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Analysis of Surface Wave Excitation and Plasma Production by Slot Antenna

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- Motivation
- 3D Electromagnetic Wave Code: PAF/WF
- Excitation of Axisymmetric Surface Wave:
  (Comparison of 2D and 3D Analyses)
- Summary

Integrated Plasma Analysis Code

- **Self-Consistent Analysis of RF Plasma Production**
  - **Arbitrary Device Configuration**
  - **Realistic RF Excitation**
  - **Fluid-Particle Hybrid Model**
  - **Fast Computation**
- **PAF**: Plasma Analysis with **Finite element method**
  - **WF**: Wave field solver (3D): **this presentation**
  - MF: Time dependent Maxwell equation solver [Plan]
  - **TF**: Diffusive transport model (2D)
  - FF: Dynamic fluid model [Plan]
  - **PF**: Particle-in-(triangle) cell model (2D)
  - **MG**: Mesh generator
  - **MX**: Parallelized matrix solver

XX: under development

PAF/WF: 3D Wave Analysis Code

- **Steady-state electric field**: $\tilde{\boldsymbol{E}}(\boldsymbol{r}, t) = \boldsymbol{E}(\boldsymbol{r})\, \mathrm{e}^{-\mathrm{i}\,\omega t}$
- **Maxwell's equation**:

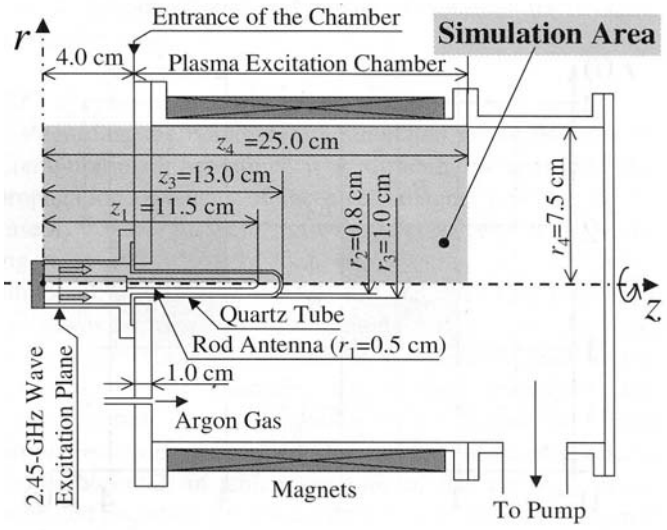
$$\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{E} - \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} = \mathrm{i}\,\omega\mu_0 \boldsymbol{j}_{\mathrm{ext}}$$

  - $\overleftrightarrow{\epsilon}$: Dielectric tensor (Cold plasma including neutral collision)
- **Excitation**:
  - Antenna (Given current profile)
  - Waveguide (Co-axial, circular, rectangular)
  - Electrode
- **Numerical Method**
  - Finite element method with tetrahedron elements
  - Variables: Line integral of $\boldsymbol{E}$ along the ridges of tetrahedrons

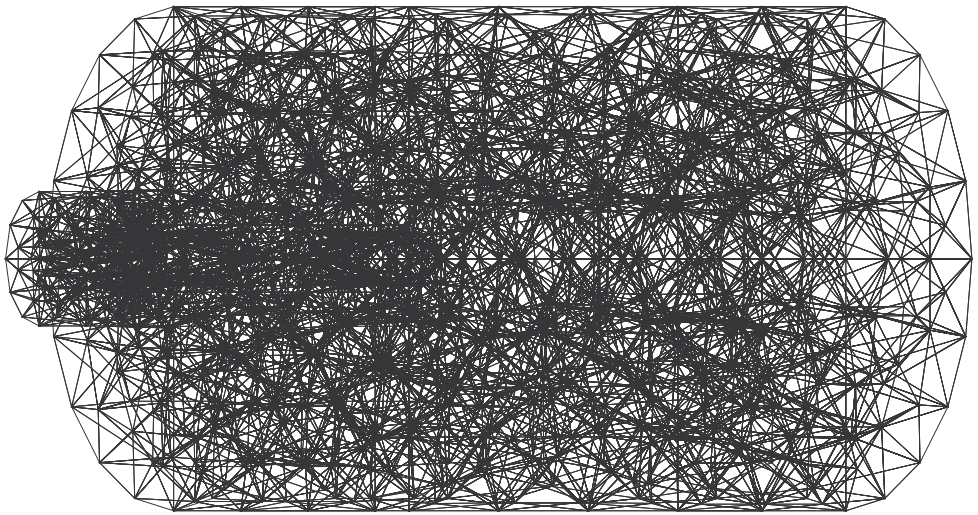
Excitation of Azimuthally Symmetric Surface Wave

- **Numerical Analysis of Azimuthally Symmetric Surface Wave**
  - **H. Kousaka and K. Ono: JJAP 41 (2002) 2199**
  - Electromagnetic Fields in a Microwave Plasma Source
  - **FDTD**: Finite-Difference Time-Domain method
  - Excitation by Coaxial Wave Guide: $f = 2.45\,\mathrm{GHz}$

Configuration

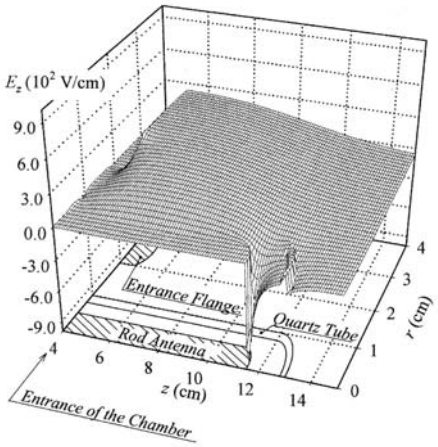


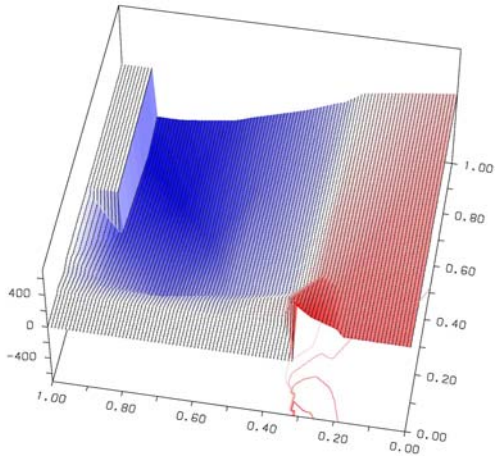
Elements in 3D Analysis

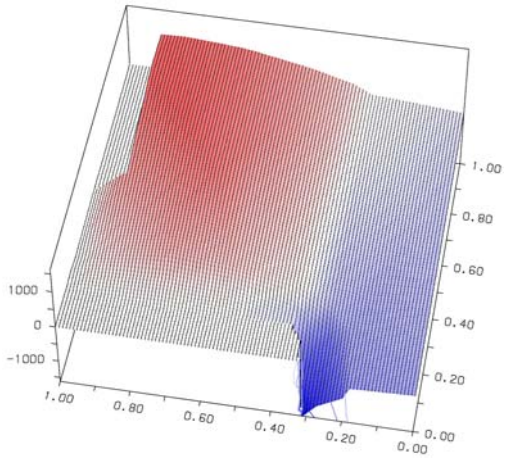


Comparison of 2D and 3D Analyses: $E_z(r, z)$

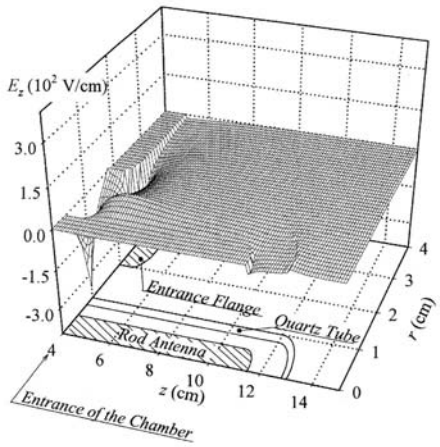
$n_e = 10^{16}\,\mathrm{m}^{-3}$

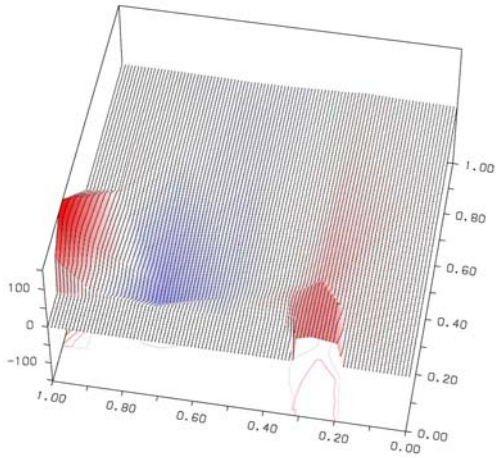


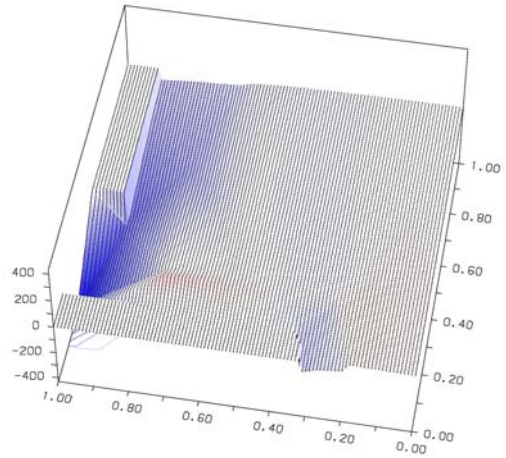




$n_e = 10^{17}\,\mathrm{m}^{-3}$



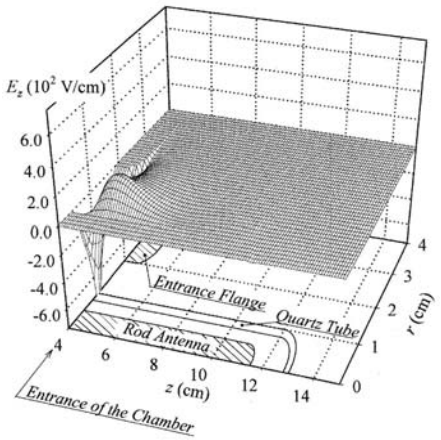


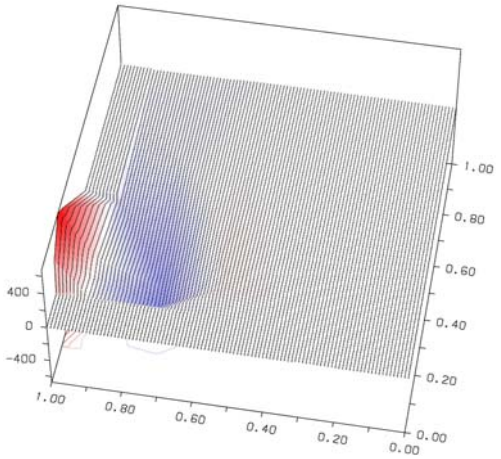


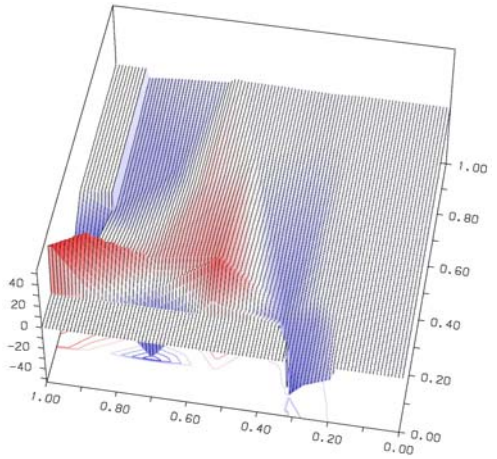
2D 3D (Real part) 3D (Imag part)

Comparison of 2D and 3D Analyses: $E_z(r, z)$

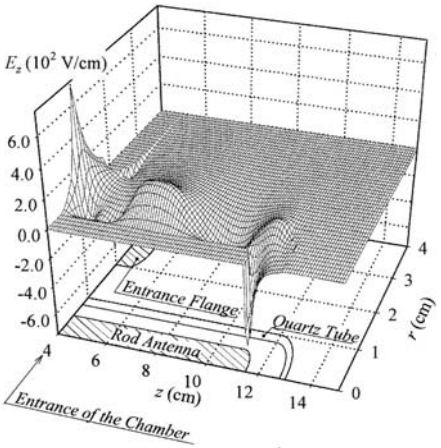
$n_e = 2 \times 10^{17}\ \mathrm{m}^{-3}$

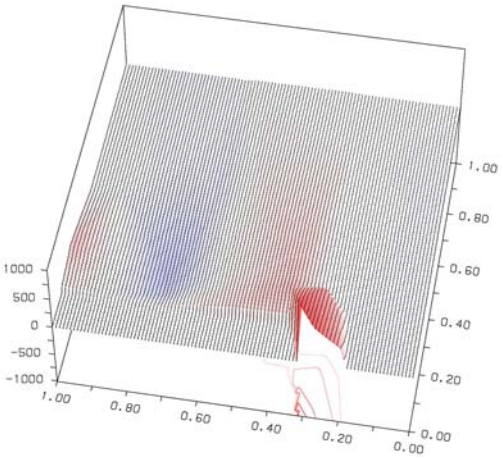


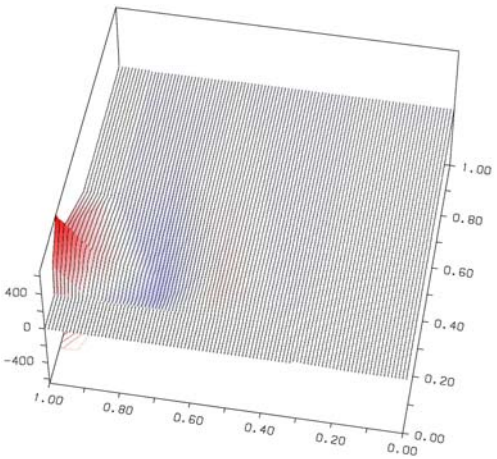




$n_e = 3 \times 10^{17}\ \mathrm{m}^{-3}$







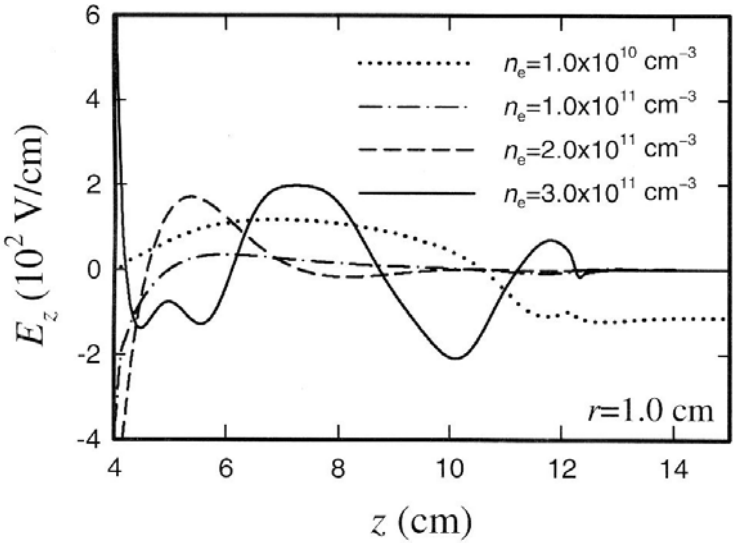
2D 3D (Real part) 3D (Imag part)

Comparison of 2D and 3D Analyses: $E_z(z)$

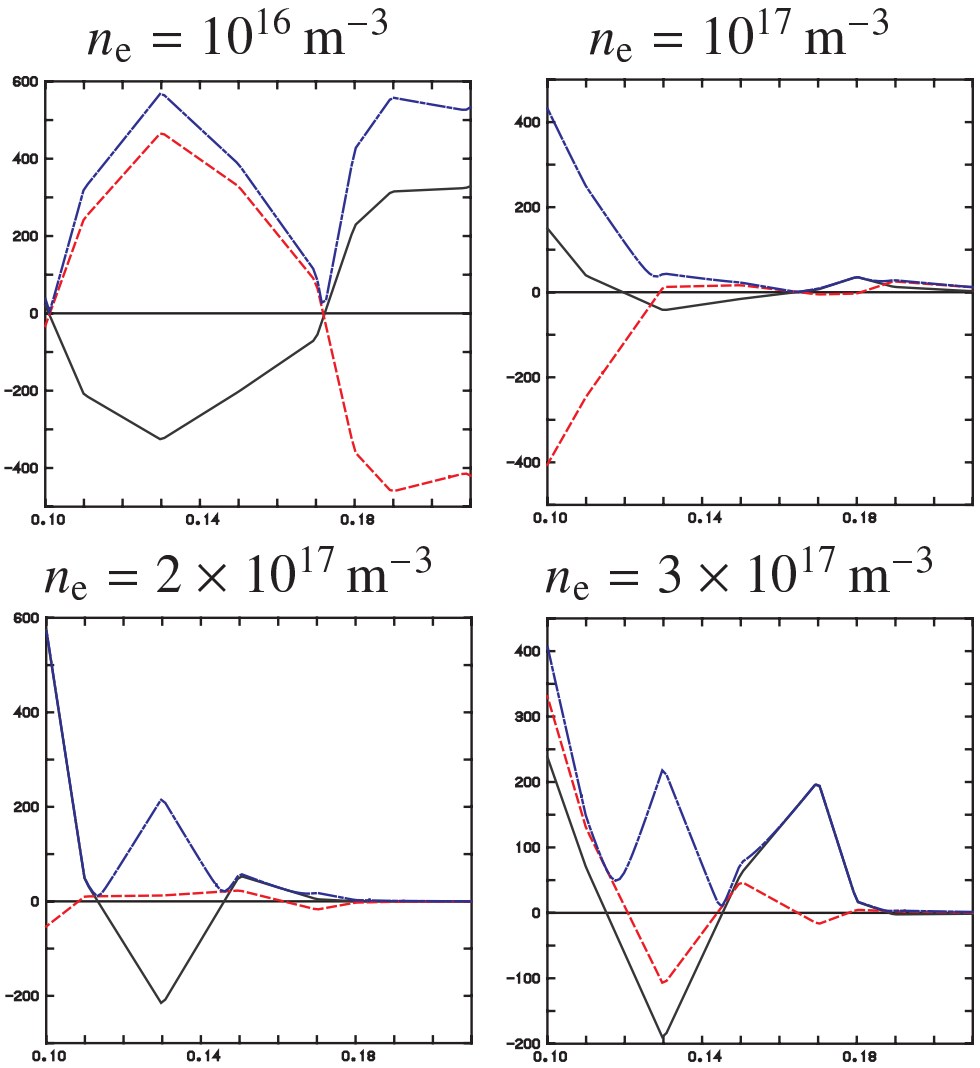
2D Analysis

Ref.: H. Kousaka and K. Ono

JJAP 41 (2002) 2199



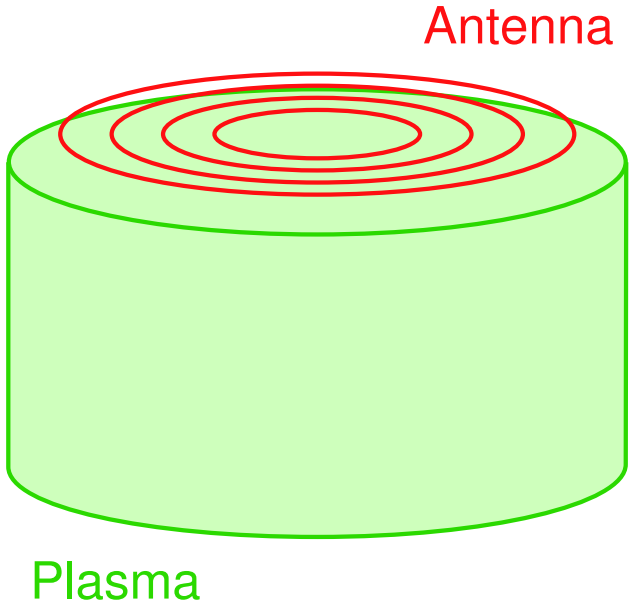
3D Analysis

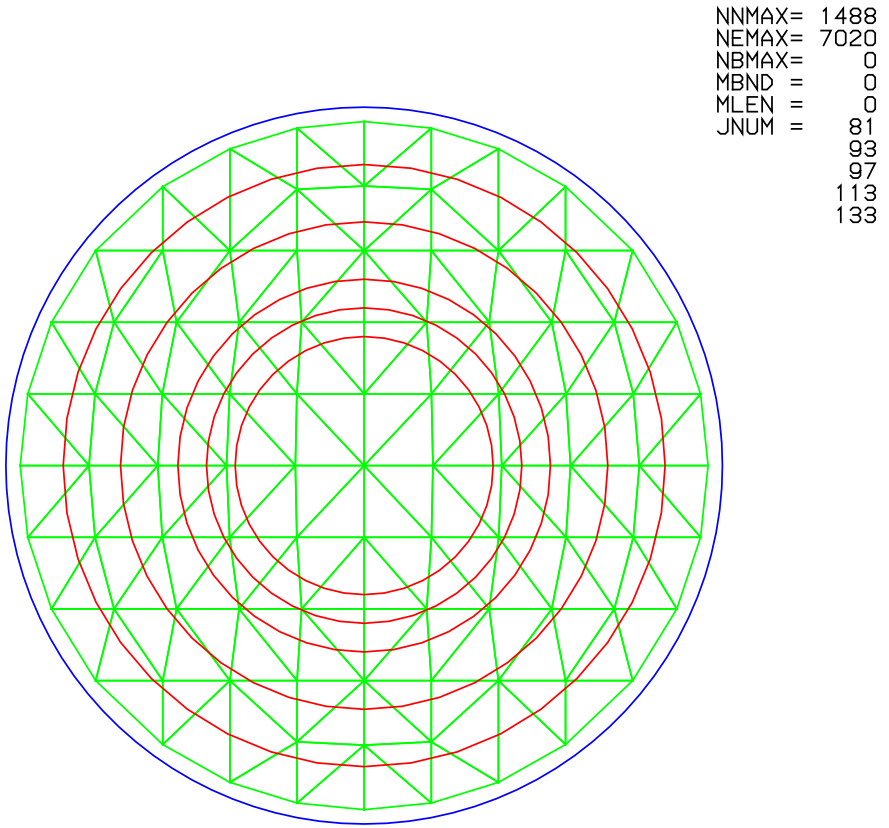


- In the high density case, spatial resolution is not sufficient

Example of ICP by Multi Loop Antenna

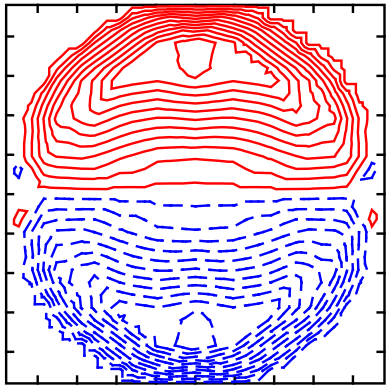
- **Cylindrical plasma**
  - Diameter=0.48 m
  - Height=0.3 m
- **RF**
  - Frequency=13.56 MHz



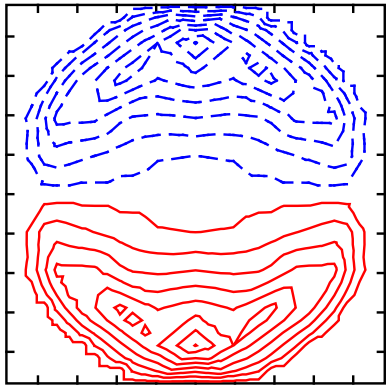


EM Field and P_{abs} at slightly below antenna

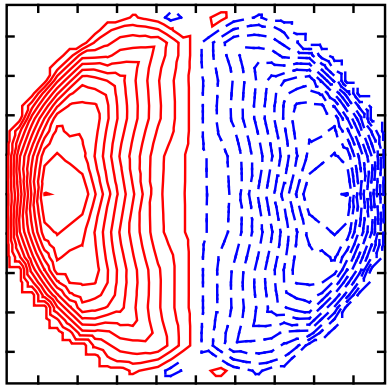
```
RF   = 13.560    BB   =  0.000    M= 2 0 0 2 6 0 IJ  AJ  PHASE       R            X
NNMAX=  1488     XYZ MAX=  0.240  0.240  0.300  1  0.3     0.0  6.839E-03  1.425E+00
NEMAX=  7020     XYZ MIN= -0.240 -0.240  0.000  2  0.3     0.0  1.929E-02  1.756E+00
 NK NM PABS        NK NM PABS                   3  0.3     0.0  2.785E-02  2.433E+00
  1  0  2.90E-01                                4  1.0     0.0  1.333E-01  1.430E+01
 NS     PA       PZ       PN       PZCL     PABS  5  1.0     0.0  1.030E-01  1.365E+01
  1  5.49E-04 -1.   5.00E-03  0.03  2.90E-01
  2  3.99E+01  1.   5.00E-03  0.00  1.33E-07
```



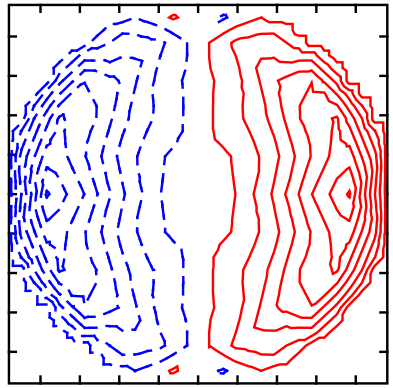
EXR(XY) Z=0.16
MAX= 1.43E-01
MIN=-1.43E-01
STP= 1.25E-02



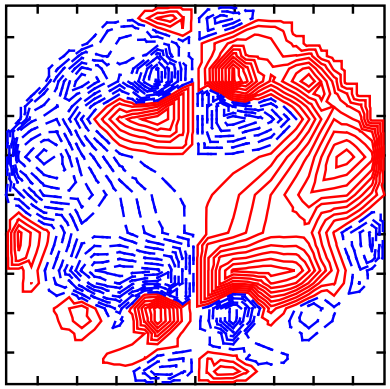
EXI(XY) Z=0.16
MAX= 7.56E+00
MIN=-7.56E+00
STP= 1.00E+00



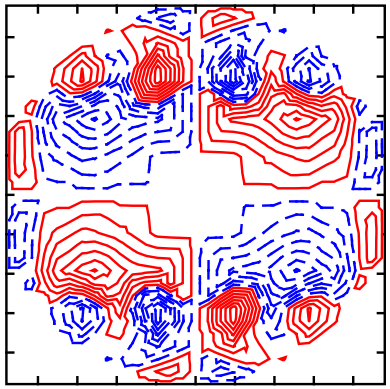
EYR(XY) Z=0.16
MAX= 1.44E-01
MIN=-1.44E-01
STP= 1.25E-02



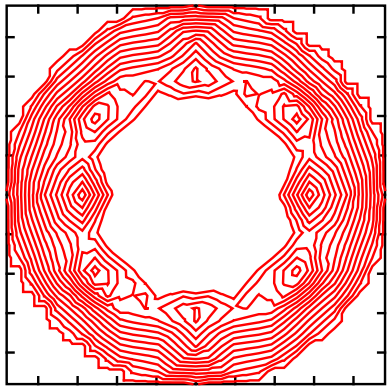
EYI(XY) Z=0.16
MAX= 7.64E+00
MIN=-7.64E+00
STP= 1.00E+00



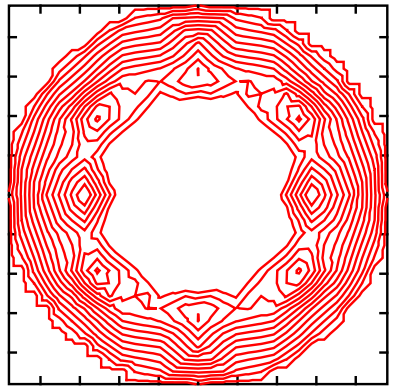
EZR(XY) Z=0.16
MAX= 2.44E-02
MIN=-2.44E-02
STP= 2.50E-03



EZI(XY) Z=0.16
MAX= 1.79E+00
MIN=-1.79E+00
STP= 2.50E-01



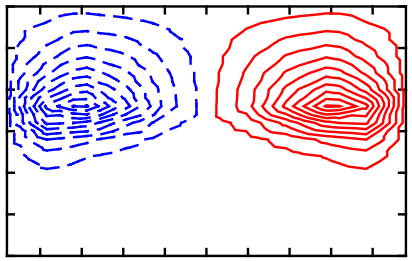
P1C(XY) Z=0.16
MAX= 8.61E+01
MIN= 0.00E+00
STP= 5.00E+00



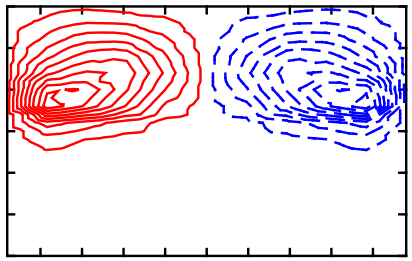
P2C(XY) Z=0.16
MAX= 3.94E-05
MIN= 0.00E+00
STP= 2.50E-06

EM Field and P_{abs} at $x = 0$

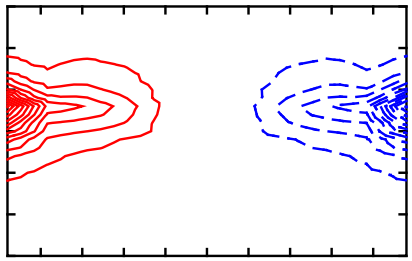
```
RF   = 13.560    BB   =  0.000    M= 2 0 0 2 6 0 IJ  AJ  PHASE       R            X
NNMAX=  1488     XYZ MAX=  0.240  0.240  0.300  1  0.3     0.0  6.839E-03  1.425E+00
NEMAX=  7020     XYZ MIN= -0.240 -0.240  0.000  2  0.3     0.0  1.929E-02  1.756E+00
 NK NM PABS        NK NM PABS                    3  0.3     0.0  2.785E-02  2.433E+00
  1  0  2.90E-01                                4  1.0     0.0  1.333E-01  1.430E+01
 NS     PA      PZ      PN      PZCL     PABS    5  1.0     0.0  1.030E-01  1.365E+01
  1  5.49E-04 -1.   5.00E-03  0.03   2.90E-01
  2  3.99E+01  1.   5.00E-03  0.00   1.33E-07
```



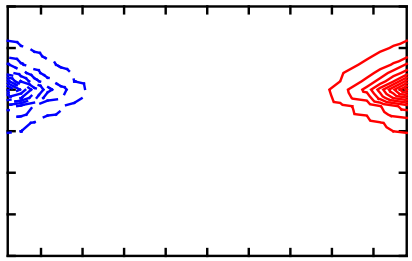
EXR(YZ) X=0.0
MAX= 2.41E-01
MIN=-2.40E-01
STP= 2.50E-02



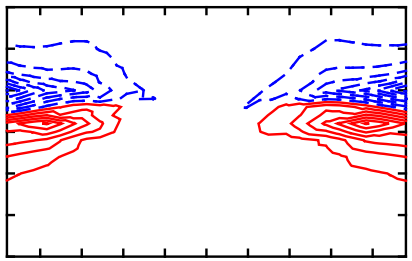
EXI(YZ) X=0.0
MAX= 2.32E+01
MIN=-2.32E+01
STP= 2.50E+00



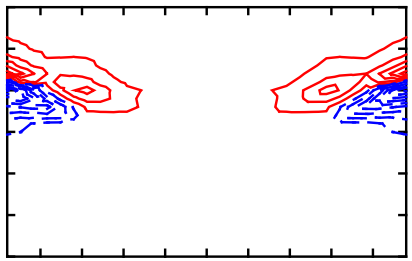
EYR(YZ) X=0.0
MAX= 5.84E-08
MIN=-5.86E-08
STP= 5.00E-09



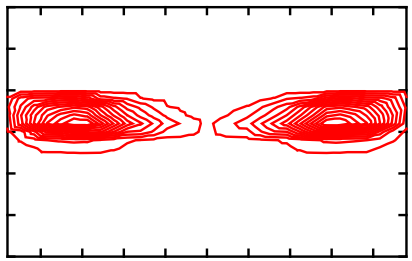
EYI(YZ) X=0.0
MAX= 4.85E-05
MIN=-4.85E-05
STP= 5.00E-06



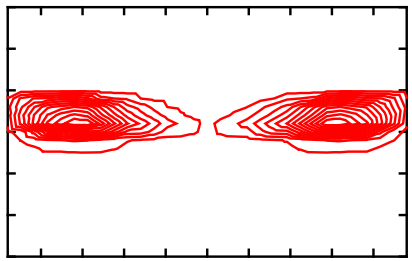
EZR(YZ) X=0.0
MAX= 6.62E-09
MIN=-7.90E-09
STP= 1.00E-09



EZI(YZ) X=0.0
MAX= 5.02E-06
MIN=-8.75E-06
STP= 1.00E-06



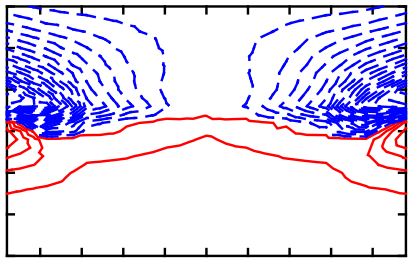
P1C(YZ) X=0.0
MAX= 6.83E+01
MIN=-1.30E-13
STP= 5.00E+00



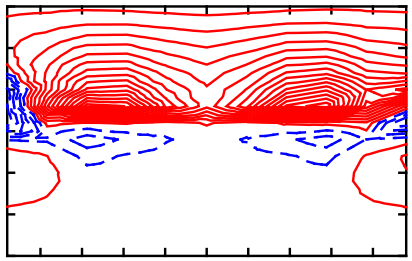
P2C(YZ) X=0.0
MAX= 3.13E-05
MIN= 0.00E+00
STP= 2.50E-06

EM Field and P_{abs} at $y = 0$

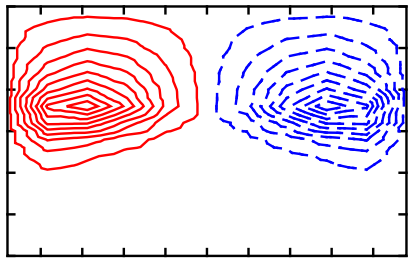
```
RF   = 13.560    BB   =  0.000    M= 2 0 0 2 6 0 IJ  AJ  PHASE       R            X
NNMAX=  1488     XYZ MAX=  0.240   0.240   0.300   1  0.3     0.0   6.839E-03   1.425E+00
NEMAX=  7020     XYZ MIN= -0.240  -0.240   0.000   2  0.3     0.0   1.929E-02   1.756E+00
 NK NM PABS        NK NM PABS                      3  0.3     0.0   2.785E-02   2.433E+00
  1  0  2.90E-01                                  4  1.0     0.0   1.333E-01   1.430E+01
 NS     PA       PZ       PN       PZCL     PABS   5  1.0     0.0   1.030E-01   1.365E+01
  1   5.49E-04 -1.   5.00E-03   0.03   2.90E-01
  2   3.99E+01  1.   5.00E-03   0.00   1.33E-07
```



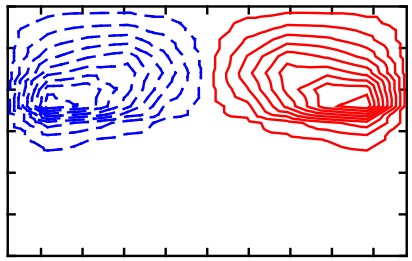
EXR(XZ) Y=0.0
MAX= 1.11E-03
MIN=-4.48E-03
STP= 2.50E-04



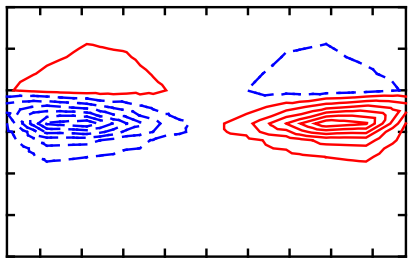
EXI(XZ) Y=0.0
MAX= 8.18E-05
MIN=-3.21E-05
STP= 5.00E-06



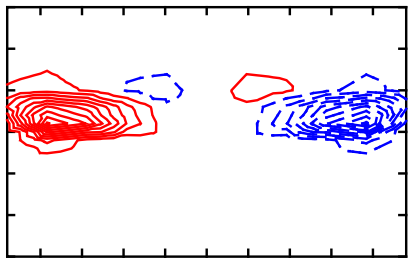
EYR(XZ) Y=0.0
MAX= 2.33E-01
MIN=-2.33E-01
STP= 2.50E-02



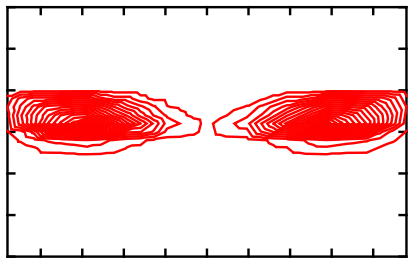
EYI(XZ) Y=0.0
MAX= 2.32E+01
MIN=-2.32E+01
STP= 2.50E+00



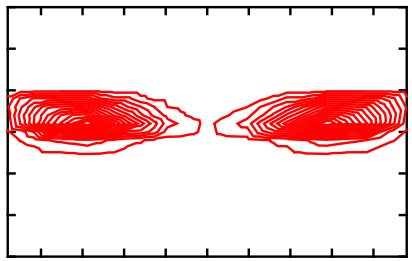
EZR(XZ) Y=0.0
MAX= 1.57E-02
MIN=-1.57E-02
STP= 2.50E-03



EZI(XZ) Y=0.0
MAX= 2.42E-04
MIN=-2.43E-04
STP= 2.50E-05



P1C(XZ) Y=0.0
MAX= 8.61E+01
MIN=-1.20E-13
STP= 5.00E+00



P2C(XZ) Y=0.0
MAX= 3.94E-05
MIN= 0.00E+00
STP= 2.50E-06

Summary

- As a part of PAF code system, we have developed a three-dimensional wave code PAF/WF in order to analyze the wave structure in a bounded plasma.
- As an example of three-dimensional analysis, excitation of axisymmetric surface waves in microwave plasma source was studied. The results are compared with the two-dimensional FDTD computation result reported by Kousaka and Ono (2002).
- Even though the element size is much larger than that of the two dimensional analysis, fundamental behaviors of the surface wave were reproduced by the newly developed code.