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LHC Note 213
PS/DI/Note 92-14 Rev.
2 December 1992

# Partial Test of the PS Complex as LHC Proton Injector

R. Bossard, R. Cappi, G. Daems, R. Garoby, B. Godenzi, S. Hancock, K. Hübner, H. Koziol, A. Krusche, M. Martini, K.D. Metzmacher, J.P. Riunaud, K. Schindl (editor), H. Schönauer, C. Steinbach, P. Têtu, M. Thivent, H. Ullrich, M. Vretenar, D.J. Warner.

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- acceleration in the PSB with RF systems (h=1, h=2) as foreseen for LHC filling to 1.4 GeV;
- two-batch filling of the PS at 1.4 GeV with the first batch dwelling for 1.2 sec at DQ (space charge) ~ 0.2;
- emittance conservation during PS acceleration.

The beam will be ejected to TT2 where its final transverse emittances will be measured; note that it will not have the longitudinal bunch spacing of 15 or 25 ns requested by the LHC. The test will require two weeks of dedicated (that is no other user) machine time, preferably at the end of a year, possibly in December 1993.

**Distribution:**
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## 1. INTRODUCTION

In order to test the concept of PS proton operation for LHC, a *Demonstration Experiment* with a beam from one PSB ring is proposed to be carried out towards the end of 1993.

A single bunch, created in PSB ring 3, is accelerated to about 1.4 GeV and transferred to the PS. After dwelling during 1.2 sec on the PS front porch at 1.4 GeV, a second bunch from PSB ring 3 is injected (double-batch filling). These two bunches are accelerated to 26 GeV/c, followed by ejection into the transfer channel towards the SPS (TT2) where their intensity and emittance would be measured.

Some minor modifications will enable the PSB main magnet supply as well as the PSB-PS beam transport elements (kickers, septa) to be ramped to about 1.4 GeV because of the *low duty cycle envisaged*: just two cycles per supercycle would be used. The PSB ring 3 is chosen because it is at the same level as the PS. Hence, the beam transport does not require operation of vertical deflection magnets at 1.4 GeV (nor between Linac2 and PSB at 50 MeV).

The single bunches are generated and accelerated in PSB ring 3 by prototype h=1 and h=2 RF systems; acceleration in the PS is performed with the standard 3-10 MHz RF systems on h=8. These are the RF harmonics foreseen for the LHC filling scheme.

The low duty cycle operation of the PSB (and beam transfer equipment) precludes delivering proton beams to any other PS client during this experiment, which would last about two weeks including all the hardware adjustments and concomitant technical tests. The experiment will require full concentration of the competent specialists in order to have a chance to succeed, therefore even delivery of leptons during this test cannot be envisaged. In view of all this, it is proposed to schedule this experiment for two weeks at the end of 1993, just before the annual shutdown.

Although this test does not yet provide the 140 (84) bunches of 15 (25) ns spacing finally required by the LHC, it permits checking most of the ingredients of the PS upgrading for the future LHC filling scheme, and in particular measuring the achievable transverse beam brightness.

The proposed PS upgrading for the nominal LHC proton filling scheme is briefly recalled in Chap.2, and Chap.3 deals with experimental data obtained so far. A more detailed description of the proposed beam test is presented in Chap.4 (comparison with the full scheme), Chap.5 (required hardware modifications), Chap.6 (schedule of the MD).

## 2. UPGRADING OF THE PS COMPLEX FOR LHC PROTON FILLING

The proton beam characteristics requested by the LHC are, at PS extraction (26 GeV/c) [1]:

| | |
|---|---|
| - Number of particles per bunch ($N_b$) | $10^{11}$ |
| - bunch spacing | 15 (25) ns |
| - transverse emittances ($\varepsilon$*, r.m.s. normalised) | 3.0 $\mu$m |
| - longitudinal emittance | 0.5 eVs |

Obviously the PS will require a 66.8 (40.0) MHz system to provide the bunch spacing. All the other ingredients of the PS upgrade [2],[3] aim at a 2-3 fold increase in beam brightness ($N_b/\varepsilon^*$) in the PS with respect to the beams available at present.

### 2.1. Brighter beams from Linac2

A new RFQ, nominal current 200 mA, will be installed in front of Linac2 in the 1993 winter shut-down, in replacement of the 750 kV Cockcroft-Walton preaccelerator. This should enable Linac 2 to deliver 180 mA (possibly after a minor upgrade of the 200 MHz RF chains) instead of 140 mA to the PSB.

### 2.2 Reduction of space charge in the PSB by double-batch filling of the PS

In the "20-bunch-mode" filling scheme of the PS used at present, one PSB batch (four rings, 5 bunches each) fills the PS (20 bunches) (Fig. 1a). With only one bunch in each PSB ring, the timings of the PSB-PS transport kickers can be adjusted so as to squeeze the four bunches into half the PS circumference; the second half is then filled by a second batch (Fig. 1b). With this technique, the intensity per PSB burst is halved and the space-charge tune shift at 50 MeV is reduced from $\Delta Q \sim 0.8$ (unmanageable) to $\sim 0.4$. The necessity of double-batch filling is illustrated by Fig.2 where the horizontal densities at PSB injection of presently operational beams are compared to the one required by the LHC. Three-turn injection will be used for LHC operation, unless a breakthrough in Linac2 performance with RFQ2 will provide the necessary margin for single-turn injection.

### 2.3. Reduction of space charge in the PS by increasing the PSB energy

The double-batch filling of the PS has a major drawback: the first of the two PSB batches has to dwell during 1.2 sec on the PS front porch while awaiting the injection of the second batch. If this were at 1 GeV, the Laslett tune shift $\Delta Q$ would amount to $>0.3$, which cannot be sustained in this storage mode without damage to the beam brightness (see chap.3 for experimental evidence). Hence it is proposed to increase the PSB output energy from 1 to 1.4 GeV, to reduce $\Delta Q$ to $\sim 0.2$.

## 3. EXPERIMENTAL DATA AVAILABLE

Although none of the devices needed for filling the LHC with protons is yet installed in the PS complex, and hence the nominal beam cannot be produced, meaningful beam experiments have been performed recently.

### 3.1. How to create the high-brilliance beam

A first series of tests in the Linac2 - PSB - PS chain dealt with ways to produce a beam with the highest possible brilliance $N_b/\varepsilon^*$ as well as the measurement of transverse beam profiles with various intruments at 1 GeV [4]. In these tests, the Linac2 current was raised, for short pulses (< 20 μs), from 130 to 165 mA by increasing the source current and the acceptance of the low-energy beam transport (LEBT), and setting the RF power levels in the Linac tanks beyond their operational limits. This beam was injected into the PSB by 3-turn betatron stacking, a process which makes full use of its dense core; it has to sustain a vertical space-charge Q-spread of 0.4 for a short time near 50 MeV. Initially, the most promising scheme to generate a bright beam in the PSB was thought to be single-turn injection, but in experiments the beam suffered from excessive transverse blow-up (yet unexplained), incompatible with LHC specifications (see Fig.2).

### 3.2. Emittance measurements and cross-checking of beam profile monitors

Four different devices are used to measure transverse beam profiles:
(i) BEAMSCOPE in the PSB which determines the amplitude distribution in either plane (here on the 1 GeV PSB flat top);
(ii) three SEMgrids in the PSB "Measurement Line" (at 1 GeV), and
(iii) three SEMgrids in the PS ring, both monitoring emittance and matching on the beam trajectory, by means of (standardised) detectors, read-out electronics, software;
(iv) a fast wire scanner in the PS which may be triggered at various instants along the 1 GeV front porch.

Results for a beam with LHC-type transverse emittances are compiled in Fig.3 ($\varepsilon^*$ vs. device). The error bars shown are an educated guess of the uncertainties and inherent measurement errors:
- BEAMSCOPE measures amplitude distribution, whereas the other devices measure projected density profiles; the transformation from one representation to the other is a non-trivial exercise (in particular in presence of non-zero lattice dispersion) and gives rise to errors.
- Beam sizes are much smaller than usual, hence only a few SEMgrid wires are covered, increasing the uncertainties.
- The dispersion, together with the (unknown) correlation between betatron amplitude and momentum, plays a non-negligible role for these small beams.

Nevertheless, the emittances determined with the four devices agree rather well (Fig.3). Some of the wire scanner measurements were done at the end of the PS flat top, showing that there is virtually no blow-up during 1.2 sec for this test beam (1.8 $10^{12}$ p in 5 bunches of 53 ns length, $\varepsilon^* \sim 2.5$ μm, the nominal emittance at PS injection). This beam apparently sustains an incoherent space charge de-tuning of $\Delta Q \sim 0.2$ without loss in brightness.

### 3.3. Increase of PSB output energy: how much is required?

In a very recent experiment, the space-charge tune spread the nominal LHC beam would experience at energies between 1 GeV and 1.4 GeV in the PS was simulated at 1 GeV by changing the bunching factor $B_f$.

A round beam ($\varepsilon^*$ equal in both planes) with betatron tunes Qx ~ Qy ( ~6.25 in PS) and N protons in the PS ring if it were completely filled, experiences a tune spread of

$$\Delta Q = - \frac{N r_p}{8 \pi B_f \beta \gamma^2 \varepsilon^*} F$$

where F ~ 1 is a form factor due to image effects. In this formula, the particle distribution in the real x-y plane is assumed uniform. For a bunch of length $\tau$ in a stationary bucket of length $L_b$ and parabolic line density, the bunching factor

$$B_f = \frac{\text{average line density}}{\text{peak line density}} = \frac{2 \tau}{3 L_b}$$

To illustrate the relevance of the beam tests performed (chaps 3.1, 3.2), the scaling between the test beam and the nominal beam for LHC is given below, showing that the $\Delta Q$ was virtually the same in the tests as in the nominal LHC scheme.

| Beam | T (GeV) | $\beta\gamma^2$ | N | $\varepsilon^*$ (μm) | h PS | $L_h$ (ns) | $\tau$ (ns) | $B_f$ | F | $\Delta Q/\Delta Q_{1GeV}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Test LHC | 1 | 3.73 | $7.2\ 10^{12}$ | 2.5 | 20 | 120 | 55 | 0.306 | 1.08 | 1 |
| Nom. LHC | 1.4 | 5.69 | $1.44\ 10^{13}$ | 2.5 | 8 | 286 | 190 | 0.443 | 1.10 | 0.92 |

From the table one concludes that there will be no transverse blow-up of the nominal LHC beam at 1.4 GeV in the PS since the test beam did not change its transverse emittance during the 1.2 sec PS front porch. But maybe a more modest PSB energy increase would do as well?

This uncertainty could be largely removed with the following experiment: $\Delta Q$ at an energy lower than 1.4 GeV is simulated by decreasing $B_f$ by means of bunch shortening, which in turn is readily obtained by increasing the RF voltage on the 1.2 sec PS front porch at 1 GeV. For this experiment, the beam characteristics were quite similar to the "test LHC" beam compiled in the table above. The following parameters were varied in the PS:
- the RF voltage between 10 and 200 kV, for 800 ms
- the vertical betatron tune $Q_y$.

The transverse blow-up was monitored by wire scanner measurements after the beam had dwelled for 1.2 sec.

Fig.4 shows the results: $(\varepsilon_x^* + \varepsilon_y^*)/2$ obtained at the end of the flat top is plotted against the relative $\Delta Q_y$ (reference: nominal LHC beam at 1.4 GeV = 1). Also shown is the energy which corresponds to the same $\Delta Q_y$ scaled with $\beta\gamma^2$. Note that indicating a relative value for $\Delta Q$ rather than an absolute one removes uncertainties about the particular transverse distribution. On the figure, one sees that the beam experiences blow-up for any $\Delta Q$ higher than anticipated for the nominal LHC beam; marginally higher tune spreads may be accomodated by raising $Q_y$.

The conclusion of this experiment is: **To avoid blow-up of the first PSB burst in the PS, the PSB energy has to be increased to 1.4 GeV.**

### 3.4. A historical note

It may be worth recalling that the PSB energy was already raised once from 0.8 to 1 GeV [5] in 1987, motivated primarily by the high brilliance of the antiproton production beam presented to the PS after funnelling bunches from two pairs of PSB rings. The stronger space charge effects in the PS called for an increase of the PSB energy. In fact, this upgrade proved also beneficial to the other high intensity beam (SPS fixed target physics) where new record intensities were achieved.

## 4. THE 1993 BEAM TEST

These machine studies, together with appropriate scaling of space-charge effects in the PS, suggest that the proposed LHC filling scheme (PS part) will work. However, the beam behaviour after the forthcoming modifications in the PS complex opens up "uncharted territory", in particular:
(i) Behaviour and optimisation of Linac2 with some 200 mA from the newly installed RFQ2 (to be studied in Spring 1993);
(ii) new cavities h=1 (and h=2 for bunch flattening) in the PSB, changing the bunch spectrum and instabilities; their immunity against beam loading;
(iii) beam behaviour in the PSB between 1 and 1.4 GeV;

| Full Scheme | Test |
|---|---|
| RFQ2 installed | RFQ2 installed (1993 shut-down) |
| Linac2 200 mA in 20 μs in PPM | Linac2 200 mA in 20 μs, dedicated |
| PSB h=1, all rings | PSB h=1 prototype in ring 3 |
| PSB h=2, all rings | PSB h=2 prototype in ring 3 |
| PSB accelerating to 1.4 GeV on all cycles (except ISOLDE) | PSB accelerating one ring to 1.4 GeV on two cycles during 14.4 sec (Bρ +26%) |
| PSB to PS line: all elements at 1.4 GeV and pulsed (ejection, recombination, transfer, injection PS, all +26%) | PSB to PS line: only elements dealing with level 3 to be increased by 26%, on 2 cycles in 14.4 sec |
| Two PSB cycles to fill PS (2*4 bunches) | Two PSB cycles to fill PS (2*1 bunches) |
| In PS, acceleration of 8 bunches on h=8 to 26 GeV/c | In PS, acceleration of 2 bunches on h=8 to 26 GeV/c |
| De-bunching and re-bunching on h=140 (h=84) in PS at 26 GeV/c for LHC bunch spacing: 15 ns (25 ns) | Ejection of 1 (2) bunches and transverse profile measurement on new SEMfil in TT2 |

Table 1: Ingredients of the LHC filling scheme vs. the proposed beam test 1993

(iv) two-batch filling of the PS, with concomitant difficulties in the timing and computer control systems;
(v) conservation of transverse beam brightness during the 1.2 sec PS front porch (scaling correct?);
(vi) acceleration in the PS on a new harmonic h=8, conservation of transverse beam emittance during first part of acceleration (specially tailored dB/dt);
(vii) measurement of the very small beam at 26 GeV/c with new SEMgrids in TT2.
Table 1 gives a comparison of the proposed beam test with the nominal LHC filling scheme; the PSB-PS recombination scheme for the test is shown in Fig.1c.

Most of the unknown issues have a chance to be explored during the proposed Machine Development (MD) session lasting about two weeks[6]. It should be emphasised, however, that some of the territory will remain uncharted:
(i) Beam performance with h=1/h=2 and in the new energy range 1 to 1.4 GeV of any PSB ring other than 3;
(ii) behaviour of the full beam intensity (8 bunches of 1.8 $10^{12}$ = 1.44 $10^{13}$ p/pulse) on the PS front porch and during PS acceleration. This may give rise to additional modes of coupled-bunch instabilities and more beam loading on the cavities.
(iii) De-bunching (from h=8) and re-bunching (h=140 or 84) at 26 GeV/c.

## 5. REQUIRED HARDWARE MODIFICATIONS

Most of the hardware modifications will be performed *ad hoc* for the test and put back to the initial state afterwards. For this reason, the proposed MD session should be dedicated to the test (no other PS user), and should be scheduled at the end of a run, preferably at the end of 1993. During the test, the PS complex will be operating with a 14.4 sec supercycle, out of which only the first two (1.2 sec) cycles are active, while the non-active part of the supercycle serves as cool-down time for otherwise overheated equipment. The following hardware will have to undergo modifications:

*(i) PSB Main Supply: the increase from 1 to 1.4 GeV (26% in Bρ)* implies raising the dipole field from 6870 to 8670 G (no sign of saturation yet expected) which in turn requires increasing the peak current from ~3200 to ~4000 A. This will be done by switching a fourth rectifier-inverter group (now spare) in series with the other three. The average power and thus the dissipation will be kept low because of the special supercycle. Several smaller adjustments and the installation of a new DCCT for precise current measurement are foreseen.

*(ii) A prototype h=1 (0.6 - 1.7 MHz) cavity* will be installed in PSB ring 3 during the 1993 Winter shut-down, enabling (hopefully) the system to be run-in with beam before the test.

(iii) The frequency range of the existing h=5 cavity in ring 3 will be lowered by adding capacitance in parallel to the accelerating gap; *the cavity will then operate at h=2* for bunch flattening in the 50-100 MeV range. Tests with beam on the modified cavity may possibly be performed during 1993.

*(iv) PSB-PS transport DC magnets for level 3 and their power supplies:* All field levels have to be raised by 26%. BESMH, BT3DVT10,20, BTBHZ10, PISMH42 have to operate beyond their rating. The technique proposed there is to use "trapezoid" ramping of these supplies: high currents during 1.2 sec (just for the two

PSB cycles), followed by a much lower current during the non-active part of the supercycle. The rise times of the ramps are not below 0.4 sec so as to avoid adverse eddy current effects in some of the magnets with non-laminated yokes. Forthcoming tests on BESMH, the most critical element, will allow assessing the proposed technique.

*(v) PSB ejection (BE3KFA) and PS injection (PIKFA45) kickers:* BE3KFA power supply and magnets will not support the 26% higher charging voltage. A development pulse generator, under test at present, will be used to pulse the magnet. When short-circuited, it will provide the necessary kick at the expense of an increase in rise time from 60 to ~100 ns. One of the four modules of PIKFA45 will also be short-circuited to double the module's kick angle. The PSB ejection bumper magnet (BEBSW) current can be increased by 10% only; several ways of compensating this shortcoming are feasible (local or global additional orbit displacement, etc).

*(vi) Timing and Controls for double-batch filling:* Will certainly require some change for the test, but details remain to be studied.

The costs of the test proposed, in terms of manpower and funds, are summarised in Table 2. Some of the modifications are only temporary and cannot be kept for LHC operation; they are summarised as cost "a fonds perdu".

| | **Total Cost (kFr)** | | **Cost "a fonds perdu"** | |
|---|---|---|---|---|
| | kFr | man-months | kFr | man-months |
| PSB Main Supply upgrading to 1.4 GeV | 70 | 5 | 35 | 2.5 |
| RF h=1, h=2 cavities in PSB ring 3 | 100-150 | 18 | 50 | 9 |
| PSB-PS transfer (level 3) supplies upgrading +26% | 15 | 4 | 15 | 4 |
| Kickers (BE3KFA10) | 10 | 2 | 10 | 2 |
| Effort during the test | | 4 | | 2 |
| **Total Test** | **195-235** | **33** | **110** | **19.5** |

Table 2: Resources for the Beam Test

Considerable cost and effort have already been invested for indispensible improvements of instrumentation:

*(i) A second pair of flying wires,* enabling profiles to be measured twice during the PS cycle, featuring new electronics and software, will become available by mid-1993.

*(ii) High resolution SEM"fils" in TT2:* the rather small beam size to be monitored for the LHC requires many (48) thin wires with small spacing (0.25 to 0.5 mm). Installation in TT2 is scheduled for mid-1993.

## 6. TENTATIVE SCHEDULE FOR A TWO-WEEK TEST[7]

As a working hypothesis, it is assumed that the test will be scheduled for the end of 1993 and last two weeks. This has the advantage that all the initial ad-hoc hardware modifications have not to be undone hastily at the end of the test but rather in the following long shut-down. A draft schedule (obviously subject to changes which in turn depend on the outcome of forthcoming equipment tests) is sketched Fig.5. The PSB tunnel will be accessible for the first 36 hours, followed by hardware changes outside the tunnel lasting for 72 hours. The PS is scheduled to receive beam about 132 hours after the start of the MD session: **During this 5-day period, antiproton transfers from AA to LEAR may continue,** but obviously no replenishing of the stack in AA will be possible.

## 7. CONCLUSIONS

The proposed dedicated machine study provides an early, comprehensive test of the nominal PS acceleration scheme for LHC with a minimum of modifications and, hence, of resources.

In particular, it will be the first time that we test with a nominal LHC beam injected from Linac2 equipped with an RFQ

- the acceleration in the PSB with RF systems as foreseen for LHC operation;
- two-batch filling of the PS at 1.4 GeV with the first batch dwelling for 1.2 sec at $\Delta Q \sim 0.2$ and, hence, whether 1.4 GeV is the adequate PS injection energy;
- emittance conservation during PS acceleration.

Although the ejected beam will not yet have the longitudinal bunch spacing as required for LHC, this test with one PSB ring will provide fundamental insights and verify our approach at an early stage.

## 8. ACKNOWLEDGEMENTS

The authors wish to acknowledge the very active participation of many colleagues in the R&D programme preparing the PS complex as LHC proton injector.

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[7] D.Manglunki, PS/PPC Minutes 92-06, October 1992.

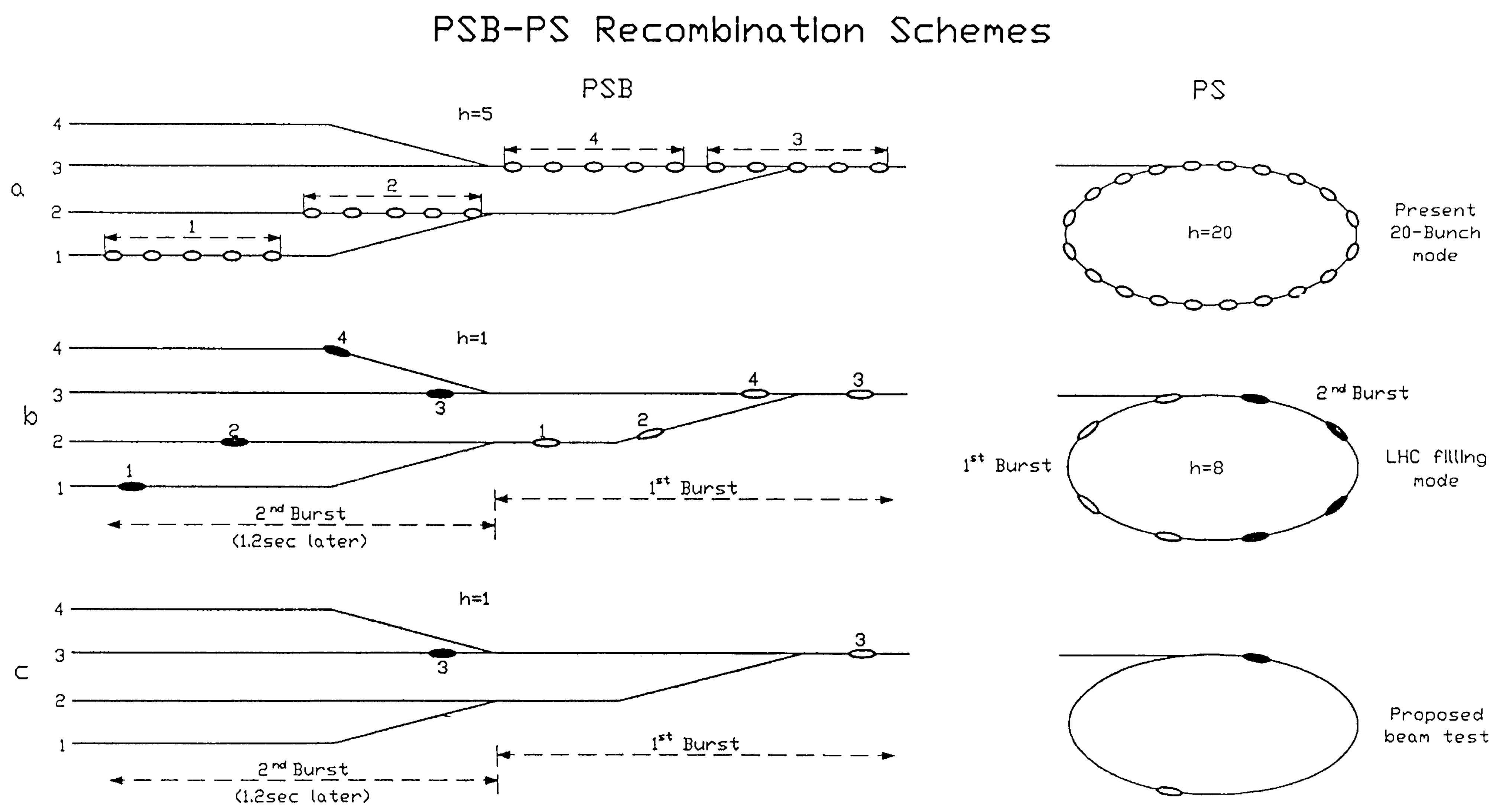
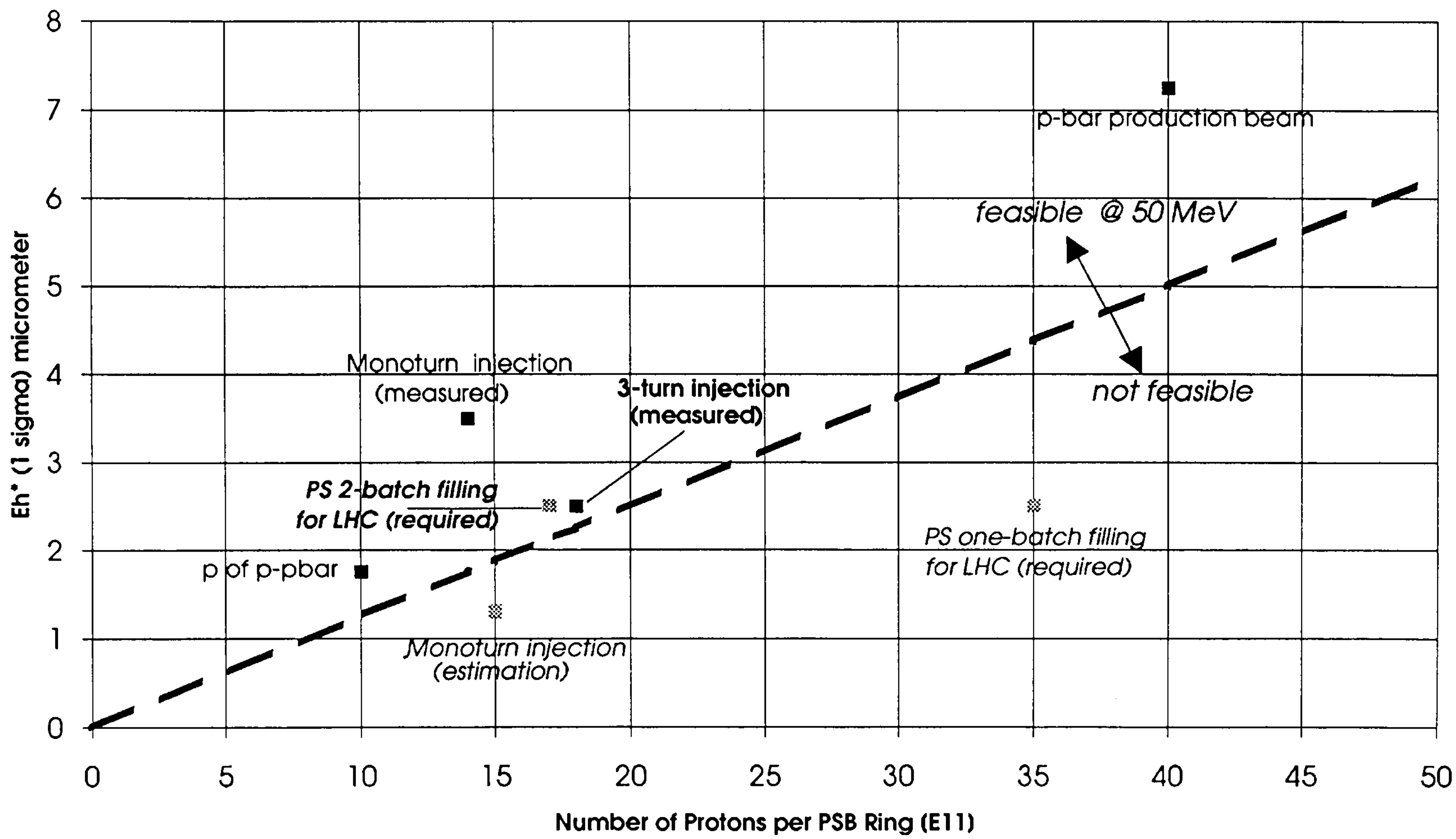



Fig.1: PSB-PS recombination schemes: present (a); proposed for the LHC filling scheme (b); proposed for the beam tests (c).
Drawing by B.Hadorn

**Fig.2: Normalised Horizontal r.m.s. Emittance in PSB vs. Number of protons per Ring**



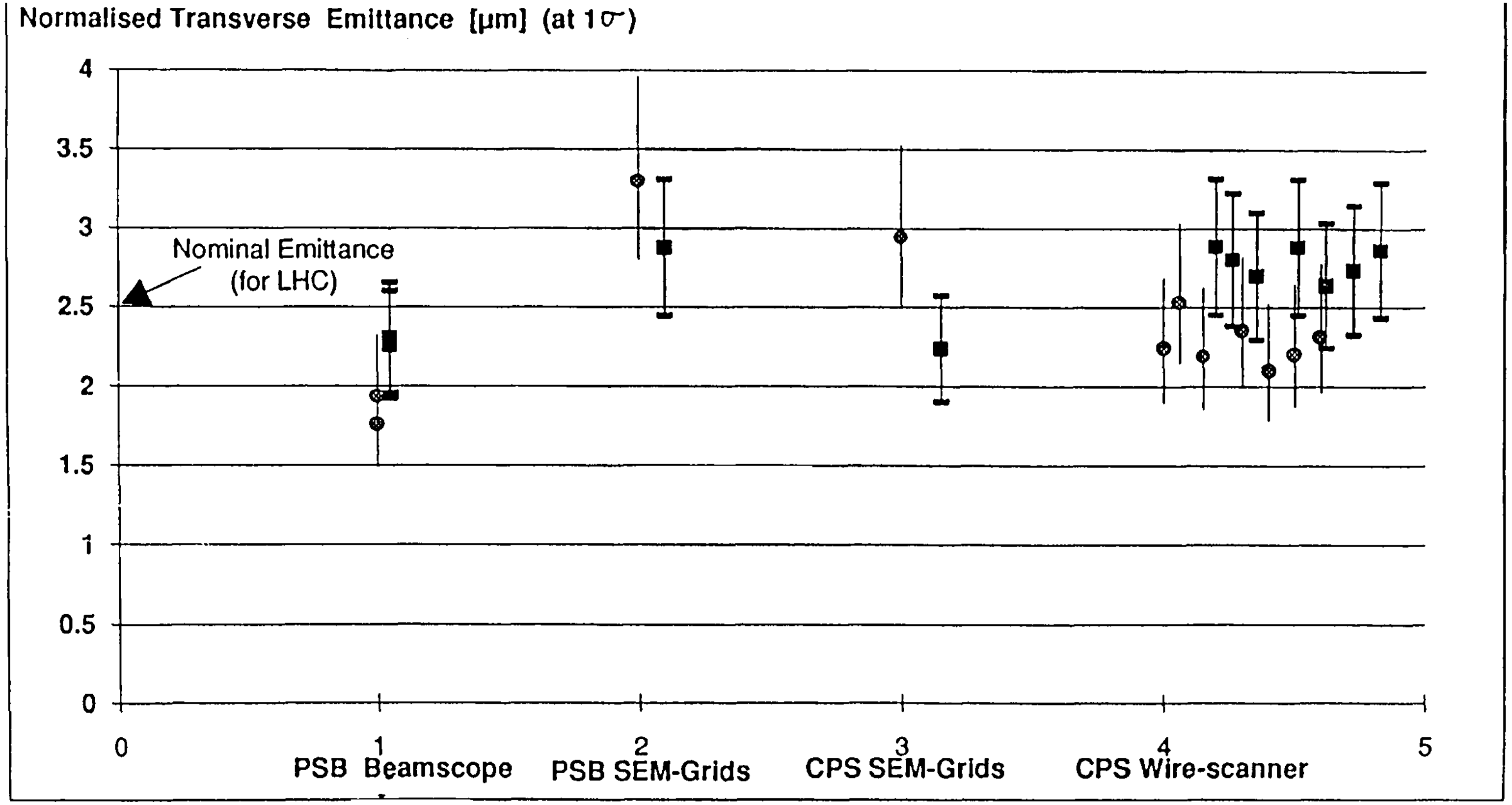



Fig.3: Transverse emittances measured with various devices in the PSB and PS at 1 GeV (circles horizontal, squares vertical), with error bars. From Ref. [4].

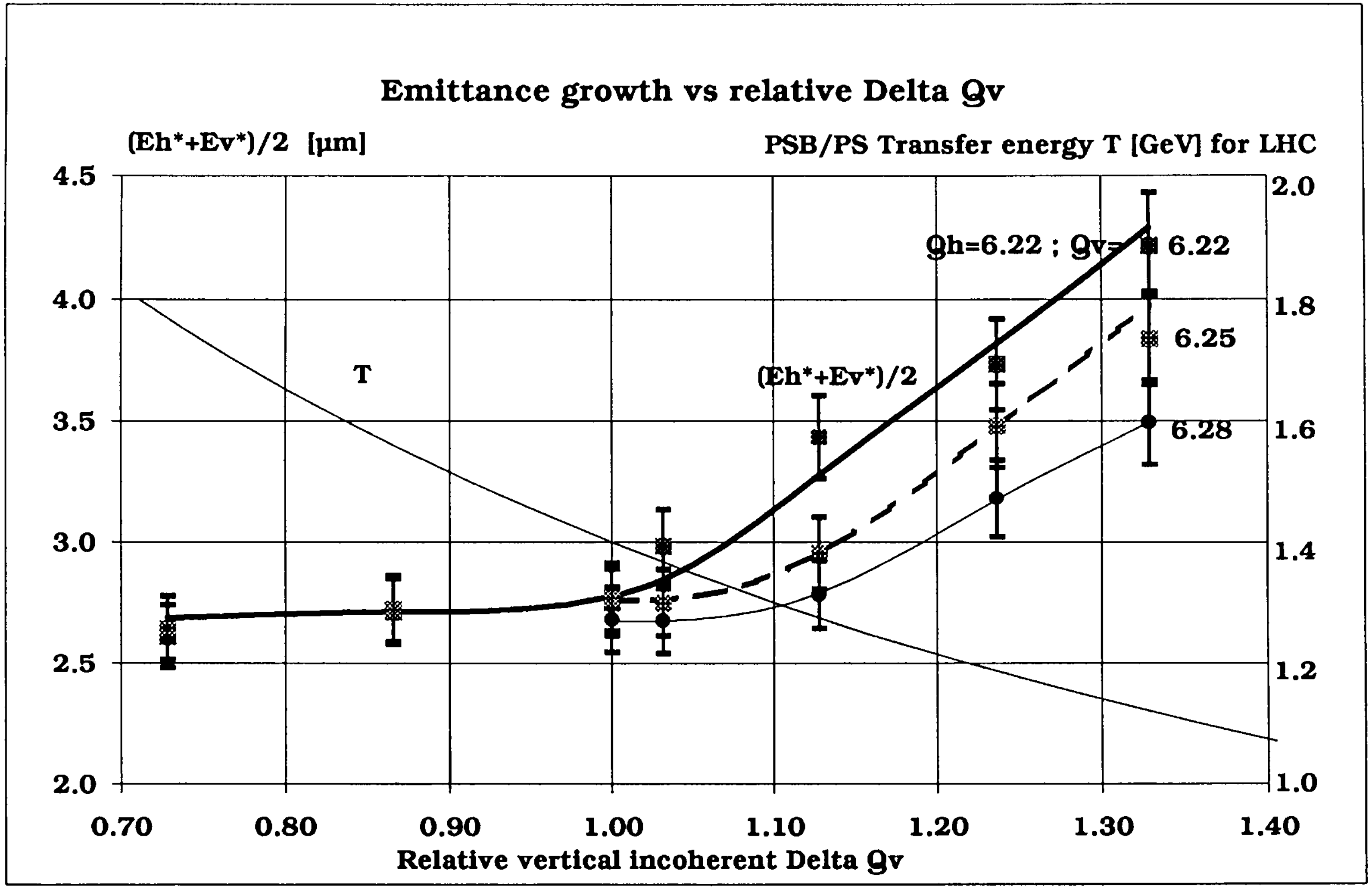



Fig. 4: Emittance growth vs. incoherent space-charge tune spread ΔQ of a LHC test beam on PS 1 GeV front porch of 1.2 sec length. ΔQ is given in relative units, with the nominal LHC beam at 1.4 GeV as reference. ΔQ is varied by changing the bunch length (RF voltage) ande hence the bunching factor $B_f$, for 800 ms during the front porch. The beam intensity is 1.6 $10^{12}$ in 5 bunches. The transverse normalised r.m.s. emittances are derived from flying-wire measurements near the end of the front porch, when the bunch length is brought back to its initial value of 50 ns.

| Day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | |
| **ACTION** | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| **Hardware changes** | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| BE3KFA Modif. in tunnel | | | | | | | | | | | | | | |
| BE3KFA Modif. outside tunnel | | | | | | | | | | | | | | |
| Main PSB Supply upgrade (fourth group, etc) | | | | | | | | | | | | | | |
| PSB h=1 cavity (should be working) | | | | | | | | | | | | | | |
| PSB h=2 cavity ring 3 (h=5 ==> h=2 change) | already working? | | | | | | | | | | | | | |
| "Trapezoid" power supplies PSB-PS Line | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| **Studies with beam** | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Linac 2 preparation (to achieve 180 mA) | | | | | | | | | | | | | | |
| PSB Injection + acceleration 1 bunch ring3 to 1.4 GeV (not extracted) | | | | | | | | | | | | | | |
| Extraction + transport + Injection PS@1.4 GeV one bunch, beam measurements | | | | | | | | No 1 GeV PSB Measuring Line | | | | | | |
| Acceleration in PS on h=8, measurement TT2 | | | | | | | | | | | | | | |
| Optimise performance | | | | | | | | | | | | | | |
| Set up timing and Program Line Sequencer for double-batch filling | | | | | | | | | | | | | | |
| Accelerate two bunches on h=8 in PS, eject TT2 | | | | | | | | | | | | | | |
| Overall optimisation + (possibly) verifications at 1 GeV + reserve | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| ***PSB tunnel open*** | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| ***Transfers AA - LEAR possible*** | | | | | | | No replenishing AA | | | | | | | |

Fig.5: Tentative Schedule for the LHC proton injector test in the PS Complex