LHC Injectors Upgrade

CERN

LHC Injectors Upgrade

Space charge in the LHC injector chain and LIU studies

Giovanni Rumolo, Hannes Bartosik

E. Benedetto, H. Damerau, A. Findlay, V. Forte, S. Gilardoni, S. Hancock, A. Huschauer, G. Iadarola, B. Mikulec, A. Molodozhentsev, Y. Papaphilippou, V. Raginel, F. Schmidt, R. Wasef

Outline

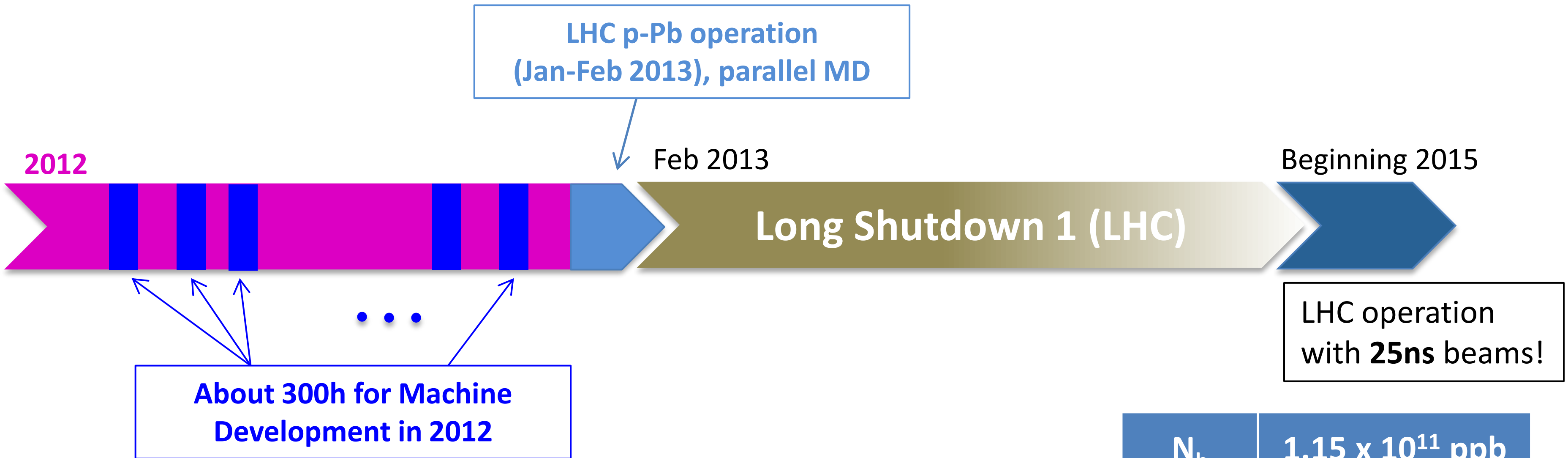
1. Space charge with present and future LHC beams in the PSB/PS/SPS

1. LIU studies on space charge
   - PSB performance, space charge @160 MeV
   - PS activities
   - High brightness beams in the SPS

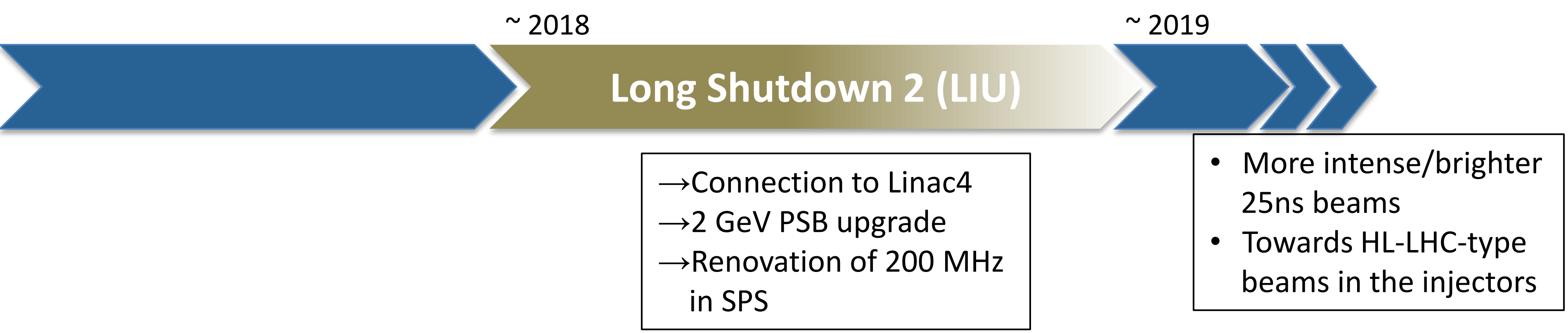
2. Summary and conclusions

LHC Injectors Upgrade

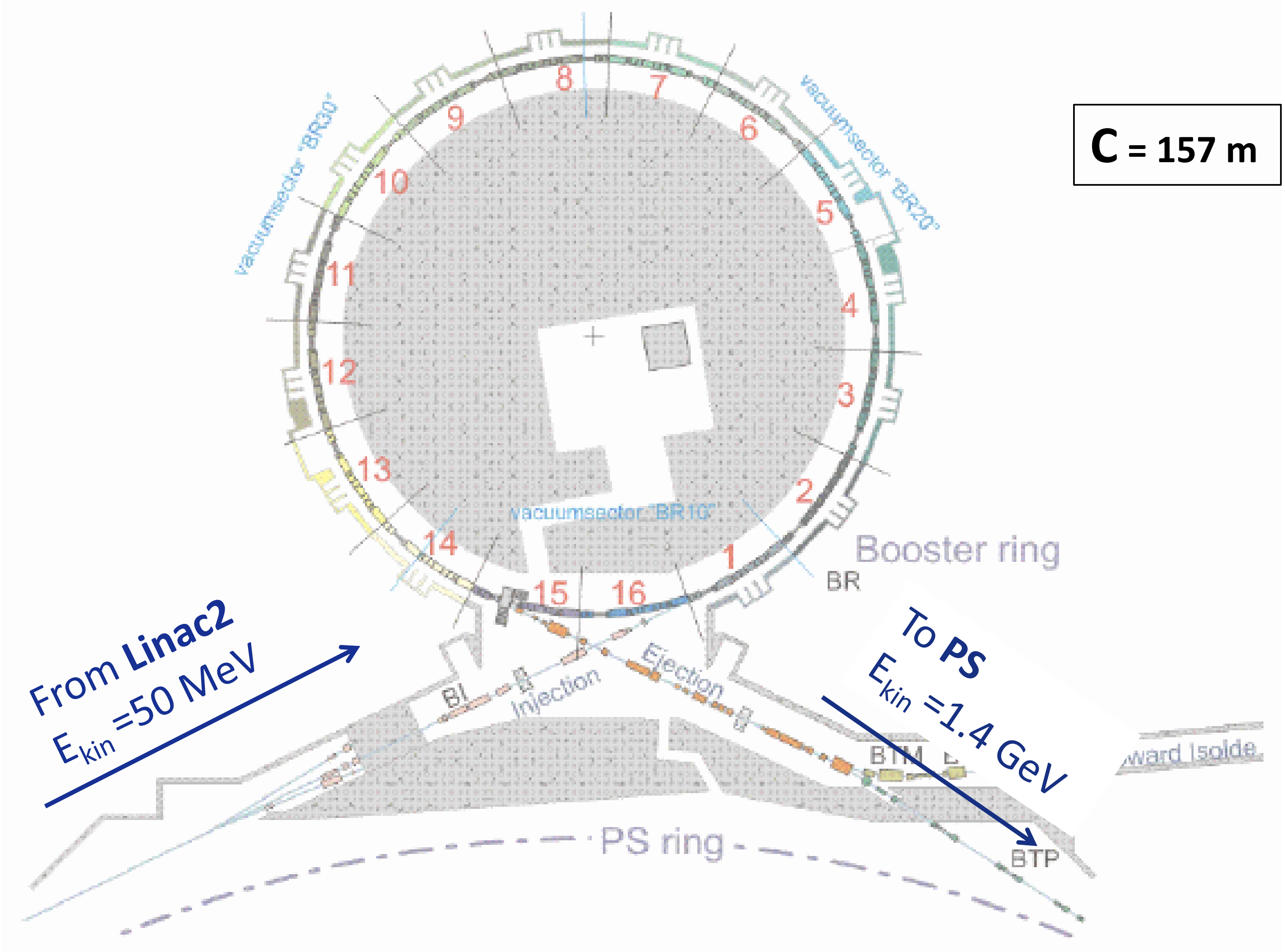
Rough timeline from 2012



N_b	1.15×10^{11} ppb
$\varepsilon_{x,y}$	2.8 (1.4) μm

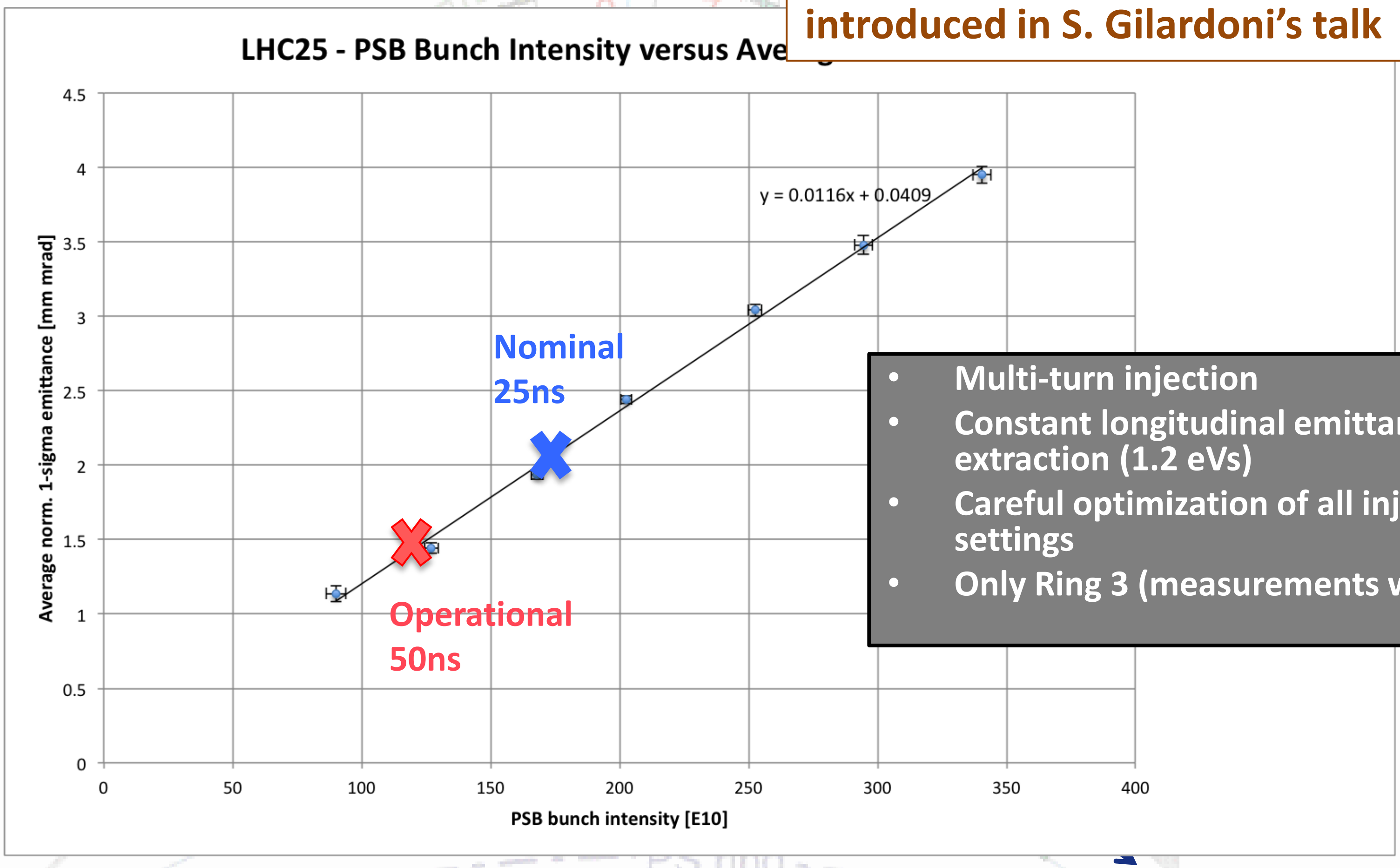


LHC beams through the four rings of the PSB
Present situation



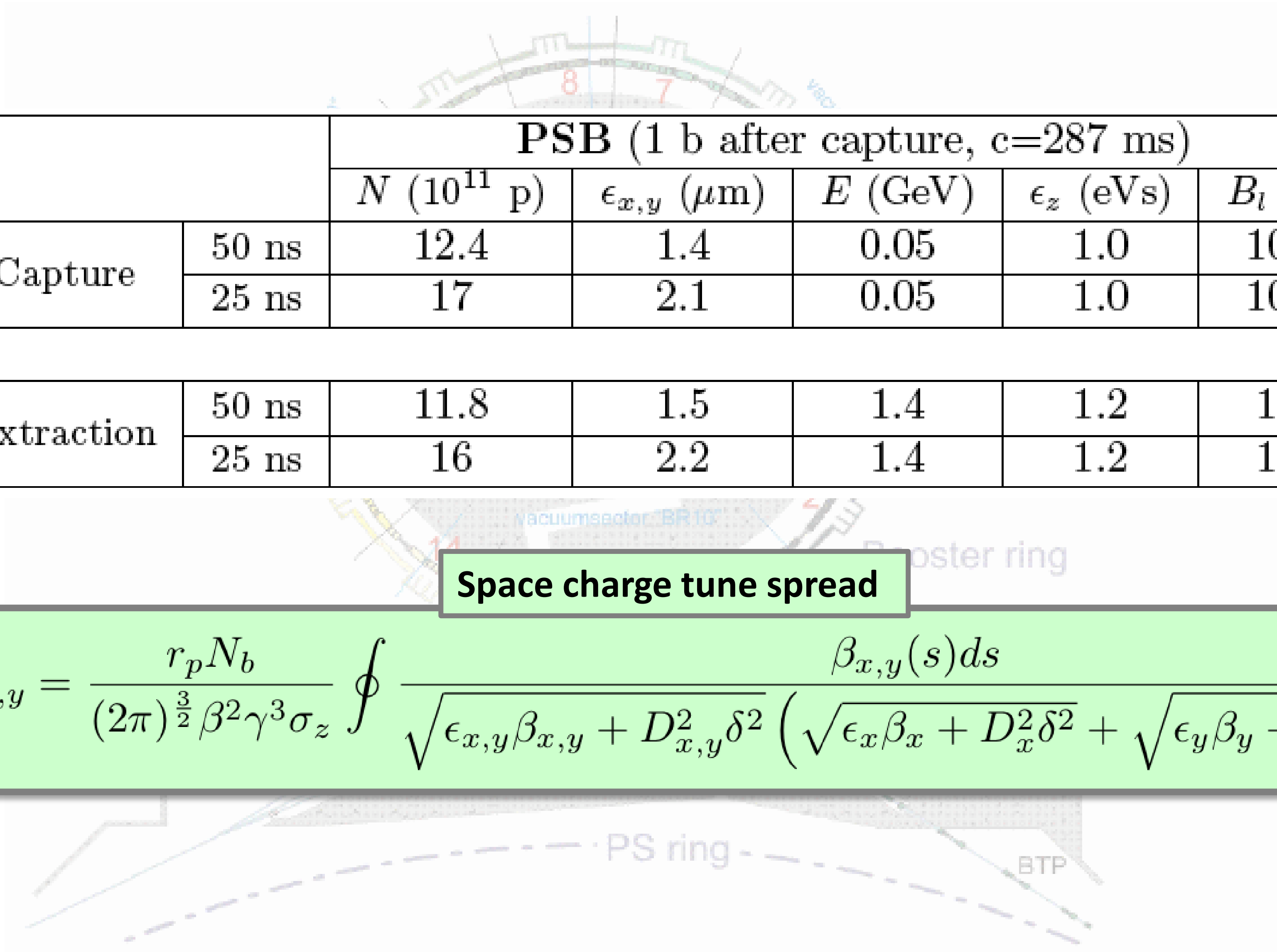
LHC beams at extraction of the PSB
Present performance (traditional production scheme)

N.B. Traditional (or standard) and BCMS production schemes introduced in S. Gilardoni's talk



- Multi-turn injection
- Constant longitudinal emittance at extraction (1.2 eVs)
- Careful optimization of all injecton settings
- Only Ring 3 (measurements with WS)

LHC beams in the PSB
Present performance (traditional production scheme)



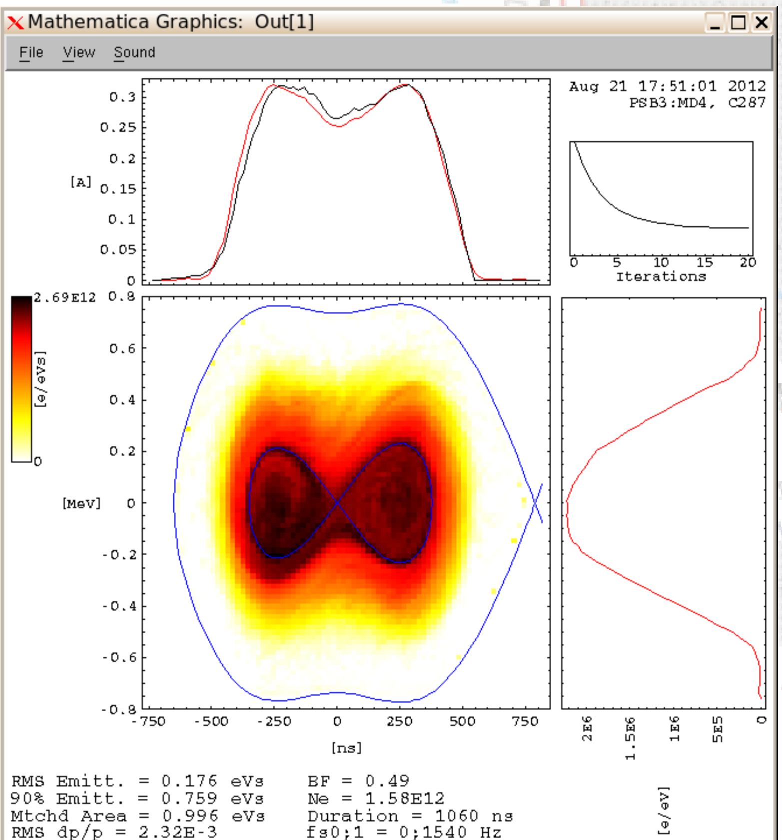
		PSB (1 b after capture, c=287 ms)				
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)
Capture	50 ns	12.4	1.4	0.05	1.0	1060
	25 ns	17	2.1	0.05	1.0	1060
Extraction	50 ns	11.8	1.5	1.4	1.2	180
	25 ns	16	2.2	1.4	1.2	180

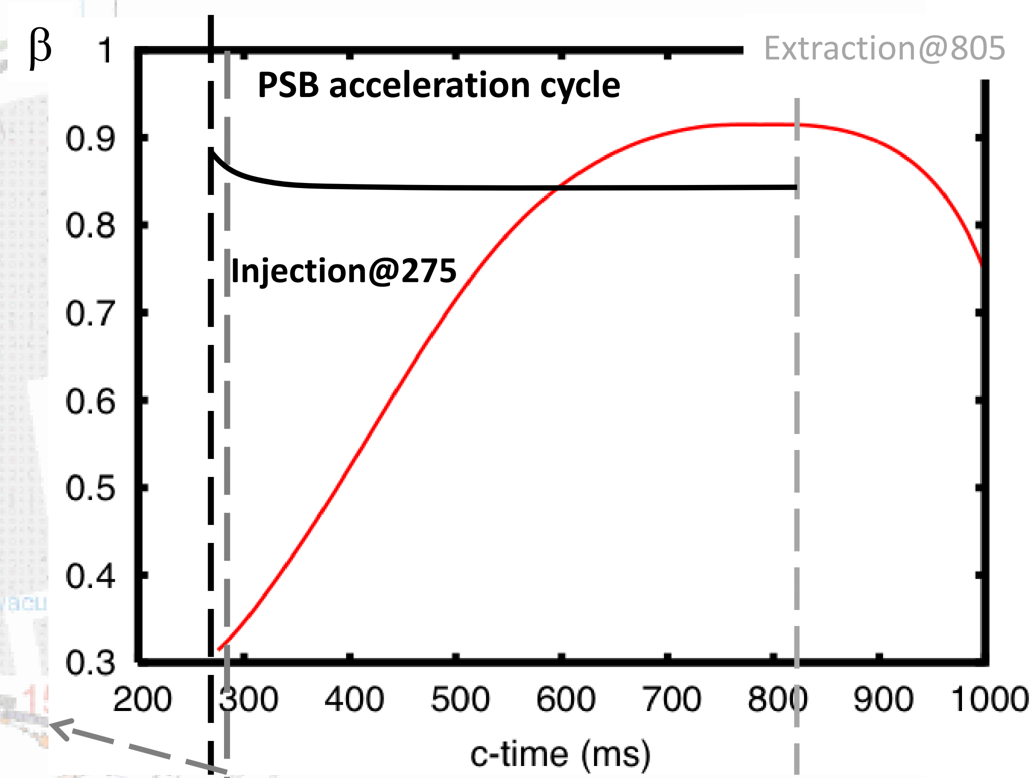
Space charge tune spread

$$\Delta Q_{x,y} = \frac{r_p N_b}{(2\pi)^{\frac{3}{2}} \beta^2 \gamma^3 \sigma_z} \oint \frac{\beta_{x,y}(s) ds}{\sqrt{\epsilon_{x,y}\beta_{x,y} + D_{x,y}^2 \delta^2} \left(\sqrt{\epsilon_x \beta_x + D_x^2 \delta^2} + \sqrt{\epsilon_y \beta_y + D_y^2 \delta^2} \right)}$$

LHC beams in the PSB
Space charge ΔQ (after capture)

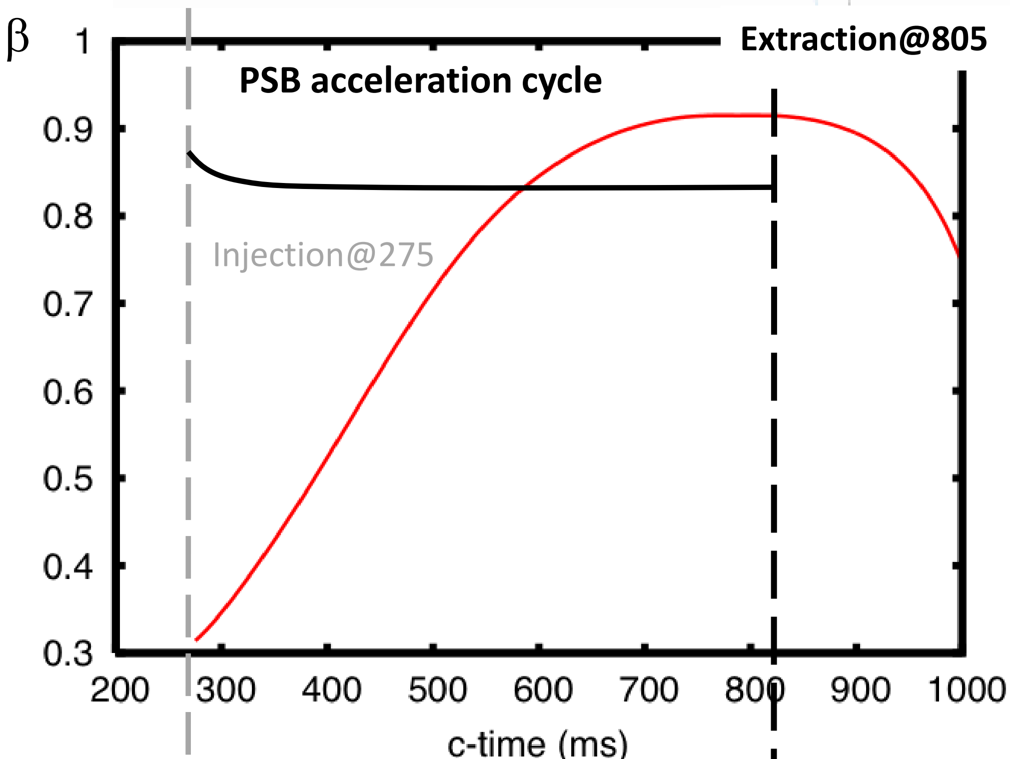
$$\Delta Q_x^{@\text{capture}} = -0.2$$
$$\Delta Q_y^{@\text{capture}} = -0.39$$



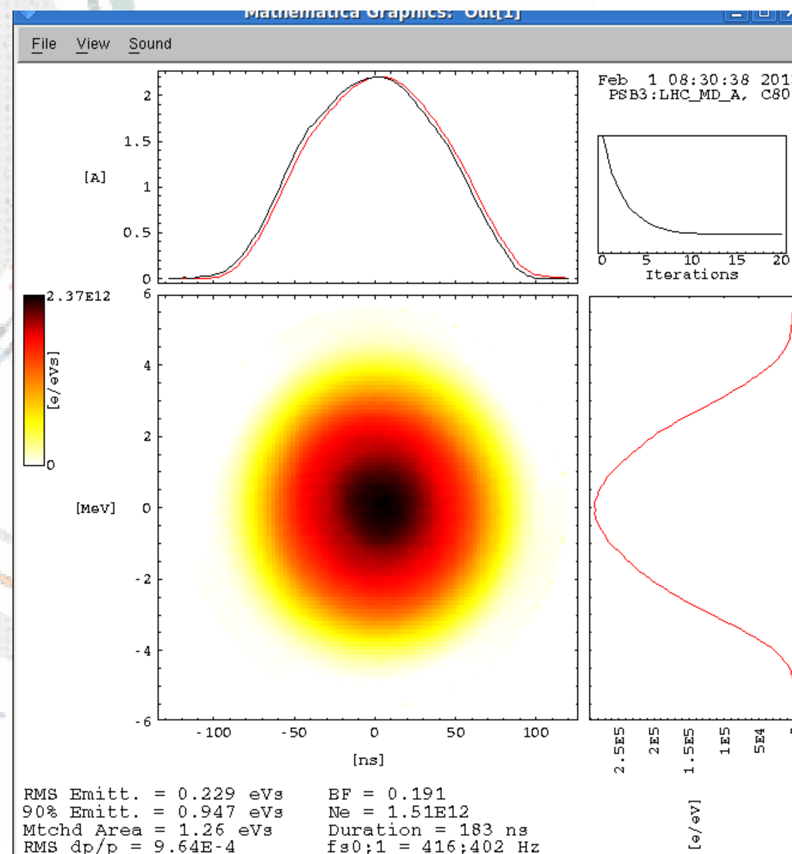


- Space charge eased at low energy thanks to the double harmonic and flattened bunch profile
- No plateau at injection energy alleviates space charge effects due to rapid acceleration

LHC beams in the PSB
Space charge ΔQ (before extraction)

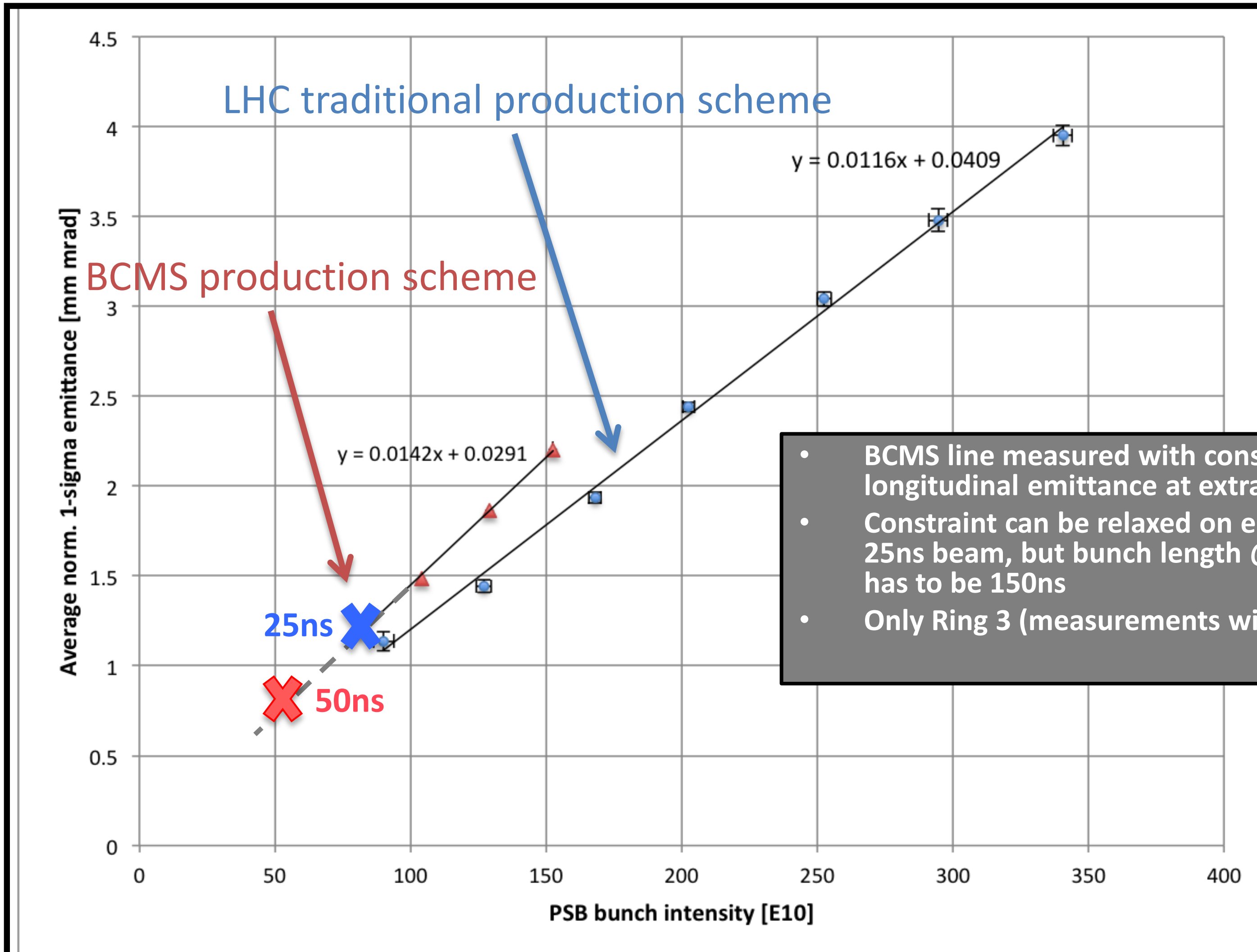


$$\Delta Q_x^{@extraction} = -0.04$$
$$\Delta Q_y^{@extraction} = -0.12$$



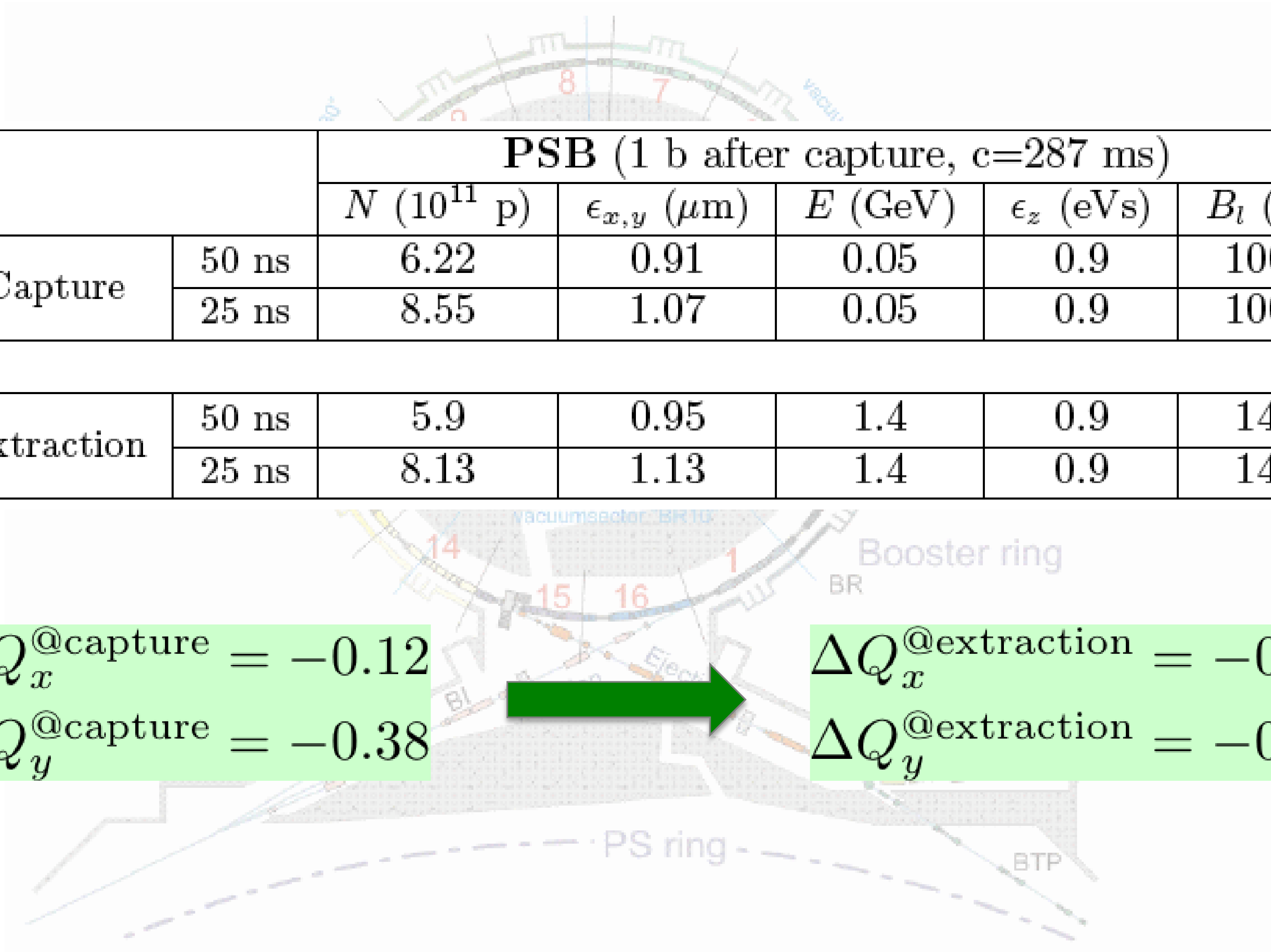
- Tune spreads about 3-5x lower (from $\beta\gamma^2$, bunch length and longitudinal distribution)
- Six of these bunches are then sent to the PS over two successive injections (4 + 2)

LHC beams at extraction of the PSB
Present performance (BCMS production scheme)



- BCMS line measured with constant longitudinal emittance at extraction (0.9 eVs)
- Constraint can be relaxed on emittances for 25ns beam, but bunch length @extraction has to be 150ns
- Only Ring 3 (measurements with WS)

LHC beams in the PSB
Present performance (BCMS production scheme)



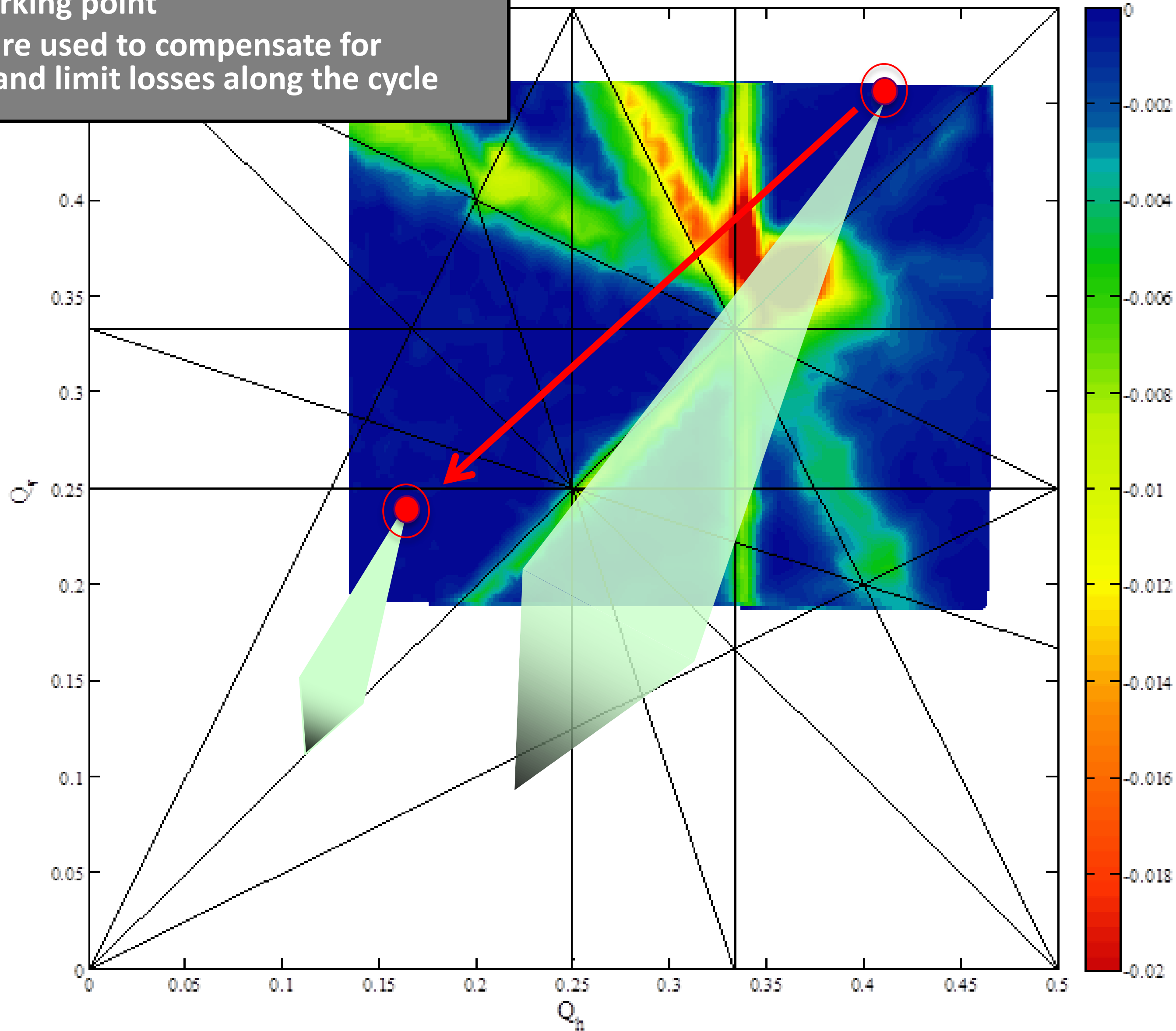
		PSB (1 b after capture, c=287 ms)				
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)
Capture	50 ns	6.22	0.91	0.05	0.9	1000
	25 ns	8.55	1.07	0.05	0.9	1000
Extraction	50 ns	5.9	0.95	1.4	0.9	140
	25 ns	8.13	1.13	1.4	0.9	140

$$\Delta Q_x^{@capture} = -0.12$$
$$\Delta Q_y^{@capture} = -0.38$$

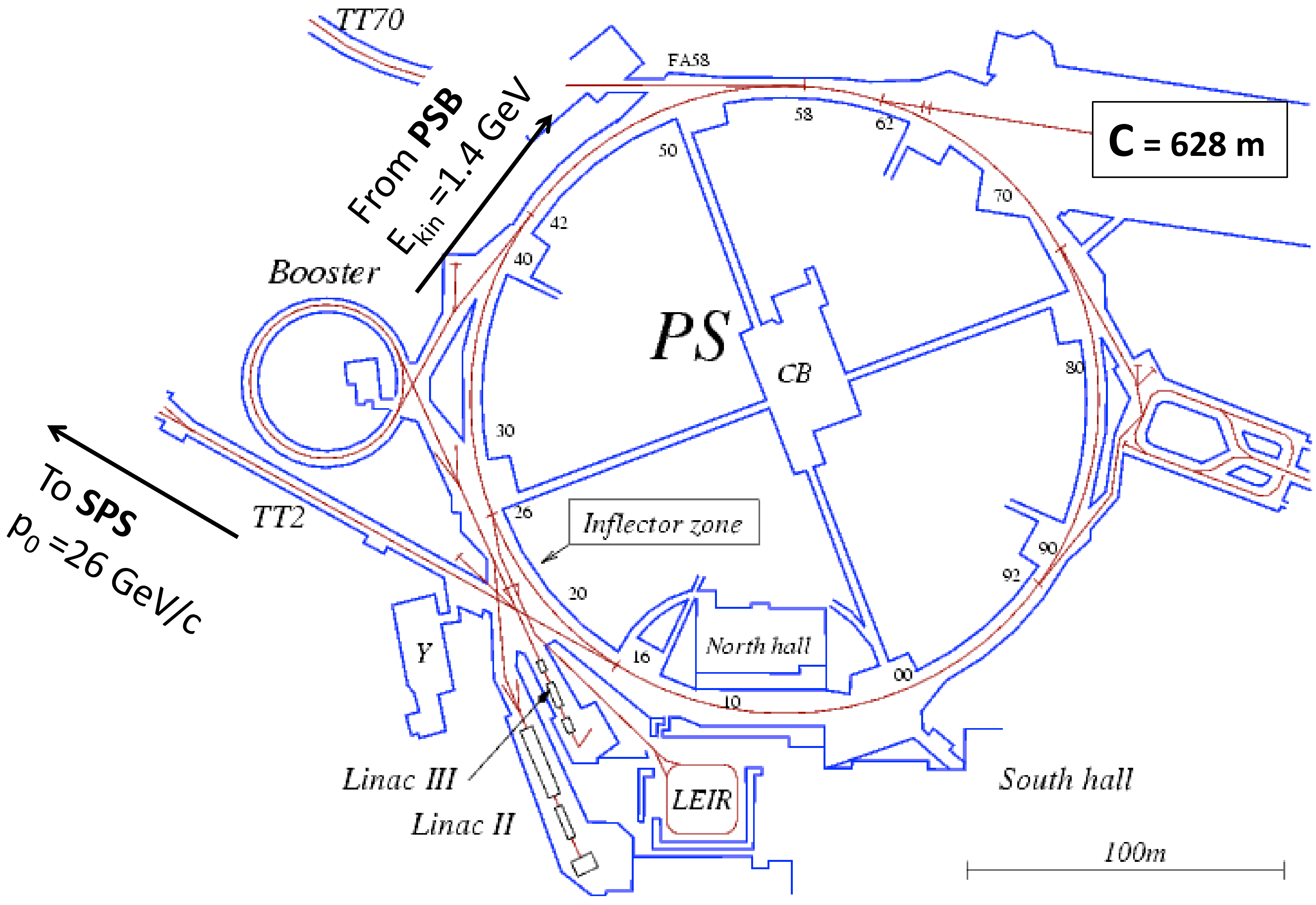
$$\Delta Q_x^{@extraction} = -0.05$$
$$\Delta Q_y^{@extraction} = -0.15$$

Evolution of the tune spread over the PSB cycle

- Dynamic working point
- Multipoles are used to compensate for resonances and limit losses along the cycle



LHC beams through the PS
Present situation



LHC beams in the PS
Present performance (traditional production scheme)

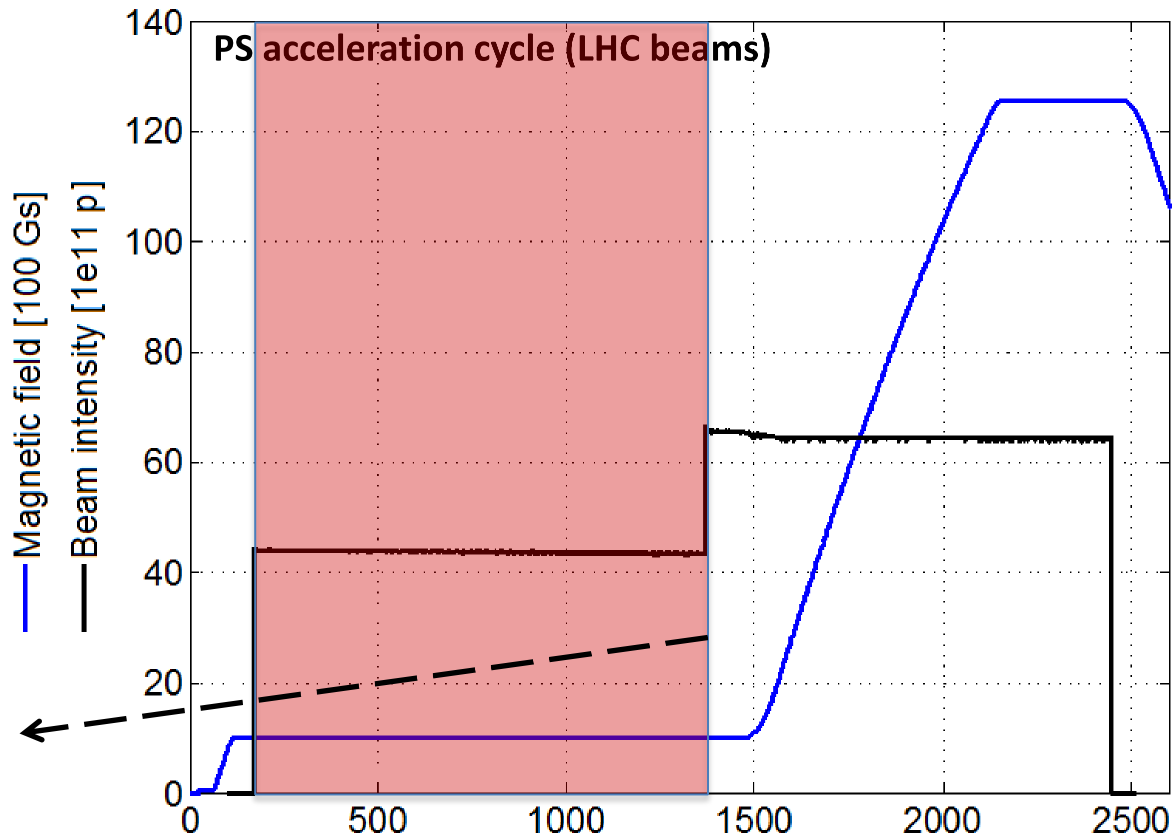
		PS (4 + 2) bunches/injection				
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)
Injection	50 ns	11.8	1.5	1.4	1.2	180
	25 ns	16	2.2	1.4	1.2	180
		(36 – 72 bunches/extraction)				
Extraction	50 ns	1.9	1.6	25	0.35	4
	25 ns	1.3	2.3	25	0.35	4

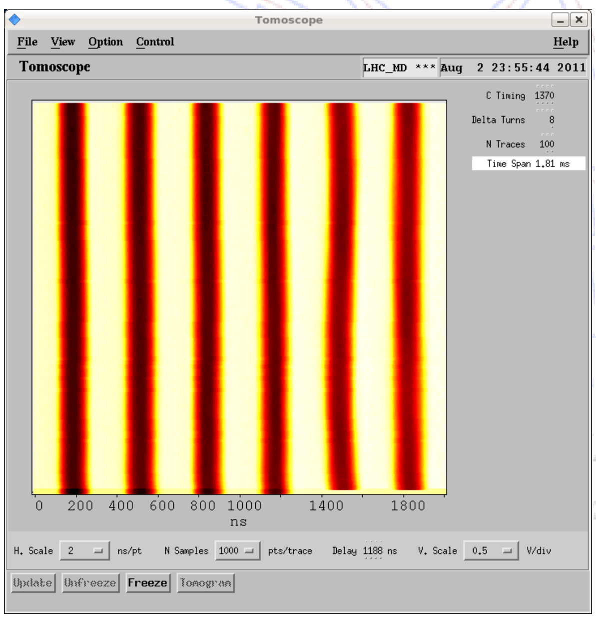
- Six PSB bunches captured (matched) in h=7 over two successive injections
- 50ns beam about twice brighter at extraction, because it undergoes one less double splitting in the PS

LHC beams in the PS
Space charge ΔQ at injection

$$\Delta Q_x^{@injection} = -0.19$$

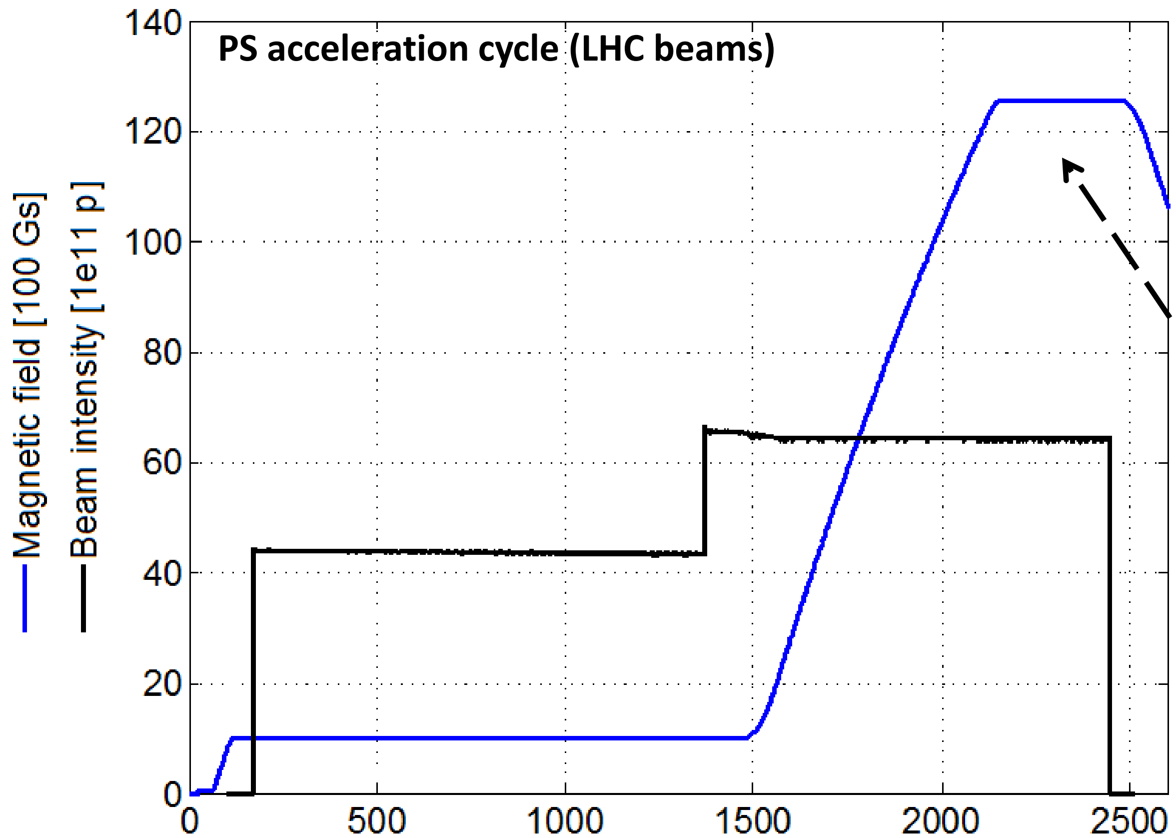
$$\Delta Q_y^{@injection} = -0.28$$



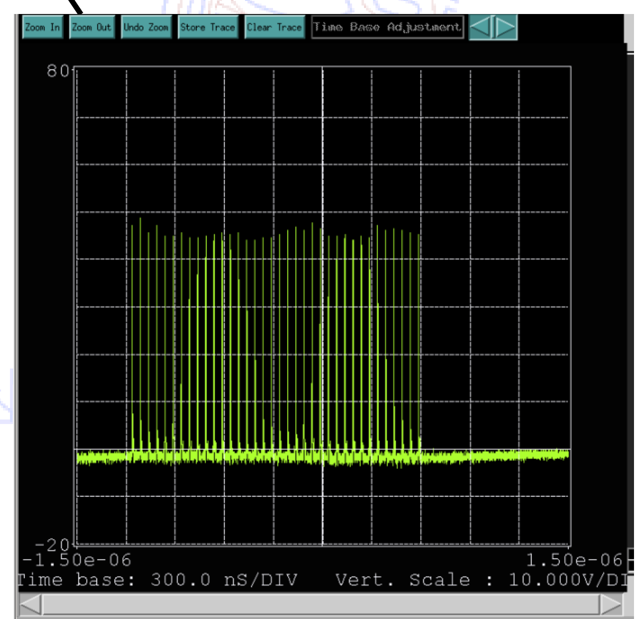


- First train of four bunches from the PSB sits for 1.2 s waiting for the second train
- After second injection, there is the triple splitting and acceleration (mitigated space charge)

LHC beams in the PS
Space charge ΔQ at extraction



$$\Delta Q_x^{@\text{extraction}} = -0.0021$$
$$\Delta Q_y^{@\text{extraction}} = -0.0076$$



- Acceleration, diluted longitudinal emittances strongly reduce space charge along the cycle
- Before extraction there is a fast bunch rotation to fit the bunches into the 5 ns buckets of the SPS

LHC beams in the PS
Present performance (BCMS production scheme)

		PS (2 × 4 bunches/injection)				
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)
Injection1	50 ns	5.9	0.95	1.4	0.9	140
	25 ns	8.13	1.13	1.4	0.9	140
		(24 – 48 bunches/extraction)				
Extraction	50 ns	1.9	1.0	26	0.35	4
	25 ns	1.3	1.2	26	0.35	4

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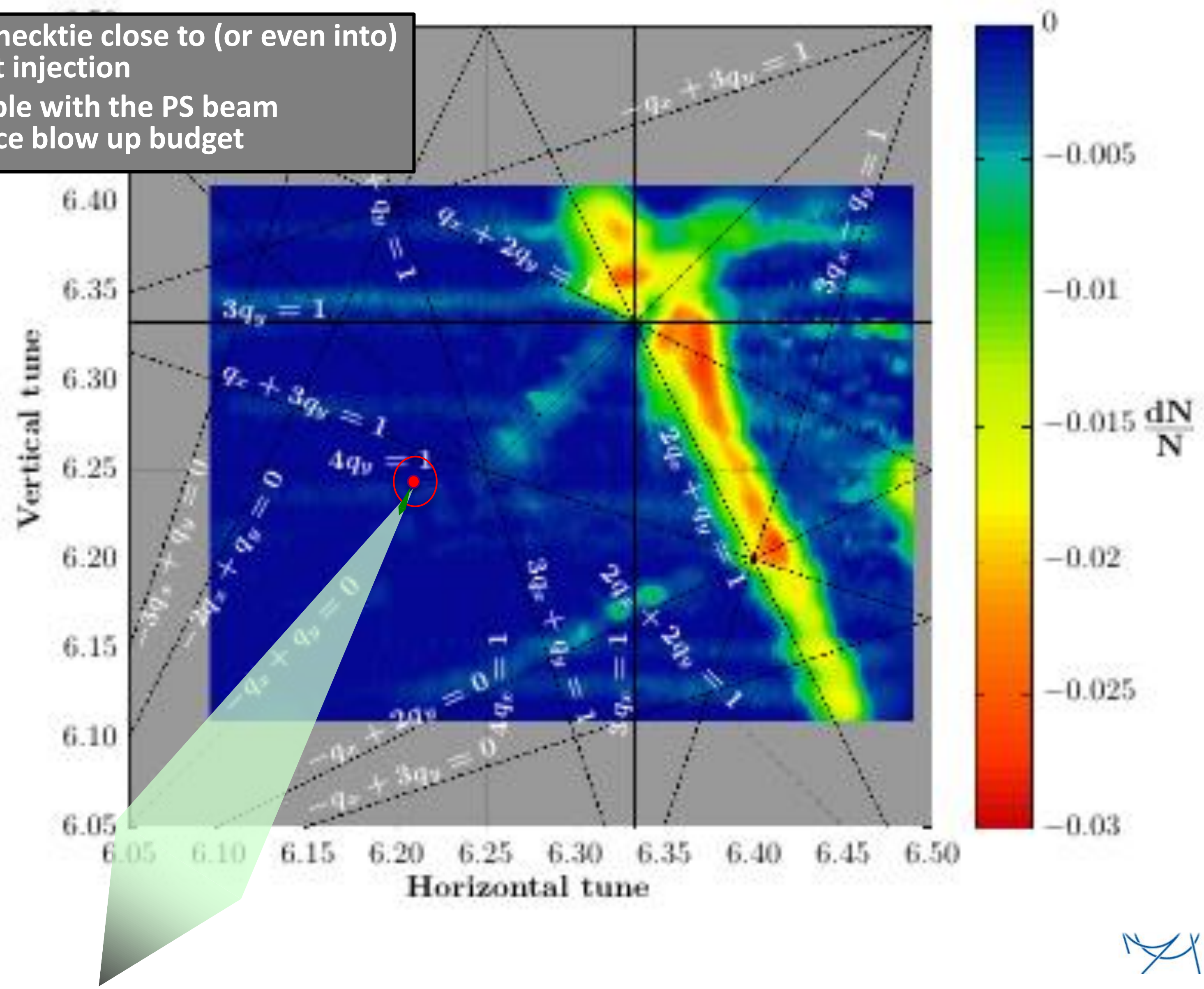
$$\Delta Q_x^{@injection} = -0.2$$
$$\Delta Q_y^{@injection} = -0.3$$

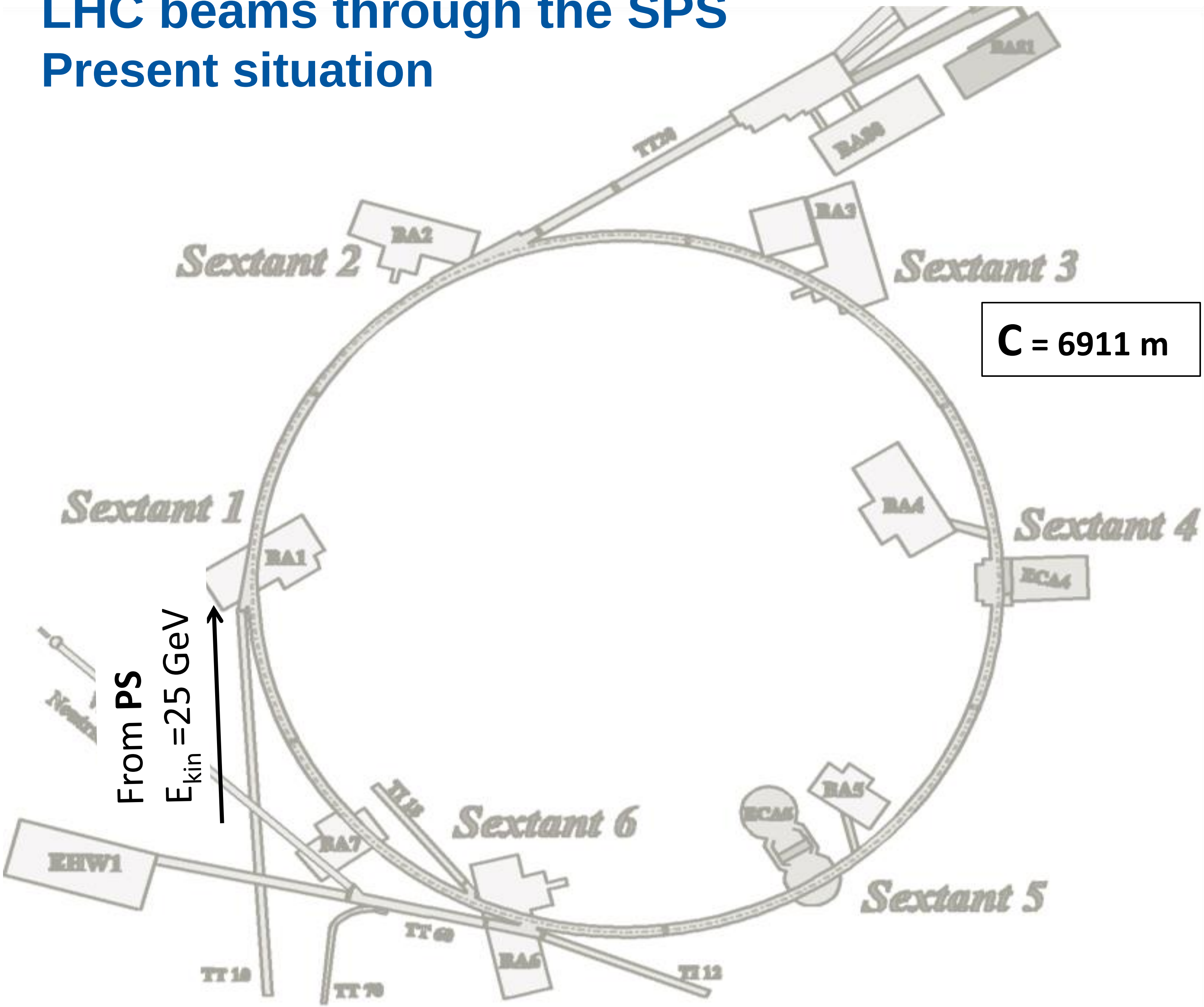
$$\Delta Q_x^{@extraction} = -0.002$$
$$\Delta Q_y^{@extraction} = -0.01$$

Tune spread at the PS injection

- Tune spread necktie close to (or even into) the integer at injection
- Still compatible with the PS beam loss/emittance blow up budget



LHC beams through the SPS
Present situation



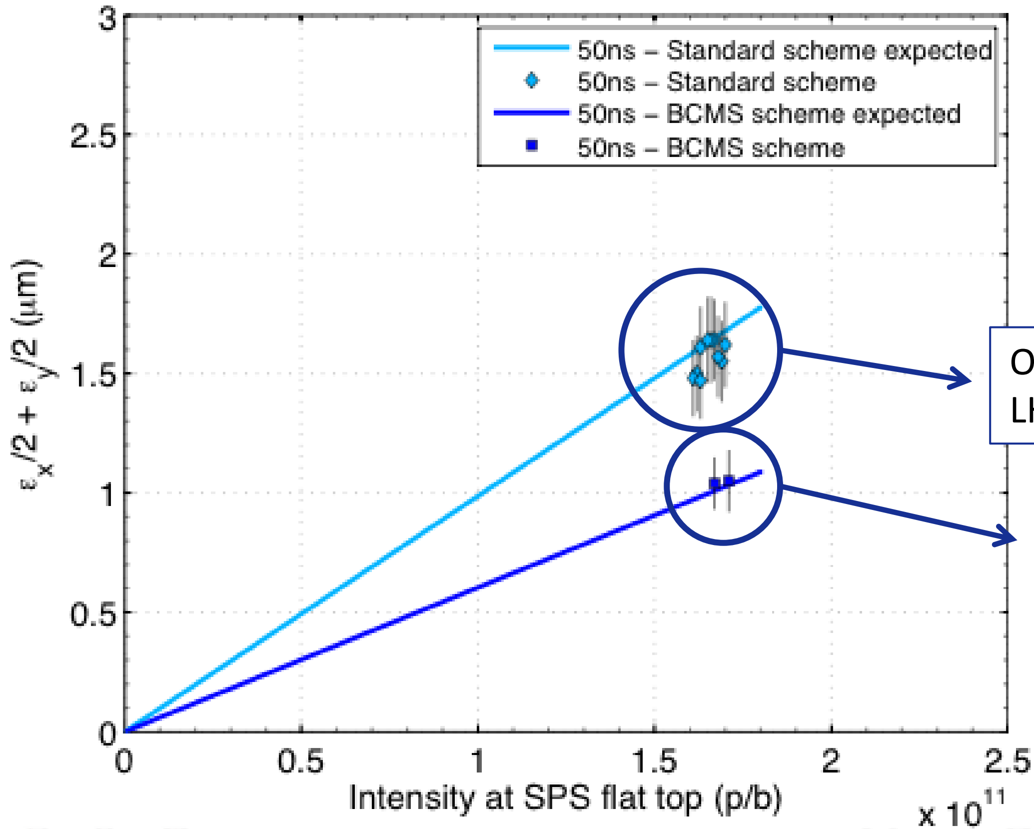
LHC beams in the SPS
Present performance

Traditional production scheme		SPS ($4 \times 36 - 72$ bunches/injection)				
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	p_0 (GeV/c)	ϵ_z (eVs/b)	B_l (ns)
Flat Bottom	50 ns	1.9	1.6	26	0.42	3
	25 ns	1.3	2.3	26	0.42	3
Extraction	50 ns	1.7	1.7	450	0.5	1.65
	25 ns	1.2	2.5	450	0.45	1.55

BCMS production scheme		SPS ($4 \times 24 - 48$ bunches/injection)				
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	p_0 (GeV/c)	ϵ_z (eVs/b)	B_l (ns)
Flat Bottom	50 ns	1.9	1.0	26	0.42	3
	25 ns	1.3	1.2	26	0.42	3
Extraction	50 ns	1.7	1.1	450	0.5	1.65
	25 ns	1.15	1.3	450	0.45	1.55

- **Bunches are injected into mismatched voltage (3 MV), which shortens them at FB**
- **Successful acceleration of higher intensity 25 ns beams is still hampered by instabilities (longitudinal, e-cloud?) and limited by the RF power**

LHC beams in the SPS
Present performance (50 ns beams)

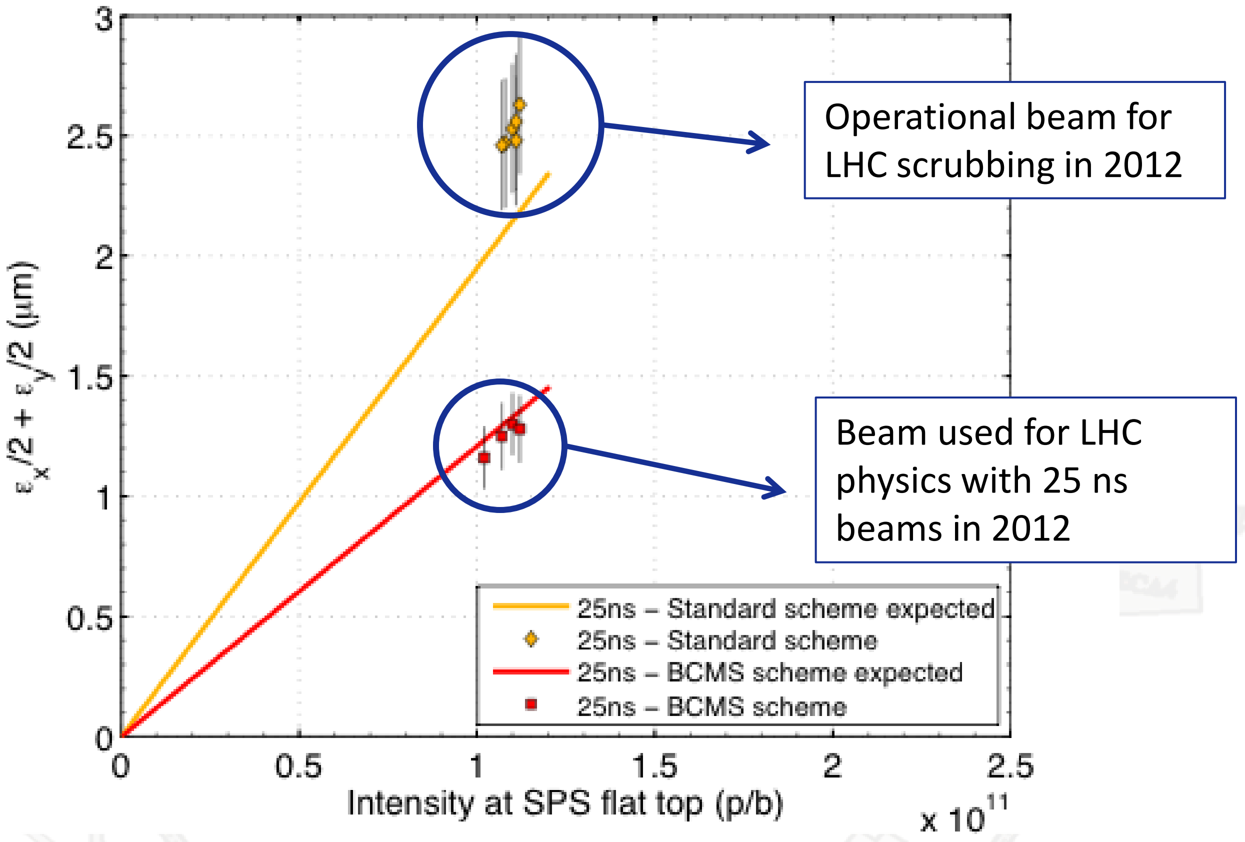


Operational beam for LHC physics in 2012

MD beam sent to LHC only once in 2012

- Expected lines derived from the brightness curve of the PSB translated into SPS flat top values (with emittance and loss budgets in the PS – 5% – and in the SPS – 10%)

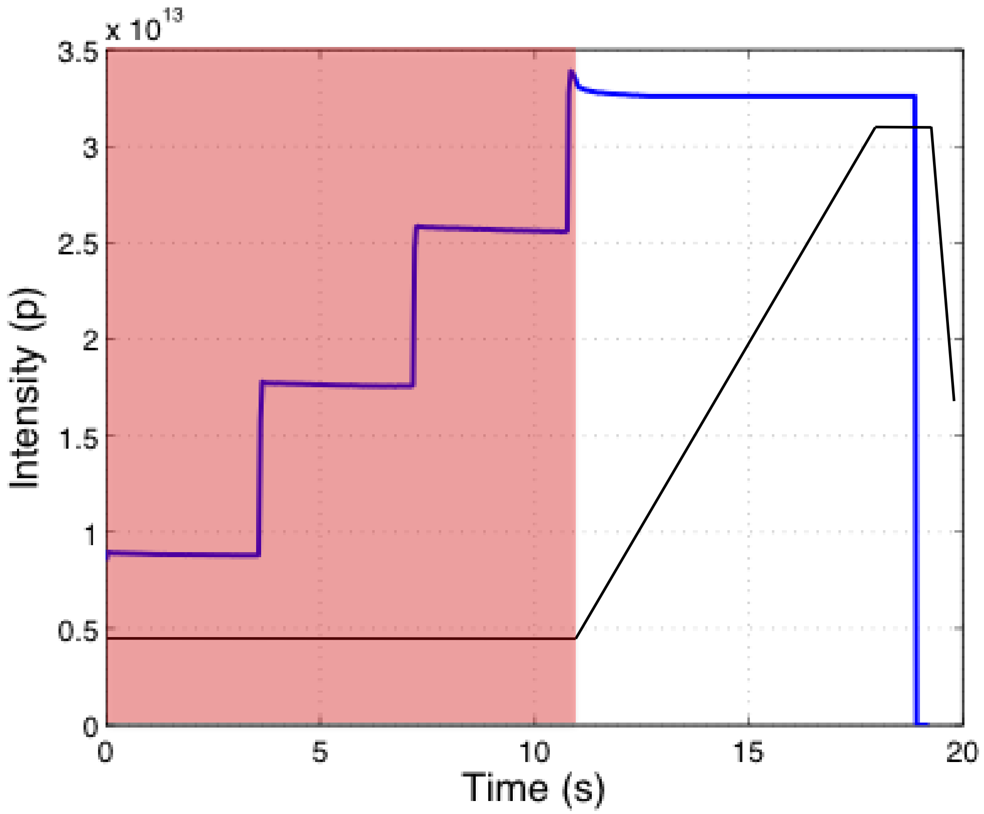
LHC beams in the SPS
Present performance (25 ns beams)



- Expected lines derived from the brightness curve of the PSB translated into SPS flat top values (with emittance and loss budgets in the PS – 5% – and in the SPS – 10%)
- The traditional 25 ns beam exhibits extra losses and/or emittance growth (slow losses at the SPS FB? electron cloud in the PS?)

LHC beams in the SPS
Space charge ΔQ on the injection plateau

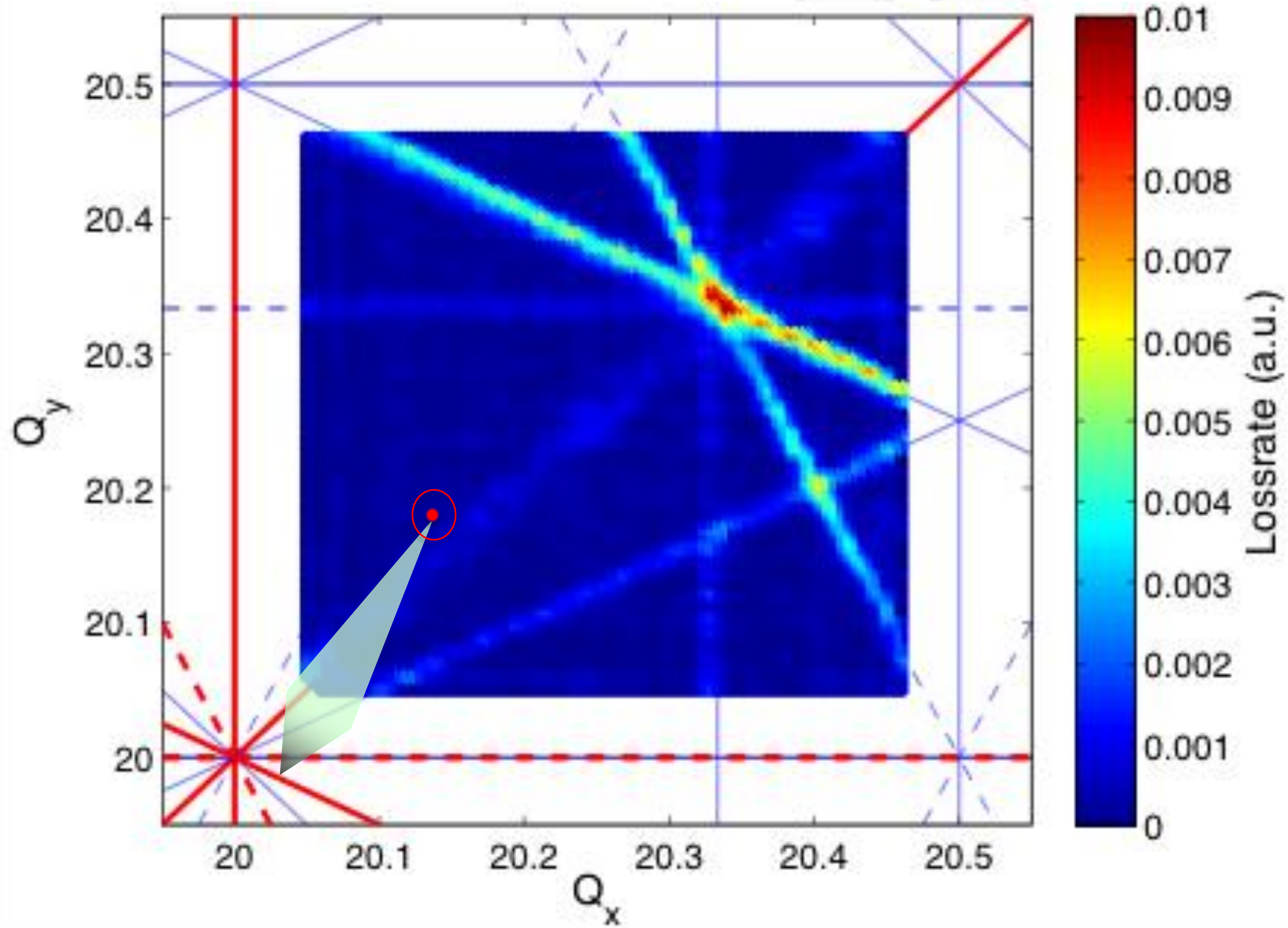
$$\Delta Q_x^{@\mathrm{FB,trad}} = -0.07$$
$$\Delta Q_y^{@\mathrm{FB,trad}} = -0.14$$



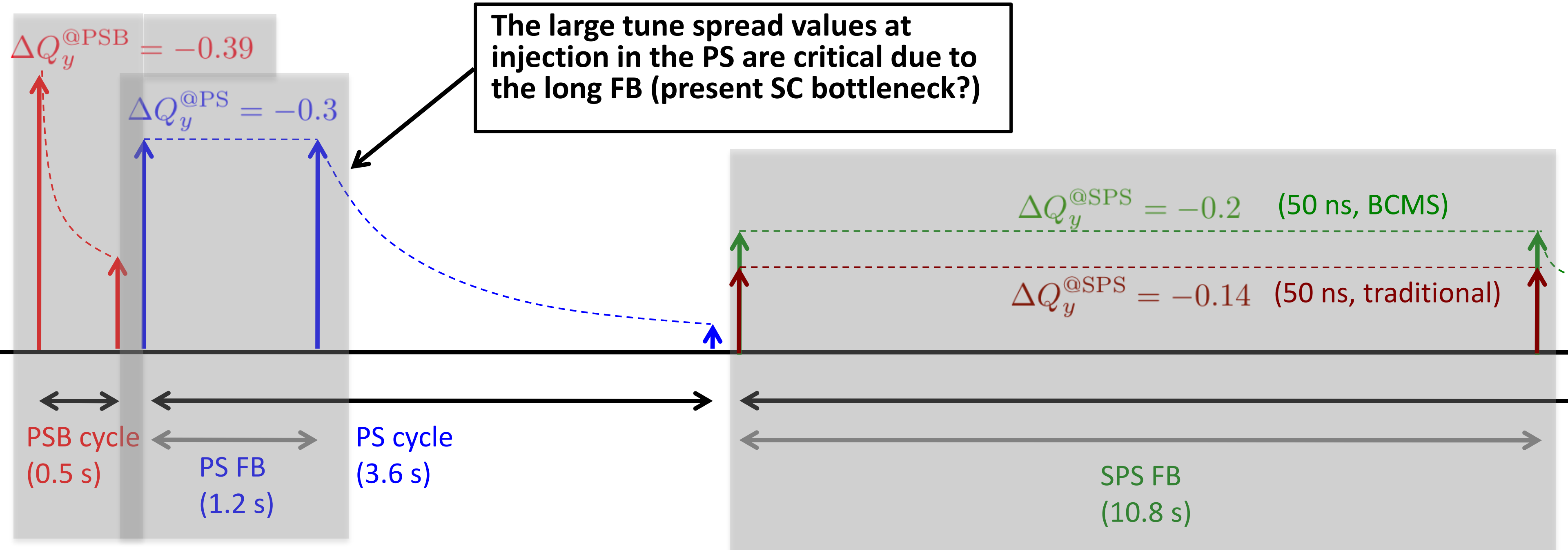
$$\Delta Q_x^{@\mathrm{FB,BCMS}} = -0.1$$
$$\Delta Q_y^{@\mathrm{FB,BCMS}} = -0.2$$

- Quoted tune spreads refer to 50 ns beams, which are twice brighter than 25 ns.
- First trains of 36 (24) or 72 (48) bunches from the PS sit for several seconds at injection energy

Tune spread at the SPS injection



Present LHC beams – a schematic overview
Evolution of space charge ΔQ_y across the injector chain



Large tune spreads at PSB injection can be handled thanks to efficient resonance compensation, dynamic working point and rapid cycling

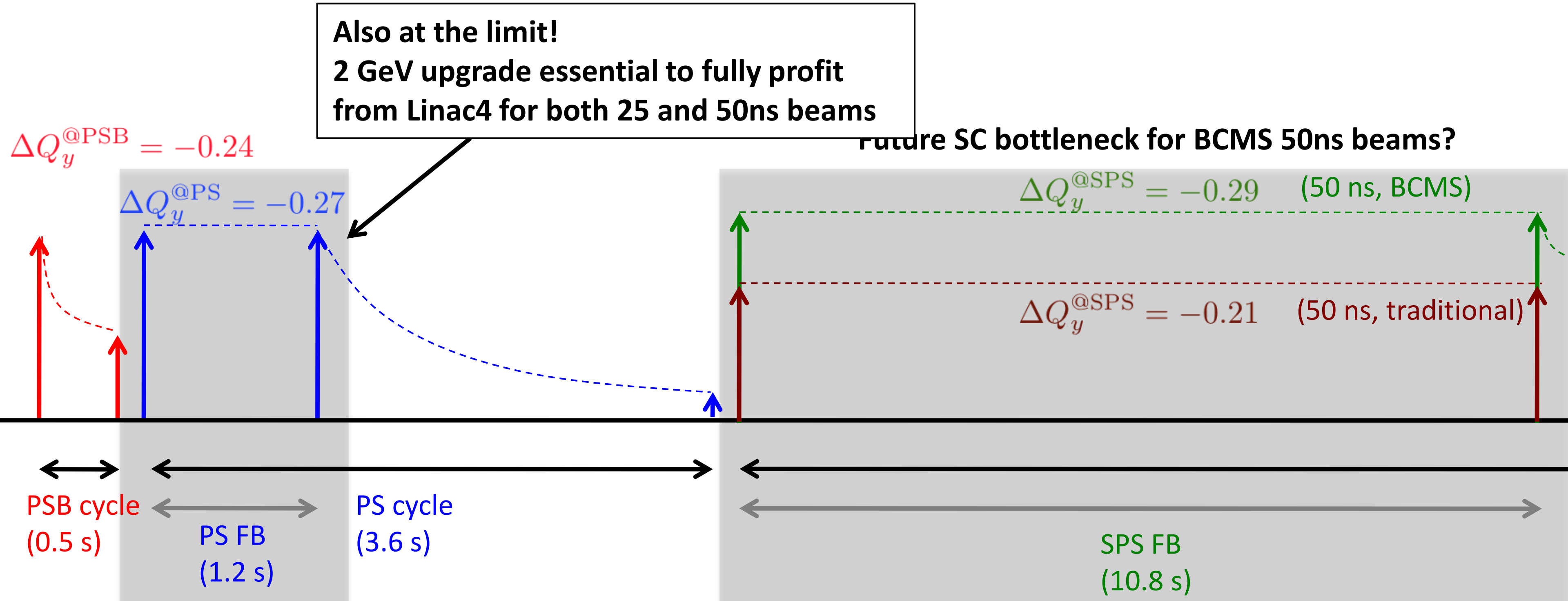
- Tune spreads in the order of 0.2 seem to be acceptable at the SPS FB
- Slow losses are observed with larger emittance beams, suggesting a different mechanism for degradation than space charge

Future LHC beams (post-LS2)

Evolution of space charge ΔQ_y across the injector chain

- Assume Linac4 ➔ Injection into the PSB @160 MeV and with H^- allows for doubled brightness (with 10% margin)
- Assume 2 GeV upgrade of the PSB extraction/PS injection energy
- Assume at the SPS extraction
  - → Present intensity for the 50ns beams
  - → 40% larger intensity than present for the 25ns beams (thanks to the 200 MHz RF system renovation)

Future LHC beams (post-LS2)
Evolution of space charge ΔQ_y across the injector chain



- Assume Linac4 → Injection into the PSB @160 MeV and with H^- allows for doubled brightness (with 10% margin)
- Assume 2 GeV upgrade of the PSB extraction/PS injection energy
- Assume at the SPS extraction
  - → Present intensity for the 50ns beams
  - → 40% larger intensity than present for the 25ns beams (thanks to the 200 MHz RF system renovation)

Ongoing LIU space charge activities in the PSB/PS/SPS

- Is the requirement $\Delta Q < 0.25$ a hard limit ? Only with long injection plateau?
  - ✓ Effect of larger tune spreads in the PSB
  - ✓ Possibility of resonance compensation (PS, SPS) not only for lattice but also for SC induced resonances
  - ✓ How close can one go to an integer ? What are the effects in terms of losses and emittance blow up and on which time scale?

- Emittance growth induced by space charge
  - ✓ WP scan and optimization in order to stay in the budgets
  - ✓ Use experimental data in controlled conditions for validation of the existing simulation tools (especially on the long term behavior)

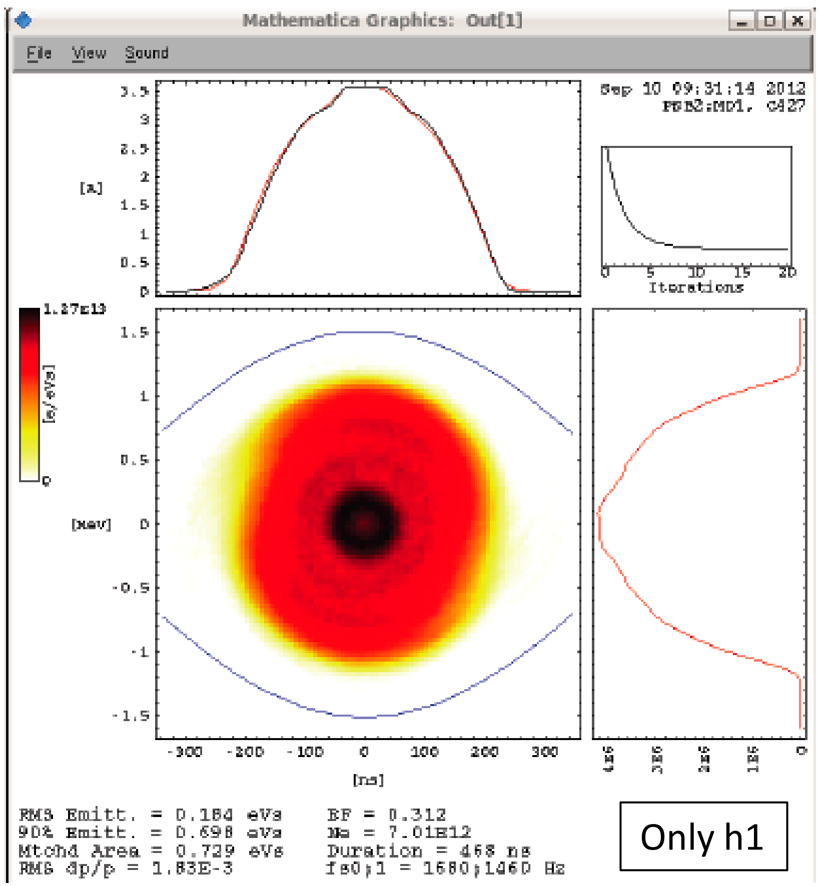
- Miscellaneous
  - ✓ Interaction between SC and impedances (headtail modes in SC dominated beams, effect on TMCI threshold)
  - ✓ Studies of the bunch-by-bunch brightness for different batches in the SPS

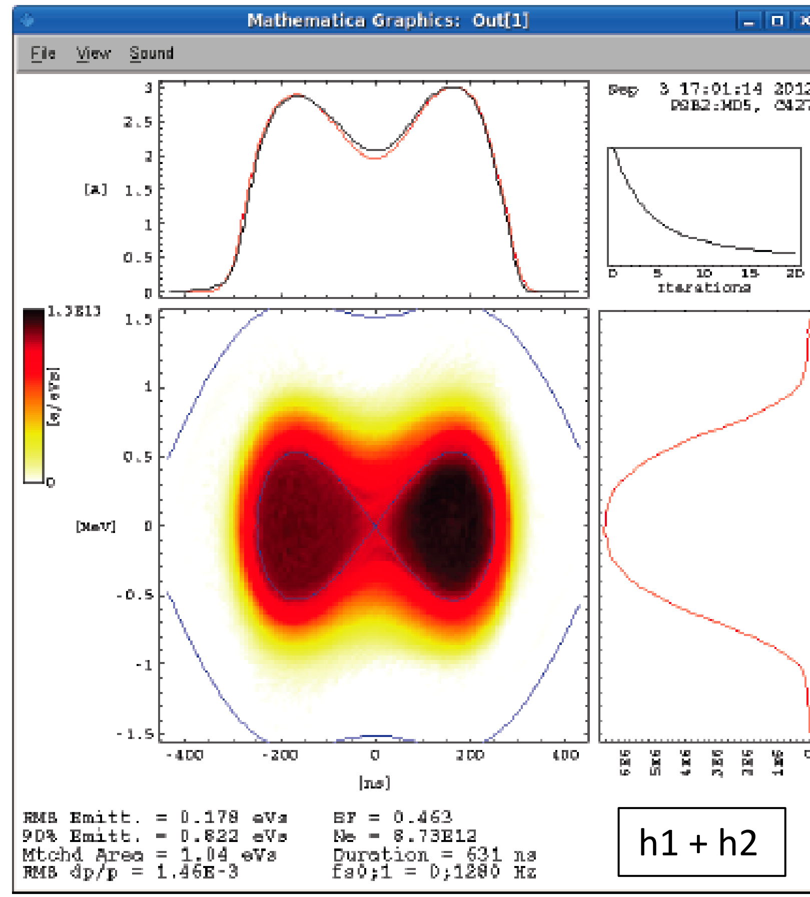
PSB: SC beam studies (I)

1. Space charge tune spreads for high intensity beams (ISOLDE-type beams)
   - → Intensity scans
   - → Monitor emittances and beam losses in the low energy part of the cycle (between 50 and 160 MeV)

1. Use different RF programs
   - → First and second harmonic cavities tuned in phase and counterphase
   - → Only first harmonic cavities

PSB: SC beam studies (I)

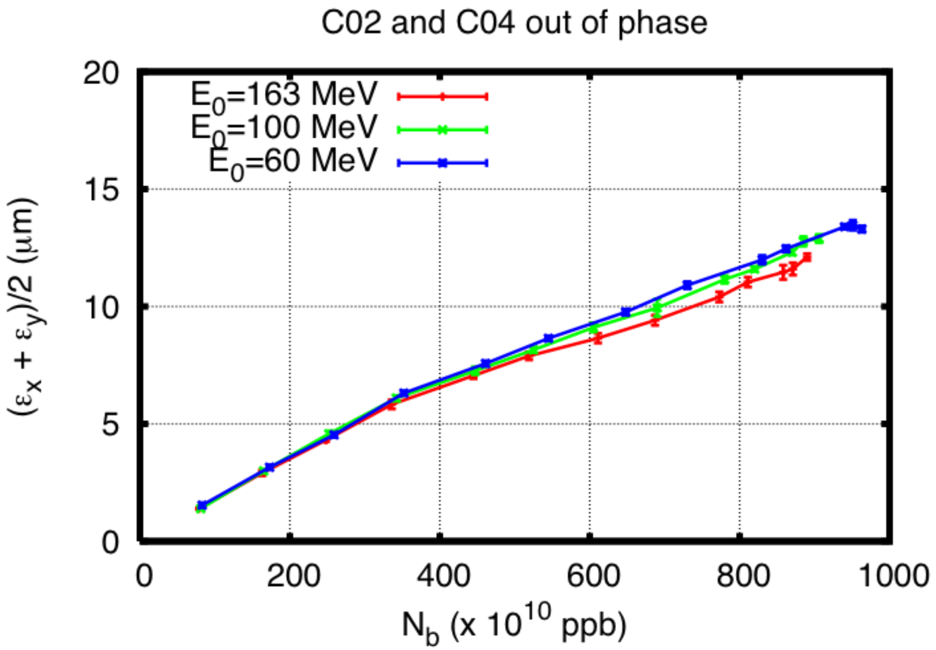


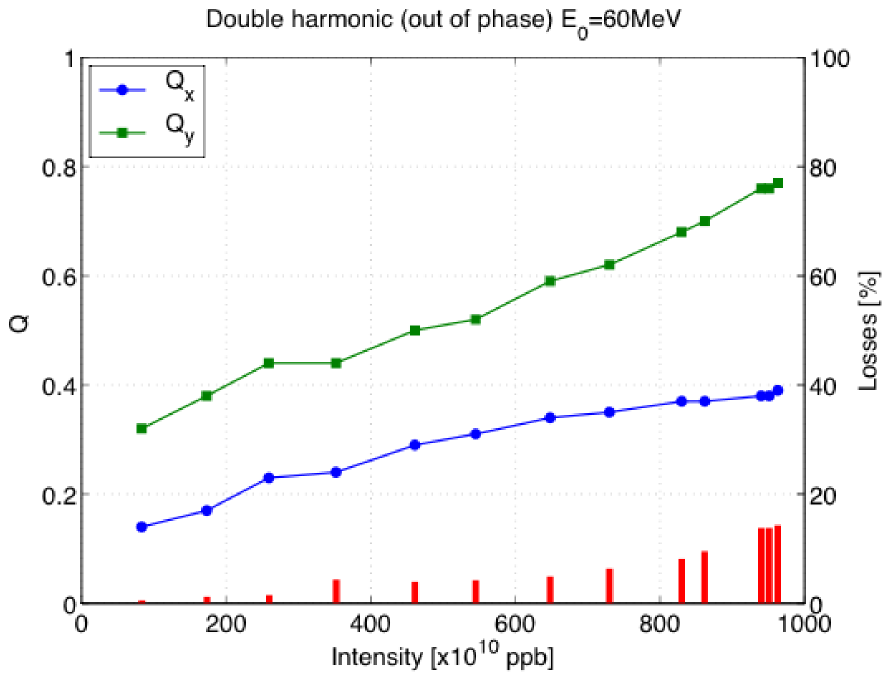


13 turns injected from Linac2

B. Mikulec, A. Findlay, V. Raginel, G. Rumolo, G. Sterbini

PSB: SC beam studies (I)

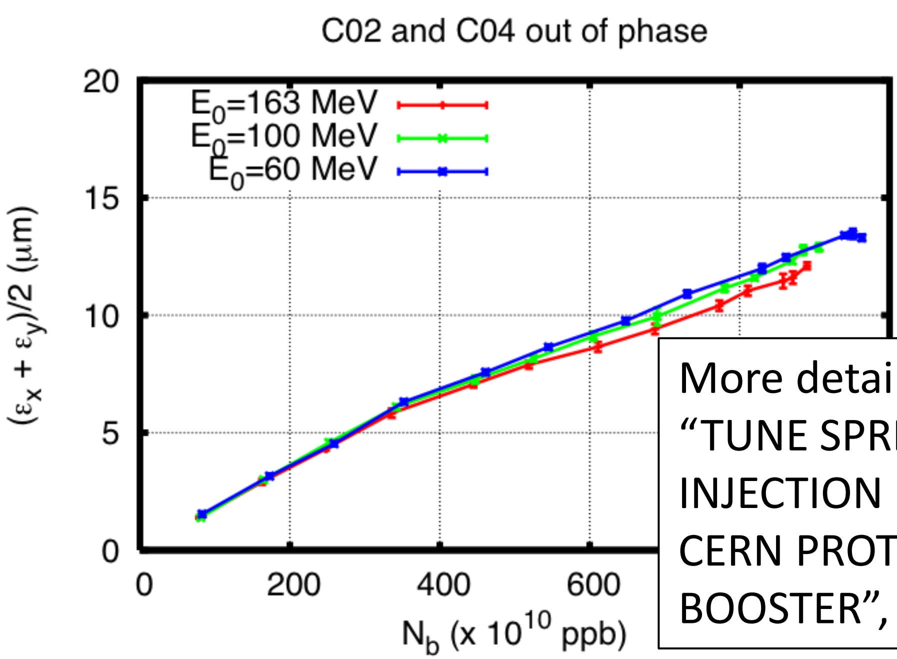


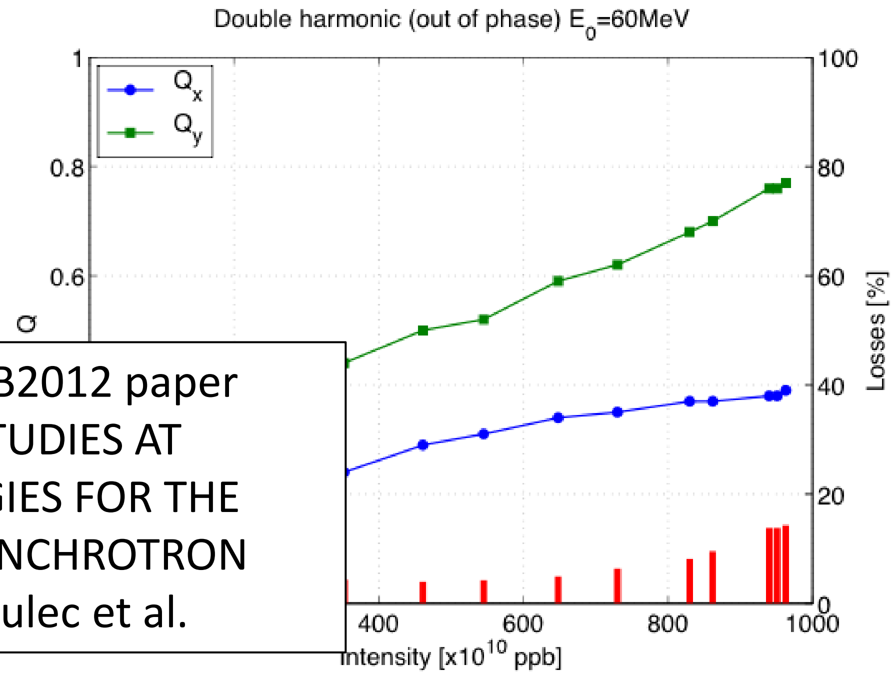


- Calculated tune spreads (based on measured parameters) up to almost 0.8 @60 MeV for the highest intensities
- Corresponding losses of more than 15%
- No evident sign of emittance blow up from 60 to 163 MeV

B. Mikulec, A. Findlay, V. Raginel, G. Rumolo, G. Sterbini

PSB: SC beam studies (I)





More details in HB2012 paper "TUNE SPREAD STUDIES AT INJECTION ENERGIES FOR THE CERN PROTON SYNCHROTRON BOOSTER", B. Mikulec et al.

- **Calculated tune spreads (based on measured parameters) up to almost 0.8 @60 MeV for the highest intensities**
- **Corresponding losses of more than 15%**
- **No evident sign of emittance blow up from 60 to 163 MeV**

B. Mikulec, A. Findlay, V. Raginel, G. Rumolo, G. Sterbini

PSB: SC beam studies (II)

1. Working point studies at 160 MeV
   - → Static working point close to integer, intensity effects
   - → Dynamic tune variation approaching the integer
   - → Half integer resonance crossing
   - → Automatic tune scans, including design and implementation of radial tune scans

1. Use of correctors
   - → Normal/skew quadrupoles, normal/skew sextupoles, effect of corrector dipoles (orbit correction) when approaching the integer
   - → Efficiency of correction in terms of losses
   - → Resonant driving term analysis and kicker response to derive magnetic model of PSB (M. Mcateer et al.)

2. Benchmark with SC simulation tools

See talk of V. Forte, E. Benedetto

PS: Past studies on SC

1. Emittance growth and losses due to space charge (G. Franchetti et al.)
   - → Exciting resonances and approaching the line in different SC conditions
   - → Reproduce evolution with SC simulation code

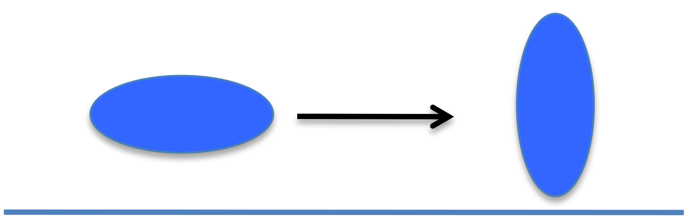
1. Emittance growth for extra-bright bunches (R. Steerenberg, S. Gilardoni et al.)
   - → Blow up along the injection plateau
   - → Experience with different working points

2. Tune diagrams at 1.4 and 2 GeV (E. Benedetto, A. Huschauer et al):
   - → Define machine resonances
   - → Scan different working points in terms of beam quality preservation

Extreme space charge MD (2010)

	N_b (x 10^{10} p)	$\varepsilon_{x,y}$ (μm)	$4\sigma_t$ (ns)	ΔQ_y
LHC50 SB rebucketed	150.0-190.0	2.5-3.0	130	**-0.34**

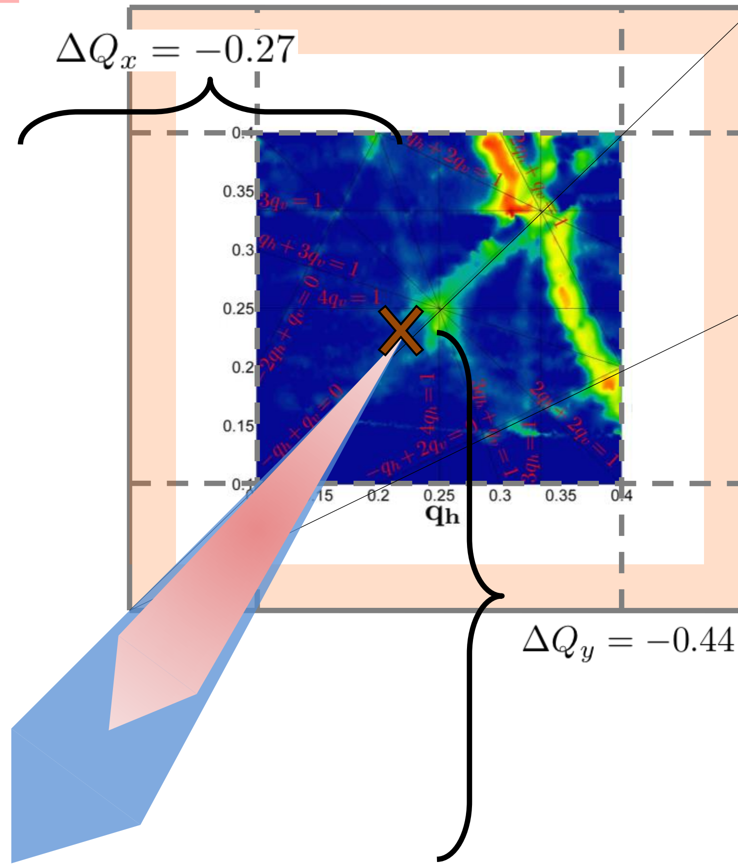
H. Damerau, S. Gilardoni, S. Hancock, R. Steerenberg



Bunch adiabatically shortened with 10MHz cavity **@1.4 GeV** FB (130ns → 90ns)

Large tune spreads in both horizontal and vertical plane, however no loss observed

Emittance growth by up to 60% measured on the 1.2sec plateau



PS: SC & resonance compensation in 2012/2013

1. Emittance growth and losses due to space charge
   → Approaching the integer and crossing other resonance lines
   → Determined as a function of the Laslett tune shift
   → Effect of space charge excited resonance lines (4th order resonance)

1. Tune scans and resonance compensation
   → Compensation of 3rd order resonances ($3q_y=1$ and $2q_x+q_y=1$)
   → Correction of octupolar component of the PFW using several distributed octupoles

2. Other mitigation options (before the 2 GeV upgrade…):
   → New injection optics for LHC beams with larger dispersion
   → Flattened bunch profiles
   → Acceleration-deceleration between injections

See talks of A. Huschauer, R. Wasef

A. Huschauer, R. Wasef, S. Gilardoni

SPS: SC beam studies

1. Single bunch emittance growth and losses due to space charge on long injection plateau
   → Studies done with high brightness single bunch (>4 x 10^{11} p/b in Q20)
   → Approaching the integer
   → Tune scans
   → Q20 vs Q26 optics

1. Multi-bunch studies (emittance blow up & transmission)
   → Use of high brightness BCMS 50 ns beams
   → Train dependence of emittance blow up (to determine the effect of the length of the injection plateau)

See talk of H. Bartosik

H. Bartosik, A. Molodozhentsev, Y. Papaphilippou, F. Schmidt

Summary and conclusions

- **Evolution of tune spread across the LHC injector chain has been calculated for present LHC-type beams**
  - Large values in the PSB with no visible detrimental effect thanks to resonance compensation, dynamic WP and rapid cycling
  - Large values in the PS, could be present bottleneck to reach more?
  - BCMS 50 ns is the most critical beam in the SPS – with ΔQ up to -0.2 – but no degradation with WP slightly moved upwards

- **Evolution of tune spread across the LHC injector chain has been calculated for future (post-LS2) LHC-type beams**
  - The main SC limitation for high brightness 50 ns beams will be the SPS@injection
  - 2 GeV upgrade of the PSB needed to have ΔQ within tolerance at PS injection and fully benefit from the increased brightness in the PSB

- **Ongoing studies in PSB/PS/SPS**
  - PSB: performance vs. tune spreads, emittance growth and loss studies @160 MeV to be compared with simulation codes
  - PS: SC effect of 1.2 s plateau, resonance compensation, SC mitigation
  - SPS: SC effect on long injection plateau in different beam conditions

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN

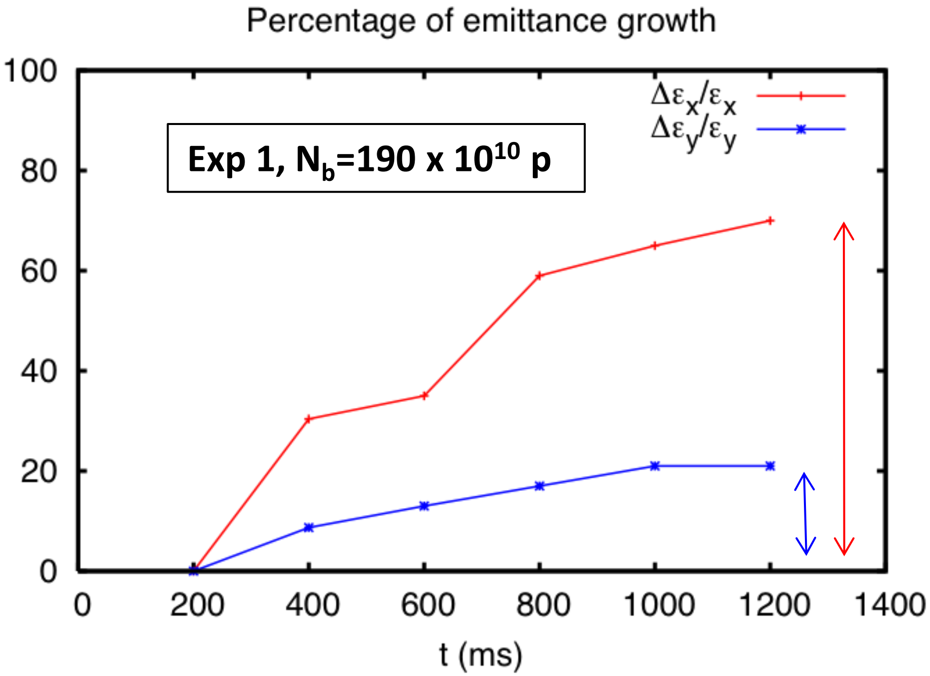
Extreme space charge MD (2010)

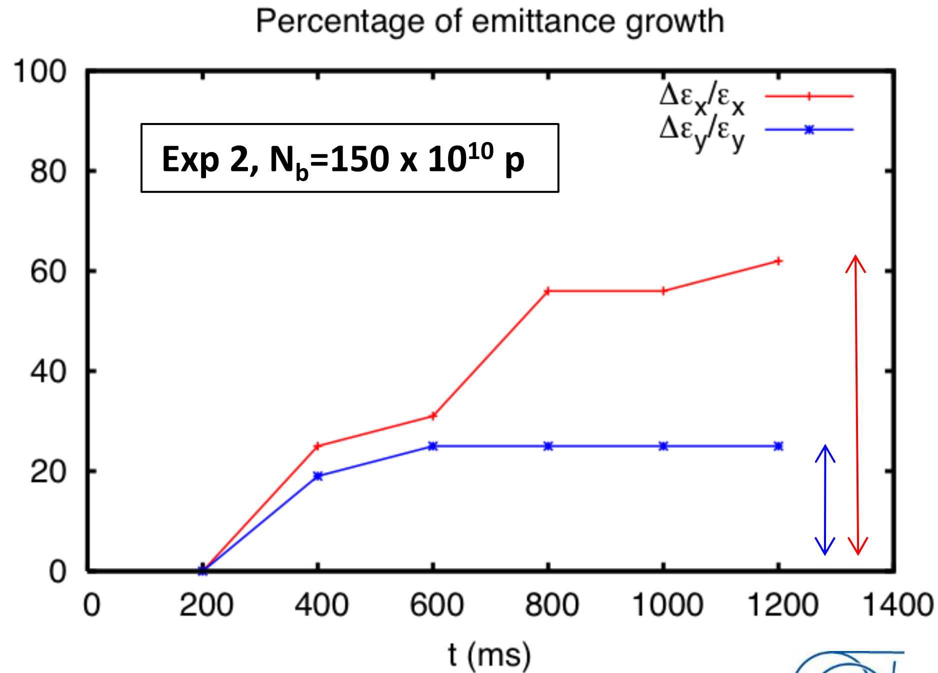
	N_b (x 10^{11} p)	$\varepsilon_{x,y}$ (μm)	$4\sigma_t$ (ns)	ΔQ_y
LHC50 SB rebucketed	150.0-190.0	2.5-3.0	130	**-0.34**

H. Damerau, S. Gilardoni, S. Hancock, R. Steerenberg

20% ε_y growth over 1.2sec

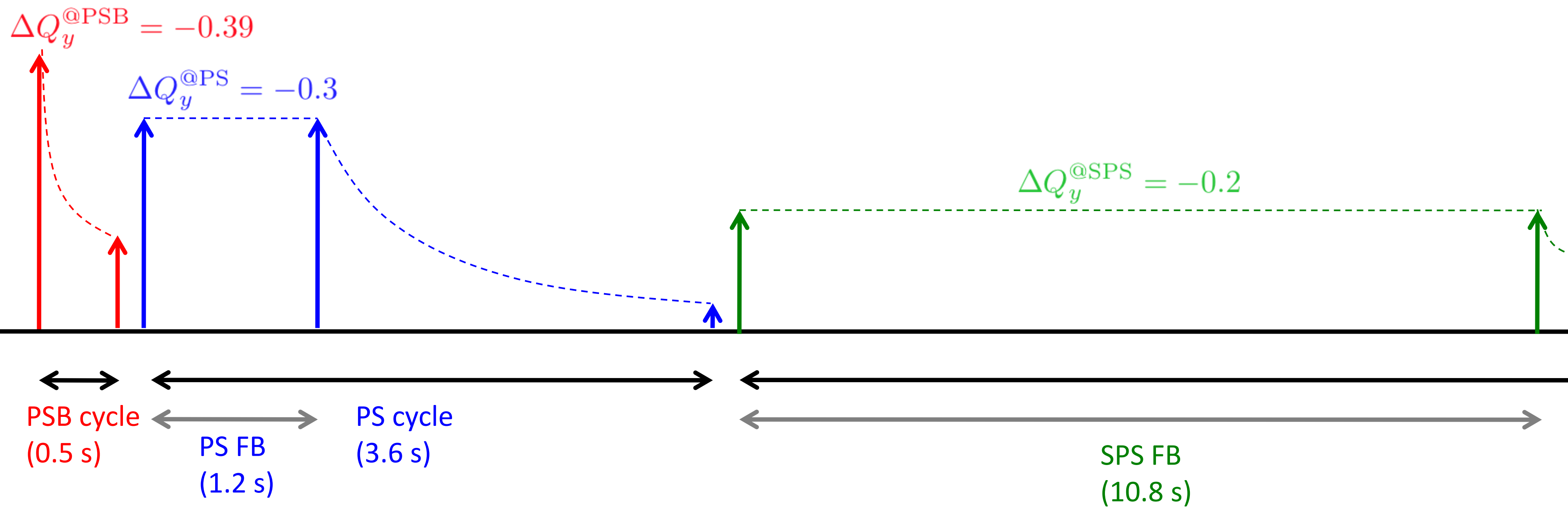
65% ε_x growth over 1.2sec





Present LHC beams – a schematic overview
Evolution of space charge ΔQ_y across the injector chain

Example → BCMS beam (the most critical)



- **Large tune spreads at PSB injection can be handled thanks to efficient resonance compensation, dynamic working point and rapid cycling**
- **The large tune spread values at injection in the PS are more critical due to the long FB (present SC bottleneck?)**
- **Tune spreads in the order of 0.2 are acceptable at the SPS FB, slow losses are observed with larger emittance beams, suggesting a different mechanism for degradation than space charge**