF Cavity Design
- Figures of Merit -

- **The Transit Time Factor, T**
  - While the particle crosses the cavity, the field is also varying -> less acceleration -> the particle sees only a *fraction* of the peak voltage -> T is a measure of the reduction in energy gain caused by the sinusoidal time variation of the field in the cavity.

\[
T = \frac{\int_{-L/2}^{L/2} E(0, z) \cdot \cos \frac{2\pi z}{\beta \lambda} \, dz}{\int_{-L/2}^{L/2} E(0, z) \, dz}
\]
RF Cavity Design
- Figures of Merit -

- The Quality Factor, Q

\[ Q_0 = \frac{2\pi \cdot \text{stored energy}}{\text{energy consumed per period}} = \frac{2\pi W}{TP_0} = \frac{U}{P_0} \]

- To first order, the Q-value will depend on the conductivity of the wall material only
- High Q -> narrower bandwidth -> higher amplitudes
- But, more difficult to tune, more sensitive to mechanical tolerances (even a slight temperature variation can shift the resonance)
- Q is dimensionless and gives only the ratios of energies, and not the real amount of power needed to maintain a certain resonant mode
- For resonant frequencies in the range 100 to 1000 MHz, typical values are 10,000 to 50,000 for normal conducting copper cavities; \(10^8\) to \(10^{10}\) for superconducting cavities.
RF Cavity Design
- Figures of Merit -

Shunt Impedance
- a measure of the effectiveness of producing an axial voltage $V_0$ for a given power dissipated

$$r_s = \frac{V_0^2}{P_0}$$

- Effective Shunt Impedance per unit length

$$ZT^2 = \frac{r}{L} = \frac{(E_0 T)^2}{P_0 / L}$$

- Typical values of $ZT^2$ for normal conducting linacs is 30 to 50 M$\Omega$/m. The shunt impedance is not relevant for superconducting cavities.
RF Cavity Design
- Figures of Merit -

• \( r/Q \)
  
  • measures the efficiency of acceleration per unit of stored energy at a given frequency

\[
\frac{r}{Q} = \frac{(V_0 T)^2}{\omega U}
\]

• It is a function only of the cavity geometry and is independent of the surface properties that determine the power losses.
RF Cavity Design
- Figures of Merit -

• The Kilpatrick limit
  • High Field -> Electric breakdown
  • Maximum achievable field is limited

\[ f = 1.64 E_k^2 e^{-8.5/E_k} \]
RF Cavity Design
- Figures of Merit -

• Slightly different story for SC cavities (see example 4):
  – r/Q (characteristic impedance)
  – G (Geometric Factor - the measure of energy loss in the metal wall for a given surface resistance)
  – Epeak/Eacc - field emissions limit (Eacc limit)
  – Bpeak/Eacc – quench limit (sc breakdown)
  – Higher Order Modes – manage and suppress HOM (e.g.: dipole modes can degrade the beam -> suppression scheme using HOM couplers)
  – Kcc – Cell to cell coupling
  – Multicell cavities: Field Flatness
  – Optimise geometry to increase both r/Q and G resulting in less stored energy and less wall loss at a given gradient (low cryogenic losses)
  – Optimise geometry to reduce Epeak/Eacc and Bpeak/Eacc
  – Find optimum Kcc. (e.g.: a small aperture increases r/Q and G (!), but reduces Kcc. A small Kcc increases the sensitivity of the field profile to cell frequency errors.)
Introduction to Poisson Superfish

- You will need a laptop running Windows. If you have Linux/MacOS install VMWare/Wine.
- Please download and install Poisson Superfish. To do this go to the following address and follow the instructions: [http://laacg1.lanl.gov/laacg/services/download_sf.phtml](http://laacg1.lanl.gov/laacg/services/download_sf.phtml)
- Please download the example files to your computer from the JAI website.
- An extensive documentation can be found in the Superfish home directory (usually C:/LANL).
  - Have a look at the SFCODES.DOC file. Table VI-4 explains how the object geometry is defined in Superfish (page 157).
  - For a list of Superfish variables, see SFINTRO.doc, Table III-3 (page 76)
- For any questions, email Emmanuel (emmanuel.tsesmelis@cern.ch) or Ciprian (ciprian.plostinar@stfc.ac.uk). Good luck!
Introduction to Poisson Superfish

- Poisson and Superfish are the main solver programs in a collection of programs from LANL for calculating static magnetic and electric fields and radio-frequency electromagnetic fields in either 2-D Cartesian coordinates or axially symmetric cylindrical coordinates.
- Finite Element Method

**Solvers:**
- **Automesh** – generates the mesh (always the first program to run)
- **Fish** – RF solver
- **Cfish** – version of Fish that uses complex variables for the rf fields, permittivity, and permeability.
- **Poisson** – magnetostatic and electrostatic field solver
- **Pandira** – another static field solver (can handle permanent magnets)
- **SFO, SF7** – postprocessing
- **Autofish** – combines Automesh, Fish and SFO
- **DTLfish, DTLCells, CCLfish, CCLcells, CDTfish, ELLfish, ELLCAV, MDTfish, RFQfish, SCCfish** – for tuning specific cavity types.
- **Kilpat, Force, WSFPlot**, etc.
For the accelerating mode \((\text{TM}_{010})\), the resonant wavelength is:

\[
\lambda = \frac{\pi D}{x_1}
\]

\[
x_1 = 2.40483
\]

\(x_1\) - first root of the zero-th order Bessel function \(J_0 (x)\)

-> Resonant frequency independent of the cell length
-> Example: a 40 MHz cavity (PS2) would have a diameter of ~ 5.7 m
-> In the picture, CERN 88 MHz
Poisson Superfish Examples
- A Pillbox cavity -

Superfish input file

```
PS2 40 MHz Pillbox Cavity

PARTICLE H-,
$reg kprob=1, ; Superfish problem
dx=5, ; X mesh spacing
Freq=40, ; Starting frequency in MHz
iclyin=1

xdri=46.,ydri=287 $ ; Drive point location
$po x=0.0,y=0.0 $ ; Start of the boundary points
$po x=0.0,y=287 $ $po x=92,y=287 $ $po x=92,y=0.0 $ $po x=0.0,y=0.0 $ 

```

---

All calculated values below refer to the mesh geometry only.
Field normalization (MMN = 0): 
\[ E_0 = 1,000,000 \text{ V/m} \]
Frequency = 30,000 MHz
Particle rest mass energy = 908,772,000 MeV
Kinetic energy = 29,598 MeV
Normalizing factor for \( E_B = 1,000 \text{ MHz/V} \) = 540,073
Transit-time factor = 0.000953
Stored energy = 26,252,900 Joules

Using standard room-temperature copper.
Surface resistance = 1.64966 millimho
Normal-conductor resistivity = 1.741/10 microOhm-cm

Operating temperature = 20,000 K
Power dissipation = 25,942,920 kW
\( Q = 2 \pi \sqrt{L / C} \)
\[ L = 402,911 \text{ Hm} \]
\[ C = 2 \times 10^4 \text{ F} \]
\[ R = 8,090 \text{ Ohm} \]

Wake loss parameter = 0.8,090

Average magnetic field on the outer wall = 7372.89 \text{ T/m} = 156.388 \text{ mm/kcm}^2
Maximum \( B \) (at \( 2 \times R = 74,449 \text{ mm/kcm}^2 \)) = 7372.89 \text{ T/m} = 156.388 \text{ mm/kcm}^2

Ratio of peak fields \( B_{peak} / B_0 \) = 1.007518 E-8 Mm/kcm
Peak-to-average ratio \( E_{avg} / E_0 \) = 0.0011

Wall segments:

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
\text{Segment} & \text{Area} & \text{Width} & \text{Height} & \text{Power} & \text{Yield} & \text{Size} \\
\hline
1 & 0.0000 & 287.00 & 1225E-06 & 25.96 & 154.64 & 9.0000 \times 1.093E-02 \\
\hline
\text{Total} & & & & 25.96 & \\
\hline
\end{array}
\]

---
Poisson Superfish Examples
- A DTL-type cavity -

• Drift Tube Linac Cavity

CERN Linac4 DTL prototype

Special Superfish input geometry
Poisson Superfish Examples
- A DTL-type cavity -

Superfish input file

Geometry file

Solution
Poisson Superfish Examples
- An elliptical cavity -

• Often used in superconducting applications
Poisson Superfish Examples
- An elliptical cavity -

Superfish input file

Geometry file

Solution 1 Cell

Solution 5 Cell Cavity
Example: Possible 400 MHz Cavity
- Like the LHC 400 MHz RF
- 4-cell cavity
- 4 cavities/SC Cryomodule configuration
Poisson Superfish Examples - LHeC Cavities -

• Example: Possible 721.4 MHz Cavity
  – SPL-like cavities (slightly smaller)
  – 5-cell cavity
Poisson Superfish Examples
- The ACOL Cavity -

• A 9.5 MHz cavity for bunch rotation in the CERN Antiproton Collector.

• Low Frequency Pillbox-type cavities are challenging because of their large dimensions

• Alternatives:
  – Ferrite Dominated Cavities (Bias current in the ferrite -> Small cavity & Tuning, Typical gap voltage ~ 10 kV, Long beam line space required for higher voltages)
  – High gradient magnetic alloy loaded cavity (70 kV)
  – Oil loaded, Ceramic gap loaded cavity
Poisson Superfish Examples
- The ACOL Cavity -

- **Air-core RF cavity**: large capacitive electrode -> lower frequency

**Different models**

**ACOL Cavity**
Initial Design

**Figure 2**: Cavity cross-section.

ACOL Cavity
Final Model (Built)
Poisson Superfish Examples
- The ACOL Cavity -

- Pillbox Cavity, 2.5/1.64m, f= 91.8 MHz
- Pillbox Cavity, with drift nose, 2.5/1.64m, f= 56 MHz
- Pillbox Cavity, with one electrode, 2.5/1.64m, f= 12 MHz
- Pillbox Cavity, with two electrodes, 2.5/1.64m, f= 9.23 MHz
Poisson Superfish Examples - Ferrite Loaded Cavities -

- Used when variable resonance is needed. Long history
- The torus of the ferrite encircles the beam path
- Ferrite properties are important (limit the cavity capabilities)
- Bias current $\rightarrow$ Variable magnetic field $\rightarrow$ Variable magnetic permeability of the ferrite $\rightarrow$ Frequency change
- The structure can be thought of as a resonant transformer in which the beam constitutes a one-turn secondary winding.
- Frequencies domain: 100 kHz and 60 MHz
- Typical gap voltage of up tens of kV
- Different requirements (large frequency ranges, rapid swings, space, etc) $\rightarrow$ various designs.
## Ferrite Loaded Cavities – Examples (from I. Gardner)

<table>
<thead>
<tr>
<th>Synchrotron</th>
<th>No. of Cavities</th>
<th>No. of Gaps per cavity</th>
<th>Tuning Range (MHz)</th>
<th>Accelerating Time (s)</th>
<th>Max. df/dt (MHz/s)</th>
<th>Gap Capacity (pF)</th>
<th>Ind. Range (μH)</th>
<th>Type of Ferrite</th>
<th>( B_{\text{max}} ) in Ferri (T)</th>
<th>Bias Current (Amps)</th>
<th>Tuning System BW (kHz)</th>
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<td>325</td>
<td>2200</td>
<td>6.8 - 1.3</td>
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### Notes
- \( B_{\text{max}} \): Maximum magnetic field strength
- Bias Current: The maximum bias current required for proper operation
- Tuning System BW: Bandwidth of the tuning system
Poisson Superfish Examples
- Ferrite Loaded Cavities -

**Six ferrite blocks**: Epsilon = 14.5, Mu = 1.5

**Five ceramic-spacers**: Epsilon = 10.0, Mu = 1.0

**Ceramic vacuum window**: Epsilon = 9.0, Mu = 1.0

Cavity length: 116 cm

Number of gaps: 1
Now, use your imagination!