Operational Scenarios with Linac4 within the PS Complex

B. Mikulec BE/OP

Overview

- Introduction
- Changes for PSB operation with Linac4
- PSB beam production with Linac2
- First concepts of PSB beam production with Linac4
- Single batch LHC beam transfer between PSB and PS
- Summary

Remark

- *Concentrate on PSB and neglect for moment PS*
  - As PSB extraction energy will stay as is and main beam parameters will remain valid (except intensity), first assumption that the situation for the PS will not change (this is not completely true and will be shortly addressed at the end)
  - Single batch transfer between PSB and PS of LHC25/50/75ns beams treated as separate point

Introduction

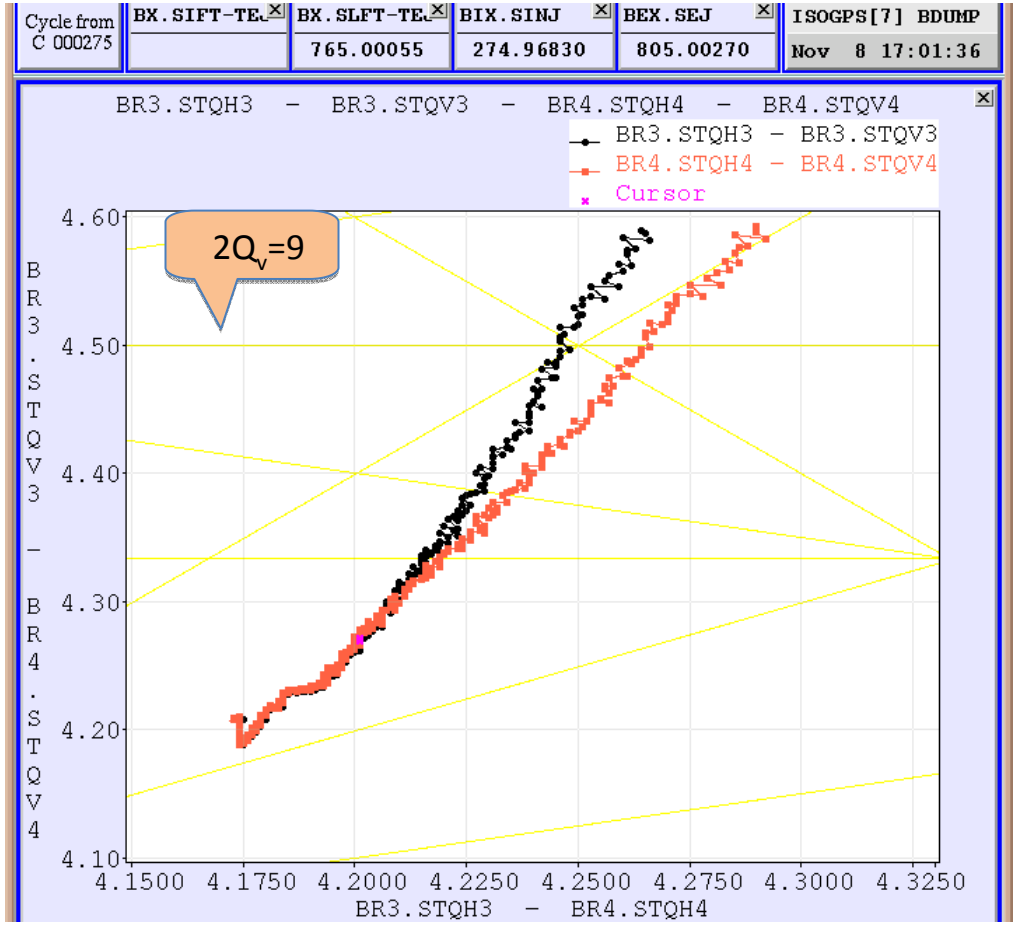
Main changes for PSB with Linac4 replacing Linac2:

1. *Increased injection energy 50 → 160 MeV*
   - Reduction of space charge effects; same direct space-charge tune shift with twice the brightness
   - 2 x brightness is required for single batch transfer of LHC beam to PS; reduction of LHC filling time; increased int. luminosity
2. *New injection scheme* (presentation W. Weterings):
   - H- charge-exchange injection; stripping foil; Linac4 chopping
     - Preserve increased brightness until complete capture through painting of PSB acceptance (see C. Carli, B. Goddard)
     - Remark: H^- charge-exchange injection new for CERN
   - New distributor, remove septum and other hardware changes
     - Losses on septum for conventional multi-turn injection disappear!
     - No (easy) way back to Linac2 operation…

➢ Required to produce ultimate LHC beam of 1.7 10^{11} ppb (with double-batch transfer?).

Increased Brightness for PSB Beams

- Dynamic working point to cope with Laslett tune shift of ~0.5 (vert.) at 50 MeV.



- To inject at 160 MeV should allow intensity increase for all beams due to reduced space-charge tune shift
- LHC-type beams:
  - Double intensity within unchanged emittances
- High intensity beams for PS:
  - Increase intensity by less than a factor 2
  - Operational margin to adjust transverse emittances to needs of PS

PSB Beam Production

PSB Beam Zoo

- *A huge variety of beams with diverging specifications is produced at PSB*
  - Intensity range per ring covers 4 orders of magnitude (from a few 10^9 to $>10^{13}$ protons per ring)
  - Long. emittances from 0.2-2.3 eVs
  - Transverse normalized emittances between <1 and >20 π mm mrad
- *Have to make sure that we can still produce all these beams with Linac4…*
  - How to achieve **all** beams within specifications?
    - Chopper, transv./long. painting, number of turns, adequate beam instrumentation, PSB RF, synchronisation, blow-up, …
    - Losses

LHC-type Beams from PSB with Linac2

user	description	h	rings	intensity per ring	emittance (rms) x [mm mrad] (n.) y [mm mrad] (n.) z [eVs] at extraction	dp/p [10^{-3}]	bunch length at extraction [ns]	energy [GeV]
LHC25A LHC25B	25ns LHC beam	1	1,2,3,4 3+4	nominal: **1.6E12** (optional 1/10, 1/5, 1/3,1/2*, 2/3)	2.5 2.5 1.3	2.0	180	1.4
LHC75A LHC75B	75ns LHC beam	1	1,2,3,4 3+4	0.8-5.4E11	2.5 2.5 0.9	2.0	150	1.4
LHCPILOT	early LHC beam	1	3	0.5E10	2.5 2.5 0.3	1.0	85	1.4
LHCPROBE	early LHC beam	1	3	0.5-2.0E10	<1 <1 0.2	1.0	75	1.4
LHCINDIV	single bunch physics beam	1	1-4	2.0-12E10	2.5 2.5 0.3	1.0	80	1.4

* LHC50

Other Physics Beams from PSB with Linac2

user	description	h	rings	intensity per ring	emittance (rms) x [mm mrad] (n.) y [mm mrad] (n.) z [eVs] at extraction	dp/p [10^{-3}]	Bunch length at extraction total, [ns]	energy [GeV]
SFTPRO	SPS fixed target	2	1,2,3,4	3.5E12	6.0-8.0 5.0-6.0 1.6	2.7	180	1.4
CNGS	CNGS beam	**2**	1,2,3,4	0.6-8.0E12	varying varying 1.6	2.7	180	1.4
EASTA	PS East Hall	1	3	2.0-3.0E11	3.0 1.0 1.1	2.0	150	1.4
EASTB	PS East Hall	1	2,3	1.0E11	3.0 1.0 1.1	2.0	150	1.4
EASTC	PS East Hall	1	3	4.5E11	3.0 1.0 1.1	2.0	150	1.4
AD	AD beam	1	1,2,3,4	4.0E12	7.0-8.0 6.0 1.7	2.2	190	1.4
NORMHRS NORMGPS	ISOLDE HRS and GPS	**1**	1,2,3,4	up to 1E13	<15.0 <9.0 2.3	2.7	230	1.0/1.4
STAGISO	ISOLDE staggered beam	1	2,3,4	depending on experiment	<5.0 <4.0 <1.6	<2.0	230	1.0/1.4
TOF	nTOF beam	1	1,2,3,4	9.0E12	~20 ~10 2.1	2.9	230	1.4

Linac4/PSB Basics

- *H^- source*: 45 keV, 80 mA, 0.4 ms pulse length, up to 2 Hz repetition rate, 0.25 πmmmrad norm. rms emittance
  - first 20 μs of source pulse unstable
- Nominal peak current (average over filled Linac4 buckets) out of Linac4: 65 mA
- *Linac4 RF frequency*: 352 MHz (LEP klystrons)
  - Does not fit PSB buckets (0.992 MHz revolution frequency at injection; PSB revolution ~355 Linac4 bunches)
  - Remove (for high intensity/brillance) in average 133 out of the 355 Linac4 bunches with chopper at 3 MeV
  - Average Linac4 current (1-(133/355))*65 mA: ~ 40 mA
- *Distributor:*
  - *Chopper* needs to remove in addition Linac4 bunches during rise-time of distributor (~500 ns) to switch between the 4 superposed PSB rings
  - Chopper rise-time should ideally be <(2.84-0.8) ns to rise and fall between bunch gaps (which is not the case – see next slide)

Chopper Characteristics

- Limitations of chopper driver:

Limitation	Consequence
$T_{rise/fall}$<3.6 ns (10%-90%) $T_{rise/fall}$<4.1 ns (3%-90%)	Loose part of one Linac4 bunch further down the line (>2.04 ns)
25 ns < T_{ON} < 1000 ns	Can cut out max. 1 PSB turn
T_{OFF} > 40 ns	A min. of 14 Linac4 bunches will pass between 2 chopper actions

Some Numbers…

Linac4 current	# particles/Linac4 bunch
65 mA	$1.15\ 10^9$
40 mA	$0.70\ 10^9$

- <u>65 mA</u>: $1.15\ 10^9$ x 355 ~ $4.08\ 10^{11}$ protons/PSB turn
  - ➢ With 100 turns the current max. intensity per ring can in principle be more than tripled.

Production of Nominal LHC 25ns Beam

First considerations:

- Required intensity per PSB ring (2 bunches/ring; including transmission losses further down in chain):
  - 3.2 10^{12} p → 2783 bunches → ~8 turns @ 65 mA
- Inject into accelerating bucket (10 Tm/s or 1.2 T/s) to minimize space-charge effects
  - Take into account varying synchrotron energy of PSB or of each ring
- Transverse phase-space painting (presentation B. Goddard)
- Energy modulation (ΔE=±1.2 MeV) with last 2 PIMS cells to paint long. phase-space (presentation C. Carli)
  - Prerequisite: Synchronization of energy modulation with PSB RF
  - Coarse synchronization of PSB RF with chopper to switch on Linac4 beam only when particles end up inside PSB bucket
  - Proposal to use triangular shaped modulation with period of 20 turns
    - Not compatible with 8 turn injection (→ reduce source current or inject more turns and chop out fractions leading to non-homogeneous long. phase space)
  - Requires synchronization between RF systems of the 4 PSB rings for switching between rings

Production of LHCINDIV

- Min. intensity: 2 10^{10} p → ~18 Linac4 bunches ~1/20 turn @ 65 mA
- Max. intensity: 12 10^{10} p → ~105 Linac4 bunches ~⅓ turn @ 65 mA

- Currently, lose >50% of Linac2 beam at injection and a factor of 10-60 due to longitudinal shaving and blow-up.

First thoughts on production strategy with Linac4:

- To obtain small long. emittance (0.3 eVs) inject directly into one h2 bucket
- Adjust final long. emittance with long. blow-up (C16 cavity)
- No need for long. painting; moreover not useable (~20 turns needed) due to small intensity and chopper limitations

Production of LHCINDIV - Continued

- Min. intensity: 2 10^{10} p → ~18 Linac4 bunches ~1/20 turn @ 65 mA
- Max. intensity: 12 10^{10} p → ~105 Linac4 bunches ~⅓ turn @ 65 mA

Continue on production strategy with Linac4:

- For max. intensity have to inject in principle only <⅓ turn and for min. intensity 1/20th.
  - Min. number of selectable turns should be reduced to <1/10; remember max. ON-time of chopper 1 μs and min OFF-time 40 ns (14 Linac4 pulses will pass)
  - Cannot use active transverse painting as a min. of ~3x3 turns would be required (or will beam filament?)
  - Should one apply transverse blow-up (via transverse damper at suitable frequencies; not foreseen, but requested by PSB)?
- Different strategy: inject ~10 turns
  - Transverse painting
  - Longitudinal shaving for intensity reduction and removal of tails
  - Losses acceptable? (factor 30-200 compared to the current 20-120), but not so much in absolute terms?)

Production of Other Beams

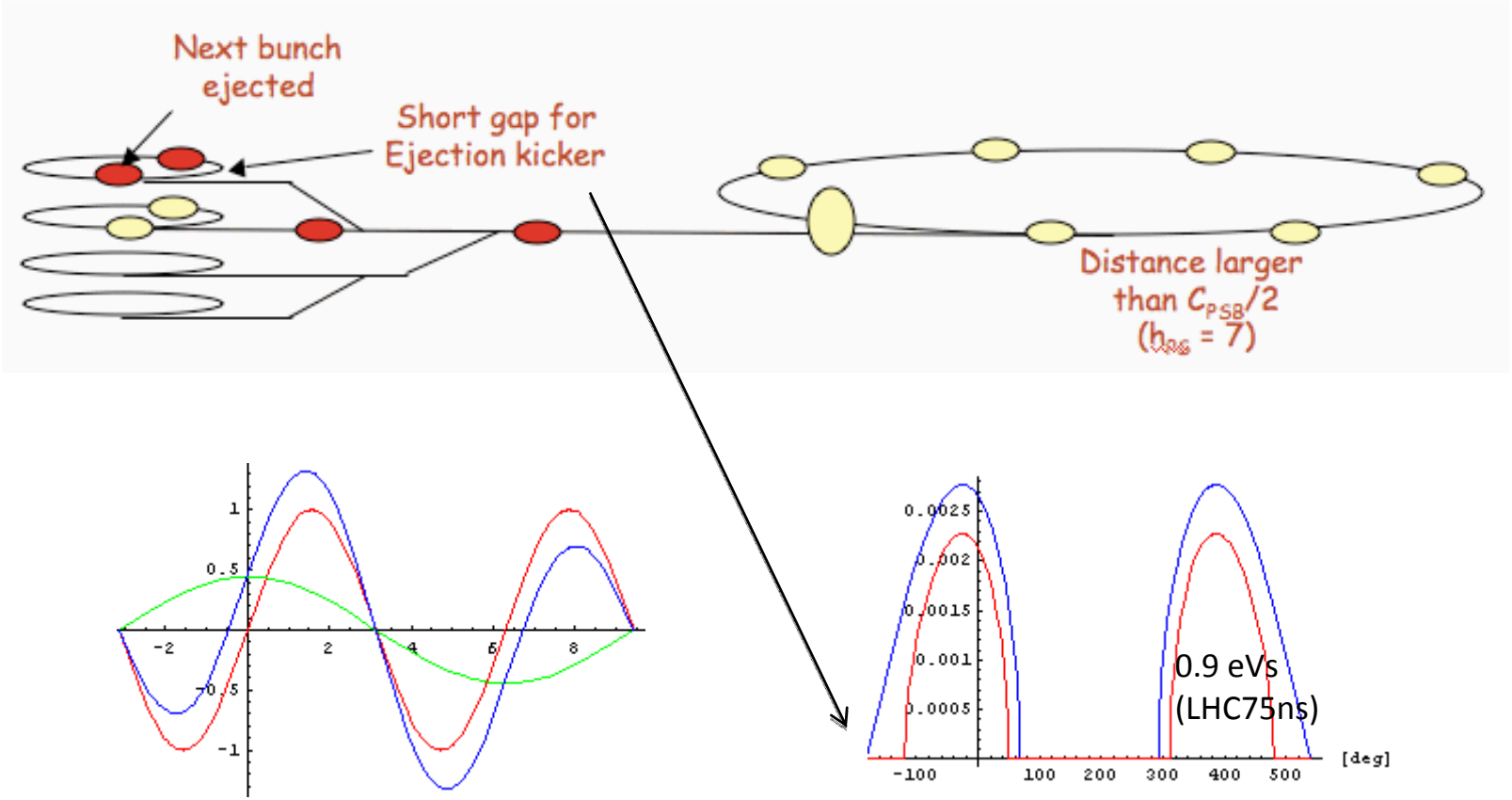
- For LHCPILOT and LHCPROBE similar considerations apply as for low intensity LHCINDIV beam (LHCPILOT: need to inject in principle only 2-5 Linac4 bunches!)
- High intensity beams will rely on transverse and long. phase space painting
- Large transverse emittance beams (MTE beams) should still be studied
  - approach again integer resonance or
  - use transverse phase space painting
    - inject many turns off-centre in small h2 bucket, use filamentation and chop out rest?

Single Batch Transfer of LHC-type Beams Between PSB and PS

Single Batch Transfer - Introduction

- LHC25/50/75 beams are presently produced with double batch transfer
  - A first PSB cycle fills 4 out of 7 PS buckets (4 rings with 1 bunch/ring)
  - A second PSB cycle fills another 2 PS buckets (2 rings with 1 bunch/ring)
- For single batch injection, 3 PSB rings will be used in h2, but adding a h1 component
  - Needed to match h7 used in PS to capture LHC25/50/75 beams
  - Bunches not anymore evenly spaced in ring (bunch spacing increased from 1/8th of the PS circumference to 1/7th)
  - If the separation of the bucket centers (327 ns to match h7 in PS) would be the criterion, theoretically a voltage ratio of 0.445 (=3.5 kV/8 kV) would be needed, but as buckets are not symmetric, the h1 voltage component can be reduced
- Synchronization has to be done on h1 to assure that the extraction kicker rises always during the short inter-bunch distance
  - Acceptance limit: rise-time of PSB extraction kicker (102/106 ns); currently barely sufficient for 75 ns variant (bunch length ~150 ns)

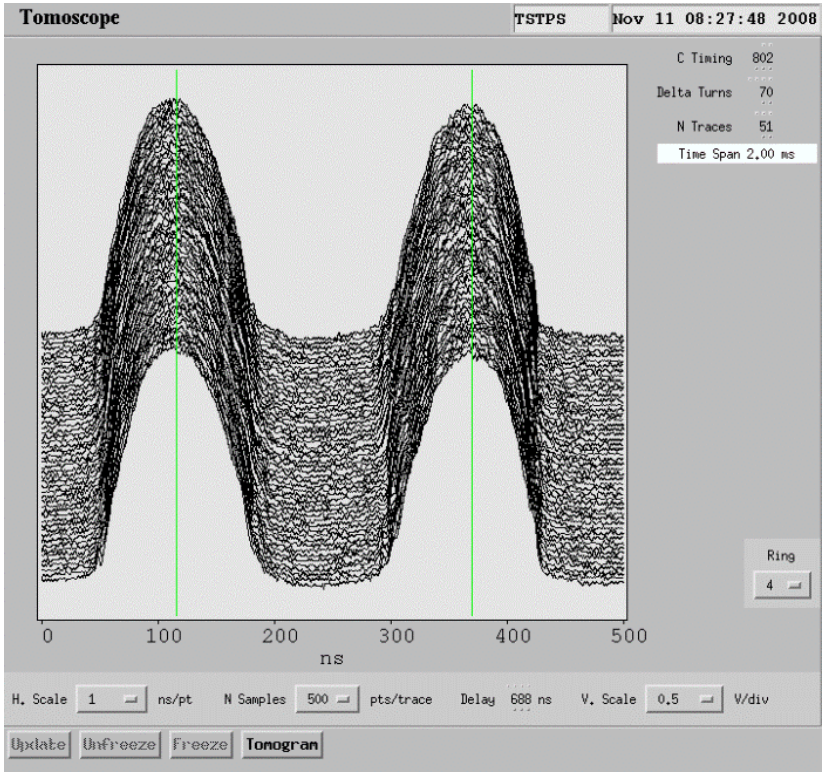
Single Batch Transfer – Introduction2

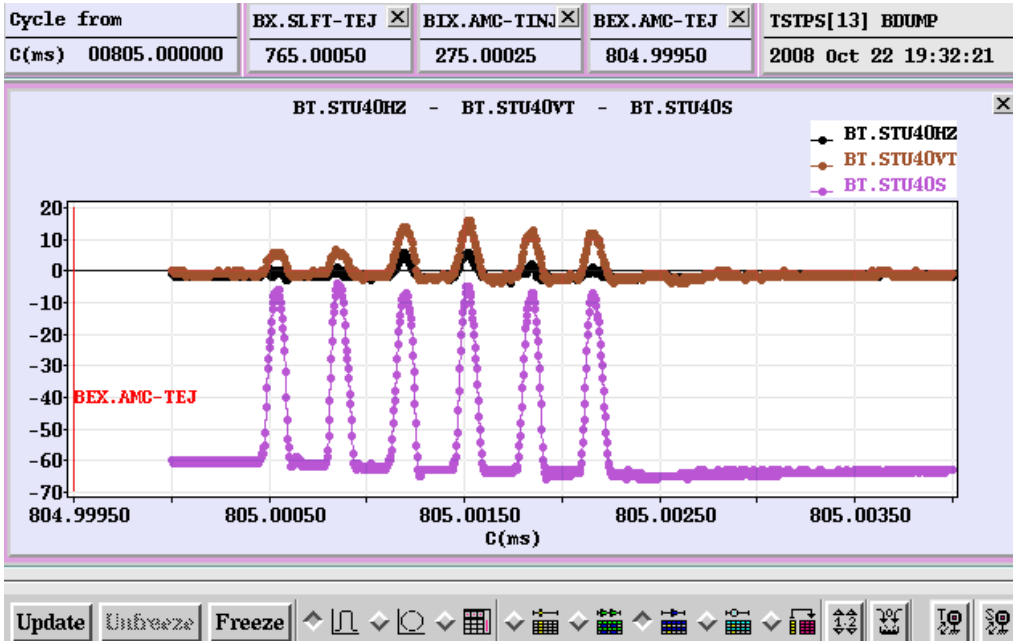


h1/h2 voltage ratio yields asymmetric bunches

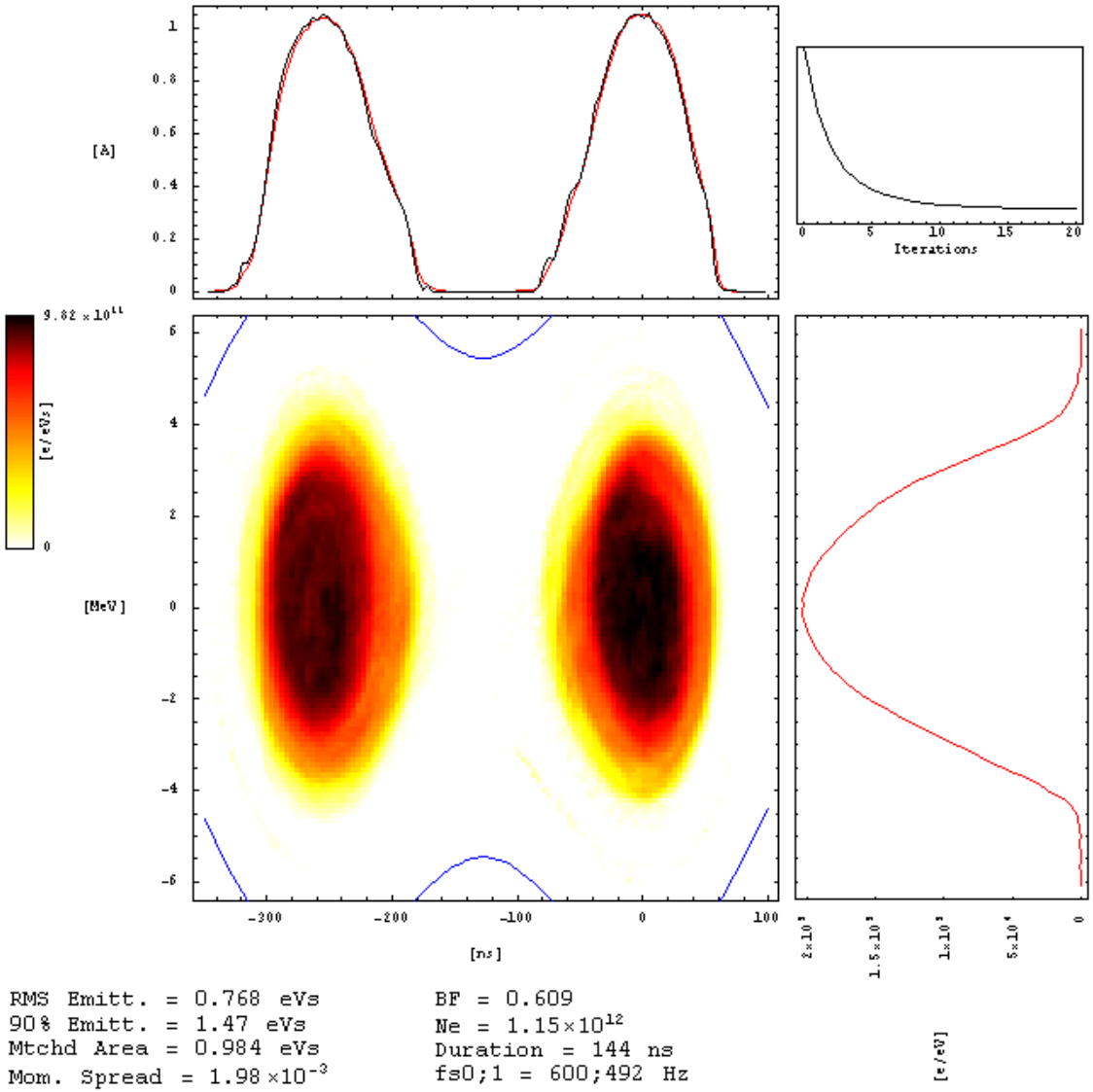
Single Batch Transfer – MD Results

- h1 voltage: 2.5 kV instead of 3.5 kV (and h2 voltage is suspected to be <8 kV from later data analysis) to leave slightly more time for the extraction kickers
- Also improves matching with PS (more acceptance margin)
- 6 bunches were extracted with ~320 ns bunch-to-bunch distance





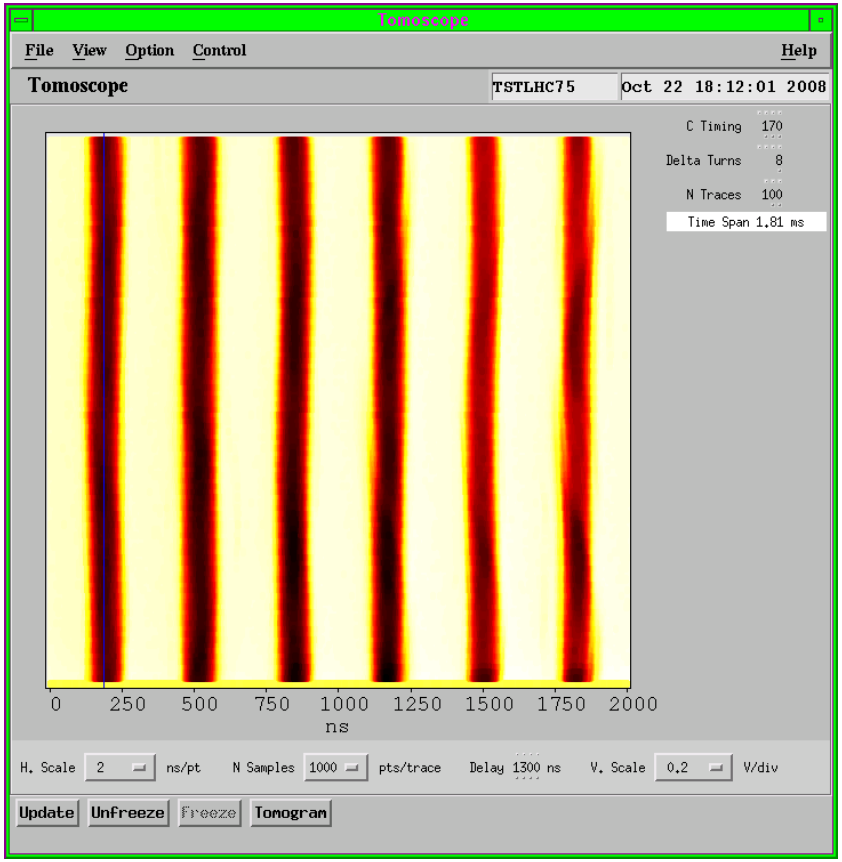
Single Batch Transfer – PSB MD Results

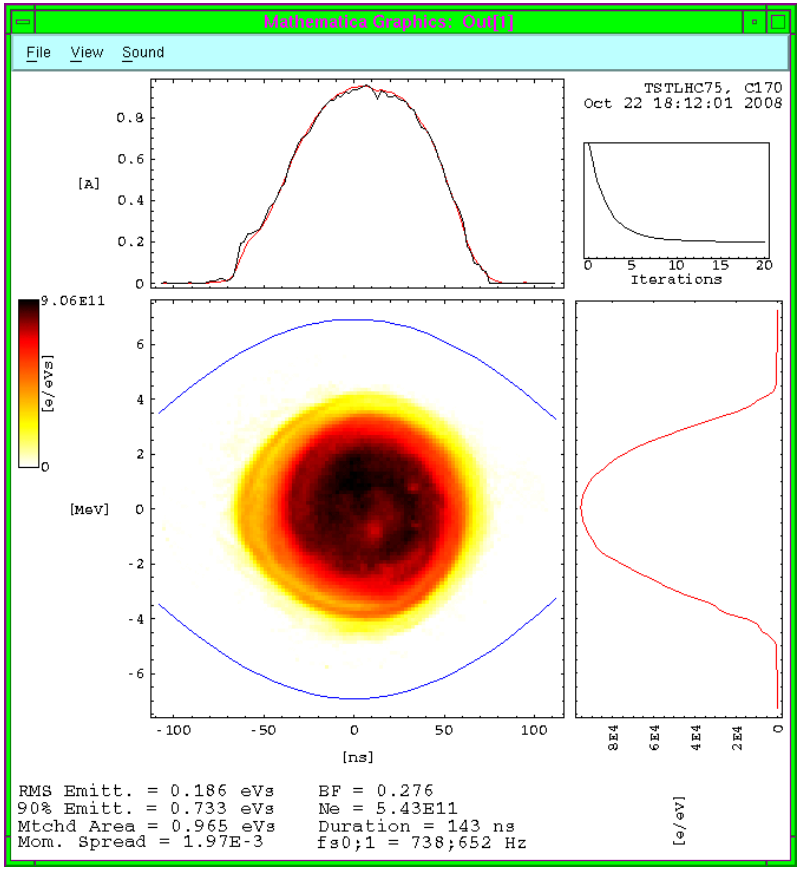


- Intensity: 1.15 10^{12}
- Bunch length: 144 ns
- 90% emittance: 0.735 (0.733 in PS)

Remark: reconstruction converges better with a h2 voltage of 7.2 kV instead of 8 kV

Single Batch Transfer – PS MD Results





- Small oscillations should be reducible with better energy matching (but negligible compared with 'normal life')
- Improve steering through PSB-to-PS transfer line (ring2 intensity loss…)

Single Batch Transfer – LHC50 Results

- After success with LHC75 beam we tried to produce LHC50 in PSB in a single batch (but no time anymore to send beam to PS)

	R2	R3	R4	Required
ε_h wire scanner (1σ) mm mrad norm.		2.5		<2.5
ε_h SEMgrids (1σ) mm mrad norm.	2.46	2.59	2.65	<2.5
E_v wire scanner (1σ) mm mrad norm.	2.11	2.17		<2.5
ε_v SEMgrids (1σ) mm mrad norm.	1.88	2.49	2.5	<2.5
Longitudinal ε tomogram (matched) eVs	1.1 (exaggerated?)	0.95-1.1 (exaggerated?)	1.1 (exaggerated?)	1.1 (exaggerated?)
Bunch length ns	144-148	135-150	145-146	150

Issues for PS – Single Batch Transfer

- LHC25/50ns emittance will be too small (cf. 1.3 eVs) at PS injection → blow-up on a longer injection plateau before triple splitting
  - Already for LHC75ns the voltage ratio has to be relaxed, which was shown to be acceptable (only double splitting)
- Short bunches at PSB to PS transfer lead to excessive direct space charge tune shift for 25 ns LHC beams
  - Bunch rotation to increase bunch length within ¼ synchrotron oscillation
  - Very fast longitudinal blow-up to lengthen bunches

General Issues for PS

- Ultimate LHC beam:
  - Beam-loading?
  - Coupled bunch instabilities after transition?

Summary

- The PSB is an extremely versatile machine and should stay as is with Linac4!
  - Should have the possibility to inject either in a stationary or an accelerating bucket
  - Assure functionality of transverse and long. painting
  - Transverse damper
- Minimize losses at high energy
  - If losses, where? (Collimation?)
- Have to work on more concrete and detailed beam production schemes
- Implement single batch transfer for LHC(50/)75 beams already with Linac2 as soon as possible

Thanks to many colleagues for their contribution, in particular

K. Hanke, C. Carli, S. Hancock, A. Findlay, A. Blas, M. Paoluzzi, J. Tan, M. Chanel, …