Probe measurements at different cathode angles in a magnetized RF plasma column

E. Faudot, A. Cherukulappurath Mana, F. Brochard, S. Heuraux, N. Clarke

P. Hiret[2], R. Steiner[2], L. Marot[2]

S. Alberti[3], I. Furno[3]

[1] *Institut Jean Lamour, Université de Lorraine-CNRS, ARTEM* F-54000*, Nancy, France*

[2] *Département de Physique, Université de Bâle, Bâle, Suisse*

[3] *École Polytechnique de Lausanne, Swiss Plasma Center, Lausanne, Suisse*

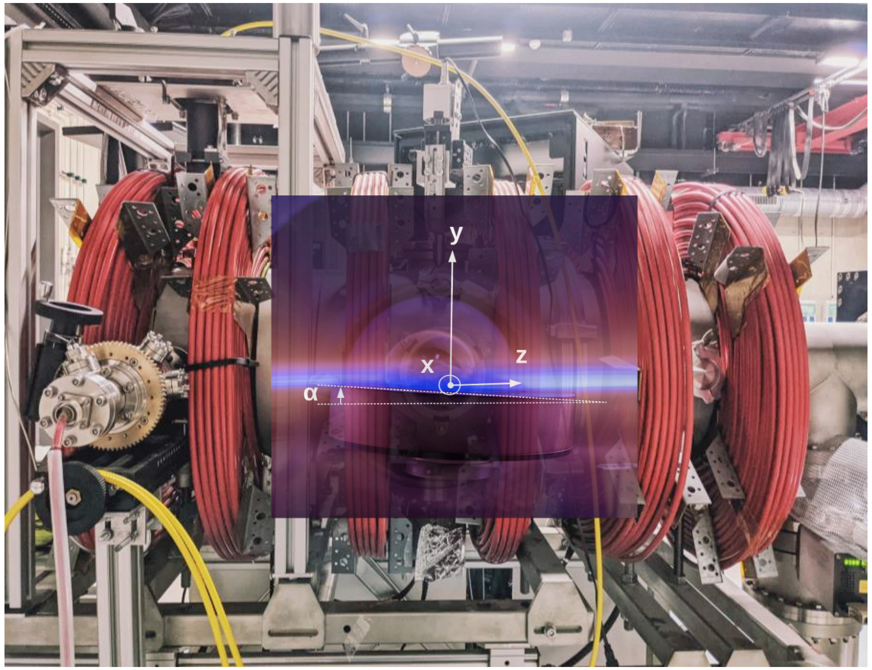
ANR SHEAR

RF Plasma and Physics of the RF sheath
ALINE experiment

Goal: fundamental study on RF plasma and RF sheath Physics to explain hot spots, impurity generation during ICRH heating, and improvements of mirror cleaning for ITER (ANR SHEAR)

Recall: Aline experiment[1] was built to study RF sheath Physics (B_o= 0-0.1T, $v=10^5$-$2.\ 10^7$ Hz) permitting to establish RF sheath model[2]

Aline



Objectives: Use the knowledge of RF sheath Physics to build a control the particles flux on the antenna , and mirror cleaning (ANR SHEAR)

Collaborators: EPFL Lausanne, Univ Basel

Results: 3D potentiel maps, Infared maps of the RF electrode, study on the control of the particles flux under RF fields

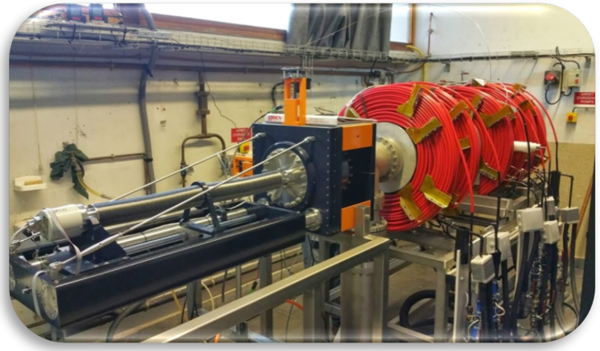
Limitations: unmagnetized ions, B_o too low

-Conférence invitée, X-Palaiseau "Detached fusion plasma and Sheath Physics

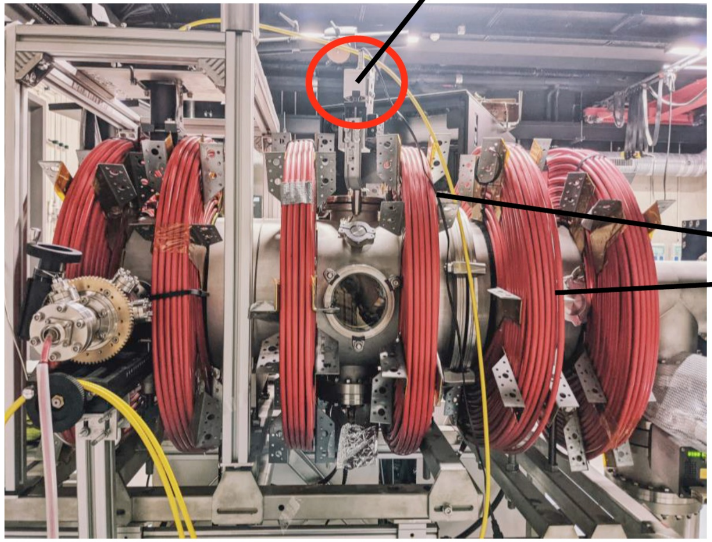
-ITER meeting: review on RF sheath Physics

[1] E. Faudot et al Rev. Sci. Instrum. **86** (2015) 063502

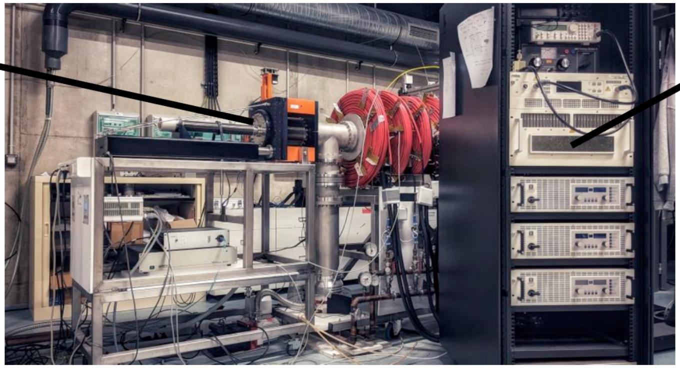
[2] E. Faudot et al IEEE TPS 50 (2022) 799-809



A Linear Machine (ALINE)



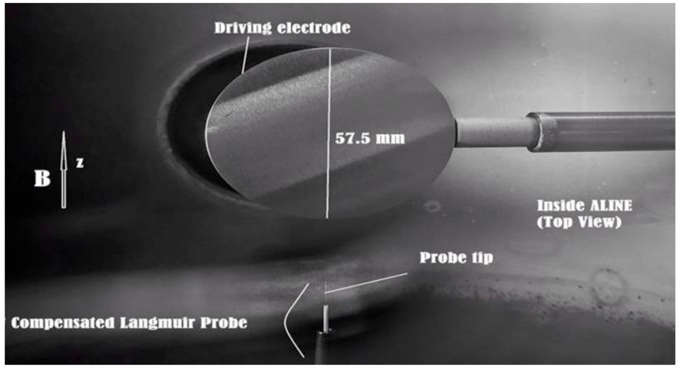
ALINE- Experimental setup and electrode



RF Generator Amplifier
Maximum power out : 600W
Frequency range :10kHz-250MHz

Magnetic field Coils (6)
75 Turns (water cooled coils)
Maximum B : 0.1T

Dimensions
Length : 1 m
Diameter :30 cm

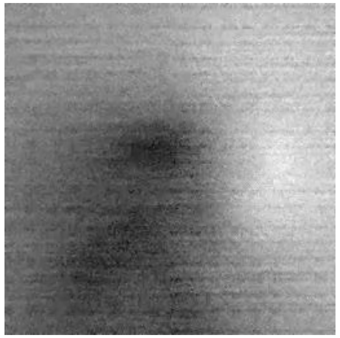


RF Compensated Langmuir Probe
L_p : 1cm
D_p : 0.075mm

B_o= 0-0.1T, ν_{RF}=10^5-2. 10^7 Hz, P_{RF}= 1-600 W, n_e= 10^{15}-10^{17} m^{-3}

Fast camera

. Acquisition rate : 1Mfps (640x32)
or 640 x 480 at 326000fps
. High sensitivity: ISO 160000 Monochrome

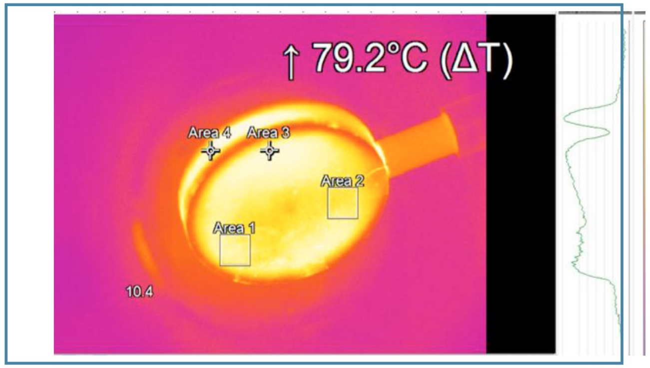


He plasma,
DC coupling,
Al RF antenna
f = 37.8 MHz
P_{RF} = -9 dBm
P_n = 0.96 Pa
B ~ 60 mT
10^5 fps

After treatment with TRACK

IR camera

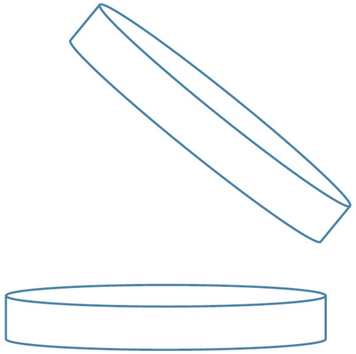
- Optical resolution: 382 x 288 pixels
- Image frequency: 80 Hz
- Temperature coefficient: ± 0.05% / K 1)
- Measurement accuracy (at ambient temperature of 23 ± 5 ° C): ± 2% with a minimum of ± 2 ° C



IR camera and IR image(right)

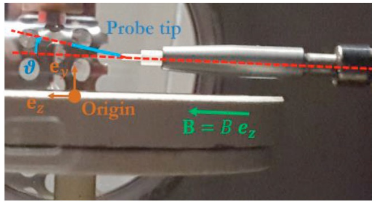
Parameters and Variables

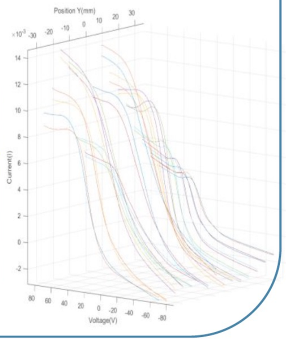
Avg. Density : 10^{15}-10^{17} m^{-3}
Avg. electron temperature : 5eV
Pressure : 1.6 Pa
Gas : Helium
Coupled Power : 20-200W
Angle of the electrode : 0^0-90^0
Applied Magnetic field : 0.025T, 0.1T



Probe Measurements

- A self compensated RF Probe
- Voltage ramp : -70 to 70V/-40 to 100V
- 20 Sweeps
- 65KHz frequency



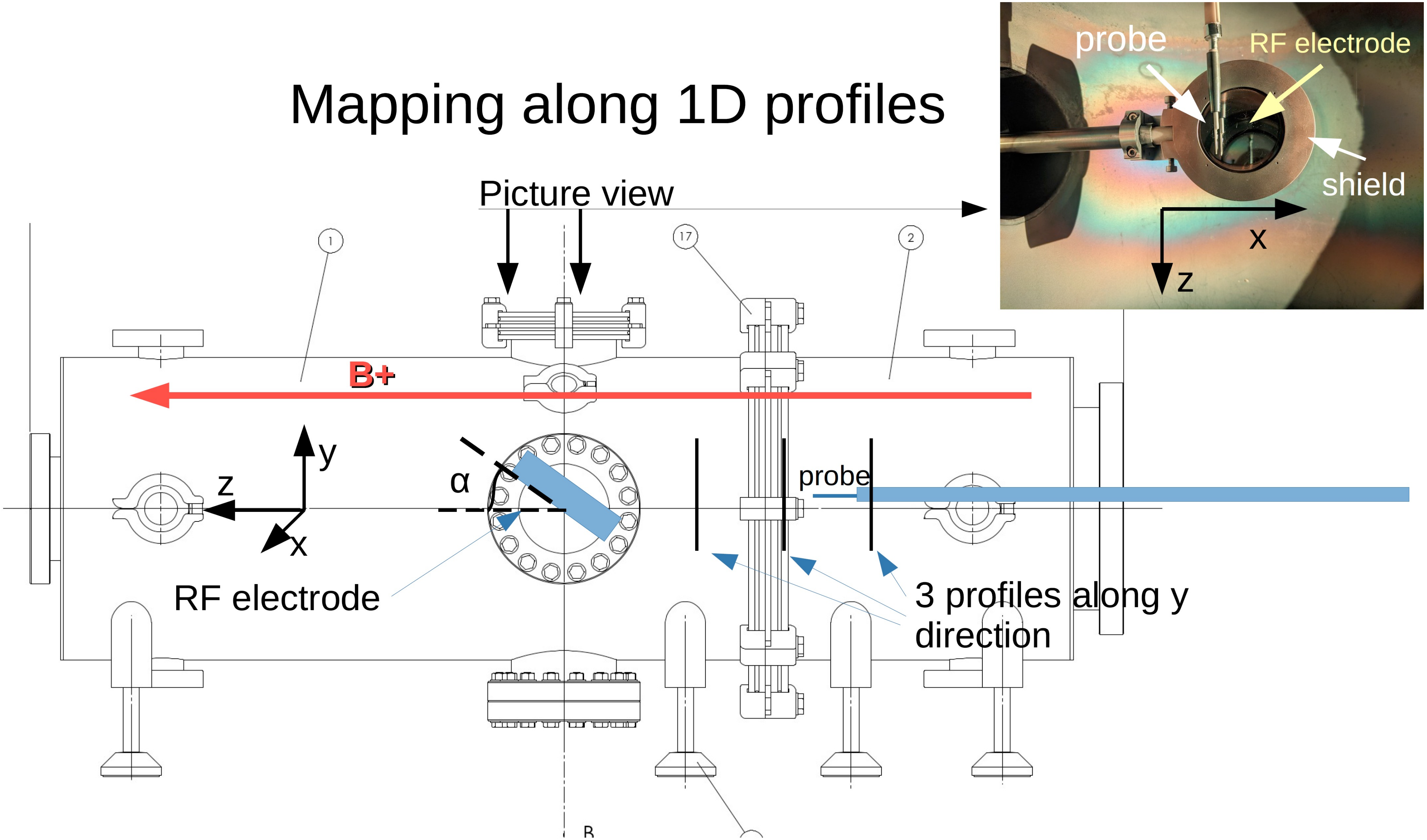


IV probe characteristics

Description of the ALINE Device

B_o= 0-0.1T, ν_{RF}=10^5-2. 10^7 Hz, P_{RF}= 1-600 W, n_e= 10^{15}-10^{17} m^{-3}

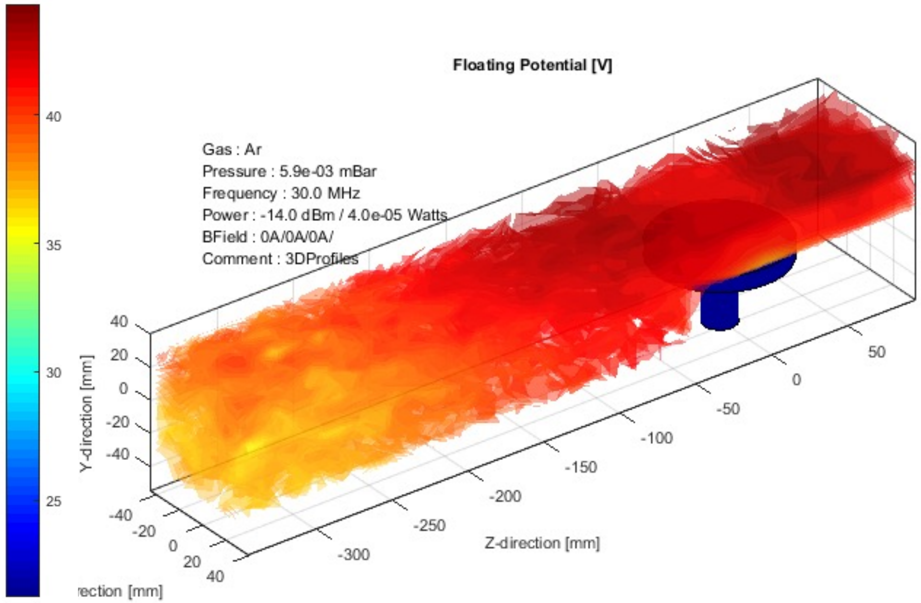
Mapping along 1D profiles



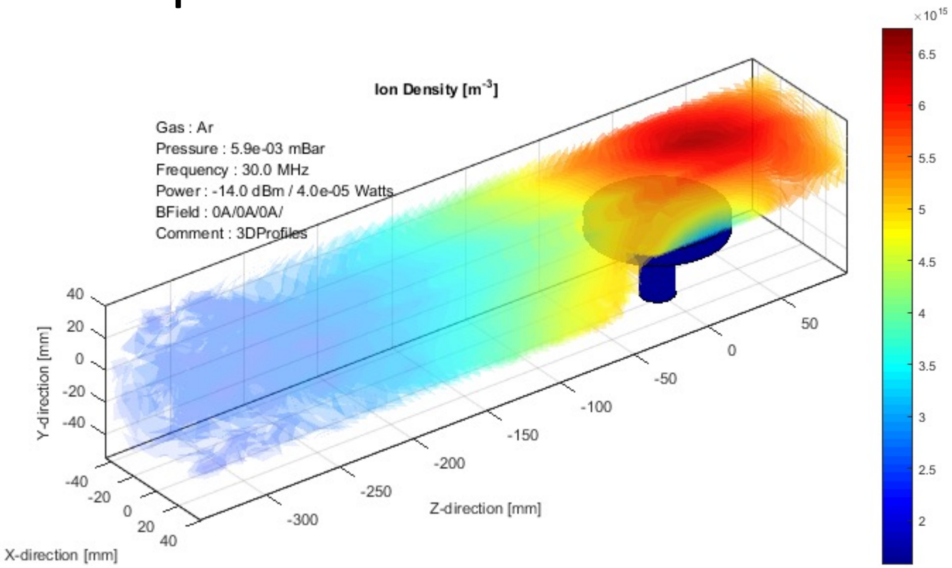
Rev. Sci. Instrum. **86**, 063502 (2015)

Results from ALINE Device

3D maps using compensated Langmuir probe In unmagnetized plasma



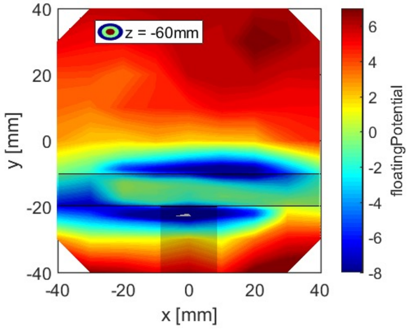
Gas : Ar
Pressure : 5.9e-03 mBar
Frequency : 30.0 MHz
Power : -14.0 dBm / 4.0e-05 Watts
BField : 0A/0A/0A/
Comment : 3DProfiles



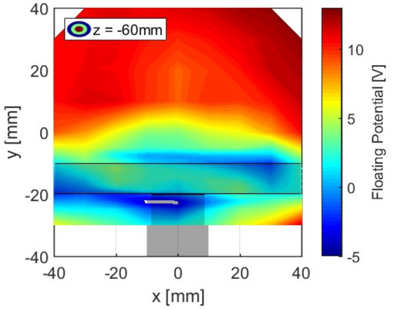
Gas : Ar
Pressure : 5.9e-03 mBar
Frequency : 30.0 MHz
Power : -14.0 dBm / 4.0e-05 Watts
BField : 0A/0A/0A/
Comment : 3DProfiles

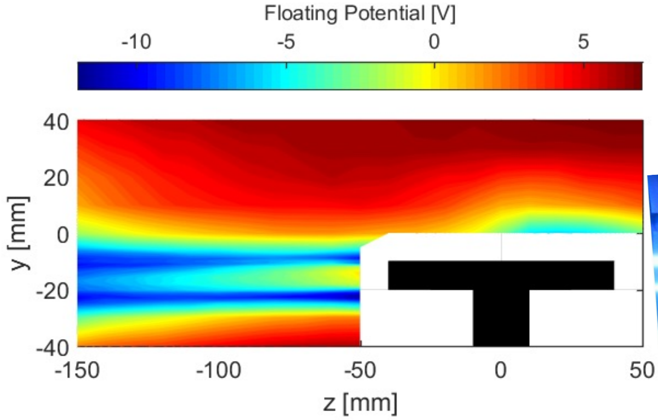
magnetized plasma

B=100 mT



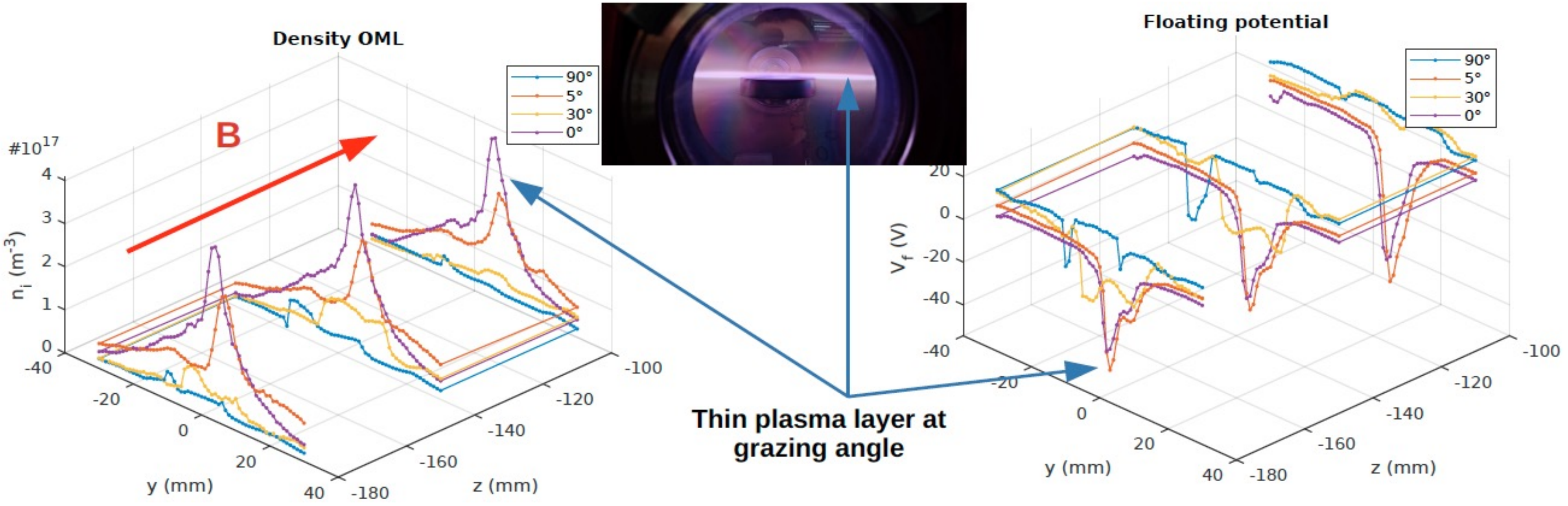
B=50 mT





Faudot et al Rev. Sci. Instrum. **86**, 063502 (2015)

Density and floating potential profiles at 4 cathode angles



Thin plasma layer at grazing angle

Density profile plots at z= -100 mm, -140 mm, and -180 mm (origin at electrode center) .
Tilt angle of the electrode in the cartige.
Density at grazing angles > 5 x higher than at 30°.

Floating potential plots: The most negative structures observed for 0° and 5° tilt angle. The amplitude decreases with the distance to the RF electrode due to collisions and diffusion.

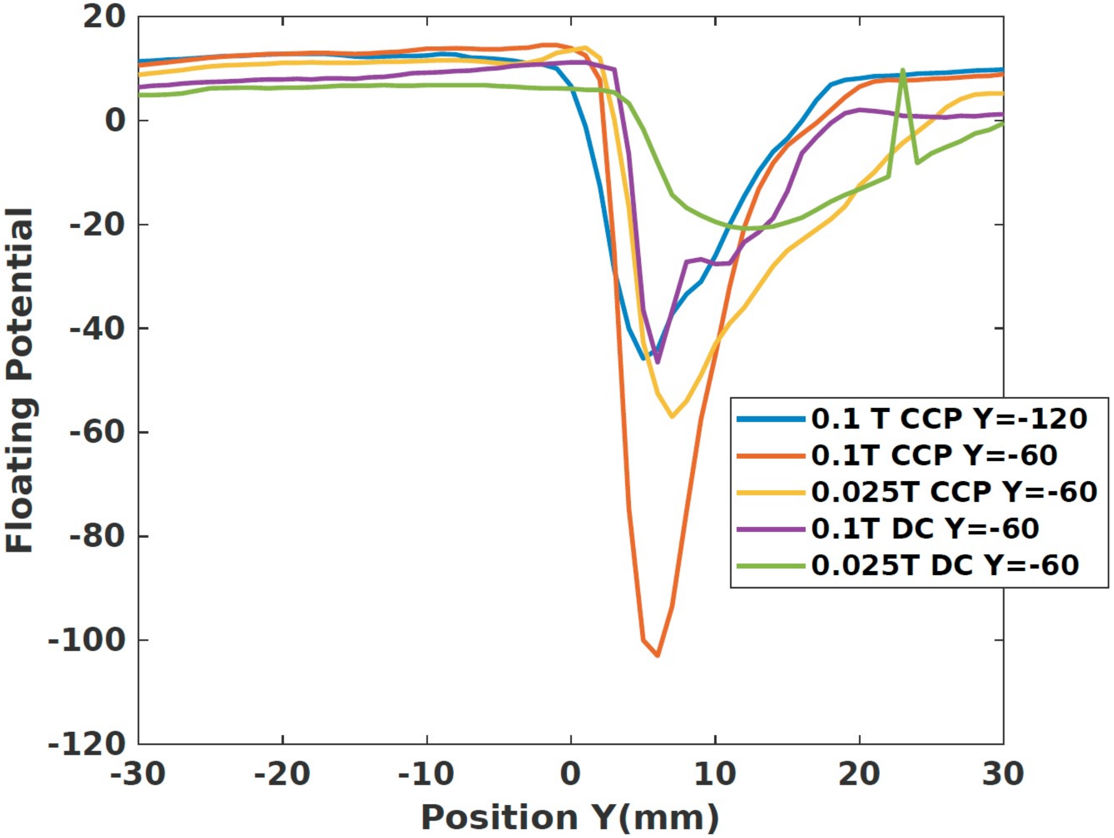
Unexpected strong negative floating potentials
To be studied in more details

Faudot *et al* *AIP Conf. Proc.* 2984, 060001 (2023)

Negative floating potentials both observed in capacitive and direct coupling at 0° angle

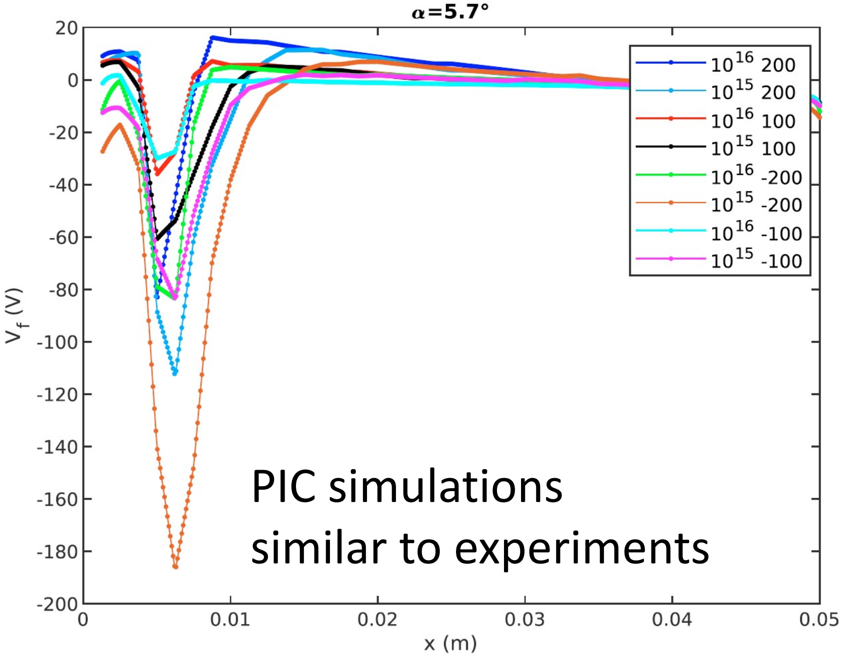
Typical discharge parameters

- → B=0,1 T
- → P_{RF}= 50 W at f=25MHz
- → He pressure : 1.5 Pa



The negative floating potential on the probe appears as well in direct coupling (DC in legend) discharges, but with less intensity.

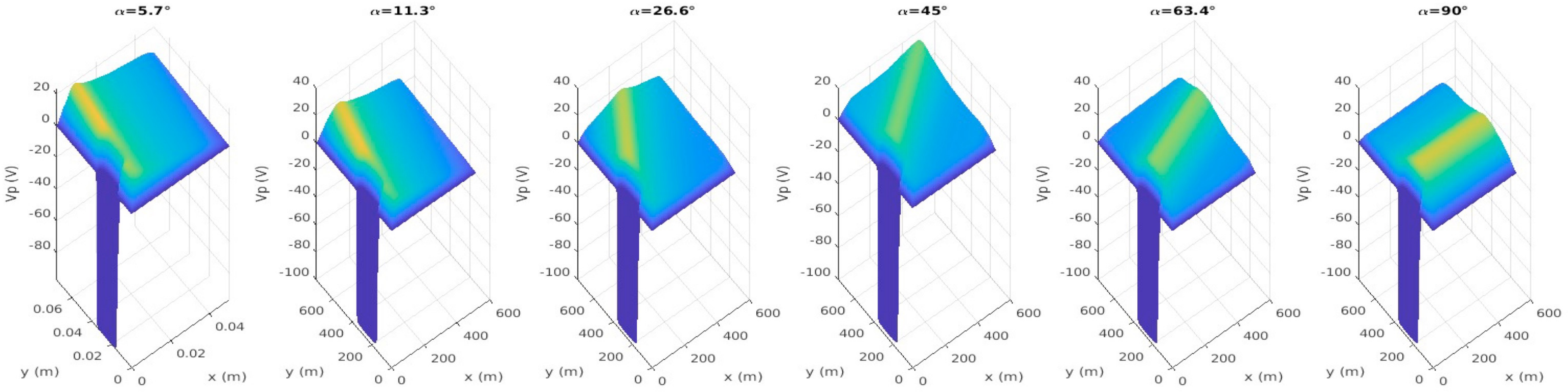
The electron acceleration in the sheath, more efficient at grazing angle seems responsible for the negative floating potentials

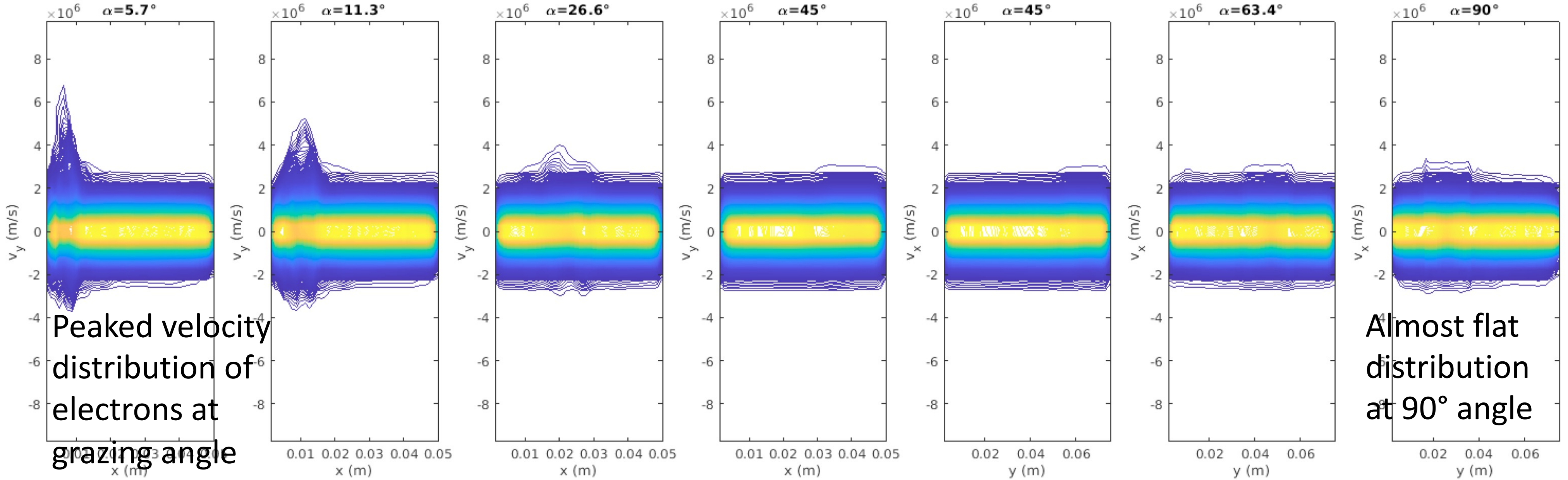


PIC simulations similar to experiments

EEDF from PIC simulations at 6 different magnetic field angles

PIC simulations parameters using GPU: 8 million particles (grid 768x512), rectangular box (5cm x7,5 cm), RF voltage : 100 V, DC voltage : -100 V, f=25 MHz, electrode width : 2 cm magnetic field angle from 5,7° to 90°



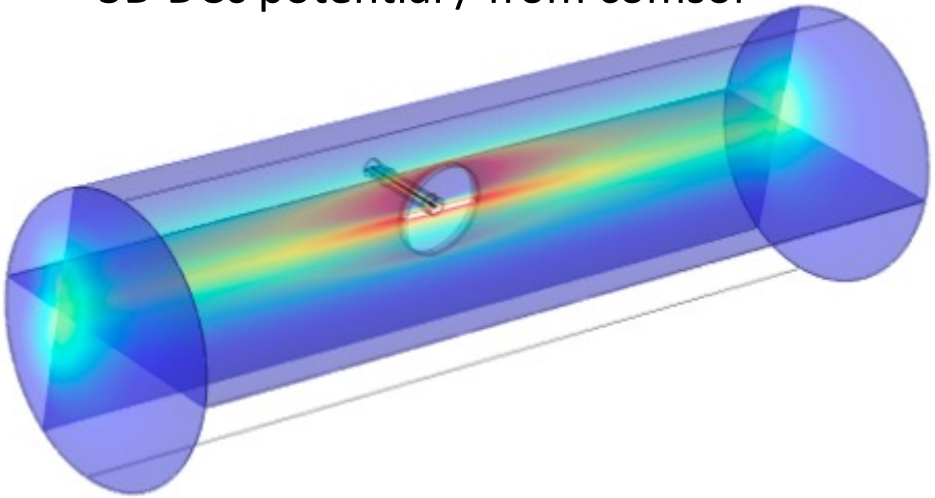


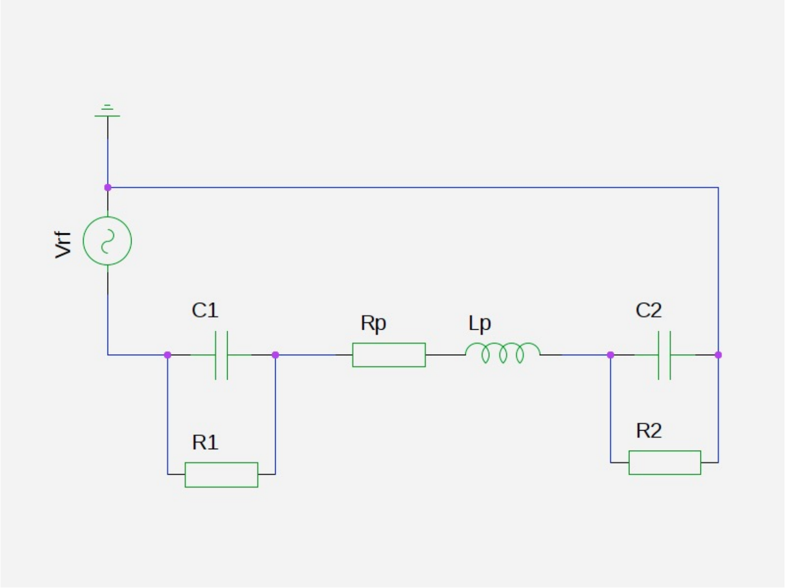
Peaked velocity distribution of electrons at grazing angle

Almost flat distribution at 90° angle

Modeling of the ALINE RF discharge

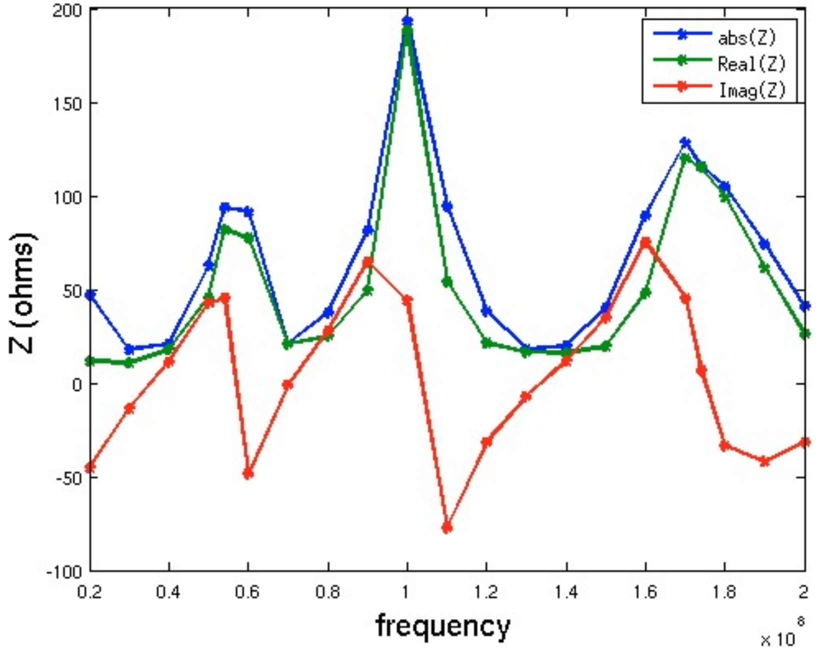
3D DCc potential / from comsol





Equivalent circuit for cable+plasma + sheaths

Equivalent circuit for plasma + sheaths



gas He

n_0 10^{14} m^{-3}

T_e 5 eV

ν_m 2.10^8 s^{-1}

R_1 13111 Ω

R_2 102008 Ω

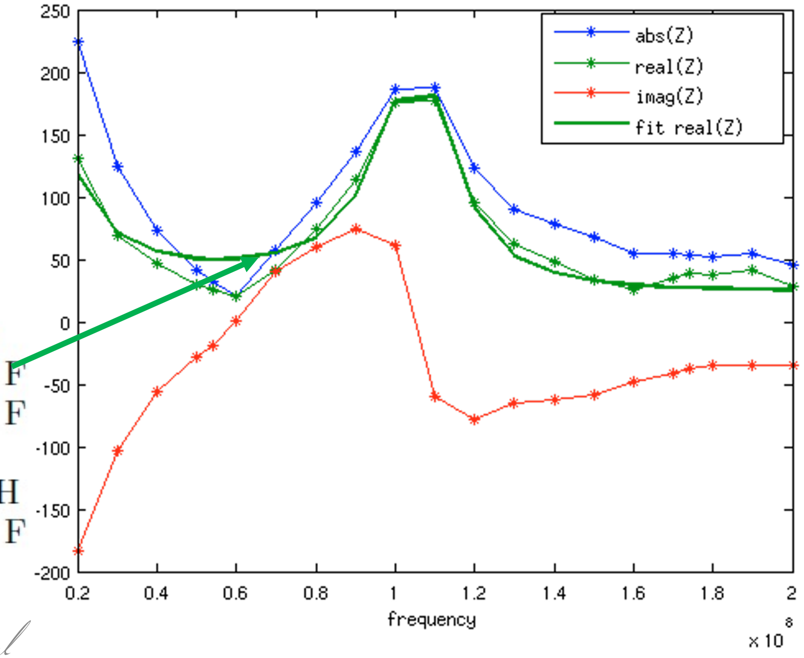
C_1 $8,9.10^{-12}$ F

C_2 $1,1.10^{-11}$ F

R_p 16,7 Ω

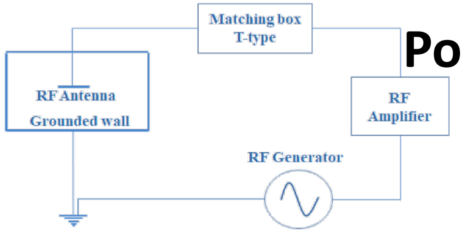
L_p $8,1.10{-}8$ H

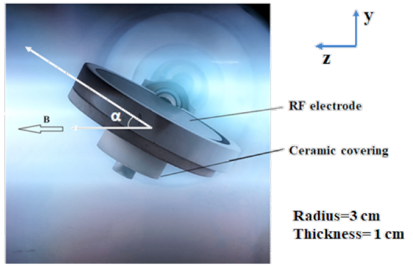
C_p $2,7.10^{-11}$ F



Rev. Sci. Instrum. **86**, 063502 (2015)

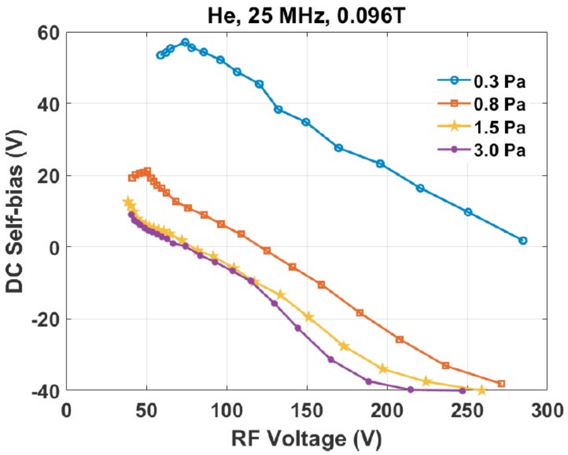
Positive self-bias in a magnetized CCP discharge

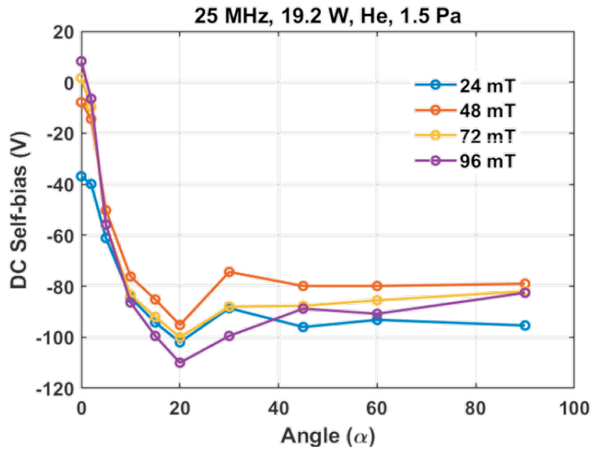




ALINE plasma parameter.

Quantity	Ions (He^+)	Electrons
Density(n)(m^{-3})	$1-60\times10^{16}$	$1-60\times10^{16}$
T (eV)	0.026	3-6
$\lambda_{mfp}(cm)$	1.50	1.4-5.2
$\nu_c\ (s^{-1})$	380×10^3	3×10^9
$\nu_p\ (s^{-1})$	$7-23\times10^6$	$635-2000\times10^6$
$\omega_c/\nu_{(e/i)N}$	0.1-5.6	17-967





Modelling: based on quasineutrality

$$\Gamma^i = n\mu_\perp E_\perp + \Gamma^e_\parallel\left(\frac{4r_L}{\pi R} + \sin\alpha\right)$$

$$\mu_\perp = \mu/(1+\frac{\omega_{ce}^2}{\nu_{eN}^2}) \quad \Gamma^e_\parallel = nc_e \quad c_e = \sqrt{\frac{k_B T_e}{2\pi m_e}}$$

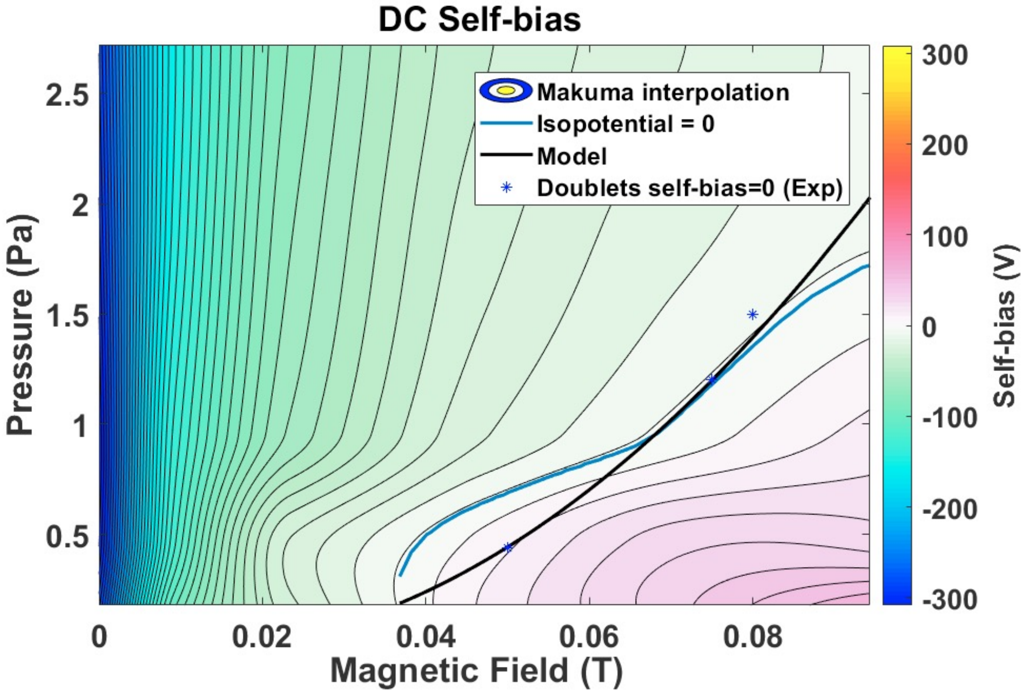
Critical angle $\tilde{E}_\parallel/\pi$ sin(α) ~α

$$\alpha = \frac{C_s - \mu_\perp < \tilde{E} >}{c_e} - \frac{4r_L}{\pi R} \qquad \tilde{E} = \tilde{V}/\gamma\lambda_{De}\left(\frac{V_{rf}}{T_e}\right)^{3/4}$$

α= 0 =>Critical collision rate

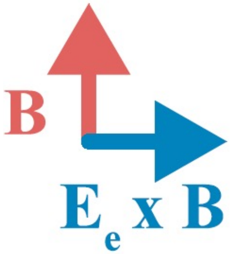
$$\nu_{eN}^2 - \nu_{eN}\frac{e\tilde{E}}{m_e\left(C_s - c_e\left(\frac{4r_L}{\pi R}+\alpha\right)\right)} + \omega_{ce}^2 = 0$$

Phys. Plasmas 30, 030703 (2023)

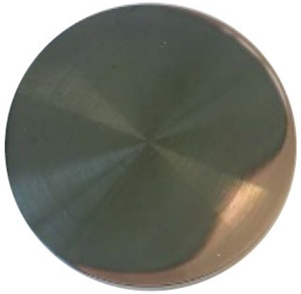


AIP Conf. Proc. 2984, 040008 (2023)

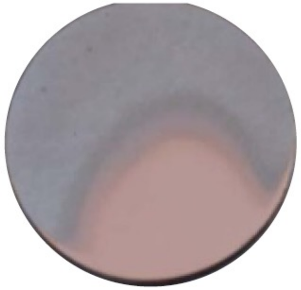
Effects of Drifts in front of tilted RF electrodes



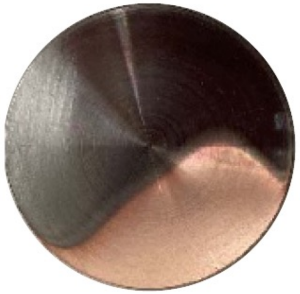
Nancy
ALINE



Bâle
LAMP



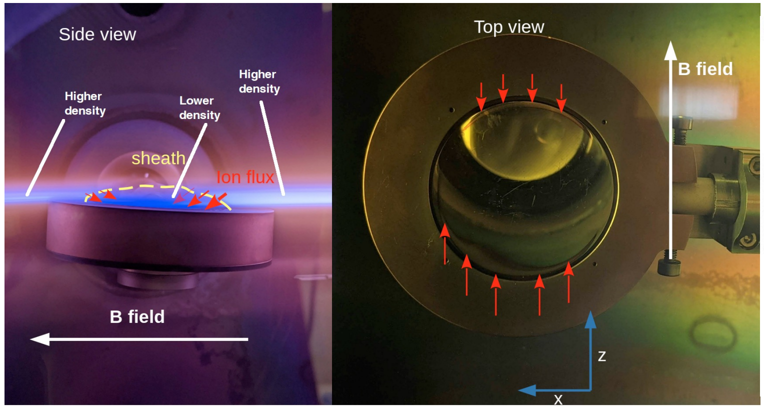
Lausanne
BUMP

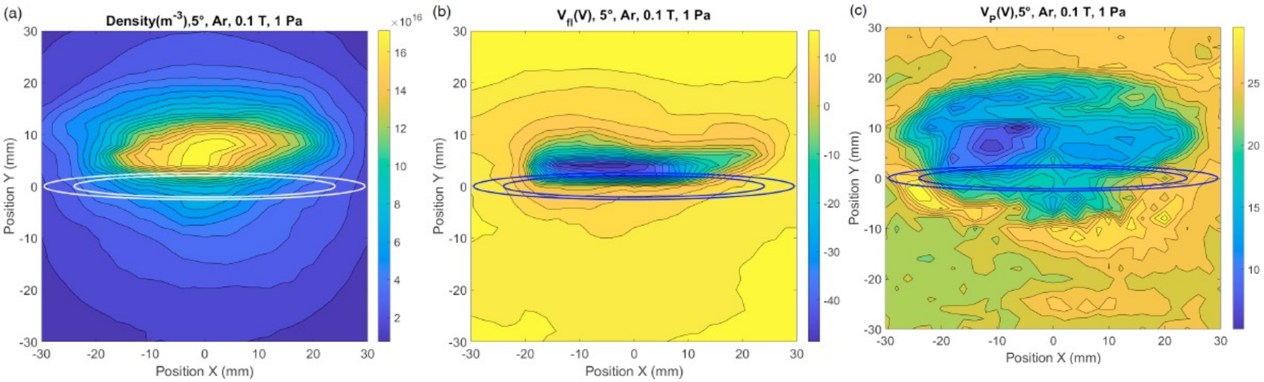


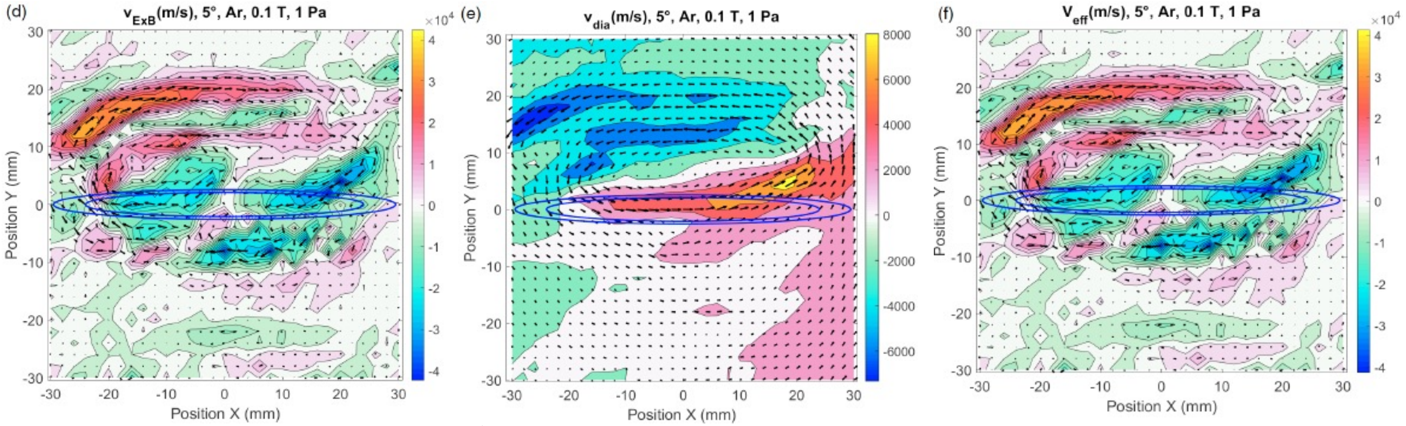
ANR SHEAR
Mirror cleaning

Plasma Sources Sci. Technol. 32 (2023) 095021

Measurements







$V_{ExB} >> V_{dia}$

31/10/2024

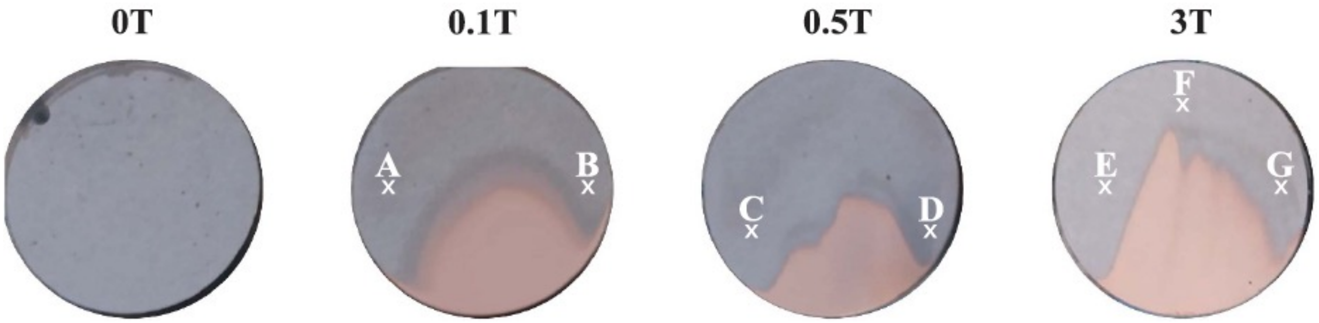
Heuraux et al

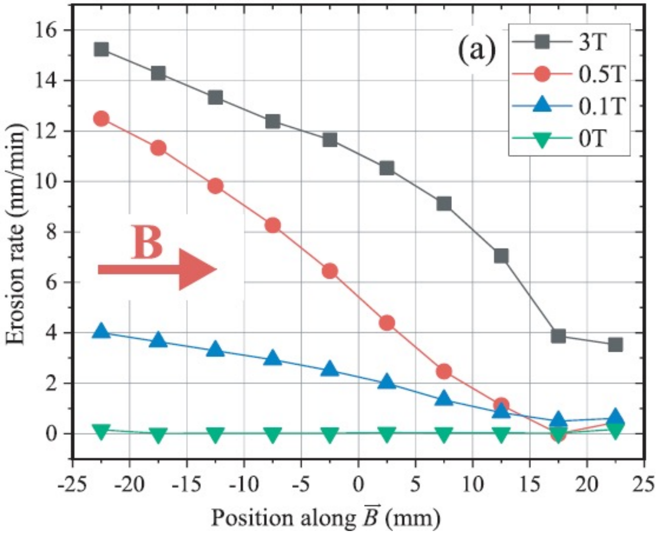
PhD Anil Cherukulappurath Mana U. of Lorraine Nov. 2023

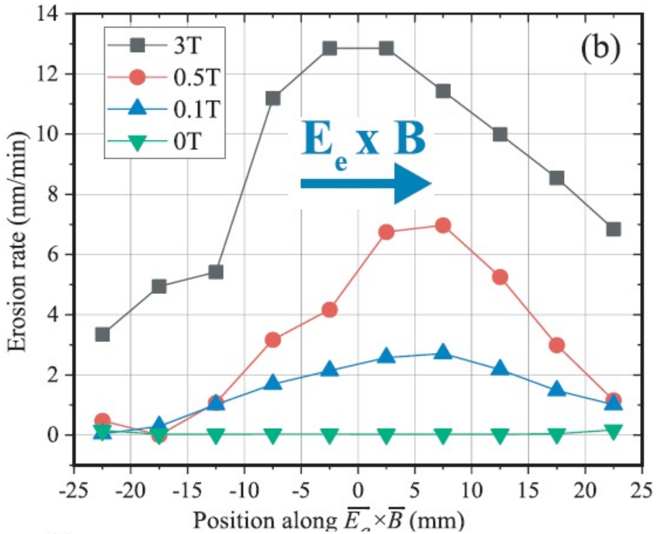
Erosion of 5° tilted RF electrodes Mo coated

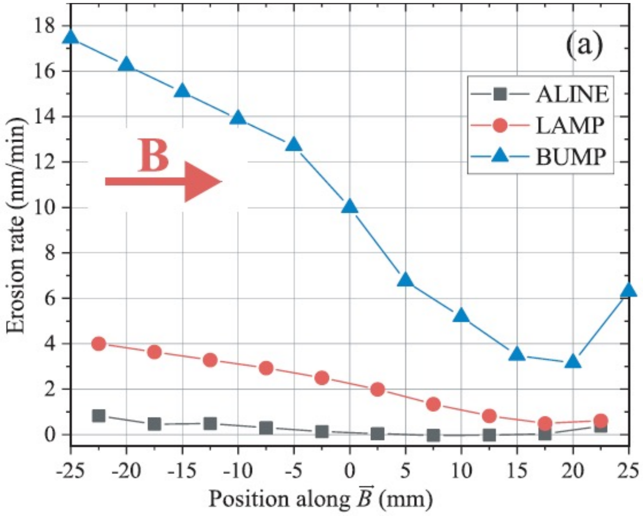
ANR SHEAR

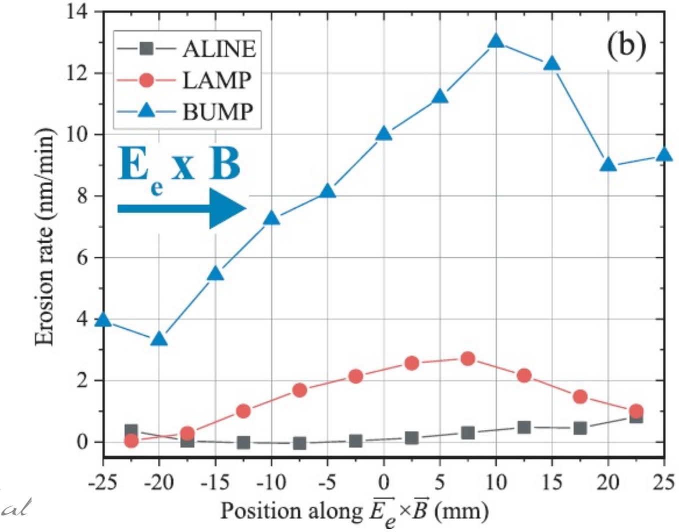
LAMP results
at Cte self-bias -100 V



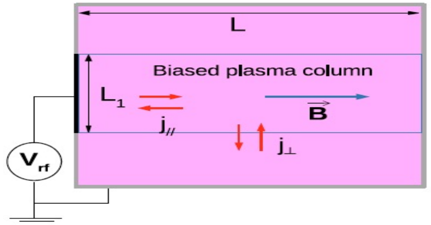








Gaine en présence de RF



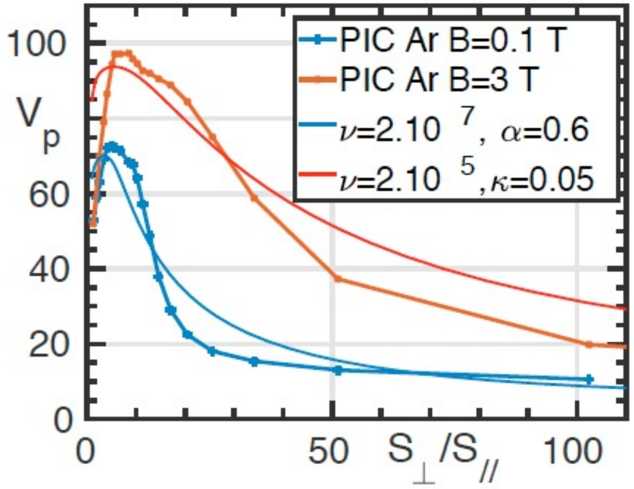
Modelling based on satured double probe

IEEE Transactions on Plasma Science 50 (2022) 799 - 809

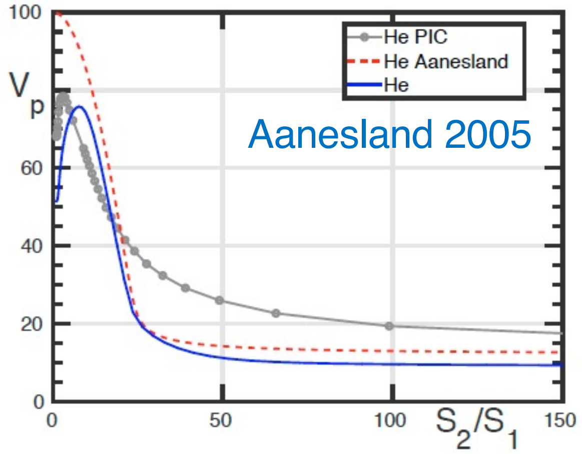
$$\phi = \frac{eV_p}{k_B T_e}$$

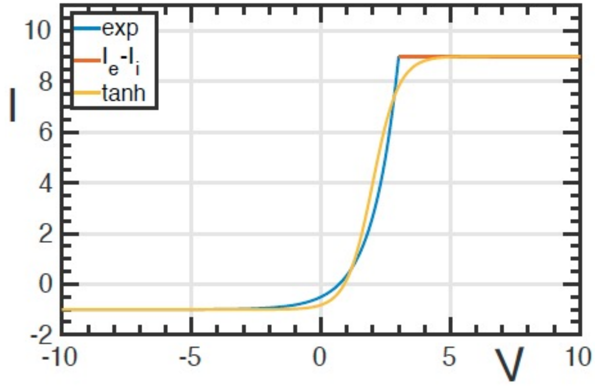
$$\langle\phi\rangle = 1 + \frac{1}{2}\ln\sqrt{\frac{S_1+S_2-A}{S_1+S_2+A}} - \frac{1}{2}\left\langle asinh\left[\frac{A.\cosh(\phi_{rf}(t)) + (S_2-S_1)\sinh(\phi_{rf}(t))}{\sqrt{(S_1+S_2)^2-A^2}}\right]\right\rangle$$

$$\phi_{rf} = \frac{eV_{rf}}{k_B T_e} \quad A = (S_1+S_2)(2j_i/j_e - 1)$$



Discharge & SOL tokamak





Issues of rectified RF potentials (sheath ⬄ diode)

=> higher particles energy i.e. ΔV ~V_{RF} (Non-Linear effects) => erosion

Modelling actuels => implementation of the sheath boundary conditions in heating codes (Myra 2017)

An improved knowledge on sheath Physics versus tilting angle => particle energy distribution function => erosion rate which drives the plasma parameter and materials choices