Tevatron Task Force

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Talk outline

1. Luminosity lifetime
    a. Current scenario
    b. Final Run II scenario
2. Beam-beam effects
3. Beam instabilities
4. Optics modeling
5. Particle loss at injection due to diffusion
6. The source of background in the particle physics detectors

   Conclusions

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1. Luminosity Lifetime

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

- **Phenomena taken into account**
  - ⇒ Interaction with residual gas
    - ♦ Emittance growth due to electromagnetic scattering
    - ♦ Particle loss due to nuclear and electromagnetic interaction
  - ⇒ Particle interaction in IPs (proportional to the luminosity)
    - ♦ Emittance growth due to electromagnetic scattering
    - ♦ Particle loss due to nuclear and electromagnetic interaction
  - ⇒ IBS
    - ♦ Energy spread growth and emittance growth due to multiple scattering
  - ⇒ Bunch lengthening due to RF noise
  - ⇒ Particle loss from the bucket due to heating of longitudinal degree of freedom
- **Phenomena ignored in the model**
  - ⇒ Beam-beam effects
  - ⇒ Non-linearity of the lattice
  - ⇒ Diffusion amplification by coherent effects
- Thus, it can be considered as **the best-case scenario**
  - ⇒ It describes well our best present stores

Interaction with Residual Gas (Luminosity lifetime backup slide)

Beam lifetime

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

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 has been adjusted to match the beam lifetime and the emittance growth rate for small intensity beam, $P=7.8\cdot10^{-10}$ Torr of N_2 equivalent
  - ➢ Coulomb scattering (~8900 hour)
  - ➢ Nuclear absorption (~608 hour)
  - ➢ Total gas scattering lifetime (~570 hour)

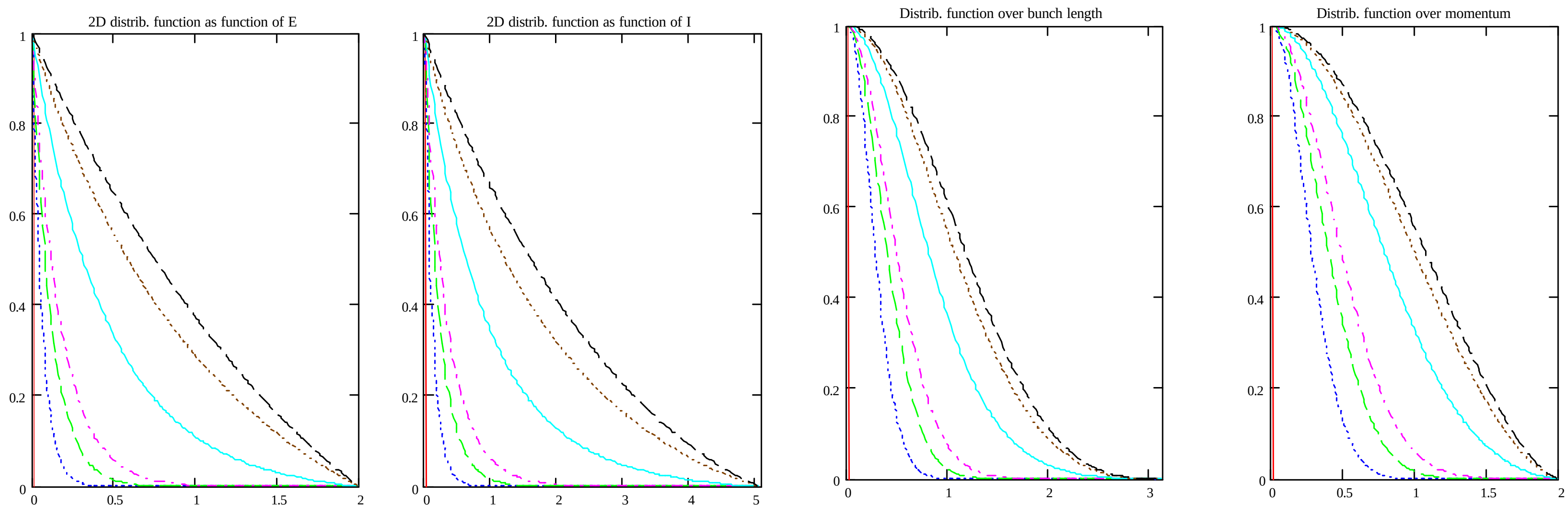
Emittance growth time

$$\frac{de_{x,y}}{dt} = \frac{2pcr_p^{\;2}}{g^2 b^3}\left(\sum_i n_i Z_i (Z_i + 1) L_{C_i}\right)\overline{b_{x,y}}$$

$$\frac{de_x}{dt} \approx \frac{de_y}{dt} \approx 0.129 \text{ mm mrad/hour}$$

Longitudinal Diffusion (Luminosity lifetime backup slide)

Diffusion equation, $\frac{\partial f}{\partial t} = D \frac{\partial}{\partial I}\left(\frac{I}{dE/dI} \frac{\partial f}{\partial I} \right)$, describing the distribution function transformation under action of constant diffusion, $D(I) = D$, is solved numerically.

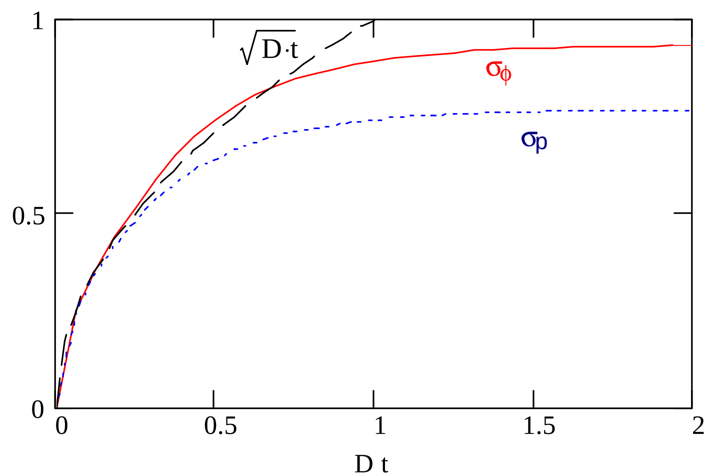


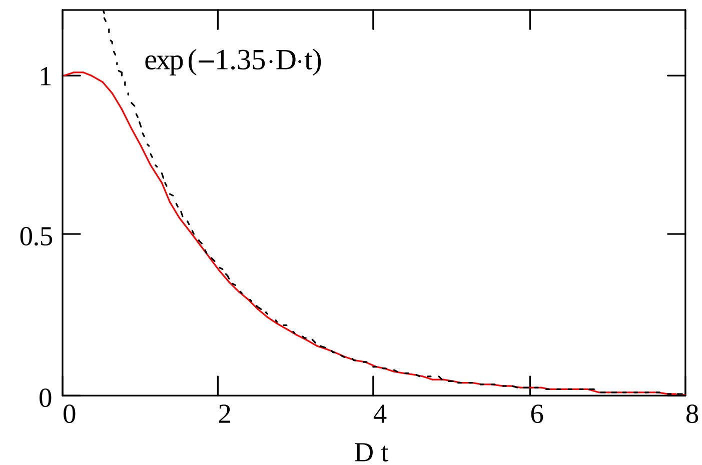
$f(I(E))$ $\quad f(I)$ $\quad f_f(f)$ $\quad f_p(p)$

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

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

Longitudinal Diffusion – continue (Luminosity lifetime backup slide)





This numerical solution yields approximate relationships between the bunch parameters:

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

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

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

Longitudinal Diffusion – continue (Luminosity lifetime backup slide)

where

$$E = \frac{p^2}{2} + \Omega_s{}^2\left(1 - \cos f\right) \quad , \qquad I = \frac{1}{2p}\oint p\,df \qquad \text{and} \quad \Gamma_s = \frac{l_{RF}\,q}{2pn_s}\left(a - \frac{1}{g^2}\right) .$$

The bunch lengthening due to RF phase noise

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

$$\left.\frac{d\left(s_f{}^2\right)}{dt}\right|_{RF} = p\Omega_s{}^2 \mathrm{P}_f\left(\Omega_s\right) \quad ,$$

where the spectral density of RF phase noise is normalized as

$$\overline{f_{RF}{}^2} = \int_{-\infty}^{\infty} \mathrm{P}_f\left(w\right)dw$$

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

$$P_{ff}\left(\Omega_s/2p\right) = 4pP_f\left(\Omega_s\right) \approx 1.2\cdot 10^{-11} \quad \mathrm{rad}^2/\mathrm{Hz}$$

$$\left.\frac{d\left(s_f{}^2\right)}{dt}\right|_{RF} \approx 533 \quad \mathrm{mrad}^2/\mathrm{hour}$$

Intrabeam Scattering (Luminosity lifetime backup slide)

- Smooth lattice approximation has been used for IBS to simplify the model
  - Comparison with exact calculations yields coincidence within 10%
- 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

$$\frac{d}{dt}\left(\theta_{\parallel}^{2}\right)\equiv\frac{d}{dt}\left(\frac{\overline{p_{\parallel}^{2}}}{p}\right)=\frac{1}{4\sqrt{2}}\frac{e^{4}N_{i}L_{C}\Xi_{\parallel}\left(\theta_{x},\theta_{y}\right)}{m_{p}^{2}c^{3}\gamma_{i}^{3}\beta_{i}^{3}\sigma_{x}\sigma_{y}\sigma_{s}\sqrt{\theta_{x}^{2}+\theta_{y}^{2}}} ,$$

$$\frac{d\varepsilon_{x}}{dt}=(1-k)\left\langle A_{x}\frac{d\theta_{\parallel}^{2}}{dt}\right\rangle_{s} , \qquad \frac{d\varepsilon_{y}}{dt}=k\left\langle A_{x}\frac{d\theta_{\parallel}^{2}}{dt}\right\rangle_{s}$$

where

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

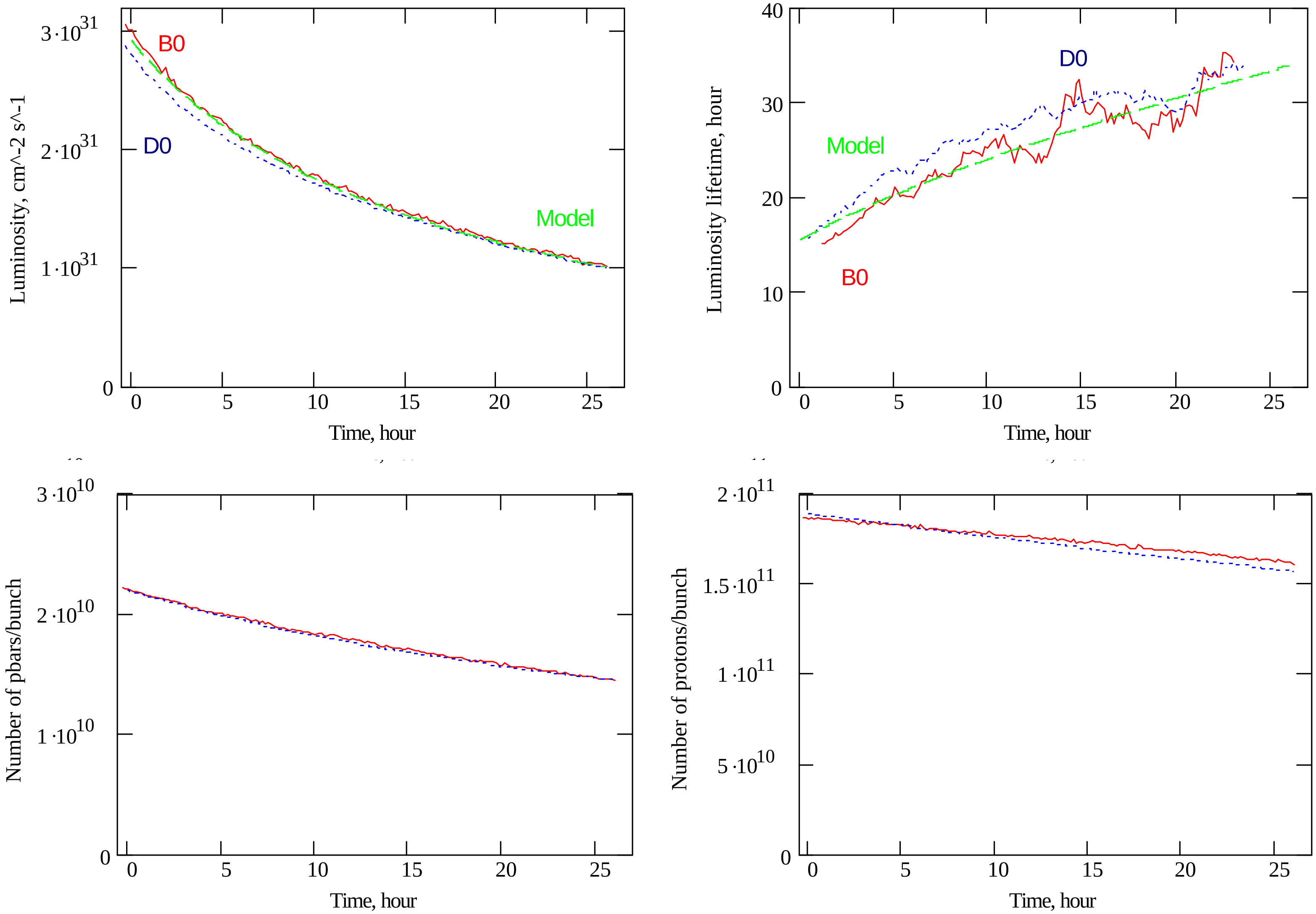
$\sigma_{x}=\sqrt{\varepsilon_{x}\beta_{y}+D^{2}\theta_{\parallel}^{2}}$, $\sigma_{y}=\sqrt{\varepsilon_{y}\beta_{y}}$, $\theta_{x}=\sqrt{\varepsilon_{x}/\beta_{x}}$ and $\theta_{y}=\sqrt{\varepsilon_{y}/\beta_{y}}$

$$A_{x}=\left.\left\langle\frac{D^{2}+\left(D'\beta_{x}+\alpha_{x}D\right)^{2}}{\beta_{x}}\right\rangle\right|_{s}$$

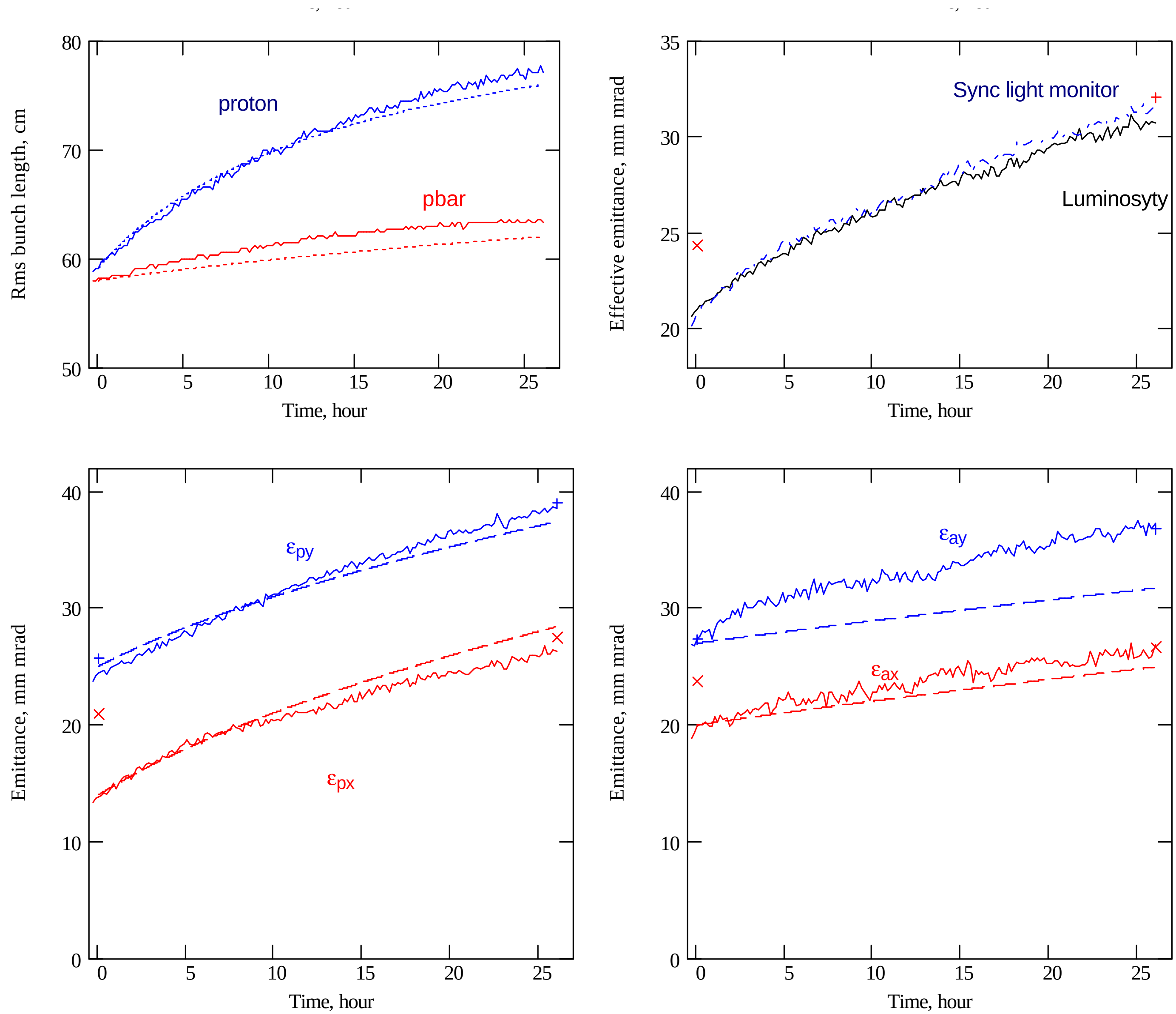
k – coupling coefficient (measurements yield that presently $k \sim 0.3$)

A_x = 19.7 cm, $\beta_x=\beta_y$ = 48.5 m, D = 2.83 m

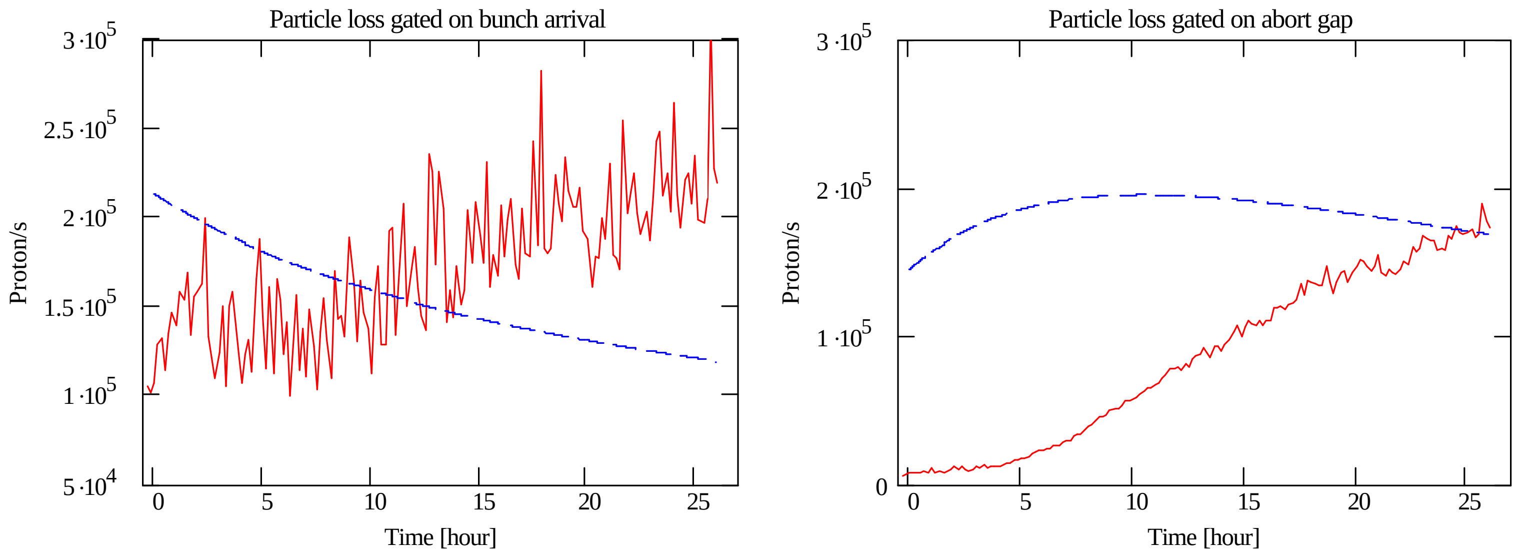
Comparison of the Model Predictions to the Store 2138 (Jan.5 2003)



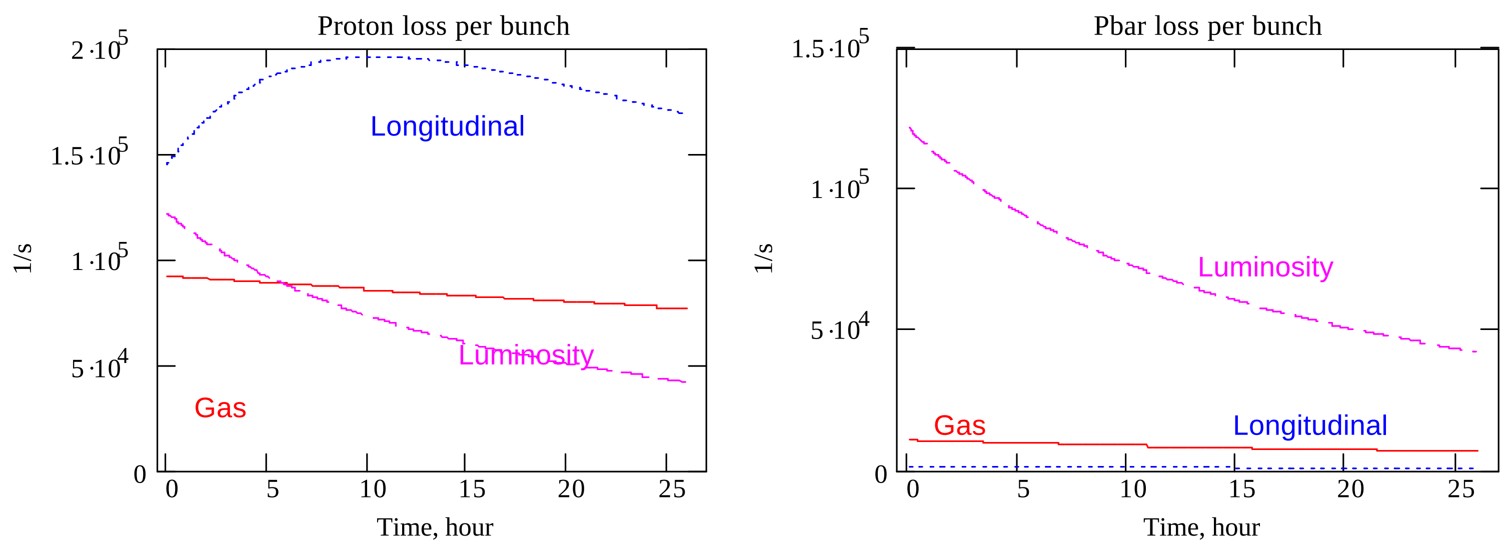
- Model overestimates the bucket losses at the store beginning ⇒ too fast decay of the proton intensity in the model



- Sync-light emittance corrections: Δe_{px}=17, Δe_{py}=5, Δe_{ax}=21, Δe_{ay}= 5 mm mrad
- Vertical pbar emittance grows significantly faster due to beam-beam effects

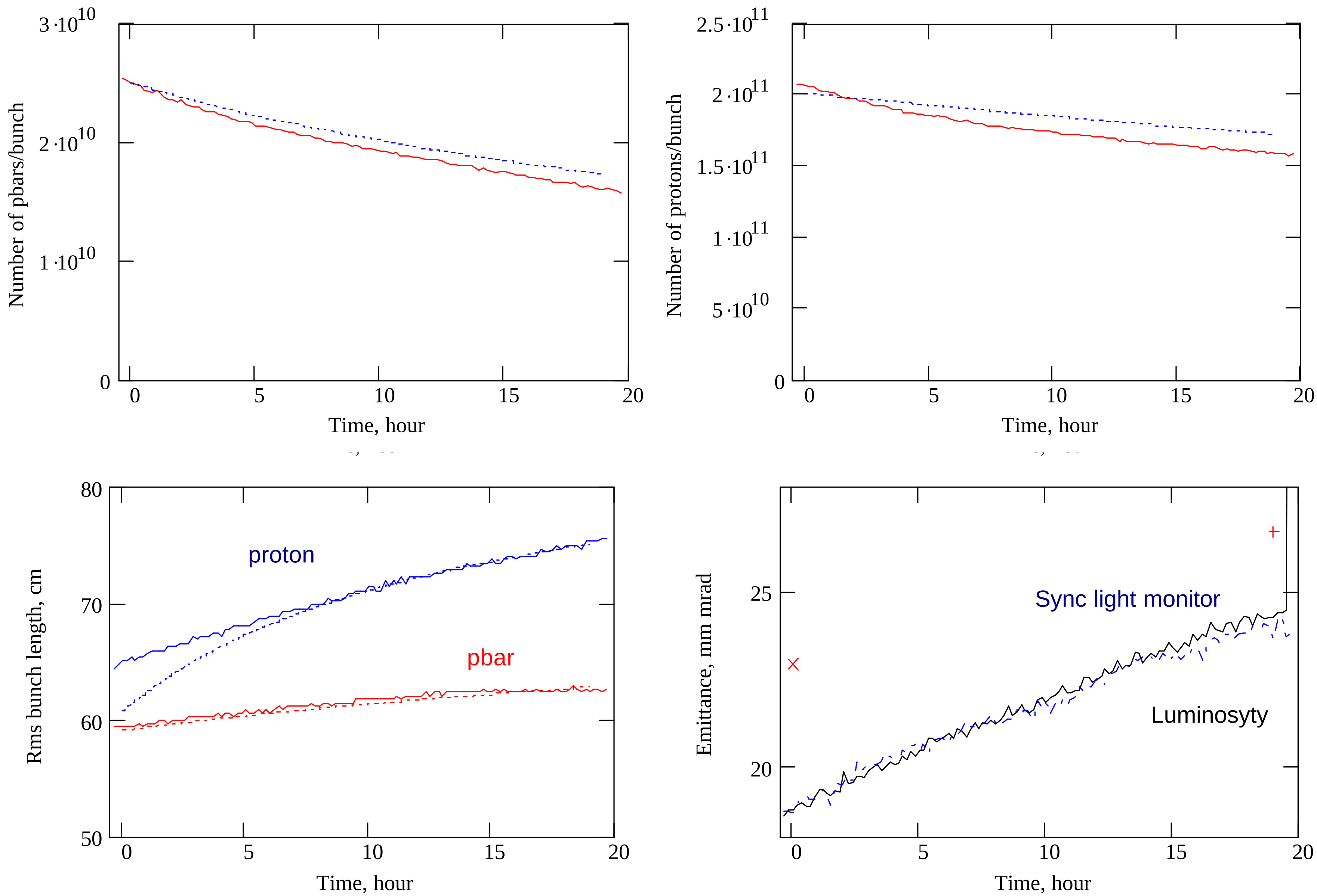


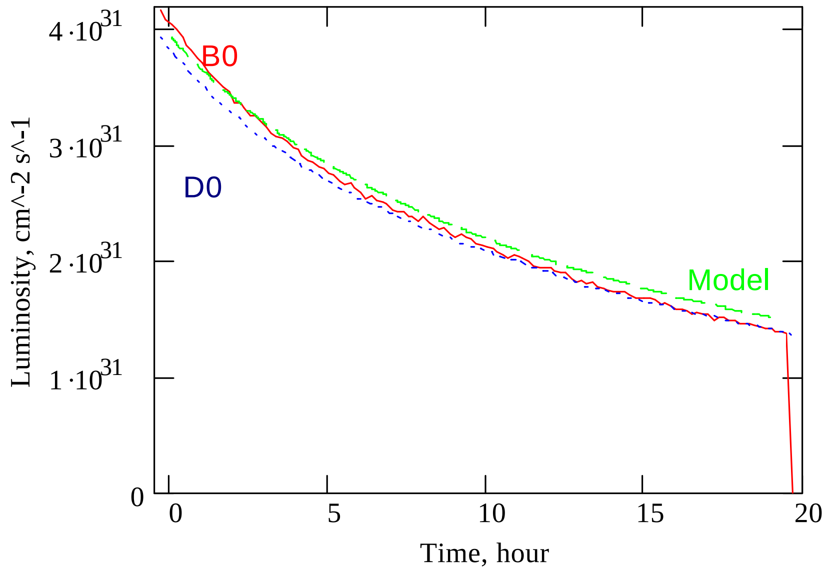
Dependence of computed (dashed lines) and measured particle loss per bunch on time

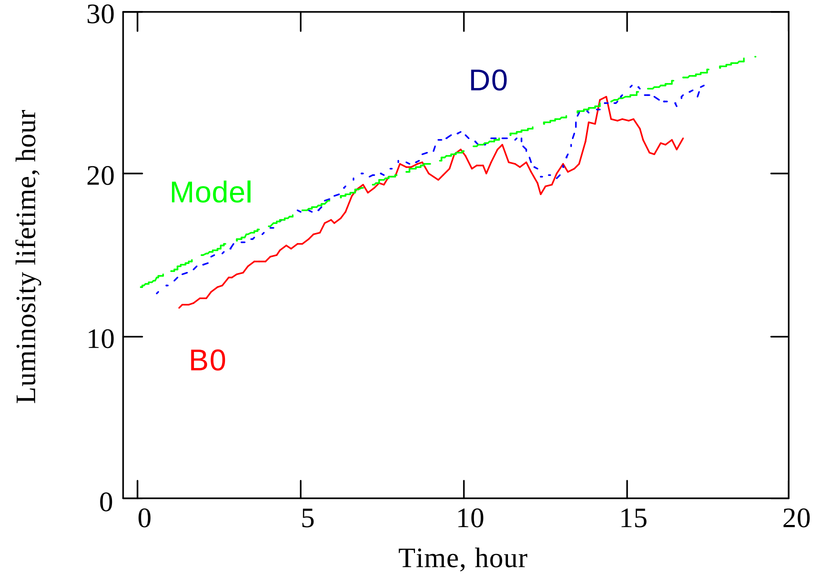


Dependence of particle loss on time computed from the model for different loss mechanisms

Record Store 2328 (March 20, 2003) is quite different







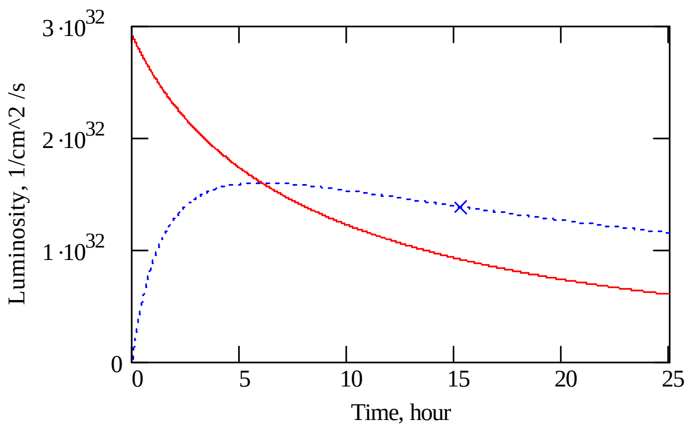
- Luminosity decays faster than in the model
  - It is mainly related to fast proton losses at the store beginning
    - Proton bunch length grows slower at the store beginning
    - Beam-beam effects in the proton beam
      - Incorrect tune or too long bunch or both
    - Most, but not all, stores have abnormal proton loss at the store beginning
  - Pbar intensity loss is larger at the store beginning
    - Beam-beam interaction causes smaller affect on pbar intensity loss than on proton intensity loss

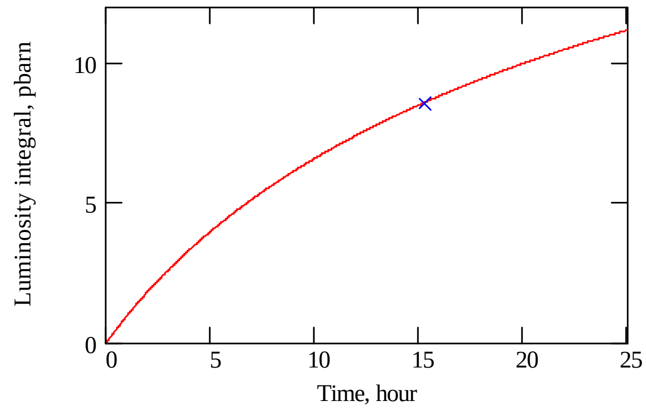
Basic Luminosity Scenario

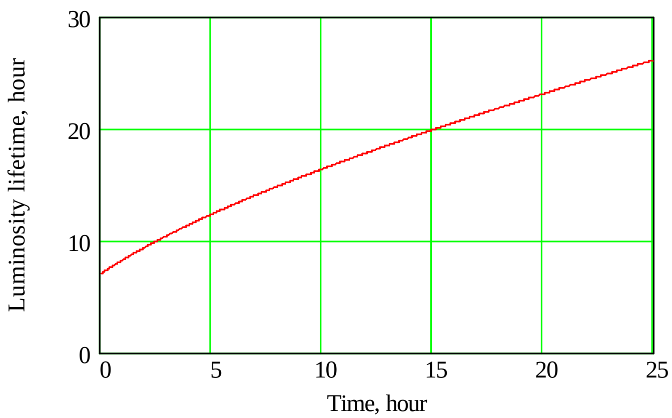
Luminosity integral is calculated presuming that:

- Machine works 46 weeks per year (6 weeks downtime or shutdown time)
- There are 48 hour downtime per week
- Shot setup time is 2 hour. It is not included into the downtime.

Balanced approach for both Tevatron and Antiproton source parameters







$N_p = 2.7 \times 10^{11}$

$N_a = 1.351 \times 10^{11}$

$\varepsilon n_{px} \cdot 10000 = 20$ mm mrad

$\varepsilon n_{py} \cdot 10000 = 20$ mm mrad

$\varepsilon n_{ax} \cdot 10000 = 20.07$ mm mrad

$\varepsilon n_{ay} \cdot 10000 = 20.07$ mm mrad

$\sigma s(\sigma_{pp}) = 50.143$ cm

$\sigma s(\sigma_{pa}) = 50.143$ cm

$T_{store} = 15.2$ hour

$\kappa = 0.2$

$dNadt \cdot 10^{-10} = 40$ mA/Hour

$N_{recycle} \cdot 10^{-10} = 0$ mA

$N_a \cdot n_b \cdot 10^{-10} = 486.4$ mA

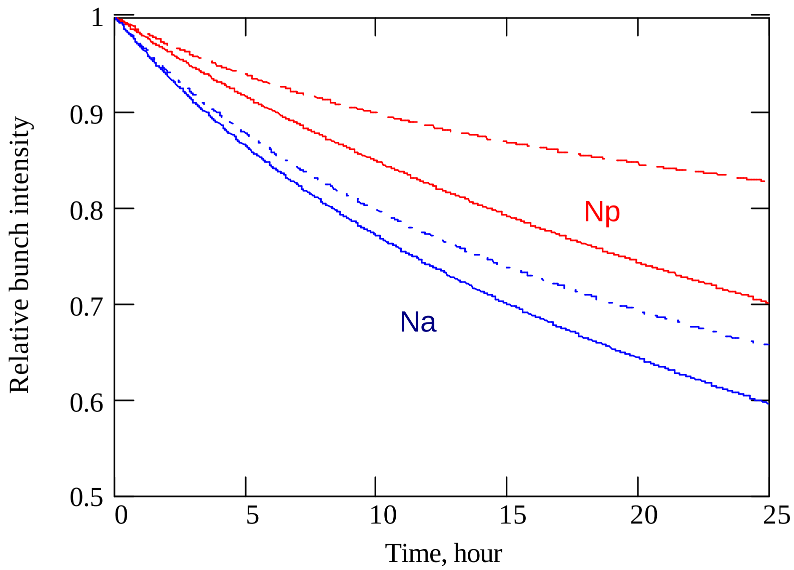
$Lum_0 = 2.907 \times 10^{32}$ $cm^{-2}s^{-1}$

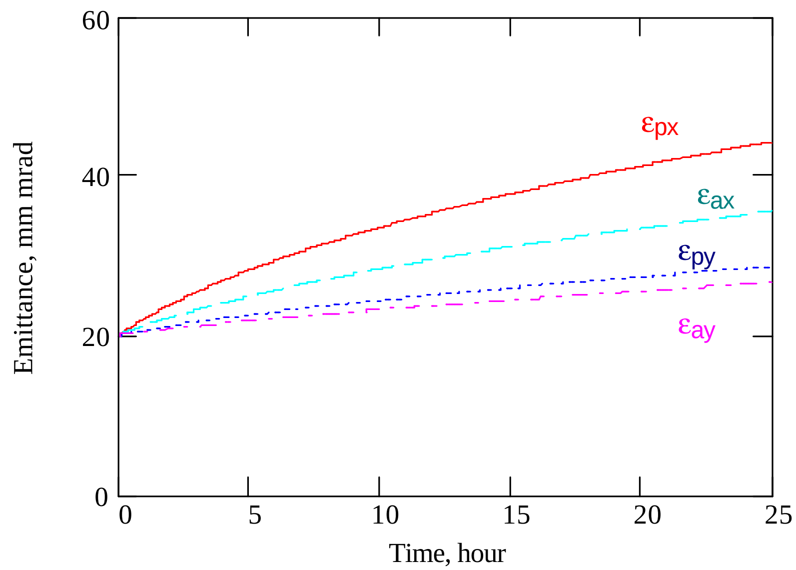
$Lum_{avrg} = 1.385 \times 10^{32}$ $cm^{-2}s^{-1}$

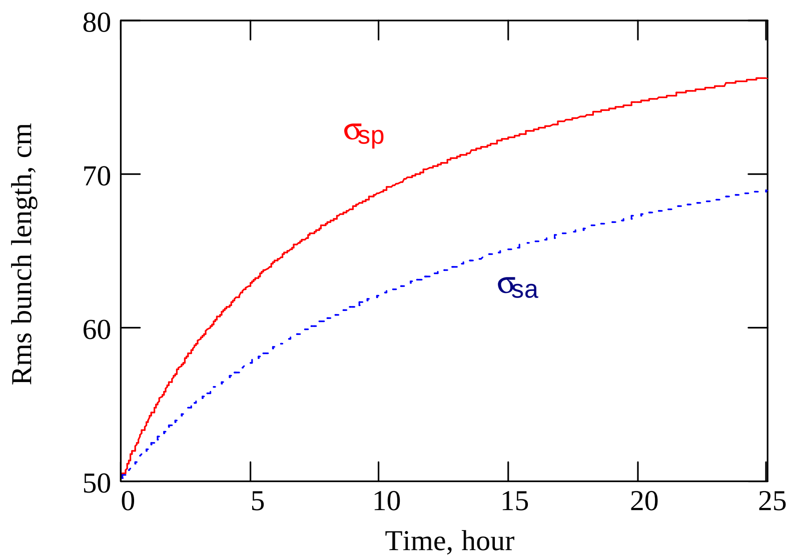
$\tau_{Lum_1} = 7.037$ hour

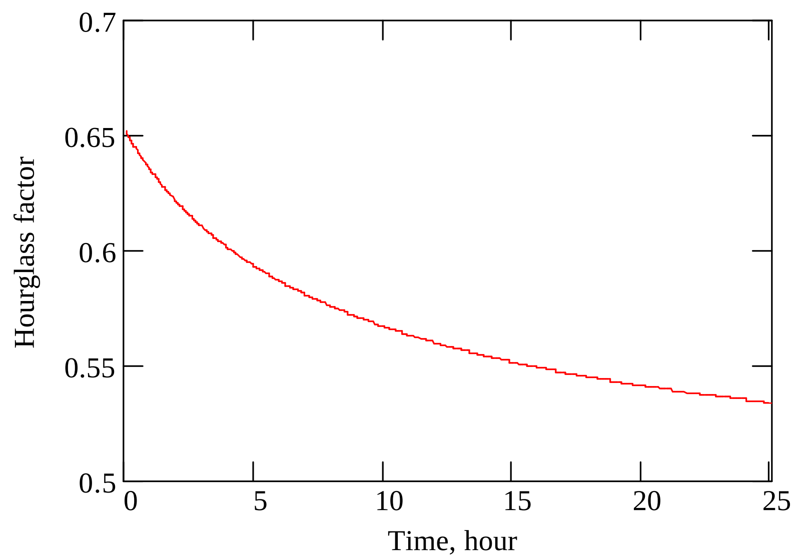
$Ldt_{year} = 2.751$ fbarn/year

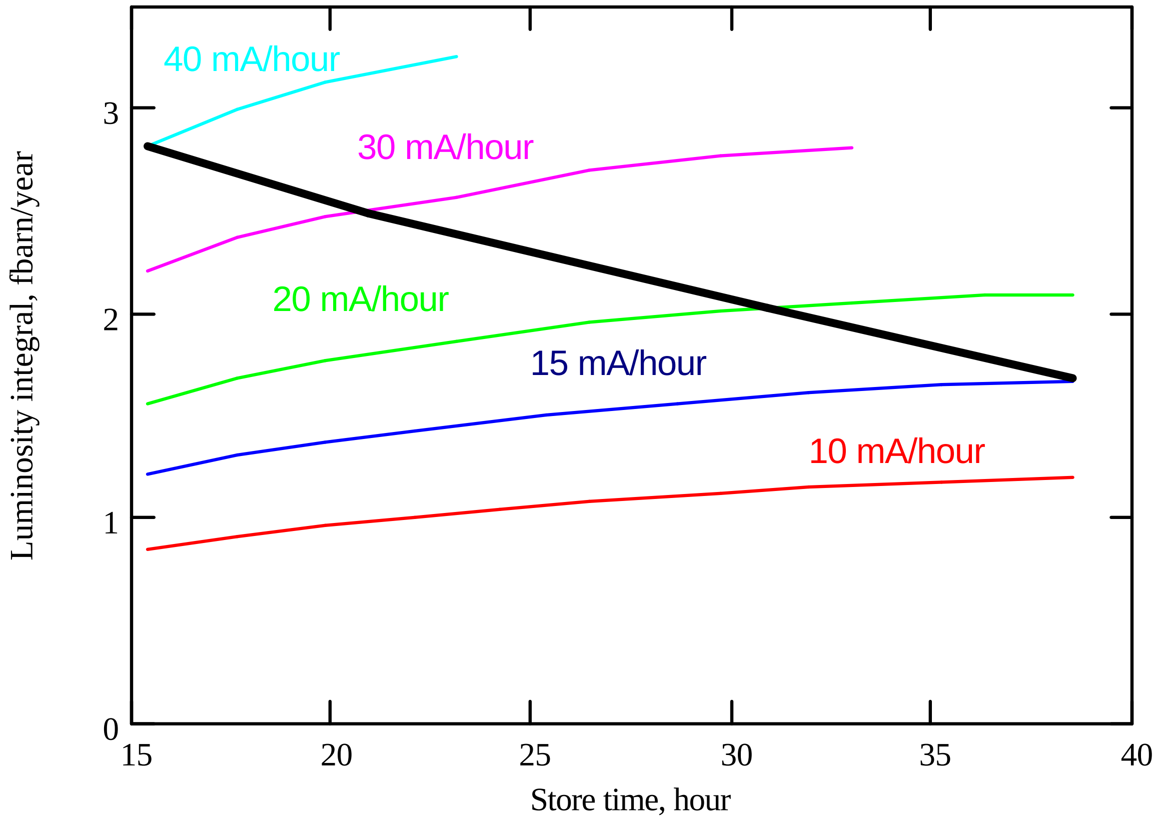
$SLum_{T_{store} \cdot 60} = 8.568$


Relative bunch intensity
1
0.9
0.8
0.7
0.6
0.5
0
5
10
15
20
25
Time, hour
Np
Na


Emittance, mm mrad
60
40
20
0
0
5
10
15
20
25
Time, hour
εpx
εax
εpy
εay


Rms bunch length, cm
80
70
60
50
0
5
10
15
20
25
Time, hour
σsp
σsa


Hourglass factor
0.7
0.65
0.6
0.55
0.5
0
5
10
15
20
25
Time, hour



Lifetime breakup at the store beginning

	hour
Luminosity	7.0
Prot.intens.	51
Pbar.intens.	29
Prot.H.emit.	9
Prot.V.emit.	30
Pbar.H.emit.	16
Pbar.V.emit.	48
Hourglass factor	32

Dependencies of luminosity integral per year on the store time for different antiproton production rates. Thick solid line shows where intensity of antiproton beam reaches $1.35 \cdot 10^{11}$ per bunch.

$$L = \frac{N_p N_{\bar{p}} f_0 n_b}{2\pi\beta^* \sqrt{(\varepsilon_{xp} + \varepsilon_{x\bar{p}})(\varepsilon_{yp} + \varepsilon_{y\bar{p}})}} H\left(\frac{\sqrt{\sigma_{sp}^{\ 2} + \sigma_{s\bar{p}}^{\ 2}}}{\beta^*} \right)$$

Present and final Run II parameters of the collider

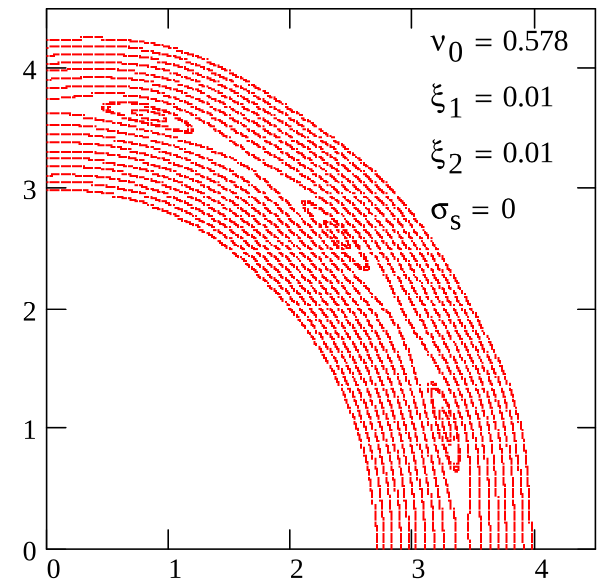
	Store 2328	Typical for April 2003	Final Run II
Number of protons per bunch, 10^{10}	20.7	20	27
Number of antiprotons per bunch, 10^{10}	2.54	2.2	13.5
Normalized 95% proton emittances, e_x /e_y, mm mrad	~14/24	~15/25	20/20
Normalized 95% antiproton emittances, e_x /e_y, mm mrad	~15/24	~16/25	20/20
Proton bunch length, cm	65	62	50
Antiproton bunch length, cm	59	58	50
Initial luminosity, 10^{30} cm^{-2}s^{-1}	40.5	35	290
Initial luminosity lifetime, hour	11	12	7.1
Store duration, hour	19	20	15.2
Luminosity integral per store, pbarn	1.71	1.2	8.65
Shot setup time, hour	2	2	2
Number of store hours per year	-	-	4800
Luminosity integral per year, fbarn	-	-	2.78
Transfer efficiency from stack to Tevatron at low-beta	60%	59%	80%
Average antiproton production rate, 10^{10}/hour	-	11	40
Total antiproton stack size, 10^{10}	166	150	610
Antiprotons extracted from the stack, 10^{10}	154	140	610

2. *Beam-Beam effects*

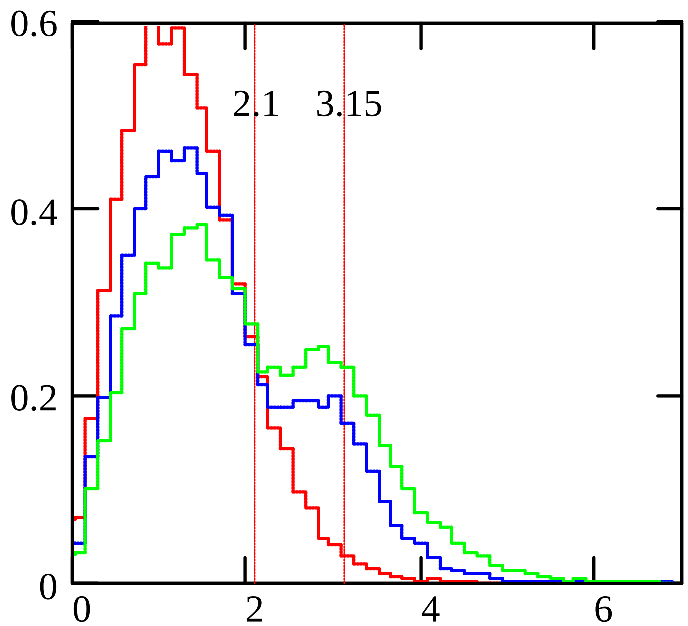
- Beam-beam effects are important at all stages
  - Injection
  - Acceleration
  - Squeeze
  - Collision
- Two types of the beam-beam effects
  - **Head-on**
    - Run IB proton bunch population of $\sim 2.7 \cdot 10^{11}$ proton/bunch was set by the head-on collisions
    - We aim to achieve the same number of protons per bunch
      - Linear beam-beam tune shift $\xi \approx 0.02$ for two interaction points
  - **Long range**
    - Much stronger than for Run IB
    - Additional tune spread within one bunch
      - $\Delta\nu \approx 5 \cdot 10^{-3}$
    - Tune spread between bunches ($N_p = 2.7 \times 10^{11}$)
      - At injection: $\Delta\nu_x \approx 5 \cdot 10^{-3}$, $\Delta\nu_y \approx 2.5 \cdot 10^{-3}$
      - At flat top: $\Delta\nu_x \approx \Delta\nu_y \approx 8 \cdot 10^{-3}$

General approach to the beam-beam effects

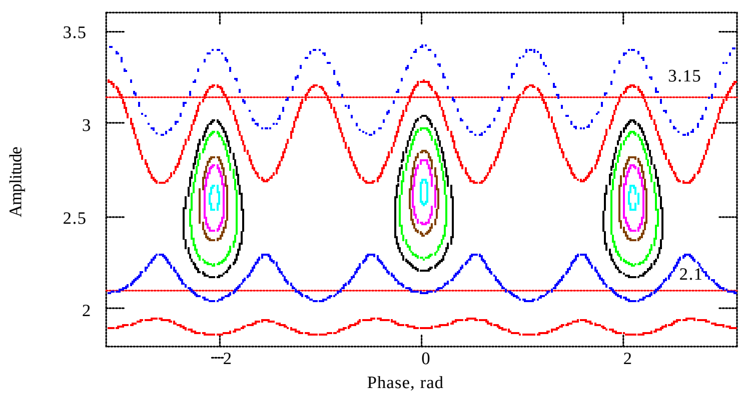
- 1 store consists of about $4\cdot10^9$ turns – too much for any computer in visible future
- **Conclusion following from parametric model study**: for correctly tuned collider at present beam intensities the beam-beam effects and machine nonlinearity do not produce harmful effects on the beam dynamics and collider luminosity while beams are in collisions
- We can not accept significant worsening of the lifetime if we want to maximize the luminosity integral
- The theory should be build as a perturbation theory to the diffusion model
- Diffusion amplification by non-linear resonance
  - Motion inside resonance island is fast comparing to the beam lifetime
    - 100-10000 turns depending on ξ and the resonance order
  - Flattening distribution function in the resonance island



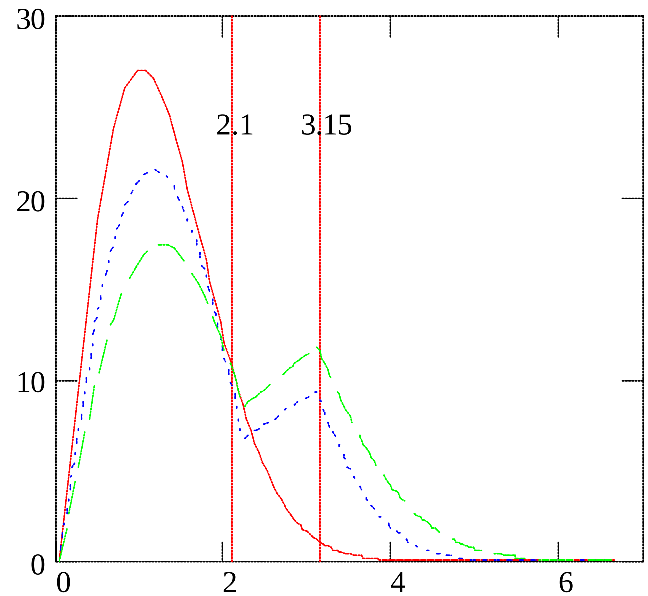
Phase trajectories in vicinity of 12-th order resonance ν_x=7/12; two Tevatron IPs but zero length of counter-rotating bunch, and zero synchrotron motion amplitude



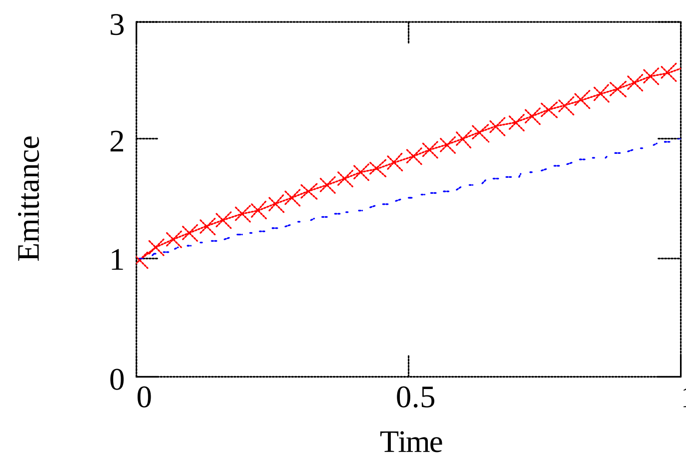
$\nu=0.325$, $\xi=0.02$, $\Delta p/p=0$, $\sigma_s << \beta^*$



Tracking of 20,000 particles for 5,000 turns in vicinity of 6-th order resonance, $\nu_x=2/6$

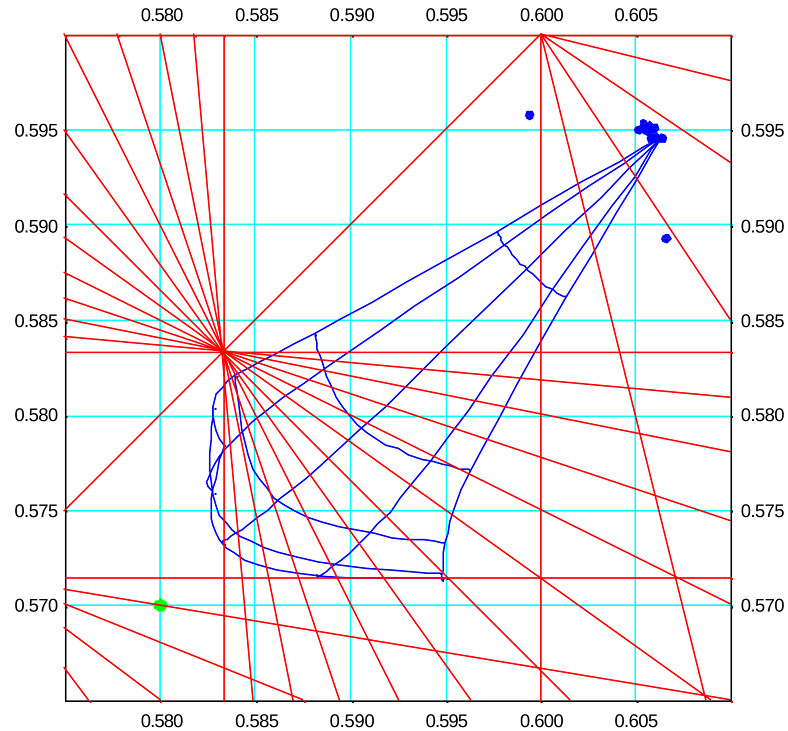


Particle distribution obtained by diffusion equation solving



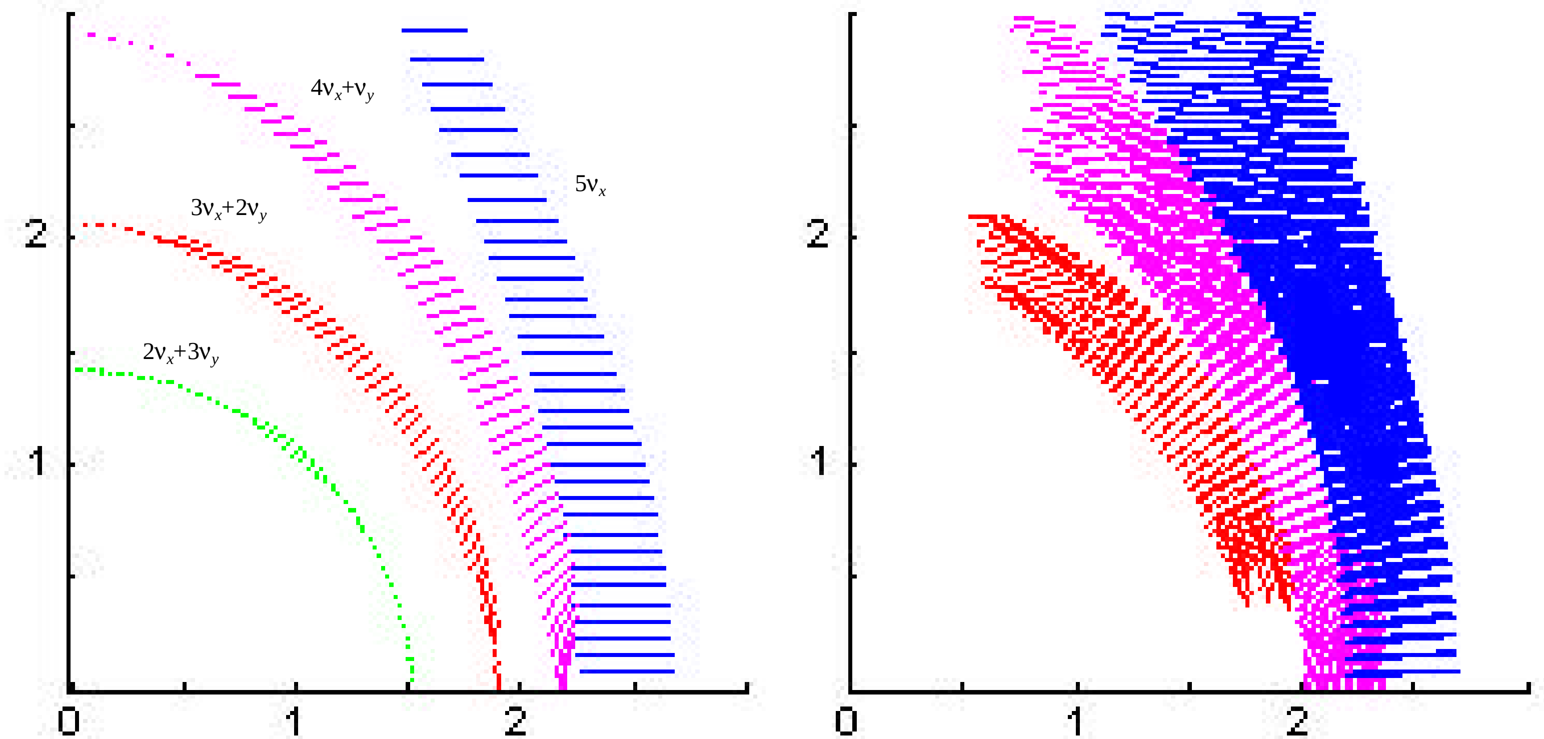
Beam-beam effects on Tevatron

- Tunes are between 5-th, 7-th and 12-th order resonances
  - 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 – $2 \cdot 0.01 = 0.02$
    - Long range within a bunch – 0.005
    - Bunch to bunch difference – 0.007
  - Protons experience only half of this because of smaller pbar intensity



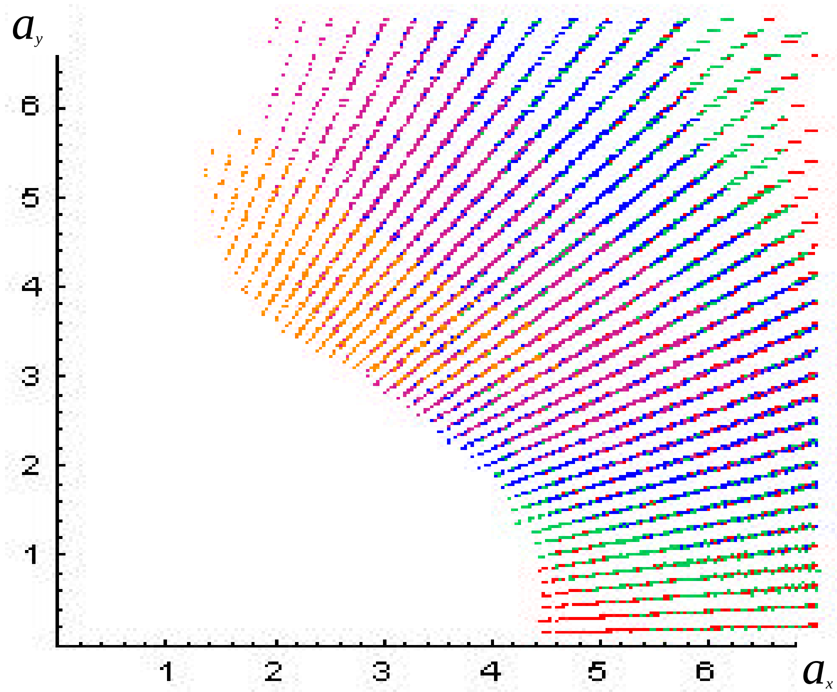
Footprint of pbar bunch #6 in the tune diagram with ν_x=0.580, ν_y=0.580 (green dot) and nominal beam parameters. Dots show small amplitude tunes for other bunches. Footprint lines go in 2σ and 22.5 deg in the space of actions (angle or $(a_x^2 + a_y^2)^{1/2}$ =const on a line). *Courtesy of Yu. Alexahin*

Long Range collisions



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

Head-on collisions



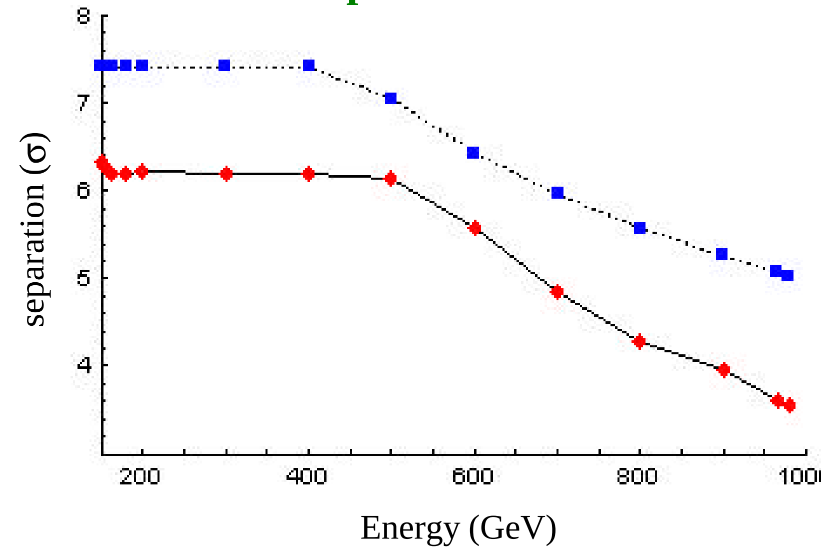
Effect of the 12th order resonances and their satellites at $d_p = 3 \cdot 10^{-4}$ ($a_s = 2$) and tunes $\nu_x = 20.58$, $\nu_y = 20.57$, $n' = 12$, $\xi = 2 \cdot 0.01$;
$12\nu_x$ (red), $10\nu_x+2\nu_y$ (green),
$8\nu_x+4\nu_y$ (blue), $6\nu_x+6\nu_y$ (violet)
$4\nu_x+8\nu_y$ (orange)
Courtesy of Yu. Alexahin

- Chosen tunes allows to avoid 5-th and 7-th order but not 12-th order resonances
- There is a pronounced effect of 12-th order resonances whose satellites overlap forming the region of dynamical diffusion starting from transverse amplitudes ≤ 4
- In the case when the nonlinear tuneshift is dominated by the beam-beam effect there is no dependence of the resonance width in the phase space on the intensity of the opposing beam
  - Therefore the protons are equally susceptible to the beam-beam resonances despite lower pbar intensity.
    - It be even more detrimental due to smaller pbar emittance and therefore higher field nonlinearity they create.
  - At present small pbar intensity the satellites of the 12th order resonances for protons do not overlap so that no wide region of dynamic stochasticity is created.

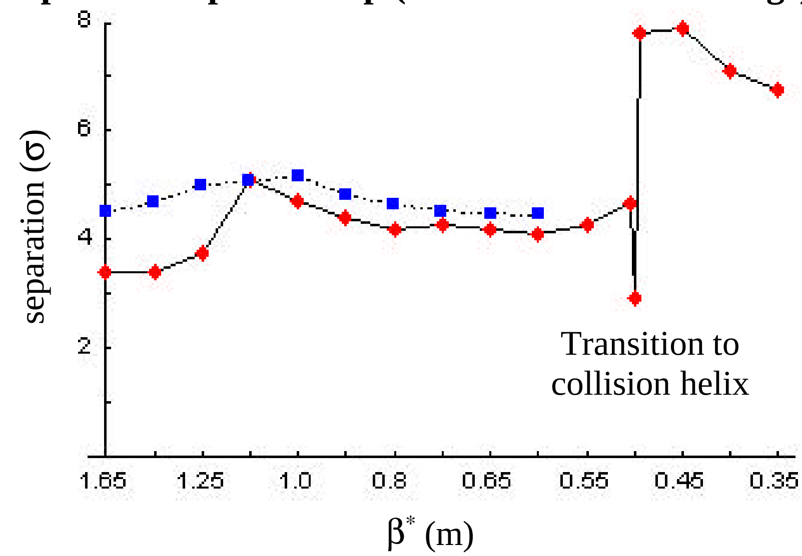
Beam separation and long range beam-beam

- For fixed separation in σ's the tune shift does not depend on energy
  - It requires U ∝√Energy
- High voltage separators are maxed-out at ~ 500 GeV
  - That reduces the beam separation at the end of acceleration by ≈ 1.4 times
- Acceleration and squeeze are the most sensitive steps from the beam-beam effects point of view
- Normally particles, which survive acceleration and squeeze, do not experience severe beam-beam effects during the store

Injection Helix after C0 Lambertson Replacement



Separation up the ramp (current and new settings)



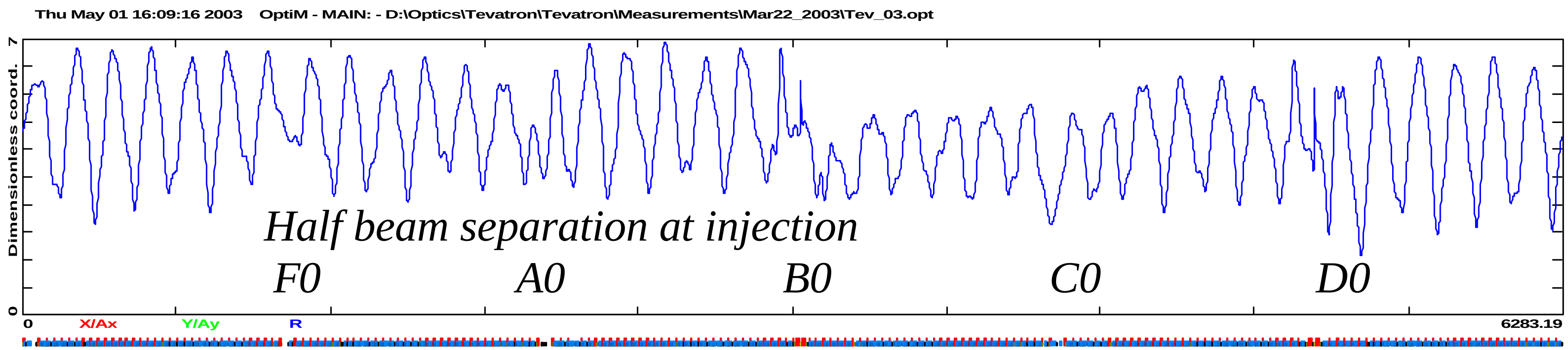
Separation on squeeze (Umax=106.5 kV, E=1 TeV)

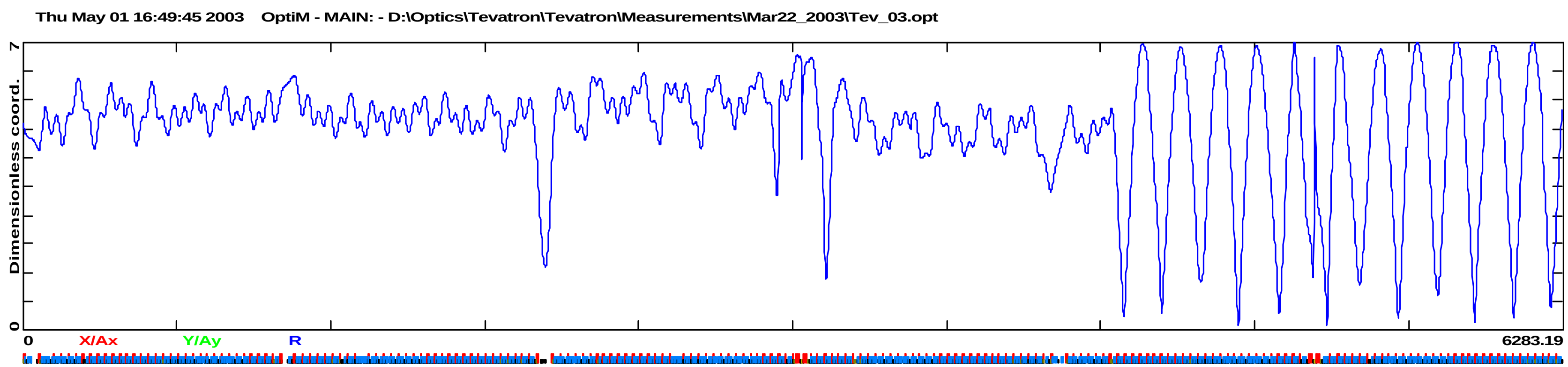
What can be done to alleviate harmful effects of long-range collisions?

- We need ~1.4 times increase of the beam separation at high energy

$$\Delta n \propto \frac{1}{a^2}$$

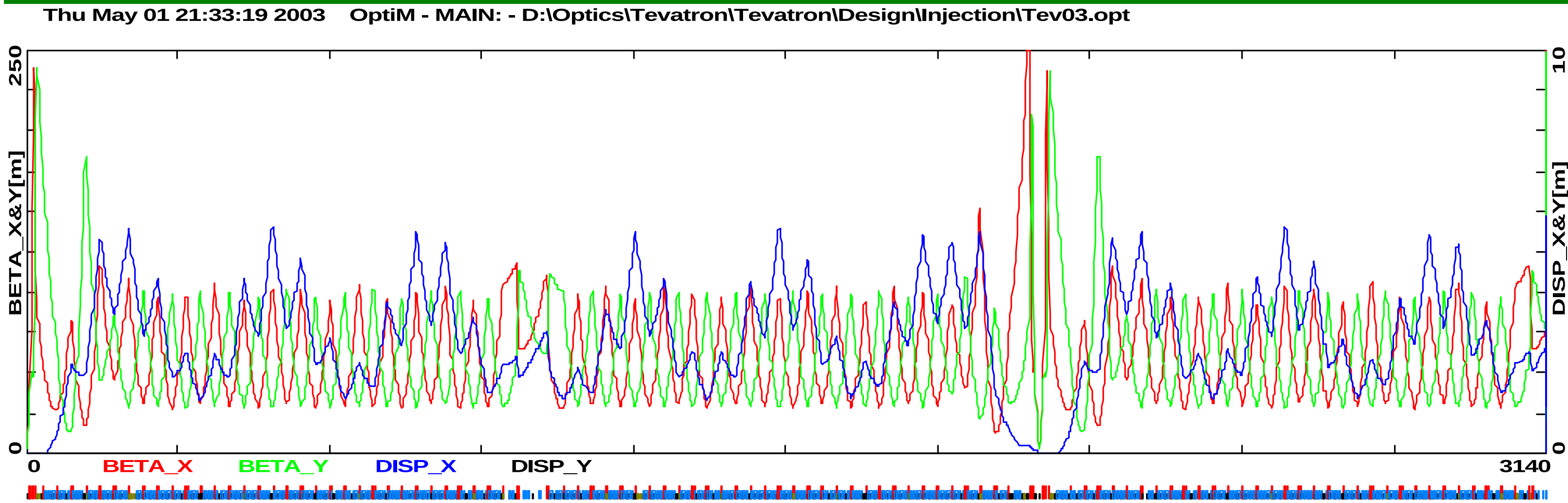
- Better optimization of helical orbits through all stages of the process



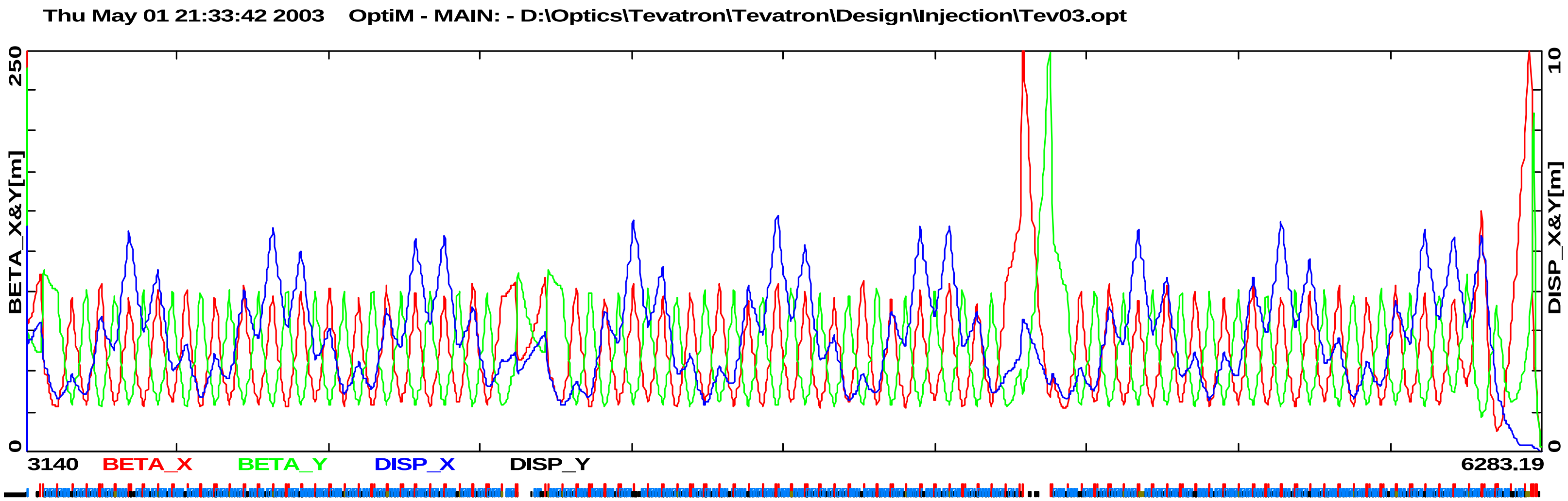


- Many degrees of freedom require long time to find the optimum
- Physical and dynamic aperture limitations need to be taken into account

Design beta-functions and dispersions at injection (Backup slide)



B0 C0 D0

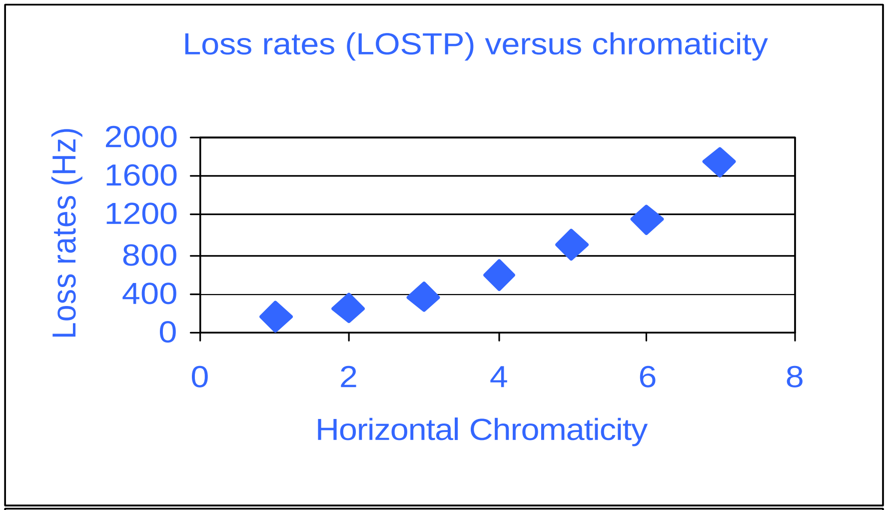


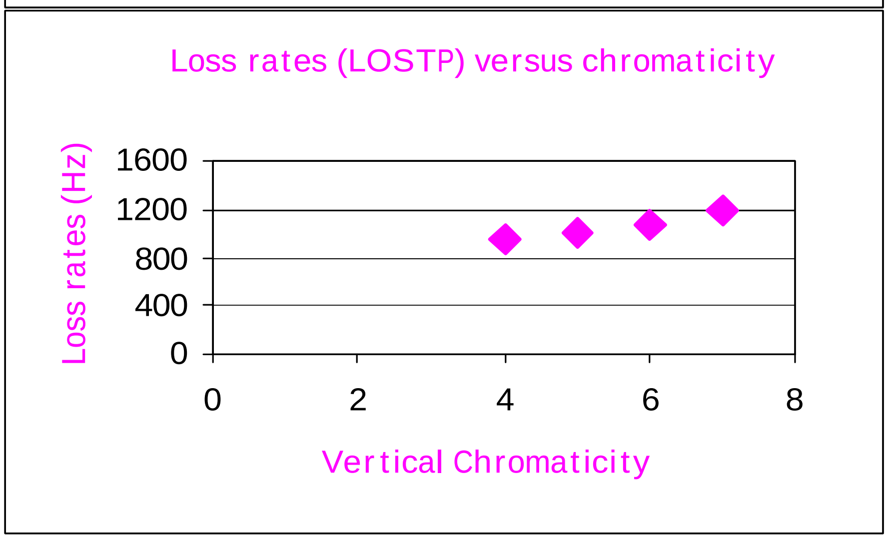
E0 F0 A0

Possible hardware improvements to address long-range collisions

- Adding new separators to correct the betatron phase imbalances along the machine
  - Optics change in A0 could additionally improve separation but presently is not a favor because of comparatively large cost involved
- Increasing voltage on the near IP separators in 1.4 times
  - Increasing voltage
    - Dielectric or semiconducting covering of the plates?
    - Training to higher voltage
  - Increasing length
    - We can use the space where non-powered Q1 quads are presently located
- Tevatron electron lens can reduce both long range and head-on tune shifts
  - Recently we achieved electron lens operation without degradation of the beam lifetime

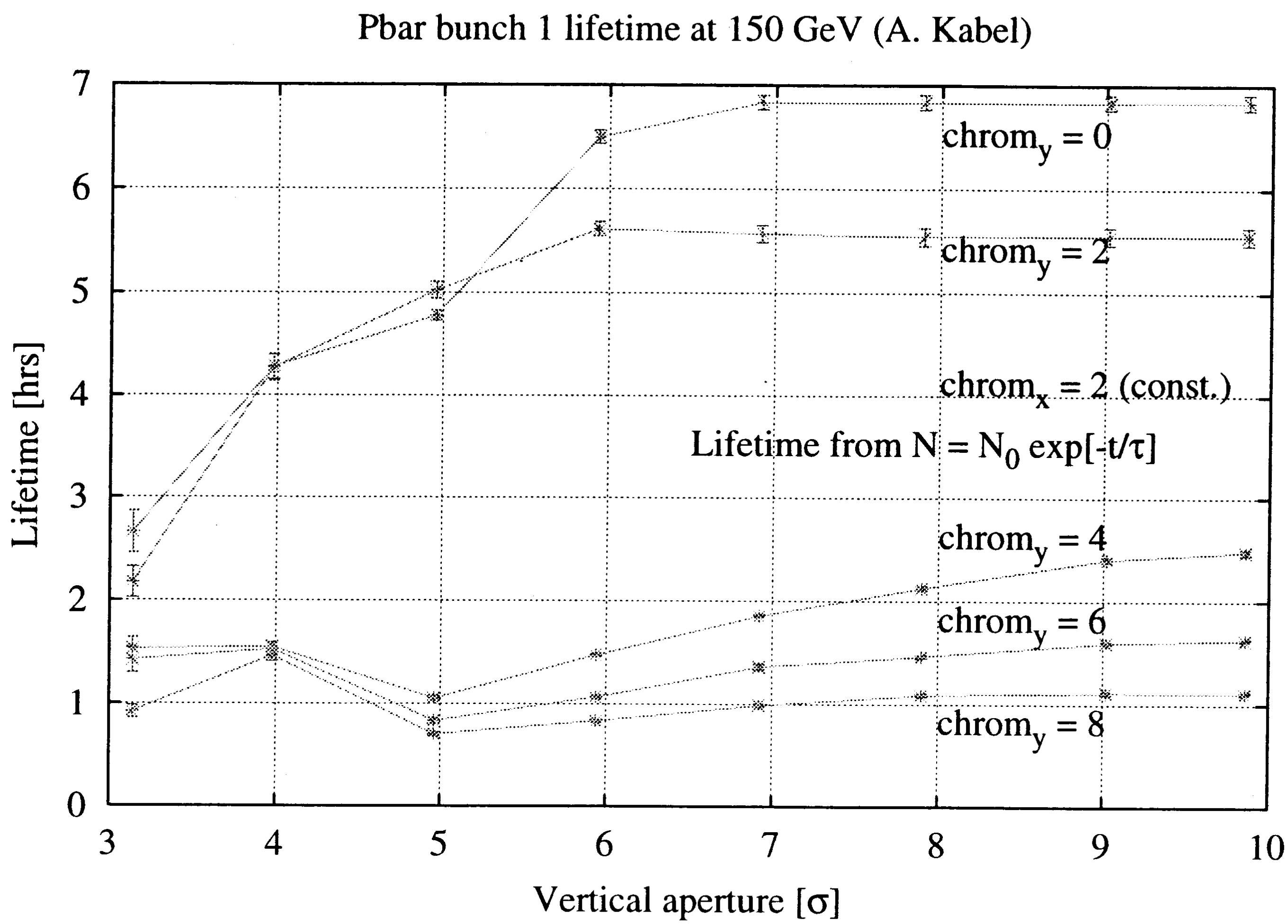
Lowering chromaticity mitigates effects of machine non-linearity and the beam-beam effects





Measured loss rates as function of chromaticity
(with protons on the pbar helix)

- Lower chromaticity is better for lifetime
- Instabilities appear ξ < 3-4
- •Run with $\xi_H = 8$, ξ_V=8 to avoid instabilities
- •Dampers allow us to lower chromaticity and improve lifetime



Lifetime of antiproton bunch 1 vs physical aperture at different vertical chromaticities in simulation by A. Kabel (SLAC).
Proton intensity per bunch $2.2 \cdot 10^{11}$, the horizontal chromaticity is fixed at 2 units.

How to perform tracking

- The number of turns is determined by minimum acceptable noise
  - Resonances with width above ~ 0.05σ need to be taken into account (5 such resonances change emittance growth time by ~25%)
  - Displacement due to diffusion during one revolution in the resonance needs to be much smaller than the resonance width
    - For 12-th order resonances one revolution is about few thousand turns
  - the step per turn needs to be about 0.1 of resonance width we obtain the minimum number of turns

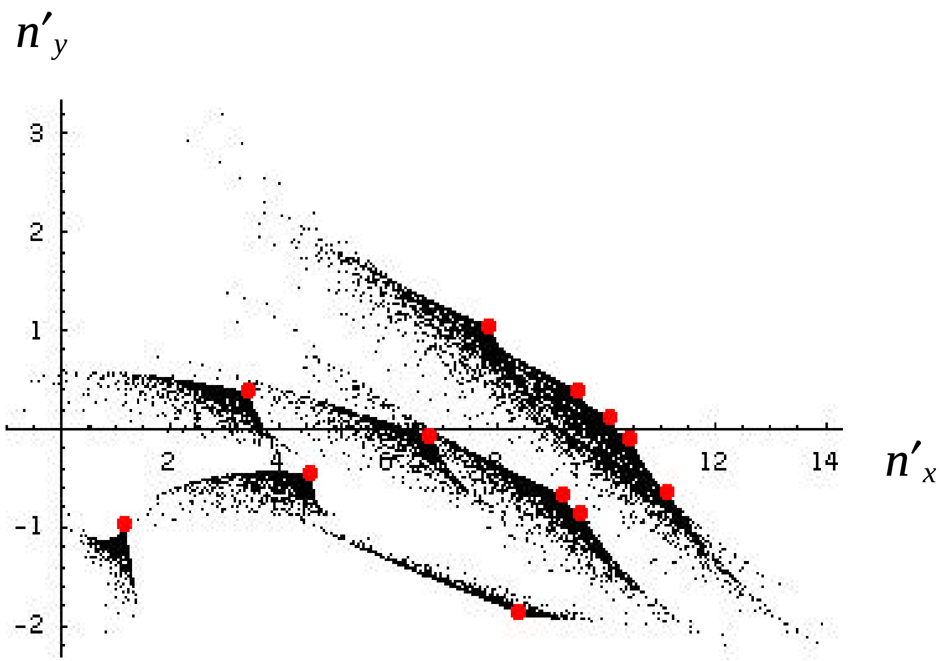
$$\Delta a \equiv \Delta\sqrt{N_{res}} << 0.05s \xrightarrow{\Delta \approx 3\cdot 10^{-4}\ s} N = \frac{\Delta e}{\Delta^2} \approx \frac{0.1}{\left(3\cdot 10^{-4}\right)^2} \approx 10^6$$

    - Number of turns is about an order of magnitude smaller if only long range collisions are present
- Number of particles is determined by
  - The statistic accuracy of emittance calculations

    1% accuracy of emittance calculations requires about 10,000 particles
  - Coverage of the phase space by particles for three dimensional phase space

    10,000 particles correspond to an average particle distance (in 3 dimensional action phase space) of about 0.05σ

Collective stability and long-range beam-beam effects



Total $\bar{p}$ distribution in the chromaticity plane, particles with zero betatron amplitudes in each of the 12 bunches in a train are shown with red circles; collision helix

Courtesy of Yu. Alexahin

- Long-range beam-beam effects modify machine chromaticity so that different bunches see different chromaticities
- If not addressed the spread of chromaticities (~ 5 units for final Run II parameters) can cause
  - The head-tail transverse instability for one or few bunches
  - It affects the instability suppression by the transverse damper due to the fact that at certain chromaticities an internal motion in the bunch becomes uncoupled with motion of the bunch center of gravity
- Instability in one beam can cause the emittance growth in both beams

Transverse stability of head-on colliding bunches (3´3 groups, two IPs)

- Two major mechanisms of stabilization in collision:
  - Landau damping by synchrotron sidebands of incoherent tunes
  - Decoherence by splitting the lattice tunes of the two beams
- The damping rate depends on the coupling parameter

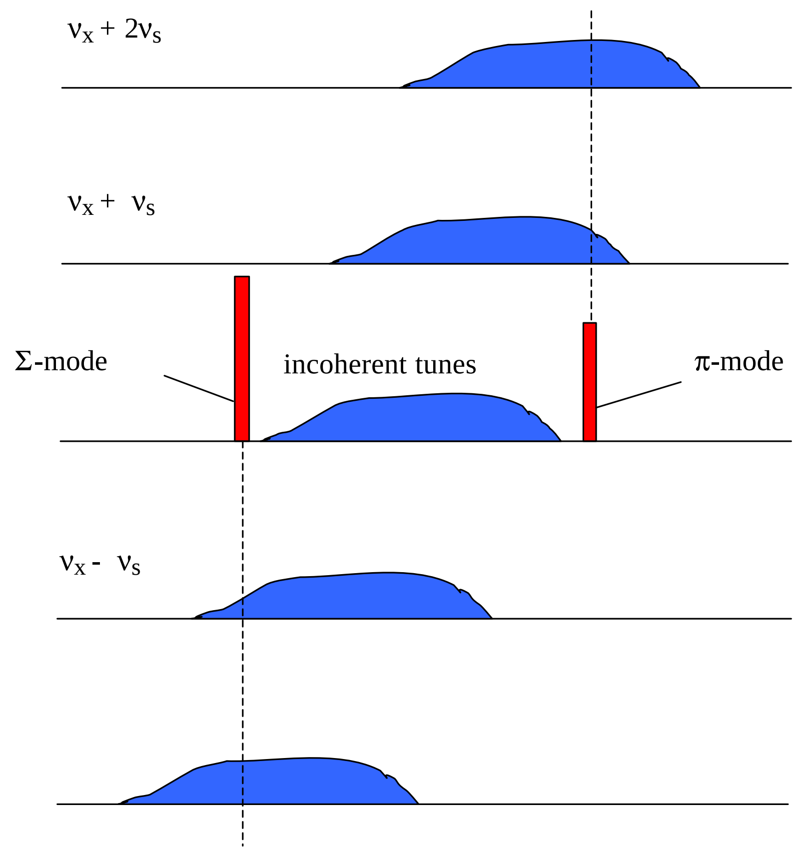
  $$k = (n'_x / a_M R - 1/b^*)^2 s_s^2$$

  and has a minimum at the chromaticity value

  $$n'_{x,y} = a_M R / b^* \approx 8$$

- so that the chromaticity should be either ≈ 0 or sufficiently high (≥ 15).
- Also, with higher proton intensity this mechanism will be less efficient due to reduction in the ratio synchrotron tune / beam-beam parameter.

Solution: tunesplit between the beams with the help of feeddown sextupoles and/or TELs

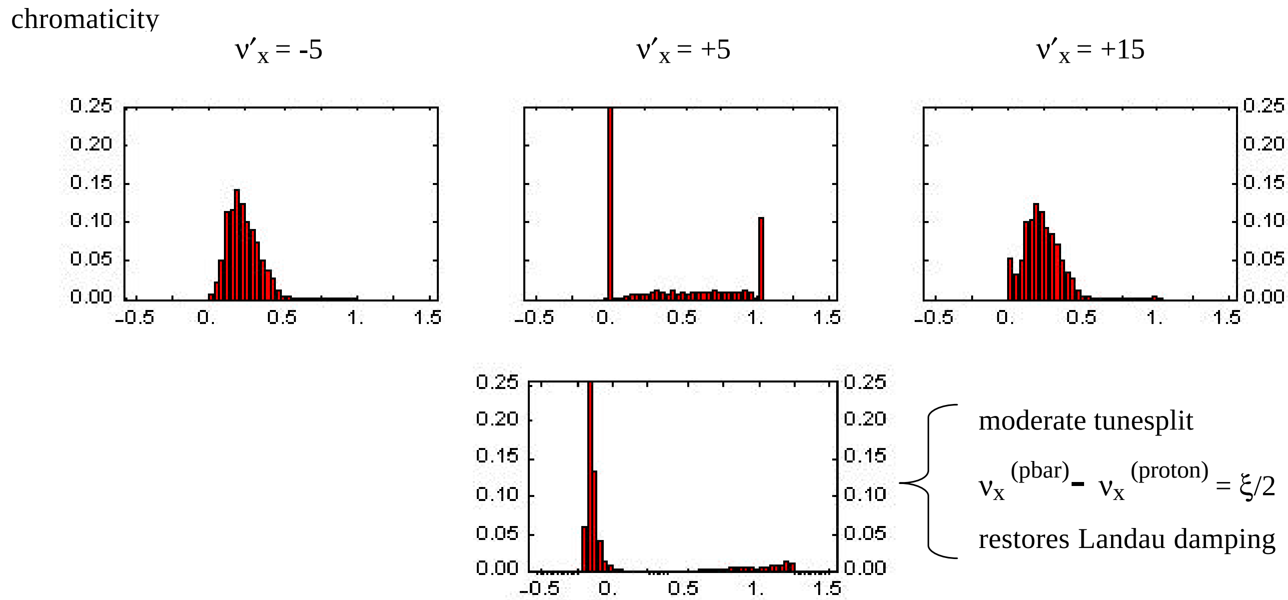


Principle of Landau damping by synchrotron sidebands
Courtesy of Yu. Alexahin

Spectra of Coherent Beam-Beam Oscillations from the Vlasov Perturb. Theory

The theory predicts no sidebands of the ***discrete*** spectral lines, just the sidebands of the so-called ***continuum*** modes with tunes distributed over the incoherent range, therefore:

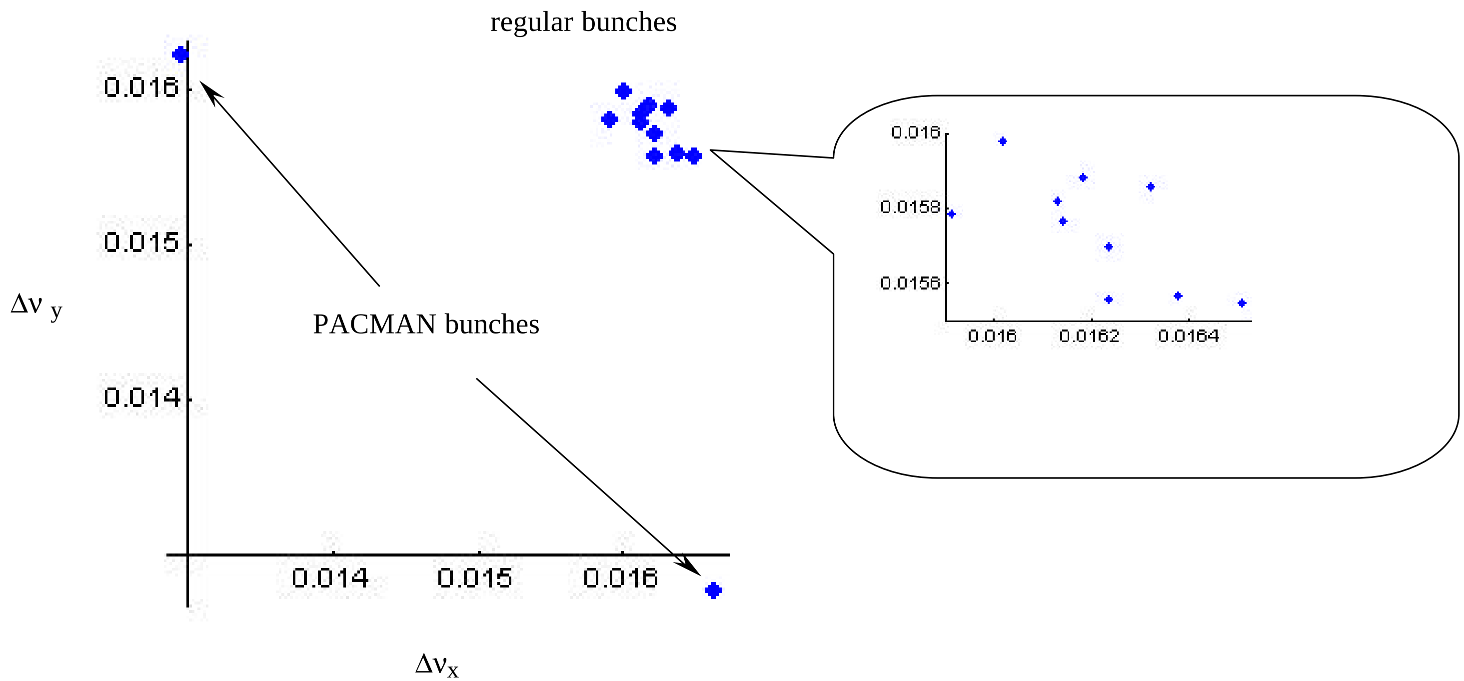
We do not expect *the head-tail modes* to be a problem with more pbars in collision



Effect of chromaticity and tunesplit on coherent beam-beam spectrum;

flat beams at IP, $\sigma_s/\beta^* = 50/35$, $\nu_s/\xi = 0.035$, $\xi = 0.02$ (two IPs)

Multibunch transverse instabilities (including beam-beam resonances) are suppressed by the bunch-to-bunch tunespread.



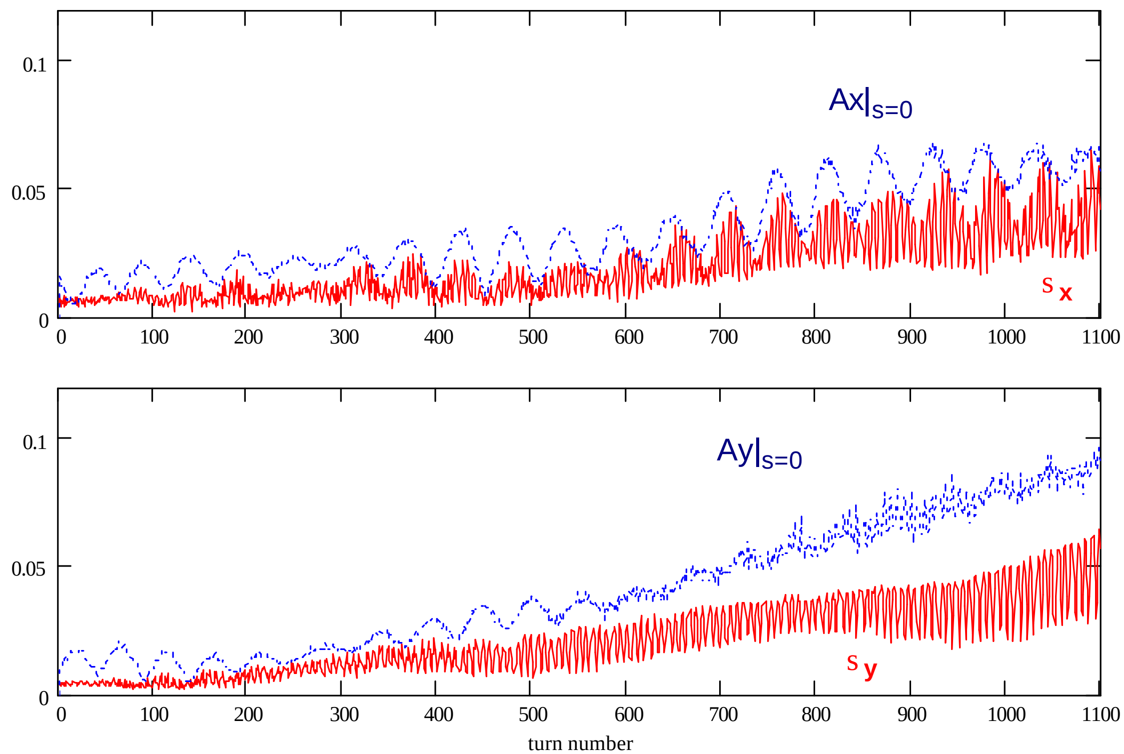
Small-amplitude tuneshifts in proton bunches in collision
Courtesy of Yu. Alexahin

3. Beam Instabilities

- Transverse Instabilities
  - Single bunch head-tail instability
  - Brings many troubles into Tevatron operations
  - Needs to be suppressed if number of protons will grow
- Longitudinal instabilities
  - Undamped dancing of bunches
    - Single bunch effect
  - Presently, it does not bring severe problems but limits desired shortening of the bunches
- Significant progress was achieved in understanding of both instabilities during last year
- It is not expected that multibunch instabilities will be degrading machine performance at the planed Run II intensities.

Transverse Head-Tail Instability

- In the most detailed recent measurements (P. Ivanov, V. Scarpine), all the features of the head-tail instability were observed
  - The instability threshold does not depend on the number of bunches;
  - When the instability is developed, the transverse amplitudes and phases have correct modulation along the bunch
- At injection, the growth rates **~150 s^{-1}** for N=2.5·10^{11} per bunch, compared to **500 s^{-1}** of the synchrotron angular frequency.
- To suppress CI, high chromaticities are required, which deteriorate the beam lifetime



Turn-by- turn measurements of betatron amplitudes of the bunch center of gravity and rms particle displacement relative to this center

Head-tail Instability Simulations

- A Monte-Carlo C++ code has been written (A. Burov) to find the impedance responsible for the instability. It allows to use
  - any given wake function(s),
  - arbitrary longitudinal distribution
  - and initial conditions,
  - and to see the transverse beam dynamics in time domain.
- The code was tested for the air-bag longitudinal distribution, where the analytical results are known, and the perfect agreement has been found.
- Performing simulations
  - with the Gaussian longitudinal distribution (close to real one, s_s = 1 m)
  - and with the impedance of resistive wall type, $Z_\perp(w) \propto (1+i)/\sqrt{w}$

  we obtained that the resistive part of total impedance is about or above 4 MΩ/m at the bunch frequency of 50 MHz
    - Presently, the model does not take into account the Landau damping, and therefore we can only quote the low boundary of the impedance
- This is
  - 4 times higher than the impedance of vacuum chamber resistive walls,
  - and 2.3 times above Run IIA handbook estimate.

Where Is the Lost Transverse Impedance?

- Transverse impedance of the Lambertson magnets compared to the chamber resistive one is

$$\frac{Z_L}{Z_c} \approx \frac{l_L \sqrt{m}}{C} \sqrt{\frac{r_L}{r_c}} \frac{b_L}{d} \frac{b_c^{\,3}}{b_L^{\,3}}$$

b_L, b_c are the distances to the resistive surface,

r_L, r_c are the resistivities,

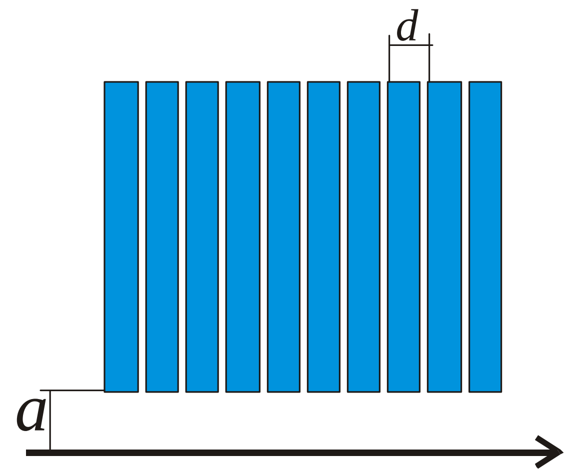
m is the magnetic permeability,

l_L is the occupied Lambertson magnet length,

C is the circumference,

d is the lamination periodicity,

and the superscripts L, c relates to the Lambertson magnets and the main chamber



$$Z_{\perp_{La\min ated}} \approx Z_{\perp} \frac{2a}{d}$$

- Substituting

$r_c / r_L = 4$, $b_L = 10$ mm, $b_c = 25$ mm, d = 1 mm, $l_L = 8{\cdot}2.8 = 22.4$ m, and $m = 100$ leads to $Z_L / Z_c \approx 2.8$, or **Z_L » 2.8 MW/m**.

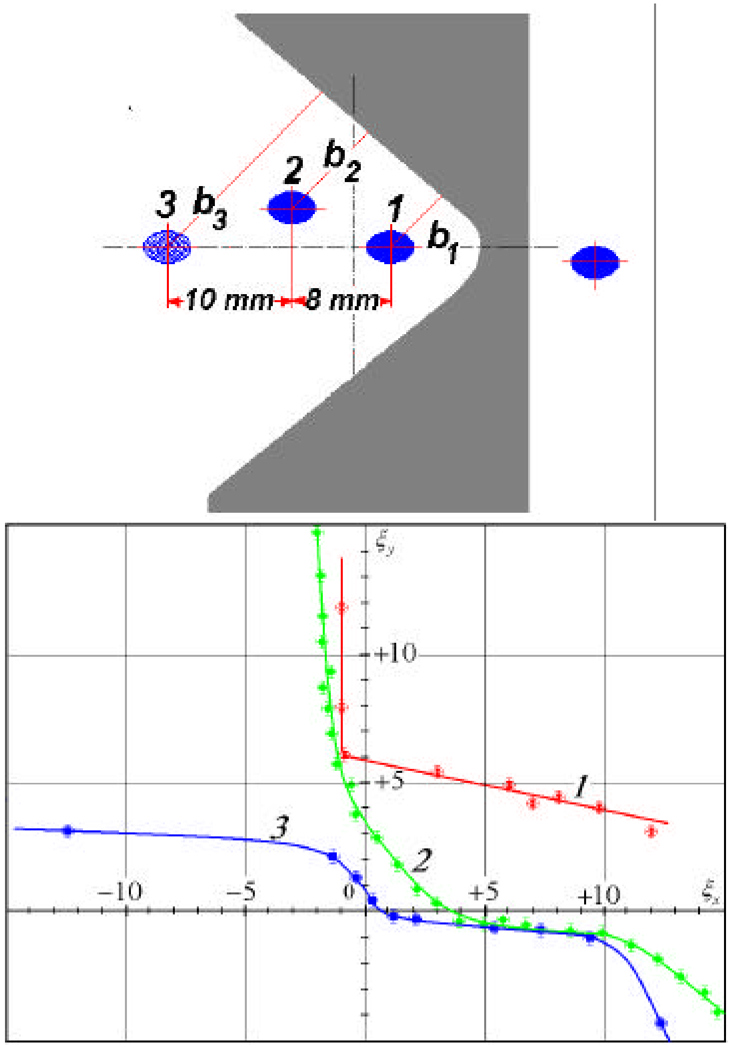
What Can Be Done?

- C0 Lambertson magnet has been removed from the Tevatron at January shutdown.
  - This yielded significant reduction of
    - transverse impedance (≈0.5 MW/m)
    - and stability boundary chromaticities
- Inner surfaces of the remaining F0 lambertson magnets are planned to be shielded in the summer
  - It should further reduce the transverse impedance to ≈ (1–1.5) MΩ/m and should solve all problems with the head-tail instability
  - Impedances measured at dif. locations

1. Injection local orbit bump: b_1≈6 mm, $Z_\perp$≈5 MW/m;

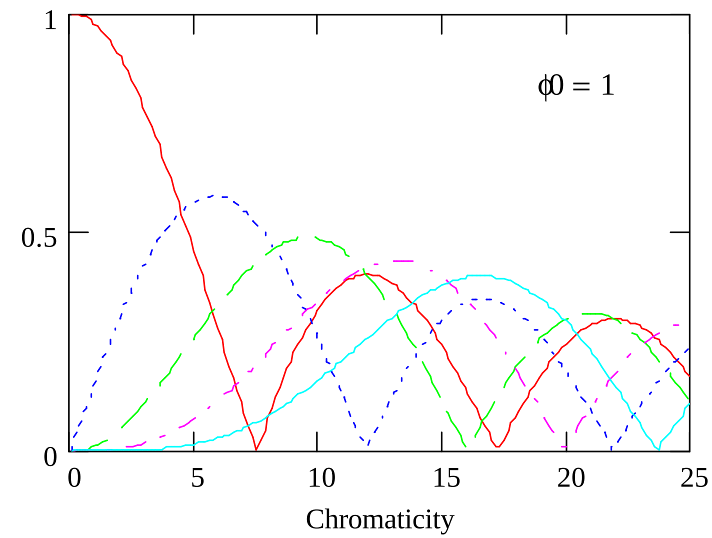
2. Central orbit: b_2≈9 mm, $Z_\perp$≈1.8 MW/m;

3\. Local orbit bump with respect to the central orbit: Δ*Y*= - 3 mm, Δ*X*= -10 mm, b_2≈17.7 mm, $Z_\perp$≈0.6 MW/m



Stability boundary as function of chromaticities for different beam positions inside injection lambertson
Courtesy of P. Ivanov

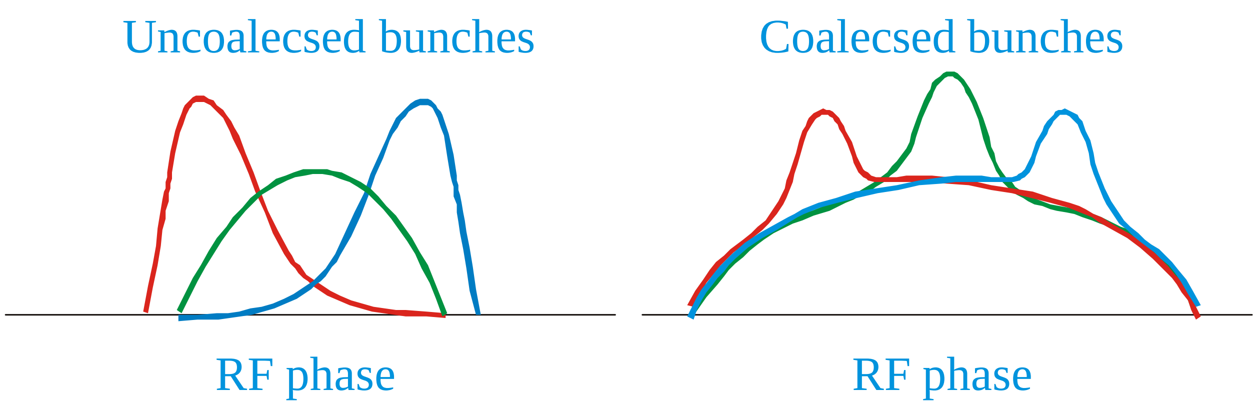
- There are two additional leverages which we already exercised and which can be used if necessary
  - Transverse bunch-by-bunch damper
    - While it is designed to damp only dipole mode it also damps the head-tail instability because in the case of non-zero chromaticity head-tail modes also have non-zero dipole moment
  - Introducing cubic (octupole) non-linearity suppresses the instability due to increasing the betatron tune spread
    - The drawback of this solution is amplified sensitivity of tunes to the closed orbit changes but it should allow machine operations at zero chromaticities



Ratio of the center-of-gravity amplitude to the particle amplitudes

Longitudinal Single Bunch Instability
(‘Dancing bunch’ effect)

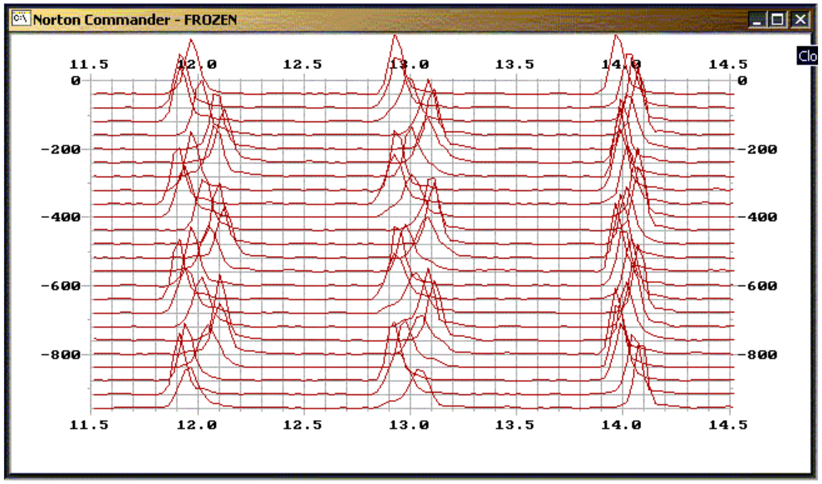
- Long-term coherent synchrotron oscillations of proton bunches are observed in Tevatron.
- Bunch shape at the oscillations differs for uncoalesced and coalesced bunches.
  - Uncoalesced bunches - oscillations persist for hours
  - Coalesced bunches – oscillations are damped during about 5 minutes
    - Longitudinal bunch-by-bunch damper accelerates the damping



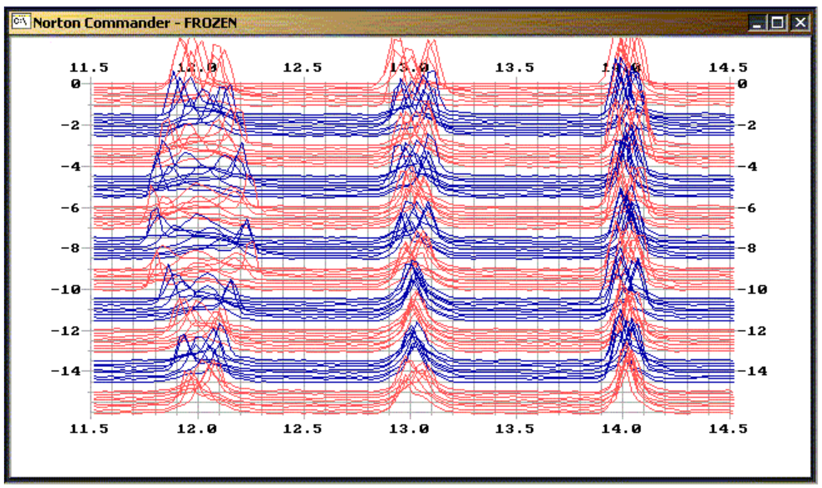
- The synchrotron tune spread would damp oscillations within seconds without coherent interactions inside bunches

The following below data relate to the uncoalesced bunches at 150 GeV.

Bunch waveforms at 150 GeV, 2×10^{11} protons in 30 bunches



40 turns from injection to 1-st scan and between scans



~1.5 min between colors. Each color includes scans in 40 turns. Hor. axis - RF phase/2p. Integer - bunch number in the batch.

Short-term data:

- Error of injection due to instability in MI !!!
- 14th bunch has different amplitude and phase.
- Constant amplitude of the oscillations and bunch length

Long-Term data:

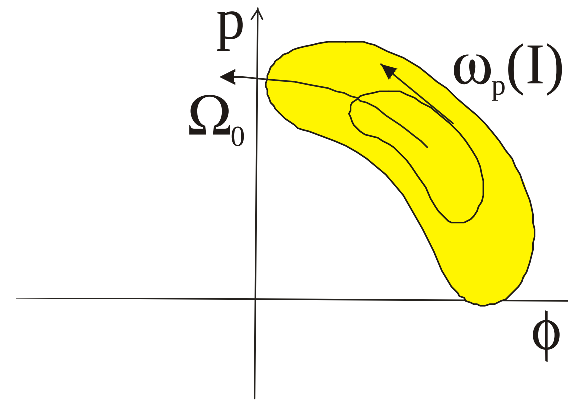
- Coherent oscillations of variable amplitude exist at least 15 min.
- No visible correlations and lengthening of the bunches.
- Slow changing amplitude, actually const bunch length,
- no correlations between bunches

8

- Effect of **inductive** longitudinal impedance separates coherent and incoherent tunes and prevents decoherence at (V.Balbekov, S.Ivanov, 1991)

$$|\Delta\Omega| > \delta\Omega_c$$

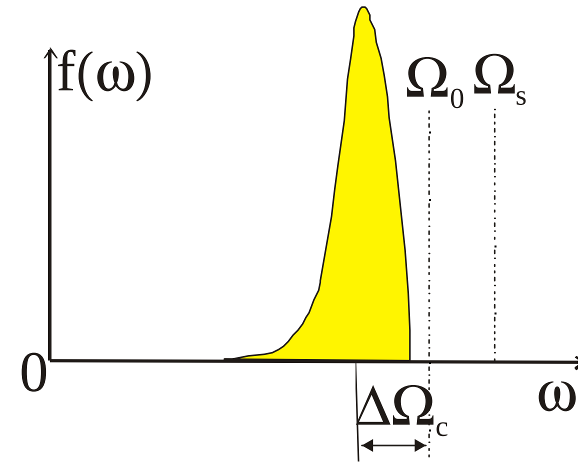
where $\delta\Omega$ is synchrotron tune spread,
$\Delta\Omega_c$ - coherent tune shift produced by the impedance.



- For Tevatron at 150 GeV it yields:

$$|Z/n|[\Omega] > 2\cdot 10^{11} f^{\,5}/N \;\approx 1\ \Omega$$

$N = 10^{10}$ - number protons per bunch,
$f = 0.5$ - bunch half-length in RF radian.



- Run IIA handbook estimate yields very close result at characteristic n ~ 1000:

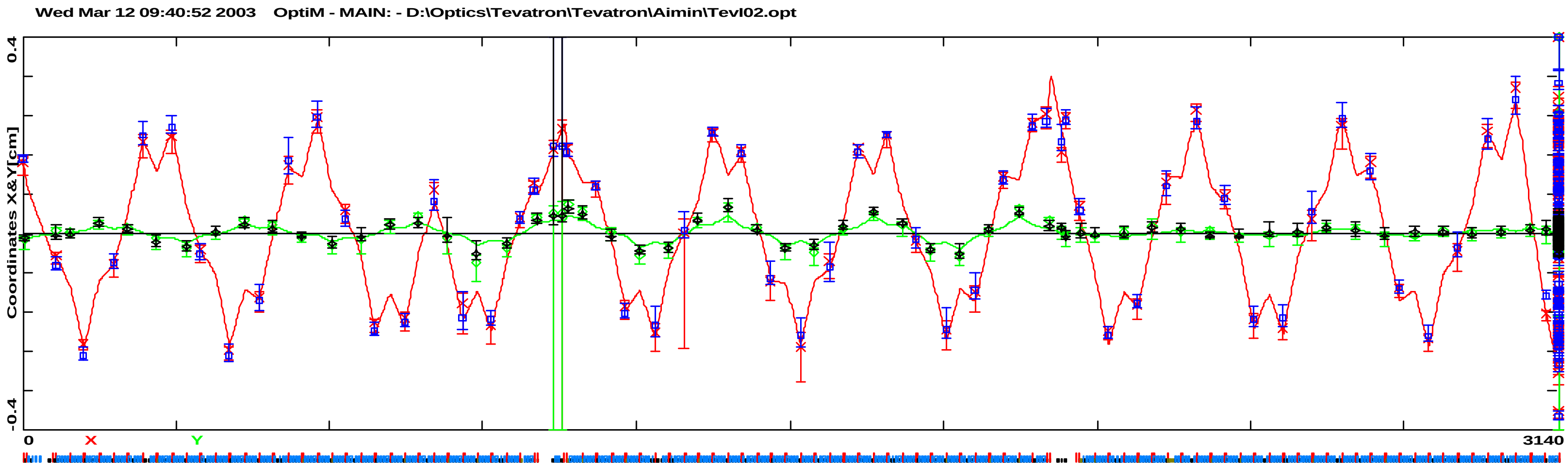
$$Z/n[\Omega] \approx i + (1+i)\frac{20}{\sqrt{n}}$$

  - ➢ But due to very strong dependence of the instability threshold on bunch length the coincidence should be considered rather qualitative than quantitative
- While removing and shielding Lambertson magnets significantly changes transverse impedance an effect on longitudinal impedance is much smaller and we do not expect significant changes of the longitudinal bunch dynamics after Lambertson removal
- It is expected that the longitudinal instability will prevent the bunch shorter then ~ 50 cm!!!
  - ➢ More studies are required

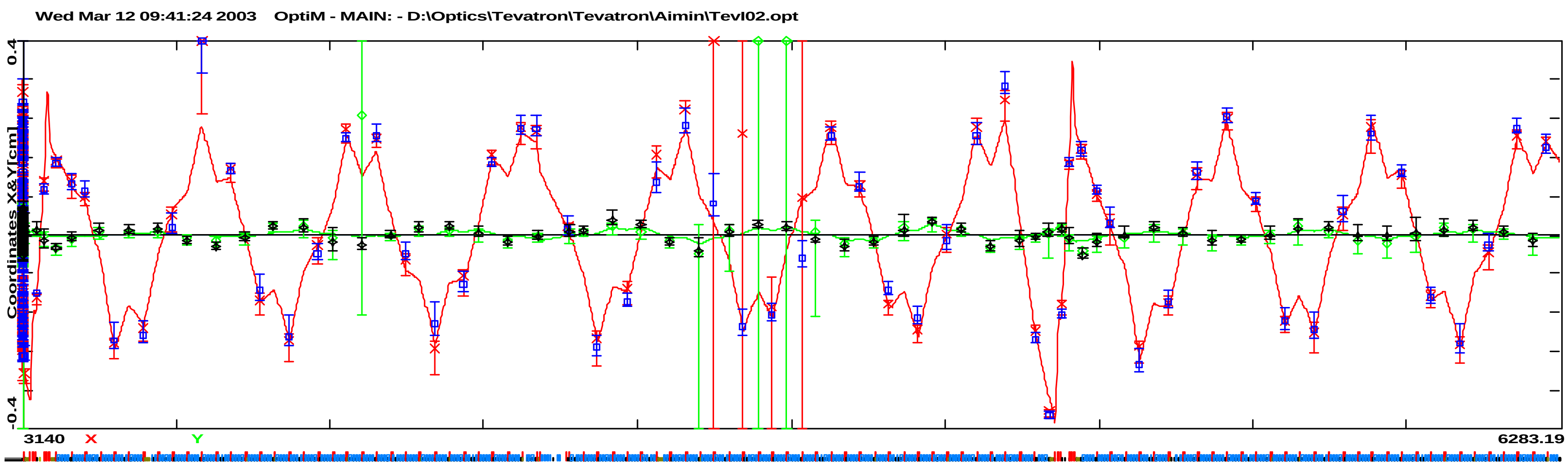
4. Optics modeling

Differential orbit measurements 150 GeV, central orbit, data were taken at Feb.20. 2003

X1: HE42 = 50 mrad

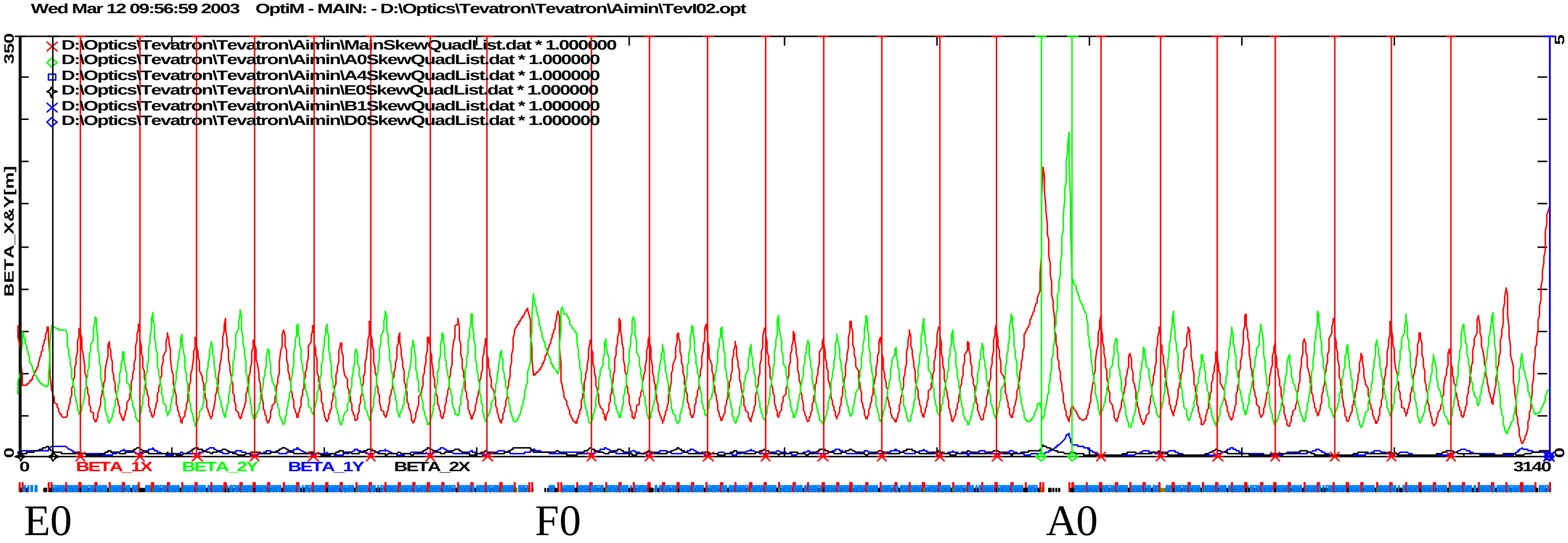


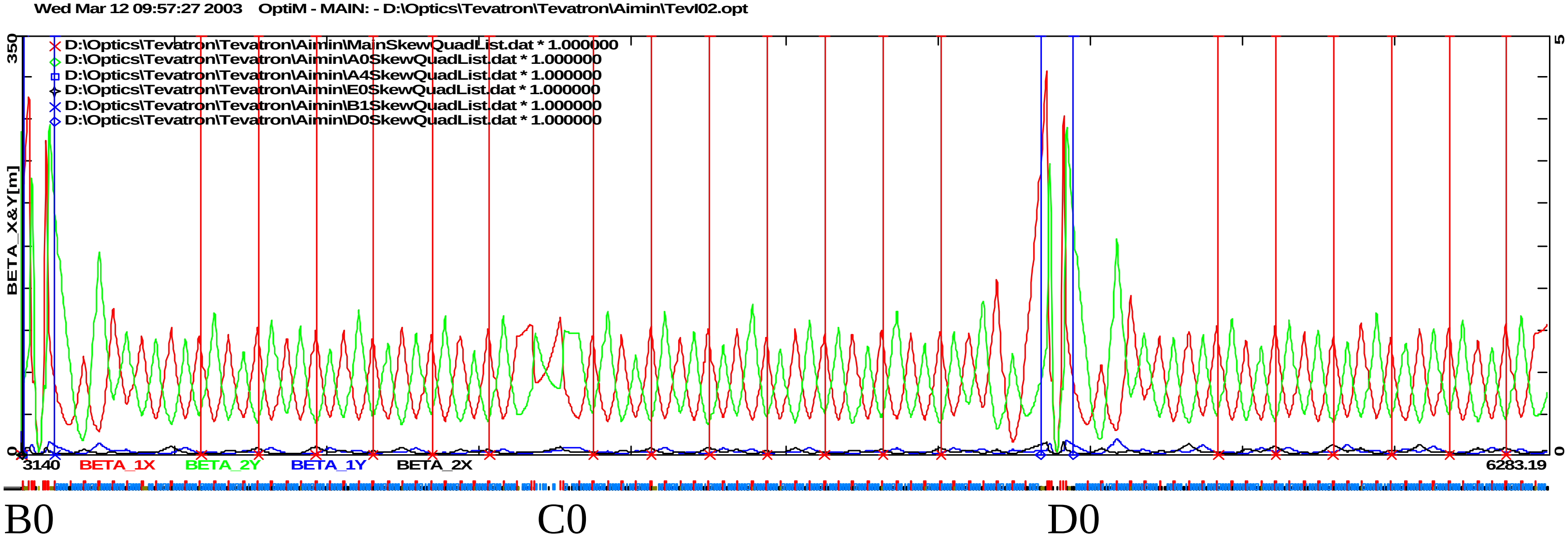
E0 F0 A0



B0 C0 D0

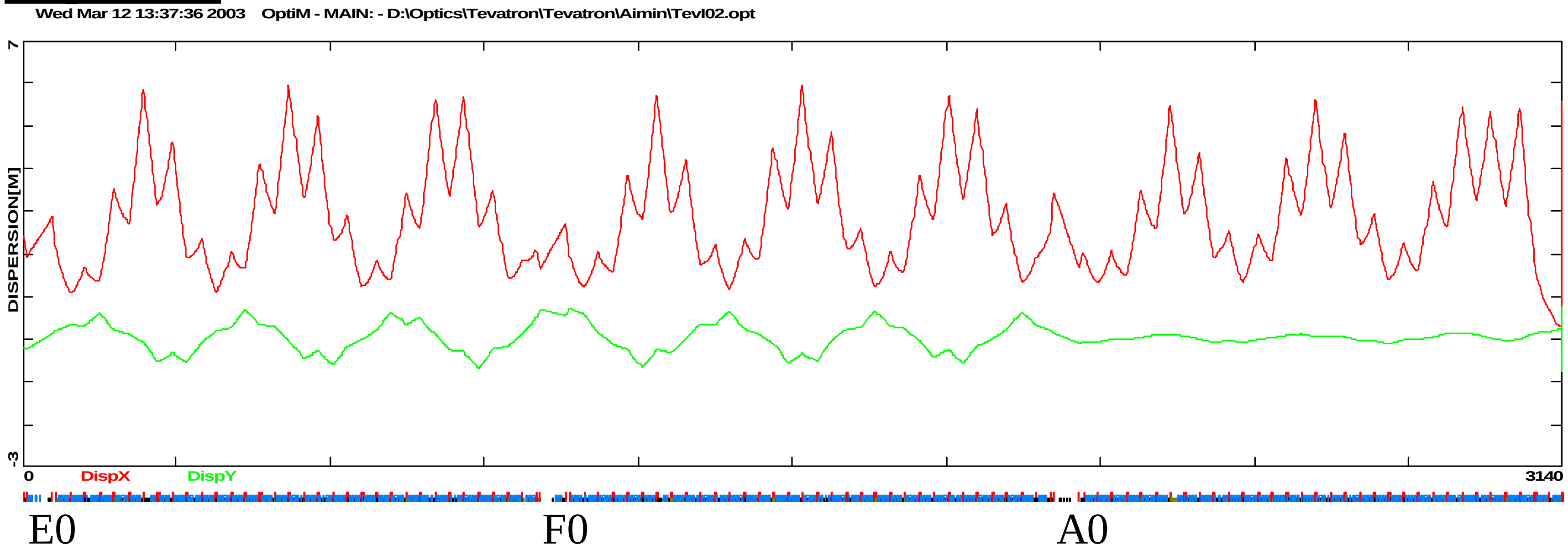
Mais-Ripken beta-functions

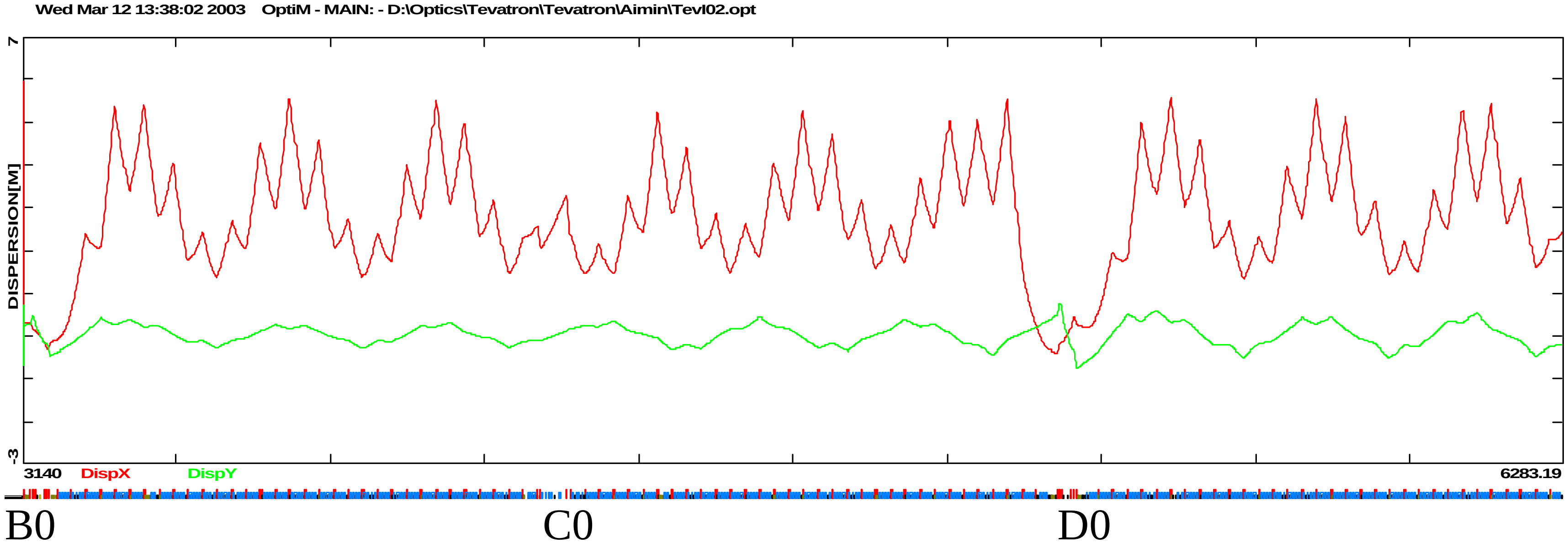




Vertical lines mark position of skew-quadrupoles

Dispersions





Fudge factors and rolls to fix linear optics

Global corrections

$F_bendq = 2%; correction of dipole edge focusing of about 1 deg

$F_mq = 0.165%; correction of main bus quad focusing

$F_Dskew = 1.44 units; skew quadrupole field of main dipoles

Point like corrections of quadrupole focusing

$F_qA0U = 1%; related to beam displacement in A0

$F_qC27 = -2%

$F_CQ7= 20%; that corresponds to 4.4% correction for regular main bus quad

$F_B0Q3F = 0.37%

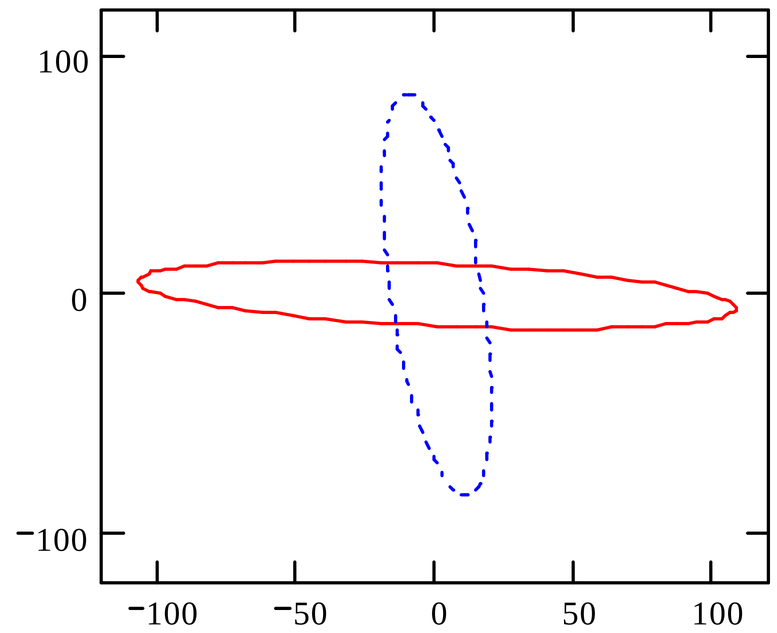
$F_D0Q3F = 0.6%;

$F_D0Q2D =1%;

Quad rolls

$Qroll_A0U = 0.5 deg; related to beam displacement in A0

$Qroll_B0Q7= -4 deg;

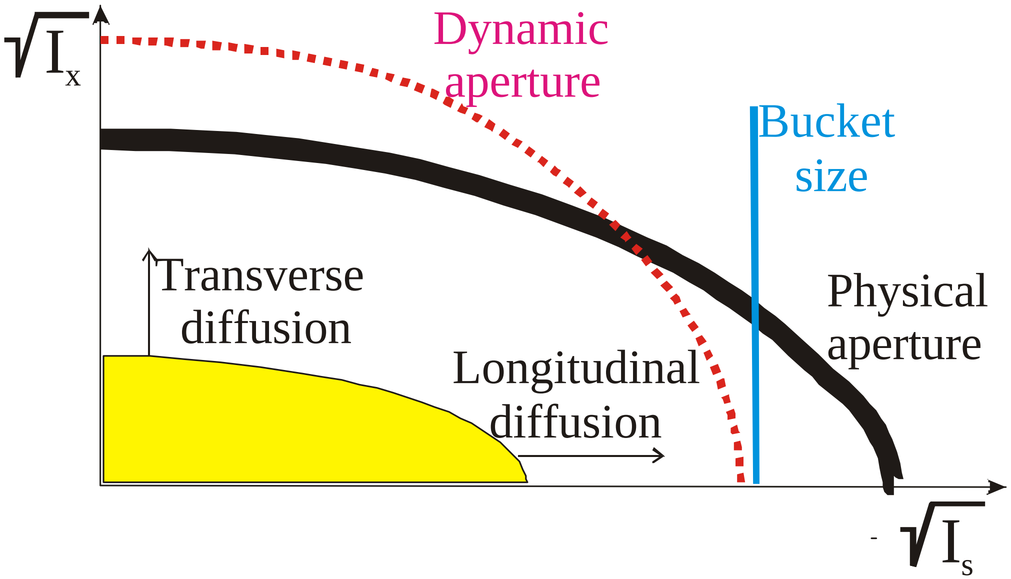


Betatron modes at the BLT location

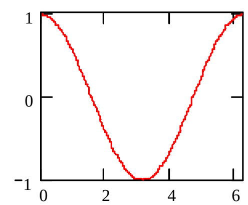
5. Particle Loss at Injection

- **Experimental observations**
  - Proton lifetime at proton helix (1– 4 hour) is much worse than at central orbit (~10 hour)
  - Lifetime is affected by the machine chromaticity
    - Smaller chromaticity improves the lifetime but its reduction is limited by head-tail instability
      - Using octupoles to stabilize the instability improves the lifetime but makes machine tuning oversensitive to the orbit changes due to the tune dependence on orbit
  - Strong dependence of the lifetime on bunch length
  - Intensity lifetime is much worse than the emittance lifetimes
    - Proton intensity decays as $N\left(1-\sqrt{t/t}\right)$
  - Additionally to mentioned above, the **pbar lifetime** is strongly affected by beam-beam effects

- ♦ **Basic mechanisms and reasons of the proton loss**

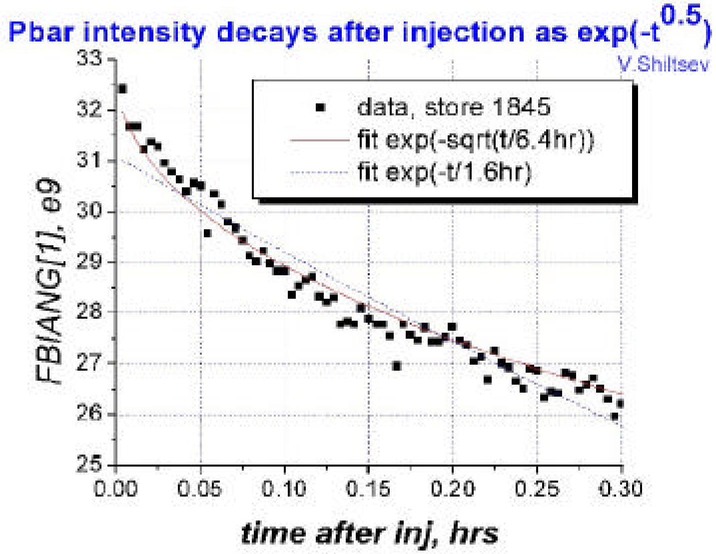


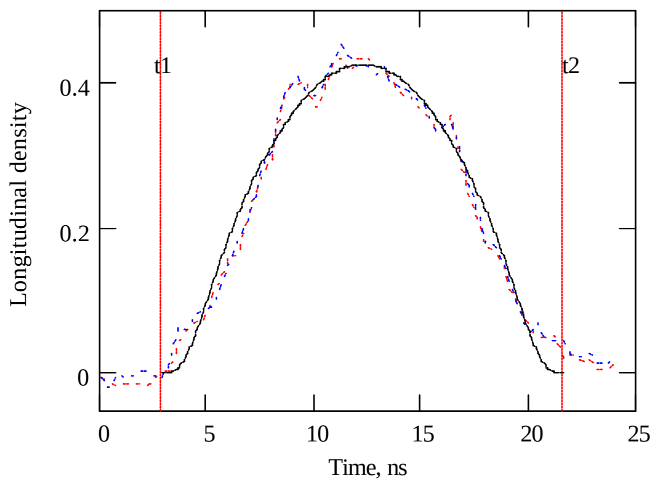
- ➢ Effects of longitudinal diffusion due to IBS and RF noise are amplified by
  - Overfilled bucket at injection
  - Shallowing the potential well near separatrix
  - Instability of particle motion at large synchrotron amplitudes



- ➢ Effects of transverse diffusion create particle loss due to
  - aperture limitations
  - and reduced dynamic aperture for particles with large synchrotron apertures
- ➢ Major transverse diffusion mechanisms are
  - the residual gas scattering ($de_x/dt|_{Gas} \approx de_y/dt|_{Gas} \approx 1.1$ mm mrad/hour)
  - and IBS ($de_x/dt|_{IBS} + de_y/dt|_{IBS} \approx 1.2$ mm mrad/hour)

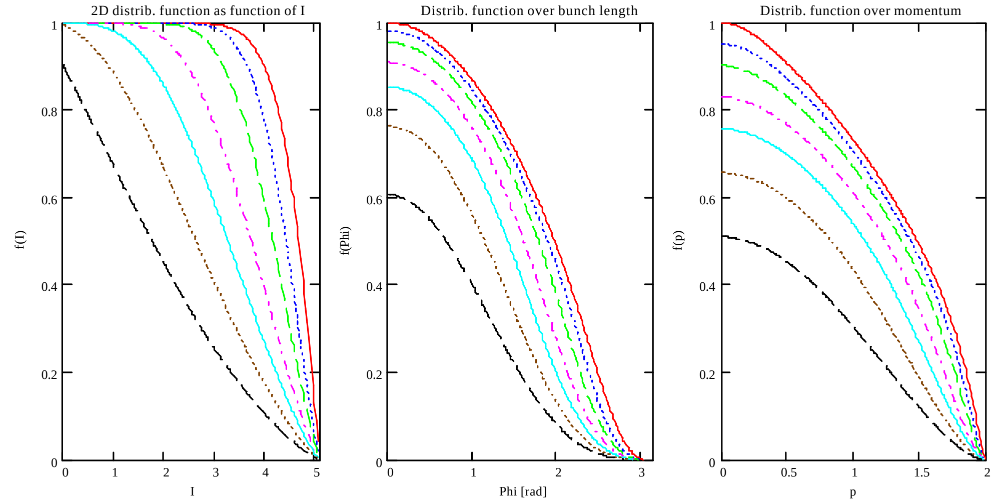
Measured dependence of proton beam intensity on time at injection

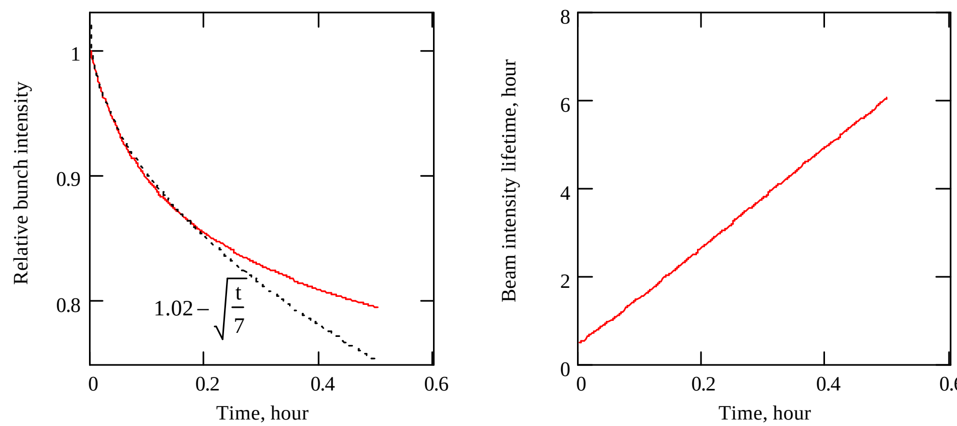




Measured and used in simulations initial longitudinal particle density

Simulations for Longitudinal Distribution





Computed emittance life times for protons of Store 1953:

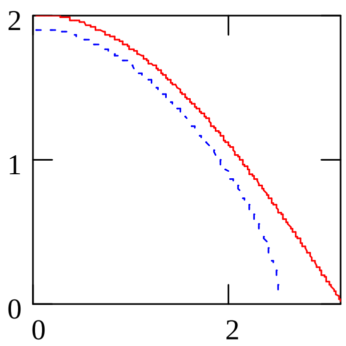
Transverse - *12 hour*

Longitudinal (uncorrected) - *48 hour*

Intensity - $1-\sqrt{t/(7\text{ hour})}$

- Both transverse and longitudinal losses cause $\exp\left(-\sqrt{t/t}\right)$ intensity decay if the beam distribution is close to the aperture limit
- We do not know a ratio of transverse to longitudinal losses but it is more probable that the longitudinal losses dominated the proton loss at injection
- After removing C0 lambertson we are gaining the transverse aperture and the longitudinal losses will almost certainly dominate for protons
- Therefore having sufficiently small longitudinal emittance of proton beam coming from MI is the only way to prevent proton losses at injection and ramp
- Taking into account the shallowing of the potential well we can write a simple estimate for a fraction of longitudinal emittance need to be free of particles

$$\frac{\Delta e}{e_{\max}} \approx 2\sqrt{\frac{T}{e_{\max}}\frac{de}{dt}}$$

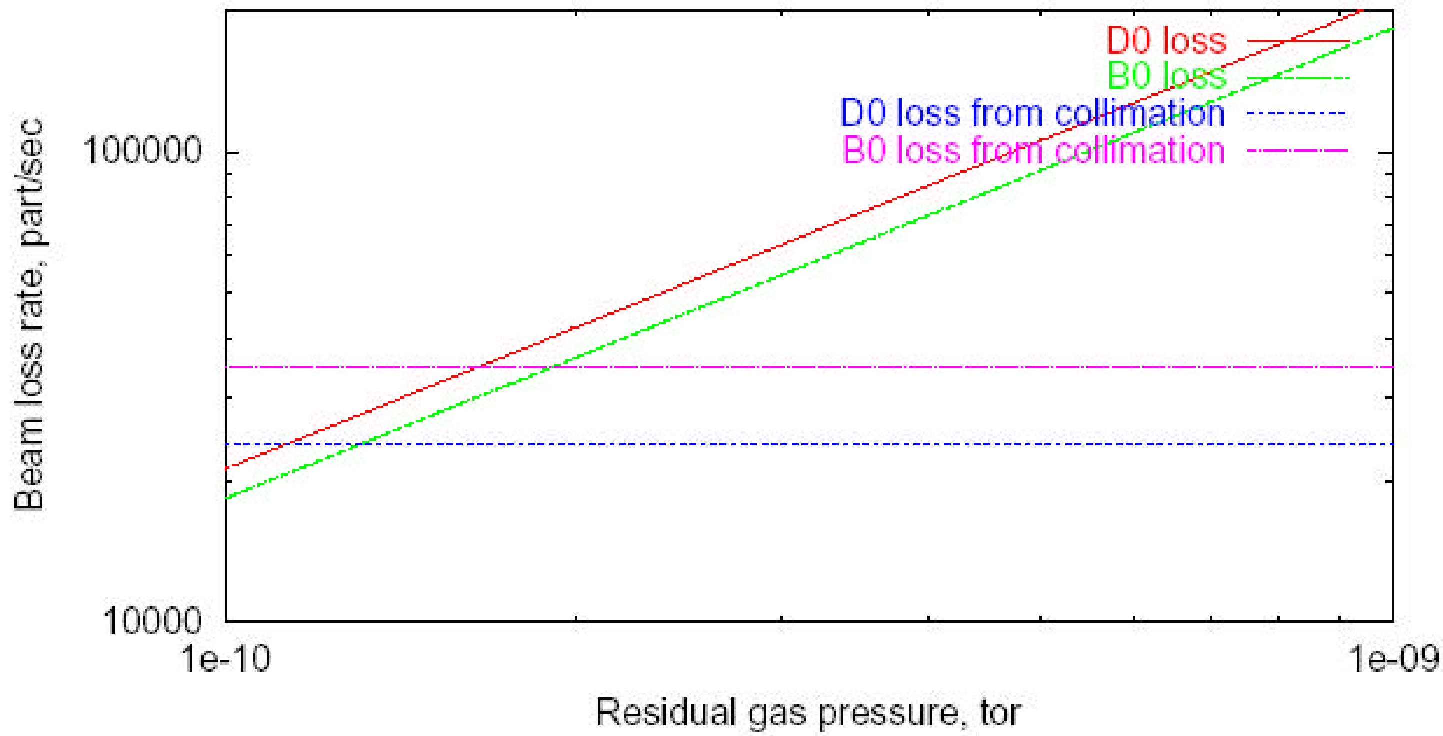


IBS determines that $e_{\max}/(de/dt) \approx 50$ hour

Then for T = 0.5 hour we obtain $\Delta e/e_{\max} \approx 0.2$ which means that ~100% of particles have to be within 90% of bucket size or $e_s \leq 3.8$ eV s

6. The Source of Background in the Particle Physics Detectors

- Two sources of the background
  - Single scattering
    - Gas scattering
    - Touschek effect (IBS)
  - Multiple scattering and diffusion
    - Gas scattering
    - IBS
    - Diffusion due to beam-beam effects
    - RF noise
- Most of the particles (~90%) are lost due to multiple scattering and diffusion
  - That determines that the protection from multiple scattering is more important
- Tevatron collimation system was optimized to intercept particles with slowly growing amplitude
  - It is based on a set of two primary and four secondary collimators to intercept background from both proton and pbar beams
    - Each collimator is designed to scrape particles vertically and horizontally from one side
  - The system is very effective to intercept particles with slowly growing amplitude, $\kappa \approx 2 \cdot 10^{-4}$
    - But it does not do a good job to intercept single scattered particles, $\kappa \approx 0.02$

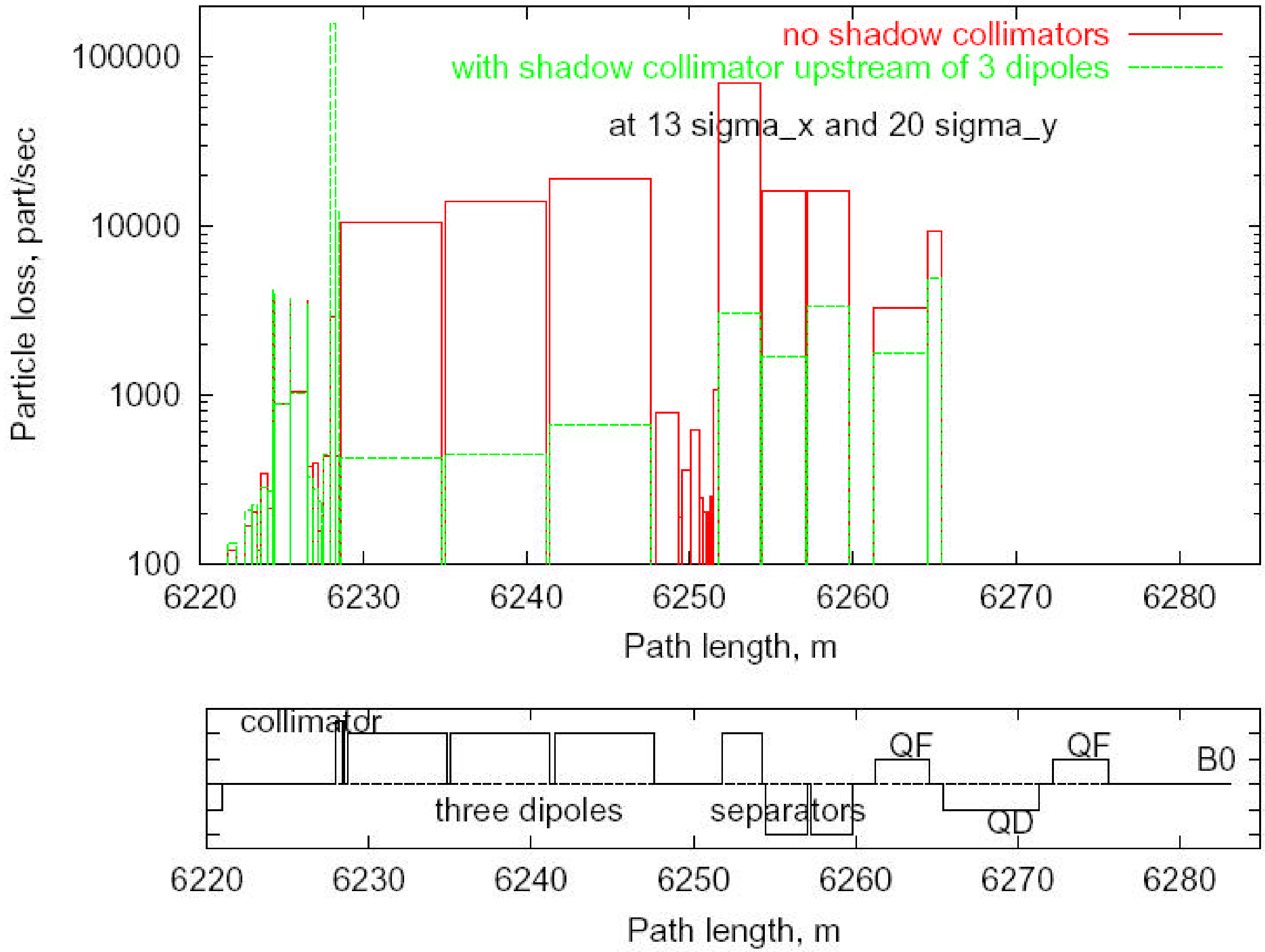


Simulated dependence of beam loss in CDF and D0 detectors as function of average Tevatron vacuum

- Recently performed simulations verified that the single scattered particles create major fraction of the detector background
  - Tevatron vacuum has been improved after summer shutdown and it improved background in detectors
- Planned luminosity growth by an order of magnitude will also cause growth of the background but in significantly smaller scale
  - The background will be determined by vacuum and if vacuum will stay the same the background will grow by 2.8 times

Reduction of the background

- We plan further vacuum improvements
- A system of shadow collimators placed at A48 and C48 straight sections in front of the CDF and D0 (upstream of the last three dipoles before the IP) allows to suppress this background by an order of magnitude



Conclusions

1. During last year we made significant progress in understanding of
   - Beam heating mechanisms and luminosity lifetime
   - Beam-beam effects
   - Transverse and longitudinal instabilities
   - Sources of background in particle physics detectors
2. We are sill far away to understand all details of the beam-beam effects and it brings most of uncertainty in predictions of the final Run II parameters
   - But as far as we know now the goal to achieve of luminosity of $\sim 3 \cdot 10^{32}$ cm^{-2}s^{-1} and luminosity integral of ~2.5 fbarn/year looks reasonable
3. The following major actions are planned to achieve the goal
   a. To mitigate beam-beam effects
      - Optimization of helical orbits for all stages
      - Increasing of high voltage separator strength and possibly installation of new separators
      - On-line tune measurements and the tune feedback

   b. To mitigate head-tail instability
      - Shielding of F0 lambertson magnet

   c. Further improving of pbar transfer efficiency
      - Coalescing improvements
      - Reducing the emittance growth at transfers