LHC Injectors Upgrade

CERN

LHC Injectors Upgrade

LIU: Exploring alternative ideas

H. Damerau

Review of LHC & Injector Upgrade Plans Workshop (RLIUP)

30 October 2013

Contributions from: H. Bartosik, R. Garoby, S. Hancock, Y. Papaphilippou, E. Shaposhnikova

Acknowledgements: G. Arduini, T. Argyropoulos, M. Benedikt, T. Bohl, C. Carli, S. Gilardoni, B. Goddard, W. Herr, W. Höfle, B. Mikulec, E. Montesinos, G. Rumolo, L. Sermeus, H. Timkó, R. Tomas, R. Wasef and many others

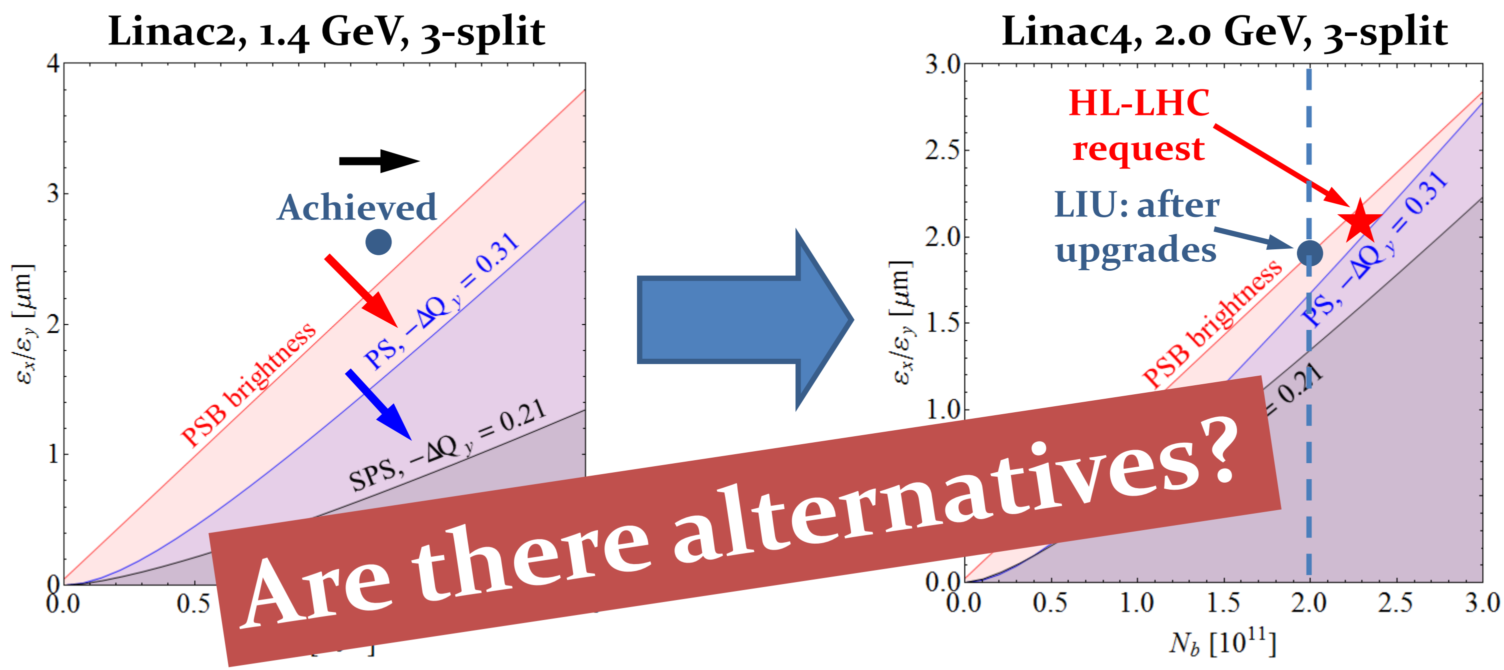
CERN

Overview

- Introduction
- Alternative schemes in the Pre-injectors
  - Manipulation schemes in the PS
  - Additional improvements
  - Special case for limited upgrades
- Alternative schemes in the SPS
  - RF power considerations
  - Transverse improvements
- Summary

Introduction: baseline upgrade plan

1. Increase brightness from Linac with PS Booster	Linac2 → Linac4
2. Reduce space charge in the PS	PSB/PS transfer energy 1.4 GeV → 2 GeV
3. Increase intensity per bunch in SPS	RF upgrade 4.2 → 7.6 MW, 4 → 6 cav.



	25 ns	50 ns
Splitting ratio PS ejection/injection	12	6
Batch length from PS	72	36

Overview of upgrade options

Basic choices + alternatives | **Additional benefit/margin**

Linac4

- Vertical painting Linac4 +? %

PSB

- Faster recombination kickers PSB-PS (with 1.4 GeV)
- Long. flat or hollow bunches +25 %
- 2.0 GeV at PSB→PS transfer

PS

- Double-batch or *h*=5 single-batch injection
- 3-split, BCMS, BCS or PBC (pure batch comp.)
- 8b+4e together with 3-split or BCMS
- Resonance compensation +? %
- Special injection optics +? %
- Long. flat or hollow bunches +25 %

SPS

- SPS RF upgrade: 4×3+2×4
- More RF power plants: 4×2+4×3 or 10×2
- Relaxed ε_l with 200 MHz in LHC
- 28 GeV at PS→SPS transfer +15 %
- Split tunes optics +5 %
- Special injection optics +? %

Baseline | Beam studies before LS1 | Beam studies possible after LS1 | Needs hardware

Assumptions

Basic assumptions for performance evaluation:

	Parameter	
L4+PSB	Transverse emittances halved compared to Linac2	~0.6 μm/10^{12}
PS	Beam loss	5%
	Transverse emittance growth	5%
	Tolerable space charge tune shift, ΔQ_y	-0.31
	Maximum bunch length at injection	Recomb. kickers
SPS	Beam loss	10%
	Transverse emittance growth	10%
	Tolerable space charge tune shift, ΔQ_y	-0.21
	Baseline intensity per bunch after RF upgrade	$2.0 \cdot 10^{11}$ ppb

- **All parameters only valid for 25 ns bunch spacing**

→ **For comparison, performances are given at extraction from SPS**

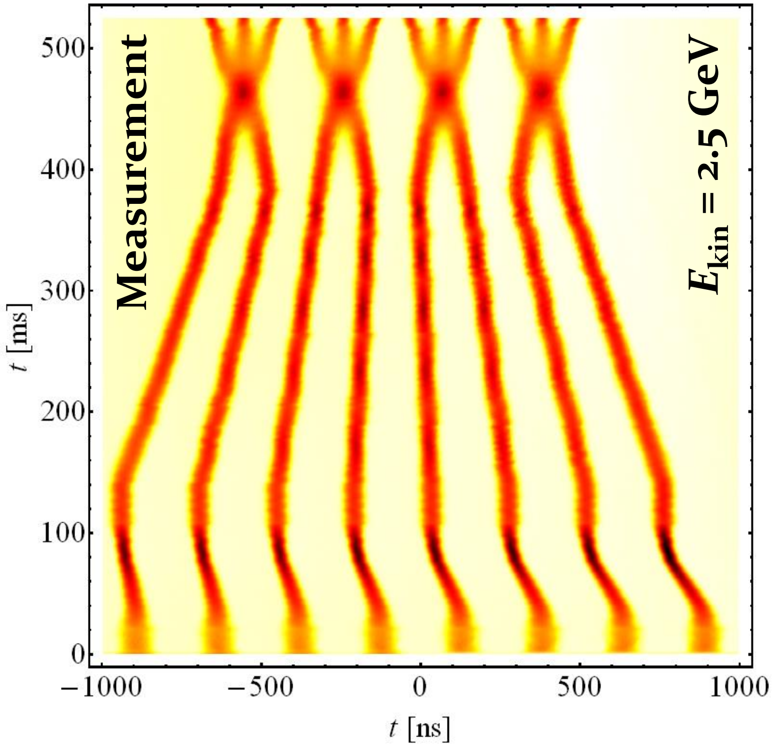
- **Caution: most considerations over-simplified**

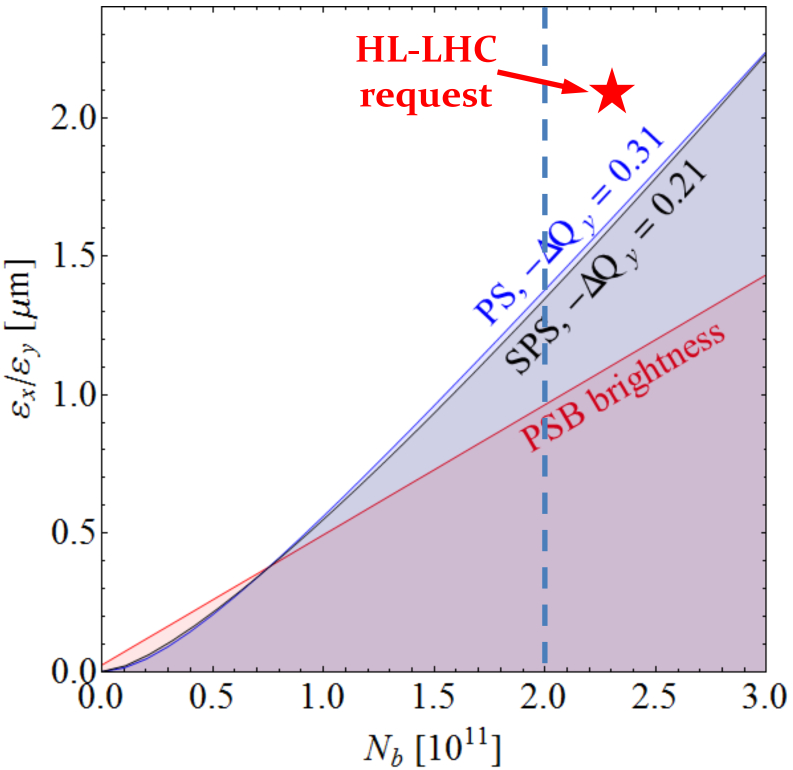
Overview

- Introduction
- **Alternative schemes in the Pre-injectors**
  - **Manipulation schemes in the PS**
  - Additional improvements
  - Special case for limited upgrades
- Alternative schemes in the SPS
  - RF power considerations
  - Transverse improvements
- Summary

Batch compression, merging, splitting

- **Effectively reduce PSB brightness by smaller splitting factor in PS**
- **Successfully made operational in 2012, baseline for 25 ns after LS1**





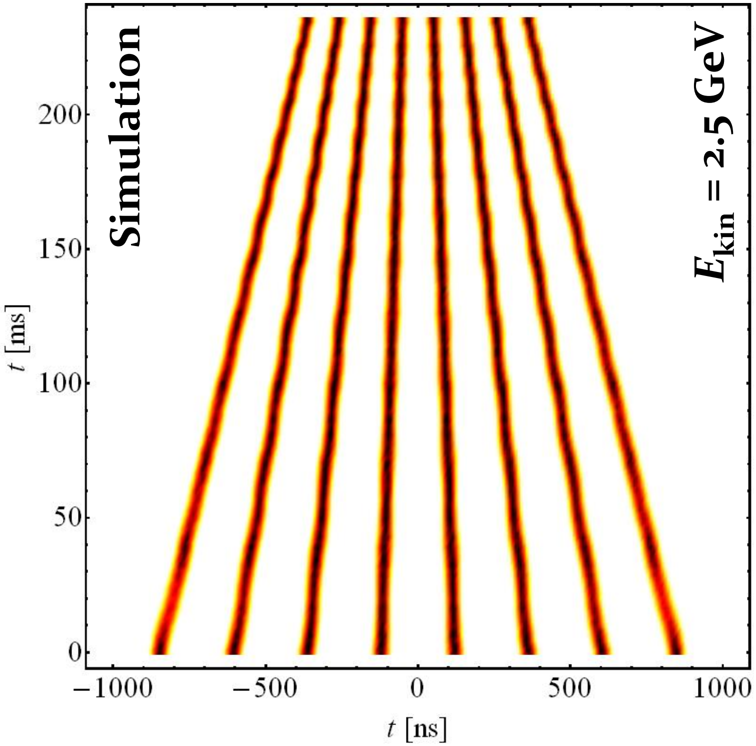
→ **Bunches split by 6 in PS: batches of 48 bunches, 6% less bunches in LHC**

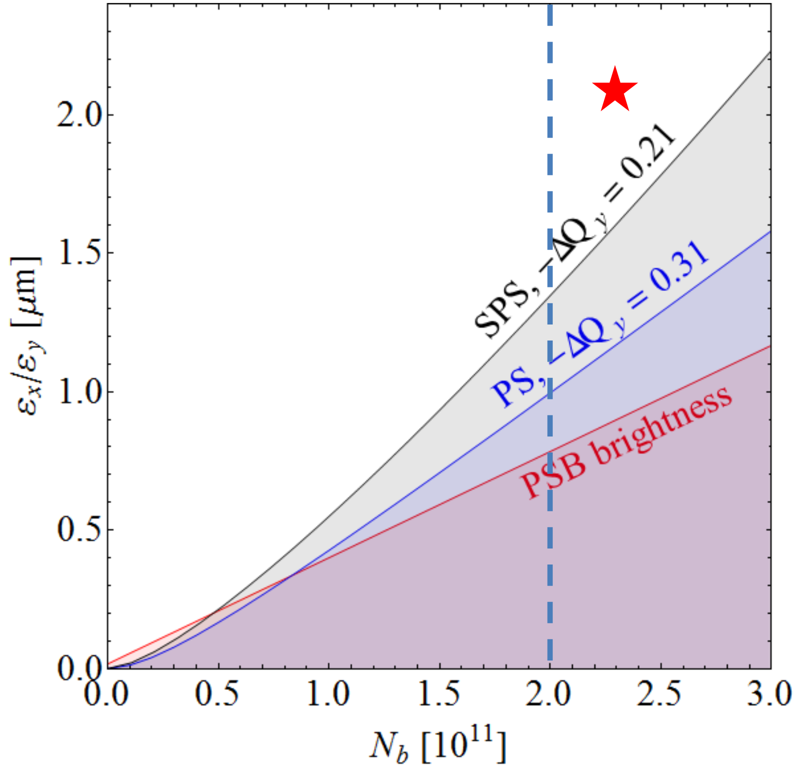
→ **Perfectly matches PS (2 GeV) and SPS space charge limits**

→ **Brightness reach beyond with HL-LHC request for 25 ns beam**

Pure batch compression

→ **Extreme case of no bunch splitting at low energy at all**





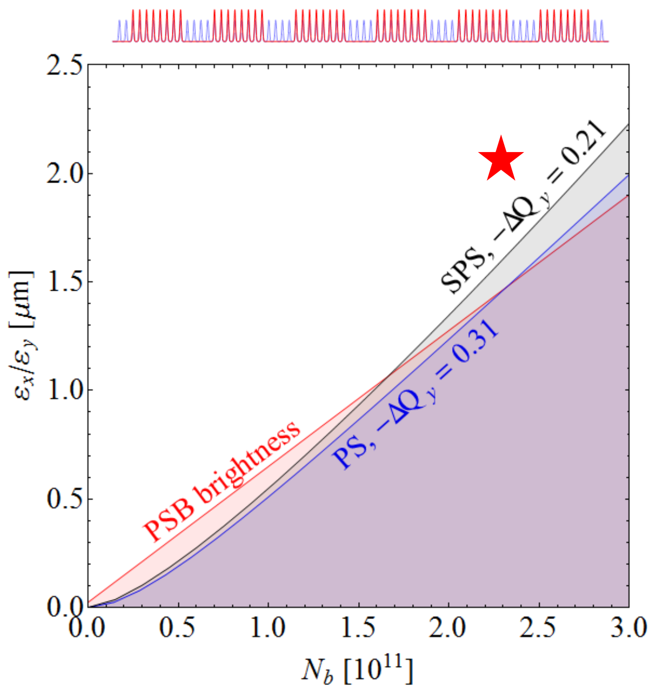
→ **Bunches split by 4 in PS: batches of 32 bunches, 13% less bunches in LHC**

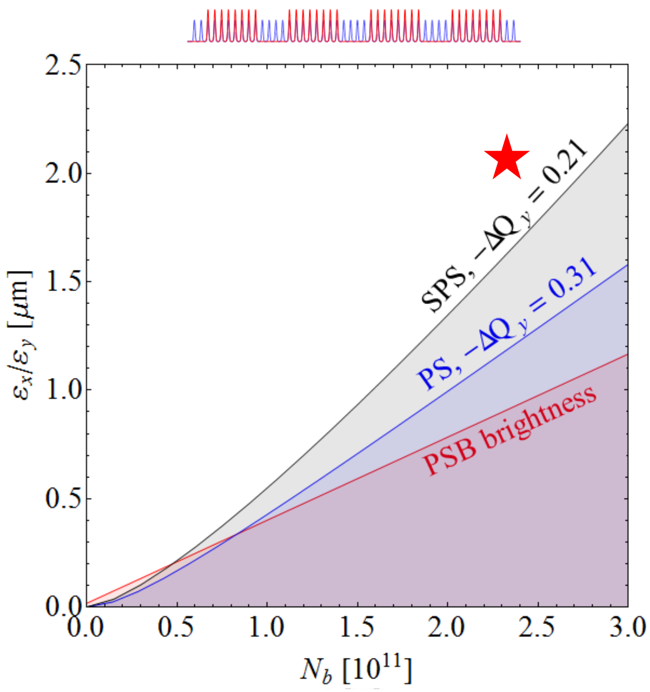
→ **Can be tested after LS1 controls upgrade of PS LLRF**

→ **Pushes SPS to space charge limitation!**

8b+4e bunch pattern schemes

- **Replace *h* = 7 → 21 triple split by direct double split, leaving empty bucket**
- **In combination with BCMS beams, merging and triple split suppressed**
- **Bunch pattern 6×(8b+4e) or 4×(8b+4e)**





→ **4 bunches missing every 8 bunches → improvement for e-cloud**

→ **50% less bunches in LHC, but with significantly higher intensity**

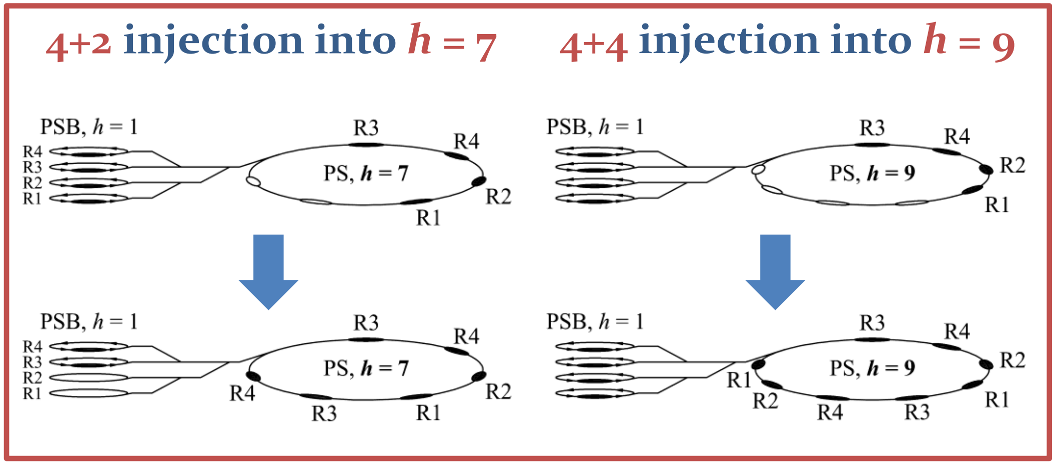
→ **To be tested with beam after LS1**

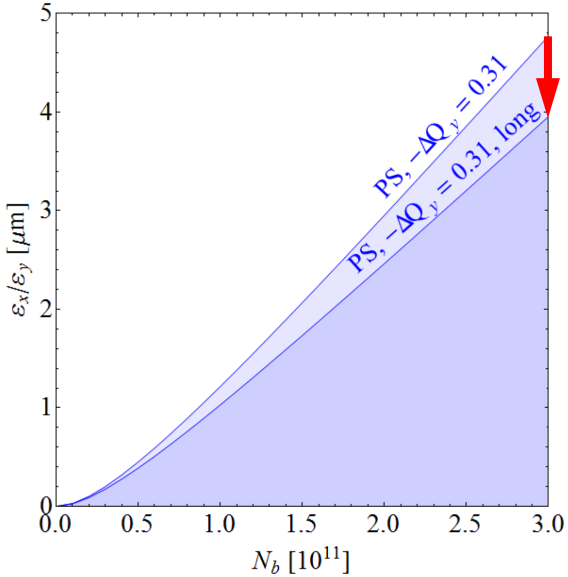
Overview

- Introduction
- **Alternative schemes in the Pre-injectors**
  - Manipulation schemes in the PS
  - **Additional improvements**
  - Special case for limited upgrades
- Alternative schemes in the SPS
  - RF power considerations
  - Transverse improvements
- Summary

Space charge reduction, longitudinal

1. **Flat-bunches**
   - → Double harmonic RF or hollow bunch distribution
   - → Space charge reduction by up to 25%
2. **Longer bunches**
   - → Bunch length at PSB-PS transfer limited by switching time between PSB rings
   - → Reducing switching time: 105 ns → 65 ns (1.4 GeV), 110 ns → 70 ns (2 GeV)



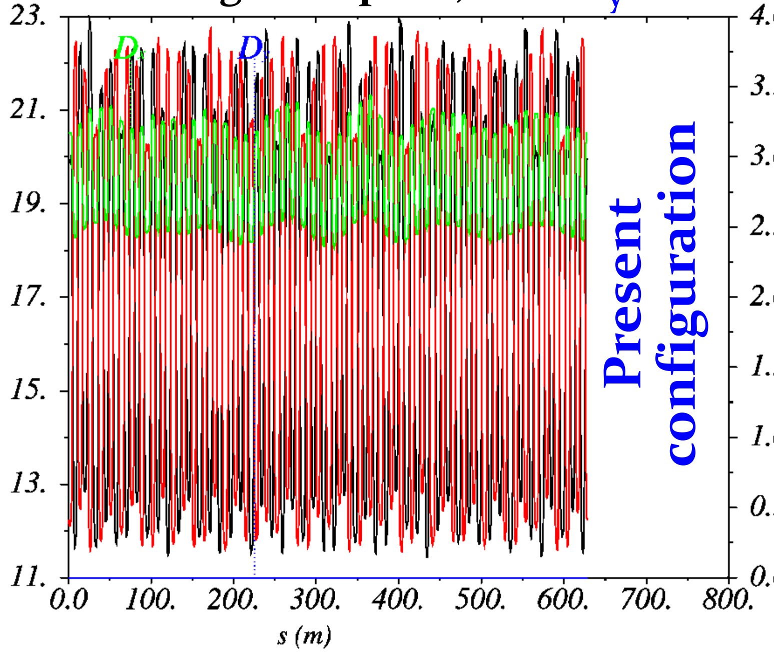


- → **Reduce ΔQ_{sc} at PS flat-bottom, potential brightness about 15%**
- → **Technically challenging even for transfer at 1.4 GeV**
- → **No interest after upgrade of to 2.0 GeV**

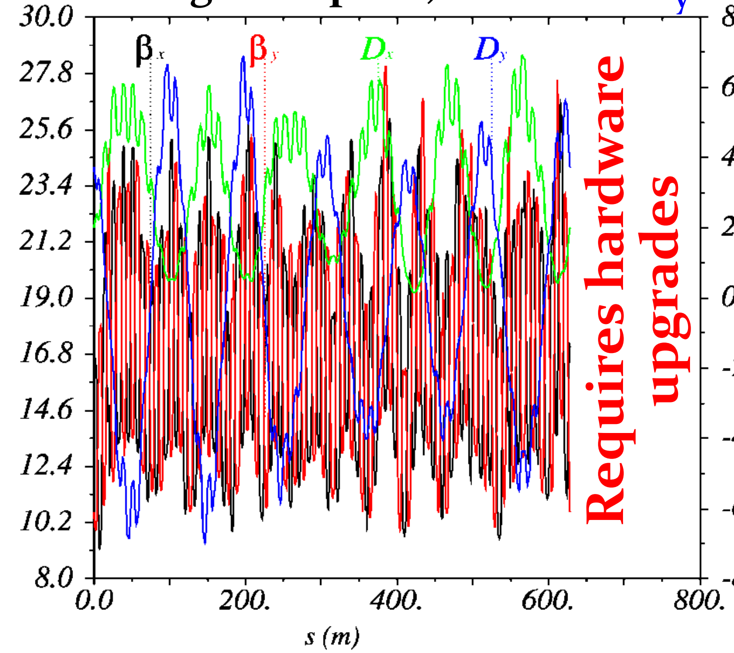
Space charge reduction, transverse

1. **Compensation of resonances ($Q_{x/y}$=0.21/0.24)**
   - → Closest resonance $4Q_y = 1$ difficult as excited by space charge
   - → Compensation of $2Q_x + Q_y = 1$ and $3Q_y = 1$ lines during studies in 2013
2. **Special optics with vertical dispersion**
   - → Introduce vertical dispersion to maximize beam size and reduce ΔQ_{sc}
   - → Optics becomes very irregular, needs simulations and beam studies
   - → Evaluate potential benefit with first beam studies after LS1

Regular optics, zero D_y



Irregular optics, non-zero D_y

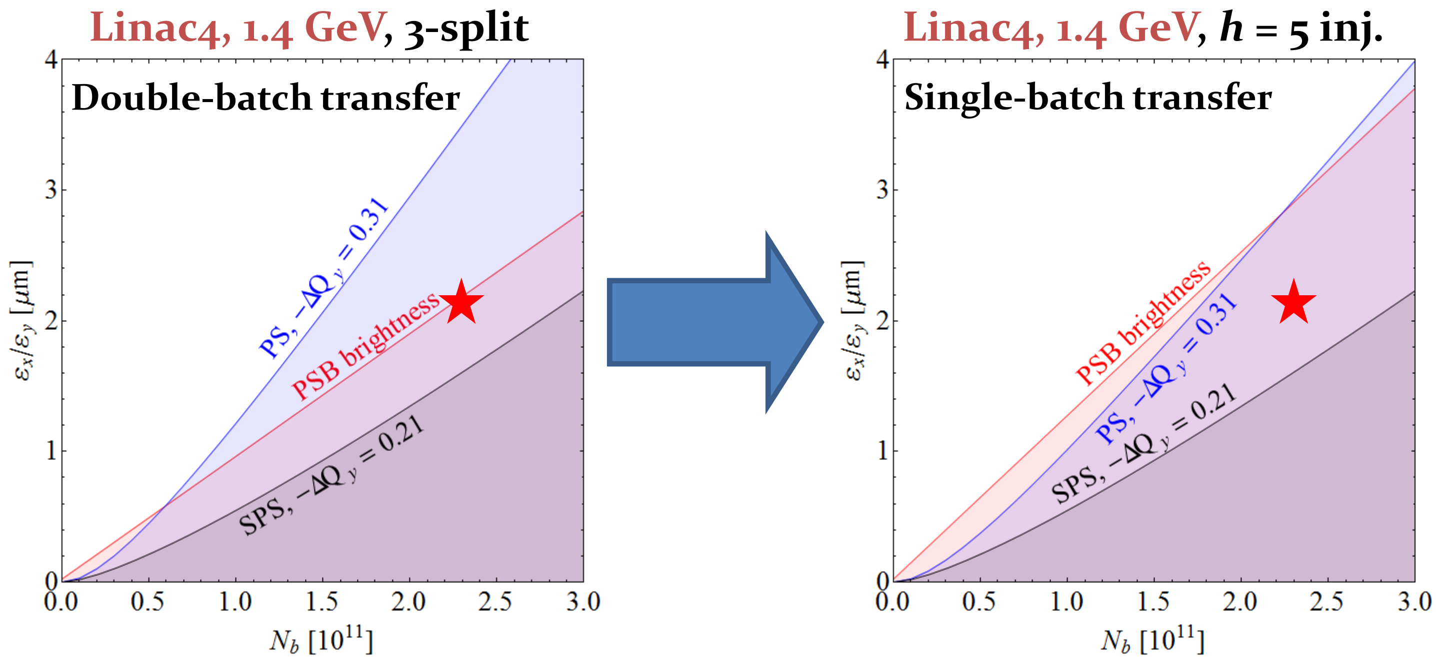


Overview

- Introduction
- **Alternative schemes in the Pre-injectors**
  - Manipulation schemes in the PS
  - Additional improvements
  - **Special case for limited upgrades**
- Alternative schemes in the SPS
  - RF power considerations
  - Transverse improvements
- Summary

Single-batch injection with Linac4

- **Combination of Linac4 with 1.4 GeV PSB→PS transfer energy unfavorable**
  → Linac4 + PSB can deliver brightness far beyond PS space charge limit
- **→ Transfer 4 long bunches from PSB to $h = 5$ in PS, then $h = 5 \rightarrow 10 \rightarrow 20 \rightarrow 21$**



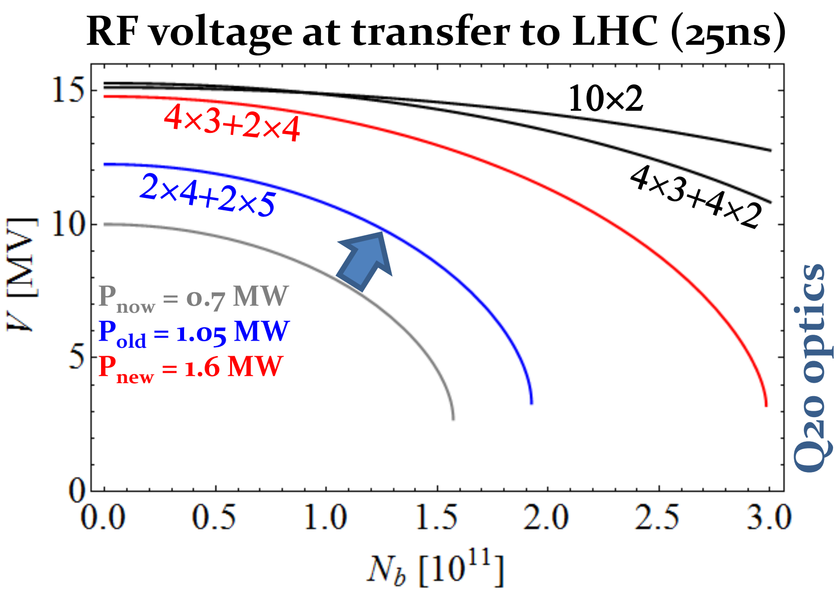
- **→ Rematches Linac4 + PSB and PS in terms of space charge**
- **→ Bunches split by 16 in PS: batches of 64 bunches, 3% less bunches in LHC**
- **→ Needs additional RF cavity at $h = 5$ or renovated cavities in PS**

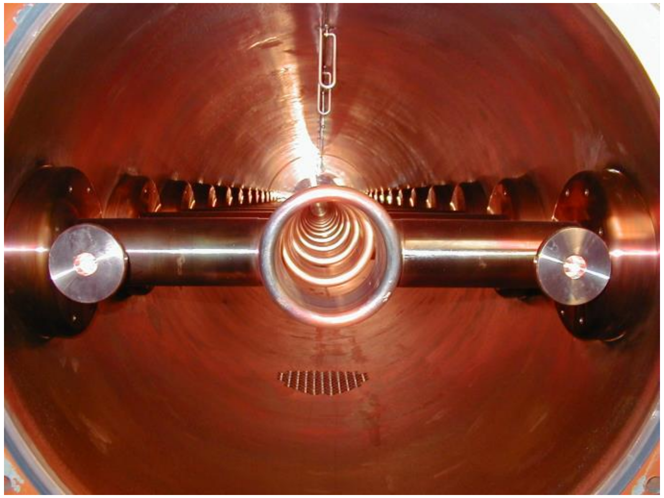
Overview

- Introduction
- Alternative schemes in the Pre-injectors
  - Manipulation schemes in the PS
  - Additional improvements
  - Special case for limited upgrades
- **Alternative schemes in the SPS**
  - **RF power considerations**
  - Transverse improvements
- Summary

Maximum intensity from SPS

- **Fixed bunch length required at SPS → LHC transfer**
- **Available RF voltage decreases with beam intensity**



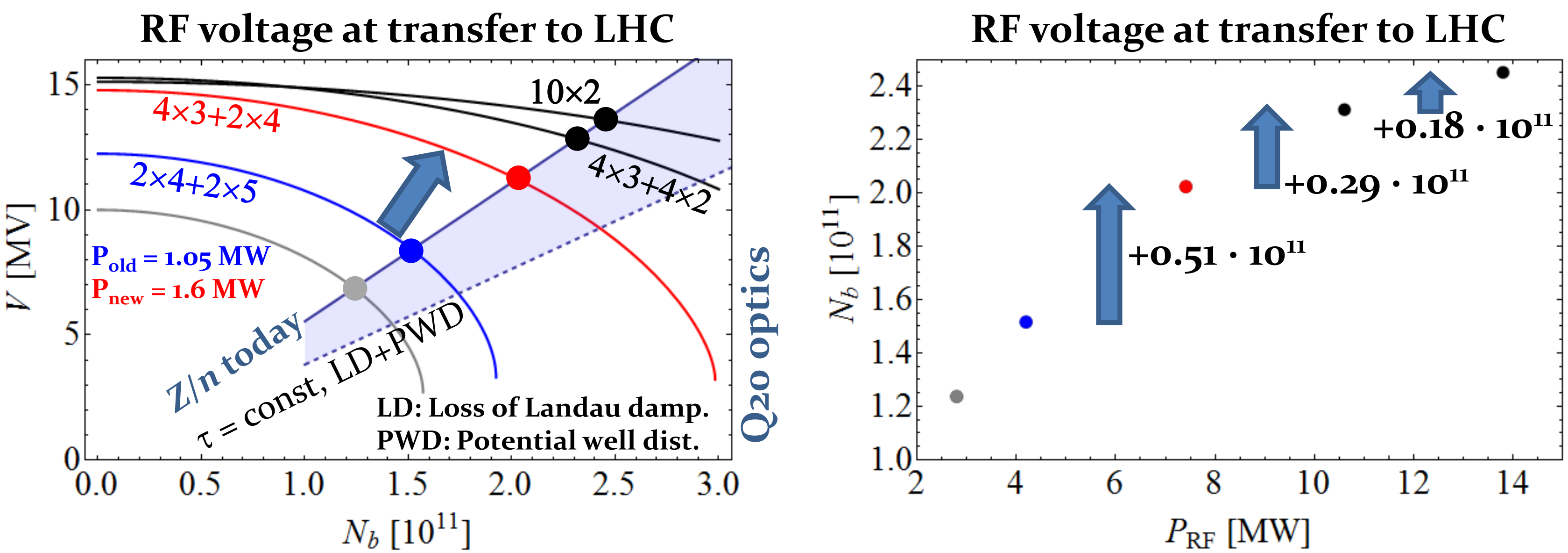


→ **Pulse amplifiers at f_{rev} for more power during beam passage (new LLRF)**

→ **Effective RF power 0.7 MW → ~1.05 MW**

Larger bunch intensity from SPS?

- **To keep longitudinal stability (Landau damping + potential well dist.)**
  - → **Longitudinal emittance increases with intensity: $\propto \sqrt{I_{RF}}$**
  - → **RF voltage requirement proportional to I_{RF}**



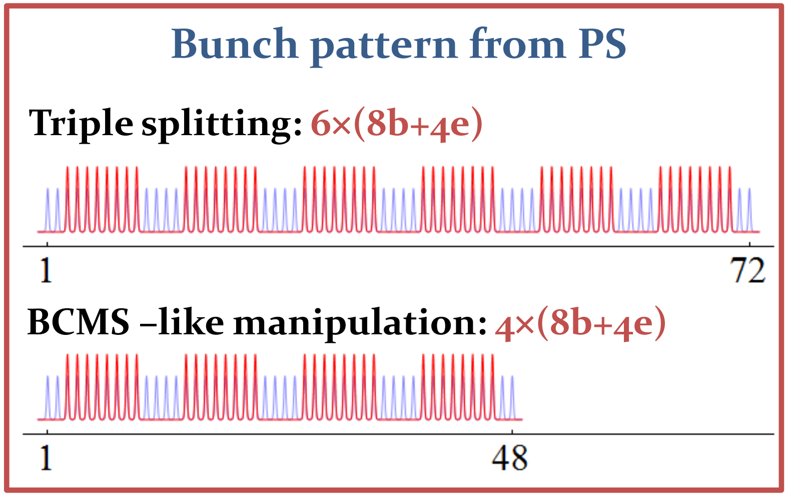
- **Baseline upgrade: shorter cavities and 2×1.6 MW RF power**

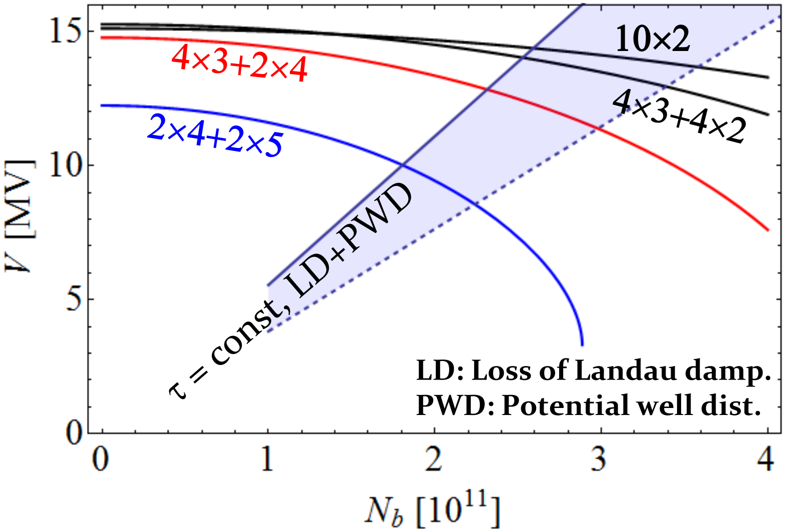
→ **$N_b \approx 2 \cdot 10^{11}$ ppb without degradation, $2.5 \cdot 10^{11}$ ppb for 10% longer bunches**

→ Even shorter cavities and more RF power?

8b+4e scheme in the SPS

- **Line density averaged over 0.3 μs ($\approx \tau_{fill}/2$) reduced by 2/3 at constant N_b**
  - → **50% more intensity per bunch for the same beam loading**
- **No benefit for single-bunch instability effects**



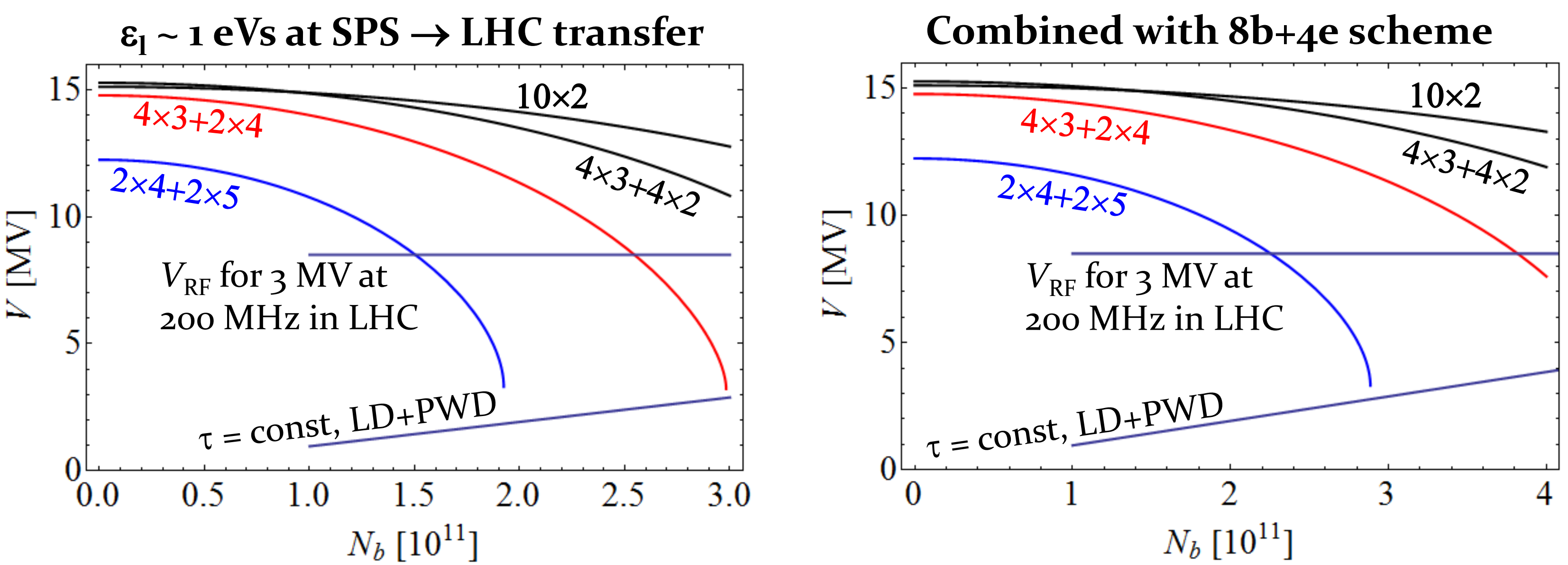


→ **$N_b \approx$ 3 · 10^{11} ppb reachable assuming SPS impedance reduction by 50%**

→ **First beam tests after LS1 possible**

200 MHz in LHC

- **Injecting with 200 MHz RF in LHC relaxes emittance constraint:**
  - → ε_l = 1.0...1.5 eVs, depending on whether transfer to 400 MHz RF
  - → No single-bunch stability issues at SPS flat-bottom

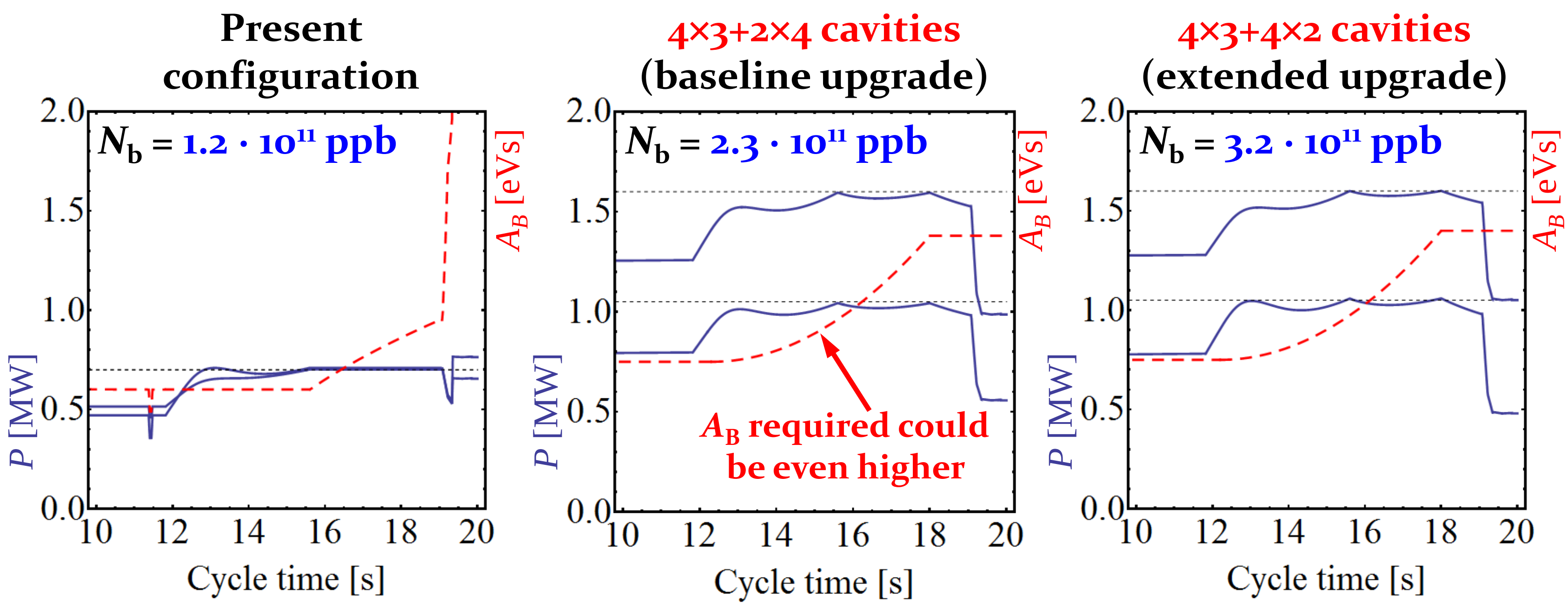


→ Larger ε_l in SPS associated with 200 MHz LHC helps on SPS flat-top

Power limitations for longitudinal emittance during acceleration?

Power Requirements during Acceleration

- Small ε_l imposed during first part of acceleration (present magnetic cycle)



→ **25 ns acceleration limit with 4×3+2×4 cavities** — **$2.3 \cdot 10^{11}$ ppb**

→ **Limit with 8b+4e scheme (density in PS)** — estimated — **$3.0 \cdot 10^{11}$ ppb**

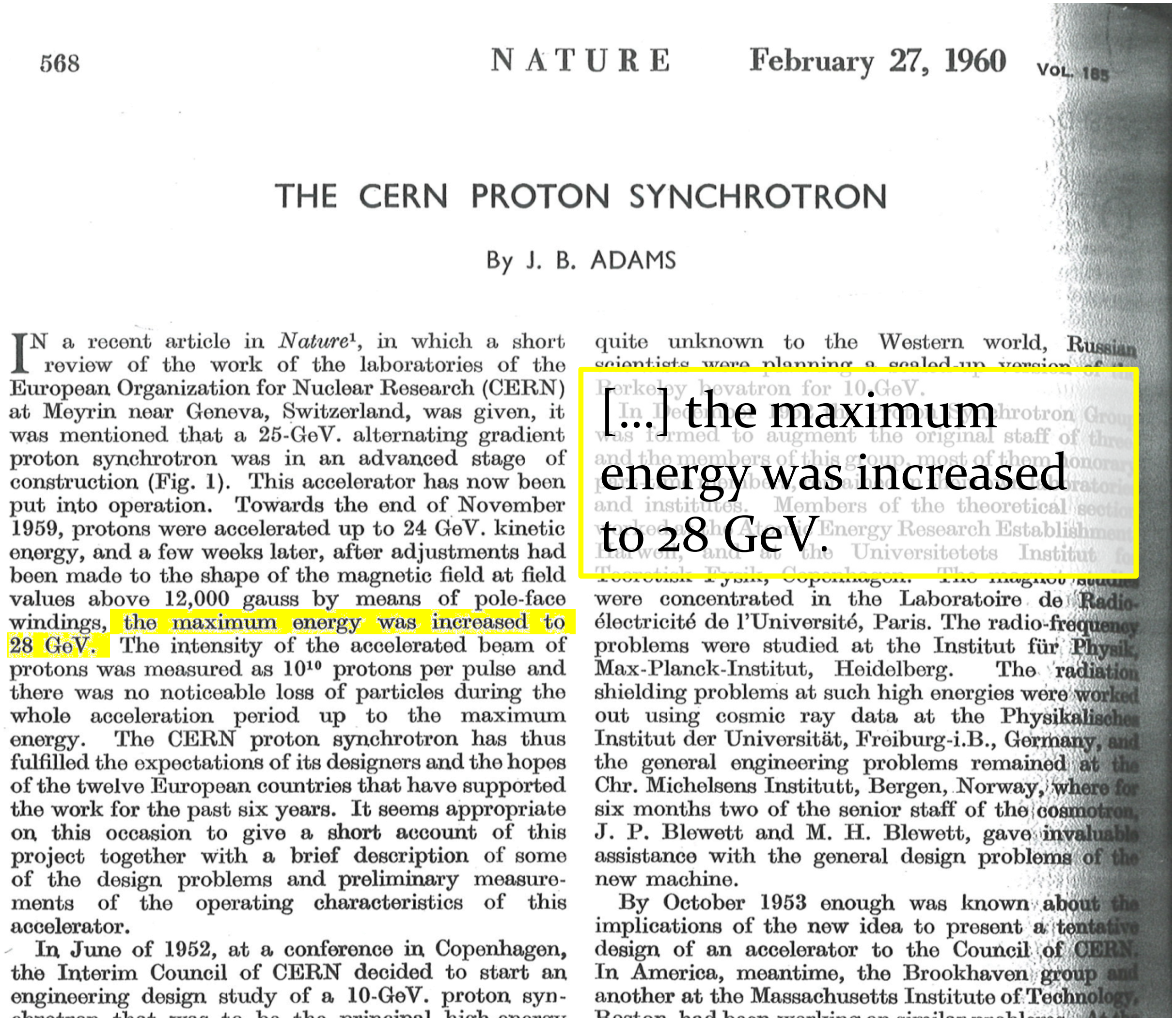
> **→ 200 MHz in LHC or 8b+4e scheme only beneficial with SPS RF upgrade**

Overview

- Introduction
- Alternative schemes in the Pre-injectors
  - Manipulation schemes in the PS
  - Additional improvements
  - Special cases for limited upgrades
- **Alternative schemes in the SPS**
  - RF power considerations
  - **Transverse improvements**
- Summary

Reducing space charge in the SPS

- Incr
  - →
  - →
  - →
- Spli
  Q_v =
  - →
  - →
- Irre
  vert
  - →



568 NATURE February 27, 1960 Vol. 185

THE CERN PROTON SYNCHROTRON

By J. B. ADAMS

IN a recent article in *Nature*[1], in which a short review of the work of the laboratories of the European Organization for Nuclear Research (CERN) at Meyrin near Geneva, Switzerland, was given, it was mentioned that a 25-GeV. alternating gradient proton synchrotron was in an advanced stage of construction (Fig. 1). This accelerator has now been put into operation. Towards the end of November 1959, protons were accelerated up to 24 GeV. kinetic energy, and a few weeks later, after adjustments had been made to the shape of the magnetic field at field values above 12,000 gauss by means of pole-face windings, the maximum energy was increased to 28 GeV. The intensity of the accelerated beam of protons was measured as 10^{10} protons per pulse and there was no noticeable loss of particles during the whole acceleration period up to the maximum energy. The CERN proton synchrotron has thus fulfilled the expectations of its designers and the hopes of the twelve European countries that have supported the work for the past six years. It seems appropriate on this occasion to give a short account of this project together with a brief description of some of the design problems and preliminary measurements of the operating characteristics of this accelerator.

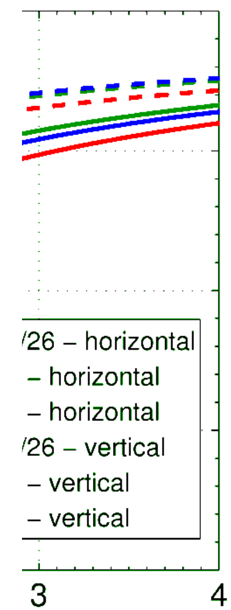
In June of 1952, at a conference in Copenhagen, the Interim Council of CERN decided to start an engineering design study of a 10-GeV. proton synchrotron that was to be the principal high-energy

quite unknown to the Western world, Russian scientists were planning a scaled-up version of the Berkeley bevatron for 10 GeV.

In December 1952, the Proton Synchrotron Group was formed to augment the original staff of three and the members of this group, most of them honorary [illegible] and institutes. Members of the theoretical section worked at the Atomic Energy Research Establishment, Harwell, and at the Universitetets Institut for Teoretisk Fysik, Copenhagen. The magnet studies were concentrated in the Laboratoire de Radio-électricité de l'Université, Paris. The radio-frequency problems were studied at the Institut für Physik, Max-Planck-Institut, Heidelberg. The radiation shielding problems at such high energies were worked out using cosmic ray data at the Physikalisches Institut der Universität, Freiburg-i.B., Germany, and the general engineering problems remained at the Chr. Michelsens Institutt, Bergen, Norway, where for six months two of the senior staff of the cosmotron, J. P. Blewett and M. H. Blewett, gave invaluable assistance with the general design problems of the new machine.

By October 1953 enough was known about the implications of the new idea to present a tentative design of an accelerator to the Council of CERN. In America, meantime, the Brookhaven group and another at the Massachusetts Institute of Technology, Boston, had been working on similar problems. At the

[...] the maximum energy was increased to 28 GeV.



→ Less possibilities and margin than in PS

Overview

- Introduction
- Alternative schemes in the Pre-injectors
  - Manipulation schemes in the PS
  - Additional improvements
  - Special cases for limited upgrades
- Alternative schemes in the SPS
  - RF power considerations
  - Transverse improvements
- **Summary**

Preliminary summary and remarks

- No magic alternative to Linac4 + 2.0 GeV + SPS RF upgrade
- Large number of schemes to increase intensity and brightness from injectors
  - → Linac4+PSB+PS may push SPS to space charge limit
- Longitudinally larger bunches in SPS possible together with RF upgrade
- Limited reach of brute-force approach for even more RF power

- Interesting alternatives can be studied in injectors after LS1
  - → PSB: Hollow bunches
  - → PS: Flat or hollow bunches, special flat-bottom optics, pure batch compression, 8b+4e schemes, higher PS-SPS transfer energy
  - → SPS: split tunes optics, higher intensity with slightly longer bunches

- Combinations of alternatives keep flexibility of injector complex to react to requests from LHC: short-, micro-, 8b+4e-batches

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN

PSB

Small upgrades beyond baseline:

- **Vertical painting at PSB injection from Linac4**
  - → **More flexibility in controlling transverse distribution**
- **Reduction of horizontal tune by one unit to increase dispersion**
- **Optimization of resonance compensation**
  - → **Potentially higher brightness (study will be pursued anyway)**

Discarded options:

- **Replacement of PSB magnets for energy above 2 GeV**
  - → **Present main magnets potentially useable up to ~2.2 GeV (M. Giovannozzi)** (http://indico.cern.ch/getFile.py/access?contribId=34&sessionId=7&resId=1&materialId=paper&confId=67839)
  - → **New magnets expensive and require excessive shutdown for installation**
- **Significantly fast cycling → Rapid cycling synchrotron (K. Hanke et al., 2011)** (https://edms.cern.ch/file/1154705/1.2/PBU-1154705-10-20.pdf)
  - → **Decision not to pursue PSB replacement by RCS**

PS

Discarded options:

- Direct H^--injection from SPL-like like prolongation of Linac4 into PS
  - → Requires down-graded SPL, transfer line and new injection system 40 MHz PS2-like acceleration system for LHC-type beams, but incompatible with other physics users (C. Carli, Chamonix 2010)
  - → (http://indico.cern.ch/getFile.py/access?contribId=36&sessionId=7&resId=2&materialId=paper&confId=67839)
- 20 ns bunch spacing from the PS (and possibly 10 ns)
  - → Interesting as RF frequencies in all machines become integer multiples
  - → Requires 50/100 MHz (h = 105/210) cavities for bunch rotation in PS
  - → Possible production scheme 8b/h9 → 16b/h18 → 32b/h36 → 32b/h35 → 96b/h105 requires even more RF system
  - → 40 ns bunch spacing practically impossible

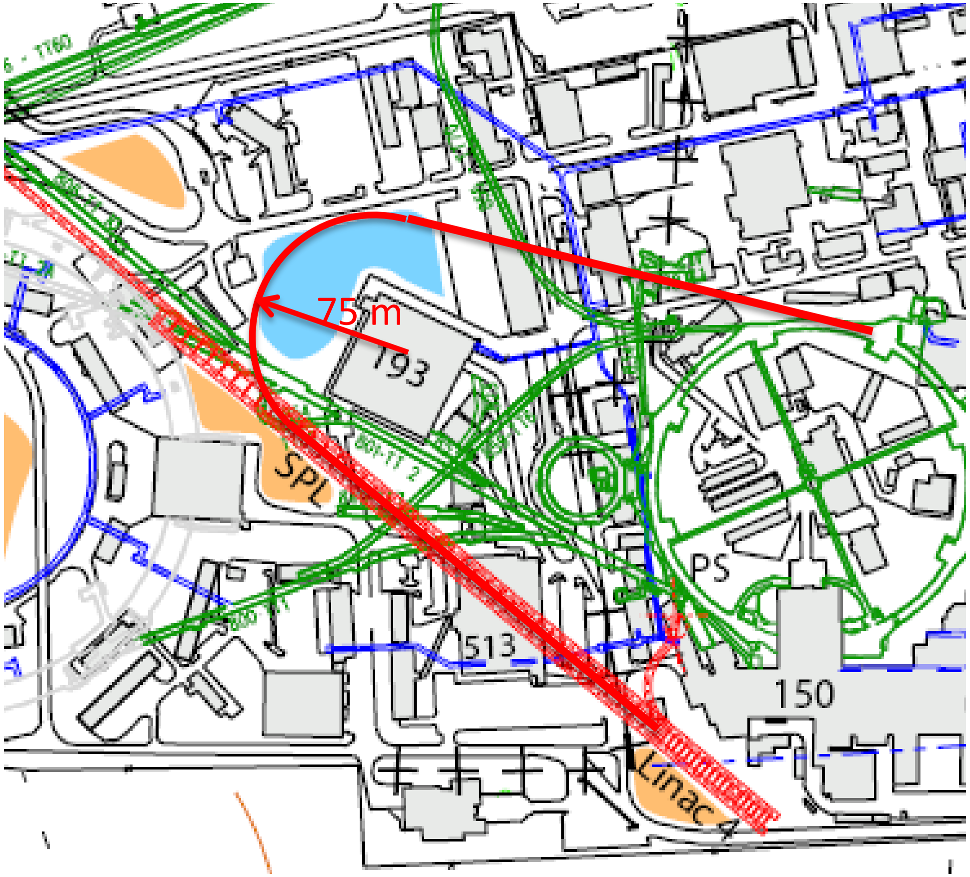
SPS

Discarded options:

- Slip-stacking in the SPS (T. Argyropoulos, E. Shaposhnikova, LIU brainstorming) (http://indico.cern.ch/getFile.py/access?contribId=16&sessionId=1&resId=1&materialId=slides&confId=138437)
  - → Many issues: beam loading, too large longitudinal emittance, etc.
- Low frequency cavities (e.g. 80 MHz, 120 MHz) in the SPS to capture longer bunches: less space charge, better stability in PS due to larger ε_l
  - → Introduces important beam stability issues in the SPS (E. Shaposhnikova) (http://paf-spsu.web.cern.ch/paf-spsu/meetings/2011/m14-04/Low_frequency_RF_Heiko.pptx)
- 400 MHz cavities for bunch compression and Landau damping in the SPS
  - → Originally foreseen for bunch compression (D. Boussard, Th. Bohl) (Part. Acc. 58, 1997, pp. 237-240 and SL/Note 93-47, http://cds.cern.ch/record/703346/files/CM-P00064463.pdf)
  - → Issues with beam loading would require non-integer harmonic number acceleration
- Bunch splitting on flat-top against e-cloud on flat-bottom; merging for higher intensity
  - → Empty buckets between bunches would require re-bucketing to lower harmonic RF system, which is excluded for stability reasons

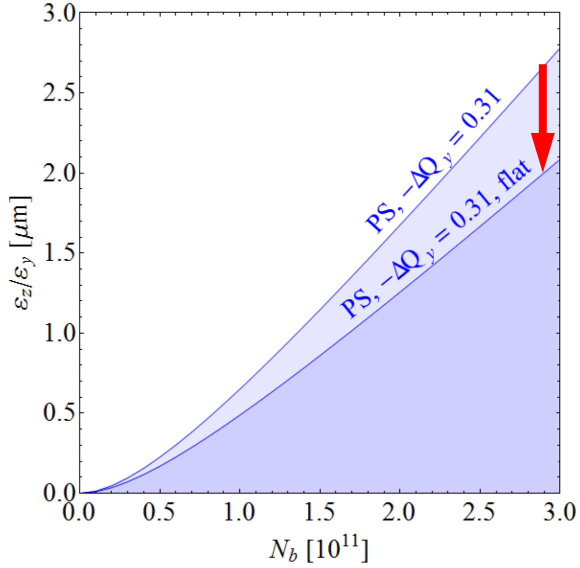
New PS Injector: SPL

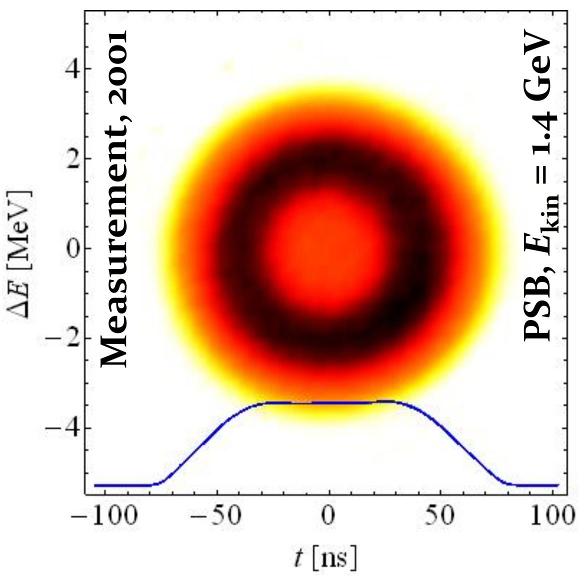
- Geometry (just to fix ideas) for 2.5 GeV:
  - Length of SPL ~300m (in addition to Linac4, extrap. from sLHC Proj. Rep. 0015)
  - ~500 m transfer line
- PS Injection
  - New H^- charge exchange injection to be constructed
  - Flexibility to generate suitable PS bunch structures (SPL chopper, painting?)
  - Close to East Hall ejection
- Simplified PS RF system with ~40MHz possible for LHC protons only (see PS2 scheme)



Space charge reduction, longitudinal

1. **Flat-bunches in double-harmonic RF system**
   - → Requires two RF systems
   - → Transfer between accelerators difficult
2. **Bunch distributions with depleted core, flat profile**
   - → Only single harmonic RF system needed
   - → Little complexity in downstream chain
   - → Even survives distribution conserving RF manipulations, e.g. pair splitting



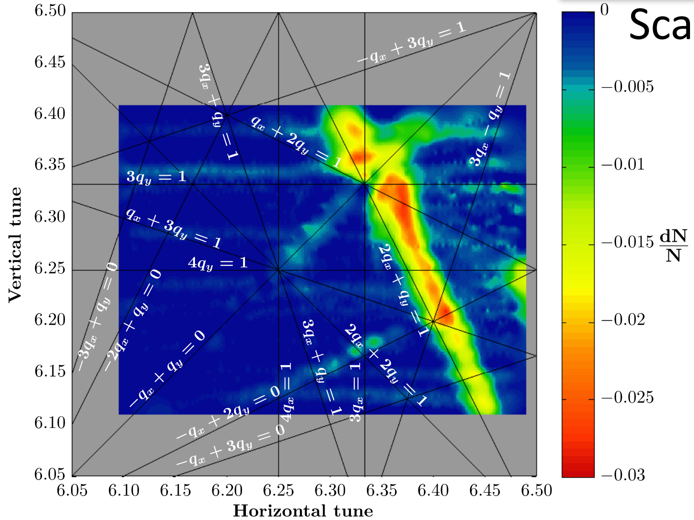


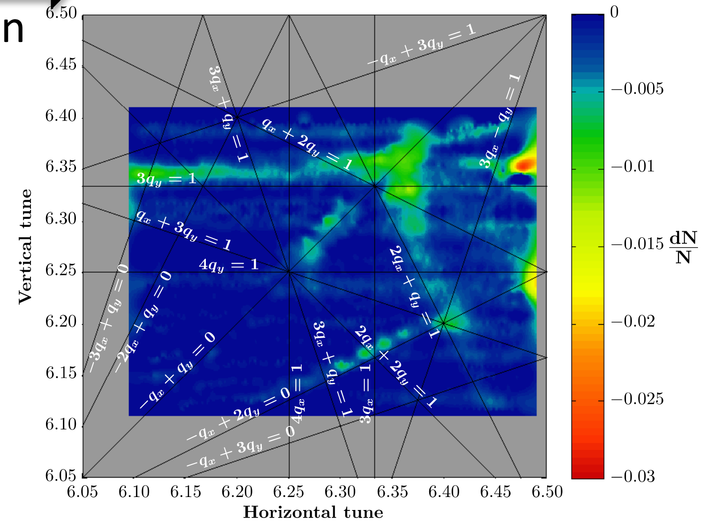
→ **Reduce ΔQ_{sc} at PS flat-bottom, potential brightness gain up to 25%**

→ **Last studies in 2001; simulations preparing new beam studies ongoing**

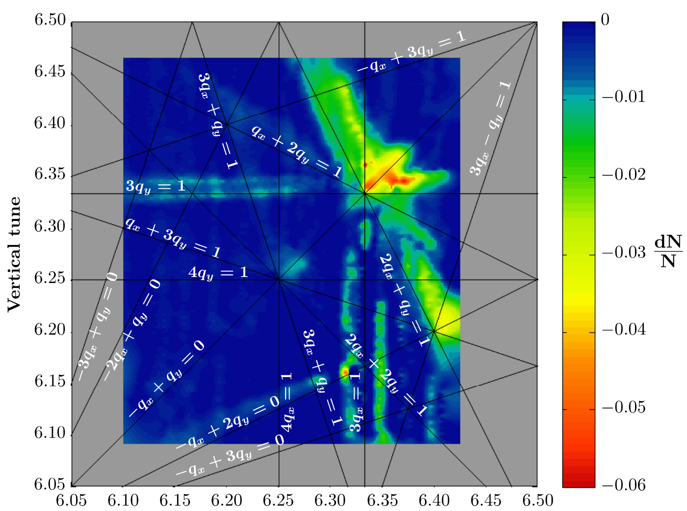
Compensation of the $2Q_x+Q_y = 19$ in the PS

Scan direction

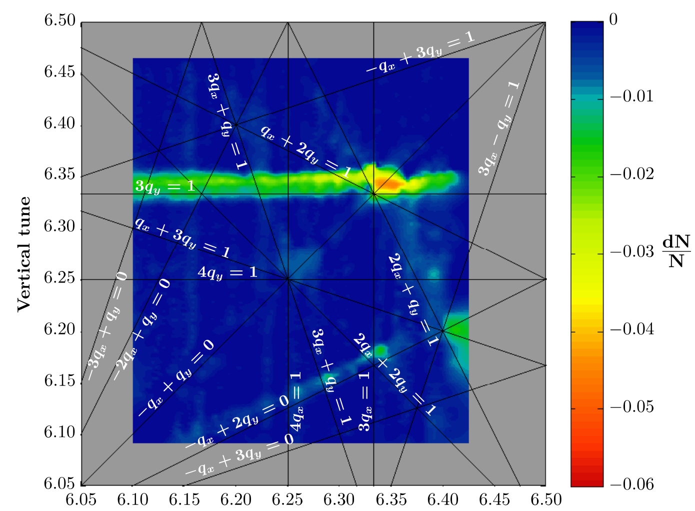




A. Huschauer, R. Wasef

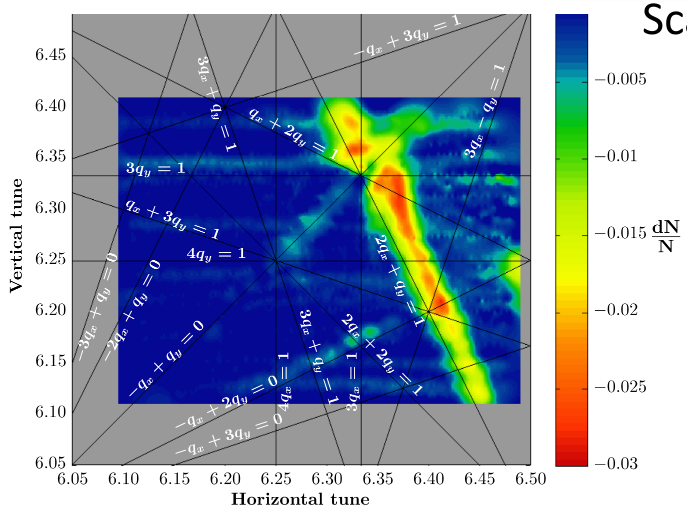


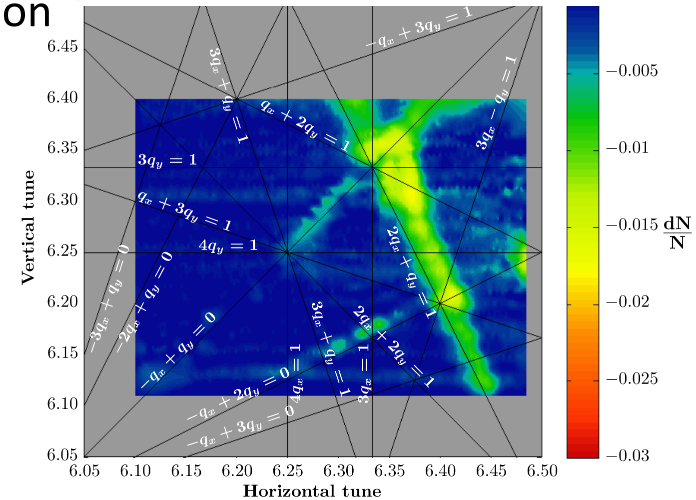
Scan direction

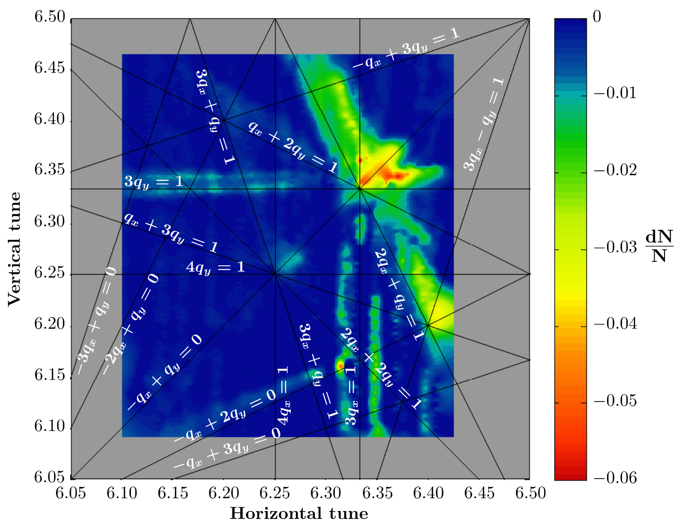


Compensation of $3Q_y = 19$ in the PS

Scan direction







Scan direction