ASTERICS ion beam extraction system optimization by simulation

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Abstract

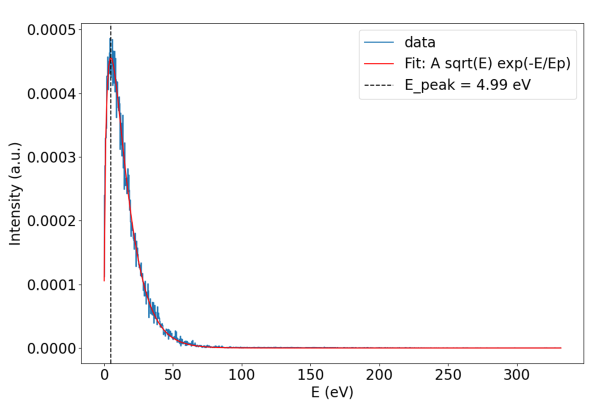
As part of the NEWGAIN project [1], the ECR ion source ASTERICS aiming at delivering a continuous beam of 10 pμA U^{34+} is under development [2]. This work reports the parametric simulation study of ASTERIC's ion extraction triode system using the IBSimu C++ library [3], focusing on an argon (Ar) beam. The simulations include the ion source 3D magnetic field and a space charge compensation model that takes into account the presence of hot electrons escaping the plasma. An initial series of simulations was carried out to identify the parameters that most strongly affect beam emittance. These key parameters were then optimized using a differential evolution algorithm to minimize the emittance of the Ar^{12+} beam. Finally, starting from the optimized settings, parametric studies were performed to evaluate how variations in the extraction gap, extraction angle, plasma-electrode curvature radius, and extraction-electrode potentials influence both the beam emittance and the extracted current.

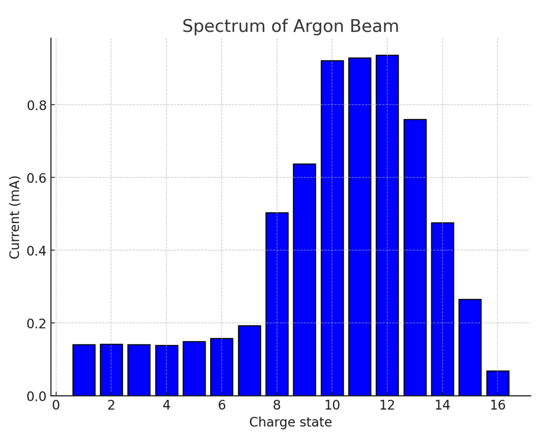
Extraction simulation with IBSimu

Ions and plasma parameters in IBSIMU :

- Plasma sheath temperature T_e = 10 eV
- Plasma potential U_p = 30 V
- Beam current density J = 90 A/m²
  - Beam current ≈ 6,5 mA
  - Ar^{12+} current ≈ 0,93 mA
- Ion transverse and parallel energy spread $T_p = T_t$ = 10 eV
- Ion energy E_0 = 0,1 eV

Ions energy distribution (E_{peak} = 5 eV)



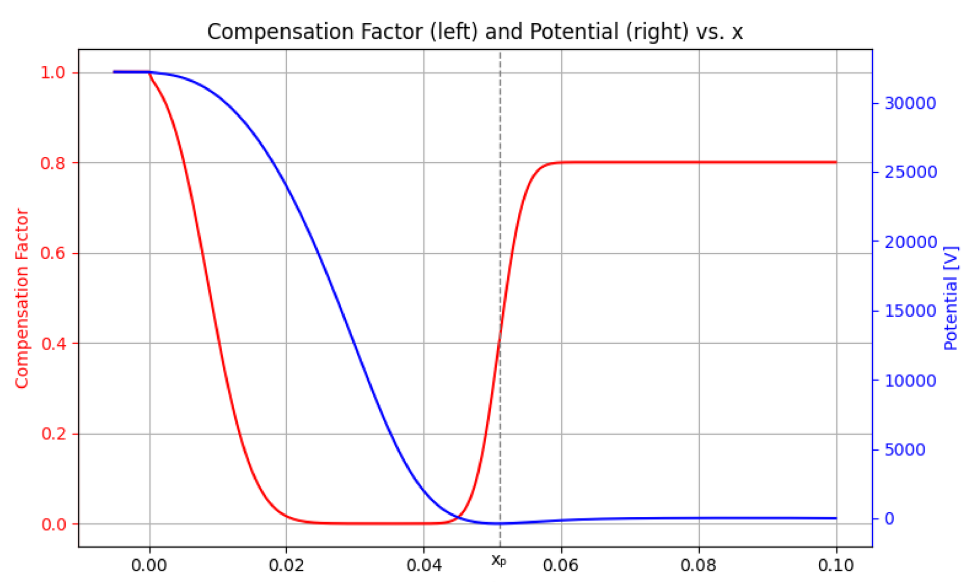


Space charge compensation profile :

- Implementation of a space charge compensation profile $f(x)$ to take into account the hot e⁻ escaping the source
- Transition between the accelerating gap and the drift region where the beam is compensated at 80%

$$f(x) = e^{-\frac{\Delta V(x)}{T_{e hot}}} + \frac{1}{2} f_c \left(1 + \mathrm{erf}\left(b(x - x_p)\right)\right)$$

- where x is the beam propagation direction,
- x_p is the coordinates corresponding to the potential minimum on the axis ($V(x_p) < 0$ location of the negative puller electrode),
- b is a smoothing parameter for the transition,
- f_c is the compensation factor in the LEBT and T_e^{hot} is the hot e⁻ temperature T_e^{hot} = 2000 eV



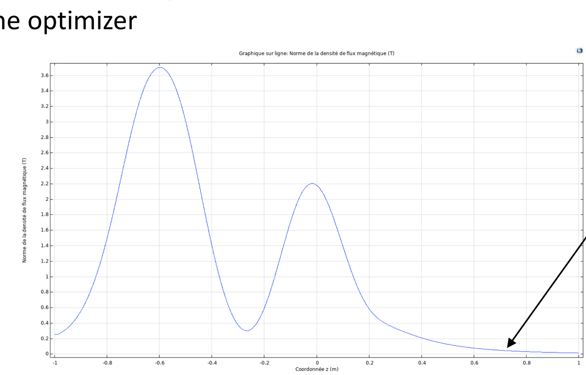
Geometry and optimization parameters

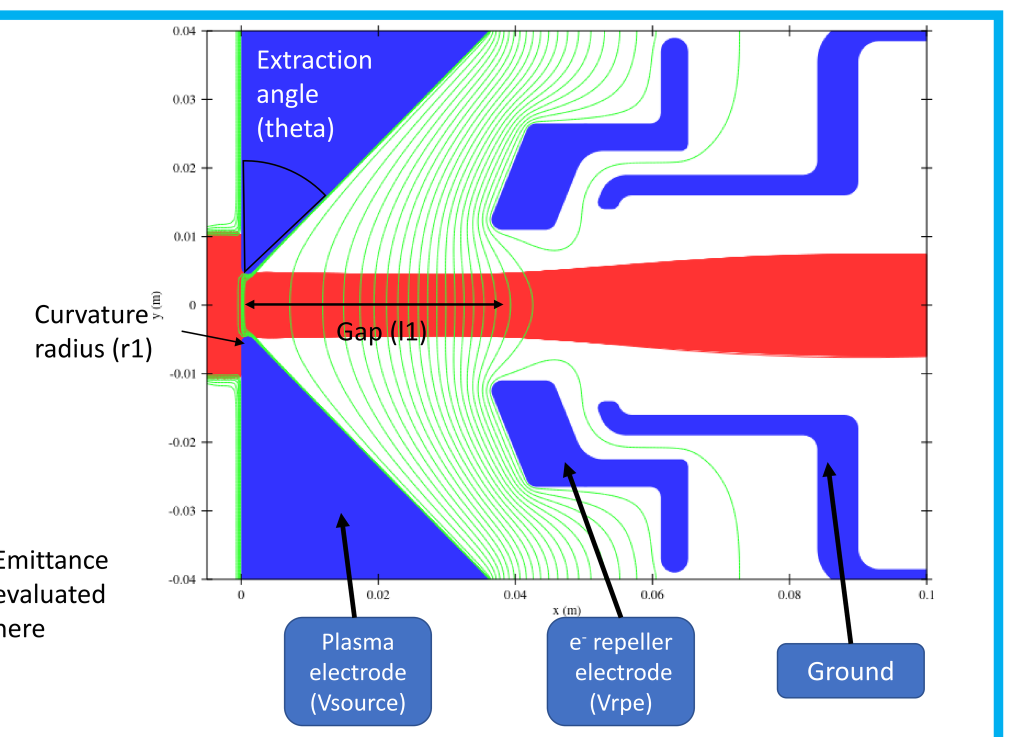
- Plasma electrode potential (Vsource) : 20kV to 40kV
- e⁻ repeller electrode (Vrpe) : -1kV to -10kV
- Gap : 22mm to 60mm
- Extraction angle : 5° to 45°

The goal is to minimize the total normalized transverse emittance

$$\varepsilon_{tot,n} = \beta\gamma\sqrt{\varepsilon_y{}^2 + \varepsilon_z{}^2}$$

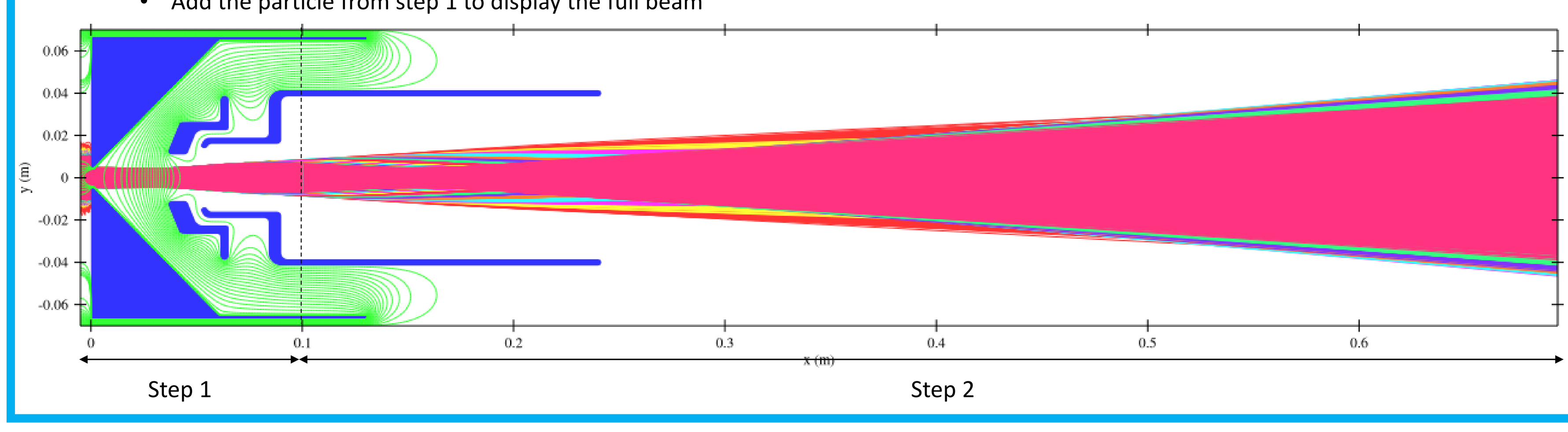
for the Ar^{12+} beam while having 0% loss.
The emittance is evaluated at the end of step 2 at x = 700mm from the extraction to avoid any fluctuations in the emittance that may influence the optimizer



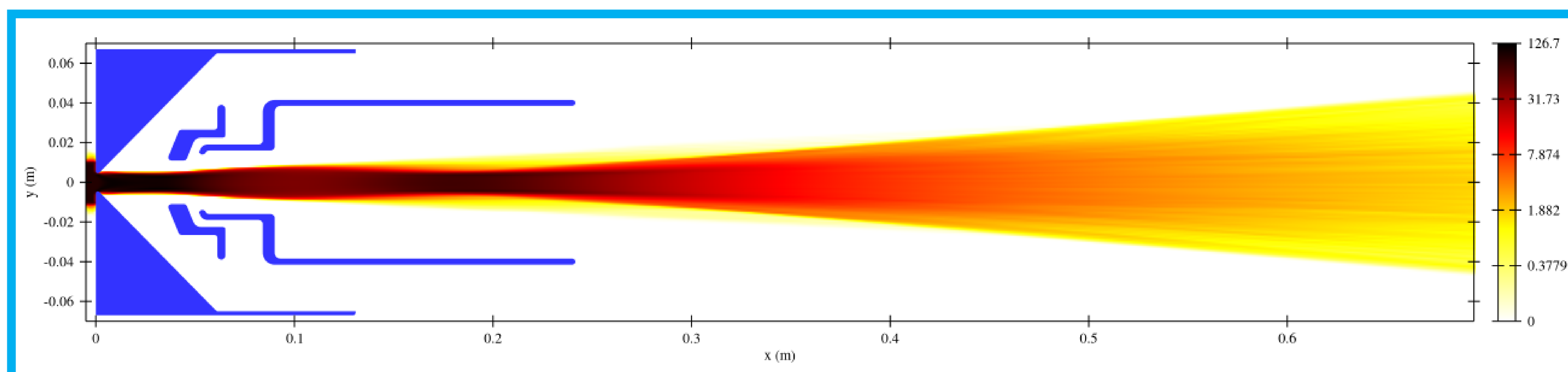


2 steps simulation

- **Step 1 :**
  - 10^6 particles
  - Mesh size 0,5 mm
  - Range up to 0,1 m in the propagation direction and 0,04 m in the transverse planes
  - Plasma model to compute the plasma sheath
  - Return the full particle data base with the trajectories
- **Step 2 :**
  - Mesh size 1 mm
  - Range up to 0,7 m in the propagation direction and 0,07 m in the transverse planes
  - Use the particle at the exit plane of step 1
  - Add the particle from step 1 to display the full beam



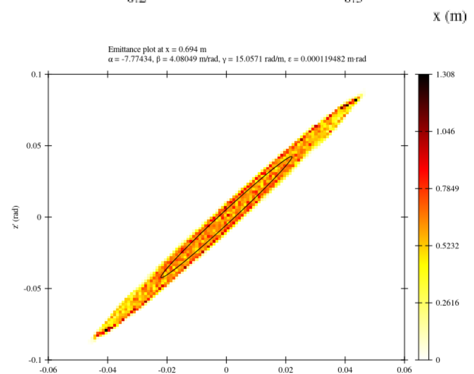
Optimization result



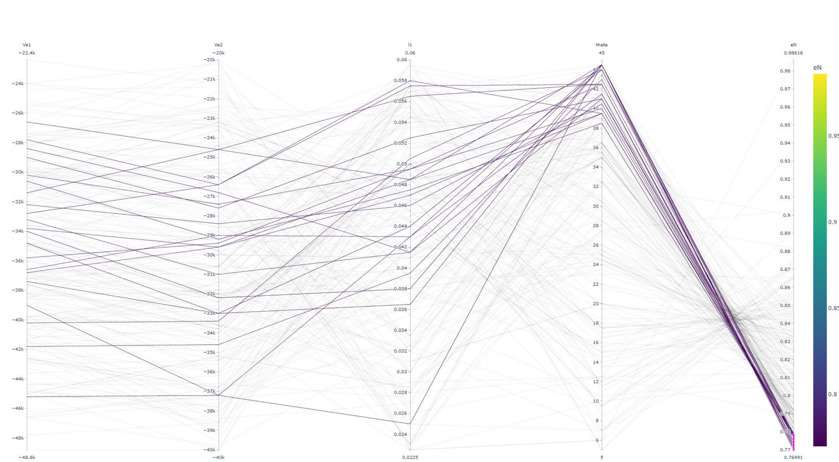
Optimization result :

- Gap = 38 mm
- Extraction angle = 44,5°
- Vsource = 32,2kV
- Vrpe = -1,8kV

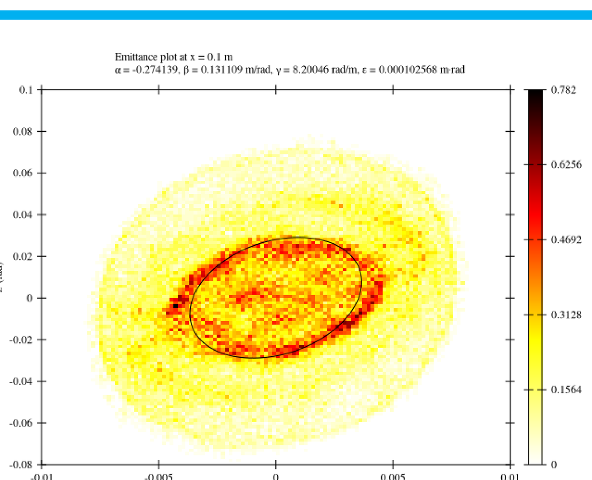
Normalized emittance at x =700mm for Ar^{12+}
$\varepsilon_{tot,n}$ = 0,77 mm.mrad
(0,245 π.mm.mrad)



Parallel plot of the optimization. Simulations with an emittance below 0,78 mm.mrad are highlighted : Except for the angle, a wide range of gap and potential allow to minimize the emittance



Preliminary test with U beam

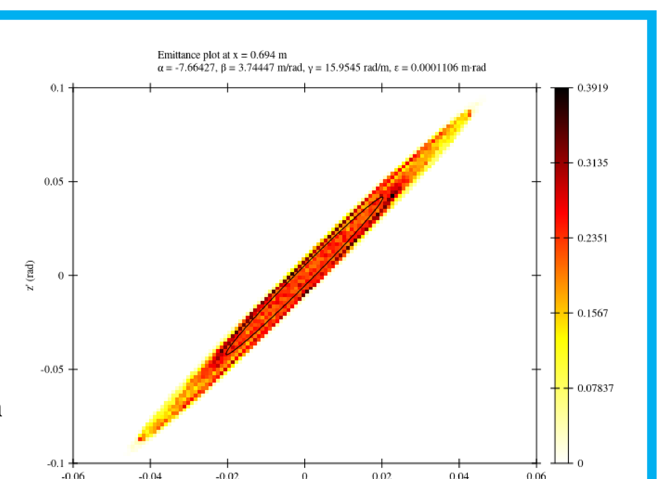


Emittance at 100mm

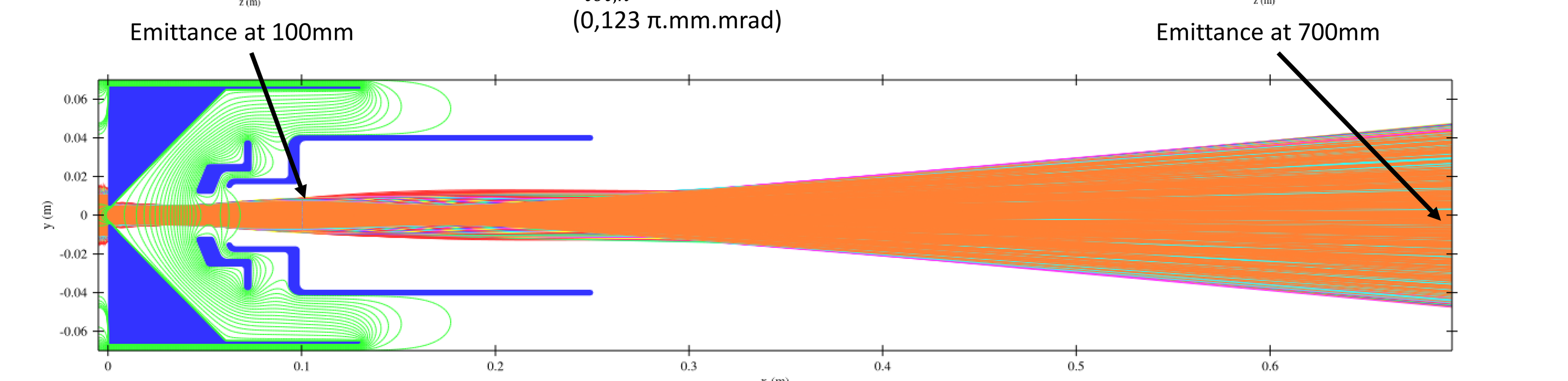
Simulation with Uranium beam :

- Total current : 5,17 mA
- Ions :
  - O 1+ to 6+
  - U 8+ to 46+
- Gap 47 mm
- Vsource : 20kV
- Vrpe = -7400V

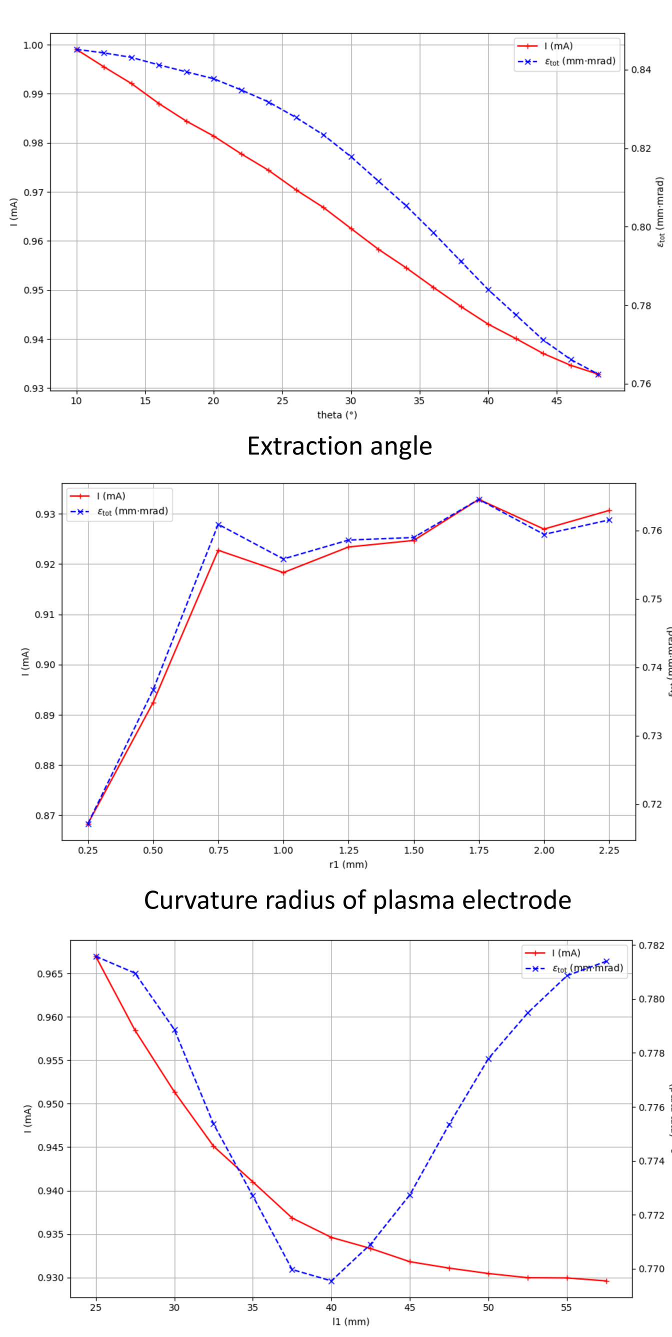
Normalized emittance at x =700mm for U^{34+} :
$\varepsilon_{tot,n}$ = 0,387 mm.mrad
(0,123 π.mm.mrad)

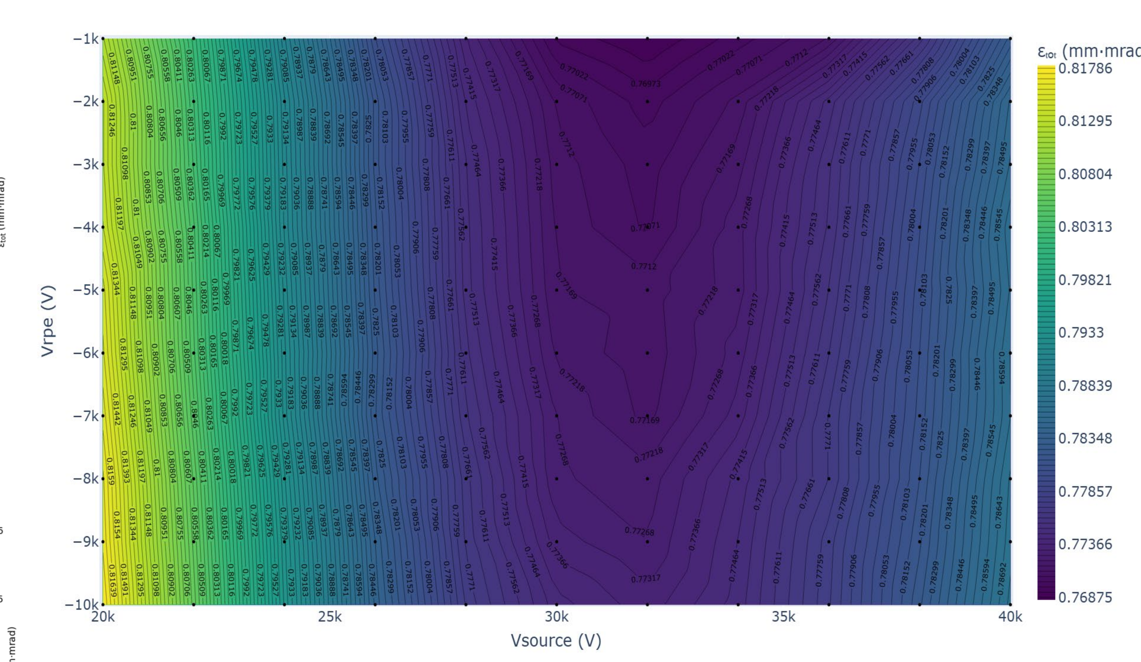


Emittance at 700mm



Parametric study





Parametric study based on optimized simulation : Variation of geometry parameters and potentials

- Gap : existence of an emittance minimum with a gap at 40 mm, decrease of current with the length of the gap
- Curvature radius : increase of emittance and current with the radius and then stable beyond r1 = 0,75mm
- Extraction angle : decrease of emittance and current with the angle. Minimum reached for the maximum angle
- Potentials : Minimum of emittance for a source potential of 32kV. Not much variation observed with the potential on the electron repeller electrode

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