Divergence-free discontinuous Galerkin method for compressible MHD equations

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$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = 0, \qquad \frac{\partial \boldsymbol{D}}{\partial t} - \nabla \times \boldsymbol{H} = -\boldsymbol{J}$$

$\boldsymbol{B}$ = magnetic flux density
$\boldsymbol{E}$ = electric field

$\boldsymbol{D}$ = electric flux density
$\boldsymbol{H}$ = magnetic field
$\boldsymbol{J}$ = electric current density

$$\boldsymbol{B} = \mu \boldsymbol{H}, \qquad \boldsymbol{D} = \varepsilon \boldsymbol{E}, \qquad \boldsymbol{J} = \sigma \boldsymbol{E} \qquad \mu, \varepsilon \in \mathbb{R}^{3\times 3} \text{ symmetric}$$

$$\begin{aligned} \varepsilon &= \text{permittivity tensor} \\ \mu &= \text{magnetic permeability tensor} \\ \sigma &= \text{conductivity} \end{aligned}$$

$$\nabla \cdot \boldsymbol{B} = 0, \quad \nabla \cdot \boldsymbol{D} = \rho \quad \text{(electric charge density)}, \quad \frac{\partial \rho}{\partial t} + \nabla \cdot \boldsymbol{J} = 0$$

Ideal compressible MHD equations

Nonlinear hyperbolic system

Compressible Euler equations with Lorentz force

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) &= 0 \\
\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (pI + \rho \boldsymbol{v} \otimes \boldsymbol{v} - \boldsymbol{B} \otimes \boldsymbol{B}) &= 0 \\
\frac{\partial E}{\partial t} + \nabla \cdot ((E + p)\boldsymbol{v} + (\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B}) &= 0 \\
\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) &= 0
\end{aligned}
$$

Magnetic monopoles do not exist: $\implies \quad \nabla \cdot \boldsymbol{B} = 0$

Divergence constraint

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = 0$$

$$\nabla \cdot \frac{\partial \boldsymbol{B}}{\partial t} + \underbrace{\nabla \cdot \nabla \times}_{=0} \boldsymbol{E} = 0$$

$$\frac{\partial}{\partial t} \nabla \cdot \boldsymbol{B} = 0$$

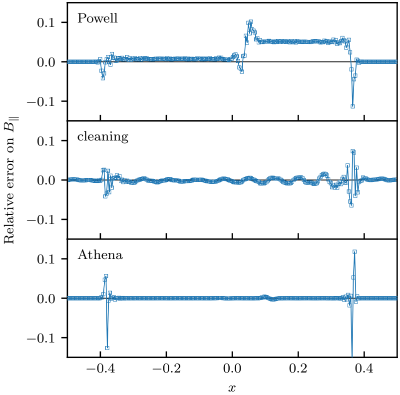
If

$$\nabla \cdot \boldsymbol{B} = 0 \quad \text{at} \quad t = 0$$

then

$$\nabla \cdot \boldsymbol{B} = 0 \quad \text{for} \quad t > 0$$

Rotated shock tube



Guillet et al., MNRAS 2019

Discrete div-free $\implies$ positivity (Kailiang)

Objectives

- Based on conservation form of the equations
- Upwind-type schemes using Riemann solvers
- Divergence-free schemes for Maxwell's and compressible MHD
  - Cartesian grids at present
  - Divergence preserving schemes (RT)
  - Divergence-free reconstruction (BDM)
- High order accurate
  - discontinuous-Galerkin
- Non-oscillatory schemes for MHD
  - using limiters
- Explicit time stepping
- Based on previous work for induction equation
  - J. Sci. Comp., Vol. 79, pp, 79-102, 2019

Some existing methods

Exactly divergence-free methods

- Yee scheme (Yee (1966))
- Projection methods (Brackbill & Barnes (1980))
- Constrained transport (Evans & Hawley (1989))
- Divergence-free reconstruction (Balsara (2001))
- Globally divergence-free scheme (Li et al. (2011), Fu et al, (2018))

Approximate methods

- Locally divergence-free schemes (Cockburn, Li & Shu (2005))
- Godunov's symmetrized version of MHD (Powell, Gassner et al., C/K)
- Divergence cleaning methods (Dedner et al.)

MHD equations in 2-D

$$\frac{\partial \mathcal{U}}{\partial t} + \frac{\partial \mathcal{F}_x}{\partial x} + \frac{\partial \mathcal{F}_y}{\partial y} = 0$$

$$\mathcal{U} = \begin{bmatrix} \rho \\ \rho v_x \\ \rho v_y \\ \rho v_z \\ \mathcal{E} \\ B_x \\ B_y \\ B_z \end{bmatrix}, \quad \mathcal{F}_x = \begin{bmatrix} \rho v_x \\ P + \rho v_x^2 - B_x^2 \\ \rho v_x v_y - B_x B_y \\ \rho v_x v_z - B_x B_z \\ (\mathcal{E} + P) v_x - B_x (\boldsymbol{v} \cdot \mathfrak{B}) \\ 0 \\ -E_z \\ v_x B_z - v_z B_x \end{bmatrix}, \quad \mathcal{F}_y = \begin{bmatrix} \rho v_y \\ \rho v_x v_y - B_x B_y \\ P + \rho v_y^2 - B_y^2 \\ \rho v_y v_z - B_y B_z \\ (\mathcal{E} + P) v_y - B_y (\boldsymbol{v} \cdot \mathfrak{B}) \\ E_z \\ 0 \\ v_y B_z - v_z B_y \end{bmatrix}$$

where

$$\mathfrak{B} = (B_x, B_y, B_z), \qquad P = p + \frac{1}{2}|\mathfrak{B}|^2, \qquad \mathcal{E} = \frac{p}{\gamma - 1} + \frac{1}{2}\rho|\boldsymbol{v}|^2 + \frac{1}{2}|\mathfrak{B}|^2$$

E_z is the electric field in the z direction

$$E_z = -(\boldsymbol{v} \times \mathfrak{B})_z = v_y B_x - v_x B_y$$

MHD equations in 2-D

Split into two parts

$$\boldsymbol{U} = [\rho,\ \rho\boldsymbol{v},\ \mathcal{E},\ B_z]^\top, \qquad \boldsymbol{B} = (B_x, B_y)$$

$$\frac{\partial \boldsymbol{U}}{\partial t} + \nabla \cdot \boldsymbol{F}(\boldsymbol{U}, \boldsymbol{B}) = 0, \qquad \frac{\partial B_x}{\partial t} + \frac{\partial E_z}{\partial y} = 0, \qquad \frac{\partial B_y}{\partial t} - \frac{\partial E_z}{\partial x} = 0$$

The fluxes $\boldsymbol{F} = (\boldsymbol{F}_x, \boldsymbol{F}_y)$ are of the form

$$\boldsymbol{F}_x = \begin{bmatrix} \rho v_x \\ P + \rho v_x^2 - B_x^2 \\ \rho v_x v_y - B_x B_y \\ \rho v_x v_z - B_x B_z \\ (\mathcal{E} + P) v_x - B_x(\boldsymbol{v} \cdot \boldsymbol{\mathfrak{B}}) \\ v_x B_z - v_z B_x \end{bmatrix}, \qquad \boldsymbol{F}_y = \begin{bmatrix} \rho v_y \\ \rho v_x v_y - B_x B_y \\ P + \rho v_y^2 - B_y^2 \\ \rho v_y v_z - B_y B_z \\ (\mathcal{E} + P) v_y - B_y(\boldsymbol{v} \cdot \boldsymbol{\mathfrak{B}}) \\ v_y B_z - v_z B_y \end{bmatrix}$$

Approximation of magnetic field

If we want $\nabla \cdot \boldsymbol{B} = 0$, it is natural to look for approximations in

$$H(div, \Omega) = \{\boldsymbol{B} \in L^2(\Omega) : \mathrm{div}(\boldsymbol{B}) \in L^2(\Omega)\}$$

To approximate functions in $H(div, \Omega)$ on a mesh $\mathcal{T}_h$ with piecewise polynomials, we need

$$\boldsymbol{B} \cdot \boldsymbol{n}$$

continuous across element faces.

Approximation spaces: Degree $k \geq 0$

Map cell K to reference cell $\hat{K} = [-\frac{1}{2}, +\frac{1}{2}] \times [-\frac{1}{2}, +\frac{1}{2}]$

$$\mathbb{P}_r(\xi) = \mathrm{span}\{1, \xi, \xi^2, \ldots, \xi^r\}, \quad \mathbb{Q}_{r,s}(\xi, \eta) = \mathbb{P}_r(\xi) \otimes \mathbb{P}_s(\eta)$$

Hydrodynamic variables in each cell

$$\boldsymbol{U}(\xi, \eta) = \sum_{i=0}^{k} \sum_{j=0}^{k} \boldsymbol{U}_{ij} \phi_i(\xi) \phi_j(\eta) \in \mathbb{Q}_{k,k}$$

Normal component of $\boldsymbol{B}$ on faces

$$\text{on vertical faces} : b_x(\eta) = \sum_{j=0}^{k} a_j \phi_j(\eta) \in \mathbb{P}_k(\eta)$$

$$\text{on horizontal faces} : b_y(\xi) = \sum_{j=0}^{k} b_j \phi_j(\xi) \in \mathbb{P}_k(\xi)$$

$\{\phi_i(\xi)\}$ are orthogonal polynomials on $[-\frac{1}{2}, +\frac{1}{2}]$, with degree $\phi_i = i$.

Approximation spaces: Degree $k \geq 0$

For $k \geq 1$,define certain *cell moments*

$$\alpha_{ij} = \alpha_{ij}(B_x) := \frac{1}{m_{ij}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} B_x(\xi,\eta)\phi_i(\xi)\phi_j(\eta)\mathsf{d}\xi\mathsf{d}\eta, \quad 0 \leq i \leq k-1, \quad 0 \leq j \leq k$$

$$\beta_{ij} = \beta_{ij}(B_y) := \frac{1}{m_{ij}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} B_y(\xi,\eta)\phi_i(\xi)\phi_j(\eta)\mathsf{d}\xi\mathsf{d}\eta, \quad 0 \leq i \leq k, \quad 0 \leq j \leq k-1$$

$$m_{ij} = \int_{-\frac{1}{2}}^{+\frac{1}{2}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} [\phi_i(\xi)\phi_j(\eta)]^2 \mathsf{d}\xi\mathsf{d}\eta = m_i m_j, \quad m_i = \int_{-\frac{1}{2}}^{+\frac{1}{2}} [\phi_i(\xi)]^2 \mathsf{d}\xi$$

α_{00}, β_{00} are cell averages of B_x, B_y

Solution variables

$$\{\boldsymbol{U}(\xi,\eta)\}, \qquad \{b_x(\eta)\}, \qquad \{b_y(\xi)\}, \qquad \{\alpha, \beta\}$$

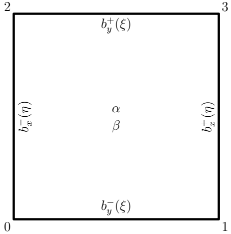
The set b_x, b_y, α, β are the dofs for the Raviart-Thomas space.

RT reconstruction: $b_x^\pm(\eta), b_y^\pm(\xi), \alpha, \beta \to \boldsymbol{B}(\xi,\eta)$

Given $b_x^\pm(\eta) \in \mathbb{P}_k$ and $b_y^\pm(\xi) \in \mathbb{P}_k$,
and set of cell moments

$$\{\alpha_{ij},\ 0 \le i \le k-1,\ 0 \le j \le k\}$$

$$\{\beta_{ij},\ 0 \le i \le k,\ 0 \le j \le k-1\}$$



Find $B_x \in \mathbb{Q}_{k+1,k}$ and $B_y \in \mathbb{Q}_{k,k+1}$ such that

$$B_x(\pm\tfrac{1}{2},\eta) = b_x^\pm(\eta), \quad \eta \in [-\tfrac{1}{2},\tfrac{1}{2}], \qquad B_y(\xi,\pm\tfrac{1}{2}) = b_y^\pm(\xi), \quad \xi \in [-\tfrac{1}{2},\tfrac{1}{2}]$$

$$\frac{1}{m_{ij}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} B_x(\xi,\eta)\phi_i(\xi)\phi_j(\eta) \mathrm{d}\xi \mathrm{d}\eta = \alpha_{ij}, \qquad 0 \le i \le k-1, \quad 0 \le j \le k$$

$$\frac{1}{m_{ij}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} B_y(\xi,\eta)\phi_i(\xi)\phi_j(\eta) \mathrm{d}\xi \mathrm{d}\eta = \beta_{ij}, \qquad 0 \le i \le k, \quad 0 \le j \le k-1$$

(1) $\exists$ unique solution. (2) Data div-free $\implies$ reconstructed $\boldsymbol{B}$ is div-free.

DG scheme for $\boldsymbol{B}$ on faces

On every vertical face of the mesh

$$\int_{-\frac{1}{2}}^{+\frac{1}{2}} \frac{\partial b_x}{\partial t} \phi_i \mathsf{d}\eta - \frac{1}{\Delta y} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \hat{E}_z \frac{\mathsf{d}\phi_i}{\mathsf{d}\eta} \mathsf{d}\eta + \frac{1}{\Delta y} [\tilde{E}_z \phi_i] = 0, \qquad 0 \le i \le k$$

On every horizontal face of the mesh

$$\int_{-\frac{1}{2}}^{+\frac{1}{2}} \frac{\partial b_y}{\partial t} \phi_i \mathsf{d}\xi + \frac{1}{\Delta x} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \hat{E}_z \frac{\mathsf{d}\phi_i}{\mathsf{d}\xi} \mathsf{d}\xi - \frac{1}{\Delta x} [\tilde{E}_z \phi_i] = 0, \qquad 0 \le i \le k$$

$\hat{E}_z$: on face, 1-D Riemann solver

$\tilde{E}_z$: at vertex, 2-D Riemann solver

DG scheme for $\boldsymbol{B}$ on cells

$$
\begin{aligned}
m_{ij}\frac{\mathsf{d}\alpha_{ij}}{\mathsf{d}t} &= \int_{-\frac{1}{2}}^{+\frac{1}{2}}\int_{-\frac{1}{2}}^{+\frac{1}{2}} \frac{\partial B_x}{\partial t}\phi_i(\xi)\phi_j(\eta)\mathsf{d}\xi\mathsf{d}\eta \\
&= -\frac{1}{\Delta y}\int_{-\frac{1}{2}}^{+\frac{1}{2}}\int_{-\frac{1}{2}}^{+\frac{1}{2}} \frac{\partial E_z}{\partial \eta}\phi_i(\xi)\phi_j(\eta)\mathsf{d}\xi\mathsf{d}\eta \\
&= -\frac{1}{\Delta y}\int_{-\frac{1}{2}}^{+\frac{1}{2}} [\hat{E}_z(\xi,\tfrac{1}{2})\phi_i(\xi)\phi_j(\tfrac{1}{2}) - \hat{E}_z(\xi,-\tfrac{1}{2})\phi_i(\xi)\phi_j(-\tfrac{1}{2})]\mathsf{d}\xi \\
&\quad +\frac{1}{\Delta y}\int_{-\frac{1}{2}}^{+\frac{1}{2}}\int_{-\frac{1}{2}}^{+\frac{1}{2}} E_z(\xi,\eta)\phi_i(\xi)\phi_j'(\eta)\mathsf{d}\xi\mathsf{d}\eta, \quad 0 \le i \le k-1, \quad 0 \le j \le k
\end{aligned}
$$

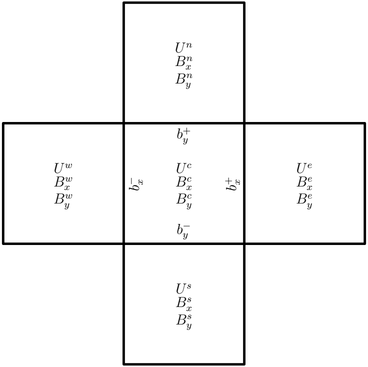
Not a Galerkin method, test functions ($\mathbb{Q}_{k-1,k}$) different from trial functions ($\mathbb{Q}_{k+1,k}$)

DG scheme for $\boldsymbol{U}$ on cells

For each test function $\Phi(\xi,\eta) = \phi_i(\xi)\phi_j(\eta) \in \mathbb{Q}_{k,k}$

$$\int_{-\frac{1}{2}}^{+\frac{1}{2}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \frac{\partial \boldsymbol{U}^c}{\partial t} \Phi(\xi,\eta) \mathsf{d}\xi \mathsf{d}\eta - \int_{-\frac{1}{2}}^{+\frac{1}{2}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \left[\frac{1}{\Delta x} \boldsymbol{F}_x \frac{\partial \Phi}{\partial \xi} + \frac{1}{\Delta y} \boldsymbol{F}_y \frac{\partial \Phi}{\partial \eta} \right] \mathsf{d}\xi \mathsf{d}\eta$$
$$+ \frac{1}{\Delta x} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \hat{\boldsymbol{F}}_x^+ \Phi(\tfrac{1}{2},\eta) \mathsf{d}\eta - \frac{1}{\Delta x} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \hat{\boldsymbol{F}}_x^- \Phi(-\tfrac{1}{2},\eta) \mathsf{d}\eta$$
$$+ \frac{1}{\Delta y} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \hat{\boldsymbol{F}}_y^+ \Phi(\xi,\tfrac{1}{2}) \mathsf{d}\xi - \frac{1}{\Delta y} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \hat{\boldsymbol{F}}_y^- \Phi(\xi,-\tfrac{1}{2}) \mathsf{d}\xi = 0$$

DG scheme for $\boldsymbol{U}$ on cells



$$\boldsymbol{F}_x = \boldsymbol{F}_x(\boldsymbol{U}^c, B_x^c, B_y^c), \qquad \boldsymbol{F}_y = \boldsymbol{F}_y(\boldsymbol{U}^c, B_x^c, B_y^c)$$

$$\hat{\boldsymbol{F}}_x^+ = \hat{\boldsymbol{F}}_x((\boldsymbol{U}^c, b_x^+, B_y^c), (\boldsymbol{U}^e, b_x^+, B_y^e)), \qquad \hat{\boldsymbol{F}}_x^- = \hat{\boldsymbol{F}}_x((\boldsymbol{U}^w, b_x^-, B_y^w), (\boldsymbol{U}^c, b_x^-, B_y^c))$$

$$\hat{\boldsymbol{F}}_y^+ = \hat{\boldsymbol{F}}_y((\boldsymbol{U}^c, B_x^c, b_y^+), (\boldsymbol{U}^n, B_x^n, b_y^+)), \qquad \hat{\boldsymbol{F}}_y^- = \hat{\boldsymbol{F}}_y((\boldsymbol{U}^s, B_x^s, b_y^-), (\boldsymbol{U}^c, B_x^c, b_y^-))$$

Constraints on $\boldsymbol{B}$

Definition (Strongly divergence-free)

We will say that a vector field $\boldsymbol{B}$ defined on a mesh is strongly divergence-free if

1. $\nabla \cdot \boldsymbol{B} = 0$ in each cell $K \in \mathcal{T}_h$
2. $\boldsymbol{B} \cdot \boldsymbol{n}$ is continuous at each face $F \in \mathcal{T}_h$

Theorem

(1) The DG scheme satisfies

$$\frac{d}{dt} \int_K (\nabla \cdot \boldsymbol{B}) \phi dx dy = 0, \qquad \forall \phi \in \mathbb{Q}_{k,k}$$

and since $\nabla \cdot \boldsymbol{B} \in \mathbb{Q}_{k,k} \implies \nabla \cdot \boldsymbol{B} =$ *constant wrt time.*
(2) If $\nabla \cdot \boldsymbol{B} = 0$ *everywhere at the initial time, then this is true at any future time also.*

Constraints on $\boldsymbol{B}$

But: Applying a limiter in a post-processing step destroys div-free property !!!

Definition (Weakly divergence-free)

We will say that a vector field $\boldsymbol{B}$ defined on a mesh is weakly divergence-free if

1. $\int_{\partial K} \boldsymbol{B} \cdot \boldsymbol{n} \mathrm{d}s = 0$ for each cell $K \in \mathcal{T}_h$.
2. $\boldsymbol{B} \cdot \boldsymbol{n}$ is continuous at each face $F \in \mathcal{T}_h$

Theorem

The DG scheme satisfies

$$\frac{d}{dt} \int_{\partial K} \boldsymbol{B} \cdot \boldsymbol{n} ds = 0$$

Strongly div-free $\implies$ *weakly div-free.*

Constraints on $\boldsymbol{B}$

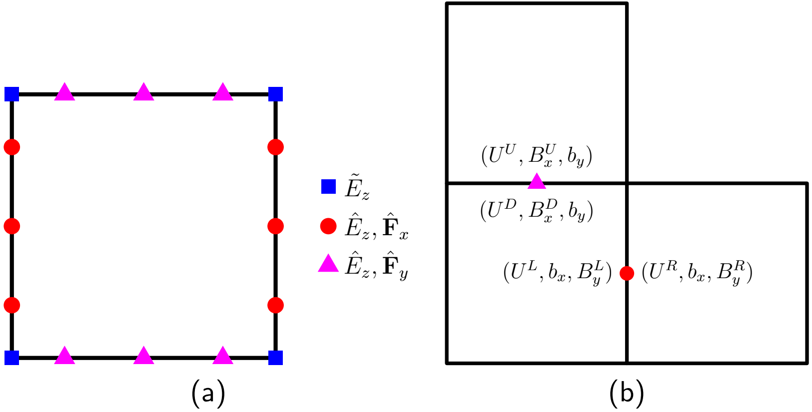
$$\int_{\partial K} \boldsymbol{B} \cdot \boldsymbol{n} \mathrm{d}s = (a_0^+ - a_0^-)\Delta y + (b_0^+ - b_0^-)\Delta x$$

where $a_0^\pm$ are face averages of B_x on right/left faces and $b_0^\pm$ are face averages of B_y on top/bottom faces respectively.

Corollary

If the limiting procedure preserves the mean value of $\boldsymbol{B} \cdot \boldsymbol{n}$ stored on the faces, then the DG scheme with limiter yields weakly divergence-free solutions.

$k+1$ point Gauss-Legendre quadrature on faces



(a) Face quadrature points and numerical fluxes. (b) 1-D Riemann problems at a vertical and horizontal face of a cell

Numerical fluxes

To estimate $\hat{\boldsymbol{F}}_x$, $\hat{E}_z$, solve 1-D Riemann problem at each face quadrature point

$$\frac{\partial \mathcal{U}}{\partial t} + \frac{\partial \mathcal{F}_x}{\partial x} = 0, \qquad \mathcal{U}(x,0) = \begin{cases} \mathcal{U}^L = \mathcal{U}(\boldsymbol{U}^L, b_x, B_y^L) & x < 0 \\ \mathcal{U}^R = \mathcal{U}(\boldsymbol{U}^R, b_x, B_y^R) & x > 0 \end{cases}$$

$$\hat{\boldsymbol{F}}_x = \begin{bmatrix} (\hat{\mathcal{F}}_x)_1 \\ (\hat{\mathcal{F}}_x)_2 \\ (\hat{\mathcal{F}}_x)_3 \\ (\hat{\mathcal{F}}_x)_4 \\ (\hat{\mathcal{F}}_x)_5 \\ (\hat{\mathcal{F}}_x)_8 \end{bmatrix}, \qquad \hat{E}_z = -(\hat{\mathcal{F}}_x)_7$$

HLL Riemann solver in 1-D

- Include only slowest and fastest waves: $S_L < S_R$
- Intermediate state from conservation law

$$\mathcal{U}^* = \frac{S_R \mathcal{U}^R - S_L \mathcal{U}^L - (\mathcal{F}_x^R - \mathcal{F}_x^L)}{S_R - S_L}$$

- Flux obtained by satisfying conservation law over half Riemann fan

$$\mathcal{F}_x^* = \frac{S_R \mathcal{F}_x^L - S_L \mathcal{F}_x^R + S_L S_R (\mathcal{U}^R - \mathcal{U}^L)}{S_R - S_L}$$

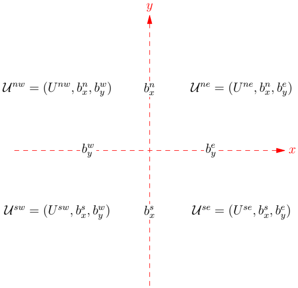
- Numerical flux is given by

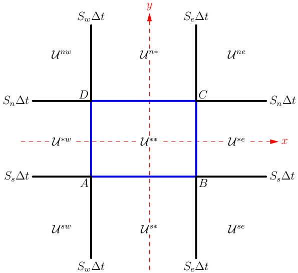
$$\hat{\mathcal{F}}_x = \begin{cases} \mathcal{F}_x^L & S_L > 0 \\ \mathcal{F}_x^R & S_R < 0 \\ \mathcal{F}_x^* & \text{otherwise} \end{cases}$$

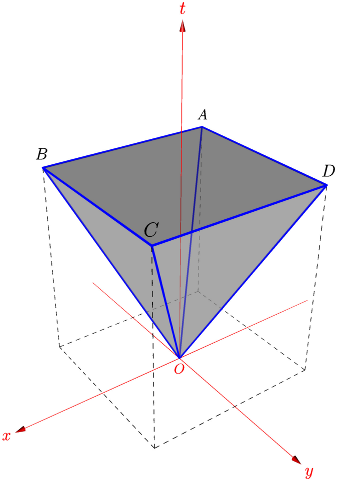
- Electric field from the seventh component of the numerical flux

$$\hat{E}_z(\mathcal{U}^L, \mathcal{U}^R) = -(\hat{\mathcal{F}}_x)_7 = \begin{cases} E_z^L & S_L > 0 \\ E_z^R & S_R < 0 \\ \frac{S_R E_z^L - S_L E_z^R - S_L S_R (B_y^R - B_y^L)}{S_R - S_L} & \text{otherwise} \end{cases}$$

2-D Riemann problem







2-D Riemann problem

Strongly interacting state

$$B_x^{**} = \frac{1}{2(S_e - S_w)(S_n - S_s)} \Big[2S_e S_n B_x^{ne} - 2S_n S_w B_x^{nw} + 2S_s S_w B_x^{sw} - 2S_s S_e B_x^{se} - S_e(E_z^{ne} - E_z^{se}) + S_w(E_z^{nw} - E_z^{sw}) - (S_e - S_w)(E_z^{n*} - E_z^{s*}) \Big]$$

$$B_y^{**} = \frac{1}{2(S_e - S_w)(S_n - S_s)} \Big[2S_e S_n B_y^{ne} - 2S_n S_w B_y^{nw} + 2S_s S_w B_y^{sw} - 2S_s S_e B_y^{se} + S_n(E_z^{ne} - E_z^{nw}) - S_s(E_z^{se} - E_z^{sw}) + (S_n - S_s)(E_z^{*e} - E_z^{*w}) \Big]$$

Jump conditions b/w $**$ and $\{n*, s*, *e, *w\}$

$$E_z^{**} = E_z^{n*} - S_n(B_x^{n*} - B_x^{**})$$
$$E_z^{**} = E_z^{s*} - S_s(B_x^{s*} - B_x^{**})$$
$$E_z^{**} = E_z^{*e} + S_e(B_y^{*e} - B_y^{**})$$
$$E_z^{**} = E_z^{*w} + S_w(B_y^{*w} - B_y^{**})$$

2-D Riemann problem

Over-determined, least-squares solution (Vides et al.)

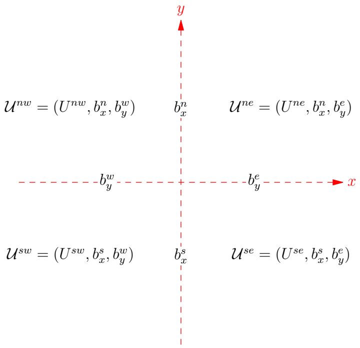
$$E_z^{**} = \frac{1}{4}(E_z^{n*} + E_z^{s*} + E_z^{*e} + E_z^{*w}) - \frac{1}{4}S_n(B_x^{n*} - B_x^{**}) - \frac{1}{4}S_s(B_x^{s*} - B_x^{**}) + \frac{1}{4}S_e(B_y^{*e} - B_y^{**}) + \frac{1}{4}S_w(B_y^{*w} - B_y^{**})$$

Consistency with 1-D solver

$$\mathcal{U}^{nw} = \mathcal{U}^{sw} = \mathcal{U}^L$$
$$\mathcal{U}^{ne} = \mathcal{U}^{se} = \mathcal{U}^R$$

then

$$E_z^{**} = \hat{E}_z(\mathcal{U}^L, \mathcal{U}^R) = \text{1-D HLL}$$



HLLC Riemann solver

1-D solver

- Slowest and fastest waves S_L, S_R, and contact wave $S_M = u_*$
- Two intermediate states: $\mathcal{U}^{*L}$, $\mathcal{U}^{*R}$
- No unique way to satisfy all jump conditions: Gurski (2004), Li (2005)
- Common value of magnetic field $\boldsymbol{B}^{*L} = \boldsymbol{B}^{*R}$
- Common electric field $E_z^{*L} = E_z^{*R}$, same as in HLL

2-D solver

- Electric field estimate E_z^{**} same as HLL
- Consistent with 1-D solver

Limiting procedure

Given $\boldsymbol{U}^{n+1}, b_x^{n+1}, b_y^{n+1}, \alpha^{n+1}, \beta^{n+1}$

1. Perform RT reconstruction $\Longrightarrow \boldsymbol{B}(\xi,\eta)$. Apply TVD limiter in characteristic variables to $\{\boldsymbol{U}(\xi,\eta), \boldsymbol{B}(\xi,\eta)\}$.
2. On each face, use limited left/right $\boldsymbol{B}(\xi,\eta)$ to limit b_x, b_y

$$b_x(\eta) \leftarrow \mathrm{minmod}\left(b_x(\eta), B_x^L(\tfrac{1}{2},\eta), B_x^R(-\tfrac{1}{2},\eta)\right)$$

   Do not change mean value on faces.

3. Restore divergence-free property using divergence-free-reconstruction
   1. Strongly divergence-free: need to reset cell averages α_{00}, β_{00}
   2. Weakly divergence-free: α_{00}, β_{00} are not changed

$$\nabla \cdot \boldsymbol{B} = d_1 \phi_1(\xi) + d_2 \phi_1(\eta)$$

Divergence-free reconstruction

For each cell, find $\boldsymbol{B}(\xi,\eta)$ such that

$$B_x(\pm\tfrac{1}{2},\eta) = b_x^\pm(\eta), \quad \forall \eta \in [-\tfrac{1}{2},+\tfrac{1}{2}]$$

$$B_y(\xi,\pm\tfrac{1}{2}) = b_y^\pm(\xi), \quad \forall \xi \in [-\tfrac{1}{2},+\tfrac{1}{2}]$$

$$\nabla\cdot\boldsymbol{B}(\xi,\eta) = 0, \qquad \forall(\xi,\eta)\in[-\tfrac{1}{2},\tfrac{1}{2}]\times[-\tfrac{1}{2},\tfrac{1}{2}]$$

We look for $\boldsymbol{B}$ in (Brezzi & Fortin, Section III.3.2)

$$\mathrm{BDM}(k) = \mathbb{P}_k^2 + r\nabla\times(x^{k+1}y) + s\nabla\times(xy^{k+1})$$

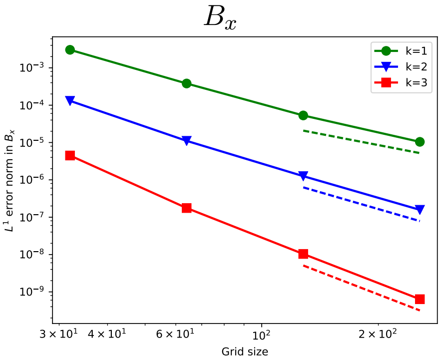
- For $k=0,1,2$, we can solve the above problem
- For $k\ge 3$, we need additional information
  - $k=3$: $b_{10}-a_{01}=\omega_1 = \nabla\times\boldsymbol{B}(0,0)$
  - $k=4$: ω_1 and $b_{20}-a_{11}=\omega_2 \approx \frac{\partial}{\partial x}\nabla\times\boldsymbol{B}$, $b_{11}-a_{02}=\omega_3\approx\frac{\partial}{\partial y}\nabla\times\boldsymbol{B}$
  - ω_1, etc. are known from α,β
- For more details, see `https://arxiv.org/abs/1809.03816`

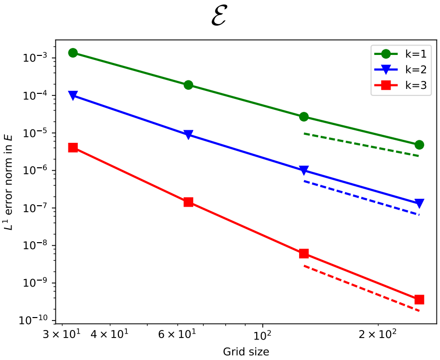
Algorithm 1: Constraint preserving scheme for ideal compressible MHD

Allocate memory for all variables;
Set initial condition for $\boldsymbol{U}, b_x, b_y, \alpha, \beta$;
Loop over cells and reconstruct B_x, B_y;
Set time counter $t = 0$;
while $t < T$ **do**
    Copy current solution into old solution;
    Compute time step Δt;
    for *each RK stage* **do**
        Loop over vertices and compute vertex flux;
        Loop over faces and compute all face integrals;
        Loop over cells and compute all cell integrals;
        Update solution to next stage;
        Loop over cells and do RT reconstruction $(b_x, b_y, \alpha, \beta) \to \boldsymbol{B}$;
        Loop over cells and apply limiter on $\boldsymbol{U}, \boldsymbol{B}$;
        Loop over faces and limit solution b_x, b_y;
        Loop over faces and perform div-free reconstruction;
    end
    $t = t + \Delta t$;
end

Numerical Results

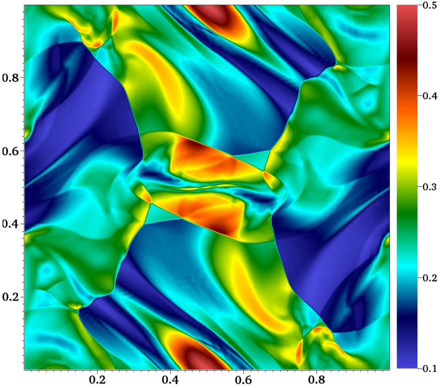
Smooth vortex



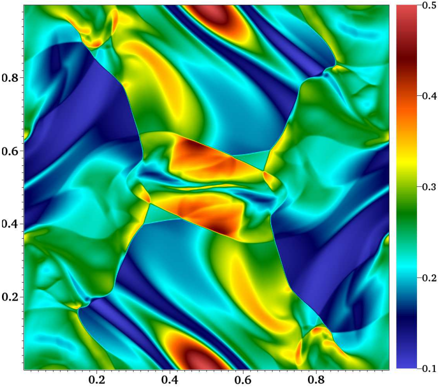


Orszag-Tang test

Density, $t = 0.5$, 512×512 cells

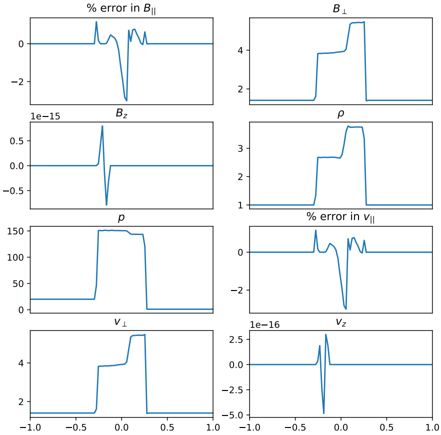


Weakly div-free

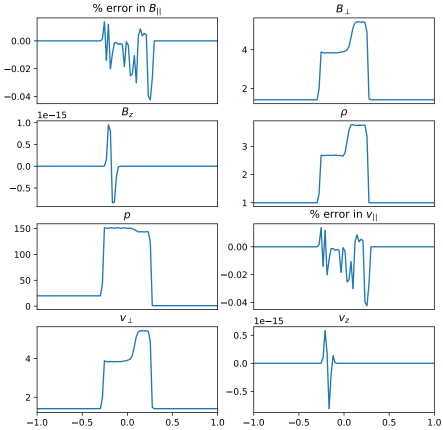


Strongly div-free

Rotated shock tube: 128 cells, HLL



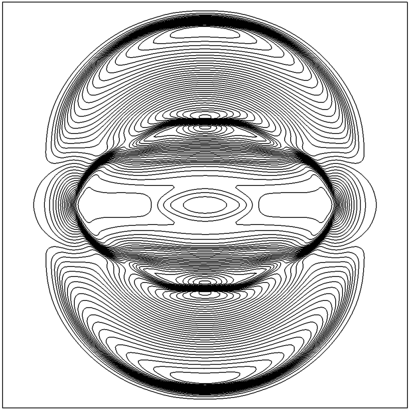
weakly div-free



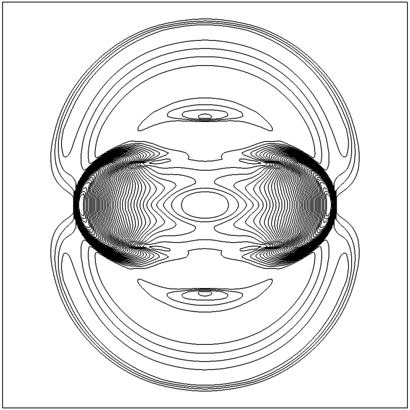
strongly div-free

Blast wave: 200×200 cells

$$\rho = 1, \quad \boldsymbol{v} = (\ 0,\ 0,\ 0), \quad \mathfrak{B} = \frac{1}{\sqrt{4\pi}}(100,\ 0,\ 0), \quad p = \begin{cases} 1000 & r < 0.1 \\ 0.1 & r > 0.1 \end{cases}$$



$B_x^2 + B_y^2$



$v_x^2 + v_y^2$

Summary

- Div-free DG scheme using RT basis for $\boldsymbol{B}$
- Multi-D Riemann solvers essential
  - consistency with 1-d solver is not automatic; ok for HLL and HLLC (3-wave); what about HLLD ?
- Div-free limiting needs to ensure strong div-free condition
  - Reconstruction of $\boldsymbol{B}$ using div and curl
- Extension to 3-D seems *easy*, also AMR
- Extension to unstructured grids (use Piola transform)
- Limiters are still major obstacle for high order
  - WENO-type ideas
  - Machine learning ideas (Ray & Hesthaven)
- No proof of positivity limiter for div-free scheme
  - Not a fully discontinuous solution
- Extension to resistive case: $\boldsymbol{B}_t + \nabla \times \boldsymbol{E} = -\nabla \times (\eta \boldsymbol{J})$, $\boldsymbol{J} = \nabla \times \boldsymbol{B}$

$$\frac{\partial B_x}{\partial t} + \frac{\partial}{\partial y}(E_z + \eta J_z) = 0, \ \frac{\partial B_y}{\partial t} - \frac{\partial}{\partial x}(E_z - \eta J_z) = 0, \ J_z = \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}$$

Numerical results: 2-D Maxwell equation

$$
\begin{aligned}
\frac{\partial D_x}{\partial t} - \frac{\partial H_z}{\partial y} &= 0 \qquad (1)\\
\frac{\partial D_y}{\partial t} + \frac{\partial H_z}{\partial x} &= 0 \qquad (2)\\
\frac{\partial B_z}{\partial t} + \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} &= 0 \qquad (3)
\end{aligned}
$$

where

$$
(E_x, E_y) = \frac{1}{\varepsilon(x,y)}(D_x, D_y), \qquad H_z = \frac{1}{\mu(x,y)} B_z
$$

Divergence-free constraint: $\nabla \cdot \boldsymbol{D} = 0$

Flux reconstruction on faces for D_x, D_y, and DG scheme on cells for B_z

Riemann solvers to estimate numerical fluxes at faces/vertices

Plane wave propagation in vacuum

$N_x \times N_y$	$\|\boldsymbol{D}^h - \boldsymbol{D}\|_{L^1}$	Ord	$\|\boldsymbol{D}^h - \boldsymbol{D}\|_{L^2}$	Ord	$\|B_z^h - B_z\|_{L^1}$	Ord	$\|B_z^h - B_z\|_{L^2}$
16×16	3.0557e-07	—	3.5095e-07	—	1.9458e-04	—	2.5101e-04
32×32	1.1040e-08	4.79	1.3428e-08	4.71	1.1275e-05	4.11	1.4590e-05
64×64	5.0469e-10	4.45	6.1548e-10	4.45	6.7924e-07	4.05	8.9228e-07
128×128	2.6834e-11	4.23	3.3945e-11	4.18	4.1802e-08	4.02	5.5449e-08

Table: Plane wave test, degree=3: convergence of error

$N_x \times N_y$	$\|\boldsymbol{D}^h - \boldsymbol{D}\|_{L^1}$	Ord	$\|\boldsymbol{D}^h - \boldsymbol{D}\|_{L^2}$	Ord	$\|B_z^h - B_z\|_{L^1}$	Ord	$\|B_z^h - B_z\|_{L^2}$
8×8	2.4982e-07	—	2.8435e-07	—	2.5514e-04	—	3.2612e-04
16×16	6.3357e-09	5.30	7.2655e-09	5.29	6.4340e-06	5.31	8.5532e-06
32×32	1.7113e-10	5.21	2.0807e-10	5.13	1.9021e-07	5.08	2.5521e-07
64×64	5.1213e-12	5.06	6.4133e-12	5.02	5.9026e-09	5.01	7.9601e-09
128×128	1.5949e-13	5.00	2.0054e-13	5.00	1.8412e-10	5.00	2.4890e-10

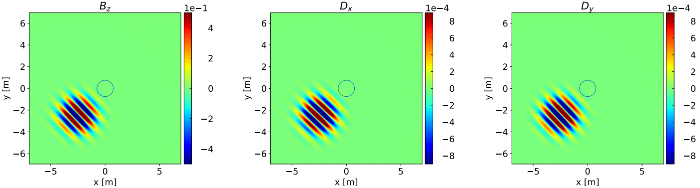
Table: Plane wave test, degree=4: convergence of error

$$\text{Error} = O(h^{k+1})$$

Refraction of Gaussian pulse by disc

$\epsilon_r = 5 - 4\tanh((\sqrt{x^2+y^2} - 0.75)/0.08) \in [1, 9]$, radius = 0.75 m

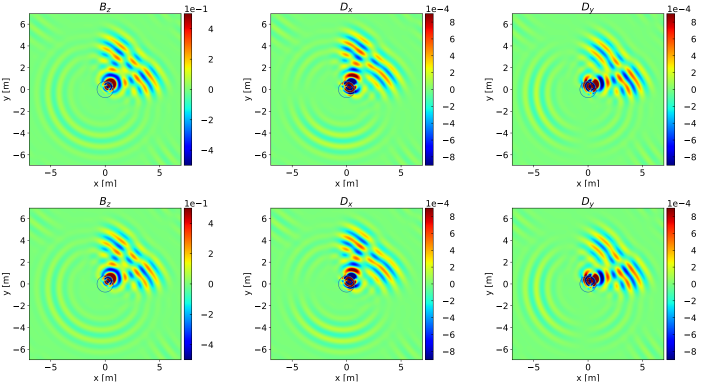
Initial condition, $\lambda = 1.5m$



Refraction of gaussian pulse by disc

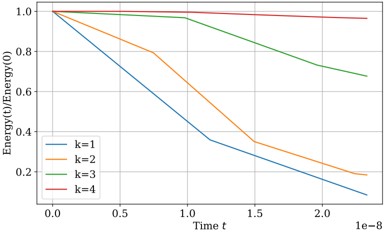
$\epsilon_r = 5 - 4\tanh((\sqrt{x^2+y^2} - 0.75)/0.08) \in [1, 9]$

$$t = 23.3\ ns$$

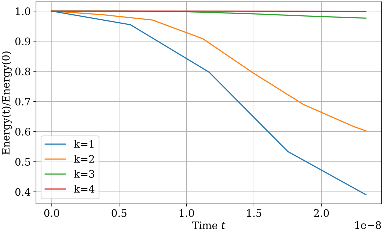


200×200 cells. Top row: $k = 3$, bottom row: $k = 4$

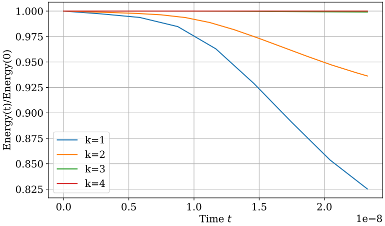
Refraction of gaussian pulse by disc: energy conservation



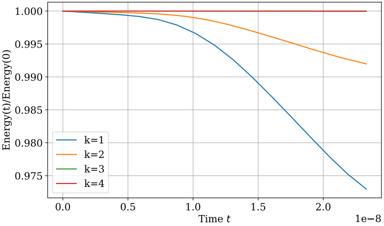
100×100



200×200



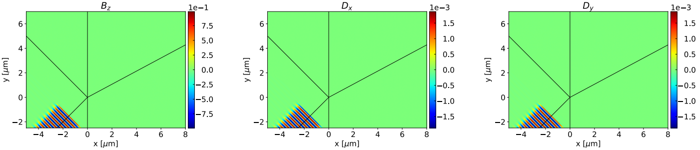
400×400



800×800

Refraction of plane wave: $\varepsilon_0 \leq \varepsilon \leq 2.25\varepsilon_0$

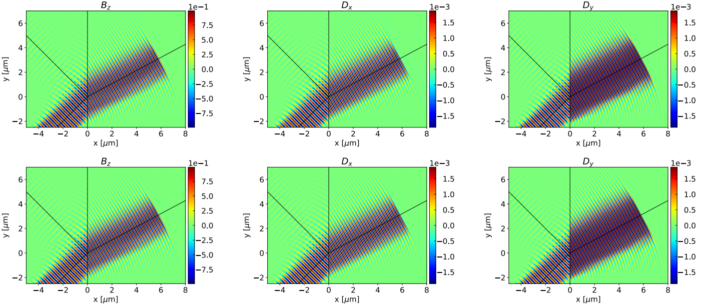
$\epsilon_r = 1.625 + 0.625\tanh(x/10^{-8})$, $\lambda = 0.5\mu m$



Initial condition

Refraction of plane wave: $\varepsilon_0 \leq \varepsilon \leq 2.25\varepsilon_0$

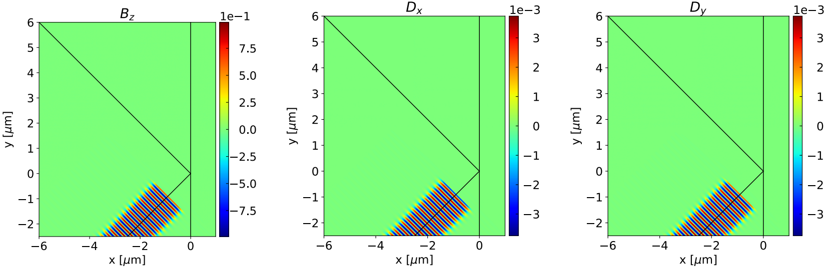
$\epsilon_r = 1.625 + 0.625\tanh(x/10^{-8})$, $\lambda = 0.5\mu m$



650×475 cells. $t = 4 \times 10^{-14}s$. Top row: $k = 3$, bottom row: $k = 4$

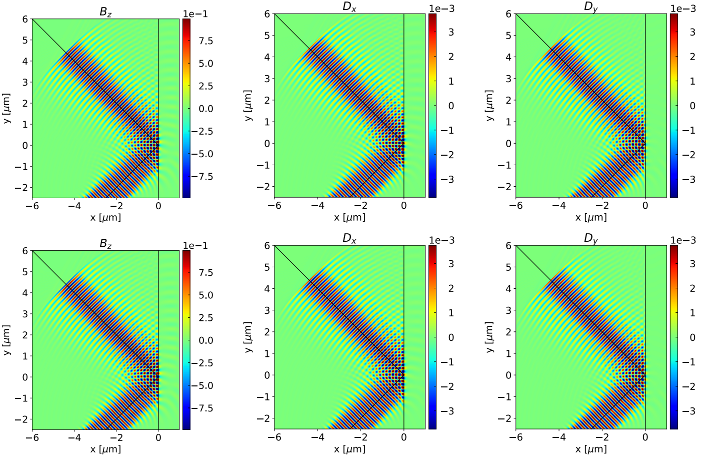
Total internal reflection of plane wave: $4\varepsilon_0 \geq \varepsilon \geq \varepsilon_0$

$\epsilon_r = 2.5 - 1.5\tanh(x/4 \times 10^{-8}),\ \lambda = 0.3\mu m$



Initial condition

Total internal reflection of plane wave: $4\varepsilon_0 \geq \varepsilon \geq \varepsilon_0$



350×425 cells. $t = 5 \times 10^{-14} s$. Top row: $k = 3$, bottom row: $k = 4$