Radiative damping in dielectric structures

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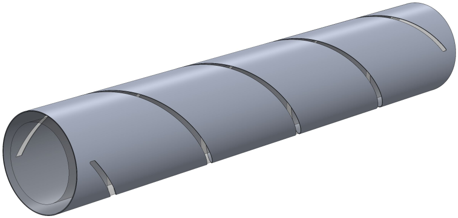
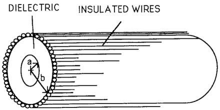


Controlling modes in a wakefield structure
A drive beam passing through any structure excites a whole spectrum of modes. We want a knob that selects which ones survive. Taking the familiar metal-coated dielectric tube as our base, we consider cutting slots or patterns into the cladding, allowing chosen modes to radiatively damp to free space.

Possible applications would include

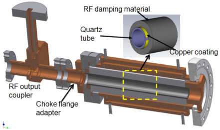
- **BBU suppression.** The deflecting dipole mode HEM_{11} drives beam breakup. Damp it selectively while leaving the accelerating monopole mode TM_{01} intact.
- **Beam dynamics manipulation.** Mode content sets the transverse wake, which dictates the beam dynamics experienced by the witness bunch.
- **Engineered radiation.** The same leakage can also be used as a source. Helical slots convert the Cherenkov wake into high-power free-space OAM.

Prior work

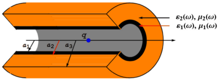


Chojnacki et al., J. Appl. Phys. 69, 6257 (1991)
Selective radiative damping of dipole modes. Longitudinal conductors surrounded by RF absorbing material. Companion theory paper is Gao & Ho, J. Appl. Phys. 70, 3955 (1991). (ANL)

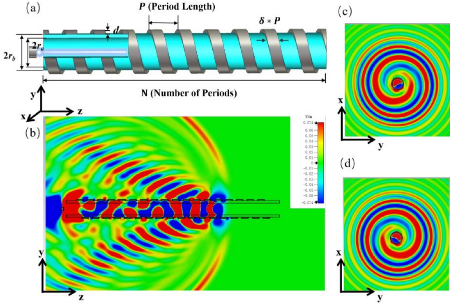
Conde et. al 2009, Proc. PAC09
"Transverse mode damped dielectric structure, to demonstrate the use of longitudinal slots and RF absorbers." (ANL)



Jing et al., Appl. Phys. Lett. 103, 213503 (2013)
Longitudinal slots etched into quartz tube's outer copper cladding. Surround by SiC-AlN RF absorbing tube. (Euclid TechLabs, ANL, SLAC)



Ivanyan et al., PRAB, 041301 (2020)
No slots. Wall of finite conductivity wall with lossy dielectric can provide mode selectivity. (CANDLE, DESY)



Zhang et al., Opt. Express 34, 18569 (2026)
Helical slots couple TM_{01} mode to radiative $e^{im\phi}$ OAM radiation of chosen azimuthal index m. Mildly relativistic electrons with $\beta = 0.8$.

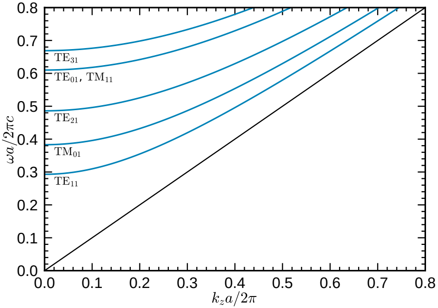
Cylindrical waveguide solutions

Along the waveguide's metal wall, surface currents and charges are induced such that the electromagnetic boundary conditions are satisfied,

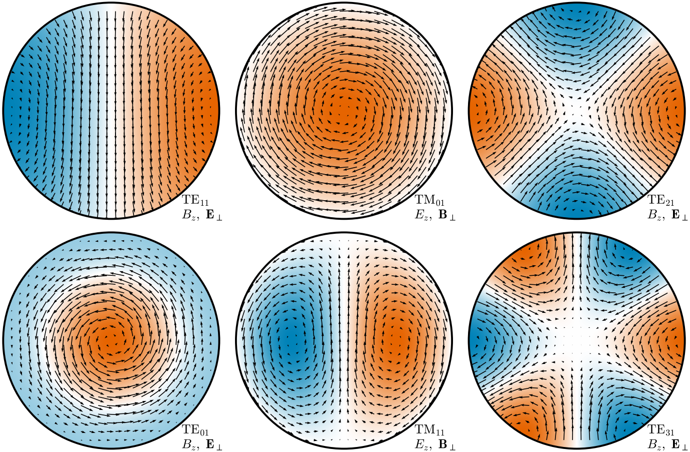
$$\sigma = \epsilon \mathbf{E} \cdot \mathbf{n}, \quad \mathbf{K} = \frac{1}{\mu} \mathbf{n} \times \mathbf{B}, \quad \mathbf{n} \times \mathbf{E} = 0, \text{ and } \mathbf{B} \cdot \mathbf{n} = 0.$$

Modes separate into two families of solutions, with azimuthal index m and radial index n,

- TM_{mn} with nonvanishing longitudinal electric field E_z.
- TE_{mn} with nonvanishing longitudinal magnetic field B_z.



In vacuum, these modes are all superluminal and thus do not couple to the beam. We will remedy this by introducing an inner dielectric layer, but it is still helpful to be familiar with these simpler solutions, as they are the solutions to the metal-coated dielectric tube in the thin dielectric limit.



Of special note are the three lowest frequency modes:

- TE$_{11}$ is a transversely deflecting dipole ($m = 1$) mode.
- TM$_{01}$ is a longitudinally accelerating ($m = 0$) mode.
- TM$_{21}$ is a transversely deflecting ($m = 2$) mode.

Cylindrical waveguide solutions

For $m > 0$, the modes are azimuthally twofold degenerate, so that we may choose any pair of orthogonal combinations. Convenient choices are the helical basis and the standing-wave basis,

$$\begin{Bmatrix} J_m(k_\perp r)e^{+im\phi} \\ J_m(k_\perp r)e^{-im\phi} \end{Bmatrix} \quad \text{and} \quad \begin{Bmatrix} J_m(k_\perp r)\cos m\phi \\ J_m(k_\perp r)\sin m\phi \end{Bmatrix},$$

respectively. In a transverse plane, the mode's *phase* is modulated azimuthally in the helical basis, while the mode's *amplitude* is modulated azimuthally in the standing-wave basis.

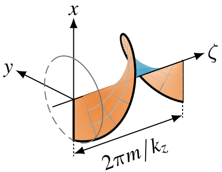
Along the z-axis, a mode moves with phase velocity $v_z = \omega/k_z$. Thus we choose to analyze the mode in terms of comoving coordinate $\zeta = z - v_z t$ with $k_z z - \omega t = k_z\zeta$. Longitudinal fields are then of the form

$$E_z = \begin{cases} E_0 J_m(k_\perp r)\cos(k_z\zeta \pm m\phi) & \text{helical} \\ E_0 J_m(k_\perp r)\cos(m\phi)\cos(k_z\zeta) & \text{standing-wave} \end{cases}$$

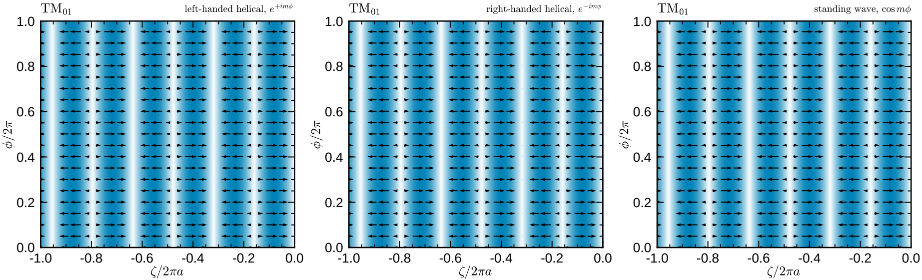
We can trace out a helical surface of constant phase,

$$\phi_0 = k_z\zeta \pm m\phi.$$

For the upper "+" sign, the azimuthal angle ϕ decreases as ζ increases. The corresponding surface of constant phase traces a helicoid that winds *clockwise* as ζ increases, as viewed from $+\zeta$, looking back toward the origin. We define this mode as being *left-handed*, in the spatial "snapshot-in-time" sense.

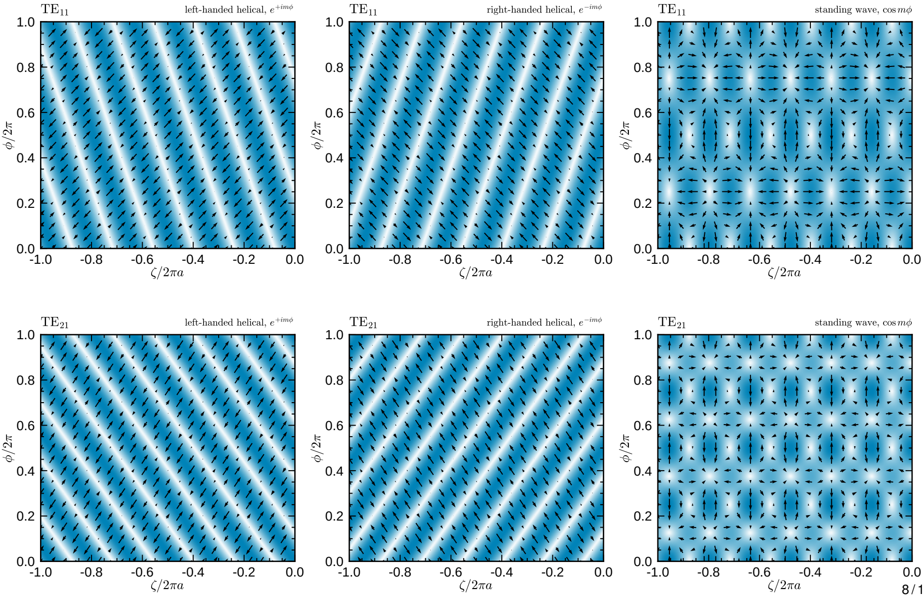


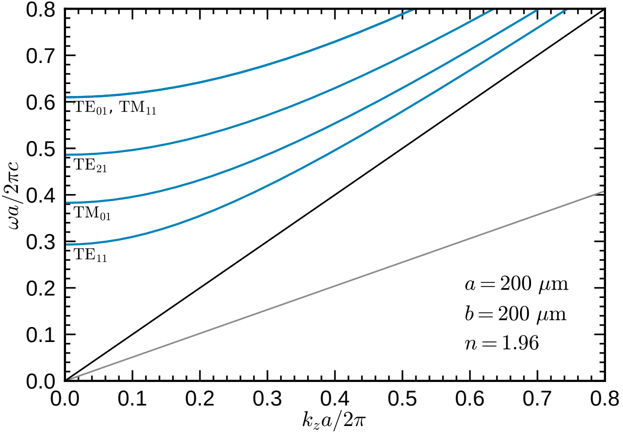
No matter what basis you use, TM_{01} surface currents are longitudinal.



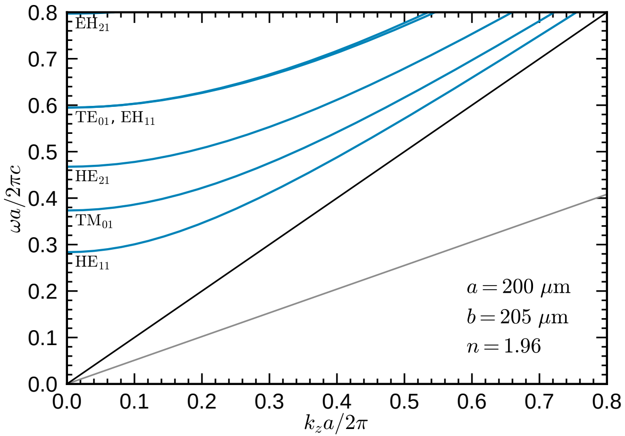
Cylindrical waveguide solutions

TE_{11} and TE_{21} have both non-vanishing azimuthal and longitudinal surface currents, but they are much simpler when the modes are expressed in the helical basis.





- As promised, we introduce a dielectric lining. This brings the dispersion curves down so that they cross the light line.
- For $m \neq 0$, the mode's longitudinal electric and magnetic fields couple at the vacuum/dielectric boundary and thus these modes are no longer purely TM or TE.
- First letter of these hybrid modes denotes its dominant longitudinal field.



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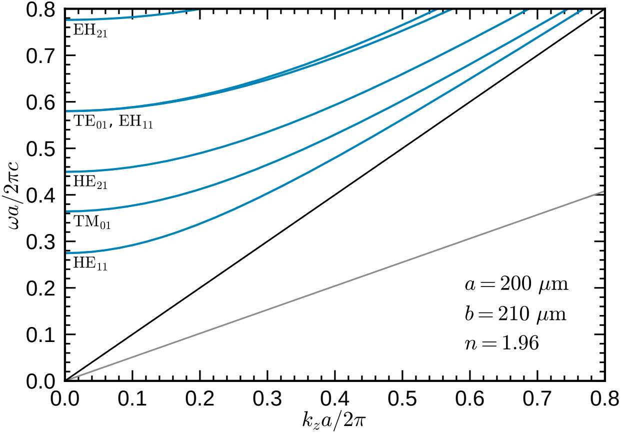

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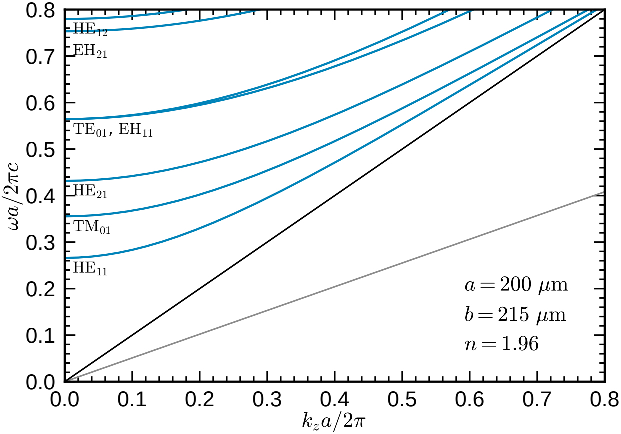

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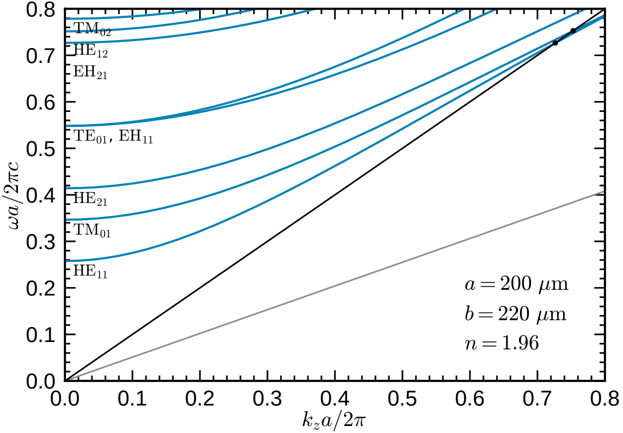

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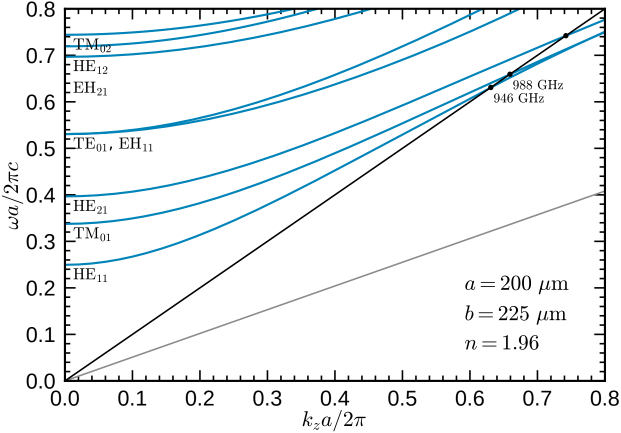
Metal-coated tube waveguide solutions



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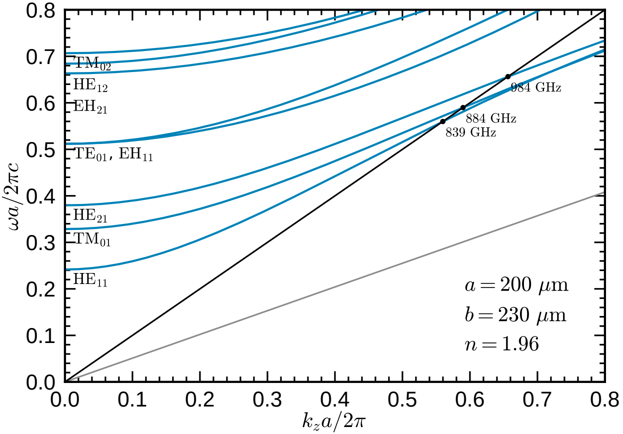

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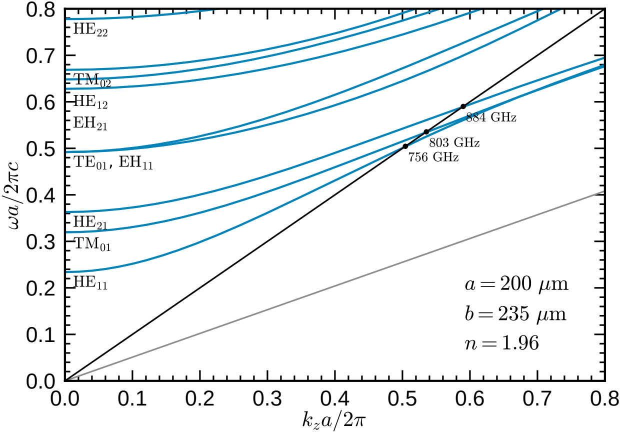

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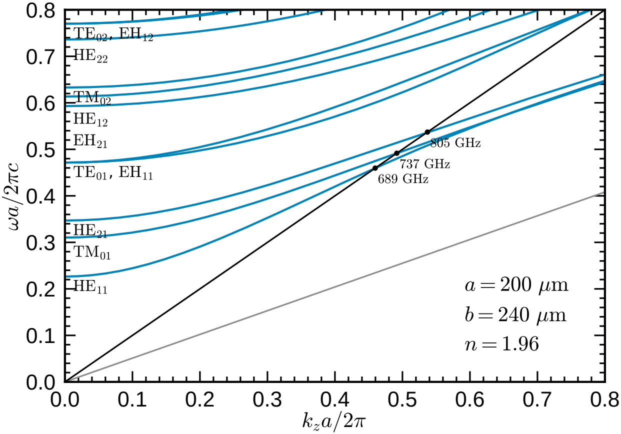

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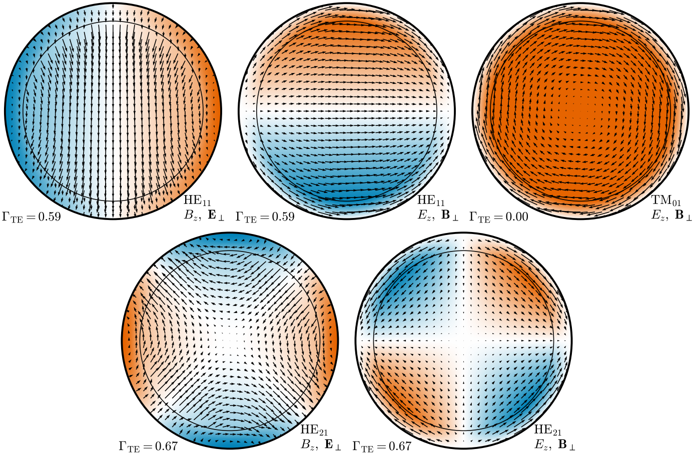

- As promised, we can still recognize the homogeneous vacuum heritage of the hybrid modes.
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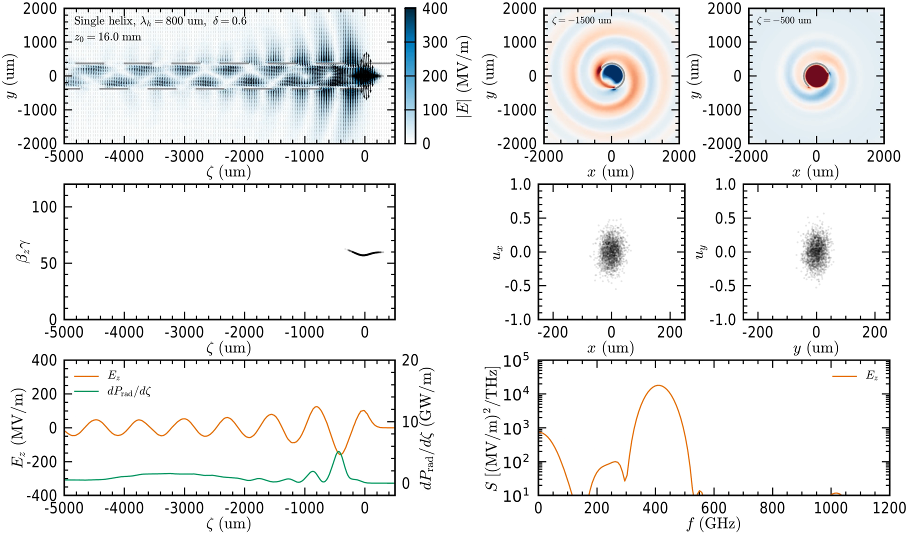
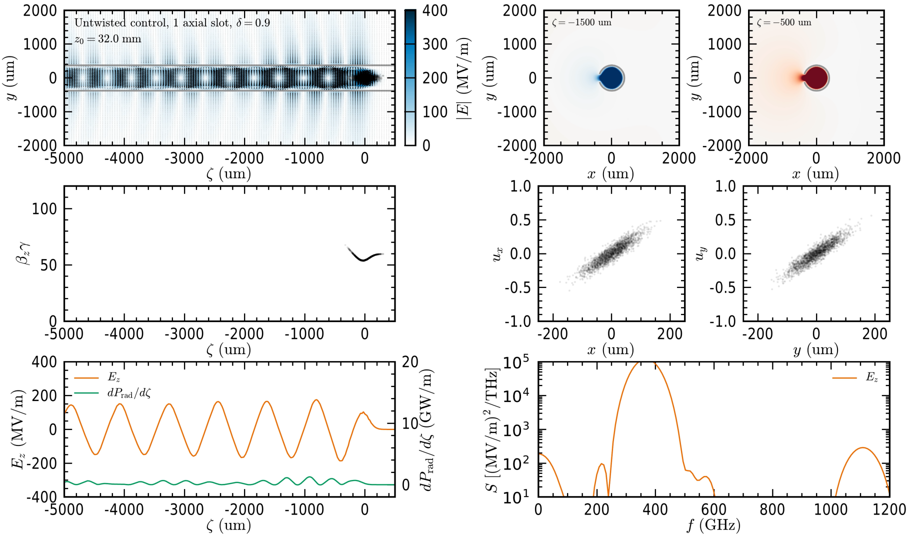
$$\Gamma_{TE} \equiv \frac{U_{TE}}{U_{TE} + U_{TM}}$$

WarpX simulation results



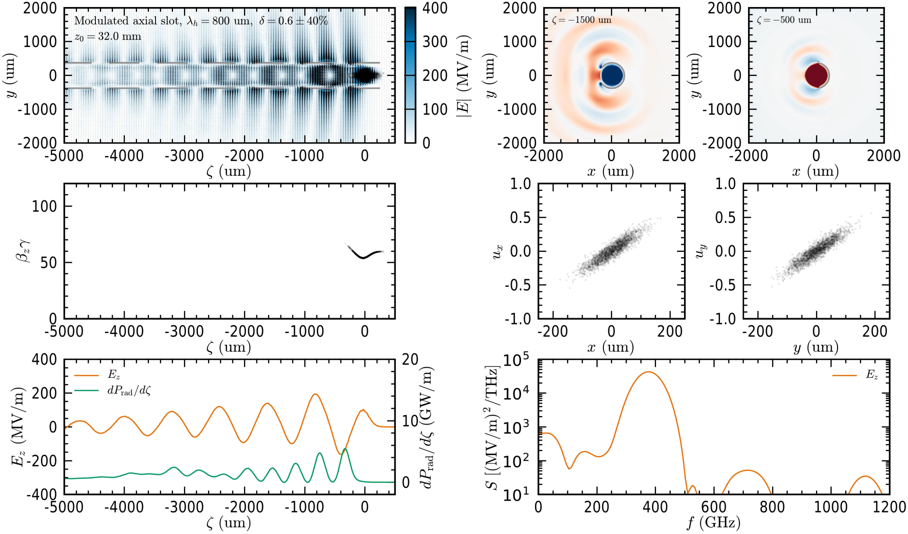
- Single helical slot. Tube has overall 60% metallization.
- 30 MeV beam is on-axis. Structure directly couples TM_{01} mode to free-space radiating OAM.

WarpX simulation results



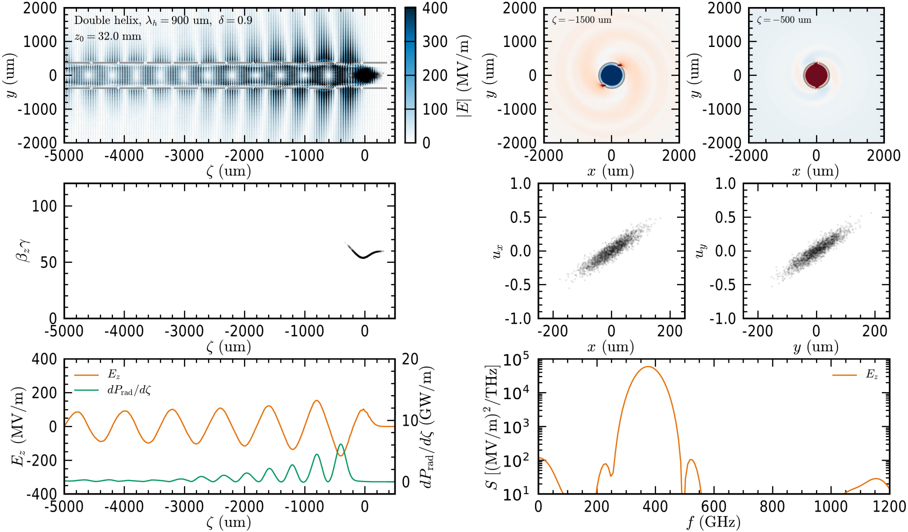
- Single uniform longitudinal slot. Tube has overall 90% metallization.
- Very little radiation.

WarpX simulation results

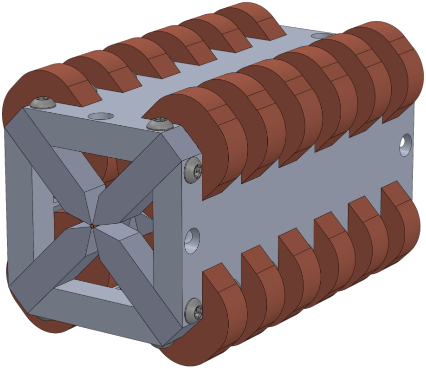


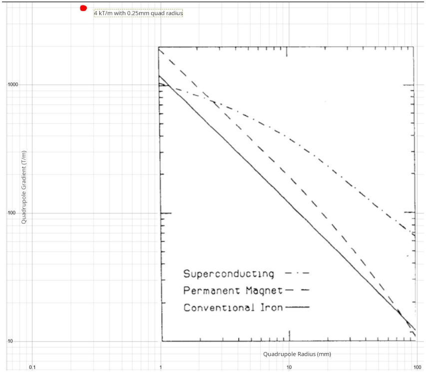
- Single modulated longitudinal slot. Tube has overall 60% metallization with a 40% slot modulation width. Strong radiation.
- The modulation length along ζ is same as earlier helix example.

WarpX simulation results



- Double helix. Tube has overall 80% metallization.
- Strong selective damping of the dipole mode.





- Looking at combining radiative damping with strong focusing.
- With small bore and Permendur, can achieve high quadrupole strengths, at least a few kT/m.