Theoretical studies of IBS in the SPS

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Outline

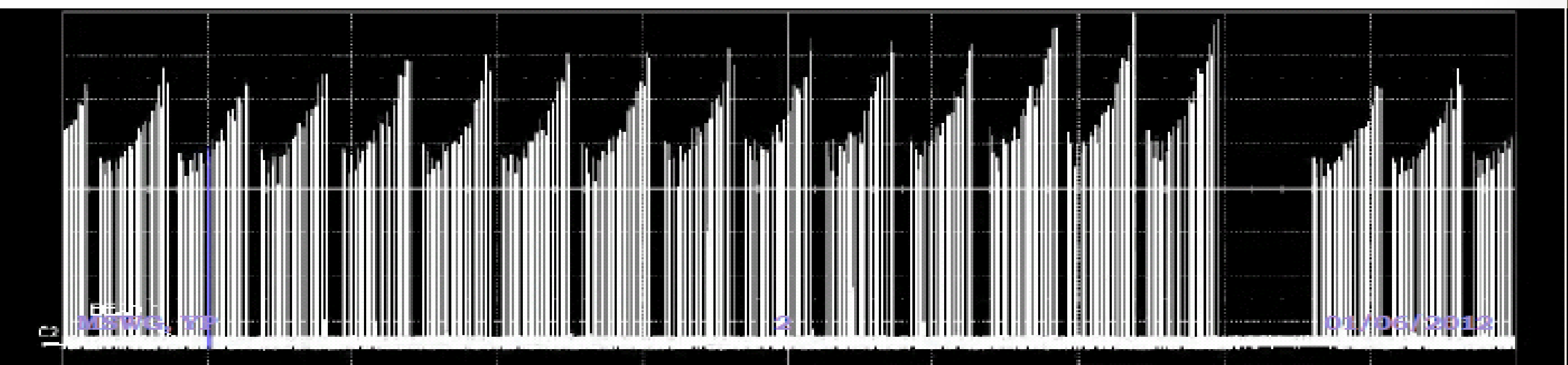
- Motivation
- Scattering effects and computational tools
- IBS simulations for ions in Q26 and Q20
- Bunch length measurements and Touschek scattering
- Lifetime after RF noise optimisation
- Measurements for fixed target beam
- Conclusions

Motivation

Thomas' presentation during LMC 116 (23/11/2011) on "Dispersion of lead ion beam parameters at the SPS flat top – Longitudinal aspects"

- Observation of bunch length and current decay during the SPS flat bottom
  - Growing with time spend in flat bottom, i.e. larger for 1st batch
  - Attributed to combination of RF Noise, Intrabeam Scattering (IBS) and space charge
- Not a real limitation for LHC but interesting to investigate how to overcome this problem
- Proposal to try Q20 optics for reducing IBS and space-charge due to larger beam sizes

Y. Papaphilippou, MSWG, 01/06/2012



Single and Multi-particle Coulomb scattering effects

- Single-particle scattering or “Touschek” effect
  - Large angle scattering events leading to the loss of one or both particles → Beam loss
- Multiple Coulomb scattering effect or “Intrabeam scattering”
  - Small angle scattering events leading to the redistribution of the beam phase space
    - Above transition → Always emittance growth
    - Below transition → Equilibrium exists (Damping of the emittance is also possible)
    - In the presence of Synchrotron radiation (e^+/e^- beams or very high energy hadron beams) equilibrium also exists (SR damping counteracts IBS growth)

➡ See also the talk of K. Cornelis in the MSWG meeting of 23 April 2013: http://indico.cern.ch/conferenceDisplay.py?confId=242146

Computational tools for IBS

- Piwinski and BM formalisms implemented in Mathematica
  - Both analytical considering Gaussian beams

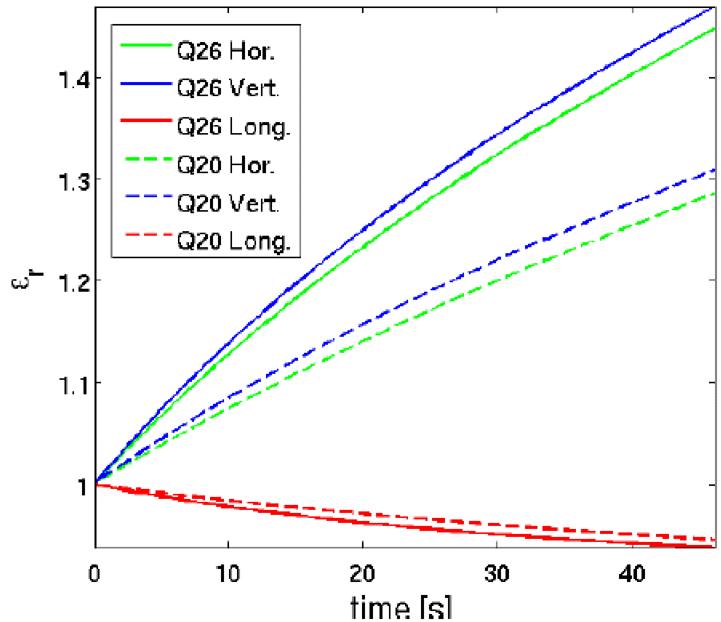
- BM formalism implemented in MADX
  - IBS module has been debugged and cross-checked with the Mathematica implementation for different lattices (LHC, CLIC DR, SLS) giving very good agreement → confidence that it produces the correct results
  - the user should be careful as conflicts (especially if RF is on) can produce “unrealistic” results.

- To go from the IBS growth rates to the emittance evolution with time:

$$\varepsilon_x = \varepsilon_{x0}\, e^{2*t*Tx}$$
$$\varepsilon_y = \varepsilon_{y0}\, e^{2*t*Ty}$$
$$\sigma_p = \sigma_{p0}\, e^{2*t*Tl}$$

T_x, T_y, T_l : IBS growth rates

Theoretical IBS calculations for Q20 and Q26 optics

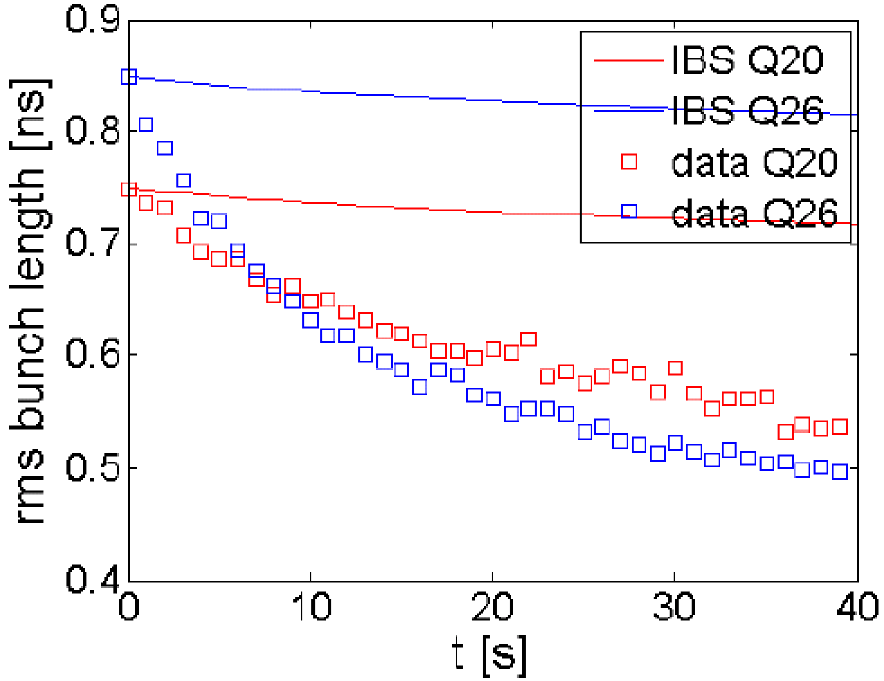


Parameters	Value
Bunch population [10^8]	2.4
Pb^{82+} classical radius [m]	5×10^{-17}
Relativistic γ/β	7.31/0.99
rms bunch length [m]	0.3
rms energy spread	3.25×10^{-4}
Transverse norm. emittances [mm-mrad]	0.8×10^{-4}

SPS ion beam parameters as delivered to the LHC during the 2011 run

- The larger dispersion and beam sizes of the Q20 optics has a positive impact to the IBS effect (~15% reduced effect in the transverse plane, almost the same in the longitudinal plane)
- In a cycle duration of 40 sec a large effect is expected in the transverse plane
- Bunch length reduction expected in the longitudinal plane (bunch length reduction was observed in beam measurements → IBS a candidate to explain the effect)

IBS theoretical expectations Vs observations



Constant transverse emittances measured: ($\varepsilon_{x,y}$ = 0.8 μm-rad) Precision of measurement?

- Comparison with beam measurements showed that the observed effect in the longitudinal plane is much stronger than expected, while no transverse emittance blow up was observed → IBS is not the only effect there

Touschek or “Touschek-like” effect

- Considering the general lifetime expression and assuming a general quadratic form of the current decay with time:

$$\frac{1}{\tau} = -\frac{1}{I}\frac{dI}{dt}, \quad \frac{dI}{dt} = -\frac{I}{b} - \frac{I^2}{a}$$

$$I(t) = \frac{\alpha I_0 e^{-t/b}}{b I_0 (1 - e^{-t/b}) + \alpha}$$

α: Touschek parameter
b: lifetime factor due to other effects (linear) such as RF noise

- Non-relativistic round beam approach
  Ref: “The Touschek effect in strong focusing storage rings”, A. Piwinski, DESY 98-179, Nov. 1998

$$\frac{1}{T_\ell} = \left\langle \frac{c r_p^2 \beta_x \beta_z \sigma_h N_p}{8\sqrt{\pi}\beta^2\gamma^4\sigma_{x\beta}^2\sigma_{z\beta}^2\sigma_s\sigma_p} \int_{\tau_m}^{\infty} \left(\frac{\tau}{\tau_m} - 1 - \frac{1}{2}\ln\frac{\tau}{\tau_m}\right) e^{-\tau B_1} I_o(\tau B_2) \frac{d\tau}{\tau^{3/2}} \right\rangle$$

$$\tau_m \equiv \delta_{acc}^2 = \frac{2 n_e V_{rf}}{\pi h \eta_p \beta_r^2 E n}$$

The minimum acceptance of the machine → For the SPS this is the RF acceptance (not directly applicable for filled buckets)

$$\alpha = \frac{e n_e 8\sqrt{\pi}\beta^2\gamma^2\sigma_z\sigma_p\epsilon_x\epsilon_y}{r_e^2 c T_o \langle \sigma_H F(\delta_m) \rangle}$$

Numerical example – Q20 Vs Q26

- Using the same parameters as for the IBS calculations:

Parameters	Value
Bunch population [10^8]	2.4
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SPS ion beam parameters as delivered to the LHC during the 2011 run

α_{Q20}=0.3038 mA-sec

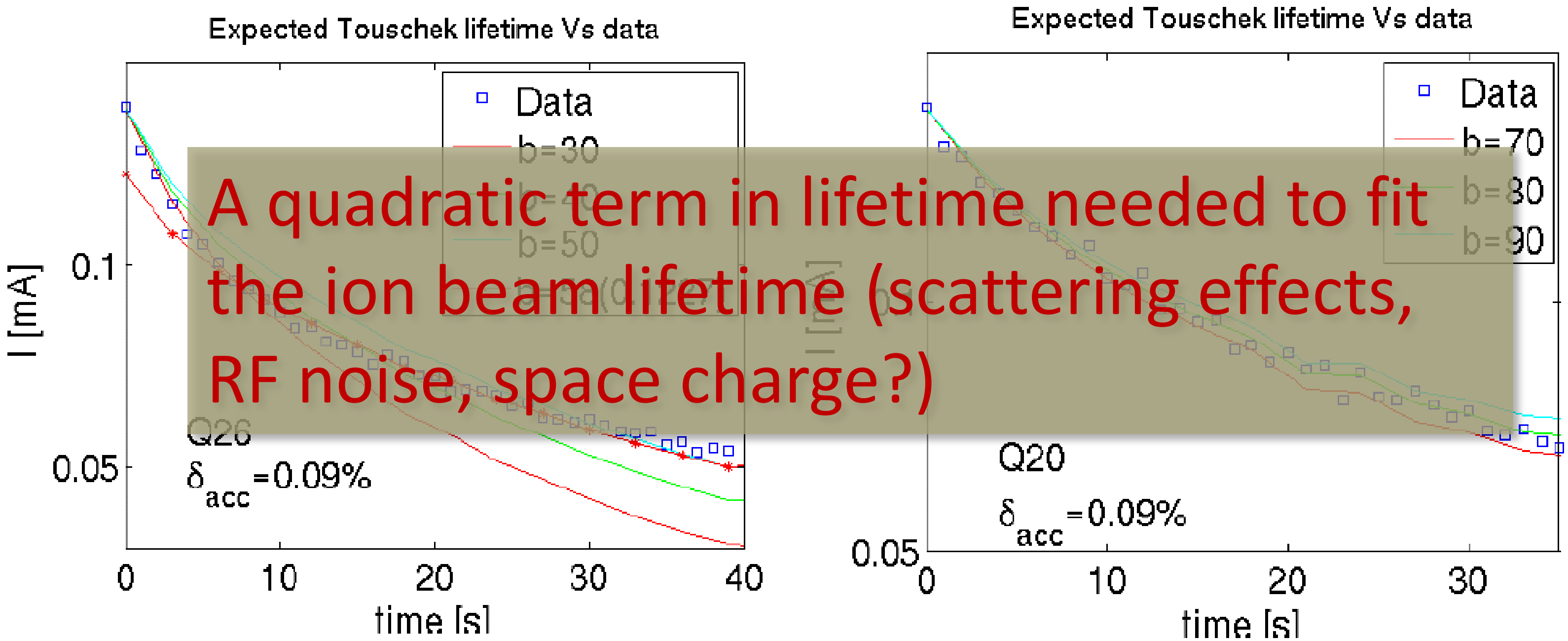
α_{Q26}=0.1546 mA-sec

→ The Touschek contribution to the lifetime expression is expected to be a factor of 2 larger for the Q26 optics.

- Incoherent space charge tune shift for the above parameters:

$\delta Q_{y,Q26}$=-0.15, $\delta Q_{y,Q20}$=-0.13

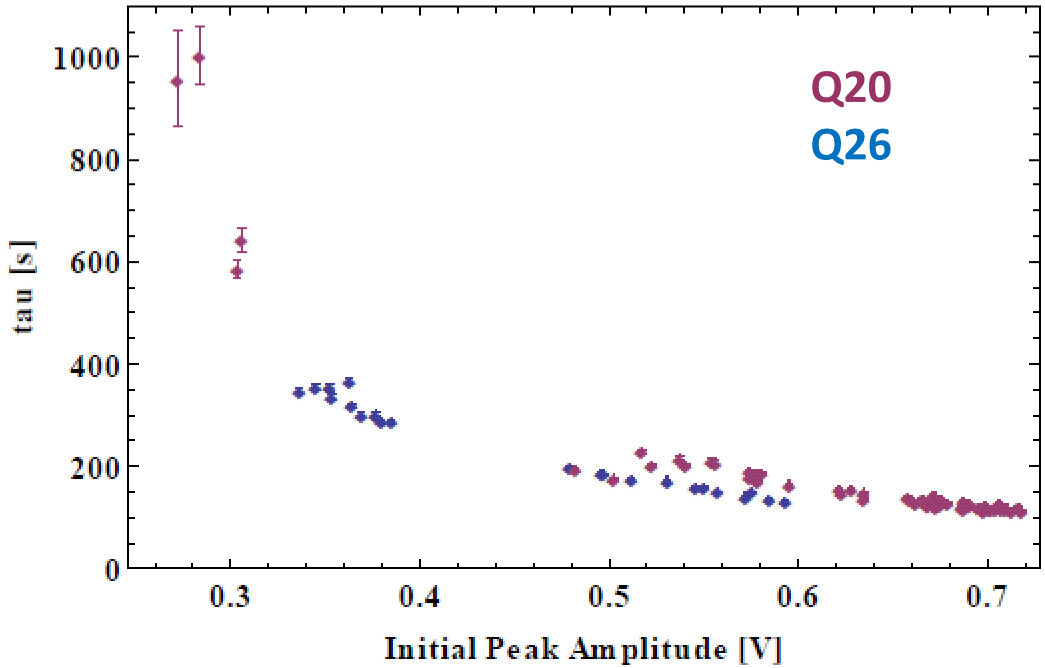
Comparison with data



A quadratic term in lifetime needed to fit the ion beam lifetime (scattering effects, RF noise, space charge?)

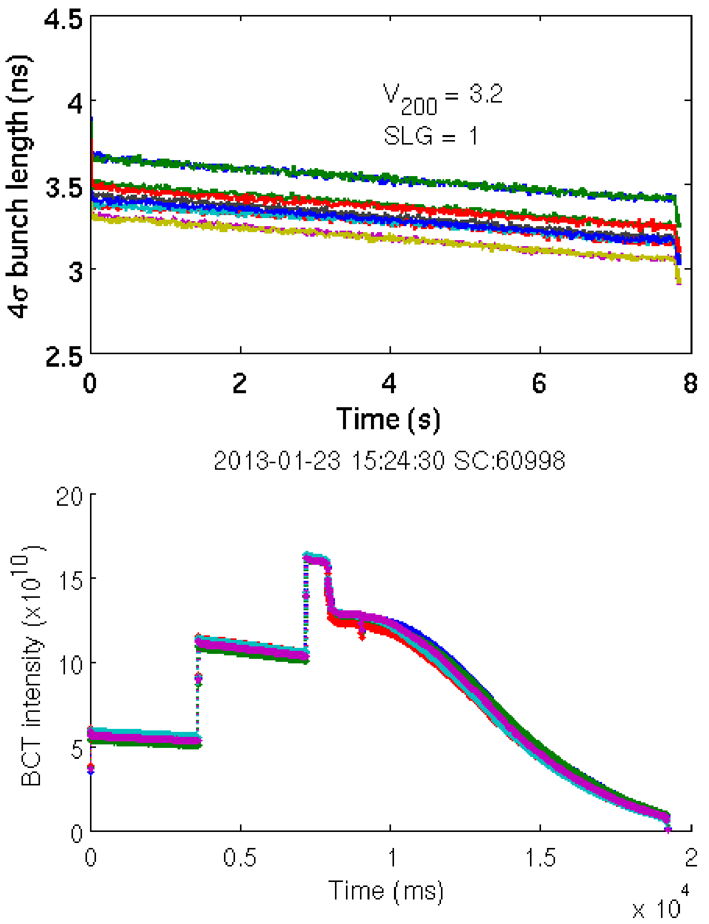
- Calculations considering constant transverse emittances
- The Touschek lifetime sensitive to the acceptance → Calculations for different acceptance values with δ_{acc}=0.09 % giving the best fit (theoretical one 0.12%)
- Q26: Considering fast losses in the beginning that cannot be included in the b factor (e.g. space charge) a "Touschek like" behavior applies to the data if we ignore the first data points
- Q20: A "Touschek like" behavior applies to all data

RF noise optimization



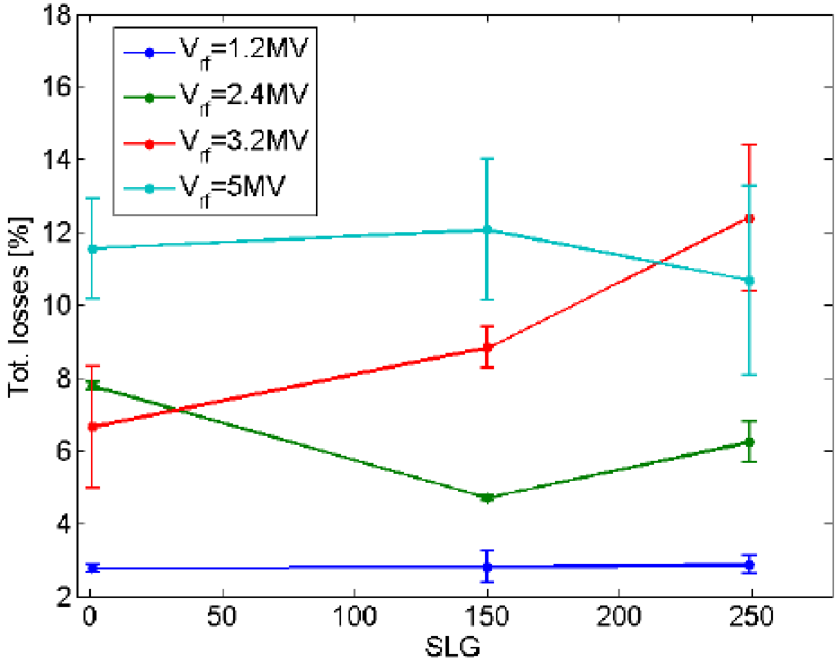
- An upgrade and optimization of the low-level RF system in 2012 minimized the contribution of the RF-noise to the beam lifetime (see T. Bohl, MSWG 2013-04-23, Note-2013-02)
- Better lifetime for the Q20 than the Q26 as expected by the theoretical calculations

January 2013 MD Data



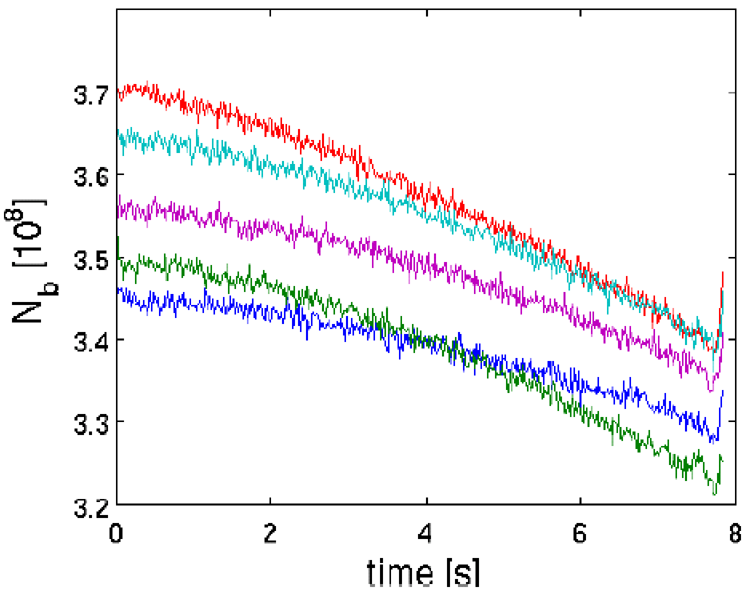
- Measurements with the fixed target (FT) ion beam with different working point than the one of the LHC ion beam
  - Fractional part of the tune above the half integer and below the third order resonance lines
- Life time data along the flat bottom were collected for different RF voltage and Synchro-loop Gain settings

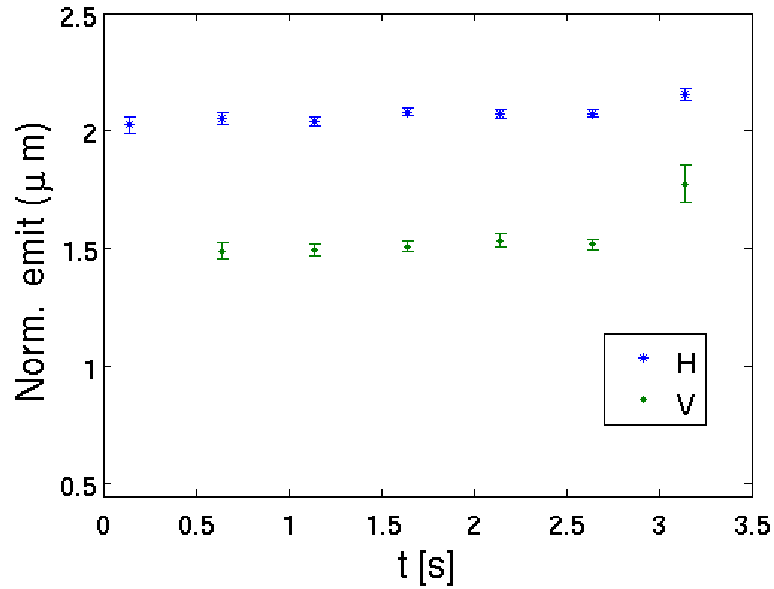
January 2013 MD Data



- The total losses are minimized for the lower RF voltage (1.2MV) and for this the dependence on the SLG is minimal
- Operational experience over the years showed that the optimal RF voltage for the operation of the SPS is 3.2 MV. For this voltage losses are minimized for the smallest SLG (SLG=1)

January 2013 MD Data





- Lifetime at the flat bottom for V_{rf}=3.2MV and SLG=1
- The life time follows a very different than "Touschek-like" behavior
- Both transverse emittances were measured to be constant along the flat bottom, ε_x = 2 μm-rad and ε_y = 1.5 μm-rad → much larger than expected (0.8 μm-rad) and with a non-Gaussian beam profile
- Indication of space charge (reminder: this was a FT beam with WP close to the half integer)

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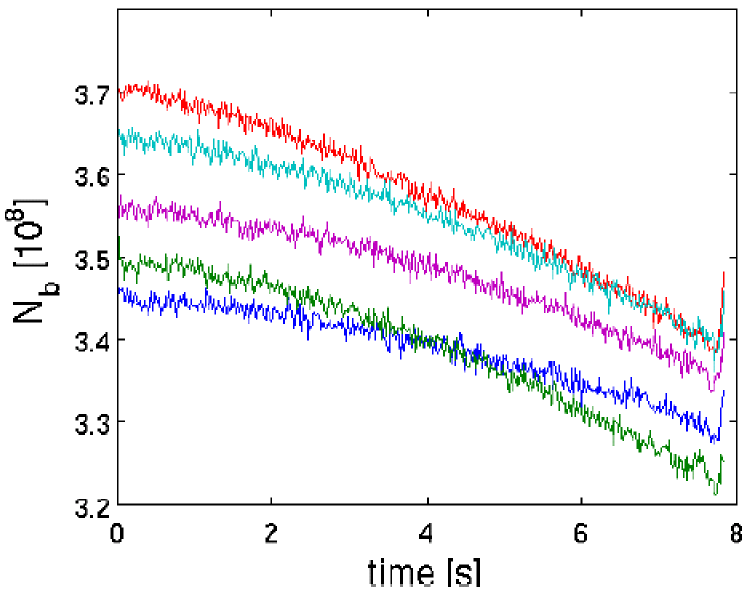

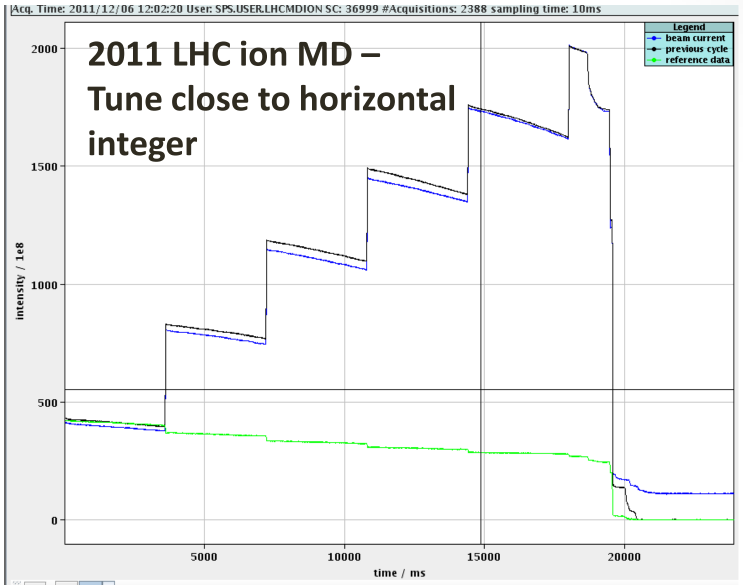

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- Indication of space charge (reminder: this was a FT beam with WP close to the half integer)
- Same effect was observed in 2011 MD data when the LHC I-beam WP was put close to the integer resonance

Conclusions

- Ion beam lifetime in SPS flat bottom is limited by a combination of RF noise, scattering and space-charge effects
- Lifetime curves could be fitted with a Touschek like current decay dependence (quadratic)
- RF noise greatly improved lifetime in 2013 run
- Lifetime with Q20 is better than in Q26 as expected by theoretical model
- For fixed target beam, lifetime curve indicates that space-charge may be dominant
- Perspectives for modeling
  - Modify Touschek formalism for "filled" buckets
  - Include effect of RF noise and space-charge (SIRE IBS code extension)
- Repeat measurements at SPS flat bottom for different working points and bunch currents for understanding interplay of scattering effects with space-charge
  - Lifetime, bunch length (longitudinal emittance) but also transverse emittance measurements

The BM formalism

$$\frac{1}{T_i} = 4\pi A(log) \left\langle \int_0^\infty d\lambda \frac{\lambda^{1/2}}{[det(L+\lambda I)]^{1/2}} \left\{ TrL^{(i)} Tr\left(\frac{1}{L+\lambda I}\right) - 3TrL^{(i)}\left(\frac{1}{L+\lambda I}\right)\right\}\right\rangle$$

$$L = L^{(p)} + L^{(x)} + L^{(y)},$$

$$L^{(p)} = \frac{\gamma^2}{\sigma_p^2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$L^{(x)} = \frac{\beta_x}{\varepsilon_x}\begin{pmatrix} 1 & -\gamma\phi_x & 0 \\ -\gamma\phi_x & \gamma^2\mathcal{H}_x/\beta_x & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$L^{(y)} = \frac{\beta_y}{\varepsilon_y}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \gamma^2\mathcal{H}_y/\beta_y & -\gamma\phi_y \\ 1 & -\gamma\phi_y & 1 \end{pmatrix},$$

$$(log) = f_{\mathrm{CL}} \ln\left(\frac{\gamma^2\varepsilon_x\sqrt{\beta_y\varepsilon_y}}{r_0\beta_x}\right)$$

$$\phi_{x,y} \equiv D'_{x,y} - \frac{\beta'_{x,y}D_{x,y}}{2\beta_{x,y}},$$

$$\mathcal{H}_{x,y} = \frac{1}{\beta_{x,y}}\left[D_{x,y}^2 + \left(\beta_{x,y}D'_{x,y} - \frac{1}{2}\beta'_{x,y}D_{x,y}\right)^2\right]$$