Child-Langmuir-limited current in the negative ion source NIO1

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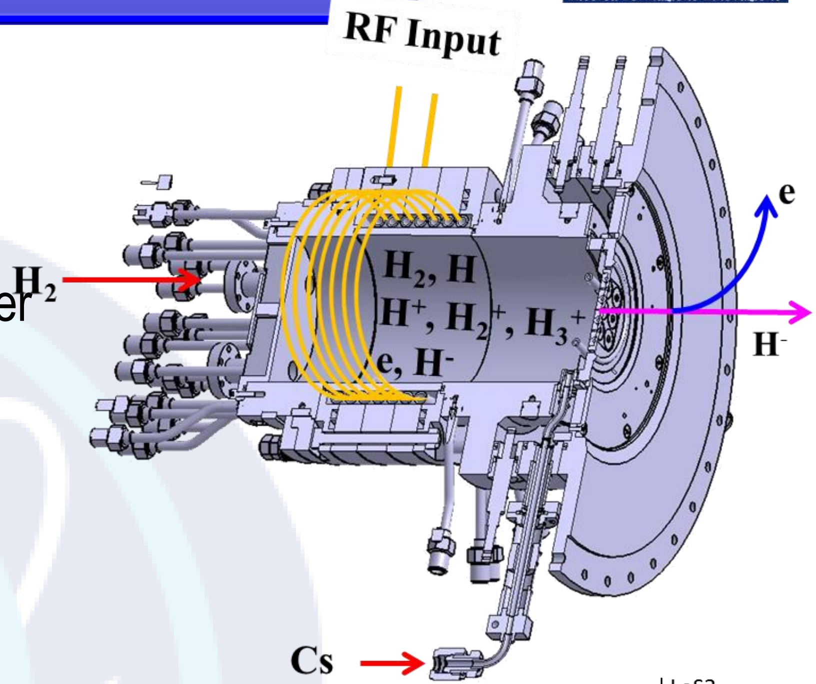
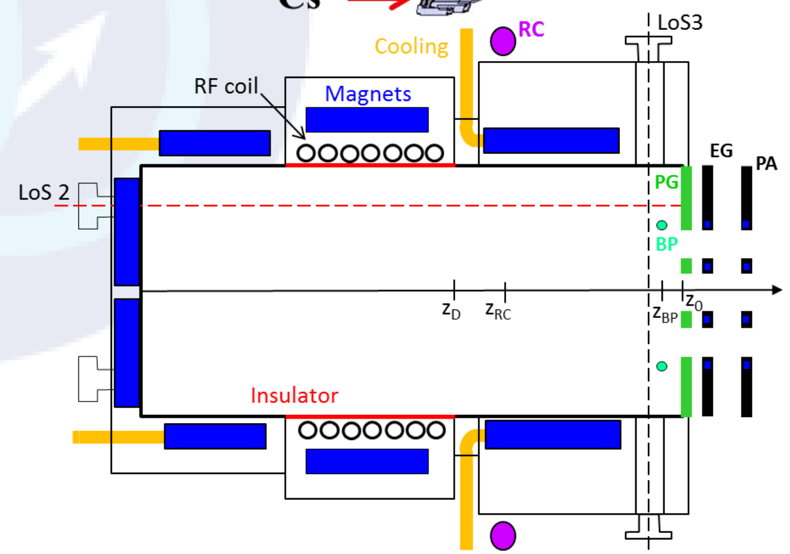
Abstract

Negative ion sources are the first stage of several types of accelerators, ranging from medical applications to materials testing and to heating systems for nuclear fusion devices. One of the most important aspects of the sources is the amount of extracted ion current, which depends on the extraction voltage and on the availability of ions inside the source plasma; this situation is described by the Child-Langmuir law, which can be extended to include an initial ion velocity. In the case of negative ions, plasma electrons also play a role in the definition of the maximum extractable ion current, which can be significantly decreased for the possibly combined effects of large electron current and magnetic field configuration; double species might also be included in an extended Child-Langmuir law. The present contribution describes the main issues of a theory of the electrostatic extraction of particles from the meniscus, the plasma boundary which forms at the apertures of a negative ion source in the aforementioned conditions. A normalised treatment might be adopted, which is suitable for application to different types of plasmas. Data from the flexible multi-aperture RF-based caesium-free negative ion source NIO1 are studied, which exhibit saturation in the extracted negative oxygen current depending on the plasma parameters.

NIO1 experiment

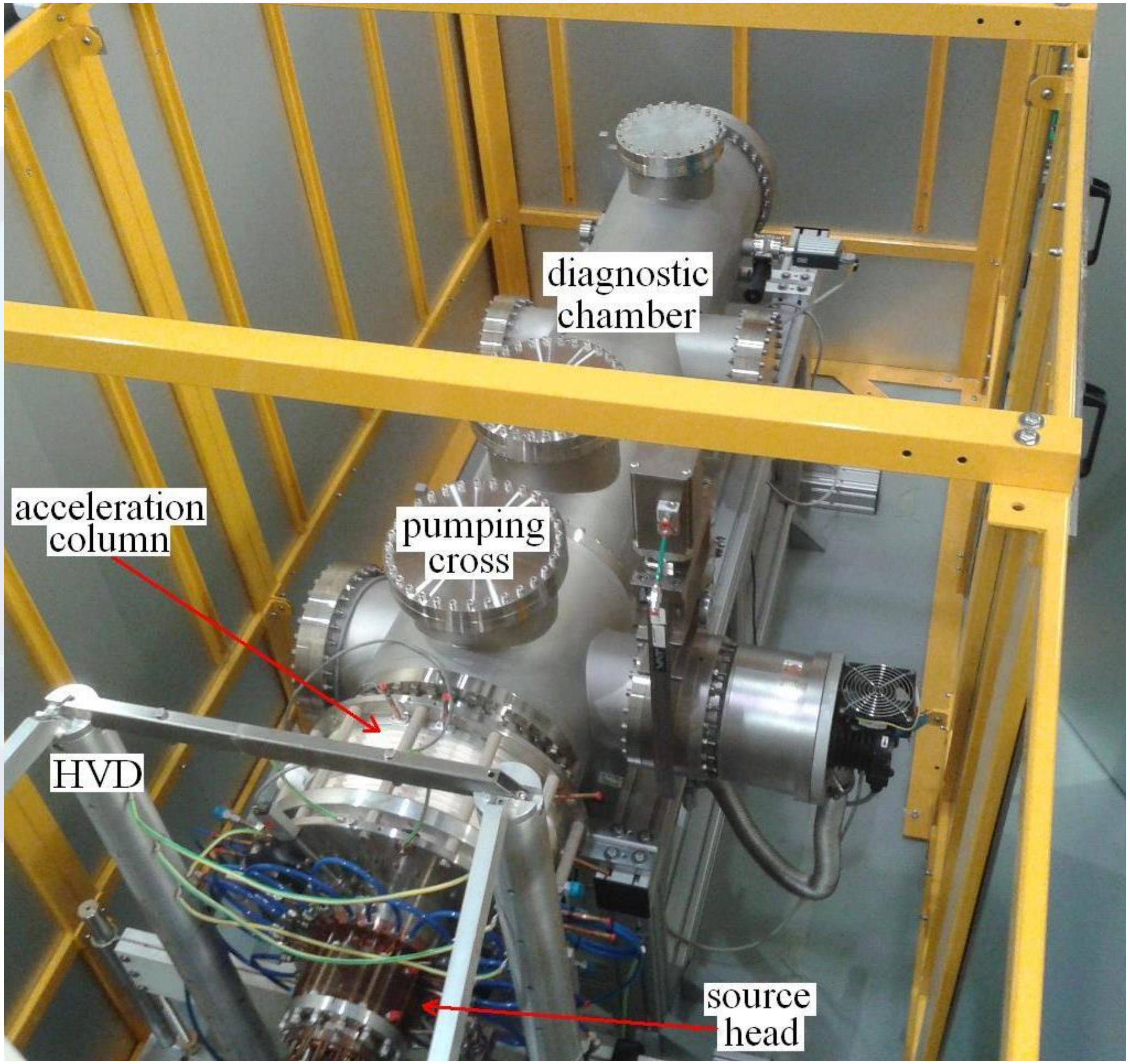
- Source of Negative ions
  - Inductively-Coupled Plasma: RF, 2 MHz
  - Multi-stage Accelerator: PG, EG, PA, Repeller
  - Steady state (cw) operation
  - Operated with different gases: Air, H2, O2
- Design values: 130 mA of H- at 60 KeV
- Present performances (without caesium)
  - $I_{H-} \leq 7$ mA,
  - $I_{O-} \leq 3$ mA,
- Different B configurations possible
- E-H mode transition





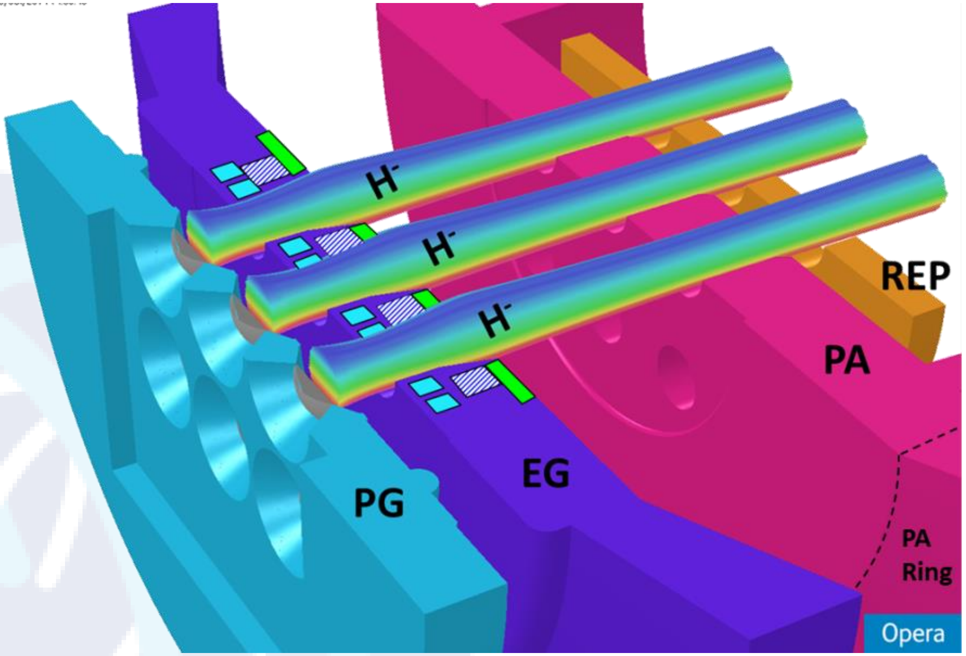
Negative Ion Optimization, phase 1 (NIO1)

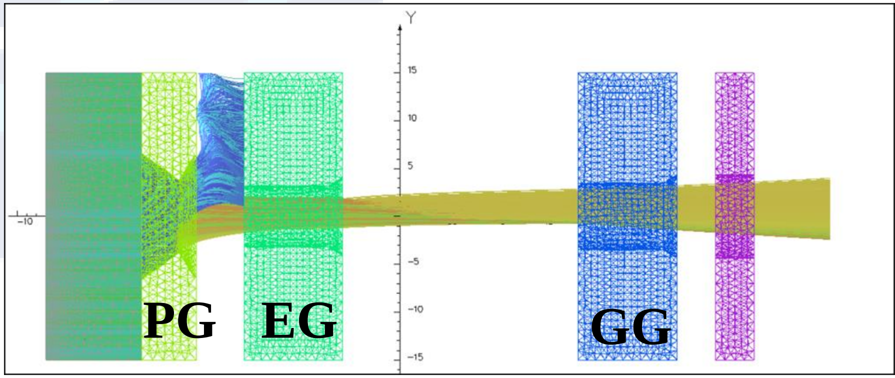
- Source of negative ions
- ICP plasma (RF):
  - 2MHz, 2.5kW
- Multi-stage accelerator:
  - PG, EG, PA, Repeller
- Steady state operation
- Different filling gasses:
  - H_2, air, O_2, O_2/Ar mix
- Target parameters:
  - I_{H-} = 130mA
  - E_{beam} = 60keV



Acceleration and deflection of particles

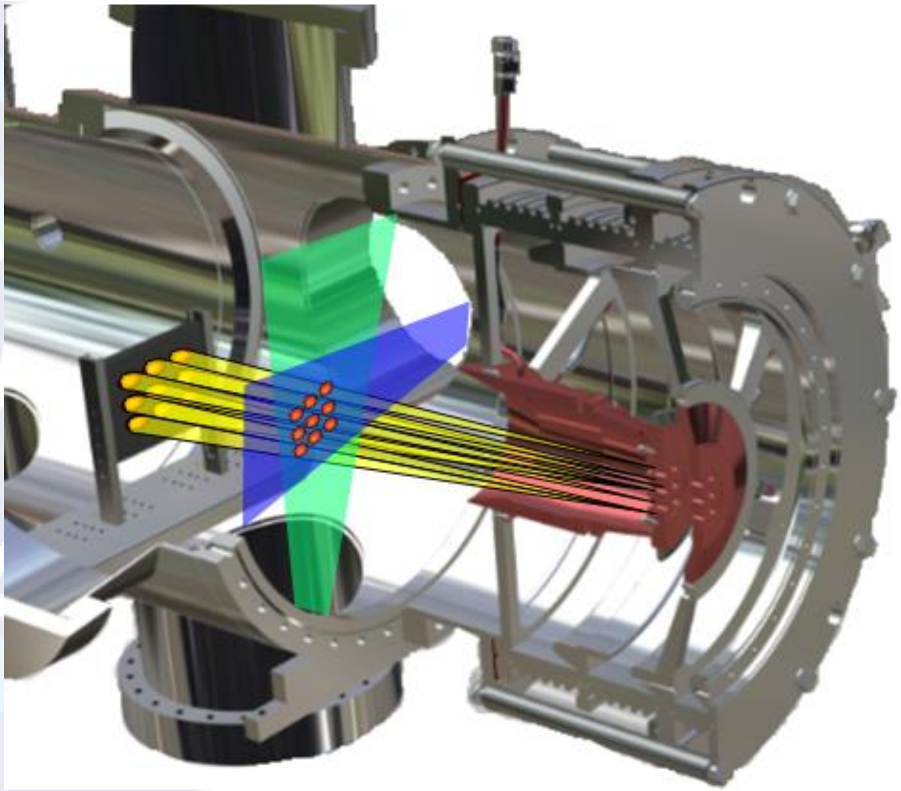
- Optics formed by extraction grid
- Co-extracted electrons deflected onto EG thanks to perm. magnets
- Collision of H^- with background H_2
  - H not accelerated to full energy
  - H^+ and H_2^+ back-streaming
  - electrons deflected onto grids
- H^- beam ionising H_2
- H_2^+ compensating for H^- space charge
  - H^- beam can propagate





NIO1 diagnostic systems

- Source:
  - Spectroscopy (many Lines of sight)
  - cavity ring down
  - Langmuir probes
- Beam:
  - Electric Measurements (H- /e- current)
  - Graphite fibre calorimeter+ IR camera
  - Beam emission Spectroscopy
  - 2D CCD and linear CCD
- Beam plasma:
  - Langmuir probe
  - Retarding field energy analyzer



Richardson & Child laws

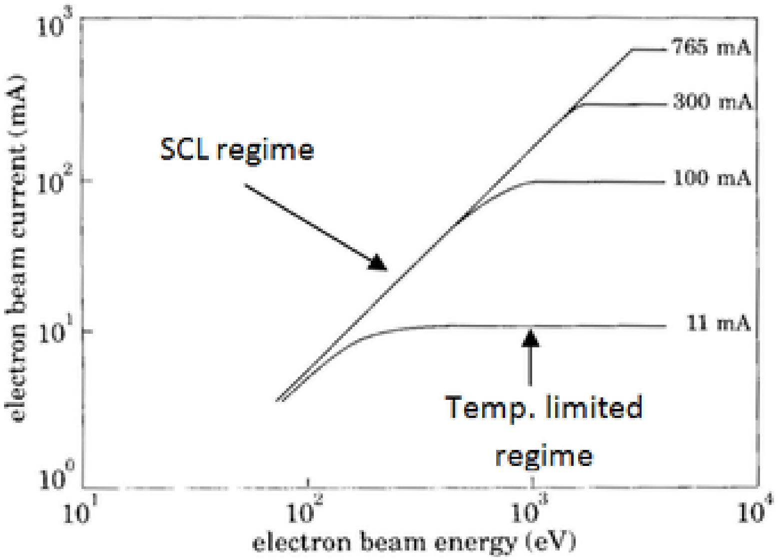
- Thermionics studies electron emission from conductor
- Richardson: extracted current VS cathode temperature
  - not enough energy if the cathode too cold

$$j_R = A_o T^2 \exp\left(-\frac{W}{kT}\right)$$

- Child: extracted current VS extraction voltage
  - space charge limits emission

$$j_{CL} = \frac{4\varepsilon_o}{9d^2}\sqrt{\frac{2q}{m}}V_a^{3/2}$$

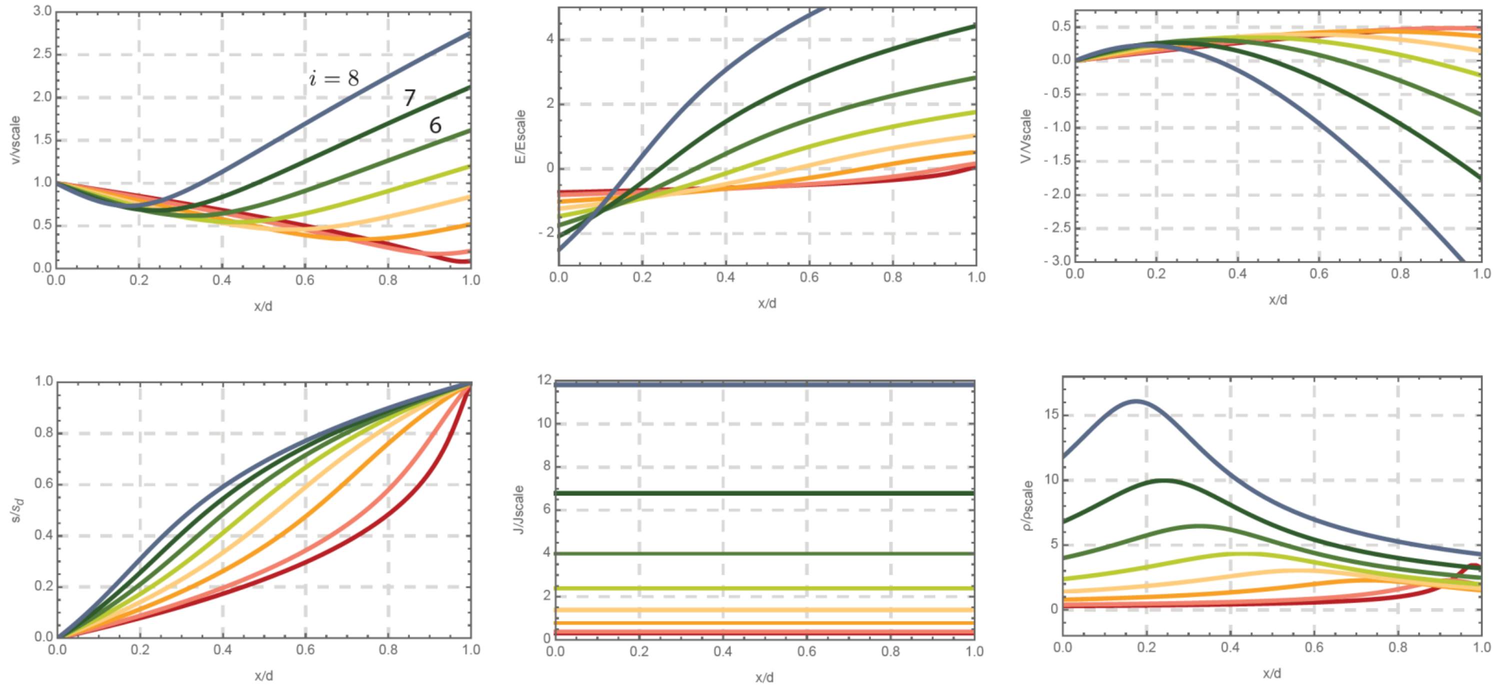
- The overall extracted current is the lower



Single particle model

- Hypotheses:
  - 1D; no divergence of the beam (optics)
  - steady-state: decoupled Maxwell equations
  - small currents: only external B
- Adimensional formulation; treatment with s and x

$$J[s] = J_0$$
$$E[s] = E_0 + J_0\ s$$
$$v[s] = v_0 + E_0\ s + J_0 \frac{s^2}{2}$$
$$x[s] = v_0\ s + E_0 \frac{s^2}{2} + J_0 \frac{s^3}{6}$$
$$V[s] = \frac{1}{2}\left(v[s]^2 - v_0^2\right)$$
$$\rho[s] = J[s]/v[s]$$



Two-species model

- Superposition of effects

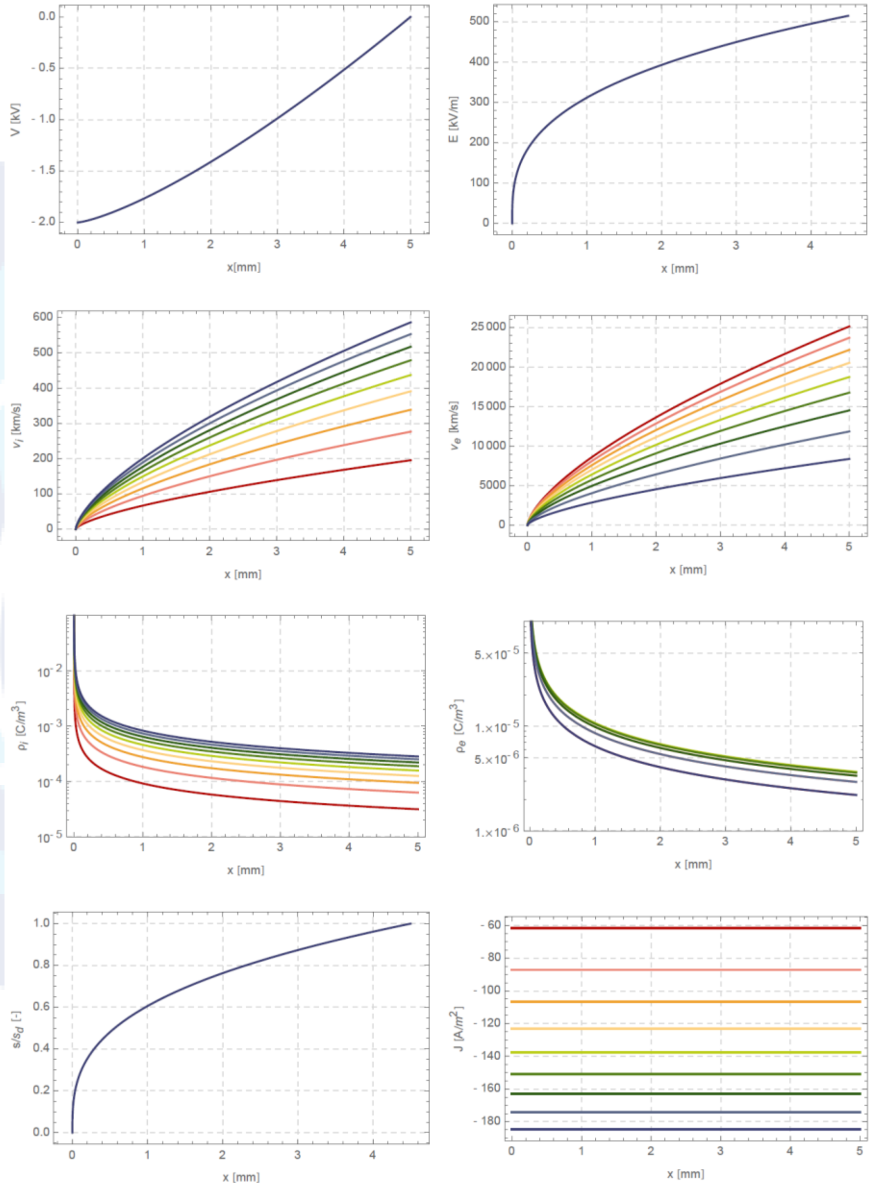
$$J[s] = J_0$$

$$E[s] = E_0 + J_0\ s$$

$$x_i[s] = v_{i0}\ s + \gamma_i E_0 \frac{s^2}{2} + \gamma_i J_0 \frac{s^3}{6}$$

$$V[x] = \frac{1}{2\gamma_i}\left(v_i[x]^2 - v_{i0}^2\right)$$

$$\rho[x] = J_0 \frac{\gamma_e}{v_i[x]}\left(\frac{v_i[x]}{v_e[x]} + \frac{\gamma_i}{\gamma_e}\right)$$



Child-Langmuir law generalisation

- Two species
- Non-zero initial speed

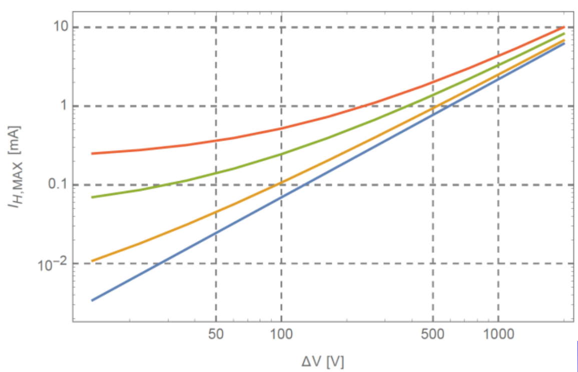
$$E_{0,\max} = -\frac{2v_{i0}}{\gamma_i \; s_d}$$

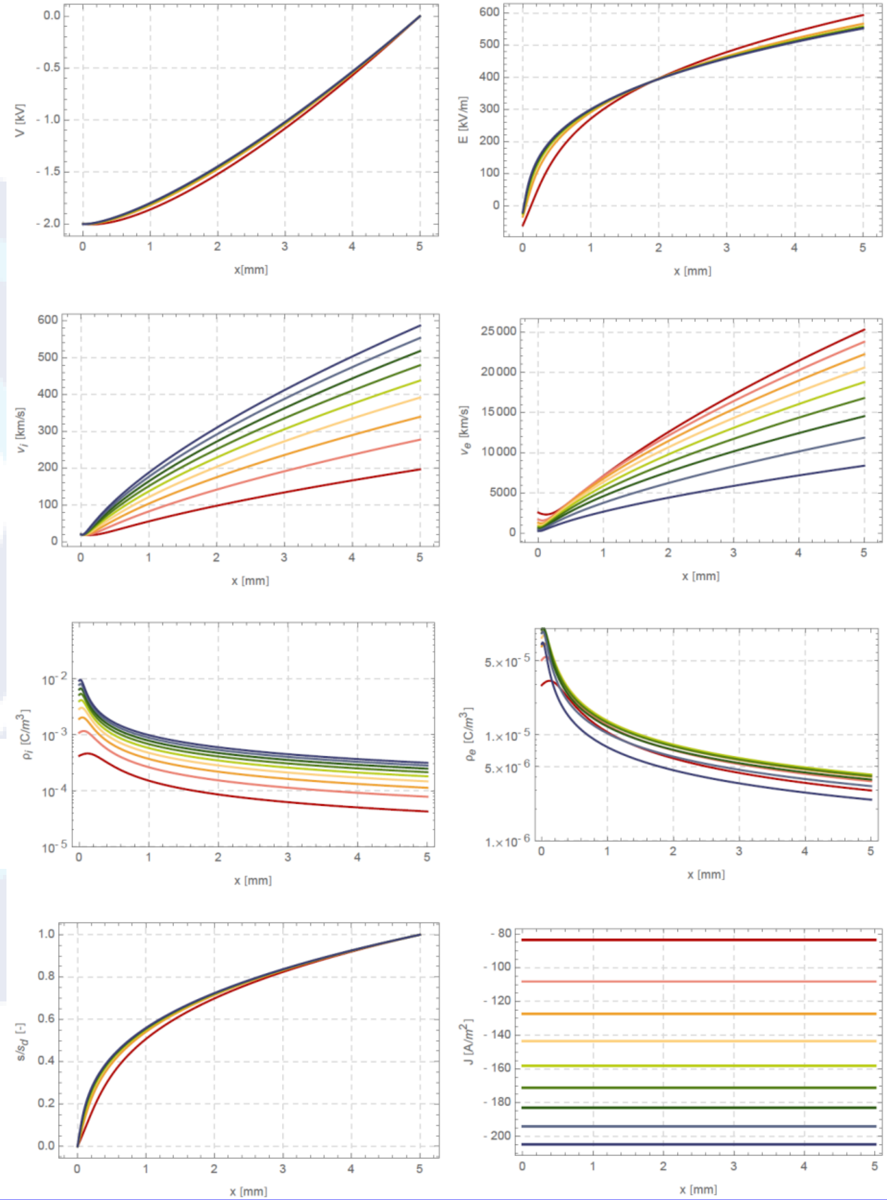
$$s_{d,\min} = \sqrt[3]{\frac{6d}{J_0 \; \gamma_i}}$$

$$V_{d,\min} = -\frac{1}{2\gamma_i} v_{i0} \sqrt[3]{36d^2 J_0} + \frac{1}{8\gamma_i}\left(36d^2 J_0\right)^{2/3}$$

$$J_{\max} = \frac{2}{\gamma_i \; 9d^2}\left(v_{i0} + \sqrt{v_{i0}^2 + 2\gamma_i \; V_d}\right)^3$$

$$J_{\max[\mathrm{SI}]} = \frac{2J_{\mathrm{scale}}}{9\gamma_i (d_{[\mathrm{SI}]}/L)^2}\left(\frac{v_{0[\mathrm{SI}]}}{v_{\mathrm{scale}}} + \sqrt{\left(\frac{v_{0[\mathrm{SI}]}}{v_{\mathrm{scale}}}\right)^2 + 2\gamma_i \frac{V_{d[\mathrm{SI}]}}{V_{\mathrm{scale}}}}\right)^3$$





Oxygen data in NIO1: I-V curves

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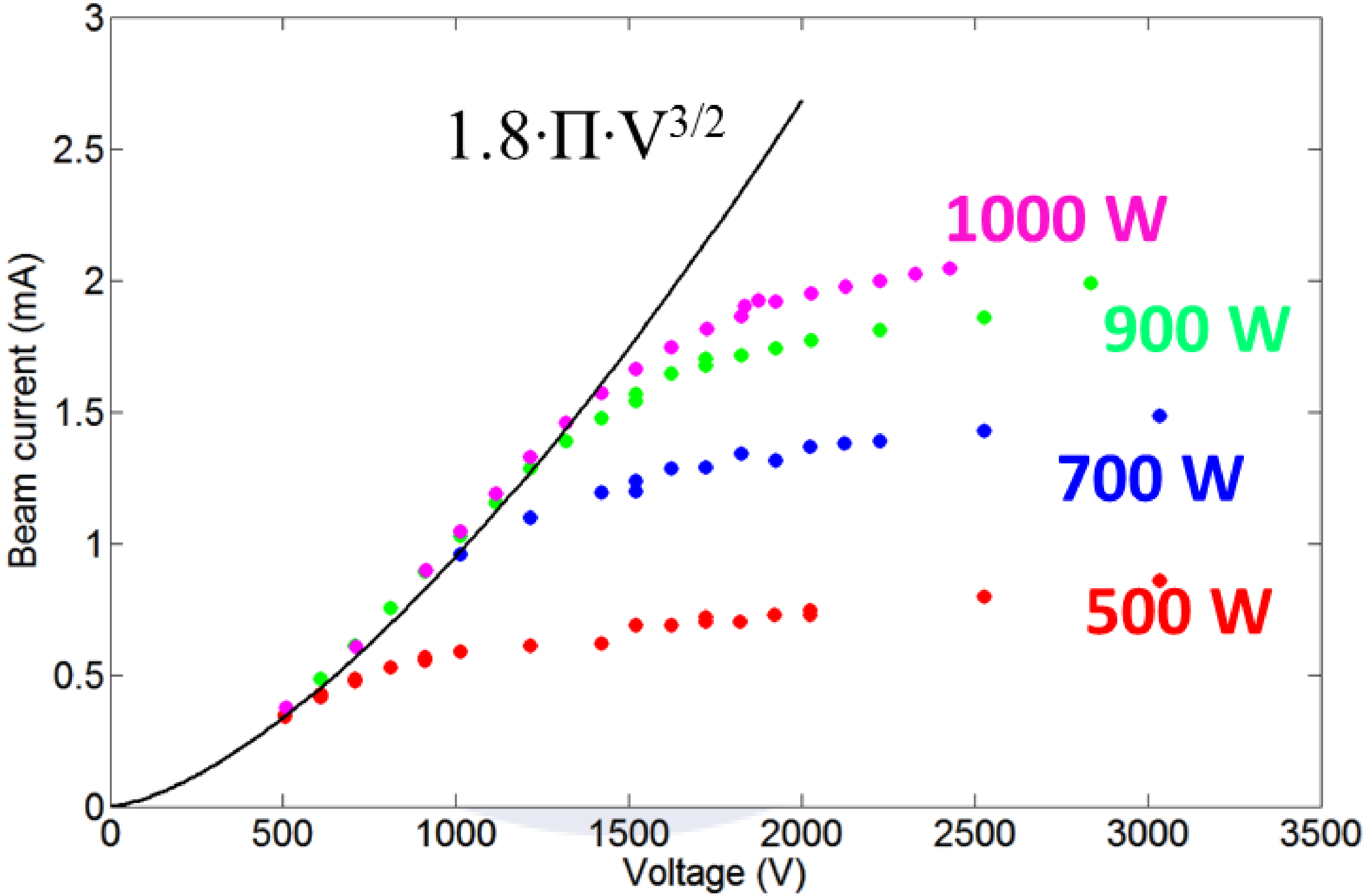
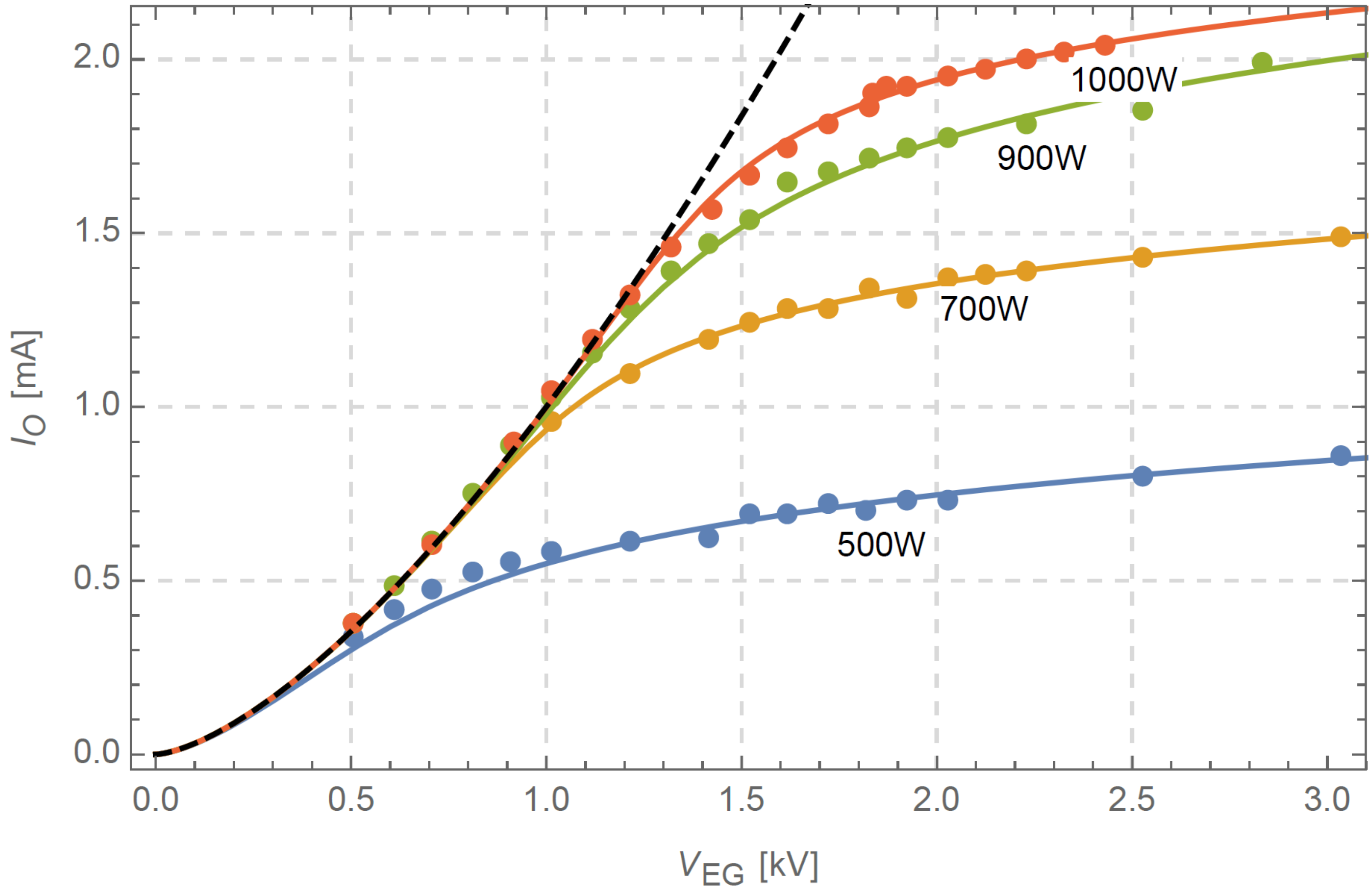
O^- beam
p=0.35 Pa

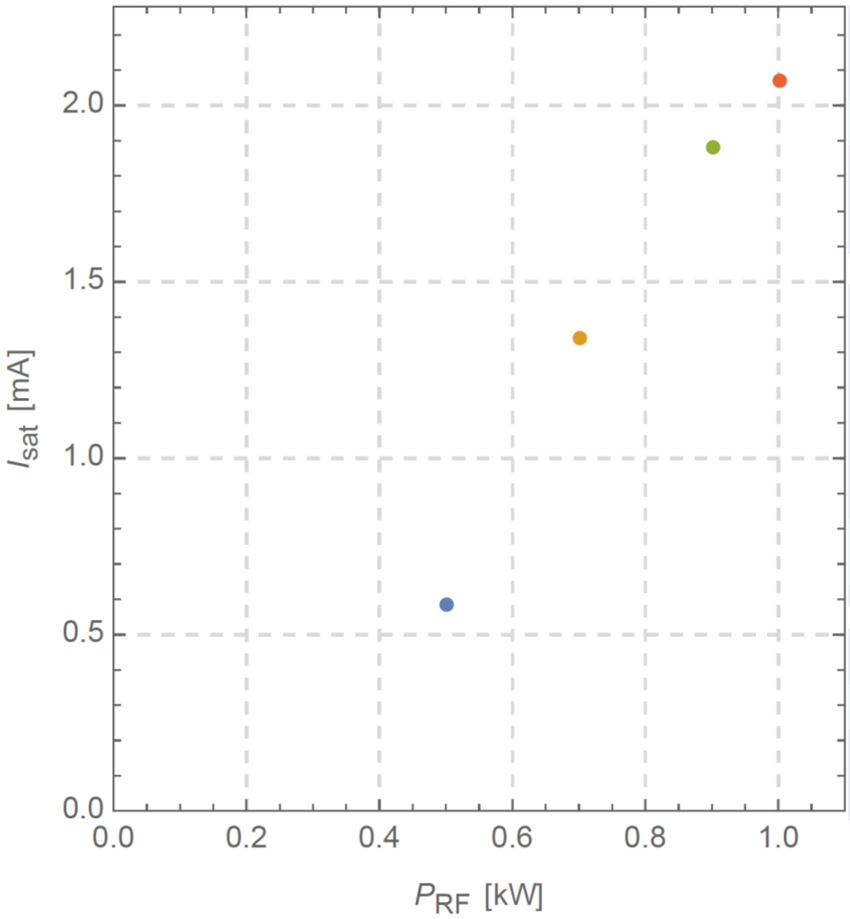


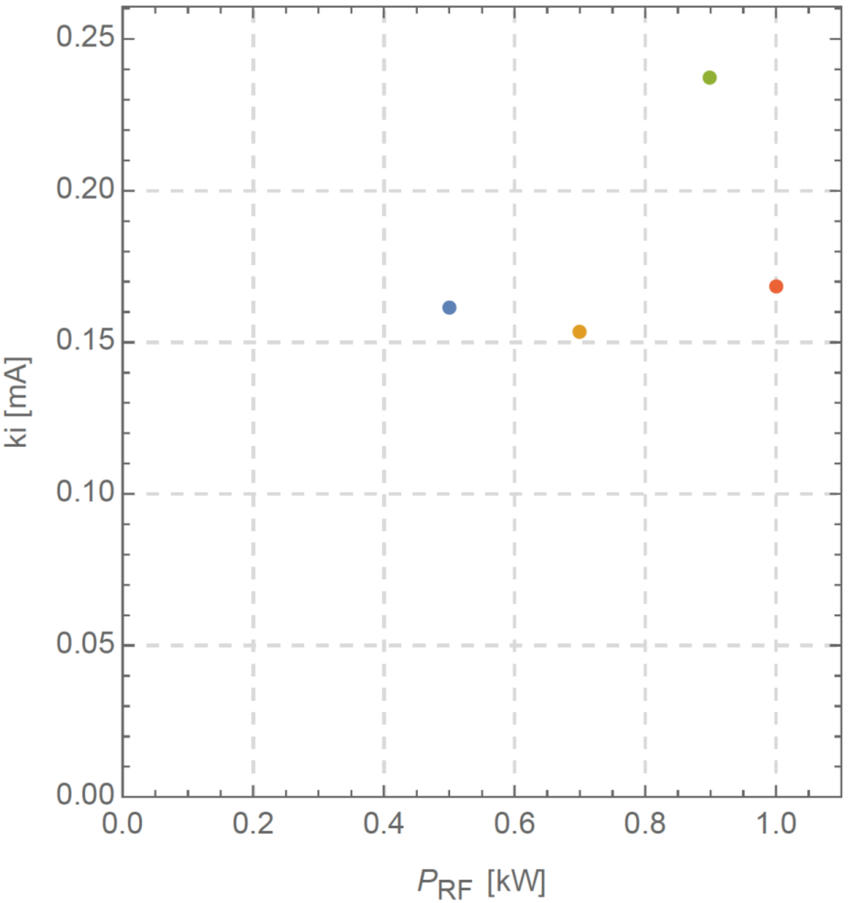
Oxygen data in NIO1: I-V curves



$$V_{EG} = I\left(1 + \exp\left(\left(I - I_{sat}\right)/k_i\right)\right)^{2/3}$$

Oxygen data in NIO1: fit parameters





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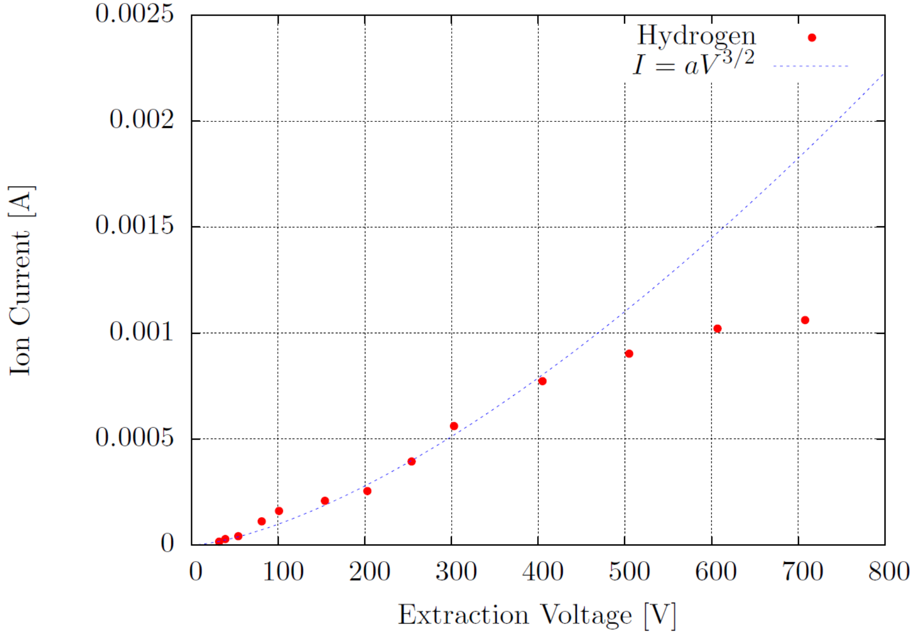
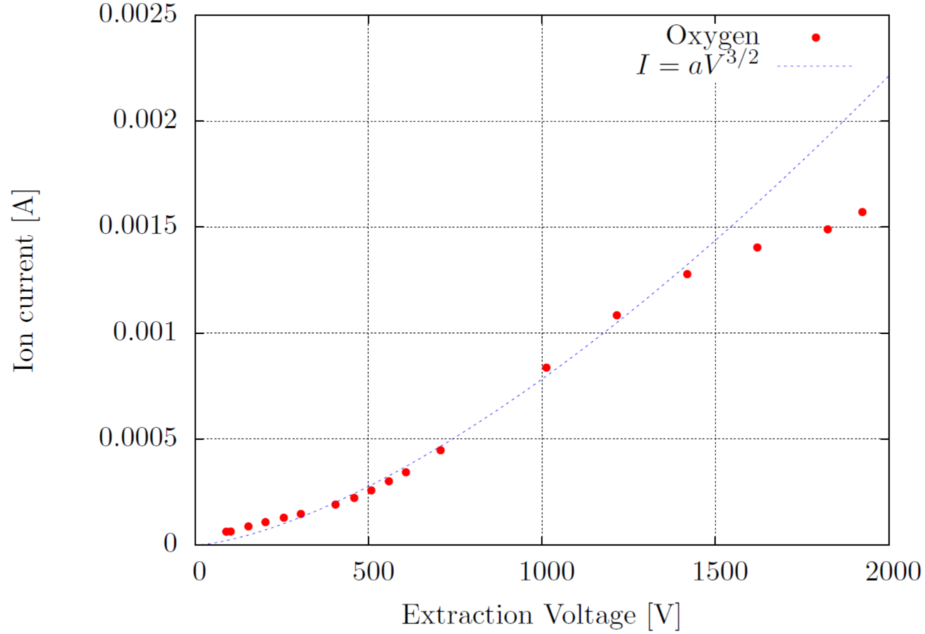
Comparison of oxygen and hydrogen

$$\frac{\Pi_O^{teor}}{\Pi_H^{teor}} = \sqrt{\frac{m_H}{m_O}} = 3.99$$

Gas	a^{fit} ($\times 10^{-8}$ A/V$^{3/2}$)
0	2.46 ± 0.07
H	9.85 ± 0.29





Summary

- The present paper presents a phenomenological interpretative model for the current extracted and accelerated from an ion source; the model reduces to the usual Child-Langmuir law at low voltages, whereas at high voltage it reproduces the saturation observed in experiments. The saturation seems to depend on the source parameters and can be interpreted as ruled by the availability of particles inside the source