Detailed characterization of a five-dimensional phase space distribution

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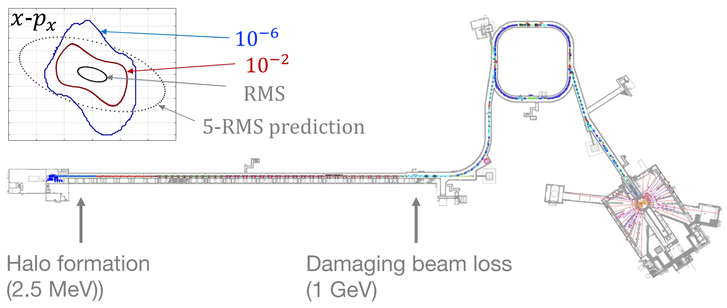
High-dimensional phase space measurements may be necessary for loss-level beam control.

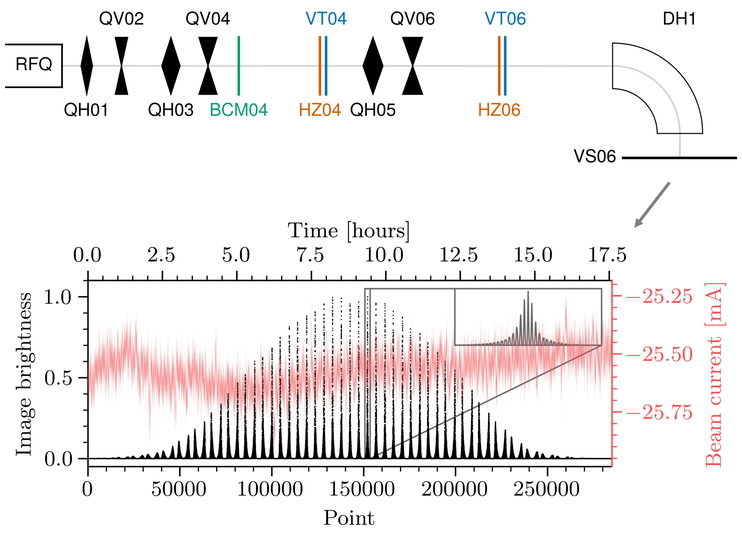
Beam halo plagues high-power hadron accelerators with strict fractional beam loss requirements ($< 10^{-6}$). Halo is difficult to predict due to its low density and sensitivity to initial/boundary conditions, including the initial particle distribution in six-dimensional (6D) phase space.



If coupled with an accurate accelerator model, high-dimensional phase space measurements could enable halo-level beam control and, therefore, the construction of intensity-horizon linacs. Here, we focus on the use of such measurements to identify features that are invisible to typical diagnostics.

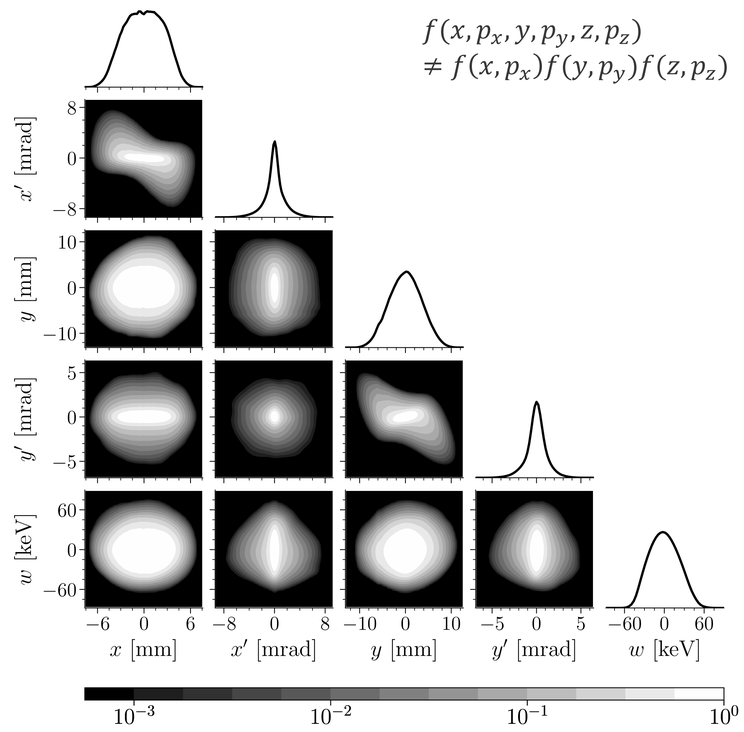
5D phase space measurements at the SNS Beam Test Facility (BTF) provide unprecedented detail.

Using three slits, a dipole, and a fluorescent screen, the conditional distribution $f(p_y, p_z \mid x, y, p_x)$ is measured in a single shot. Scanning the slits in a nested loop and interpolating generates a high-resolution (64^5), relatively high-dynamic-range (10^3) image of $f(x, p_x, y, p_y, p_z)$.

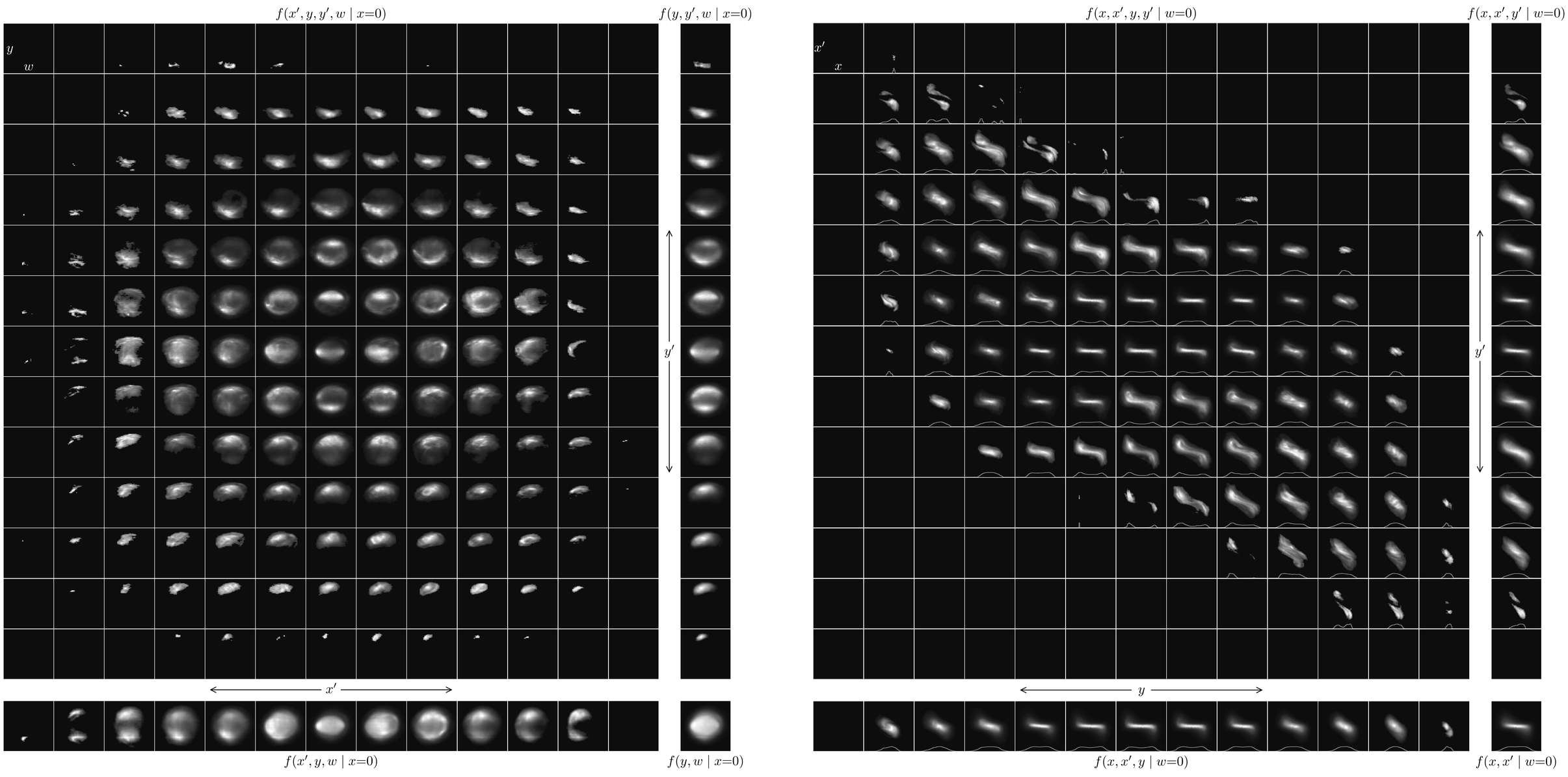


2D projections are easy to visualize but mask relationships between three or more variables.

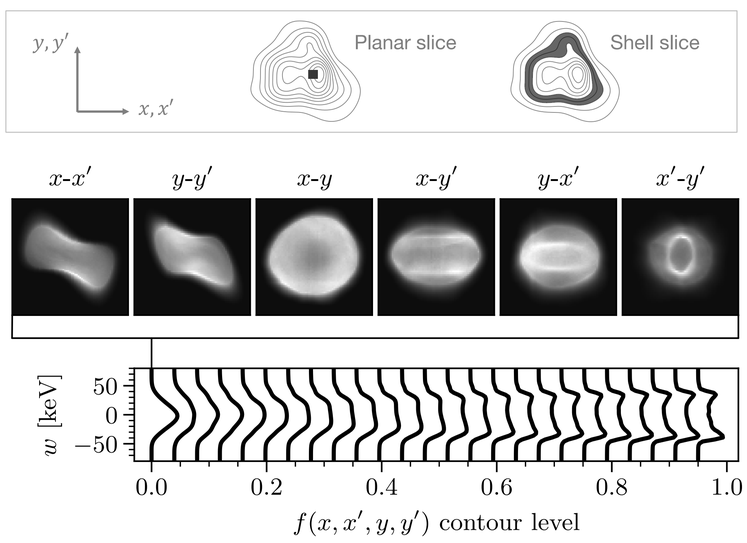
$$f(x, p_x, y, p_y, z, p_z) \neq f(x, p_x) f(y, p_y) f(z, p_z)$$



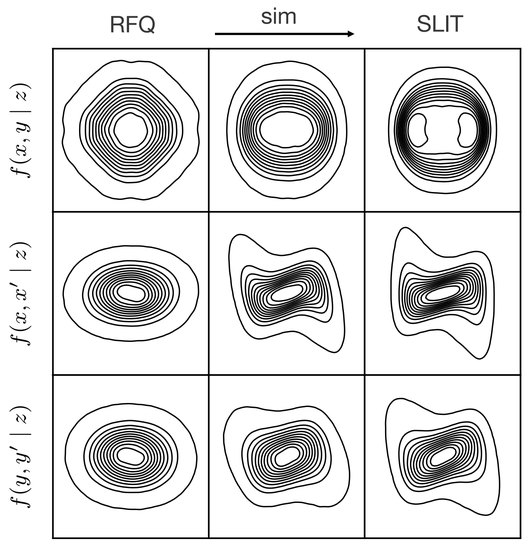
Slices reveal core hollowing in both transverse and longitudinal phase space.



Non-planar slicing highlights radial dependence in high-dimensional subspaces.



Hollowing is likely driven by nonlinear space charge forces in the RFQ and MEBT.



Future work will focus on detailed simulation benchmarks at the end of the SNS-BTF beamline.

Lattice model errors currently dominate and will be addressed with beam-based calibrations. The lattice will be upgraded to a straight layout.

Due to the absence of longitudinal focusing in the BTF, the following maximum entropy reconstruction may suffice for benchmarking efforts:

$$f(x, p_x, y, p_y, z, p_z) = f(x, p_x, y, p_y, p_z) f(z, p_z) / f(z).$$

Parallel studies are investigating new interpolation and sampling methods in preparation for high-resolution (potentially unstructured) 6D scans.

The dynamics leading to longitudinal hollowing in the RFQ are not fully understood, nor are the effects of the hollowing on the long-term beam dynamics.

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