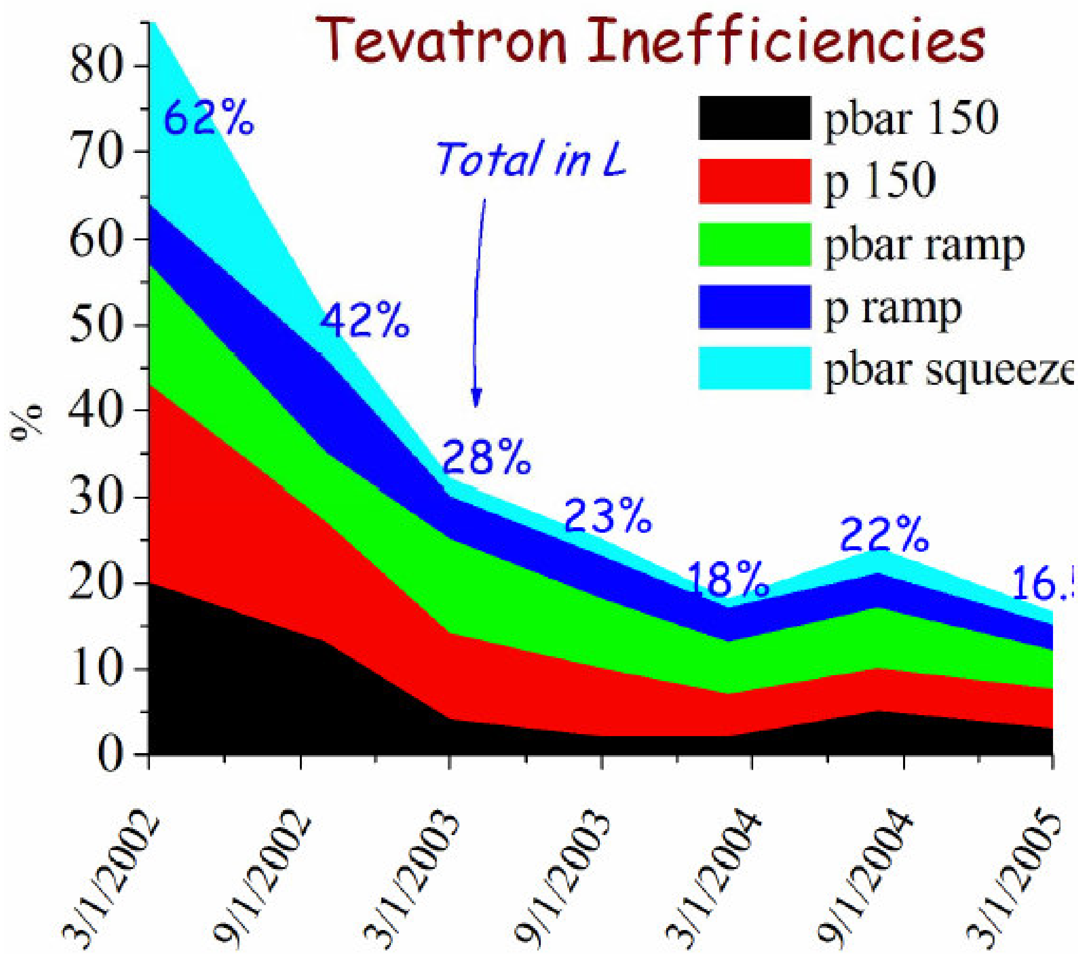
Tevatron Beam-Beam Issues

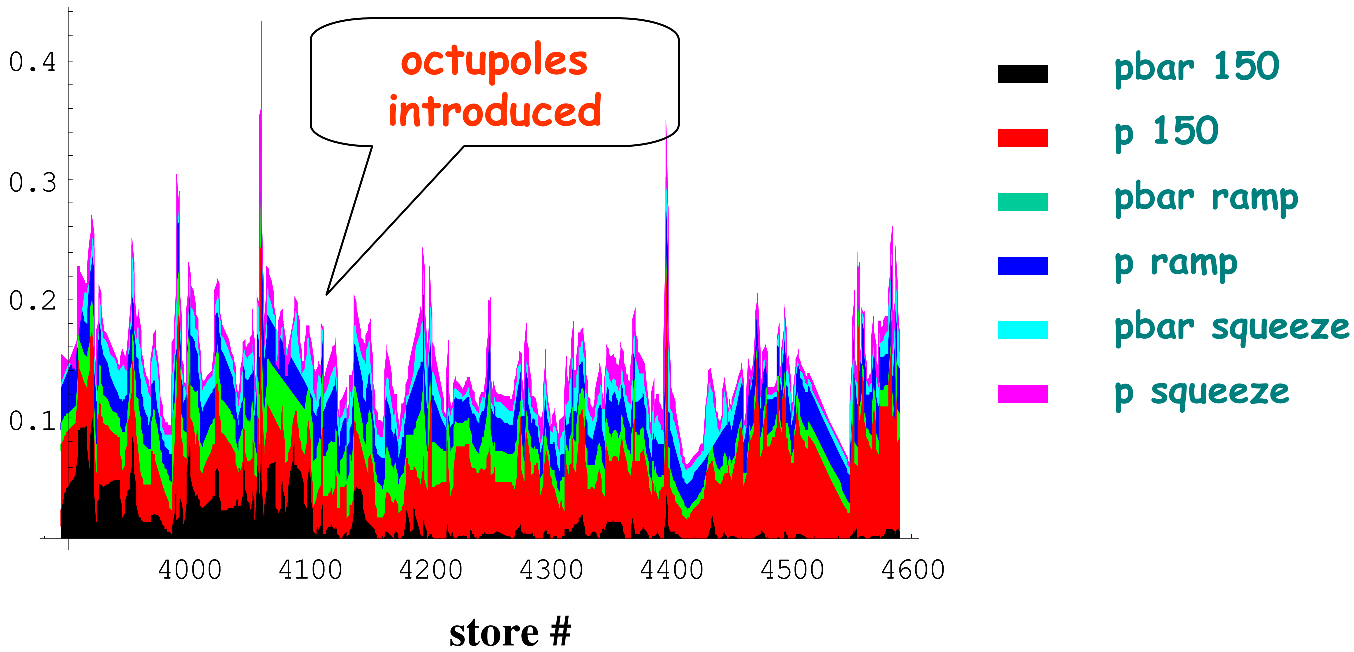
- Present situation & cures
  - losses @ injection/acceleration/squeeze
  - emittance blowup @ initiate collisions
  - lifetime in colliding beams
- Ongoing studies of new Working Point options
- Tentative plan of action

Tevatron Efficiency Progress in 2002-2004 (V.Shiltsev)



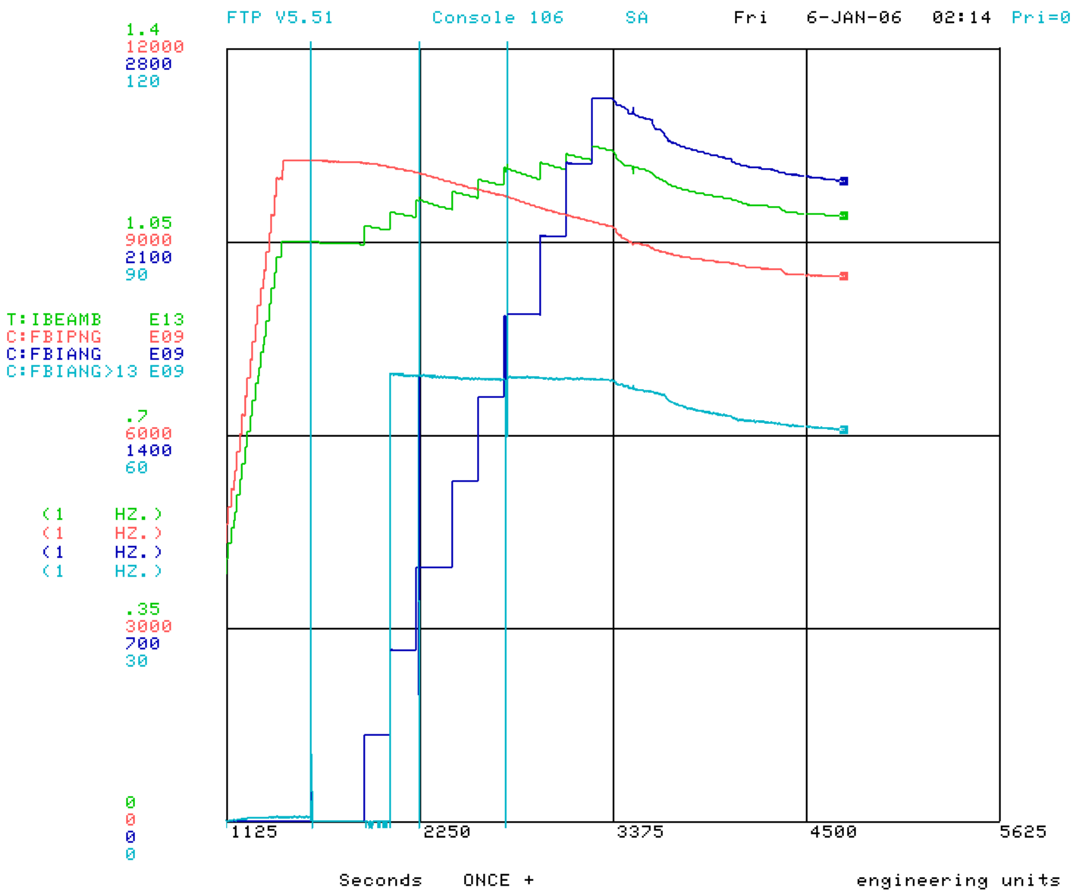
- Reasons are:
  - Tev helices
  - Apertures
  - Octupoles
  - Tune up
  - MI long emittance
  - Extra cooling in AA during inj (Tev lifetime is good)
  - Small emittances from RR

Tevatron Efficiency in 2005



With increase in Na the proton losses at pbar injection became a major problem.

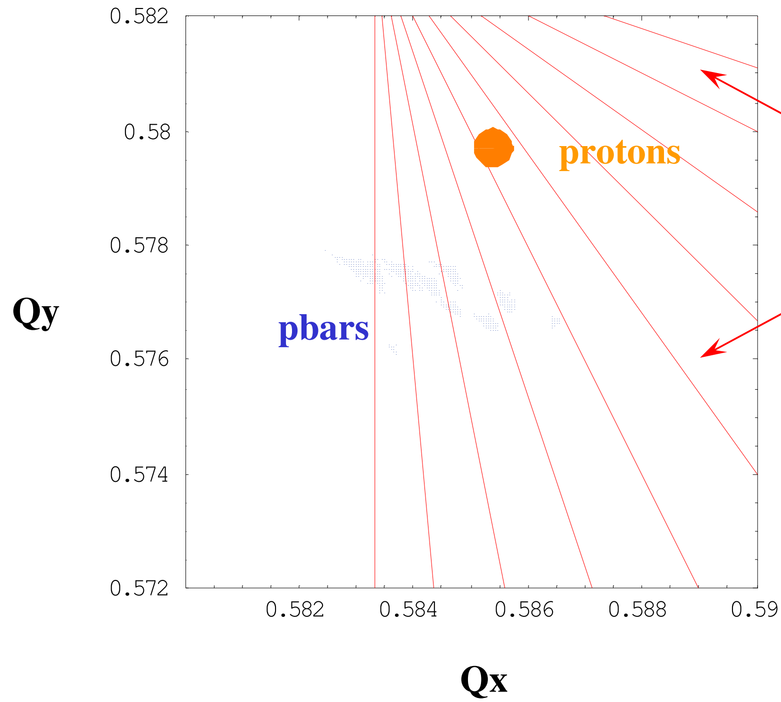
Tevatron Efficiency in the Record Store #4581 (01/06/06)



Again, there are high proton losses at pbar injection (and halo removal)

What makes life at 150 for protons more difficult than for pbars?

Protons and pbar tunes at injection



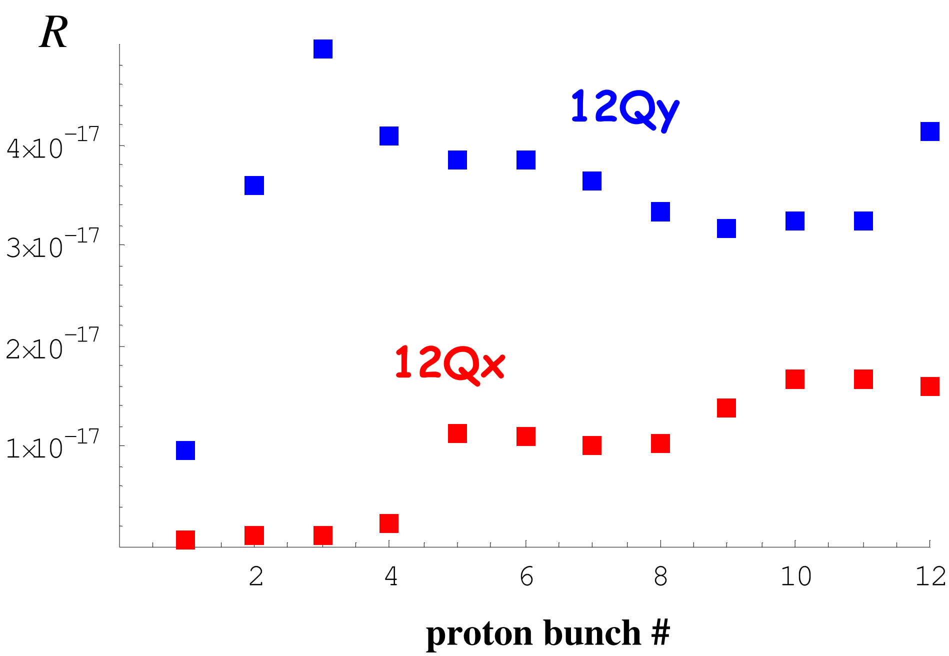
12th order resonances:

mQx+nQy=integer

m+n=12

protons see 12th order resonances with higher "n" – more vertical

12th order resonances excited by pbars @ injection



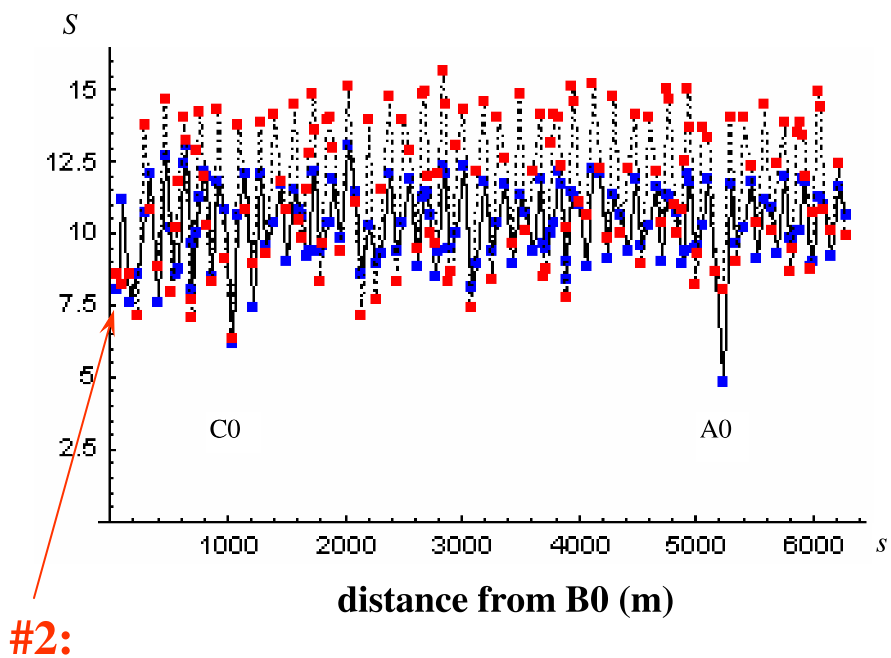
$$\frac{dI}{dn} = R,$$

$$\langle I \rangle = \varepsilon_{95\%} / 6\pi\gamma = 1.6 \cdot 10^{-8}$$

Get away from 12Qy resonance!

The resonance driving terms were calculated for the respective betatron amplitude = 3σ (reference emittance 15π), Na=50e9/bunch

Separation between the beams with injection cogging



$$S = \sqrt{(\Delta x / \sigma_{x\beta})^2 + (\Delta y / \sigma_{y\beta})^2}$$

- "radial" separation (reference emittance 15π mm·mrad)

■ - Jan 2002 helix

■ - May 2002 helix

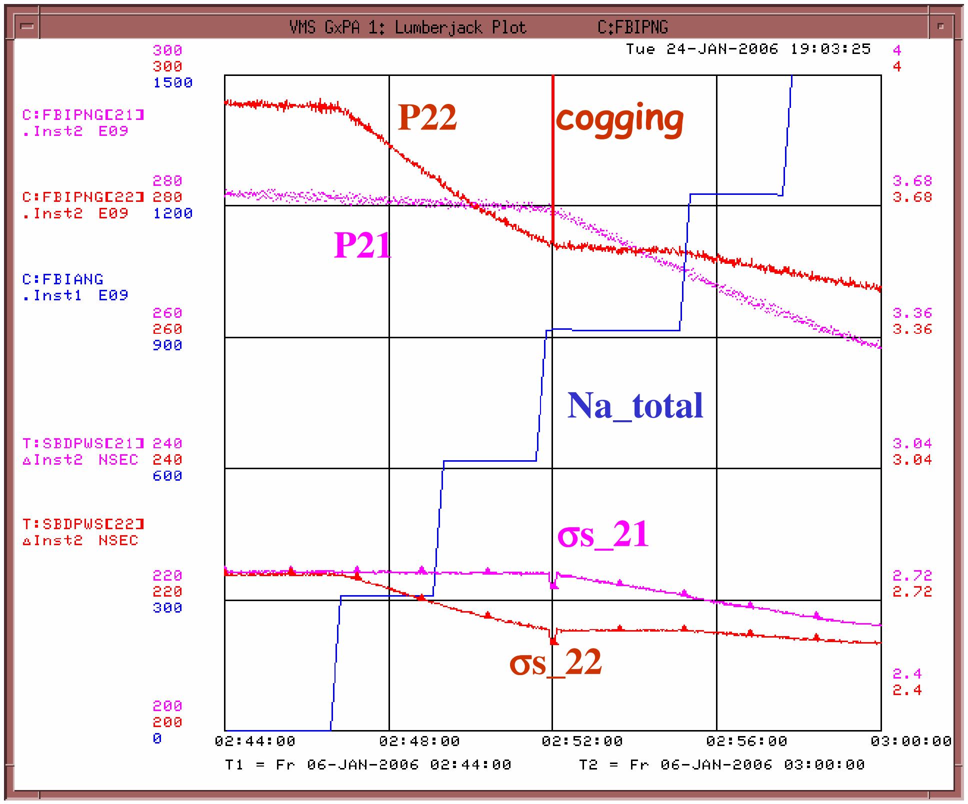
The new helix reduced the total beam-beam effect, while increasing it at one point, #2.

Δx=5.3mm, βx=26.5m,
Δy=0.5mm, βy=111.6m

- at this point the first proton bunches (and the last pbar bunches) in the trains do not interact at all.

After the first pbar transfer P22 interacts there with A1, while P21 does not interact

Proton losses during pbar injection (Store #4581)



P22 suffers high losses after the first transfer since it sees A1 at IP#2 while P21 starts seeing pbars there only after the cogging.

Length of the p-bunches interacting @IP#2 shrinks – protons with large synchrotron amplitudes are being lost

Proton losses during pbar injection

Why pbars fare better than protons at injection:

- tunes are farther from Qy=7/12
- chromaticity ~0
- twice smaller emittance!

Cures:

- Move proton tunes above 7/12 (C49 file prepared but not tried in HEP)
- Introduce "5-star" helix

helix	separator voltage (kV)					S_{min}	tuneshifts		RDTs (m/turn)	
	B11H	B17H	B11V	C17V	C49V		$\|\Delta \nu_x\|$	$\|\Delta \nu_y\|$	$\|R_{50}\|\cdot 10^{11}$	$\|R_{07}\|\cdot 10^{13}$
Jan 2002	0	61.7	0	-61.7	0	4.83	.0045	.0020	1.95	7.06
May 2002	-37	64.3	-22.6	-58.8	0	6.01	.0028	.0019	0.92	1.77
"5 star"	-18.9	61.8	5.9	-68.4	21.8	7.34	.0020	.0009	0.80	0.55

Incoherent BB effects at collision

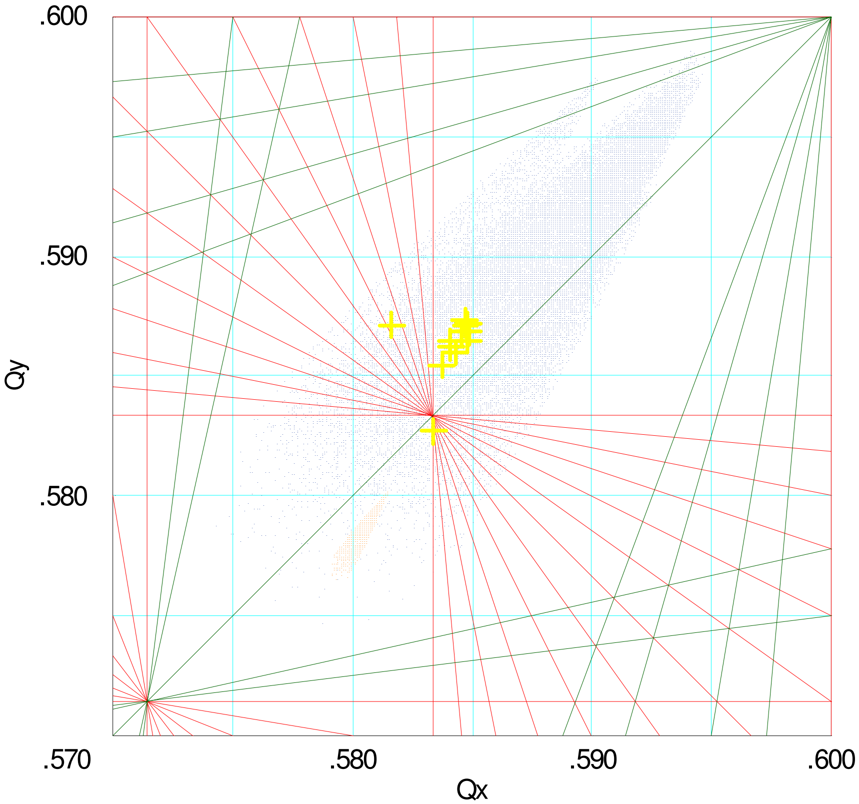
Manifestations:

- Pbar (and sometimes proton) emittance blowup at the start of HEP
- Proton and (to lesser degree) pbar non-luminous losses

Problems:

- Not enough room for pbar tunes between 5^{th} and 12^{th} order resonances
- Large BB-induced split in chromaticity: $C_h^{pbar} - C_h^{proton} \sim 7$
- Large emittance ratio $\varepsilon^{proton}/\varepsilon^{pbar}$ (good for pbars, not for protons)
- Reduced separation at the nearest parasitics after the optics upgrade

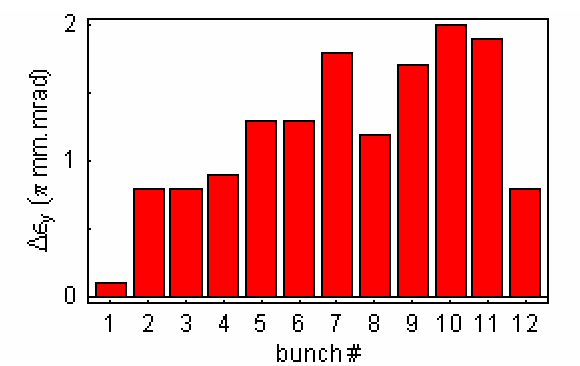
BB tunespread at collision



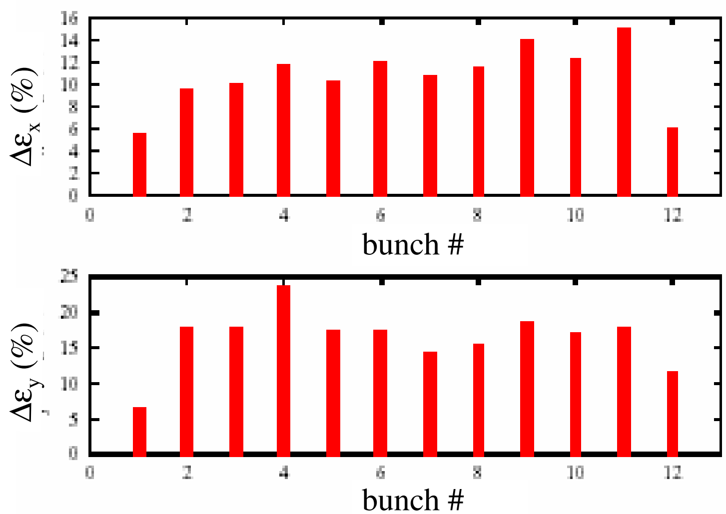
- Pbars are subjected to 5th and 12th order resonances ⇒ emittance blow-up and losses;
- Protons were subjected only to 12th order resonances ⇒ losses, but now they may see 5th order as well due to:
  - change in the WP (10/19/05)
  - higher pbar intensity

Calculated tune distribution of protons (orange) and pbars (blue) in collision and measured bunch-by-bunch 1.7GHz Schottky tunes (yellow) in store 3867, 07/28/2004

Pbar emittance blowup at initiate collision (scallops)



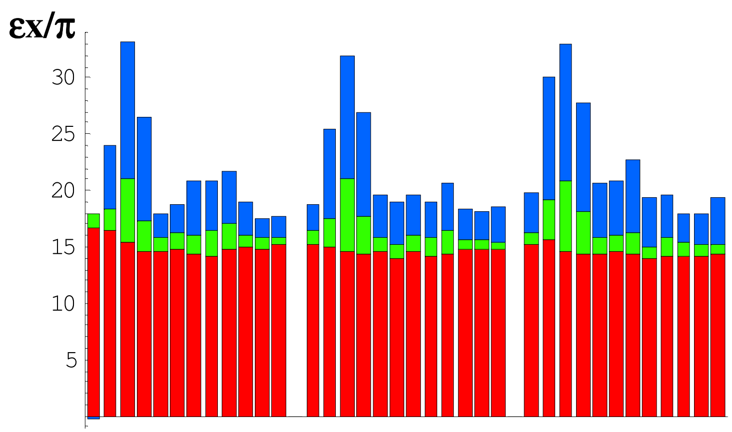
Antiproton vertical emittance growth in 15min of collisions (store #3554, 06/02/04). Only one train shown due to 3-fold symmetry.



Emittance growth obtained by tracking simulations with the LIFETRAC code (A.Valishev)

5th order resonances (in cooperation with linear coupling) are the culprits!

Proton emittance blowup at initiate collision (store #4581)

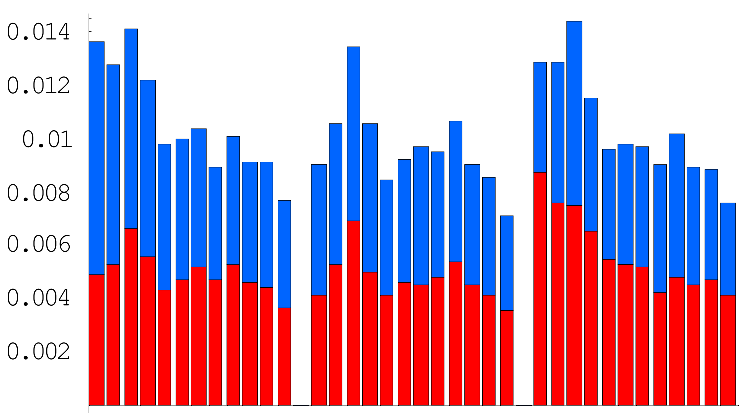


start of HEP

initiate collisions

end of squeeze

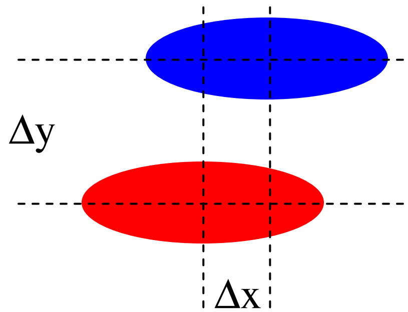
- the leading 4 proton bunches in each train reach Qx=3/5 because they collide with higher brightness pbar bunches from the first 3 transfers;
- however, the first p-bunches do not suffer since they do not meet pbars at upstream parasitic IPs (where $\beta x \gg \beta y$)



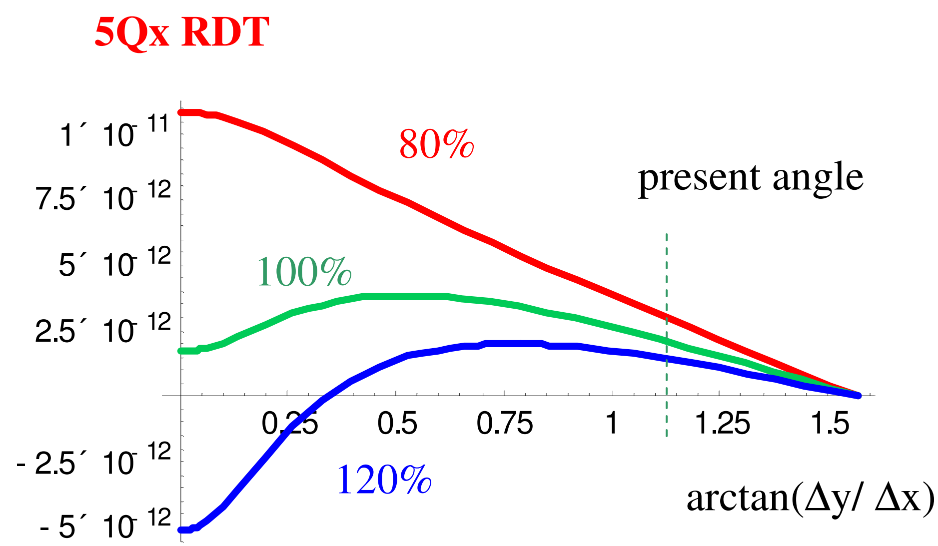
head-on collisions at D0

head-on collisions at CDF

5^{th} order resonances due to nearest LR interactions



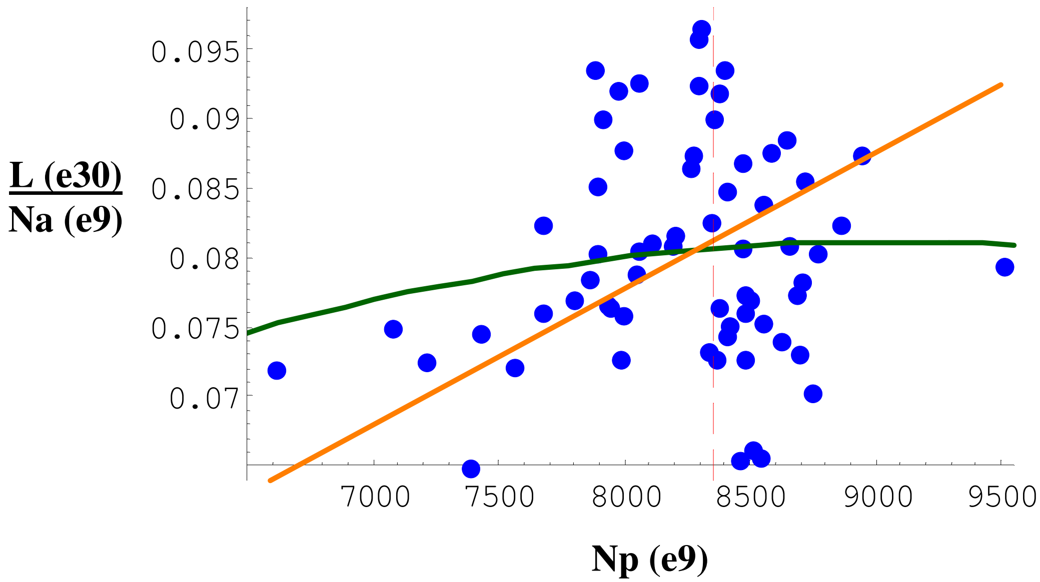
At upstream parasitic IPs the separation is mainly vertical (~2σx), at the downstream - horizontal



To minimize excitation of 5^{th} order resonances separation should be increased vertically at the upstream IPs and horizontally at the downstream IPs

Driving term of 5Qx resonance from upstream IP at 3σ amplitude as function of the separation angle

How much luminosity we lose to the "scallops"?



linear fit:
$L/Na=9.7*10^{-6}Np$

quadratic fit:
$L/Na=1.8*10^{-5}Np$
$\times(1-5.5*10^{-5}Np)$

Specific Luminosity in Stores with β^*=28cm (4395-4590)

- quadratic fit over-dramatize the beam-beam effect on luminosity
- according to linear fit L=240e30 at Na=2500e9 and Np=10000e9
- however, there is an obvious reduction in L/Na at Np>8500e9, to achieve such luminosity "scallops" must be eliminated

Effect of β^*=28cm optics on separation

Changes in optics:

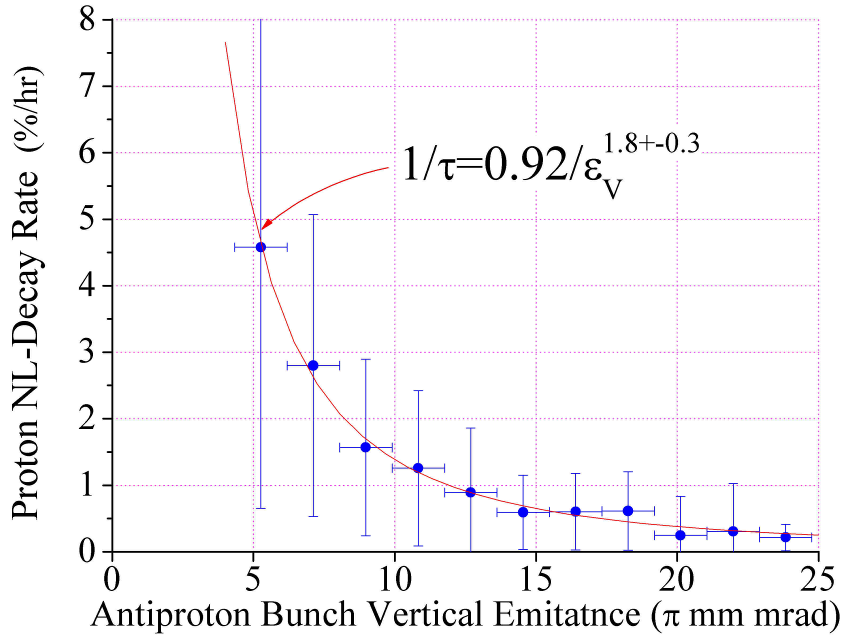
caused reduction in voltages of D11H and C49V separators which provide main separation around D0

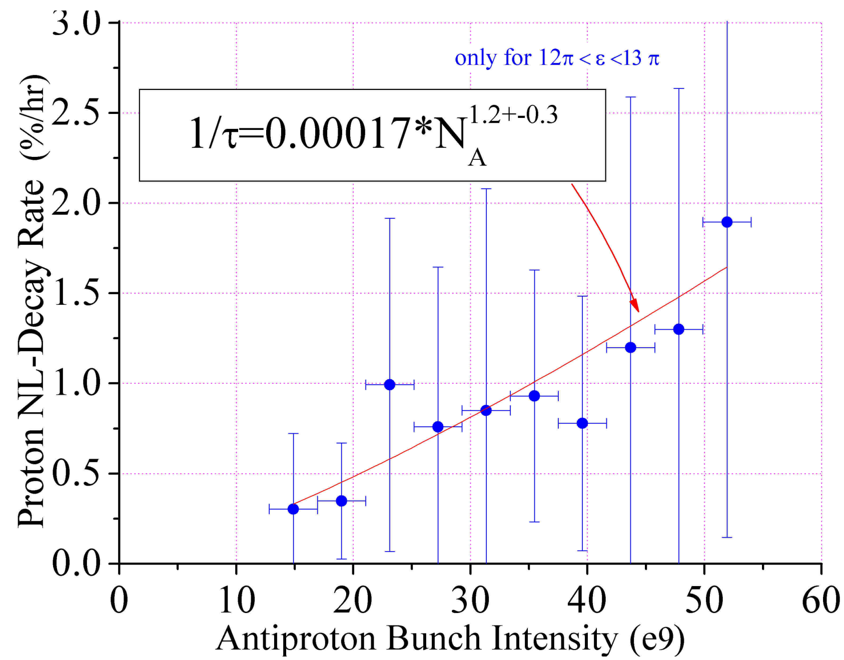
date	B11H	B17H	C49H	D11H	D48H	A49H
05/13/04	105	45.72	104	96	61.96	104
01/07/05	99.43	43.33	100	96.15	64.75	100
01/06/06	100	58.99	83.24	88.70	29.07	100

date	B11V	C17V	C49V	D11V	D17V	A17V	A49V
05/13/04	110	56.1	102.6	115	–	20.44	86.86
01/07/05	100	54.37	94.8	100	92.7	40	100
01/06/06	98.19	47.76	87.23	97.62	98.38	13.61	101.2

Additional B48V and A17H separators will allow to increase D11H and C49 voltages, just as D17V separator permitted to increase A49V voltage by 14% despite decrease in D11V

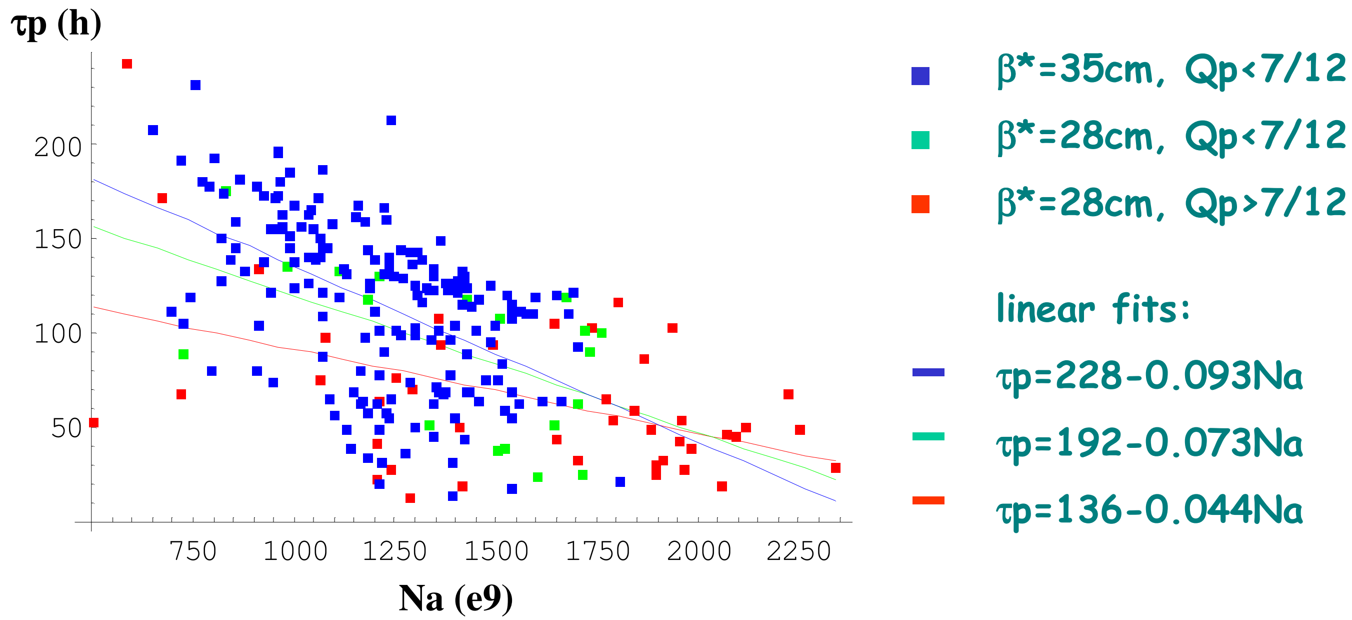
BB-induced proton losses in collision (V.Shiltsev)





V. Shiltsev's analysis of the proton non-luminous losses (stores during a few monthes after the fall 2004 shutdown)

BB-induced proton losses in collision (2005-2006)



- moving the proton tunes above 7/12 produced no big improvement in the lifetime due to large store-to-store variation in tunes
- orbit correction to a predefined "golden orbit" is necessary to reduce such variation (V.Ranjbar is doing this)
- proton tunes should be kept from sliding down in the course of the store just as it was done for pbars

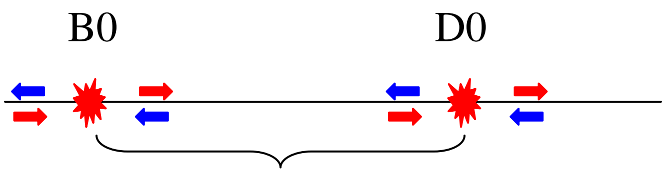
Incoherent BB effects at collision

Cures:

- Increase beam separation installing additional separators
- Lower pbar chromaticity with rearranged differential chromaticity octupoles (A.Valishev)
- Compress pbar tune footprint with TELs (S.Kamerdzhiev)
- Achieve intrinsic cancellation of 12^{th} order resonances by redistribution of phase advances between IPs
- Move tunes to a new working point (A.Valishev)

Redistribution of the betatron phase advances

Idea: let 12th order resonance driving terms from the two groups of IPs cancel each other



$$\phi_{\underline{m}} = 2\pi(m_x\mu_x + m_y\mu_y) - (m_xQ_x + m_yQ_y - n)\theta$$

$$R_{\underline{m}}^{total} = R_{\underline{m}}^{B0} + e^{i\phi_m} R_{\underline{m}}^{D0}$$
$$= 0 \quad if \quad \phi_{\underline{m}} = \pi \times odd\_integer$$

optics	ϕ (12Q_x)	ϕ (12Q_y)
design β*=35cm	169.8π	169.8π
TBT β*=28cm	170.3π	170.0π

- the default phase advances are most unfavorable
- the required corrections are at the limit of tuning quads, use of the LB trim quads may be necessary

Moving to a new Working Point

Two options under consideration:

- tunes above 1/2 (HI WP), on the pbar helix: 20.53, 20.52
- tunes above 2/3 (SPS WP), on the pbar helix: 20.676, 20.672

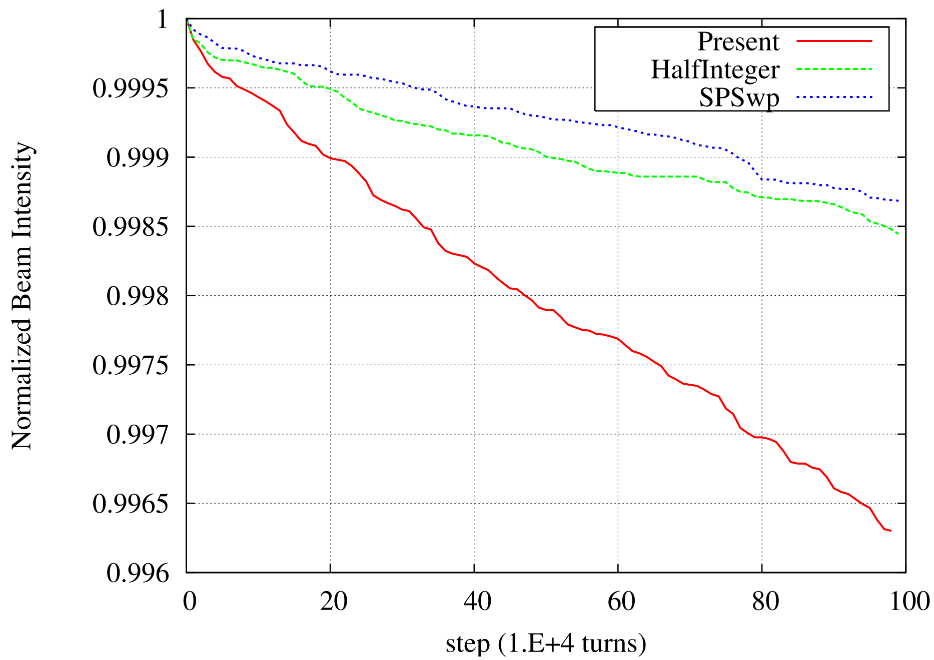
Resonances of order ≤ 16 in these regions:

- HI WP: 8/15=.5333, 7/13=.5385, 6/11=.5455
- SPS WP: 11/16=.6875, 9/13=.6923

Expected difficulties:

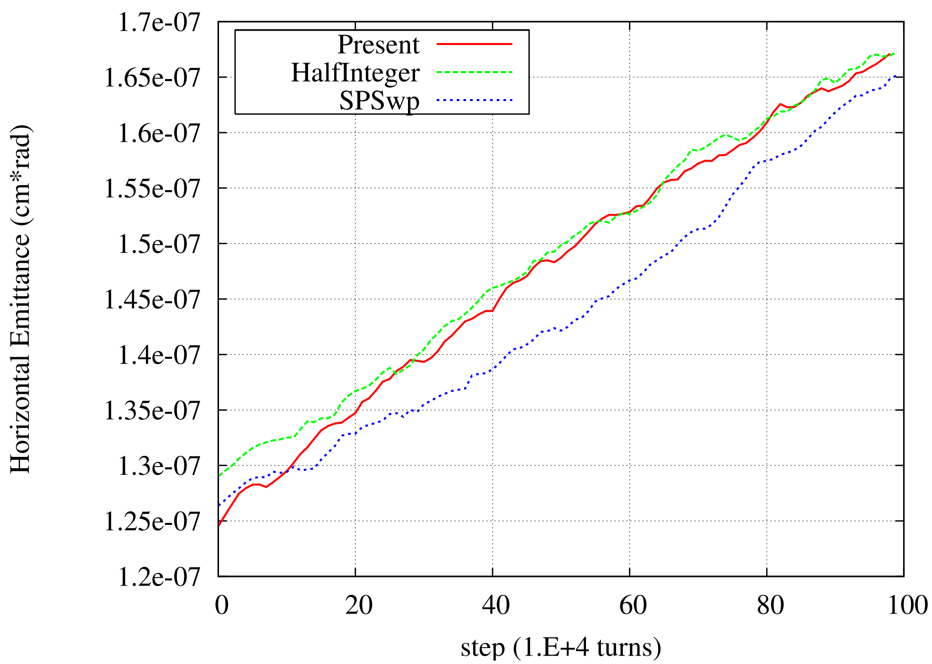
- HI WP: strong (resonancely enhanced) beta-beating, especially chromatic beta-beating which requires rearrangement of SF and SD into a number of subfamilies (A.Valishev)
- SPS WP: strong 3rd order resonances excited by the lattice sextupoles and beam-beam interaction
- tight control of the tunes (and therefore of the closed orbit) is necessary at all stages from injection to HEP (V.Ranjbar)

Beam-Beam simulations at new WPs (A.Valishev)



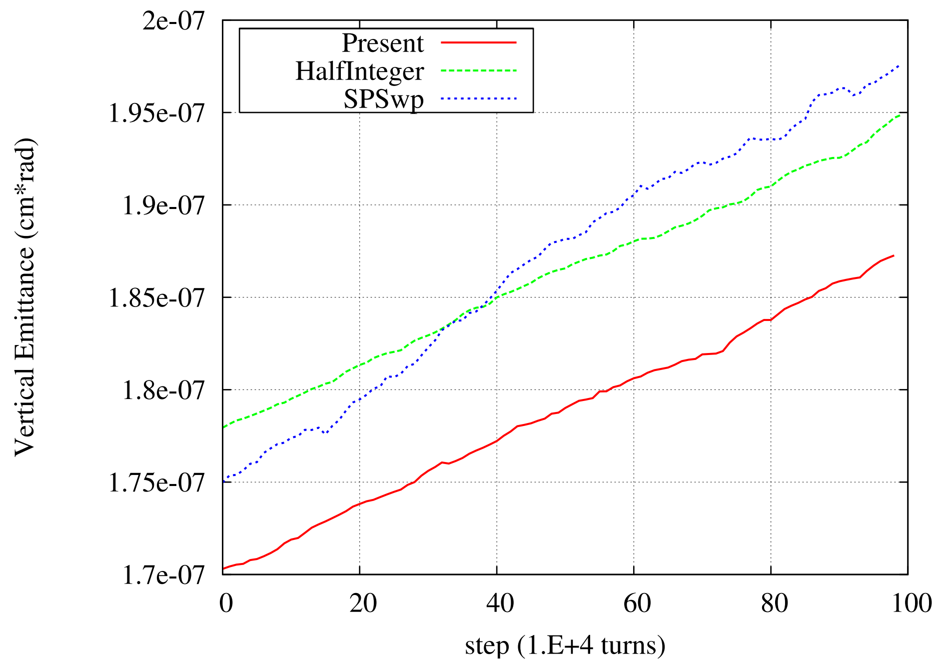
Normalized pbar intensity at HEP vs number of turns (10^6 total) in the presence of BB interaction (ξ=0.01/IP) and external noise, machine nonlinearities not included

Beam-Beam simulations at new WPs (A.Valishev)



Horizontal emittance vs number of turns

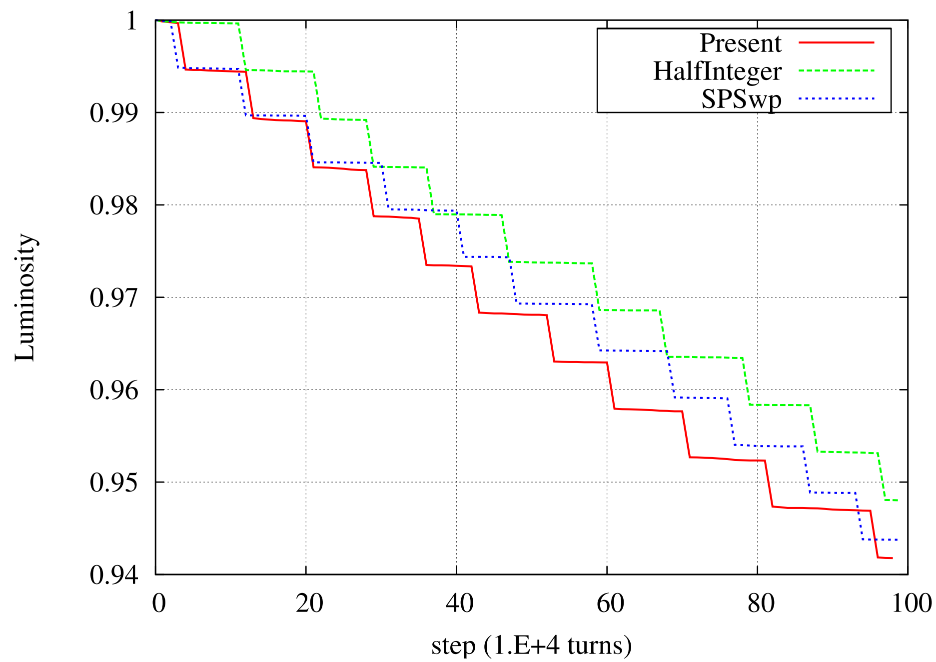
Beam-Beam simulations at new WPs (A.Valishev)



Vertical emittance vs number of turns

- difference in the initial values - BB closed orbit not taken into account
- higher growth rate for SPS WP may indicate a problem

Beam-Beam simulations at new WPs (A.Valishev)

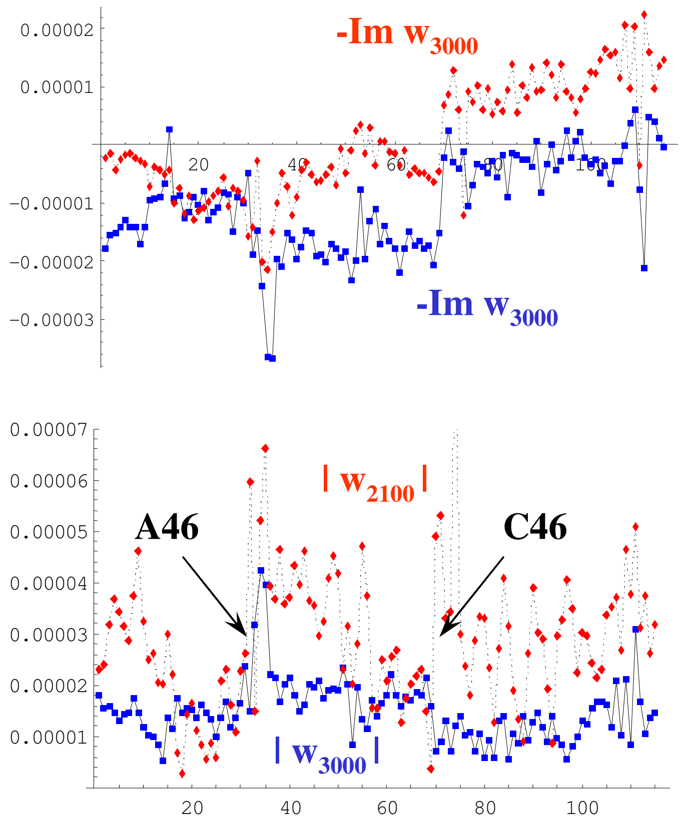


Normalized luminosity vs number of turns

The computed effect on luminosity is about the round-off error,

tune scans for larger ξ may reveal the true potential of the new WPs

TBT measurement of 3rd order RDT



Generating functions of Qx±2Qx resonances vs HBPM number starting from HF19

Measured and computed resonances driving terms at 150:

case	Res.	Re R	Im R	| R |
nominal	$3Q_x$	5.1	3.4	6.1
MAD, S6 only	$3Q_x$	4.1	4.0	5.7
S6=0, S6A0=200A	$3Q_x$	−1.7	−1.1	2.0
nominal	$3Q_y$	− 0.9	− 0.2	0.9

- 3Qx RDT is almost entirely produced by S6 feeddown sextupoles
- their replacement with S6A0 will solve the problem (if it arises)

SPS Working Point Outlook

3rd order RDT due to BB at 150 (analytics):

helix	$3Q_x$	$2Q_x + Q_y$	$Q_x + 2Q_y$	$3Q_y$
nominal	4.0	7.7	8.7	3.5
"5-star"	3.7	5.9	7.3	2.3

- The situation with 3rd order resonances looks at 150 manageable, if needed:
  - excitation of 3Qx by lattice nonlinearities can be compensated with S6A0 feeddown sextupoles
  - excitation by beam-beam can be reduced by switching to "5-star" helix
- In 07/12/05 machine studies it was possible to get as close as Qy=.67
- SPS WP requires 1-2 shifts tuning to be tried in a low lumi HEP

Tentative plan of action

- Try redistribution of phase advances at LB – if works, fix proton losses at 150 by
  - moving p-tunes above 7/12
  - switching to "5-star" helix
- If it fails try SPS WP mitigating 3rd order resonances (if needed) by using S6A0 (and switching to "5-star" helix)
- If it fails work on half-integer tunes option