Tomographic Longitudinal Phase Space Reconstruction of Bunch Compression at ISIS

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Introduction

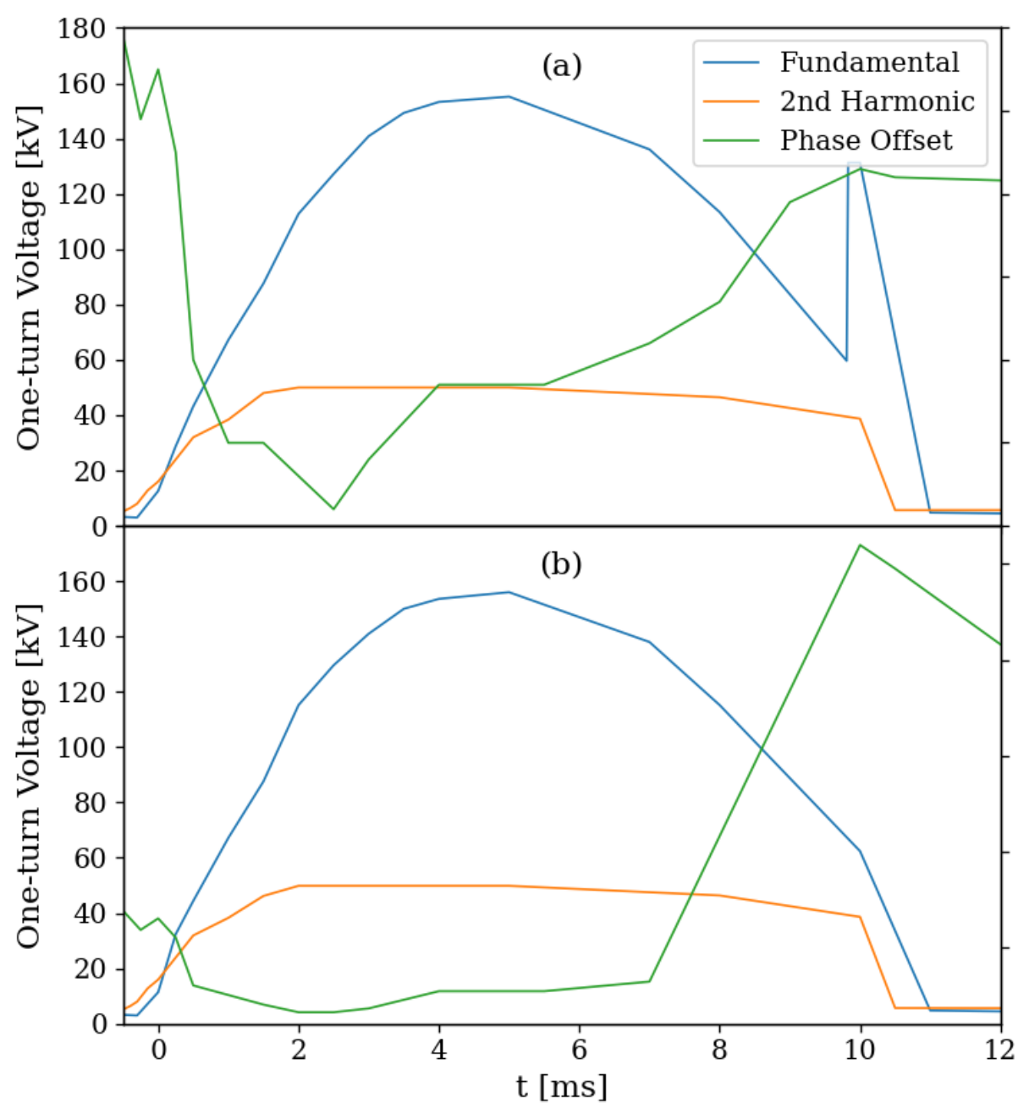

Figure 1: RF programs for two bunch compression schemes employed in the ISIS RCS: (a) bunch rotation, (b) Θ_{12}-ramp compression

The ISIS rapid-cycling synchrotron (RCS) accelerates high-intensity proton beams (3×10^{13} ppp) from 70 MeV to 800 MeV at a rate of 50 Hz. Acceleration occurs over the rising edge of the sinusoidal dipole field, facilitated by six fundamental (1RF, h=2) radio-frequency (RF) systems and four 2nd-harmonic (2RF, h=4) RF systems. Proton beams are delivered to two neutron target stations, TS1 and TS2, which receive proton pulses at rates of 40 and 10 Hz respectively. Alongside production of neutrons, a small portion of the ISIS TS1 pulse is used to produce muons for muon spectroscopy (μSR). This occurs at an intermediate graphite target positioned on the extracted beam transport line to TS1.

Shorter proton pulses ($\lesssim$ 60 ns) provide greater resolution for μSR experiments, and there is an ongoing effort to develop compression schemes in the ISIS RCS towards this end. These compression schemes make use of synchrotron RF manipulations.

Tomography is an important tool in the development of these methods, as well as for the longitudinal setup of the RCS in general, though reconstruction of the proton beam's longitudinal phase space (LPS). Simulations and measurements of two bunch compression schemes for ISIS are presented here.

Bunch Compression

Bunch rotation (Fig. 1a) is a two stage process, where the proton bunch is first elongated through a gradual reduction in the peak 1RF voltage relative to uncompressed settings. The bunch LPS is then rotated through a sharp increase in the 1RF voltage close to extraction (Fig. 2a). Careful timing of the 1RF peak is required, to ensure that extraction occurs at the point of minimum bunch length in the LPS rotation (Fig. 3a). This bunch compression method has already been employed for several years at ISIS to improve μSR measurements, and is very effective in producing short proton pulses. However, extraction timing in ISIS is established to occur within a 350 μs window on a pulse-to-pulse basis, and as such μSR experiments experience a degree of jitter in the extracted bunch length.

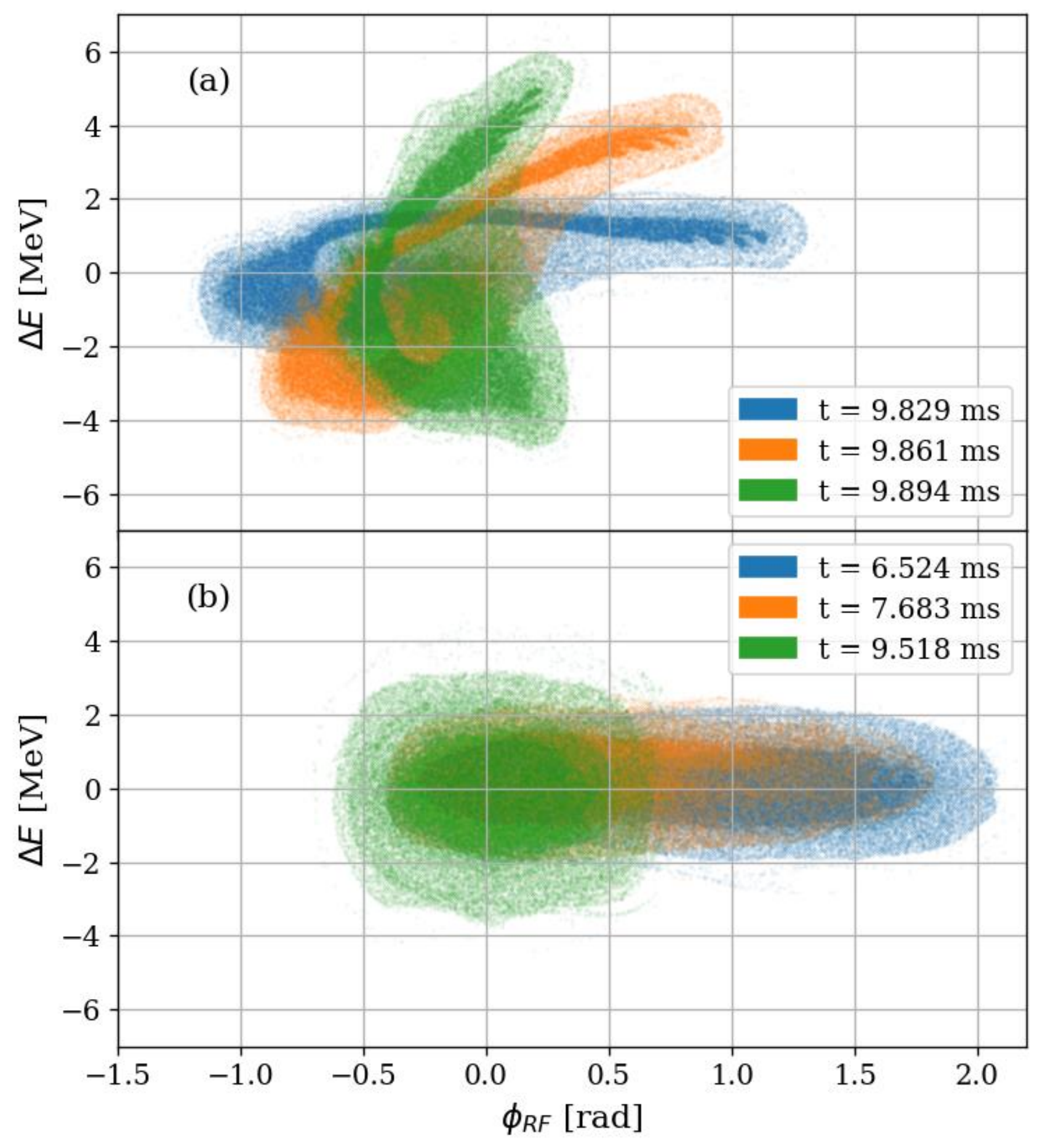

Figure 2: Simulated beam LPS for (a) bunch rotation and (b) Θ_{12}-ramp bunch compression methods

A second method uses a gradual ramp in the phase offset between the 1RF and 2Rf harmonics from 7 ms to the end of the machine cycle (Fig. 1b). This ramped scheme slowly converts the RF bucket into a highly asymmetric compressing bucket. As the bucket is deformed, the beam is "captured" around one of the fixed points, and quasi-adiabatically "squeezed" (Fig. 2b). An advantage of this method is the lack of dependence upon beam extract timing (Fig. 3b), with the potential of providing greater stability of the extracted bunch length.

The two bunch compression methods have been tested and validated on the ISIS RCS. Longitudinal information of the two recirculating proton bunches is obtained through beam position monitor (BPM) data. The ISIS BPMs are of the capacitative, split-cylinder type, where the summed signal of the two electrodes provides a measure of the instantaneous beam current in the monitor. Owing to fast (0.5 GHz) digitisation using an NI PXI, time-resolved turn-by-turn data is gathered. Profile measurements are re-binned to 720 bins per profile. These measurements are presented alongside simulations using a code built in-house to model the longitudinal dynamics of the ISIS RCS.

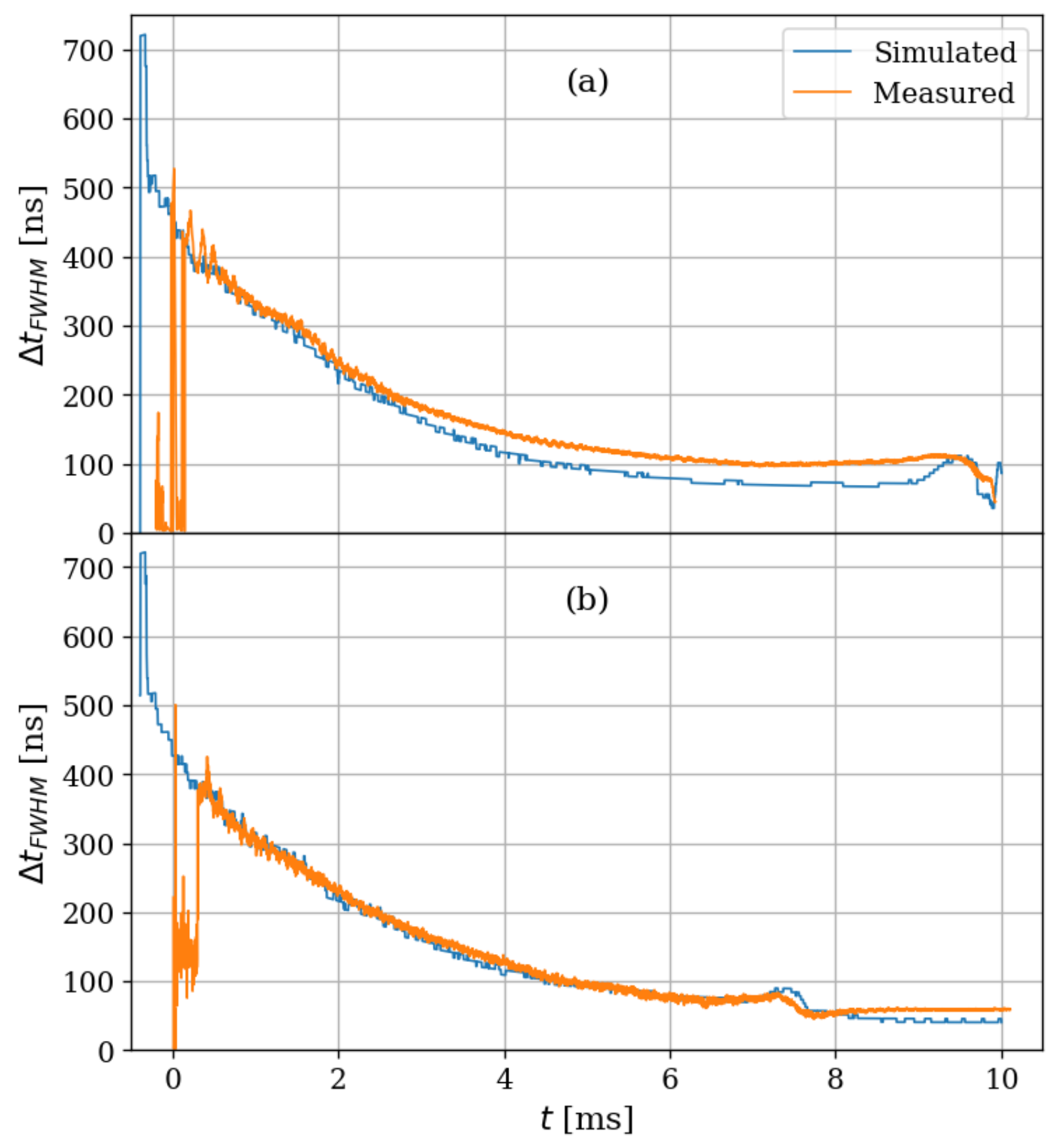

Figure 3: Comparison of proton bunch length (FWHM) through the machine cycles in simulation and measurement for (a) bunch rotation and (b) Θ_{12}-ramp bunch compression methods

Tomography

Tomography is used to reconstruct the beam's LPS from a set of longitudinal profiles. The longitudinal profiles are imaged at different phases of the synchrotron oscillation of the LPS. This information is then combined with a longitudinal simulation code to project the likely beam energy distribution and infer the LPS.

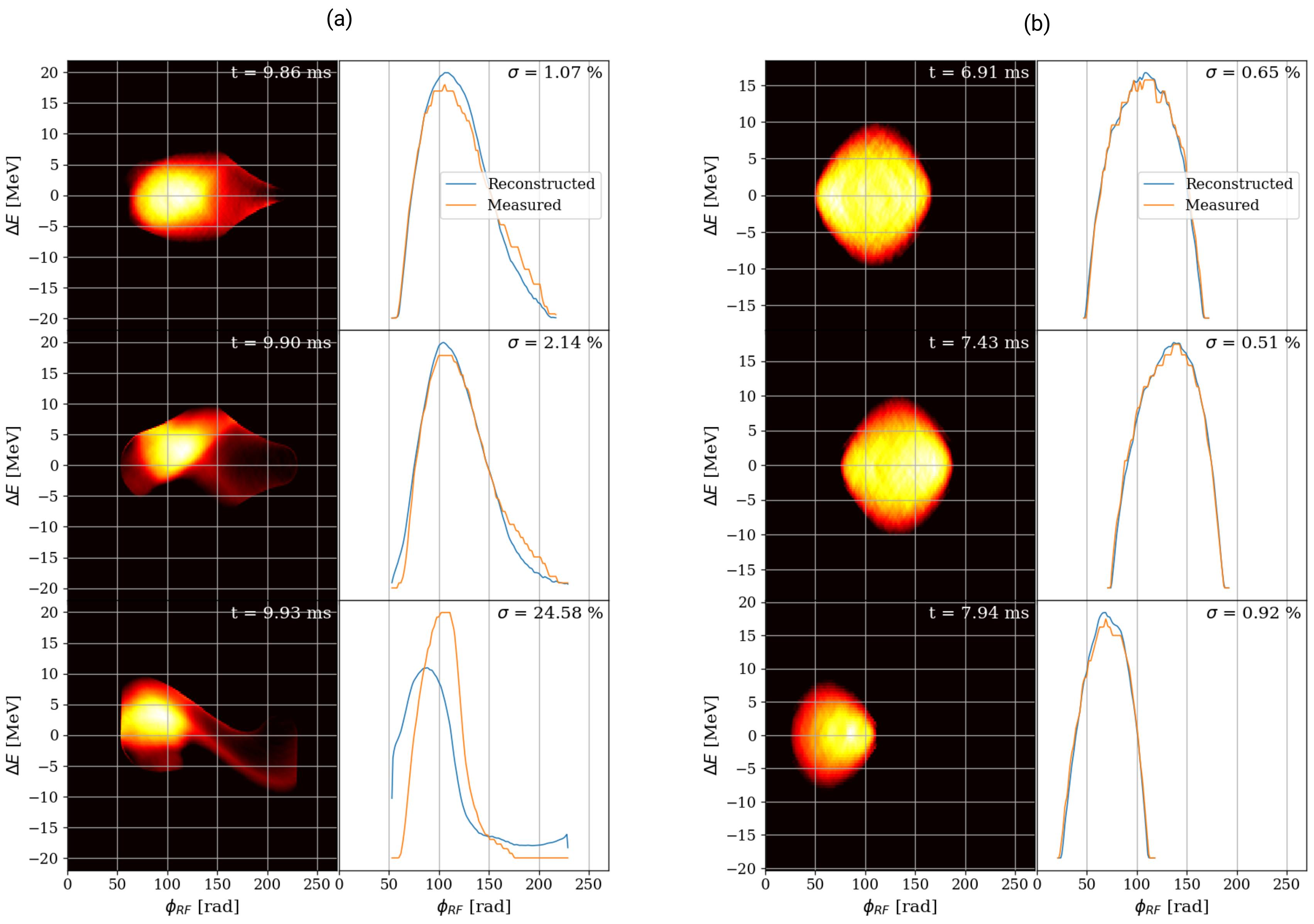

Figure 4: Tomographic reconstruction of LPS for the (a) bunch rotation and (b) Θ_{12}-ramp bunch compression . Rotation of the LPS is observed in (a), but points close to extraction show poorer agreement between reconstructed and measured longitudinal beam profiles. Reconstructed profiles agree well for the Θ_{12}-ramp method, but the energy spread far exceeds what is expected from simulations.

The CERN tomography code is a well-established tool, recently re-written in Python and C++. Here it has been used to recreate the ISIS proton beam LPS at extraction in both bunch compression methods. Some difficulty has been encountered currently in the usage of tomography for ISIS, due to the RCS mode of operation. In the case of bunch rotation (Fig. 4a), generally good fits (~1-2% error) are obtained, except for the final LPS reconstruction at the point of extraction. It is believed that this is primarily caused by a lack of viable frames. In other reconstructions, an equal number of measurements are taken into account either side of the reconstruction point. This is not possible for the final point, only profiles measured before extraction can be considered.

For the Θ_{12}-ramp compression method (Fig. 4b), good fits to the measured profiles are found for all points (<1% error), but the calculated energy spread of the LPS far exceeds that expected from simulations (Fig. 3b). This may be due to the assumed-constant value of Θ_{12} in the tomography code.

Conclusions

Tomography shows potential for development of bunch compression schemes, as well as other aspects of longitudinal set-up at ISIS, such as longitudinal injection painting. Despite this, further work is required to improve tomographic reconstruction, such as increasing longitudinal profile measurement resolution, performing bunch rotation earlier in cycle (for development purposes only) in order to properly resolve the minimum bunch length phase of the LPS rotation, and incorporating a varying value for Θ_{12} in tomography.