IBS - A View from the Tevatron

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Electron-Ion Collider Workshop
March 15-17, 2004
Jefferson Lab

Talk outline

1. Introduction
2. Parametric model of the Luminosity evolution
3. Interplay of Diffusion and Beam-beam effects

   Conclusions

1. Introduction

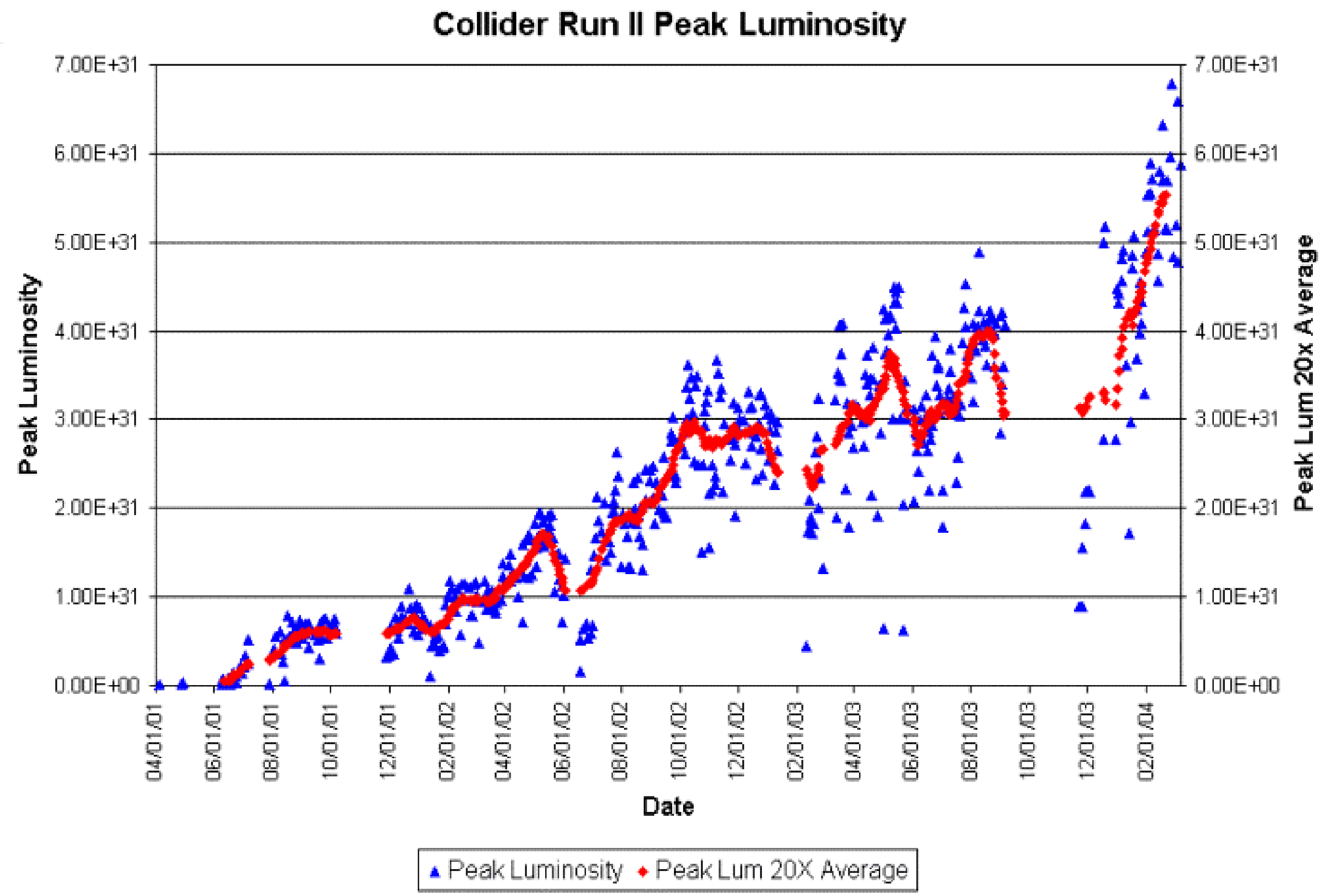
IBS in the Tevatron complex

- Electron cooler (4.3 MeV, energy recuperation, part. loss from collec. ~10^{-5})
  - Single scattering introduces tails in longitudinal distr. ⇒ particle loss from the collector of electrons
- Accumulator
  - Transverse IBS depends strongly on lattice functions
  - Two lattices
    - Stacking lattice – optimized for antiproton stacking
    - Shot lattice – optimized for final cooling
- Recycler
  - Longitudinal bunch compression to decrease IBS
    - Longitudinal and transverse temperatures are expected be equal for cooled beam
- Tevatron
  - IBS major effect leading to the luminosity decay

IBS physics

- Standard theory (Bjorken-Mtingwa, Piwinsky)
  - Gaussian distributions in all degrees of freedom
  - Not self-consistent
  - Single scattering is neglected
  - Formulas are quite complicated but still not sufficiently accurate in many practical application
- In many practical cases including colliders the long. temperature is much smaller than the trans. one in the beam frame
  - Significant simplification in theory
  - Single and multiple scattering can be treated together by comparatively simple integro-differential equation
  - As a rule in data analysis the IBS has to be considered together with other mechanisms affecting evolution of the distribution function
    - Gas scattering
    - Noises (RF noise, EMI, quad motion, *etc.*)
    - Beam-beam effects
    - Electron or stochastic cooling

Peak luminosity during Run II



- Steady growth for three years of Run II
- Peak luminosity is close to Run IIA (no electron cooling) design of $8\cdot10^{31}$ cm^{-2}s^{-1}
- There is potential for further luminosity growth (factor ~ 1.5) before electron cooling is available
- Final design peak luminosity is $30\cdot10^{31}$ cm^{-2}s^{-1} (4 –5 times of present best)

2. Parametric Model of Luminosity Evolution in Tevatron

The model takes into account the major beam heating and particle loss mechanisms

- **Phenomena taken into account**
  - ⇒ Interaction with residual gas
    - ♦ Emit. growth and particle loss due to E-M and nuclear scattering
  - ⇒ Particle interaction in IPs (proportional to the luminosity)
    - ♦ Emit. growth and particle loss due to E-M and nuclear scattering
  - ⇒ IBS
    - ♦ Energy spread and emittance growth due to multiple scattering
    - ♦ Particle loss due to single scattering (Touschek effect)
  - ⇒ Longitudinal dynamics
    - ♦ Nonlinearity and finite size of potential well
    - ♦ Bunch lengthening due to RF noise and IBS
    - ♦ Particle loss from the bucket due to single IBS (Touschek effect) and due to heating longitudinal degree of freedom (multiple IBS and RF noise)
    - ♦ Absence of tails after acceleration

- **Phenomena presently ignored in the model**

⇒ Beam-beam effects

- ♦ Important for first few hours into the store

⇒ Non-linearity of the lattice

- ♦ Plays no role in during a store

⇒ Diffusion amplification by coherent effects including strong-strong beam-beam effects

- ♦ We have no evidence that it makes any effect in Tevatron

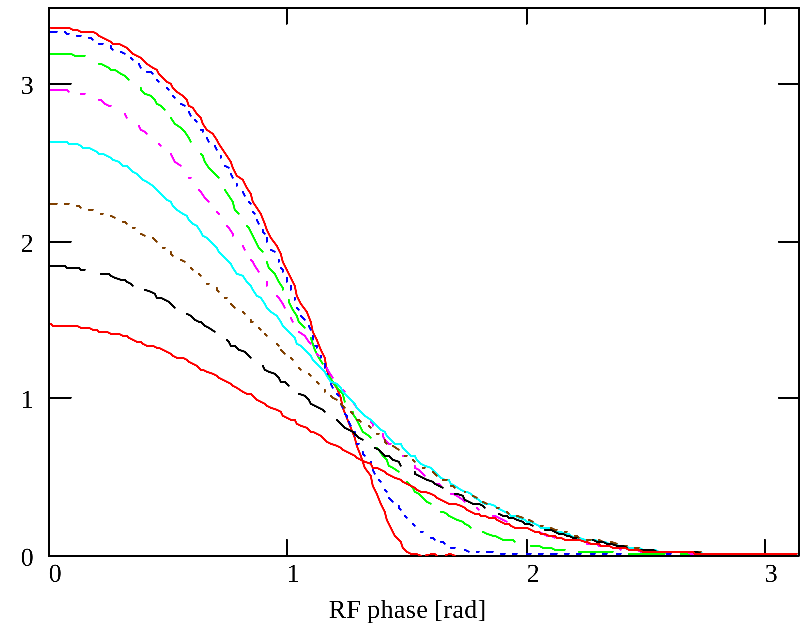
- **Thus, the model presents the best-case scenario**

⇒ It describes comparatively well our present stores

Beam Evolution in Longitudinal Degree of Freedom

- Longitudinal acceptance grows from 4 to 10 eV s during acceleration
  - ➢ Absence of tails after acceleration
- Interplay of single and multiple scattering
- The model based on a solution of integro-differential equation which describes both single and multiple IBS

$$\frac{\partial f}{\partial t} = \int_0^\infty W(I,I')\big(f(I',t) - f(I,t)\big)\mathrm{d}I'$$

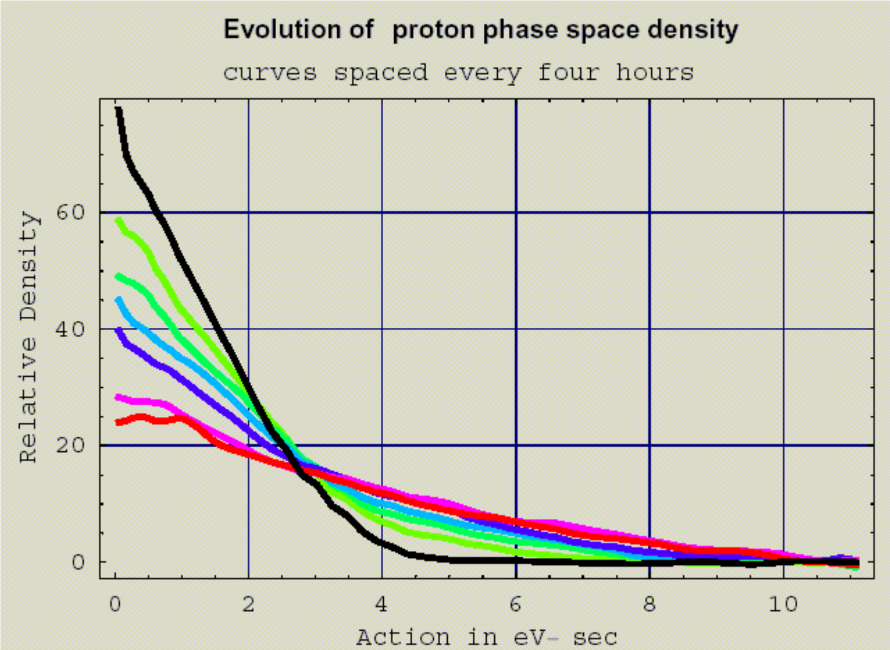


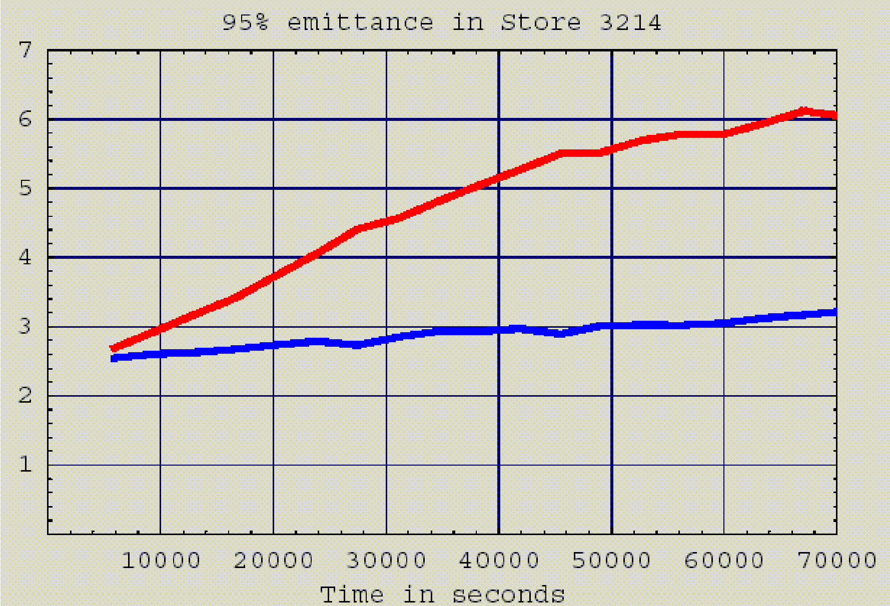
Numerical simulation of the longitudinal bunch profile evolution

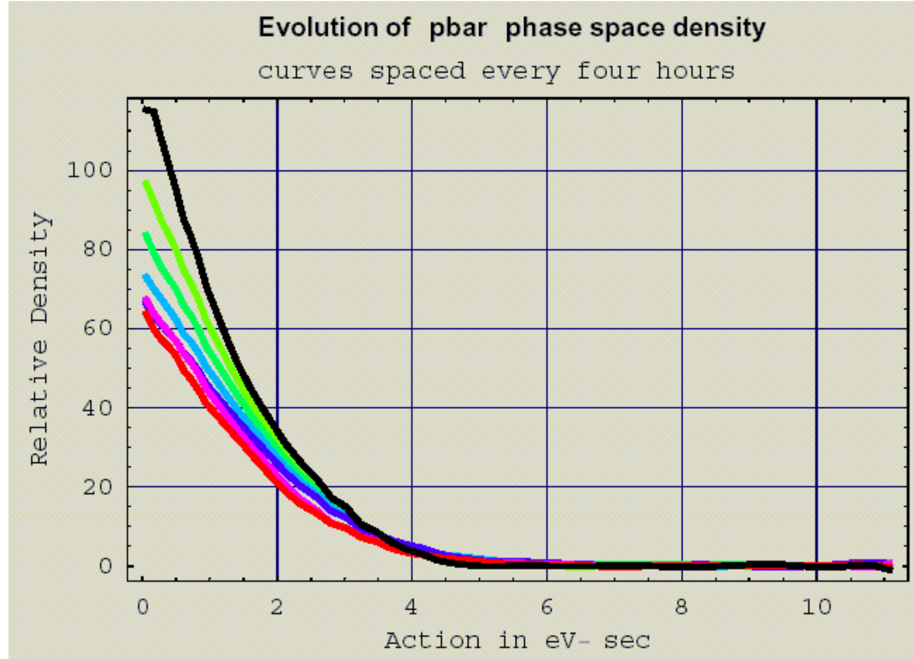
Here the kernel is (*A. Burov, Private communications, 2003*)

$$\tilde{W}(E,E') = \frac{Dw_0 ww'}{L_C (E-E')^2}\begin{cases} \dfrac{1}{2w} + \dfrac{I}{E'-E} \quad , & E' \geq E + dE \ , \\ \dfrac{1}{2w'} + \dfrac{I'}{E-E'} \quad , & E' \leq E - dE \ , \end{cases}$$

Measurements of beam distribution in the longitudinal phase space







A. Tollestrup , Feb. 2004.

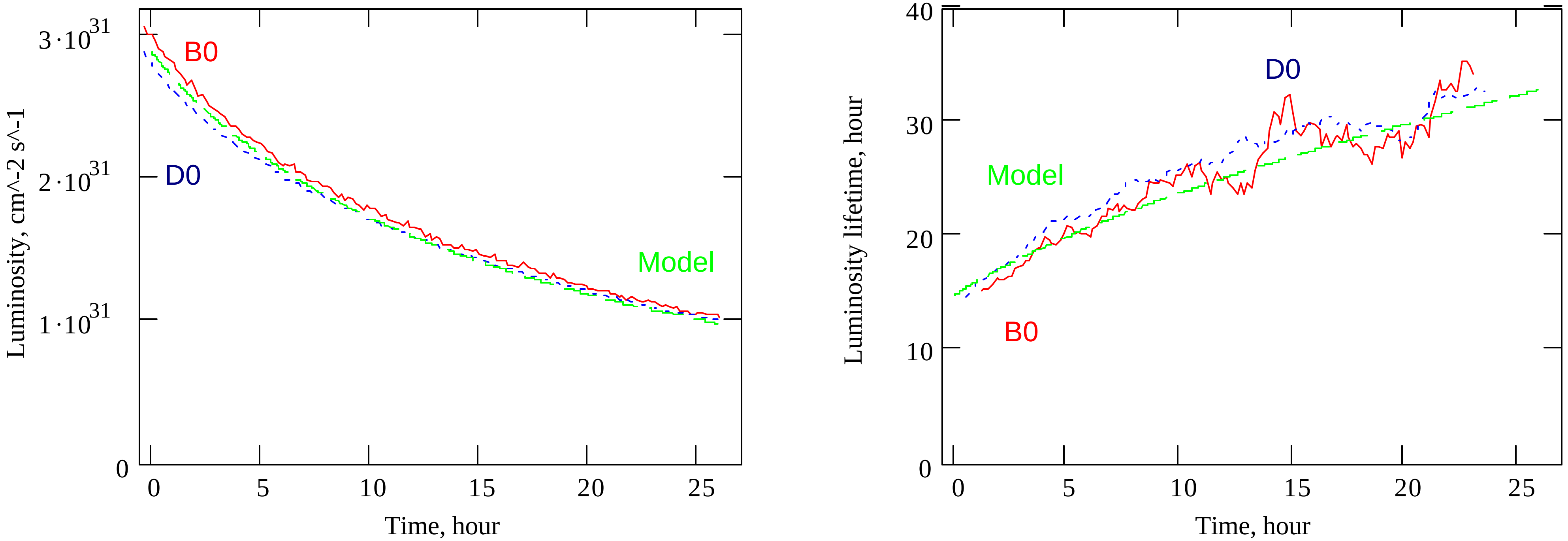
- Distribution functions are computed from signals of the resistive wall monitor (SBD)
- Entire bucket of 4.2 eV·s is filled at injection
- There is no long. emittance growth during acceleration
- Entire proton bucket of 10.7 eV·s is filled at the end of store

Parametric model of luminosity evolution

- Compromise between simplicity of the model and accuracy of the description
  - Finite accuracy of the measurements
- System of eight ordinary differential equations

$$\frac{d}{dt}\begin{bmatrix} e_{px} \\ e_{py} \\ s_{pp}^{2} \\ N_{p} \\ e_{ax} \\ e_{ay} \\ s_{pa}^{2} \\ N_{a} \end{bmatrix} = \begin{bmatrix} 2de_{px}/dt\big|_{BB} + de_{px}/dt\big|_{IBS} + de_{px}/dt\big|_{gas} \\ 2de_{py}/dt\big|_{BB} + de_{py}/dt\big|_{IBS} + de_{py}/dt\big|_{gas} \\ ds_{pp}^{2}/dt\big|_{total} \\ -N_{p}t_{scat}^{-1} - dN_{p}/dt\big|_{L} - 2Ls_{p\bar{p}}/n_{b} \\ 2de_{ax}/dt\big|_{BB} + de_{ax}/dt\big|_{IBS} + de_{ax}/dt\big|_{gas} \\ 2de_{ay}/dt\big|_{BB} + de_{ay}/dt\big|_{IBS} + de_{ay}/dt\big|_{gas} \\ ds_{pa}^{2}/dt\big|_{total} \\ -N_{a}t_{scat}^{-1} - dN_{a}/dt\big|_{L} - 2Ls_{p\bar{p}}/n_{b} \end{bmatrix}$$

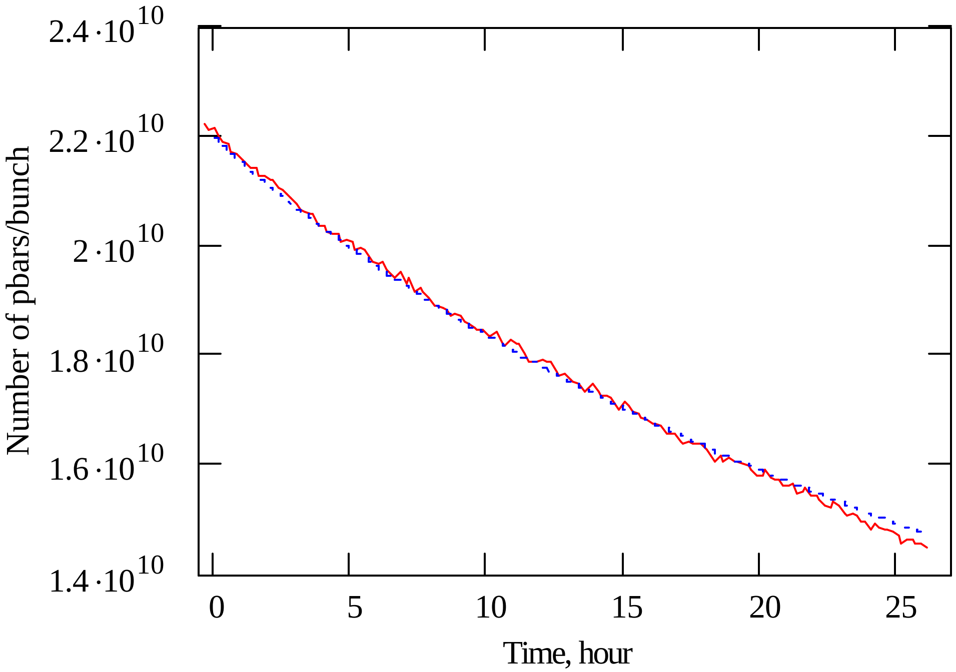
Luminosity Evolution



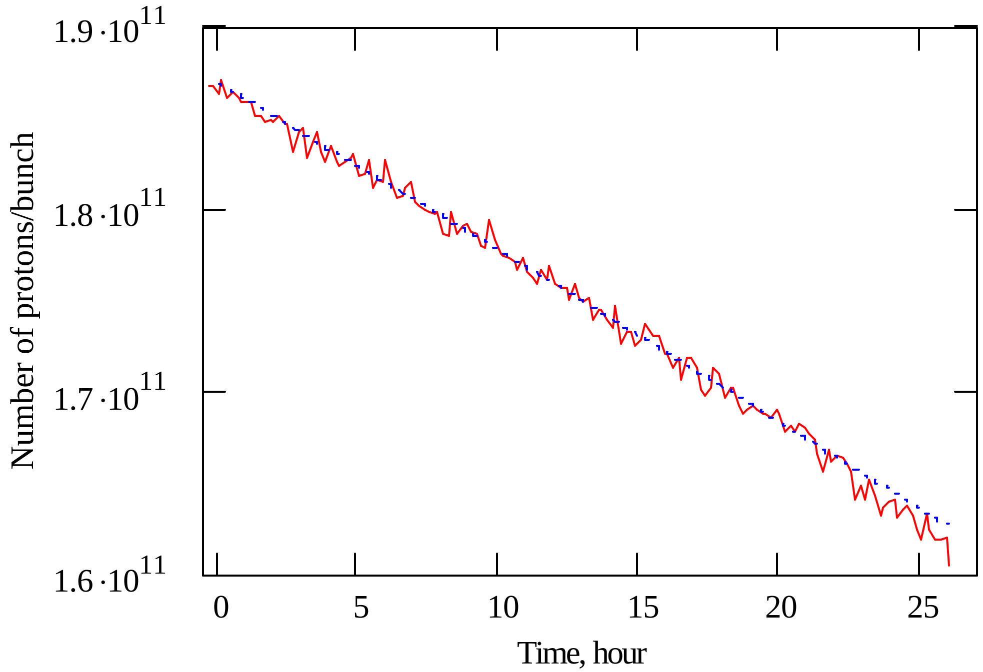
Good regular store !!! (Store 2138, Jan.5 2003)

- Three free parameters are used in the model
  - Residual gas pressure - P=$1\cdot10^{-9}$ Torr of N_2 equivalent
  - Spectral density of RF noise- $P_{ff}(f_s)\approx 5\cdot 10^{-11}\quad \mathrm{rad}^2/\mathrm{Hz}$ (70μrad in Δf=100Hz)
  - X-Y coupling - k = 0.4 (strong coupling due to beam-beam effects)
- Their values are not very critical for the luminosity prediction but important for detailed comparison

Bunch population per bunch (Store 2138)

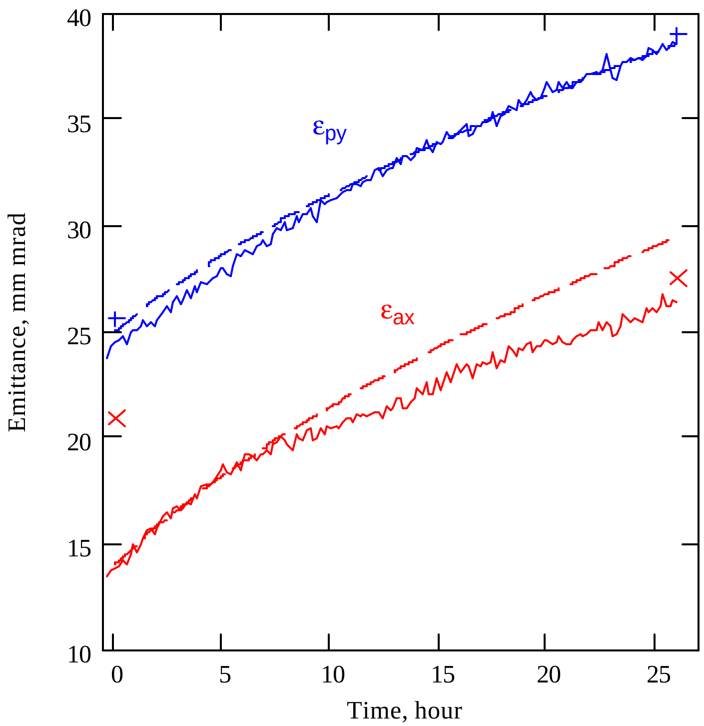


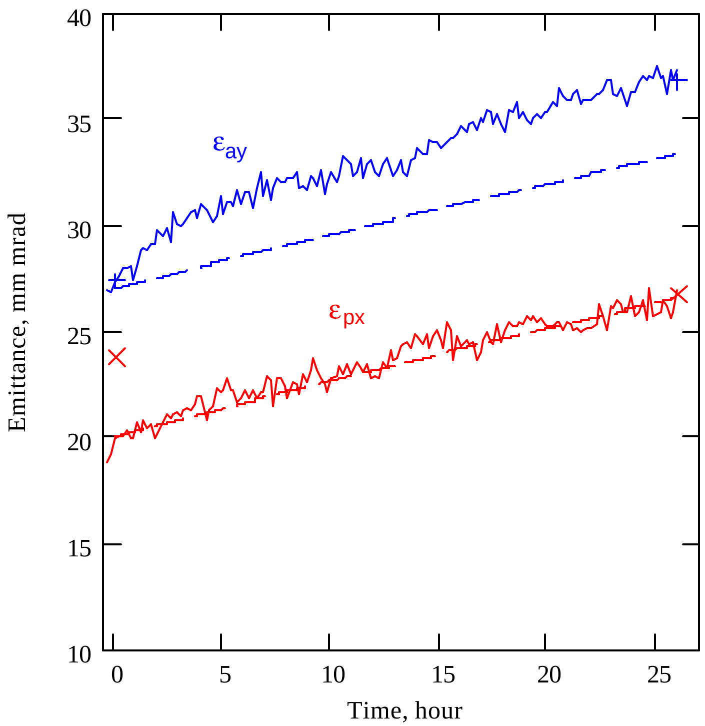
Pbars

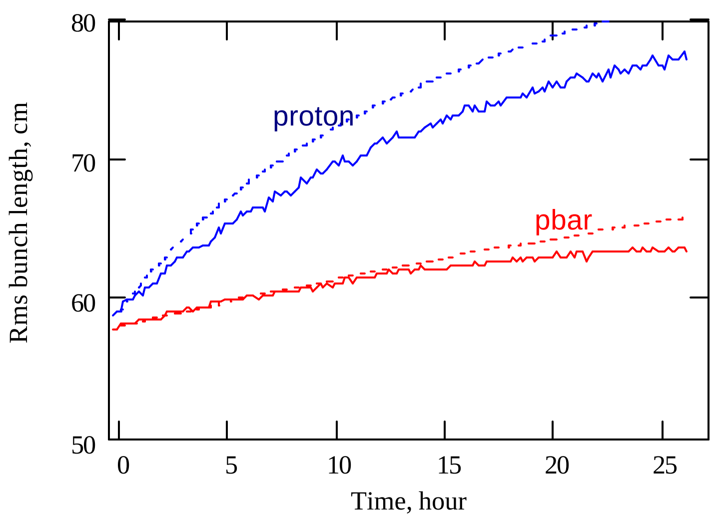


Protons

- **At the store beginning**
  - Pbar loss is large due to large initial luminosity
  - Proton loss is small due to short bunch length/absence of tails and, consequently, low longitudinal loss
- **Model describes well the particle loss during the store**

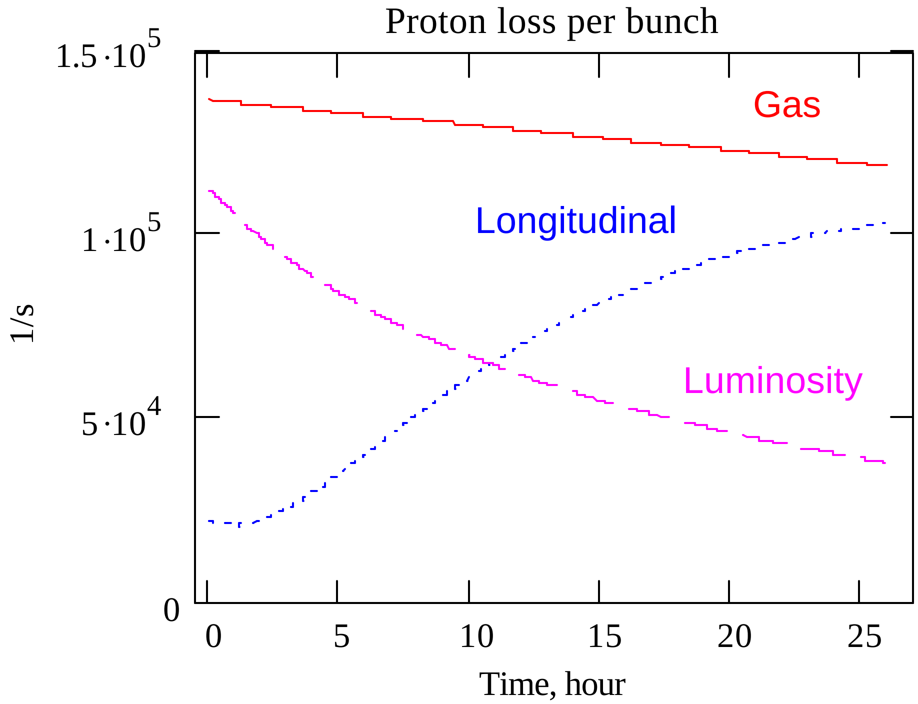


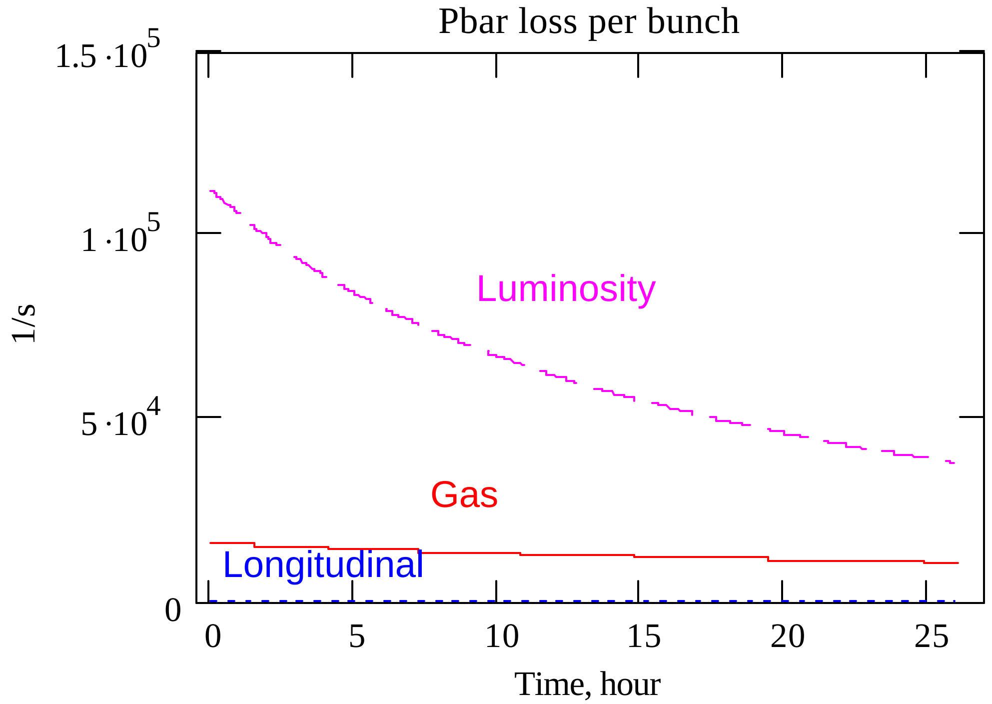




Emittances and bunch lengths on time for Store 2138

- **Beam-beam effects ?**
  - Vertical pbar emit. grows faster at the store beginning
  - Pbar bunch length does not grow at the second half of

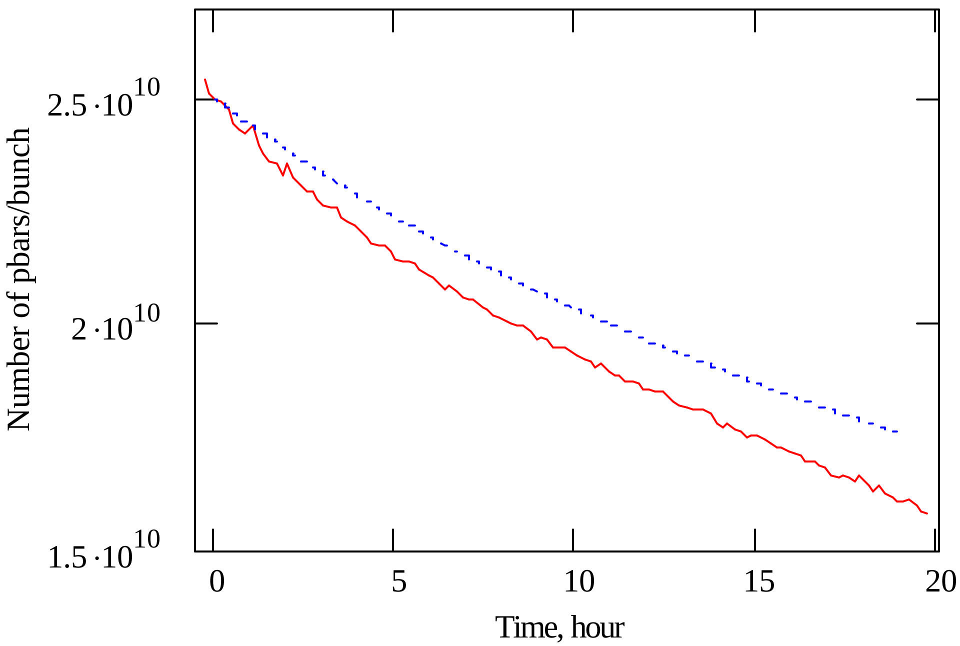


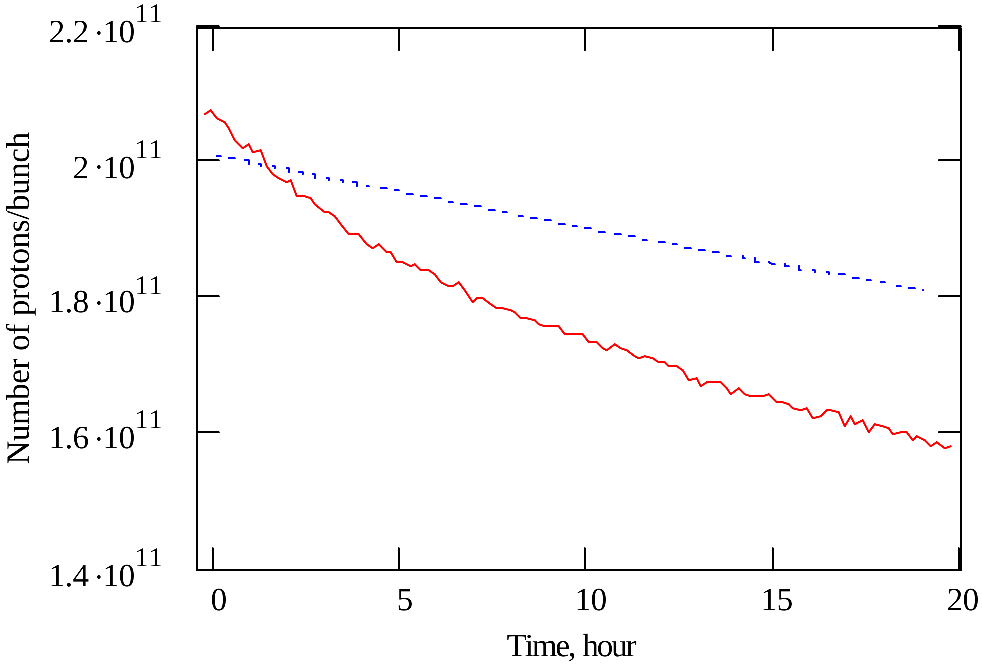


Particle loss computed for different loss mechanisms for Store 2138.

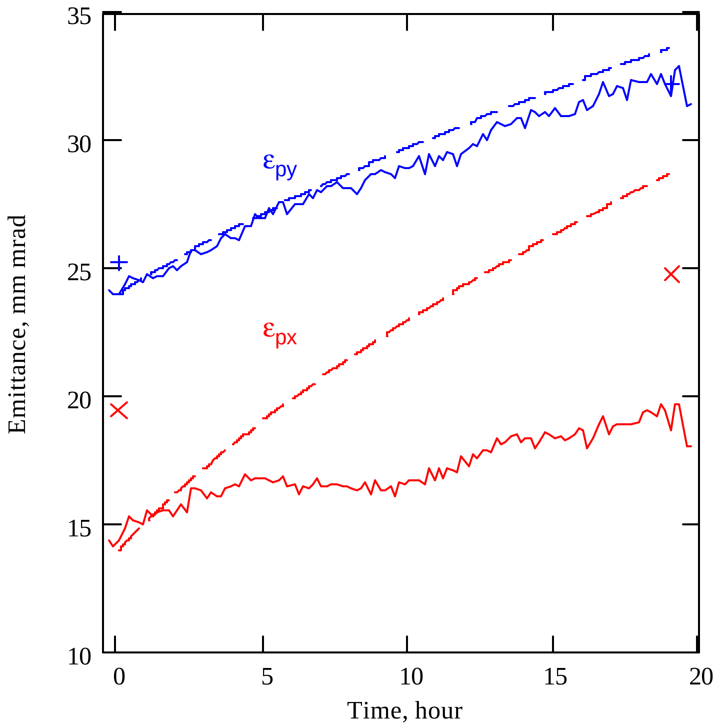
Comparison of Model Predictions to Store 2328 (Mar. 20 2003)

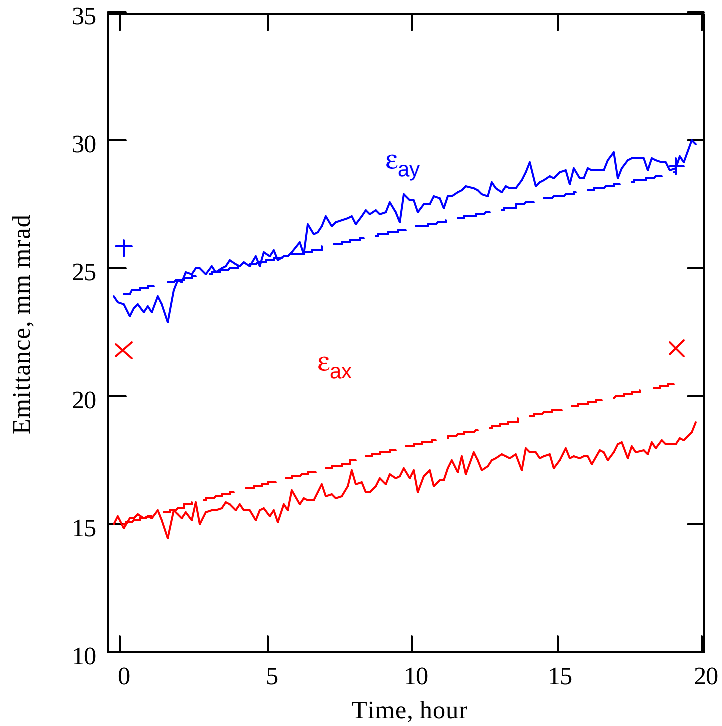
The store is strongly affected by the beam-beam effects !!!

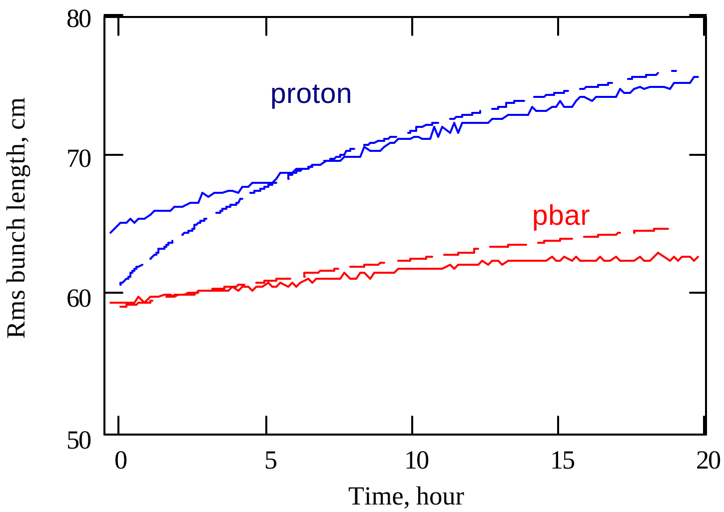




- At the store beginning both proton and pbar bunch intensities decay faster than the model predictions
  - Incorrect tune or too long bunch or both

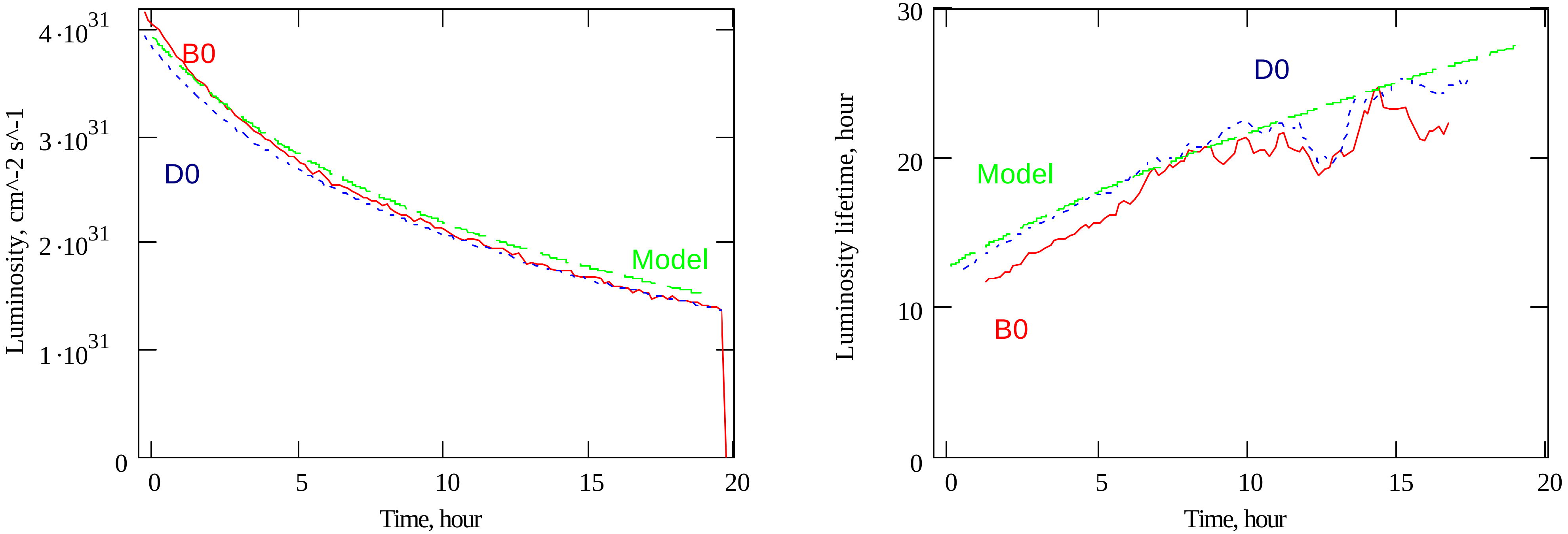






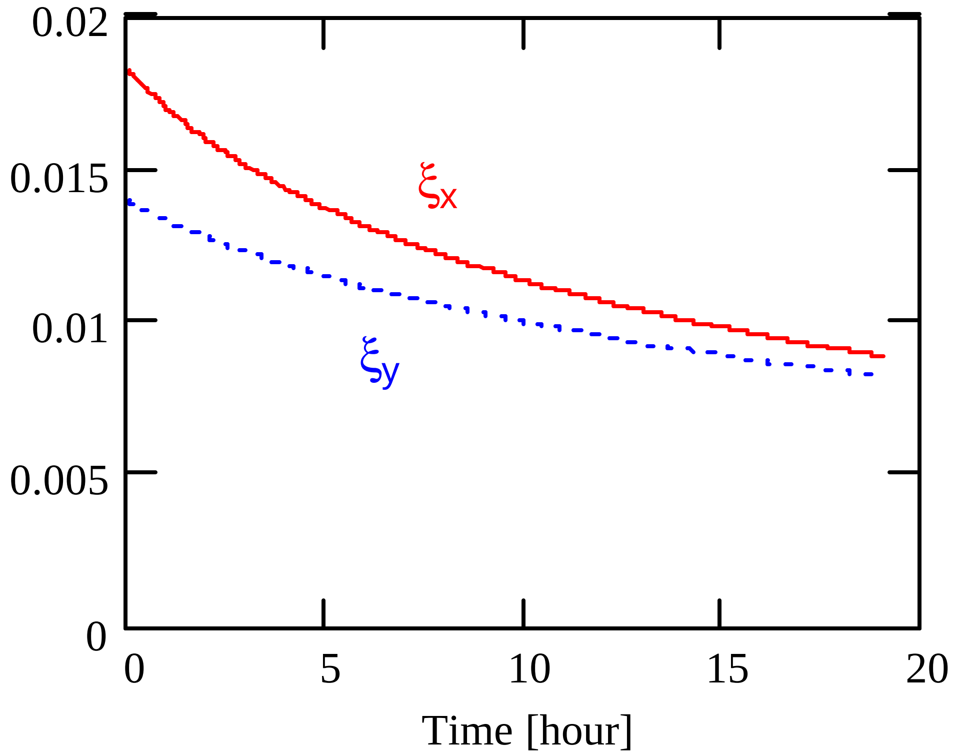
Emittances and bunch lengths on time for Store 2328

- **Beam-beam effects ?**
  - Proton bunch length and hor. emit. grow slower at the store beginning
    - Protons with large synchrotron amplitudes are lost due to beam-

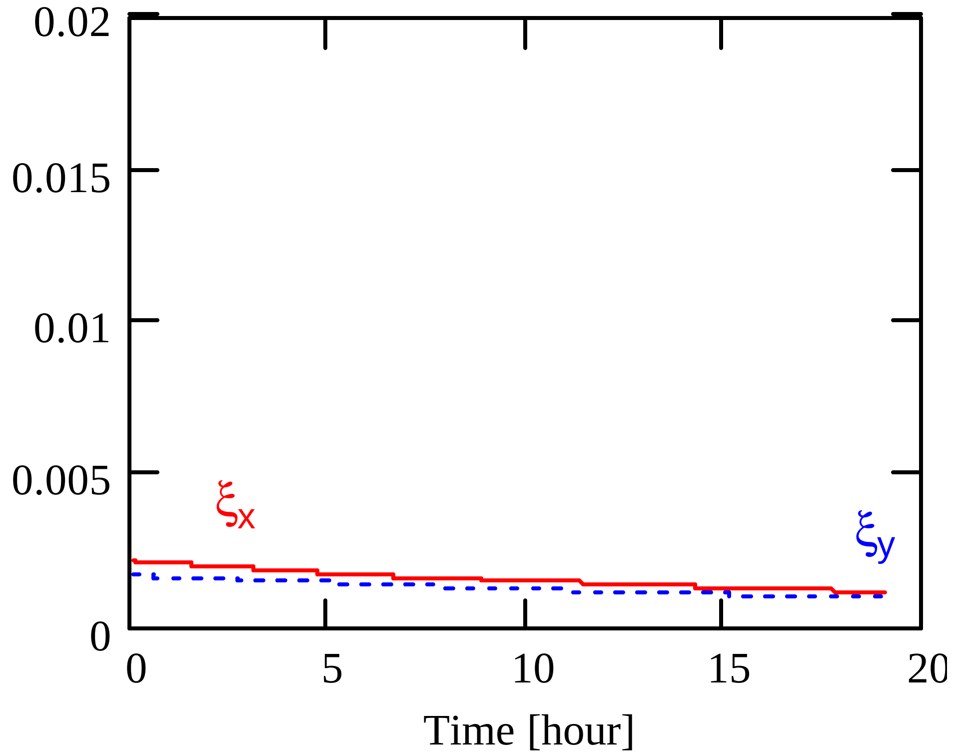


- Luminosity decays faster than the model predictions but the difference is small

Computed beam-beam linear tune shifts for Store 2328



Pbars

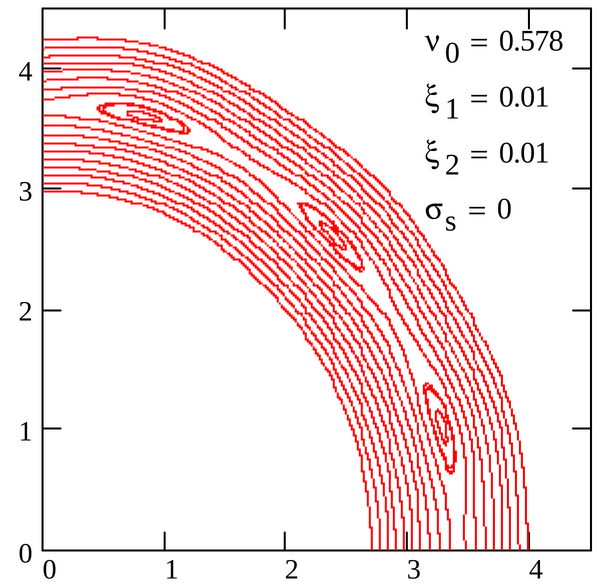


Protons

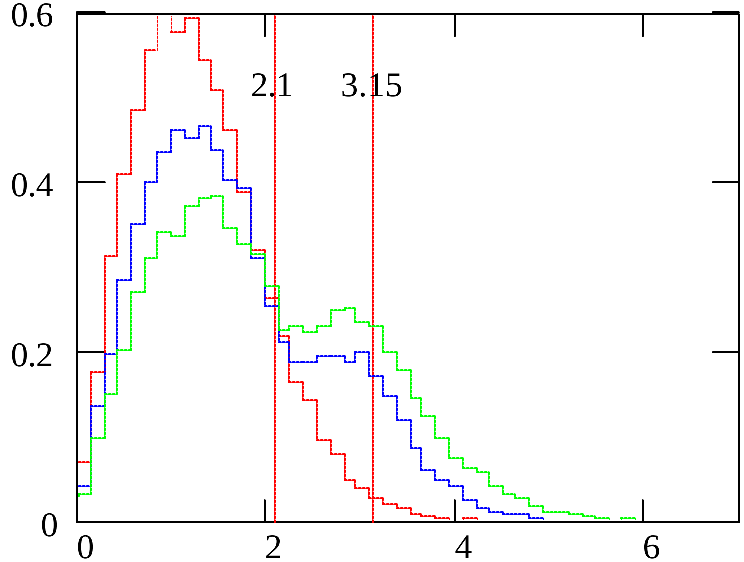
- We already close to the design linear tune shift of 0.02 for pbar beam (~80%)
  - and only about 20% for proton beam

3. Interplay of Diffusion and Beam-Beam effects

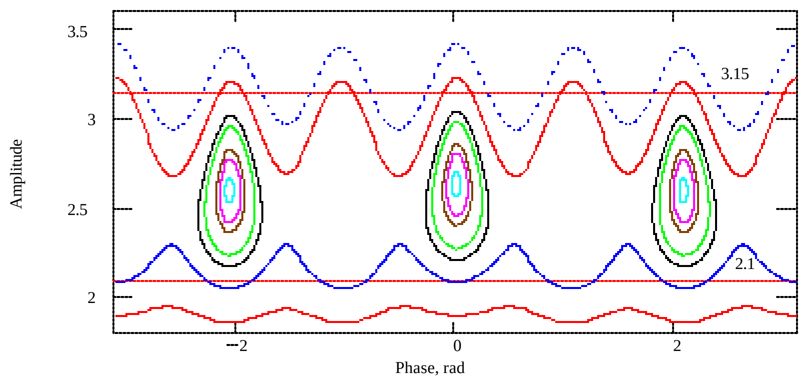
- 1 store ~ $4 \cdot 10^9$ turns – too much for any computer in visible future
- **Conclusion following from parametric model study**: for correctly tuned collider at present intensities the beam-beam effects and machine nonlinearity do not produce harmful effects on the beam dynamics while beams are in collisions
- We can not accept any significant worsening of the lifetime if we want to maximize the luminosity integral
- Theory should be build as perturbation theory to the diffusion model
- Diffusion amplification by resonances
  - Motion inside resonance island is fast comparing to the beam lifetime
    - 100-10,000 turns depending on ξ and the resonance order
  - Flattening distribution over resonance



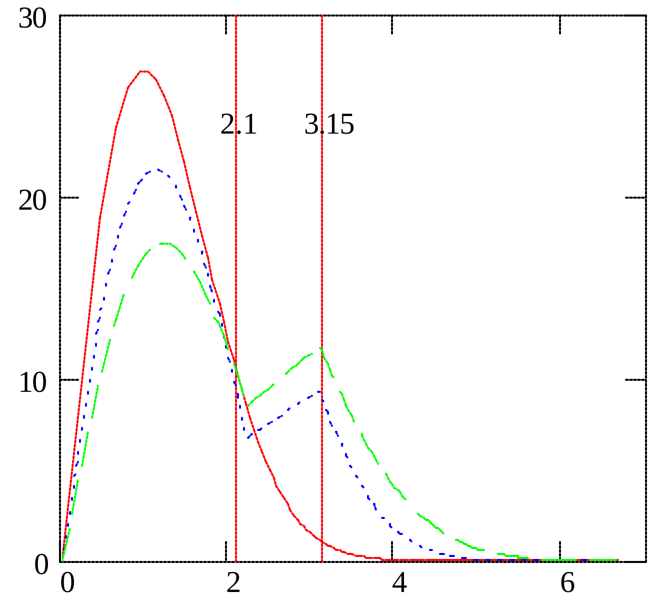
Phase trajectories in vicinity of 12-th order resonance ν_x=7/12; two Tevatron IPs but zero length of counter-rotating bunch, and zero synchrotron motion amplitude



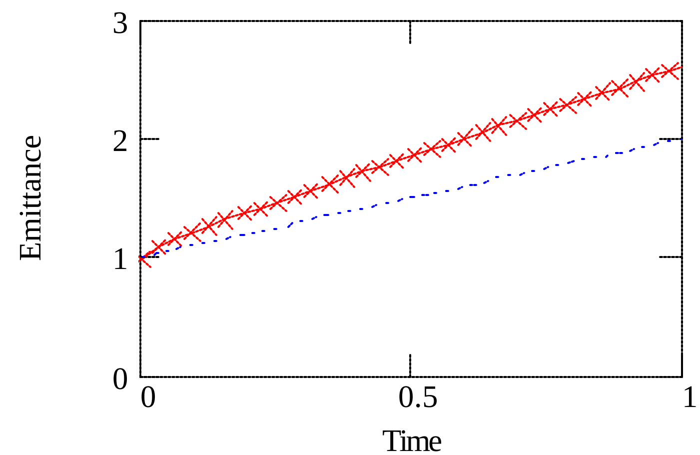
ν=0.325, ξ=0.02, $\Delta p/p$=0, s_s <<



Tracking of 20,000 particles for
turns in vicinity of 6-th order
resonance, n_x=2/6



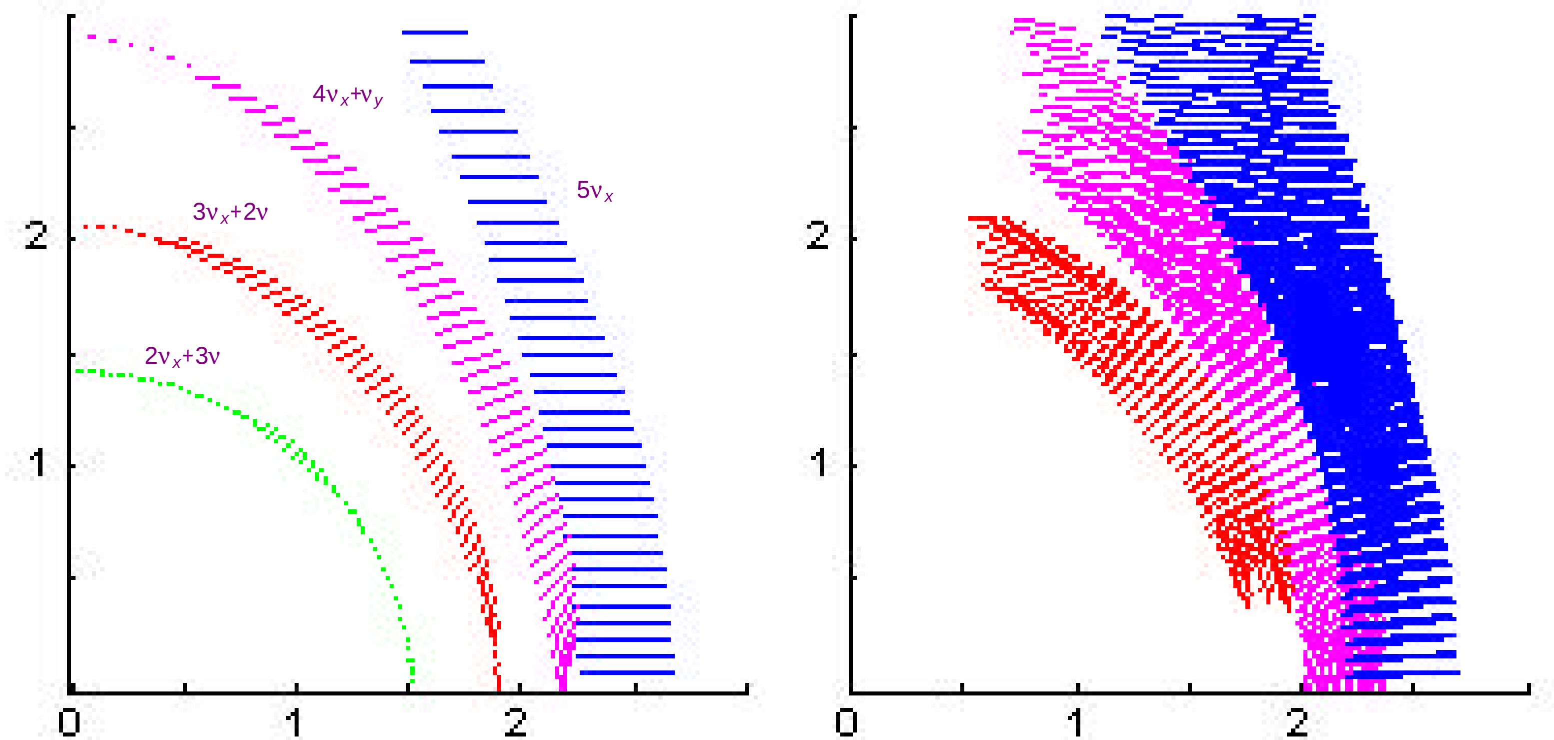
Particle distribution obtained
by diffusion equation solving



b^*

5,000

Long Range collisions



$d_p = 0$ $\qquad$ $d_p = 1.25 \cdot 10^{-4}$

Swing of the normalized transverse amplitudes on the 5th order resonances and their synchrotron satellites at synchrotron amplitude $d_p = 0$ (left) and $d_p = 1.25 \cdot 10^{-4}$ (right), lattice chromaticity is zero, $n_x = 20.585$, $n_y = 20.575$.

Courtesy of Yu. Alexahin

Beam-beam simulations with Lifetrack *(D. Shatilov, BINP, Novosibirsk)*

- Features
  - Weak-strong code, symplectic
  - Linear maps between IPs
  - Gaussian distribution in the strong beam
  - Measured coupling for both beams is taken into account
  - Build-in chromaticities of the tunes and the beta-functions
  - Presently, use ~50% of PC farm of 64 Pentium processors
  - In near future we plan to increase computing power by factor of four
- Preliminary results
  - Still testing the code and physics behind it
  - $\sim(2\text{-}5)\cdot 10^6$ turns are required to get to the right scaling
  - Strong effect of optics distortions on the beam-beam

Conclusions

1. During last three years we made significant progress in understanding how IBS affects the Tevatron complex operation
2. It includes
   a. Mitigation of IBS in Accumulator with dual lattice operation
   b. Quantitative understanding of Tevatron luminosity evolution
   c. Building credible scenario of recycler operation
3. We are still far away to understand all details of the interplay between the beam-beam effects and IBS
   - Significant progress has been achieved during last year

Interaction with Residual Gas

Beam lifetime

$$t_{scat}^{-1} = \frac{2pcr_p^{\,2}}{g^2 b^3}\left(\sum_i n_i Z_i (Z_i + 1)\right)\left(\frac{\overline{b_x}}{e_{mx}} + \frac{\overline{b_y}}{e_{my}}\right) + \sum_i n_i s_i cb$$

where: $\overline{b_{x,y}} = \frac{1}{C}\int b_{x,y}\, ds \approx 70\ \text{m}$

e_{mx}, e_{my} – acceptances are chosen to be $6^2 \cdot 20$ mm mrad

- Average vacuum is adjusted to match the beam lifetime and the emittance growth rate for small intensity beam, $P=1 \cdot 10^{-9}$ Torr of N_2 equivalent
  - Coulomb scattering (~6000 hour)
  - Nuclear absorption **(~400 hour)**
  - Total gas scattering lifetime **(~380 hour)**
  - Gas composition used in the simulations

Gas	H_2	CO	N_2	C_2H_2	CH_4	CO_2	Ar
Pressure [nTorr]	1.05	0.18	0.09	0.075	0.015	0.09	0.15

Emittance growth time due to gas scattering

$$\frac{de_{x,y}}{dt} = \frac{2pcr_p^{\,2}}{g^2 b^3}\left(\sum_i n_i Z_i (Z_i + 1) L_{C_i}\right)\overline{b_{x,y}} \quad \Rightarrow \quad \frac{de_x}{dt} \approx \frac{de_y}{dt} \approx 0.2\ \text{mm mrad/hour}$$

- Beam based measurements of vacuum were carried out in July 2003. Analysis will follow.

Scattering in IP

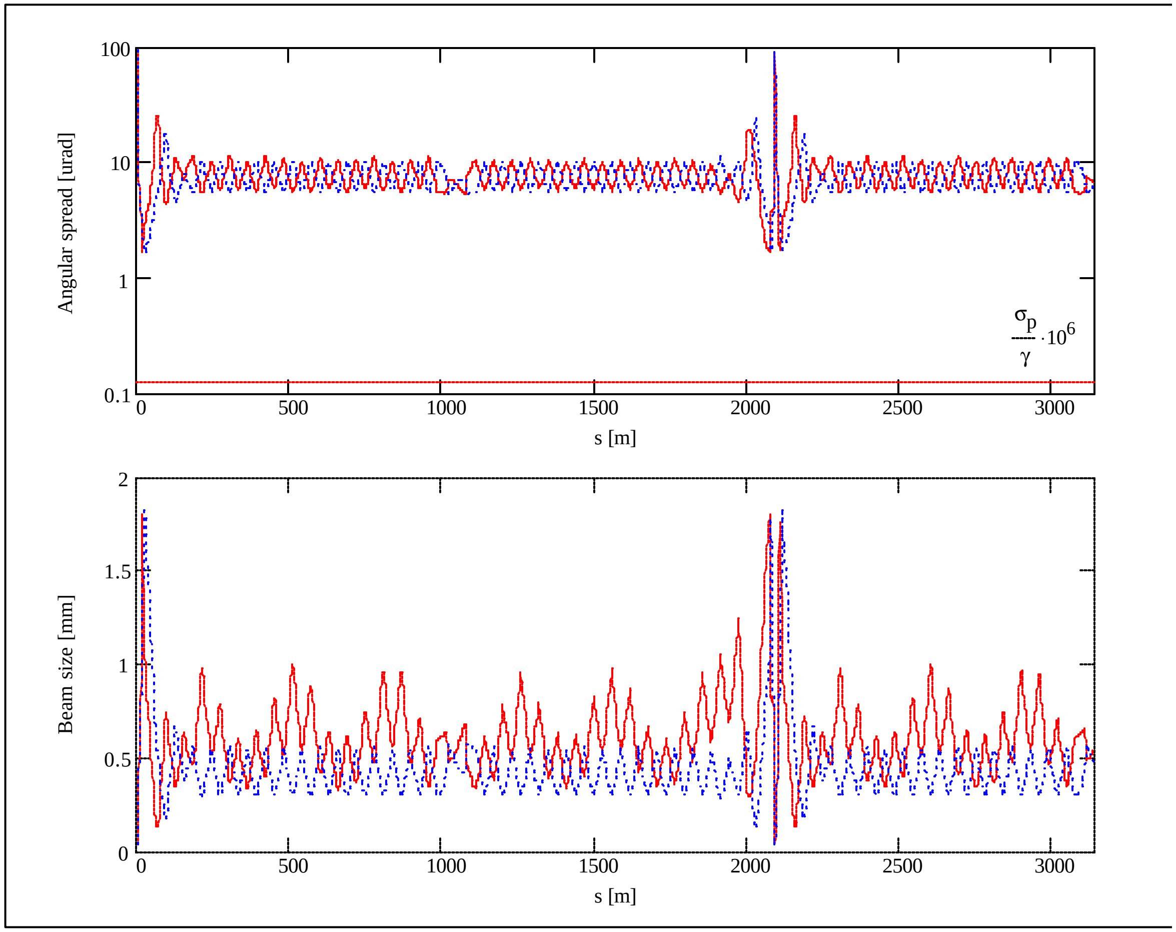
- Nuclear interaction
  - Main mechanism for loss of antiprotons
  - $p-\overline{p}$ cross-section ~ 69 mbarn
    - Inelastic – 60 mbarn
    - Elastic – 15 mbarn
      - 40% scatters within the beam (3σ)
- Electromagnetic scattering
  - Emittance growth

$$\frac{d\varepsilon_{x,y}}{dt}=\frac{4r_p^{\,2}NL_{bb}f_0}{\gamma^2\beta^3\sqrt{\left(\varepsilon_{px}+\varepsilon_{py}\right)\left(\varepsilon_{ax}+\varepsilon_{ay}\right)}}$$

  - $d\varepsilon/dt \approx 0.01$ mm mrad and is negligible in comparison with gas scattering

Intrabeam Scattering

- Pancake distribution function allows one to use simple IBS formulas
- Integration over Tevatron lattice was carried out and results were compared to the smooth lattice approximation
  - Comparison yielded coincidence within 10%
- Therefore the smooth lattice approximation has been used for IBS to simplify the model



- The following corrections has been taken into account
  - Bunch length correction due to non-linearity of longitudinal focusing
  - Average dispersion and dispersion invariant, A_x, were calculated using lattice functions

Backup slide

Intrabeam Scattering (Continue)

$$\frac{d}{dt}\left(q_{\|}^{2}\right) \equiv \frac{d}{dt}\left(\frac{\overline{p_{\|}^{2}}}{p}\right) = \frac{1}{4\sqrt{2}}\frac{e^{4} N_{i} L_{C} \Xi_{\|}\left(q_{x}, q_{y}\right)}{m_{p}^{2} c^{3} g_{i}^{3} b_{i}^{3} s_{x} s_{y} s_{s} \sqrt{q_{x}^{2}+q_{y}^{2}}} \quad ,$$

$$\frac{de_{x}}{dt} = (1-k)\left\langle A_{x}\frac{dq_{\|}^{2}}{dt}\right\rangle_{s} \quad ,$$

$$\frac{de_{y}}{dt} = k\left\langle A_{x}\frac{dq_{\|}^{2}}{dt}\right\rangle_{s}$$

where

$$\Xi_{\|}(x,y) \approx 1 + \frac{\sqrt{2}}{p}\ln\left(\frac{x^{2}+y^{2}}{2xy}\right) - 0.055\left(\frac{x^{2}-y^{2}}{x^{2}+y^{2}}\right)^{2},$$

$s_{x} = \sqrt{e_{x} b_{y} + D^{2} q_{\|}^{2}}$, $s_{y} = \sqrt{e_{y} b_{y}}$, $q_{x} = \sqrt{e_{x}/b_{x}}$ and $q_{y} = \sqrt{e_{y}/b_{y}}$

$$A_{x} = \left\langle \frac{D^{2} + \left(D' b_{x} + a_{x} D\right)^{2}}{b_{x}} \right\rangle \Bigg|_{s}$$

k – coupling coefficient (measurements yield that presently $k \sim 0.4$)

A_x = 19.7 cm, $b_x = b_y$ = 48.5 m, D = 2.84 m

Beam Evolution in Longitudinal Degree of Freedom

- Diffusion mechanisms
  - IBS
    - Multiple and single scattering
  - RF noise
    - Phase noise
    - Amplitude noise
- Diffusion differently depends on action for all three mechanisms

- The first iteration of the model solved diffusion equation in a sinusoidal potential well under constant diffusion, $D(I) = D$,

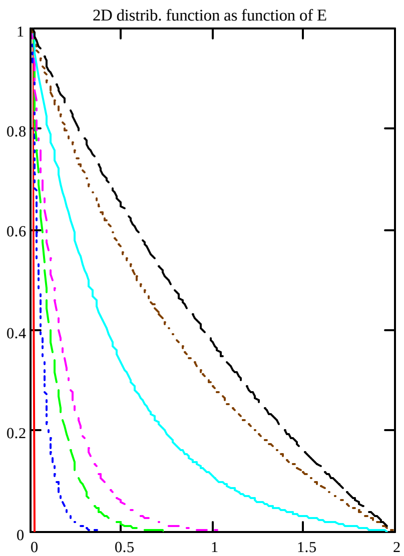
$$\frac{\partial f}{\partial t} = D \frac{\partial}{\partial I}\left(\frac{I}{dE/dI} \frac{\partial f}{\partial I} \right)$$

where

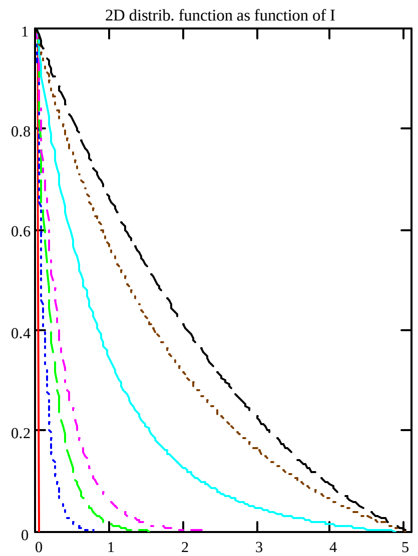
$$E = \frac{p^2}{2} + \Omega_s{}^2 (1 - \cos\varphi) \qquad , \qquad I = \frac{1}{2\pi} \oint p\, d\varphi$$

  - Equation is solved numerically for initial distribution $f(I) = \delta(I)$
  - The boundary condition $f(I) = 0$ at the RF bucket boundary is used

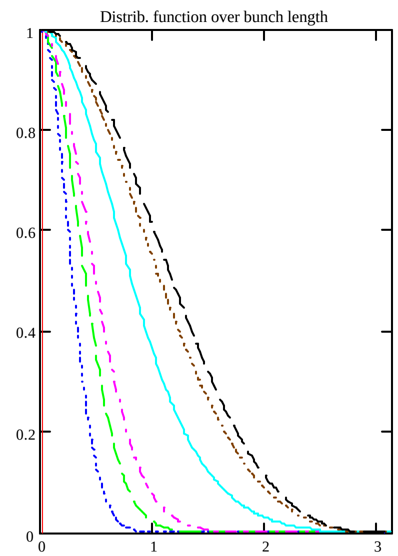
Beam Evolution in Longitudinal Degree of Freedom (continue)



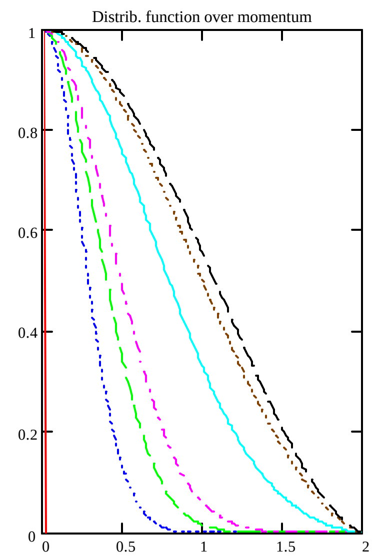
$f(I(E))$



$f(I)$



$f_f(f)$

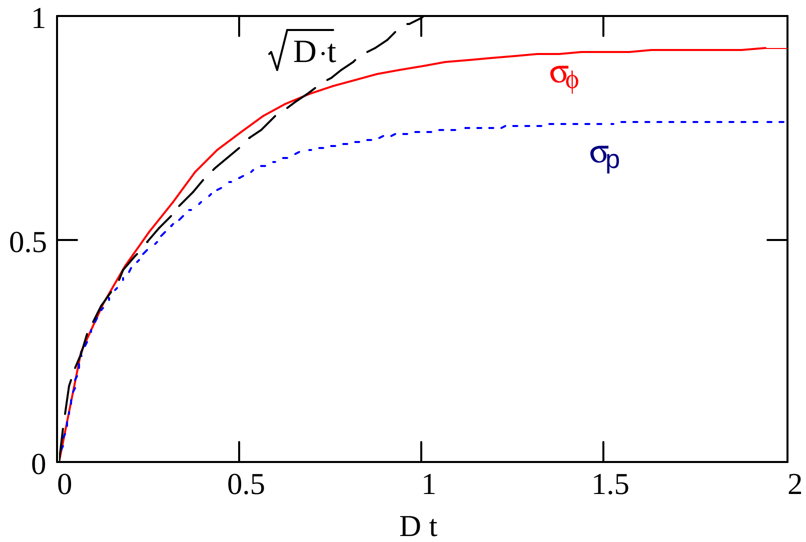


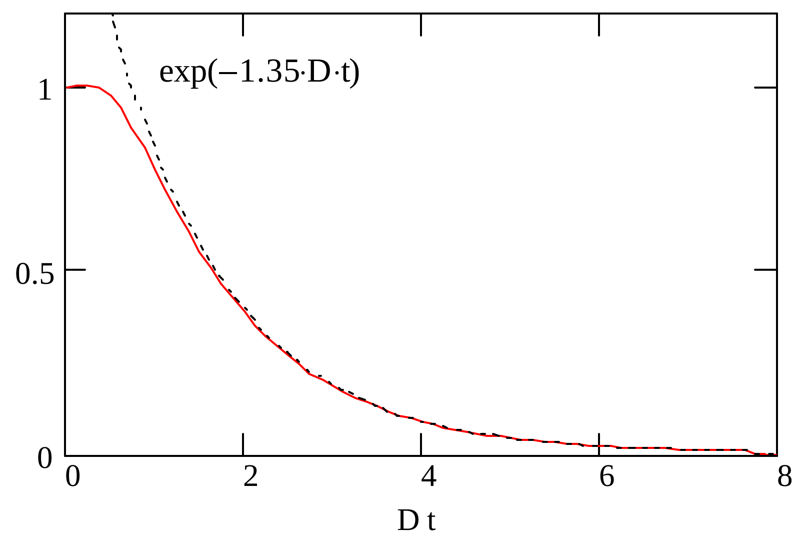
$f_p(p)$

Distribution functions as functions of the beam energy, action, longitudinal coordinate and the particle momentum deviation

where: $\int_0^{I_{max}} f(I)dI = 1$, $f_f(f) = \int_{-p_{max}(f)}^{p_{max}(f)} f(I(f,p))dp$, $f_p(p) = \int_{-f_{max}(p)}^{f_{max}(p)} f(I(f,p))df$.

Beam Evolution in Longitudinal Degree of Freedom (continue)





- Asymptotic behavior
  - Shape of distribution function does not depend on time
  - Exponential decay of beam intensity

Beam Evolution in Longitudinal Degree of Freedom (continue)

To find compromise between completeness and simplicity of the model the following approximate relations were deduced from the numerical solution:

$$s_s \approx \Gamma_s s_{\Delta p/p}\left(1+\frac{1}{4}\left(\frac{2s_{\Delta p/p}}{\Delta P/P|_{sep}}\right)^2+\frac{1}{6}\left(\frac{2s_{\Delta p/p}}{\Delta P/P|_{sep}}\right)^3\right)$$

$$\frac{1}{N}\frac{dN}{dt}\approx\frac{2.425\,(2ps_s)^7}{l_{RF}{}^7+1.65\,(2ps_s)^7}\left(\left(\frac{2p\Gamma_s}{l_{RF}}\right)^2\left.\frac{d\left(s_{\Delta p/p}{}^2\right)}{dt}\right|_{IBS}+\left.\frac{d\left(s_f{}^2\right)}{dt}\right|_{RF}\right)$$

$$\left.\frac{d\left(s_{\Delta p/p}{}^2\right)}{dt}\right|_{total}\approx\left(1-\left(\frac{2s_{\Delta p/p}}{0.765\Delta P/P|_{sep}}\right)^5\right)\left(\left.\frac{d\left(s_{\Delta p/p}{}^2\right)}{dt}\right|_{IBS}+\left(\frac{l_{RF}}{2p\Gamma_s}\right)^2\left.\frac{d\left(s_f{}^2\right)}{dt}\right|_{RF}\right)$$

where $\Gamma_s=\left(a_M-1/g^2\right)q\,l_{RF}/(2pn_s)$ is the parameter of longitudinal focusing

Beam Evolution in Longitudinal Degree of Freedom (continue)

The bunch lengthening due to RF phase noise

- At small amplitude the bunch lengthening due to RF phase and amplitude noise is determined by its spectral density at synchrotron frequency,

$$\left.\frac{d\left(s_f^{\,2}\right)}{dt}\right|_{RF} = p\,\Omega_s^{\,2}\left(P_f\left(\Omega_s\right)+\frac{1}{2}s_f^{\,2}P_A\left(2\Omega_s\right)\right) \quad ,$$

where the spectral density of RF phase noise is normalized as

$$\overline{d f_{RF}^{\,2}} = \int_{-\infty}^{\infty} P_f(w)dw \quad , \quad \frac{\overline{dA_{RF}^{\,2}}}{A_{RF}^{\,2}} = \int_{-\infty}^{\infty} P_A(w)dw$$

- Spectral density and bunch lengthening measurement are in decent agreement, and they yield that

$$P_{ff}\left(\Omega_s/2p\right) = 4pP_f\left(\Omega_s\right) \approx 5\cdot 10^{-11} \quad \mathrm{rad}^2/\mathrm{Hz}$$

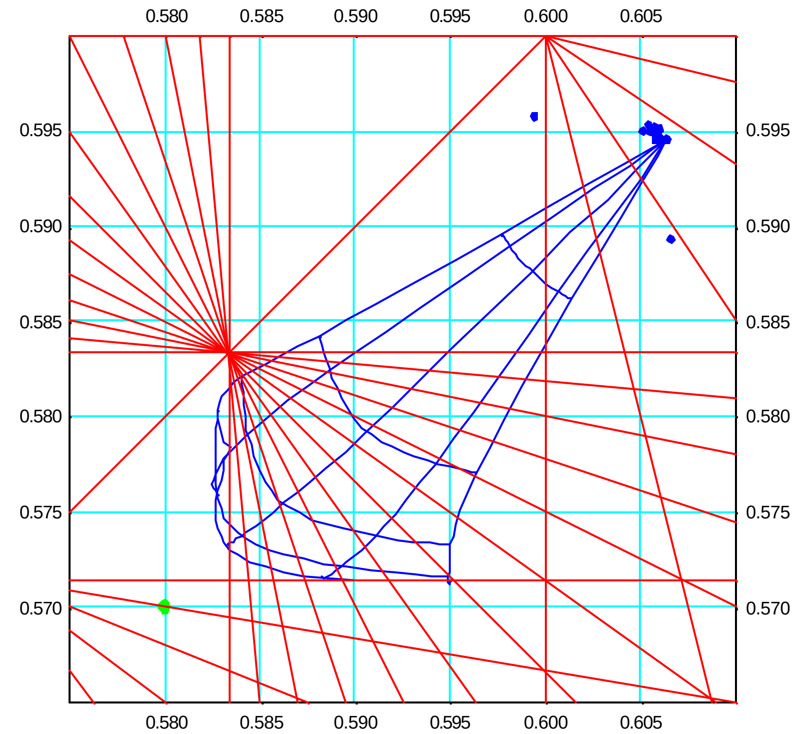
$$\left.\frac{d\left(s_f^{\,2}\right)}{dt}\right|_{RF} \approx 2200 \quad \mathrm{mrad}^2/\mathrm{hour}$$

Beam-beam effects

- Beam-beam effects are important at all stages
  - Injection
  - Acceleration
  - Squeeze
  - Collision
- Two types of the beam-beam effects
  - **Head-on**
    - Run IB proton bunch population of ~$2.7\cdot10^{11}$ proton/bunch was set by the head-on collisions
    - We aim to achieve the same number of protons per bunch
      - Linear beam-beam tune shift $\xi \approx 0.01$ for each of two interaction points
  - **Long range**
    - Much stronger than for Run IB
    - Additional tune spread within one bunch
      - $\Delta\nu \approx 5\cdot10^{-3}$
    - Tune spread between bunches ($N_p=2.7\times10^{11}$)
      - At injection: $\Delta\nu_x \approx 5\cdot10^{-3}$, $\Delta\nu_y \approx 2.5\cdot10^{-3}$
      - At flat top: $\Delta\nu_x \approx \Delta\nu_y \approx 8\cdot10^{-3}$

Beam-beam effects (continue)

- Tunes are between 5-th and 7-th, and on 12-th order resonance
  - 5-th and 7-th order are excited by long large and lattice nonlinearity
  - 12-th order are excited by head-on
- Long range interactions make different tune shifts for different bunches
  - It can and must be mitigated
- Distance between 5-th and 7-th order resonances is 0.0285
  - Pbars from Protons
    - Head-on – 2·0.01=0.02
    - Long range within a bunch – 0.005
    - Bunch to bunch difference – 0.007
  - Protons experience only half of this due to smaller pbar intensity



Footprint of pbar bunch #6 in the tune diagram with ν_x=0.580, ν_y=0.580 (green dot) and nominal beam parameters. Dots show small amplitude tunes for other bunches. Footprint lines go in 2σ and 22.5 deg in the space of actions (angle or $(a_x^2 + a_y^2)^{1/2}$ =const on a line). *Courtesy of Yu. Alexahin*