Possible improvements to the existing pre-injector complex in the framework of continued consolidation

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and

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Main assumptions

- The performance analysis assumes that Linac4 injects into the PSB.
- The target consists of maximising the bunch intensity of the LHC beam with 25 ns spacing.
- Criterion:
  - Control the space charge tune shift $$\Delta Q \propto -\frac{N_b}{\beta \gamma^2 \varepsilon_n}$$
  - Reference parameters
    - ε_n = 2.5 μm
    - Bunch length = 180 ns

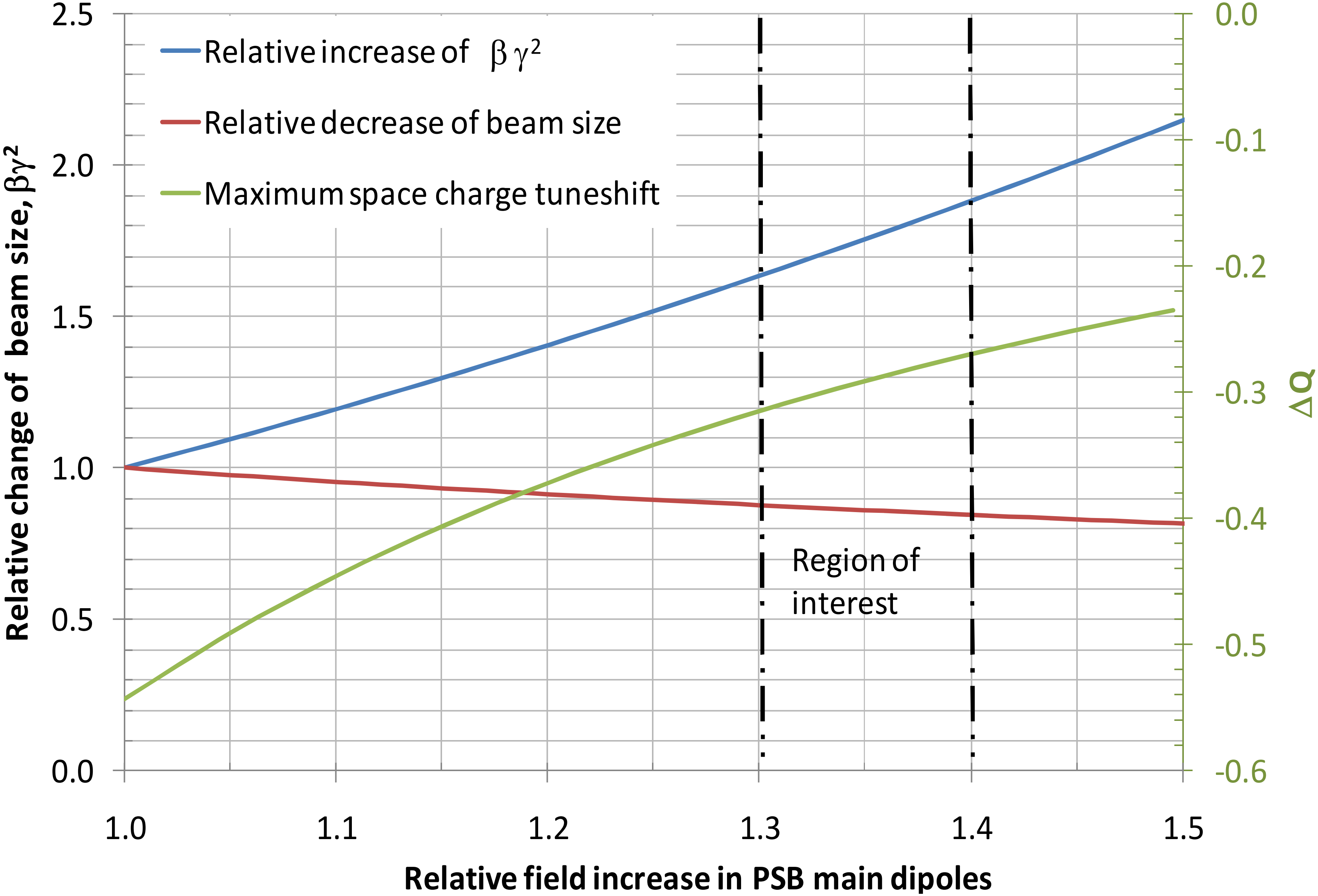
    Nominal parameters used for the PSB upgrade from 1 GeV to 1.4 GeV
  - Constraint $$|\Delta Q| \leq 0.3$$
- For a detailed analysis of Linac4 performance reach see the presentation by M. Vretenar.

Performance reach of pre-injector complex

- Changes since the upgrade of PSB in preparation of LHC:
  - Longitudinal splitting introduced in the PS
  - Harmonic number reduced from 8 to 7 in the PS at injection
  - Six bunches are injected in double batch in the PS
- With Linac4:
  - Maximum intensity/ring (limited by space charge effect at PSB injection): 3.6×10^{12} p

How much of this intensity can be injected into the PS respecting the space charge tune shift limit?

Space charge tune shift and energy



Additional considerations

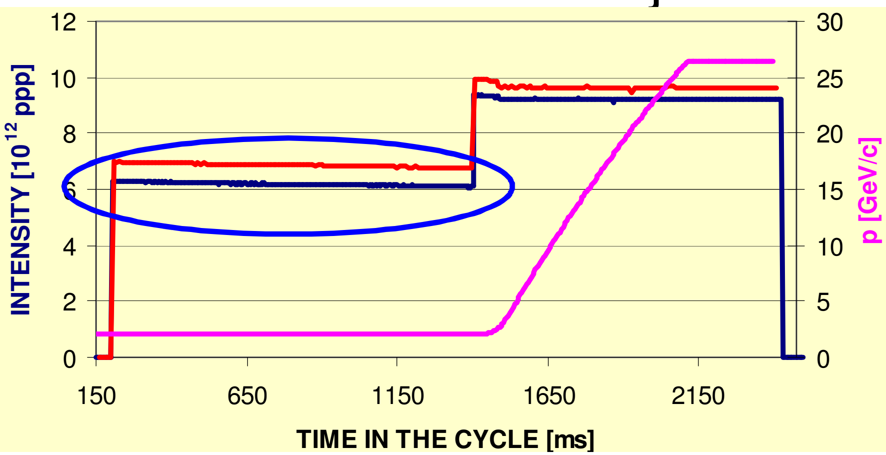
Bunches at PS injection

Bunches at PS extraction

- 3.6×10^{12} x 6 = 3×10^{11} x 72: compatible with tune shift criterion if the PSB field can be increased by 40%.
- 3.24×10^{12} x 6 = 2.7×10^{11} x 72: compatible with tune shift criterion if the PSB field can be increased by 30% (also compatible with hardware capability, see later).
- The change of harmonic number makes it possible to use longer bunches.
- Bunch length increase up to about 200 ns seems realistic (to be confirmed by MDs) and compatible with triple splitting requirements.
- The PSB intensity could be increased proportionally.

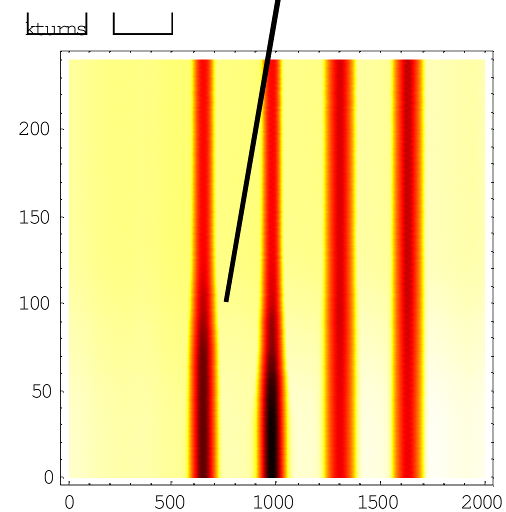
PS: transverse instabilities - I

- Nominal LHC beam experiences:
  – Slow losses on injection flat-bottom

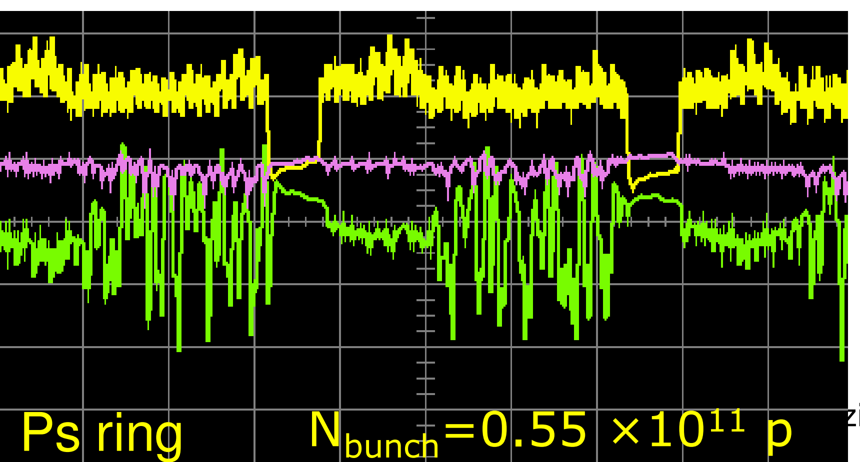


Interplay between space charge and longitudinal dynamics. Trapping de-trapping phenomena.

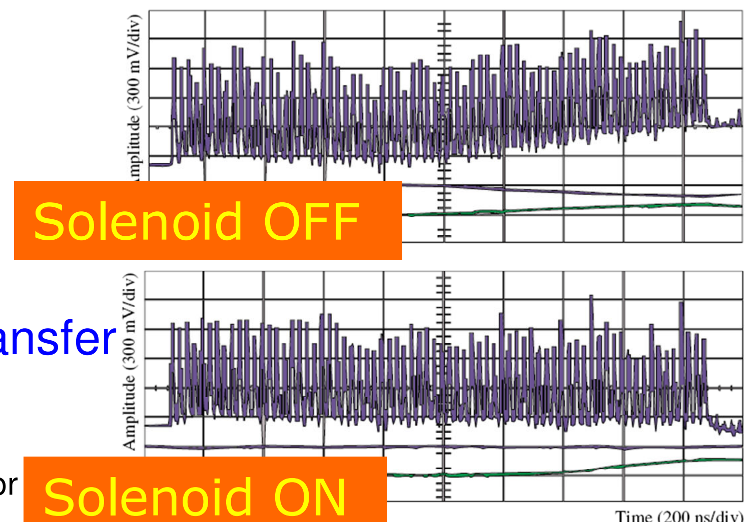
Bunch shortening



  – Transverse instabilities on extraction flat top. Type (single bunch, coupled bunch) still to be determined, but linked with electron-cloud effects.

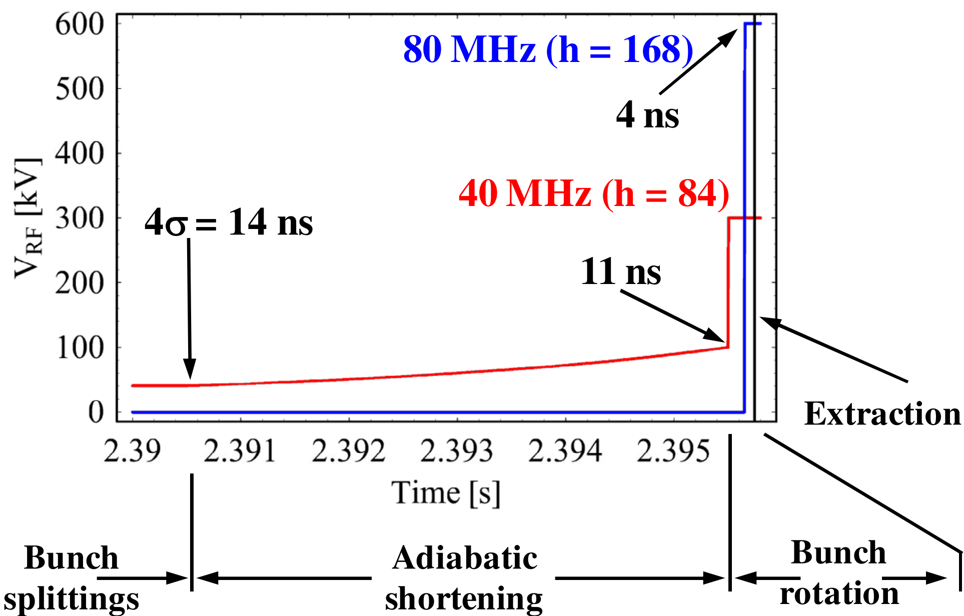


TT2 transfer line



PS: transverse instabilities - II

- Nominal performance:
  - 1.3×10^{11} p/b with 25 ns: bunches are unstable at top energy if shorter than ~12 ns (rise time few ms).
- Extrapolation to higher intensities:
  - Not easy: it requires a complete study. However, possible cures are:
    - Injection:
      - Improved working point control (tune and chromaticity).
    - Top energy:
      - Control bunch length (avoid too short bunches) and perform bunch rotation faster than with nominal RF-gymnastics
      - Transverse damper
      - Cure electron-cloud effects, e.g., vacuum chamber coating



PS: longitudinal instabilities - I

- Nominal LHC beam suffers from longitudinal coupled bunch instabilities (dipole mode).
- Nominal performance:
  - 1.3×10^{11} p/b with 25 ns spacing are stabilised with the longitudinal feedback system (10 MHz cavities in sections 86 and 96 used for acceleration and for damping the instabilities)
- Extrapolation to higher intensities:
  - In 2009 $\sim1.4\times10^{11}$ p/b with 25 ns spacing were accelerated using the spare 10 MHz cavity in section 11 as a dedicated kicker for the coupled-bunch feedback. A beam with a twice as small ε_l was successfully stabilised.

PS: longitudinal instabilities - II

- Extrapolation to higher intensities:
  - Assuming scaling of instability threshold as N_b/ε_l, then $\sim 2.8\times10^{11}$ p/b should be stable with nominal ε_l and a dedicated feedback up to top energy.
  - RF manipulations and longitudinal splitting at at high energy not tried during the tests because of a too small longitudinal emittance.
  - Detailed study of beam stability during the flat-top RF manipulations is required.

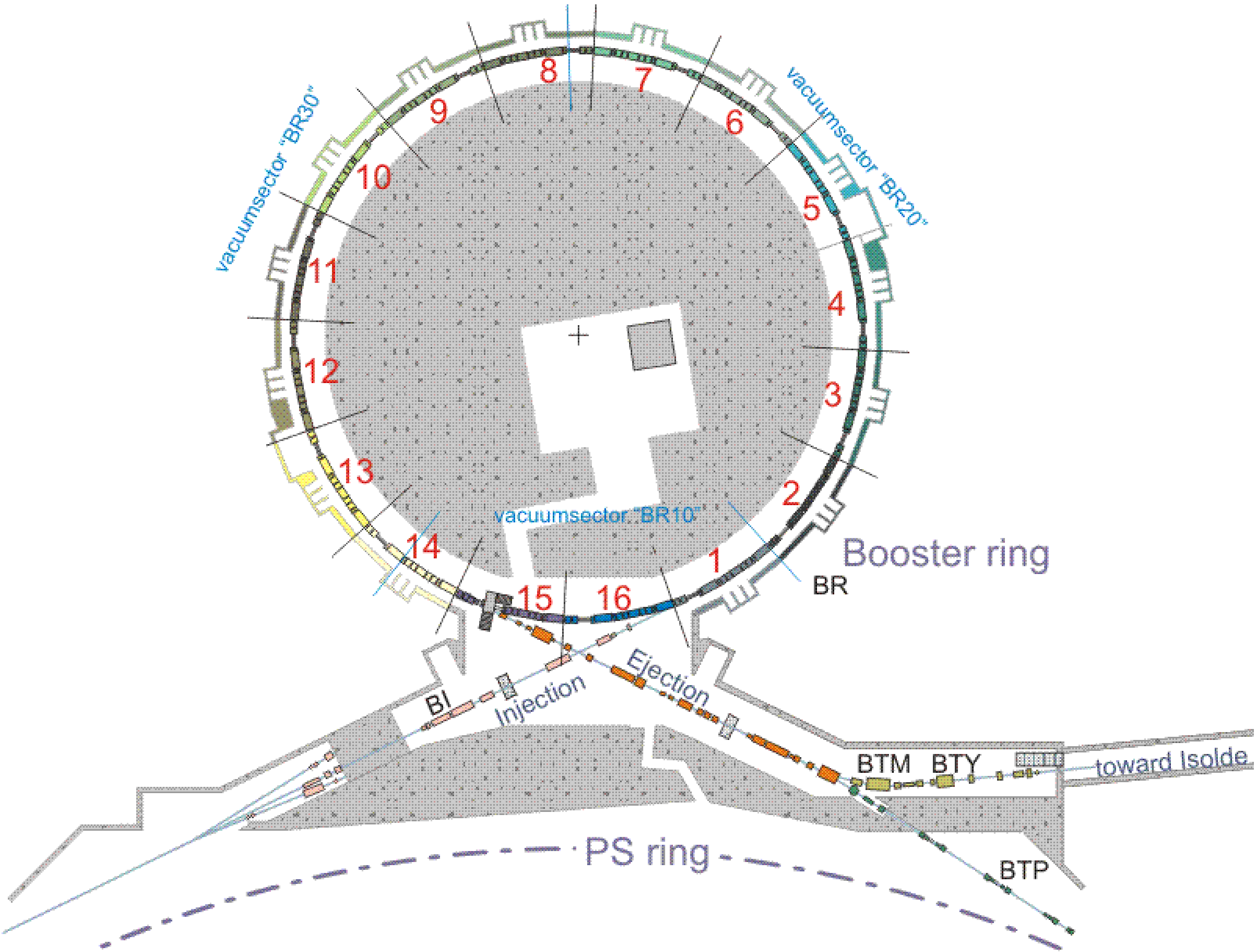
To increase the PSB extraction energy

- PSB:
  - Main magnets
  - Main power supply
  - RF
  - Septa and kickers
- Transfer and measurement line
  - Magnets
  - Septa and kickers
  - Power converters

- PS injection:
  - Septum and kicker
  - Injection slow bump

NB: in this proposal the extraction energy for the ISOLDE beams is unchanged.

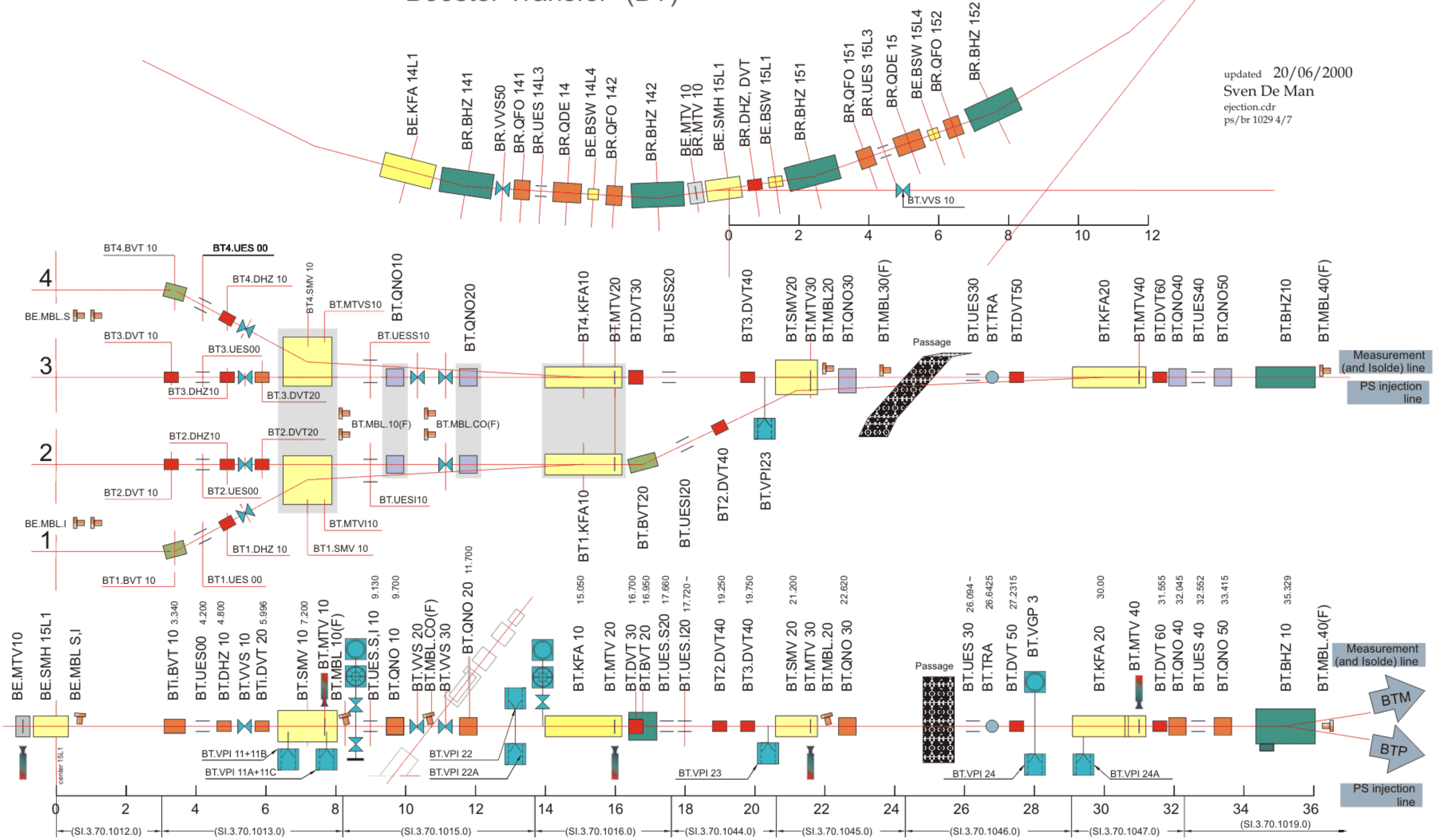
PSB, extraction lines, and PS



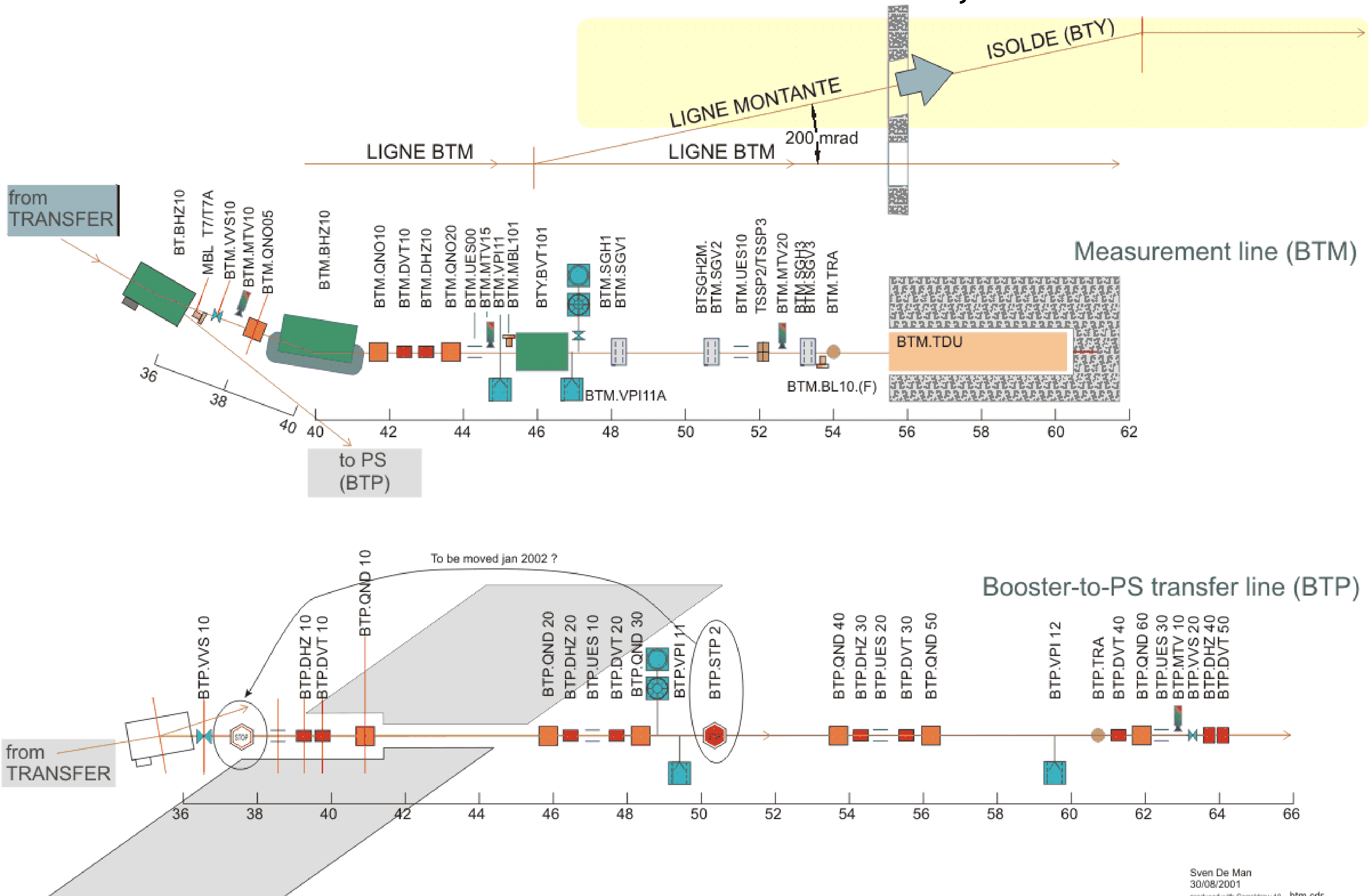
PSB extraction line: BT

Ejection and recombination:

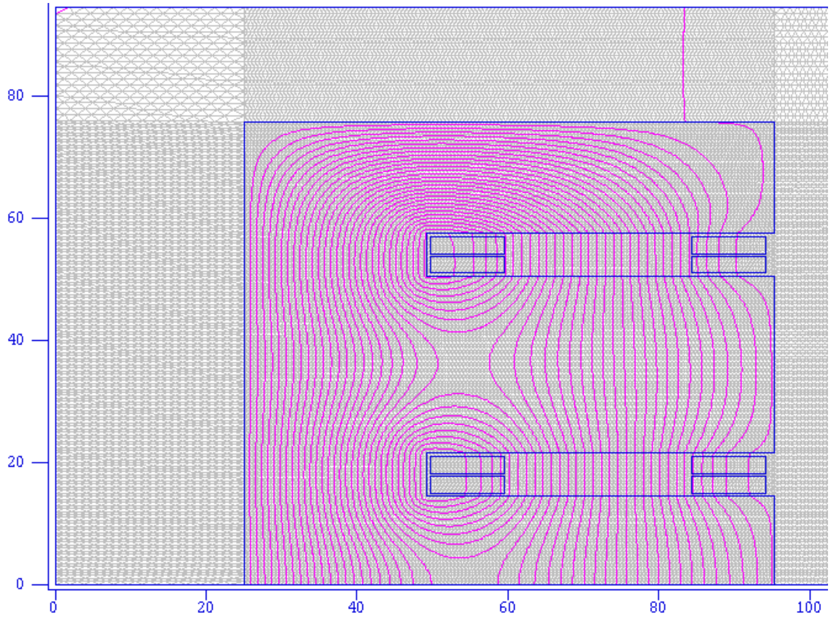
"Booster Transfer" (BT)

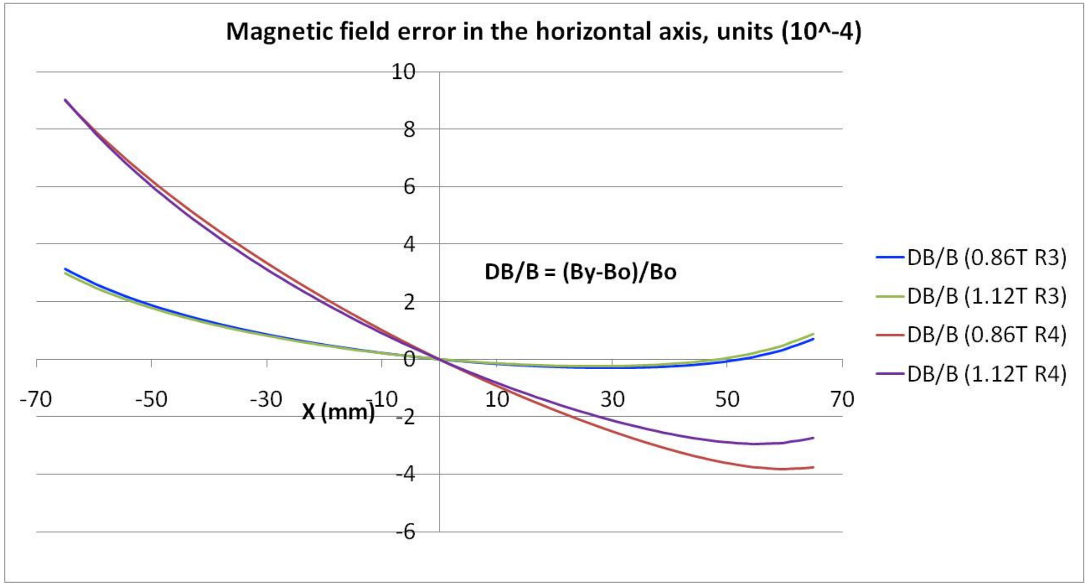


PSB transfer lines: BTP, BTM



PSB: main dipoles





BR.BHZ Normal configuration	Present	+30%
FIELD STRENGTH (T)	0.86	1.12
PEAK CURRENT (A)		
Inner Rings	4032	5255
Outer Rings	4065	5515
POWER COMSUMPTION (kW)	49	83
Q (@ ΔT= 28 K) (l/min)	26	44
ΔT (@ Q = 26 l/min) (K)	28	47

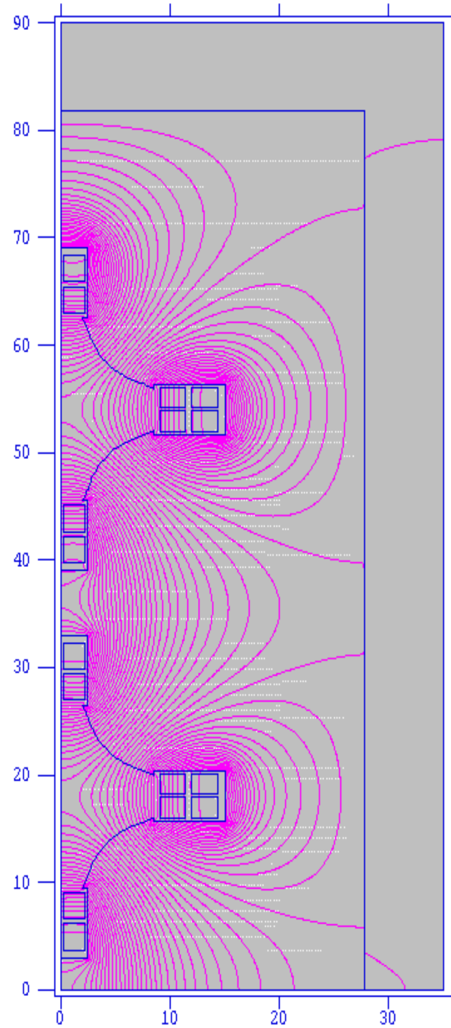
Findings:

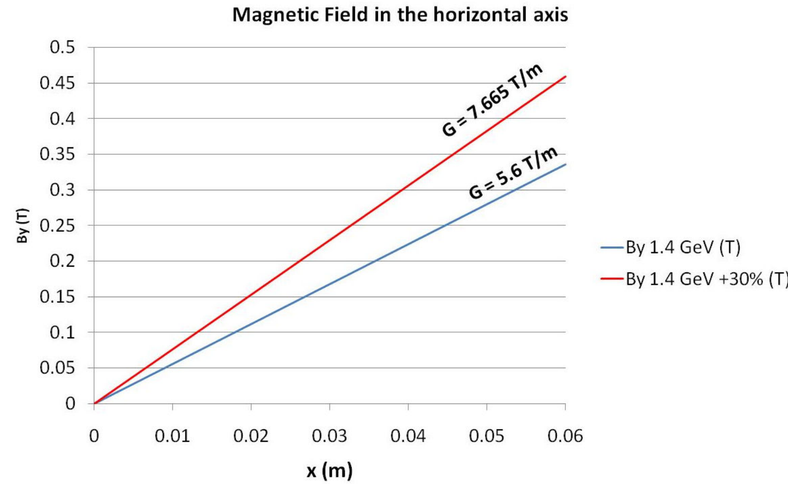
- Increase of field strength seems feasible
- Field quality is not affected
- Due to higher saturation, the outer rings have to be supplied with an higher current differential than present
- This effect may be reduced by introducing laminated side plates (currently solid)
- This preliminary study is being cross checked with measurements
- Cooling to be reviewed

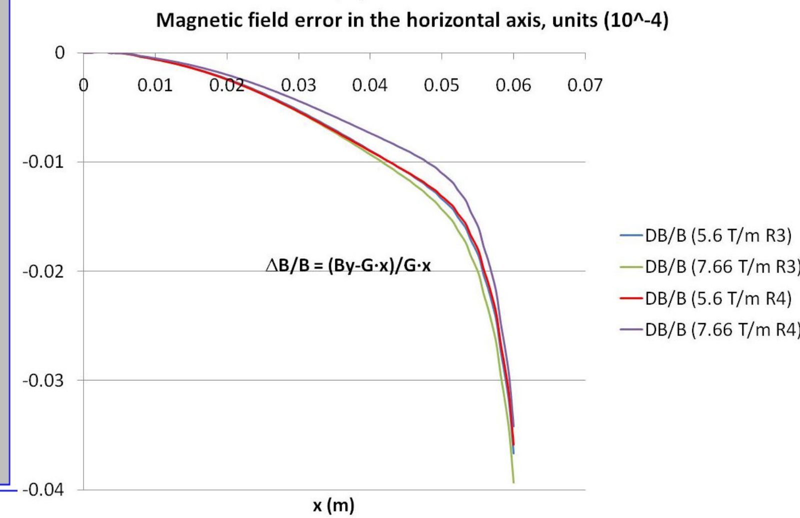
PSB: main quadrupoles

BR.QF	PRESENT	+%30
FIELD GRADIENT (T/m)	5.60	7.66
PEAK CURRENT (A)	4032	5255
POWER COMSUMPTION (kW)	16	27
Q (@ ΔT= 20 K) (l/min)	12	20
ΔT (@ Q = 12l/min) (K)	20	34

BR.QD	PRESENT	+%30
FIELD GRADIENT (T/m)	5.60	7.66
PEAK CURRENT (A)	4032	5255
POWER COMSUMPTION (kW)	11	19
Q (@ ΔT= 20 K) (l/min)	8	14
ΔT (@ Q = 8.3l/min) (K)	20	34







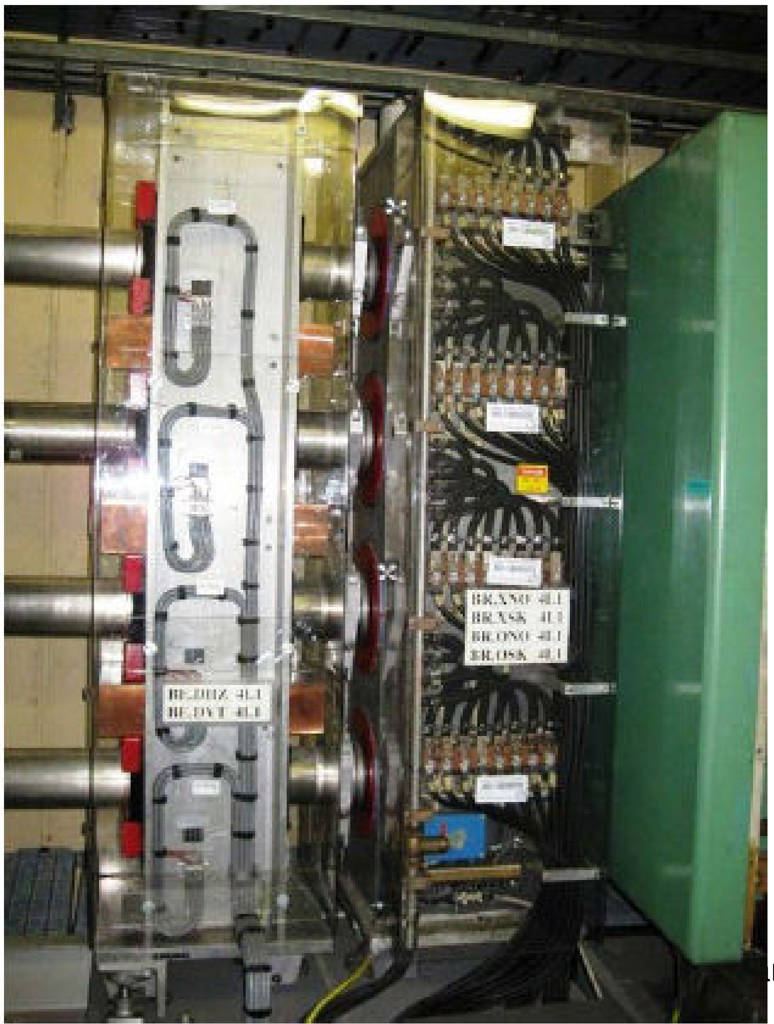
Findings:

- Increase of field strength seems feasible
- Field quality is not affected
- This preliminary study is being cross checked with measurements

PSB: other magnets

Dipole corrector

Multipole corrector (quadrupole, sextupole, octupole)



- Special multipole magnets have enough margin.

Power converters

- The main power converter cannot cope with the increased extraction energy. A new one is required. A new trim power converter for the outer rings is also needed.
- NB: the increased Bdot would allow delivering beam to ISOLDE on a 0.6 s basis. Hence, once could envisage:
  - Beam to ISOLDE on 0.6 s PSB magnetic cycle -> a factor of two increase in beam delivered to ISOLDE
  - Beam to PS based on 1.2 s PSB magnetic cycle
- Only a few power converters of transfer lines magnets and septa can be recuperated.
- Hardware consolidation is foreseen (see presentation by S. Baird).
- Synergies with other projects possible.

RF

- The proposed increased energy would bring f_{rev} to 1.81 MHz, hence slightly outside the range of C02 cavities. It can be easily fixed by shifting the whole frequency range.
- A vigorous consolidation programme (see presentation by S. Baird) will be beneficial for the PSB energy upgrade.

Kickers: PSB

Findings:

- Increase of field strength seems feasible
- The rise time of the kickers might increase by 1-5 ns.
- New magnets and tanks are needed.
- The actual tank should also be upgraded to serve as a spare which does not exist for the moment.
- No margin left.

				BE.KFA			BSW	
Beam kinetic energy (GeV)	**Kick multiplicator compared with 1.4 GeV**	**Required voltage (kV)**	**Magnet**	**Switch**	**PFN**	**Required current (A)**	**Magnet**	**Generator**
2	1.3	55.25	New magnets & tank	ok	ok	682.5	ok	ok

Kickers: Transfer line and PS

Findings:

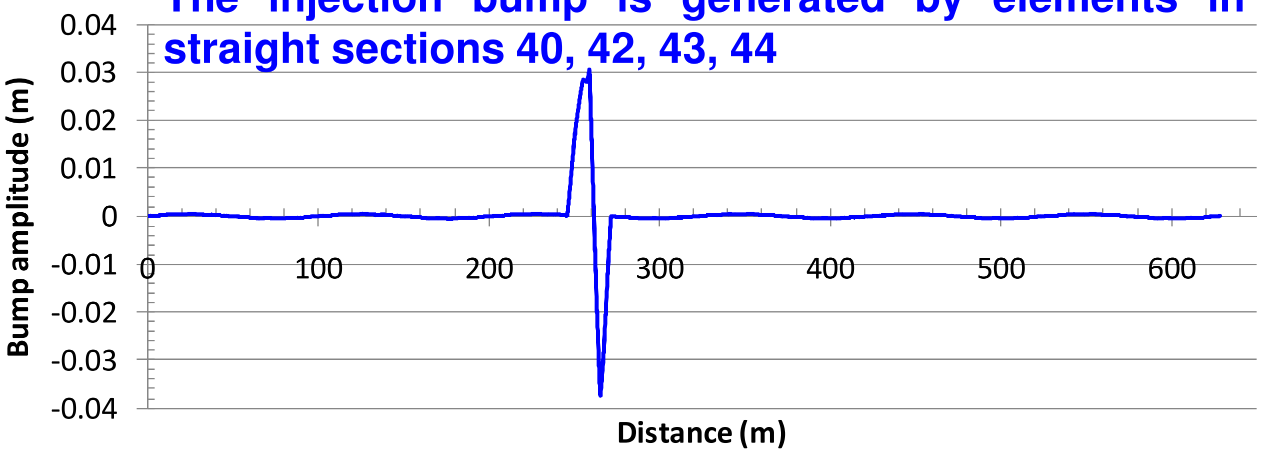
- Increase of field strength seems feasible
- The rise time of the kickers might increase by 1-5 ns.
- A change of ferrite grade is recommended for BT.KFA10.
- No margin left.
- Increase of strength up to 1.8 is feasible in short-circuit mode, only, but:
    - Flat top ripple increased: 2% -> 3 %
    - Rise time increased (2-98)%: 42 ns -> 68 ns
    - Fall time increased (2-98)%: 68 ns -> 87 ns
- If the system cannot be used in short-circuit mode, development of 2 new generators is required and 2 new magnets have to be added in the PS. The present system will stay.

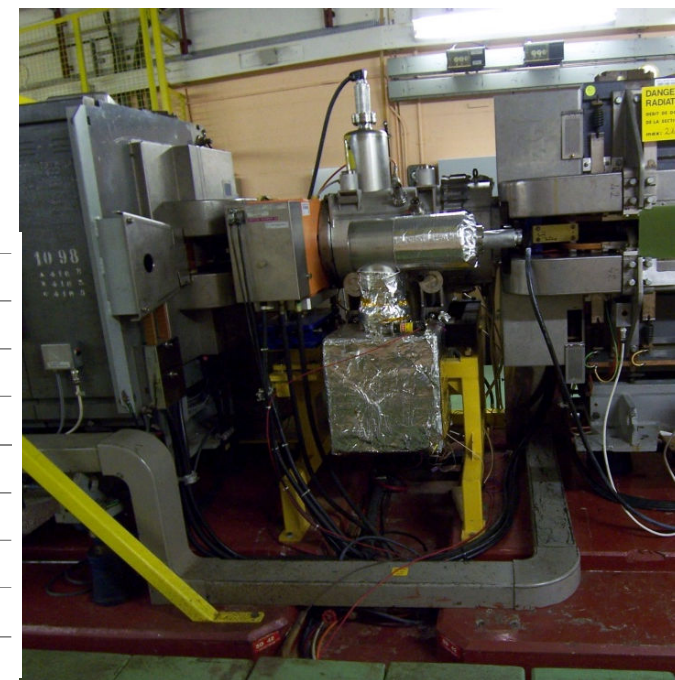
		BT.KFA10				BT.KFA20				KFA45				
Beam energy (GeV)	**Kick multiplicator compared with 1.4 GeV**	**Required voltage (kV)**	**Magnet**	**Switch**	**PFN**	**Required voltage (kV)**	**Magnet**	**Switch**	**PFN**	**Required voltage (kV per module)**	**Magnet**	**Switch**	**PFN**	**Module in short-circuit mode**
2	1.3	55.25	ok, but ferrite change recommended & new tank possibly	ok	ok	36.4	ok	ok	ok	104	ok	ok	ok	**Yes**

Magnets and septa

- Transfer and measurement lines magnets:
  - Margin probably available, but verification is in progress (special care for saturation effects and different energies for PS and ISOLDE).
- Septa:
  - PBS extraction: Enough margin is available (30-40%). Modifications only needed for the internal bus bars and cooling.
  - BT: Strength margin up to 20% maximum. New septa are needed.
  - PS injection: Septum has definitely no strength margin. A longer device should be envisaged, thus implying a re-design of the injection slow bump.

The injection bump is generated by elements in straight sections 40, 42, 43, 44





Implementation

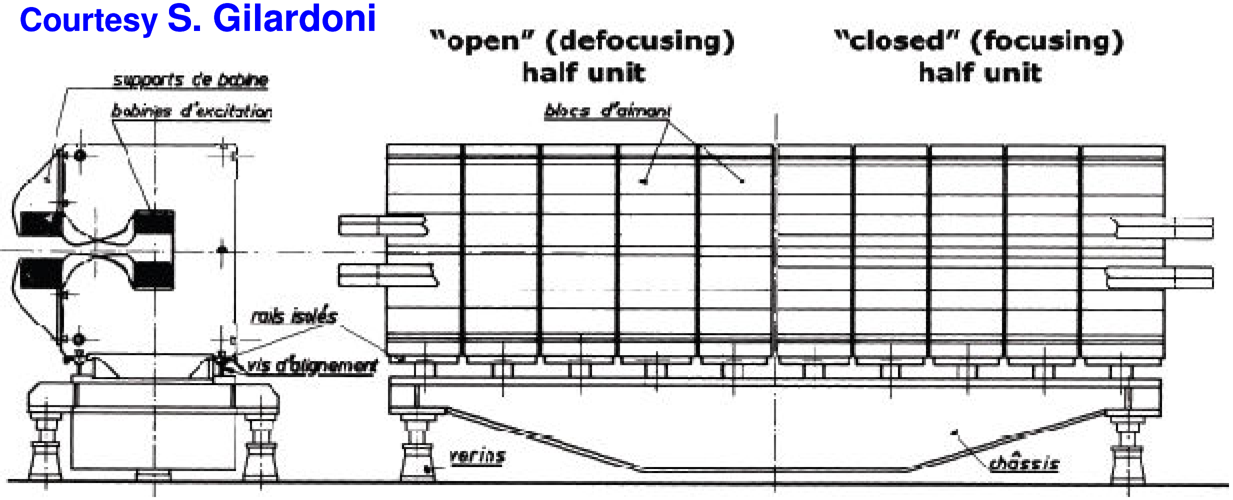
- In general:
  - Three to four years are considered necessary to develop and build the new hardware required for the increase of the PSB extraction energy.
  - One long (eight months) or two short shutdowns to install the new hardware.

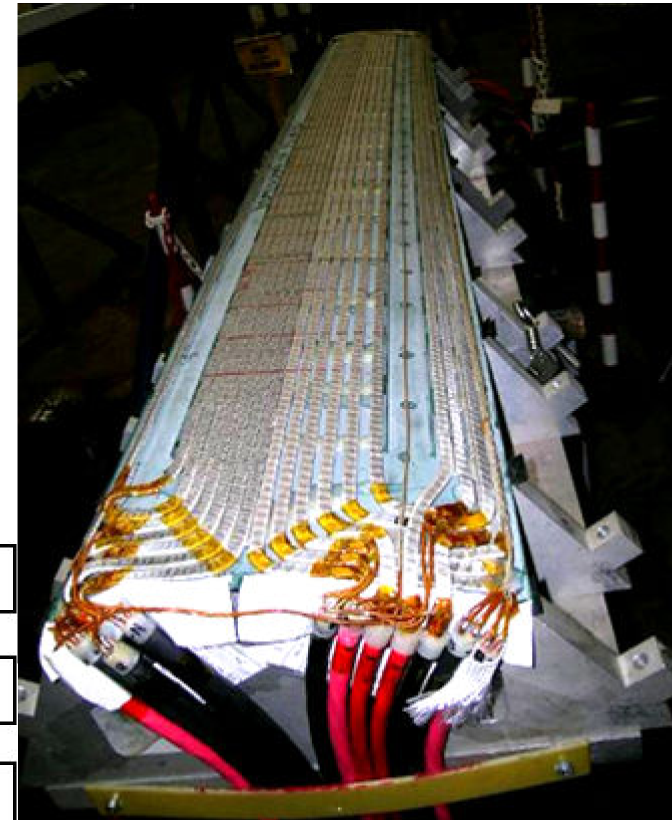
Intermediate summary

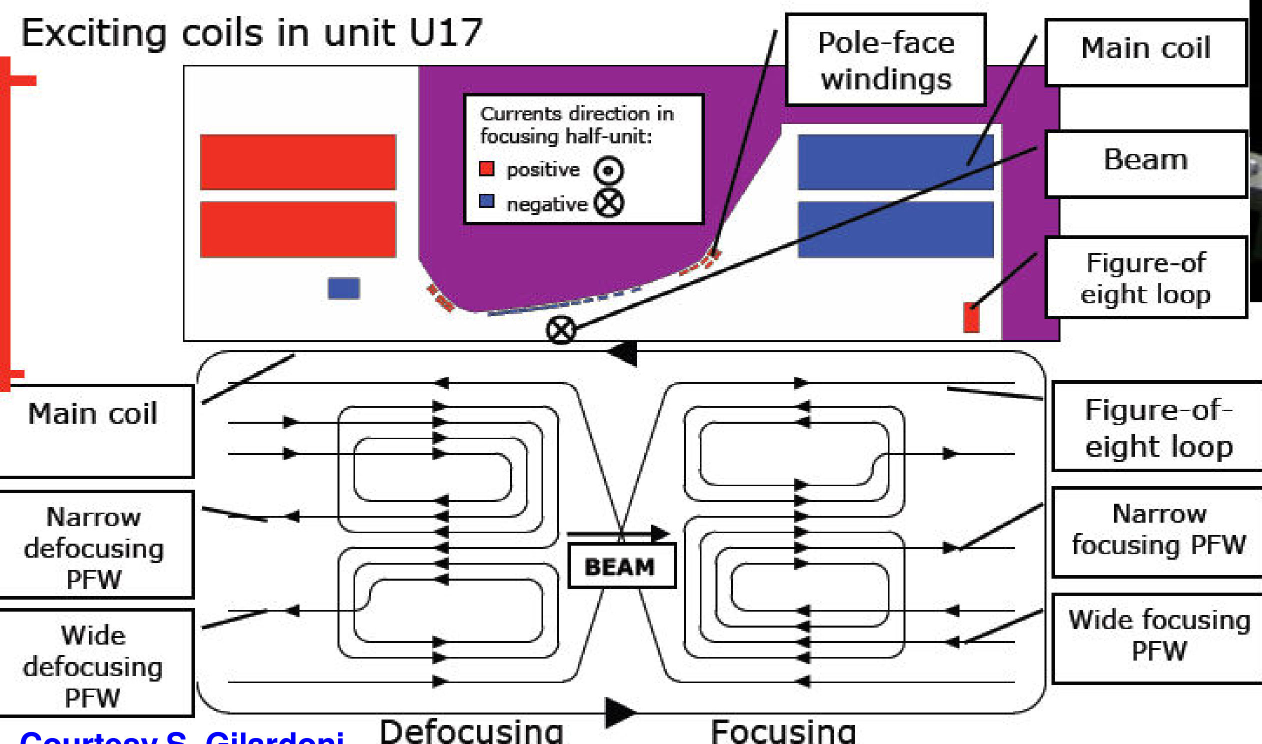
- Improvement: increase PSB extraction energy (2 GeV) to match new PSB space charge limits due to advent of Linac4. Possibility to generate LHC bunches of 2.7×10^{11} p (or even higher with longer bunches) with 25 ns spacing.
- Time line for implementation of new PSB extraction energy:
  - Three to four years (design and construction of new hardware)
  - One to two shutdowns (hardware installation)
- Other areas of study in view of additional improvements:
  - PS working point control.
  - Pulsing PS faster (26 GeV/c in 1.2 s). Potential gain: reduce LHC filling time by 14%-16%.
  - Vacuum pipe layout. Potential gain: increase aperture, reduce impedance, cure electron-cloud.
  - Losses at PS extraction (new thin septum or additional thin septum). Potential gain: reduce the systematic and unavoidable 2-3% losses for high intensity beams for SPS fixed target physics programme.

PS - other improvements: main magnets - I

Courtesy S. Gilardoni







Courtesy S. Gilardoni

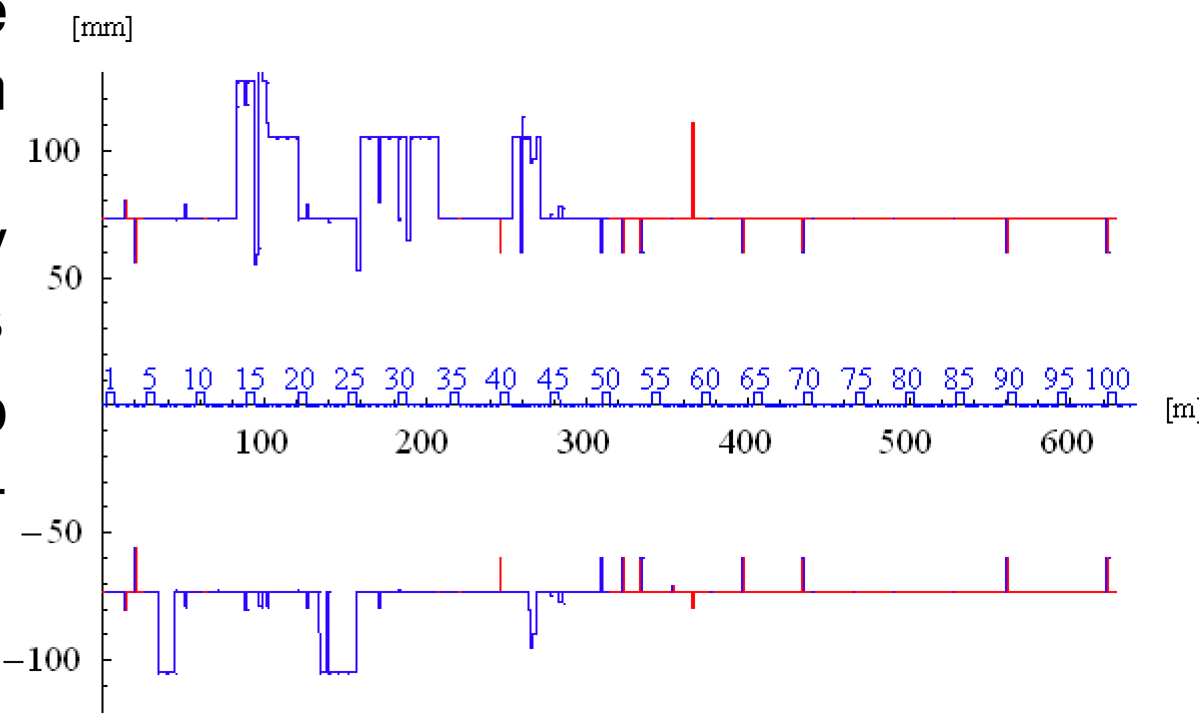
$$\begin{pmatrix} \Delta Q_h \\ \Delta Q_v \\ \Delta \xi_h \\ \Delta \xi_v \end{pmatrix} = A \begin{pmatrix} \Delta I_{FN} \\ \Delta I_{FW} \\ \Delta I_{DN} \\ \Delta I_{DW} \\ \Delta I_{8L} \end{pmatrix}$$

PS - other improvements: main magnets - II

- Under the assumption of a vigorous maintenance plan (see presentation by S. Baird) the PS main magnets will not be a source of limitation for the PS complex.
- However, the pole-face windings and figure-of-eight loop are a potential limitation (but difficult to quantify) as:
  1. No magnetic model exists, yet -> no accurate predictive approach available to specify working point
  2. Five currents are available to control four physical parameters -> optimisation required (or additional parameter to be controlled)
  3. RMS limit for these circuits might prevent using the full capabilities of the new PS main power supply (i.e., 26 GeV/c in 1.2 s). In view of faster cycling, it is worth stressing that the main magnets are also a potential bottleneck (mechanical stress, Eddy currents).
- First two points are being considered: the third one should be addressed too.

PS - other improvements: vacuum pipe layout

- A review of the PS vacuum pipe layout should be made in order to
  - Improve aperture (10% already gained at injection due to increased energy). This effort is already on-going and should be continued.
  - Estimate the potential gain in longitudinal impedance by improving transitions
  - Propose means to combat electron-cloud



PS - other improvements: losses at extraction

- Beam losses for Fixed Target beams have been removed from the electrostatic septum in section 31 (Continuous Transfer -> Multi-Turn Extraction).
- The choice of the longitudinal structure for the SPS (de-bunched beam) has made extraction losses on the magnetic septum unavoidable.
- The losses correspond to about 2-3% of the extracted intensity.
- Possible solutions:
  - One thinner septum in section 16 (anticipated in MTE DR).
  - Two septa: the existing plus a thinner one (electrostatic septum currently used by CT in section 31?)
  - Detailed study (optics and integration) to be performed.

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