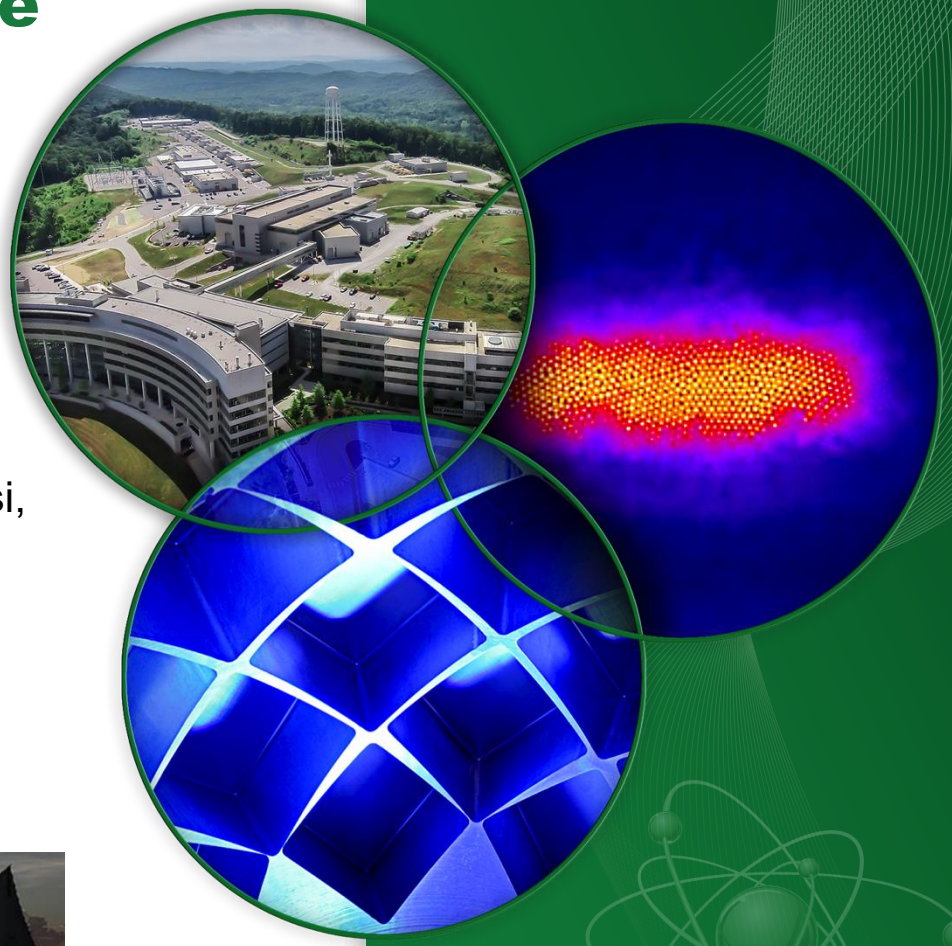
Simulations of Beam Chopping for Potential Upgrades of the SNS LEBT Chopper



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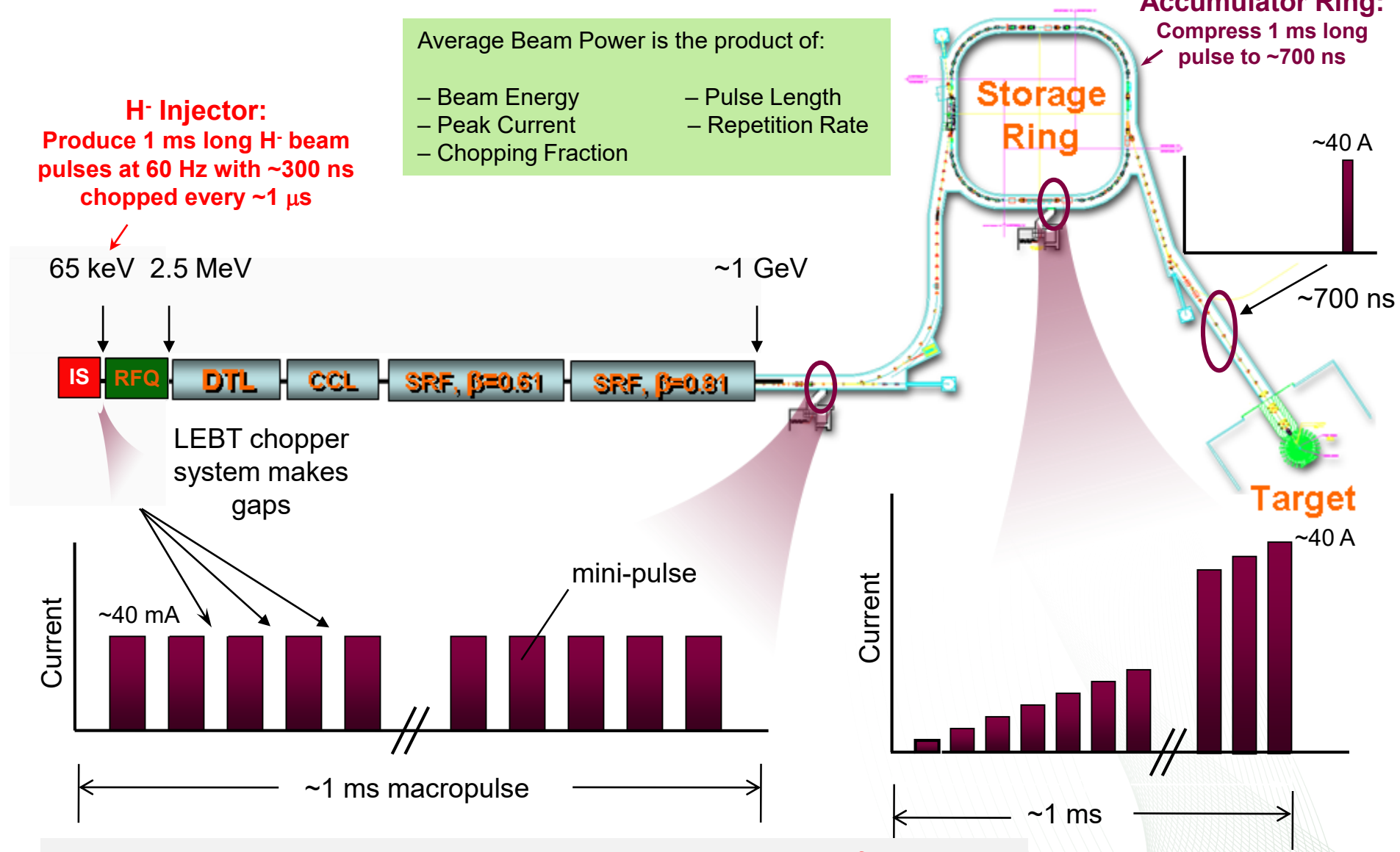
The SNS accelerator system overview

Average Beam Power is the product of:

– Beam Energy
– Peak Current
– Chopping Fraction
– Pulse Length
– Repetition Rate

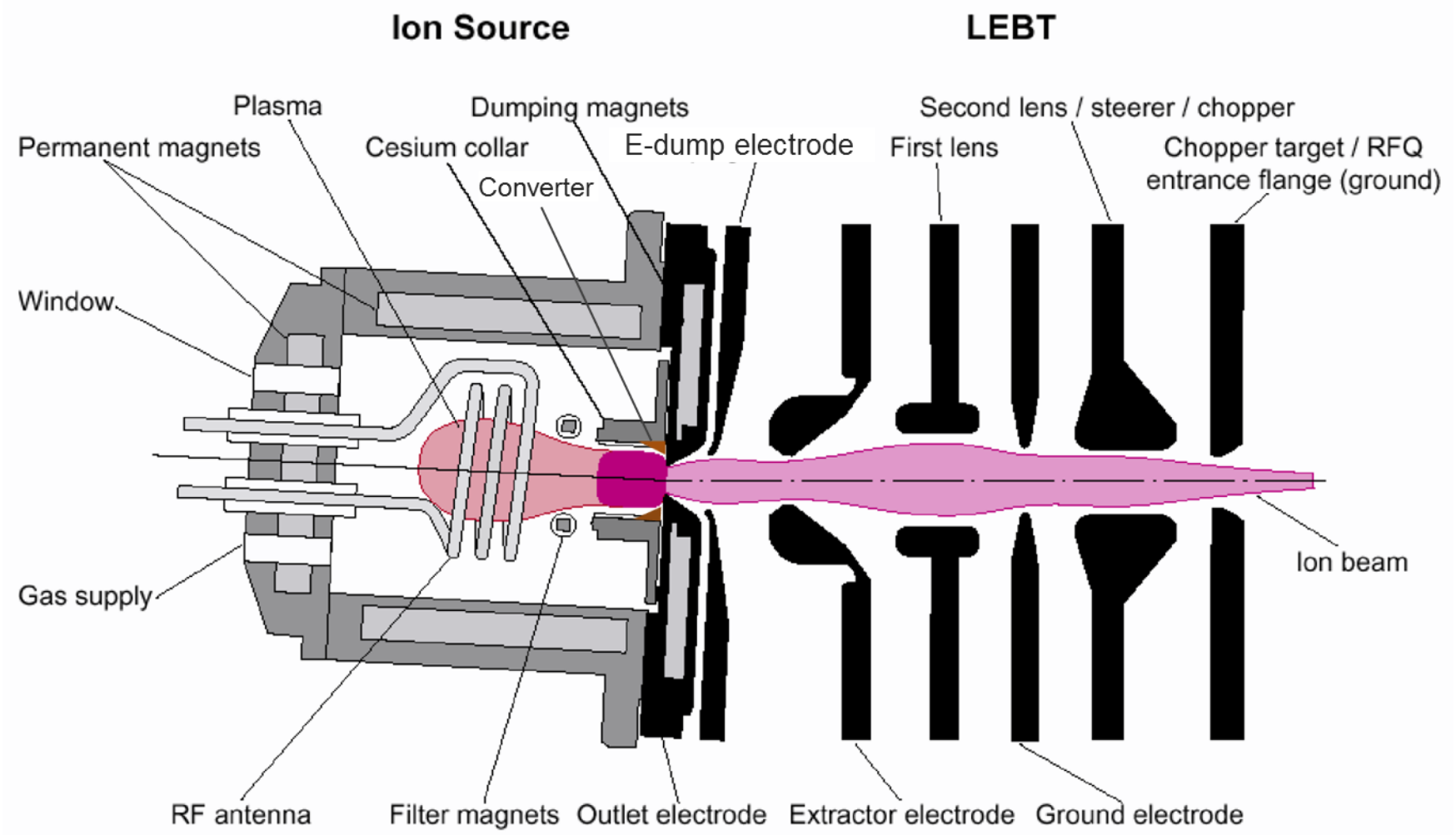
H⁻ Injector:
Produce 1 ms long H⁻ beam pulses at 60 Hz with ~300 ns chopped every ~1 μs

Accumulator Ring:
Compress 1 ms long pulse to ~700 ns



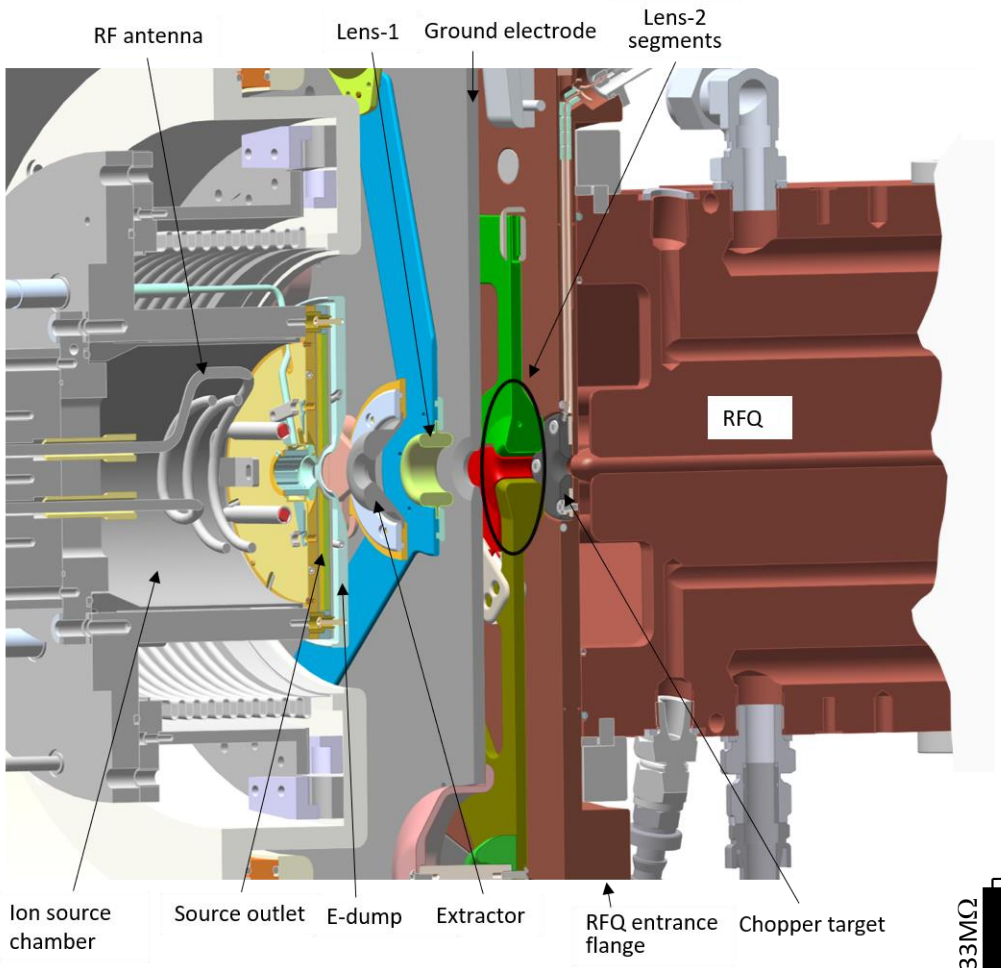
The charge exchange injection and clean extraction requirement of the accumulator ring needs chopped H⁻ beam from the linac.

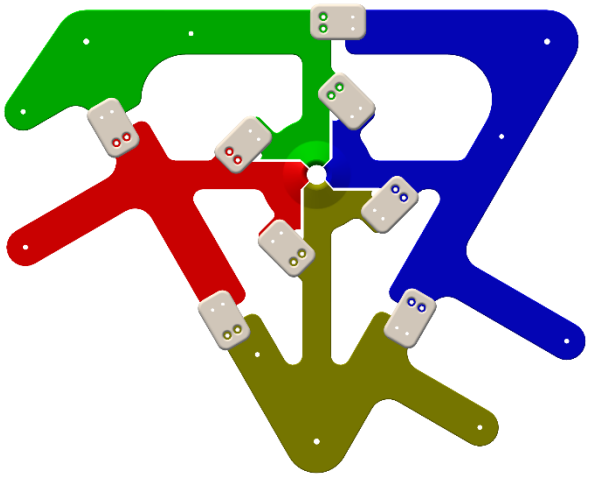
The SNS H^- injector

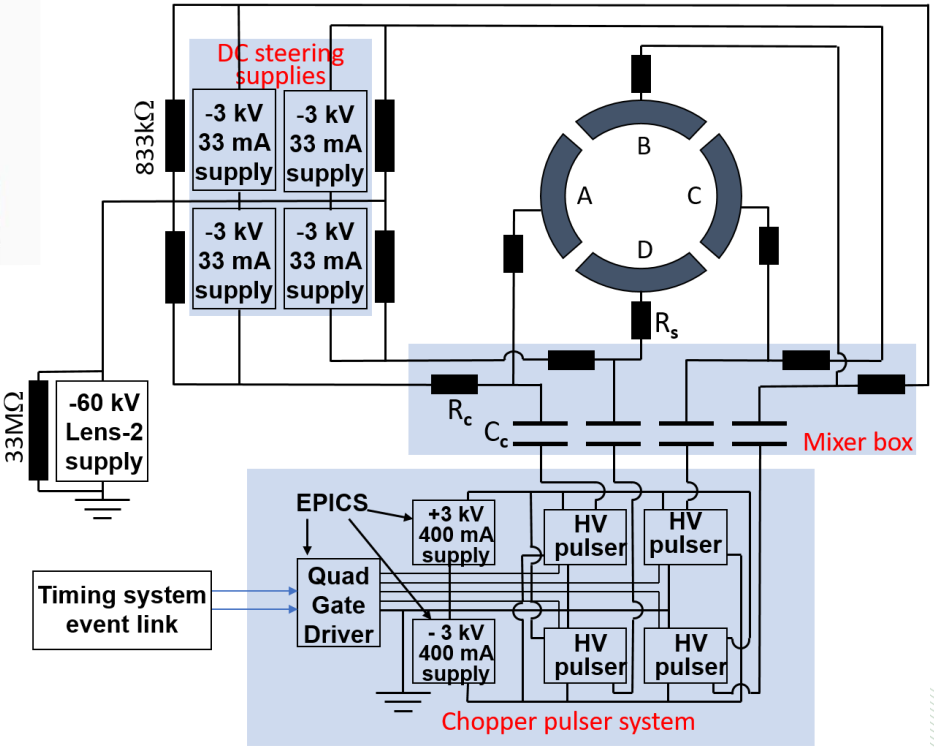


- An RF-driven, Cs-enhanced, multi-cusp H^- ion source
- A compact 2-lens electrostatic low energy beam transport (LEBT)
- The injector is capable of delivering over 60 mA H^- beam at 6% duty-factor (1.0 ms pulse length, 60 Hz) for several months without hands-on maintenance

The beam chopping is accomplished in the LEBT in front of the RFQ







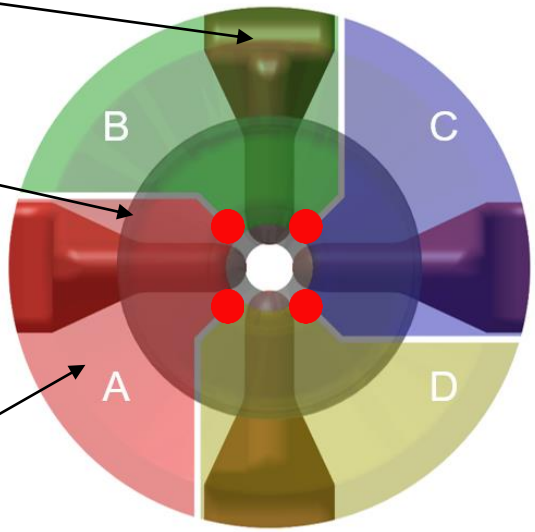
The lens-2 is azimuthally split into 4 quadrants to facilitate superimposing individual voltages on top of the focusing voltage for beam steering, chopping or totally blanking.

How the beam is chopped? - with the present chopping pattern

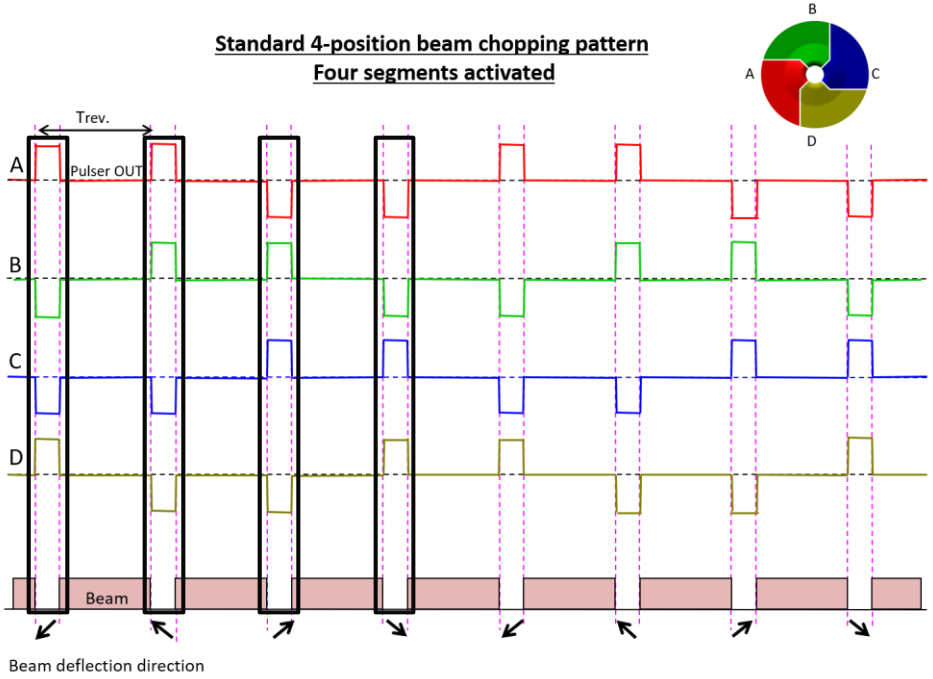
RFQ vanes 16 mm behind the chopper target front-face

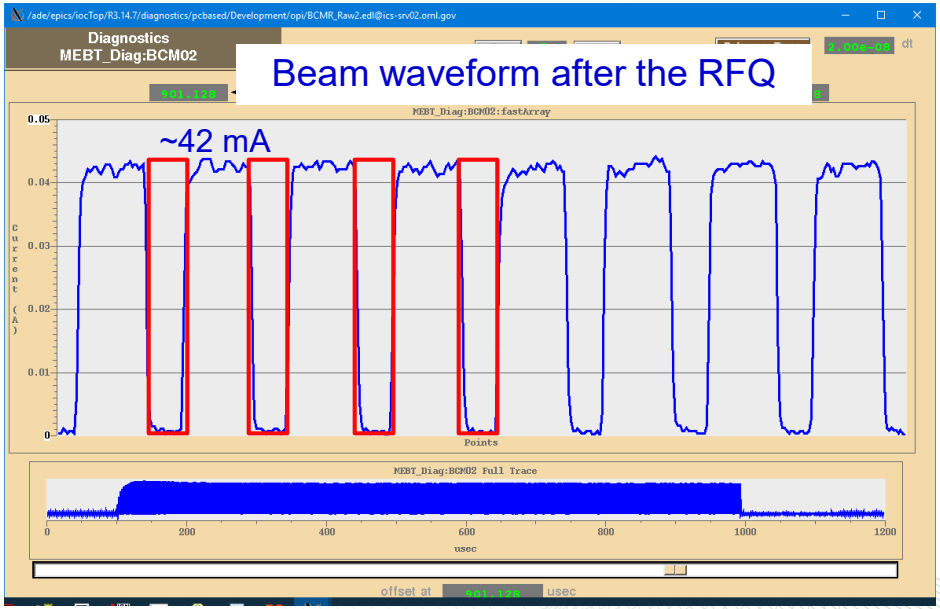
Chopper target 10 mm behind the lens-2, I.D. 7.5 mm, O.D. ~50 mm

Lens-2 segments A, B, C, an D



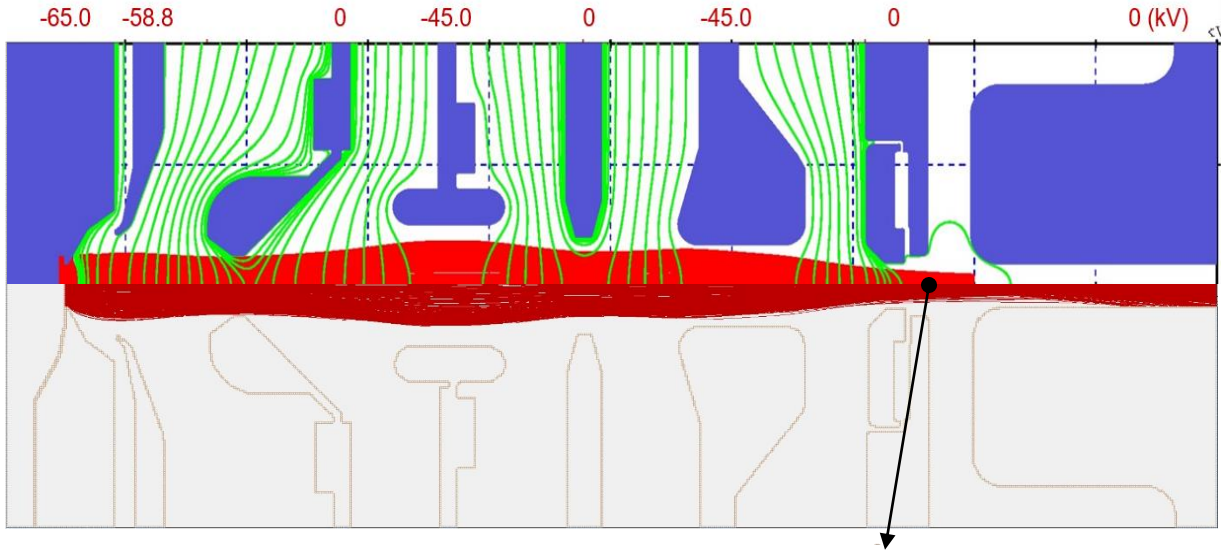
- Chopping: bipolar voltages, typically ±2.5 kV, activated at the accumulator ring revolution frequency (~1 MHz) and applied on the two opposite pairs of the lens-2 segments chop the beam, i.e. deflecting the beam out of the RFQ acceptance.
- Chopper target: A donut-shape plate made of TZM material at the RFQ entrance is designed to receive and drain the chopped beam. The fraction of the beam intercepted at the chopper target is dependent on the chopping strength.
- Ions on the RFQ vane tips: lens-2 is oriented in a way that the beam deflection is in the directions where the ions which were not intercepted at the chopper target enters the RFQ off-axis and/or off-angle between the vanes minimizing their impacts on the vane tips.
- The waveforms of the 4 chopping voltages are configured in a manner which rotates the deflection sequentially to 4 different directions to reduce the local heat load on the chopper target.





Approach of Beam Simulation

- shown with beam injection case

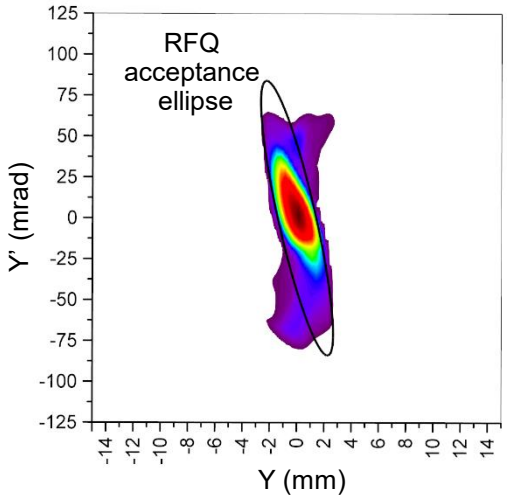


X-X' (or Y-Y') plot of the injected beam vs. the RFQ acceptance ellipse at the RFQ injection reference plane

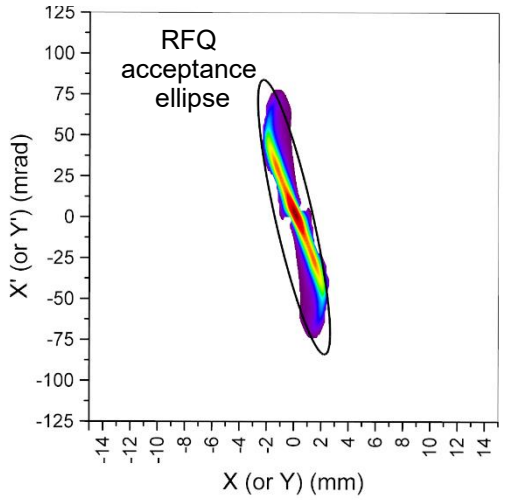
(RFQ acceptance ellipse: normalized rms emittance $\varepsilon_{n,rms}$ = 0.35 π mm·mrad α = 1.6, β = 0.06 mm/mrad, the ellipses drawn are 4 x ε_{rms})

- SIMION 8.1 code
- 65 keV H^- ions
- Coulomb repulsion with 1.5×10^{-8} C/0.25 μs to simulate space charge effect of a 60 mA beam
- 10000 macro particles in the simulation (checked results consistency against with 20000 and 50000 macroparticles)
- Uniform density distribution at the emission surface
- The RFQ vane tips are shown, but the fields were not modeled
- Result was checked against PBGUNS (a 2-D code with plasma emission model) simulation and measured data to be in reasonable agreements

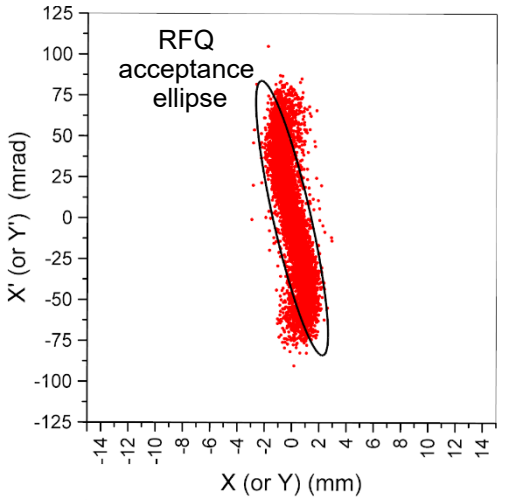
measured



PBGUNS simulation



SIMION



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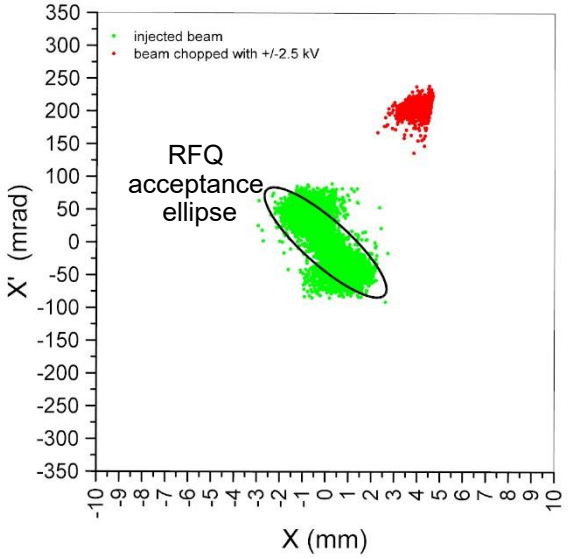
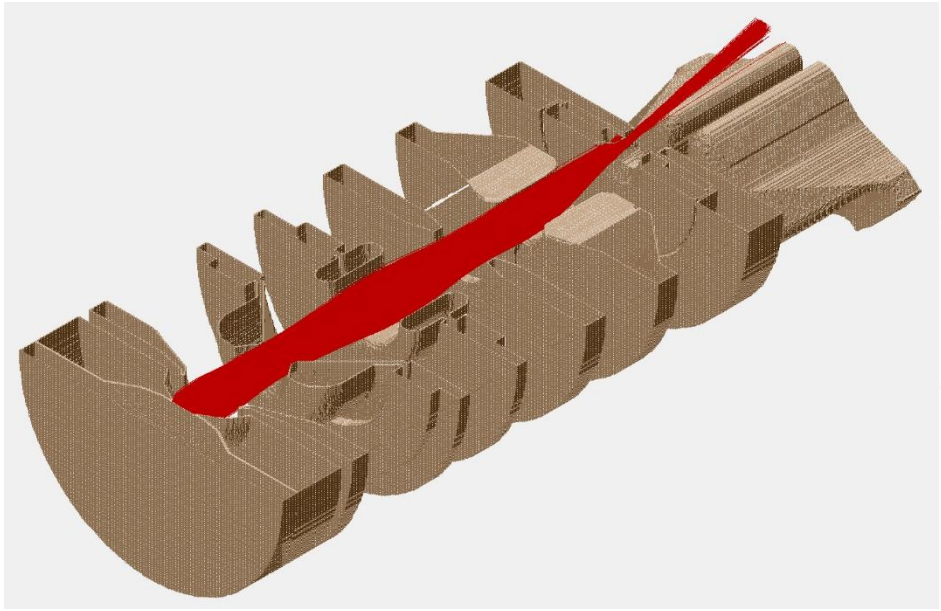
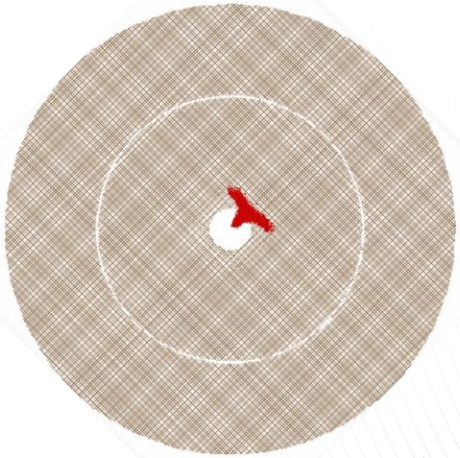
Simulations of beam chopping, 2 pairs, ±2.5 kV

Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

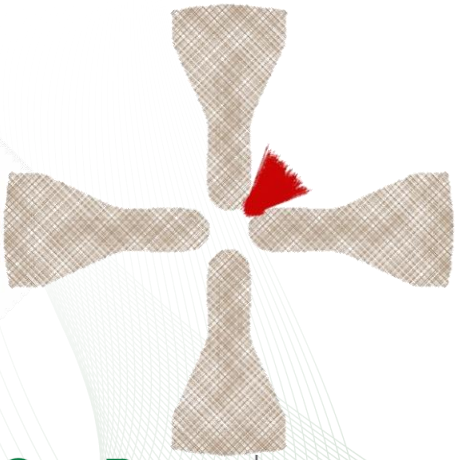




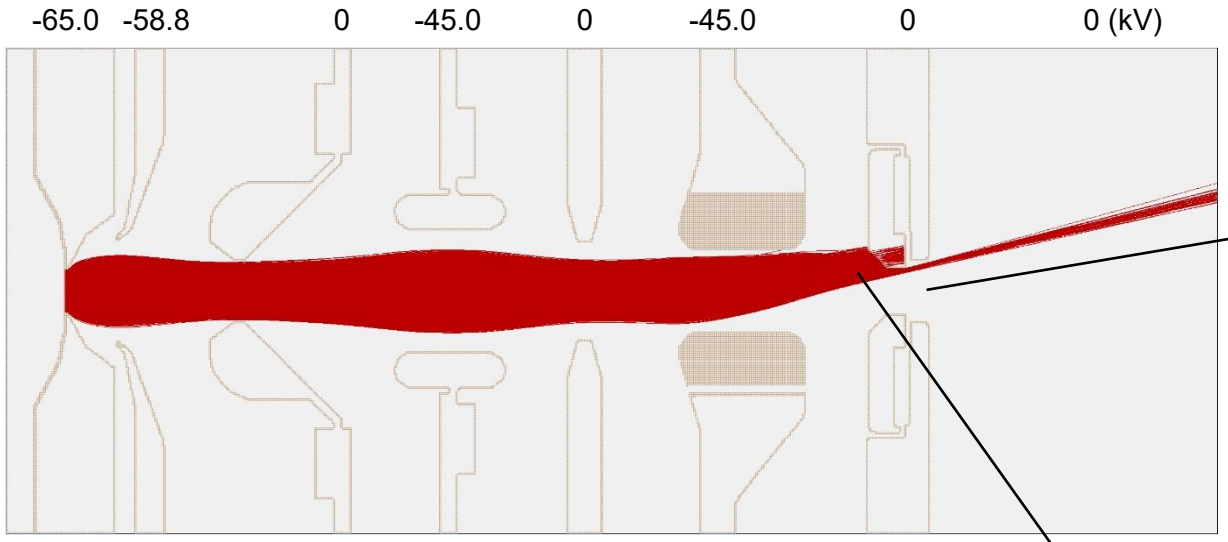
Beam profile at the chopper target front-face



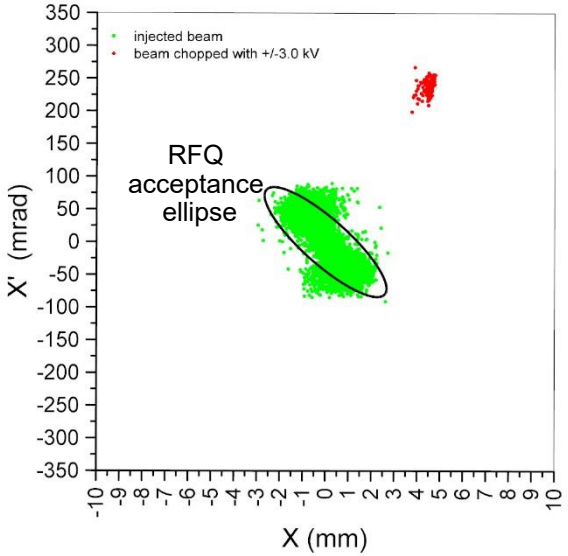
Deflected beam inside the RFQ cavity

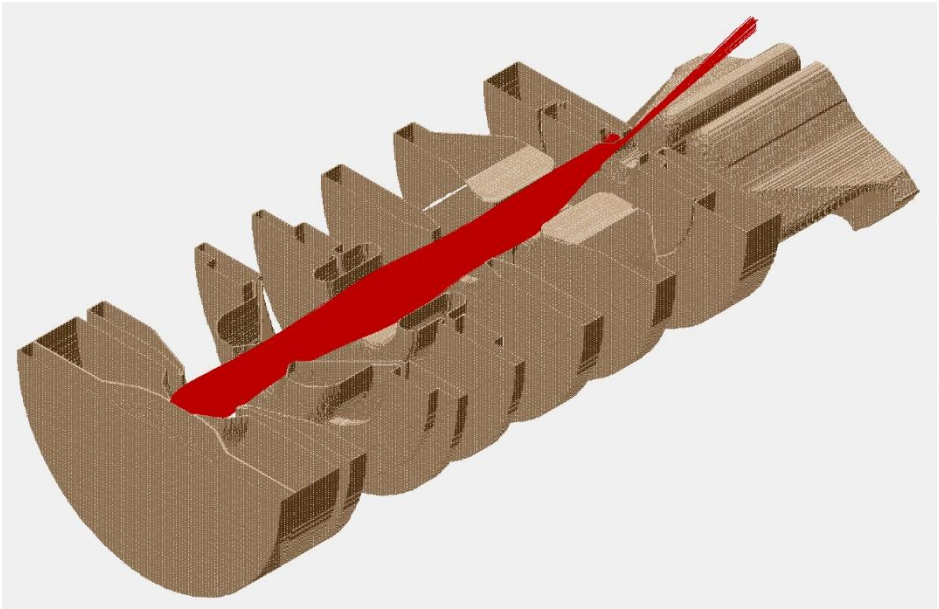


Simulations of beam chopping, 2 pairs, ±3.0 kV

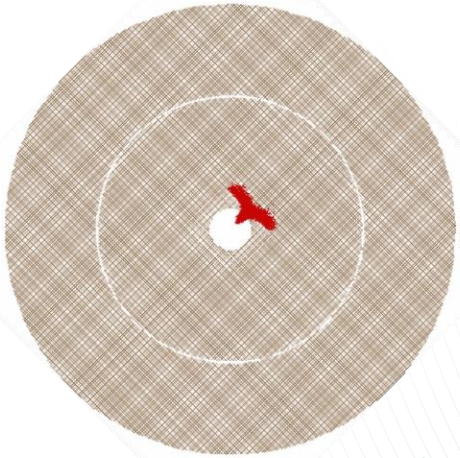


Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

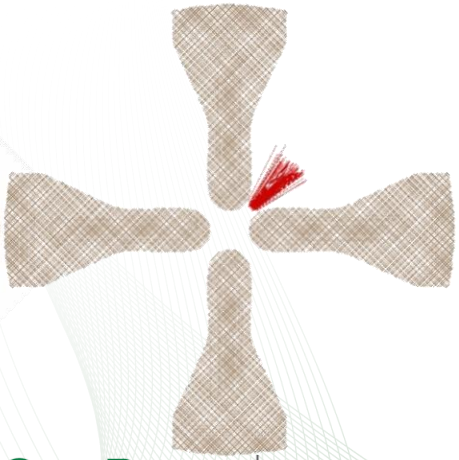




Beam profile at the chopper target front-face

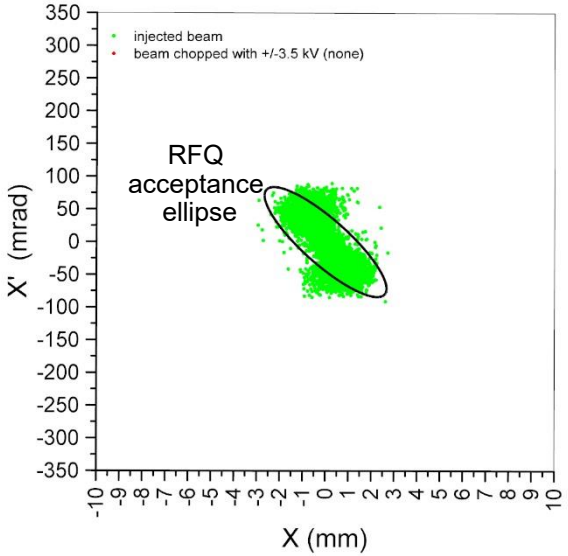


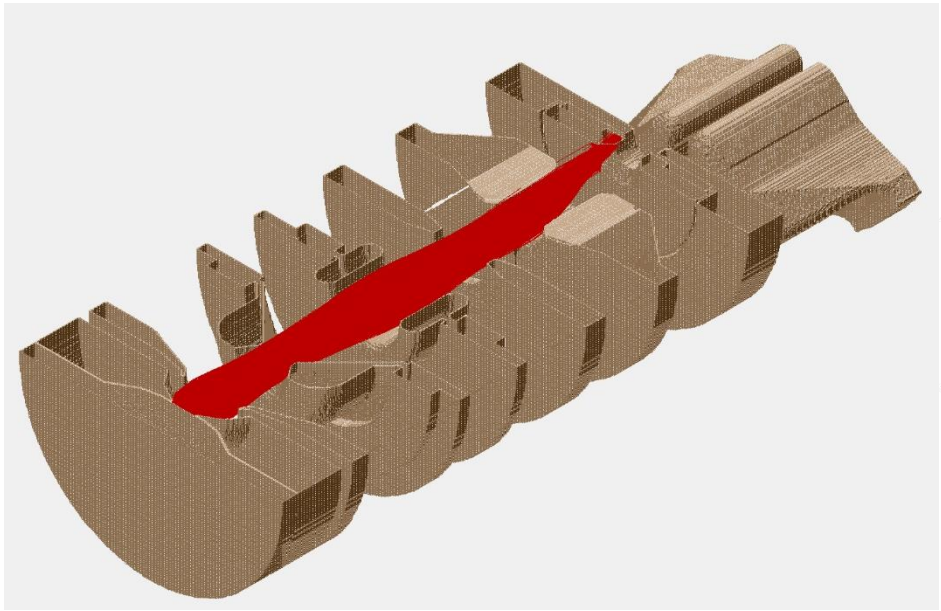
Deflected beam inside the RFQ cavity



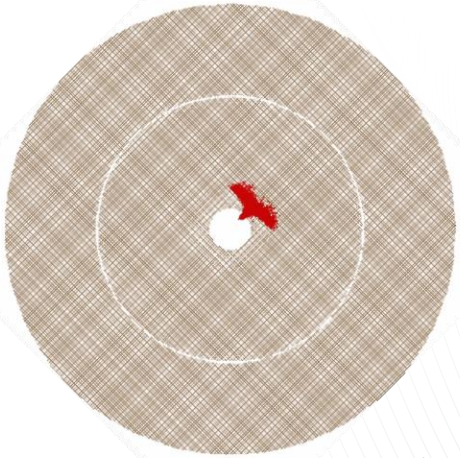
Simulations of beam chopping, 2 pairs, ±3.5 kV

Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

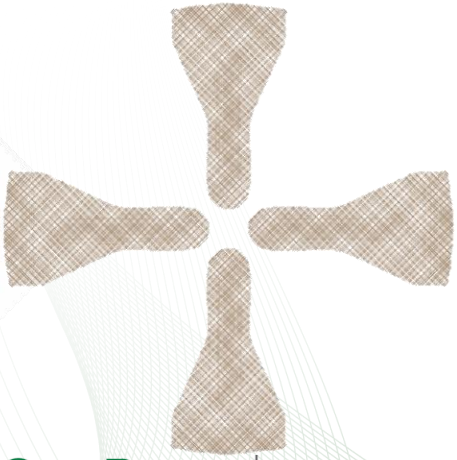




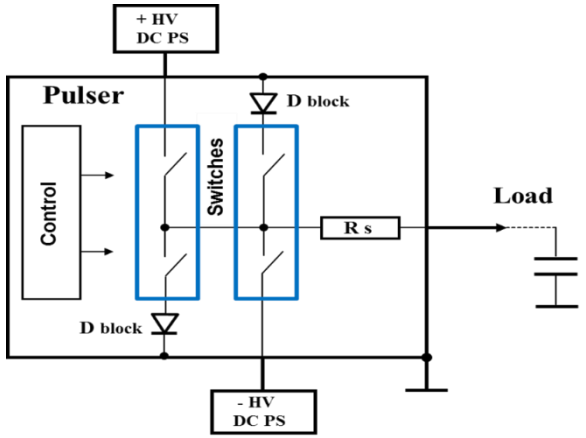
Beam profile at the chopper target front-face



Deflected beam inside the RFQ cavity



Ongoing upgrades efforts on the chopper HV pulser

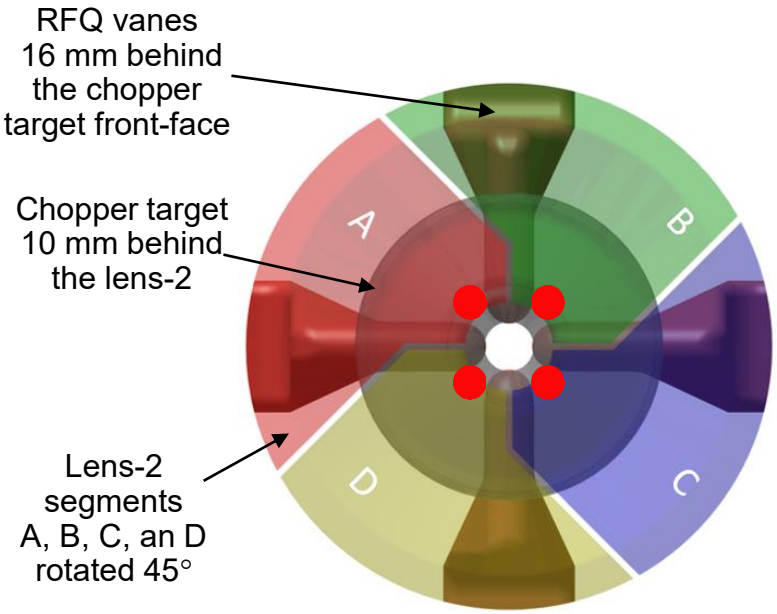


- BEHLKE Electronic GmbH HTS 81-06-GSM modules with HFS-option
- High voltage blocking diodes
- Output series resistor

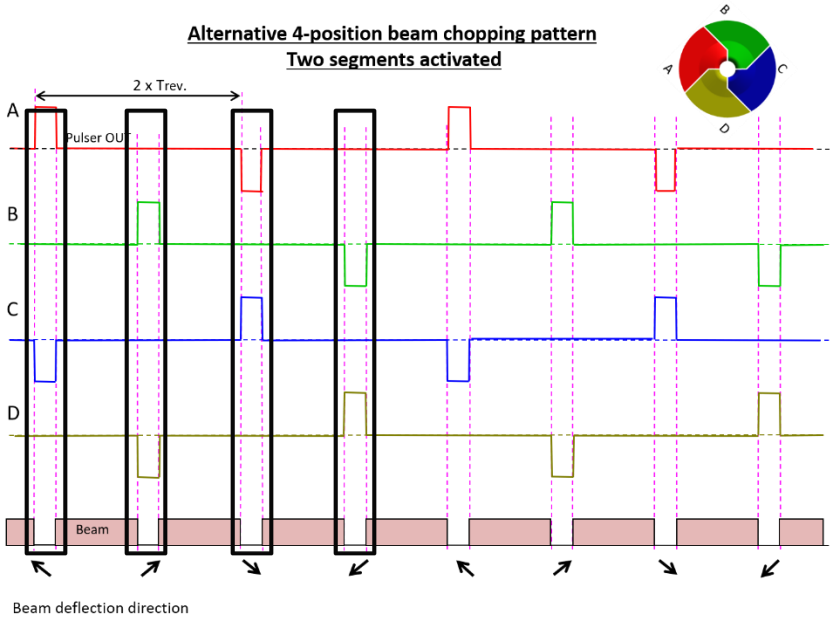
- The existing pulsers are nearing obsolete in terms of spares and are also limited to about ±2.5kV due to arcing and heat dissipation issues with the HV switches
- The new pulser has been tested to be capable of driving ±3.5kV
- Further development can increase the voltage to ±5kV
- In the meantime, new alternative chopping patterns are explored, which involve only two or even just one pulser being activated at a time during beam chopping, to significantly reduce the stress on the HV switches.

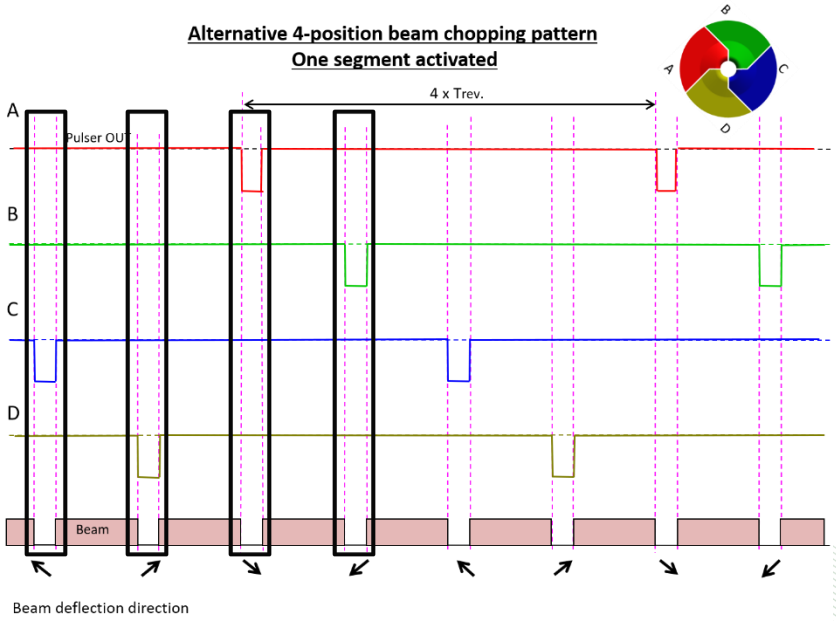
	Existing pulse generator	New pulse generator
Output pulse voltage	+/-2.5kV	+/-3.5kV
Minimum Pulse width	180ns	150ns
rise/fall time	50-60ns	≤ 40ns
Timing stability	+/-10ns	+/-5ns

The proposed alternative chopping patterns



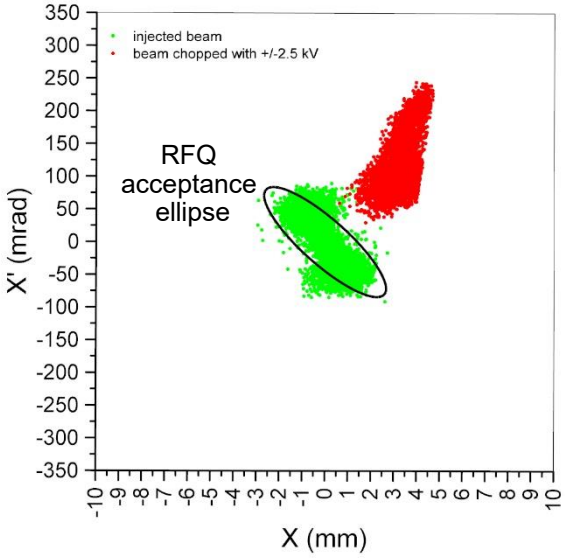
- Bipolar voltages applied on the two opposite segments or a negative voltage applied on only one segment of the lens-2 chop the beam. Each of the segments is activated at ½ or ¼ of the ring revolution frequency i.e. 0.5 MHz or 0.25 MHz instead of 1 MHz.
- Lens-2 is rotated by 45° from the existing setup so that the beam deflection is still in the directions where the beam not intercepted by the chopper target enters the RFQ cavity between the vanes minimizing their impacts on the vane tips.
- The waveforms of the 4 chopping voltages are configured in a manner that the beam is still sequentially dumped to 4 different spots to reduce the local heat load on the chopper target.

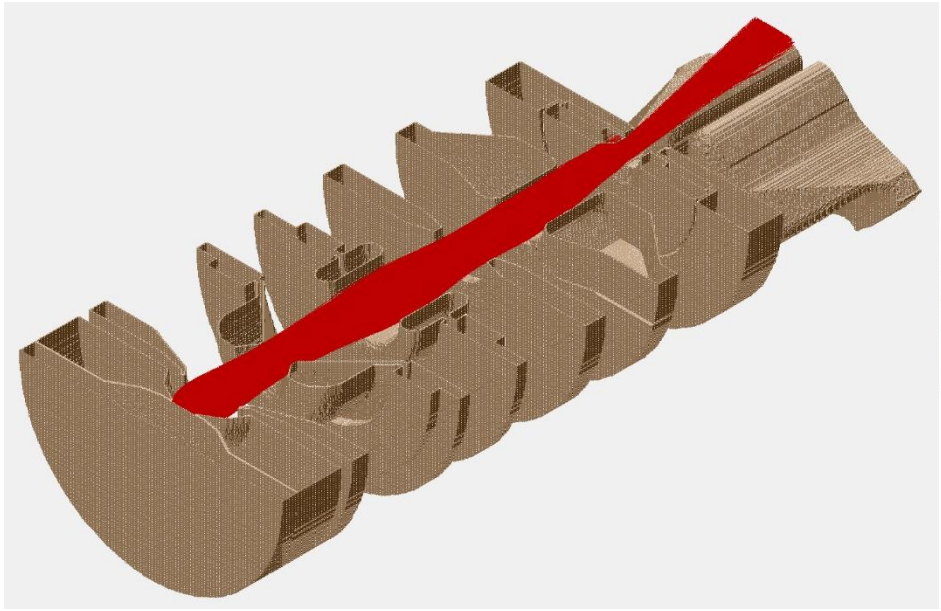




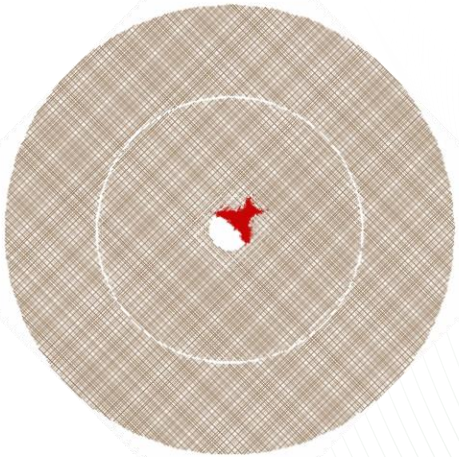
Simulations of new chopping pattern, 2 segments, ±2.5 kV

Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

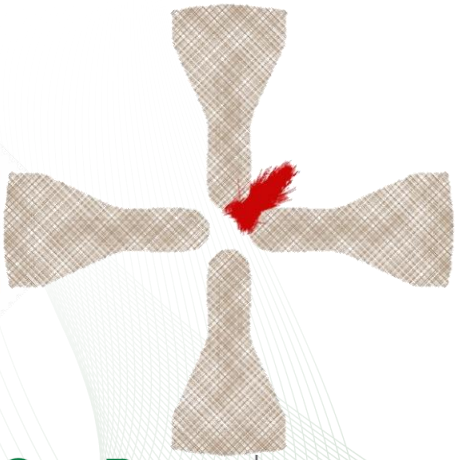




Beam profile at the chopper target front-face

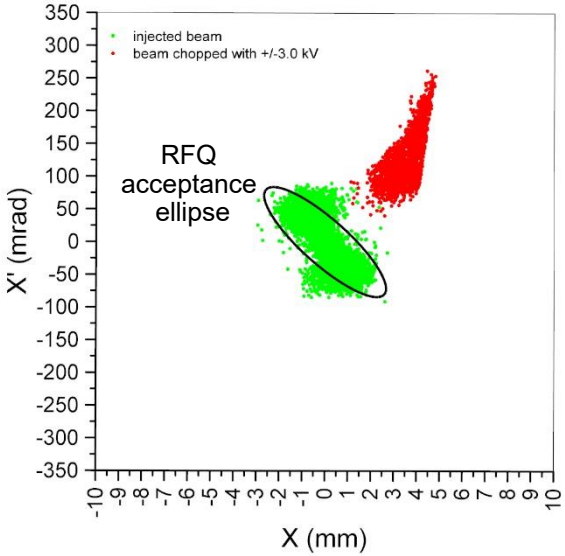


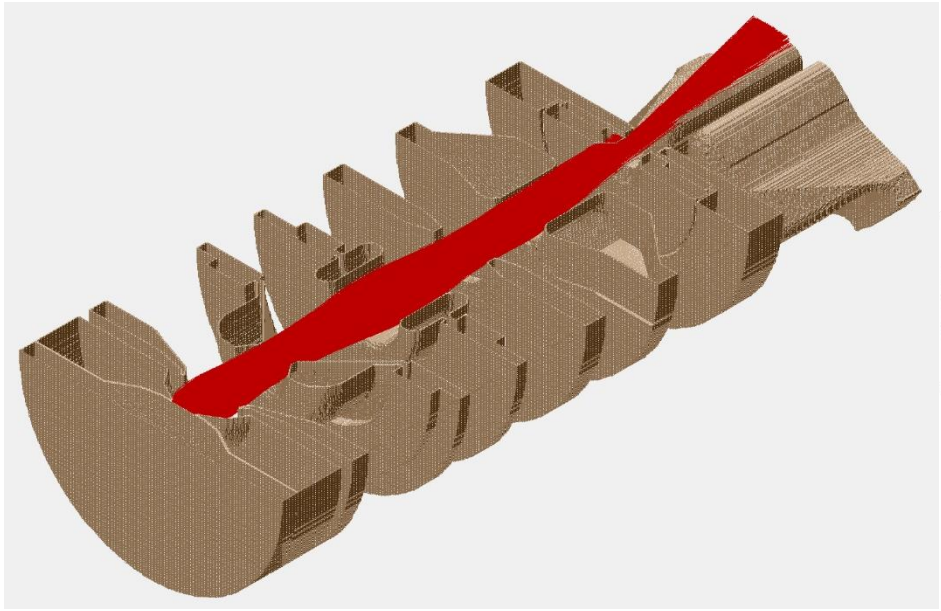
Deflected beam inside the RFQ cavity



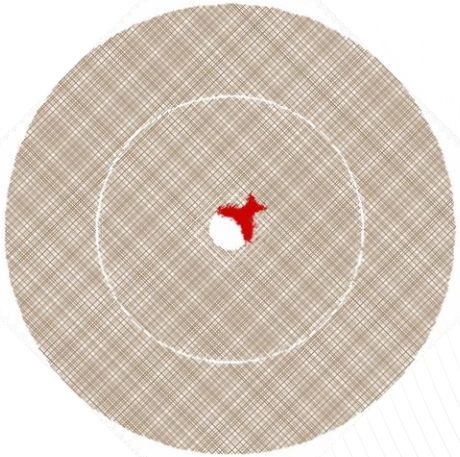
Simulations of new chopping pattern, 2 segments, ±3.0 kV

Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

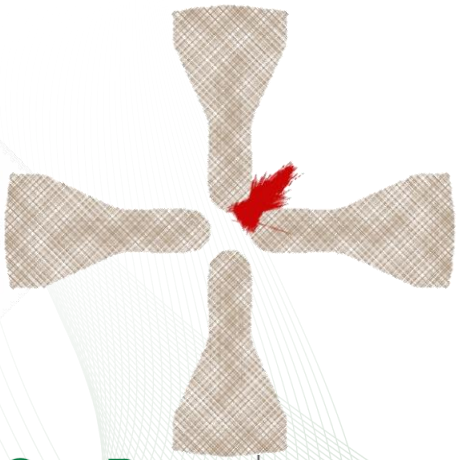




Beam profile at the chopper target front-face

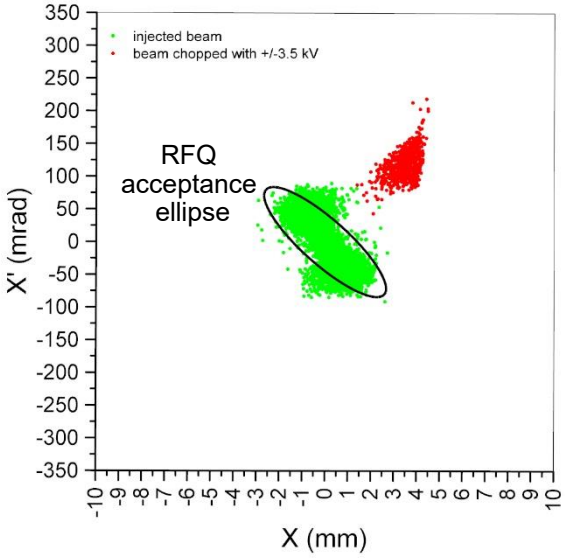


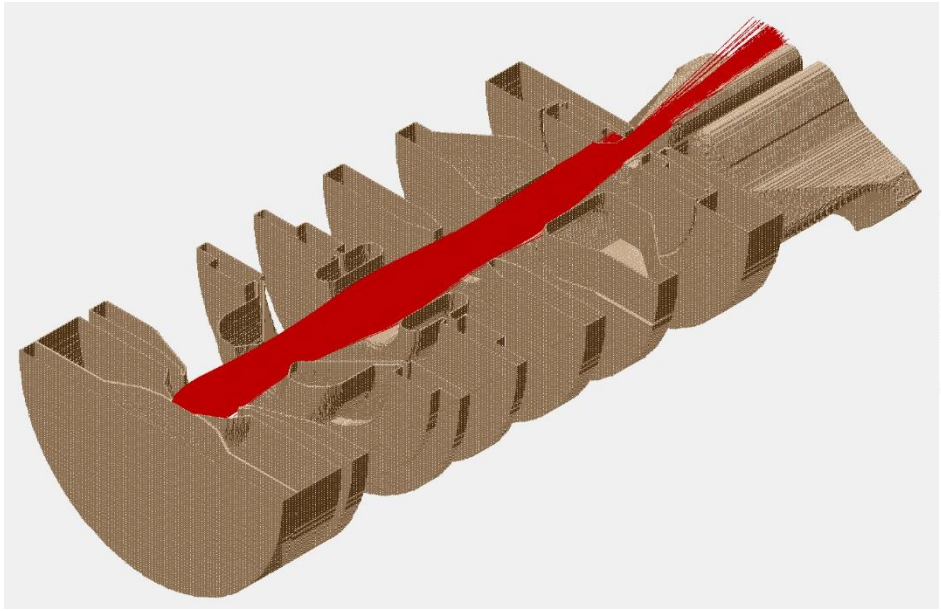
Deflected beam inside the RFQ cavity



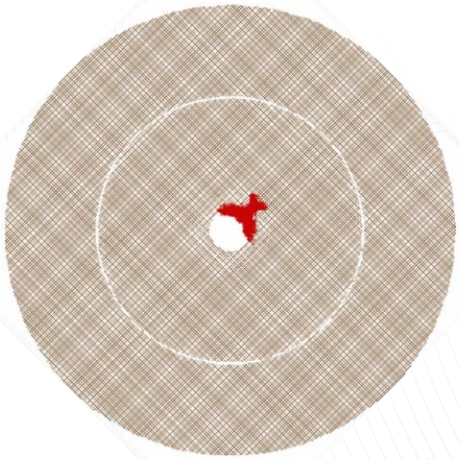
Simulations of new chopping pattern, 2 segments, ±3.5 kV

Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

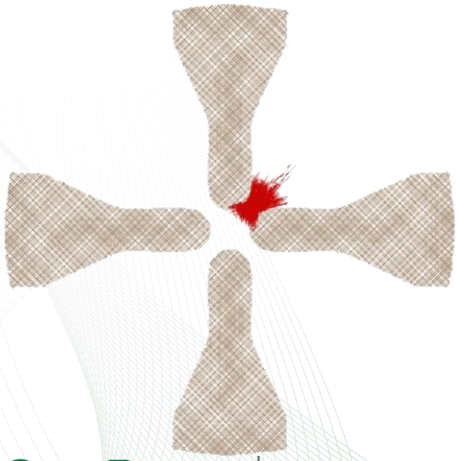




Beam profile at the chopper target front-face

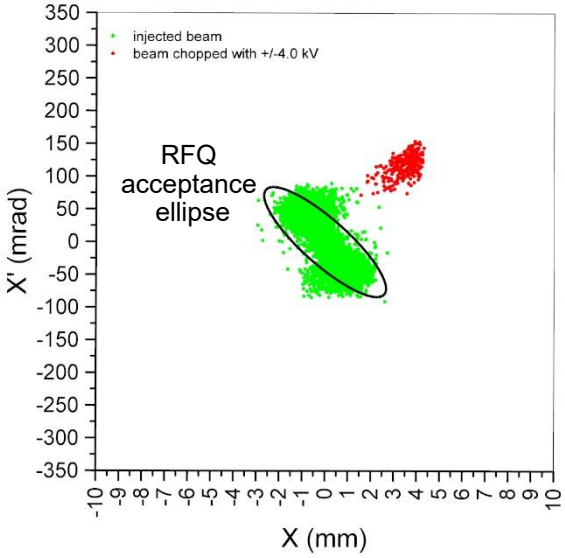


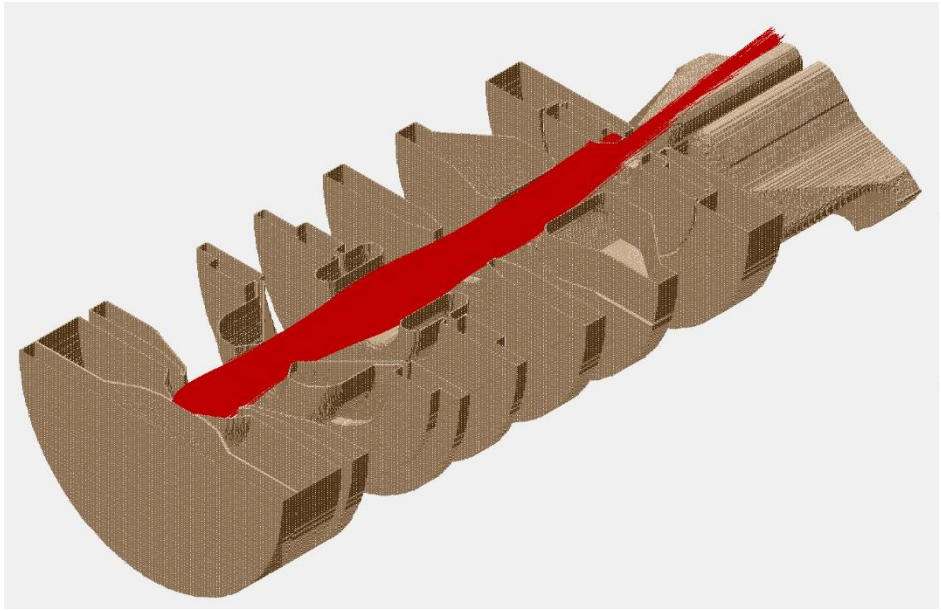
Deflected beam inside the RFQ cavity



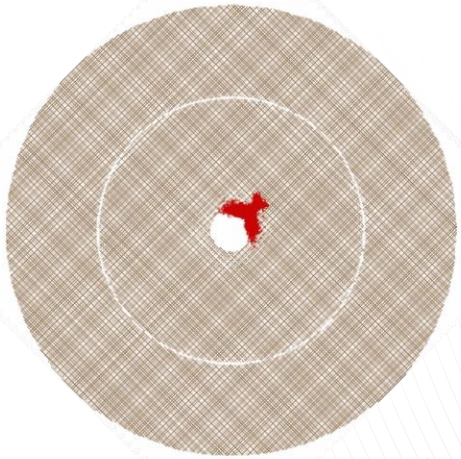
Simulations of new chopping pattern, 2 segments, ±4.0 kV

Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

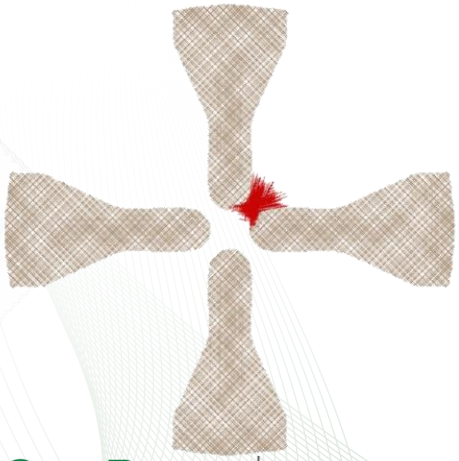




Beam profile at the chopper target front-face

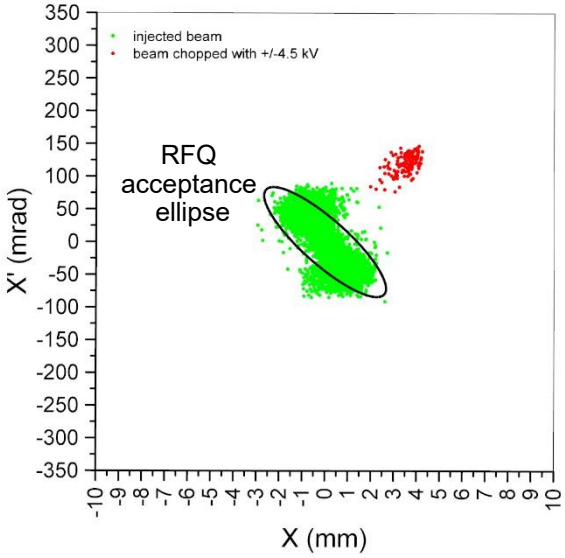


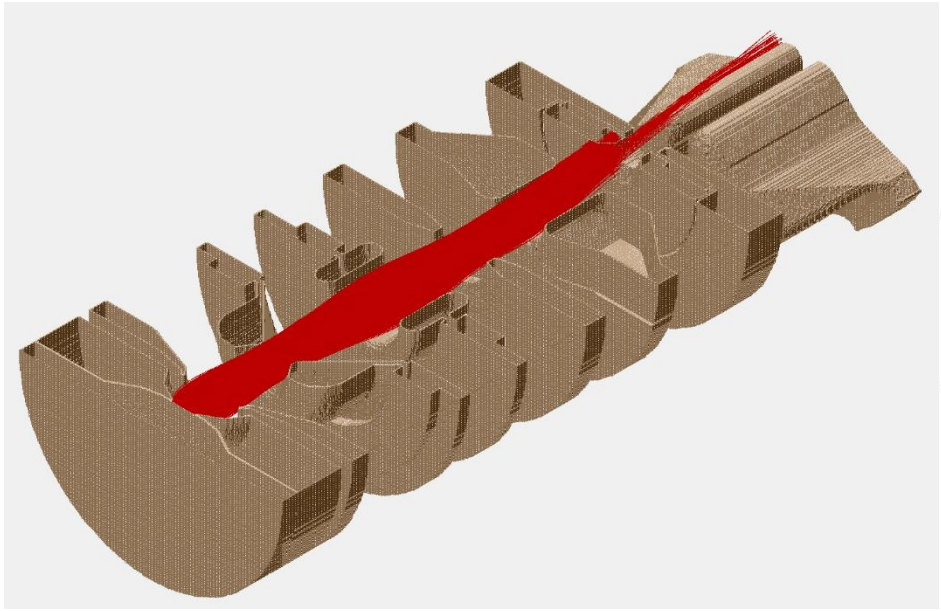
Deflected beam inside the RFQ cavity



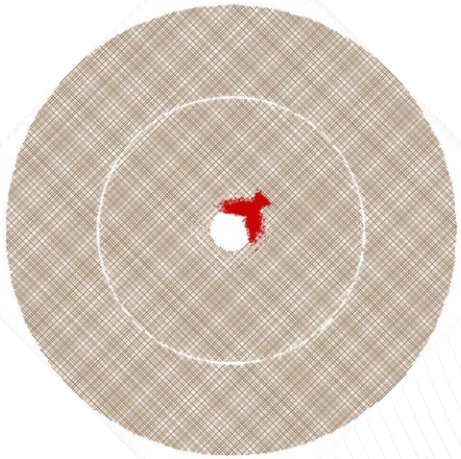
Simulations of new chopping pattern, 2 segments, ±4.5 kV

Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

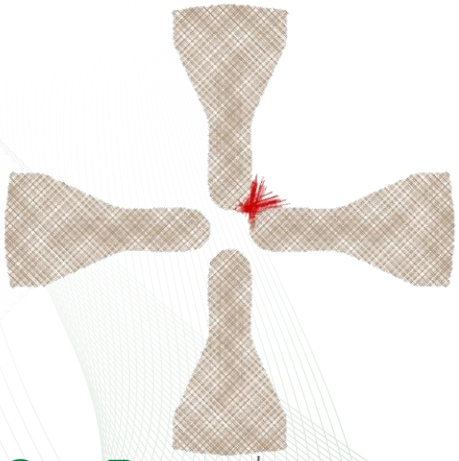




Beam profile at the chopper target front-face

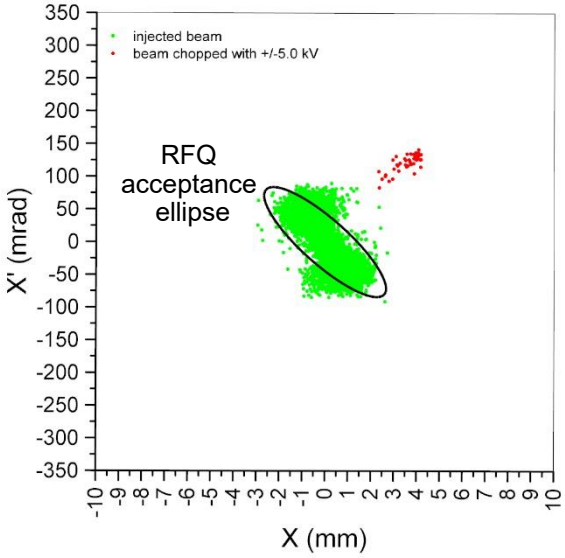


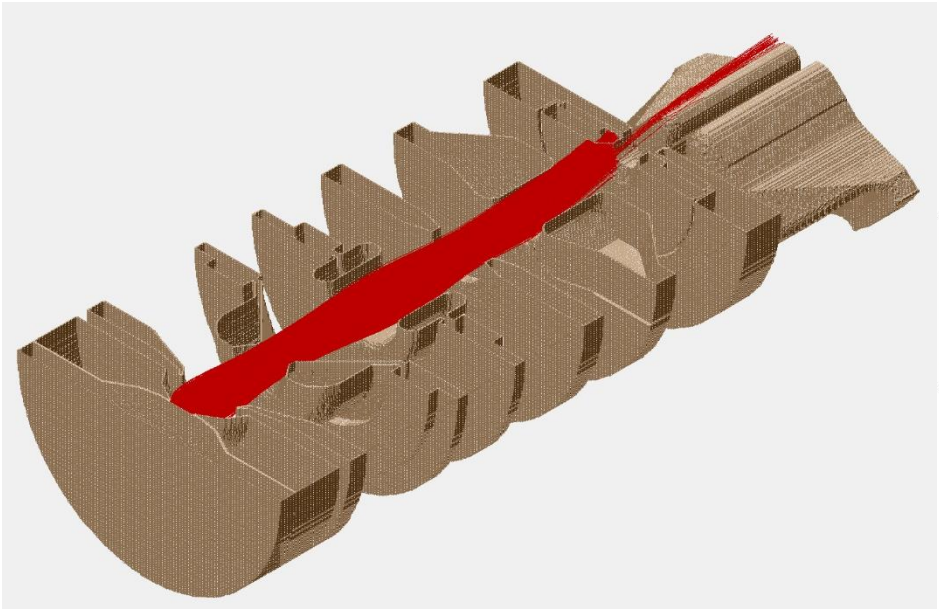
Deflected beam inside the RFQ cavity



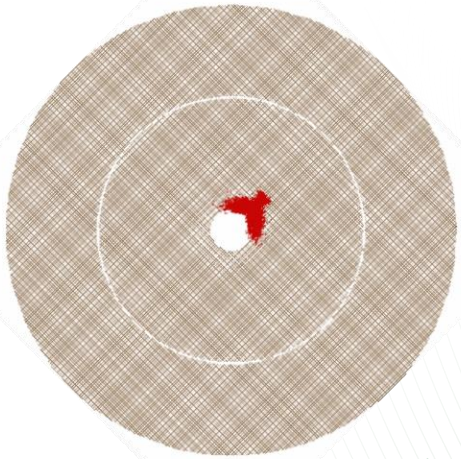
Simulations of new chopping pattern, 2 segments, ±5.0 kV

Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam

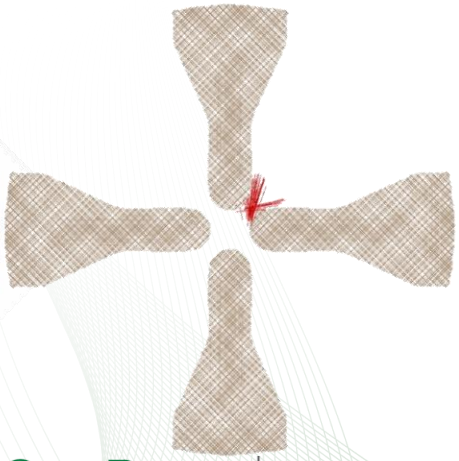




Beam profile at the chopper target front-face

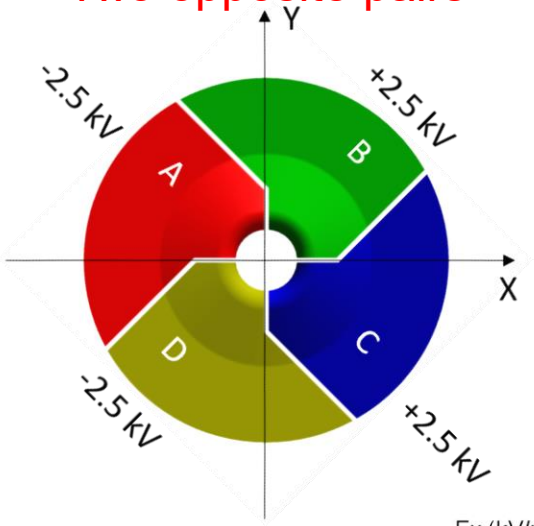


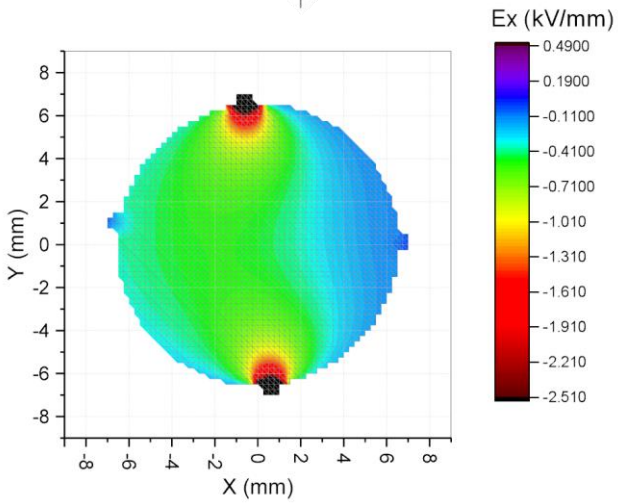
Deflected beam inside the RFQ cavity



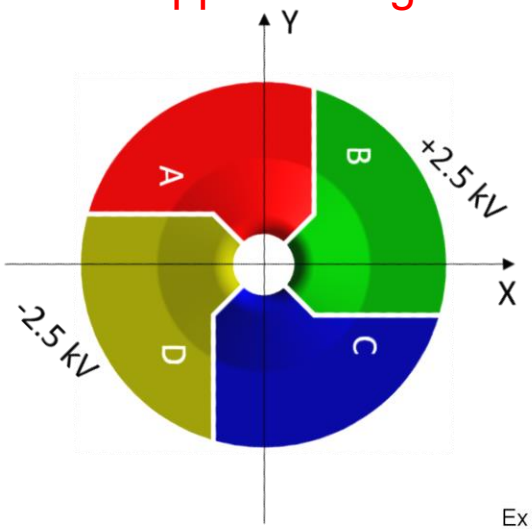
Comparison of the field distribution

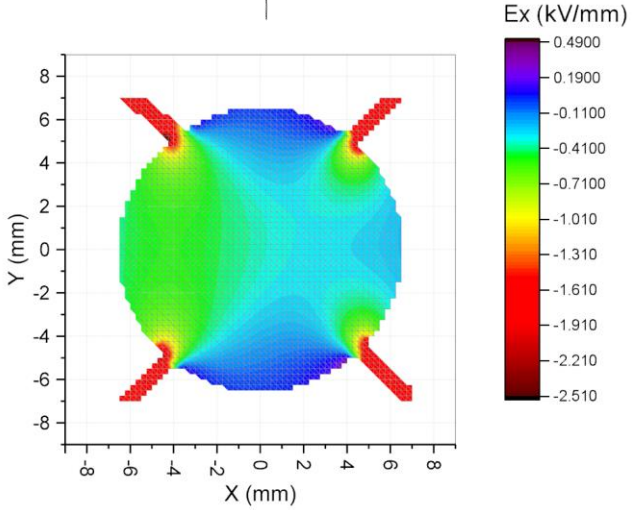
Two opposite pairs



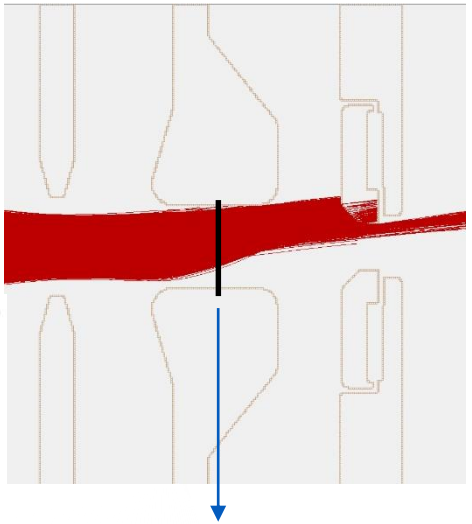


Two opposite segments





±4.0 kV

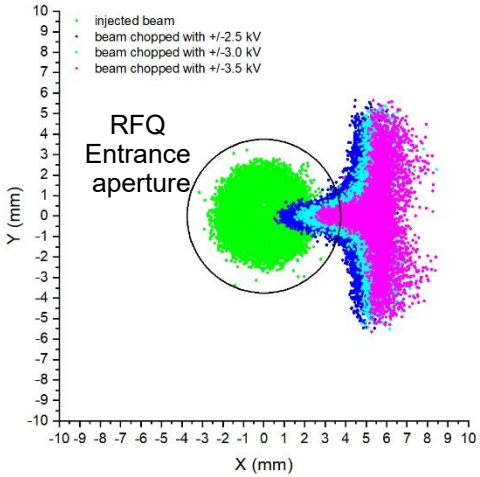


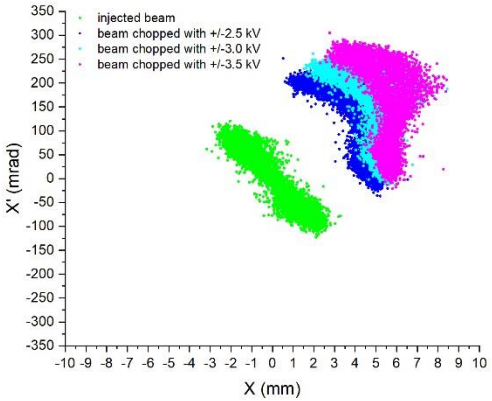
The Ex field plots on the left were sampled at this longitudinal place in the X-Y cross-section

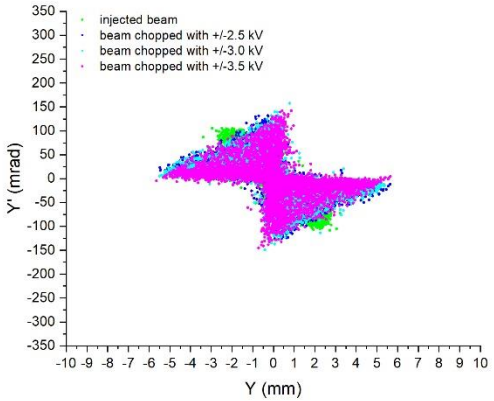
For same voltage difference, the Ex field is substantially lower for the case of 2-segment chopping pattern, especially in the outer region along the Y axis. So, much higher voltage difference is needed to achieve the deflection for the outer ions, but the ions in the middle of the beam will start to be scraped at the lens-2 if the voltage amplitude becomes too high, e.g. 4.0 kV or above.

Comparison of beam chopping
- at the chopper target front-face

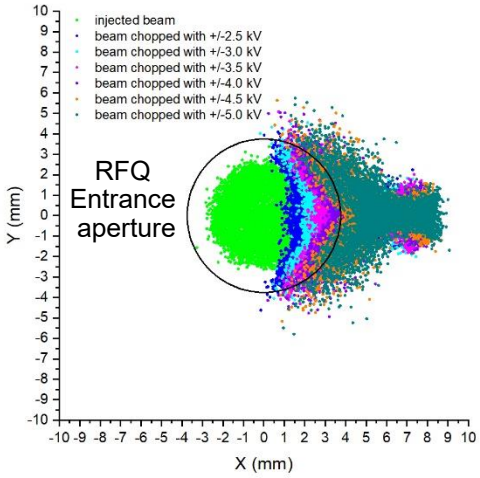
Two opposite pairs of segments with bipolar voltages

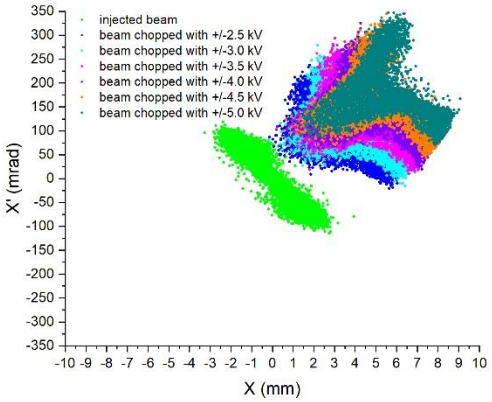


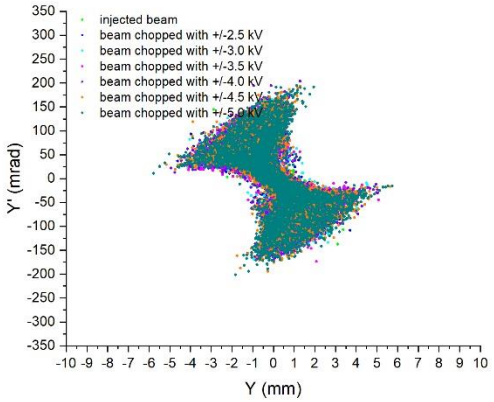




Two opposite segments with bipolar voltages

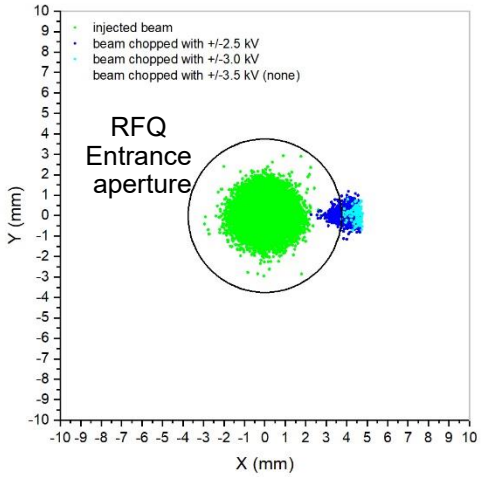


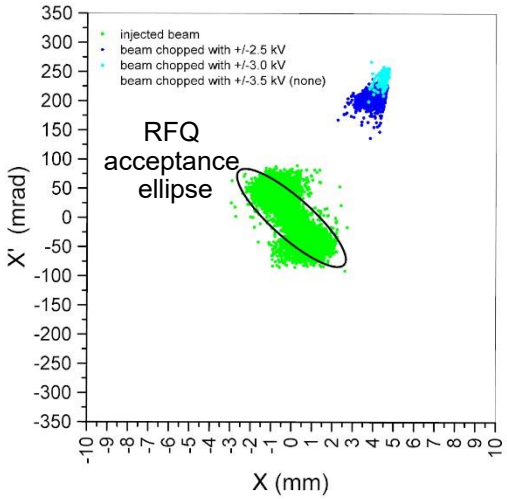


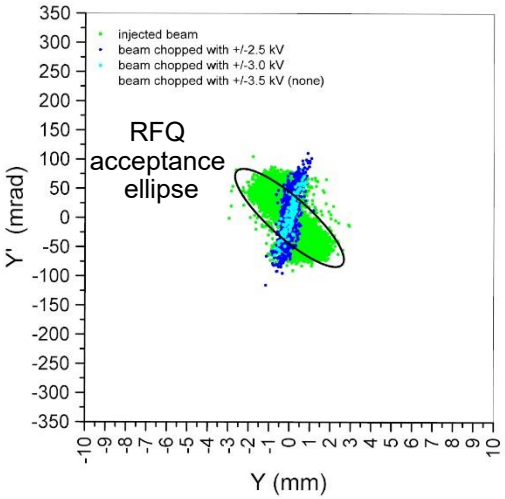


Comparison of beam chopping
- at the RFQ reference plane

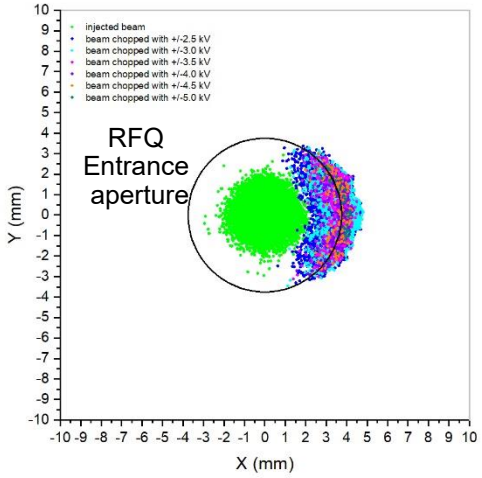
Two opposite pairs of segments with bipolar voltages

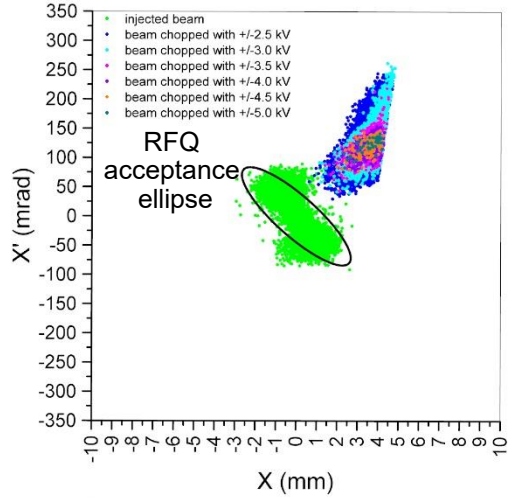


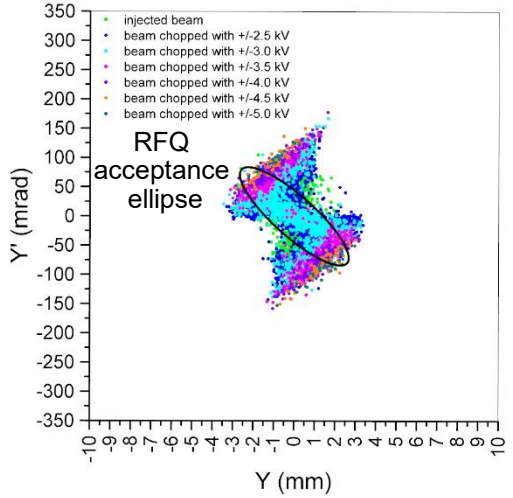




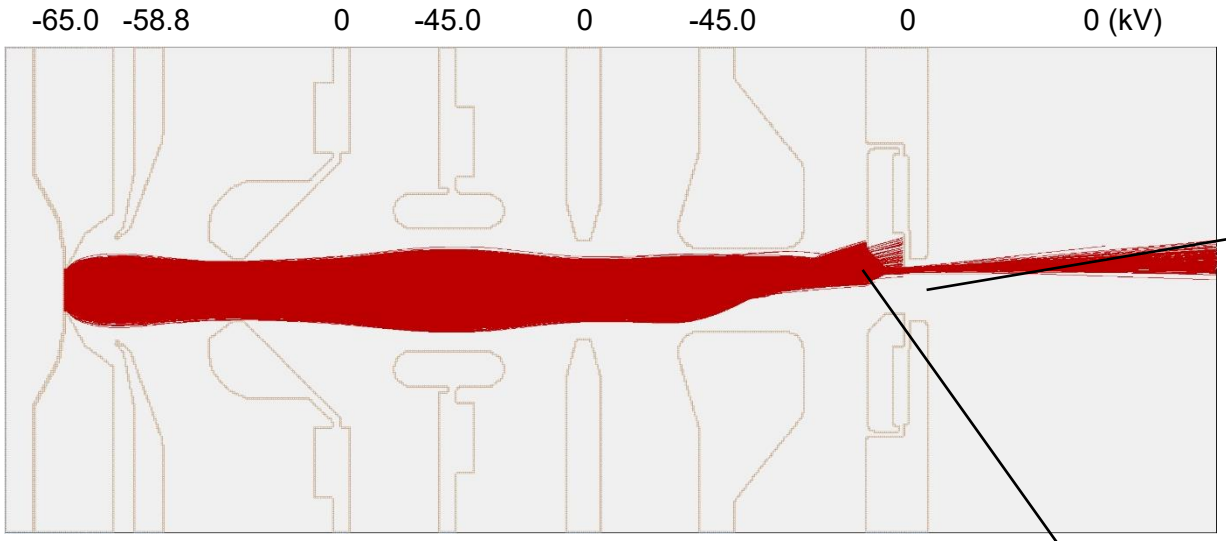
Two opposite segments with bipolar voltages



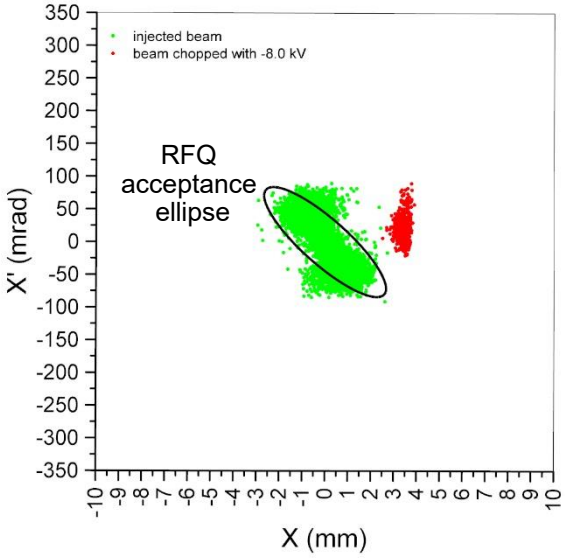


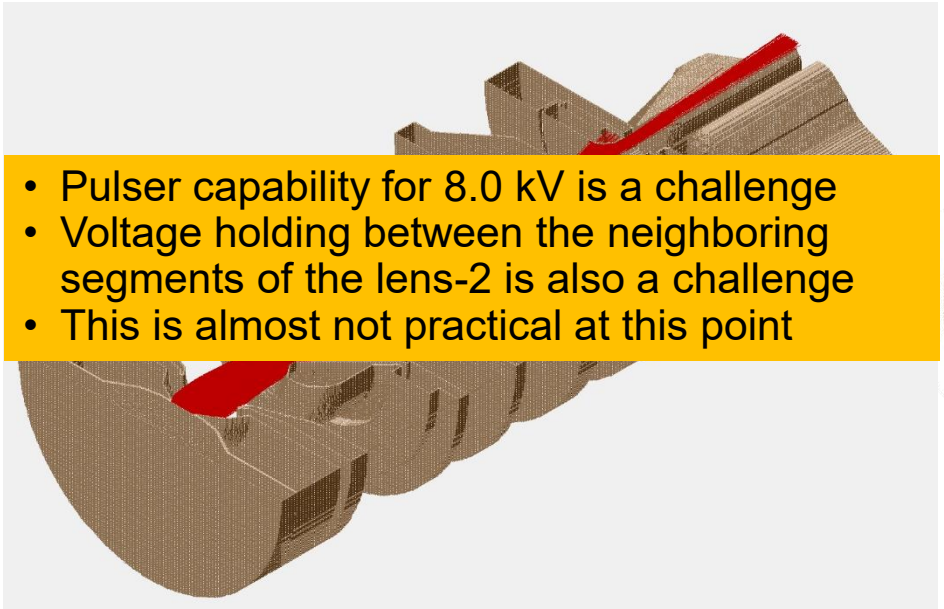


Simulations of new chopping pattern, one segment, -8.0 kV



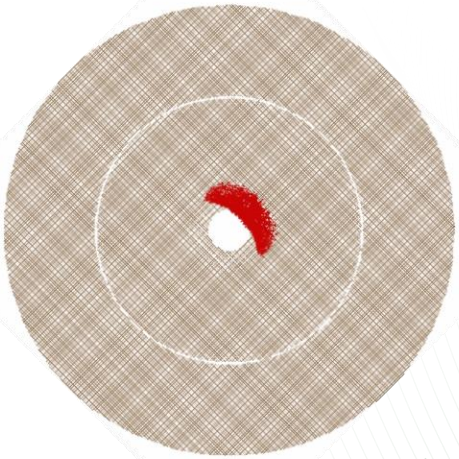
Deflected beam reaching the RFQ reference plane (plotted in X-X' phase space vs. the acceptance ellipse and injected beam



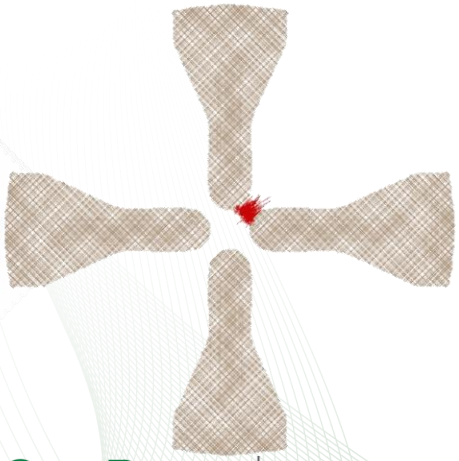


- Pulser capability for 8.0 kV is a challenge
- Voltage holding between the neighboring segments of the lens-2 is also a challenge
- This is almost not practical at this point

Beam profile at the chopper target front-face

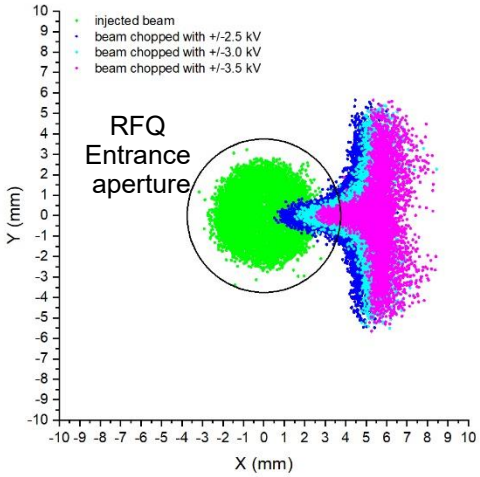


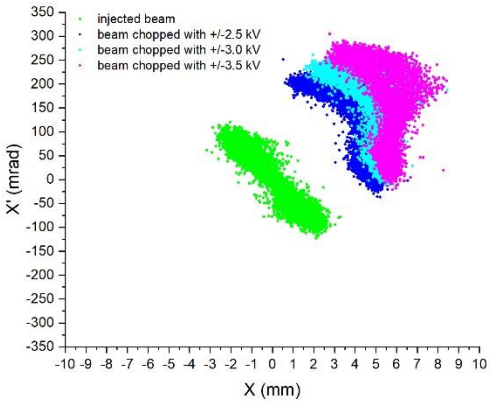
Deflected beam inside the RFQ cavity

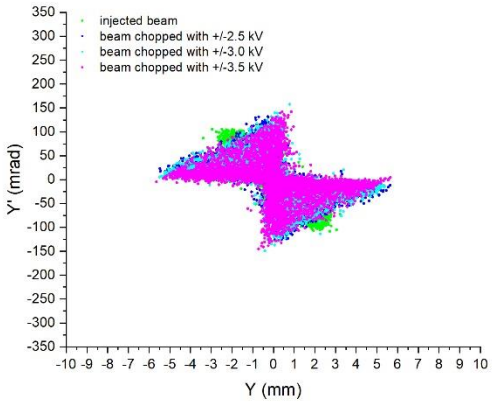


Comparison of beam chopping
- at the chopper target front-face

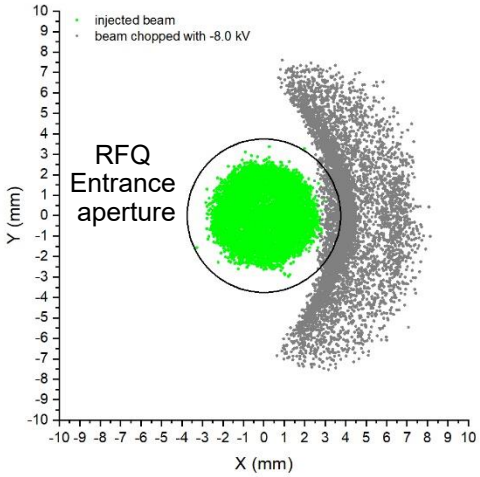
Two opposite pairs of segments with bipolar voltages

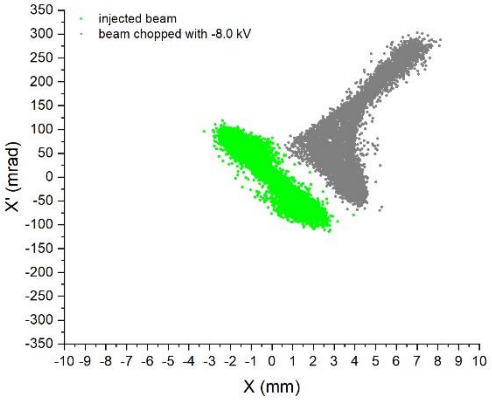


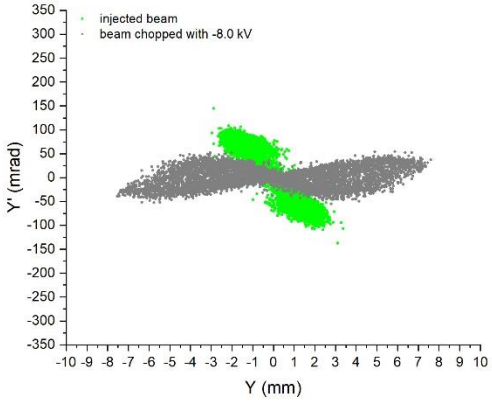




Only one segment with negative -8.0 kV

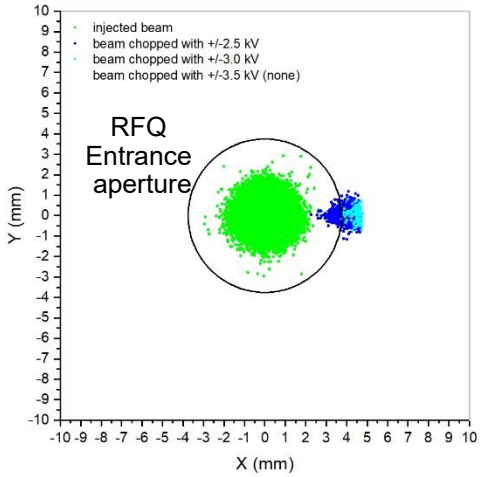


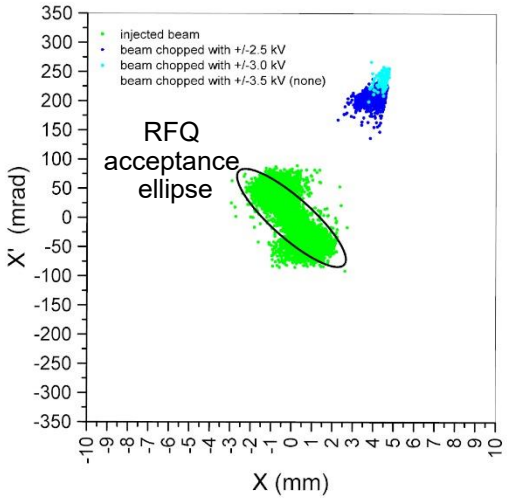


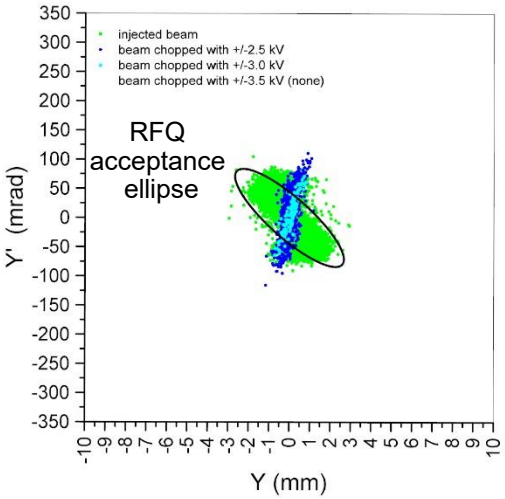


Comparison of beam chopping
- at the RFQ reference plane

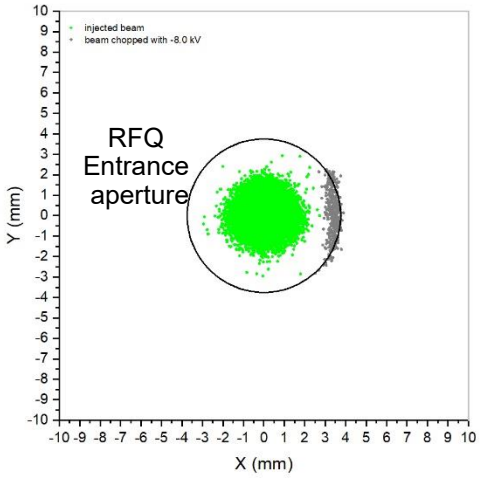
Two opposite pairs of segments with bipolar voltages

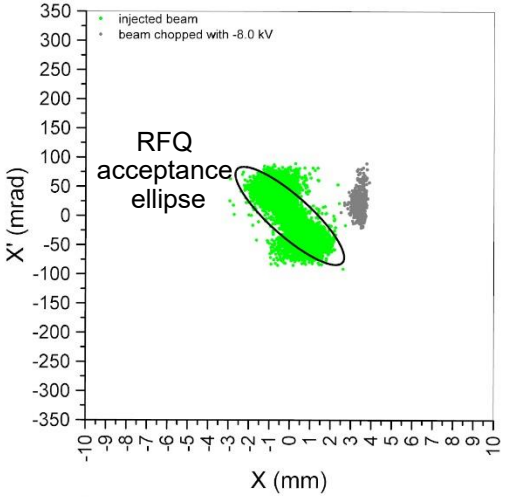


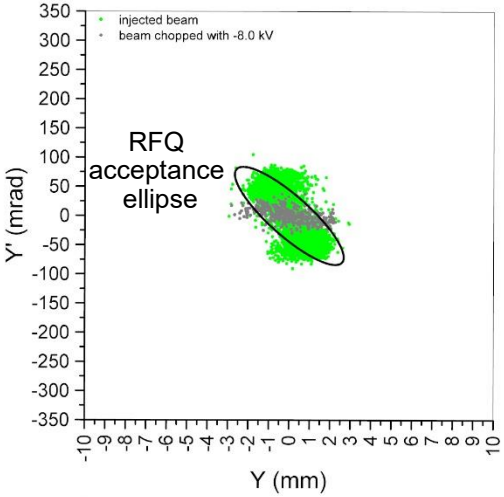




Only one segment with negative -8.0 kV







Chopping patterns	±2.5 kV	±3.0 kV	±3.5 kV	±4.0 kV	±4.5 kV	±5.0 kV
two opposite pairs	Chopping: good Beam distr. on chopper target: ok Ions impacting on RFQ vanes: some ions Ions scraped on lens-2: not a concern HV switch freq.: 1 MHz	Chopping: good Beam distr. on chopper target: ok Ions impacting on RFQ vanes: lesser ions Ions scraped on lens-2: not a concern HV switch freq.: 1 MHz	Chopping: excellent Beam distr. on chopper target: ok Ions impacting on RFQ vanes: almost none Ions scraped on lens-2: some concern HV switch freq.: 1 MHz			
two Opposite segments	Chopping: marginal Beam distr. on chopper target: ok Ions impacting on RFQ vanes: many ions Ions scraped on lens-2: not a concern HV switch freq.: 0.5 MHz	Chopping: marginal Beam distr. on chopper target: ok Ions impacting on RFQ vanes: many ions Ions scraped on lens-2: not a concern HV switch freq.: 0.5 MHz	Chopping: ok Beam distr. on chopper target: ok Ions impacting on RFQ vanes: many ions Ions scraped on lens-2: some concern HV switch freq.: 0.5 MHz	Chopping: ok Beam distr. on chopper target: ok Ions impacting on RFQ vanes: some ions Ions scraped on lens-2: some concern HV switch freq.: 0.5 MHz	Chopping: ok Beam distr. on chopper target: ok Ions impacting on RFQ vanes: some ions Ions scraped on lens-2: serious concern HV switch freq.: 0.5 MHz	Chopping: ok Beam distr. on chopper target: ok Ions impacting on RFQ vanes: lesser ions Ions scraped on lens-2: serious concern HV switch freq.: 0.5 MHz
one segment				**-8.0 kV** Chopping: ok Beam distr. on chopper target: good, spread on larger area Ions impacting on RFQ vanes: some ions Ions scraped on lens-2: some concern HV switch freq.: 0.25 MHz		

Summary

- An overview of the SNS accelerator system was given along with an introduction to its H^- injector and beam chopper system.
- Beam simulations were conducted for the present beam chopping pattern which involve activation of all four HV pulsers at the same time. Simulations indicate voltage amplitude higher than the presently limited 2.5 kV is desired for lesser ions impacting on the RFQ vane tips.
- The limitations with the present HV pulser system and ongoing upgrade efforts to enable higher voltage capability were discussed.
- In the meantime, possible alternative beam chopping patterns which involve activation of only two or even just one pulser at a time were explored.
  - The new chopping patterns will significantly reduce the stress on the HV switches due to reduced duty-factor.
  - But, beam simulations suggest higher voltage amplitude is required to deflect the beam, especially for the ions at larger radii along the axis perpendicular to the deflection axis.
  - Beam scraping inside the lens-2 electrode will be a concern if the voltage amplitude is too high, e.g. 4.0kV or above.
  - The fraction of the beam that is deflected but able to enter the RFQ is wider in size increasing its chance of impacting on the vane tips.

Thank you for your attention!