2002년도 한국물리학회 가을학술논문발표회
10. 24 – 10. 26
한양대학교

PIC Simulation for Reflection of 5.0 GHz Microwave Launched by KSTAR LHCD Coupler*

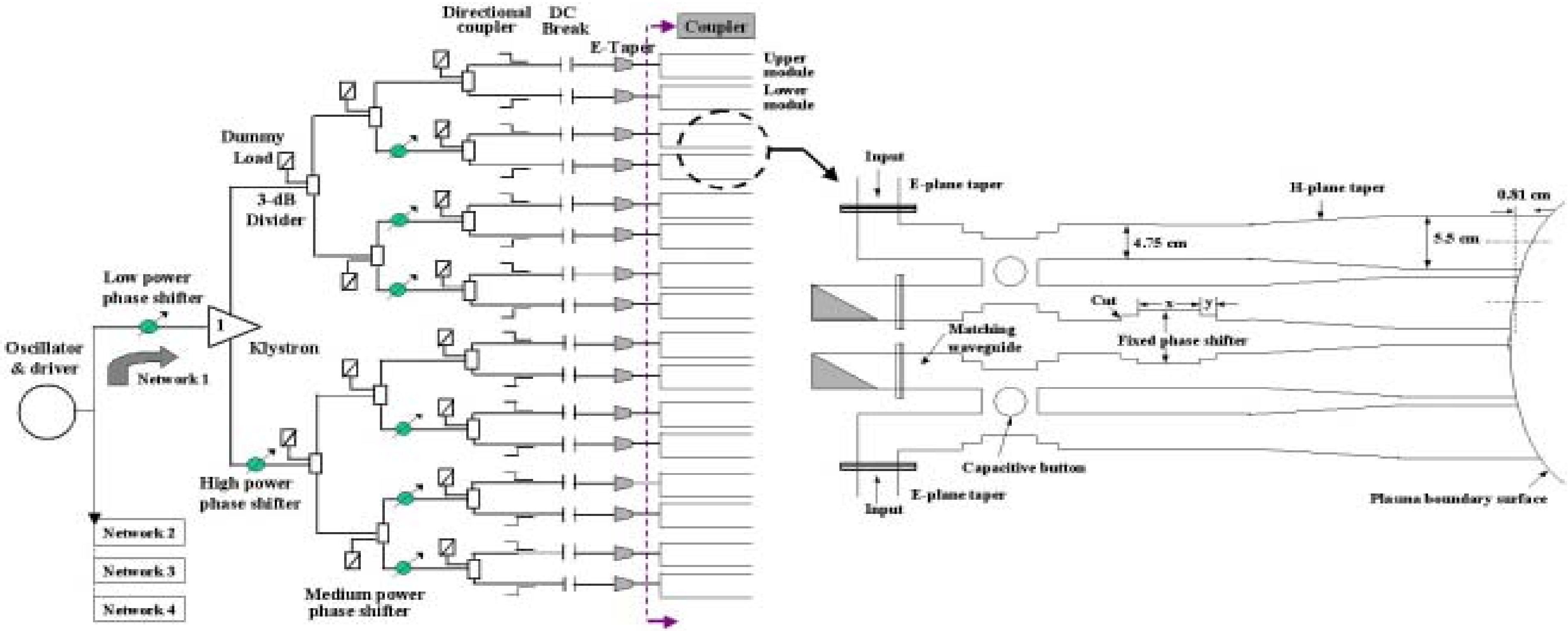
배 영순**,** 조 무현**,** 남궁 원 **(**포항공과대학교**)**

* Work Supported by KBSI

KSTAR 5.0-GHz LHCD System

Introduction

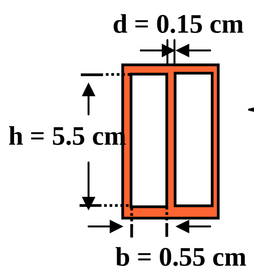
- The KSTAR Lower-Hybrid (LH) coupler launches 5.0 GHz microwave to the high density and high temperature plasma with the edge density of ~10^{12} cm^{-3}.
- The RF power will be delivered through approximately 40 m long parallel transmission lines composed of waveguide components, such as DC breaks, 3 dB dividers, E-bends, H-bends, oversized straight pieces, phase shifters, and etc. from 4 klystron tubes to the coupler. Approximately 20 % of the insertion loss is expected, and we plan to deliver at least more than 1.5 MW microwave power.



5.0-GHz LH Coupler

Introduction

- The coupler is being designed in collaboration with the Princeton Plasma Physics Laboratory. It will be composed of two modules that are assembled at upper and lower positions. Each module has a waveguide antenna of 2 rows of 32 guidelets near the plasma. Therefore, the KSTAR front coupler is composed of 4 rows of 32 guidelets, and each klystron feeds 8 columns of guidelets of the waveguide antenna.

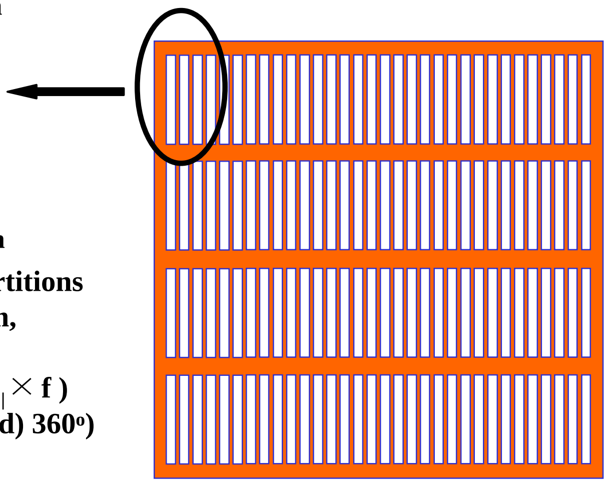


4 rows × 32 columns partitions

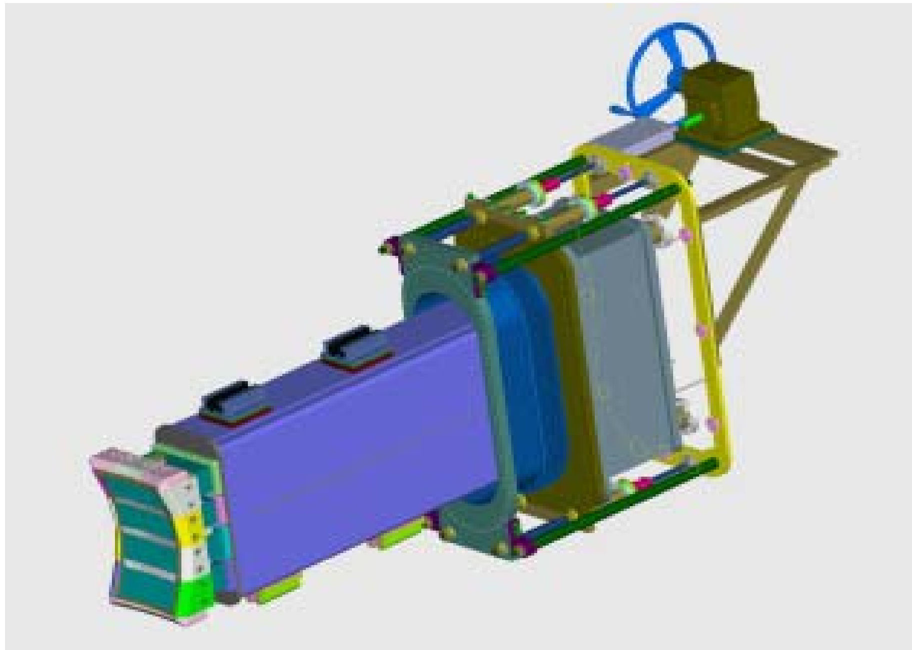
h = 5.5 cm, b = 0.55 cm,

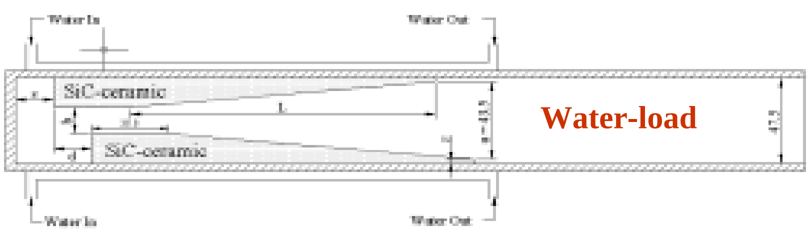
d = 1.5 cm, $\triangle\phi = 90^o$

$$\Rightarrow n_{\|} = k_{\|} \times c/\omega = c / (\lambda_{\|} \times f) = c \times \triangle\phi / (f \times (b+d)\, 360^o) = 2.15$$

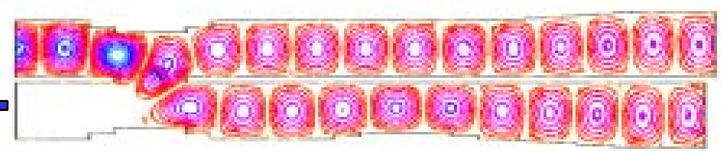


Front view of the KSTAR 5.0 GHz coupler





put



Same phase between two vertical outputs

Septum plate

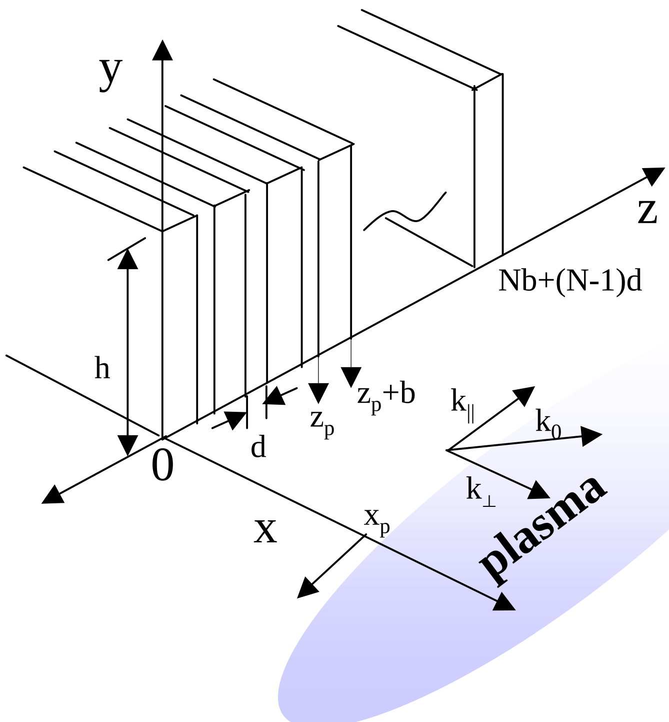
Simulations

Introduction

- Brambilla code simulation
  - Average reflection coefficients are calculated for different edge densities and for different linear density gradients in cases of 4-waveguide coupler and 32-waveguide coupler.
  - Power spectrums launched from the coupler are calculated for different phase difference between waveguide.
  - Electric fields are also calculated inside waveguide and in the plasma.
- XOOPIC simulation for 4-waveguide coupler
  - Average reflection coeffiecients are calculated for different edge densities of homogenious plasma.
  - Wave progagation in the plasma are seen in model region for the xoopic simulation.
  - Electric fields in the plasma are plotted as a function of the toroidal direction.
- HFSS simulation for 32-waveguide coupler
  - Far-field radiation pattern and its electric fields are calculated for the vacuum boundary using the Perfectly Matched Layer (PML).

Brambilla code simulation

Wave Coupling in front of LH Grill



1. Electric and magnetic fields in the wave guides (x < 0, inside)

$$E_z^{WG} = \sum_{p=1}^{N} e^{i\phi_p}\theta_p(z)\left\{\sum_{n=0}^{\nu}\left(\alpha_{np}e^{ik_n x} + \beta_{np}e^{-ik_n x}\right)\cos\frac{n\pi(z-z_p)}{b} + \sum_{n=\nu+1}^{\infty}\beta_{np}e^{\gamma_n x}\cos\frac{n\pi(z-z_p)}{b}\right\}$$

$$B_y^{WG} = -ik_0\sum_{p=1}^{N} e^{i\phi_p}\theta_p(z)\left\{\sum_{n=0}^{\nu}\frac{1}{ik_n}\left(\alpha_{np}e^{ik_n x} - \beta_{np}e^{-ik_n x}\right)\cos\frac{n\pi(z-z_p)}{b} - \sum_{n=\nu+1}^{\infty}\frac{\beta_{np}}{\gamma_n}e^{\gamma_n x}\cos\frac{n\pi(z-z_p)}{b}\right\}$$

$$E_x^{WG} = -\frac{i}{k_0}\frac{\partial B_y}{\partial z}$$

$$\theta_p(z) = \begin{cases} 1 & for\ \ z_p \le z \le z_p + b \\ 0 & otherwise \end{cases}, \quad k_n = \sqrt{k_0^2 - \left(\frac{n\pi}{b}\right)^2} \quad \gamma_n = \sqrt{\left(\frac{n\pi}{b}\right)^2 - k_0^2}$$

k_n : propagating mode and γ_n : evanescent mode

3. Plasma-loaded grill (x_p)

$$\frac{d^2E_z}{dx^2} + k_\perp^2\frac{\varepsilon_{zz}(x)}{\varepsilon_{xx}(x)}E_z = 0 \quad (k_0^2 = k_\perp^2 + k_\parallel^2)$$

$$\varepsilon_{xx} = \varepsilon_{yy} = S = 1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2 - \omega_{ci}^2}$$

$$\varepsilon_{xy} = -\varepsilon_{yx} = -iD = -i\left(\frac{\omega_{pi}^2\omega_{ci}}{\omega(\omega^2 - \omega_{ci}^2)} - \frac{\omega_{pi}^2\omega_{ce}}{\omega(\omega^2 - \omega_{ce}^2)}\right)$$

$$\varepsilon_{zz} = P = 1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{\omega_{pi}^2}{\omega^2}, \quad \varepsilon_{xz} = \varepsilon_{zx} = \varepsilon_{yz} = \varepsilon_{zy} = 0$$

x_p is the distance from the wall to the plasma edge.

2. Electric and magnetic fields for x > 0 (vacuum)

$$E_z^V = \int_{-\infty}^{+\infty}\left[\sigma(k_\parallel)e^{ik_\perp x} + \rho(k_\parallel)e^{-ik_\perp x}\right]e^{-ik_\parallel x}dk_\parallel$$

$$B_y^V = -k_0\int_{-\infty}^{+\infty}\left[\sigma(k_\parallel)e^{ik_\perp x} - \rho(k_\parallel)e^{-ik_\perp x}\right]e^{-ik_\parallel x}\frac{dk_\parallel}{k_\perp}$$

$$k_0^2 = k_\perp^2 + k_\parallel^2$$

Brambilla code simulation

Boundary Conditions

- **Factor of wave reflected from back from any obstacle located at x > 0**
- **Boundary condition at x = 0 plane ($E_z^{WG} = E_z^V$, $B_y^{WG} = B_y^V$)**
- **Using the orthogonality of the waveguide eigen-modes**
- **Continuity of E_z and B_z at the plasma edge $x = x_p$**

$$\rho(k_\parallel) = -Y(k_\parallel)\sigma(k_\parallel) \qquad |Y(k_\parallel)|^2 \le 1$$

$$Y(k_\parallel) = e^{2ik_\perp x_p}\frac{1-Z}{1+Z} \qquad for \;\; k_\parallel^2 < k_0^2$$

$$where\;,\;\; Z = i\frac{J_{1/3}\left(\frac{2}{3}k_\perp L_n\right) + J_{-1/3}\left(\frac{2}{3}k_\perp L_n\right)}{J_{2/3}\left(\frac{2}{3}k_\perp L_n\right) - J_{-2/3}\left(\frac{2}{3}k_\perp L_n\right)} \cong -iB(k_\perp/k_0)^{1/3}$$

$$Y(k_\parallel) = e^{-2k_\perp x_p}\frac{1-Z}{1+Z} \qquad for \;\; k_\parallel^2 > k_0^2$$

$$where\;,\;\; Z = \frac{I_{1/3}\left(\frac{2}{3}k_\perp L_n\right) - e^{-\pi i/3}I_{-1/3}\left(\frac{2}{3}k_\perp L_n\right)}{I_{2/3}\left(\frac{2}{3}k_\perp L_n\right) - e^{-\pi i/3}I_{+2/3}\left(\frac{2}{3}k_\perp L_n\right)} \cong e^{-\pi i/3}B(k_\perp/k_0)^{1/3}$$

$$B = \frac{\Gamma(4/3)}{\Gamma(2/3)}(9k_0 L_n)^{1/3}, \qquad L_n = \left(\frac{1}{n_c}\left(\frac{dn}{dx}\right)_{x=x_p}\right)^{-1}$$

$$n_c = 3.14\times 10^{-10}\,\omega^2 = 3.099\times 10^{11}\,cm^{-3}$$

Reflection coefficient $R = |\Gamma|^2$ with

$$\Gamma = \frac{1 - Z_1/Z_0}{1 + Z_1/Z_0}, \;\; where$$

$$Z_1 = -iN_\perp Z_0\frac{\sinh\; k_\perp x_p + Z\cosh\; k_\perp x_p}{\cosh\; k_\perp x_p + Z\sinh\; k_\perp x_p}$$

$$N_\perp = k_\perp/k_0, \qquad Z_0 = 120\,\pi$$

$$Z = i\frac{J_{1/3}\left(\frac{2}{3}k_\perp L_n\right) + J_{-1/3}\left(\frac{2}{3}k_\perp L_n\right)}{J_{2/3}\left(\frac{2}{3}k_\perp L_n\right) - J_{-2/3}\left(\frac{2}{3}k_\perp L_n\right)}$$

$$\cong -iB\,(k_\perp/k_0)^{1/3}$$

Brambilla code simulation

Wave Impedance

Cold Plasma Approximation

$$\begin{pmatrix} S-n_{\parallel}^2 & iD & n_{\perp}n_{\parallel} \\ iD & S-n^2 & 0 \\ n_{\perp}n_{\parallel} & 0 & P-n_{\perp}^2 \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0.$$

$$D(n,\omega) = An_{\perp}^4 + Bn_{\perp}^2 + C = 0.$$

$$A = S$$

$$B = (n_{\parallel}^2 - S)(S+P) + D^2$$

$$C = P\left[(n_{\parallel}^2 - S)^2 - D^2\right]$$

$$n_{\perp}^2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

Wave Impedance

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$k \times E = \omega B \ \ or \ \ n \times E = cB$$

$$E_x, E_z >> E_y \ \ and \ \ n_y \approx 0$$

$$B_x \approx 0$$

$$B_y = (n_{\parallel}E_x - n_{\perp}E_z)/c$$

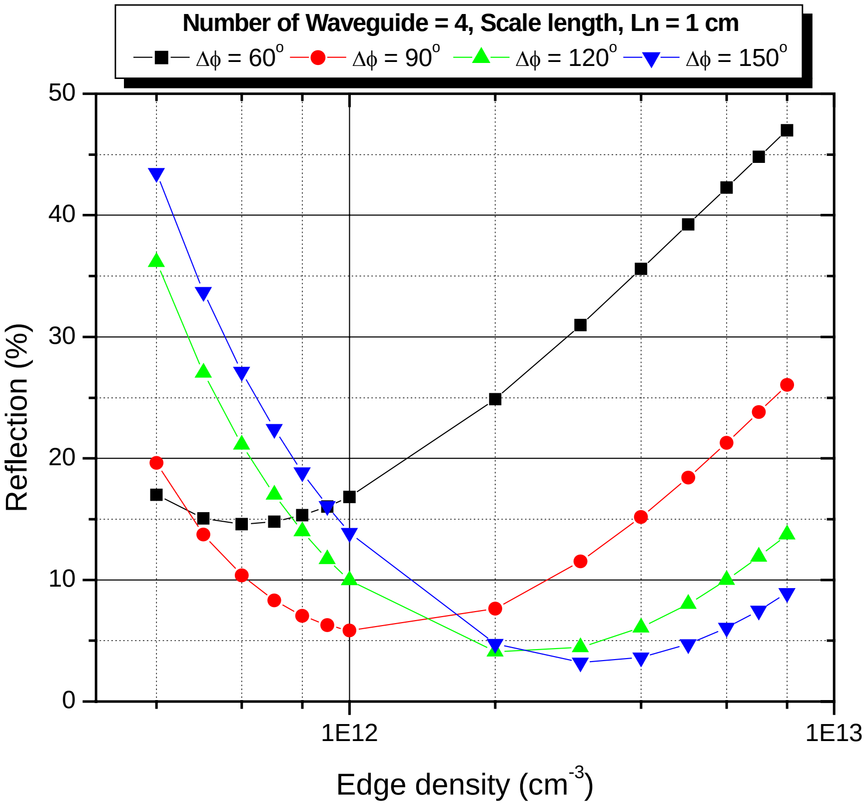
$$B_z \approx 0$$

$$Z_x = \frac{E_z}{H_y} = \frac{\mu E_z}{B_y} = \frac{\mu c E_z}{n_{\parallel}E_x - n_{\perp}E_z} = \frac{\mu c n_{\perp}}{P}$$

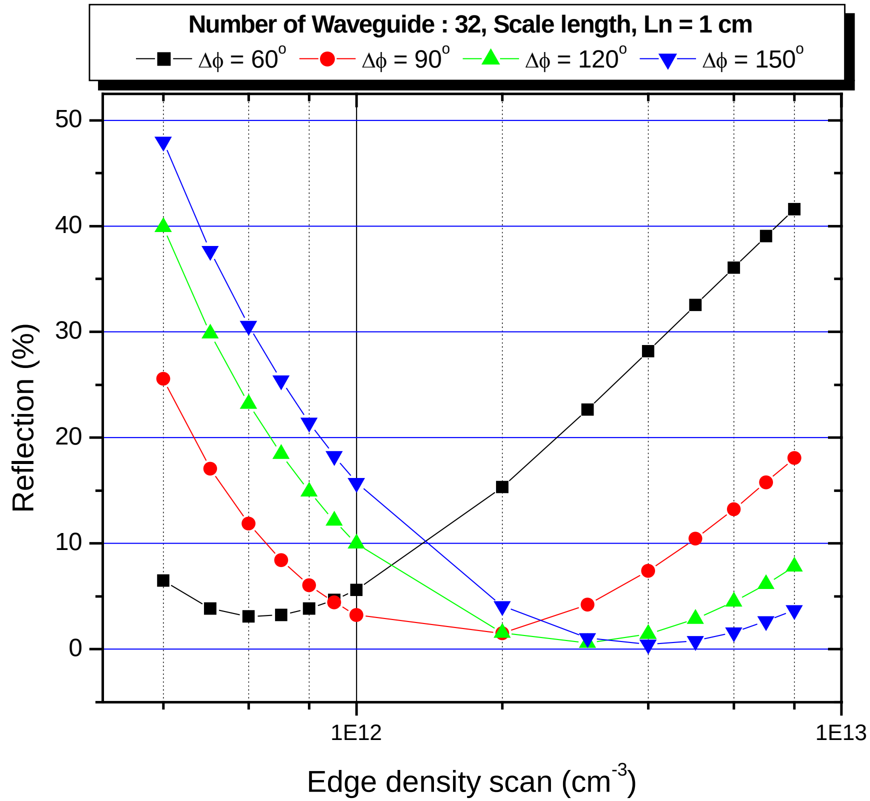
$$Z_z = -\frac{E_x}{H_y} = -\frac{\mu E_x}{B_y} = -\frac{\mu c E_x}{n_{\parallel}E_x - n_{\perp}E_z} = \frac{\mu c(P - n_{\perp}^2)}{P n_{\parallel}}$$

Average reflections for different edge densities.

Brambilla code simulation



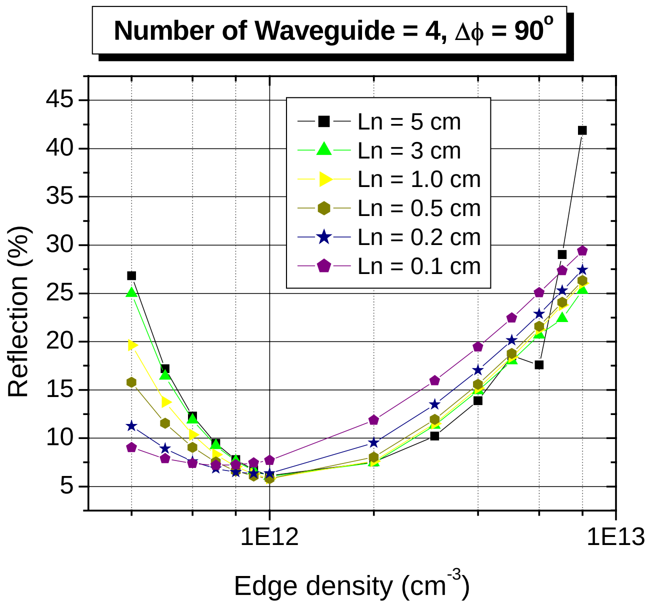
4-waveguide coupler

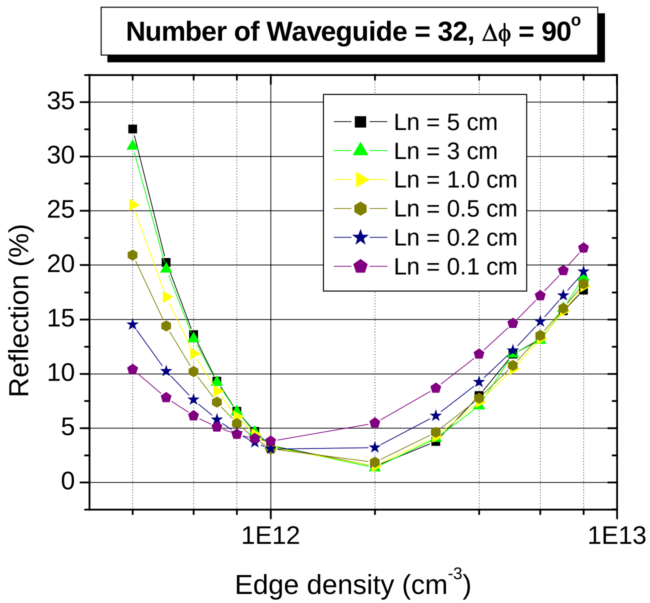


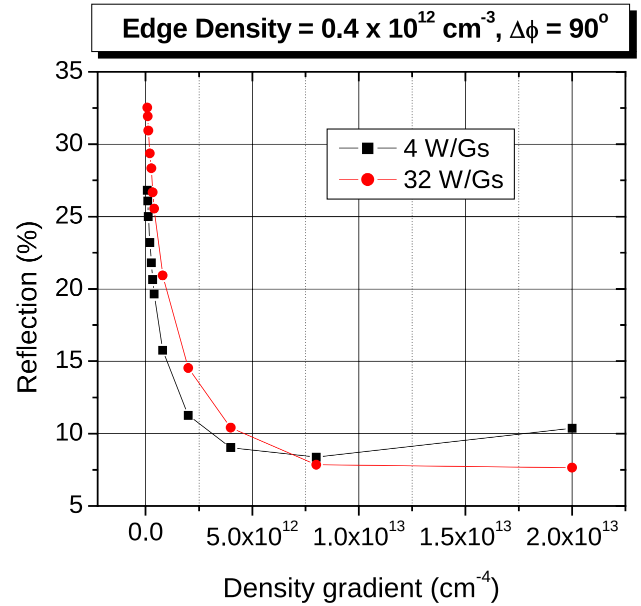
32-waveguide coupler

Brambilla code simulation

Average reflections for different linear density graidents





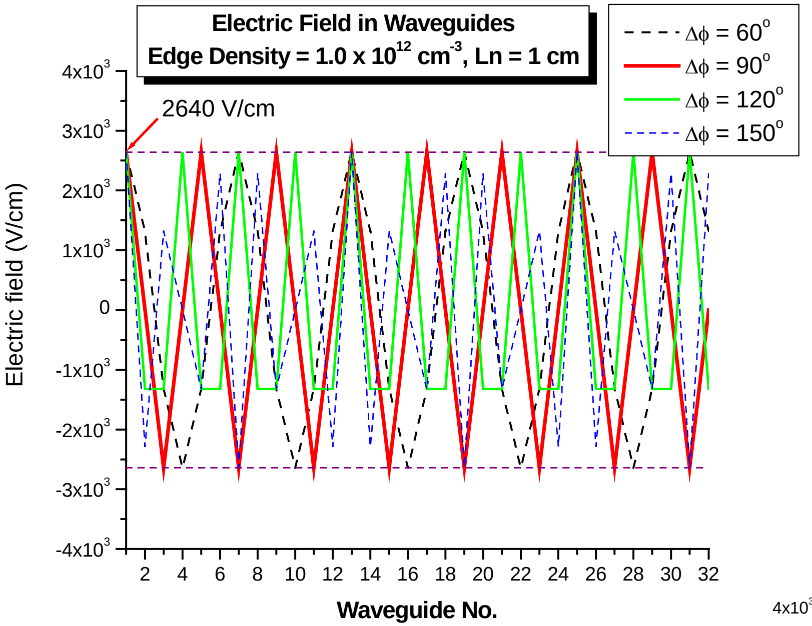


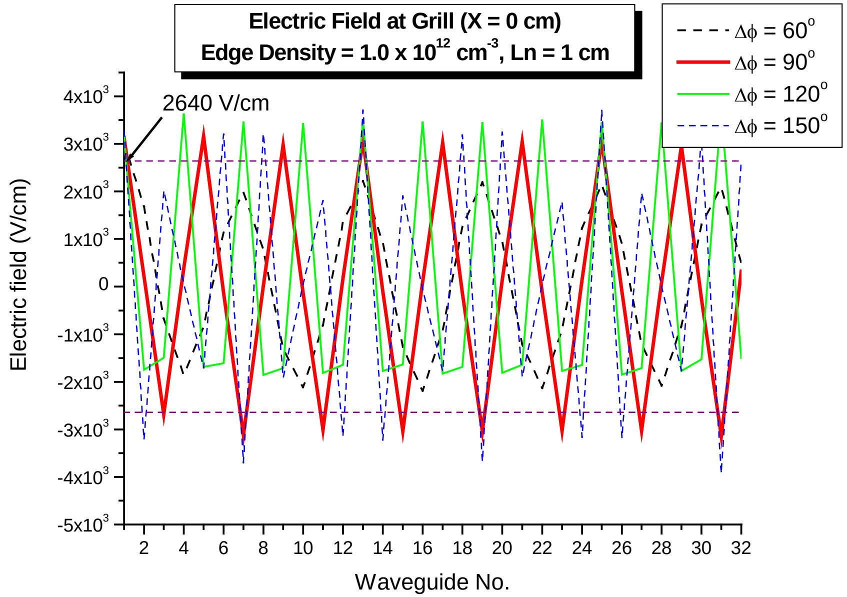
4-waveguide coupler

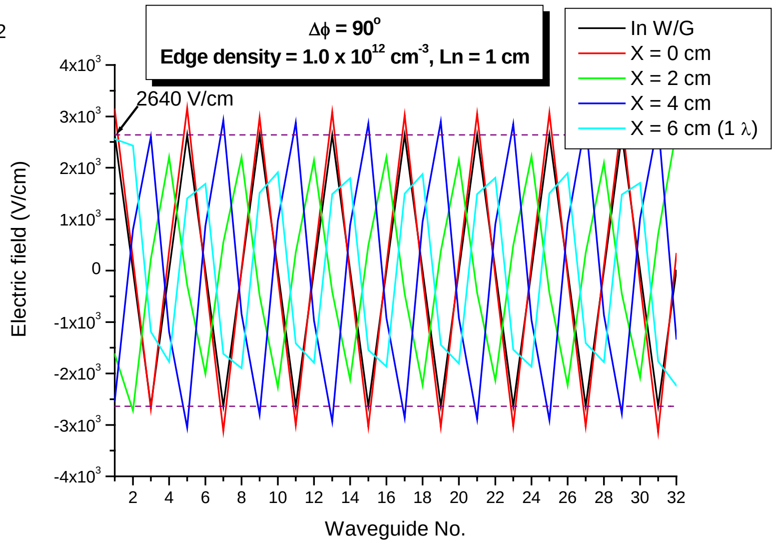
32-waveguide coupler

Brambilla code simulation

Electric fields for 32-waveguide coupler

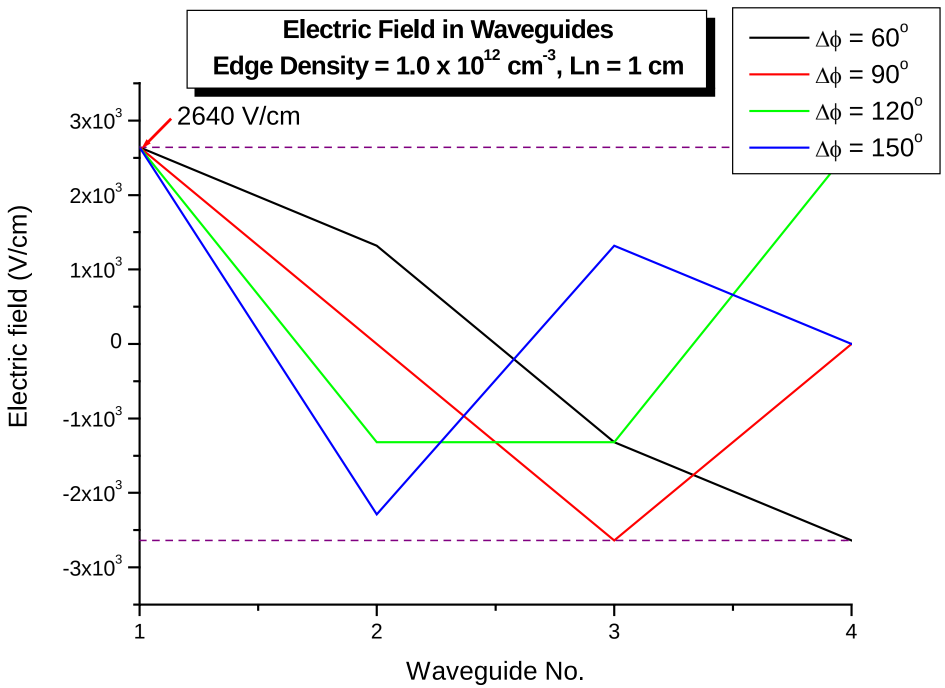


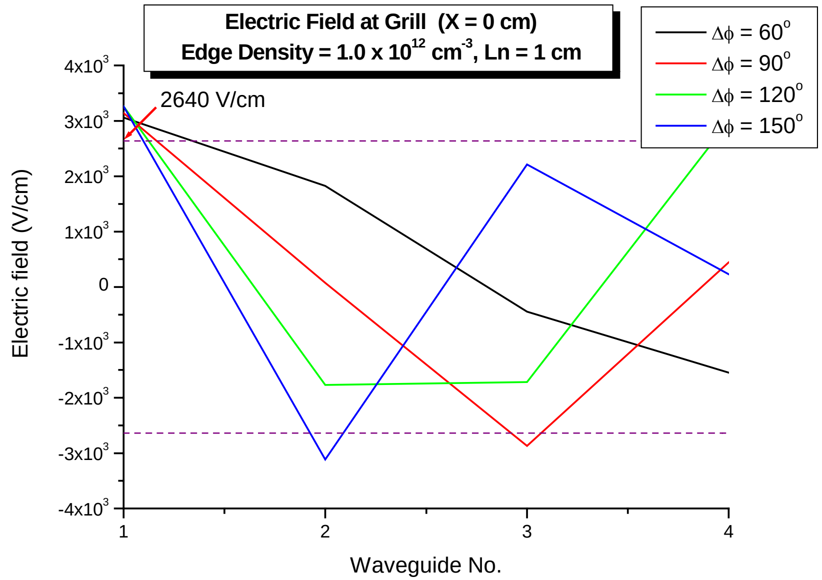


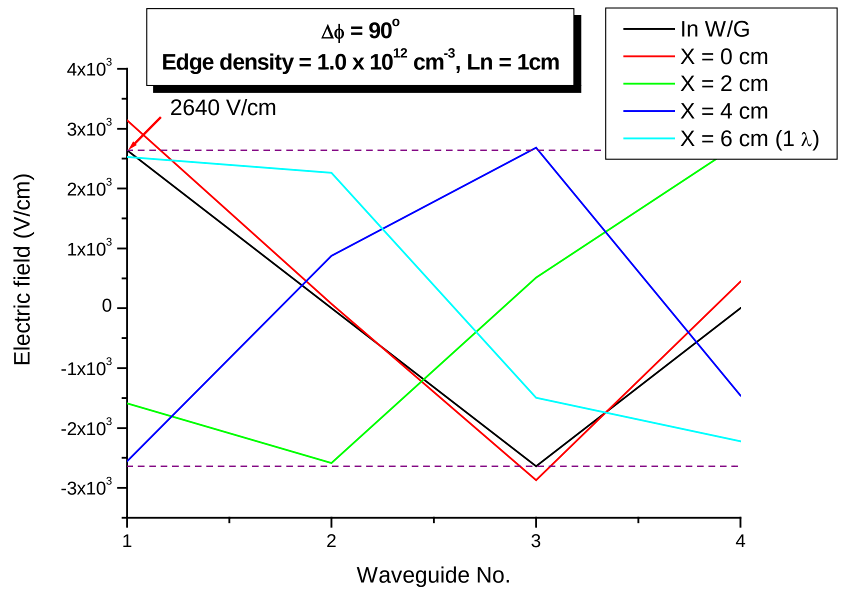


Brambilla code simulation

Electric fields for 4-waveguide coupler

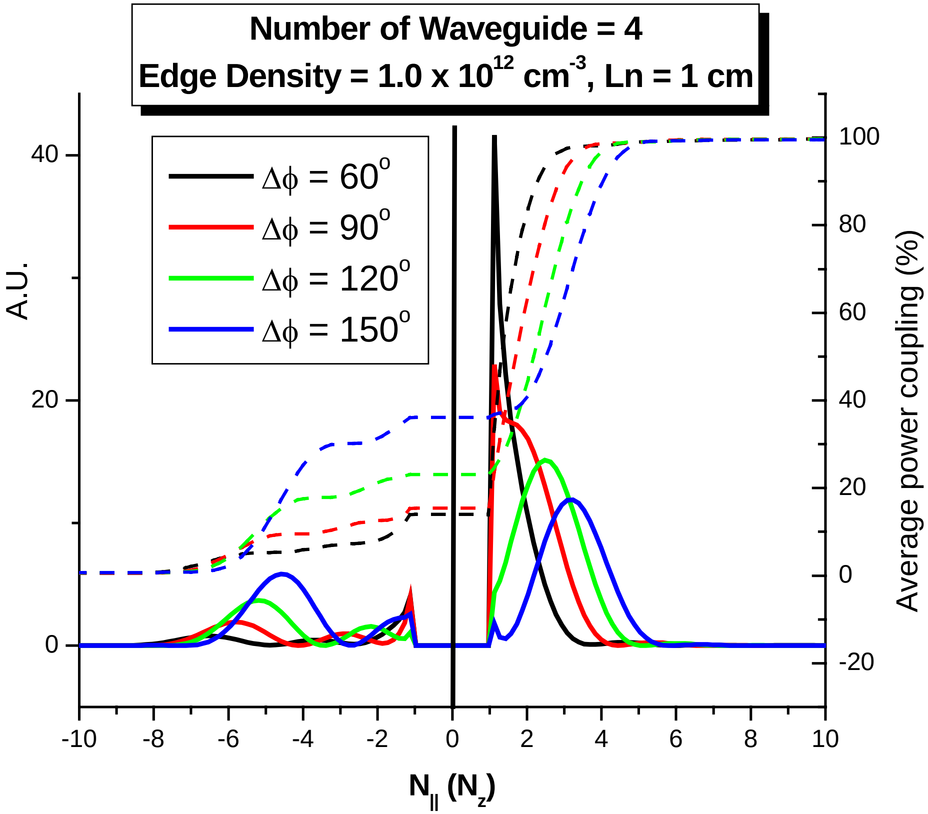




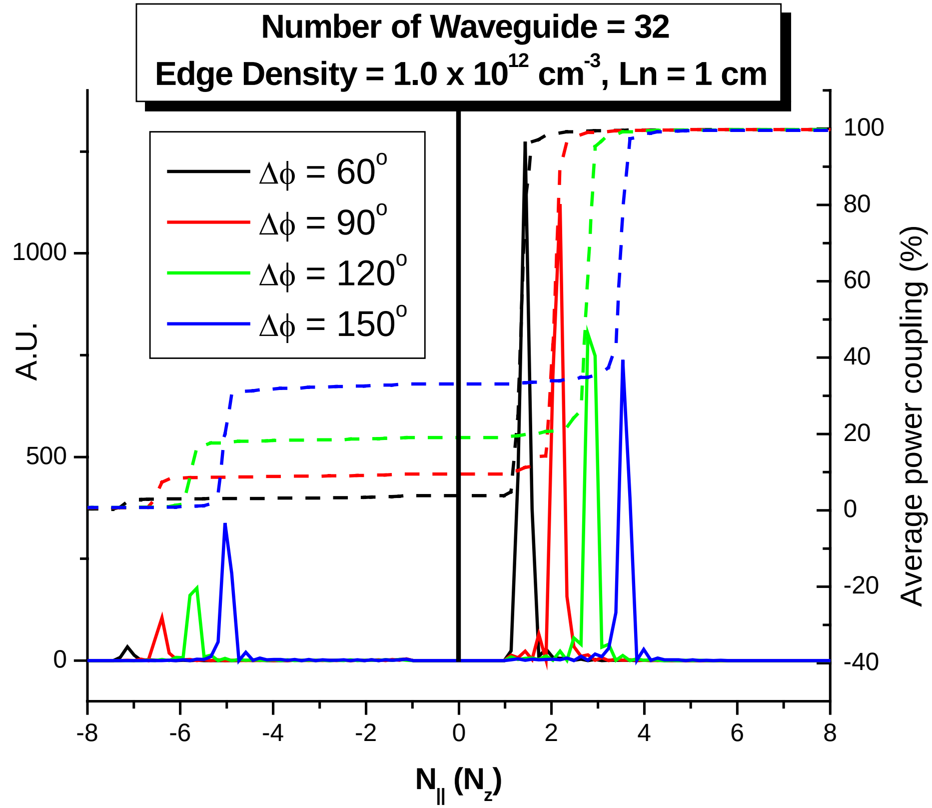


Brambilla code simulation

Power Spectrums



4-waveguide coupler

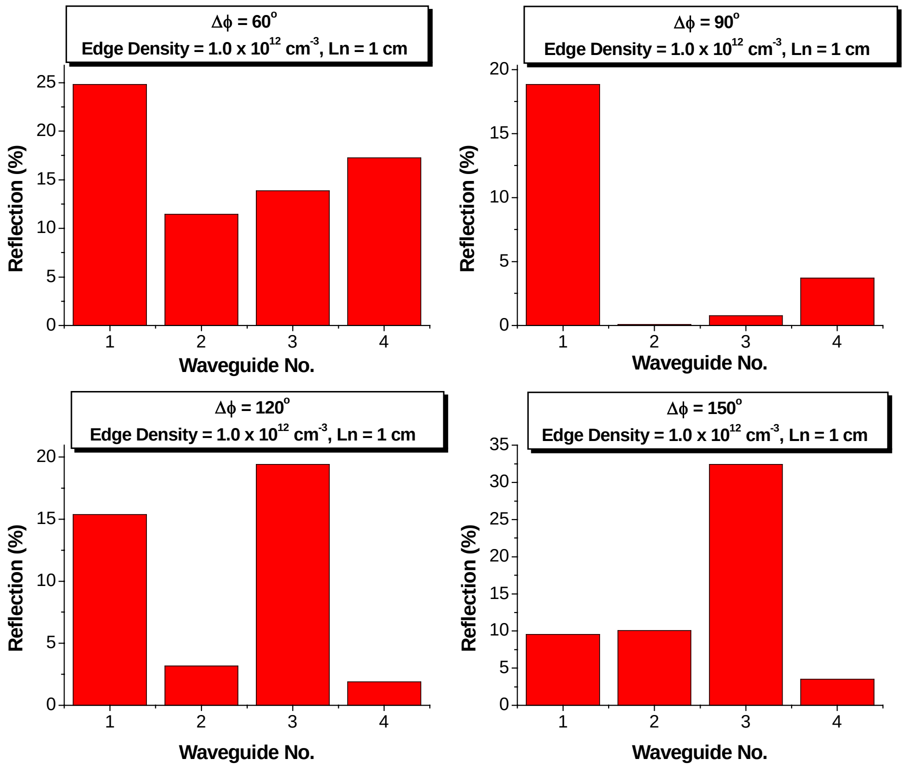


32-waveguide coupler

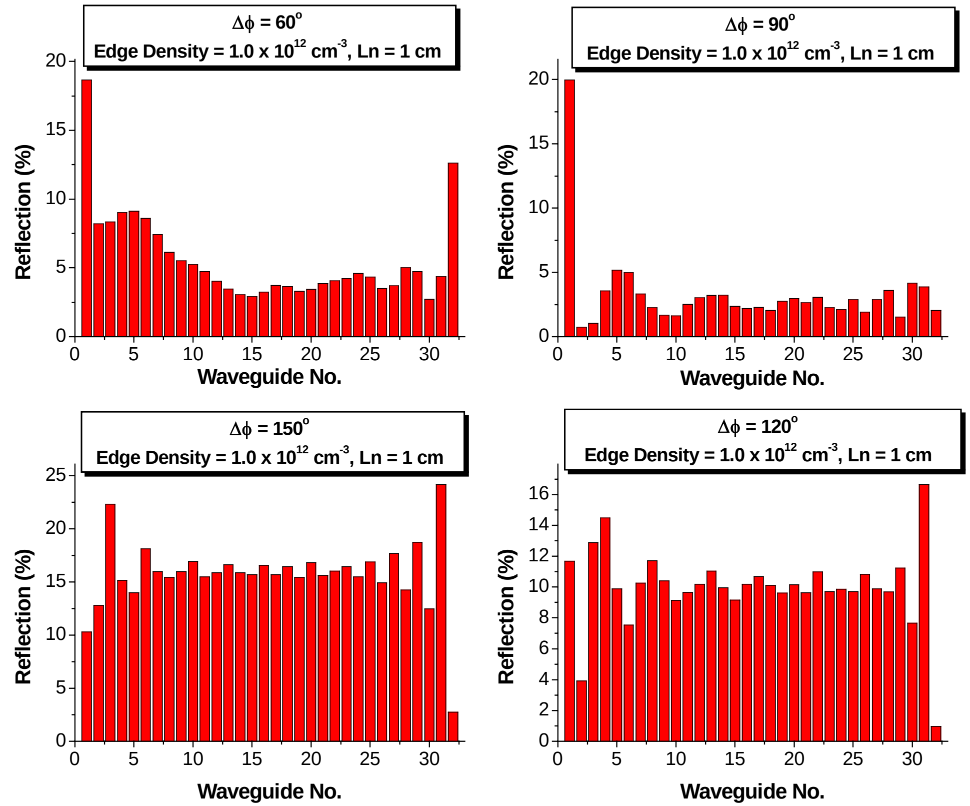
Power spectrum, $P(k_{\parallel}) = \sin c^2(k_{\parallel} b/2) \cdot \dfrac{\sin^2(N(\Delta\phi + k_{\parallel} a + k_{\parallel} b)/2)}{\sin^2((\Delta\phi + k_{\parallel} a + k_{\parallel} b)/2)}$ **with spectrum width** $W_{ml} = \dfrac{c}{\pi(a+b) f N}$

Brambilla code simulation

Reflections in each waveguides



4-waveguide coupler



32-waveguide coupler

Introduction and Modeling

XOOPIC

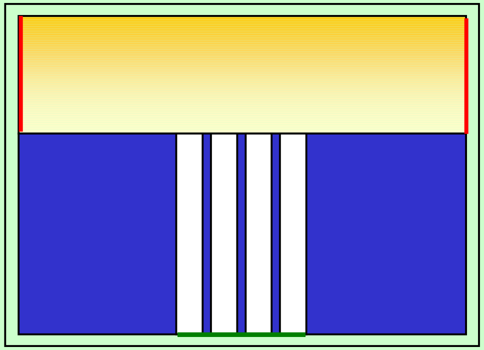
- Object-oriented 2d3v particle-in-cell code written at UC Berkeley.
  [J.P. Verboncouer, et al., Comput. Phys. Commun. 87 (1995) 199]
- Two spatial and three velocity dimensions.
- Electromagnetic and electrostatic fields.
- Relativistic and non-relativistic particles.
- Cylindrical and Cartesian geometry with orthogonal non-uniform mesh.
- Boundary conditions include e.g.
  - Free space boundaries
  - Conductors
  - Dielectrics
  - Emitting surfaces

Particle loading and Grid

- Uniform grid:
  - dz (toroidal) = dx (poloidal) = 0.2 mm
- The ratio of number of physical particles to simulation particles, *np2c* is set to 10^{-8} times as the plasma density, n, that is, *np2c* = 10^{-8} n.
- This set the number of simulation particle per cell to 4

KSTAR Model

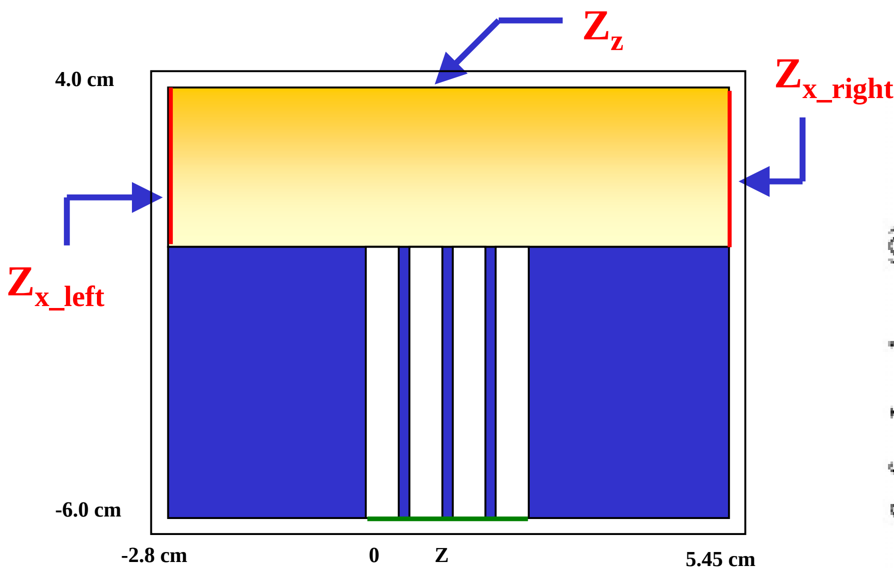
- Lower hybrid grill in KSTAR is approximated with a 2d slab geometry.
- The magnetic field points along toroidal axis.
- The poloidal direction is assumed homogeneous.
- In the figure, red boundaries are free space boundaries with a thermal particle current into the plasma to compensate the particle losses. Blue areas are ideal conductors and the green surfaces excite the lower hybrid wave. The plasma is in the orange area.

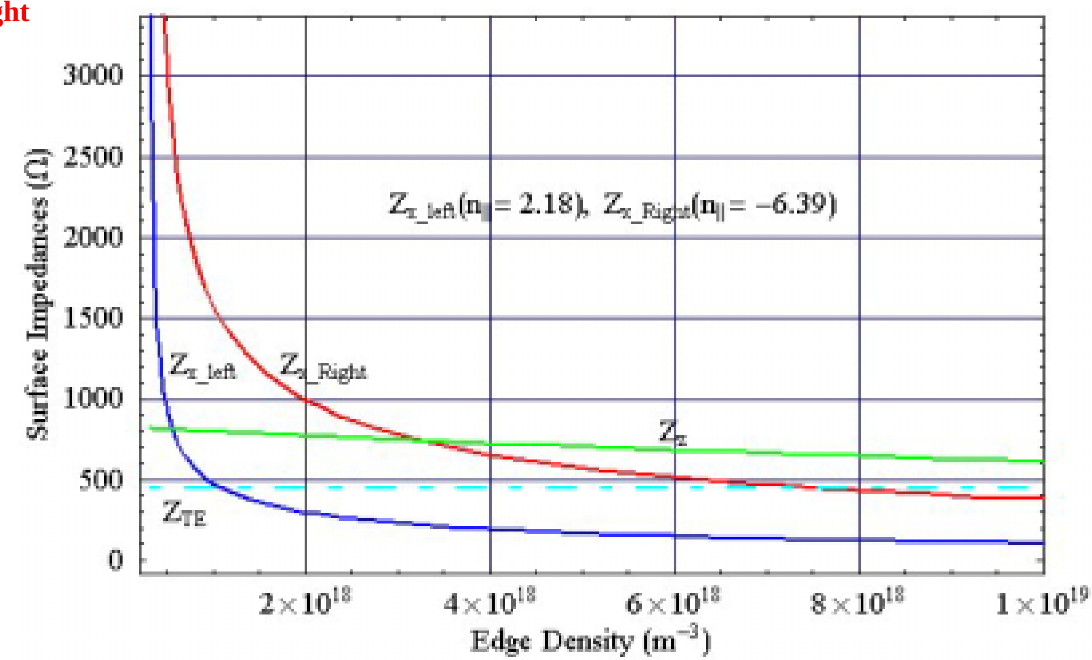


Edge temperature	T	[keV]	1
Magnetic field (at grill)	B	[T]	2.74
Frequency of the grill	f	[GHz]	5.0
Phase difference	$\Delta\phi$	[rad]	$\pi/2$
Radial length of plasma	L_x	[cm]	4
Toroidal width of plasma	L_z	[cm]	8.25
Width of a waveguide	L_{wg}	[mm]	5.5
Width of a septum	L_s	[mm]	1.5
Length of a waveguide	L	[cm]	6.0

XOOPIC simulation

Surface Impedance





$$Z_x = \frac{E_z}{H_y} = \frac{\mu E_z}{B_y} = \frac{\mu c E_z}{n_\parallel E_x - n_\perp E_z} = \frac{\mu c n_\perp}{P}$$

$$Z_z = -\frac{E_x}{H_y} = -\frac{\mu E_x}{B_y} = -\frac{\mu c E_x}{n_\parallel E_x - n_\perp E_z} = \frac{\mu c (P - n_\perp^2)}{P n_\parallel}$$

Surface impedance is calculated from the wave impedance for the homogenious plasma.

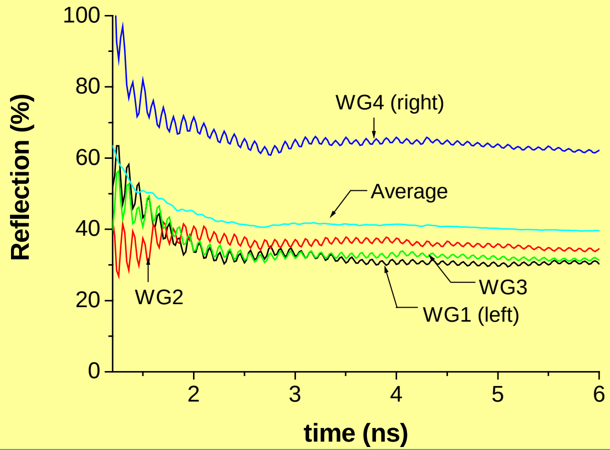
XOOPIC simulation

Reflection for Different Edge Densities

- **The reflection coefficient of the power R is determined from the radial Poynting flux.**
- **Radial Poynting flux P_x is measured near the bottom of the waveguides.**
- **For an input power P_{in} the reflection coefficient reads as**

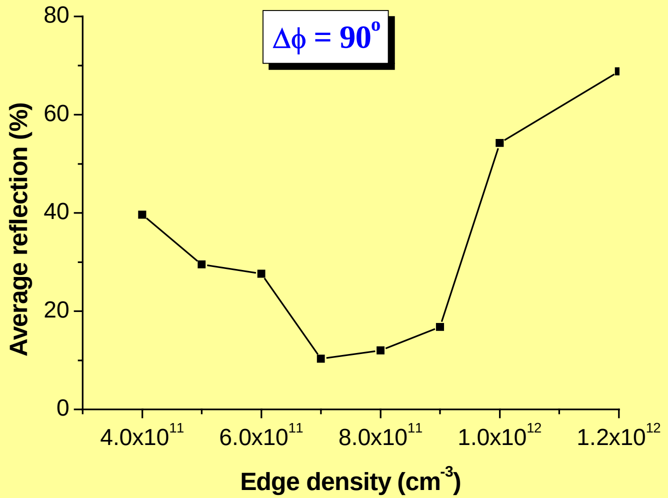
$$R = \frac{P_{in} - P_x}{P_{in}}$$

- **Figure shows the reflection coefficient for each waveguide for homogeneous plasma at the edge density $n=4x10^{17}$ m^{-3}.**
- **The reflection coefficients are averaged over two wave periods to remove the oscillation.**
- **After the initial transition the average reflection coefficient stabilises at about 3 ns.**

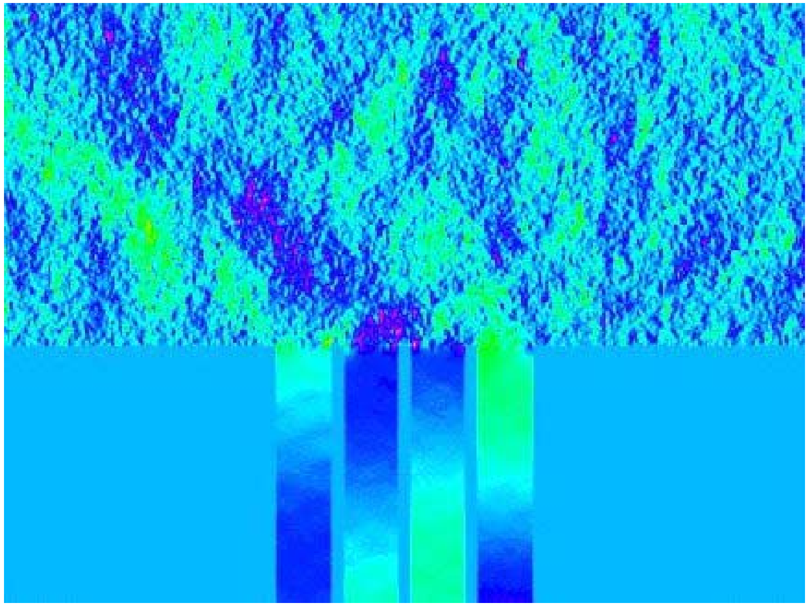


Homogeneous Density Profile

- The reflection coefficients, averaged over the waveguides, for different edge densities are plotted in the figure.
- Cut-off density $n_c=3.1x10^{17}$ m^{-3}, below which the wave does not propagate in the plasma, is marked with a dotted red line.
- The coupling of the power is seen to have a clear maximum near the density $n=7x10^{17}$ m^{-3}
- For the four waveguide launcher the average reflection at the optimum density is under 10 %.



Wave Propagation and Electric Fields

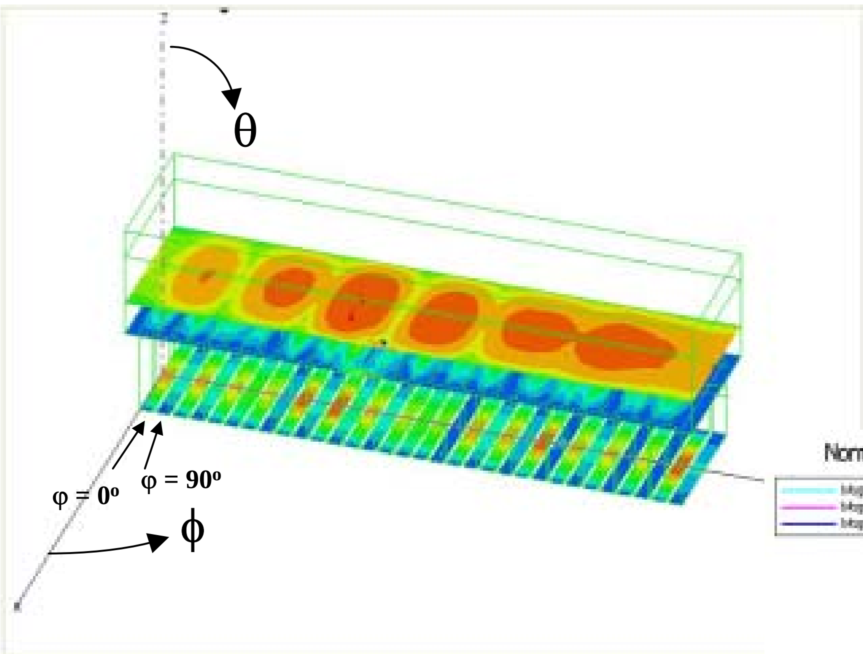


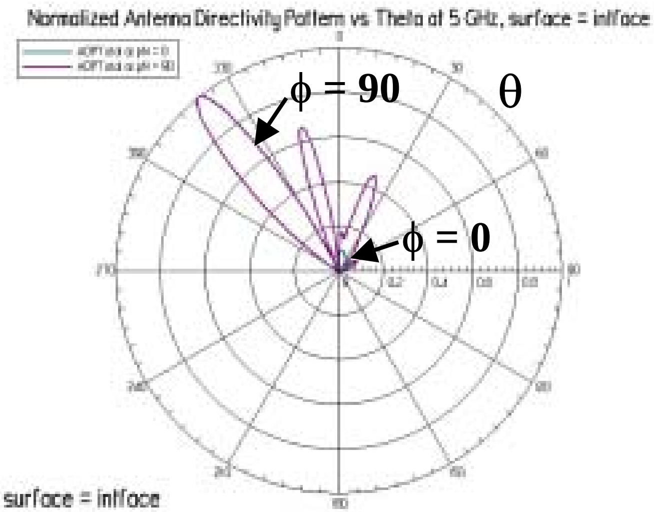
Propagation of the Wave

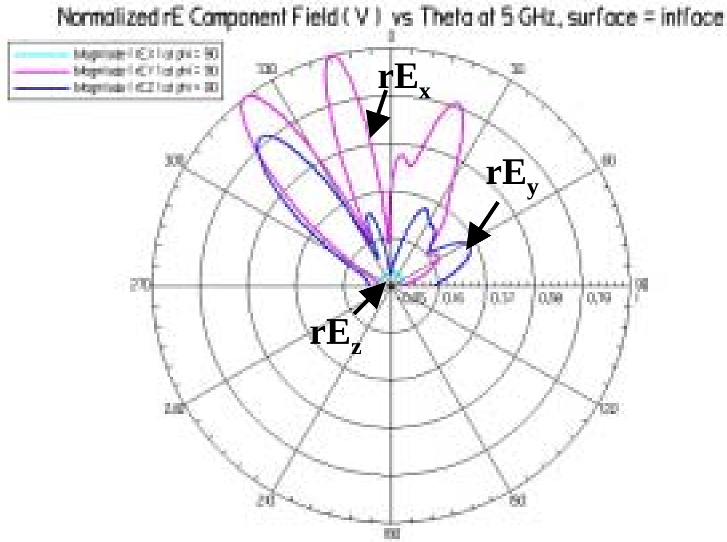
- **Noise is always present in PIC simulation. It is especially problematic if the field amplitudes are small.**
- **In the figure the toroidal electric field E_z is plotted.**
- **The first mode with parallel refractive index $n_{||} = 2.18$ propagates to the left and the second mode with $n_{||} = -6.39$ propagates to the right.**
- **Plasma edge density is $n_0 = 7 \times 10^{17}\ m^{-3}$ and the uniform density profile (homogenious plasma).**
- **The phase difference, $\Delta\varphi = \pi/2$, between the waveguides can be seen inside the waveguides.**

HFSS simulation

- Radiation into vacuum with vacuum impedance, Z = 377 Ω.
- Phase difference between waveguides, $\Delta\varphi$ = 90 deg.







Conclusion

- Brambilla code simulation
  - The reflection of the lower hybrid wave with homogeneous plasma is seen to have a minimum near the density $n = 1 \times 10^{12}$ cm^{-3} ($n = 2 \times 10^{12}$ cm^{-3}) for 4-waveguide coupler (for 32-waveguide coupler).
  - The reflection reduces by a factor of two (three) when a density gradient $n' = 8 \times 10^{12}$ m^{-4} is applied to the edge density $n = 4 \times 10^{11}$ cm^{-3} for 4-waveguide coupler (for 32-waveguide coupler).
  - The reflection rapidly increases as the cut-off density $n_c = 3.1 \times 10^{17}$ m^{-3} is approached.
- XOOPIC simulation
  - The reflection of the lower hybrid wave with homogeneous plasma is seen to have a minimum near the density $n = 7 \times 10^{17}$ m^{-3} for 4-waveguide coupler.
  - The reflection rapidly also increases as the cut-off density $n_c = 3.1 \times 10^{17}$ m^{-3} is approached.
  - In the future, the density gradient scan for the edge density near and below the cut-off density are planned.
- HFSS simulation
  - The radiation directivity has the peak value at the left theta angle, 40 deg for the phase difference of 90 deg between waveguides.
  - The parallel component of the electric field to the waveguide column has the same directivity pattern as that of the radiation.

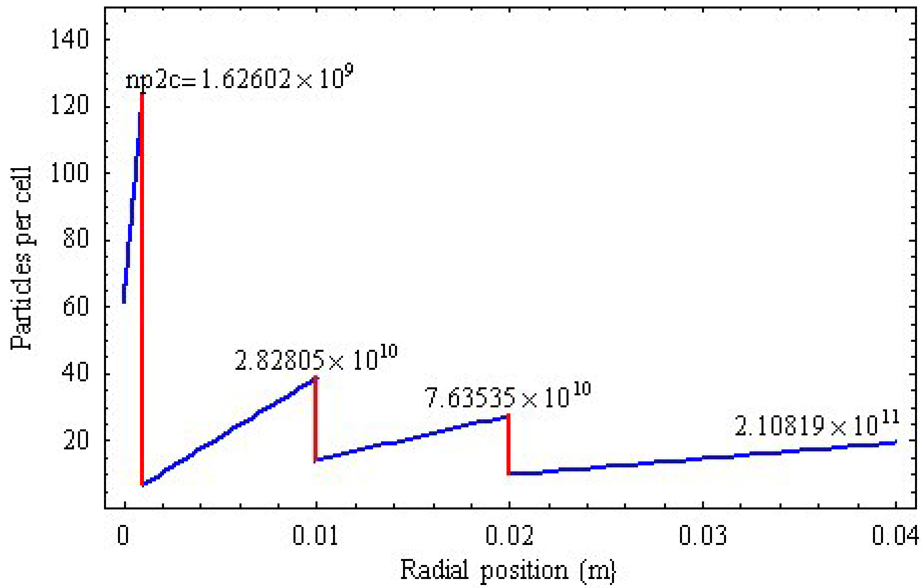
XOOPIC simulation

Particle Loading for 32 waveguides and density gradient scan

Optimum grid spacing

- **Grid spacing in toroidal direction**
  - dz (toroidal) = 0.5 mm
- **Grid spacing in poloidal region**
  - dx = step(12-k)dxwg+(A-B Ln(k))step(22-k)step(k-12)+step(k-22)dxp
  - dxwg=λ/15, A = 1.7807e-3, B=4.5209e-4, dxp = 0.2 mm
  - Plasma area : A = Lz $\times$ Lx
- **Uniform density (Homogenious plasma density)**
  - Number of particles per cell: Npc
  - Total mumber of cells: Nc = A/(dz $\times$ dx)
  - Number of simulation particle: Ns = Npc $\times$ Nc
  - Number of total number density: Nt = n $\times$ A
  - Number of physical particle to simulation particle: np2c = Nt/Ns
- **Density gradient (Ln = n/n', where n is the edge density)**
  - Four different regions: x(i), i = 1,…4 (region boundary index)
  - Number density: n(i) = n (1 + x(i)/Ln)
  - Area for each region: A(i) = Lz $\times$ (x(i) – x(i-1))
  - Number of cells: Nc(i) = A(i)/(dz $\times$ dx)
  - Number of simulation particle: Ns (i) = Npc(i) $\times$ Nc(i)
  - Number of total number density: Nt(i) = n(i) $\times$ A(i)
  - Npc(1) = Npc0 (1 + x(4)/Ln), Npc(i) = Npc(1) $(x(1)/x(i))^{1/2}$
  - Number of physical particle to simulation particle: np2c(i) = Nt(i)/Ns(i)

- Large CPU time for 32 waveguides and the density gradient for the edge density near and below the cut-off density.
- Parallel version of XOOPIC would allow these simulations to be made in a reasonable time using a real size, 32 waveguide grill.



x(1) = 0.001 m, x(2) = 0.01 m, x(3) = 0.2 m, x(4) = 0.04 m
n = 1.0 $\times$ 10^{18} m^{-3}, ∇n = 1.0 $\times$ 10^{20} m^{-4},Npc0 = 3