LHC Injectors Upgrade

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SPACE CHARGE EFFECTS AND MITIGATION IN THE CERN PS BOOSTER, IN VIEW OF THE UPGRADE.

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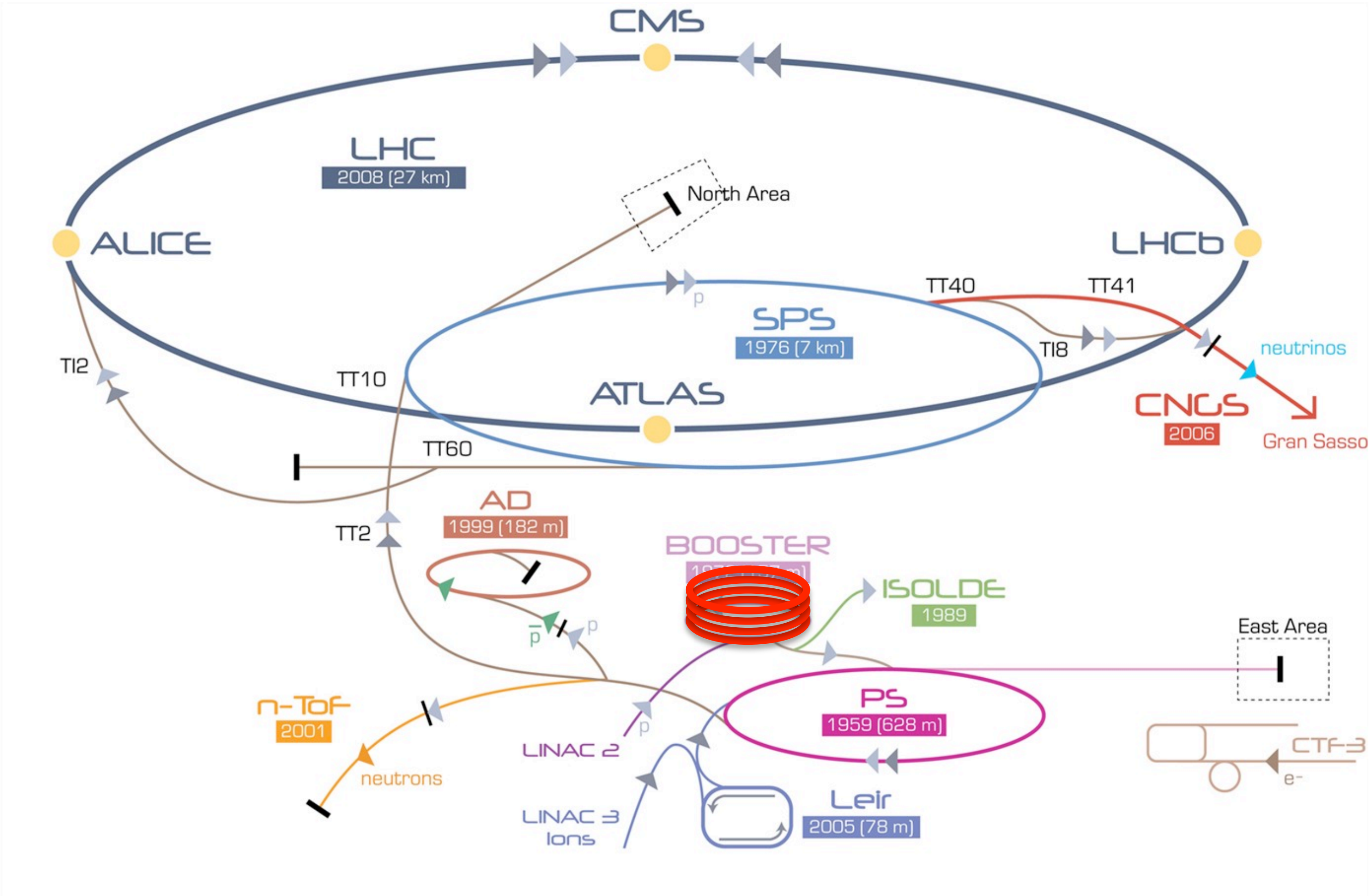
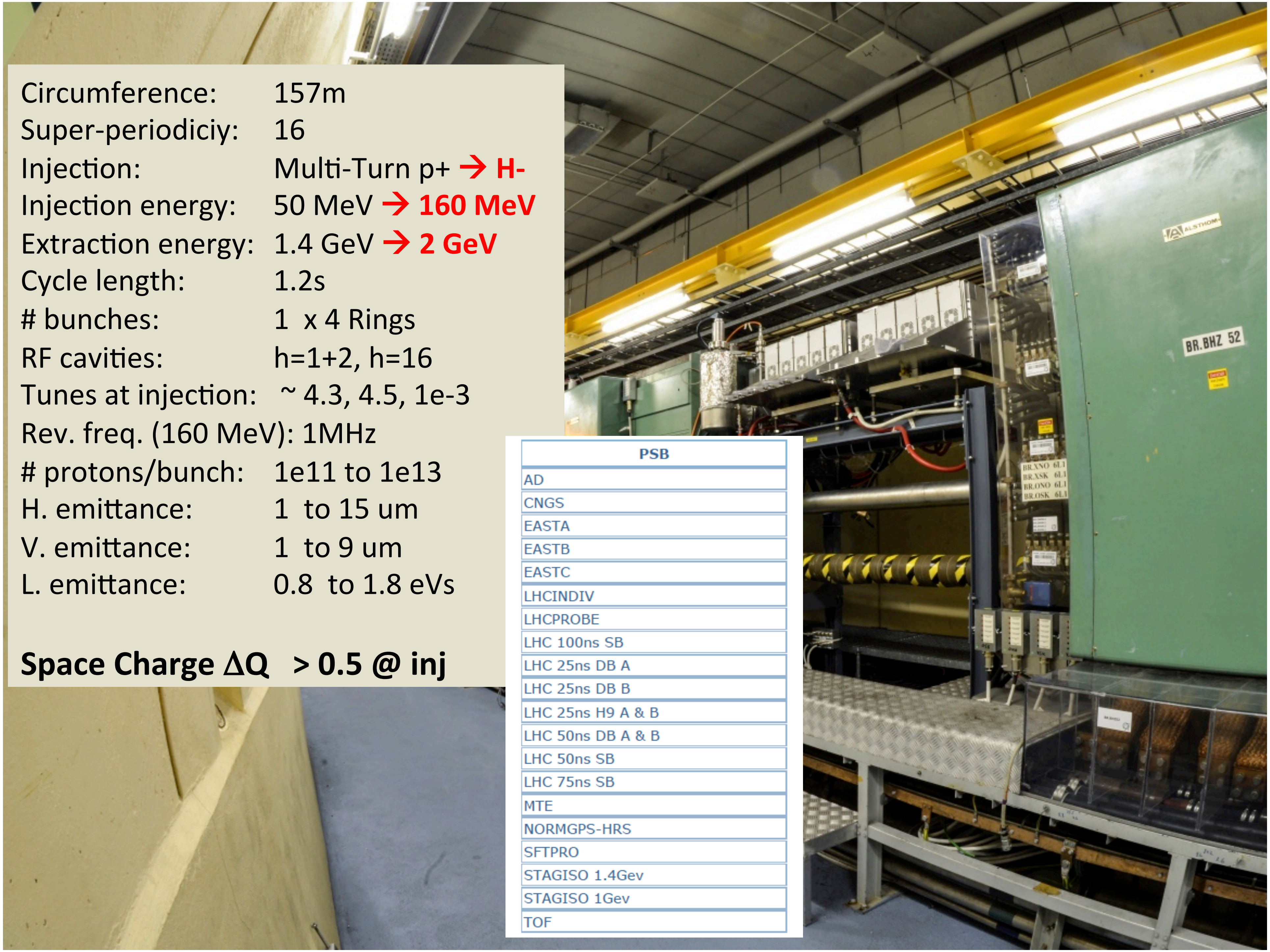
Acknowledgements: J. Abelleira, C. Bracco, A. Garcia, G.P. Di Giovanni, B. Mikulec, G. Rumolo

Intro – CERN PS Booster (PSB)

Where the LHC beams brightness is defined!





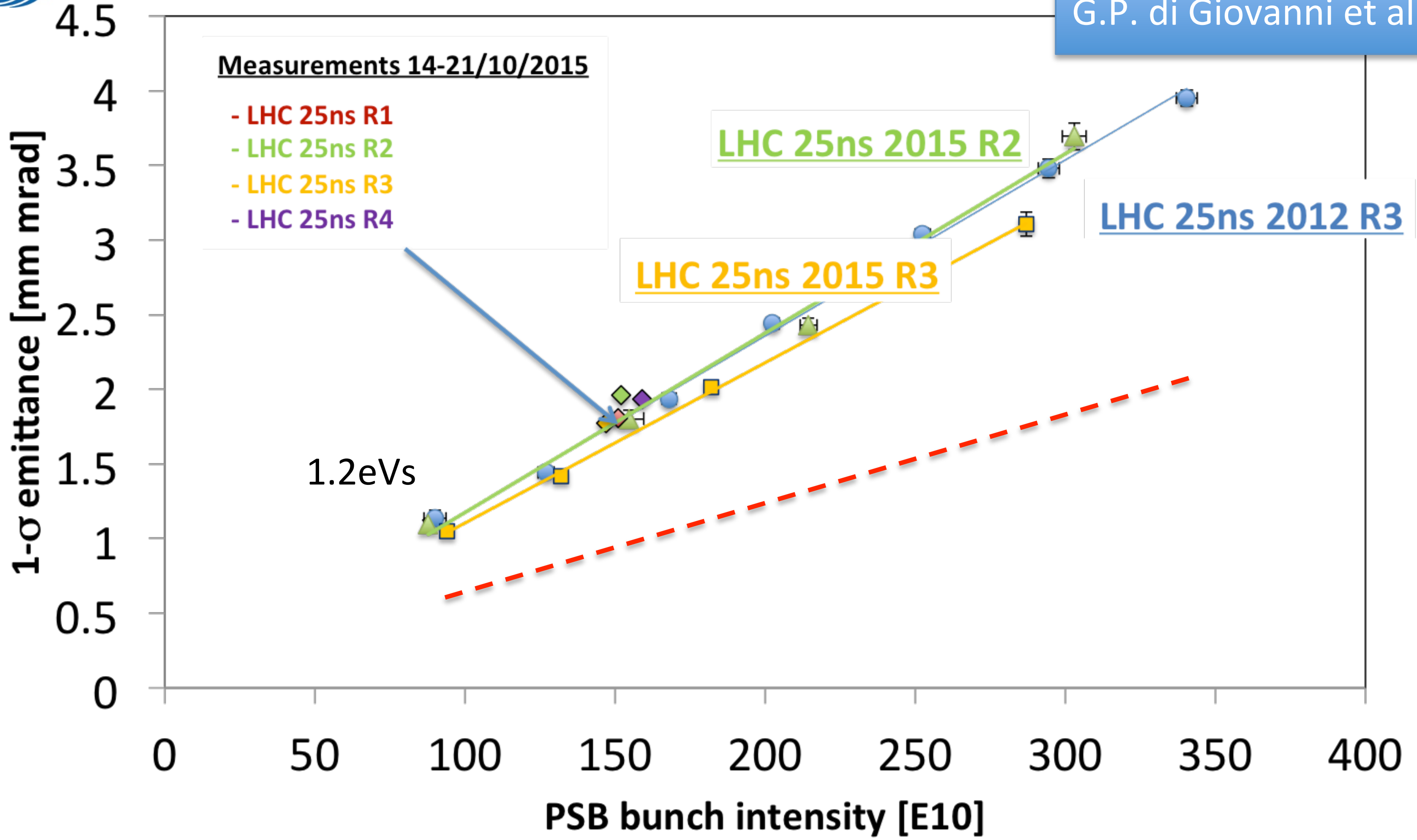
Circumference:	157m
Super-periodiciy:	16
Injection:	Multi-Turn p+ → **H-**
Injection energy:	50 MeV → **160 MeV**
Extraction energy:	1.4 GeV → **2 GeV**
Cycle length:	1.2s
# bunches:	1 x 4 Rings
RF cavities:	h=1+2, h=16
Tunes at injection:	~ 4.3, 4.5, 1e-3
Rev. freq. (160 MeV):	1MHz
# protons/bunch:	1e11 to 1e13
H. emittance:	1 to 15 um
V. emittance:	1 to 9 um
L. emittance:	0.8 to 1.8 eVs

Space Charge ΔQ > 0.5 @ inj

PSB
AD
CNGS
EASTA
EASTB
EASTC
LHCINDIV
LHCPROBE
LHC 100ns SB
LHC 25ns DB A
LHC 25ns DB B
LHC 25ns H9 A & B
LHC 50ns DB A & B
LHC 50ns SB
LHC 75ns SB
MTE
NORMGPS-HRS
SFTPRO
STAGISO 1.4Gev
STAGISO 1Gev
TOF

Intro: Beam brightness

B. Mikulec, 2012
G.P. di Giovanni et al. 2015



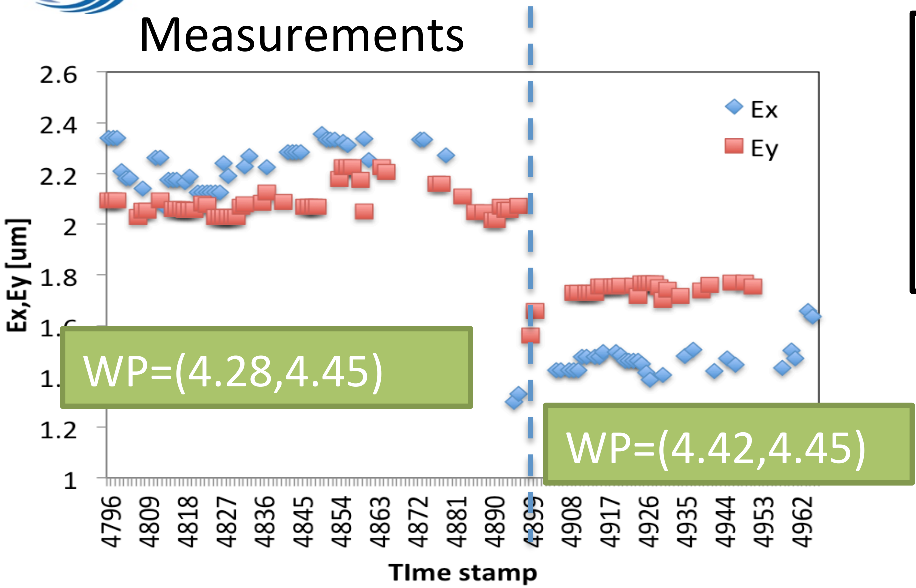
- $\Delta Q_{SC} > 0.5$
- Upgrade from 50 MeV to 160 MeV ➔ factor 2 in $\beta\gamma^2$
- H- injection ➔ loss-free + inject in the same phase space

Outline

- ✓ Can we confirm the factor 2 scaling with Space Charge simulations?
- ✓ Space Charge mitigation measures + Half-integer correction
- ✓ Non-linear optics studies – ONGOING WORK

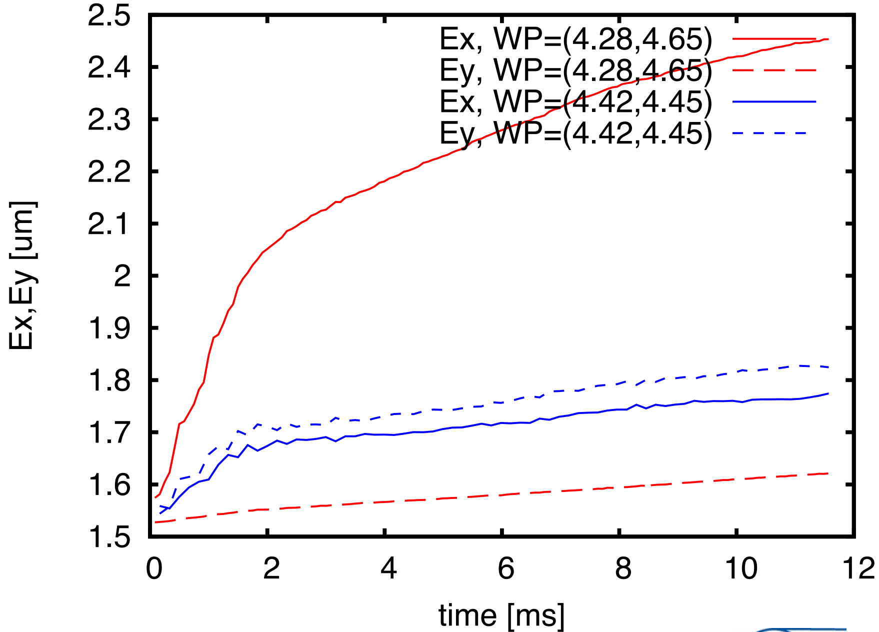
Beam brightness: benchmark @ 50 MeV inj

Measurements



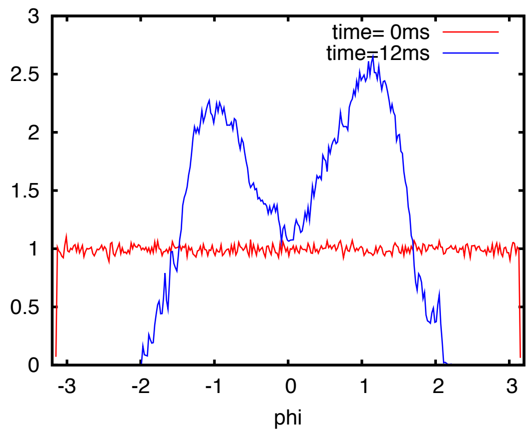
Good agreement between measurements and simple(*) simulations
- change of WP
- ~ final emittance value

Simulations with PTC-Orbit

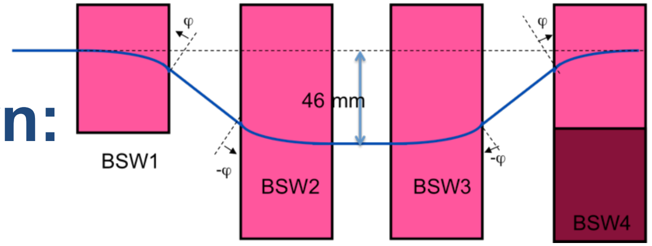


Simple model to start with:

- No MT p+ injection, matched beam
- Only SC
- Only linear latti
- RF capture

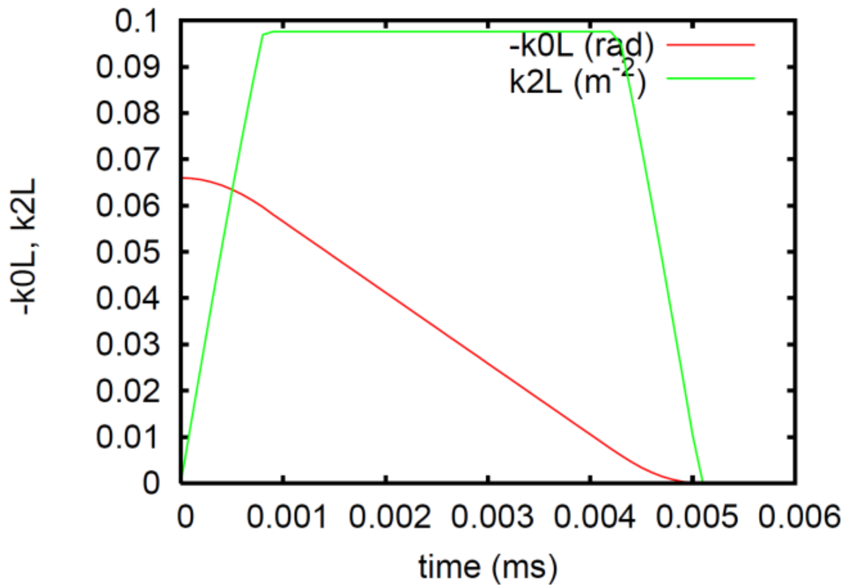


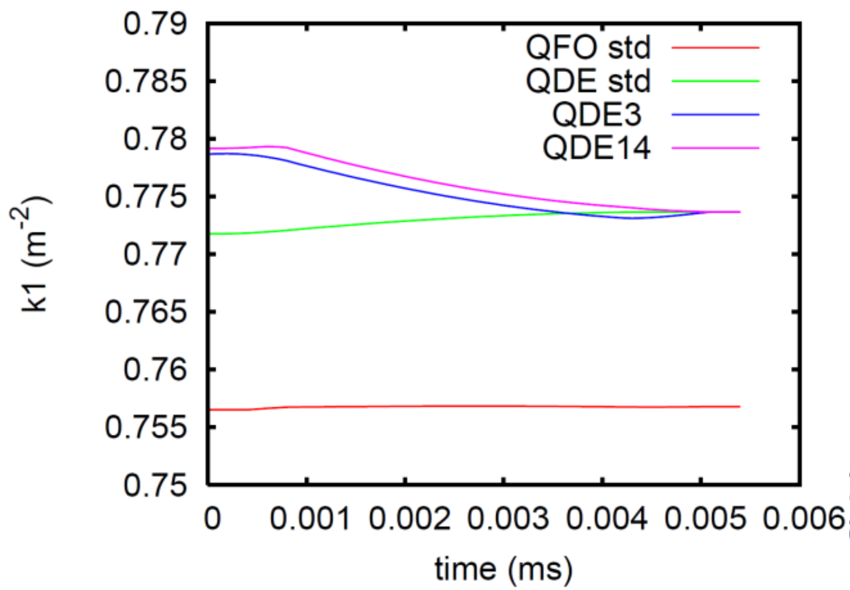
Beam brightness: simulations @ 160 MeV



- **Injection chicane magnets ramp-down:**
  - Edge effects due to rectangular magnets
  - Eddy-currents and multipolar components varying with time
  - Compensation (time varying) with trims on 2 main quads

- Chicane ramp-down shape implemented in PTC-Orbit, with errors and ripples → definition of tolerances and the function for the correctors





Beam brightness: simulations @ 160 MeV

Again a “simple” model:

- No MT H- injection, matched beam
- Only Space Charge
- Chicane + compensation in the model

See also HB2014

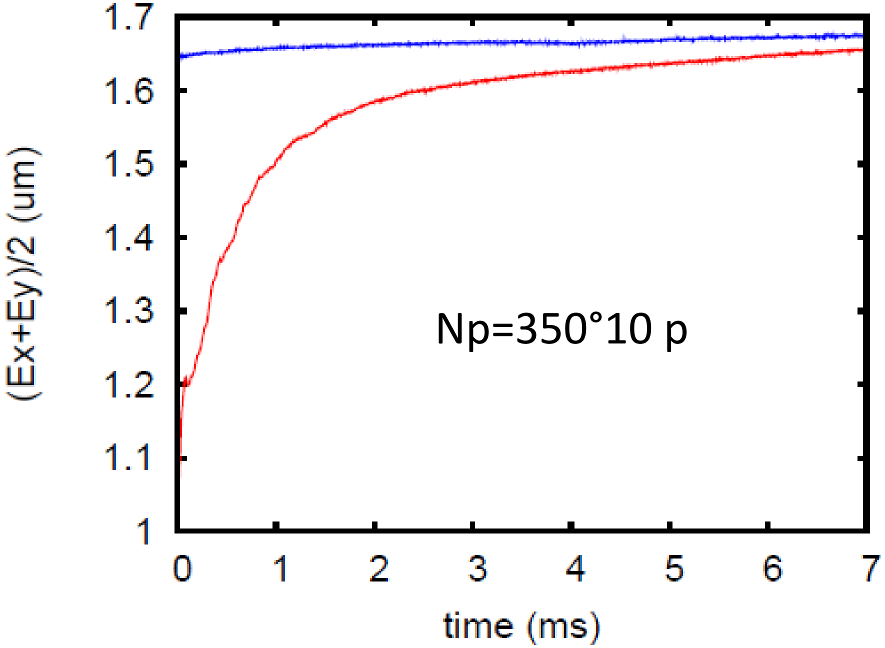
PTC-ORBIT simulations

200 SC nodes

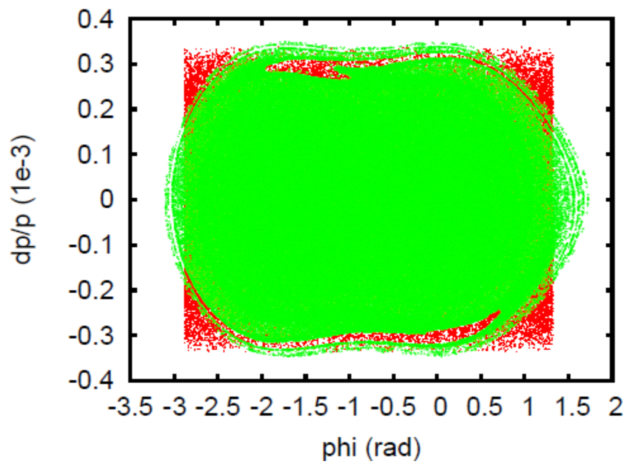
2.5 Direct SC module

64x64x128

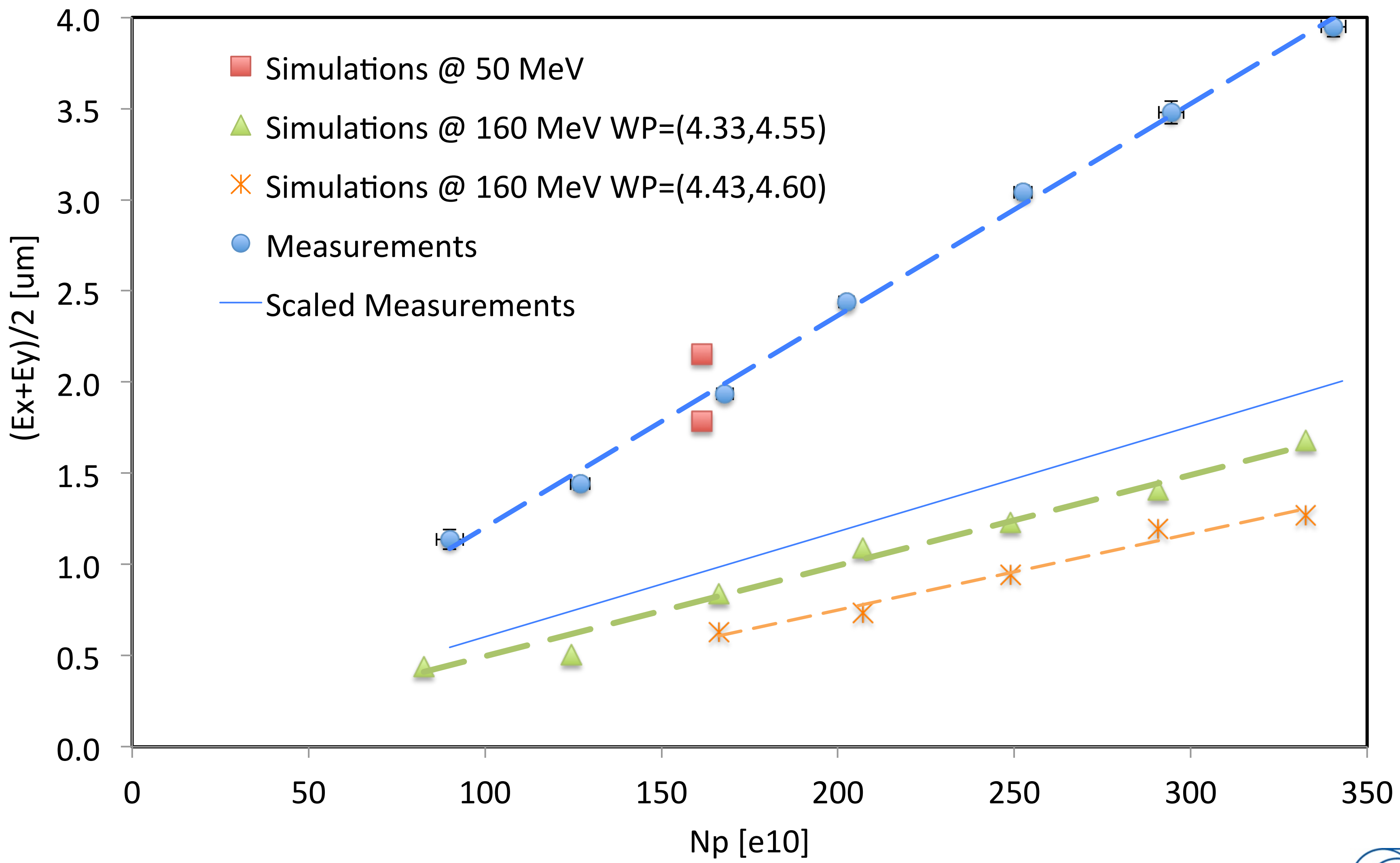
250k macroparticles



Emittance reached at the end of chicane bump ~independent of starting value



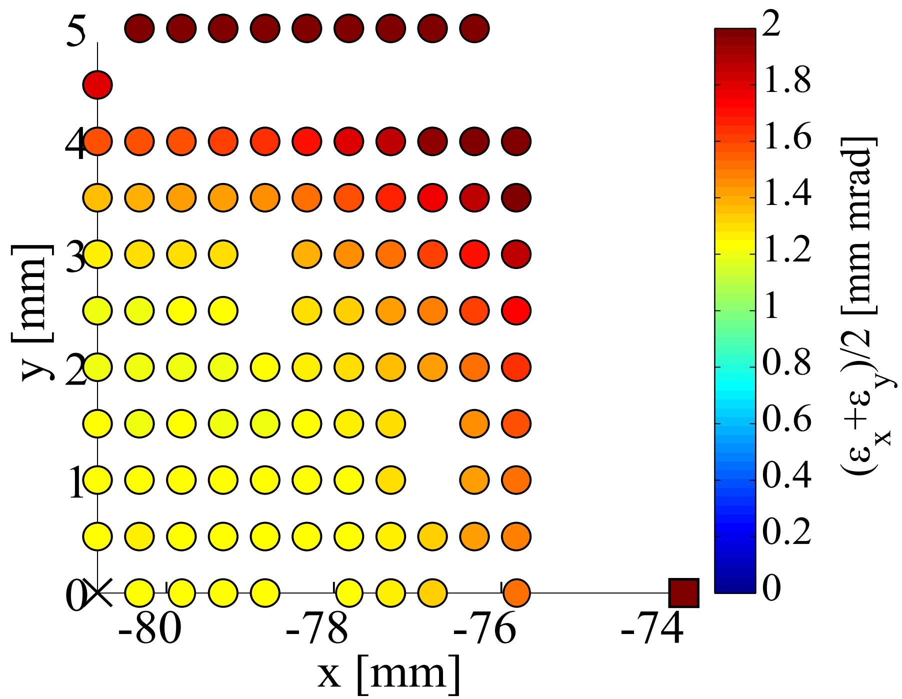
Beam brightness: simulations @ 160 MeV



Beam brightness: simulations @ 160 MeV

A more refined model:

- MT H- injection
- Stripping foil
- Chicane + compensation



MT injection with fixed offset: Final emittance as a function of injection offset. Np=350e10

- Confirmation final emittance does not depend "too much" on injection (*)
- Gives the tolerances for allowed offset mismatch at injection to be <1.7um (LIU requirements)

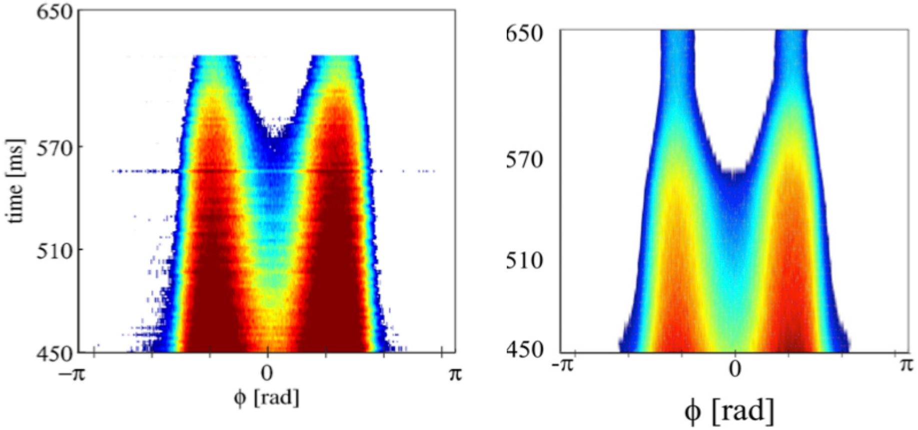
(*) for High Intensity beams however we will profit of proper painting!

Measures against Space Charge

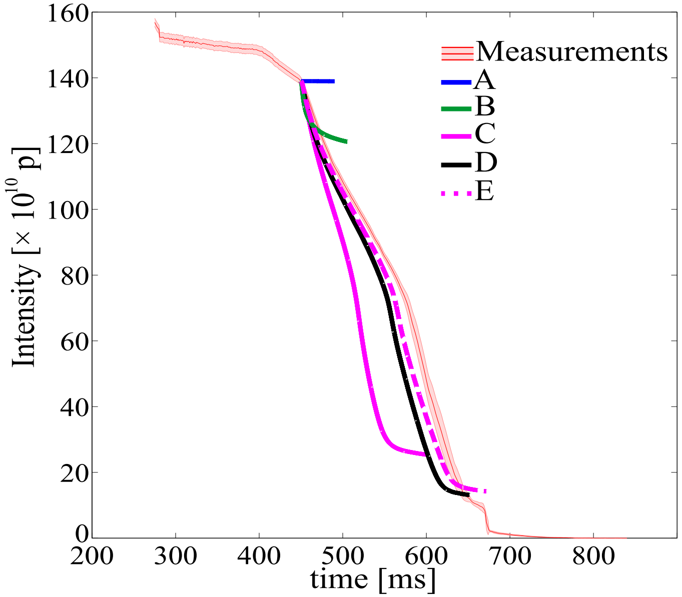
- **Double harmonic: h1+h2**
- **Acceleration** (no energy flat bottom)
  - H- injection directly on accelerating bucket
  - Today: MT injection in coast, then adiabatic capture + acceleration
- **Transverse painting:**
  - Horiz. Painting + Vert. Steering
  - Today: injection offset in both planes (V steering and delay of the bump decay wrt injection timing)
- **Working point**
  - Today limited by MT p+ injection → losses at septum
  - Not the case for H-
- **Resonance compensation:**
  - Empirical (based on loss reduction and driven by phyiscs considerations)
  - Systematic studies from turn-by-turn waiting for new BMP electronics
  - Compensation of the Half-Integer

Half-integer induced beam losses

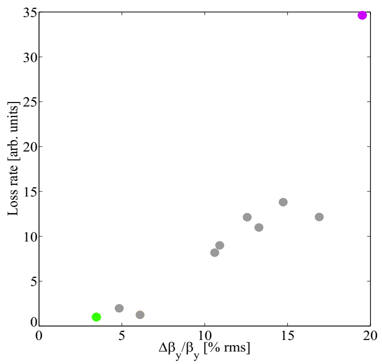
- Injection WP~(4.3,4.6)
- Affects operation if not compensated
- Subject of dedicated studies & benchmark with PTC-Orbit simulations



Waterfall plot of the measured (left) and simulated (right) longitudinal bam profile.



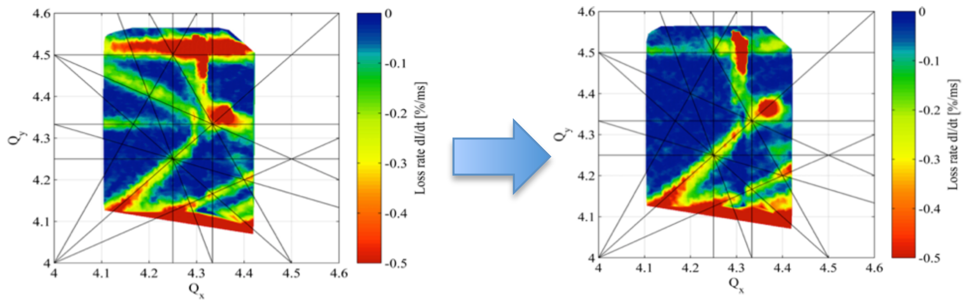
Intensity evolution vs. time.
Simulation: (A) with only space charge but no errors; (B) no space charge; (C) with quadrupolar errors (programmed Qy =4.53); (D) with quadrupolar and misalignment errors (Qy=4.53); (E) with quadrupolar errors (Qy =4.525).



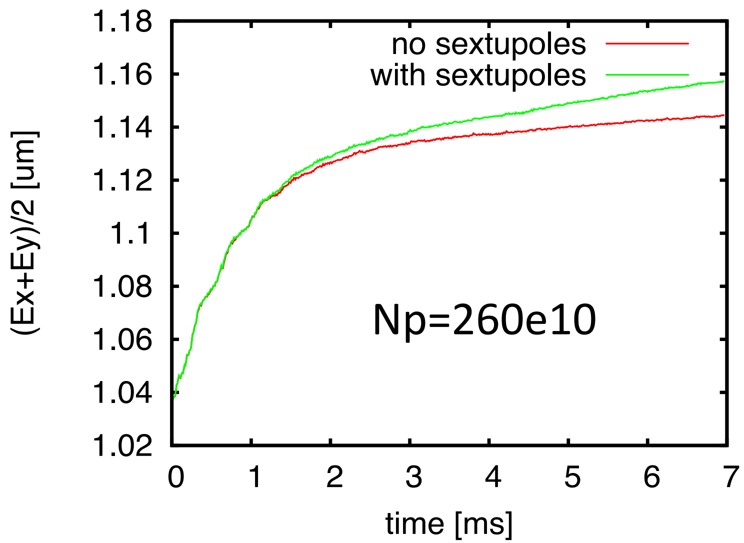
Simulations:
Loss rate depends on beta-beating

Non-linear effects

- PSB is equipped with a complete set of multipoles to correct (empirically) any higher order errors
- What if we include non-linearities in our model?



Normal		Skew	
h3000 =	0.01	h2010 =	0.06
h2100 =	0.06	h2001 =	0.07
h1020 =	0.03	h1110 =	0.17
h0011 =	0.12	h0030 =	0.07
h0002 =	0.04	h0021 =	0.18



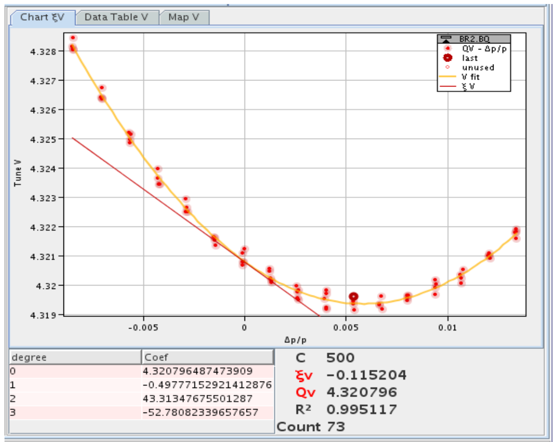
Additional emittance blow-up!
(knowing that eventually we can compensate them)

Other studies and next steps

- Driving terms excited by main dipoles not negligible

Normal	
h3000 =	0.01
h2100 =	0.02
h1020 =	0.006
h0011 =	0.01
h0002 =	0.02

- Non-linear chromaticity measurements for 2 different optics: ~good agreement with our current MADX model



Q	Q'	Q''	Measured Q'	stdev
		Standard working point		
4.20	-3.35	45	15.1	5.7
4.30	-6.84	87	44.4	13.7
		Standard working point		
3.32	-2.81	78	48.3	3
3.81	-4.97	116	112	34

- Turn-by-turn beam position measurements will be possible next year (new BPM electronics)

Conclusions

- **Can we achieve ~factor 2 brightness with 160 MeV injection?** Simulations indicate yes!
  - Simulations at 50 MeV (simple model) agree with **measurements**
  - Prediction for 160 MeV confirmed linear dependence emittance vs intensity
  - Full blown simulations to include multi-turn H- injection confirm results of simple model
  - Larger horizontal tune Qx=4.30 → 4.42 gives extra margin
- **Importance of the integer lines → blow-up**
  - Can we eventually compensate them? …all orders! :-\
- **Importance of the 2Qy=9 line**
  - Compensated in operation, (incoherent) losses explained and reproduced in simulations
- **Work to include non-linear terms in our model has started**

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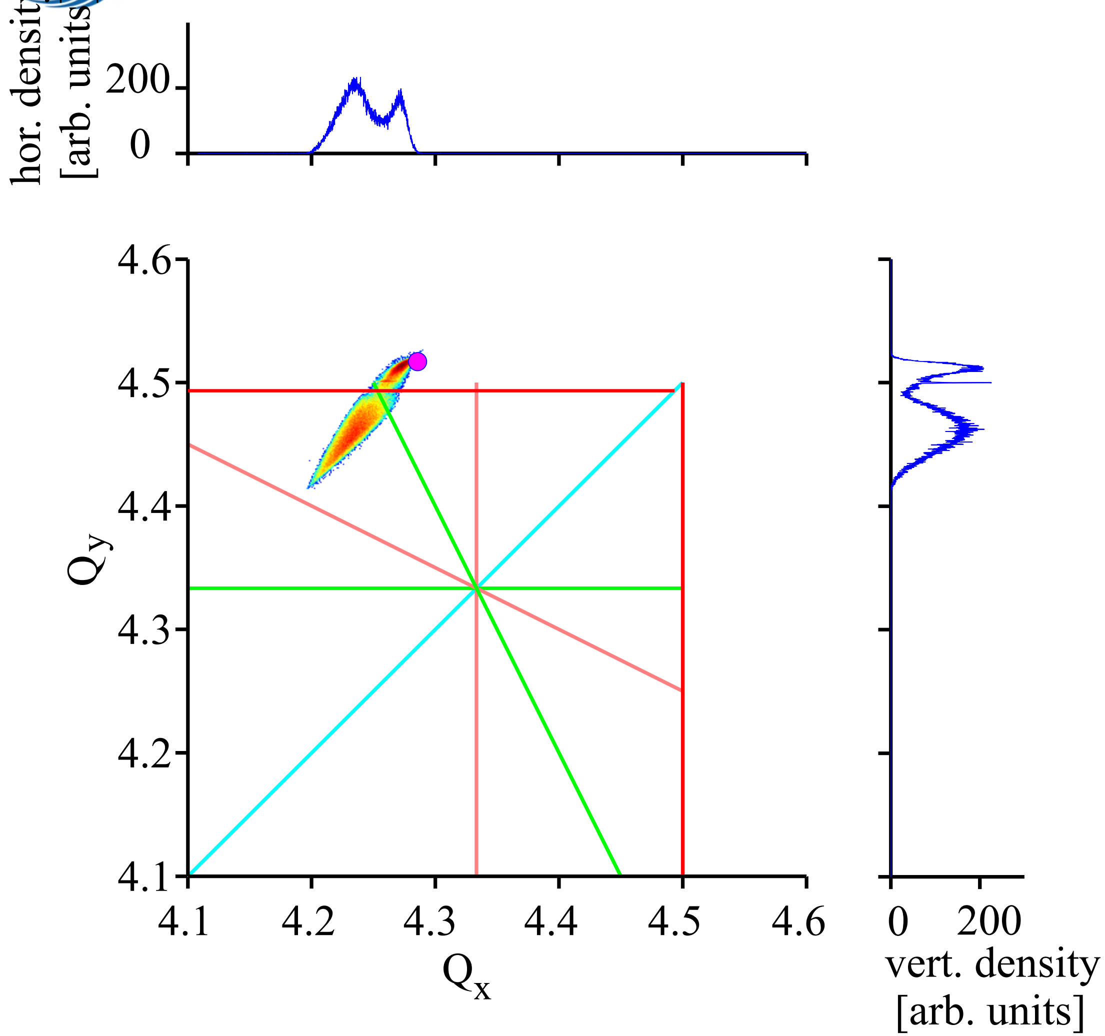
Half-integer

Table 5.3: Half-integer case - measured initial beam parameters.

Initial beam parameters	**long bunch**	**short bunch**
Intensity [10^{12} p]	1.39	1.32
ϵ_x, ϵ_y [mm·mrad]	2.64, 2.05	3.24, 2.13
RF voltage (h=1, h=2) [kV]	8, 8	8, 8
RF cavities relative phase	π	0
Total bunch length [ns]	634	400
Momentum spread (1σ)	1.35×10^{-3}	2×10^{-3}
Tune Q$_x$, Q$_y$	4.28, 4.53	4.28, 4.53
Max space charge tune shift - Eq. (1.67) $\Delta Q_x, \Delta Q_y$	-0.17, -0.2	-0.26, -0.36

Half-integer



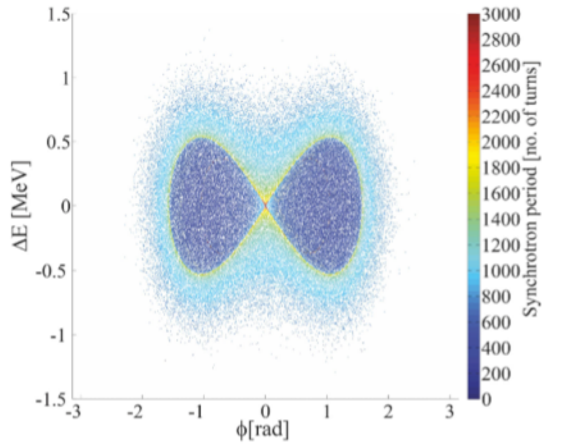
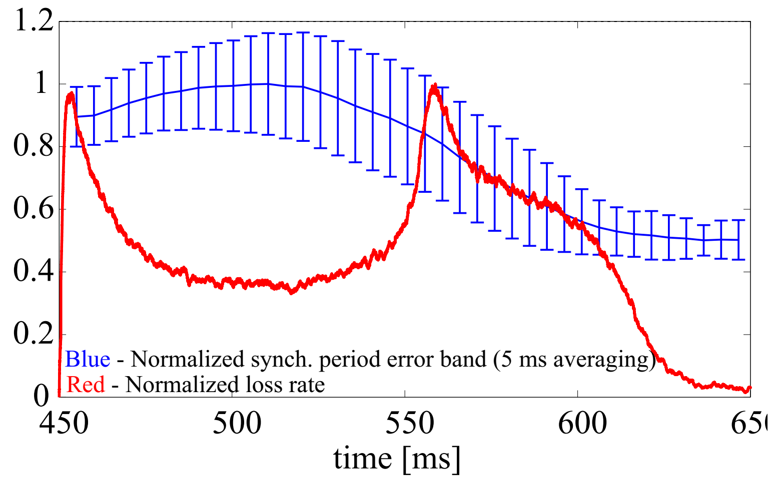
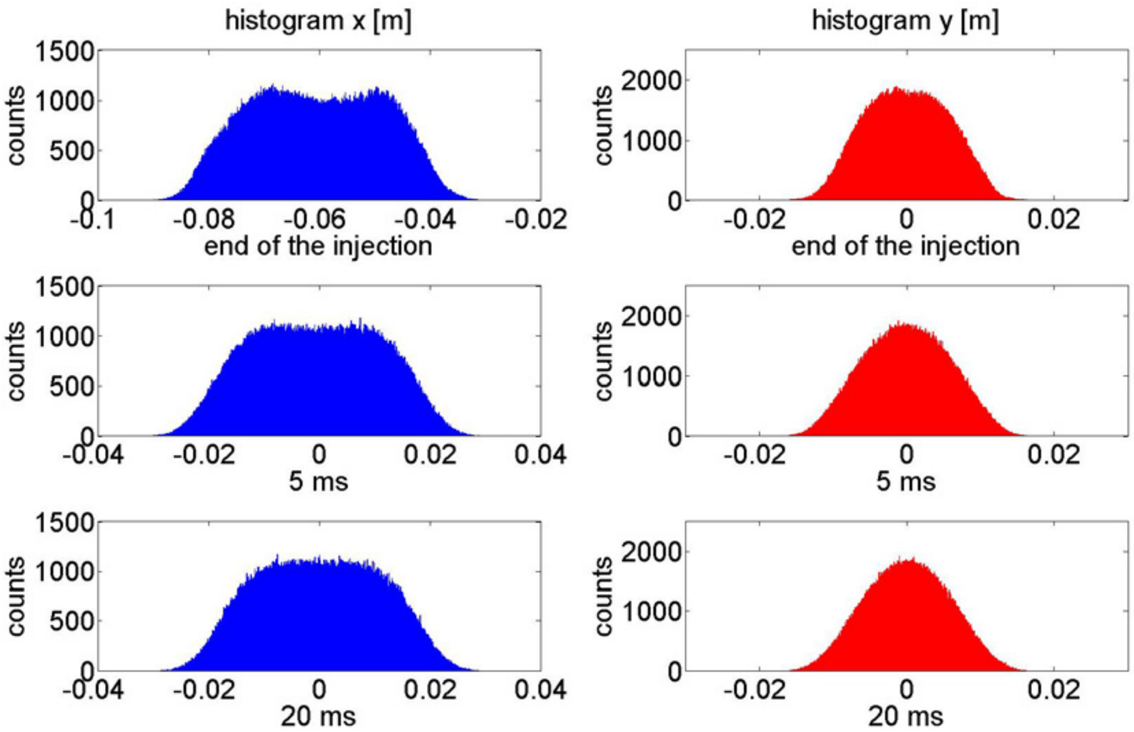


Figure 5.22: The synchrotron period variation in a double harmonics RF bucket.

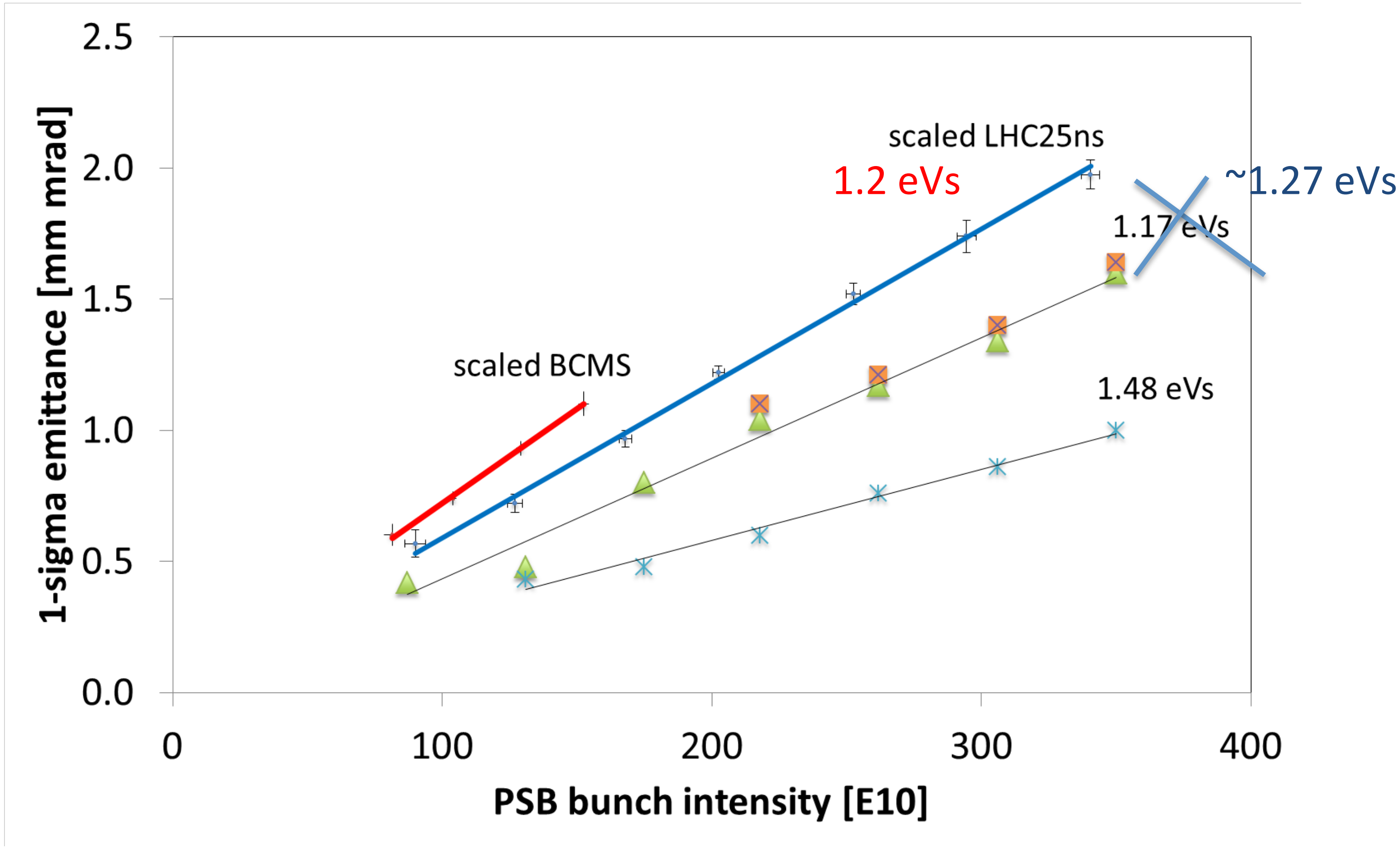


High intensity beams – up to 1.6e13



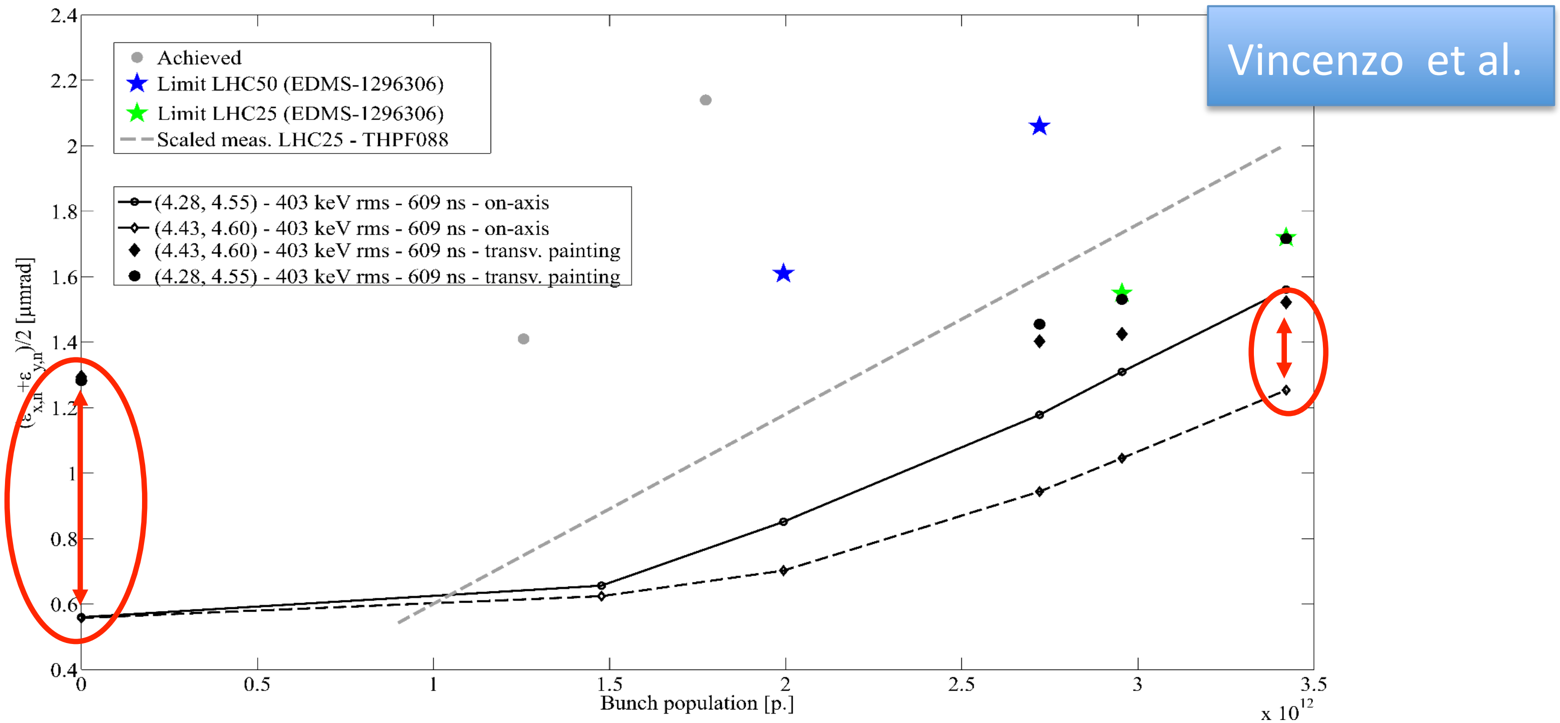
Horizontal (left) and vertical (right) beam transverse distribution at the end of the injection process (~100 µs), after 5 ms and 20 ms. Beam intensity is 1.6e13 protons and the final normalized rms emittances are 13 mm and 6 mm.

Simulations L4 - Matched beam



- On a straight line & depends on longitudinal emittance
- The slope for 1.20eVs is a factor 25% lower
- (in Orange: simulations adding 2012 measured set of errors)

Simulations L4 - full blown simulations



- Injection on-axis Vs, with transverse painting
  - KSW painting bump function input from ABT (J. Abelleira, C. Bracco)
  - Not optimized in Vertical
- Longitudinal distribution optimized (chopping factor and dp/p) (V. Forte, D. Quartullo)
- Confirmed results obtained with “matched beam”

What if L4 current was lower?

Tables assuming 60% chopping factor

For LHC

L4 current	60%	3.42E+12
mA	mA	# turns
50	30	19
45	27	21
40	24	23
30	18	31
20	12	46
10	6	92

For ISOLDE

L4 current	60%	100 turns	120 turns	150 turns
mA	mA	x1e10	x1e10	x1e10
50	30	1875	2250	2813
45	27	1688	2025	2531
40	24	1500	1800	2250
30	18	1125	1350	1688
20	12	750	900	1125
10	6	375	450	563

What if L4 current was lower? Impact on LHC

- Increase of # injected turns (from 20 to 30) will add **~Δε=0.10um**
- Can be absorbed by mismatch, painting, natural emittance evolution under Space Charge

HB2014, EB, C. Bracco et al.

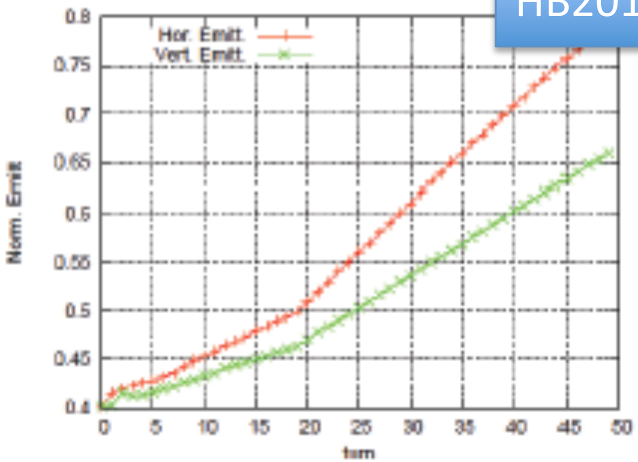


Figure 6: Simulated horizontal and vertical normalized emittance blow-up due to scattering at a 200 μg/cm² graphite foil. The multi-turn injection lasts 20 turns and the beam is not removed from the foil after injection has completed. Space-charge is not included.

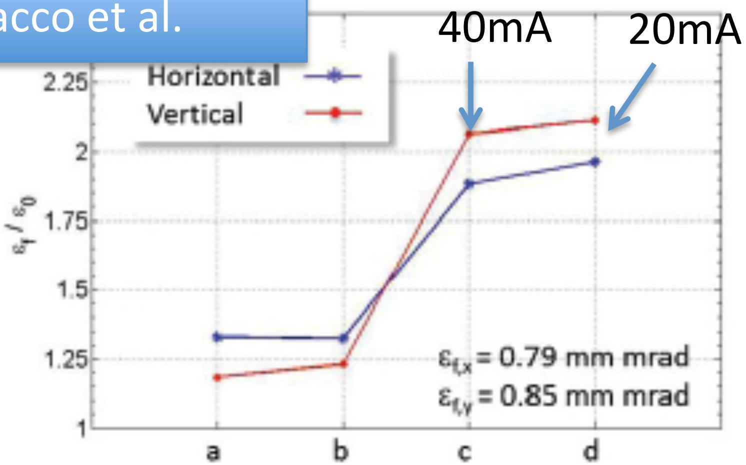
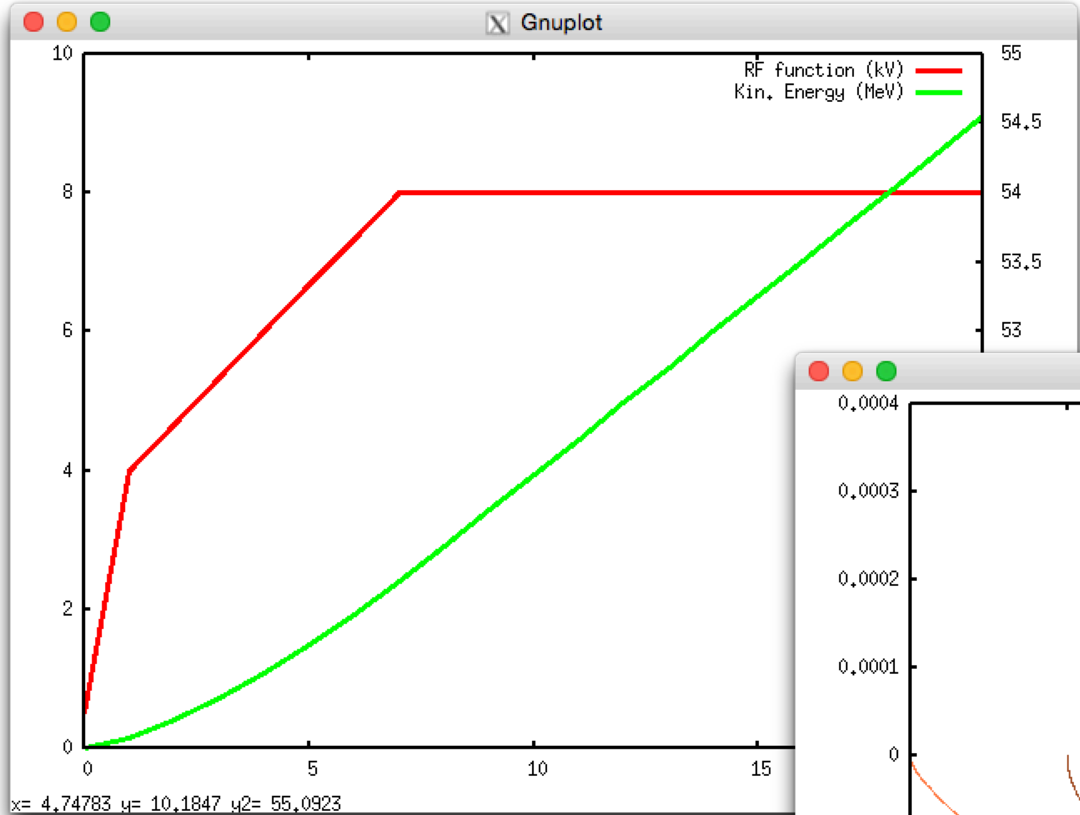
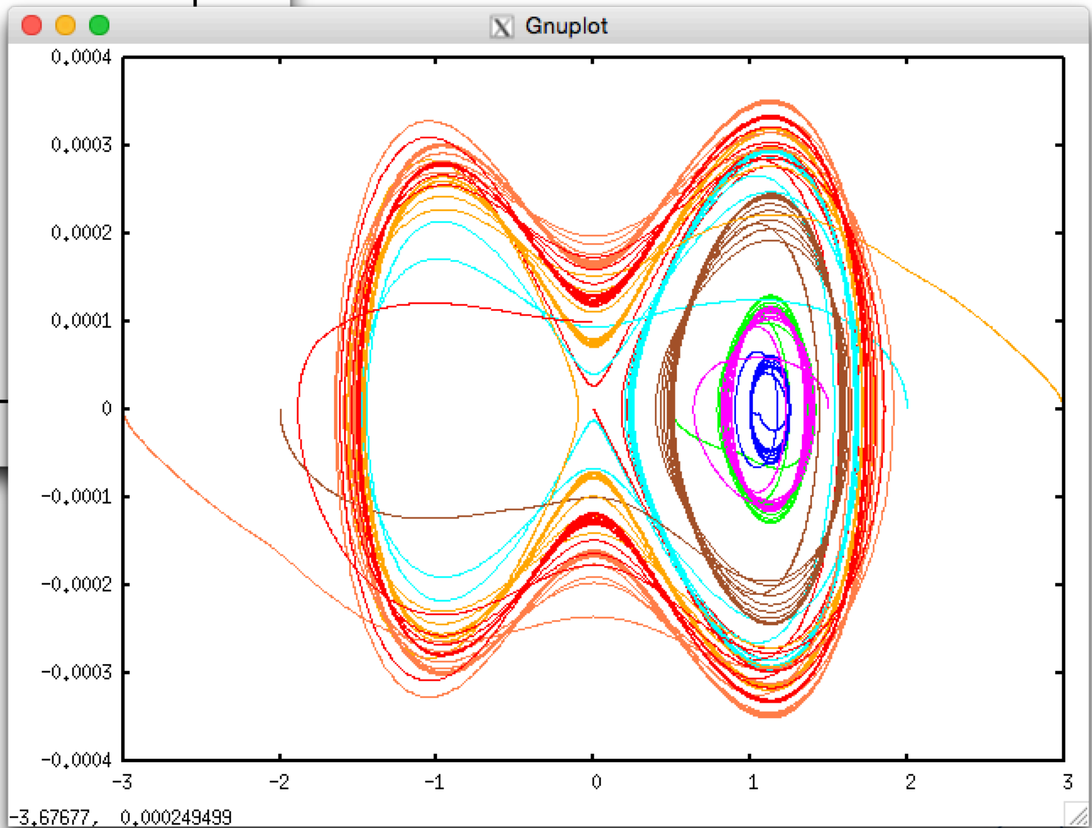


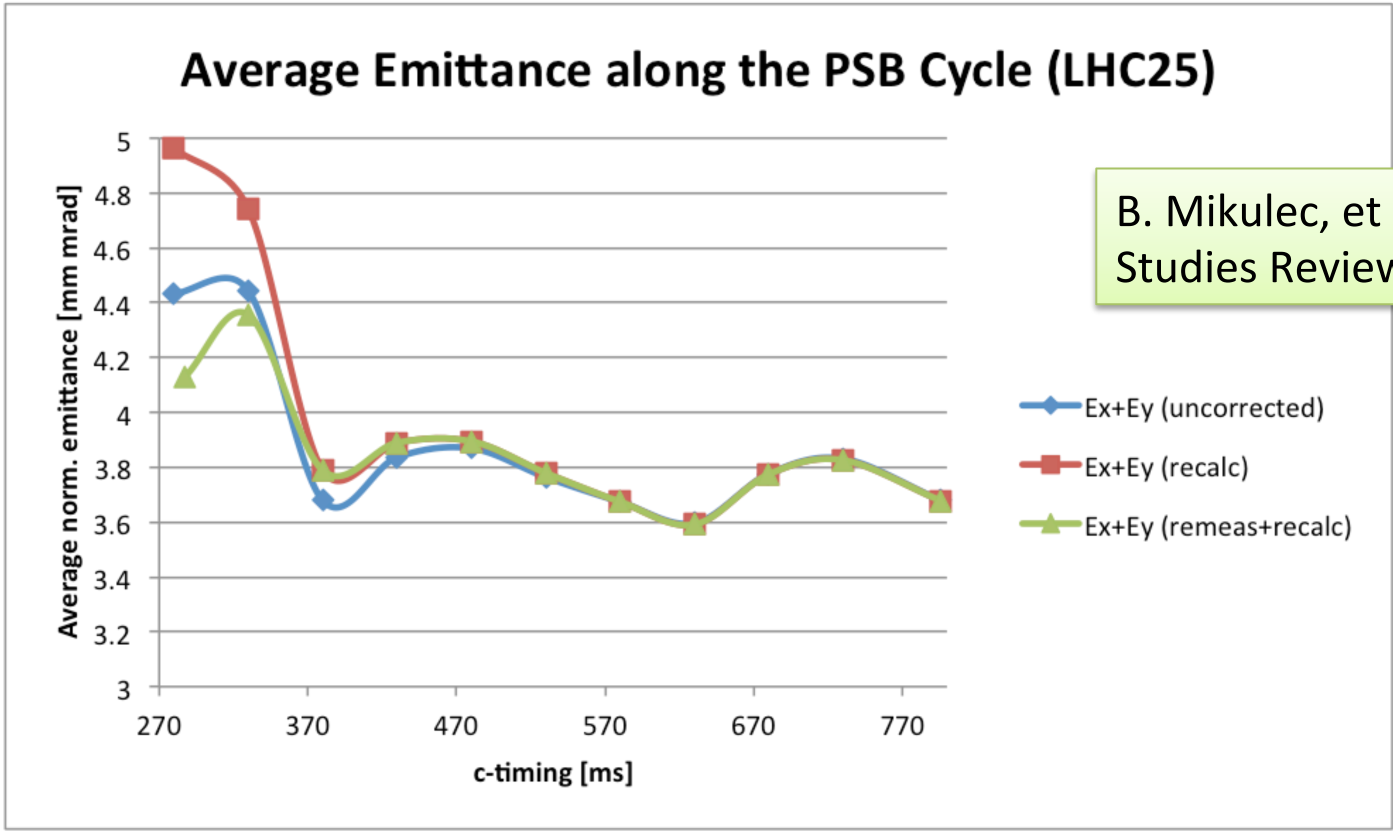
Figure 7: Ratio between final ε_f (after 100 μs) and initial emittance for different non-ideal scenarios (mismatched optics, orbit offset and reduced Linac4 current). A factor of two emittance blow-up is observed for the most conservative case (d).

Setting-up PTC-Orbit





Emittance vs. Intensity curve

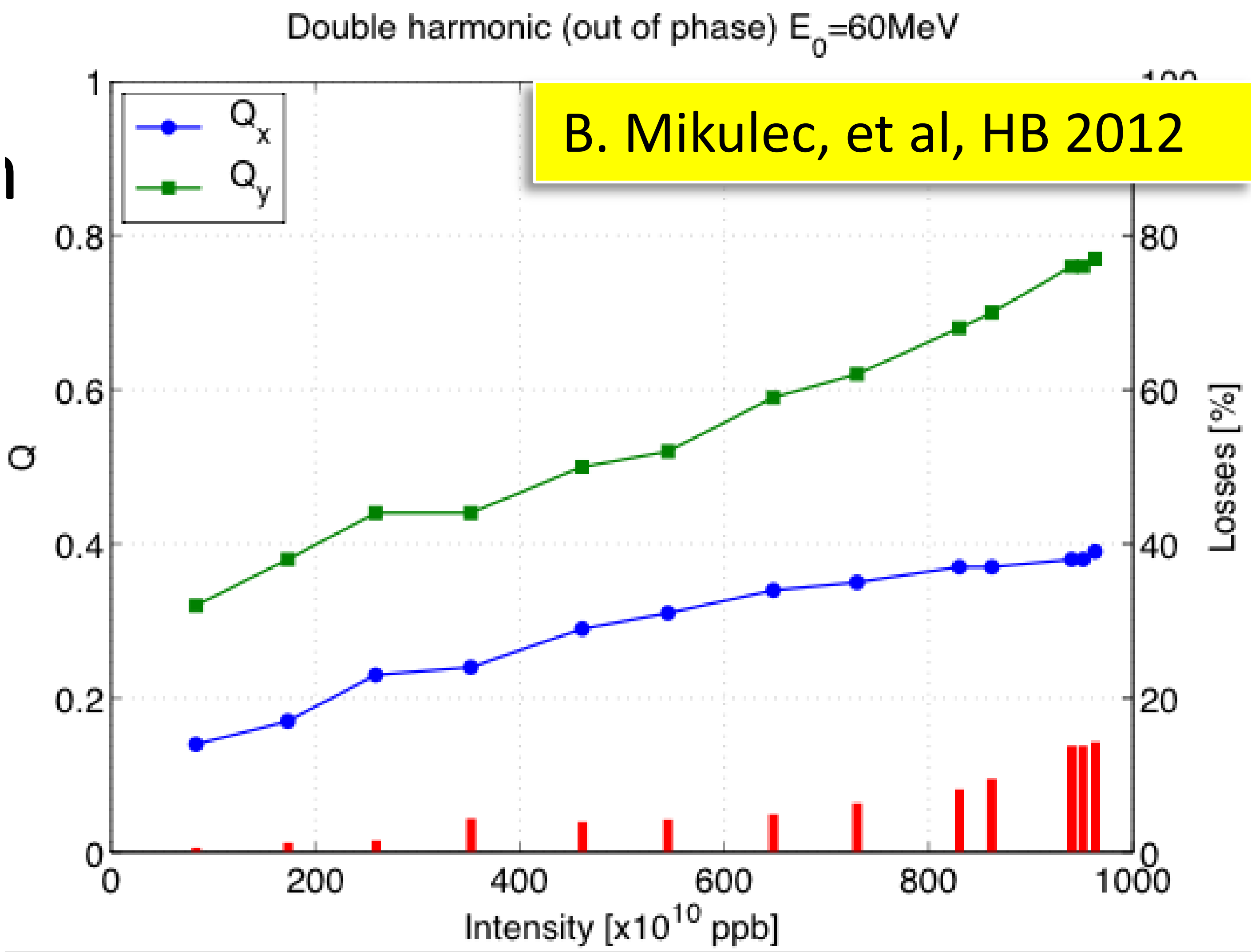


B. Mikulec, et al., LIU Beam Studies Review, 2012

Emittance is preserved along acceleration

Low energy points not understood (scattering at the wire scanners, calibration, uncertainties in dp/p,…)

Measured Space Charge tune spread and losses



Order of magnitude perturbation

- Edge effect (rectangular magnet):
  - k1L~ φ^2/2L~6e-3

- Feed-down from sextupole:
  - Int(Bdl)~c0+c1 x+c2 x^2 +…
  - x0=-50mm
  - → k1L~3.4e-3

E. Benedetto, et al. IPAC14