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NUMERICAL AND EXPERIMENTAL STUDY OF H- BEAM DYNAMICS IN J-PARC LEBT

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Abstract

Transport process of negative hydrogen ion (H-) in LEBT (Low Energy Beam Transport) is investigated by comparison of experimental and numerical results. A three dimensional Particle-In-Cell (PIC) particle transport model has been developed in order to take into account (i) axial magnetic field by two solenoids in J-PARC LEBT and (ii) radial electric field by space charge (SC) effect. Ratio of H- beam particles inside the RFQ (Radio Frequency Quadrupole) acceptance to the total particles at the RFQ entrance is calculated for different current conditions in LEBT solenoid 1 and 2. The results are compared with RFQ transmission rate measured in the J-PARC linac commissioning. The double peak of RFQ transmission rate to the solenoid applied current seen in the measurement is explained by the calculation results. The results indicate that presence of the LEBT orifice for differential pumping plays a role as a collimator to reduce emittance at RFQ entrance.

J-PARC Linac Commissioning for IS/LEBT

- H- beam extracted from the ion source (IS) is transported through the LEBT (Low Energy Beam Transport) and injected to the RFQ (Radio Frequency Quadrupole).

- Commissioning parameter in the Ion Source :
  - **AMFC** (Axial Magnetic Field Correction) coil current
    → Is plasma stability, Ion extraction plane
  - **Extraction Voltage / Acceleration Voltage**
    → Beam energy up to 51 -52 keV (RFQ longitudinal matching)
    Initial emittance of the beam in LEBT
  - **Steering electromagnet current** (STM) in horizontal/vertical directions
    → Beam axis steering in LEBT

- Commissioning parameter in the LEBT:
  - **Solenoid 1 (SOL1) and Solenoid 2 (SOL2) current**
    → Emittance reduction and Twiss matching at the RFQ entrance

Figure 1: A Schematic drawing of J-PARC IS/LEBT.

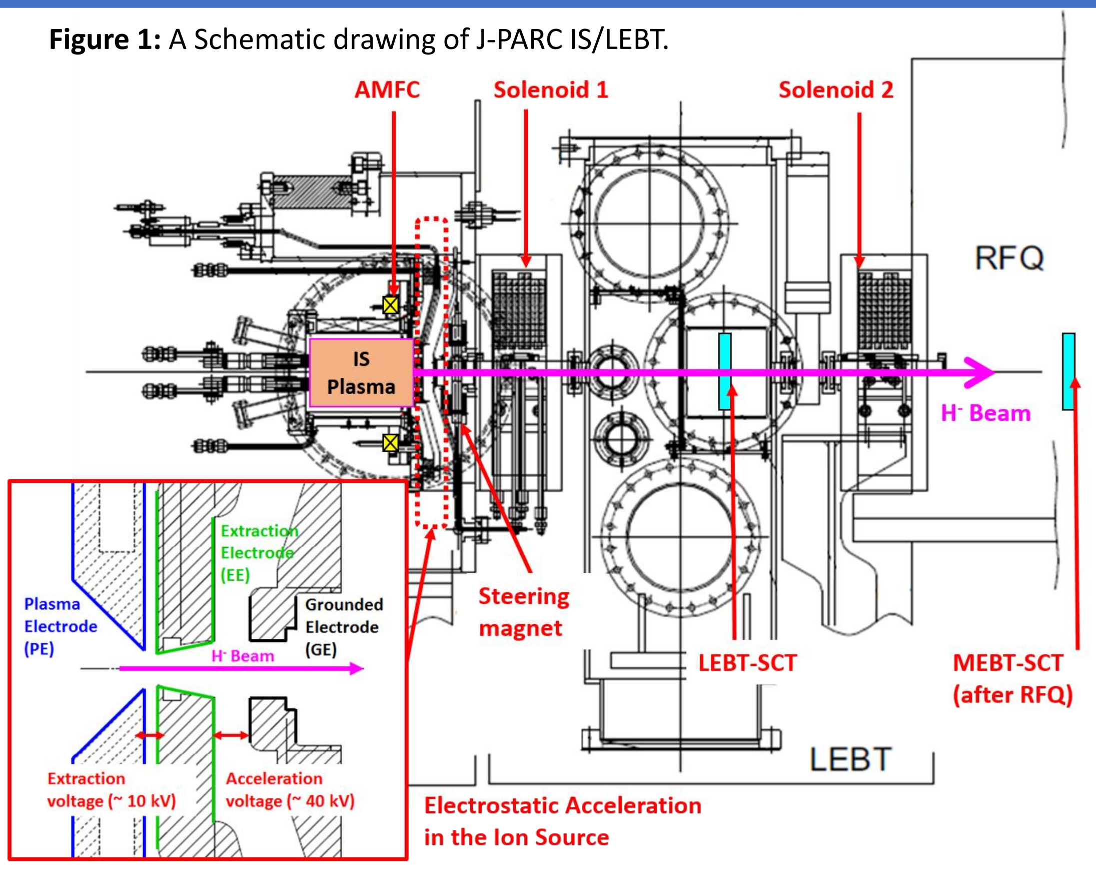

Table 1: Recent results of J-PARC linac commissioning for IS/LEBT in the LINAC 30 mA user operation (left), LINAC 40 mA user operation (center) and LINAC 60 mA accelerator study (right). As the H- beam current is increased, optimum SOL 1&2 current settings becomes higher.

Commissioning parameters	LI 30mA (2015 User operation)	LI 40 mA (2017 User operation)	LI 60 mA (2018 Acc. study)
AMFC coil (V)	0.0	2.0	4.0
Ext. voltage (kV)	9.9	9.8	10.3
Acc. Voltage (kV)	42.0	42.5	42.5
Total IS Voltage (kV)	51.9	52.3	52.8
Hori. STM (A)	-1.0	-5.0	-2.0
Vert. STM (A)	-5.5	-4.0	-5.0
LEBT SOL1 (A)	495	500	540
LEBT SOL2 (A)	600	620	680

Characteristic IS/LEBT Commissioning Results

- The IS/LEBT parameters are tuned to **optimize MEBT-SCT current** observed just after the RFQ exit or **the RFQ transmission rate** (ratio between currents observed at the LEBT-SCT in the LEBT chamber and the MEBT-SCT).

SOL 1 & 2 scan in LI 30 mA operation (Fig.2)
- **Different peaks in the RFQ transmission rate are observed in the SOL scan.**
- Former peak → SOL1 = 475 – 515 A, SOL2 = 580 – 620 A (wide)
- Latter peak → SOL2 = 575 – 615 A, SOL2 = 640 – 660 A (narrow)

STM (hori./vert.) scan (Fig.3)
- Dependence of the beam current to the horizontal STM is weak.
- The vertical STM shows single peak which corrects beam axis deviation due to Filter Magnet and Electron Suppression Magnet Field in the IS.

RFQ longitudinal matching by Acc. Voltage scan (Fig.6 & 7)
- Beam Energy is decided by total voltage of Electrostatic acceleration in the IS.
- Optimization of the RFQ transmission rate to **the total beam energy is around 52 keV** (corresponding to the Acceleration voltage up to 42 – 43 kV) while the monotonic increase is seen in the LEBT-SCT current in this range.

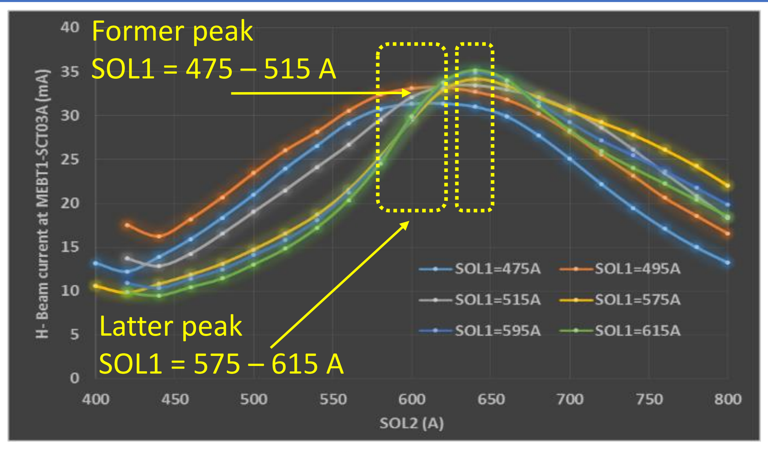

Figure 2: Dependence of MEBT-SCT current to the SOL1 and SOL2 currents in J-PARC Linac 30 mA operation.

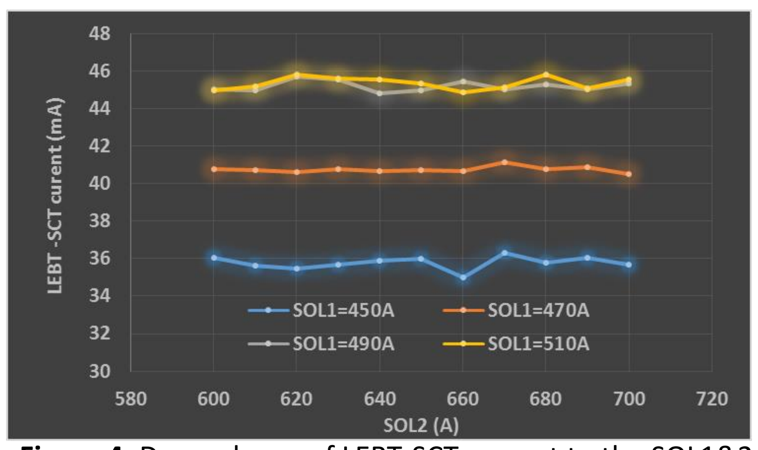

Figure 4: Dependence of LEBT-SCT current to the SOL1&2 current settings in LI 40 mA operation.

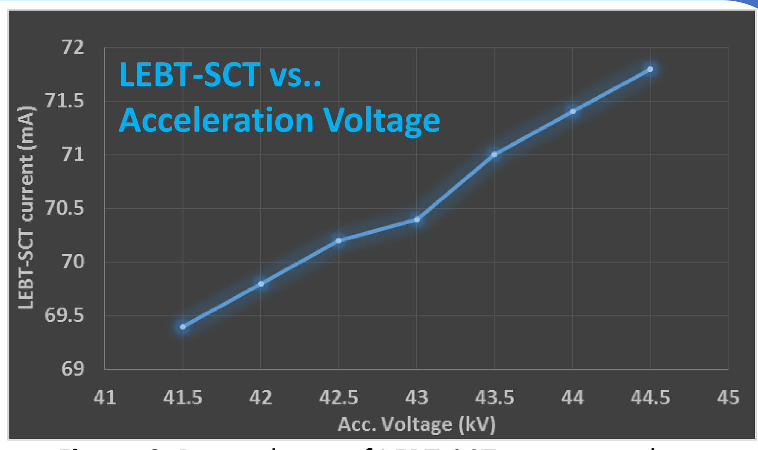

Figure 6: Dependence of LEBT-SCT current to the Acceleration Voltage in LI 60 mA operation.

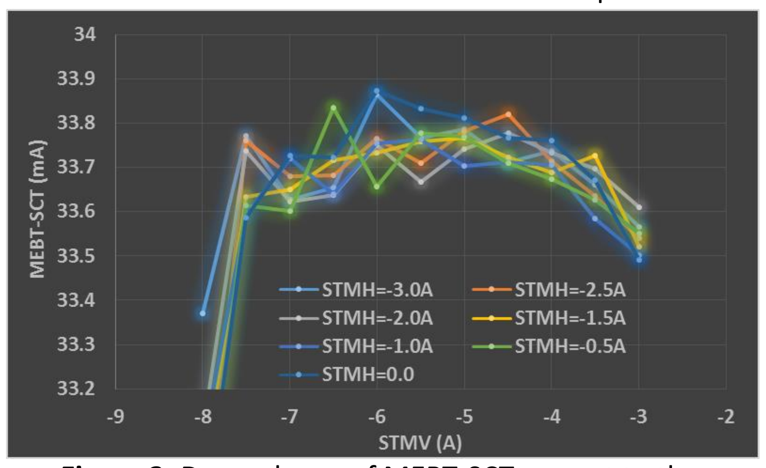

Figure 3: Dependence of MEBT-SCT current to the horizontal and vertical STM currents in LI 30 mA operation.

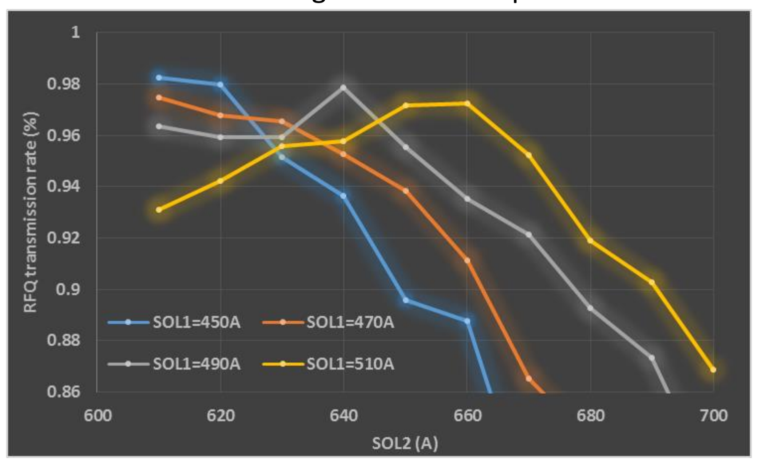

Figure 5: Dependence of RFQ transmission rate to the SOL1&2 current settings in LI 40 mA operation.

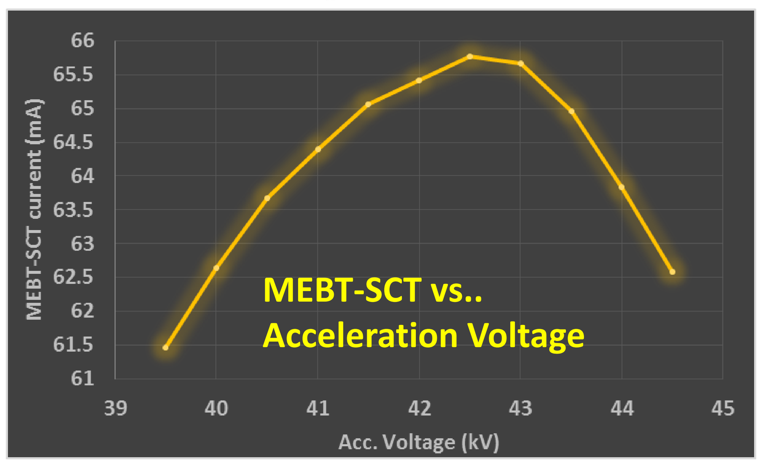

Figure 7: Dependence of MEBT-SCT current to the Acceleration Voltage in LI 60 mA operation.

Numerical Analysis for H- transport in LEBT

- Transport process of negative hydrogen ion (H-) is calculated by **a three- dimensional (3D) Particle-In-Cell (PIC) modeling** [1].
- Effect taken into account in the model;
  - Magnetic Field by SOL1 and 2 with different current settings
  - **Spatial Configuration** of the LEBT chamber and the beam duct
  - **Space Charge (SC) effect** (radial electric field)

Equation of Motions
- Individual H- particle transport is solved in electromagnetic field;

$$m_{\mathrm{H}-}\frac{d\boldsymbol{v}_{\mathrm{H}-}}{dt}=q(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}).$$

$v_{\mathrm{H}-}$: particle velocity, $\boldsymbol{E}$: electric field, $\boldsymbol{B}$: magnetic field

Poisson Equation and Radial Electric Field
- Potential distribution $\phi(r)$ in 2D radial (XY) plane is solved by the space charge distribution $\rho(r)$ obtained from given SC neutralization degree n_{SC}, H- beam current density $J_{\mathrm{H}-}$ and cross-sectional area $S_{\mathrm{H}-}$ at each longitudinal position;

$$\frac{\partial^2\phi(r)}{\partial r^2}=-\frac{\rho(r)}{\varepsilon_0}.$$

$$\rho(r)=-J_{\mathrm{H}-}\times\delta(r_{\mathrm{beam}}-r)\times(1-n_{\mathrm{SC}})/v_{\mathrm{H}-}/S_{\mathrm{H}-}$$

$$E_r=-\frac{\partial\phi}{\partial r}$$

Space Charge neutralization degree

Given parameter in the present calc.;

1. $n_{\mathrm{SC}}=100\%$ → before the orifice (where gas pressure : p_{gas}~10^{-3} Pa)
2. $n_{\mathrm{SC}}=98\%$ → between the orifice and the SOL2 center (p_{gas}~10^{-4} Pa)
3. $n_{\mathrm{SC}}=97\%$ → between the SOL2 center and the RFQ entrance (p_{gas}~10^{-5} Pa)

Conclusion

- The beam transport process in the J-PARC LEBT is investigated by comparison between the experimental results in J-PARC commissioning and the numerical results by PIC simulation. The both results show different peaks of high RFQ transmission rate for SOL1 and SOL2 current variation.
- In the case of the former peak, low emittance is obtained at the RFQ entrance as the orifice takes a role as collimator of the beam which removes growing halo components. On the other hand, for the strong SOL1 and 2 settings, the beam pass through the orifice. This leads to the relatively larger emittance at the RFQ entrance while the similarity of the beam phase space to the RFQ acceptance is obtained.
- The clarifiation of these characteristics observed in the actual commissioning leads to the high reproducibility of the beam optics in each RUN. From these results, the transimssion rate is optimized in the Linac commissioning together with LEBT-SCT current which is measured at just after the orifice to avoid beam cut off at the orifice.

Reference

[1] T. Shibata, *et al.*, "LEBT Commissioning of the J-PARC LINAC", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, paper MOPLR052, pp. 251-253.

Numerical Results

- The numerical analysis also show **two different peaks** of the RFQ transmission rate for SOL1 & SOL2 current scan.

- The **former peak** for **lower** SOL current pair (SOL1 ~ 480 A and SOL2 ~ 540 A) shows wide peak with maximum RFQ transmission rate up to 86.8 %.
- The **latter peak** for **higher** SOL current pair (SOL1 ~ 580 A and SOL2 ~ 640 A) shows narrow peak with the maximum rate up to 90.2 %.

- **Reason of the former peak**: the beam component is not focused enough by weak SOL1 and collides toward the orifice. Since the halo component is collimated at the orifice, low emittance is obtained at the RFQ entrance.
- **Reason of the latter peak**: the beam is well focused by strong SOL1 and pass through the orifice. The SC effect just after the orifice is relatively high which produces strong radial electric field. The expanding beam is focused by the strong SOL2 field. This leads to the high similarity of the phase space to the RFQ acceptance.

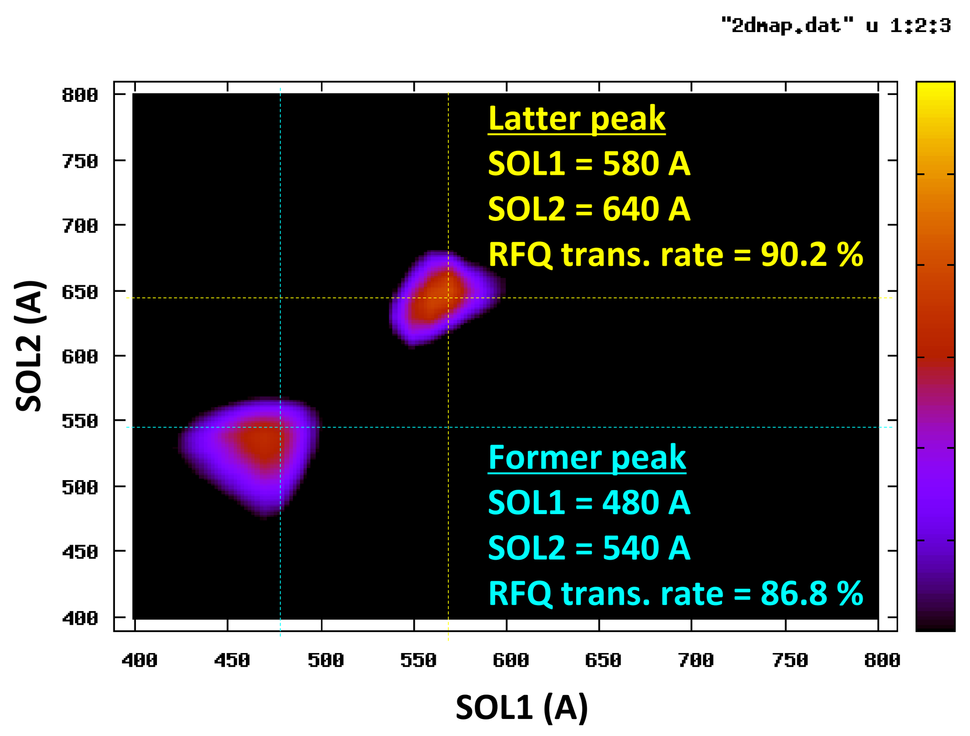

Figure 8: Calculated RFQ transmission rate dependence on the current settings of SOL1 and SOL2.

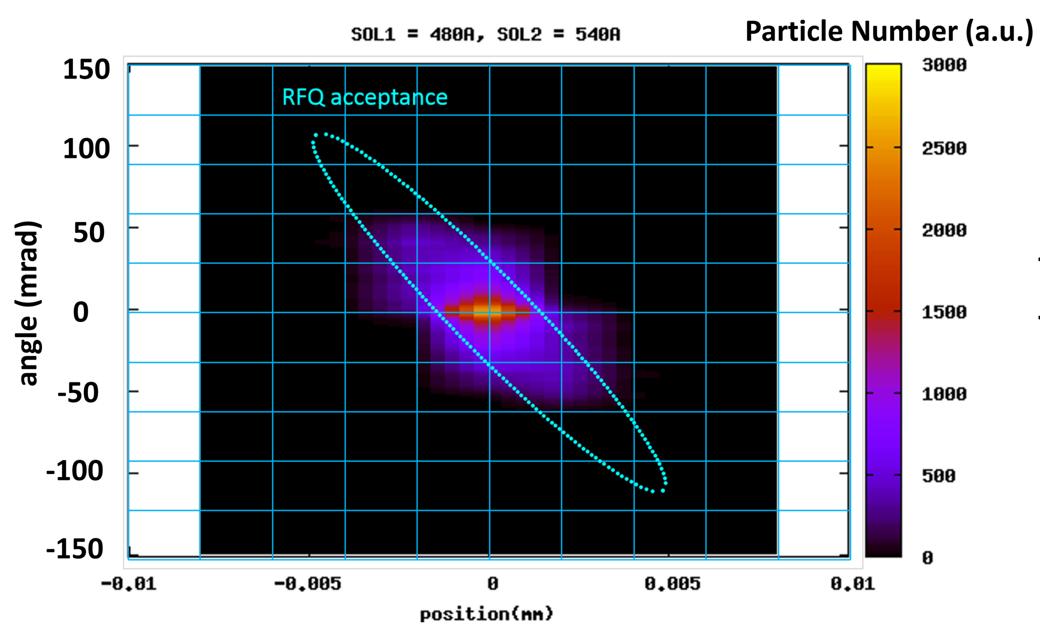

Figure 9: Calculated beam phase space at the RFQ entrance for SOL1 = 480A and SOL2 = 540 A.

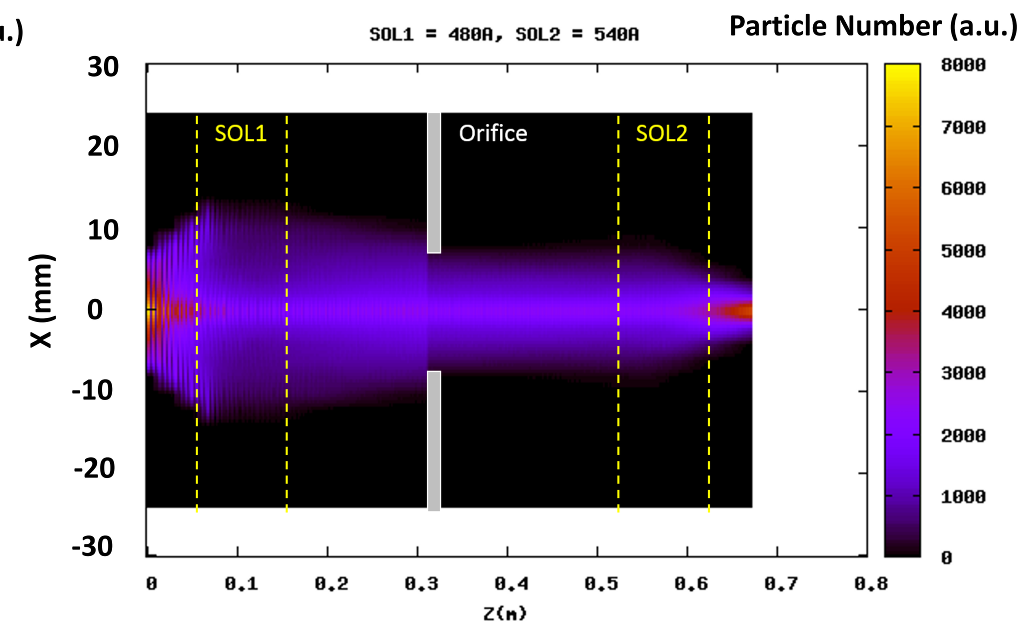

Figure 10: Calculated beam profile in the XZ plane for SOL1 = 480A and SOL2 = 540 A.

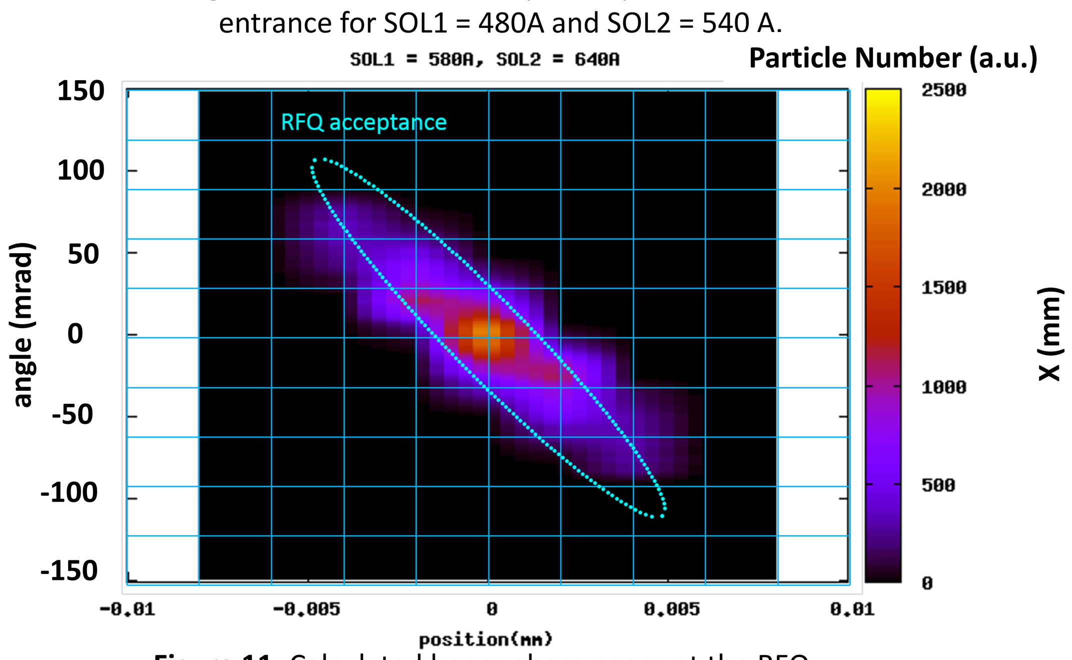

Figure 11: Calculated beam phase space at the RFQ entrance for SOL1 = 580A and SOL2 = 640 A.

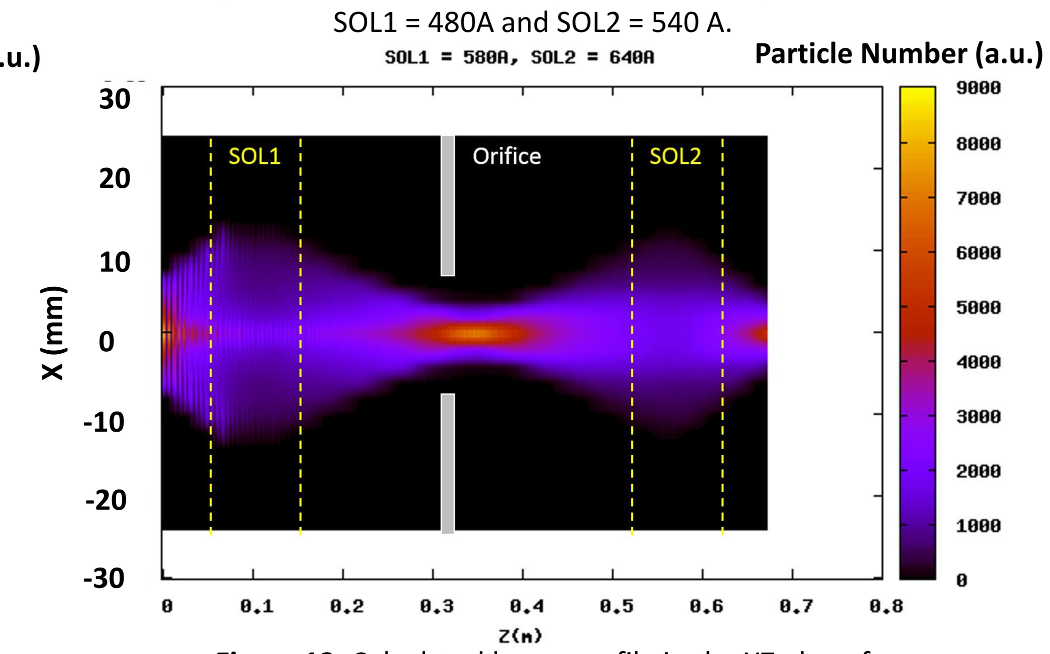

Figure 12: Calculated beam profile in the XZ plane for SOL1 = 580A and SOL2 = 640 A.