L1.4-1

Insert Misalignment in Coaxial Gyrotrons: Physical Effects and Numerical Treatment

5th ITG International Vacuum Electronics Workshop 2016

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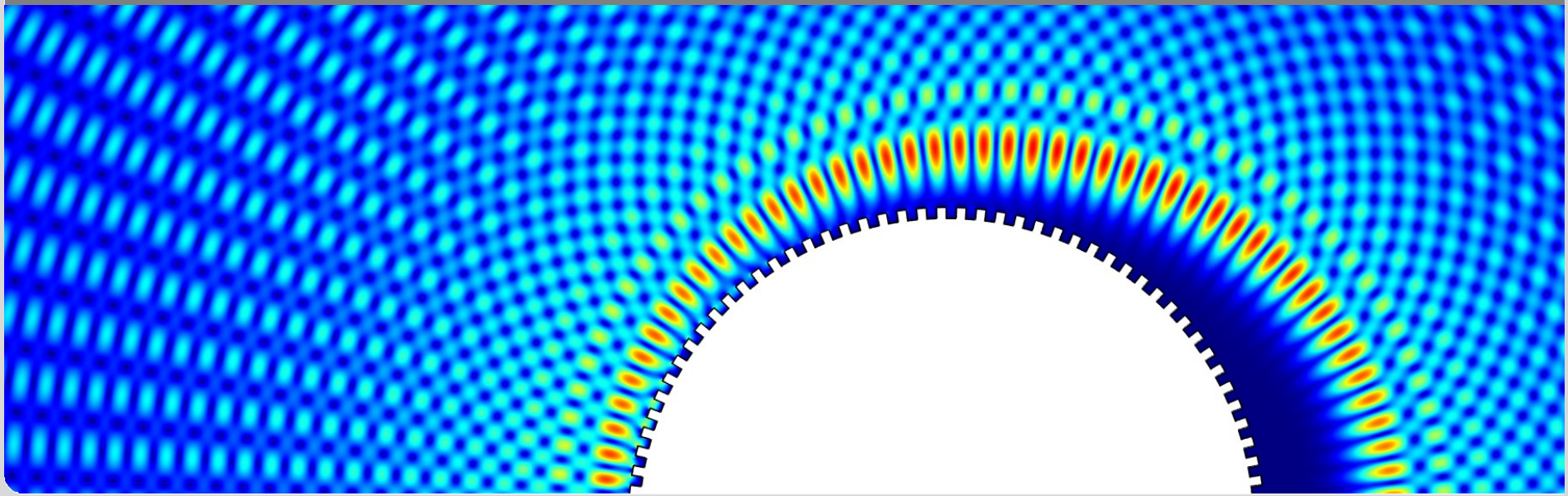

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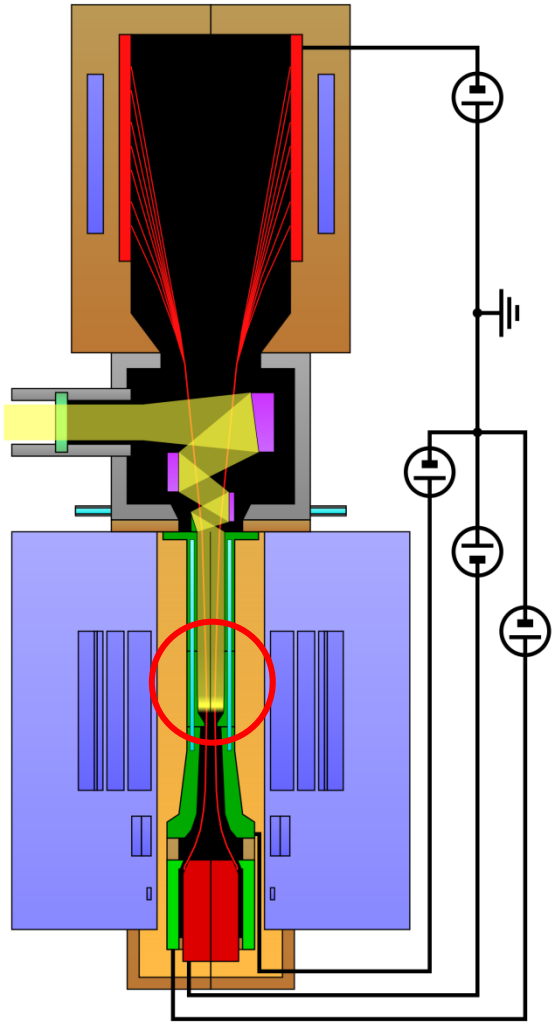
Highly Overmoded Cavities

- Microwave field generated in the gyrotron cavity
  → ohmic losses on the metallic wall

$$P_\Omega \approx \frac{2}{\chi_{mp} c} \sqrt{\frac{\pi f}{\mu_0 \sigma}} \cdot \frac{Q_{\mathrm{diff}} P_{\mathrm{out}}}{1 - \left(m/\chi_{mp}\right)^2}$$



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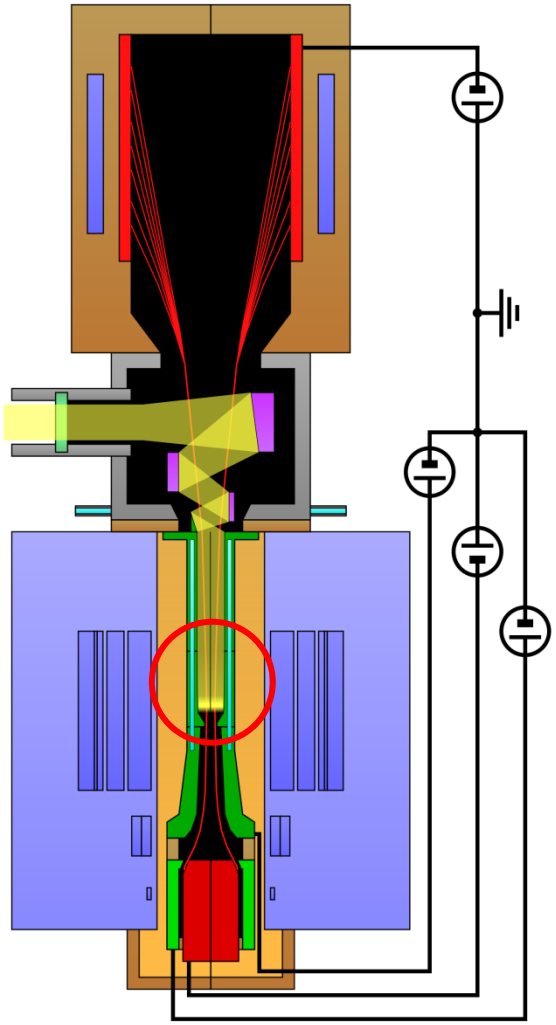

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- Limited cooling capacity per surface area
  (typical maximum loading: 2 kW/cm²)
  → large cavity radius for high power & frequ.

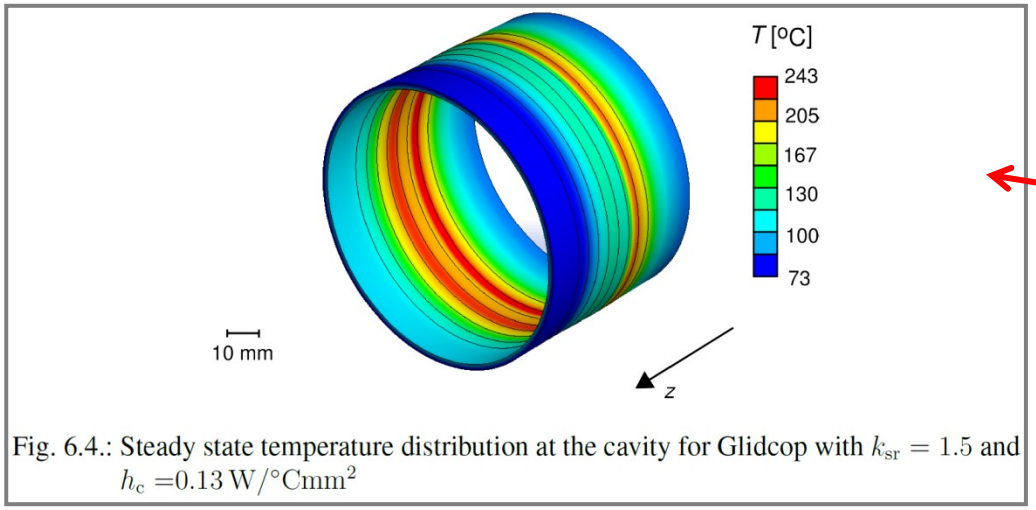
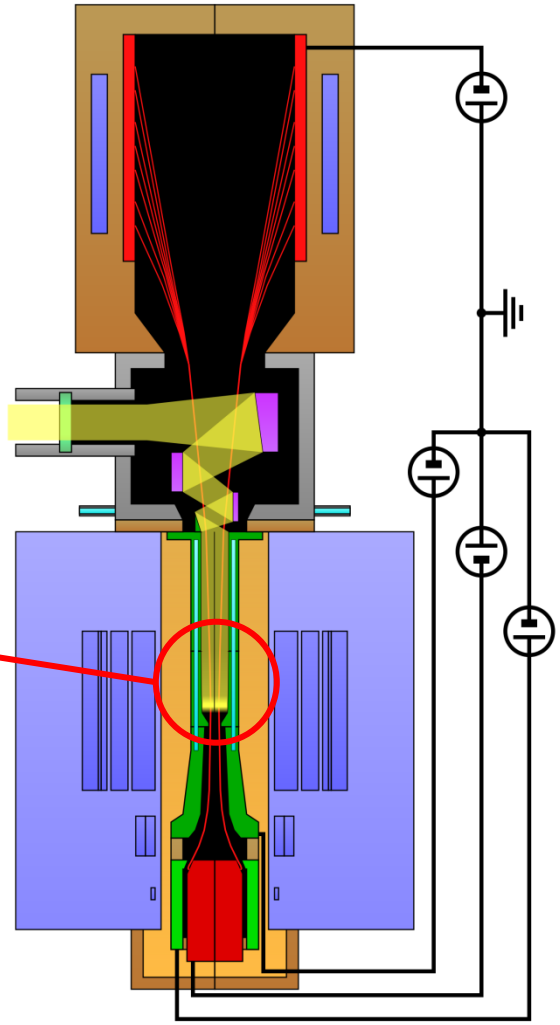


Fig. 6.4.: Steady state temperature distribution at the cavity for Glidcop with $k_{sr} = 1.5$ and $h_c = 0.13\ \mathrm{W/°Cmm^2}$

(source: PhD thesis M. Beringer, 2010)



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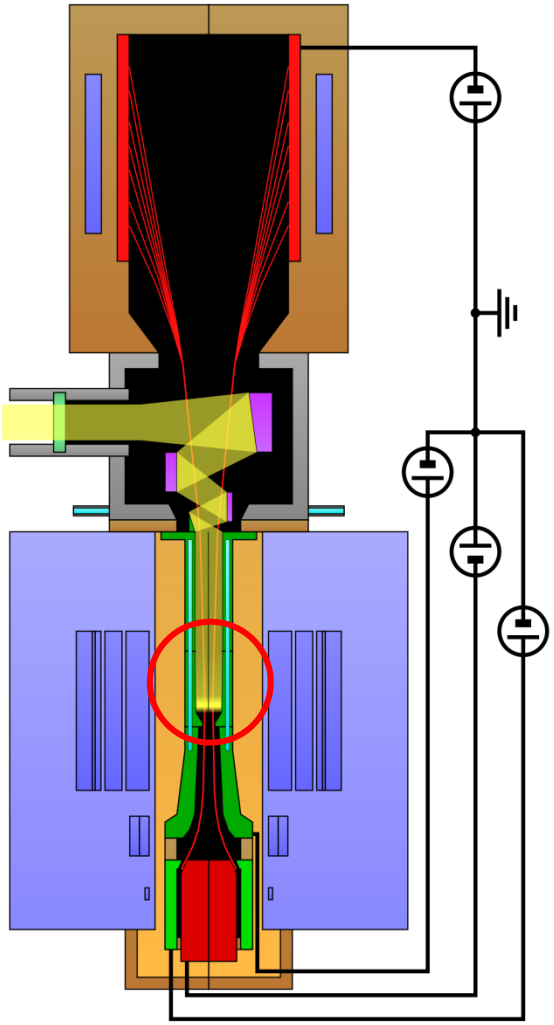
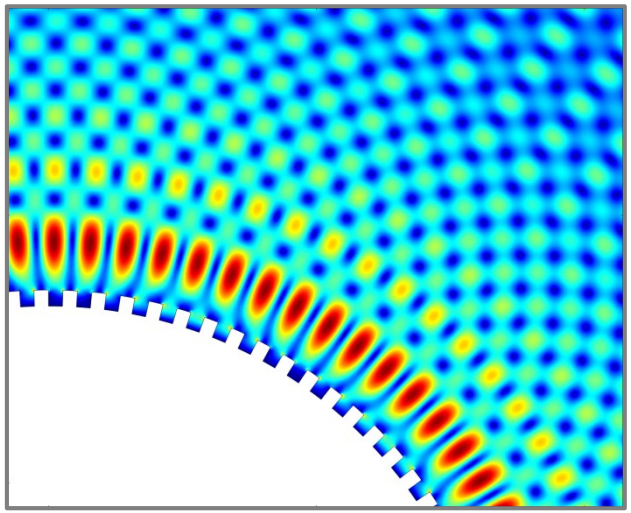
- Limited cooling capacity per surface area (typical maximum loading: 2 kW/cm²)
  → large cavity radius for high power & frequ.
- With $\omega_{\mathrm{RF}} R_{\mathrm{cav}} = \chi_{mp} c_0$, this requires high mode eigenvalues χ_{mp}
  m: azimuthal index, *p*: radial index
- Typical distance between modes: Δχ~1.5
  → spectral distance $\Delta\chi/\chi_{mp}$ decreases
  → mode competition increases
  → gyrotron operation becomes unstable

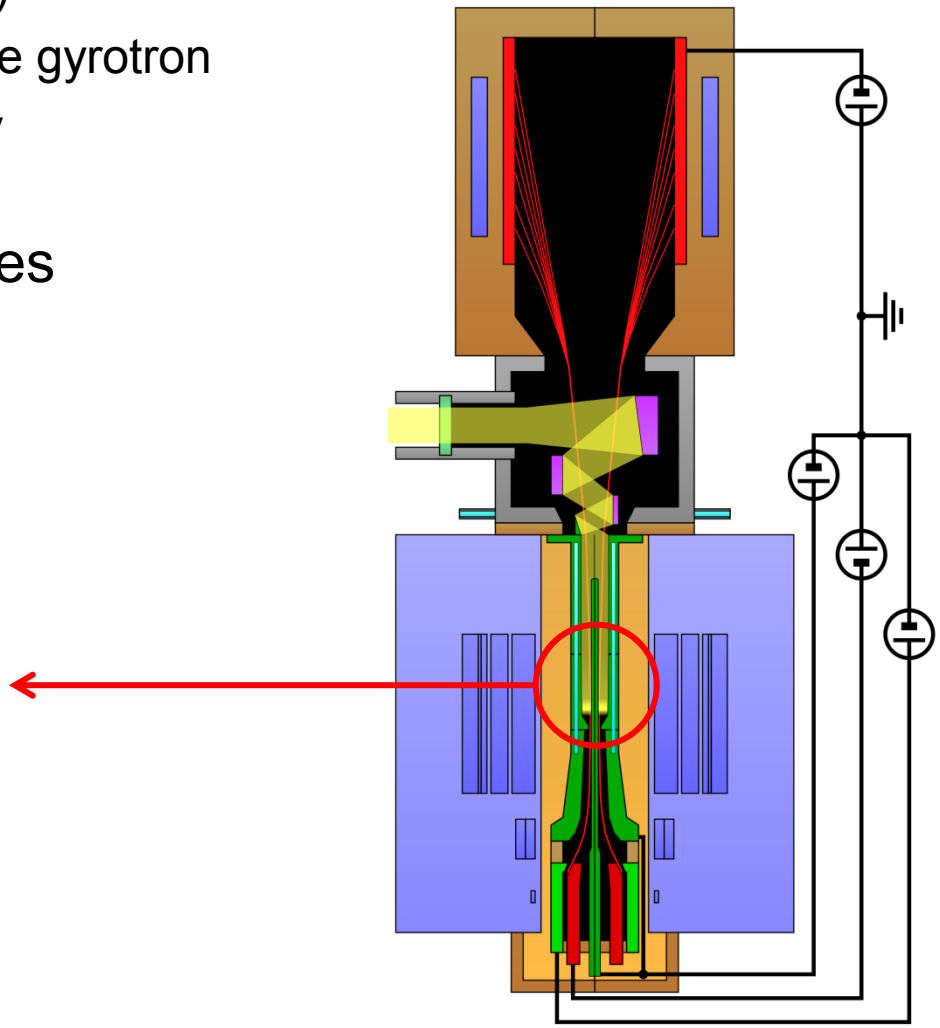


Coaxial-Cavity Gyrotrons

- (One) solution: coaxial insert
  - Metallic rod (with internal cooling)
  - Fixed in electron gun region of the gyrotron
  - In the cavity region: longitudinally corrugated & tapered
- Insert interacts with some modes

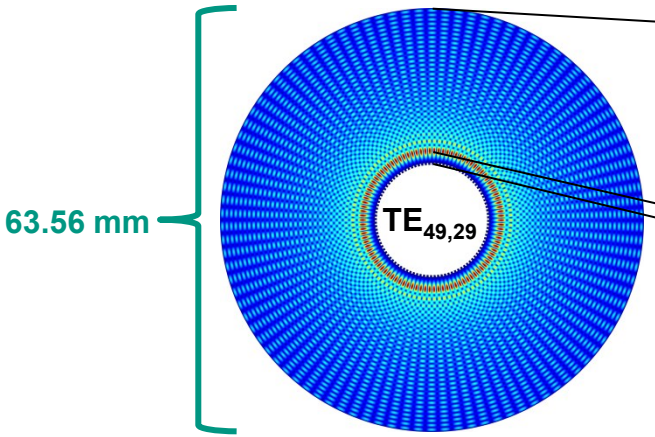
→ rarefaction of spectrum possible
→ less mode competition
→ more stable operation

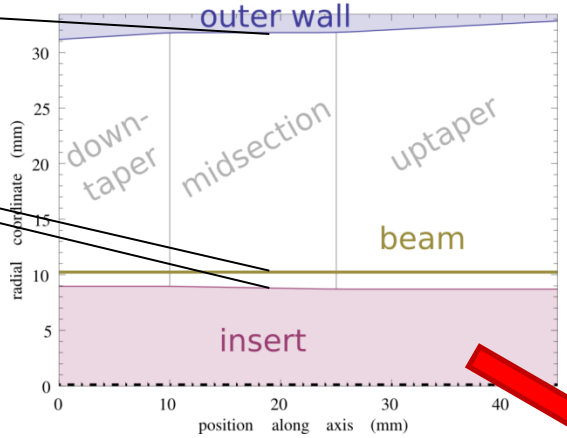


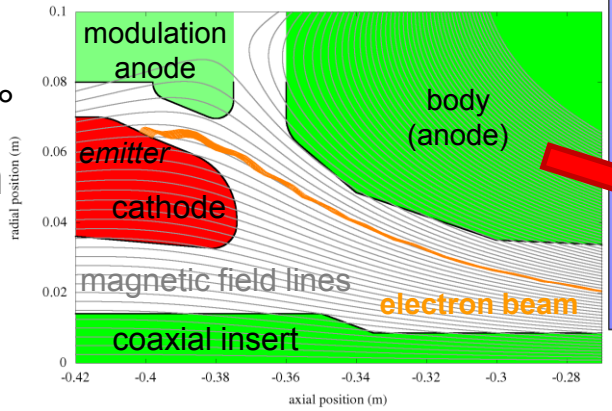


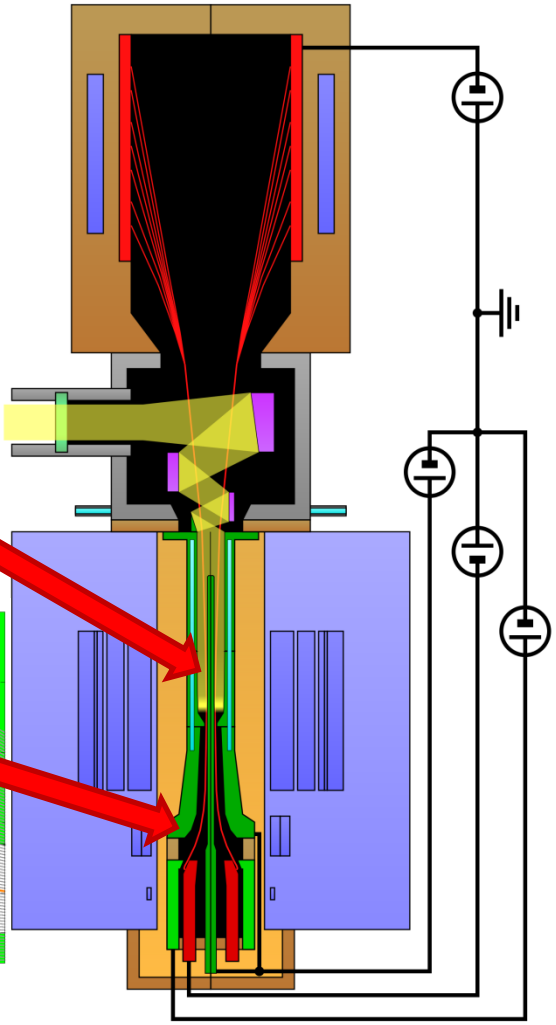
Coaxial-Cavity Gyrotrons: The 238 GHz Design

- coaxial-cavity $TE_{49,29}$ ($\chi_{49,29} \approx 158$) @ 237.5 GHz: **1.9 MW** (33 %)
- R_O=31.78 mm, R_I=8.66-8.40 mm (taper angle: -1°), r_B=10.24 mm
- 100 corrugations with depth D_{corr} = 0.3 mm
- I_B=69.3 A; U_B=85.6 kV; U_{mod}≈36 kV (α=1.22); B=9.58 T





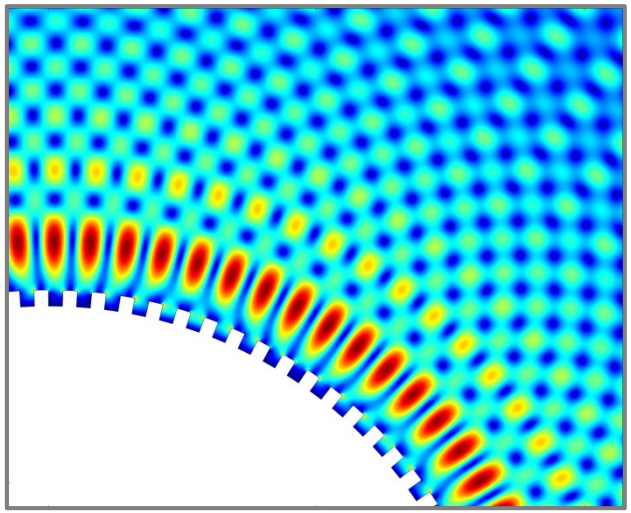


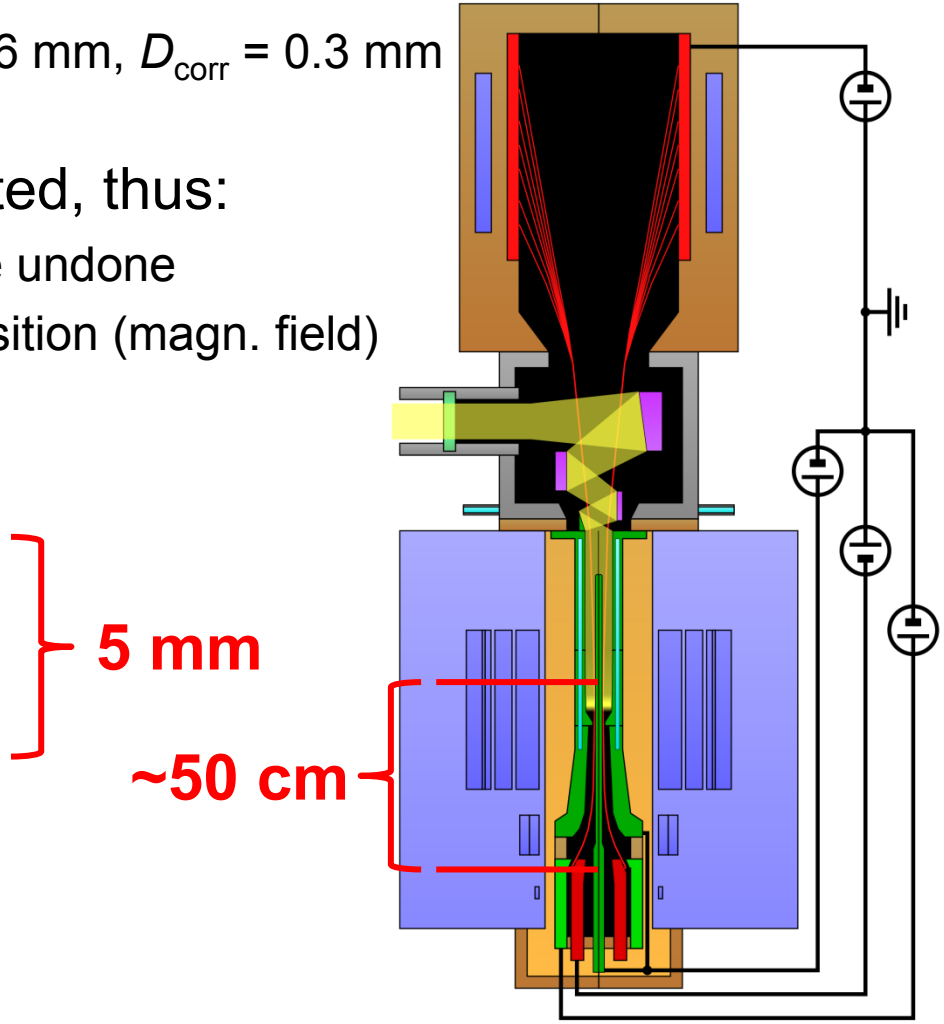


- r_{MIG}=80 mm
- r_E=65 mm, d_E=4.3 mm, θ_E=25°
- emtr. surface roughness 2 µm
- no reflected electrons
- reduced potential wells
- max. electric field: 7 kV/mm

Coaxial-Cavity Gyrotrons: The 238 GHz Design

- Technical issue:
  - insert length ≈ 50 cm
  - typ. dimensions in cavity: λ = 1.26 mm, D_{corr} = 0.3 mm
    → required tilt: < 0.1°
- Tubes are welded and evacuated, thus:
  - Possible misalignment cannot be undone
  - Only freedom: electron beam position (magn. field)





Coaxial-Cavity Gyrotrons: The 238 GHz Design

Question to design specifications:

What is the maximum tolerable insert misalignment?

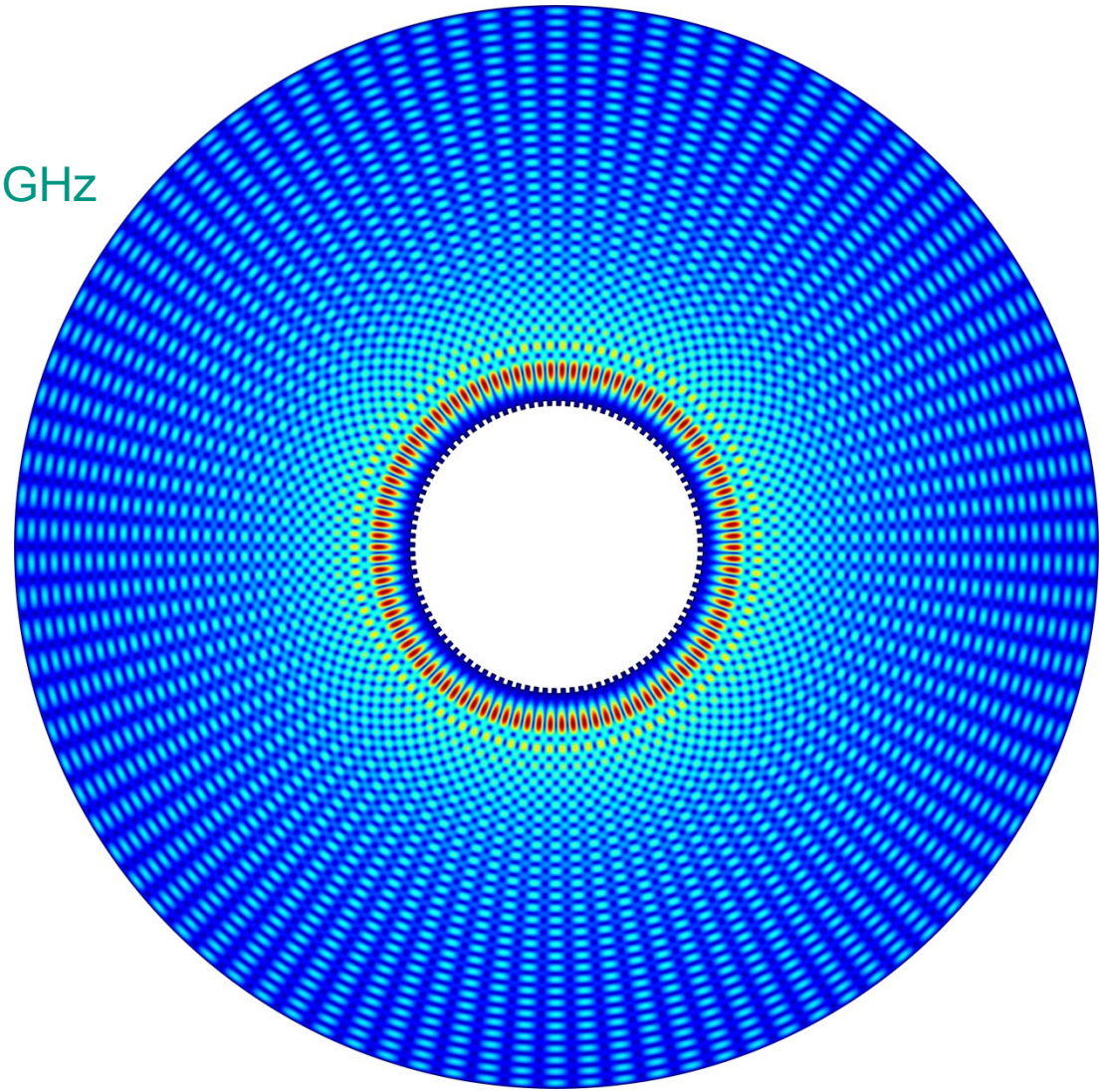
Two aspects of insert misalignment:

- **Influence on the electromagnetic modes**
- **Influence on the electron beam**

Effects of Misalignment 1: Mode Content

- Mode $TE_{49,29}$ at 0.0 mm misalignment

f_{cutoff} = 237.31 GHz



Effects of Misalignment 1: Mode Content

- Mode $TE_{49,29}$ at 0.0 mm / 1.0 mm misalignment

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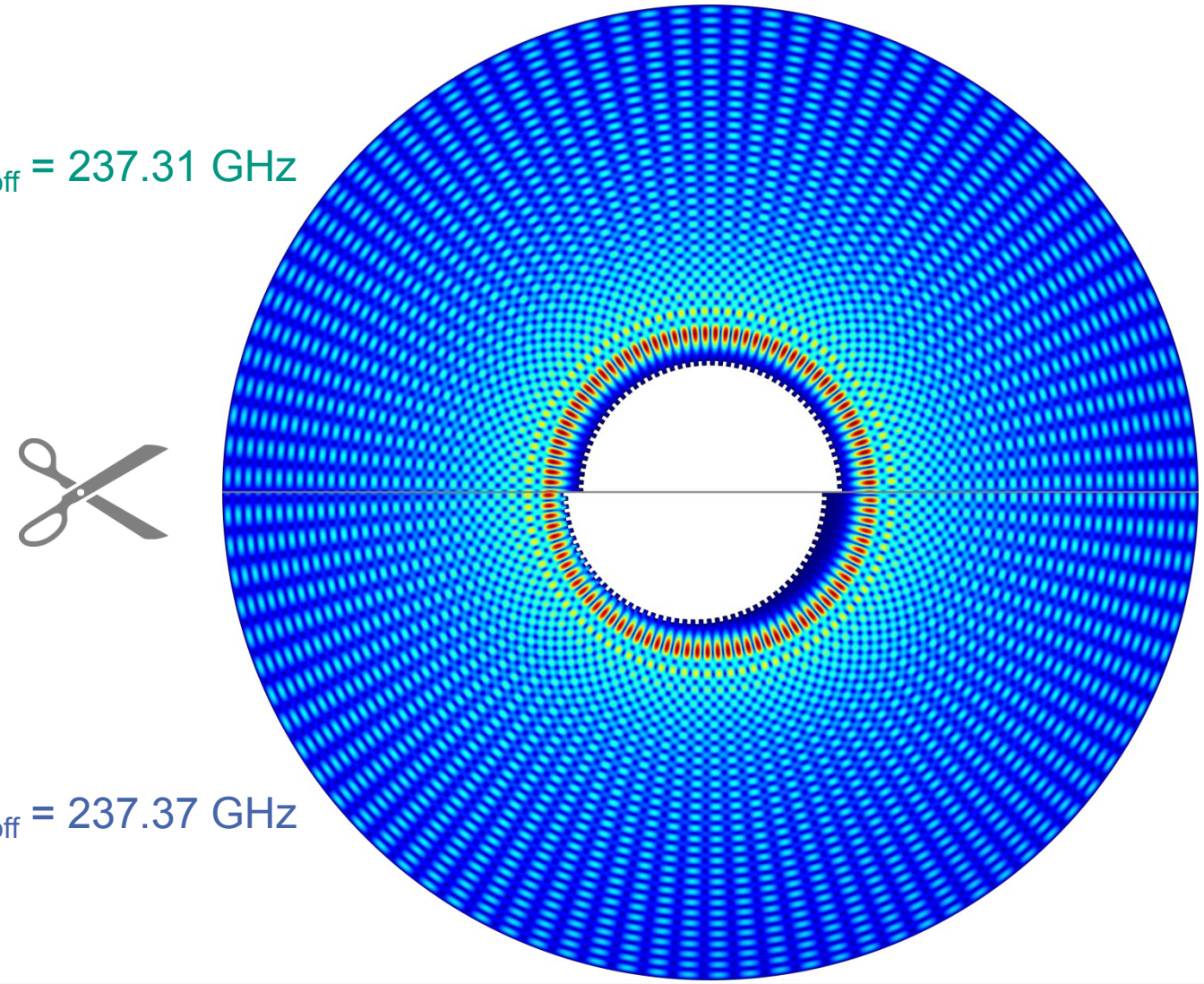

f_{cutoff} = 237.37 GHz

Effects of Misalignment 1: Mode Content

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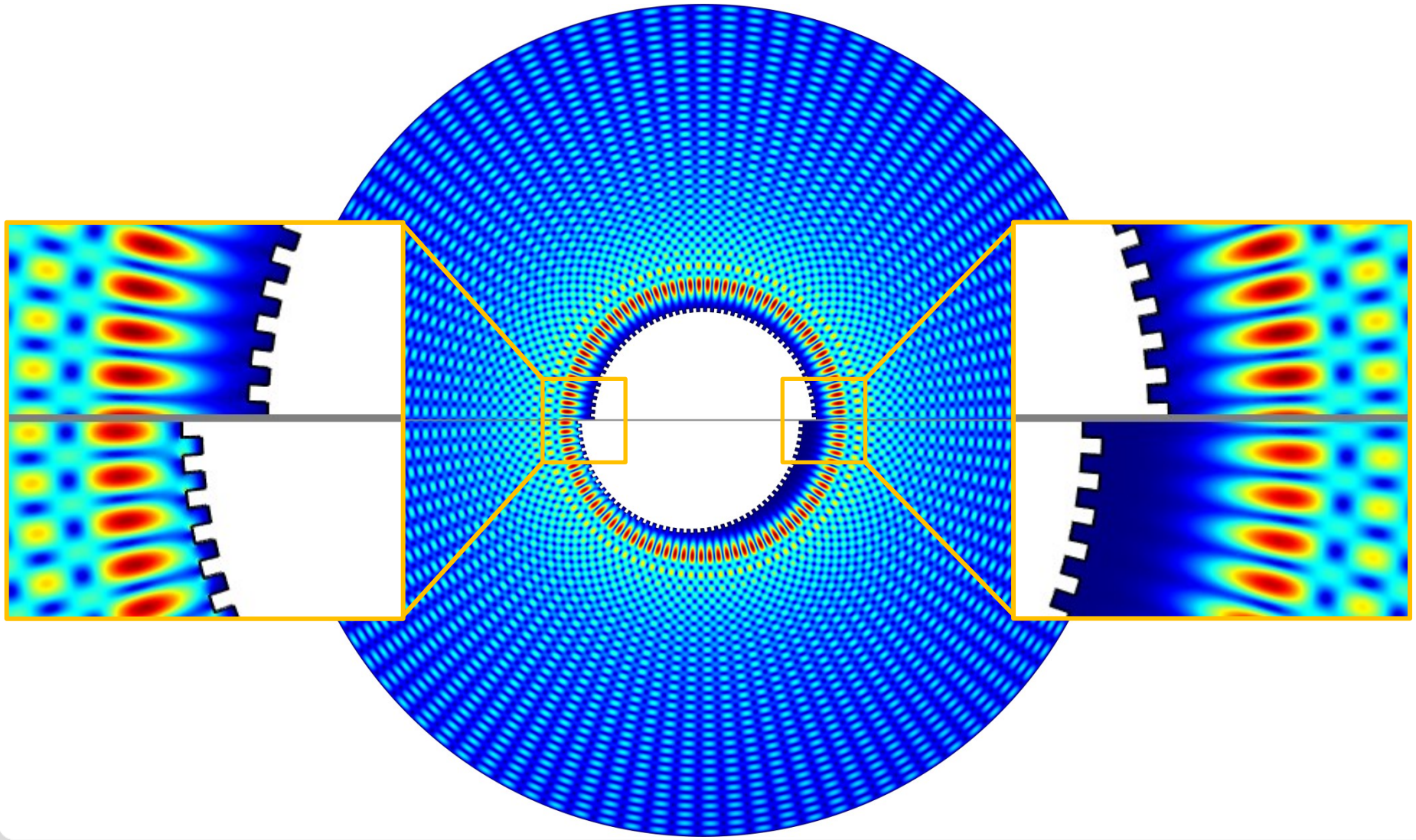

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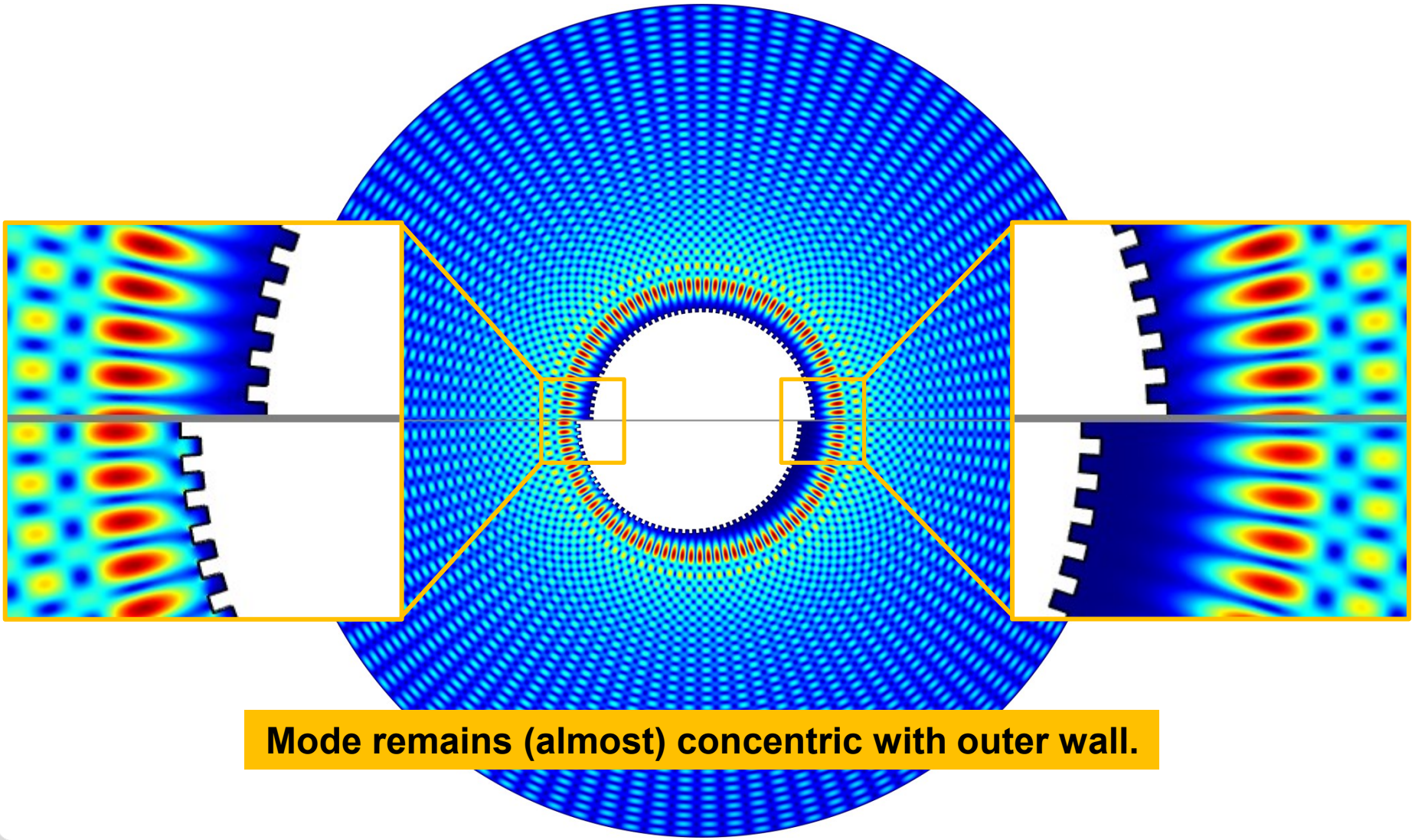

Mode remains (almost) concentric with outer wall.

Description of Misalignment: Mode Content

Small, but important changes in deformed modes, e.g.:

- Mode eigenvalue χ_{mp} (→ frequency; required precision: ~ 10^{-4} (1:1.000.000))
- Field distribution → coupling to electron beam (required precision: ~ 10^{-2})

Goal: analytic description of TE modes which works for

- Corrugated insert (Surface Impedance Model, i.e. infinitely small corrugations)
- Misalignment up to **1 mm**
- Eigenvalues up to **180**
- Eigenvalue precision of **10^{-5}**
- Azimuthal indices *m* up to **60**

and (as a code) is suitable as input for interaction codes.

Description of Misalignment: Mode Content

- Field decomposition $\hat{B}_{z,m}(r,\varphi) \sim \sum_{q=-\infty}^{\infty} K_{mq}(s,r,r',C,\delta) B_q e^{-\mathrm{i}q\varphi}$

- Modes: solutions of $\hat{B}'_{z,m}(R_\mathrm{O}) = 0$

coaxial insert boundary condition

misalignment

$$K_{mq}(s,r,r',C,\delta) = J_{q-m}(\delta) \cdot \begin{pmatrix} J_{m-s}(k_\perp r) & -N_{m-s}(k_\perp r) \end{pmatrix} \cdot \begin{pmatrix} N'_q(k_\perp r') & N_q(k_\perp r') \\ J'_q(k_\perp r') & J_q(k_\perp r') \end{pmatrix} \cdot \begin{pmatrix} 1 \\ C \end{pmatrix}$$

wall boundary condition

corrugations

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- Modes: solutions of $\hat{B}'_{z,m}(R_\mathrm{O}) = 0$
- "Small-matrix approach" vs. "Large-matrix approach"

$$K'_{m_0,\Delta m} = \begin{pmatrix} K'_{m_0-\Delta m,m_0-\Delta m} & \cdots & K'_{m_0-\Delta m,m_0+\Delta m} \\ \vdots & K'_{m_0,m_0} & \vdots \\ K'_{m_0+\Delta m,m_0-\Delta m} & \cdots & K'_{m_0+\Delta m,m_0+\Delta m} \end{pmatrix} \qquad K'_{m_{max},\Delta m} = \begin{pmatrix} K'_{0,\Delta m} & & \\ & \ddots & \\ & & K'_{m_{max},\Delta m} \end{pmatrix}$$

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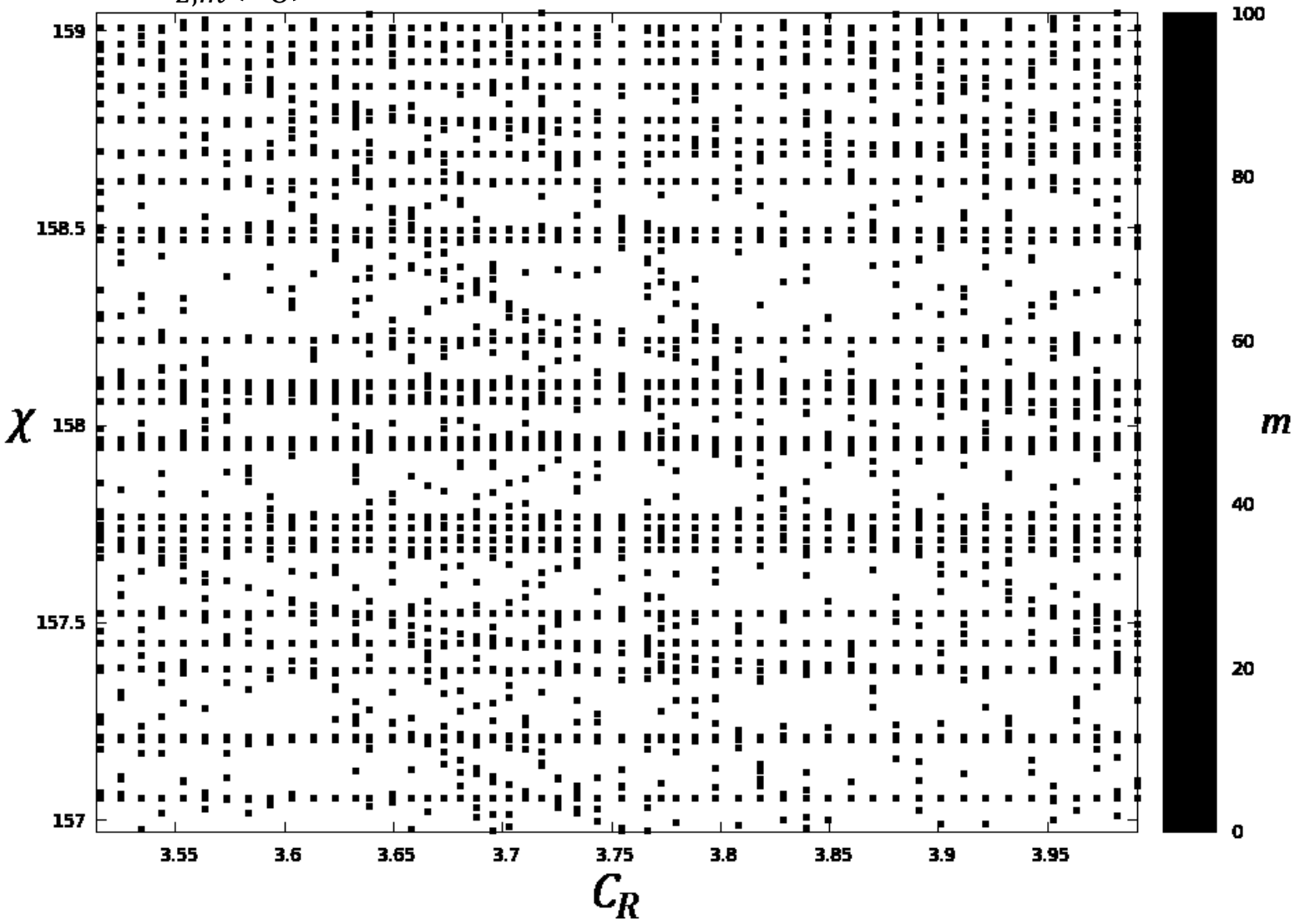
Description of Misalignment: Mode Content

Result of $\hat{B}'_{z,m}(R_O) = 0$



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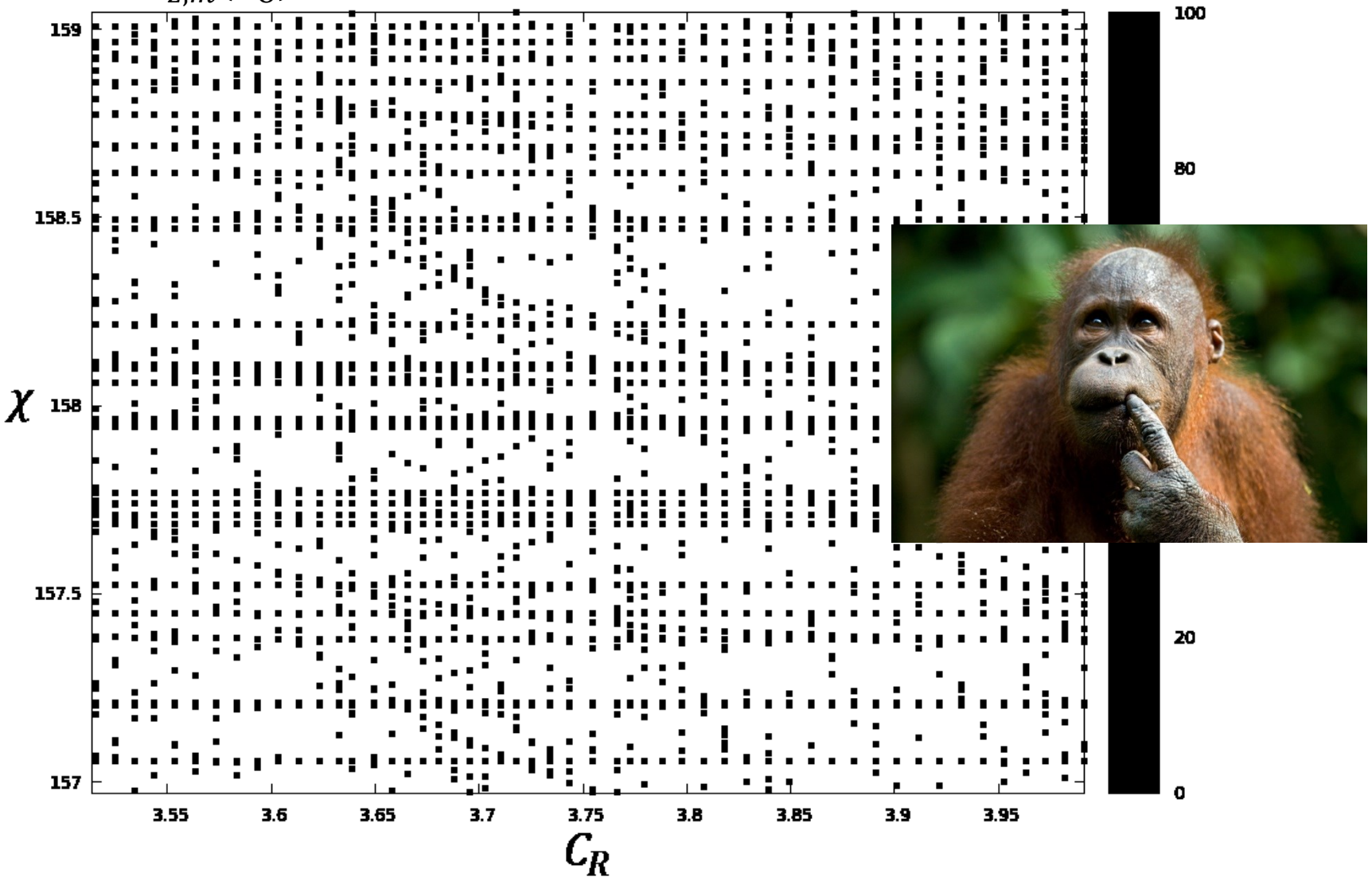

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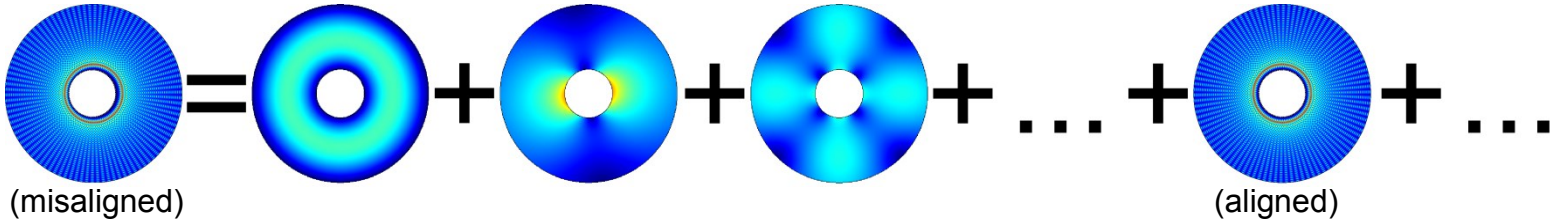
- Field decomposition $\hat{B}_{z,m}(r,\varphi) \sim \sum_{q=-\infty}^{\infty} K_{mq}(s,r,r',C,\delta) B_q e^{-\mathrm{i}q\varphi}$
- e.g. *m*=49:



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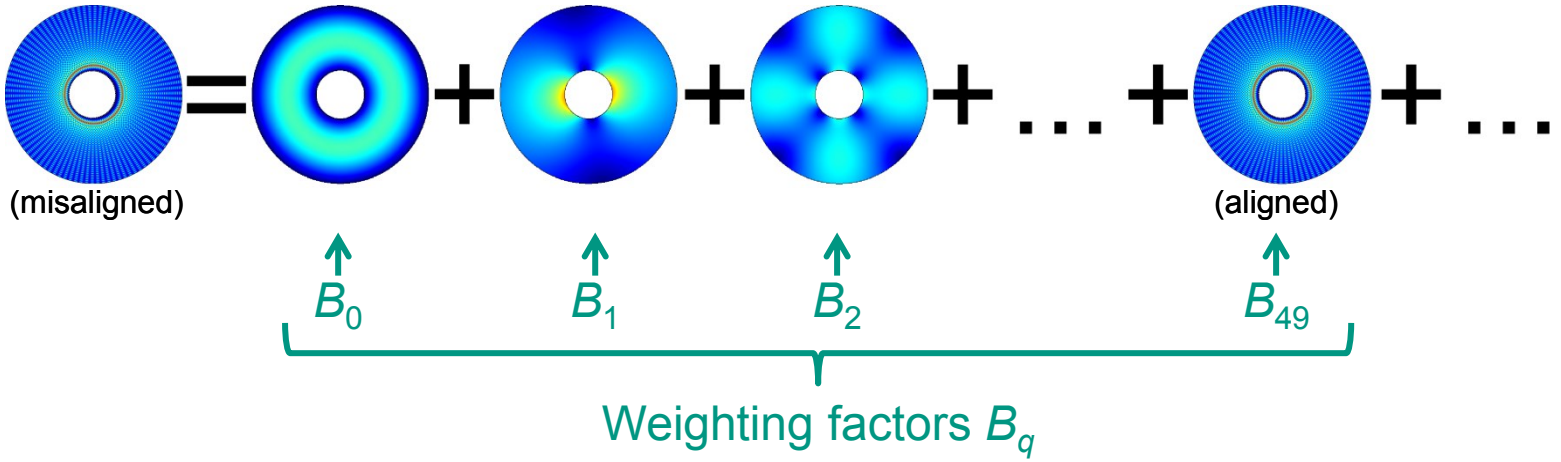

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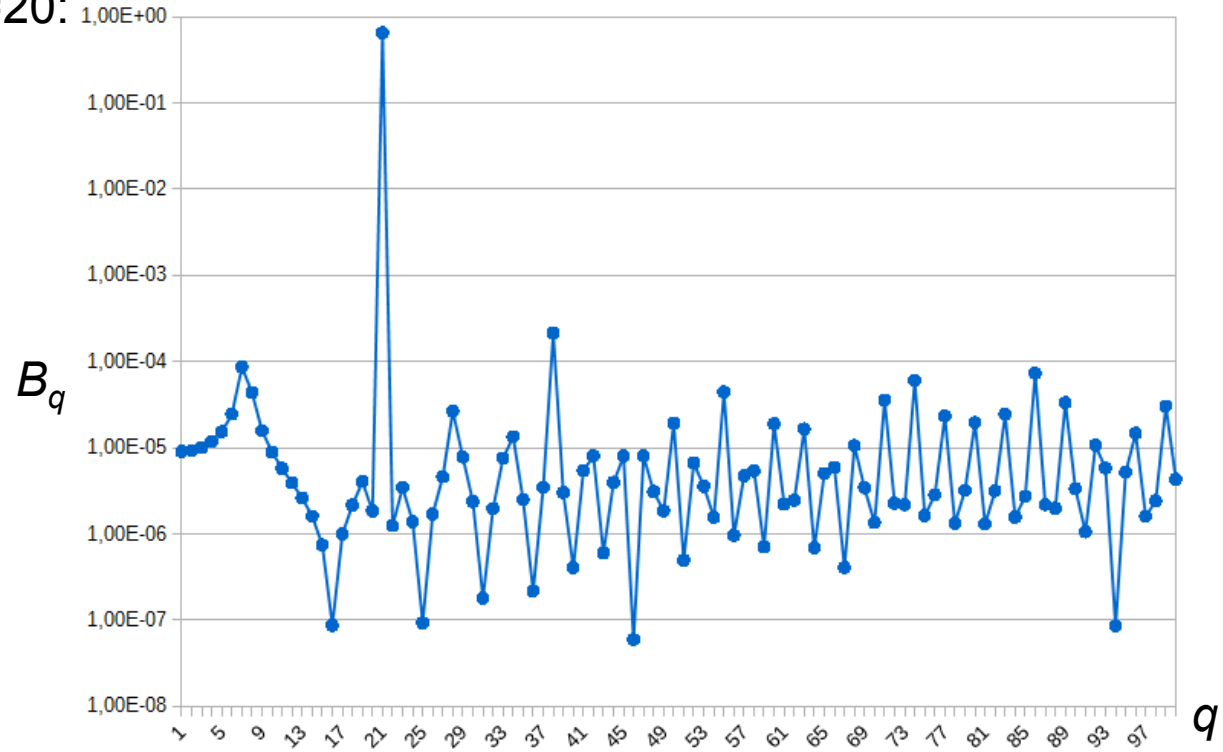

- Index *q* of largest weighting factor is used as **azimuthal index *m***.

  (largest weighting factor ~ largest energy content)

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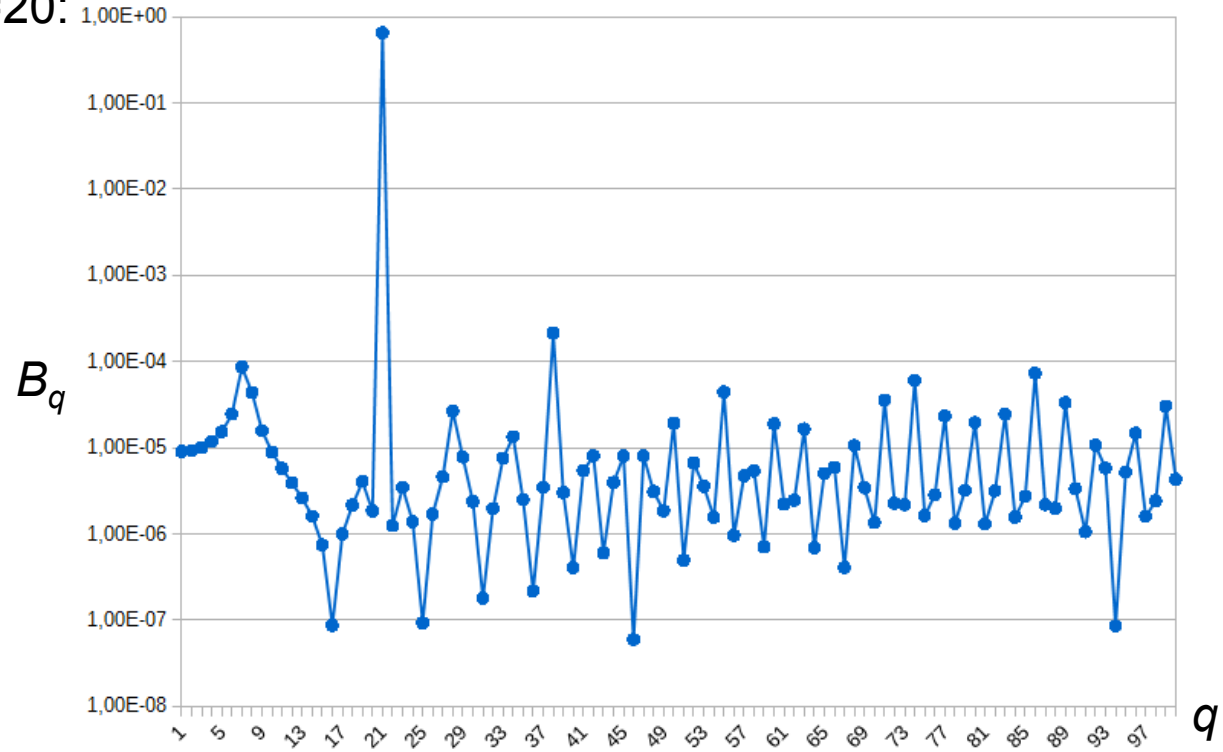
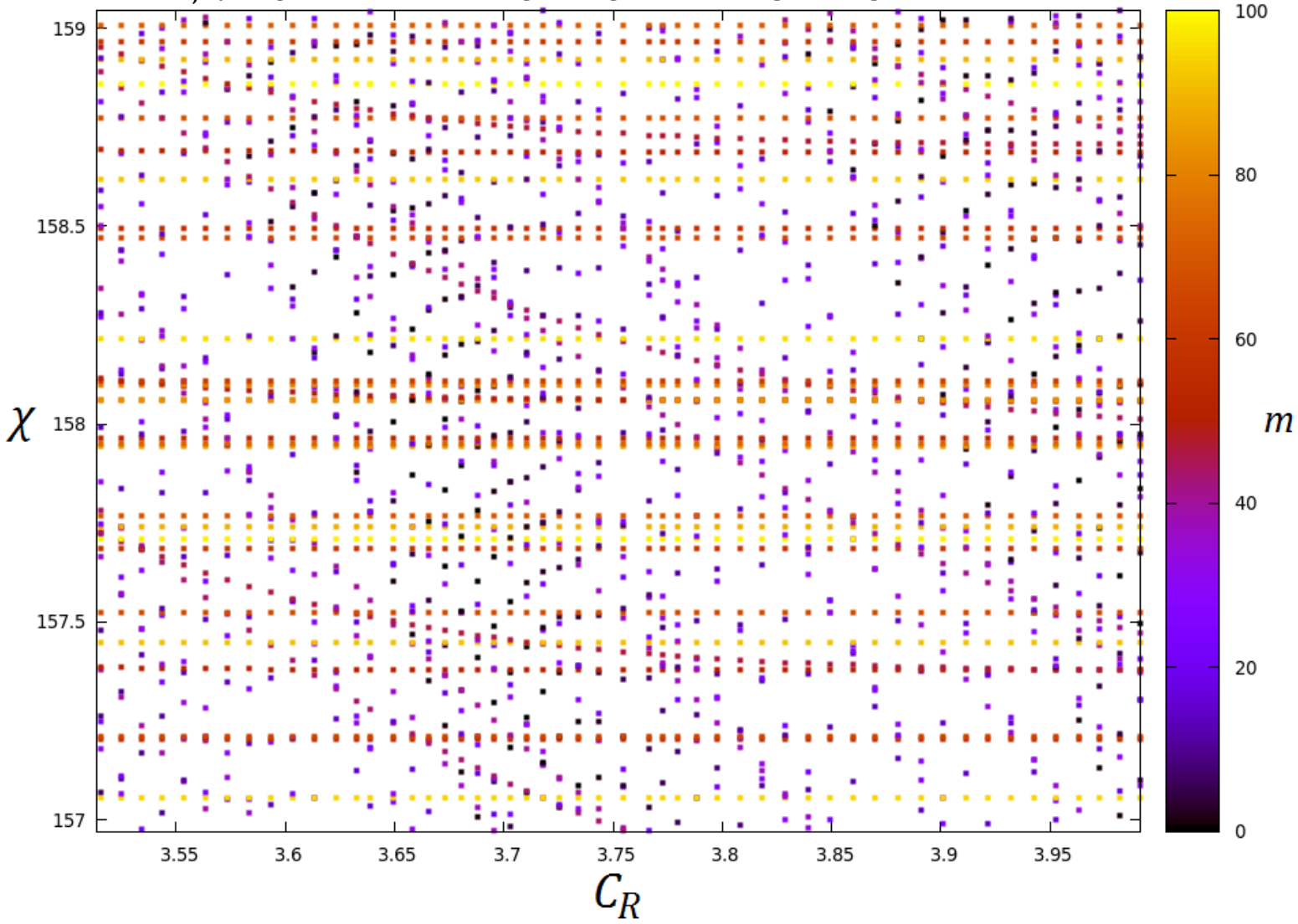


- Index *q* of largest weighting factor is used as **azimuthal index *m***.
- Number *p* of root $\chi_{mp,\mathrm{misaligned}} = k_\perp R_\mathrm{O}$ is used as **radial index *p***.

Description of Misalignment: Mode Content

Result of $\hat{B}'_{z,m}(R_O) = 0$, using largest weighting factor



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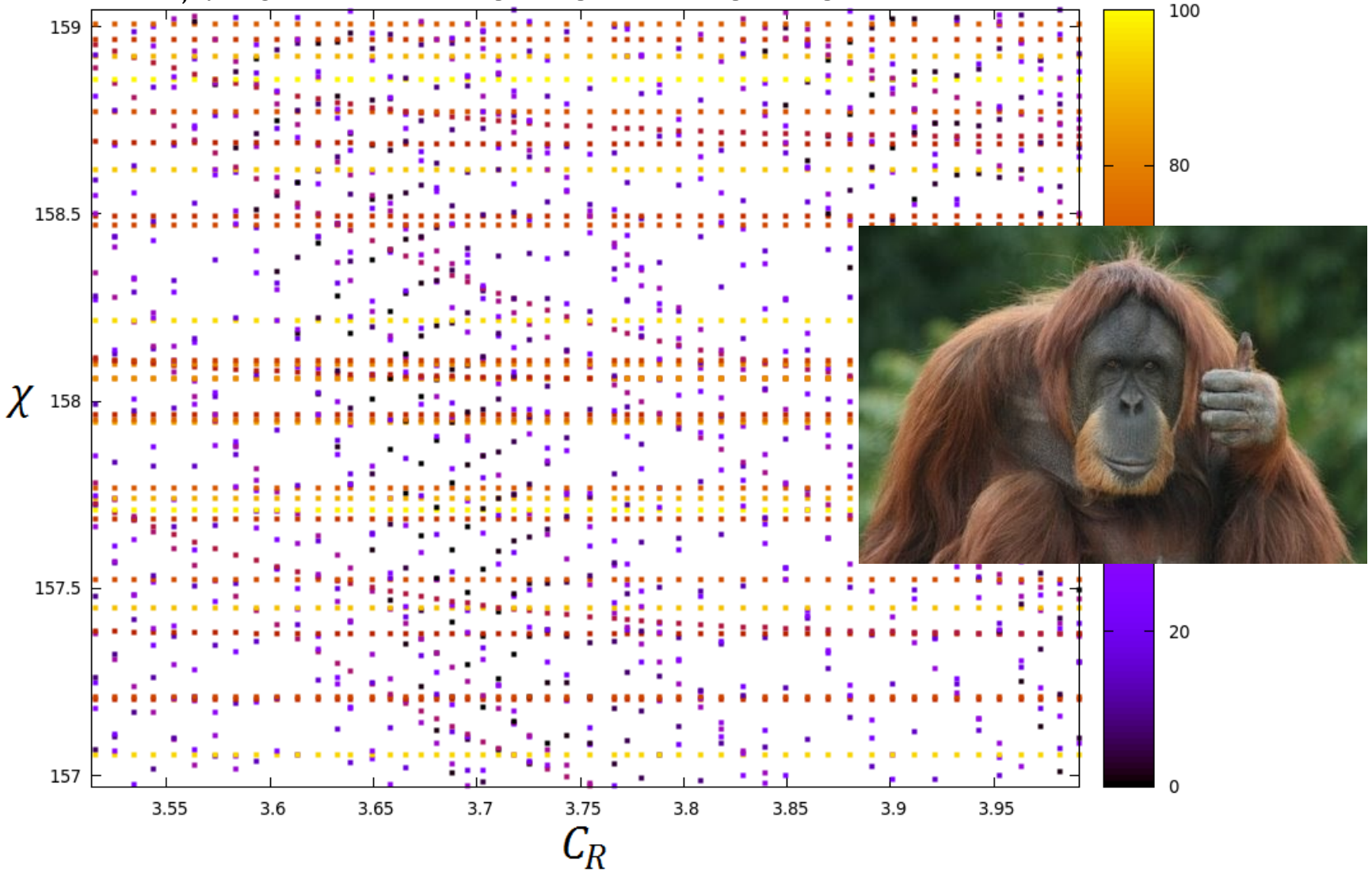
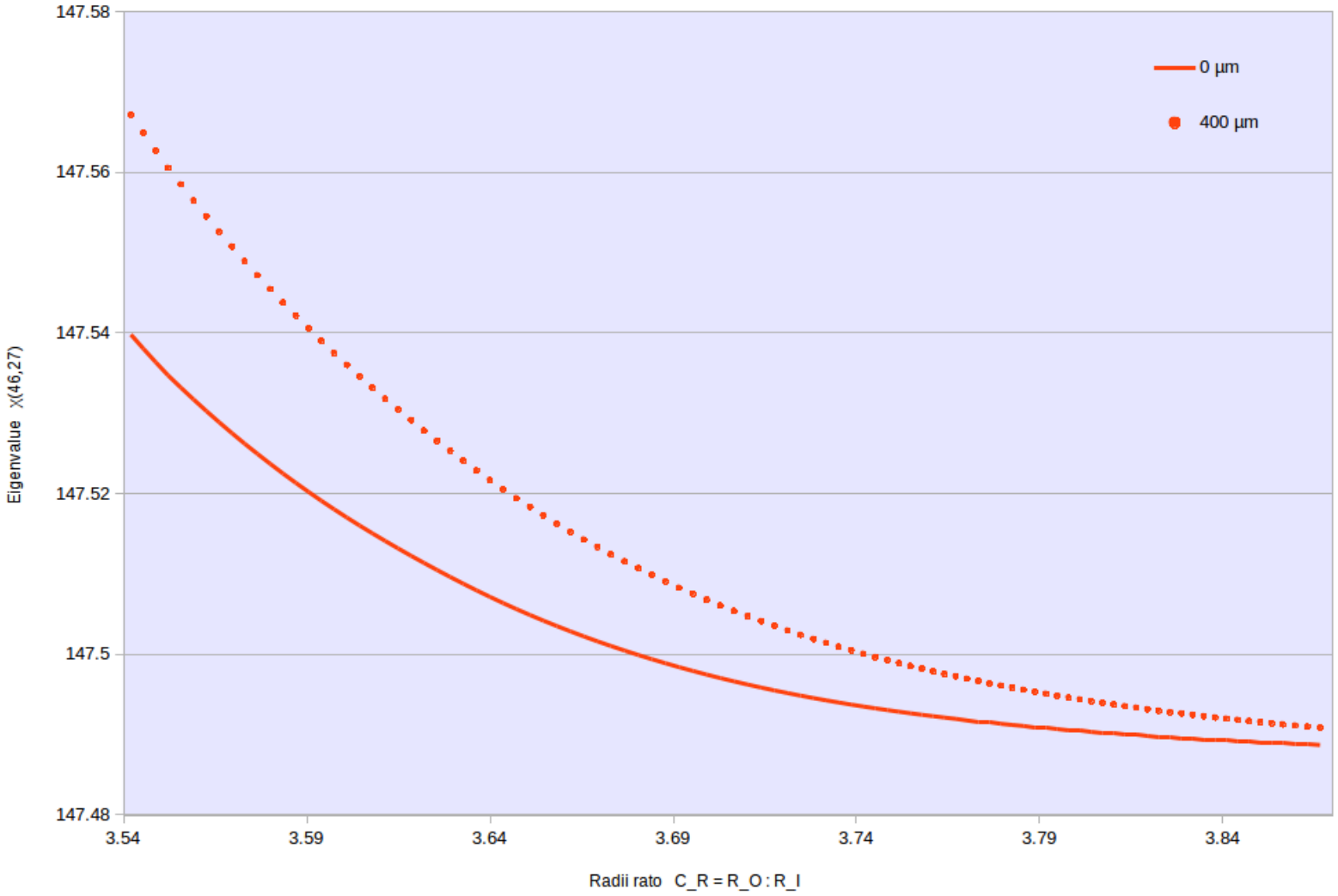


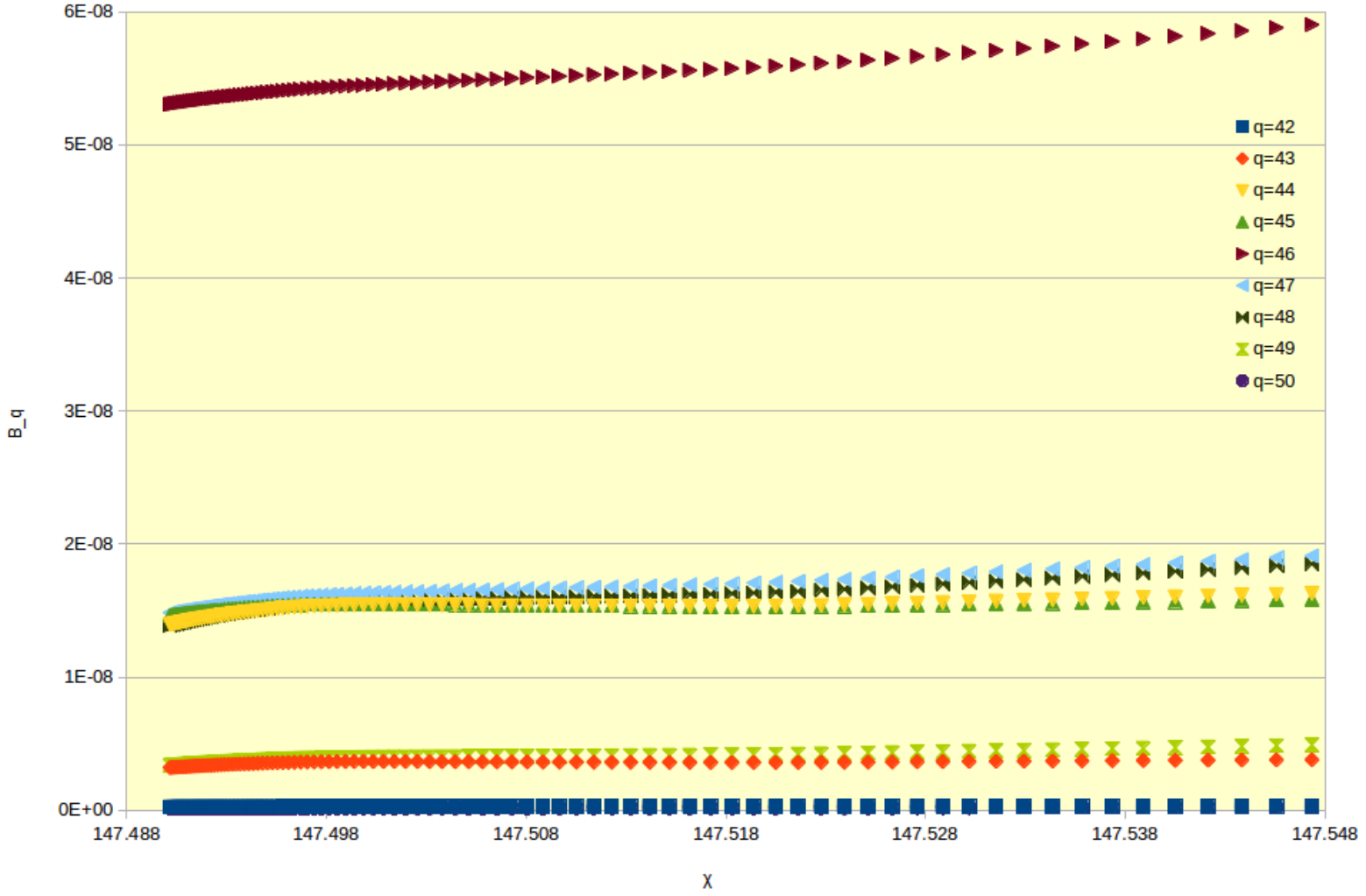
Description of Misalignment: Mode Content

$TE_{46,27}$: Eigenvalue versus misalignment



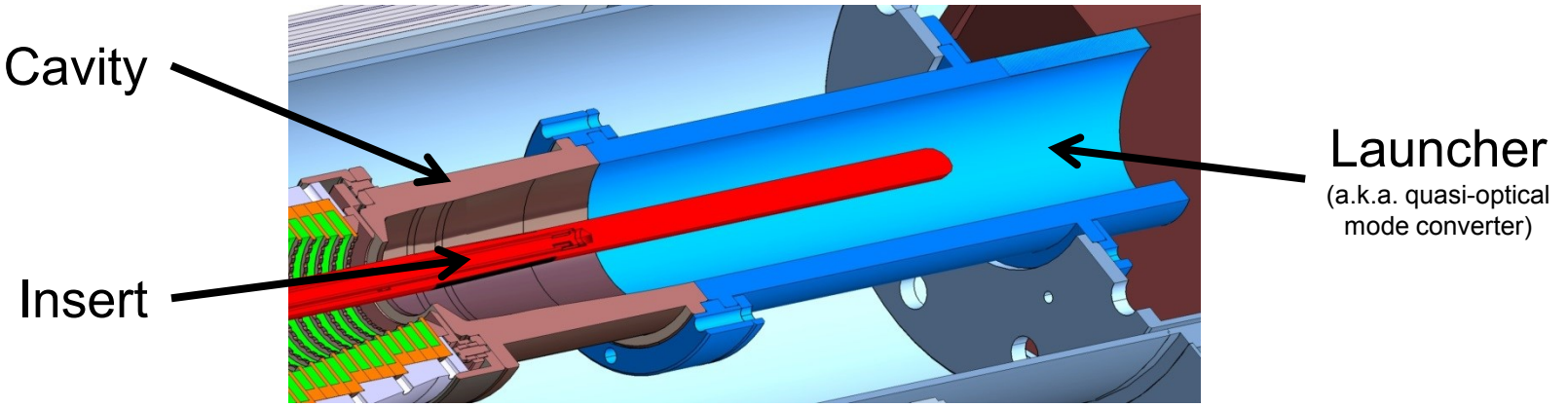
Description of Misalignment: Mode Content

$TE_{46,27}$ (300 µm): Azimuthal components versus eigenvalue



Description of Misalignment: Mode Content

- (mis)aligned insert ends after cavity → mode conversion



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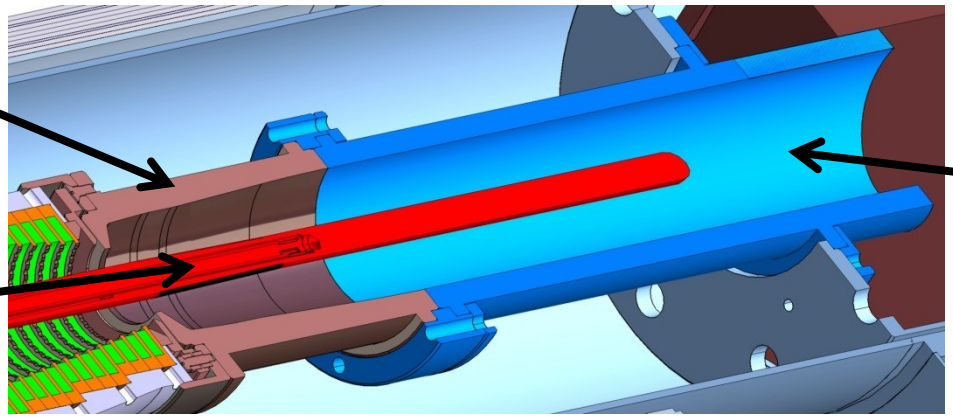
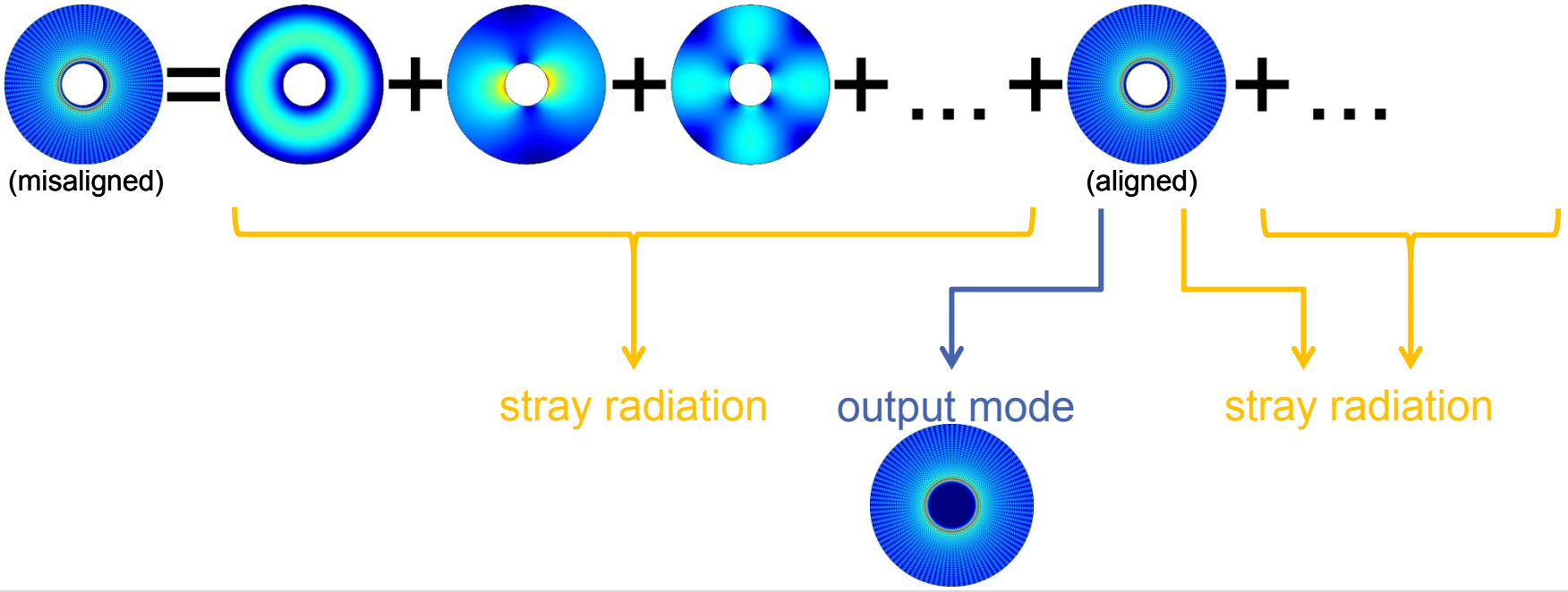
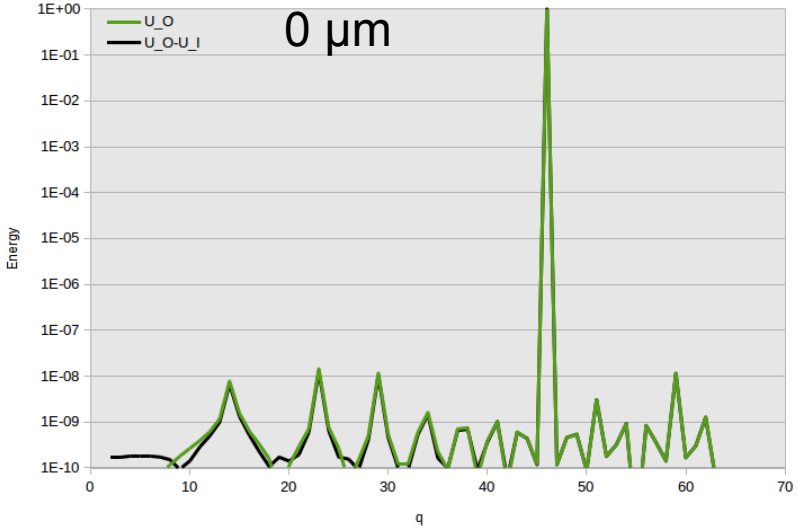
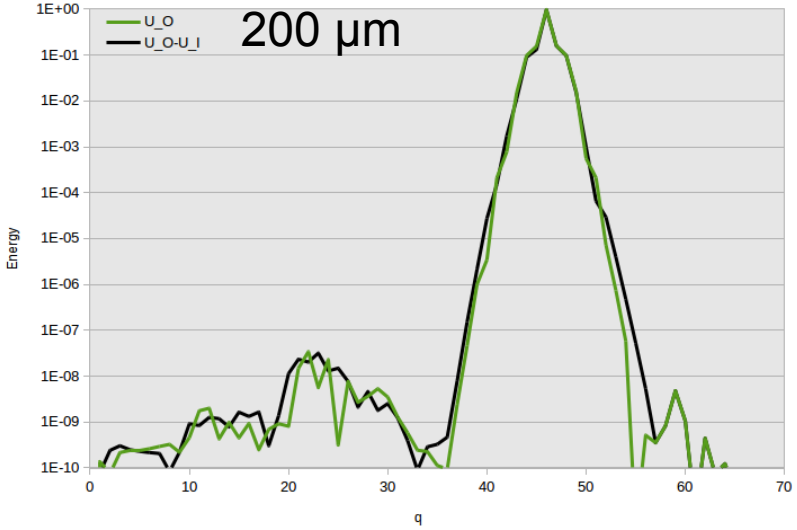


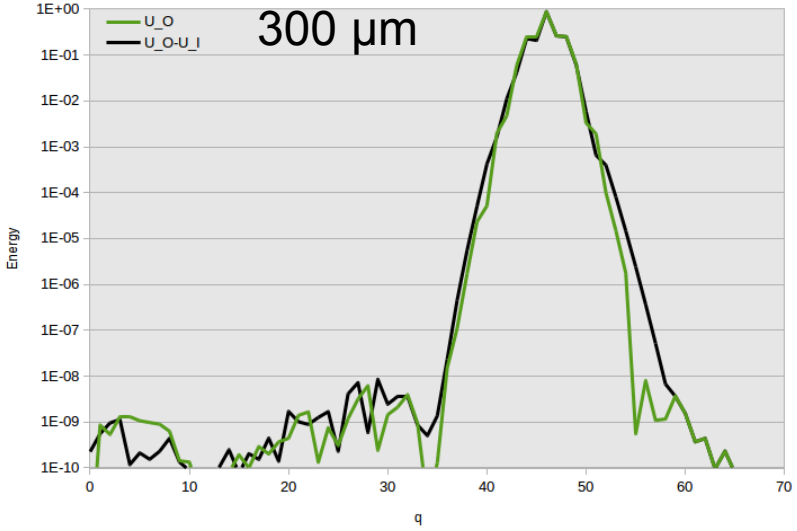


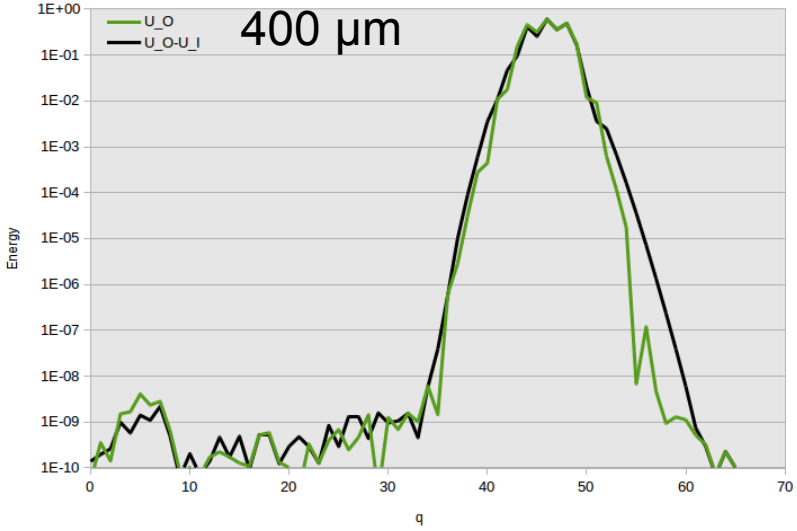
Description of Misalignment: Mode Content

$TE_{46,27}$: Energy content versus misalignment (→ stray radiation)









Description of Misalignment: Mode Content

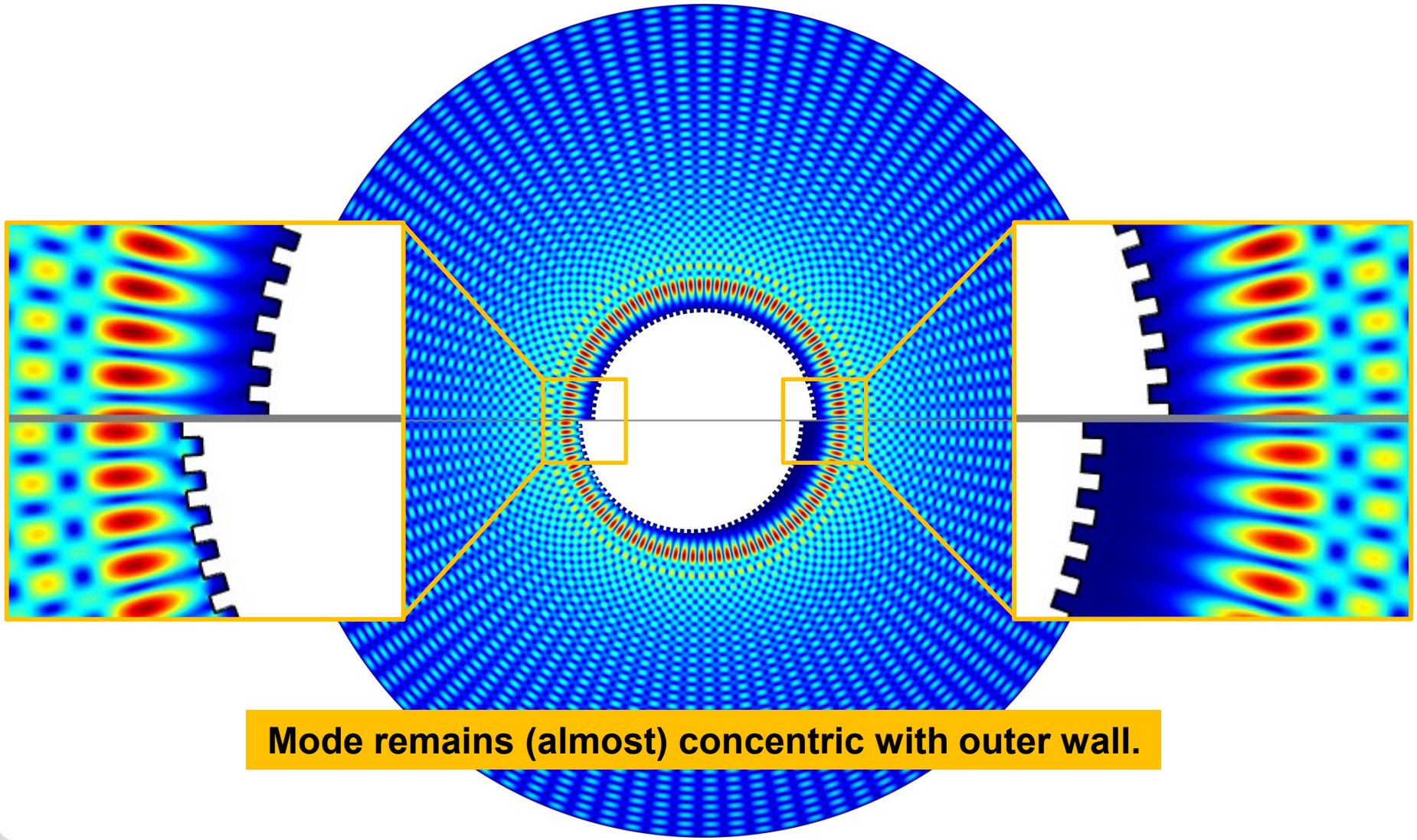
Procedure result:

- Every mode in cavities with (reasonably) misaligned insert has a label $TE_{m,p}$.
- Proper labelling ensures proper calculation of
  - axial mode profile
  - spurious mode content
  - ohmic wall loading
  - coupling to the electron beam

→ suitable for interaction simulations

Effects of Misalignment 2: Voltage Depression

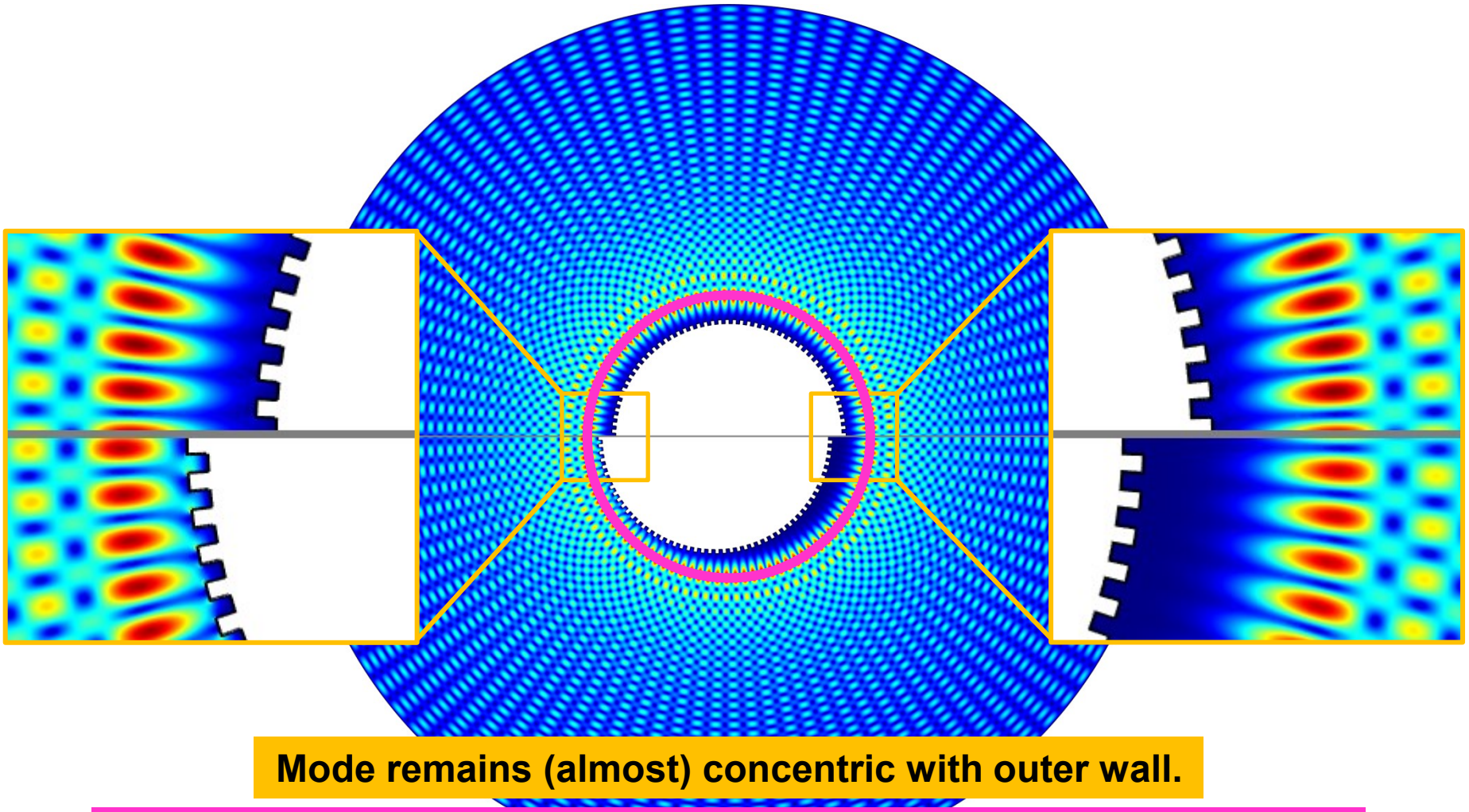
- Mode $TE_{49,29}$ at 0.0 mm / 1.0 mm misalignment



Mode remains (almost) concentric with outer wall.

Effects of Misalignment 2: Voltage Depression

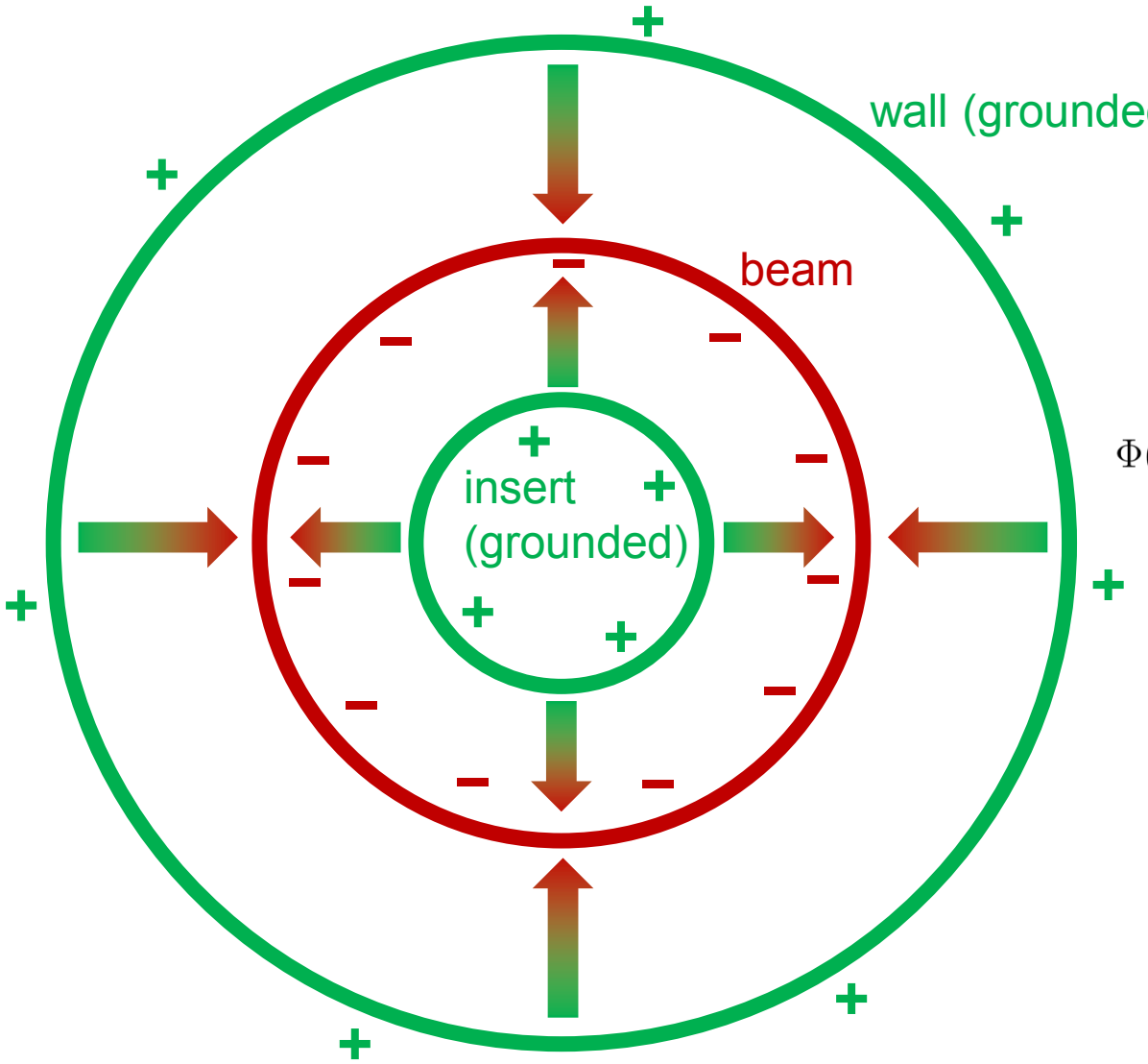
- Mode $TE_{49,29}$ at 0.0 mm / 1.0 mm misalignment



Mode remains (almost) concentric with outer wall.

For optimum coupling, the beam has to be concentric to the modes.

Effects of Misalignment 2: Voltage Depression

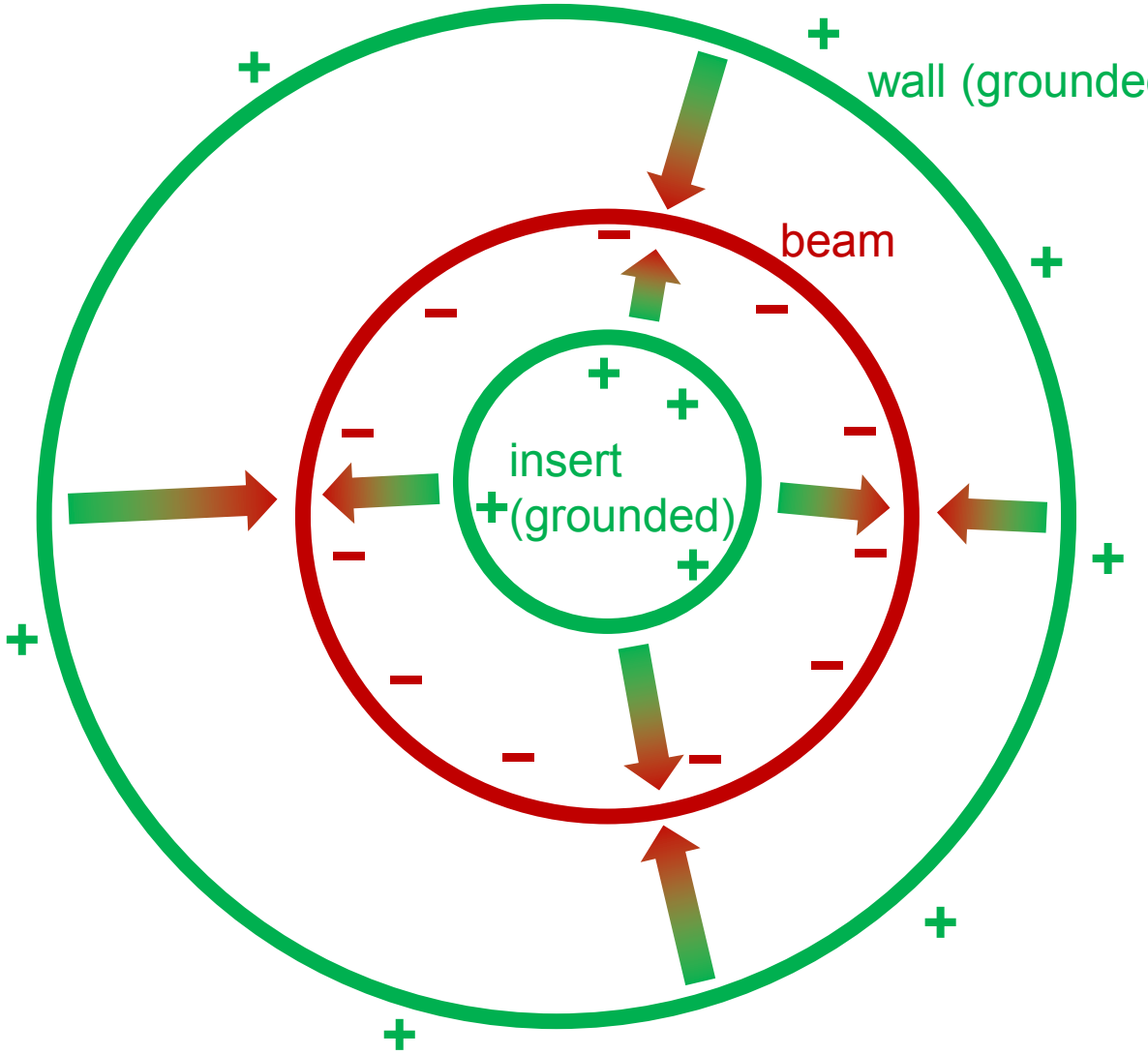


Gauss' Law
(symmetric problem) →

$$\Phi(r_b) = \frac{\kappa_b}{2\pi\varepsilon_0} \frac{\ln(r_b/R_O)\ln(r_b/R_I)}{\ln(R_O/R_I)}$$

R_I: insert radius
r_b: beam radius
R_O: wall radius
κ_b: beam line charge

Effects of Misalignment 2: Voltage Depression



asymmetric problem

?

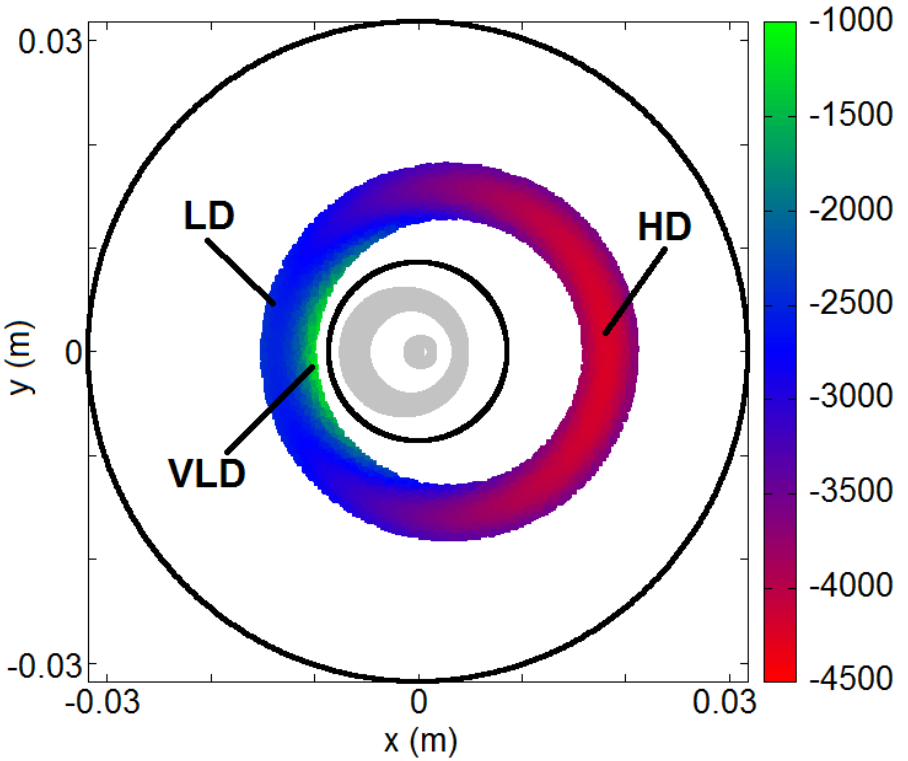
depends on azimuthal coordinate

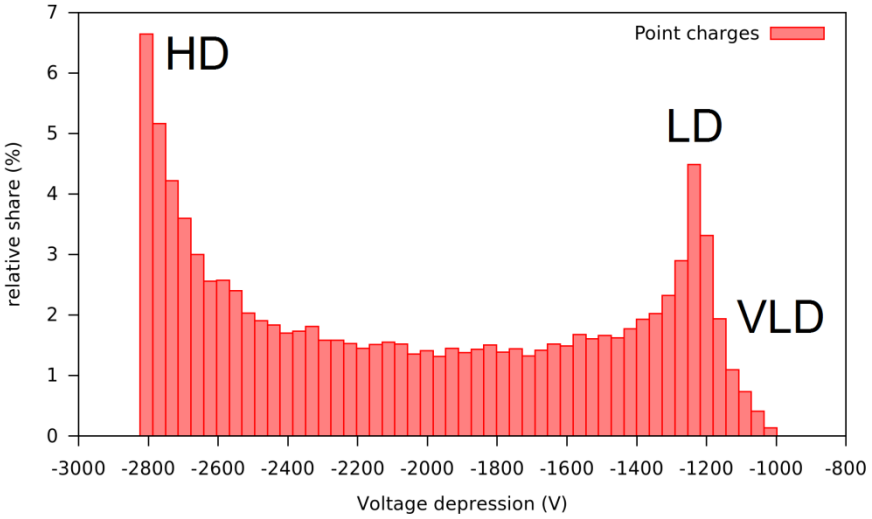
R_l: insert radius
r_b: beam radius
R_O: wall radius
κ_b: beam line charge
D_{lb}: insert-beam misal.
D_{lO}: insert-wall misal.

Description of Misalignment: Voltage Depression

… see http://dx.doi.org/10.1109/TED.2016.2592533 ...

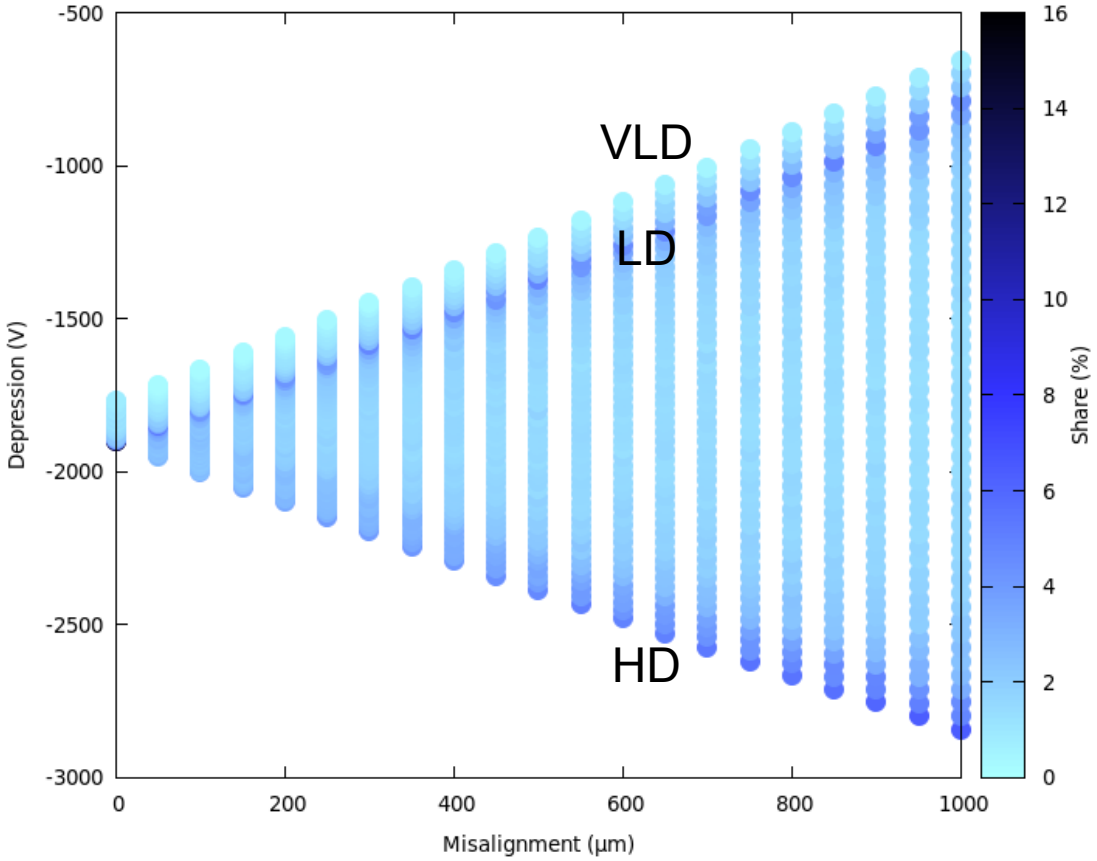
- Test design (very thick, misaligned beam):





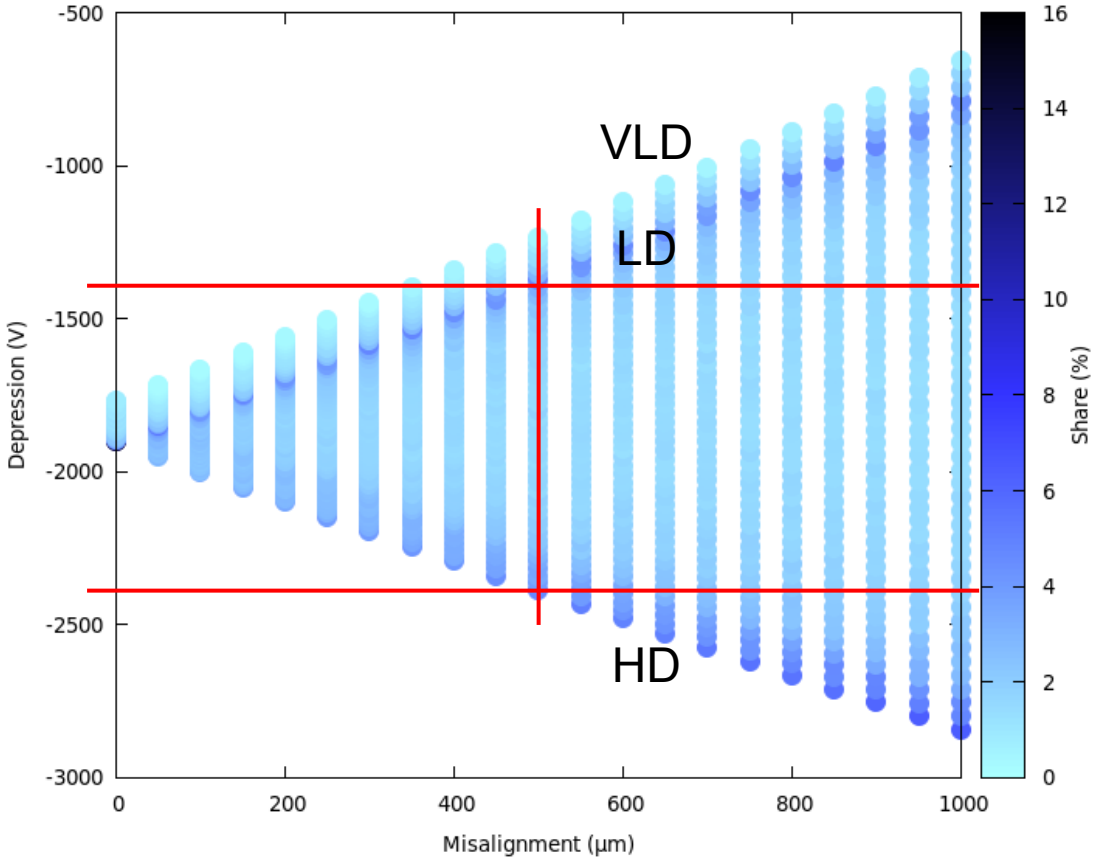
Description of Misalignment: Voltage Depression

- $TE_{49,29}$ mode gyrotron design (misaligned insert+beam):



Description of Misalignment: Voltage Depression

- $TE_{49,29}$ mode gyrotron design (misaligned insert+beam):



1 keV (1.17 %) energy variation

Conclusion and Outlook

Two new codes for interaction simulation input:

- **SCNCHIMP**: mode content of cavity with misaligned insert
  - Interface to interaction code **Euridice** (K.A. Avramidis) is written
  - Additional features: tilted insert, thick electron beam, B-field profile
  - Finished; testing is ongoing
- **WickedQueen**: electron energy spread in cavity with misalignment
  - Article on principle and benchmarking published
    (IEEE Trans. Electon Devices **63**(9), 3740-3746, Sept. 2016)

Next steps:

- **Euridice** interaction simulations with
  - Energy spread input from **WickedQueen**
  - Mode input from **SCNCHIMP**

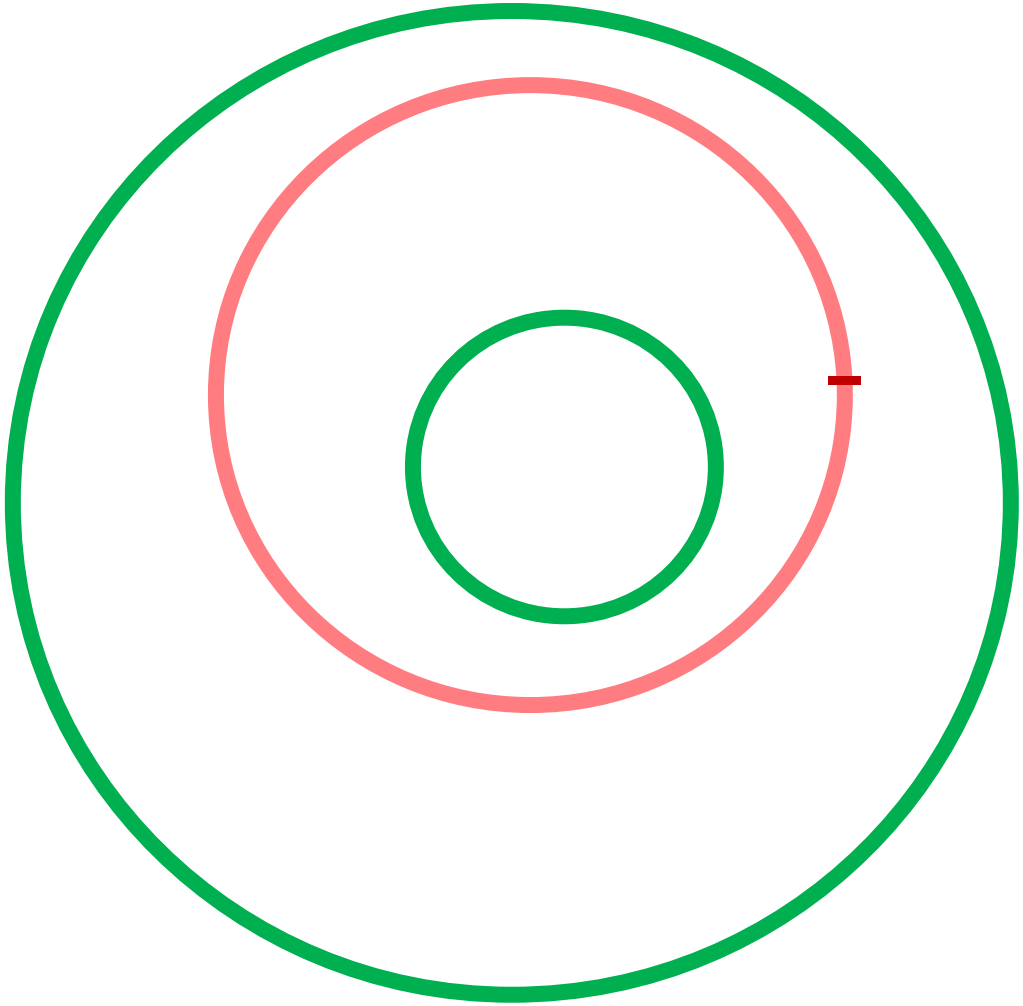
→ *Determination of maximum allowed misalignment.*

Questions/Discussion

BACKUP SLIDES

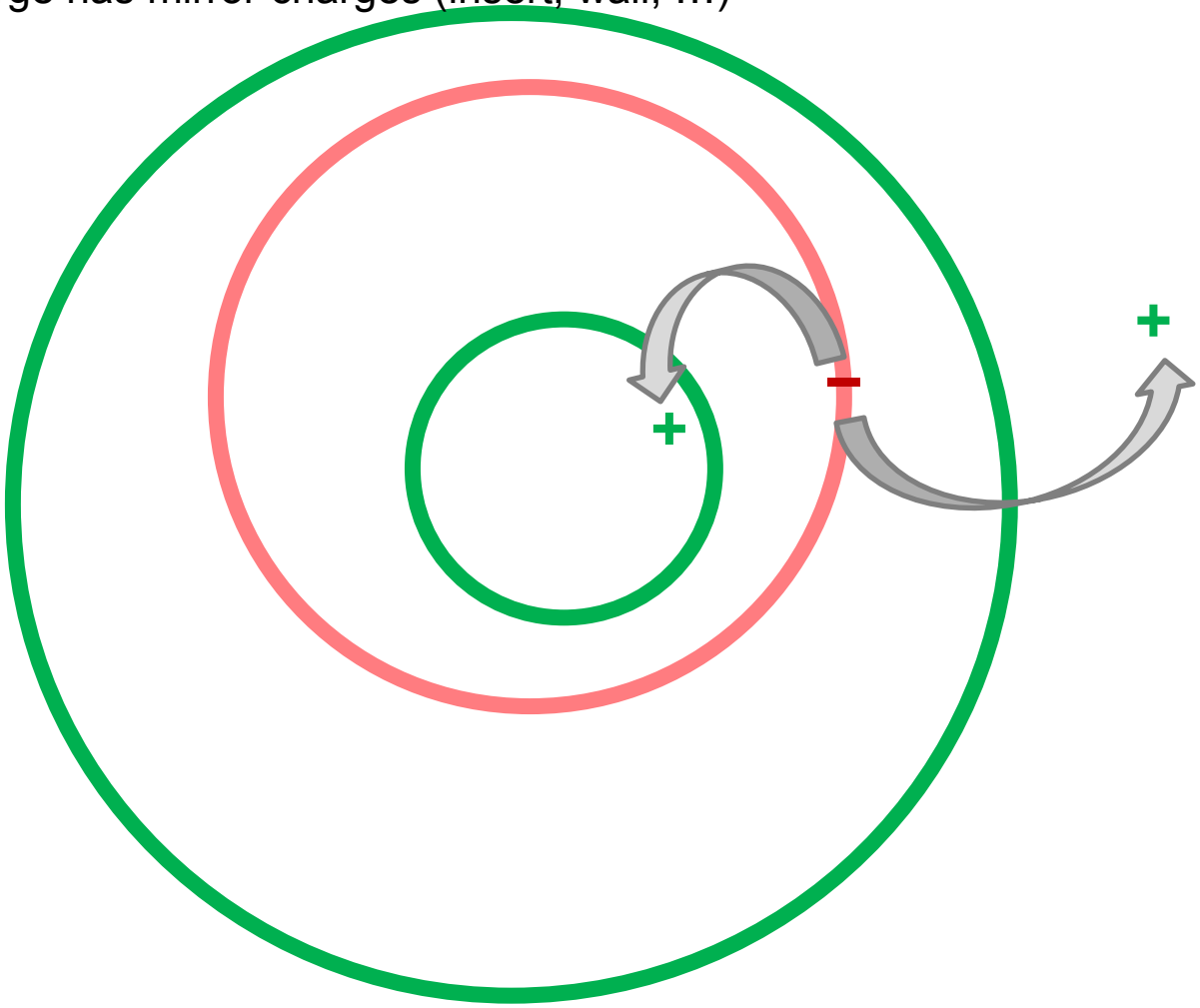
Description of Misalignment: Voltage Depression

- Basic idea:
  - Describe electron beam as (large) number of point-charges



Description of Misalignment: Voltage Depression

- Basic idea:
  - Describe electron beam as (large) number of point-charges
  - Each charge has mirror charges (insert; wall; …)



Description of Misalignment: Voltage Depression

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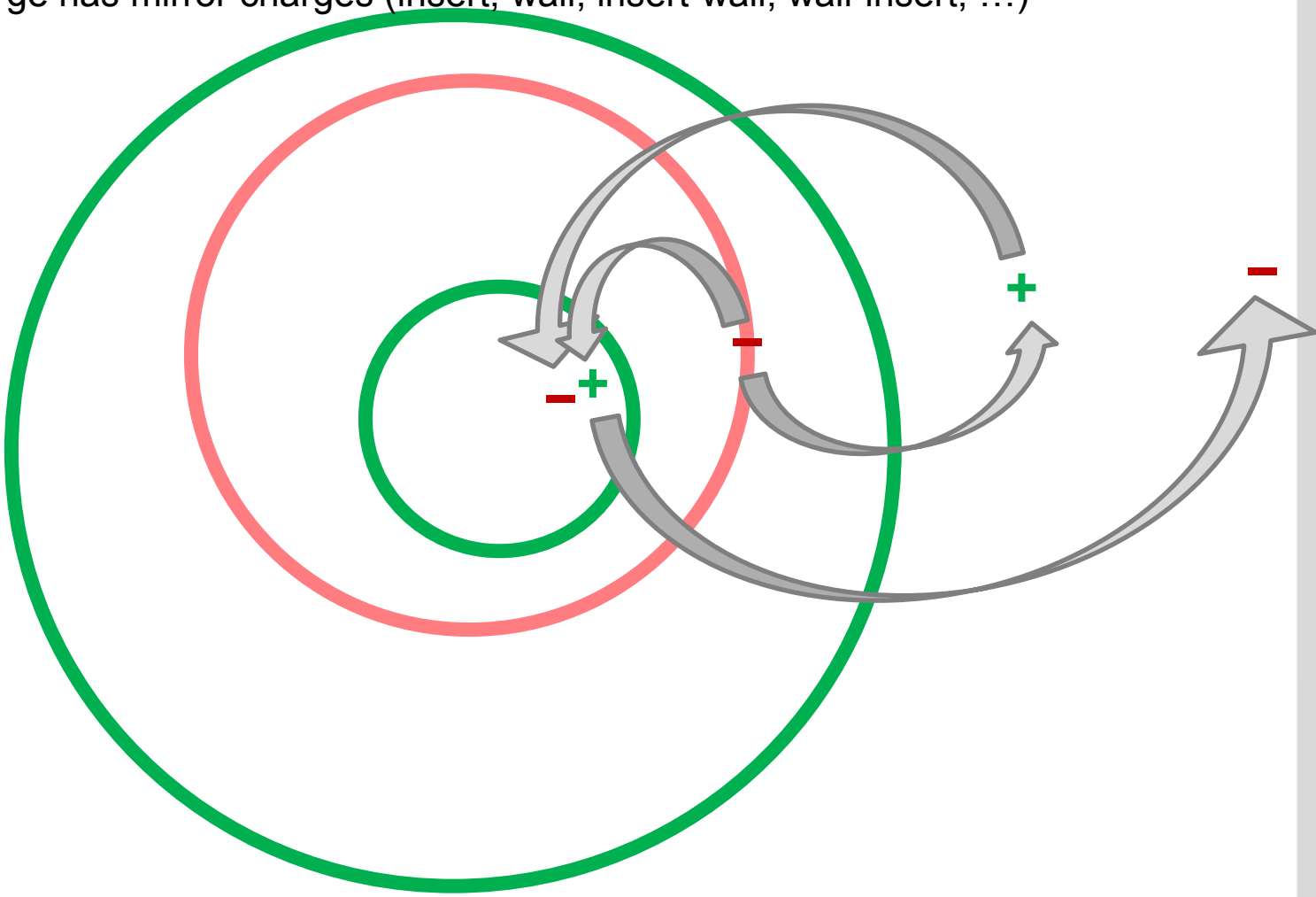
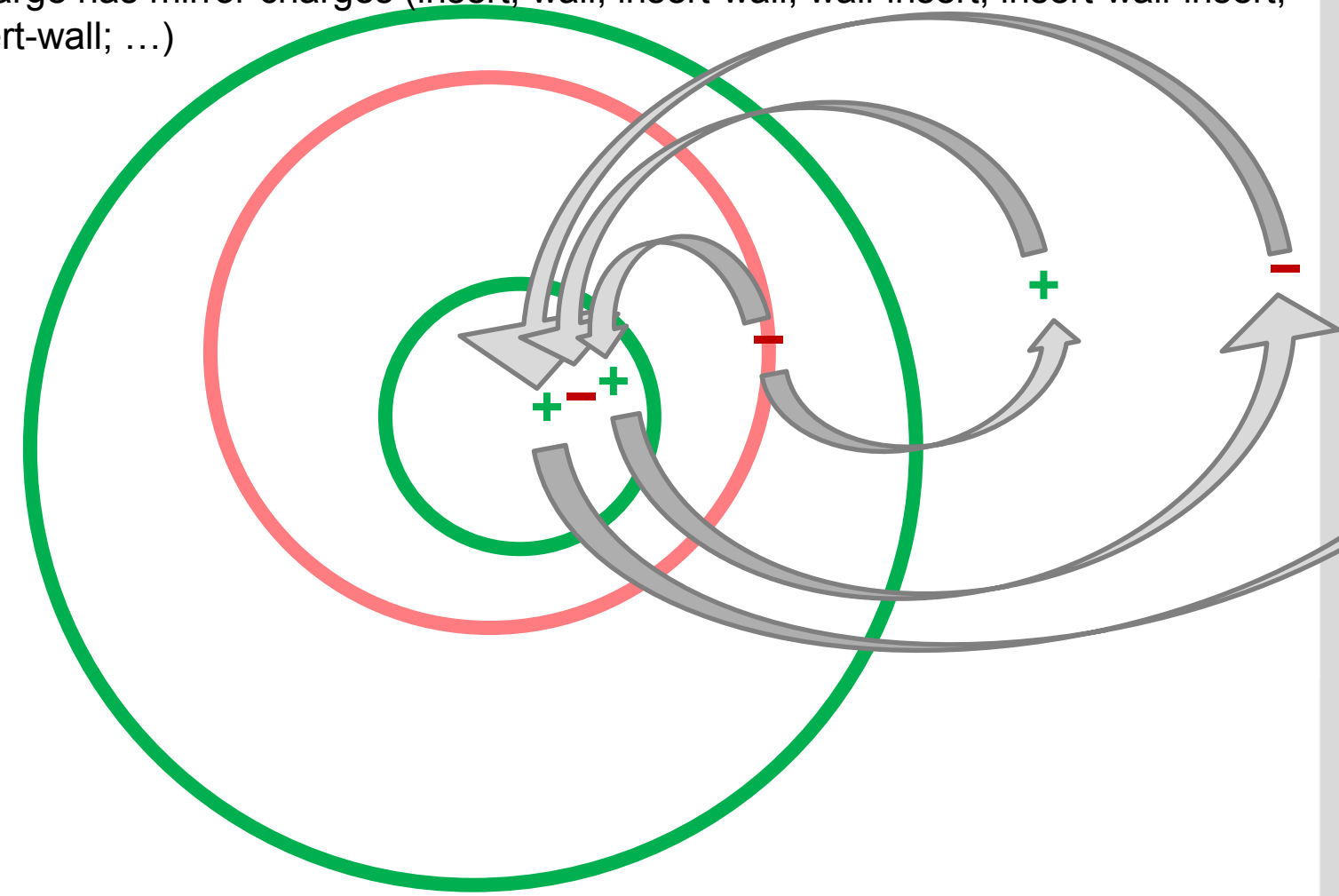


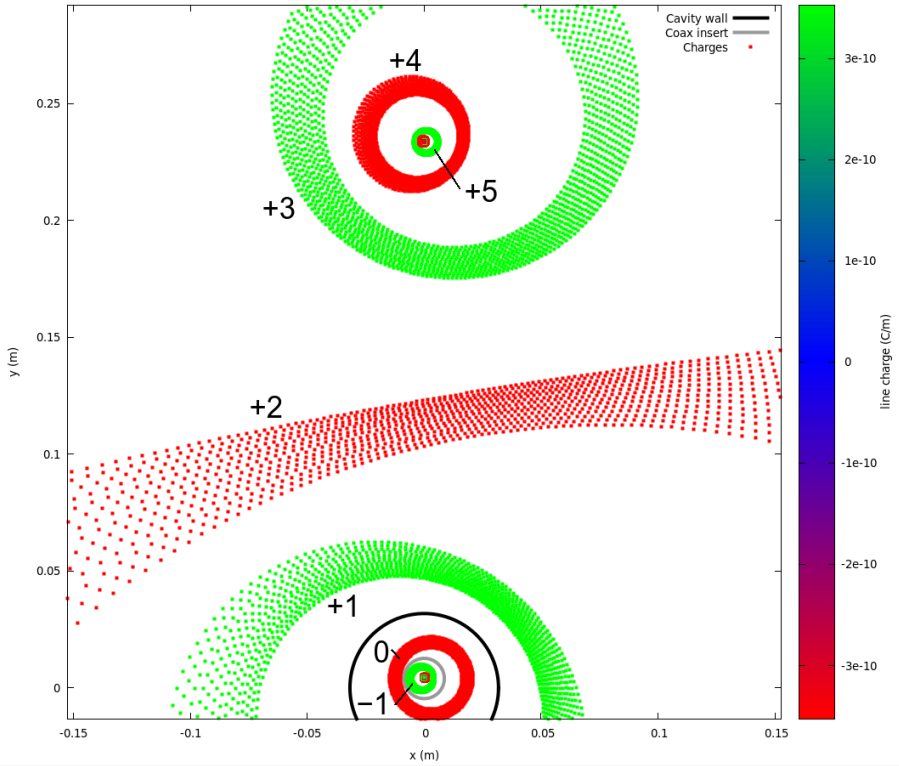
Description of Misalignment: Voltage Depression

- Basic idea (seems to fail):
  - Describe electron beam as (large) number of point-charges
  - Each charge has mirror charges (insert; wall; insert-wall; wall-insert; insert-wall-insert; wall-insert-wall; …)



Description of Misalignment: Voltage Depression

- Basic idea (which does not fail):
  - Describe electron beam as (large) number of point-charges
  - Each charge has mirror charges (insert; wall; insert-wall; wall-insert; insert-wall-insert; wall-insert-wall; …) → infinite number
- But:
  - Mirror charges converge to two distinct points of the geometry → series can be truncated



Description of Misalignment: Voltage Depression

- Basic idea (which does not fail):
  - Describe electron beam as (large) number of point-charges
  - Each charge has mirror charges (insert; wall; insert-wall; wall-insert; insert-wall-insert; wall-insert-wall; …) → infinite number
- But:
  - Mirror charges converge to two distinct points of the geometry → series can be truncated
  - Axisymmetric beams need only a few (~20) mirror charges in total