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A PROOF OF PRINCIPLE OF ASYMMETRIC BUNCH PAIR MERGING

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Abstract

Bunch splitting[1] was established as a routine operation in the arsenal of rf gymnastics in the PS Complex long before it became the saving grace of the beam for the LHC[2]. Historically, however, it was born out of the time-reversed analogue process of merging[3], in which a pair of bunches are combined. Hitherto, both operations have been performed with bunches of equal longitudinal emittance. Now an asymmetric merging process has been demonstrated. By combining a bunch with a small empty bucket, it is possible to deplete only the central density of the resultant particle distribution. This would allow bunches to be tailored with quasi-flat line densities. The details of the method are presented together with some measurements.

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1 Motivation

In one route to accelerator-driven neutrino experiments, it is proposed to stack radioactive ions (a so-called “beta-beam”) in a large decay ring[4]. Since stochastic and electron cooling are excluded at the energies envisaged, phase space dilution is an important issue in the stacking process. Asymmetric bunch pair merging circumvents the problem by enabling a small dense bunch of fresh ions to be deposited with minimal dilution at the centre (in longitudinal phase space) of a large existing stack[5].

The idea of bunch flattening by combining an empty bucket with a full one is not a new one[6], but employing asymmetric merging provides not only a conclusive proof of principle of the same but also a means of tailoring the amount of empty phase space that gets deposited.

2 Mathematical Background

At fixed energy below transition, symmetric merging (or splitting) is achieved using two rf components which are in antiphase at the nominal stable point $\varphi = 0$.

$$V_{RF}(\varphi) = V_1 \sin(\varphi) - V_2 \sin(2\varphi) \tag{1}$$

Here, V_1 is the peak rf voltage of the principal harmonic and V_2 that at double the frequency. For $V_2/V_1 = r > 0.5$, the right-hand side of this equation has an extra pair of roots,

$$\varphi = \pm \arccos\left(\frac{1}{2r}\right) \tag{2}$$

These are the additional stable phases of the two inner buckets which move together as the voltage ratio r decreases.

In the asymmetric case, the phase between the two rf components is modified.

$$V_{RF}(\varphi)/V_1 = \sin(\varphi) - r\sin[2(\varphi - \varphi_{12})] \tag{3}$$

This makes the extra roots far from trivial. Nevertheless, it is possible to evaluate the relative phase φ_{12} as a function of r such that the separation of one of these extra roots is maintained constant with respect to the unstable fixed point that lies between them. Ideally, one would aim to conserve the acceptance of one of the inner buckets as r varies, but constant separation of the unstable and stable phases of that bucket proves to be a reasonable approximation to this and is straightforward to achieve numerically by applying a contour-finding routine (see fig. 1) to the difference between the appropriate two roots of the right-hand side of eqn. (3).

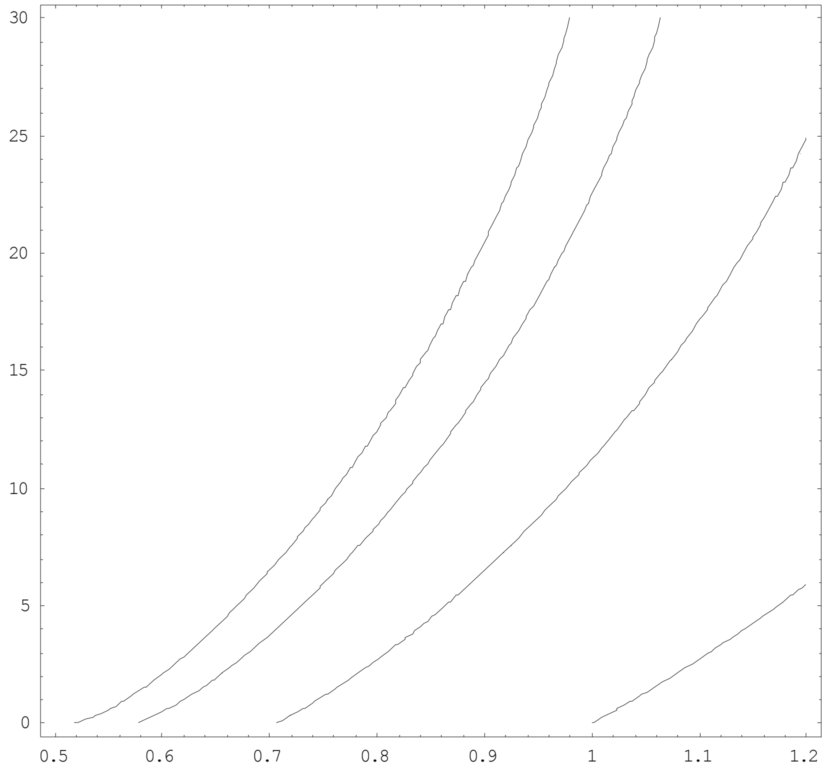


Figure 1: φ_{12} [deg] versus r such that the stable phase of the right-hand inner bucket is maintained at (from left to right) 15°, 30°, 45° and 60° with respect to its unstable phase.

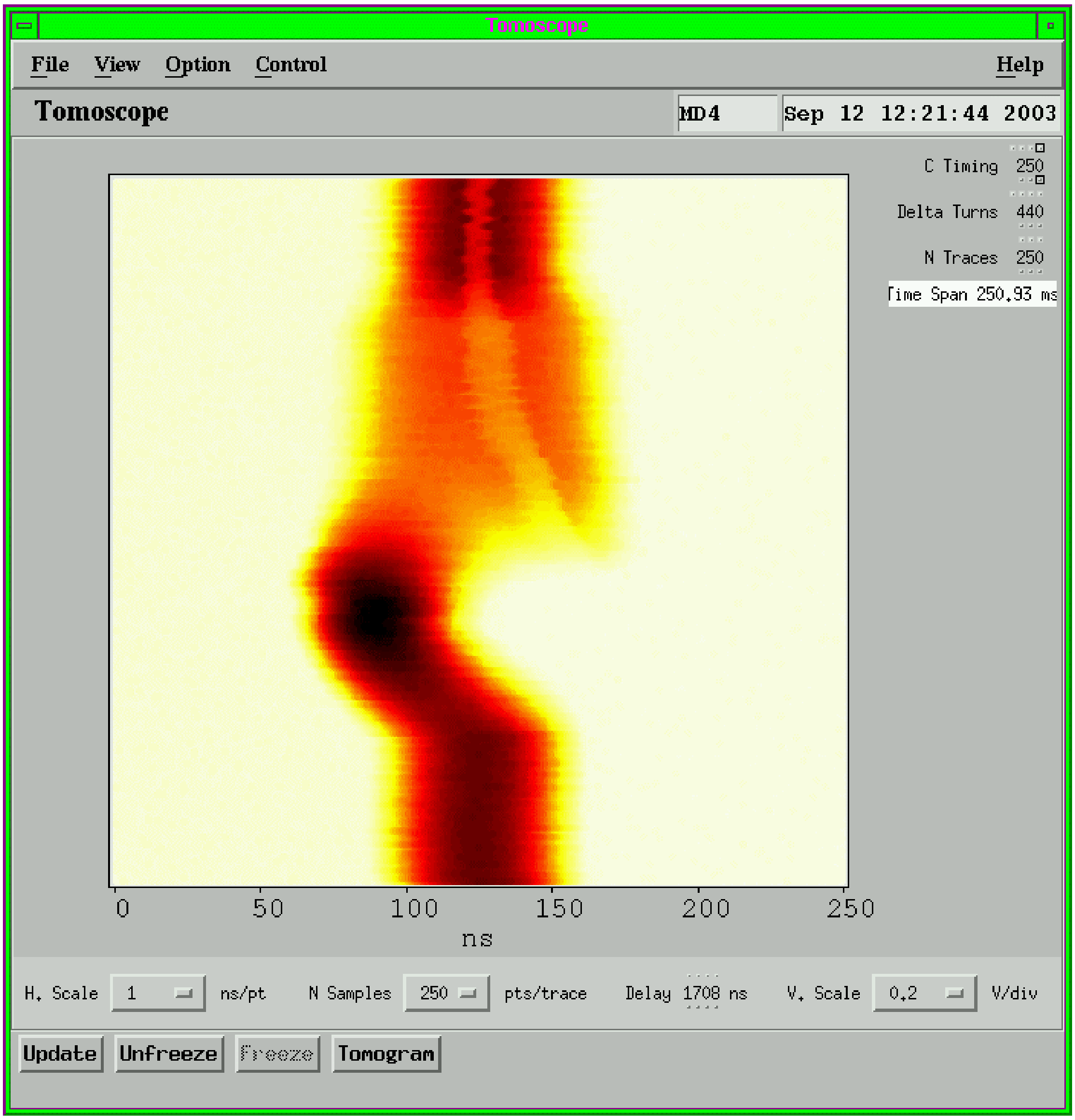
The contents of the conserved inner bucket are only merged once the voltage ratio drops below the critical value (at the bottom of fig. 1) at which the two rf components are in direct antiphase ($\varphi_{12} = 0$) and both inner buckets are the same size. Keeping $\varphi_{12} = 0$ for values of r below this limit, it follows from eqn. (2) that choosing

$$r = \frac{1}{2\cos[k(1 - t/T)]} \tag{4}$$

where T is the duration of merging and k a constant, means the inner bucket centres converge linearly with time, t.

3 Measurements

A key hardware element was a fast phase shifter[7], which enabled the phase between two sets of PS 10 MHz cavities to be precisely programmed by simply updating a digital control word. Each set comprised two cavities, with one pair operating on harmonic h=8 and the other on h=16. A single bunch of around 1.6×10^{11} protons with an emittance of 0.3 eVs was injected into a PS bucket on h=8. Transversally, the PS machine was bare and the beam was dumped internally at the end of a flat (1.4 GeV) cycle. The origin ($\varphi_{12} = 0$) for the phase shifter was determined experimentally as that constant phase which, when the h=16 voltage was raised, resulted in the bunch being split into two equal parts.



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C Timing 250

Delta Turns 440

N Traces 250

Time Span 250.93 ms

H. Scale 1 ns/pt N Samples 250 pts/trace Delay 1708 ns V. Scale 0.2 V/div

Figure 2: Waterfall plot of asymmetric merging.

An overview of the entire merging process, as recorded by the online tomoscope application[8], is shown in fig. 2. The initial bunch (at the bottom of the image) first moves to the left as the second harmonic component is raised, then empty phase space comes in from the right as this component is reduced. Ultimately, the second harmonic is turned off completely to allow the final bunch to be compared with the initial one under pure h=8 conditions.

In order to prevent the phase loop (there was no radial loop) from competing with the desired phase excursions of the bunch, the process was first established under open-loop conditions. Then, by recording the beam phase seen by a phase discriminator, the appropriate phase programme could be supplied to the beam control when, subsequently, the loop was closed. Fig. 3 (which spans the same period of time as fig. 2) shows the form of this phase programme (channel 4) together with the error signal of the loop (channel 1). The latter indicates that the loop was working no harder during all the rf manipulations than it was either before or afterwards.

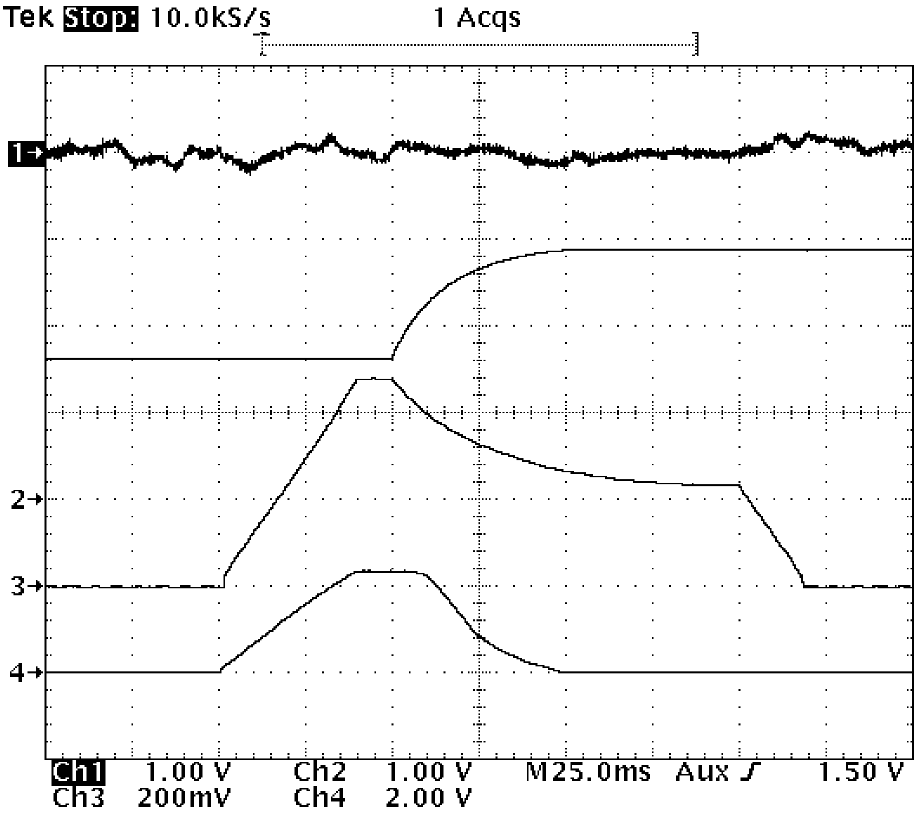
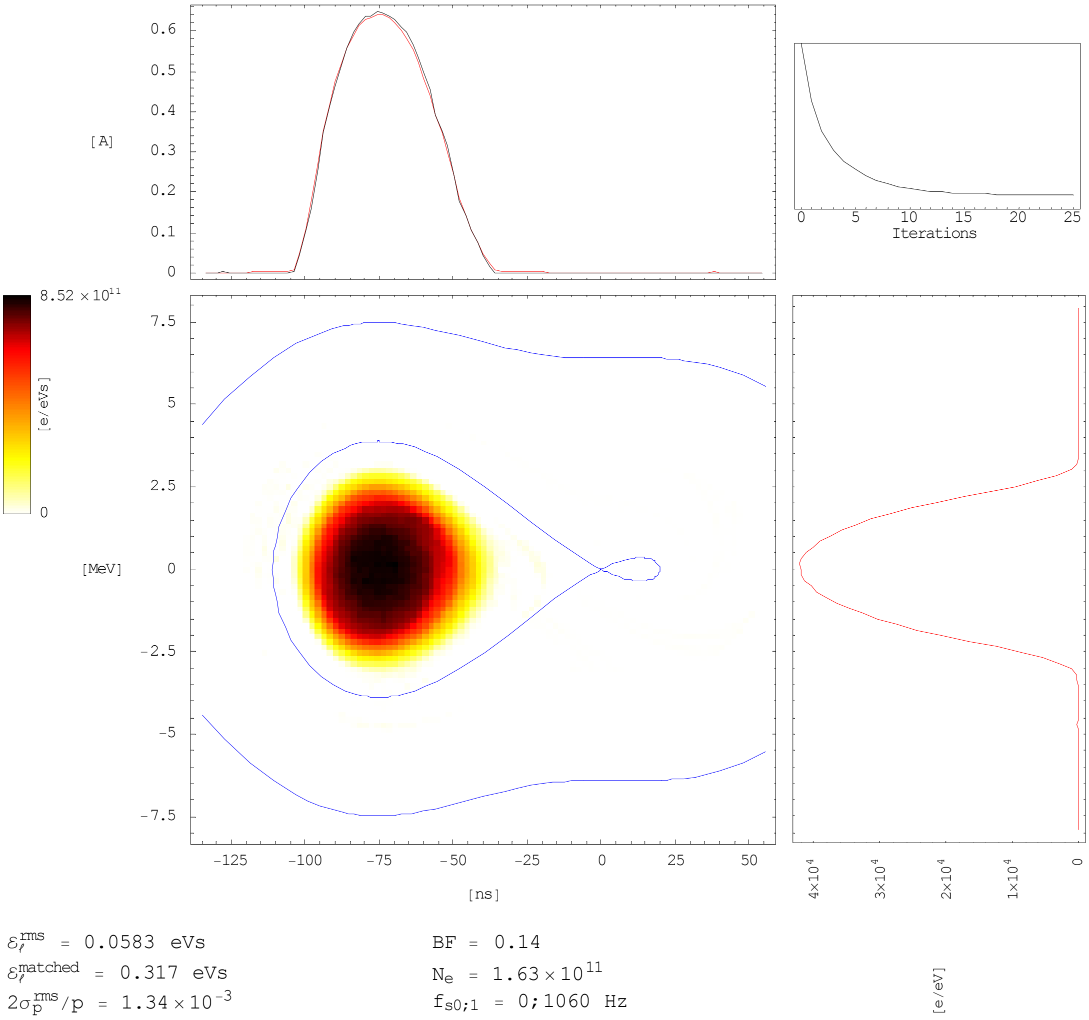


Figure 3: Oscilloscope traces of 1) phase loop error signal; 2) φ_{12} phase programme; 3) detected h=16 voltage; 4) reference phase of the beam control (operating on h=8).

The h=16 voltage and φ_{12} phase variations are also shown in fig. 3, while the h=8 voltage was constant at 40 kV throughout. After a linear rise of the h=16 voltage to establish the initial conditions for merging (see fig. 4), the voltage ratio was unity and the (h=8) phase between harmonic components was 157.5° (i.e., $\varphi_{12} = 22.5°$). After a short plateau, the h=16 voltage was reduced during 100 ms in accordance with eqn. 4 until $r = 0.5$ and, in turn, φ_{12} followed the 30° curve of fig. 1 until the two rf components were in antiphase.

By pausing the evolution of the voltage and phase programmes, it was possible to make tomographic measurements during merging. Fig. 5, which corresponds to the time at the midpoint of figs. 2 and 3, shows a well-preserved empty bucket entering the bunch as the acceptance of the populated bucket shrinks and particles bleed out around the inner separatrix.

Fig. 6 shows the resultant particle distribution in a pure h=8 bucket. This is to be compared with the initial bunch under the same machine conditions shown in fig. 7. All tomoscope settings were also rigorously the same for these two acquisitions. The bunch area is increased from 0.30 to 0.32 eVs. Cf., the acceptance of the empty inner bucket in fig. 5 is about 0.01 eVs. The peak proton density (which is indicated at the top of the colour bar in each tomogram) is conserved from fig. 7 to figs. 4 and 5 – at least, to within the fluctuations in overall intensity between the shots.



$\varepsilon_\ell^{\mathrm{rms}}$ = 0.0583 eVs

$\varepsilon_\ell^{\mathrm{matched}}$ = 0.317 eVs

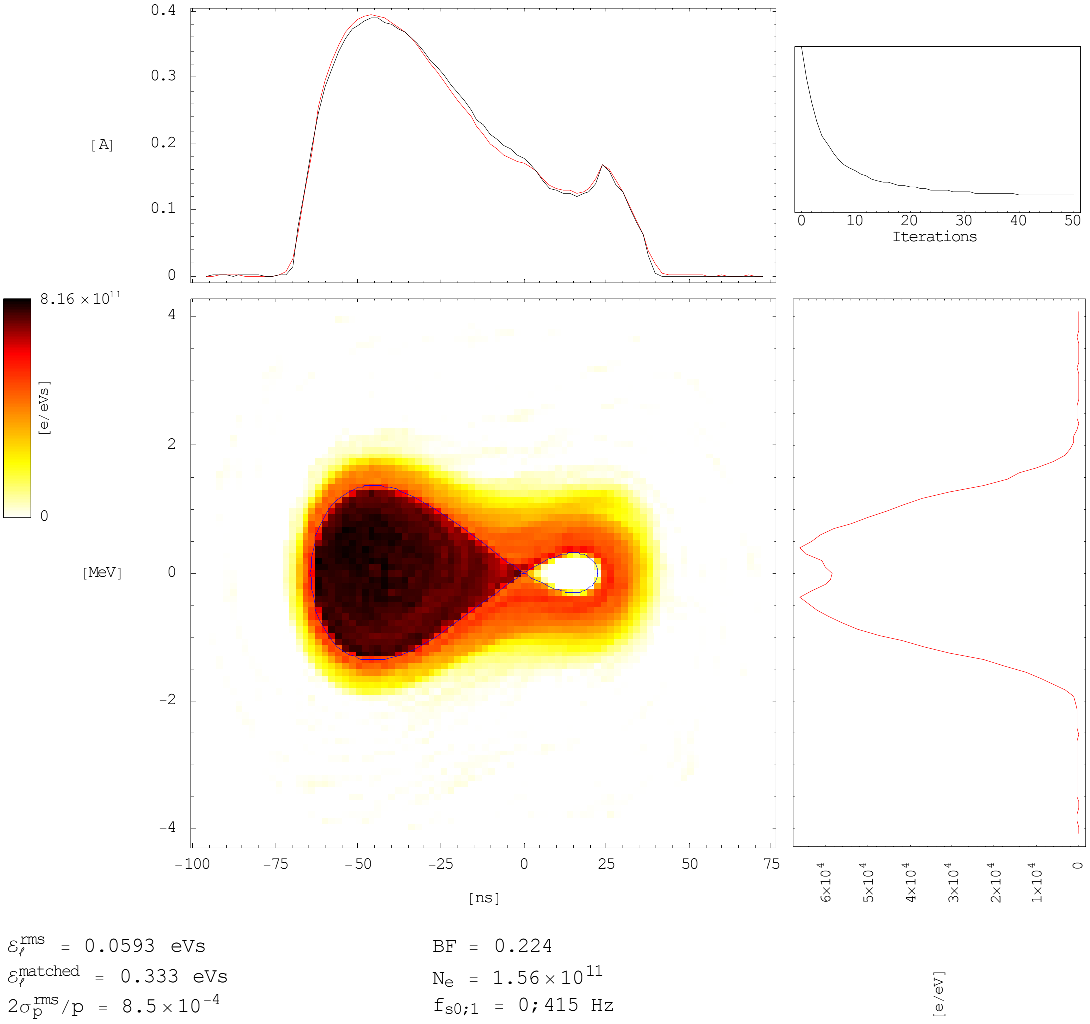
$2\sigma_p^{\mathrm{rms}}/p$ = 1.34×10^{-3}

BF = 0.14

N_e = 1.63×10^{11}

$f_{s0;1}$ = 0;1060 Hz

Figure 4: Tomogram at the start of merging.



$\varepsilon_\ell^{\mathrm{rms}}$ = 0.0593 eVs

$\varepsilon_\ell^{\mathrm{matched}}$ = 0.333 eVs

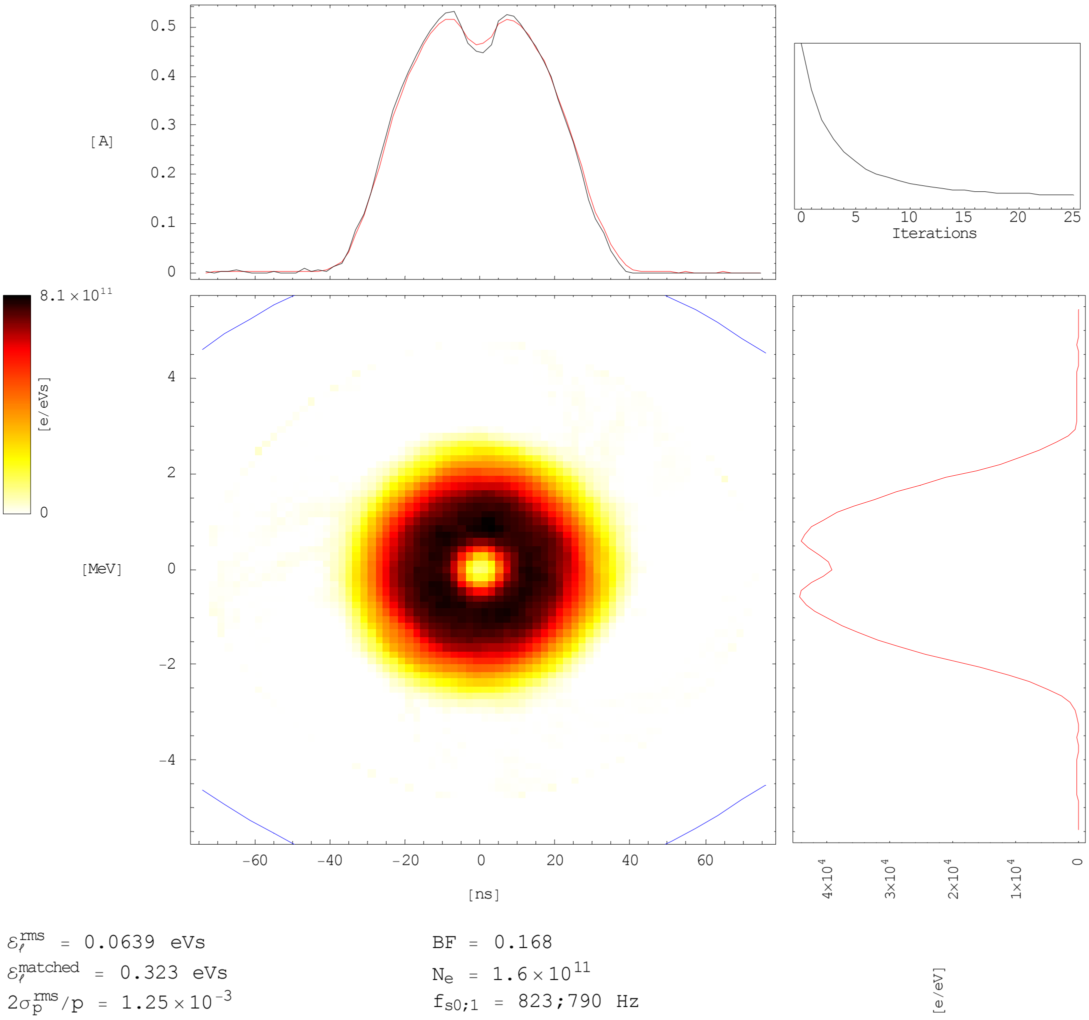
$2\sigma_p^{\mathrm{rms}}/p = 8.5 \times 10^{-4}$

BF = 0.224

$N_e = 1.56 \times 10^{11}$

$f_{s0;1}$ = 0; 415 Hz

Figure 5: Tomogram during merging.



$\varepsilon_\ell^{\mathrm{rms}}$ = 0.0639 eVs

$\varepsilon_\ell^{\mathrm{matched}}$ = 0.323 eVs

$2\sigma_p^{\mathrm{rms}}/p$ = 1.25×10^{-3}

BF = 0.168

N_e = 1.6×10^{11}

$f_{s0;1}$ = 823;790 Hz

Figure 6: Tomogram after merging.

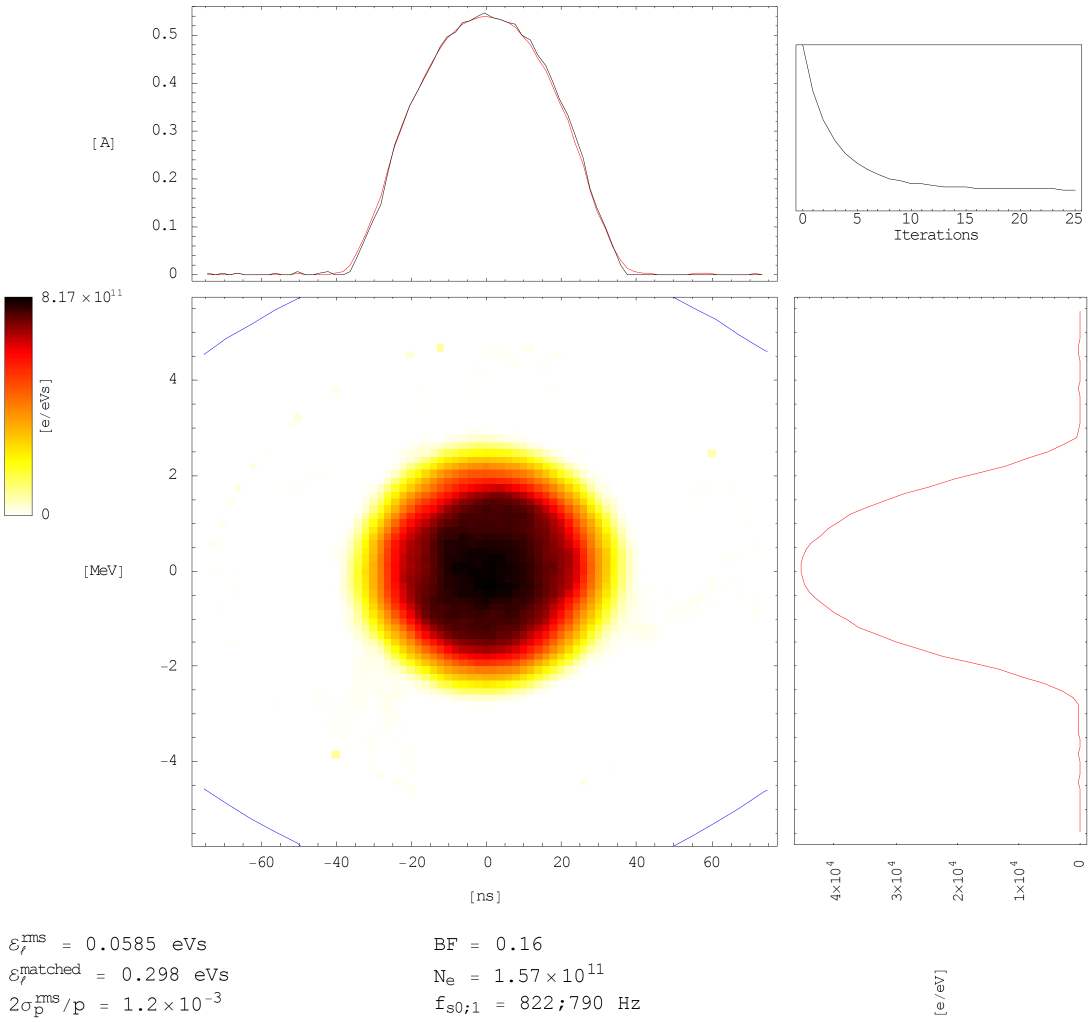


Figure 7: Tomogram before merging.

4 Concluding Remarks

Asymmetric bunch pair merging has been demonstrated, albeit with one bunch a chimera. In effect, an empty bucket was conserved during its transportation into the core of a much larger bunch where, ultimately, the empty phase space was merged with the central region of the particle distribution.

The longitudinal acceptance of the empty bucket was only approximately conserved during the process. An obvious refinement would be to calculate phase and voltage programmes such that the acceptance remains constant. This was not deemed necessary for the proof of principle. More important, perhaps, would be to consider how to repeat the experiment when space charge cannot be neglected.

The large size ratio between bunch and empty bucket was deliberately chosen to mimic the requirements of the beta-beam design. The generation of flat bunch profiles would require a less severe asymmetry and, consequently, would involve a significant longitudinal blow-up. An alternative bunch flattening scheme exists based on similarly delicate dual-harmonic manipulations but which avoids such a blow-up penalty[9].

Asymmetric bunch pair merging is an essential step in a new stacking scheme which is of potential interest in any radioactive ion storage ring where the beam lifetime sufficiently exceeds the cycling time of the injectors.

References

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