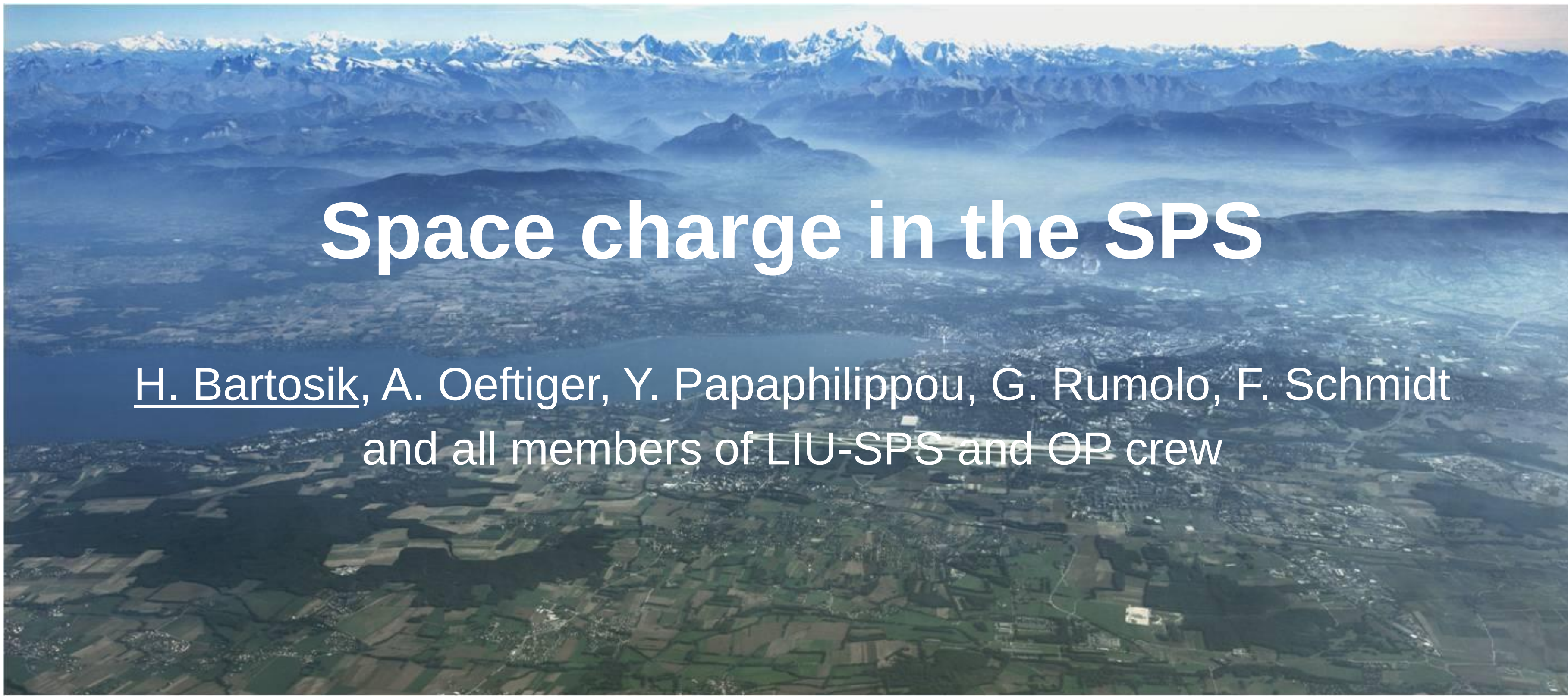
LHC Injectors Upgrade



Space charge in the SPS

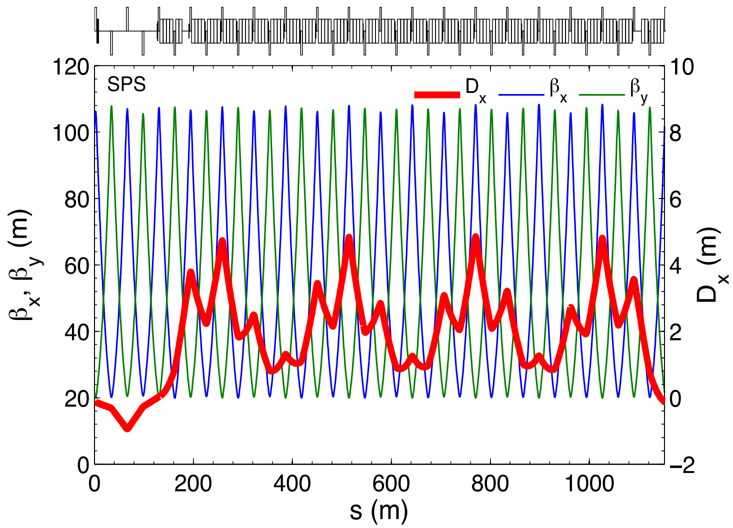
H. Bartosik, A. Oeftiger, Y. Papaphilippou, G. Rumolo, F. Schmidt
and all members of LIU-SPS and OP crew

Outline

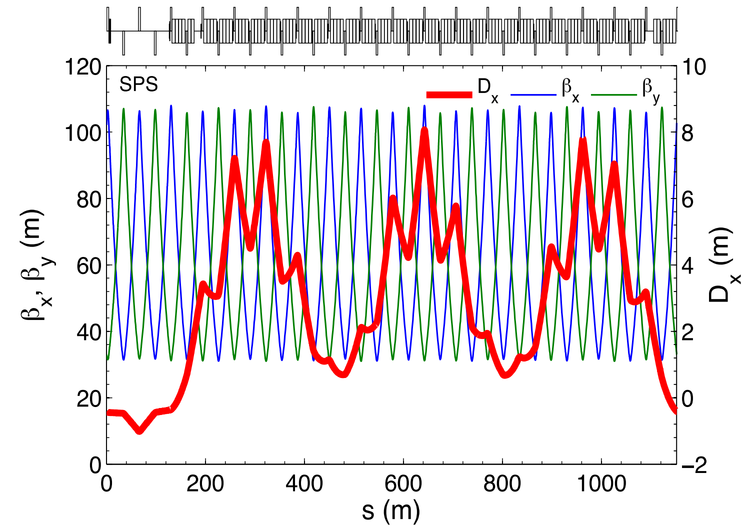
- Introduction
- Achieved beam parameters in 2012
- LIU target beam parameters
- Experimental studies with high brightness beams
- Space charge and machine modeling aspects
- Summary and conclusions

Introduction - SPS optics

"Q26" normal optics Q_x=26.13 Q_y=26.18

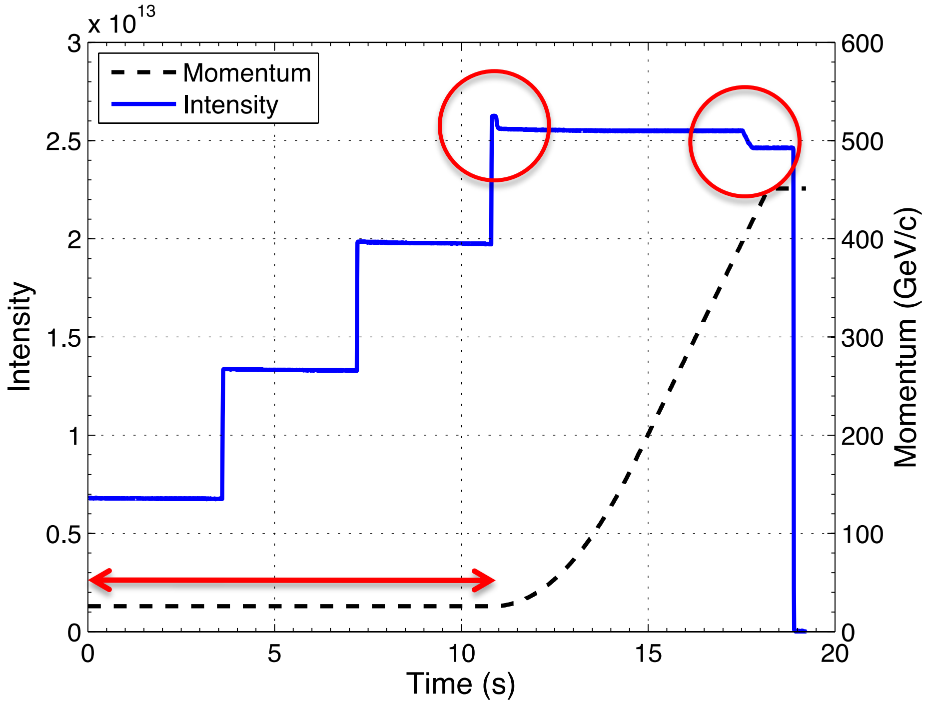


"Q20" low γ_t optics Q_x=20.13 Q_y=20.18



- **Q20 optics with low gamma transition developed to increase instability thresholds**
  - Lowering SPS working point by 6 units: from "Q26" → "Q20" (γ_t=22.8 → γ_t=18)
  - Q20 is the default optics configuration for LHC beams since September 2012
- **Implications for space charge**
  - Higher synchrotron tune (almost factor 3 higher at injection)
  - Larger dispersion → smaller space charge tune spread

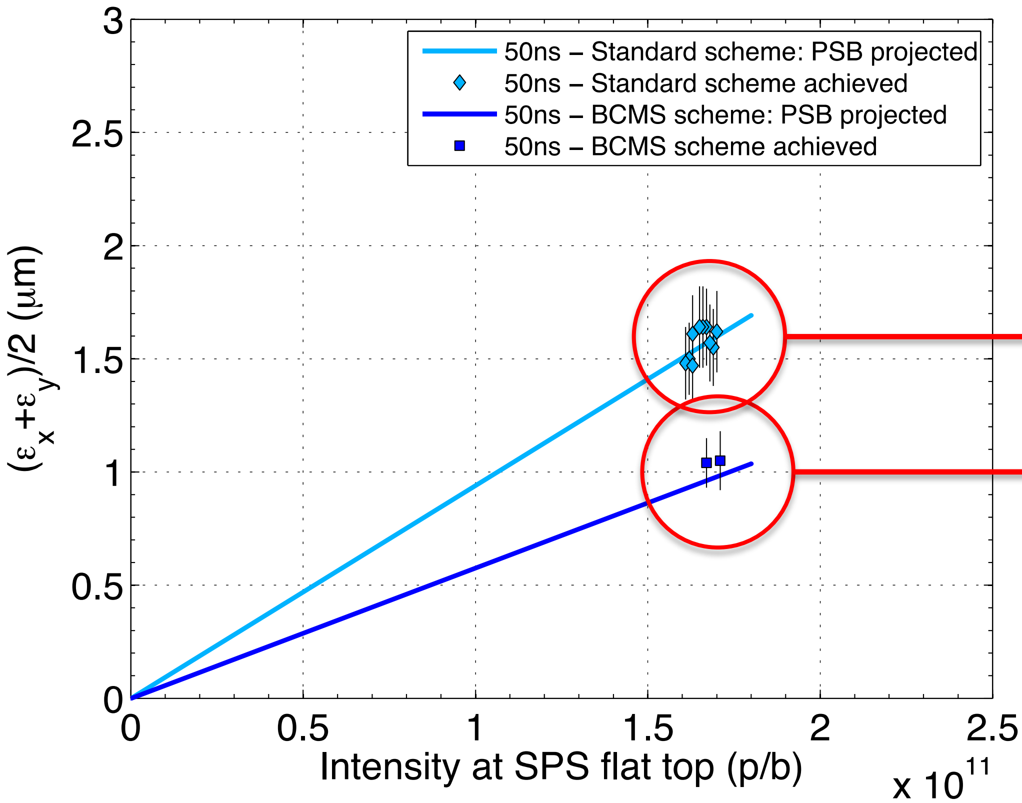
Introduction - SPS cycle for LHC beam



- **Long injection plateau (10.8s)**
  - 4 injections, 26 GeV/c
  - Maybe even longer in case of BCMS beam
- **Budget for total losses: 10%**
  - Losses at start of acceleration ~3-5%
  - Scraping at flat top ~3%
- **Budget for emittance growth: 10%**
  - Small optics mismatch at injection
  - Avoid different emittance per batch

⇒ Need to preserve high brightness for >10s with ΔQ>0.2 with “practically no degradation”

2012 beam parameters – 50 ns beam



Expected lines derived from the measured 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%)

$\Delta Q_x/\Delta Q_y$ ~ 0.08/0.14

$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.18

- **50ns standard scheme**
  - Regularly used to fill LHC at 2012 PS intensity limit
- **50ns Batch-Compression-Merging-and-Splitting (BCMS) high brightness scheme**
  - Beam sent to the LHC once to check emittance preservation and luminosity gain in LHC

LIU target beam parameters

- **Main LIU upgrades**
  - Double the PSB brightness thanks to injection at 160 MeV using H^- from Linac4
  - Raise the PS injection energy to 2 GeV for higher brightness in the PS
  - SPS RF upgrade for higher intensity, electron cloud mitigation

- **Baseline scenario: 25 ns**

SPS, 25 ns		N (10^{11} p/b)	$\varepsilon_{x,y}$ (μm)	$\Delta Q_{x,y}$
LIU	standard	2.22	1.71	(0.09, 0.16)
	BCMS	2.22	1.25	(0.12, 0.21)
HL-HLC		2.57	1.89	(0.10, 0.17)

present SPS record

- **Fallback scenario in case of problems with electron cloud in the LHC: 50 ns**

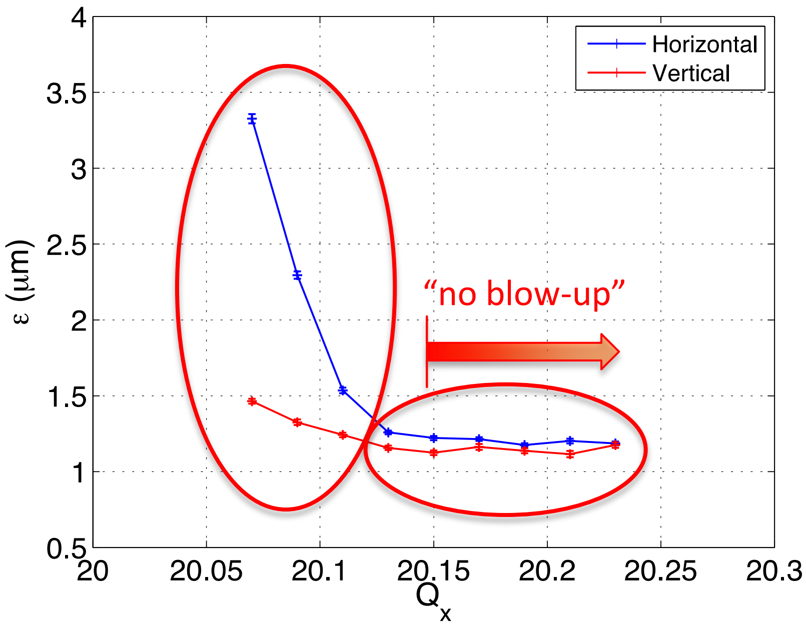
SPS, 50 ns		N (10^{11} p/b)	$\varepsilon_{x,y}$ (μm)	$\Delta Q_{x,y}$
LIU	standard	3.00	1.77	(0.13, 0.21)
	BCMS	3.00	1.77	(0.13, 0.21)
HL-HLC		4.09	2.27	(0.14, 0.24)

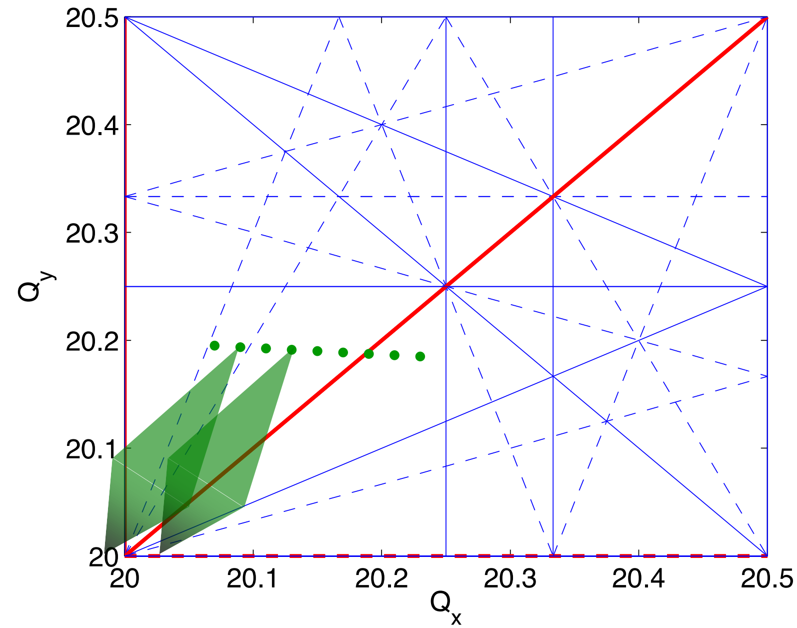
to be studied …

Experimental tune scan - horizontal

- **High brightness 50ns BCMS beam**
  - N = 1.95x10^{11} p/b (at injection)
  - ε ~ 1.15μm
  - Transmission up to flat top around 94% without scraping (very small losses on flat bottom)
  - Emittance measurement at the end of flat bottom

$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.18

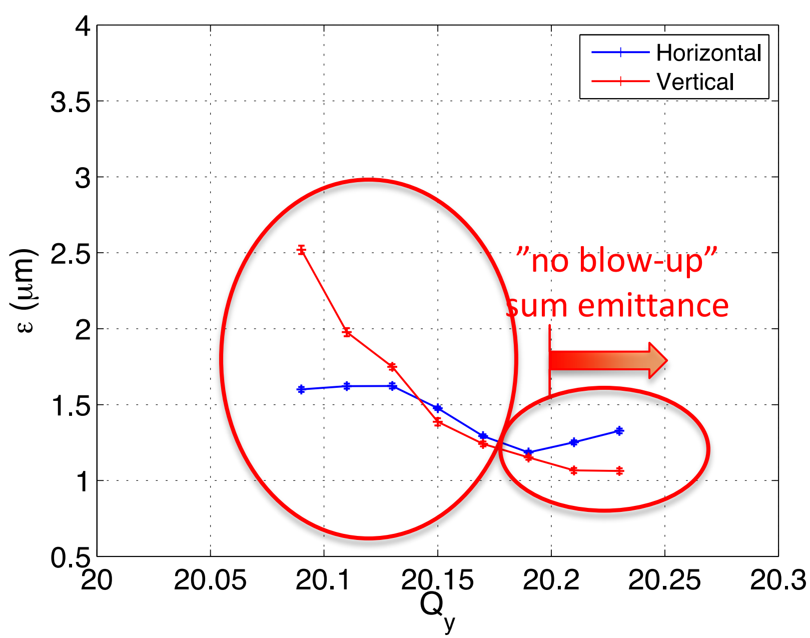


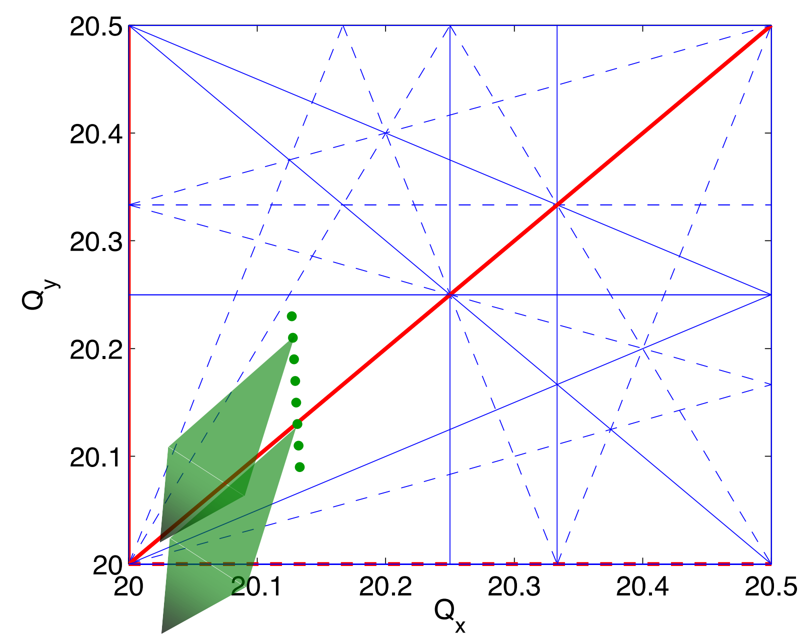


Experimental tune scan - vertical

- **High brightness 50ns BCMS beam**
  - N = 1.95x10[11] p/b (at injection)
  - ε ~ 1.15μm
  - Transmission up to flat top around 94% without scraping (very small losses on flat bottom)
  - Emittance measurement at the end of flat bottom

$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.18





Future experimental studies

- **Further explore the tune diagram**
  - Optimize working point for beams with very high brightness (“pure batch compression scheme”)
  - Study effect of resonances in strong space charge regime
  - Determine maximum tune shift acceptable in the SPS within emittance growth and loss budgets
- **Interplay with resonances excited in a controlled way for code benchmarking**
  - Further development of machine model (nonlinearities)
- **Interplay of space charge with other collective effects**
  - Impedance → transverse mode coupling instability
  - Electron cloud
- **Q20/26 split tune optics**
  - Slight reduction of space charge tune shift compared to Q20 optics

Modeling aspects and challenges

- **High energy (26 GeV) and short bunch length**
  - Complete 3D field calculation not necessary → slice approach should be ok
- **Slice-by-slice approach is needed**
  - To handle cases with intra-bunch motion
  - Large dispersion in the SPS results in significant horizontal beam size variation along the bunch
  - Approach of projecting the transverse bunch distribution to one slice and weighting the kicks with the longitudinal density can lead to numerical artifacts
- **Beam size is small compared to vacuum chambers**
  - Computationally heavy to include boundary conditions in the field calculations as large number of bins needed → presently only direct space charge considered
  - Furthermore, many different types of vacuum chamber geometries in the SPS …
- **No measurements of magnetic field errors of SPS main magnets available**
  - Modeling will largely rely on beam based measurements

Strategy for SPS simulation studies

- **Use PTC-pyOrbit for studying fast phenomena (<= 10k turns)**
  - SPS simulations with PTC-pyOrbit presently being setup → Many thanks to J. Holmes and S. Cousineau for their support and quick reactions to questions!
  - Slice-by-slice space charge calculation (as needed to deal with intra-bunch motion and beam size variation along the bunch) → first version developed and presently being tested
  - Effect of beam surroundings (indirect space charge and impedance) to be treated at a single lumped location in the ring → to be developed

- **Use (MADX) frozen space charge model for long term direct space charge effects**
  - SPS frozen space charge simulations presently being prepared
  - Code needs to be extended to take into account the dispersion function in the initialization of the space charge kicks
  - Slice-by-slice calculation will probably be difficult, but let's see …

- **Use PyHEADTAIL to study interplay with other collective effects**
  - Impedance (TMCI instability) and electron cloud
  - Need to implement space charge module

Summary

- **Regime of strong space charge for future LHC beams in the SPS**
  - Long storage time at injection energy for multiple injections from PS
  - Tight budgets for losses and emittance blow-up
  - Space charge tune shift of $\Delta Q_y = -0.21$ for baseline 25 ns scenario already demonstrated feasible
  - Expected space charge tune shift of $\Delta Q_y = -0.24$ for alternative 50 ns scenario to be studied

- **Experimental studies**
  - Tune scans performed in 2012 (BCMS beam) → achieved SPS record space charge tune shift
  - Main goal of studies in 2014/15: determine maximum tune shift acceptable in the SPS within emittance growth and loss budgets
  - Interplay of space charge and other collective effects

- **Space charge and machine modeling strategy**
  - Short term space charge effects with PTC-pyOrbit (slice-by-slice)
  - Long term effects with MADX frozen space charge
  - Rely on beam based measurements for modeling of machine nonlinearities
  - Interplay with other collective effects using PyHEADTAIL

LHC Injectors Upgrade

Thank you for your attention!

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