# Exploring FCC EMB geometry with Matlab

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# Introduction

Some particle detection optimization:

- Trade-off between detection precision and number of channels
- Geometrical constraints
- Particles traces reconstruction

=> Exploring general FCC geometry

=> Generic scientific tool : Matlab

Once the general geometry is fixed, one can go deeper in a more detailed electrodes geometry (how to extract signal from pads).

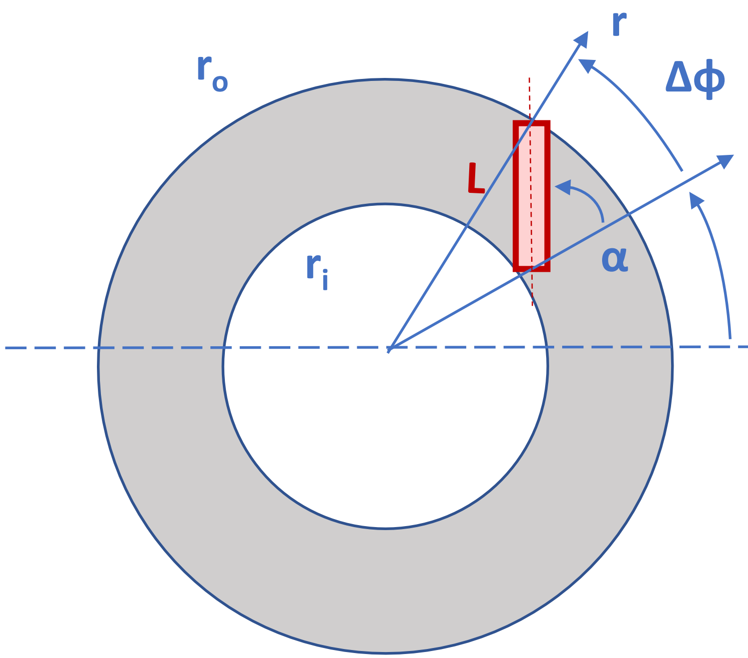
- Extract signal and cross-talk impedances involved in the signal noise ratio of the detection.
- Known formulas to evaluate these impedances are only valid in restricted conductors geometries:

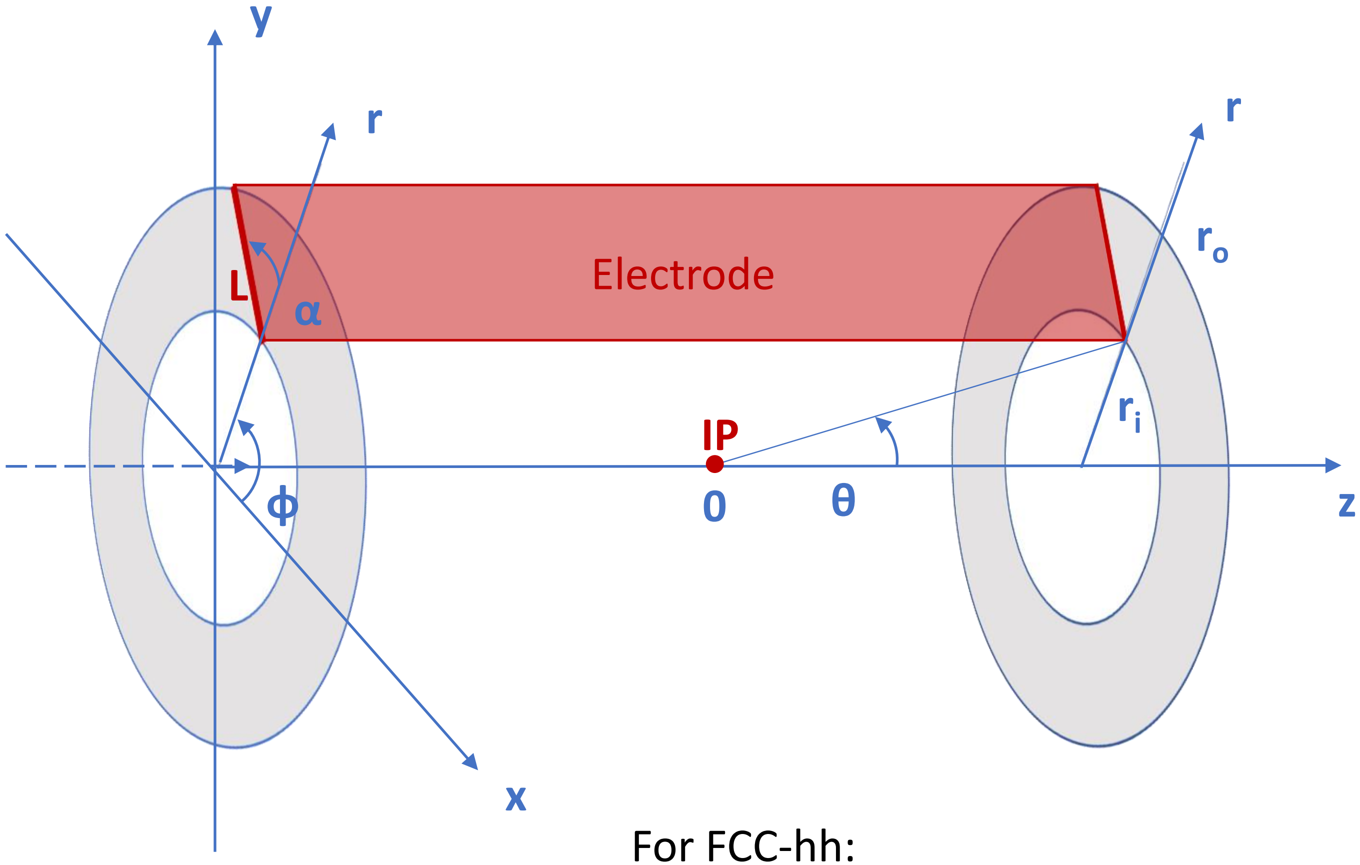
=> Solve EM equations for real geometries

=> Dedicated tools: COMSOL, FastField Solvers, Cadence Sigrity,… (FEM or BEM)

# 3D and radial view of the barrel

Radial view (r-phi)




FCC-hh : ri = 192 cm
ro = 257cm
α = 50°

FCC-ee : ri = 216 cm
ro = 256 cm
α = 50°

$$r_o \exp(i\Delta\phi) = r_i + L\exp(i\alpha)$$

$$\Rightarrow r_o^2 = \left(L + r_i\cos(\alpha)\right)^2 + \left(r_i\sin(\alpha)\right)^2$$

For FCC-hh:
-5m < z < +5m

For FCC-ee:
-3m < z < 3m

# 3D and longitudinal view of the barrel

For each electrode:

- Height divided in m segments related to angle alpha and radius r
- Longitudinally in p slices along angle theta or pseudorapidity

For FCC-hh: electrodes are divided in slices along the pseudorapidity η: Δη = 0,01

$$\eta_p = \left(p + \frac{1}{2}\right)\Delta\eta$$

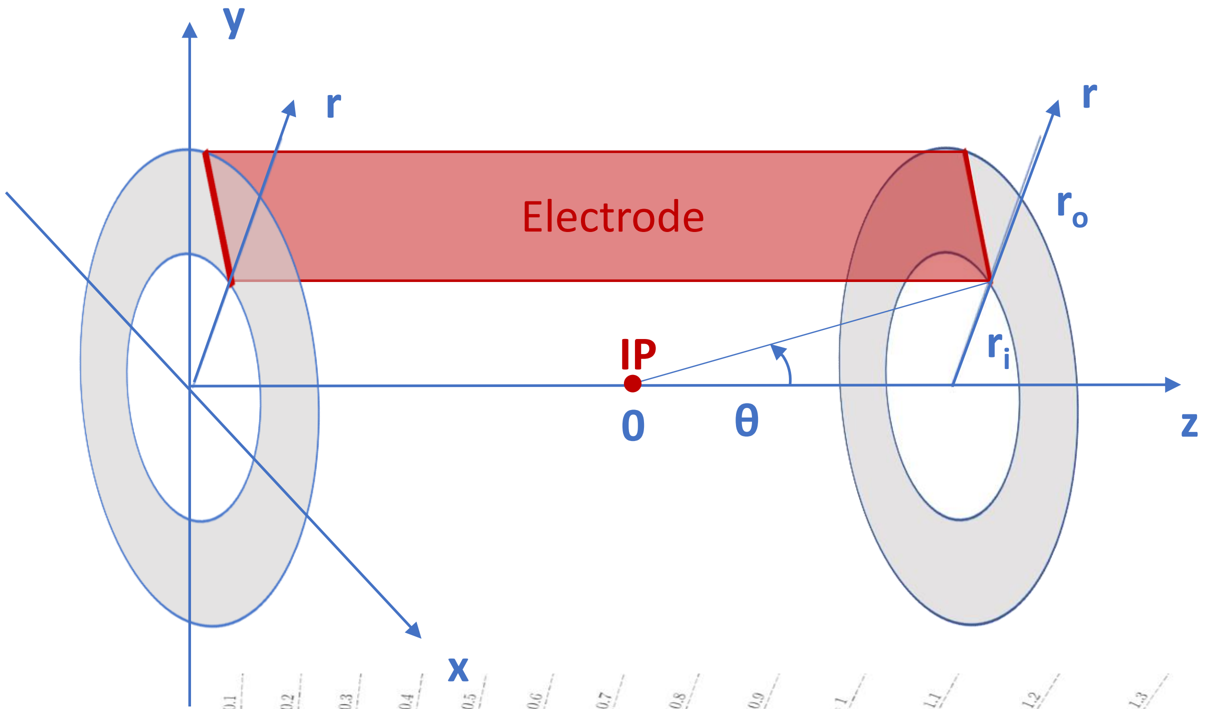
$$\theta_p = 2\arctan\left(\exp\left(-\eta_p\right)\right)$$

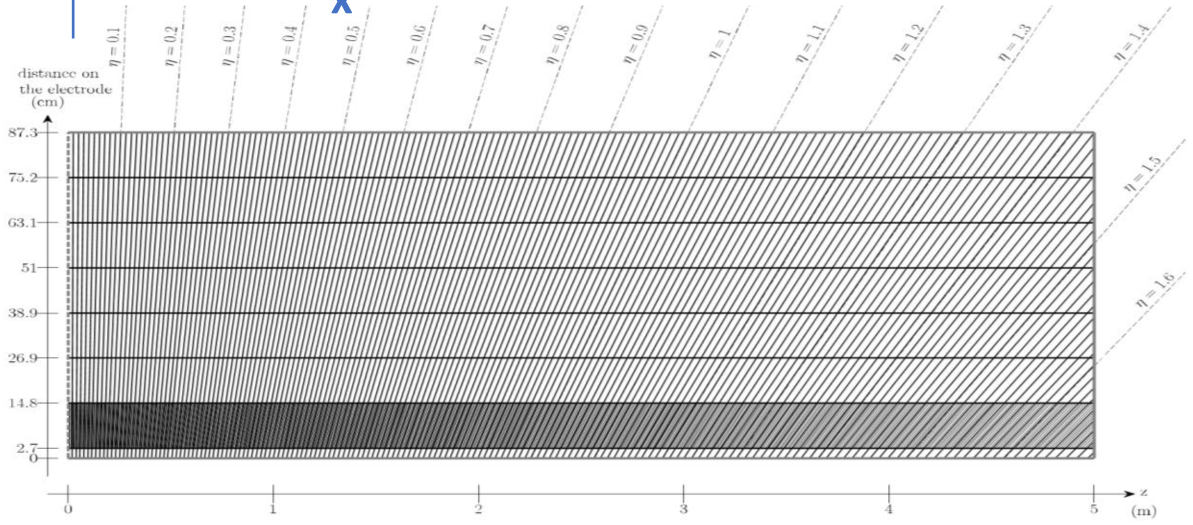
For FCC-ee: electrodes are divided in slices along the angle θ: Δθ = 0,5625°

$$\theta_p = 90° + p\ \Delta\theta$$

Definition of a cell for one electrode:

$$\left.\begin{matrix} r_m{}^2 = \left(L_m + r_i\cos(\alpha)\right)^2 + \left(r_i\sin(\alpha)\right)^2 \\ \theta_p \end{matrix}\right\} \Rightarrow z_{m,p} = r_m / \tan\left(\theta_p\right)$$



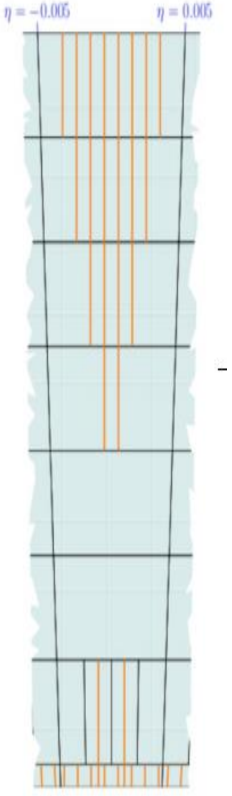




Half electrode for FCC-hh

# Details of a slice

$$r_m{}^2 = \left(L_m + r_i\cos(\alpha)\right)^2 + \left(r_i\sin(\alpha)\right)^2$$

For FCC-hh : 8 cells




| $\Delta r_m\,(cm)$ | $r_m\,(cm)$ | $L_m\,(cm)$ | $\Delta L_m\,(cm)$ |
|---|---|---|---|
| | 257 | 87,3 | |
| +9,8 | | | +12,1 |
| | 247,2 | 75,2 | |
| +9,6 | | | +12,1 |
| | 237,6 | 63,1 | |
| +9,4 | | | +12,1 |
| | 228,2 | 51,1 | |
| +9,1 | | | +12,1 |
| | 219,1 | 39 | |
| +8,8 | | | +12,1 |
| | 210,3 | 26,9 | |
| +8,5 | | | +12,1 |
| | 201,8 | 14,8 | |
| +8,1 | | | +12,1 |
| | 193,7 | 2,7 | |
| +1,7 | | | +2,7 |
| | 192 | 0 | |

Choice of constant length segments

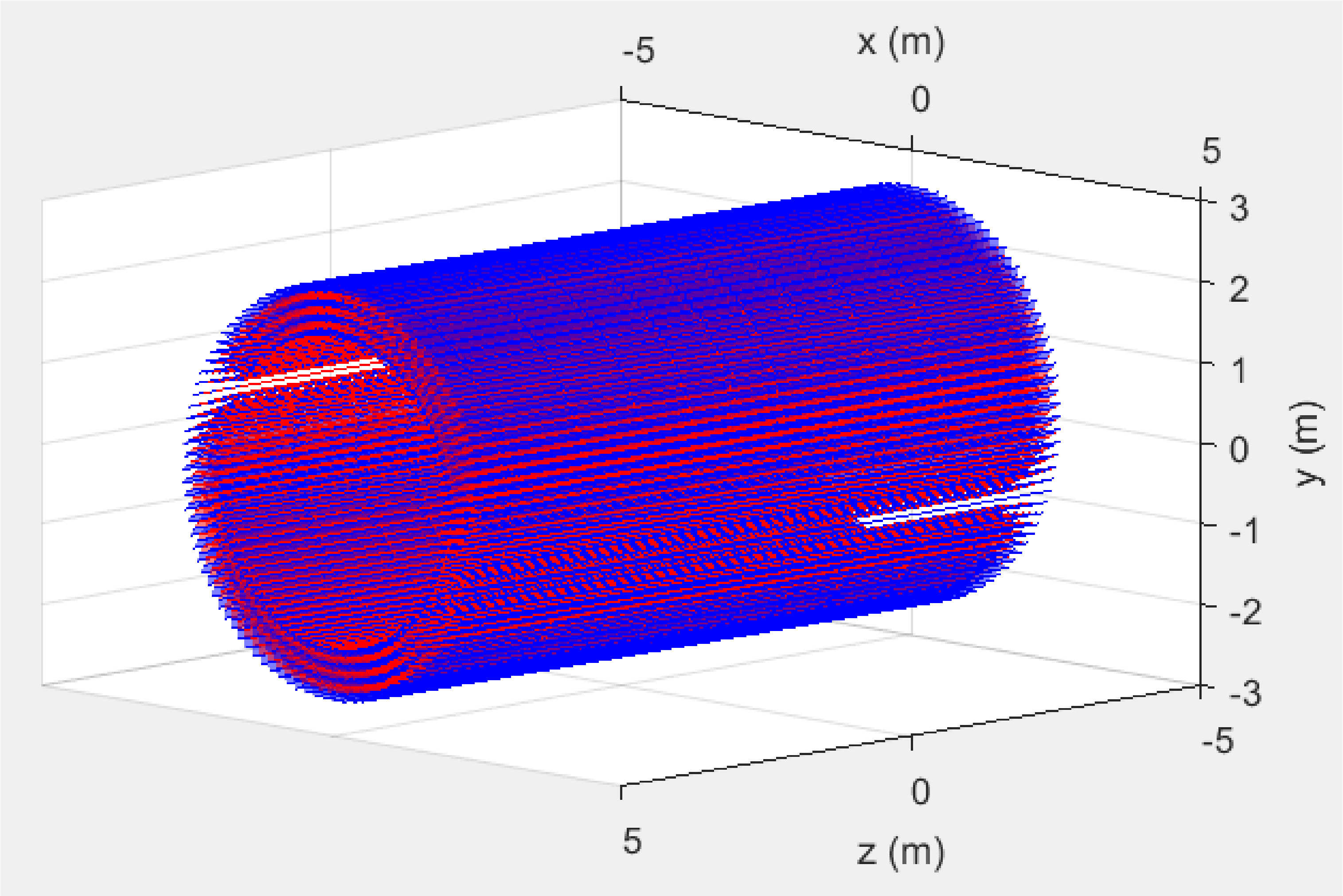
For FCC-ee: 12 cells (initial proposal)

| $\Delta r_m\,(cm)$ | $r_m\,(cm)$ | $L_m\,(cm)$ | $\Delta L_m\,(cm)$ |
|---|---|---|---|
| | 256 | 56,5 | |
| +3,5 | | | +4,6 |
| | 252,5 | 51,9 | |
| +3,5 | | | +4,7 |
| | 249 | 47,2 | |
| +3,5 | | | +4,7 |
| | 245,5 | 42,5 | |
| +3,5 | | | +4,8 |
| | 242 | 37,8 | |
| +3,5 | | | +4,8 |
| | 238,5 | 32,9 | |
| +3,5 | | | +4,9 |
| | 235 | 28 | |
| +3,5 | | | +5 |
| | 231,5 | 23,1 | |
| +3,5 | | | +5 |
| | 228 | 18 | |
| +3,5 | | | +5,1 |
| | 224,5 | 12,9 | |
| +3,5 | | | +5,2 |
| | 221 | 7,7 | |
| +3,5 | | | +5,3 |
| | 217,5 | 2,3 | |
| +1,5 | | | +2,3 |
| | 216 | 0 | |

Choice of constant radial depth segments

# Example of 3D view of the detector

View of the FCC-hh EMB with Matlab
(only 100 electrodes are drown inside the barrel)




Segments of the electrodes are colored in red and blue alternatively for odd and even segments respectively.

$$\phi_k = \phi_0 + k\frac{2\pi}{N_e}$$

$$r_m^{\,2} = \left(L_m + r_i\cos(\alpha)\right)^2 + \left(r_i\sin(\alpha)\right)^2$$

For FCC-hh: Ne=1408 electrodes

$$\eta_p = \left(p + \frac{1}{2}\right)\Delta\eta$$

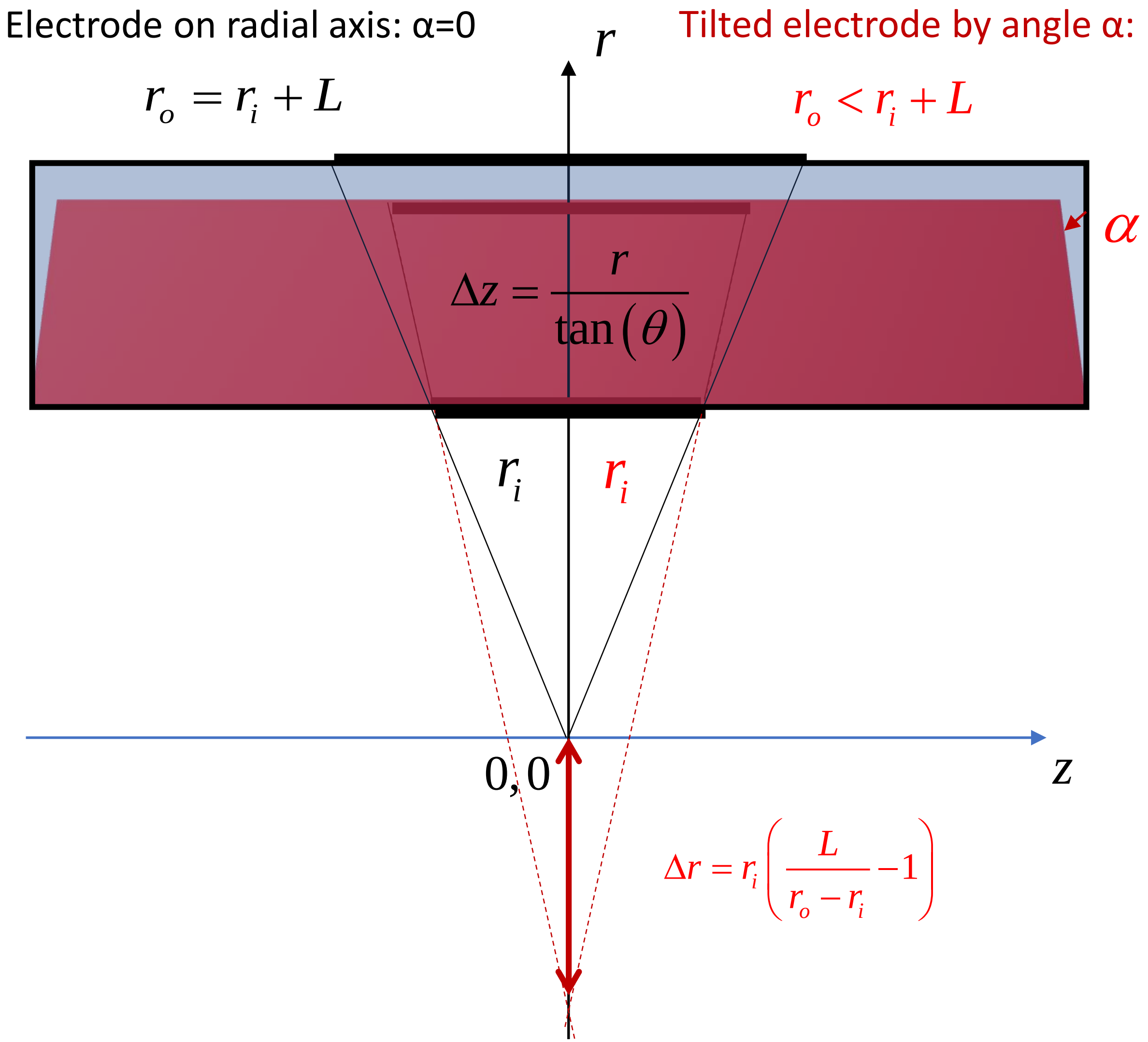
$$\theta_p = 2\arctan\left(\exp\left(-\eta_p\right)\right)$$

For FCC-ee : Ne=1536 electrodes

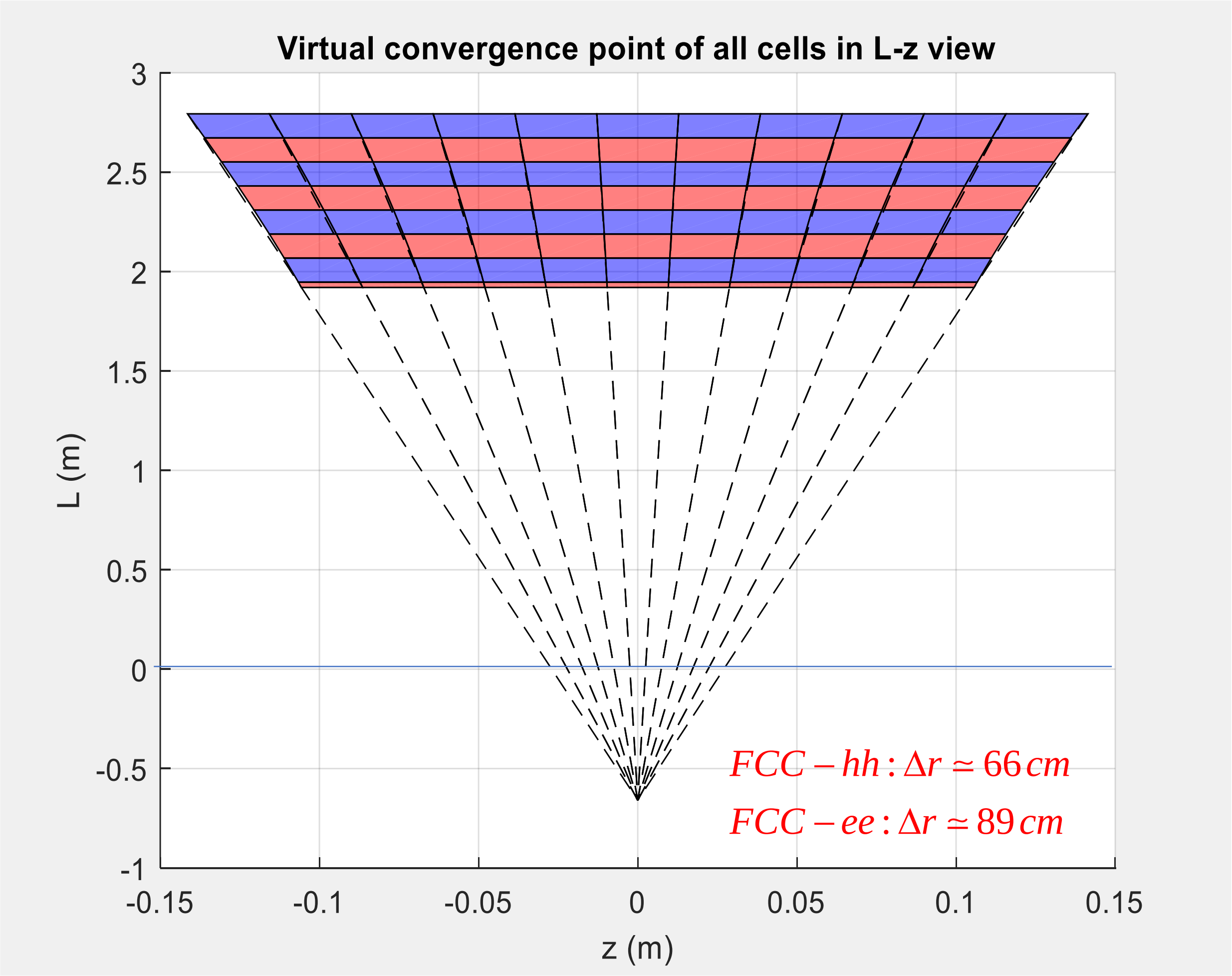
$$\theta_p = 90° + p\ \Delta\theta$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{k,m,p} = \begin{cases} r_i\cos(\phi_k) + L_m\cos(\phi_k + \alpha) \\ r_i\sin(\phi_k) + L_m\sin(\phi_k + \alpha) \\ r_m / \tan(\theta_p) \end{cases}$$

# Virtual convergence point of the cells



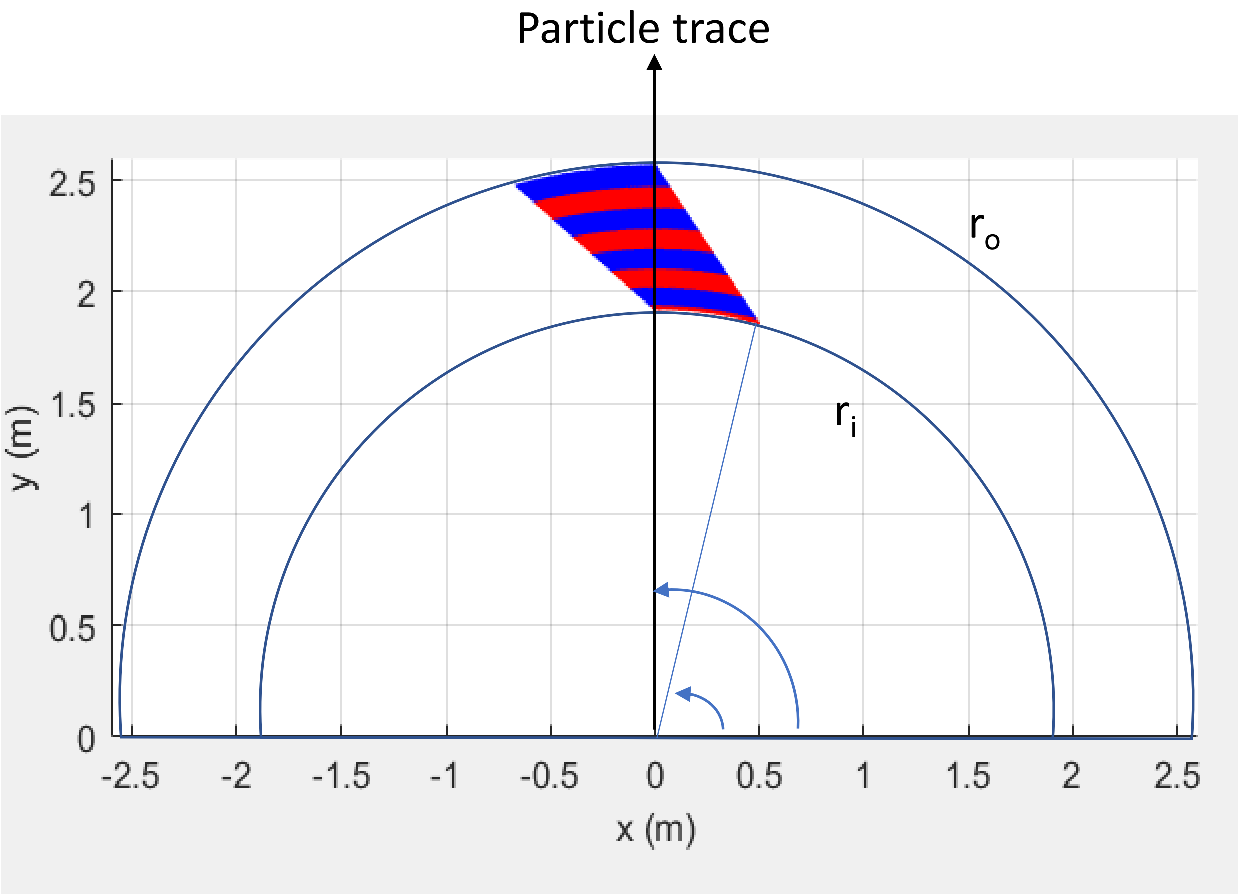

Plot coming from Matlab simulation for FCC-hh




Can be usefull to check the proper geometry of the cells during detector installation

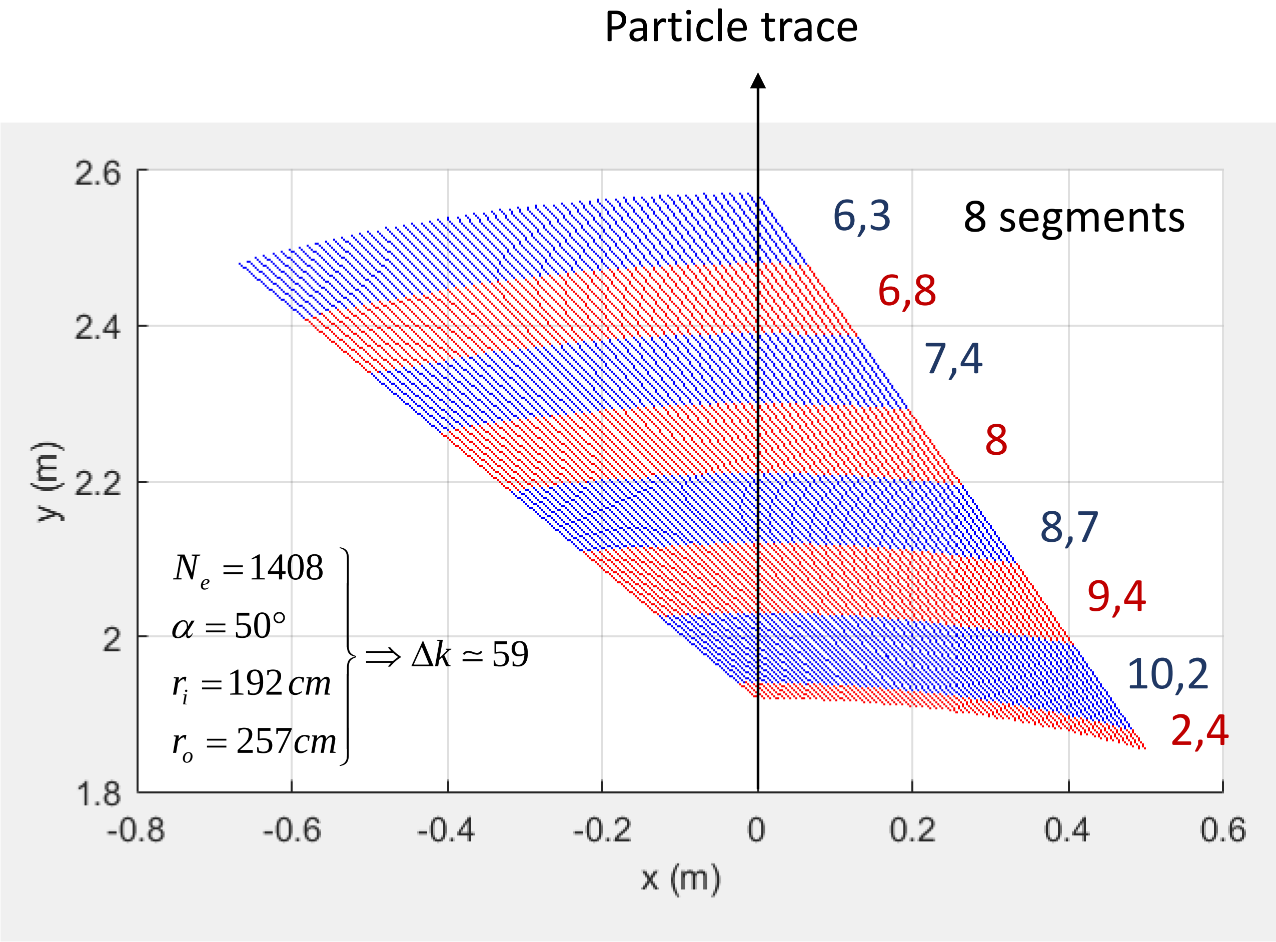
# Some details on cells properties related to their lengths

# Electrodes crossings along a particle trace for FCC-hh



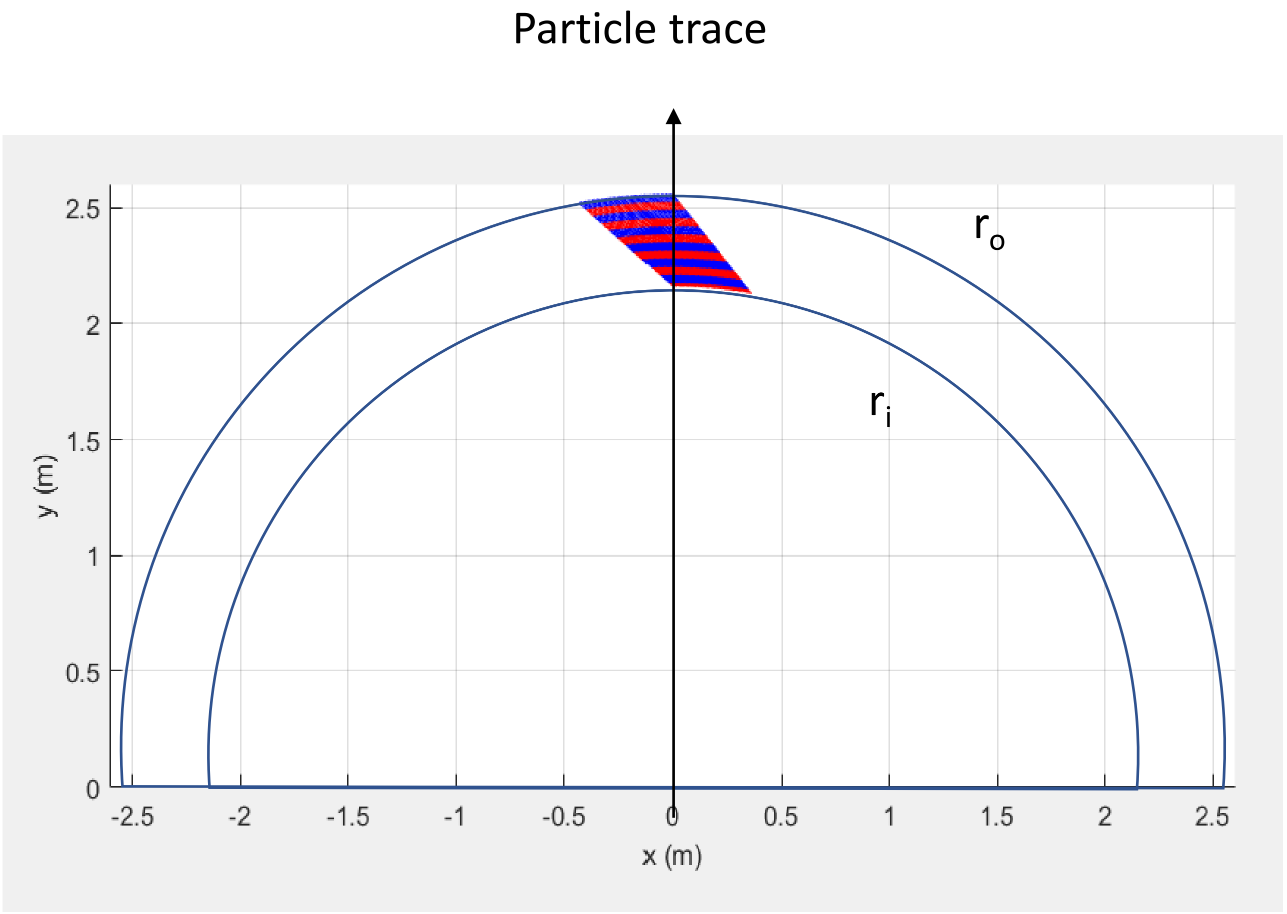

Matlab front view of a part of barrel
with 1408 electrodes for the whole barrel

$$\exp\left(i\phi_k\right)\left(r_i + L\exp\left(i\alpha\right)\right) = r_o\exp\left(i\phi_{k+\Delta k}\right)$$



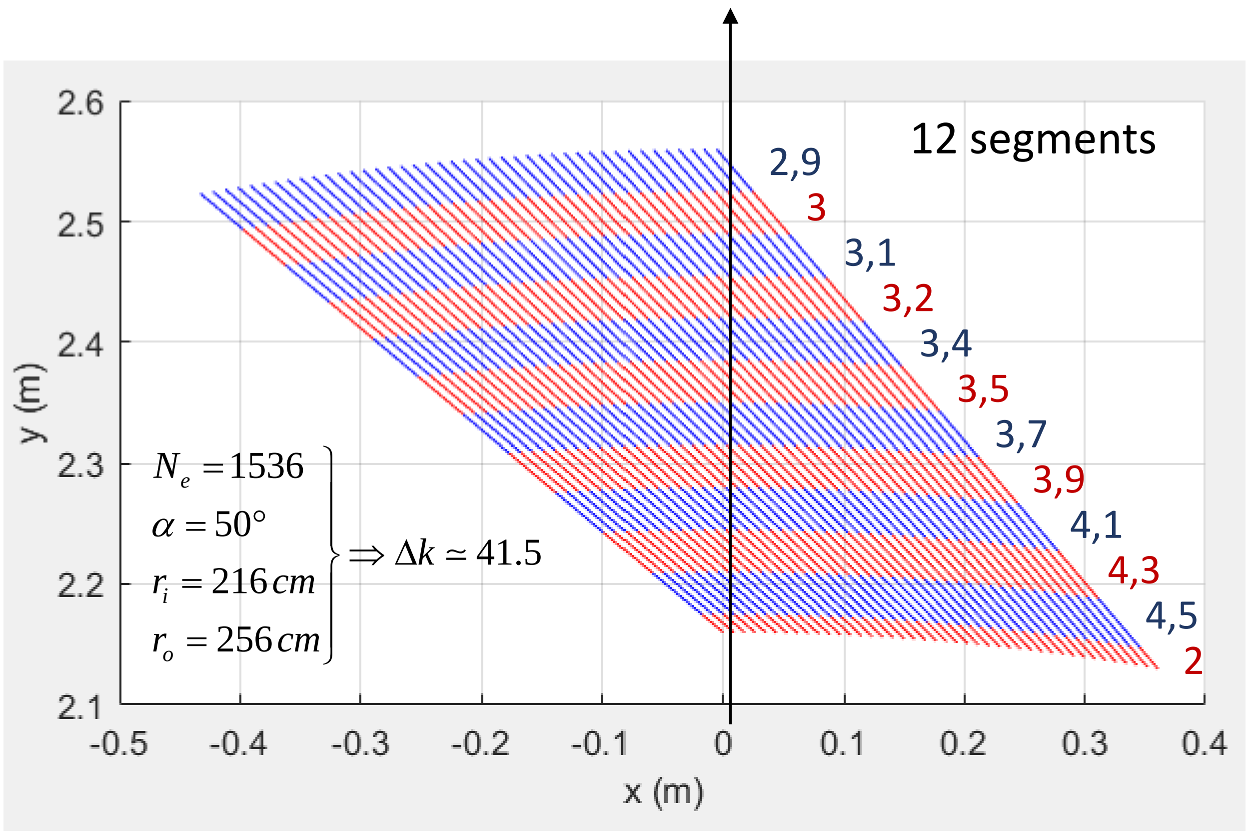

Zoom on the front view of the barrel
made of 59 electrodes necessary to cover the particle trace

# Electrodes crossings along a particle trace for FCC-ee




Matlab front view of a part of barrel
with 1536 electrodes for the whole barrel

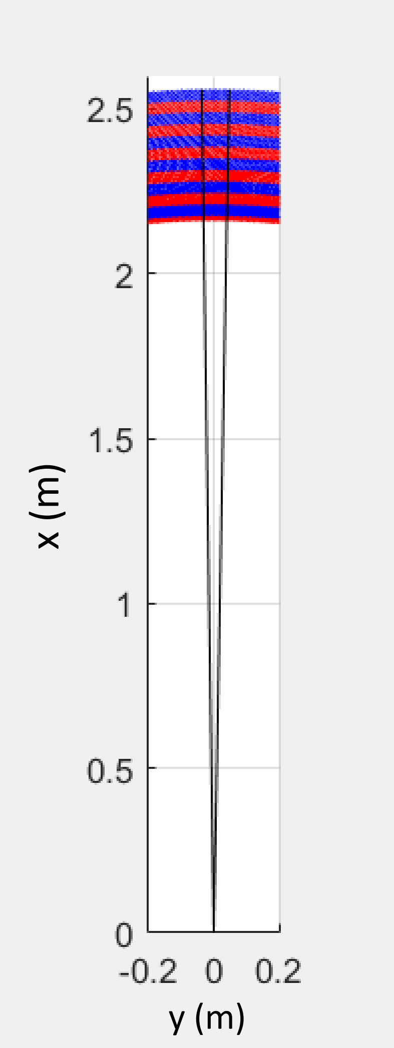
$$\exp(i\phi_k)(r_i + L\exp(i\alpha)) = r_o \exp(i\phi_{k+\Delta k})$$

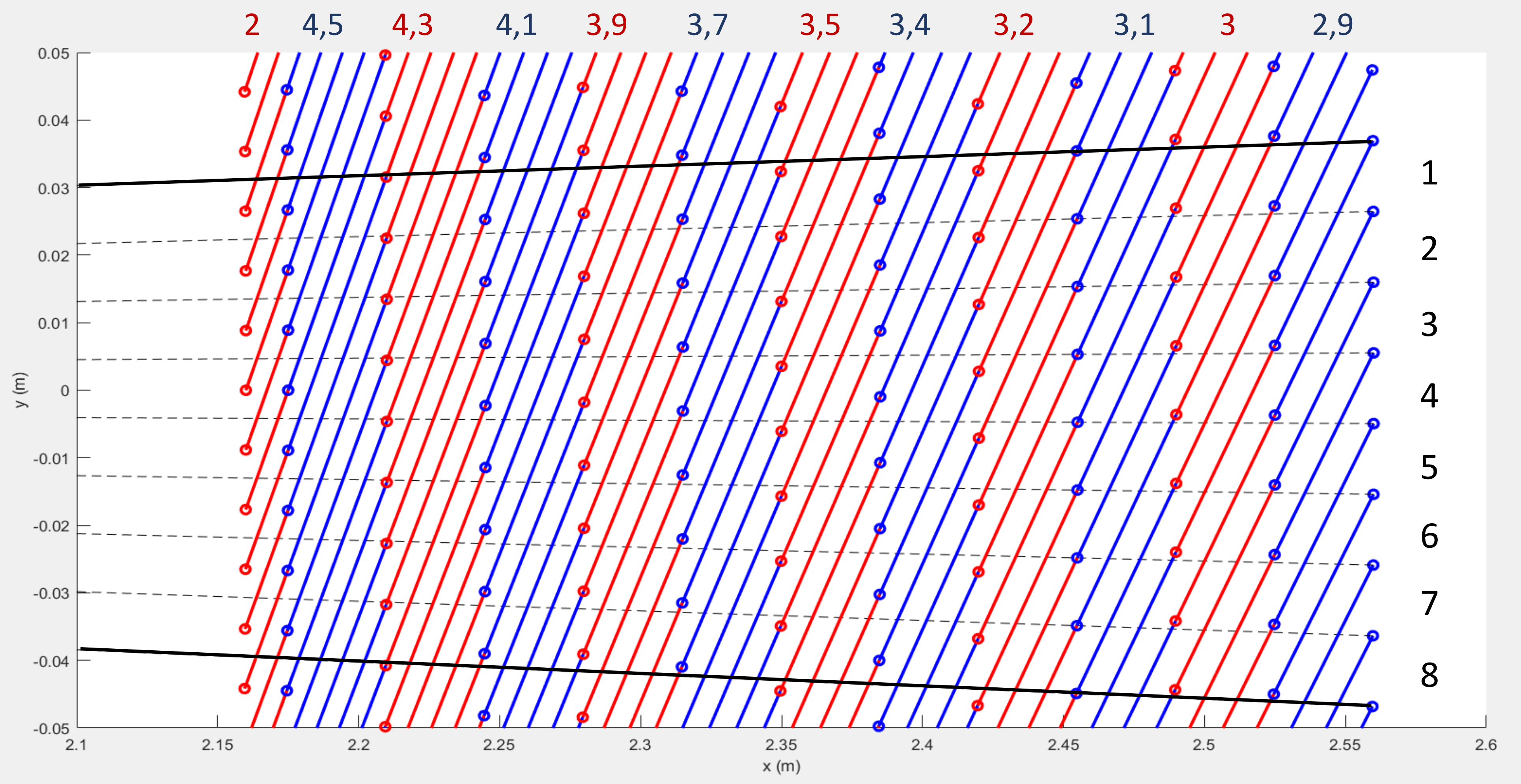



Zoom on the front view of the barrel
made of 42 electrodes necessary to cover the particle trace

# Electrodes crossings along a particle trace for FCC-ee

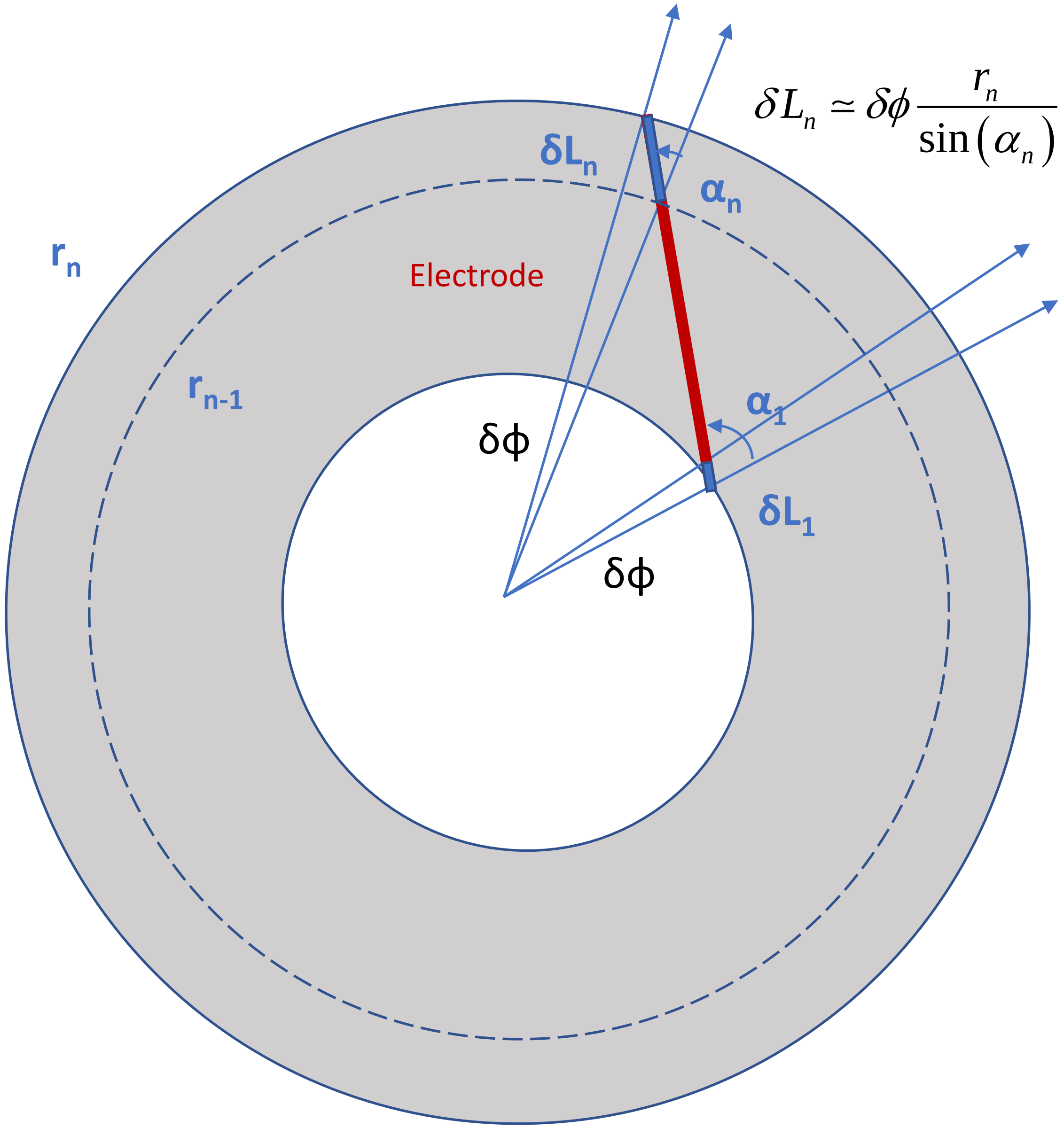
Property for a solid angle : cells are not aligned with phi




Example with 8 intervals: $\Delta\phi$ = 8 x 2pi/1536 = 32,7 mrad

# How to get aligned cells with azimuthal angle ?




To be seen under the same angle δϕ, the cell $\delta L_n$ has to be longer than $\delta L_1$ because :

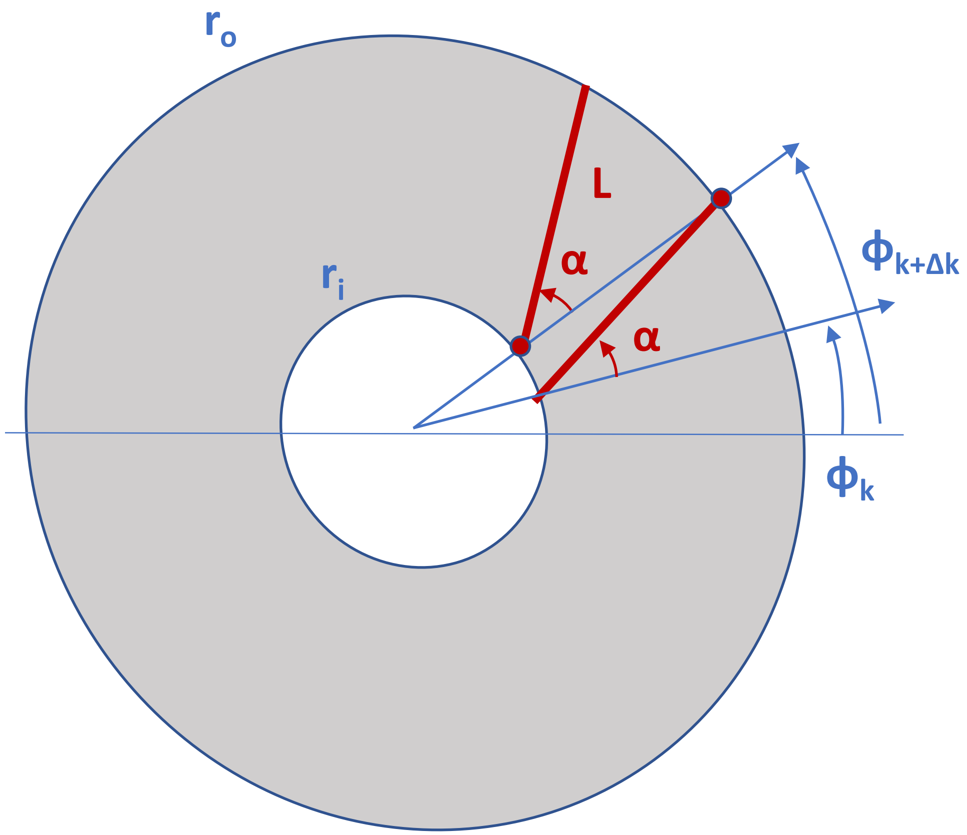
- It is further apart

  $r_n > r_1$

- Its angle $\alpha_n$ with axial direction is smaller than $\alpha_1$

  $\alpha_n = \alpha_1 - (n-1)\delta\phi < \alpha_1$

# Relation between cell's crossings and length



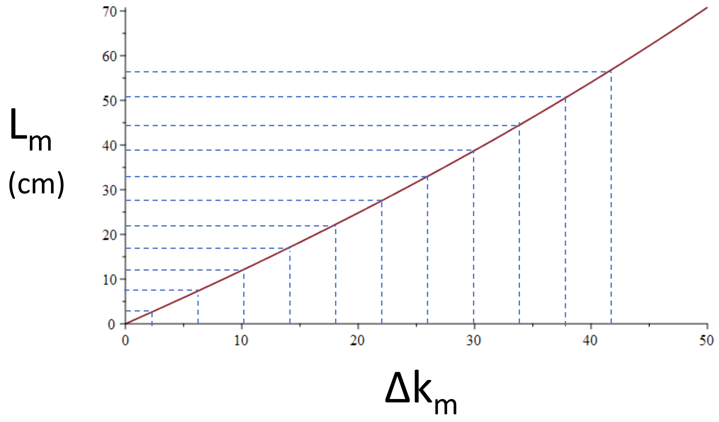

Radial view of the EMB

$$\exp(i\phi_k)(r_i + L\exp(i\alpha)) = r_o \exp(i\phi_{k+\Delta k}) \Rightarrow r_i + L\exp(i\alpha) = r_o \exp(i\phi_{k+\Delta k} - i\phi_k)$$

$$\phi_k = k\frac{2\pi}{N_e} \Rightarrow \exp\left(i\,\Delta k\frac{2\pi}{N_e}\right) = \frac{r_i + L\exp(i\alpha)}{r_o} \Rightarrow \begin{cases} \Delta k = \dfrac{N_e}{2\pi}\arctan\left(\dfrac{L\sin(\alpha)}{r_i + L\cos(\alpha)}\right) \\ L = \dfrac{r_i}{\sin(\alpha)\operatorname{cotan}\left(\Delta k\dfrac{2\pi}{N_e}\right) - \cos(\alpha)} \end{cases}$$

With $\Delta k_m$ being the cumulated crossings for the m first cells:

$$L_m = \sum_{n=1}^{m}\delta L_n = \frac{r_i}{\sin(\alpha)\operatorname{cotan}\left(\Delta k_m\dfrac{2\pi}{N_e}\right) - \cos(\alpha)}$$

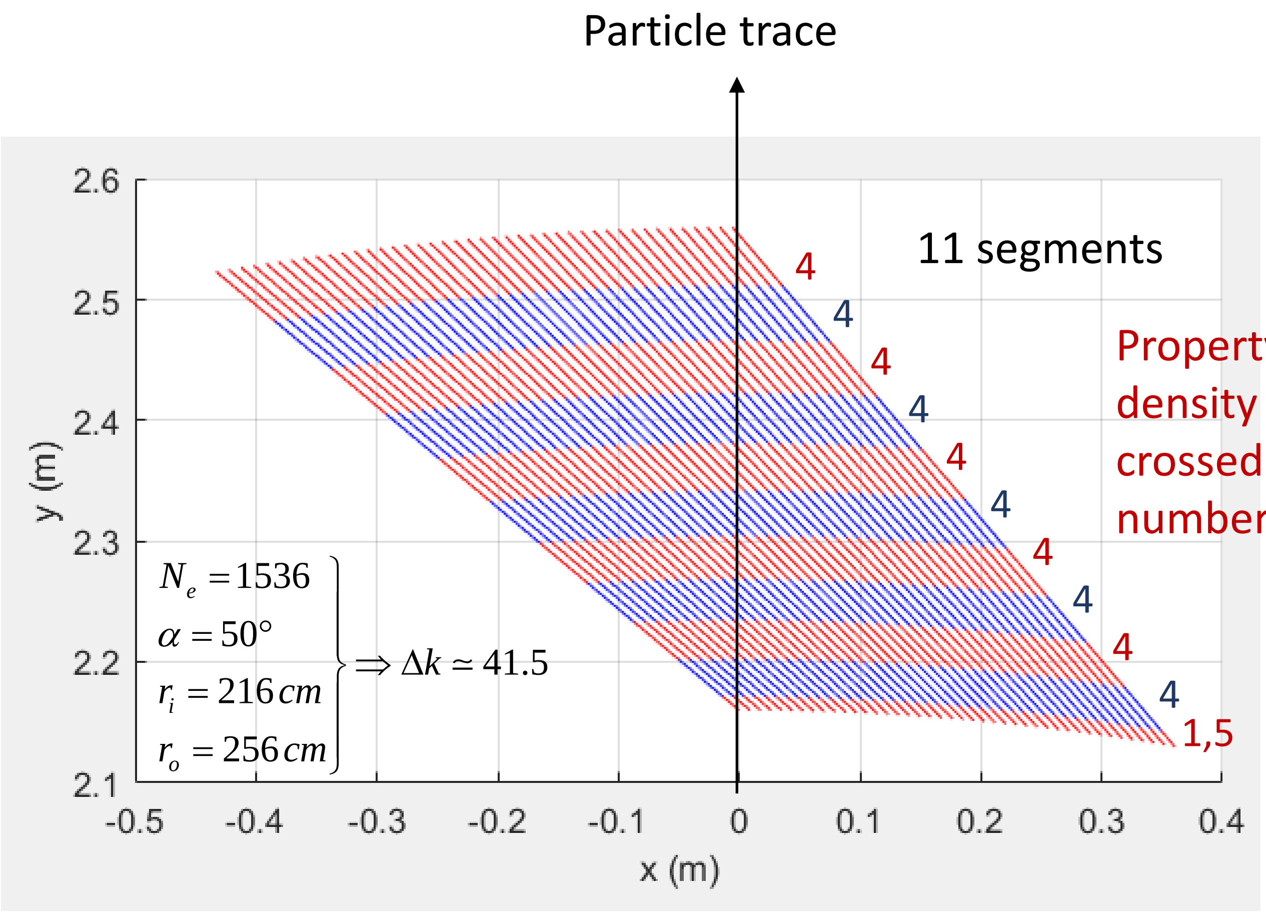



$N_e$=1536
α=50°
$r_i$=216cm

# Constant crossings with present FCC-ee geometry

For FCC-ee: $r_i$ = 216cm
11 cells

| $\Delta r_m\,(cm)$ | $r_m\,(cm)$ | $L_m\,(cm)$ | $\Delta L_m\,(cm)$ |
|---|---|---|---|
| | 256 | 56,5 | |
| +4,8 | | | +6,4 |
| | 251,2 | 50,1 | |
| +4,6 | | | +6,1 |
| | 246,6 | 44 | |
| +4,3 | | | +5,9 |
| | 242,3 | 38,1 | |
| +4,1 | | | +5,7 |
| | 238,1 | 32,4 | |
| +3,9 | | | +5,5 |
| | 234,2 | 26,9 | |
| +3,7 | | | +5,3 |
| | 230,4 | 21,6 | |
| +3,6 | | | +5,2 |
| | 226,9 | 16,4 | |
| +3,4 | | | +5 |
| | 223,5 | 11,4 | |
| +3,2 | | | +4,9 |
| | 220,2 | 6,5 | |
| +3,1 | | | +4,7 |
| | 217,1 | 1,8 | |
| +1,1 | | | +1,8 |
| | 216 | 0 | |



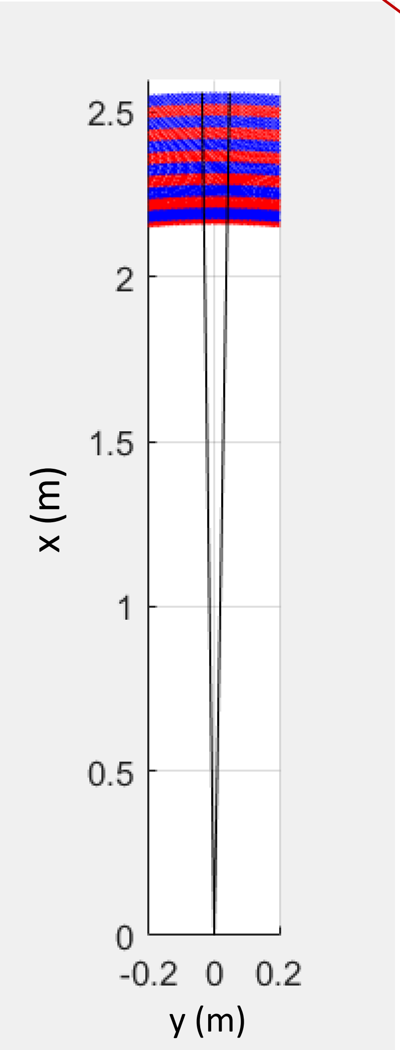

Property : constant density of cells crossed in depth if the numbers are integers

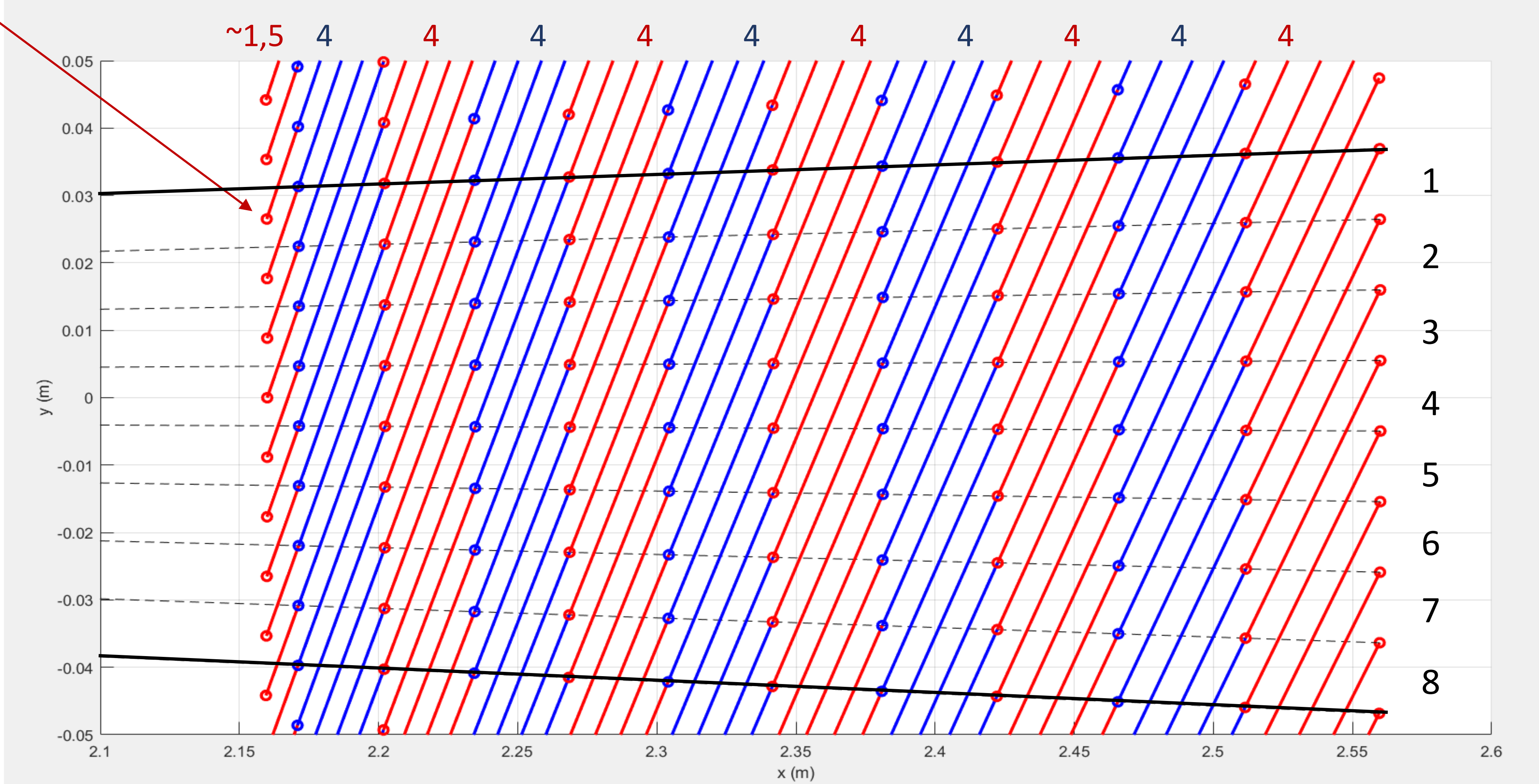
Zoom of the part of the barrel
made of 42 electrodes to cover the particle trace.

# Fractional cells crossing for the presampler

With present geometry, the 1st cell crossings is not an integer number

Property for a solid angle : segments are aligned with phi

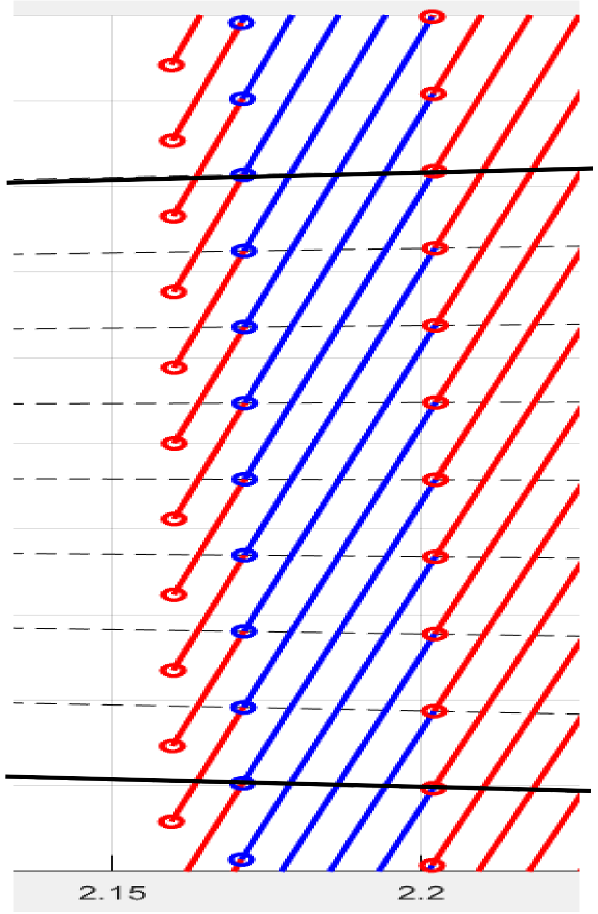



Example with 8 intervals: Δϕ = 8 x 2pi/1536 = 32,7 mrad

# Possible new electrodes segmentation for FCC-ee

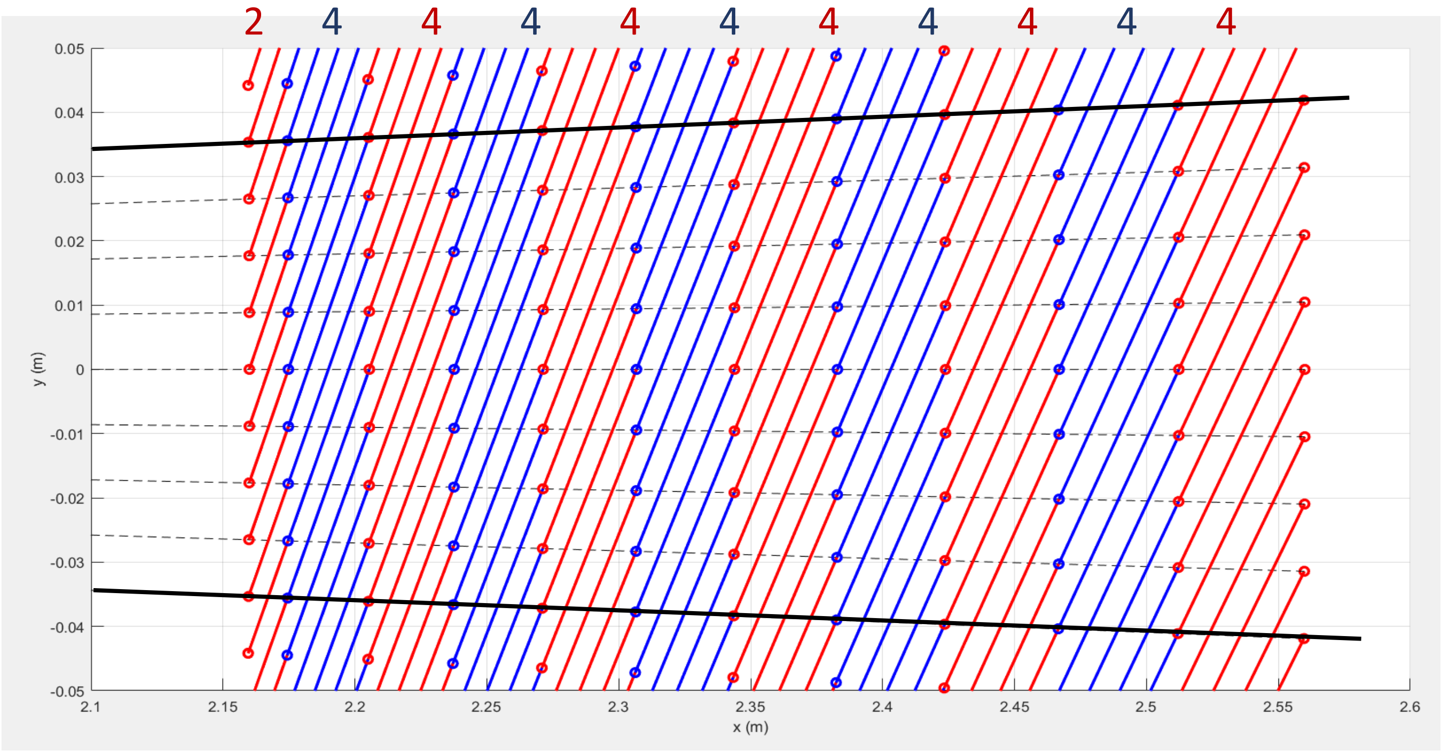
With present geometry, the 1st cell crossings is not an integer number




With 4 cells crossings along particles paths for each segment, and 10 segments for an electrode, the remaining space for the first segment is fixed.

If one wants the 1st segment to have 2 cells crossings along the particles paths, one needs:

- Either to increase the electrodes tilt by ~ 0,4°
- Or to increase the barrel depth by ~ 6 mm




Integer nb of electrodes along particles paths for all segments

# Electrodes grouping strategy

- N electrodes are crossed by an axial line

For FCC-ee: N=42 with presampler

- 2 electrodes dedicated to the short presampler

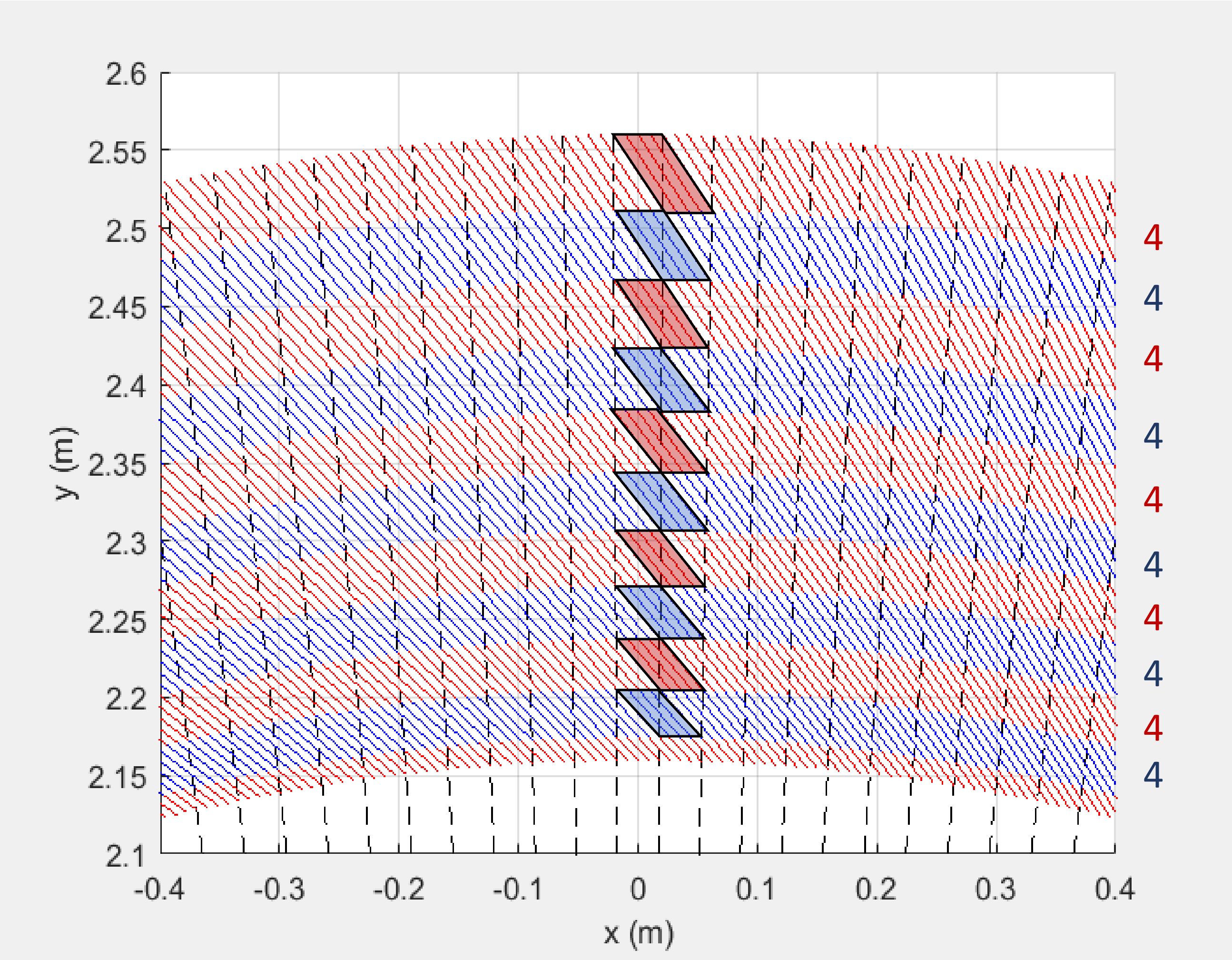
  $\Rightarrow$ N=40

- M segments along a strip (leaving out the presampler)

$\Rightarrow$ the axial line can cross the same number of electrodes in each sampling, only if N/M is an integer

- With M = 10 segments per electrode
  => N/M = 4 crossings per sampling

- With M = 8 segments per electrode
  => N/M = 5 crossings per sampling




Sampling group of 4 cells in the same segment

# Example of grouping by 4

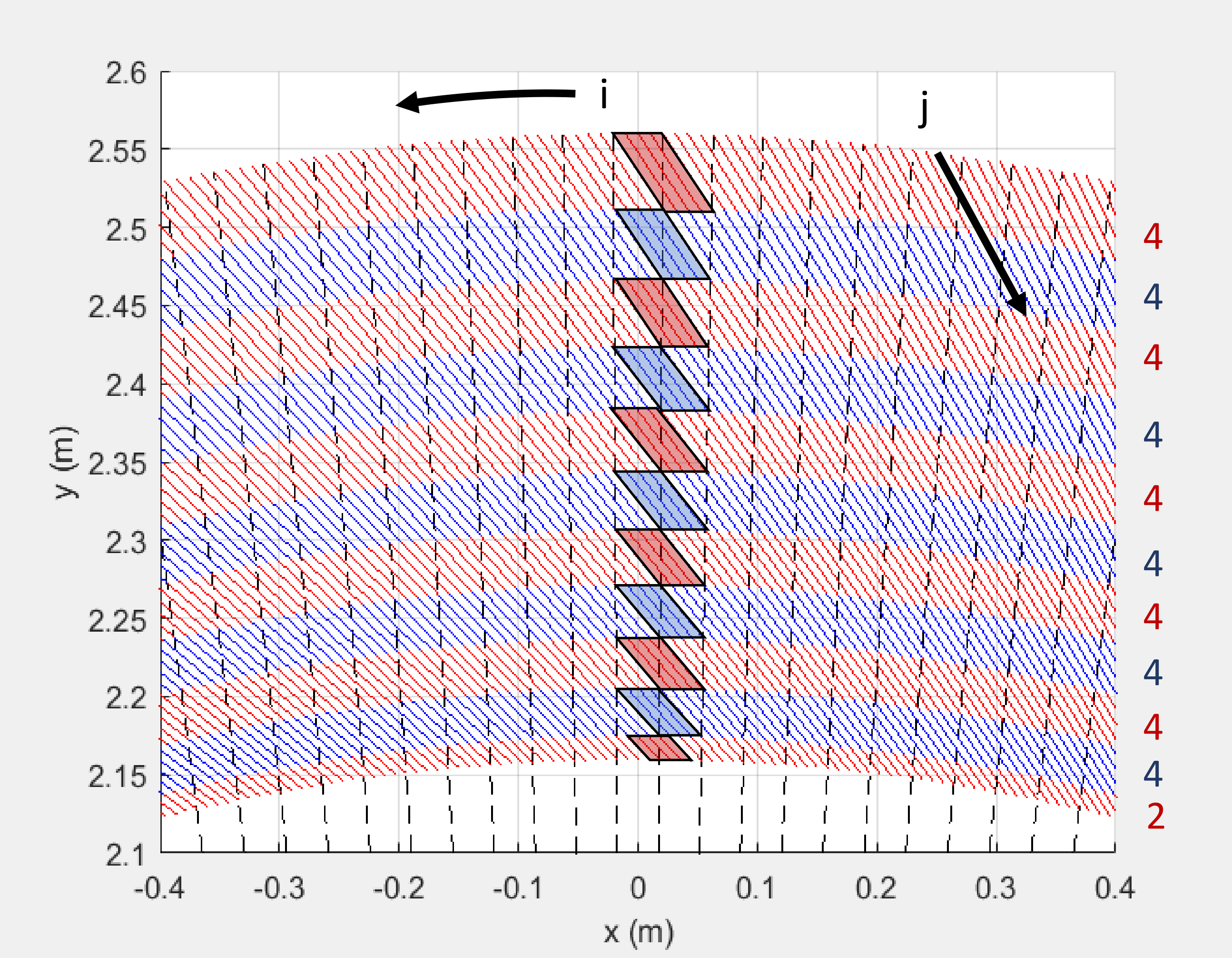
**Convenient for software and pattern recognition:**

- Group cells in azimuth by 4 (physically or numerically)
- Use i to label groups of 4 electrodes along phi.
- Defining index i which runs from 1 to 1536/4
- Use j to label group of segments along the electrode.
- Defining index j which runs from 1 to 10
  from outside to inside (leaving out the presampler)
- Use k to label cells along z (not shown)

If [i,j,k] defines a cell in space:
Then all [i+p, j+p, k] are all falling in the same solid angle, and their energy contents can be readily added in a cluster.

Typical size of the largest cell is LxH ~ 4,2 x 4,8 cm
Typical size of the presampler is LxH ~ 3,5 x 1,5 cm

Total of 1536/4*12=4608 cells for 2pi along phi

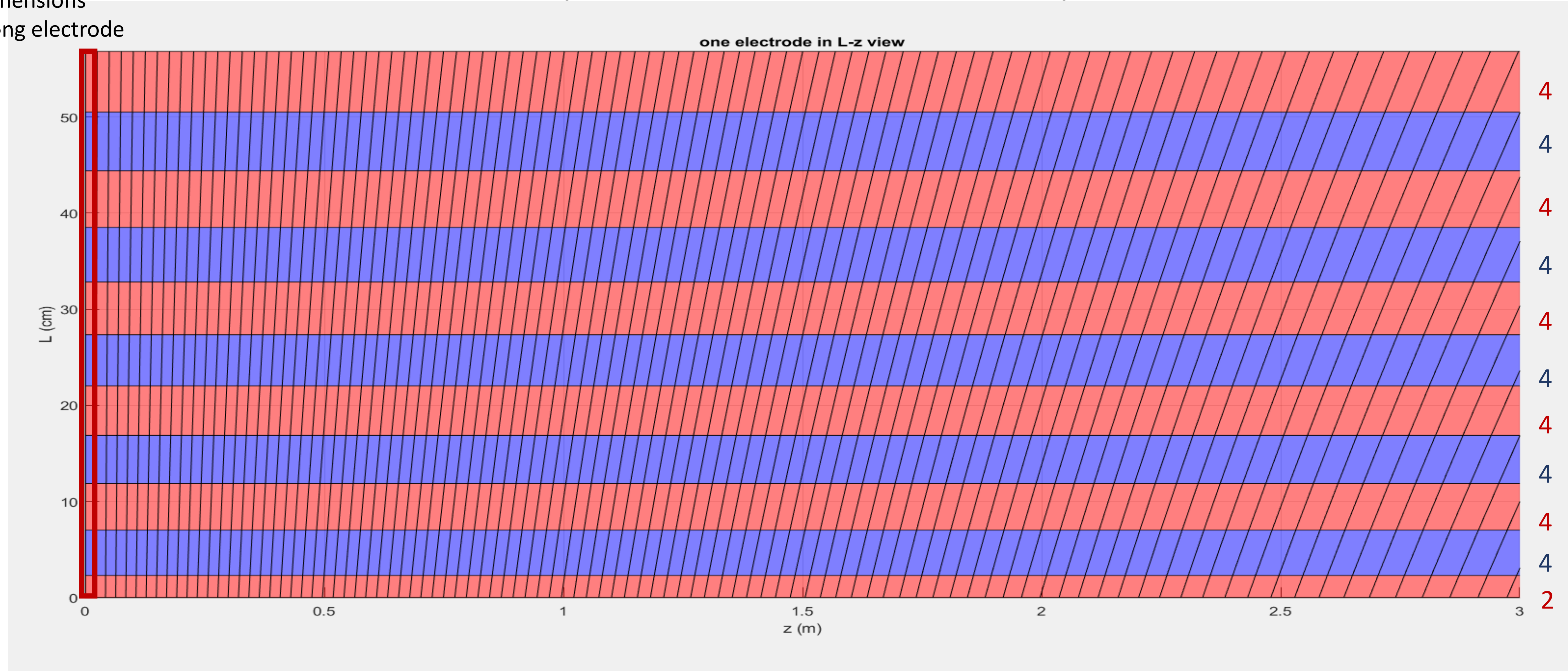



Total of 12 cells, including 1 presampler and 2 subdivisions along z for the 2nd segment of the electrode

# Possible new electrodes segmentation for FCC-ee

Longitudinal view (without double cell for 2nd segment)

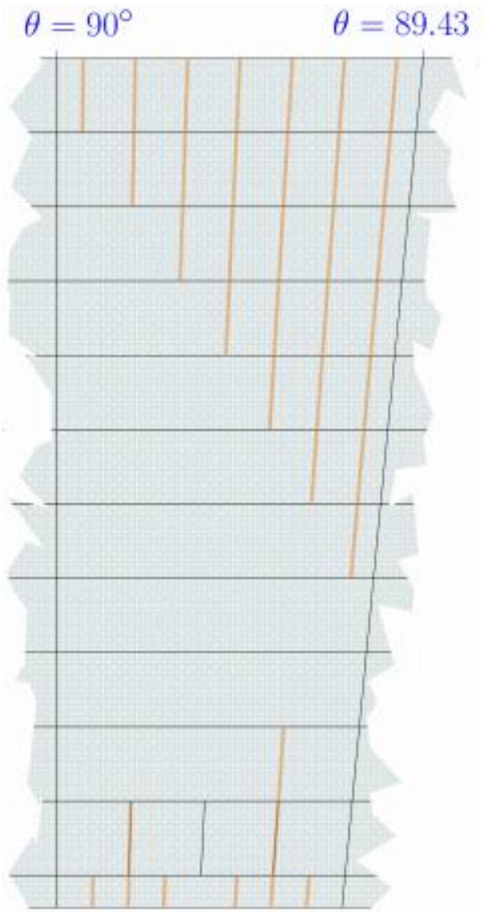
Dimensions along electrode



# Next step: Cells capacitance extraction

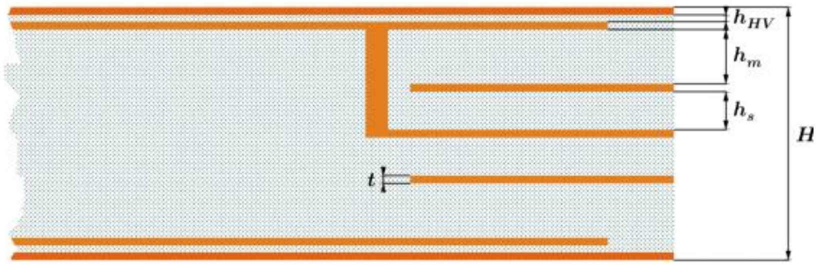
Compare different tools (FasterCap, COMSOL, Sigrity)

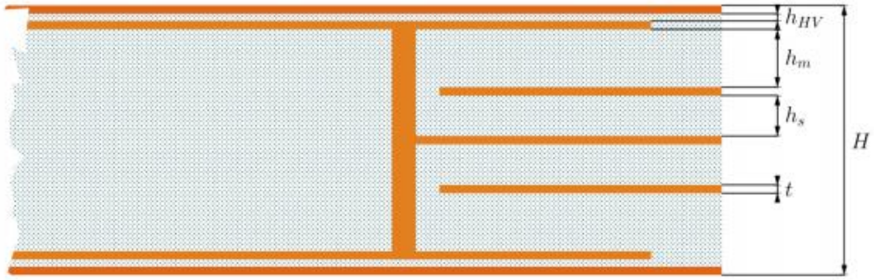
Example of a FCC-ee slice with 12 cells




Test different grouping and routing strategies

Test different layers parameters $h_{xx}$, $w_x$, t




Compare Maxwell capacitance matrix with and without routing

$$
\begin{bmatrix}
C_{11}+C_{12}+\cdots+C_{1n} & -C_{12} & \cdots & -C_{1n} \\
-C_{21} & C_{21}+C_{22}+\cdots+C_{2n} & \cdots & -C_{2n} \\
\cdots & \cdots & \cdots & \cdots \\
-C_{n1} & -C_{n2} & \cdots & C_{n1}+C_{n2}+\cdots+C_{nn}
\end{bmatrix}
$$

$H_{electrode}$= 1200 µm

$H_{absorber}$ = 2000 µm

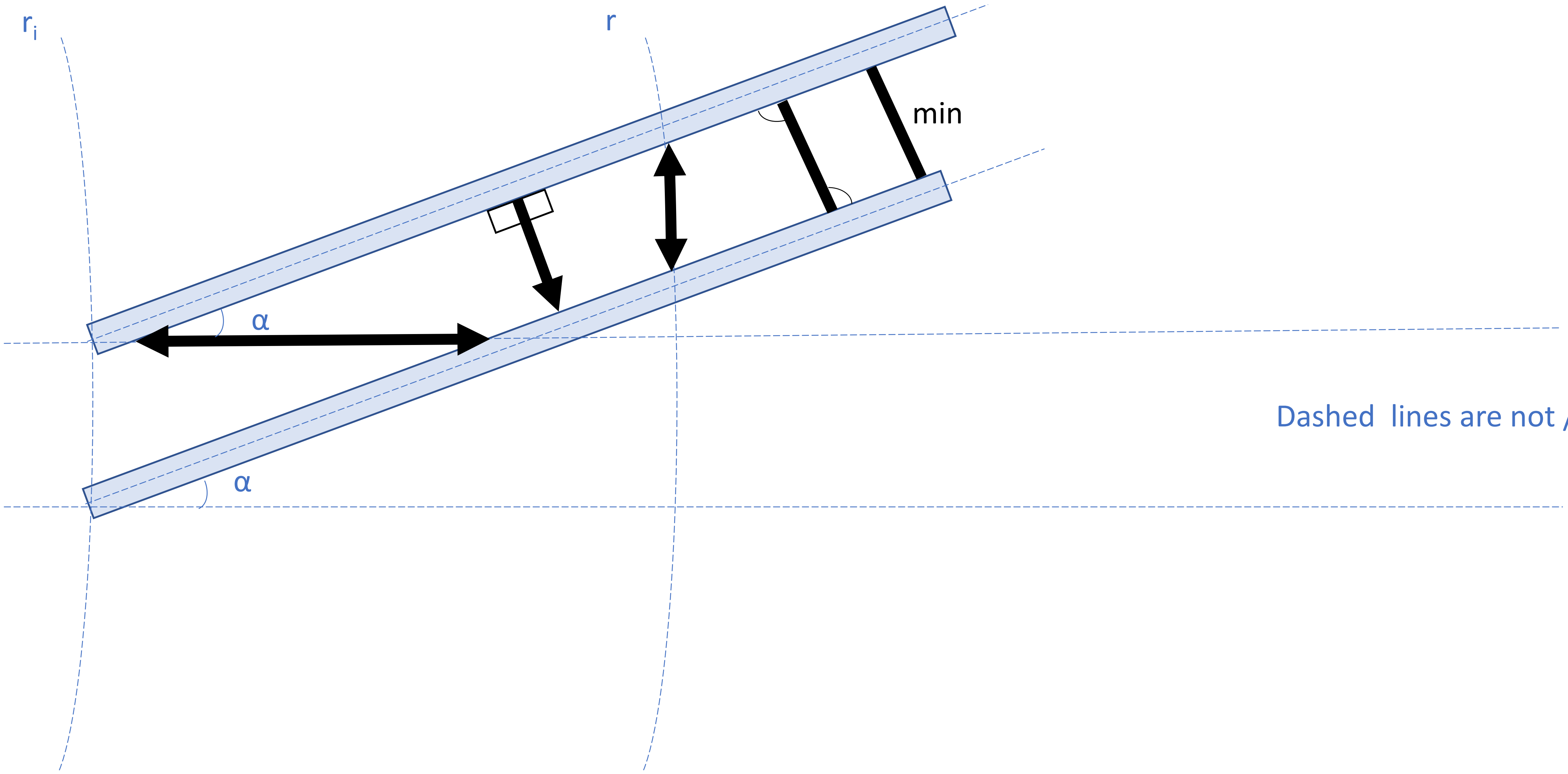
Argon gap @ $r_i$ ~ 1,24 mm

Argon gap @ $r_o$ ~ 2,39 mm

# Thank you

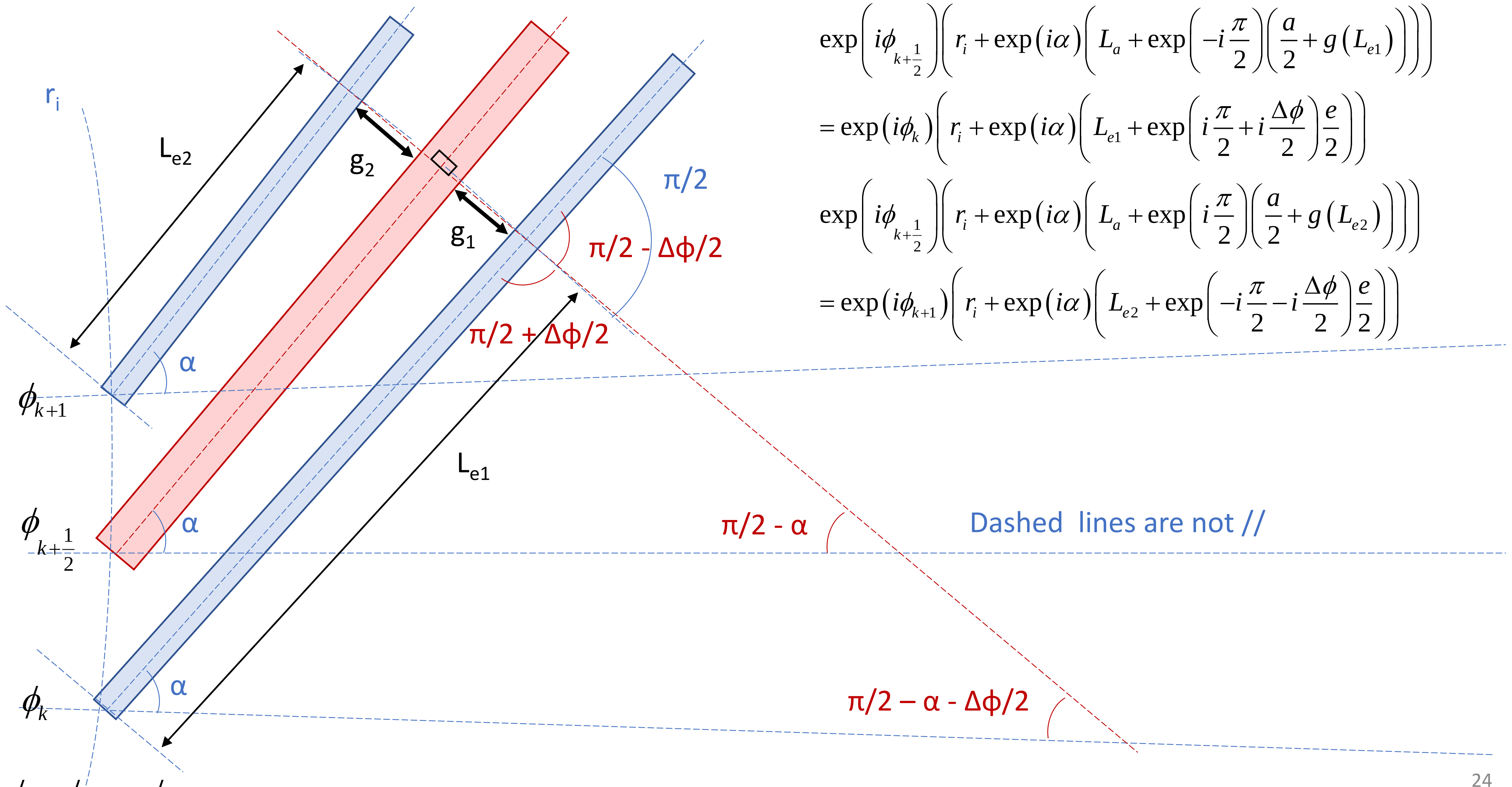
# Old slides

# Different ways to define a gap




Dashed lines are not //

# Good way to define a gap




$$\exp\left(i\phi_{k+\frac{1}{2}}\right)\left(r_i+\exp(i\alpha)\left(L_a+\exp\left(-i\frac{\pi}{2}\right)\left(\frac{a}{2}+g\left(L_{e1}\right)\right)\right)\right)$$

$$=\exp\left(i\phi_k\right)\left(r_i+\exp(i\alpha)\left(L_{e1}+\exp\left(i\frac{\pi}{2}+i\frac{\Delta\phi}{2}\right)\frac{e}{2}\right)\right)$$

$$\exp\left(i\phi_{k+\frac{1}{2}}\right)\left(r_i+\exp(i\alpha)\left(L_a+\exp\left(i\frac{\pi}{2}\right)\left(\frac{a}{2}+g\left(L_{e2}\right)\right)\right)\right)$$

$$=\exp\left(i\phi_{k+1}\right)\left(r_i+\exp(i\alpha)\left(L_{e2}+\exp\left(-i\frac{\pi}{2}-i\frac{\Delta\phi}{2}\right)\frac{e}{2}\right)\right)$$

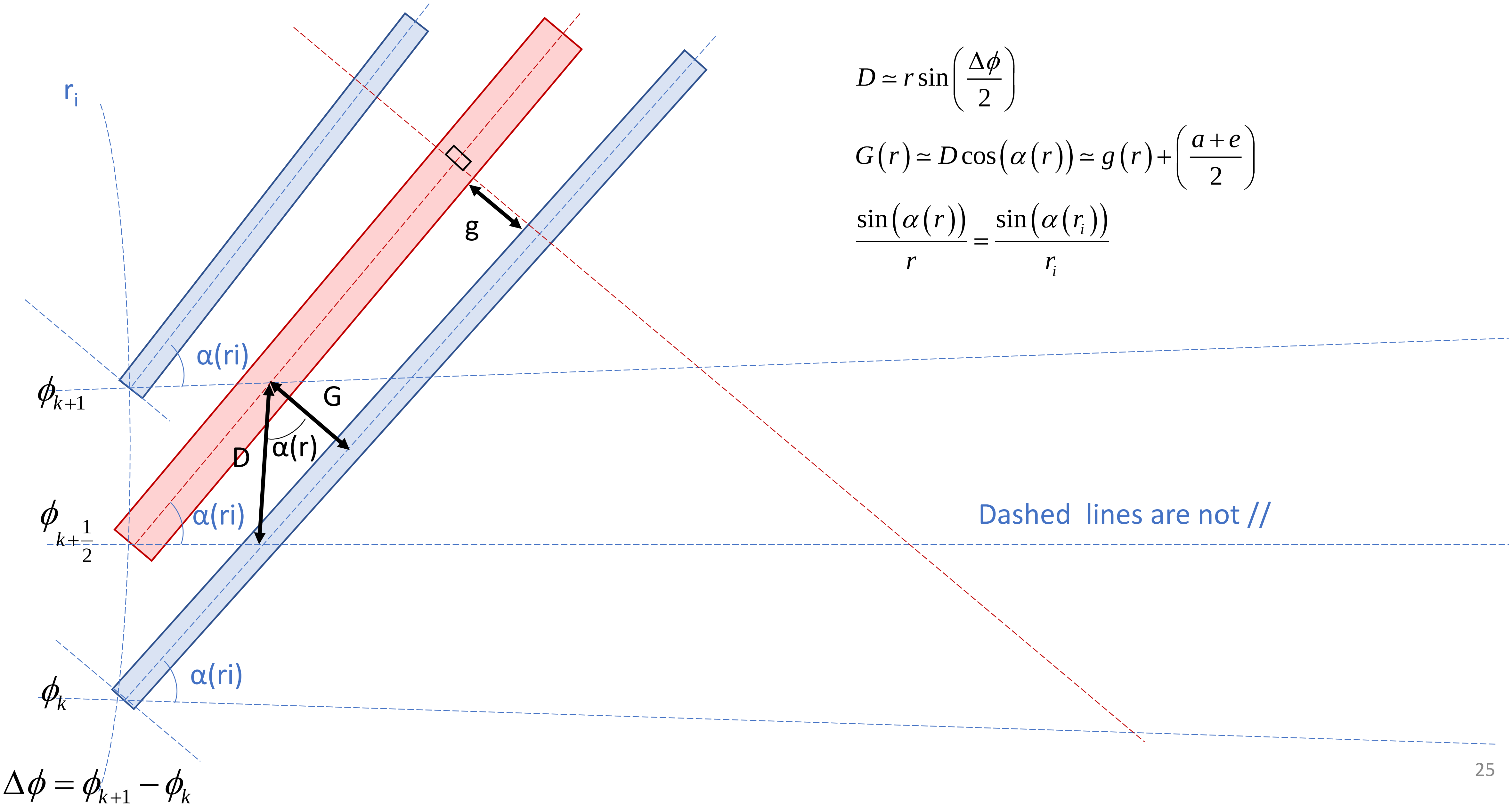
$\phi_{k+1}$

$\phi_{k+\frac{1}{2}}$

$\phi_k$

$\Delta\phi=\phi_{k+1}-\phi_k$

# Good way to define a gap (good approximation)

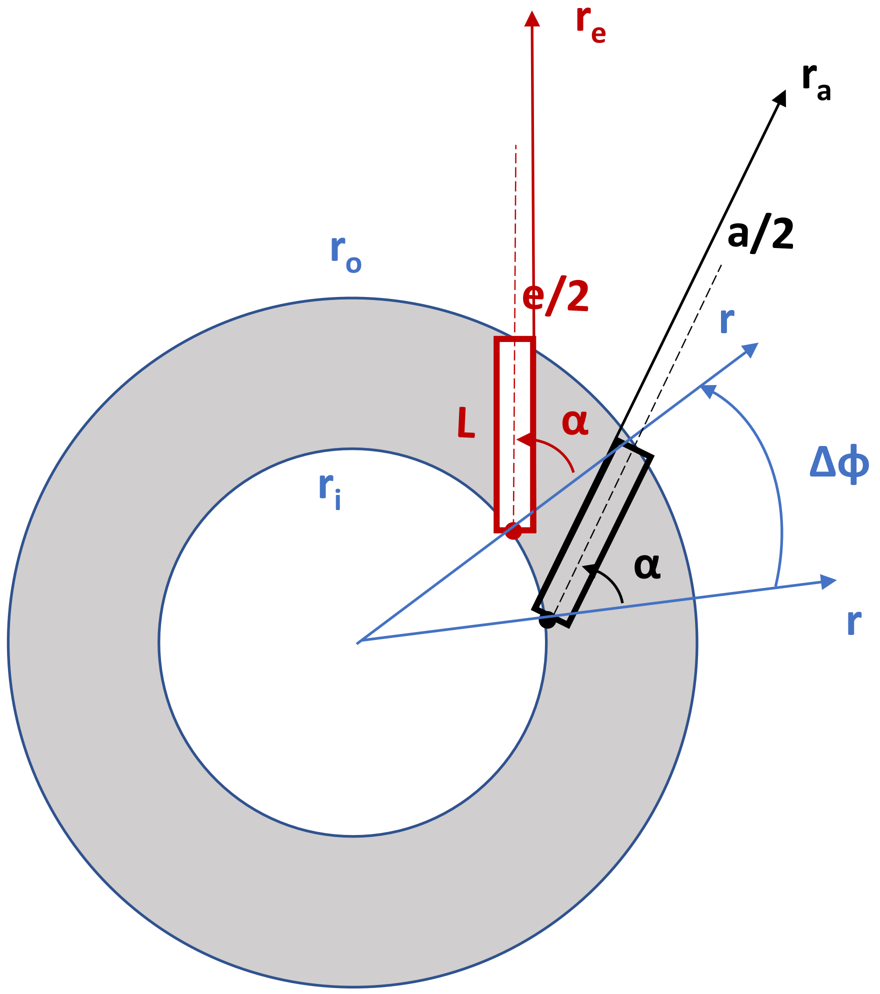



$$D \simeq r \sin\left(\frac{\Delta\phi}{2}\right)$$

$$G(r) \simeq D\cos(\alpha(r)) \simeq g(r) + \left(\frac{a+e}{2}\right)$$

$$\frac{\sin(\alpha(r))}{r} = \frac{\sin(\alpha(r_i))}{r_i}$$

# Distance between electrode and absorber




Radial view of the EMB

$$\Delta\phi = \frac{2\pi}{2N_e} = \frac{\pi}{N_e}$$

$$\begin{cases} \vec{r_a} : r_i + \frac{a}{2}\exp\left(i\alpha + i\frac{\pi}{2}\right) + r_a \exp(i\alpha) \\ \vec{r_e} : \exp(i\Delta\phi)\left(r_i + \frac{e}{2}\exp\left(i\alpha - i\frac{\pi}{2}\right) + r_e \exp(i\alpha)\right) \end{cases}$$

$$D = \min\left(\left\|\vec{r_a} - \vec{r_e}\right\|\right)$$

For each $r_e$, one solution D => $r_{a0}(r_e)$

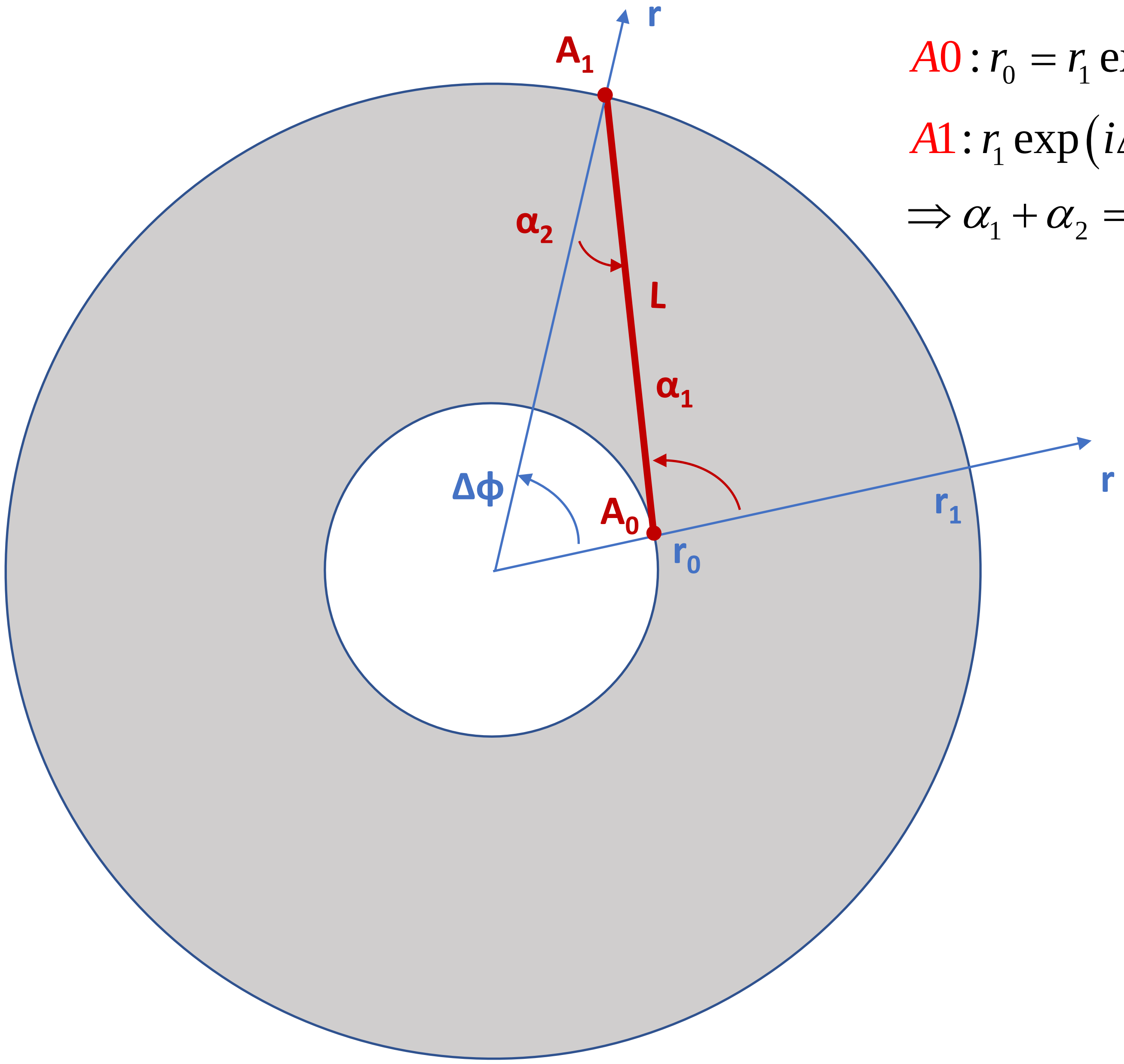
$r_{a0} < (r_o - r_i)$ => $r_e < r_{e\ max}$

e = 1,2 mm

a = 2 mm

$r_e = 0$ => D = 1,24 mm

$r_e = L = 56{,}5$ cm => D = 2,40 mm




Radial view of the EMB

$$A0: r_0 = r_1 \exp\left(i\Delta\phi\right) - L\exp\left(i\left(\Delta\phi - \alpha_2\right)\right)$$

$$A1: r_1 \exp\left(i\Delta\phi\right) = r_0 + L\exp\left(i\alpha_1\right)$$

$$\Rightarrow \alpha_1 + \alpha_2 = \Delta\phi$$