Plasma-Wave Interaction in Electrodeless Plasma Thrusters and its Optimization

PhD Student: Hugo Bergerioux
Supervisor: Mario Merino

PhD Aerospace Engineering UC3M
Doctoral Meetings 2026
2nd and 3rd June 2026

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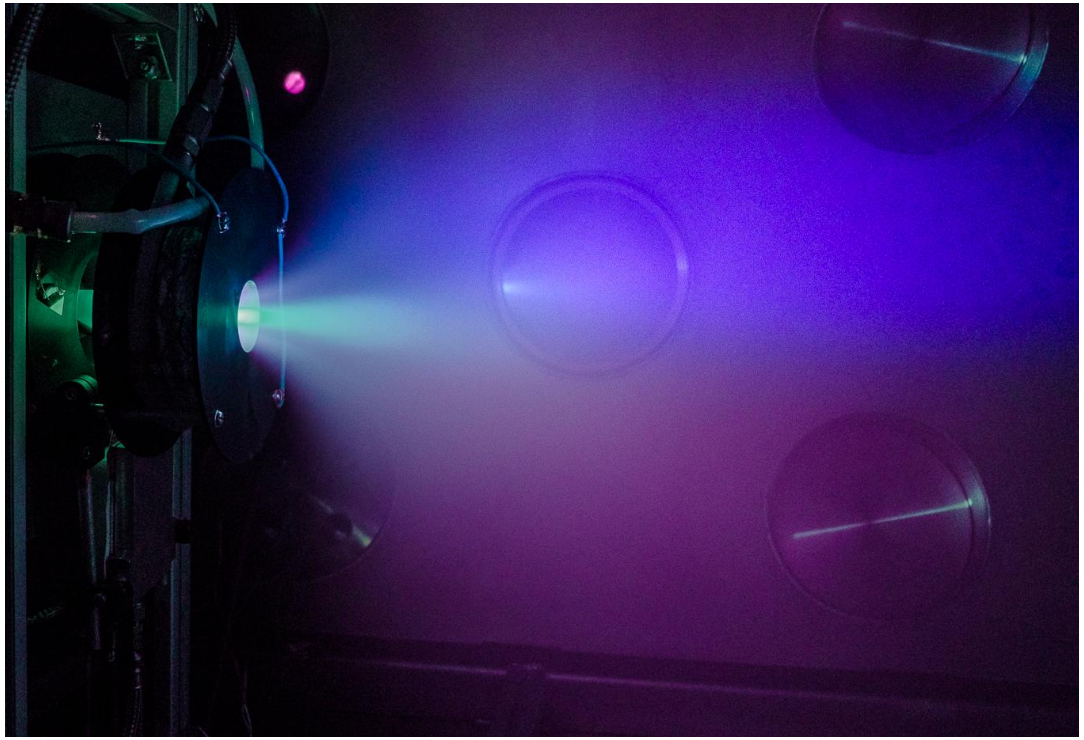
Electrodeless Plasma Thrusters (EPTs)

So far, mostly plasma thrusters **with** electrodes (Hall and Ion thrusters)

Electrodeless Plasma Thrusters
- No electrode anymore!
- Plasma heated via EM fields

Advantages:
- Durability (no electrode erosion)
- Flexibility (propellants agnostic)

(1) Helicon Plasma Thruster (HPT)
  - *(previous presentation of Andrés)*
  - Inductive power coupling
    - antenna with helicon waves



UC3M-SENER Helicon Plasma Thruster

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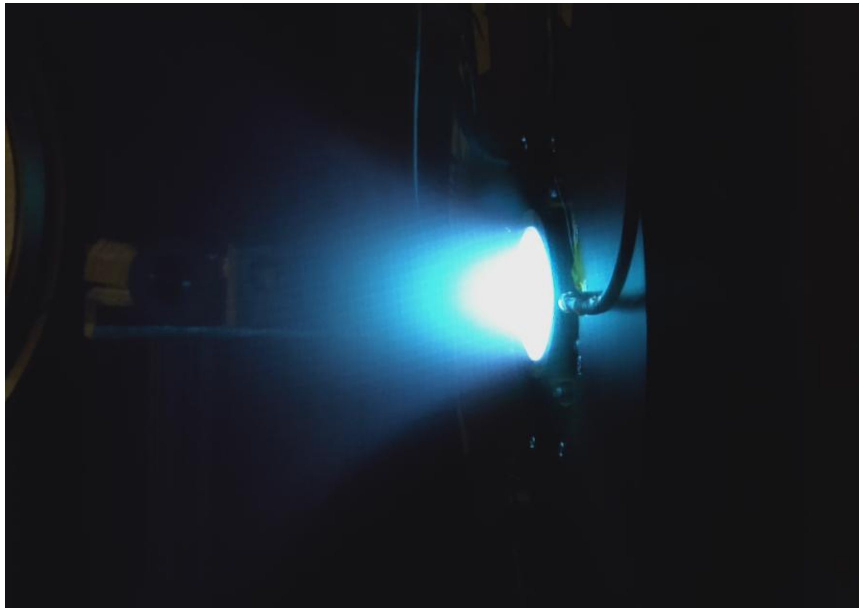
In this work, we will focus on

(2) Electron Cyclotron Resonance Thruster (ECRT)
- Resonant absorption of microwave power
- Microwave excitation through **waveguide**

→ *developed by Marco Inchingolo in the EP2 group*



Waveguide-ECRT of EP2 group

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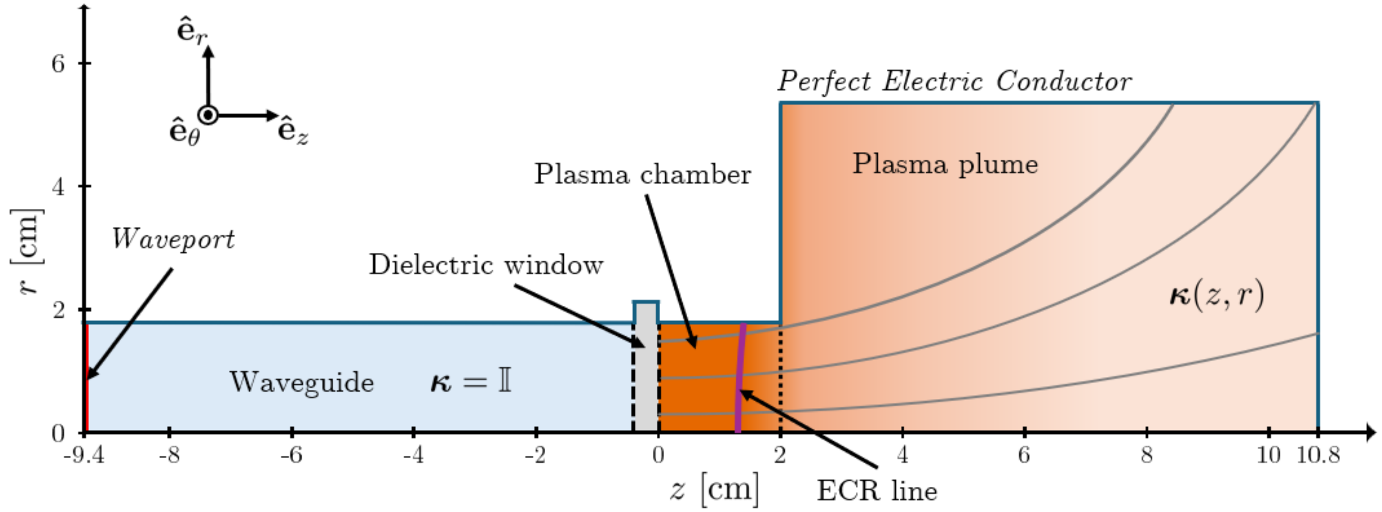

2D axisymmetric domain and boundaries for ECRT wave-simulations

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Plasma-Wave Interaction

Fundamental mechanism:
- exchange between waves and charged particles

What we want:
- Efficient, localized power coupling

→ maximize performance

Numerical freedom:
- Physical diagnostic
    - Full accessibility
    - Non-invasive
- Iterative speed over parameters
    - (geometry, plasma…)

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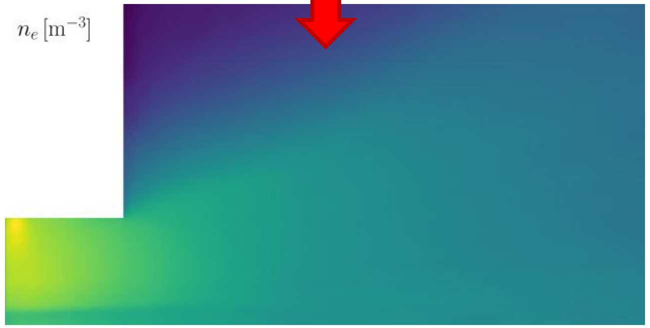
Model plasma transport

HYPHEN

HYBRID CODE
PIC for ions
Fluid for electrons



Plasma density maps
$n_s,\ \nu_e$

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Model plasma transport

Model wave propagation and interaction with plasma

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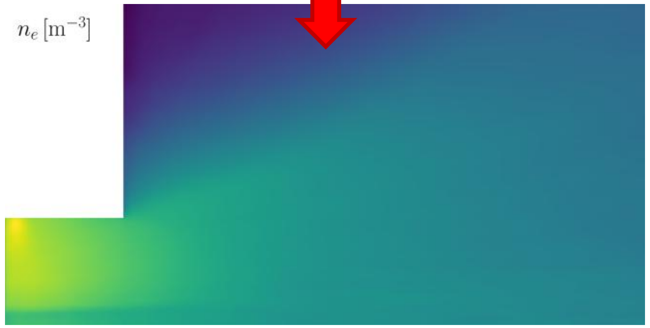
n_s, ν_e →

W-MODULE

FEM CODE
Full wave
Frequency domain



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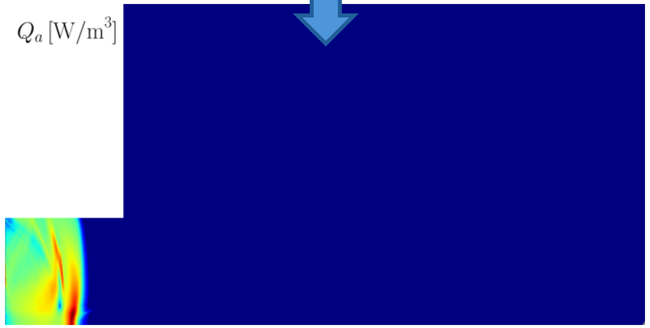

Power absorption map
Q_a

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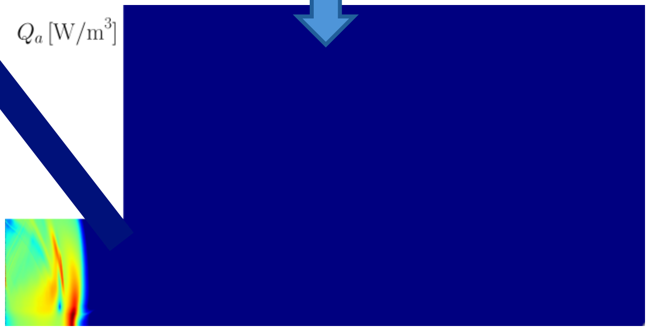


Power absorption map

In this work, we focus on the **wave module**:

Finite Element Method (FEM)

Cold plasma approximation

The Cold Plasma Model

Physical model: **Cold plasma**

- Thermal motion of particles negligible $(v_{\mathrm{th}} \ll v_{\mathrm{ph}})$

$$\boxed{\nabla \times \left(\nabla \times \hat{\boldsymbol{E}}\right) - \frac{\omega^2}{c^2}\boldsymbol{\kappa}\hat{\boldsymbol{E}} = \boldsymbol{0}}$$

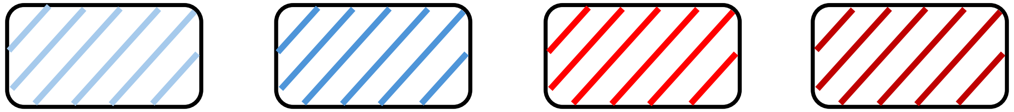
Wave equation

$$\boxed{\boldsymbol{\kappa} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix}}$$

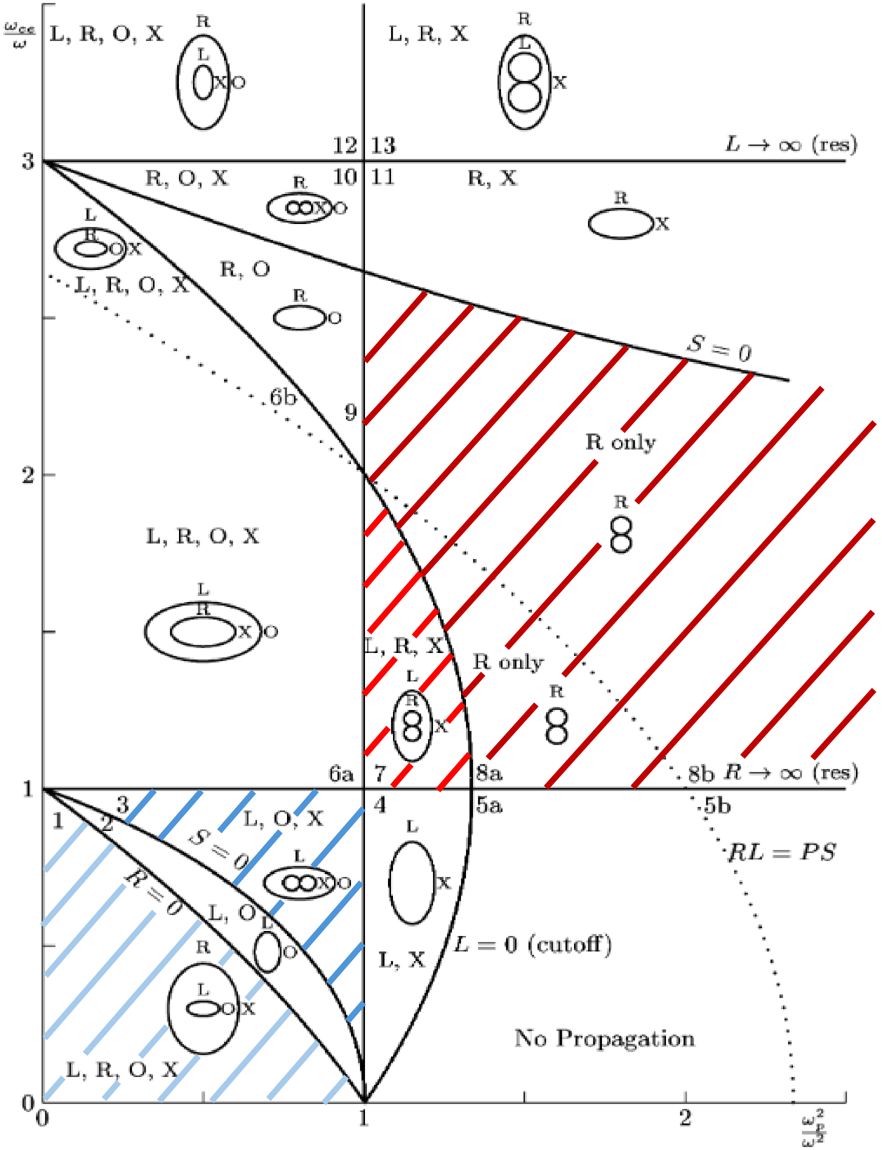
Anisotropic dielectric tensor

- Dispersion relation identifies **resonances** and cutoffs

Propagation regimes represented in the **CMA diagram**



Region I Region III Region VII Region VIII



The CMA diagram

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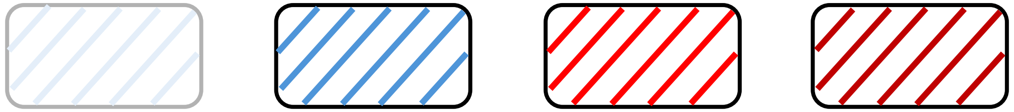
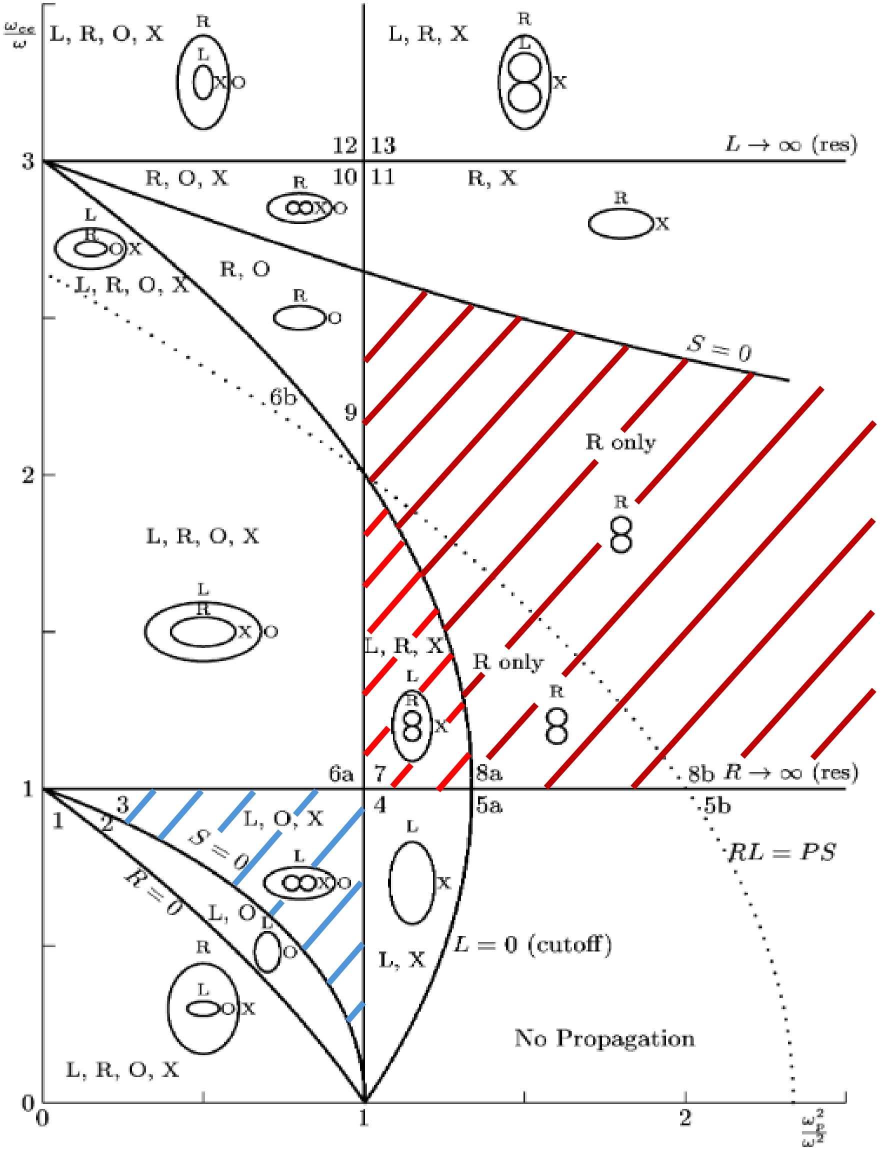


Region I | Region III | Region VII | Region VIII

$\underbrace{\text{Region III} \quad \text{Region VII} \quad \text{Region VIII}}_{}$

Regimes with resonance cones



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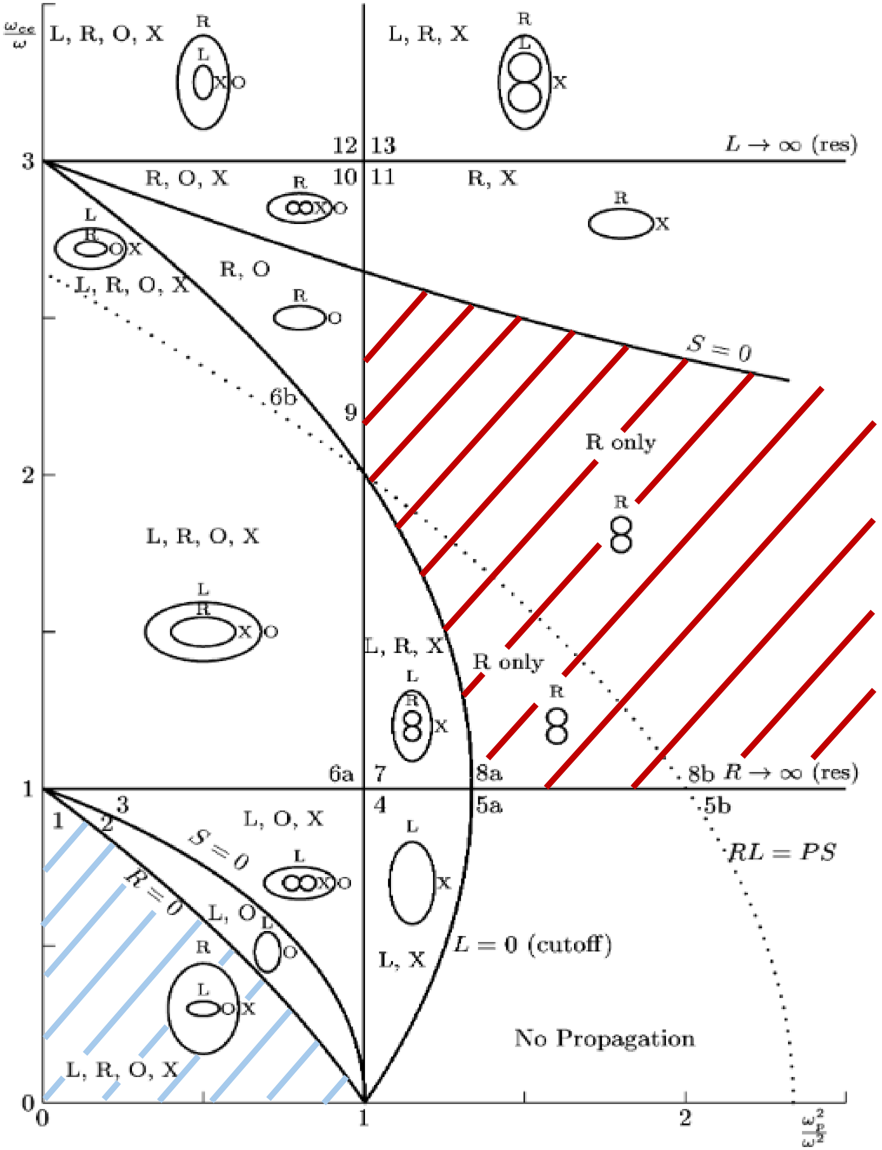
Region I | Region III | Region VII | Region VIII

Reference regions studied here



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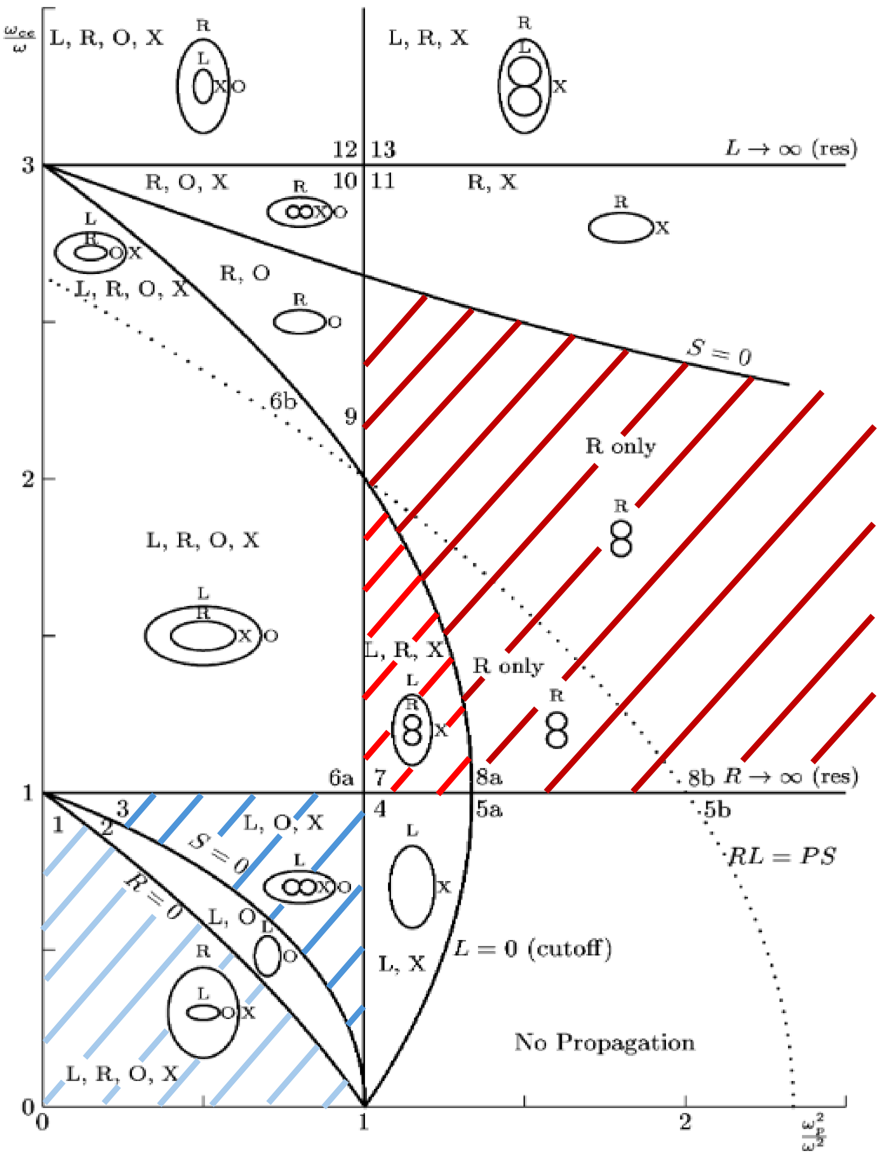
→ Propagation regimes represented in the **CMA diagram**

Region I Region III Region VII Region VIII

- Numerical strategy**: Mixed Nédélec-Lagrange FEM**

$$\mathcal{W} : \mathcal{A}(\hat{\boldsymbol{E}}, \hat{\boldsymbol{T}}) = \int_\Omega \left[(\nabla \times \hat{\boldsymbol{T}}^*) \cdot (\nabla \times \hat{\boldsymbol{E}}) - k_0^2 \hat{\boldsymbol{T}}^* \cdot \boldsymbol{\kappa}\hat{\boldsymbol{E}} \right] \mathrm{d}V + \oint_\Gamma \left[\hat{\mathbf{n}} \times (\nabla \times \hat{\boldsymbol{E}}) \right] \cdot \hat{\boldsymbol{T}}^* \, \mathrm{d}S = 0$$

The standard weak form

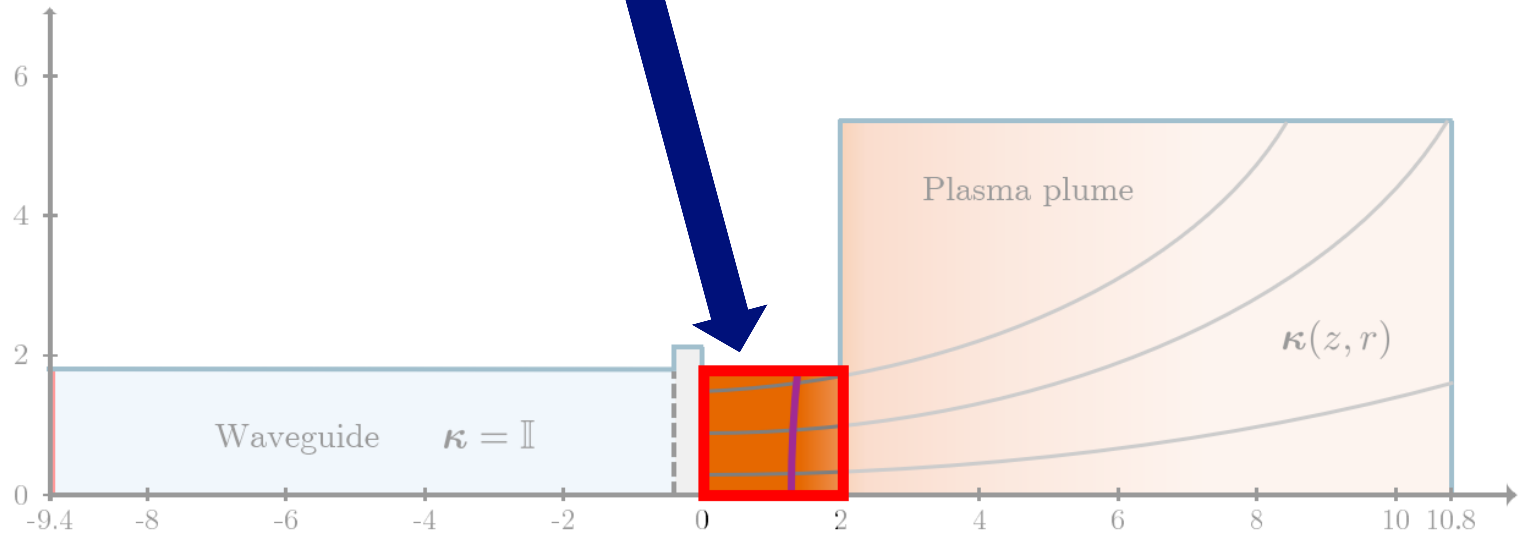


The CMA diagram

ECRT Simulations

Wave simulations of the waveguide-ECRT
- on steady-state plasma 2D maps

Present the results in the plasma discharge chamber



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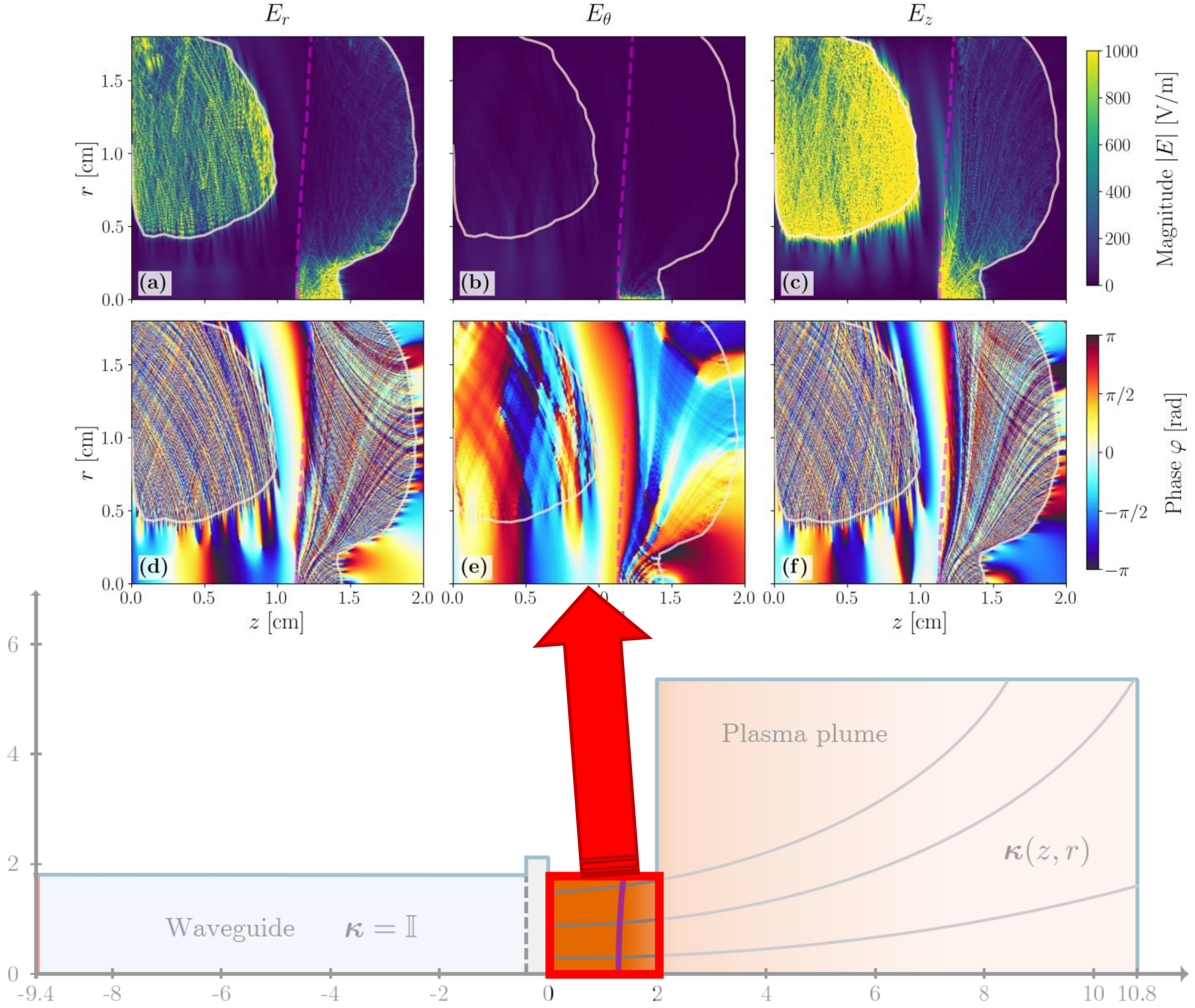
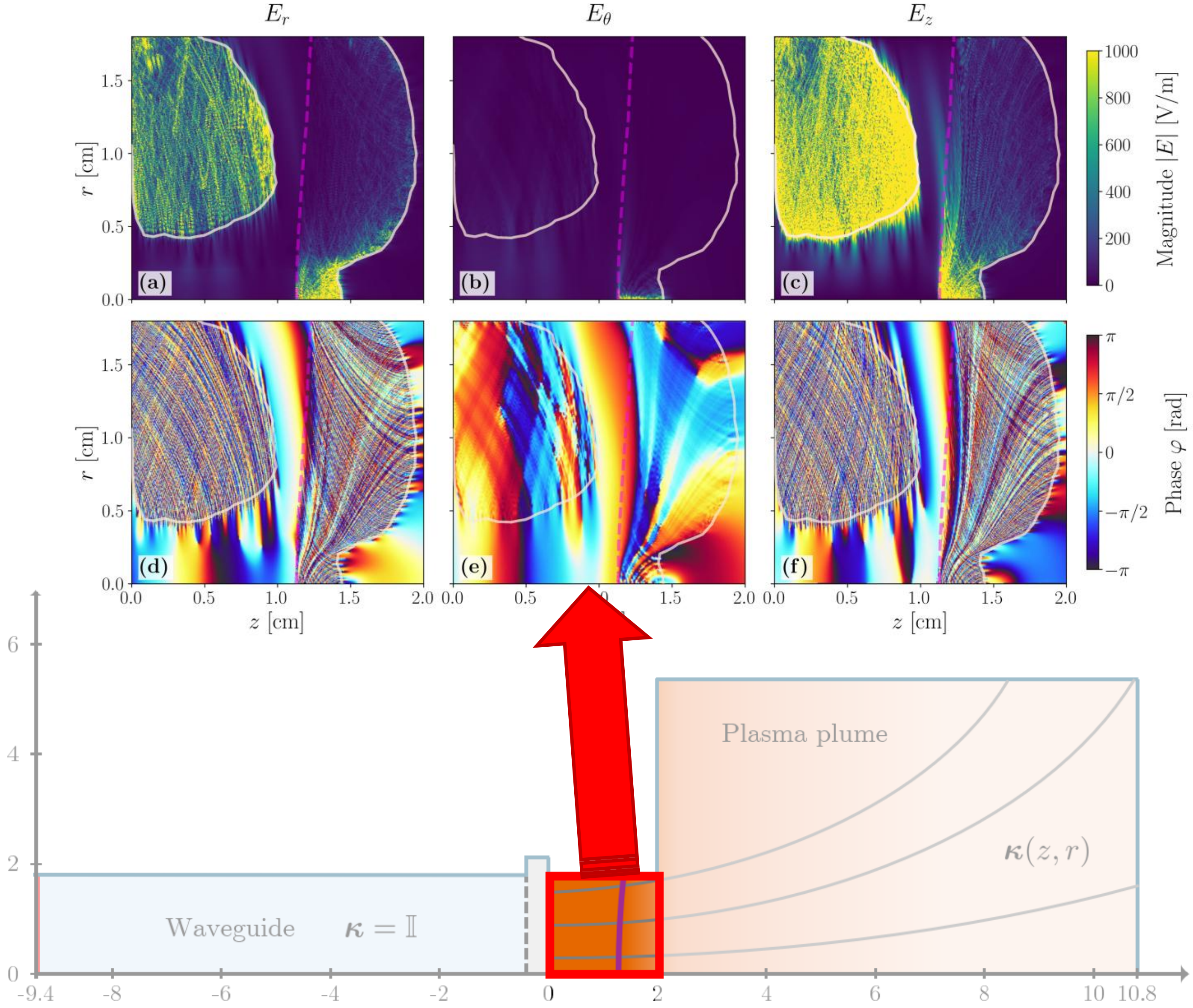


Very fine fast-oscillating structures

ECRT Simulations



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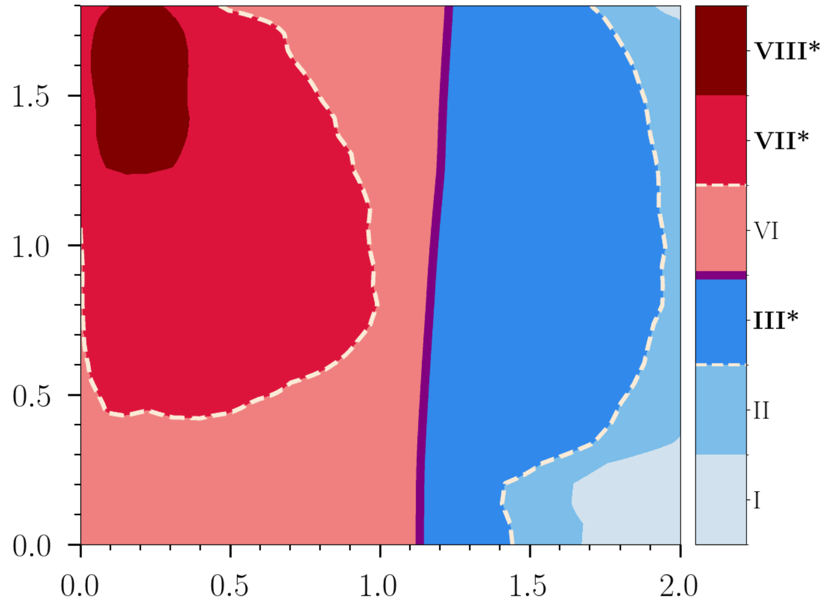
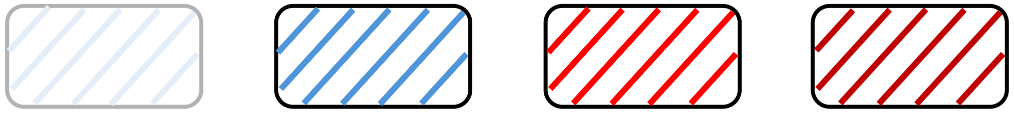


CMA regions in the plasma chamber

These patterns only appear in CMA regions that allow resonance cones!



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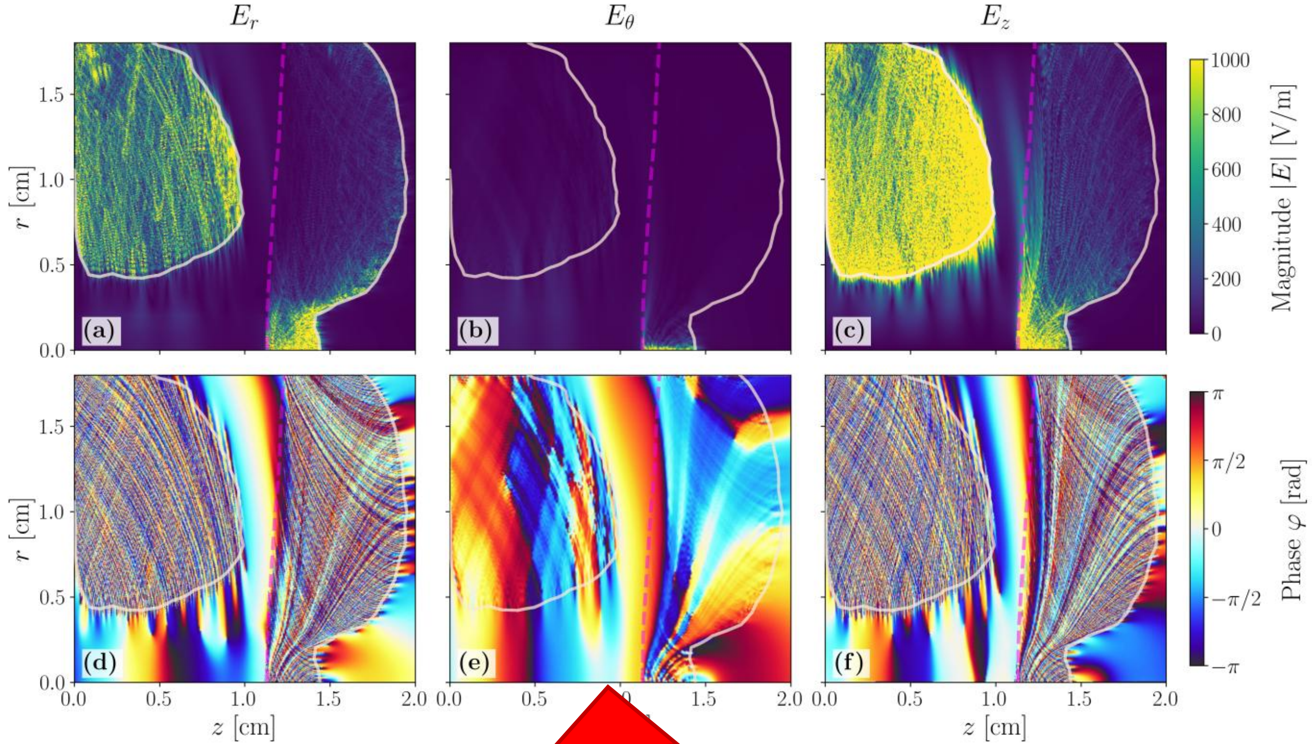

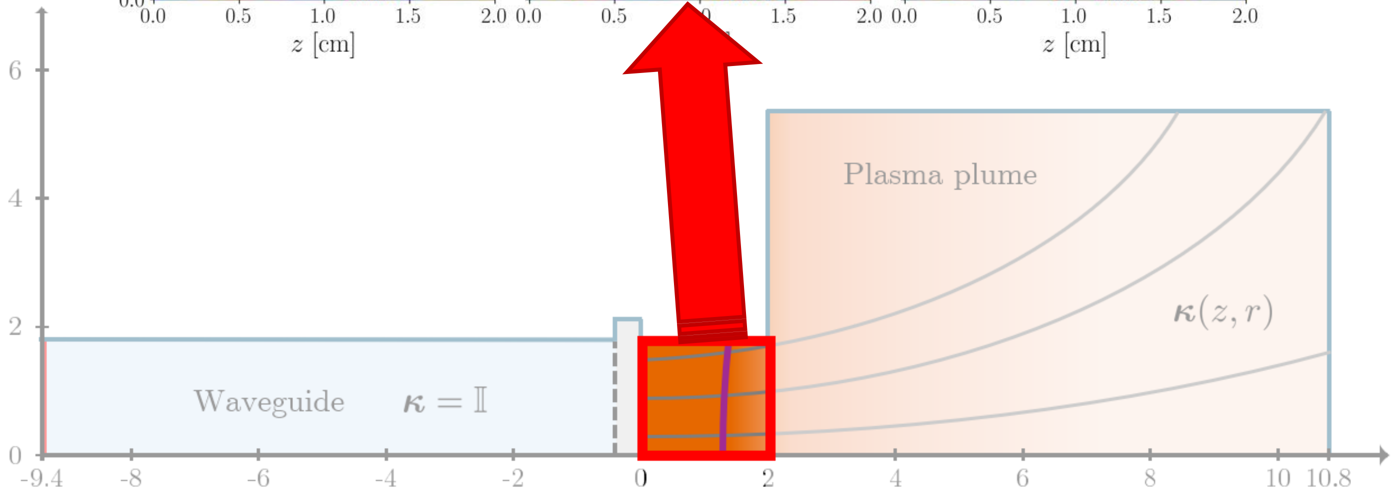

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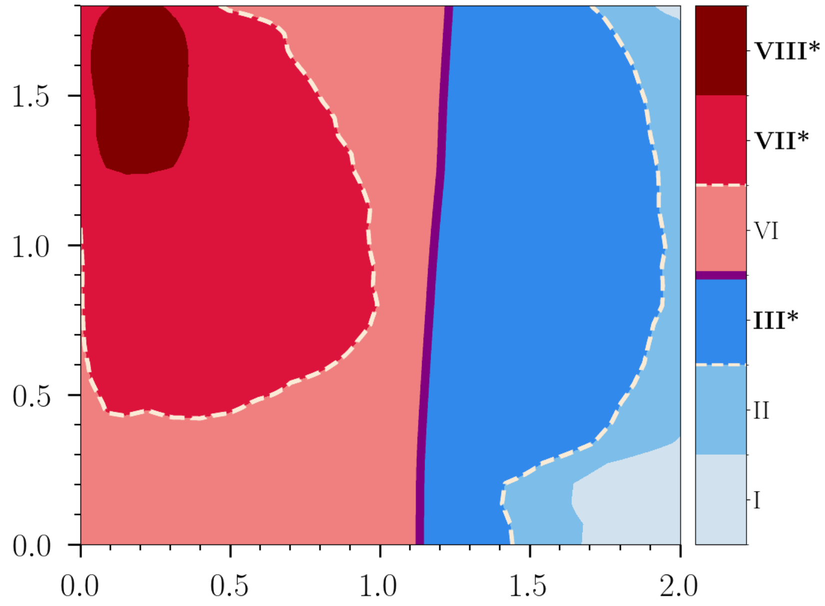

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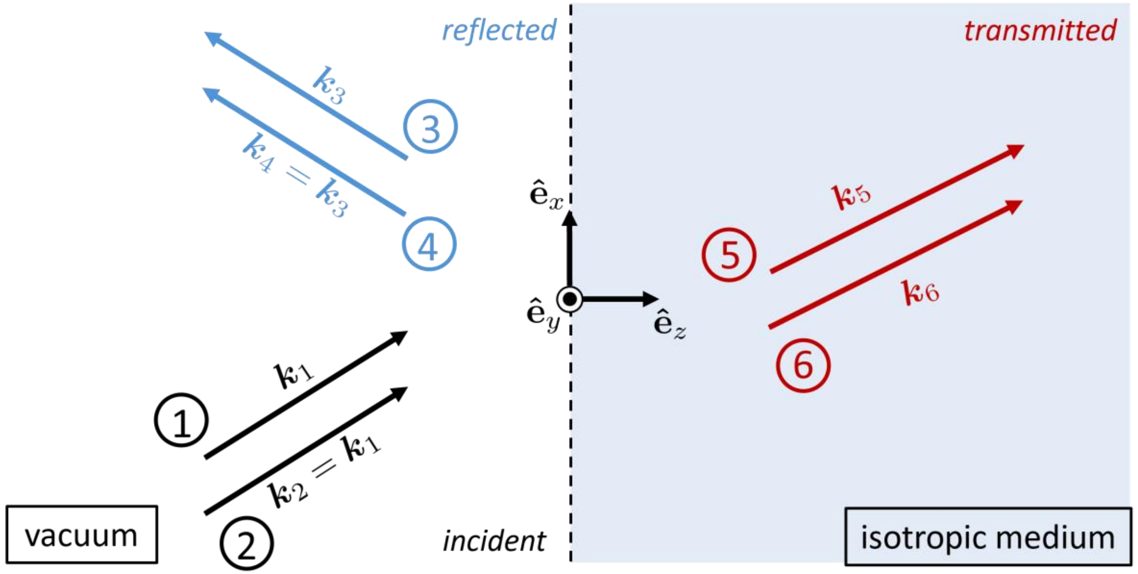
1. First problem we want to solve:
nature of these structures

Fresnel Problem

We want to develop an **analytical benchmark**

Classical Fresnel problem:

- Incident wave at interface between two homogeneous, isotropic media
- Find reflection and transmission coefficients



The classical Fresnel problem

Generalized Fresnel Problem

- We want to develop an **analytical benchmark**
- **Classical Fresnel problem**:
  - Incident wave at interface between two homogeneous, isotropic media
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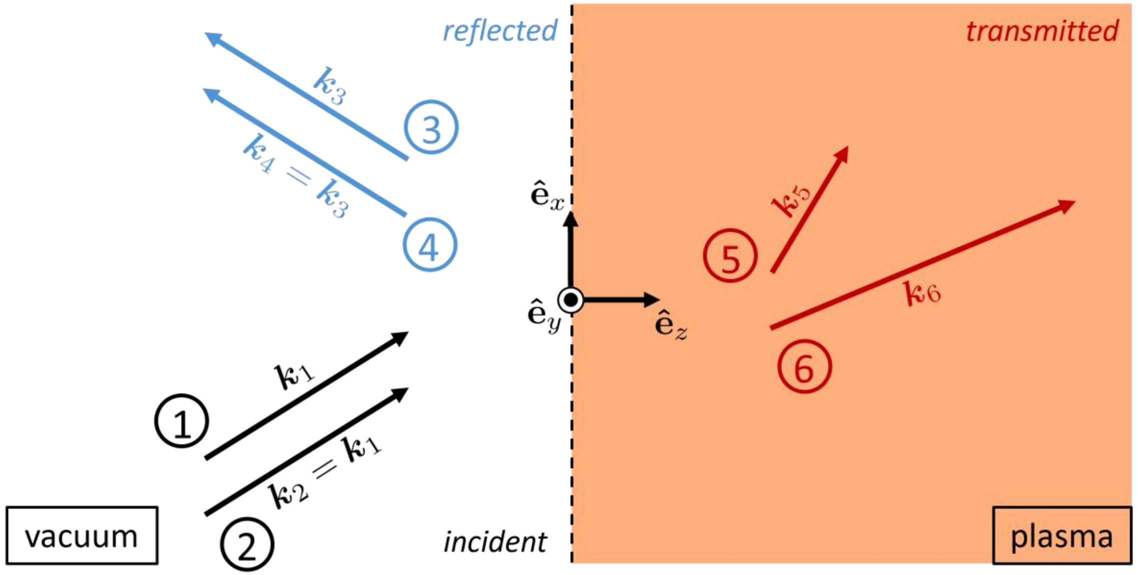
- But here we study **vacuum – plasma interface**
  - Challenge: **anisotropic property of plasma**



*The **generalized** Fresnel problem*

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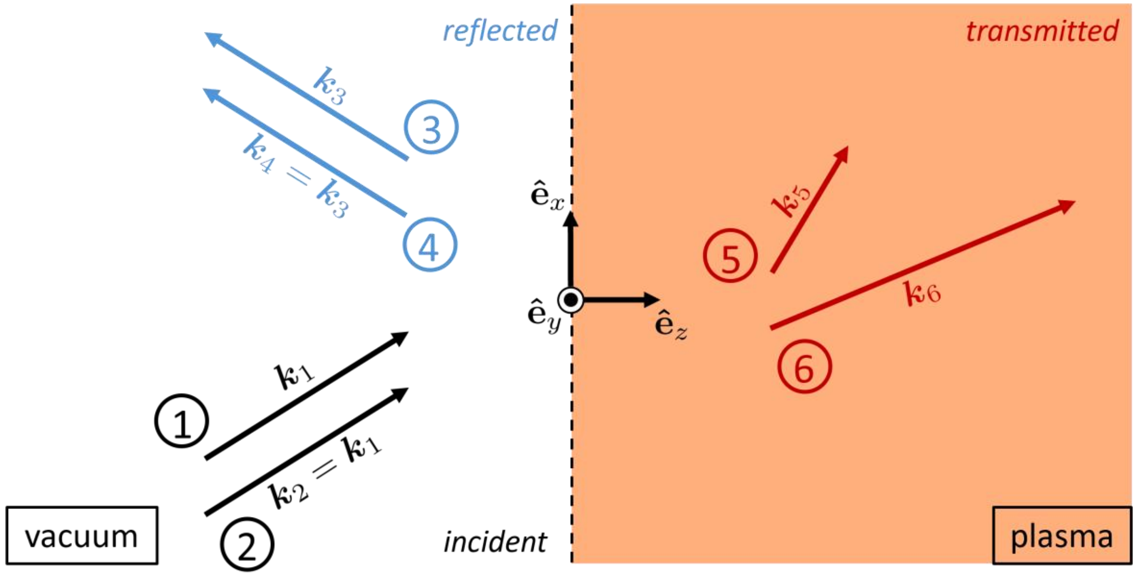

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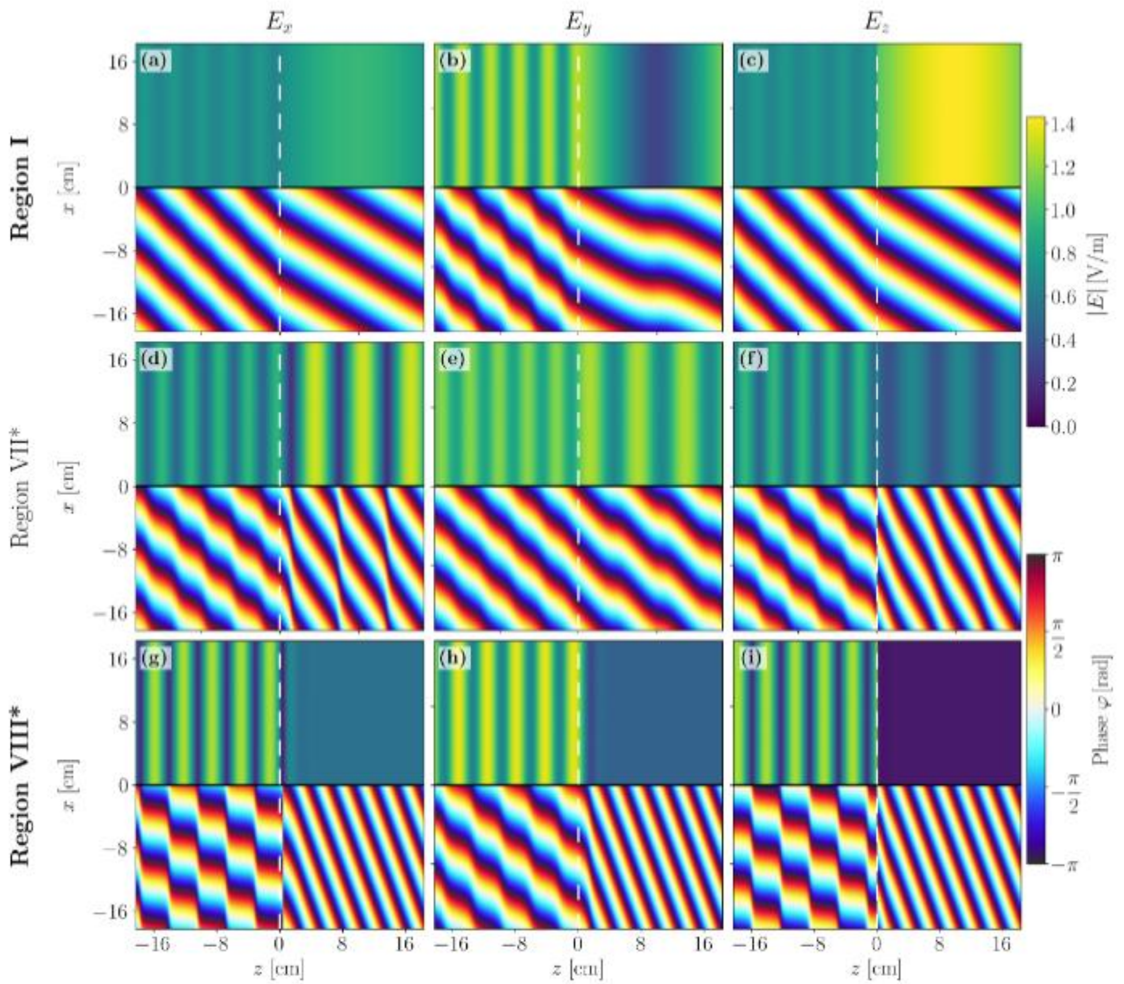


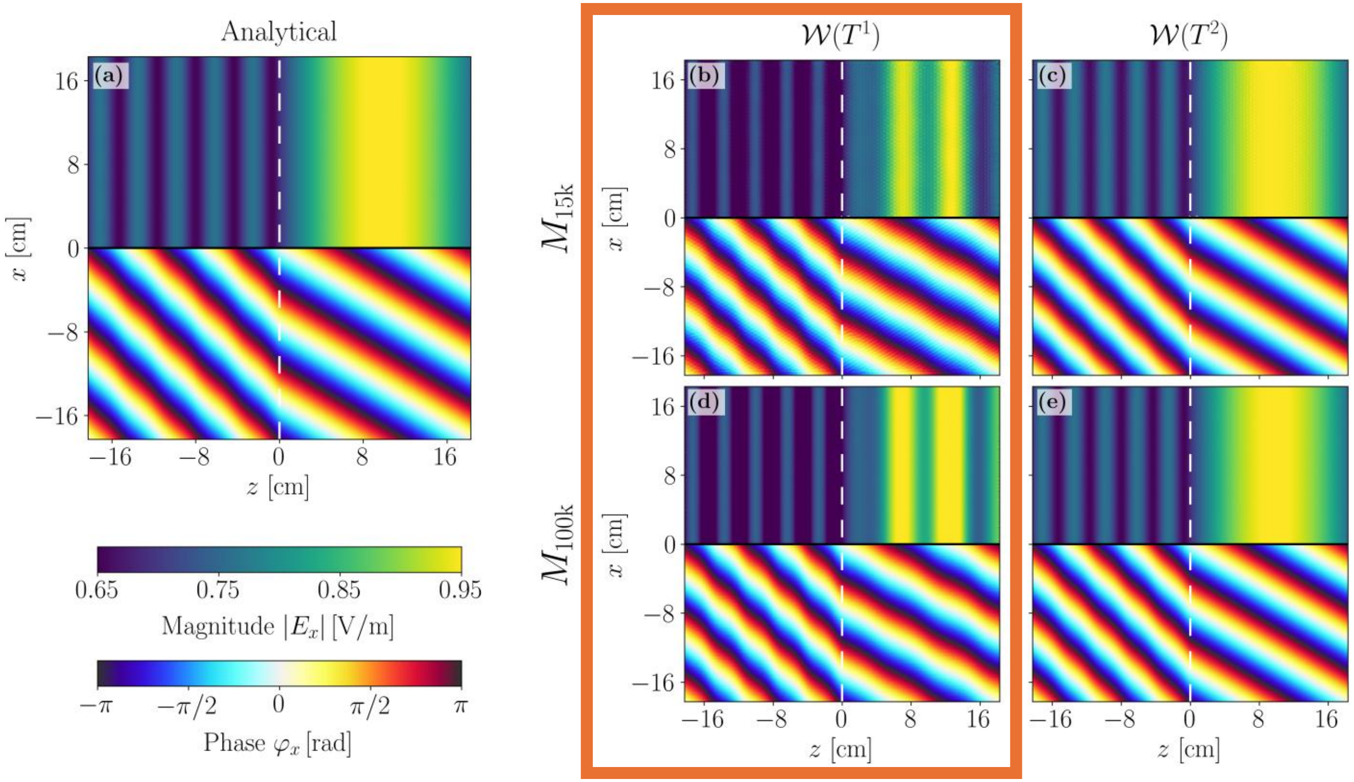
Analytical solution for the electric field

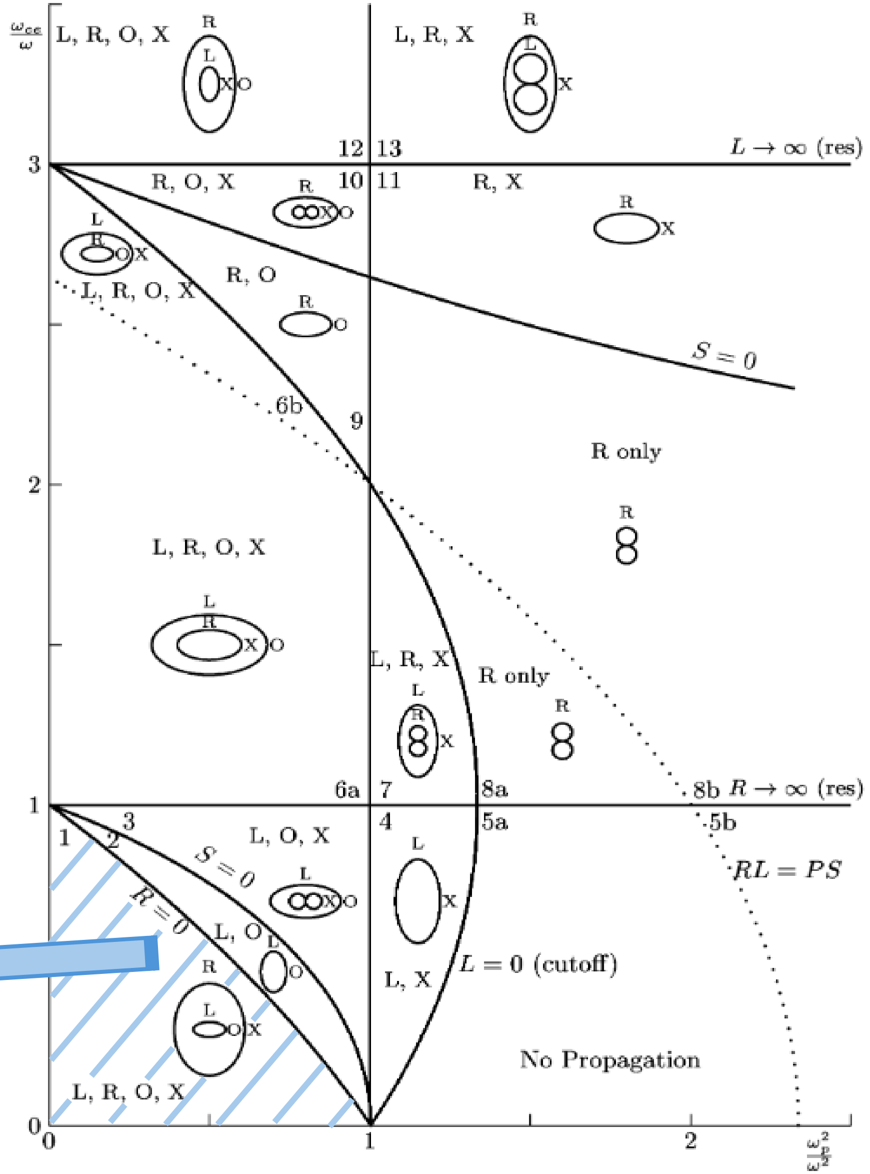
The fast-oscillating structures are numerical!

2. How to mitigate them?

Simulation Results: Region I

- **Numerical solution** for E_x in **Region I** compared to the analytical one for:
  - First order triangles





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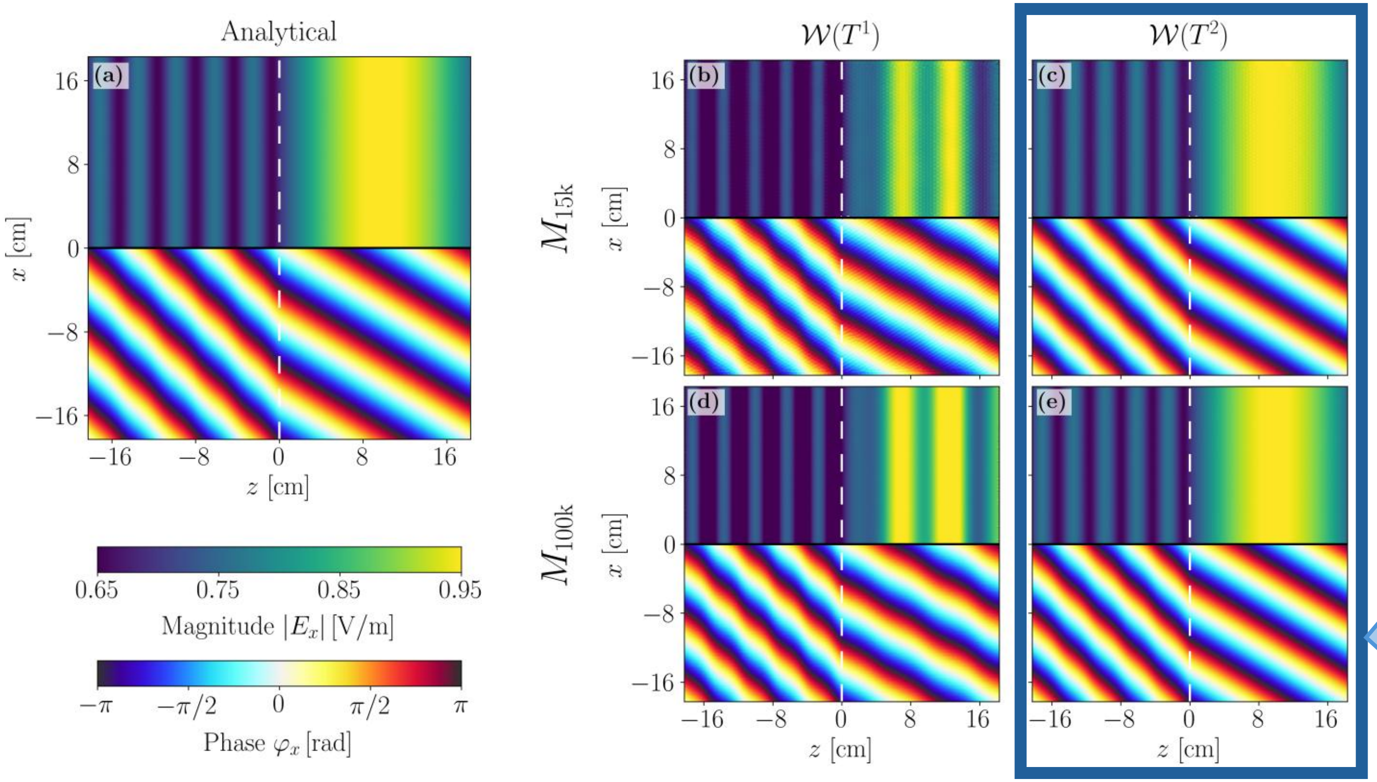

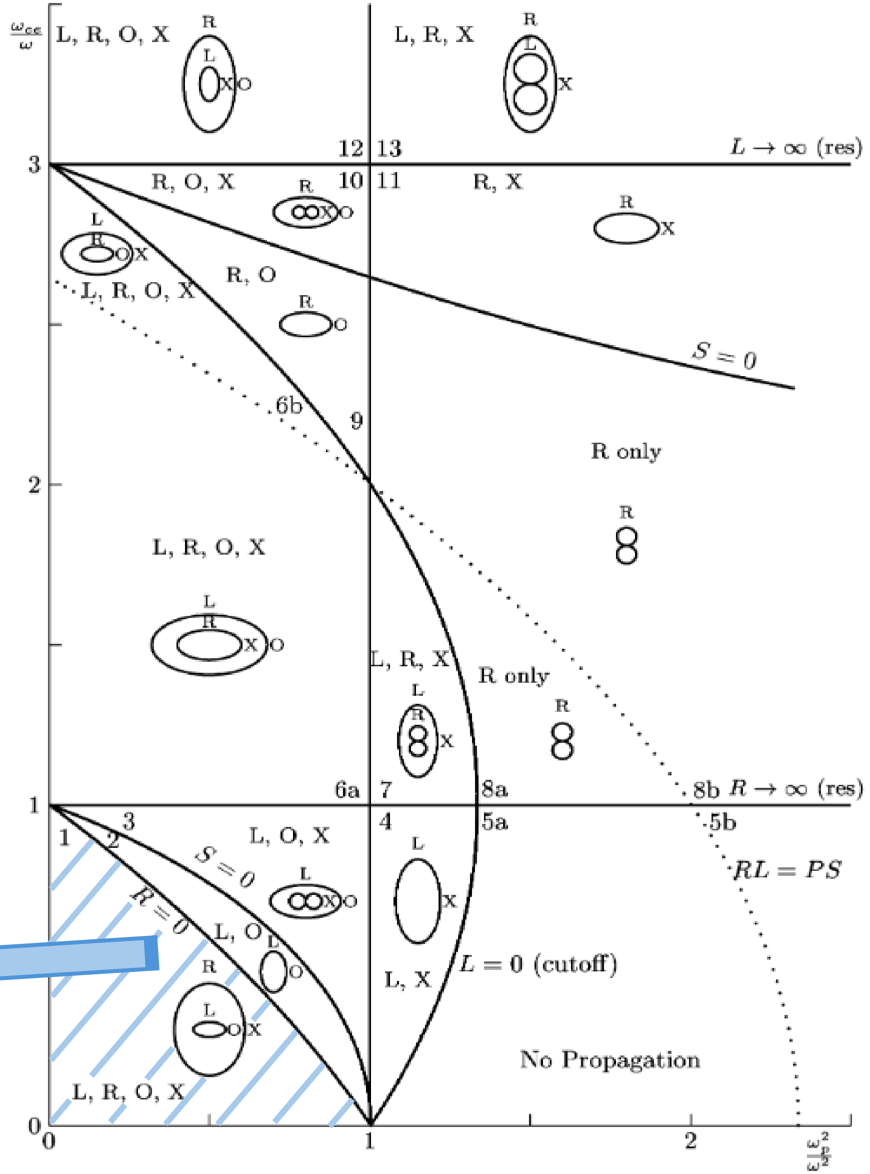

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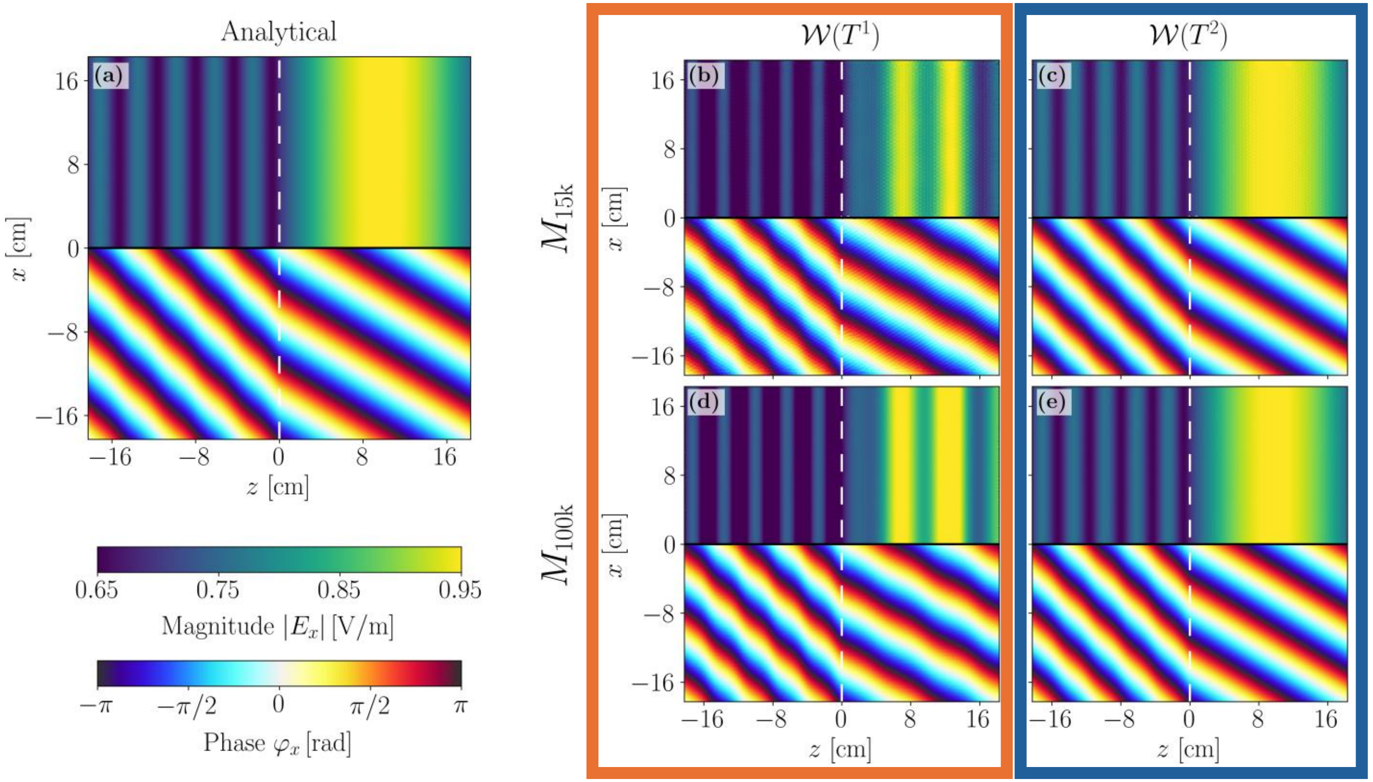
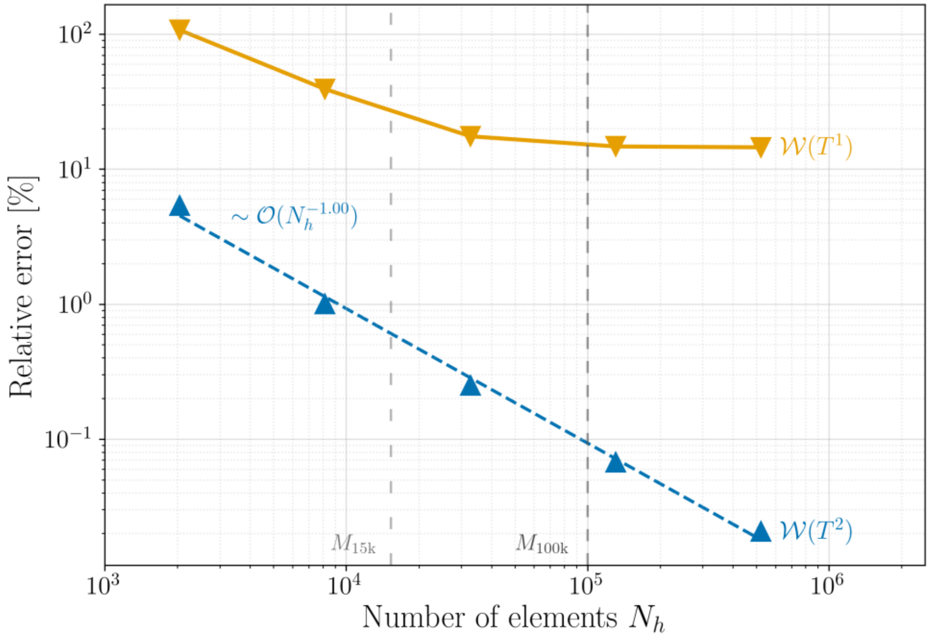


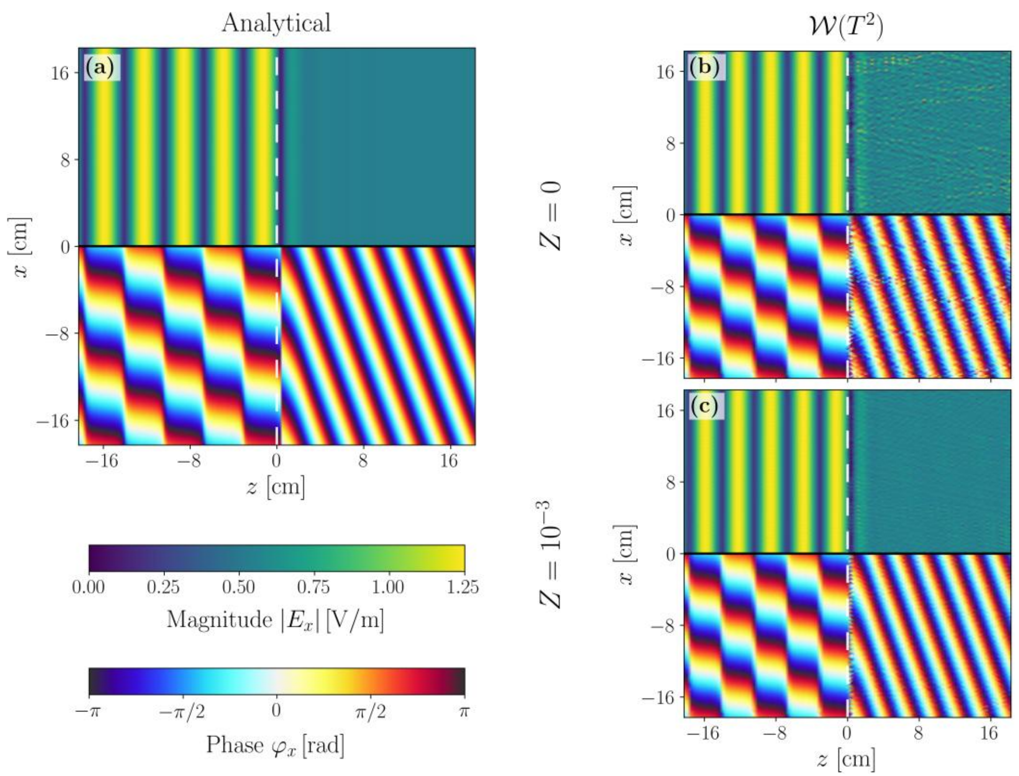


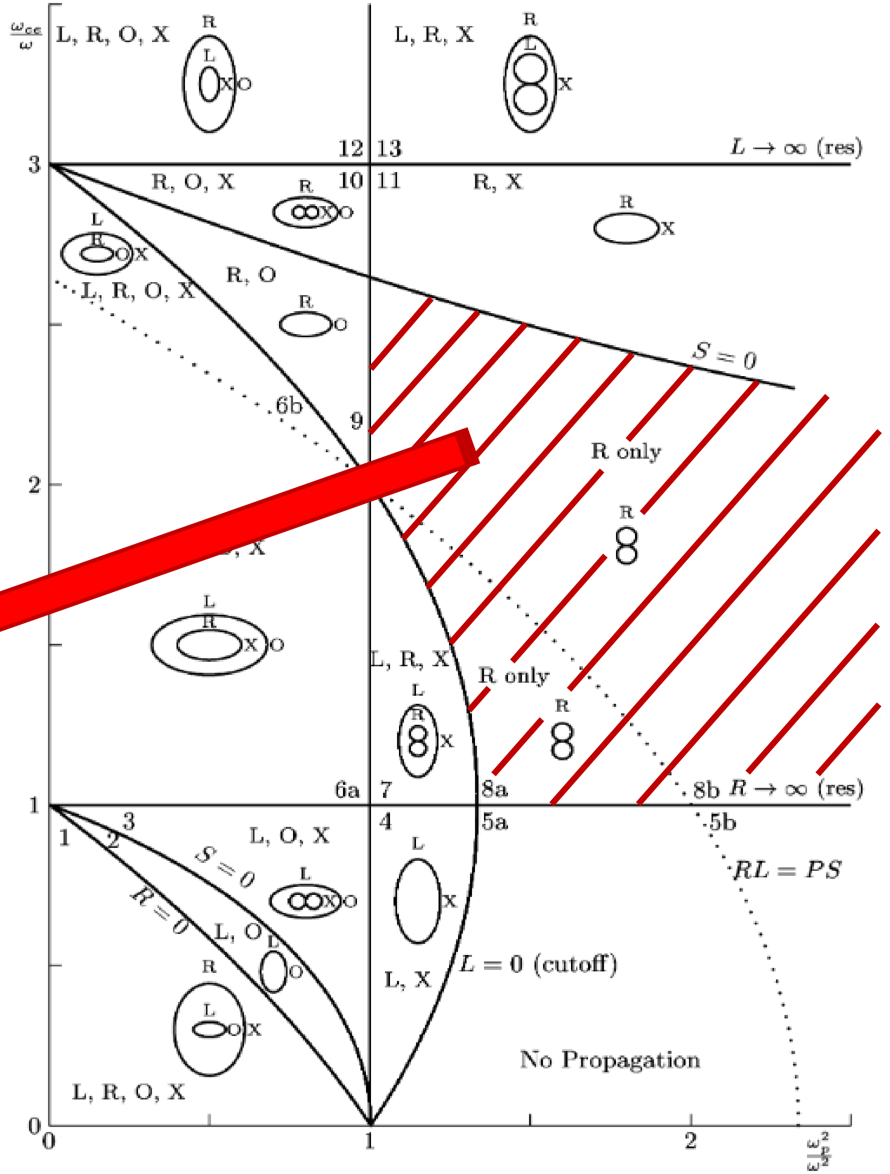
- **Convergence study:**
  - Order 1 reaches plateau regime
  - Order 2 converges as expected

→ **agreement** between analytical and numerical solutions: **validates** both

Simulation Results: Region VIII

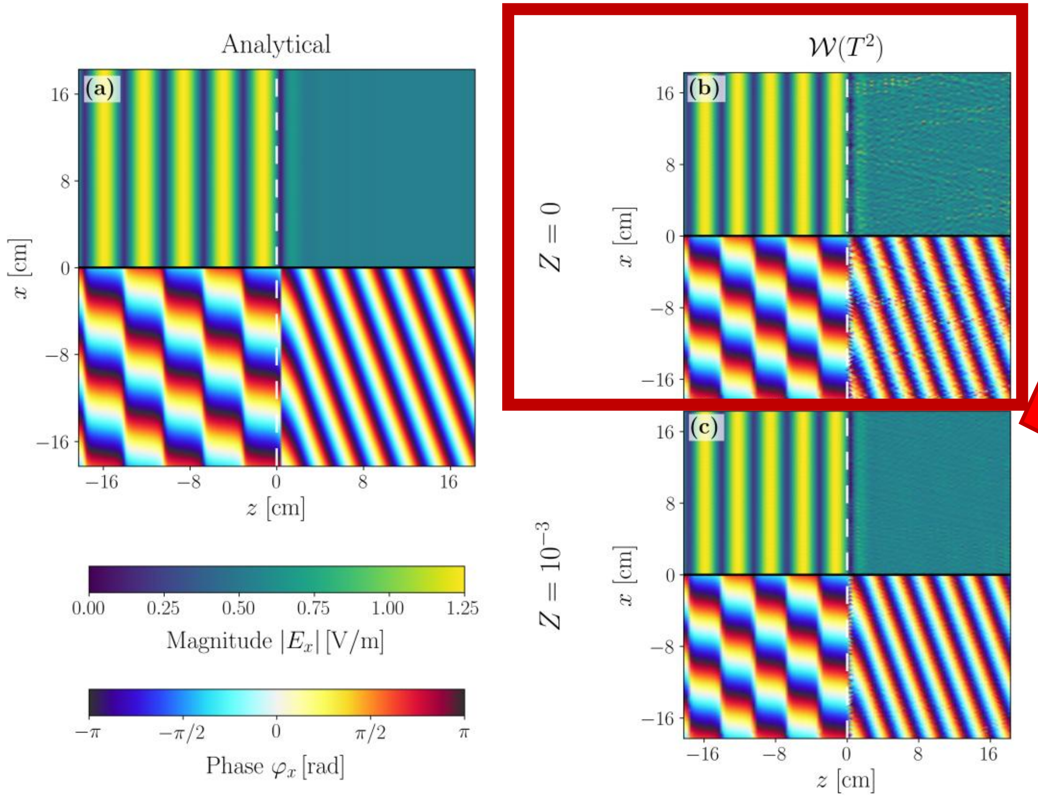
- Numerical solution for E_x in **Region VIII** for:
  - Second order triangles

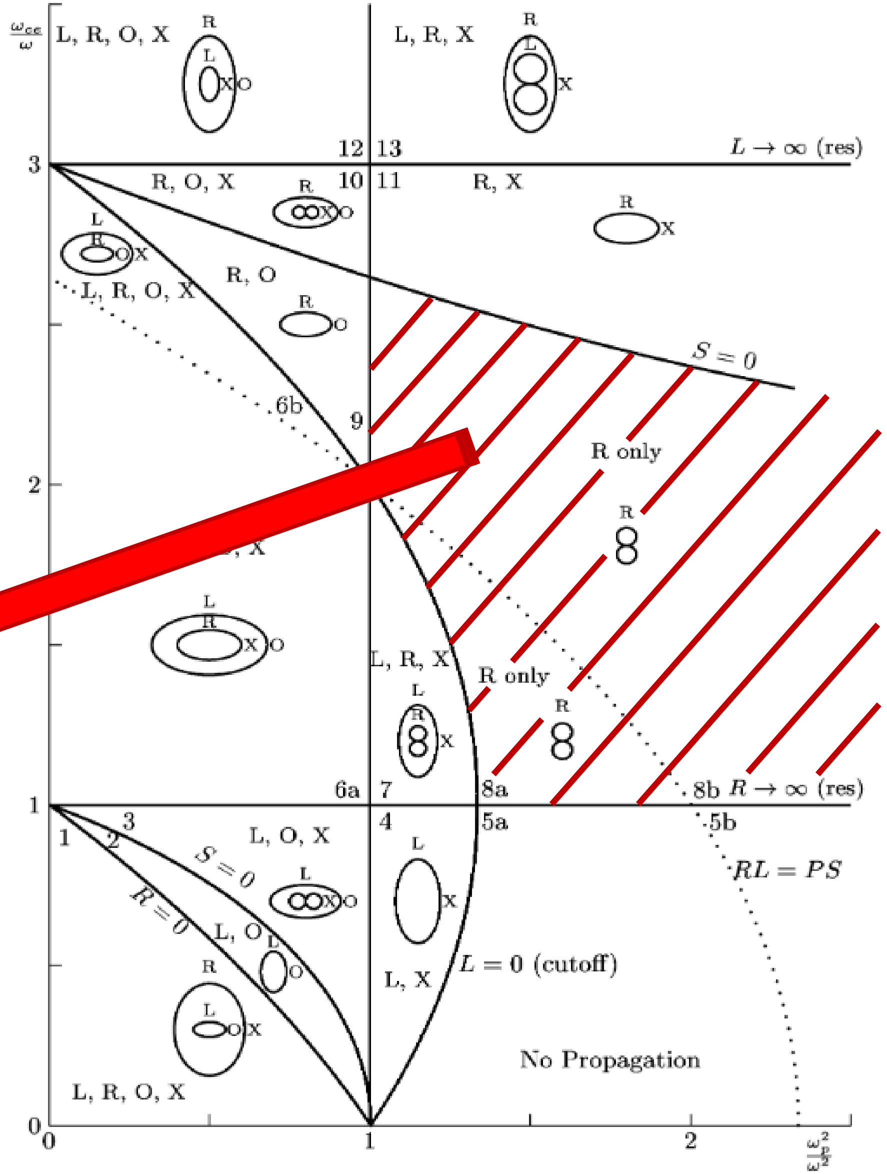




Simulation Results: Region VIII

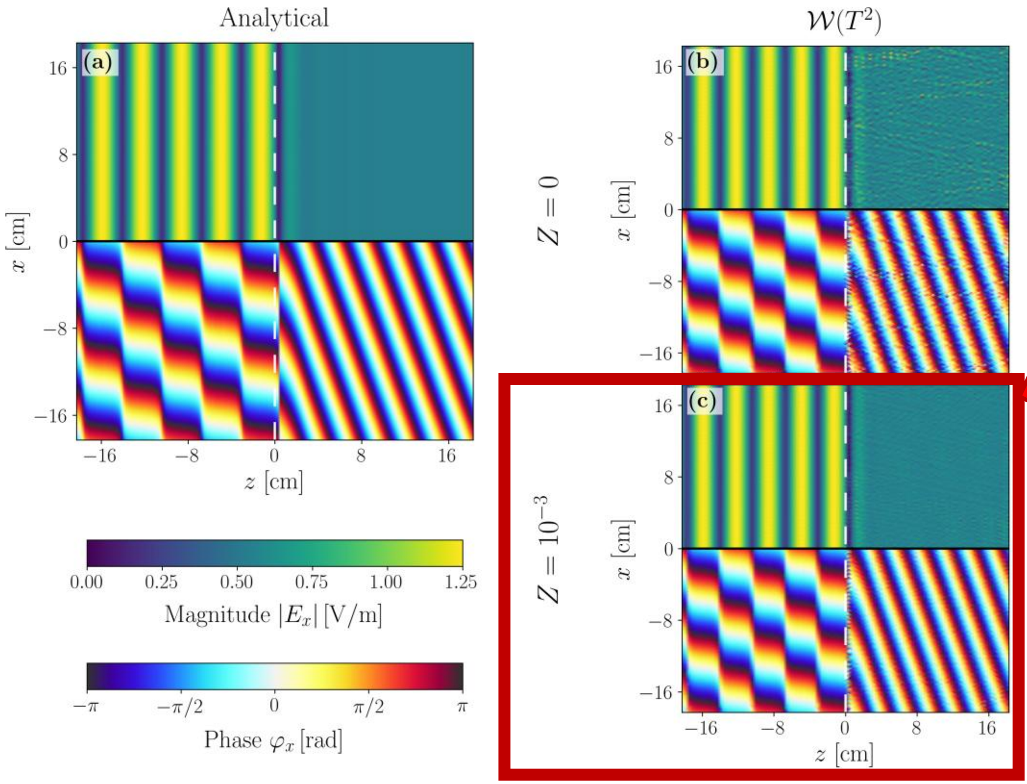
- Numerical solution for E_x in **Region VIII** for:
  - Second order triangles
    - Collisionless case

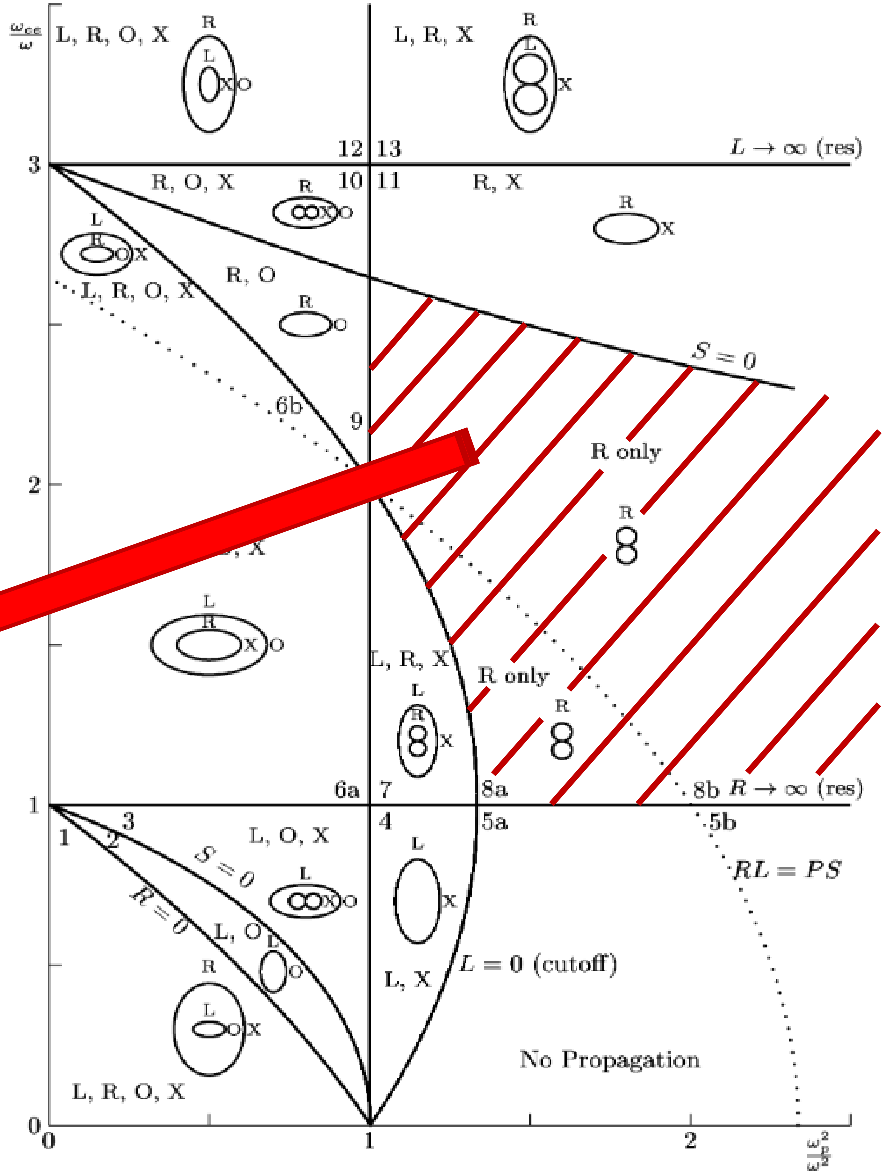




Simulation Results: Region VIII

- Numerical solution for E_x in **Region VIII** for:
  - Second order triangles
    - Collisionless case
    - Additional damping case





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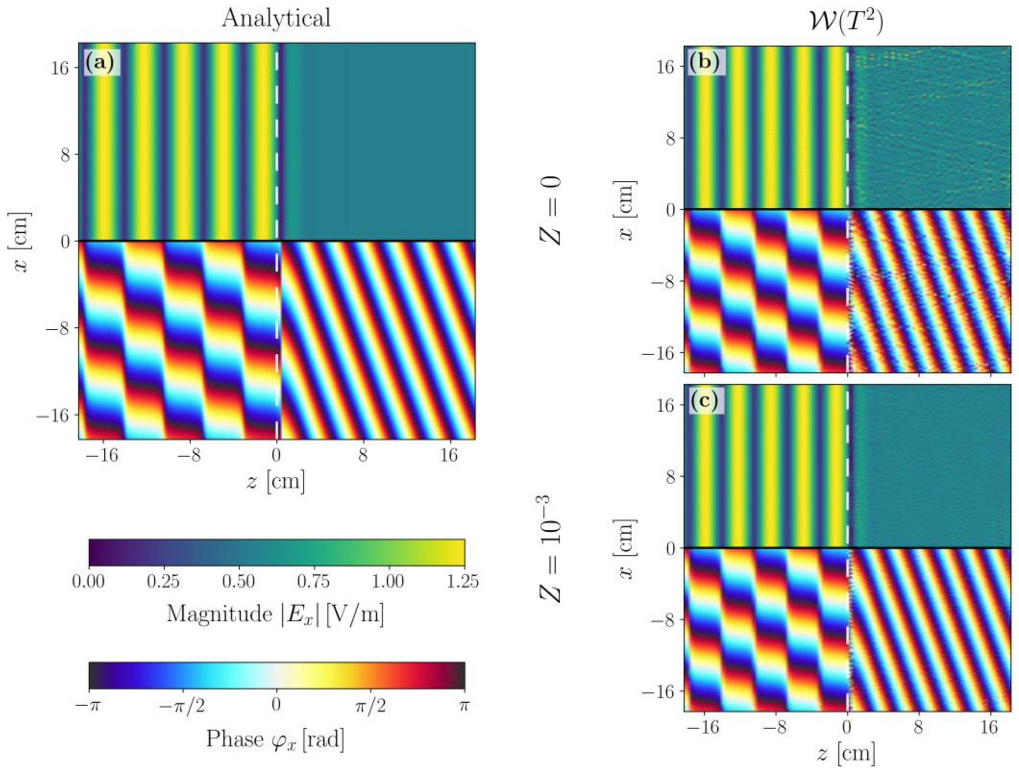

- **Constant collisionality**:
  - Defined as fraction of wave's frequency
    $Z = \frac{\nu_e}{\omega}$

→ Adding damping smoothens the solution

3. But how accurate is this?

On the Choice of Collisionality

Question: **how to select the collisionality ?**

- Remove numerical artifacts

  AND

- Solution still physically accurate

"sweet spot"

- Intuition: smallest value possible that resolves the fields

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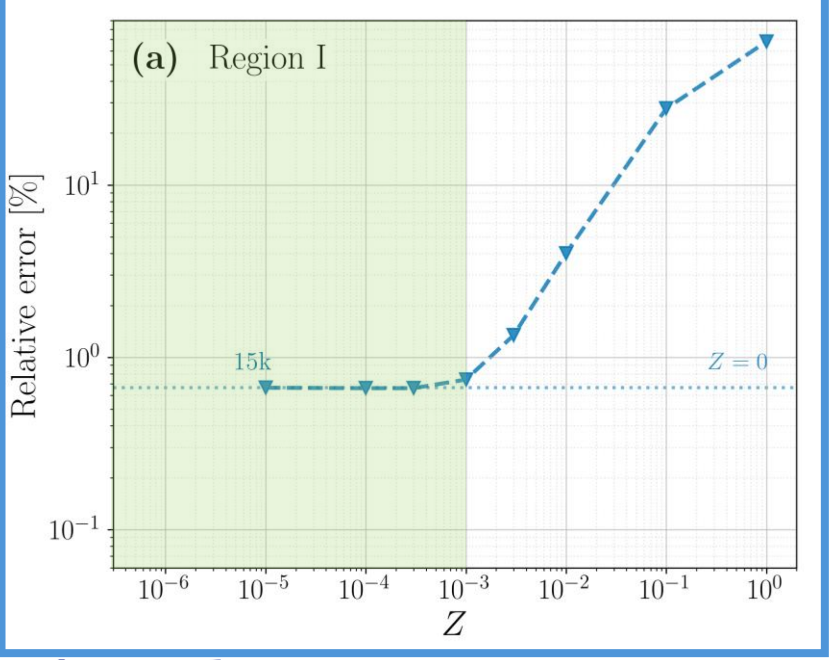

- **Region I**: threshold above which error explodes
  - Damping is too strong and affects physicality of the solution

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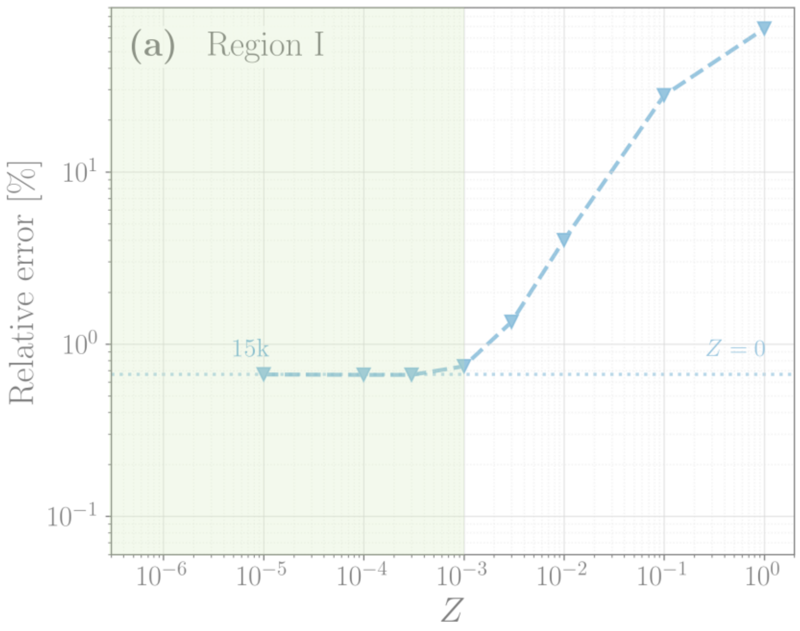

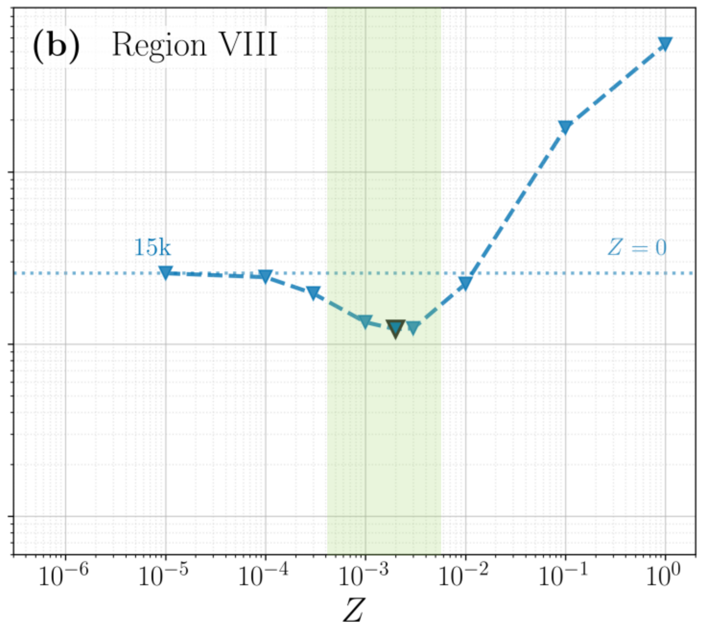

- **Region I**: threshold above which error explodes
  - Damping is too strong and affects physicality of the solution

- **Region VIII**: valley region (sweet spot)
  - Spurious solutions removed
  - Still physically accurate with analytical solution

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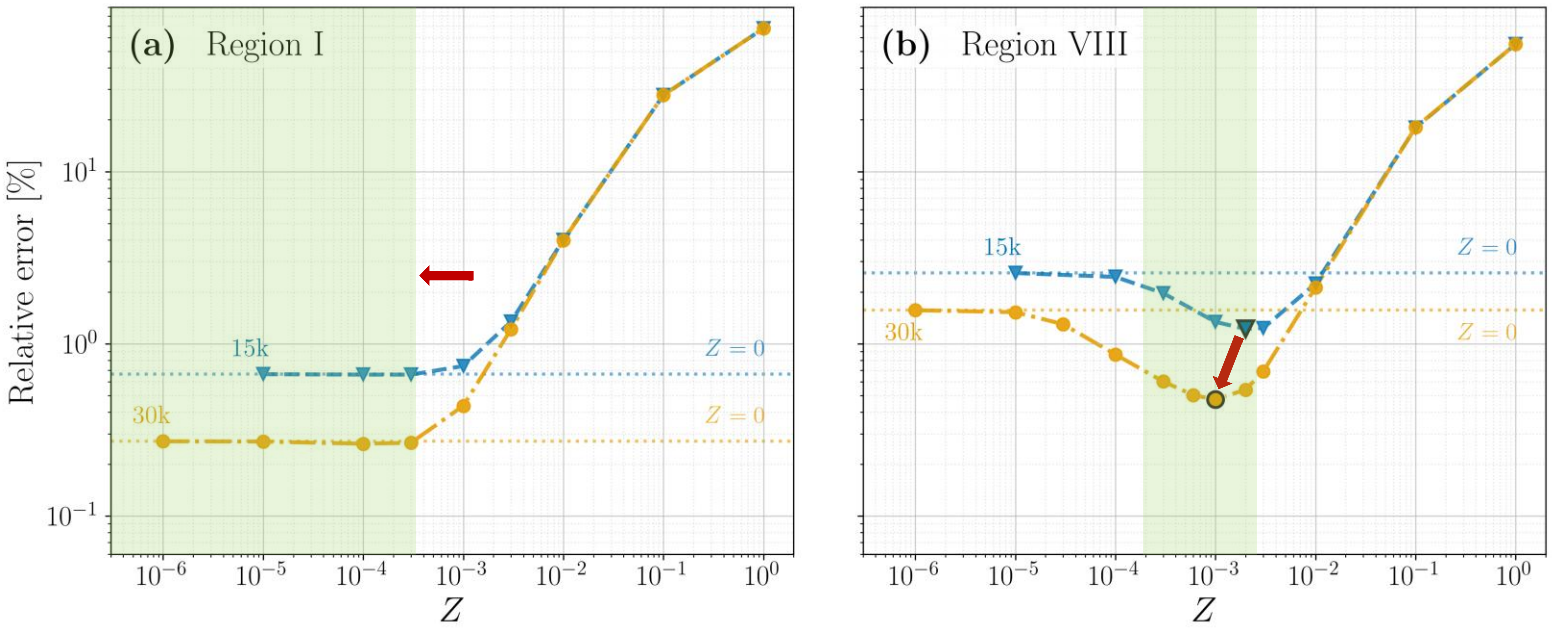

- Crucial effect: this **optimum changes with mesh size** !
  - Shifts to the left for finer mesh

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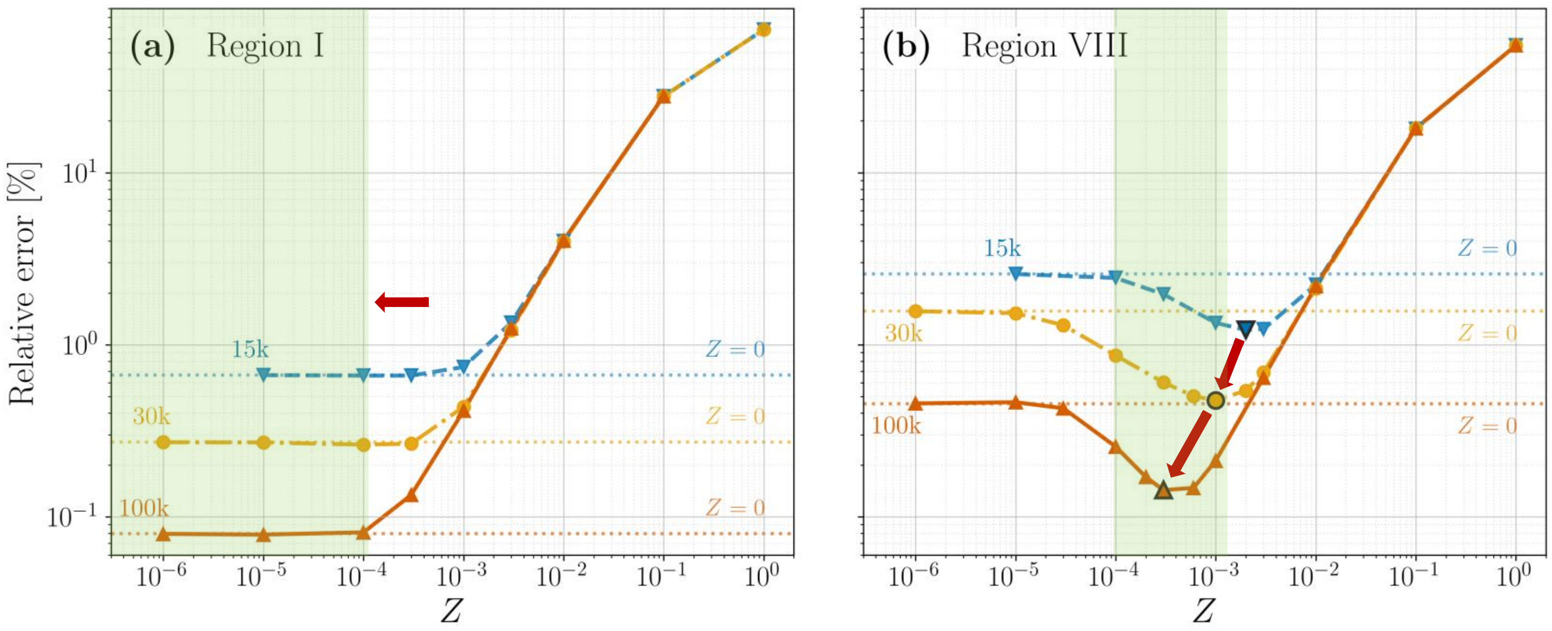

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We can try to fit the relation between the value of a rough "optimal Z" and the mesh size

- *Instead of using a fixed collisionality, what about an **adaptive one** ?*

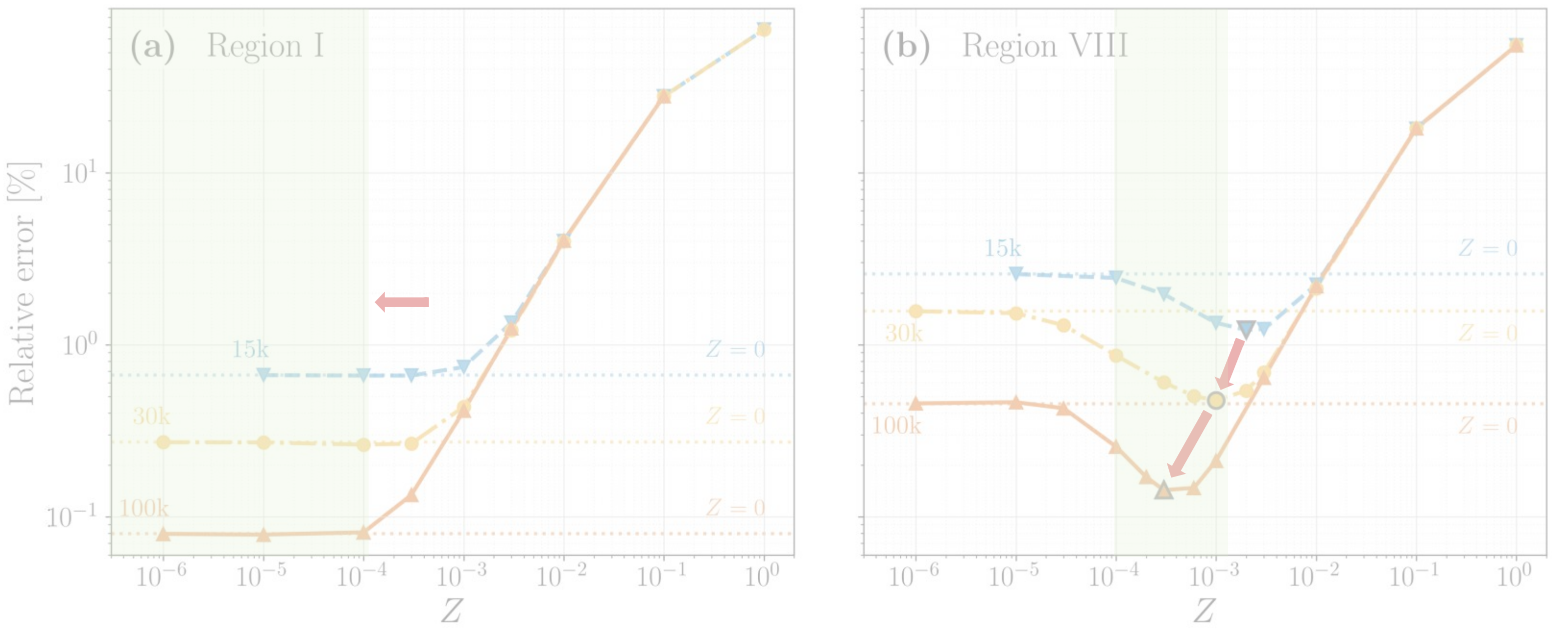
Adaptive Collisionality

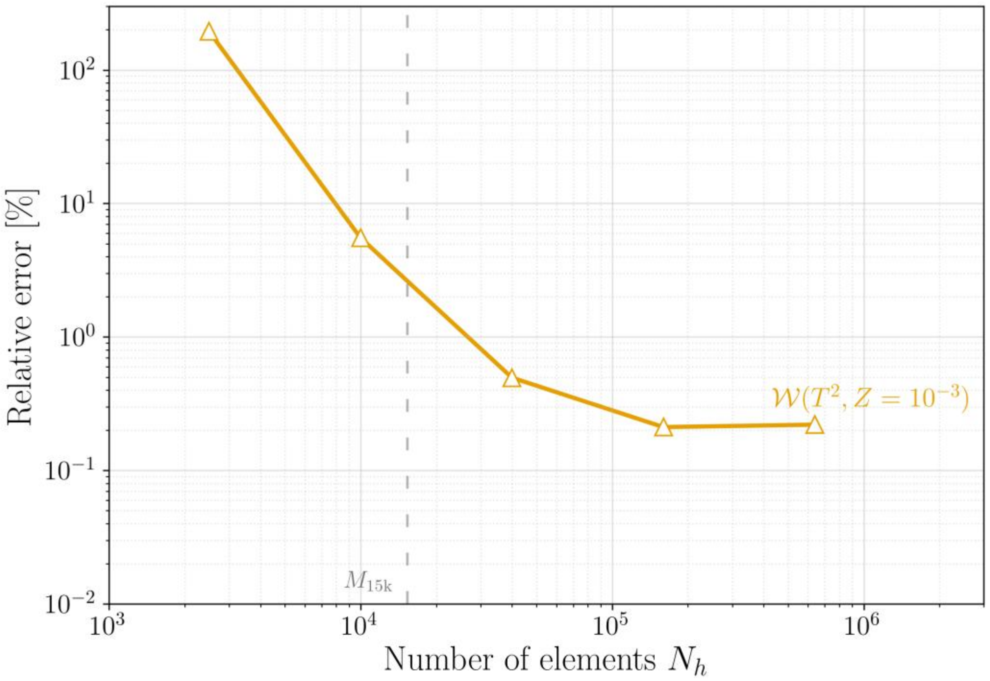
Question: **how to select the collisionality ?**

- Remove numerical artifacts
  AND
- Solution still physically accurate

} **"sweet spot"**

- Intuition: smallest value possible that resolves the fields
- A more rigorous approach: **error convergence**





Convergence in Region VIII
Fixed collisionality

Adaptive Collisionality

Question: **how to select the collisionality ?**

- Remove numerical artifacts
  AND
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"sweet spot"

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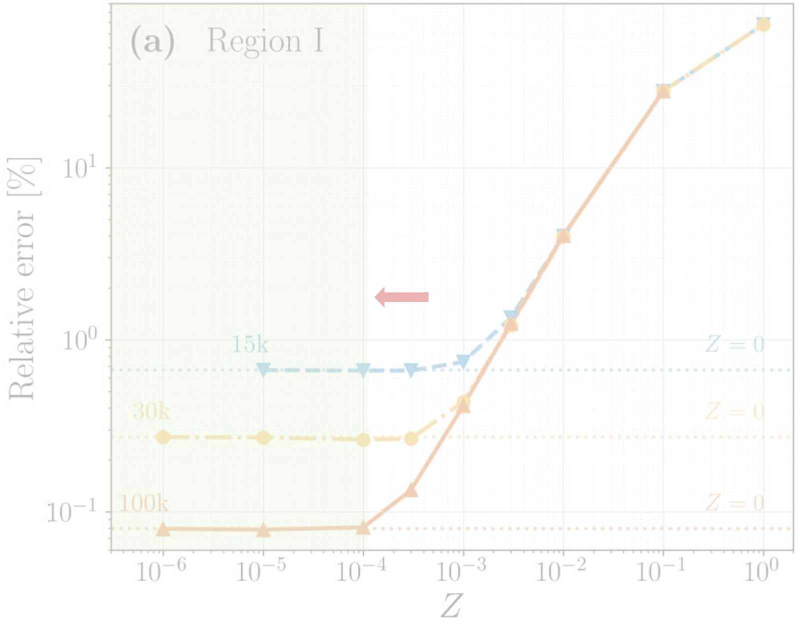
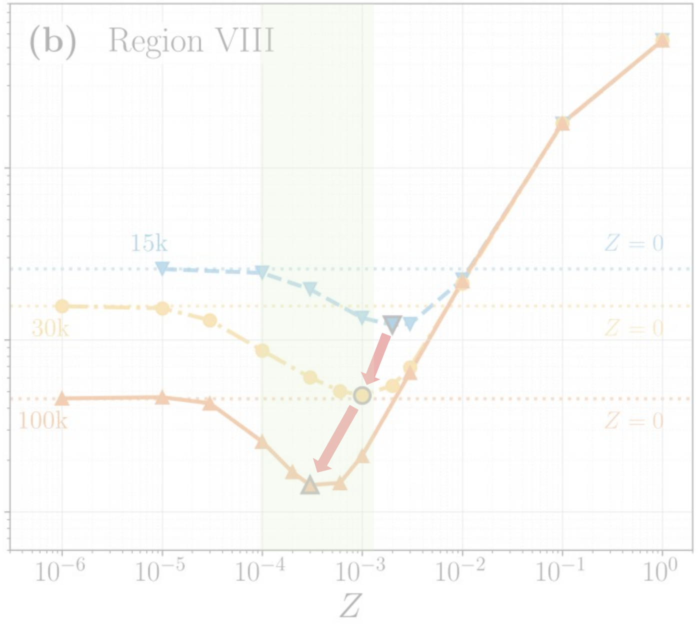
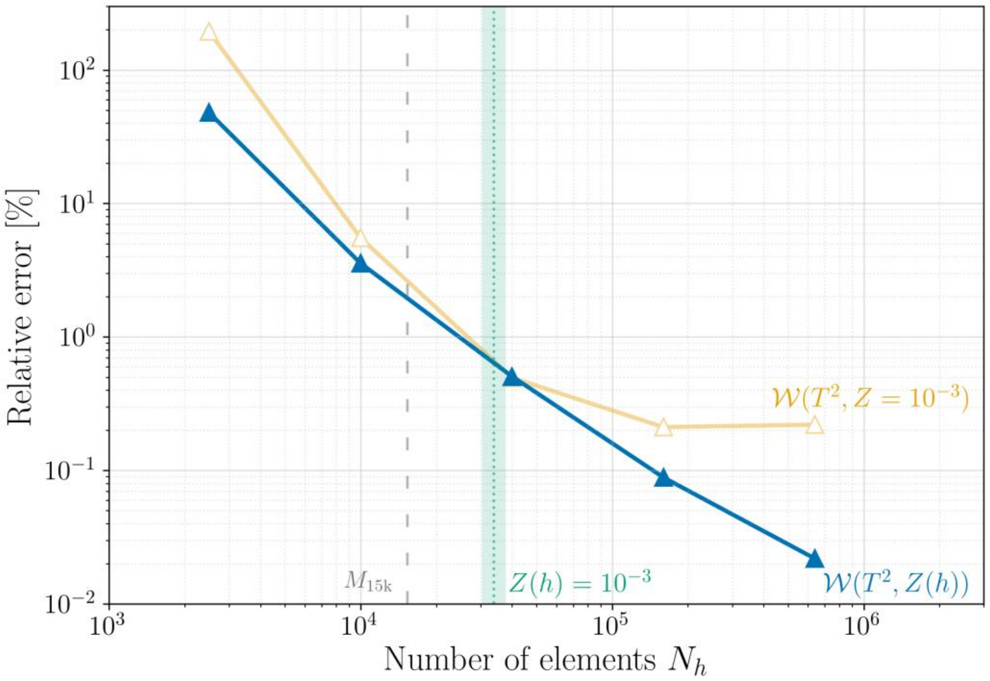
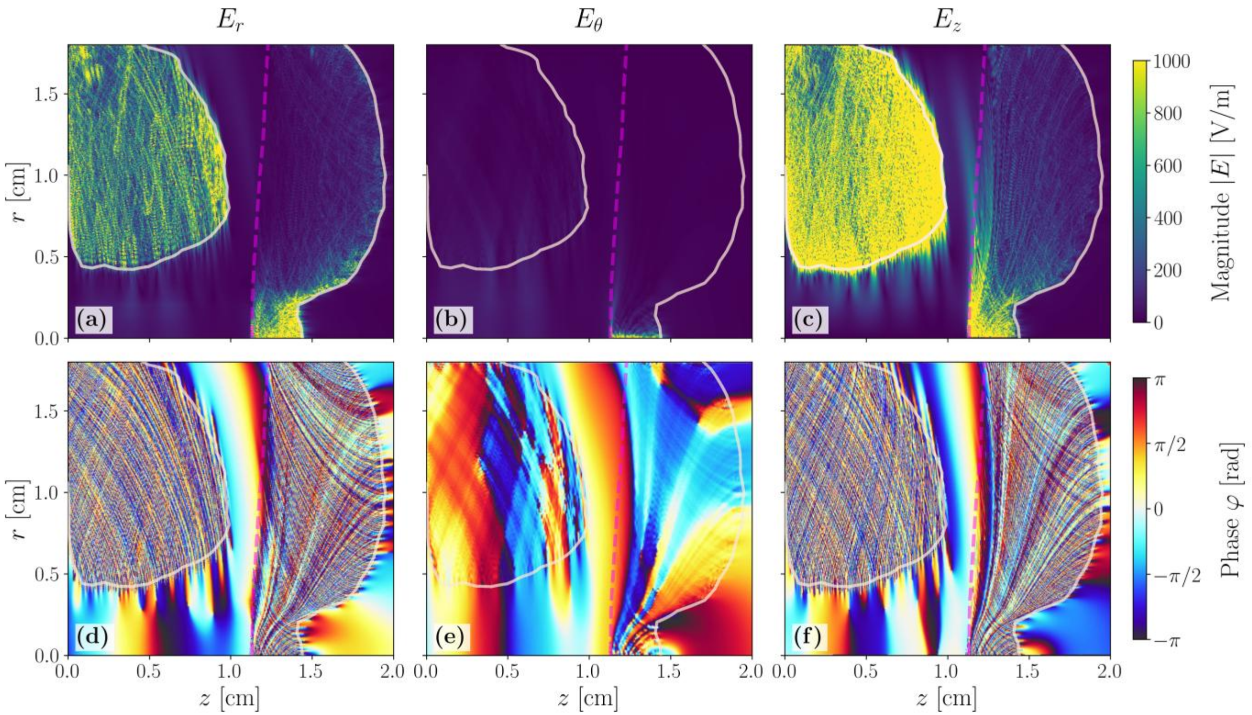






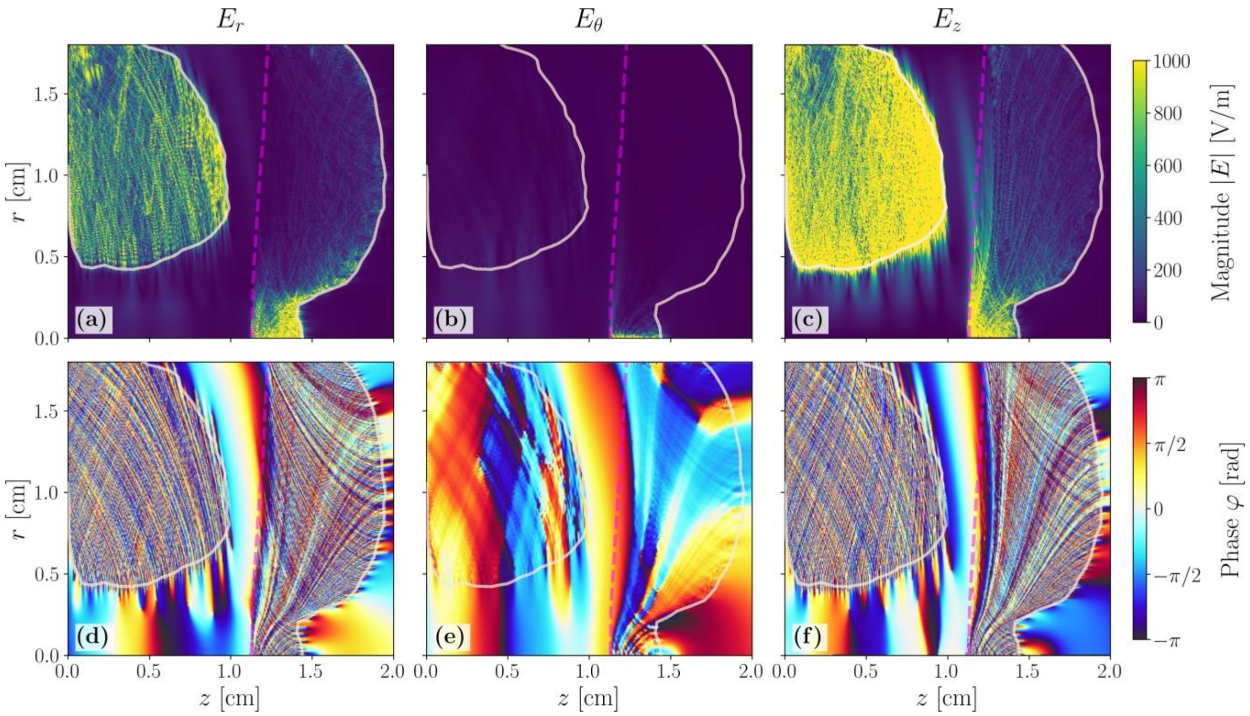
Convergence in Region VIII
***Adaptive** collisionality*

Back to the ECRT Simulations

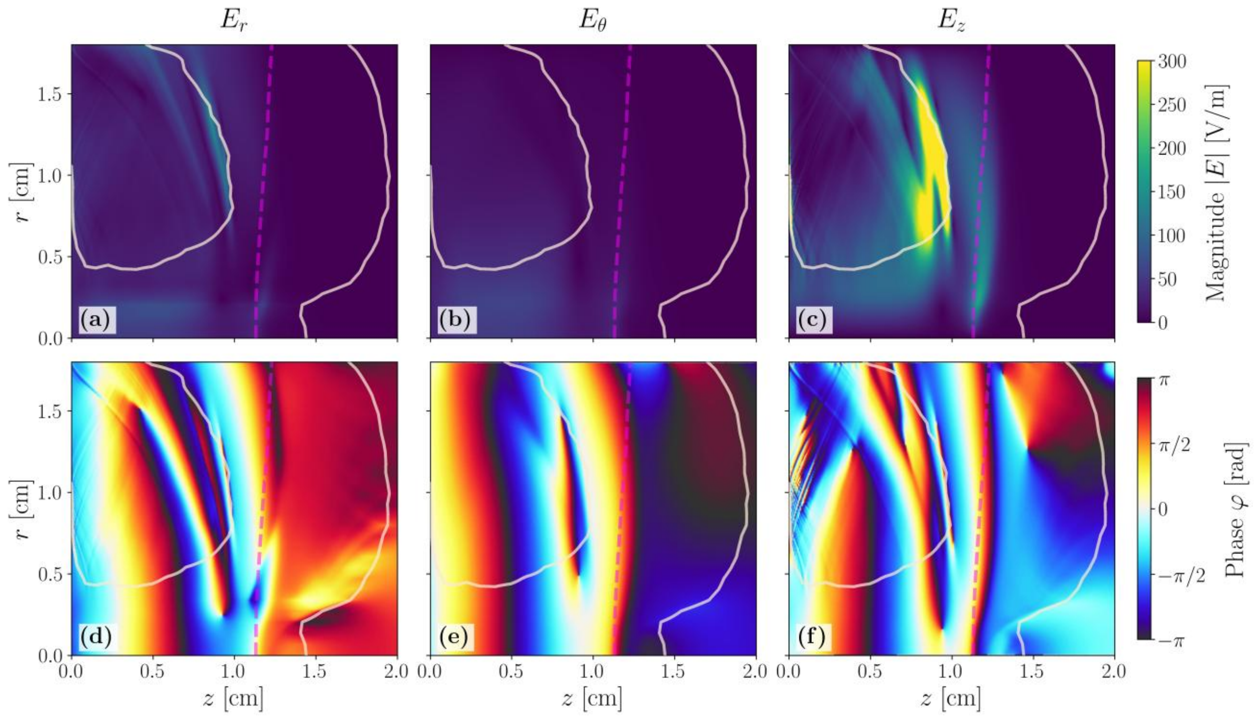


Reminder: results without additional collisionality

Back to the ECRT Simulations



Reminder: results without additional collisionality



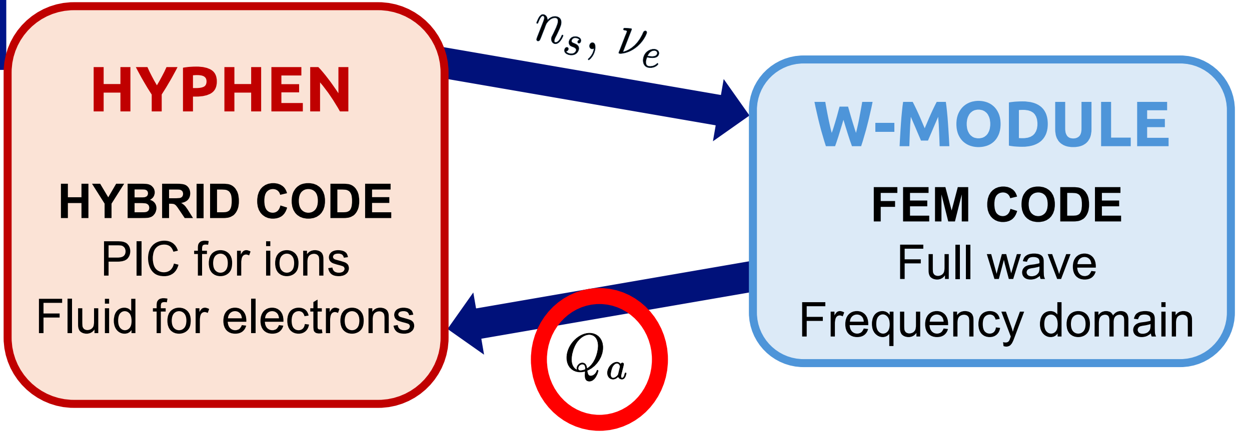
New results for $Z = 10^{-2}$

- **No more spurious solutions**

→ Fields are well resolved

Power Absorption

- Reminder: why do we do this? (in case you got lost)



Power Absorption

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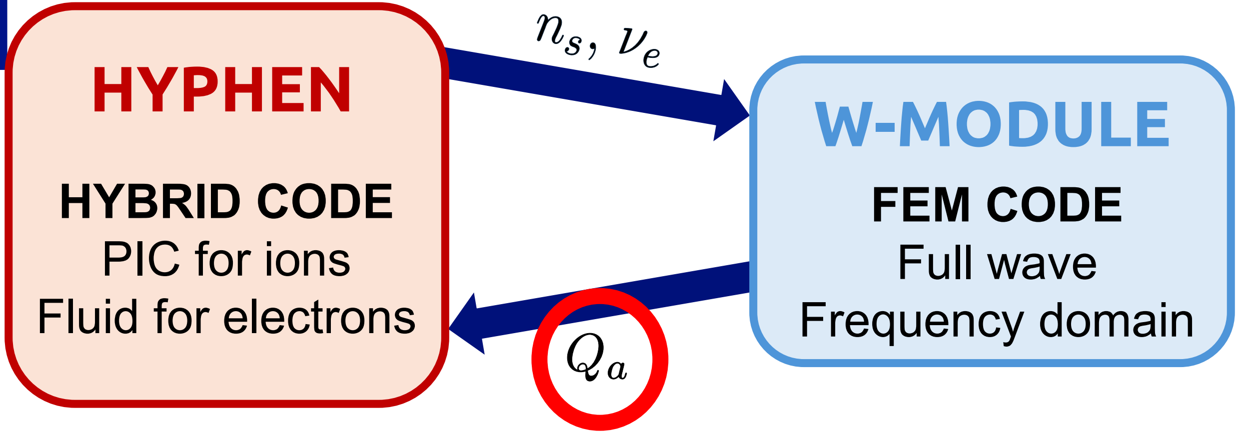

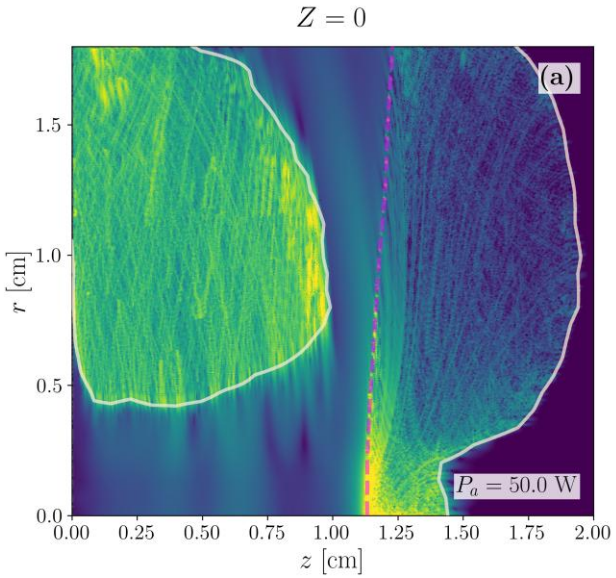

Power Absorption

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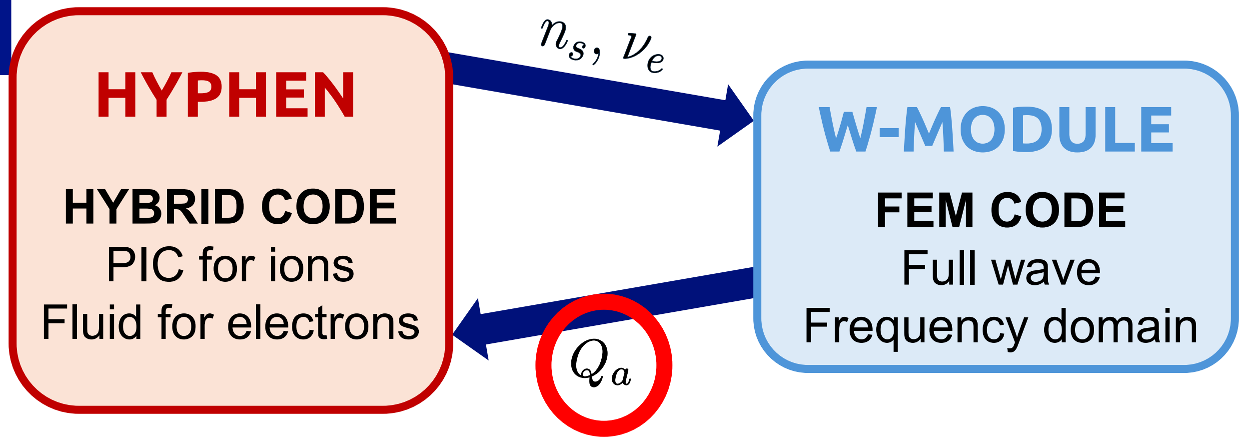
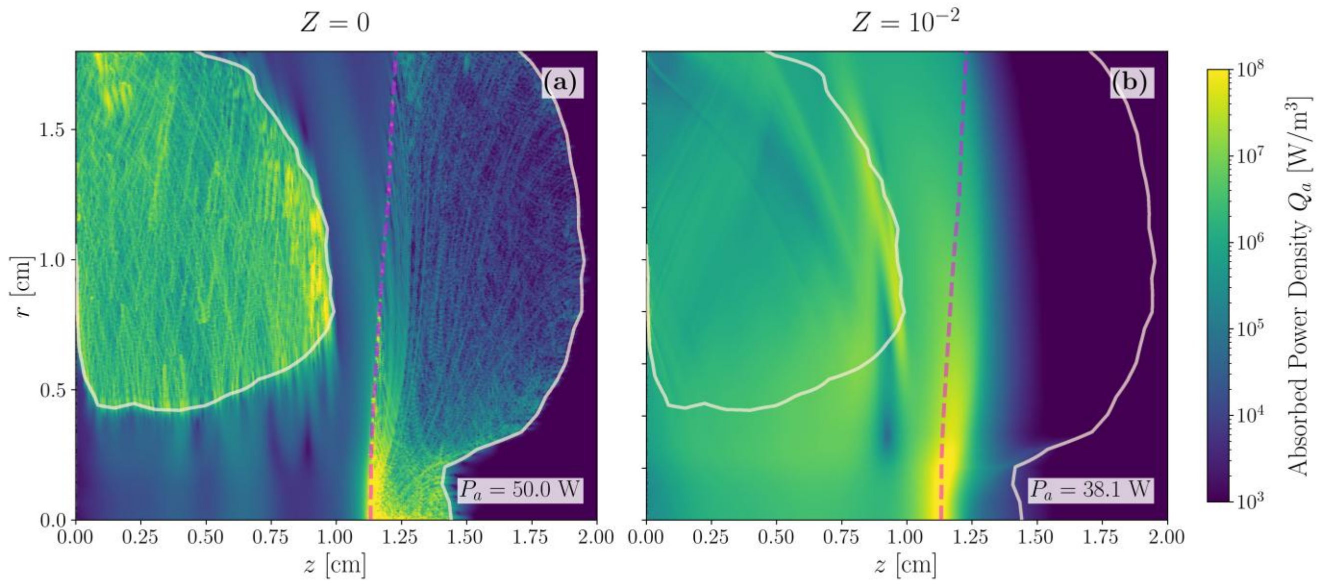


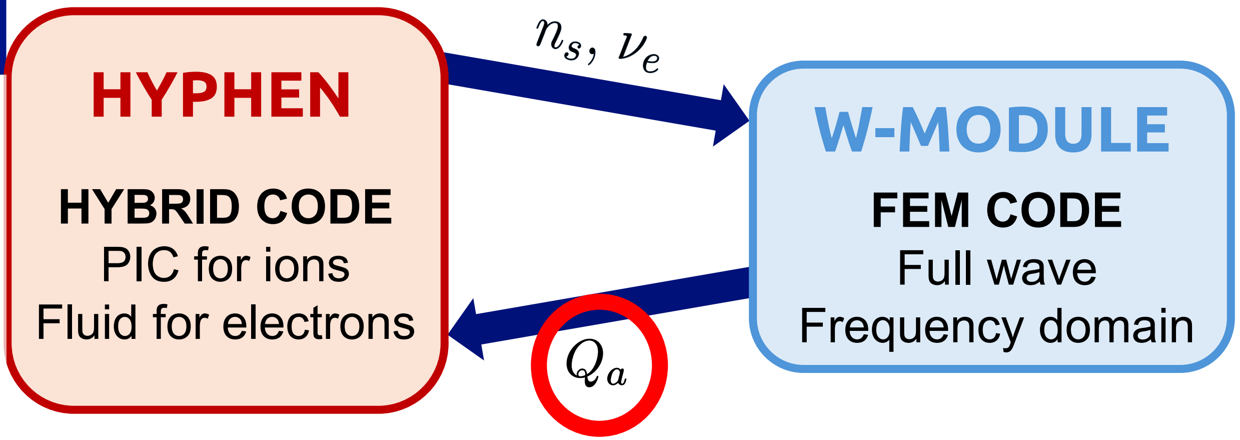


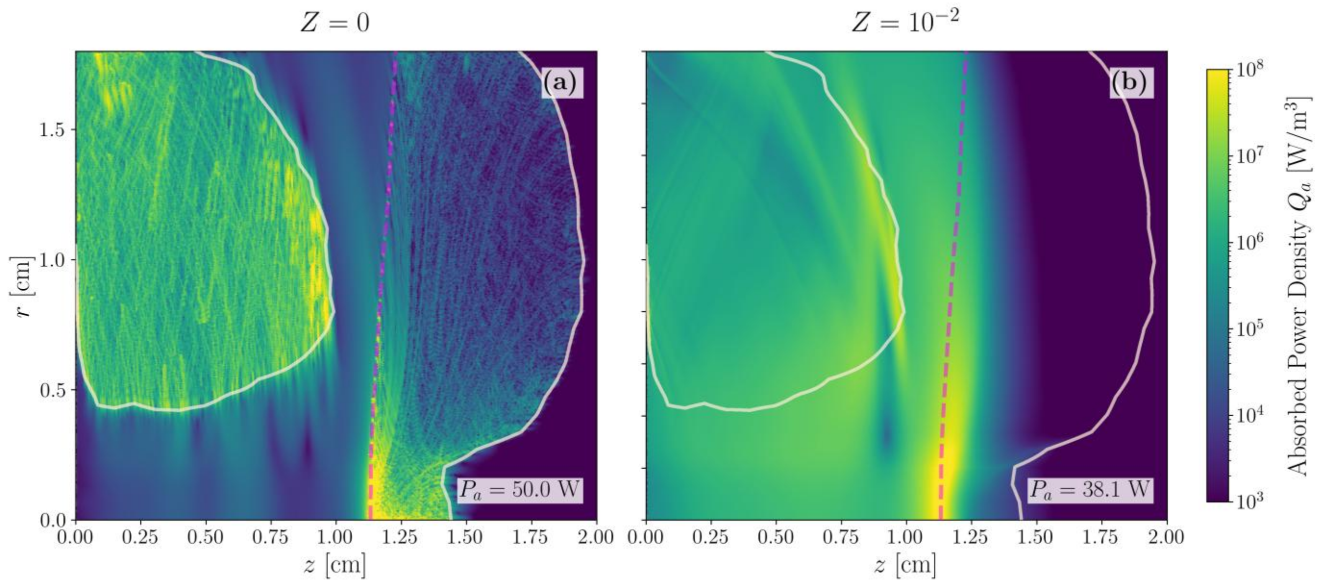
Smoother power density map

- More concentration around the ECR line

Power Absorption

- Reminder: why do we do this?





Smoother power density map

- More concentration around the ECR line

A very last comment: there are different ways of defining the damping

- Constant map of collisionality
- Locally adapting to the regions
- etc…

Anyway: first evidence shows that this choice does not impact much the power absorption

Achievements & Future works

Conferences

- H. Bergerioux, M. Merino.

"On the numerical simulation of wave-plasma interactions in electrodeless plasma thrusters"

  - presented at **International Electric Propulsion Conference** (IEPC), London, United Kingdom, September 14th-19th, 2025

- Future conference: Gaseous Electronics Conference (GEC), Chicago, US, November 2nd-6th, 2026

Journal article

- Manuscript in preparation for peer review

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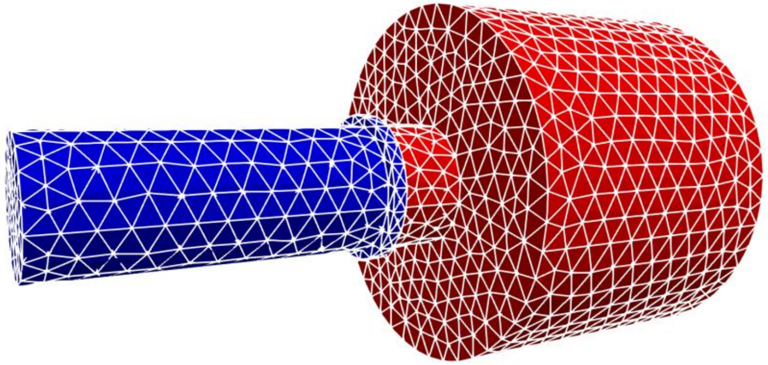
Next work: the 3D Wave Code

In EPTs, we should consider **asymmetries**

- Of the plasma ?
- Of the thruster's geometry ?

→ 2D axisymmetric code (even with azimuthal modes expansion) **is not sufficient**



3D FEM mesh of the waveguide-ECRT

Compare the **efficiency** and **accuracy** of the 3D code with the 2D one (on axisymmetric cases).

Then **explore asymmetric configurations.**

Plasma-Wave Interaction in Electrodeless Plasma Thrusters

(and its Optimization)

PhD Student: Hugo Bergerioux

Supervisor: Mario Merino

Ackowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 950466)

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ZARATHUSTRA

(And a special thanks to Marco for the steady-state plasma density maps used for the ECRT wave-simulations presented here)

Thank you!
Questions?

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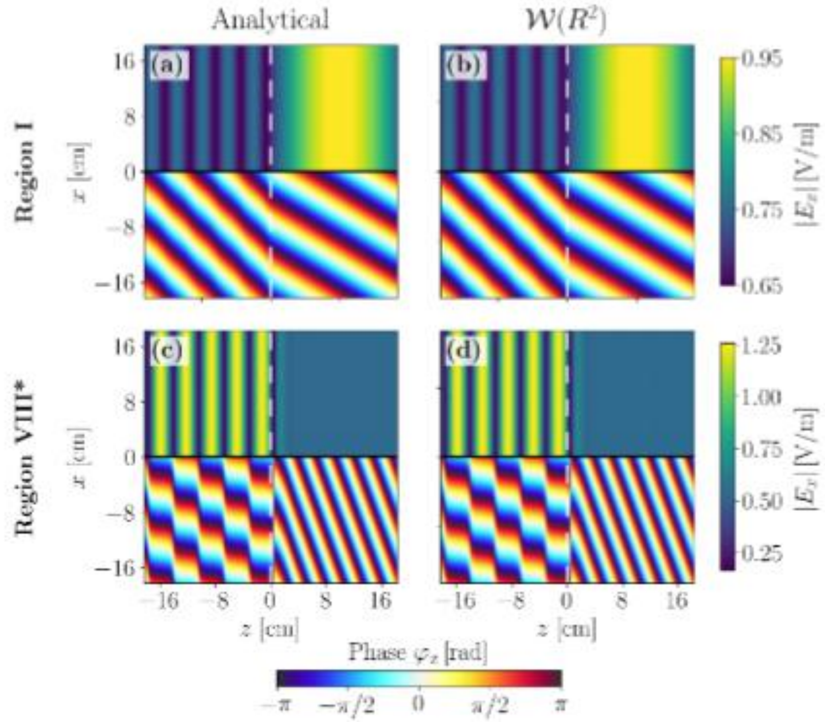
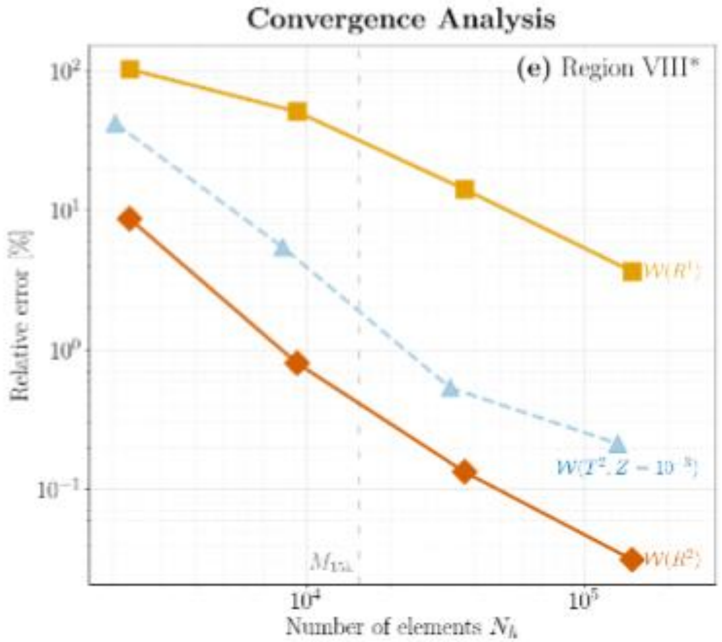
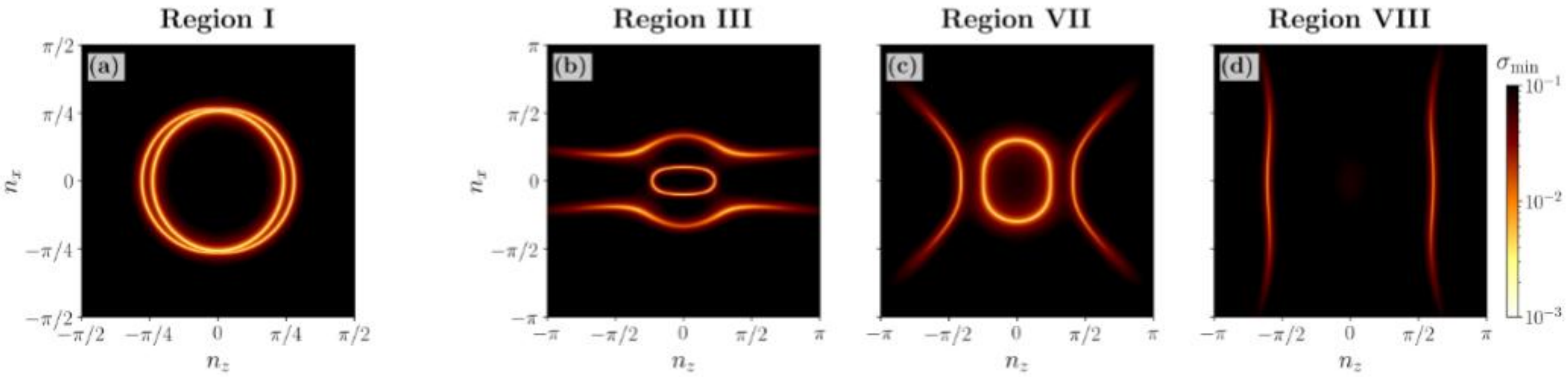
Back-up slides

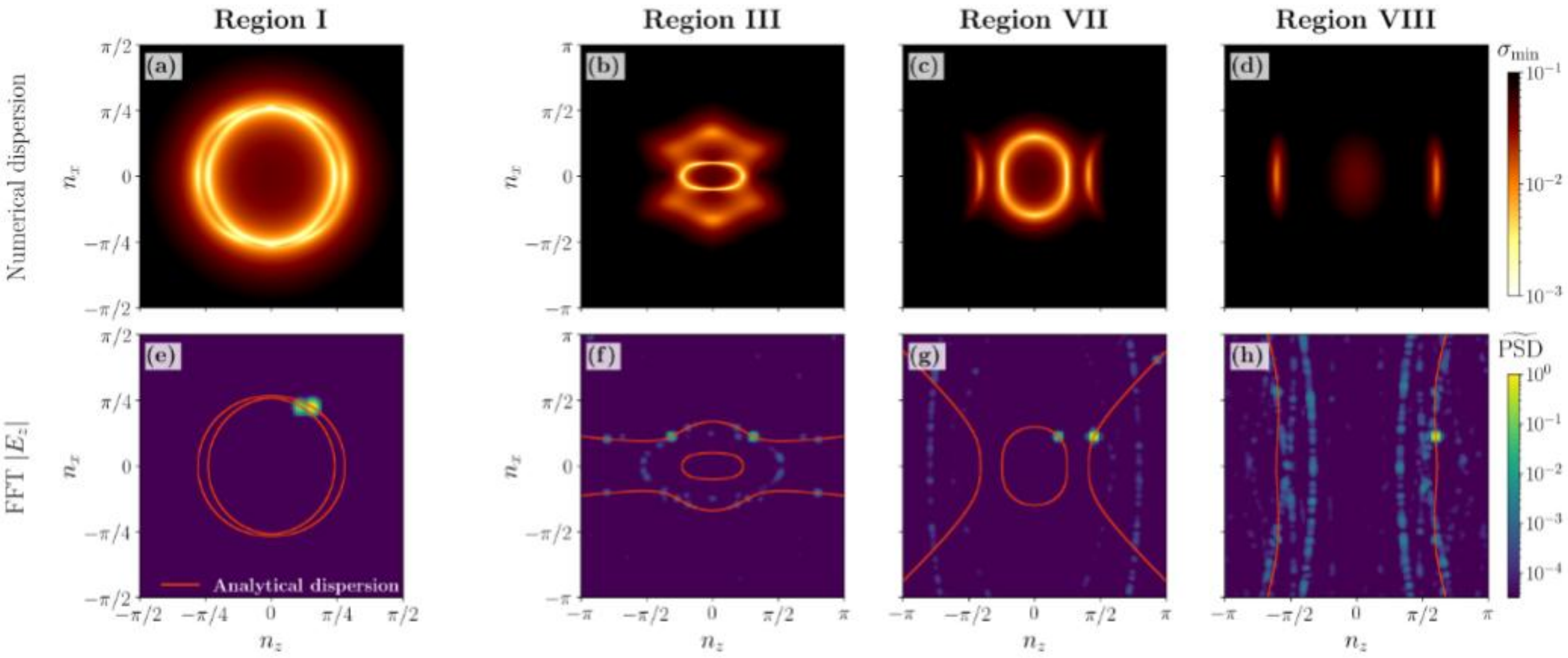
The curiosity of rectangles







Why triangles fail ?



Cold Plasma Model (more)

- Where does the collisionality actually appear?

$$\boldsymbol{\kappa} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix}, \qquad \text{with} \qquad S = \frac{R+L}{2}, \quad D = \frac{R-L}{2}$$

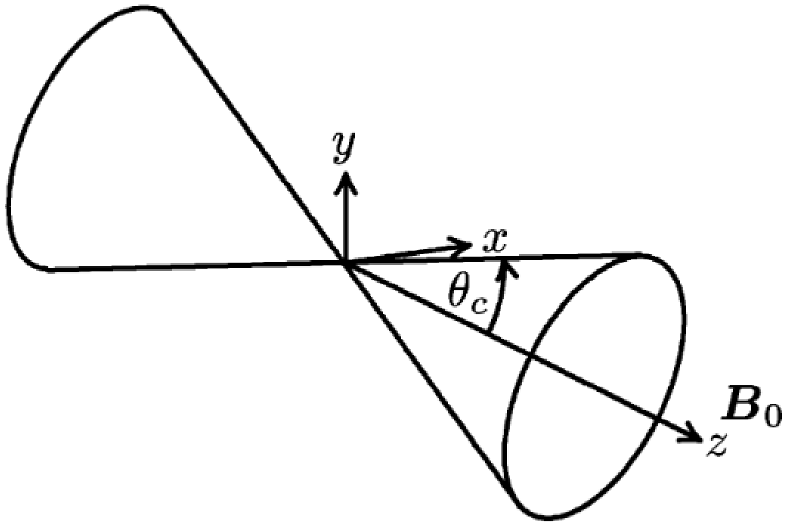
$$R = 1 - \frac{\omega_{\mathrm{pe}}^2}{\omega\left[\left(\omega + i\nu_{\mathrm{e}}\right) - \omega_{\mathrm{ce}}\right]}, \quad L = 1 - \frac{\omega_{\mathrm{pe}}^2}{\omega\left[\left(\omega + i\nu_{\mathrm{e}}\right) + \omega_{\mathrm{ce}}\right]}, \quad \text{and} \quad P = 1 - \frac{\omega_{\mathrm{pe}}^2}{\omega\left(\omega + i\nu_{\mathrm{e}}\right)}$$

Resonance cones

$$\tan^2\theta = -\frac{P\left(n^2 - R\right)\left(n^2 - L\right)}{\left(Sn^2 - RL\right)\left(n^2 - P\right)}$$

- At boundary of the cone, refractive index explodes

$$\tan^2\left(\theta_c\right) = \lim_{n\to\infty}\tan^2(\theta) = -\frac{P}{S}$$



- Wave constrained to propagate within a cone in 3D space
- As refractive index explodes, wavelength tends to 0
  - Mesh fails to resolves (in general)