SMALL RF PLASMA GENERATORS FOR AIR

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Complex plasma devices as thrusters or ion sources for fusion and their physical models at reduced size, as the negative ion source NIO1 developed by Consorzio RFX and INFN-LNL, rely on several accessories, like coil shielding, cesium vaporizers, probes and bias electrodes, which needs to be separately tested , both to avoid delays in the major source schedule and to better understand features of those accessories. A simple plasma generator can be installed on standard pumped vacuum chambers (fig 2-7). Air is used as feeding gas for economy; moreover spectroscopy of nitrogen allows for a determination of electron temperature T_e in much simpler and direct way than in the other gas cases. Simple and direct diagnostics are described. Even in the present limitation of rf power level, reasonable dense (10^{16} m^{-3}) and bright plasma can be produced (Fig 7-8), with a large degree of inductive coupling and T_e about 4 eV (+/-1 eV) according to the still compelling scaling laws from global ionization balance models. On the other hand, oscillation of the plasma potential (possibly much larger then T_e) can be studied as a function of the coil and bias configuration, and may indicate some residual capacitive coupling especially between with low power amplifiers. Effect of these fluctuations on electron and ion flows inside plasma is worth investigation. A simulation model is also described (Fig 1, 9, 10).

Azimuthal vector potential $\mathbf{A} \cong \Re(\hat{\vartheta} A_\vartheta(r,z) e^{i\omega t})$

$$\operatorname{div} \mathbf{\Gamma}_u = a u + \mu_0 \sigma \bar{U}_k$$

$$a = r^{-1} + r(i\mu_0\omega\sigma + \varepsilon_r \omega^2/c^2)$$

with $u = A_\vartheta$ and $\mathbf{\Gamma}_u = (ru_{,r}, ru_{,r})$ and $\bar{U}_k$ is the **(applied voltage on k-th turn)/2π**

Materials conductivity from tables; many plasma conductivity model [4] as

$$\langle\sigma\rangle = n_e \sigma_\parallel \qquad \sigma_\parallel = \frac{e^2}{m}[f(-\omega) + f(\omega)^*]$$

$$c_0 = \nu_c - ieB_s/m$$

$$c_1 = -eB_f/2m$$

where

$$f(\omega) = \frac{5}{4c_0 - i2\omega + 3\sqrt{4(c_0+2i\omega)^2 + 15c_1^2}}$$

B_f rf magnetic flux density, B_s static magnetic flux density, ν_c collision frequency, ω rf angular frequency

Particle conservation laws

$$C_g(n_{g0} - n_g) = 2\pi n_g \int dz\, dr\, r n_e K_{iz}$$

$$\operatorname{div} \mathbf{\Gamma}_i = \operatorname{div} \mathbf{\Gamma}_e = n_g n_e K_{iz}$$

n_{g0} input gas density, n_g gas density, $K_{iz}(T_e)$ ionization coefficient

Ion flow in the ambipolar regime:

$$\mathbf{\Gamma}_i = -D_a(\mathbf{B}_s)\,\nabla\left(n_e + s_p \frac{B_f^2}{4\mu_0 T_e}\right)$$

ambipolar flow velocity

$$\mathbf{v}_a = \mathbf{\Gamma}_i / n_e$$

$D_a(B_s)$ is the diffusion tensor; for low magnetized plasmas $D_a(0) = T_e/M\nu_i$

Metal wall b.c. $\mathbf{n}\cdot\mathbf{v}_a = u_B$ **with Bohm velocity** $u_B \cong (T_e/M)^{1/2}$

Energy flow [9]

$$-\operatorname{div}(K_e \operatorname{grad} T_e) = p_h - n_e n_g K_{iz} \mathcal{E}_{iz}$$

K_e thermal conductivity, $\mathcal{E}_{iz}$ ionization work per pair, heating power $p_h = \frac{1}{2}\Re(j_\vartheta^* E_\vartheta)$

Variable	Sim. 1	Sim. 2	Sim. 3
I_1 [A]	40	42.5	45
R_t [W]	170	262	642
R_t [ohm]	0.21	0.29	0.63
n_e [m^{-3}] max	3.4×10^{17}	4.9×10^{17}	1.1×10^{18}
n_e [m^{-3}] probe	1.3×10^{16}	1.8×10^{16}	5.4×10^{16}
σ [S/m] max	23.6	34.4	90.6
n_g/n_{g0}	0.79	0.63	0.21

Table 1. Results for plasma; vacuum gives R_t=0.07 ohm

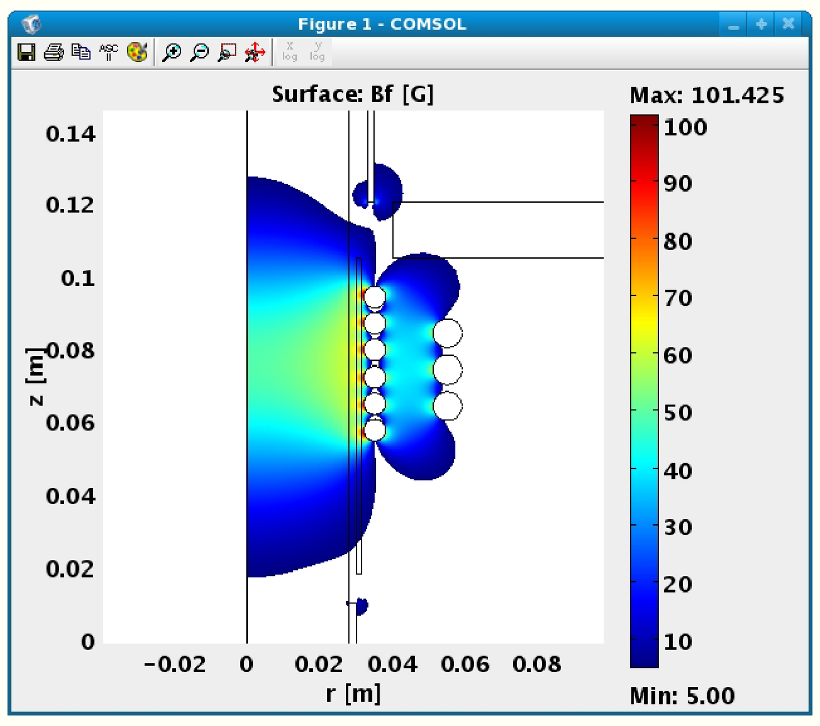


Figure 1. The rf magnetic flux density amplitude

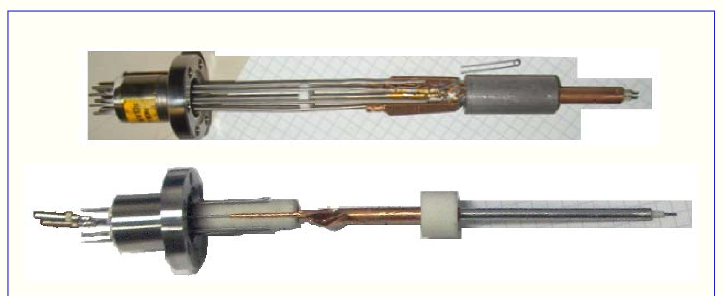


Fig 2) Some versions of Langmuir probes used (fixed position near plasma periphery)

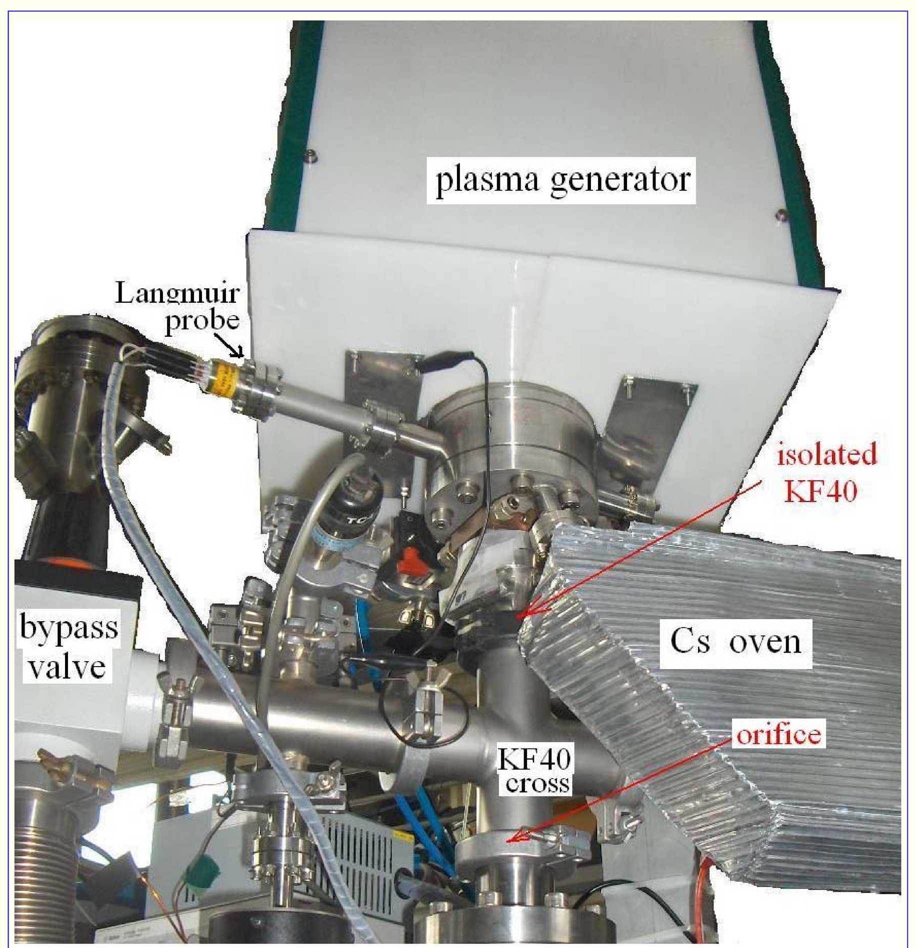


Fig 3) Photo of the test-stand: oven and vacuum connections

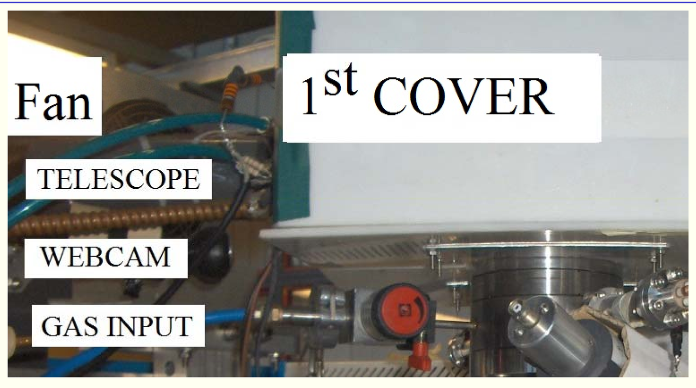


Fig 4)Plasma light is focused inside a fiber optic by a small telescope, covered by PVC tube

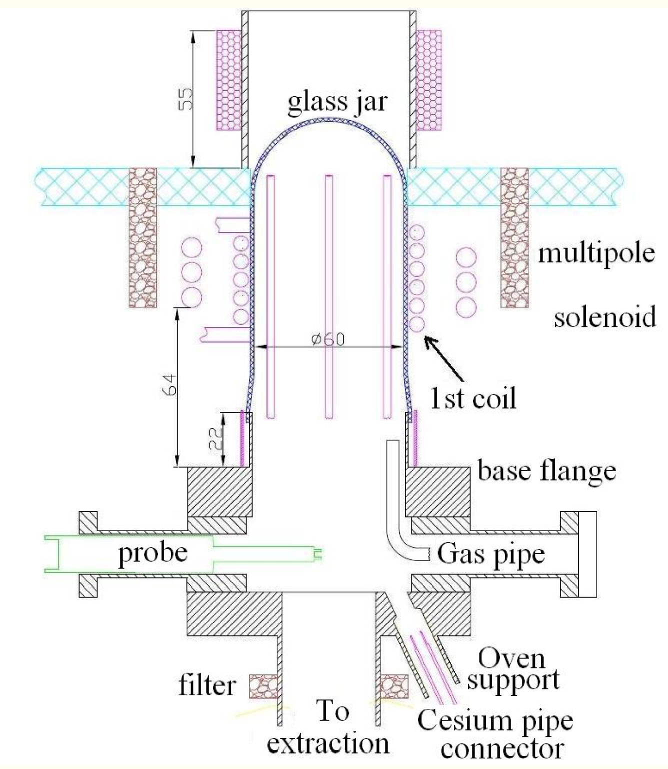


Fig 5) Plasma generator in the test stand[6]: vertical section (some line removed and gas tube displaced for visibility); dimension in mm.

Fig 6) The faraday cage (now taken away) and the containing 60 mm diameter glass jar (now replaced by a clean one)

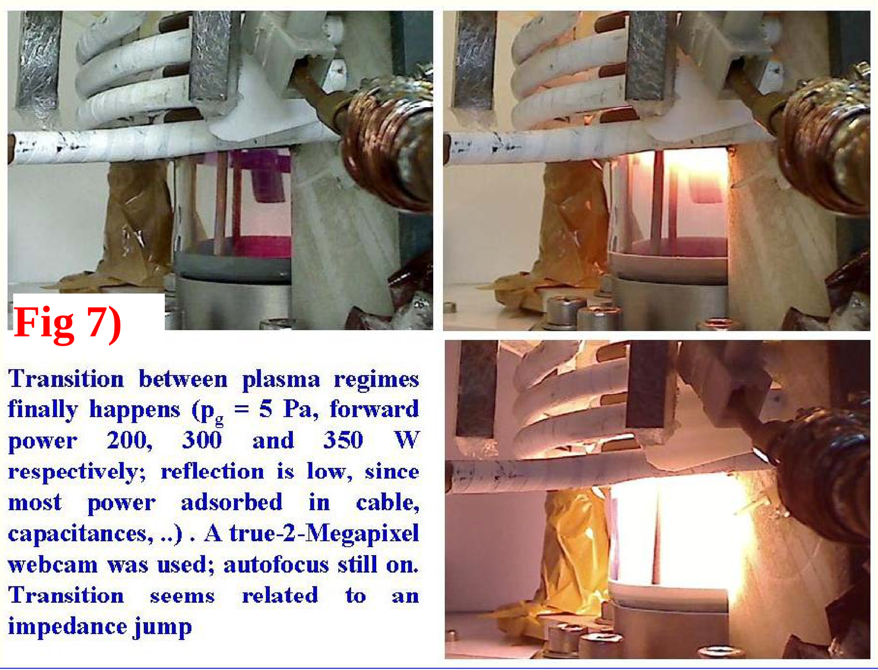
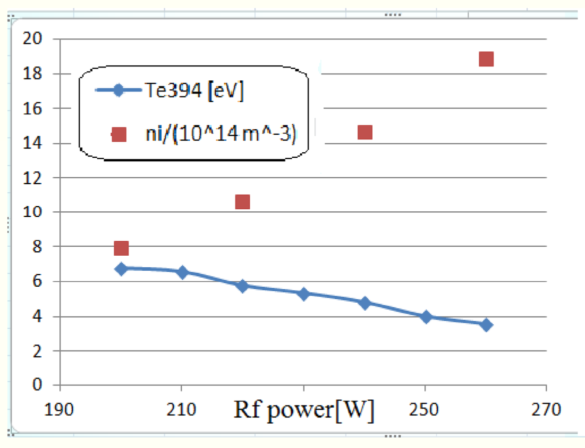


Fig 7)

Transition between plasma regimes finally happens (p_g = 5 Pa, forward power 200, 300 and 350 W respectively; reflection is low, since most power adsorbed in cable, capacitances, ..) . A true-2-Megapixel webcam was used; autofocus still on. Transition seems related to an impedance jump



$R_{391/394}$	Te [eV]
0.02	1
0.3	2
1.5	4
4	6
7	8
10	10

Table: inferred Te from N_2/N_2^+ lines, cfr Ref. 8

Fig 8) Some 2016 results (power limited by amplifier) for the optically [5,7,8] inferred temperature T_e^{394} (error +/- 10%). Ion density n_i has larger errors (a factor 2), since plasma potential fluctuation [1] are preliminarily estimated over 10 Vpp and compensated only in part. The small values of n_i are due to a filter field and the drift distance and power limits; this makes electrostatic probe analysis even more difficult [2,3]

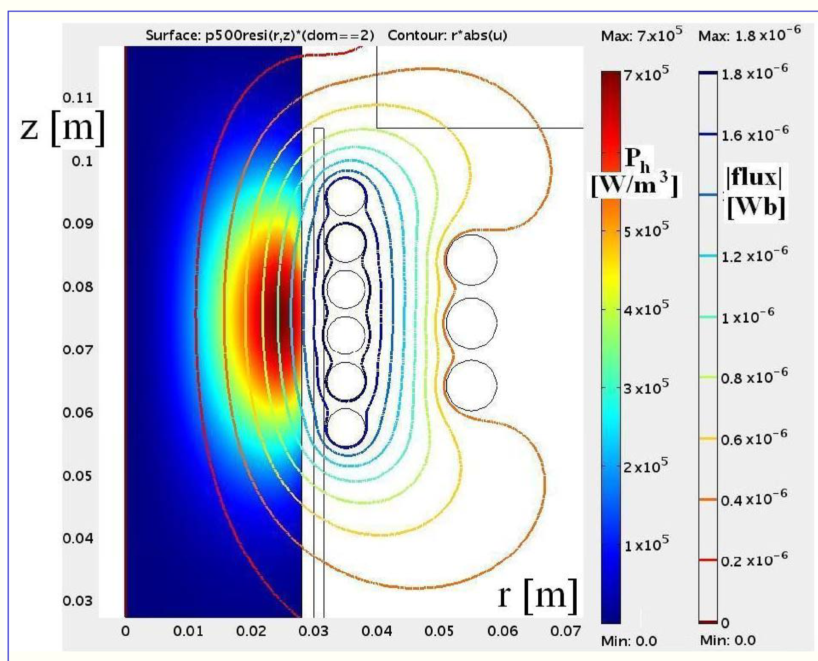


FIG 9) The rf heating power P_h for I_1=50 A and p_0 = 6 Pa; here $\omega/2\pi$= 2.14 MHz. Level lines of rf flux r | A_ϑ | also shown

Webcam view area dashed

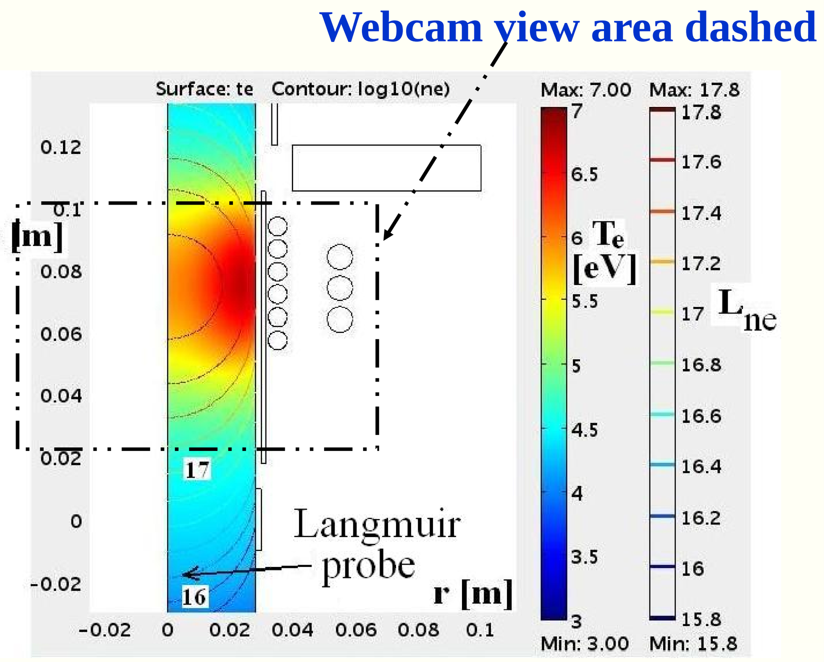


FIG 10) Electron temperature T_e in eV. Level lines of L_{ne}= $\log_{10}(n_e/n_1)$ with n_1=1 m^{-3} are also shown.

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[1] A. Boschi and F. Magistrelli, *Il Nuovo Cimento*, **29**, 487 (1963)

[2] I. D. Sudit and F. F. Chen, *Plasmas Sources Sci. Technol.*, **3**, 162 (1994)

[3] Francis F. Chen, John D. Evans, and Donald Arnush, *Phys. Plasmas*, **9**, 1449 (2002)

[4] M. Cavenago and S. Petrenko, *Rev. Sci. Instrum.*, **83**, 02B503 (2012)

[5] N Britun, M Gaillard, A Ricard, Y M Kim, K S Kim and J G Han,, *J. Phys. D: Appl. Phys.*, **40** 1022 (2007).

[6] M. Cavenago, T. Kulevoy, S. Petrenko, G. Serianni, V. Antoni, M. Bigi, F. Fellin, M. Recchia and P. Veltri, *Rev. Sci. Instrum.*, **83**, 02A707 (2012).

[7] K. Behringer and U. Fantz, *J. Phys. D*, **27** 2128 (1994).

[8] Y. Itikawa, *J. Phys. Chem. Ref. Data* , **35** 31 (2006).

[9] M. Tuszewski, Phys. Plasmas **5** , 1198 (1998)