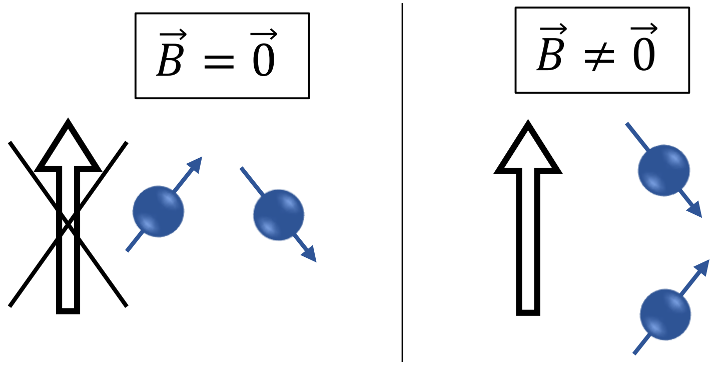
Efficient and full-wave electromagnetic analysis of MRI antennas using the Array Scanning Method

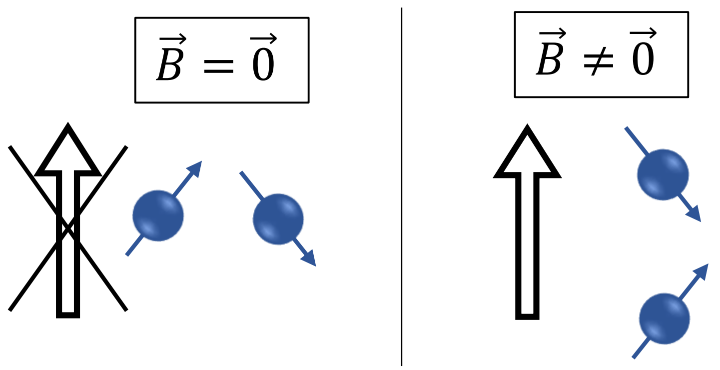
J.I. Echeveste D. Tihon M. Dubois R. Abdeddaim C. Craeye

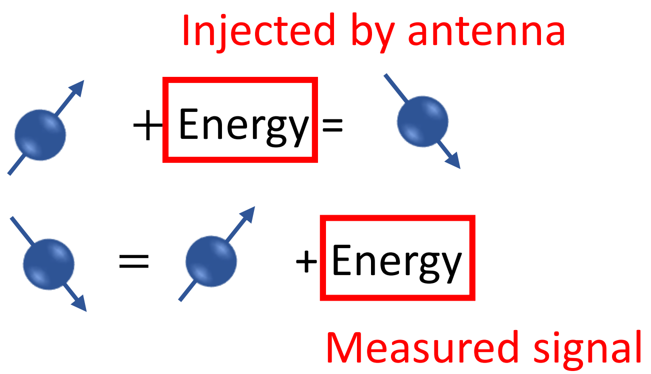
EuCAP 2018

Introduction

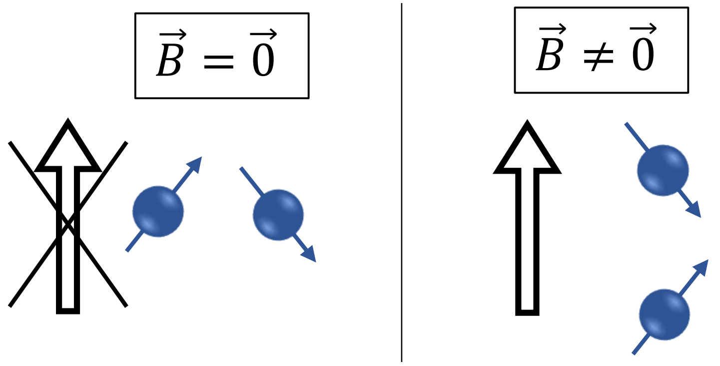


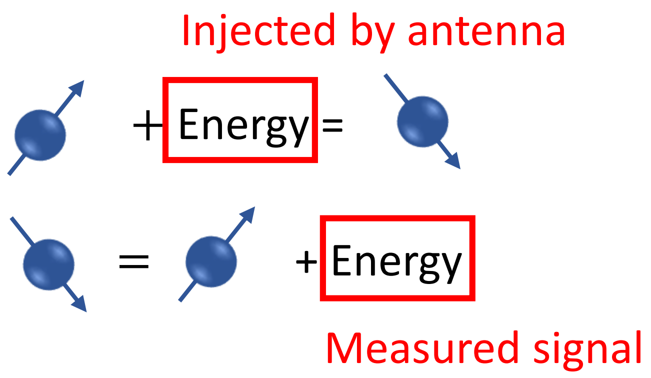
Introduction





Introduction

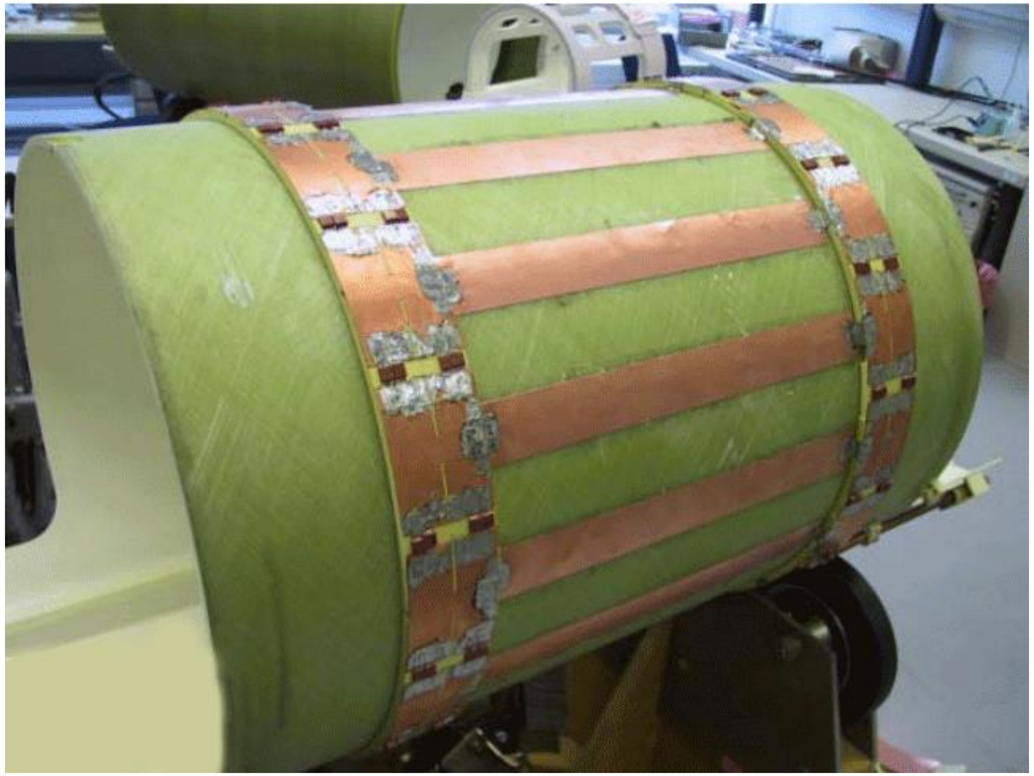




A « good » excitation:

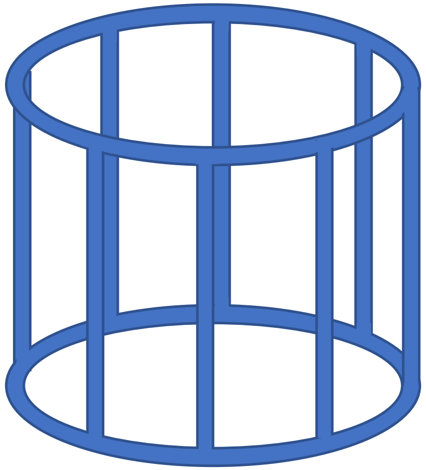
- Narrow band (42,58 MHz/T)
- Homogeneous rotating magnetic field
- Low electric field (SAR)

The Birdcage antenna

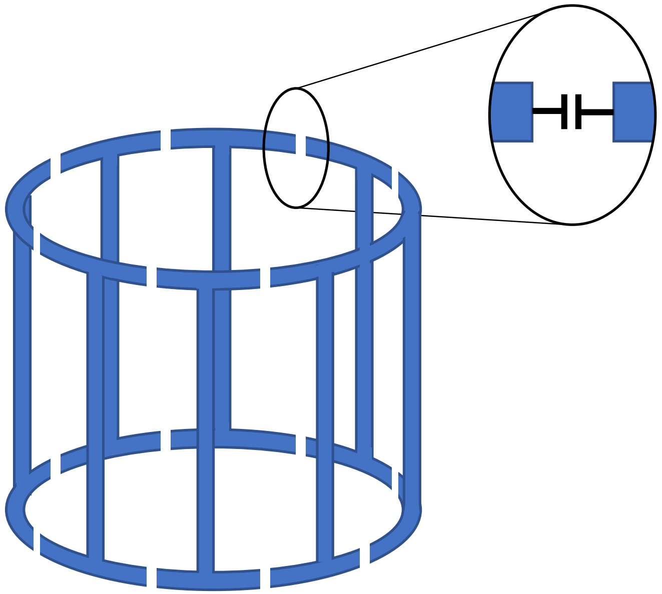


Picture from *mriquestions.com/birdcage-coil.html*

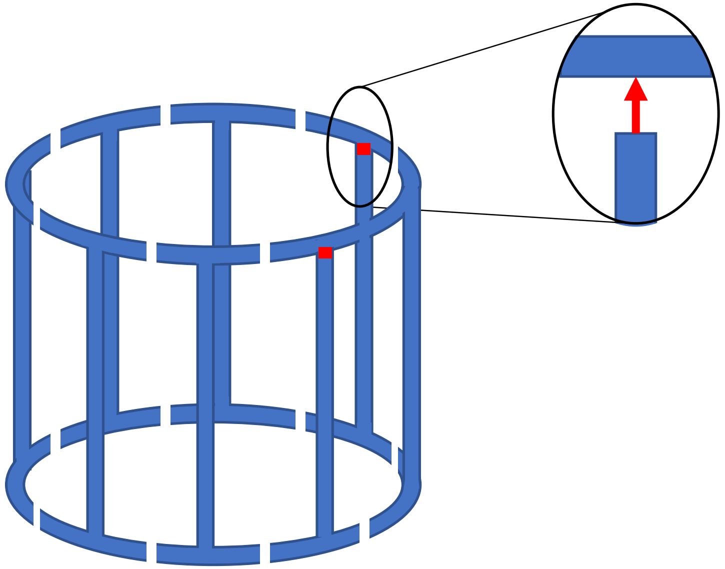
The Birdcage antenna



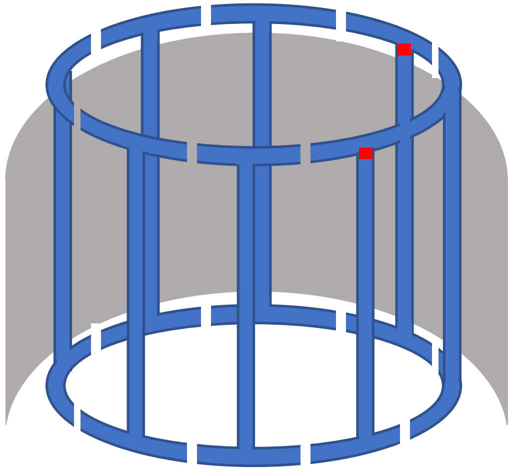
The Birdcage antenna



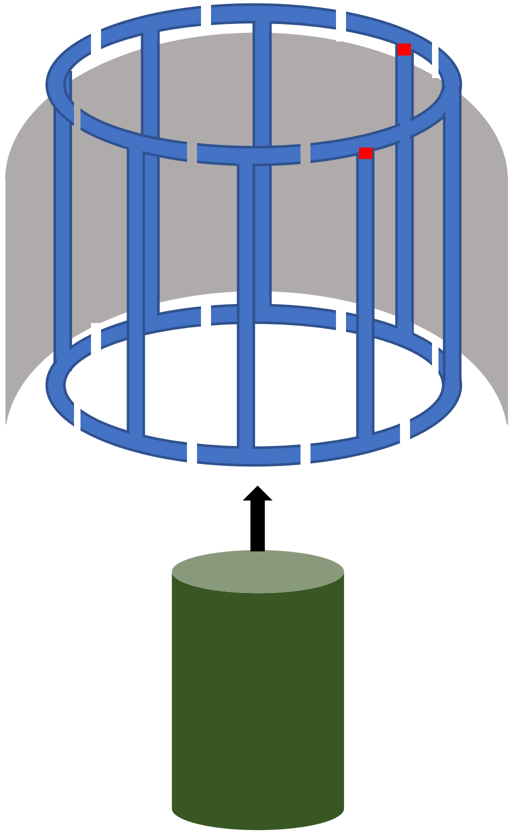
The Birdcage antenna



The Birdcage antenna



The Birdcage antenna

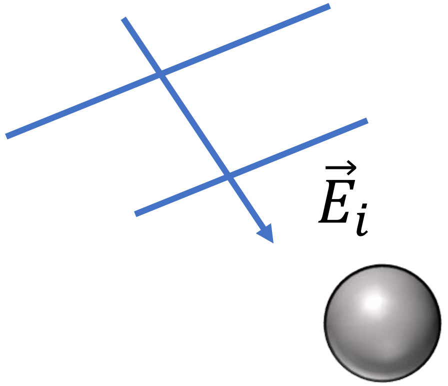


Salient features:

- Lossy dielectric and PEC
- Lumped elements and ports
- Nearly periodic
- Easy and fast design
  (capacitors, frequency sweep)

Table of contents

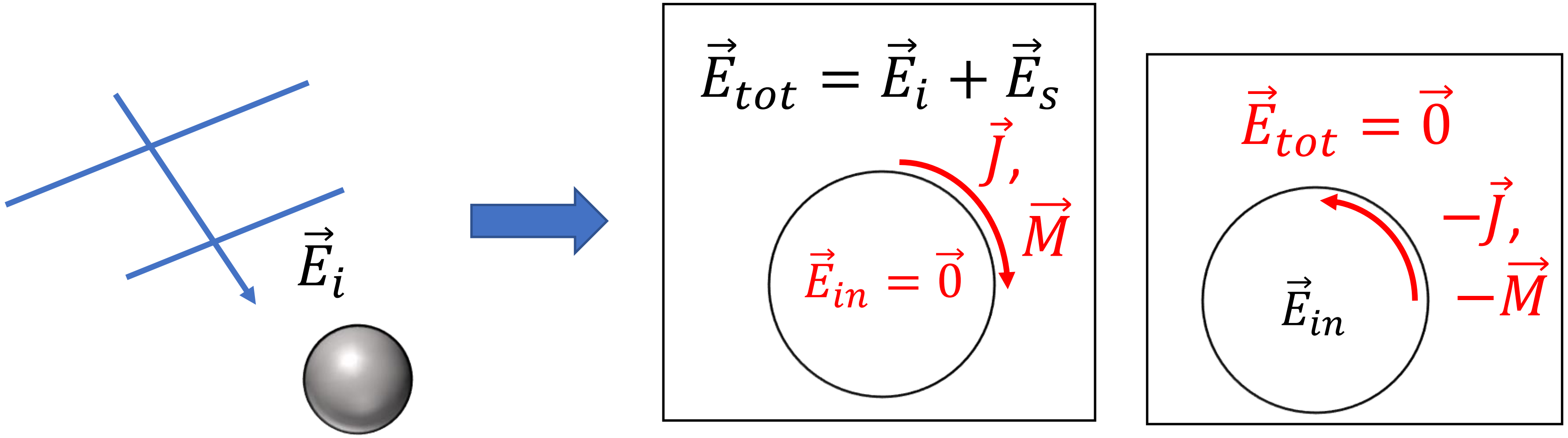
Penetrable body:



A. Poggio and C. Miller, *1973*

Method of Moments

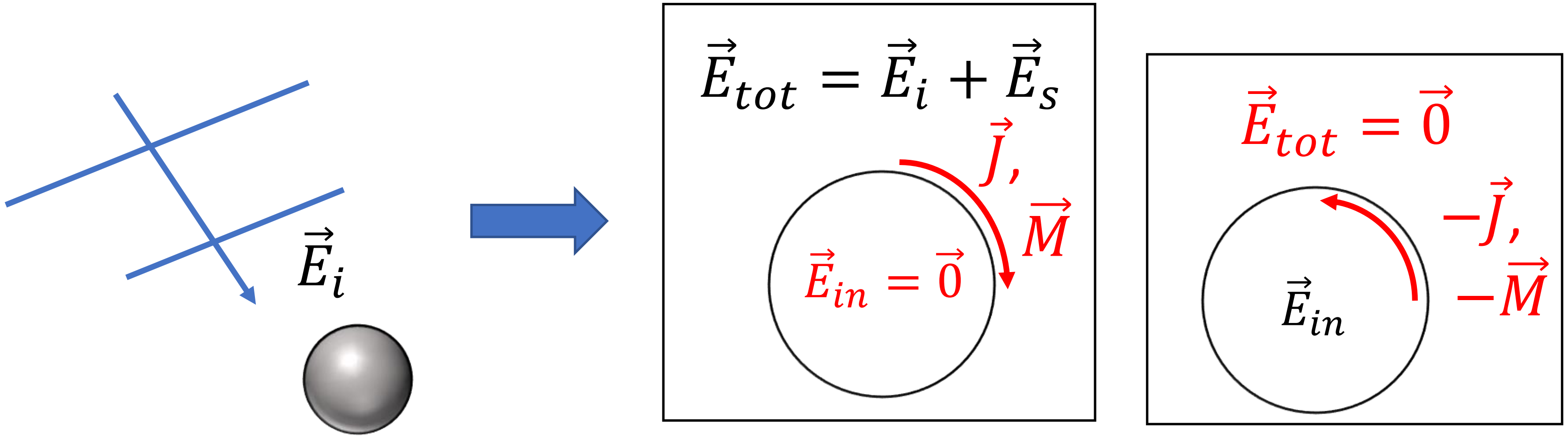
Penetrable body:



Outer problem **Inner problem**

A. Poggio and C. Miller, *1973*

Penetrable body:



Outer problem **Inner problem**

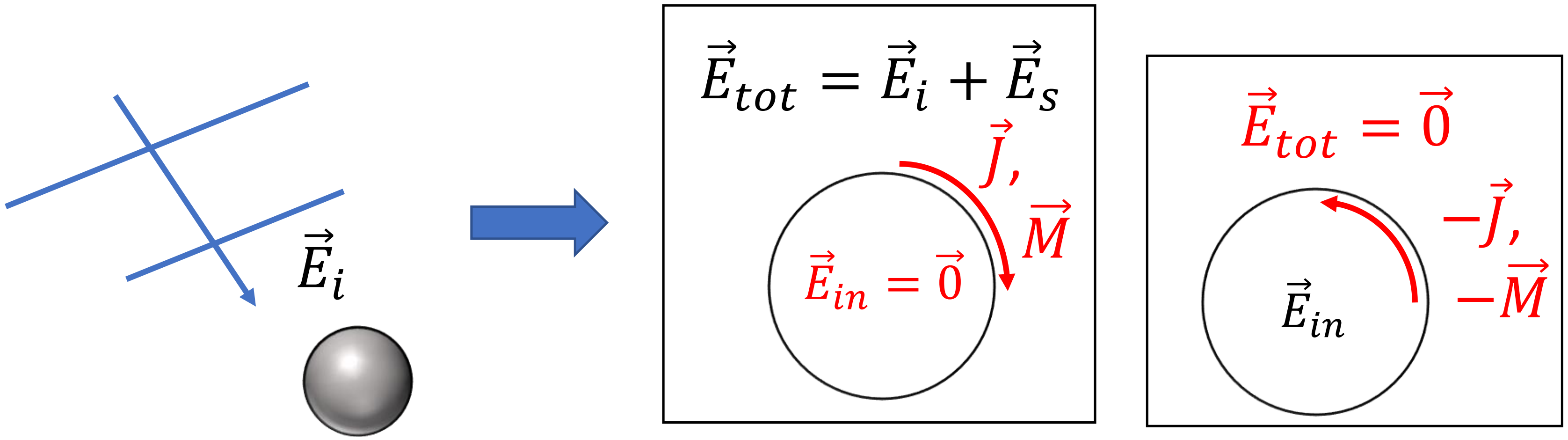
J, M?

→ Continuity of tangential fields

A. Poggio and C. Miller, *1973*

Method of Moments

Penetrable body:



Outer problem **Inner problem**

J, M?

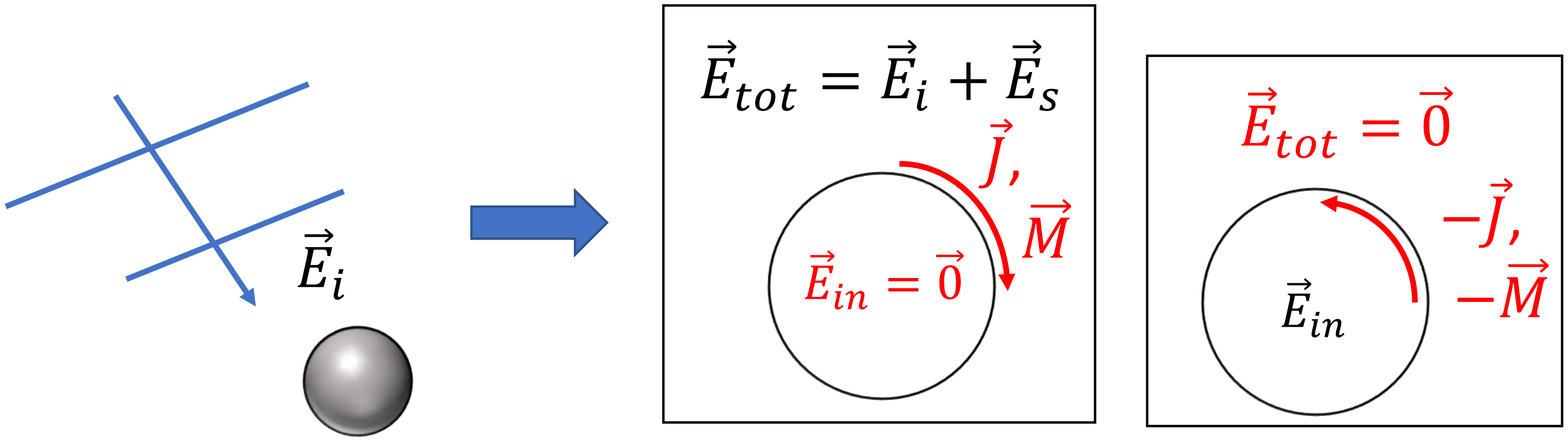
→ Continuity of tangential fields

PEC: Just the outer problem $\rightarrow \vec{M} = \vec{0}$

J? → Vanishing tangential electric field

A. Poggio and C. Miller, *1973*

Penetrable body:



Outer problem **Inner problem**

J, M? → Continuity of tangential fields

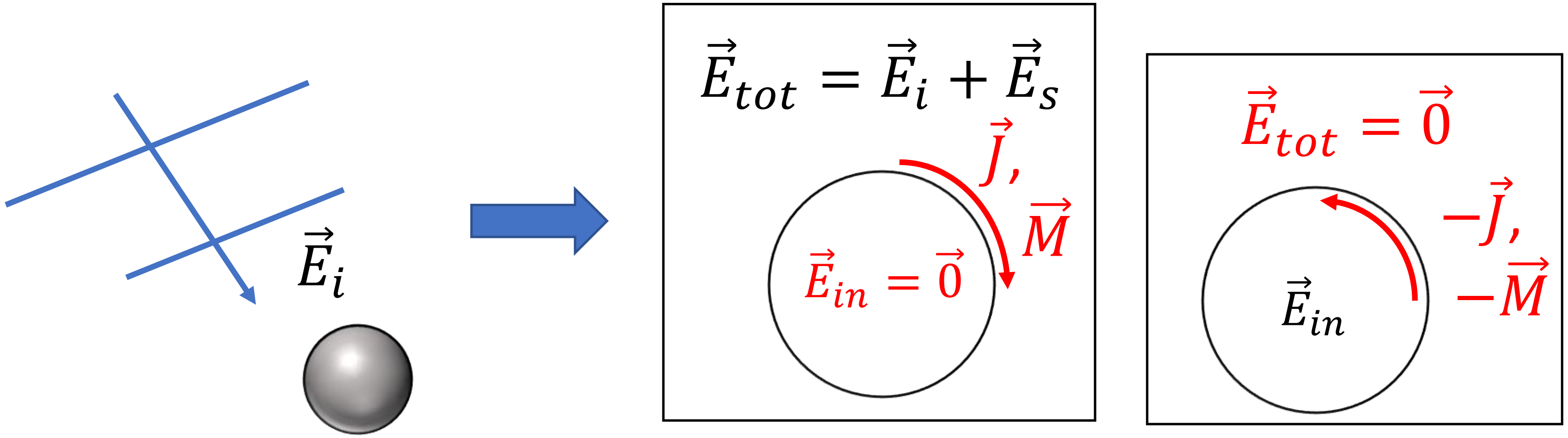
PEC: Just the outer problem $\rightarrow \vec{M} = \vec{0}$

J? → Vanishing tangential electric field

$$(Z_{in} + Z_{out})\,\mathbf{x} = -\mathbf{b}$$

A. Poggio and C. Miller, *1973*

Penetrable body:



Outer problem **Inner problem**

J, M?

→ Continuity of tangential fields

PEC: Just the outer problem $\rightarrow \vec{M} = \vec{0}$

J? → Vanishing tangential electric field

$$(Z_{in} + Z_{out})\ \mathbf{x} = -\mathbf{b}$$

Fill Z → $O(N^2)$ Invert Z → $O(N^3)$

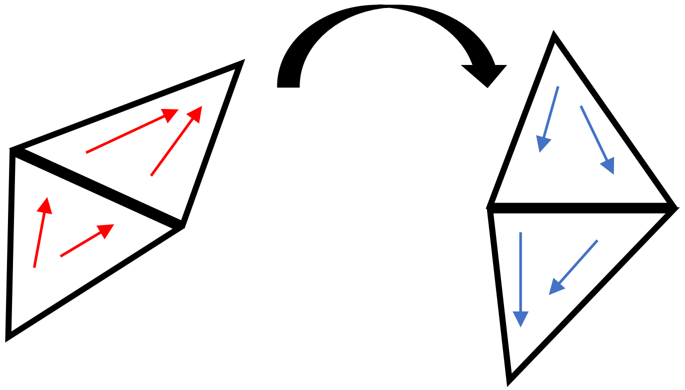
A. Poggio and C. Miller, *1973*

The Z matrix:

$$(Z_{in} + Z_{out})\,\mathbf{x} = -\mathbf{b}$$

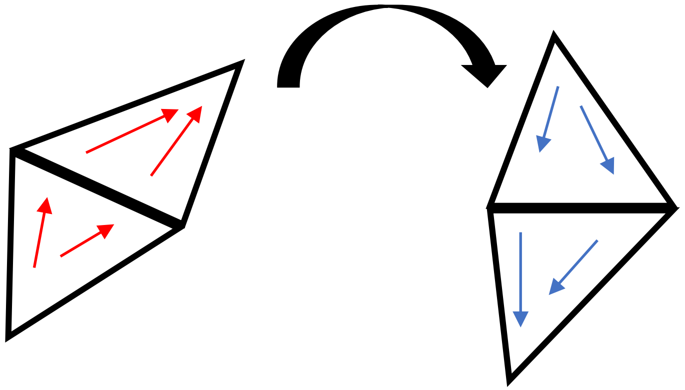
4D integral:

2D for the source, 2D for the test



The Z matrix:

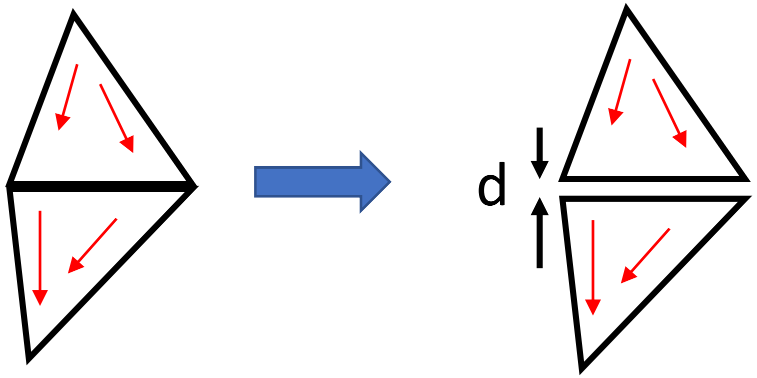
$$(Z_{in} + Z_{out})\,\mathbf{x} = -\mathbf{b}$$



4D integral:

2D for the source, 2D for the test

Lumped elements: delta-gap model



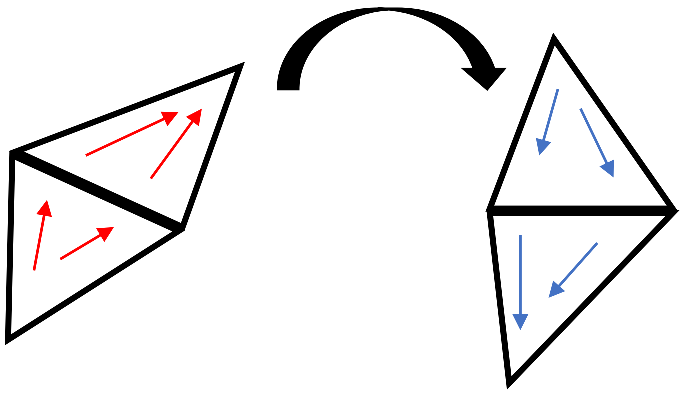
Method of Moments

The Z matrix:

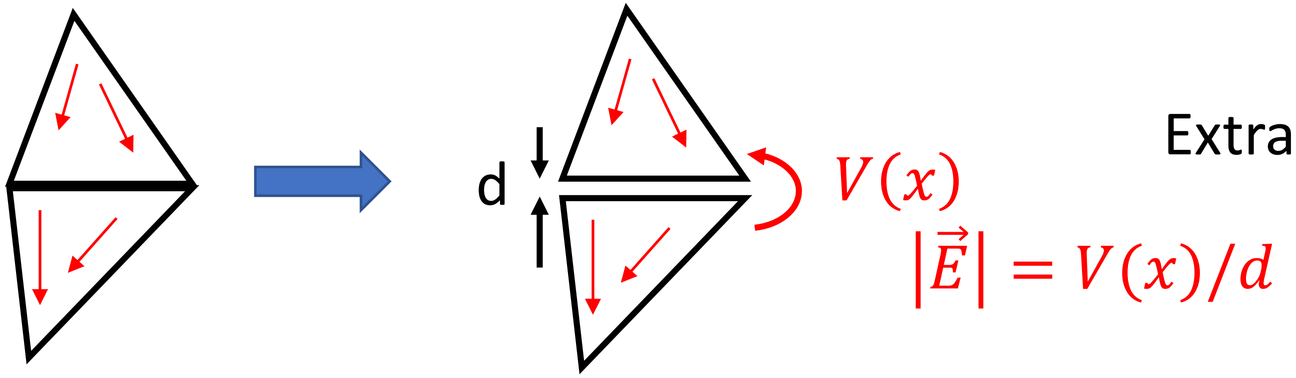
$$(Z_{in} + Z_{out})\,\mathbf{x} = -\mathbf{b}$$

4D integral:

2D for the source, 2D for the test



Lumped elements: delta-gap model



Extra $\vec{E}$ generated for the self-term

Table of contents

Frequency interpolation

The Z matrix:

4D integral of the type

$$Z(\omega) = f(\omega) \iiiint g(\mathbf{r},\mathbf{r}') \exp(-j\, k(\omega)\, R)\; dS'\, dS$$

→ Need a small R

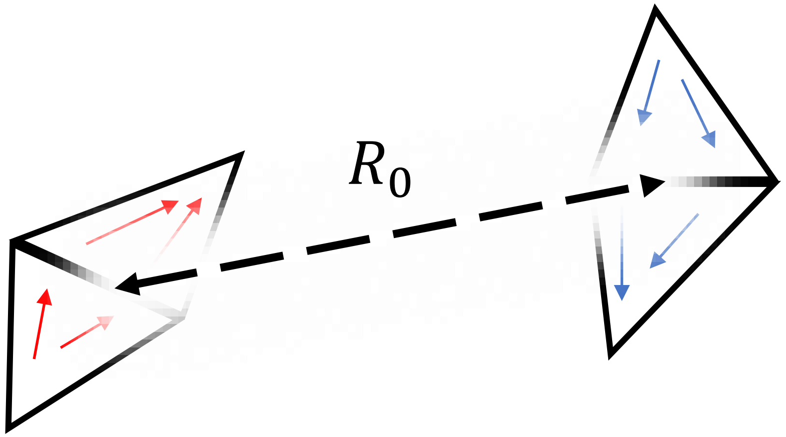
E. H. Newman, 1988

Frequency interpolation

The Z matrix:

4D integral of the type

$$Z(\omega) = f(\omega) \iiiint g(\boldsymbol{r}, \boldsymbol{r}') \exp(-j\, k(\omega)\, R)\; dS'\, dS$$



➡ Need a small R

E. H. Newman, 1988

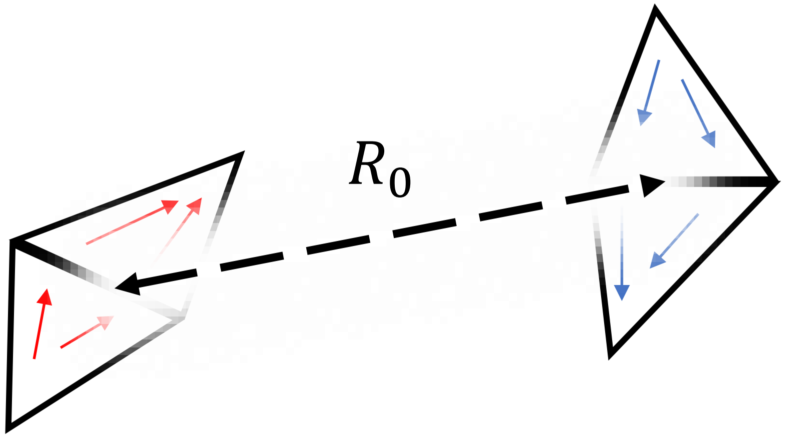
Frequency interpolation

The Z matrix:

4D integral of the type

$$Z(\omega) = f(\omega) \iiiint g(\mathbf{r},\mathbf{r}') \exp(-j\, k(\omega)\, R)\; dS'\, dS$$

Need a small R



$$Z(\omega) = f(\omega) \exp(-j\, k(\omega) R_0) \times \boxed{\iiiint g(\mathbf{r},\mathbf{r}') \exp\big(-j\, k(\omega)\, (R - R_0)\big)\; dS'\, dS}$$

Smooth with respect to ω

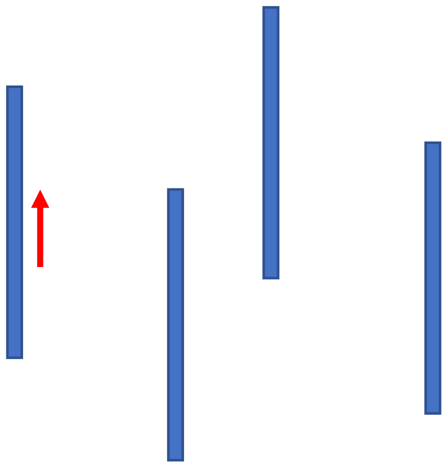
Interpolation of $\dfrac{Z(\omega)}{f(\omega)} \exp(j\, k(\omega) R_0)$

E. H. Newman, 1988

Table of contents

The Array Scanning Method

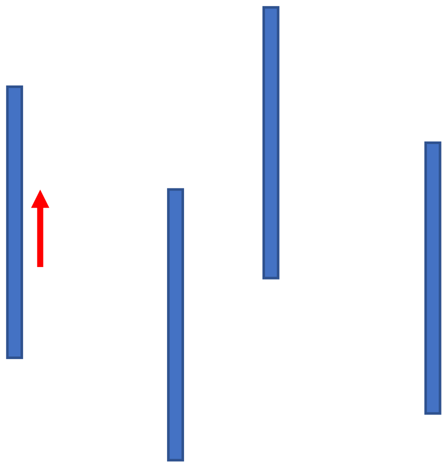
Non-periodic excitation:



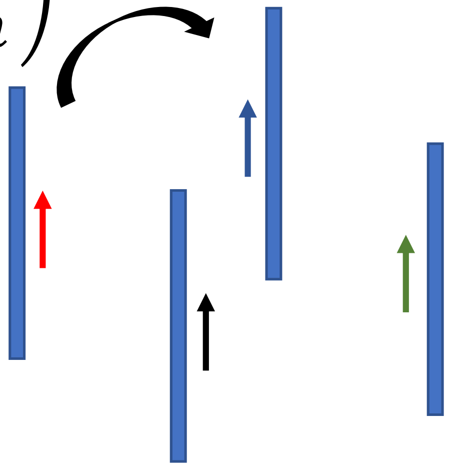
B.A. Munk and G.A. Burrel, 1979
M.A. Carr *et al.*, 2002

The Array Scanning Method

<u>Non-periodic excitation:</u>



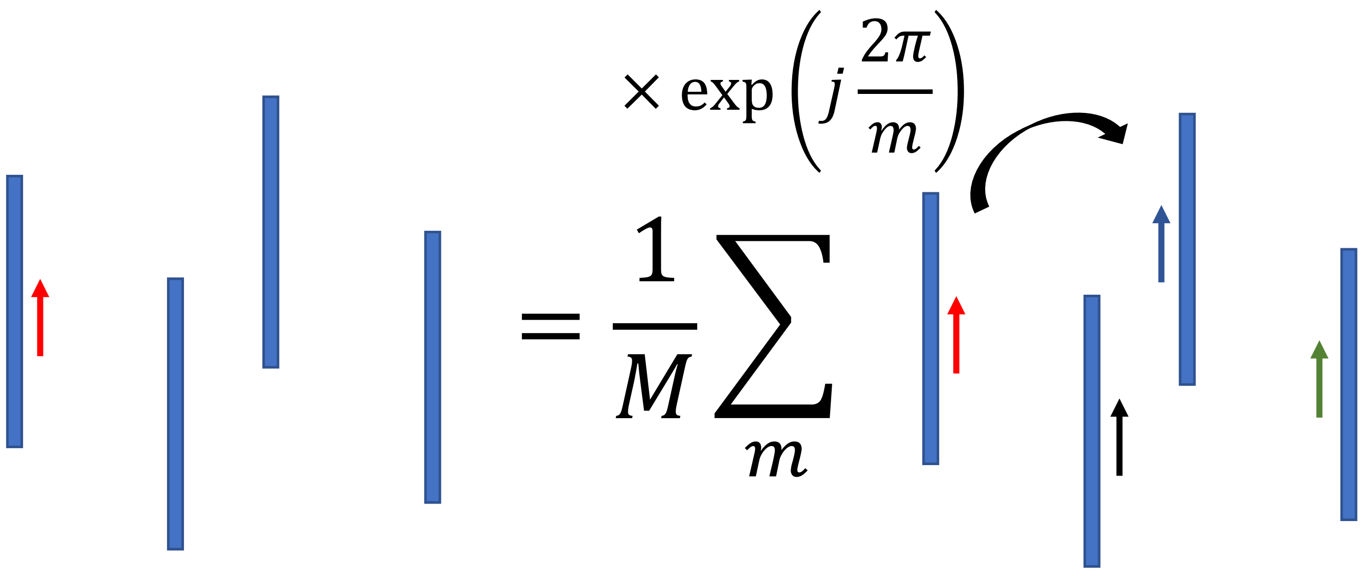
$$= \frac{1}{M} \sum_{m} \times \exp\left(j \frac{2\pi}{m}\right)$$



B.A. Munk and G.A. Burrel, 1979
M.A. Carr *et al.*, 2002

The Array Scanning Method

<u>Non-periodic excitation:</u>

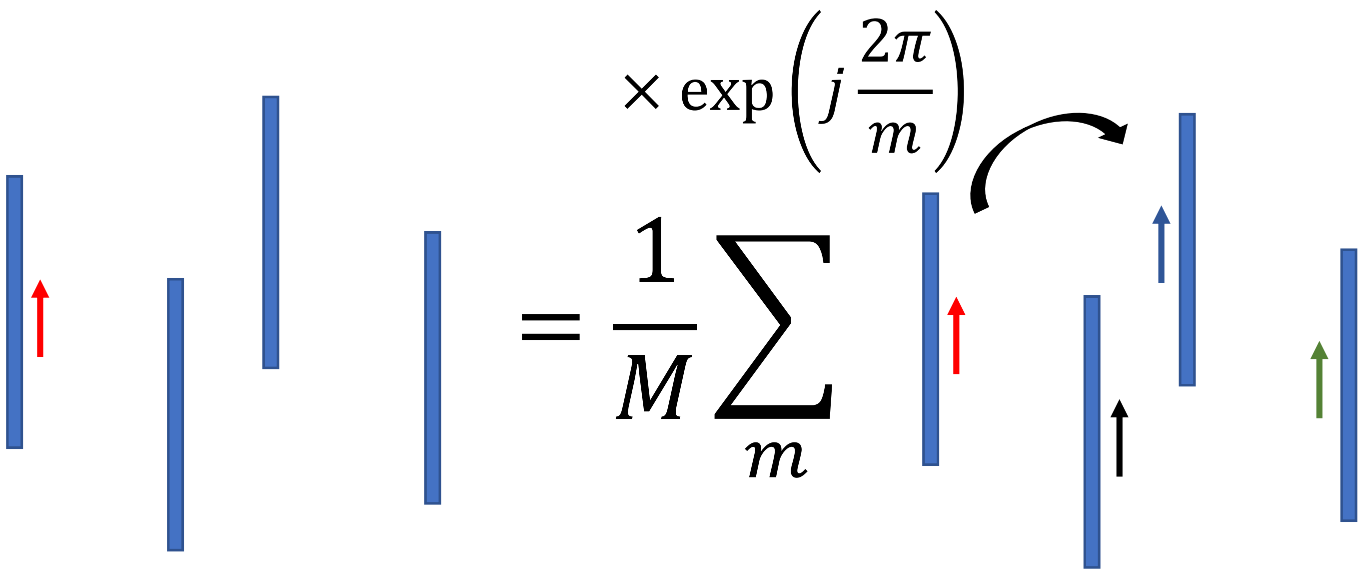


$$= \frac{1}{M}\sum_{m} \quad \times \exp\left(j\frac{2\pi}{m}\right)$$

m=0	1	1	1	1
m=1	1	j	-1	-j
m=2	1	-1	1	-1
m=3	1	-j	-1	j
total	4	0	0	0

B.A. Munk and G.A. Burrel, 1979
M.A. Carr *et al.*, 2002

Non-periodic excitation:



$$= \frac{1}{M}\sum_{m} \times \exp\left(j\frac{2\pi}{m}\right)$$

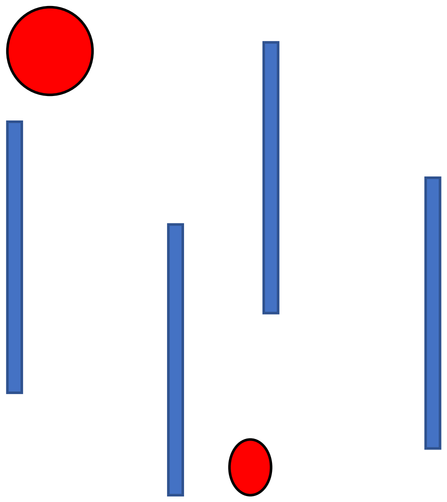
m=0	1	1	1	1
m=1	1	j	-1	-j
m=2	1	-1	1	-1
m=3	1	-j	-1	j
total	4	0	0	0

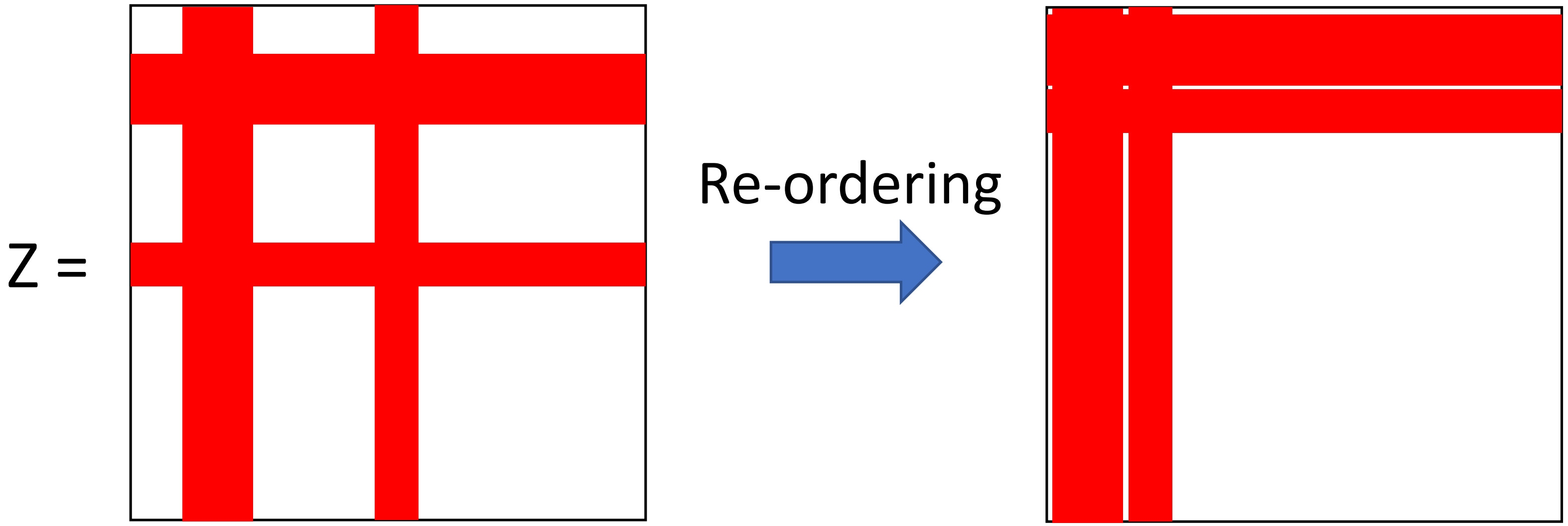
Advantages:

- Filling time: $O\left((MN)^2\right) \rightarrow O(M(N)^2)$
- Solution time: $O\left((MN)^3\right) \rightarrow O(M(N)^3)$

B.A. Munk and G.A. Burrel, 1979
M.A. Carr *et al.*, 2002

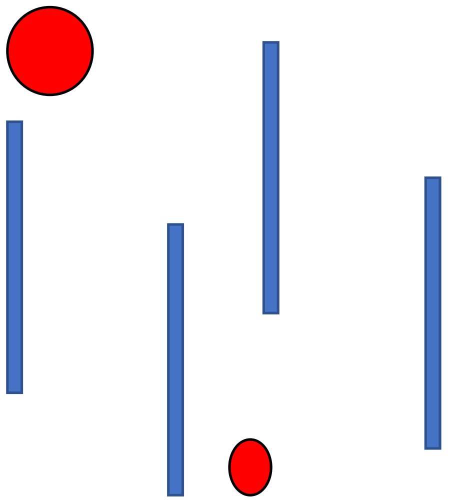
Nearly periodic structure:

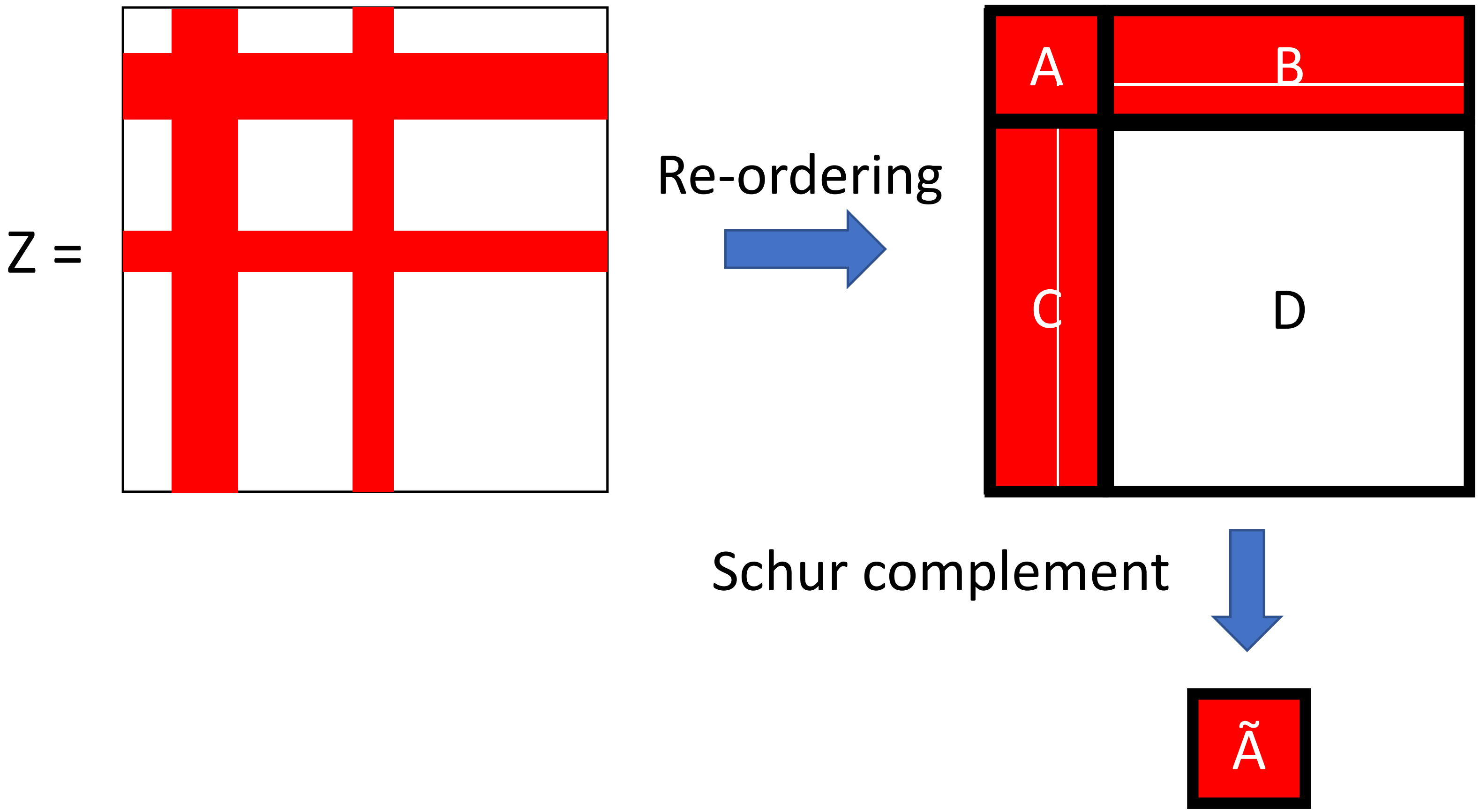




Schur complement

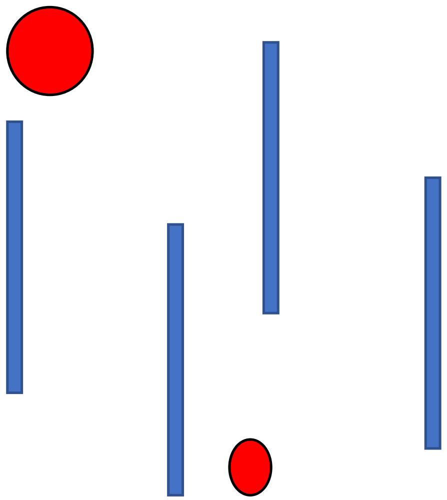
Nearly periodic structure:

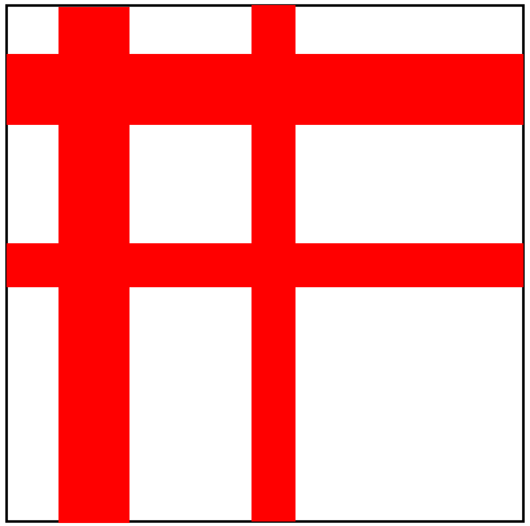




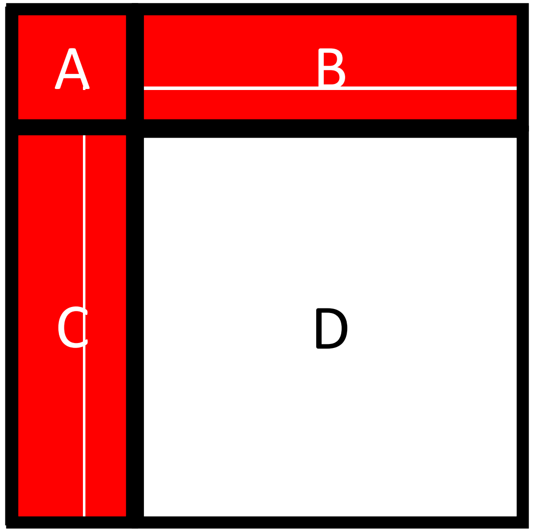
Schur complement

Nearly periodic structure:



Z = 

Re-ordering



Schur complement

Schur complement

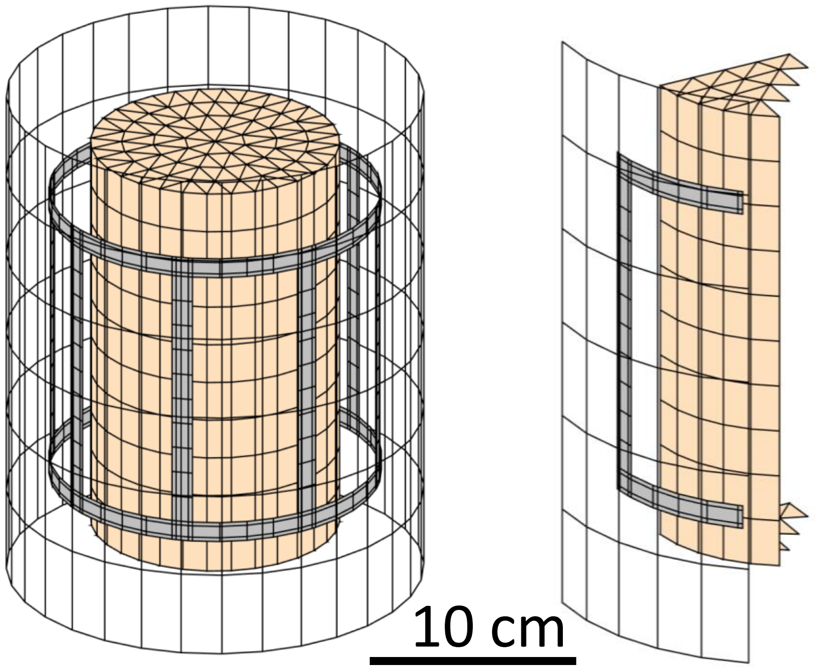
$$\left(A - C \cdot \boxed{D^{-1}} \cdot B\right) x_{red} = b_{red}$$

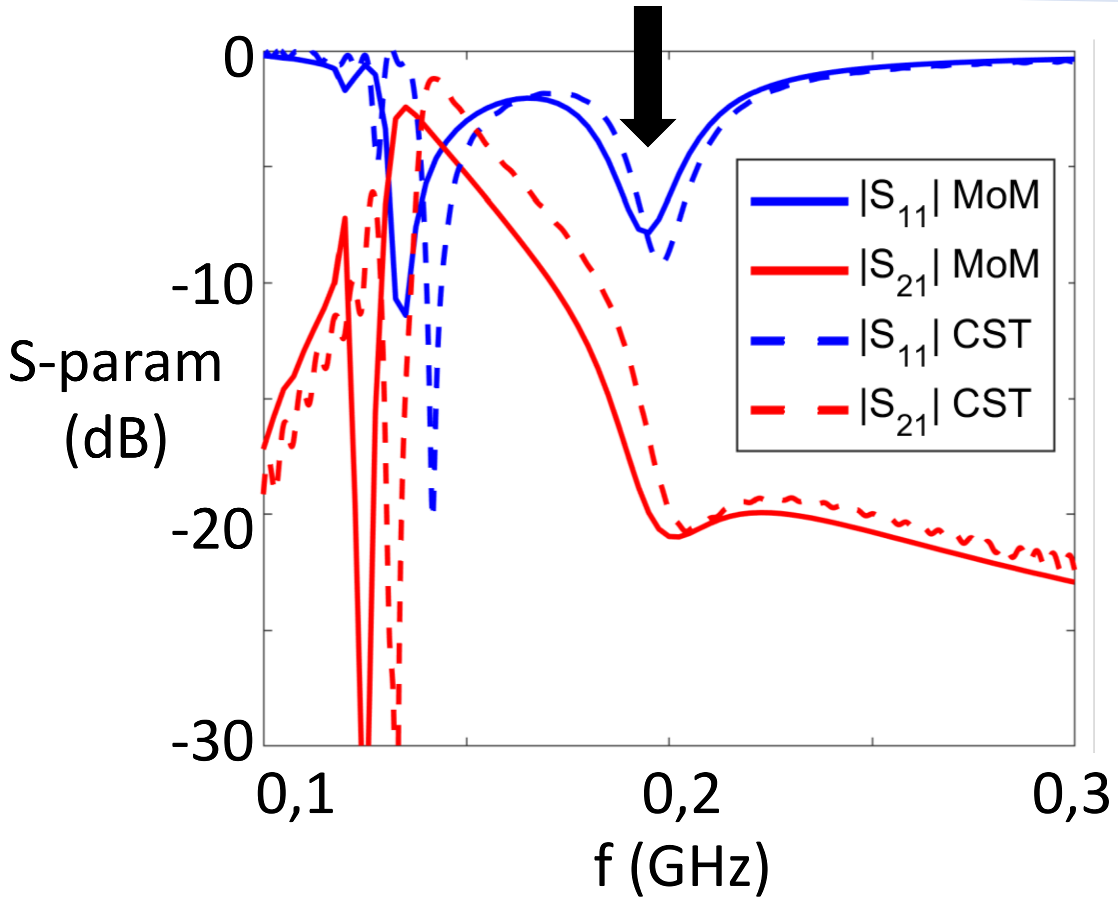
Periodic part → rapid inversion

Table of contents

Numerical validation

Simulation of birdcage antenna:

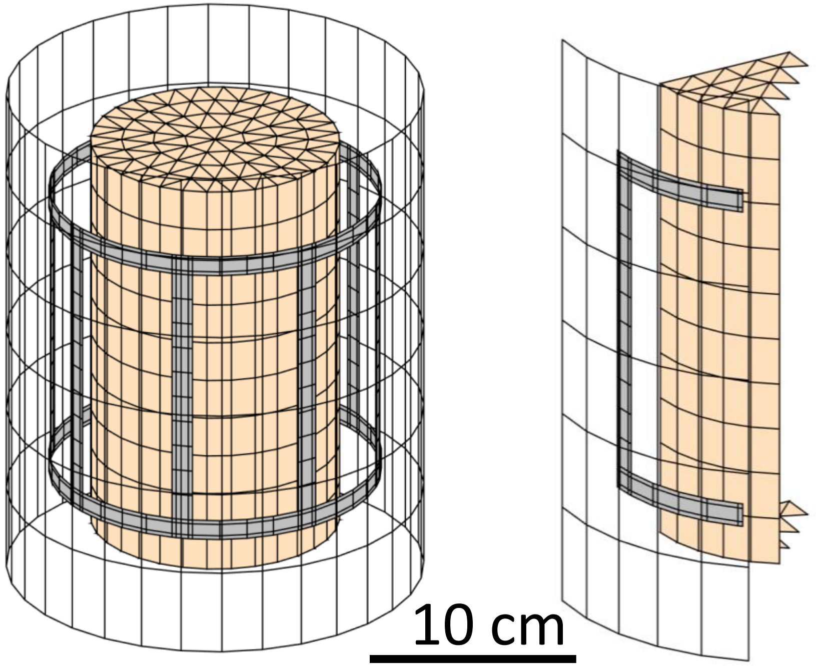




Frequency : 100-300 MHz (100 points)
Capacitance : 11 pF
Phantom : $\varepsilon_r = 61, \sigma = 0{,}8 \left[\frac{S}{m}\right]$
Frequency interpolation : 3 points

Time required: MoM : 12 minutes
CST : 40 minutes

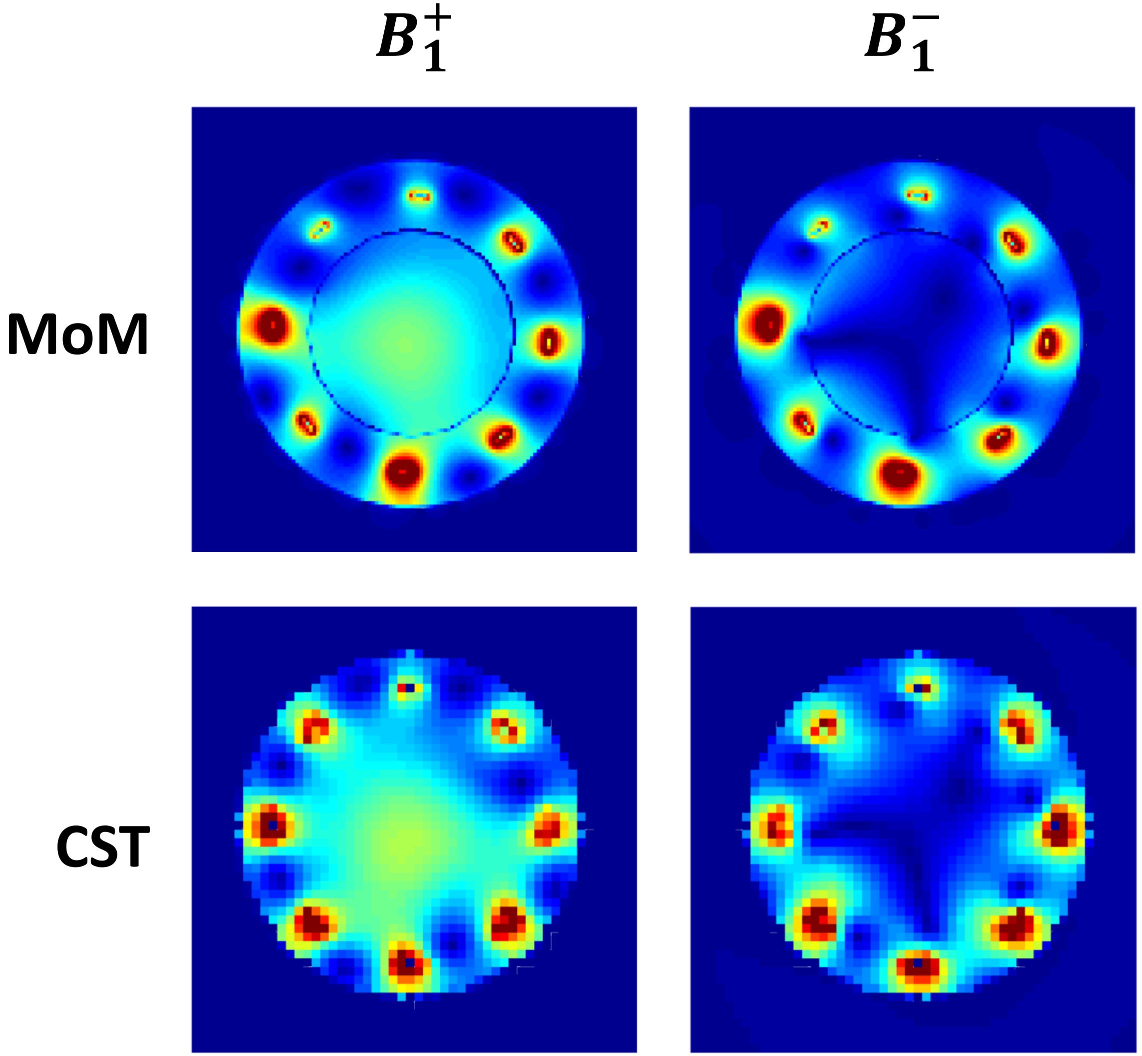
Simulation of birdcage antenna:



Frequency : 200 MHz

Capacitance : 11 pF

Phantom : $\varepsilon_r = 61, \sigma = 0{,}8 \left[\frac{S}{m}\right]$



Conclusion

Acceleration techniques:

- Frequency sweep: fast interpolation of Z
- Solution: use of the partial periodicity
- Design: rapid sweep over value of the lumped elements

Results:

- Acceleration by a factor of 3 (10 if parallelized)
- Computation for different capacitances done in negligible time

Question time

Thank you for your attention