Tevatron Task Force

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Fermilab Accelerator
Advisory Committee
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Talk outline

1. Luminosity lifetime
    a. Current scenario
    b. Final Run II scenario
2. Beam instabilities
    a. Transverse head-tail
    b. "Dancing bunches"
3. Beam-beam effects
4. Particle loss at injection
5. The source of background in the particle physics detectors

Conclusions

Major contributions for this talk came from:

Yu. Alexahin
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V. Balbekov
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V. Shiltsev
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M. Xiao

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, $P=1\cdot 10^{-9}$ Torr of N_2 equivalent
  - Coulomb scattering (~15350 hour)
  - Nuclear absorption (~306 hour)
  - Total gas scattering lifetime (~300 hour)

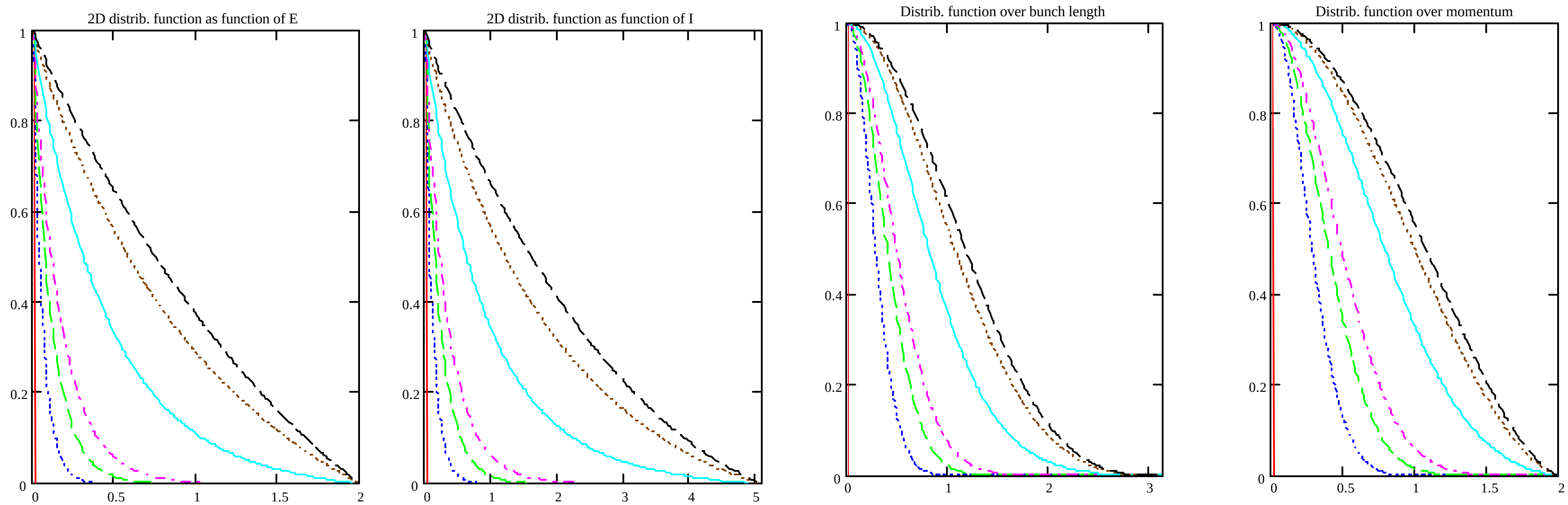
Emittance growth time

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

$$\frac{de_x}{dt} \approx \frac{de_y}{dt} \approx 0.169 \text{ mm mrad/hour}$$

Longitudinal Diffusion (Luminosity lifetime backup slide)

Diffusion equation, $\frac{\partial t}{\partial t} = \frac{D}{2}\left(\frac{\partial f}{\partial E} + I\,\frac{\partial E}{\partial I}\frac{\partial^2 f}{\partial E^2}\right)$, describing the distribution function transformation under action of constant diffusion, $D(I) = D,$ is solved numerically.

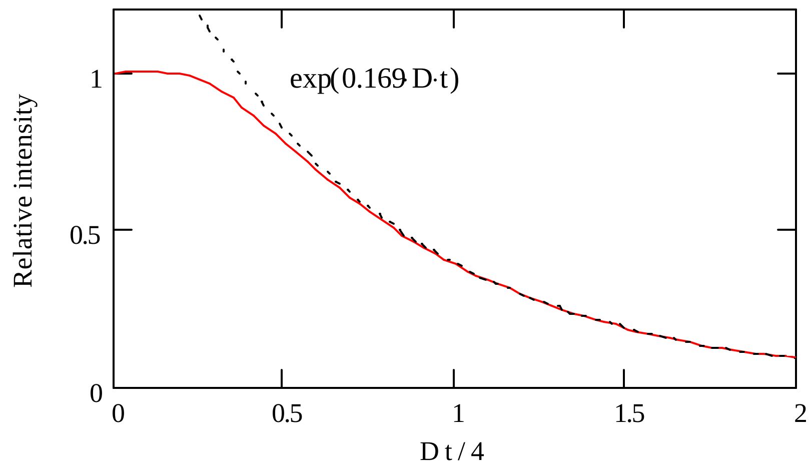


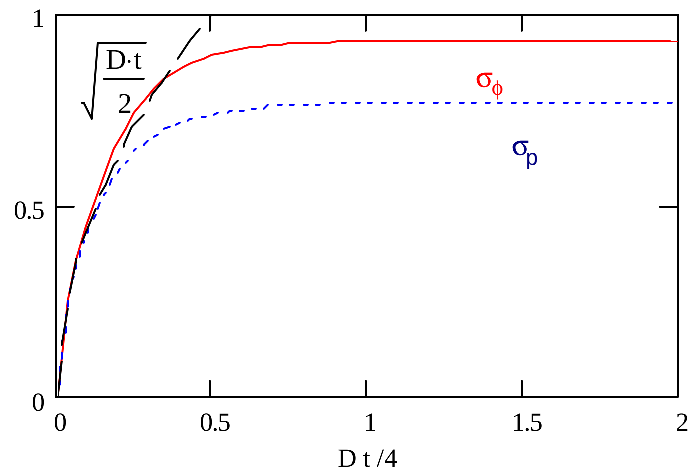
$f(I(E))$ $f(I)$ $f_f(f)$ $f_p(p)$

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

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

Longitudinal Diffusion – continue (Luminosity lifetime backup slide)





This numerical solution yields approximate relationships between the bunch parameters:

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

$$\frac{1}{N}\frac{dN}{dt} \approx \frac{2.425\,(2\pi\sigma_s)^7}{\lambda_{RF}^{\,7}+1.65\,(2\pi\sigma_s)^7}\left(\left(\frac{2\pi\Gamma_s}{\lambda_{RF}}\right)^2 \left.\frac{d\left(\sigma_{\Delta p/p}^{\,2}\right)}{dt}\right|_{IBS}+\left.\frac{d\left(\sigma_{\phi}^{\,2}\right)}{dt}\right|_{RF}\right)$$

$$\left.\frac{d\left(\sigma_{\Delta p/p}^{\,2}\right)}{dt}\right|_{total} \approx \left(1-\left(\frac{2\sigma_{\Delta p/p}}{0.765\Delta P/P|_{sep}}\right)^5\right)\left(\left.\frac{d\left(\sigma_{\Delta p/p}^{\,2}\right)}{dt}\right|_{IBS}+\left(\frac{\lambda_{RF}}{2\pi\Gamma_s}\right)^2\left.\frac{d\left(\sigma_{\phi}^{\,2}\right)}{dt}\right|_{RF}\right)$$

Longitudinal Diffusion – continue (Luminosity lifetime backup slide)

where

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

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,

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

where the spectral density of RF phase noise is normalized as

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

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

$$P_{ff}(\Omega_s/2p) = 4pP_f(\Omega_s) \approx 6\cdot 10^{-12} \quad \mathrm{rad}^2/\mathrm{Hz}$$

$$\left.\frac{d\left(s_f^{\ 2}\right)}{dt}\right|_{RF} \approx 16 \quad \mathrm{mrad}/\sqrt{\mathrm{hour}}$$

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

$$\frac{d}{dt}\left(\theta_\parallel^{\,2}\right) \equiv \frac{d}{dt}\left(\frac{\overline{p_\parallel^{\,2}}}{p}\right) = \frac{1}{4\sqrt{2}}\,\frac{e^4 N_i L_C \Xi_\parallel\left(\theta_x,\theta_y\right)}{m_p^{\,2} c^3 \gamma_i^{\,3} \beta_i^{\,3} \sigma_x \sigma_y \sigma_s \sqrt{\theta_x^{\,2}+\theta_y^{\,2}}} \quad ,$$

$$\frac{d\varepsilon_x}{dt} = (1-\kappa)\left\langle A_x \frac{d\theta_\parallel^{\,2}}{dt}\right\rangle_s \quad , \qquad \frac{d\varepsilon_y}{dt} = \kappa\left\langle A_x \frac{d\theta_\parallel^{\,2}}{dt}\right\rangle_s$$

where

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

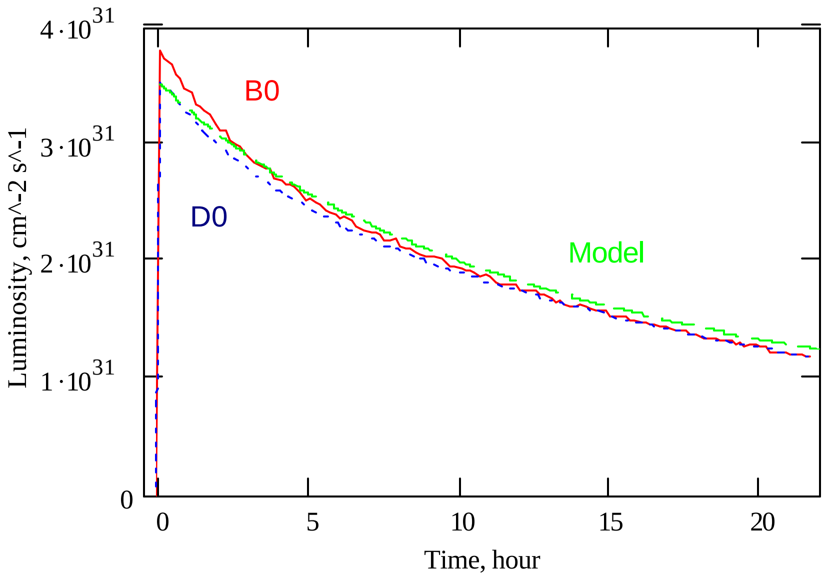
$$\sigma_x = \sqrt{\varepsilon_x \beta_y + D^2 \theta_\parallel^{\,2}}\ ,\ \sigma_y = \sqrt{\varepsilon_y \beta_y}\ ,\ \theta_x = \sqrt{\varepsilon_x/\beta_x} \text{ and } \theta_y = \sqrt{\varepsilon_y/\beta_y}$$

$$A_x = \left.\left\langle \frac{D^2 + \left(D'\beta_x + \alpha_x D\right)^2}{\beta_x}\right\rangle\right|_s$$

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

A_x = 19.7 cm, β_x=β_y = 48.5 m, D = 2.83 m

Comparison of the Model Predictions to the Store 1953 parameters



$\varepsilon n_{px} \cdot 10000 = 19$ mm mrad

$\varepsilon n_{py} \cdot 10000 = 19$ mm mrad

$\varepsilon n_{ax} \cdot 10000 = 18$ mm mrad

$\varepsilon n_{ay} \cdot 10000 = 18$ mm mrad

$\kappa = 0.3$

$\frac{\tau_{gas}}{3600} = 300.087$ hour

$d\varepsilon dt_{gas} = 0.168$ mm mrad/hour

$\sqrt{d\phi 2dt_{RF} \cdot 3600} = 0.016$ rad/hour$^{1/2}$

$N_p = 1.6 \times 10^{11}$

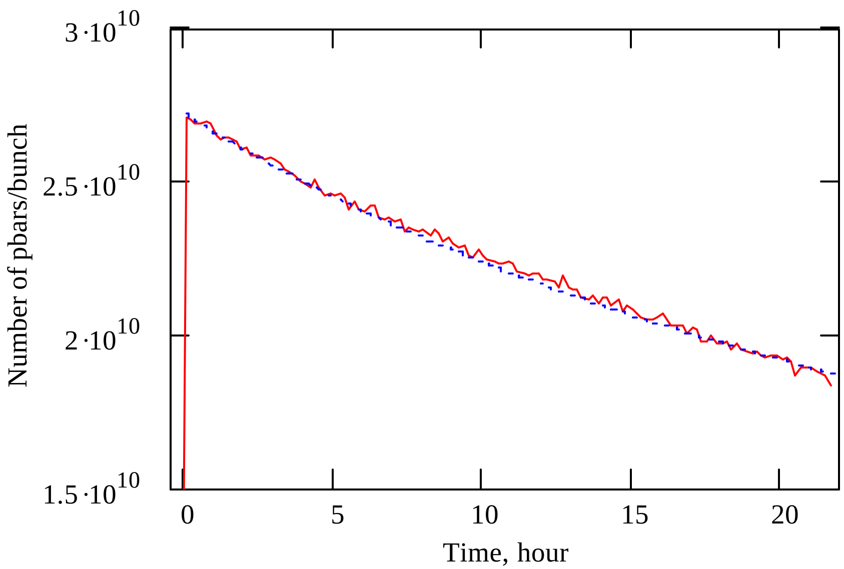
$N_a = 2.72 \times 10^{10}$

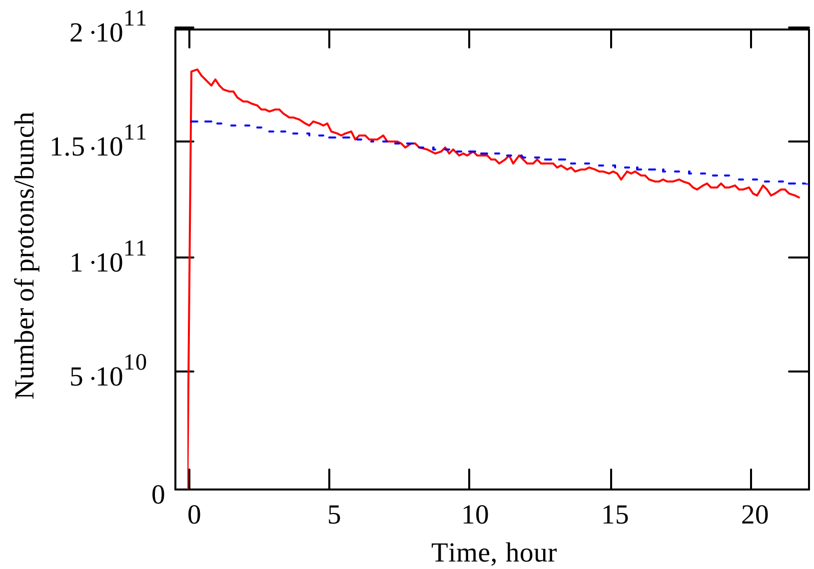
$\sigma s(\sigma_{pp}) = 59.4$ cm

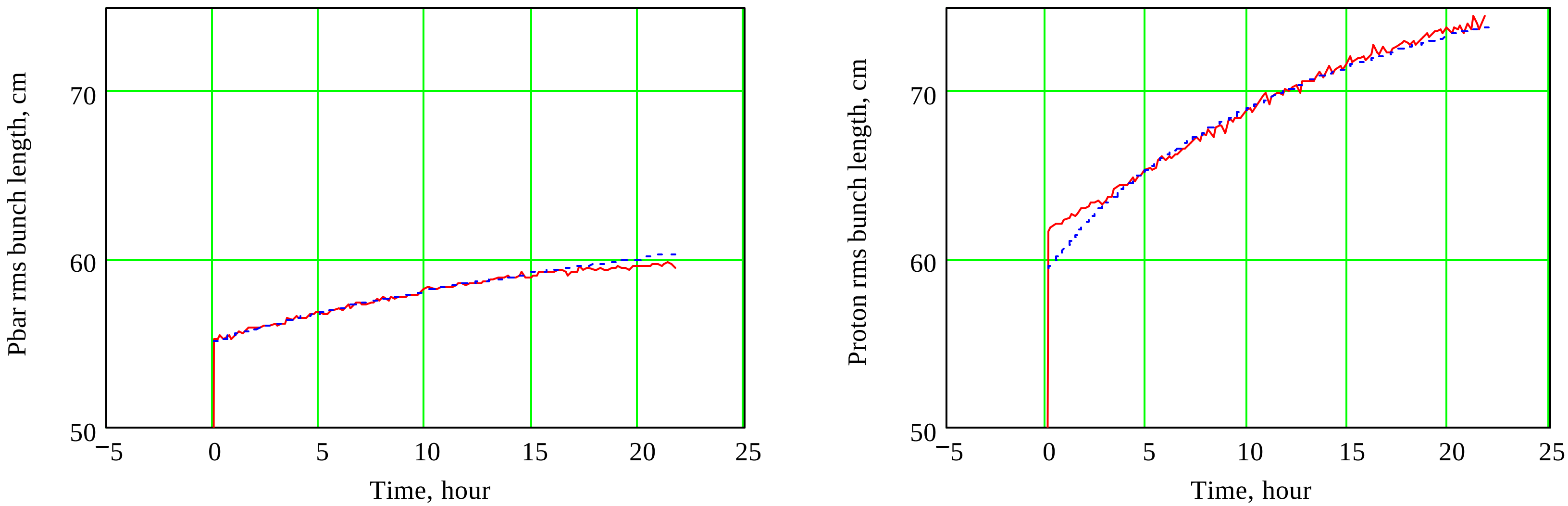
$\sigma s(\sigma_{pa}) = 55.112$ cm

$Lum_0 = 3.513 \times 10^{31}$

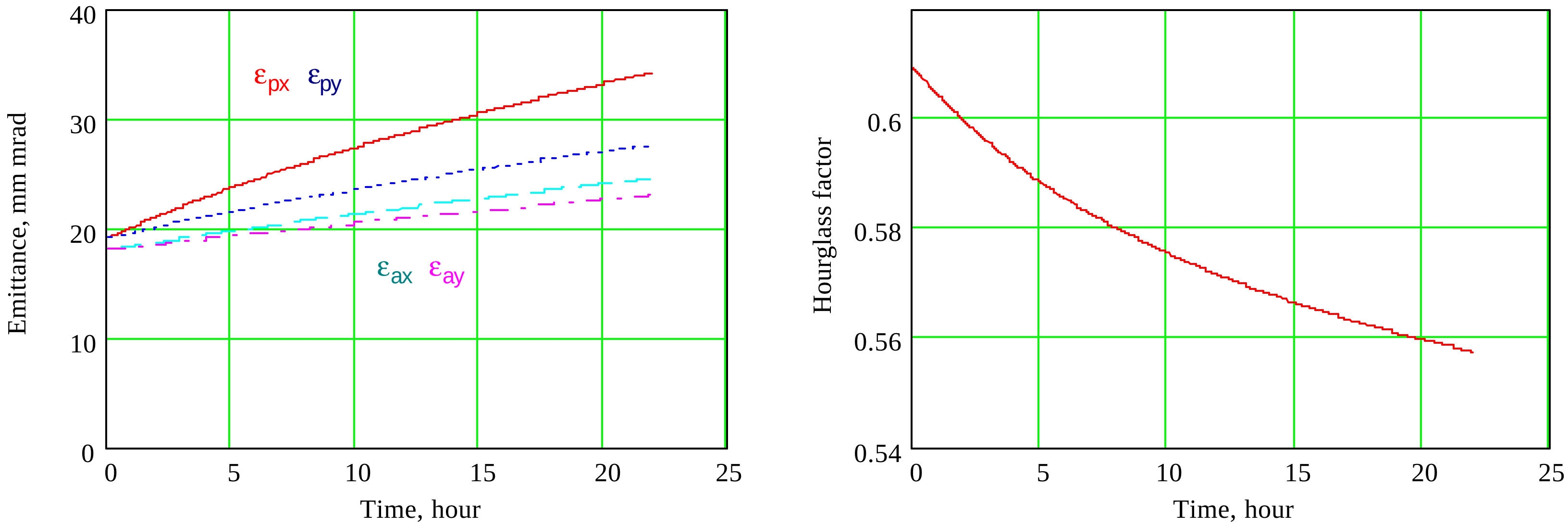
$\tau_{Lum_1} = 13.826$ hour







Measured (solid line) and computed (dashed line) rms bunch lengths for pbar and proton bunches



Model prediction for beam emittances and hourglass effect

Comments for the Store 1953

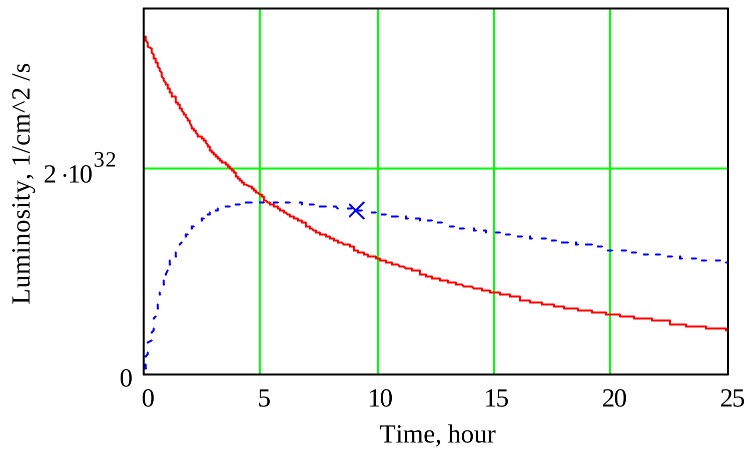
- It is one of our best stores
- In general there is decent agreement between predictions and measurements
  - Unfortunately, our emittance measurements are not sufficiently accurate for detailed comparison therefore
    - The initial values of the horizontal and vertical emittances were chosen to be equal
    - The initial emittances of proton and pbar beams were adjusted to fit the measured luminosity and bunch lengths
- There are two discrepancies between the model and the measurements at the beginning of the store
    - The proton beam intensity is decaying faster than the model prediction
    - The proton bunch length is growing slower than the model prediction
  - As we figured out later it was related to incorrect values of the proton tunes
    - The problem disappeared after minor tune correction in December 2002
  - The most probable reason is that incorrect tunes affected the motion stability for particles with large synchrotron amplitudes which caused both
      - Particle loss
      - And bunch shortening (actually it was compensated by bunch lengthening due to IBS)
    - Additional studies are required to figure out the actual reason
- **Conclusion**: for correctly tuned collider at present beam intensities the beam-beam effects and machine nonlinearity, as well as, coherent effects do not produce harmful effects on the beam dynamics and collider luminosity while beams are in collisions.

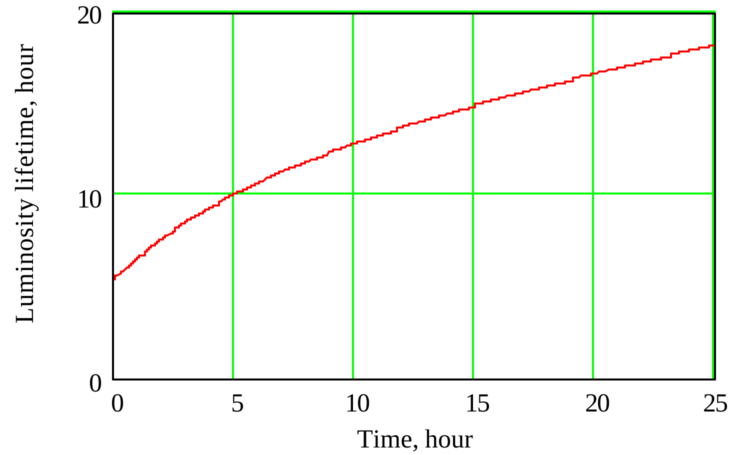
Basic Luminosity Scenario

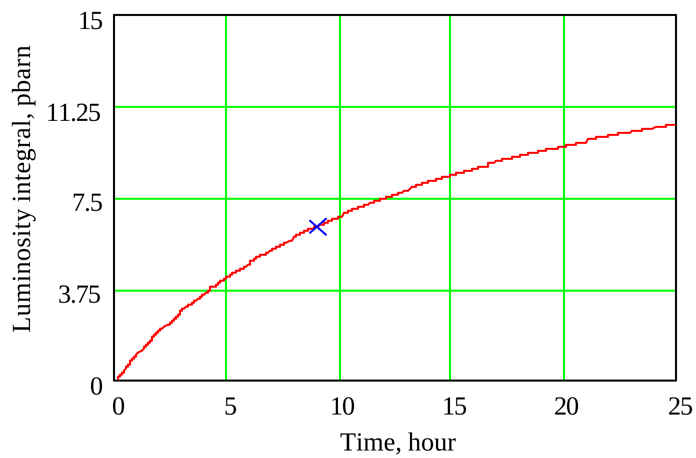
Luminosity integral is calculated presuming that:

- 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







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

$N_a = 1.346\times 10^{11}$

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

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

$\varepsilon n_{ax}\cdot 10000 = 15.059$ mm mrad

$\varepsilon n_{ay}\cdot 10000 = 15.059$ mm mrad

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

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

$T_{store} = 9$ hour

$\kappa = 0.2$

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

$N_{recycle}\cdot 10^{-10} = 178.5$ mA

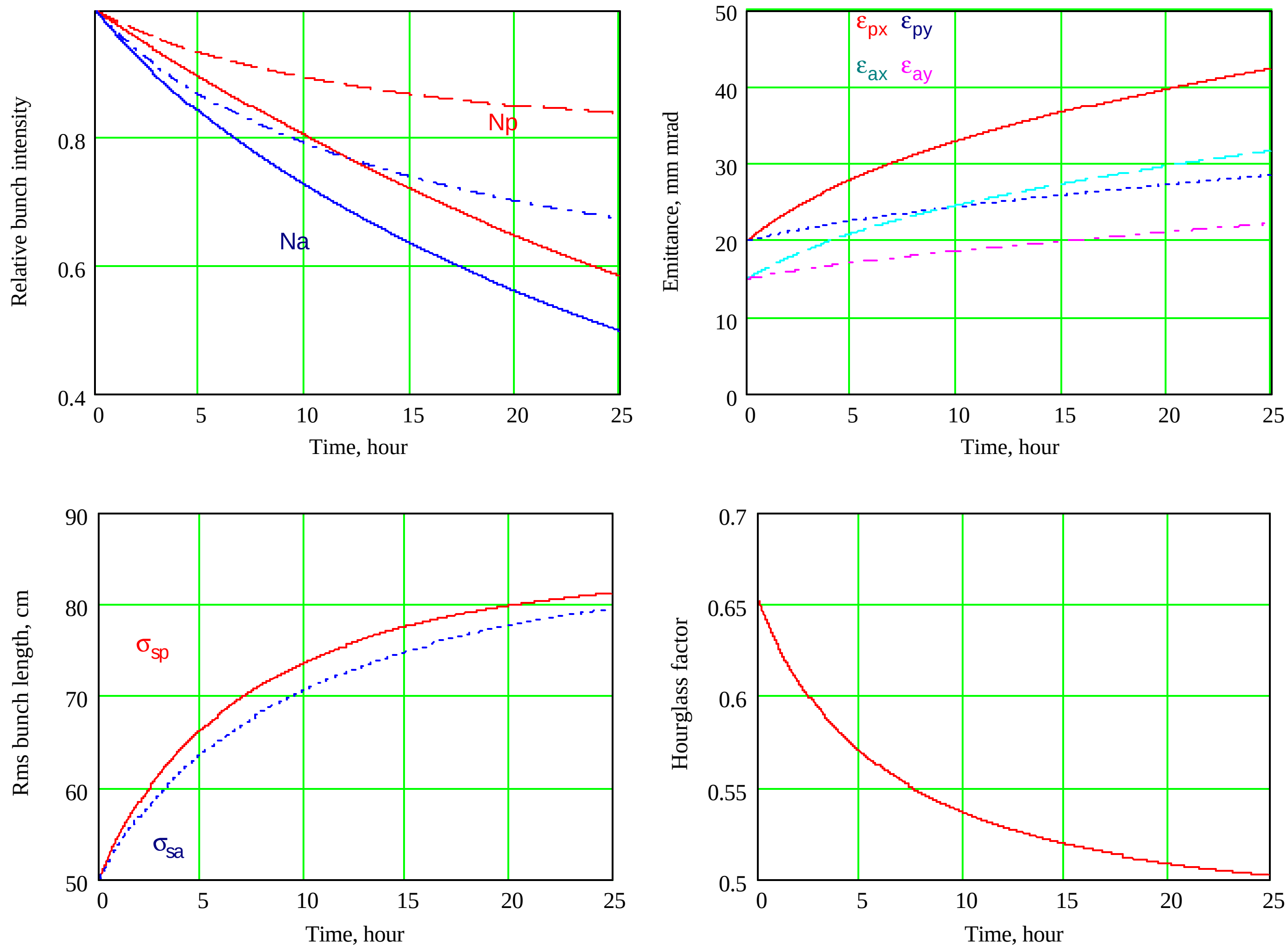
$N_a\cdot n_b\cdot 10^{-10} = 484.65$ mA

$Lum_0 = 3.31\times 10^{32}$ $cm^{-2}s^{-1}$

$Lum_{avrg} = 1.601\times 10^{32}$ $cm^{-2}s^{-1}$

$\tau_{Lum_1} = 5.401$ hour

$Ldt_{year} = 3.182$ fbarn/year



Lifetime breakup at the store beginning

	hour
Luminosity	5.4
Prot.intens.	42.5
Pbar.intens.	24.1
Prot.H.emit.	8.7
Prot.V.emit.	28.9
Pbar.H.emit.	9.0
Pbar.V.emit.	27.7
Hourglass factor	22.0

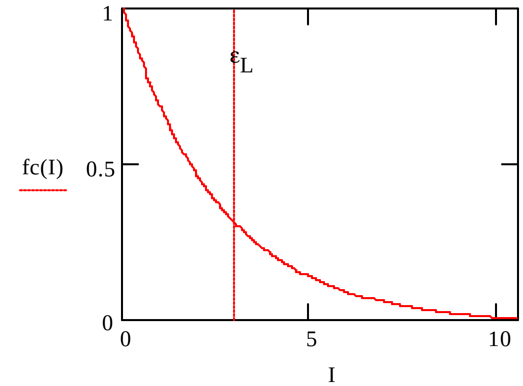
$$L = \frac{N_p N_{\bar p} f_0 n_b}{2\pi \beta^* \sqrt{\left(\varepsilon_{xp} + \varepsilon_{x\bar p}\right)\left(\varepsilon_{yp} + \varepsilon_{y\bar p}\right)}} H\left(\frac{\sqrt{\sigma_{sp}^{\ 2} + \sigma_{s\bar p}^{\ 2}}}{\beta^*}\right)$$

Efficiency of the Antiproton Recycling

Transverse efficiency into 30 mm mrad acceptance, k_{tr}	0.969
Longitudinal efficiency into 3 eV s acceptance, k_L	0.727
Fraction of stores with successfully decelerated protons, $k_{success}$	0.7
Fraction of antiprotons survived at the store end, k_{Tev}	0.747
Total efficiency of pbar recycling, $k_{Tev}\ k_{success}\ k_L k_{tr}$	**0.368**

Pbar production (1 mA»10^{10} pbars)

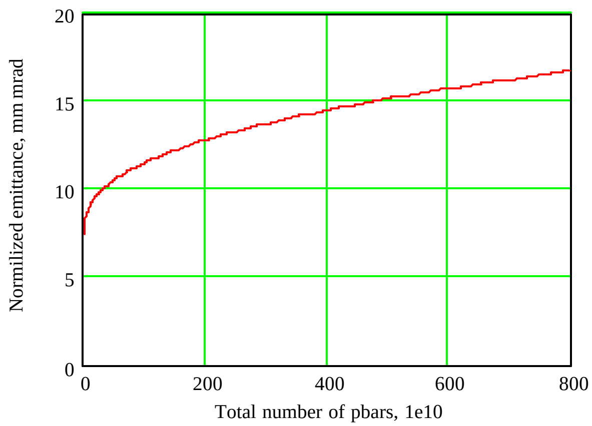
Average antiproton production rate	40 mA/hour
Store time	9 hour
Total number of stacked pbars	360 mA
Total number of recycled pbars	178 mA
Total number of pbars extracted from recycler	538 mA
Pbar utilization factor	0.9
Total number of pbars at flat top	**484 mA**

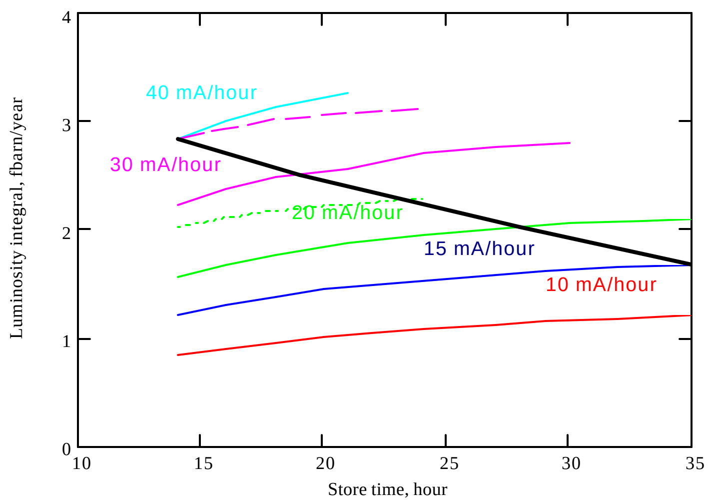


Dependence of the longitudinal distribution function on the action at the end of a store

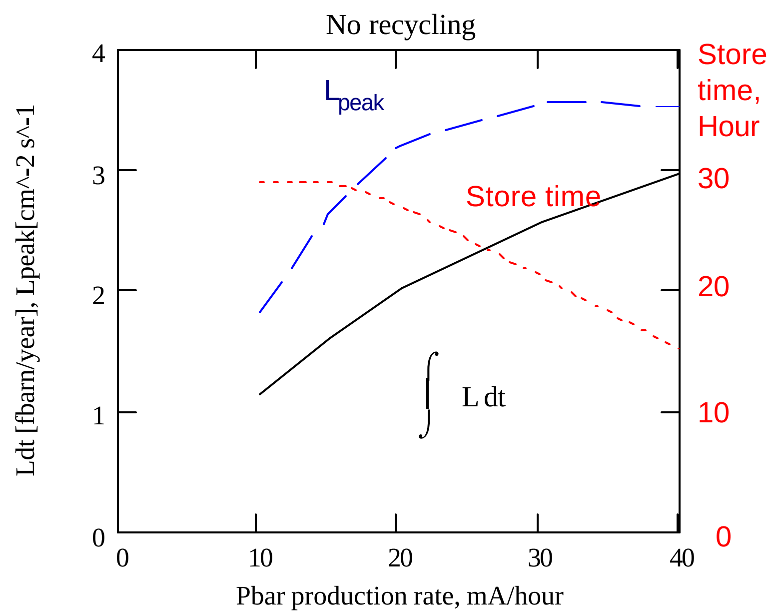
Luminosity Dependence on Antiproton Production

$$\varepsilon_{pbar}(N) := 7.5 + 7 \cdot \left(\frac{N}{400 \cdot 10^{10}}\right)^{\frac{2}{5}}$$





Solid lines – no recycling
Dashed lines – with recycling
Solid black line $N_{pbar}=1.35\cdot10^{11}$ /bunch



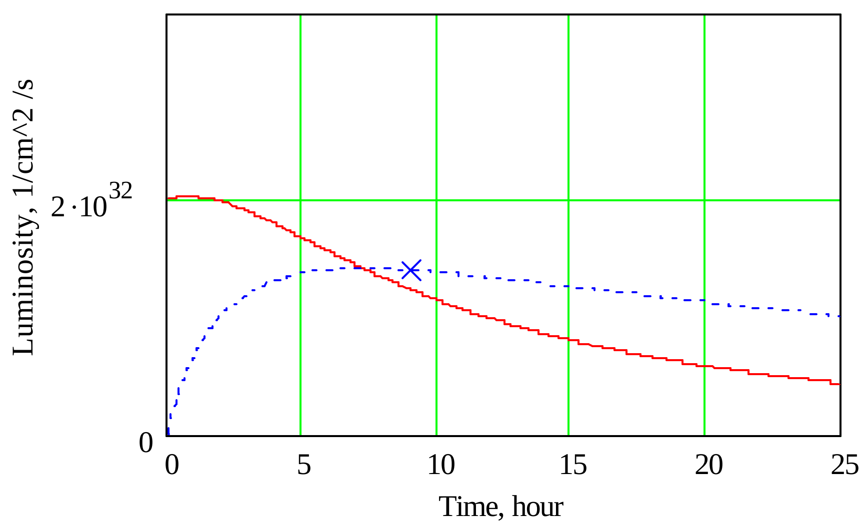
In this comparison we presume that

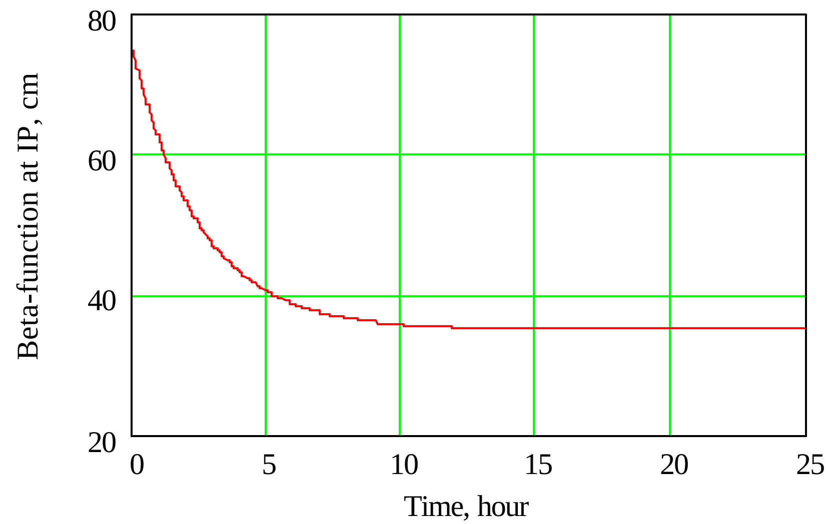
- Transverse emittance depends on beam intensity in according with IBS scaling
- Longitudinal emittance does not depend on beam intensity
- Shot setup time for both cases with and without recycling is two hour

Effect of Luminosity Leveling and Pbar Production on the Luminosity

	L_{peak}, 10^{32} cm^{-2}s^{-1}	$\int Ldt$ fbarn/year	Store length, hour	Pbar production, mA/hour	$\dfrac{\int Ldt}{\int Ldt\big\vert_{basic}}$
Basic	3.31	3.182	9.00	40+recycle*	100%
Basic with luminosity leveling	2.025	2.796	8.83	40+recycle*	87.8%
Basic with reduced pbar production	3.31	2.884	13.10	30+recycle*	90.6
Basic without recycling	3.31	2.85	13.45	40	89.5
Basic with reduced pbar production and no recycling	3.31	2.54	17.95	30	79.9

* We presume that in both cases with and without recycling the shot setup time is 2 hour





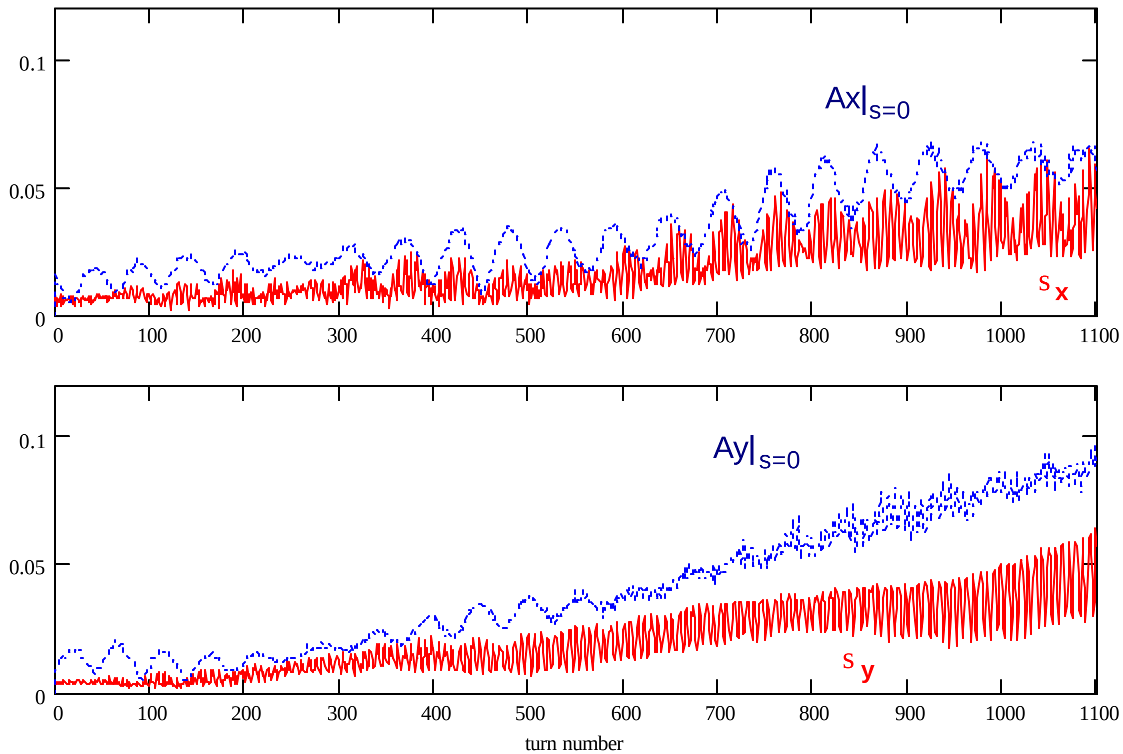
Dependence of the luminosity and beta-function at IP for luminosity leveling scenario

2. 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

- 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?

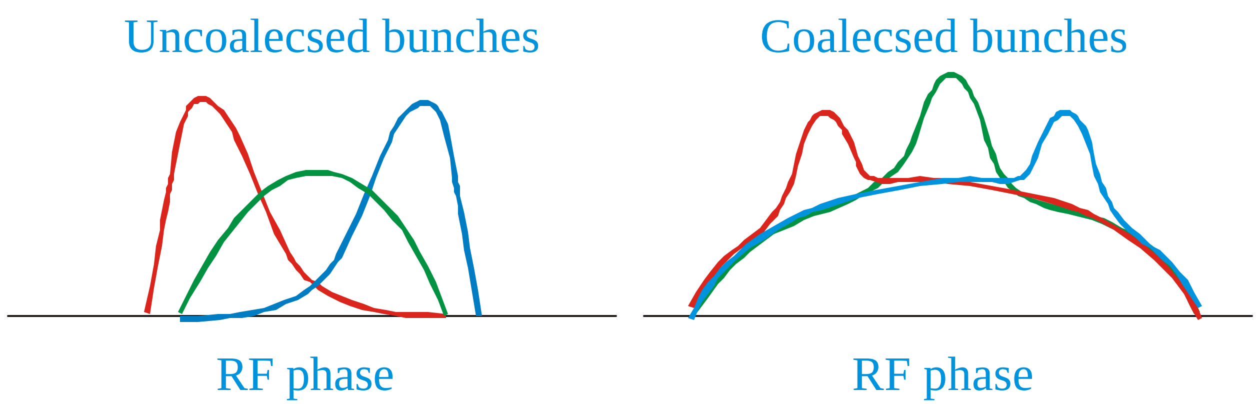
- C0 Lambertson magnet has been removed from the Tevatron at this (January) shutdown.
  - This has to give 30-50% of the impedance reduction.
- Inner surfaces of the remaining F0 Lambertson magnets are planned to be shielded from the beam in the summer
  - That should further reduce the Tevatron transverse impedance to about 1 MΩ/m and should greatly reduce problems with the head-tail instability
- 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

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.

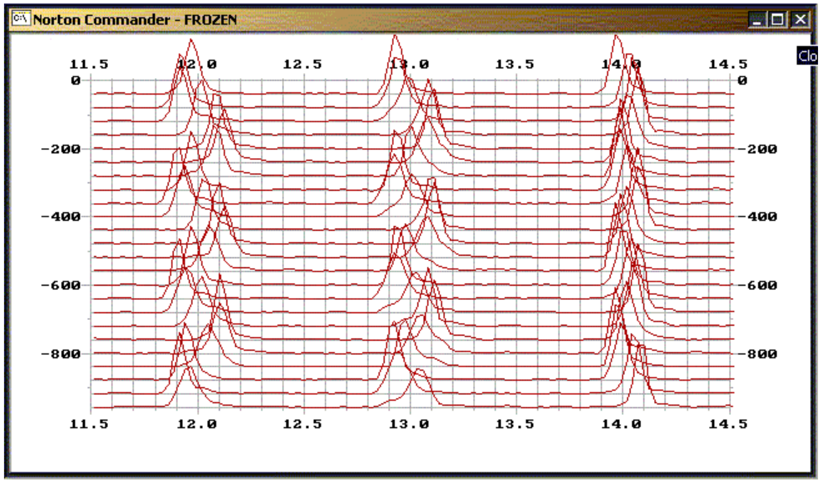
- ➢ Uncoalesced bunches - oscillations persist for hours
- ➢ Coalesced bunches – oscillations are damped during about 5 minutes
  - Longitudinal bunch-by-bunch damper accelerates the damping



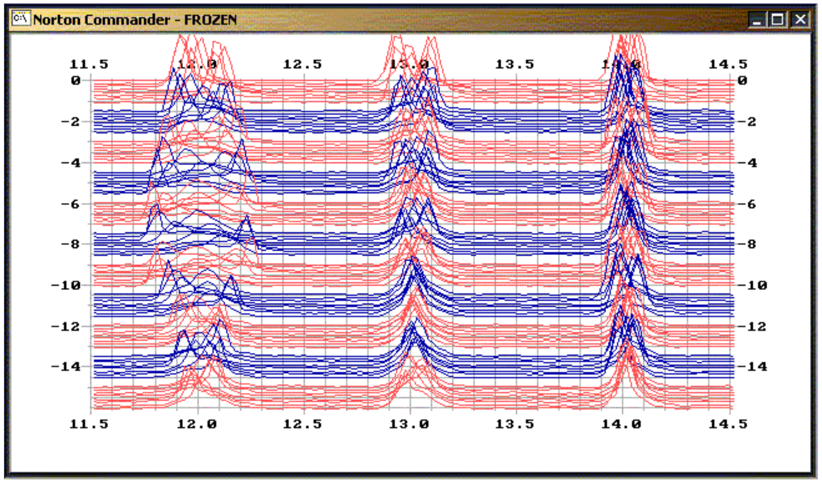
♦ The synchrotron tune spread would damp oscillations within seconds without coherent interactions inside bunches

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

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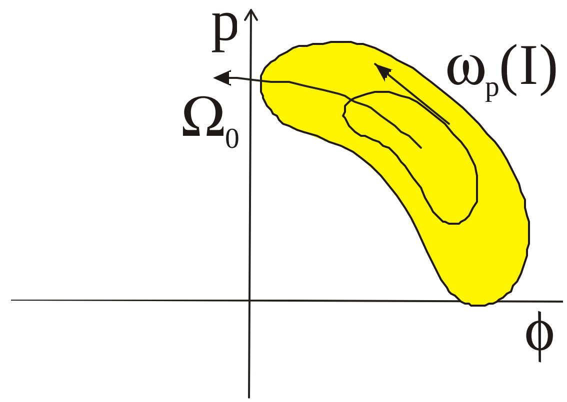
- Effect of **inductive** longitudinal impedance separates coherent and incoherent tunes and prevents decoherence at (V.Balbekov, S.Ivanov, 1991)

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

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



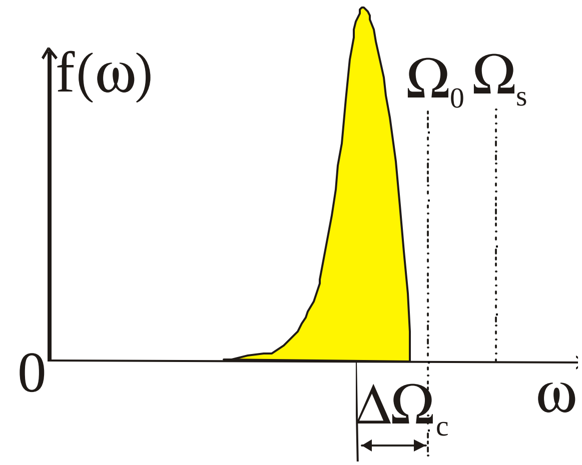
- For Tevatron at 150 GeV it yields:

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

$N = 10^{10}$ - 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:

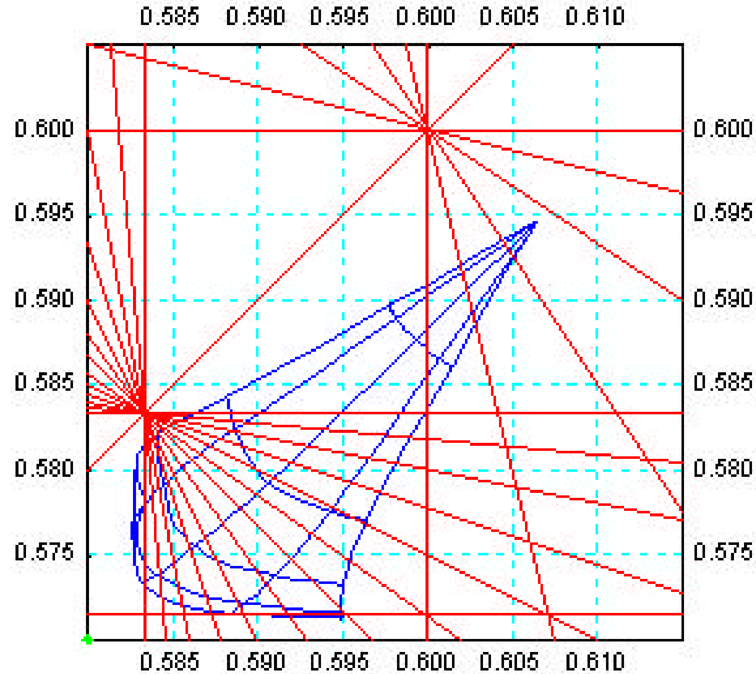
$$Z/n[\Omega] \approx i + (1+i)\frac{20}{\sqrt{n}}$$



  - 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

3. Beam-Beam effects

- 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 $\xi \approx 0.02$ for two interaction points
      - Tunes are between 5-th, 7-th and 12-th order resonances
  - 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: $\Delta\nu_x \approx \Delta\nu_y \approx 8\cdot10^{-3}$
    - Presently, the long range beam-beam effect is the major limitation of proton intensity increase



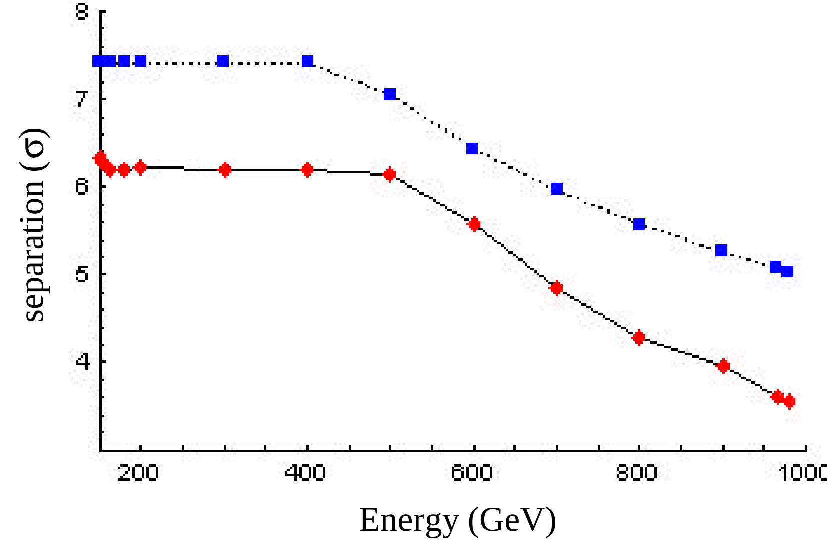
Pbar bunch #6 "footprint" at the design proton intensity $N_p=2.7\times10^{11}$. Both head-on and long-range collis. Radial lines drawn with 2s step. Bare lattice tunes .580, .570 chosen to get off 5th order resonances but not to sit on the 7th order. Coupling through the beam-beam force not taken into account

- **Long range beam-beam effects**
  - For fixed separation in σ's the tune shift does not depend on energy
    - It requires $U \propto \sqrt{Energy}$
  - 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
- What can be done to alleviate harmful effects of long-range collisions
  - Better optimization of helical orbits
  - Optics change in A0 should additionally help with beam separation
  - Increasing voltage on the separators

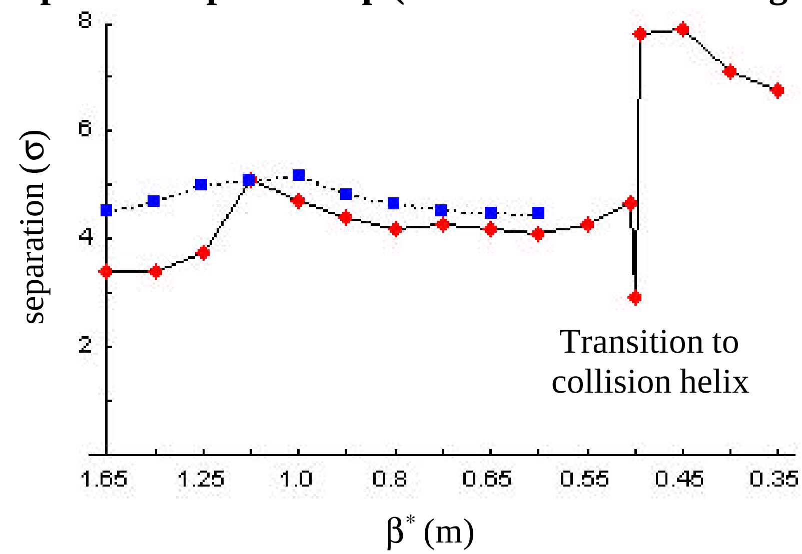
$$\Delta n \propto \frac{1}{a^2}$$

    - Adding new separators is also possible
  - Reducing initial emittance of the pbar beam
  - Tevatron electron lens can reduce both long range and head-on tune shifts

Injection Helix after C0 Lambertson Replacement



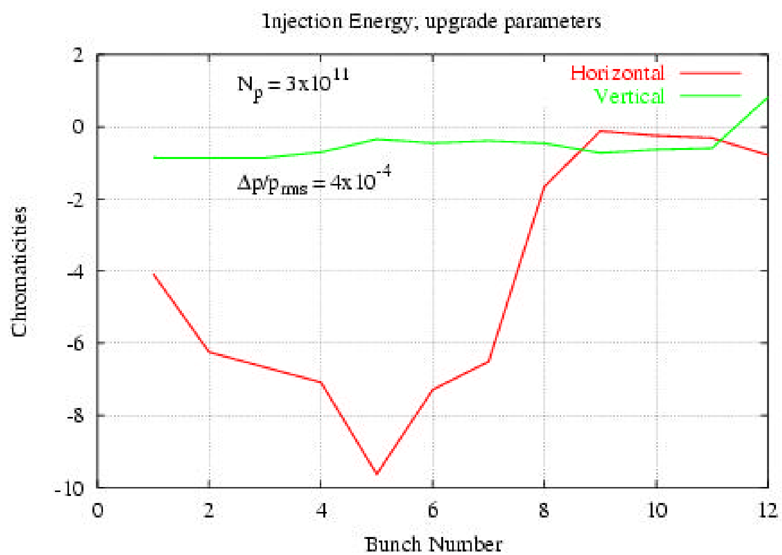
Separation up the ramp (current and new settings)

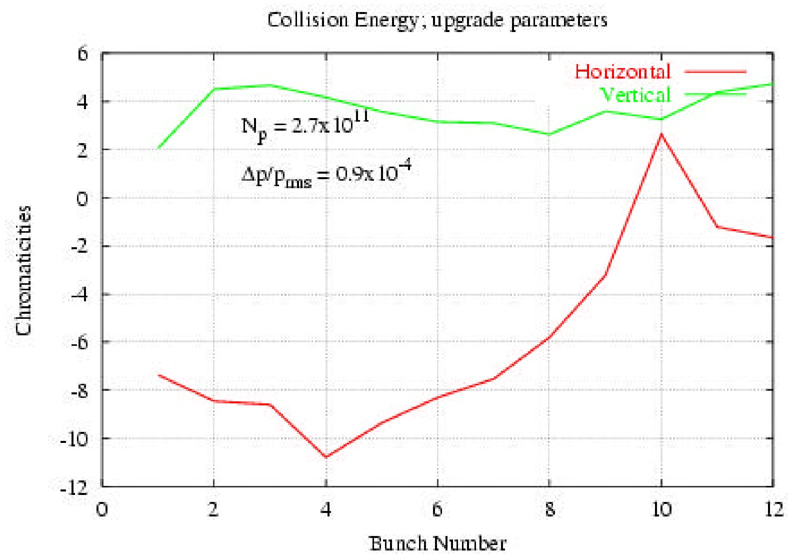


Separation on squeeze (Umax=106.5 kV, E=1 TeV)

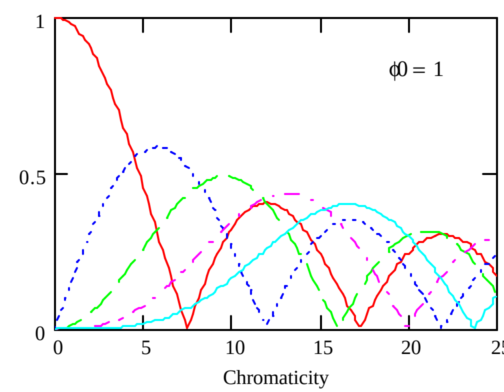
Collective stability and long-range beam-beam effects

♦ Long-range beam-beam effects modify machine chromaticity so that different bunches see different chromaticities





♦ If not addressed the spread of chromaticities (~ 10 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



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

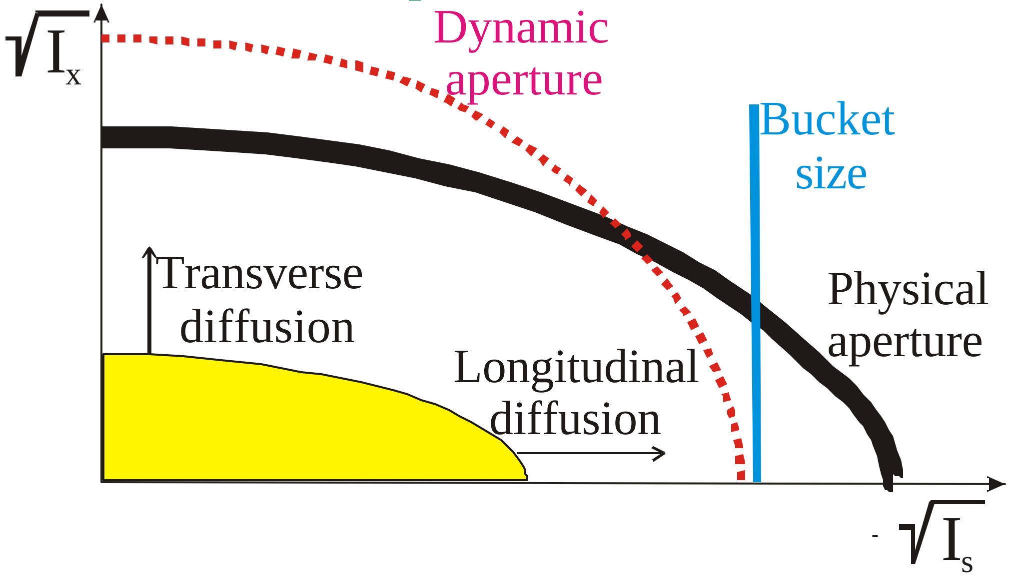
132 ns scenario

- There is considerable risk and uncertainty even in increasing the proton bunch population to $2.7\cdot10^{11}$ /bunch for present 36 by 36 bunch operating scenario
- 132 ns scenario implies
  tripling the number of bunches
  and tripling the total proton charge in the ring
  - It will increase the strength of long-range beam-beam effects by additional factor of three so that it will be 5 times higher than presently achieved total proton current
    - We do not know how we could deal with long range beam-beam effects at such proton beam intensity
- Taking into account that 3 fbarn/year can be achieved with 36x36; and the luminosity leveling can be used to limit the peak luminosity we believe that we need to stop further work on the 132 ns scenario

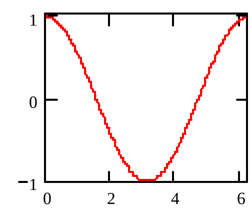
4. Particle Loss at Injection

- **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**

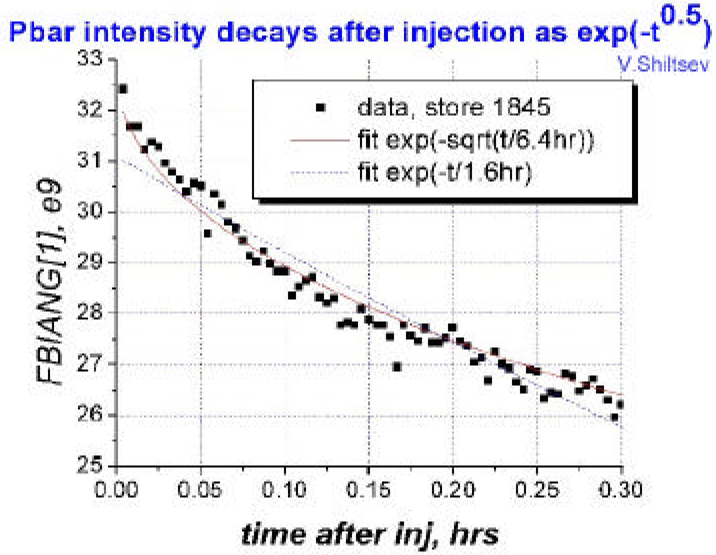


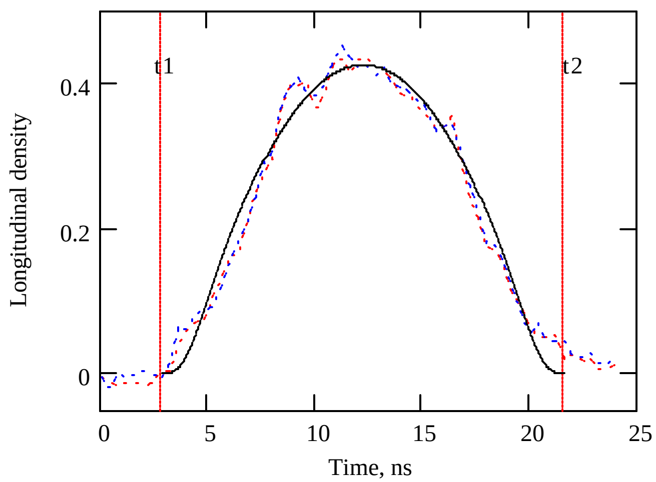
- Effects of longitudinal diffusion due to IBS and RF noise are amplified by
  - Overfilled bucket at injection
  - Shallowing the potential well near separatrix
  - Instability of particle motion at large synchrotron amplitudes



- 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)

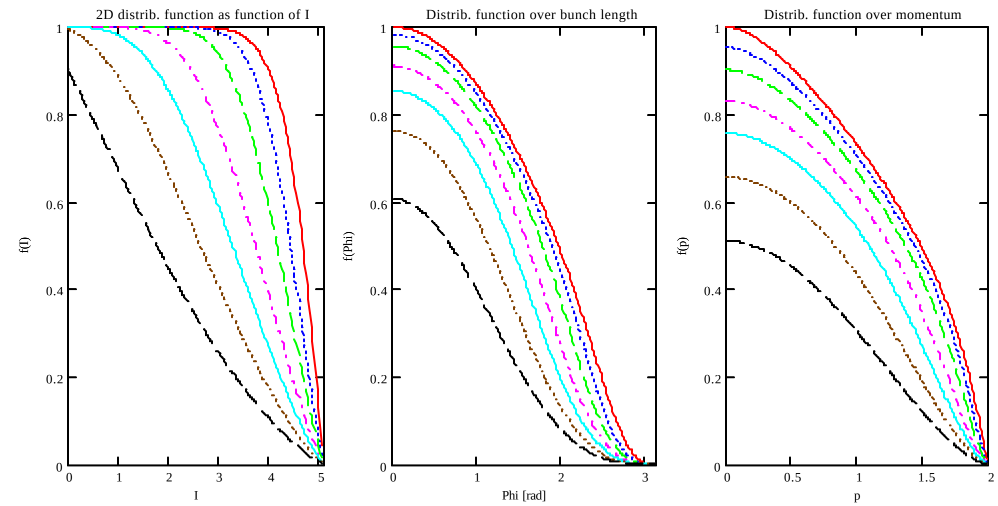
Measured dependence of proton beam intensity on time at injection

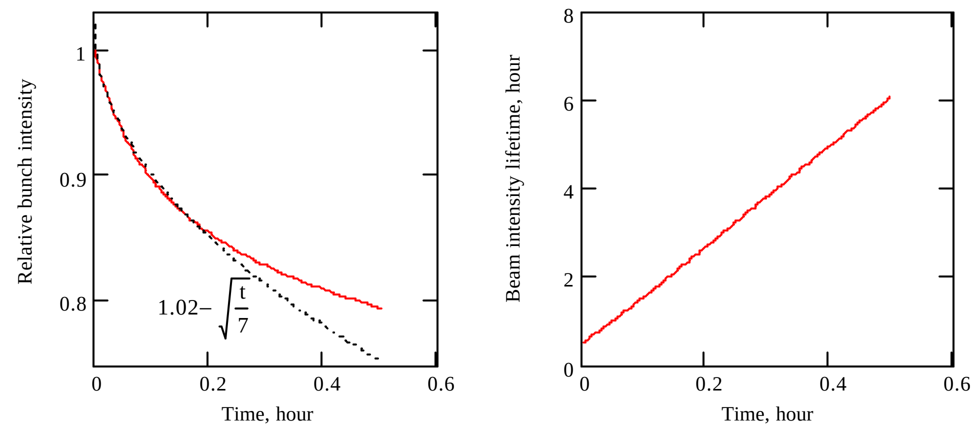




Measured and used in simulations initial longitudinal particle density

Simulations for Longitudinal Distribution





Computed emittance life times for protons of Store 1953:

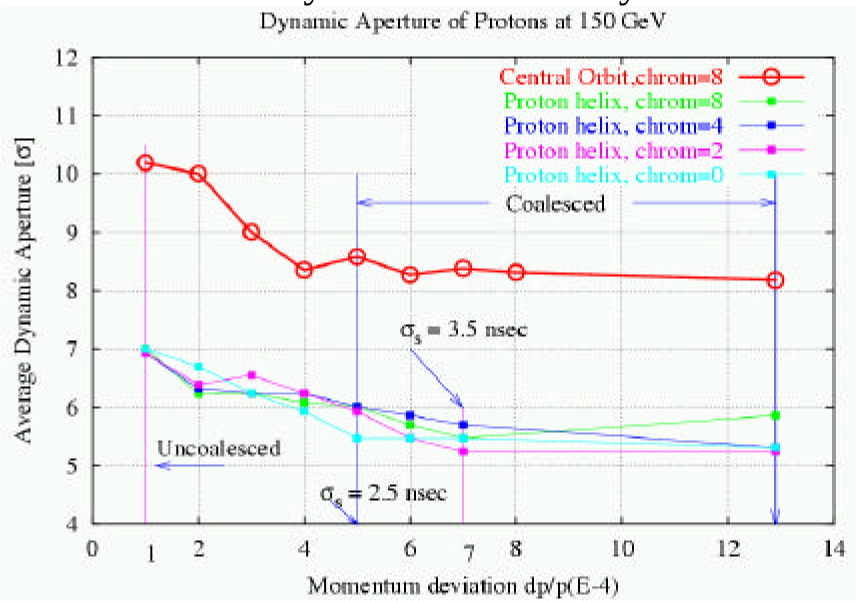
Transverse - *12 hour*

Longitudinal (uncorrected) - *48 hour*

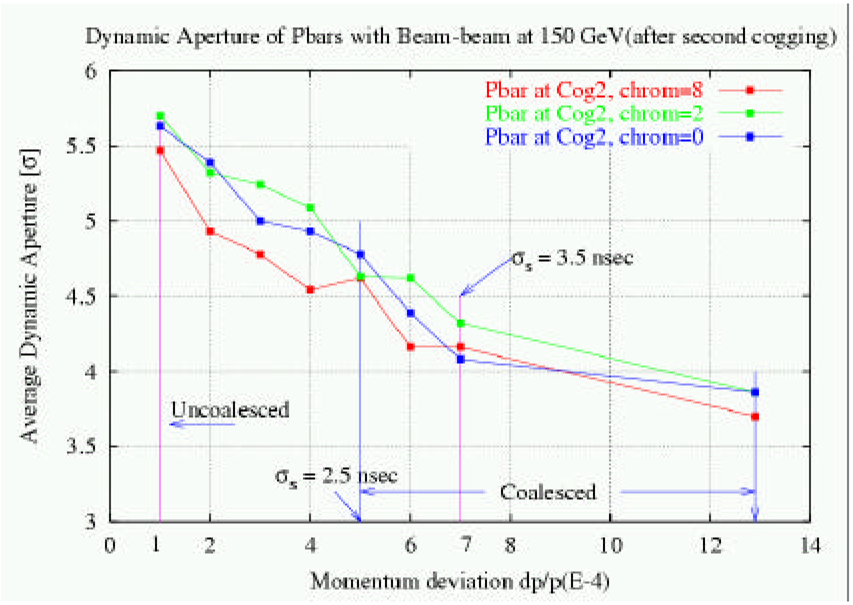
Intensity - $1-\sqrt{t/(7\text{ hour})}$

Numerical simulations of proton/pbar dynamic apertures for different chromaticities

- The above simulations take only longitudinal particle loss from the bucket
- They produce close results but do not address the lifetime dependence on chromaticity
  - Most probable reason
    - Reduction of dynamic aperture for particles with large amplitudes due to an increase machine non-linearity with chromaticity



All known non-linearities are included for protons (e_p = 25 mm mrad)



Only beam-beam effects are included for antiprotons (e_{pbar} = 20 mm mrad)

- The simulations do not exhibit significant effect on the dynamic aperture while measurements point out that it should be there
  - We ignore orbit displacement in simulations
  - We are not sure that all the non-linearities are correctly included
  - More studies both theoretical and experimental are required

♦ Both transverse and longitudinal losses cause $\exp\left(-\sqrt{t/t}\right)$ intensity decay if the beam distribution is close to the aperture limit

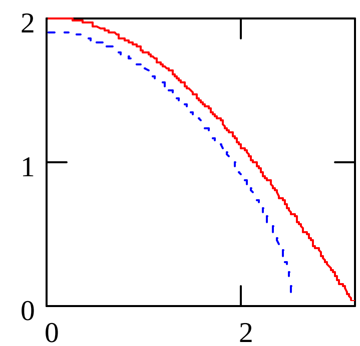
♦ We do not know a ratio of transverse to longitudinal losses but it is more probable that the longitudinal losses dominated the proton loss at injection

♦ 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 emmitance 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

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

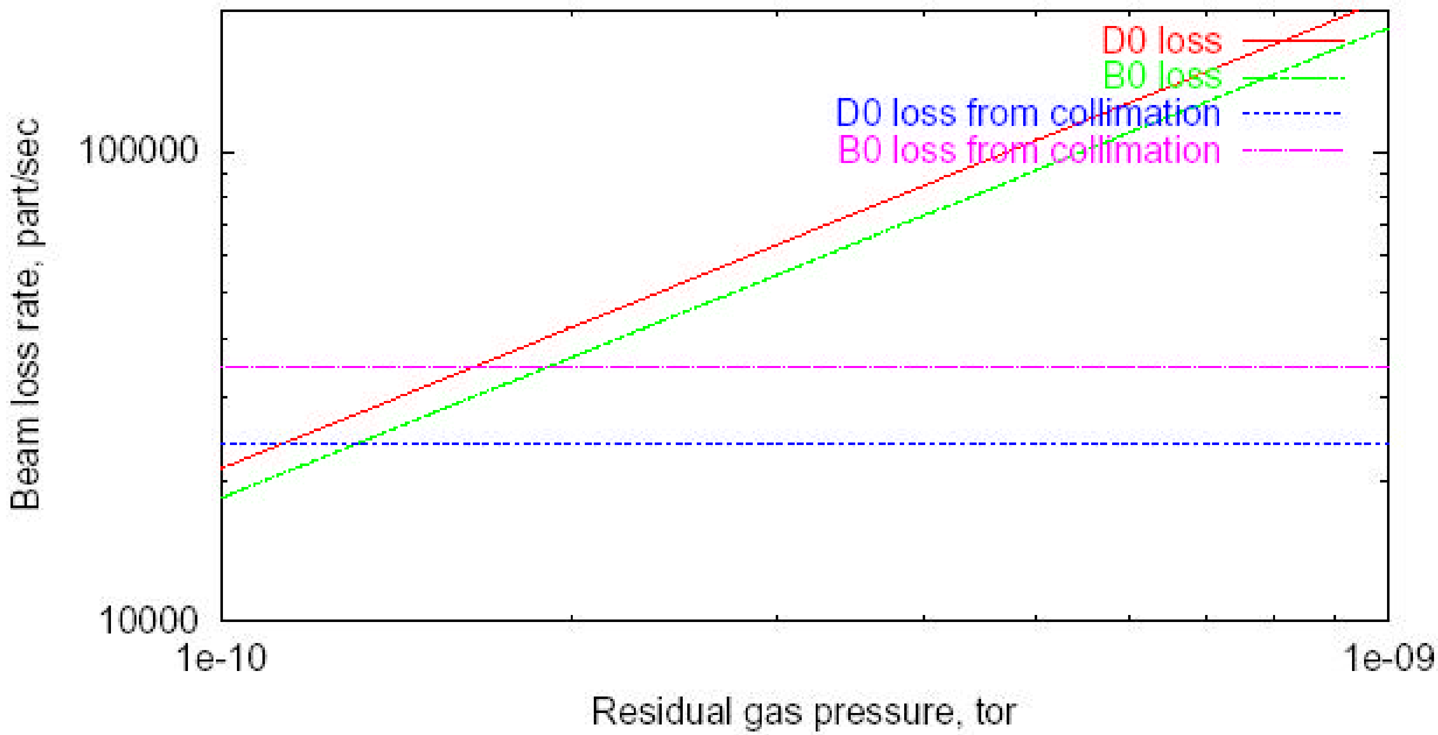


IBS determines that $e_{\max}/(de/dt) \approx 50$ hour

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

5. 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, $\kappa \approx 2\cdot10^{-4}$
    - But it does not do a good job to intercept single scattered particles, $\kappa \approx 0.02$

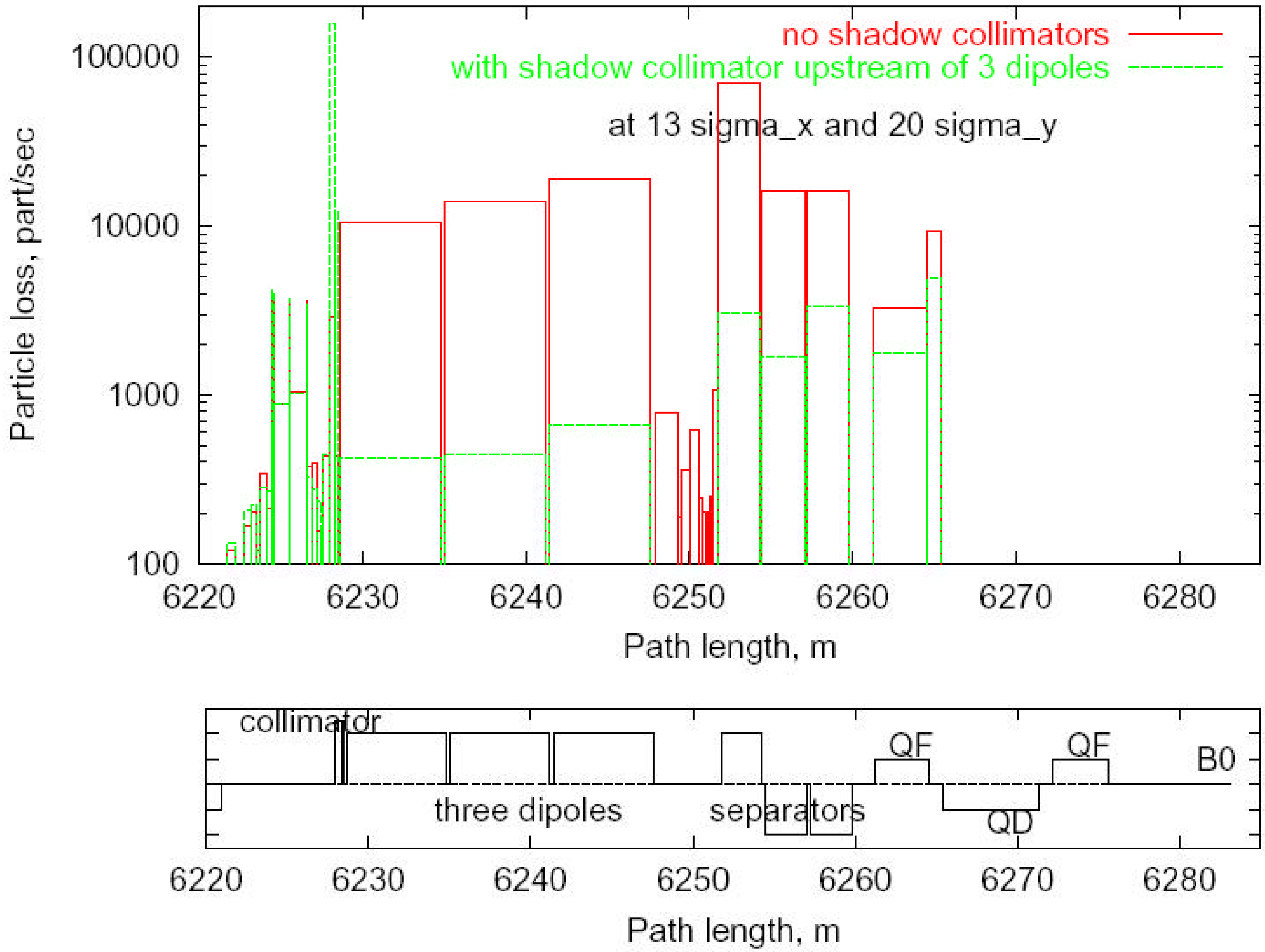


Simulated dependence of beam loss in CDF and D0 detectors as function of average Tevatron vacuum

- 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
    - 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 luminosity
3. To make progress in understanding of the beam-beam effects we will need significant contribution into
    - instrumentation,
    - theory
    - and experimental studies.