Beam-beam compensation at the Tevatron

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FNAL

Why beam-beam compensation?

- At **injection energy** (150 GeV)

  long-range forces cause pbar losses (5-15%)

- During **the ramp**

  long-range forces cause pbar losses (5-15%)

- During **the low-beta squeeze**

  long-range forces cause p and pbar losses (< 5%)

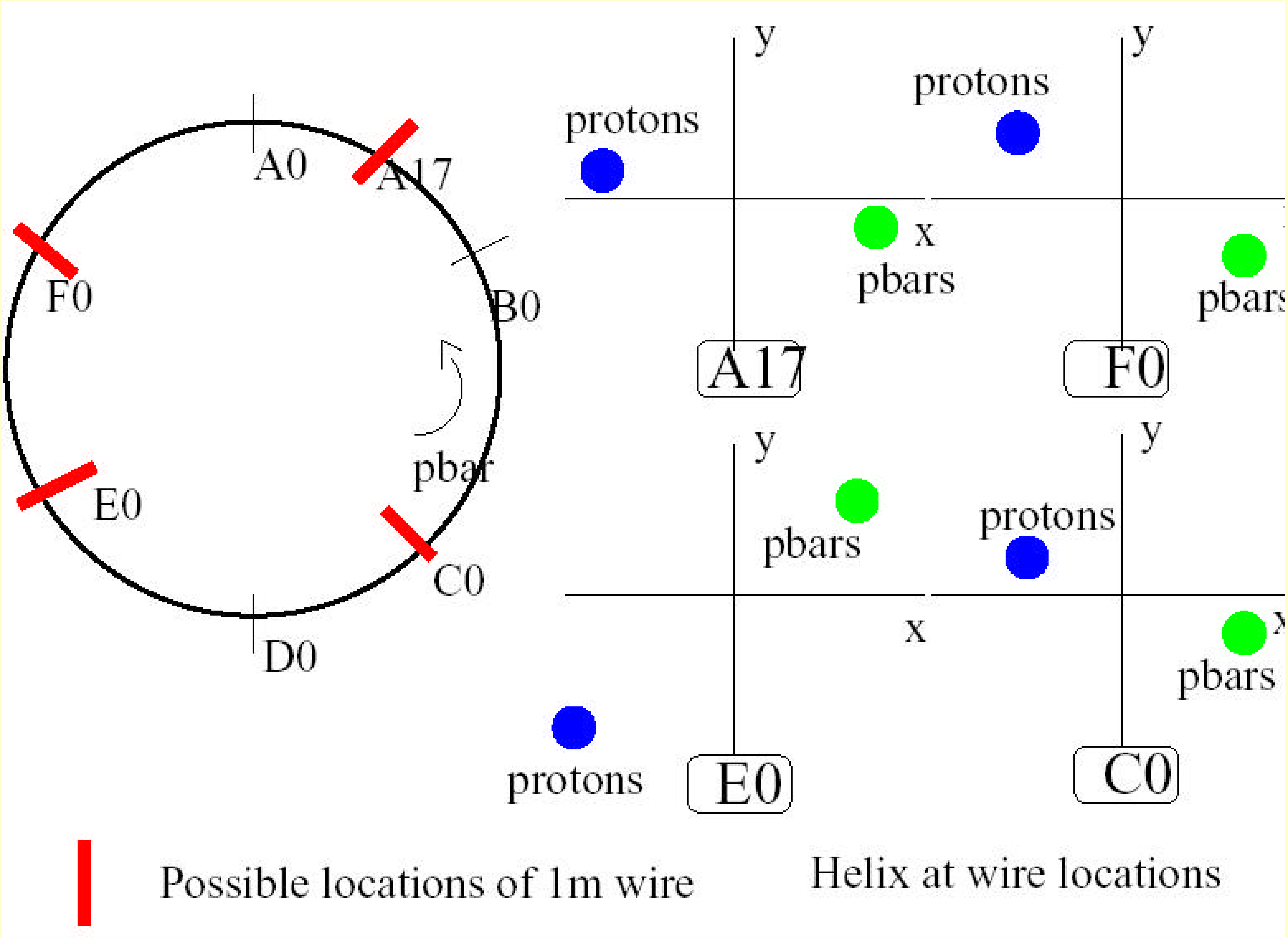
- During **collisions**

  head-on and long-range forces cause emittance growth and occasionally large detector backgrounds (from protons) and lifetimes < 20hrs.

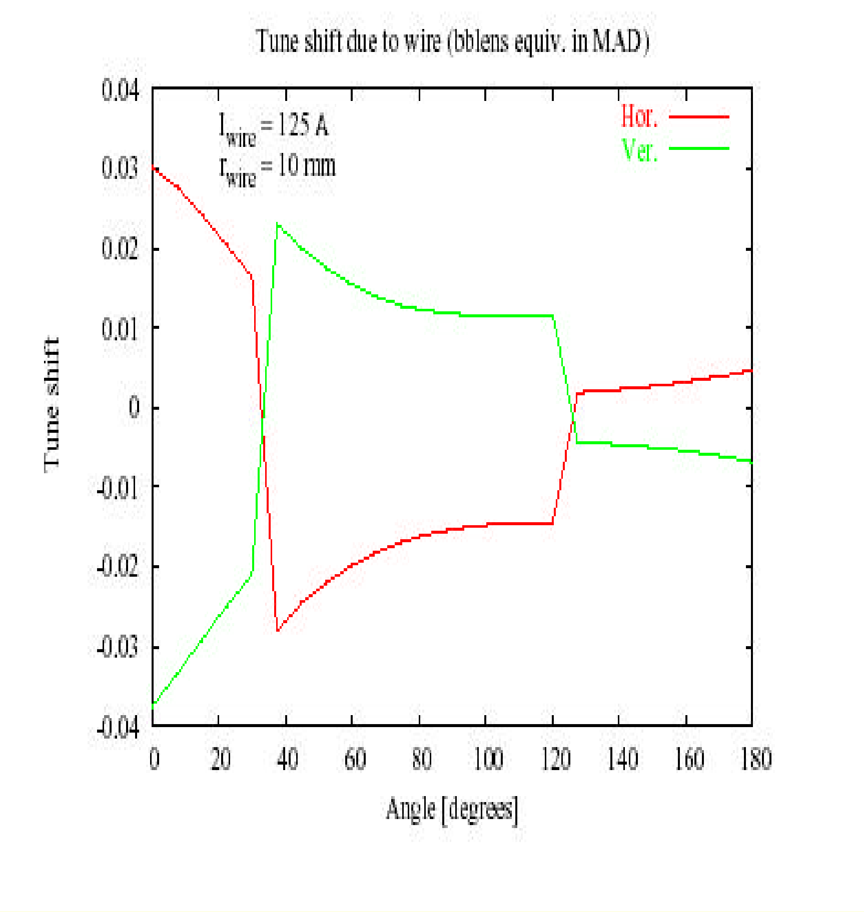
Wire Compensation Strategies

- Proposed for the LHC by J.P. Koutchouk
  Compensation in the Tevatron is more complicated.
- Compensation of individual resonances driven by the long-range interactions (analytical)
- Minimizing the norm of the nonlinear map using DA methods (COSY Infinity)
- Lifetime and beam density profiles from tracking with FNAL weak-strong code
- Optics and dynamic aperture using MAD & Sixtrack

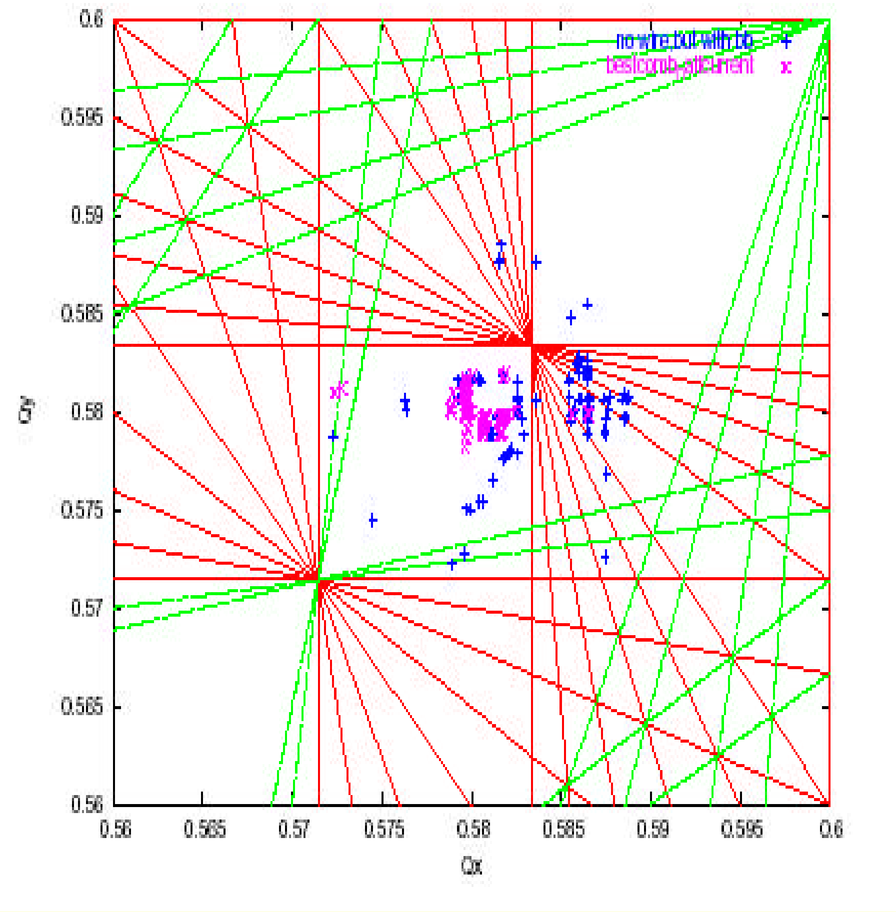
Wire locations and helices



Tunes and Footprints



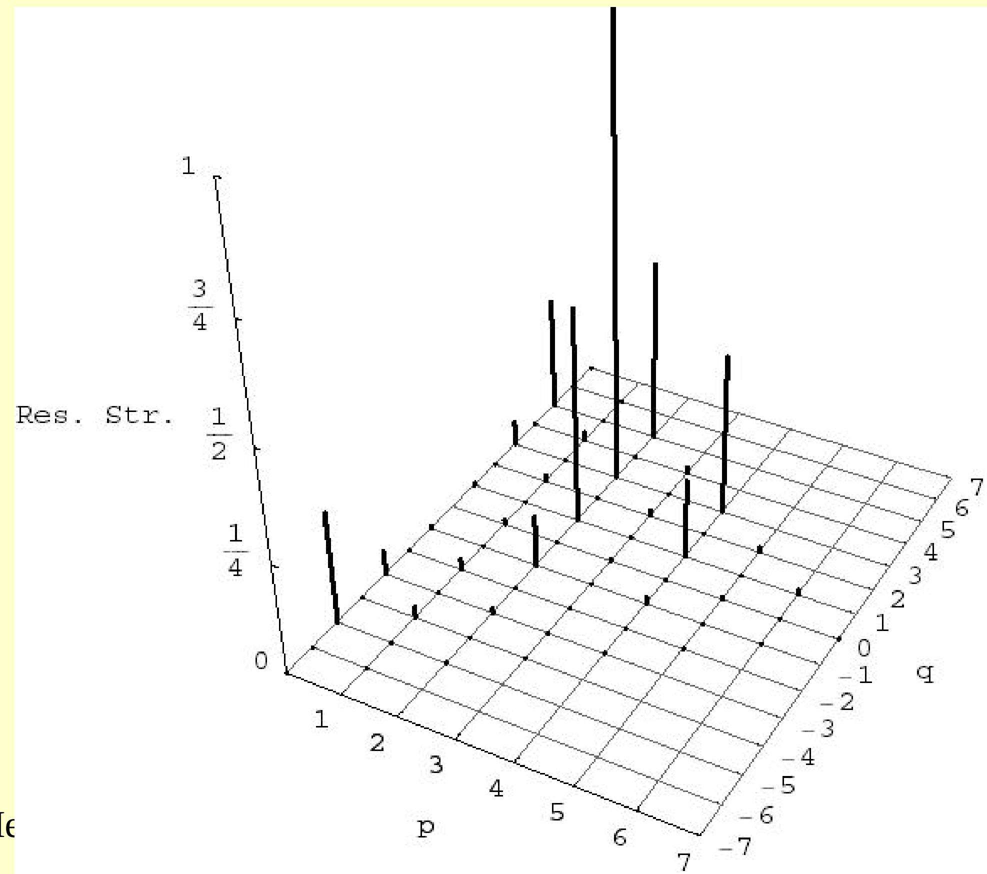
Tune Shift vs Azimuthal position of wire



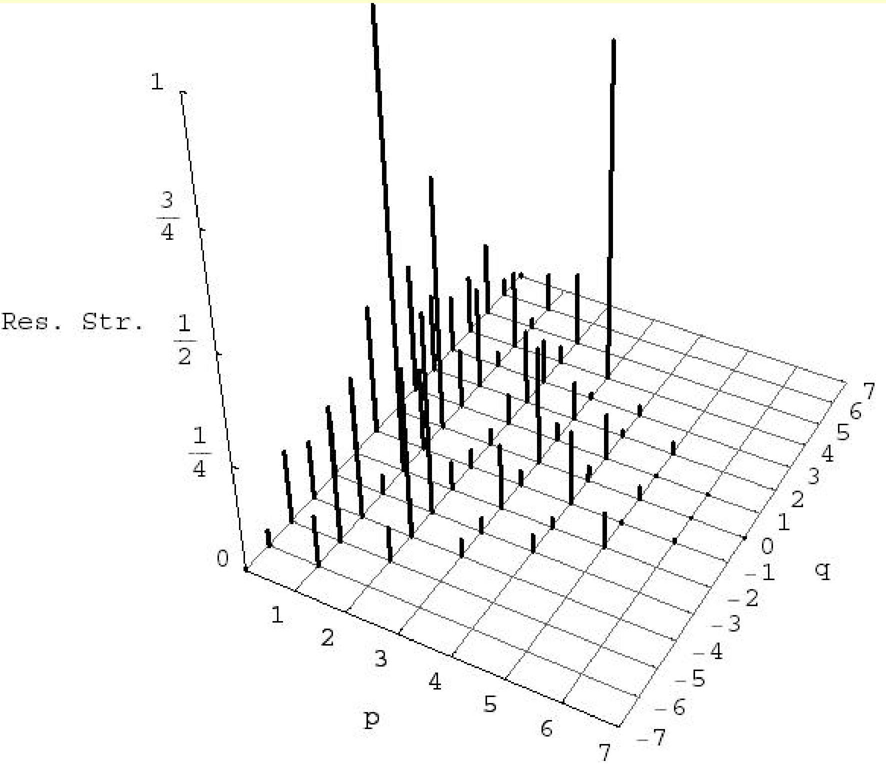
Tune footprint w/wo wire

Resonances vs angle of wire

90 deg



45 deg



Resonance Compensation

Seventh order resonance driving terms in the Hamiltonian

$$U_7 = Re\sum_p \sum_{m_x,m_y;m_x+m_y=7} [U^{7,bb}_{m_x,m_y,p} + U^{7,wire}_{m_x,m_y,p}] e^{i(m_x\nu_x+m_y\nu_y-p)\theta} \quad (1)$$

Wire contribution

$$U^{7,wire}_{m_x,m_y,p} = B_W R \sum_{N=6,8,10,...} \sum_m C_{N,m;m_x,m_y;p} J_x^{m/2} J_y^{(N+1-m)/2} \quad (2)$$

$$C_{N,m;m_x,m_y;p} = (...) \sum_{jw} (b_N, a_N) \beta_x^{m/2} \beta_y^{(N+1-m)/2} e^{i(m_x\psi_x(\theta)+m_y\psi_y(\theta)+p\theta)} \quad (3)$$

$\sum_{N=6,8,10,...}$ includes contributions from main and sub-resonances.

Beam-beam contribution

$$U^{7,bb}_{m_x,m_y,p} = (...) \sum_{j,bb} N_p [\int ...] e^{i(m_x\psi_x(\theta)+m_y\psi_y(\theta)+p\theta)} \quad (4)$$

Dependence on the actions (J_x, J_y) is contained in $[\int ...]$ and does not factor out

$\Rightarrow$ Compensation in principle only works at a specific amplitude

Strategy

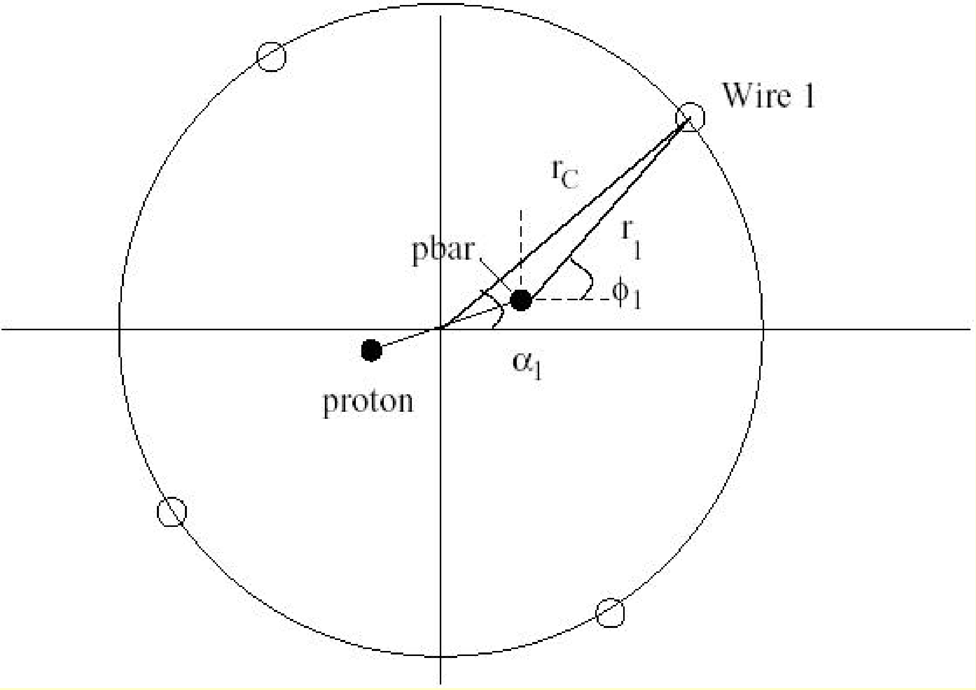
- 1 wire at each location

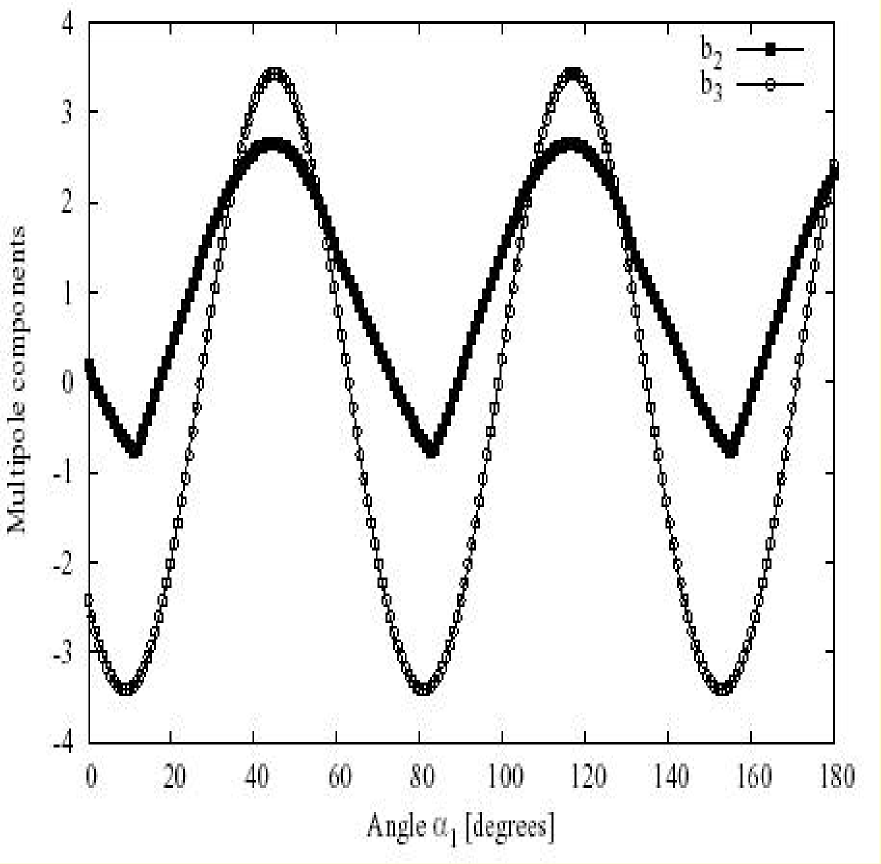
  Compensate the strongest resonances $7\nu_y = p$ and $2\nu_x + 5\nu_y = p$ with $a_6(1), ...a_6(4)$ from the 4 wires. If a solution exists, then at a given radius this determines the azimuthal location and hence the $b_6(1), ..., b_6(4)$.

- Multiple wires at each location

  Solutions may exist if none found in Step 1 or other resonances can be compensated.

Multiple wires at one location





Multipole expansions of wires

Field of several infinitely long wires

$$B_y + iB_x = \frac{\mu_0}{2\pi} I_W \sum_{j=1}^{N_W} \sum_{n=0}^{\infty} [-\cos(n+1)\phi_j + i\sin(n+1)\phi_j] \left[\frac{(x+iy)^n}{r_j^{(n+1)}}\right] \quad (1)$$

$$\begin{aligned} r_j &= [(r_C\cos\alpha_j - r_{\bar p}\cos\theta_{\bar p})^2 + (r_C\sin\alpha_j - r_{\bar p}\sin\theta_{\bar p})^2]^{1/2} \\ \phi_j &= \arctan\left[\frac{(r_C\sin\alpha_j - r_{\bar p}\sin\theta_{\bar p})}{(r_C\cos\alpha_j - r_{\bar p}\cos\theta_{\bar p})}\right] \end{aligned} \quad (2)$$

Usual multipole expansion

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n) \left[\frac{x+iy}{R_{ref}}\right]^n \quad (3)$$

$\Rightarrow$

$$b_n = -\sum_{j=1}^{N_W} \cos(n+1)\phi_j \left[\frac{\langle r_W\rangle}{r_j}\right]^{n+1}, \quad a_n = \sum_{j=1}^{N_W} \sin(n+1)\phi_j \left[\frac{\langle r_W\rangle}{r_j}\right]^{n+1} \quad (4)$$

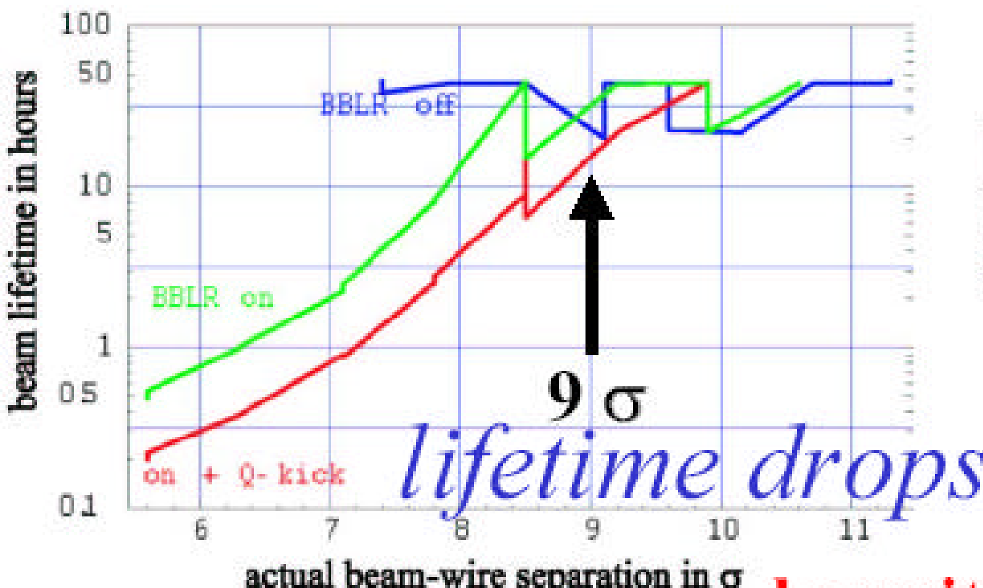
where the main field B_0 and reference radius are

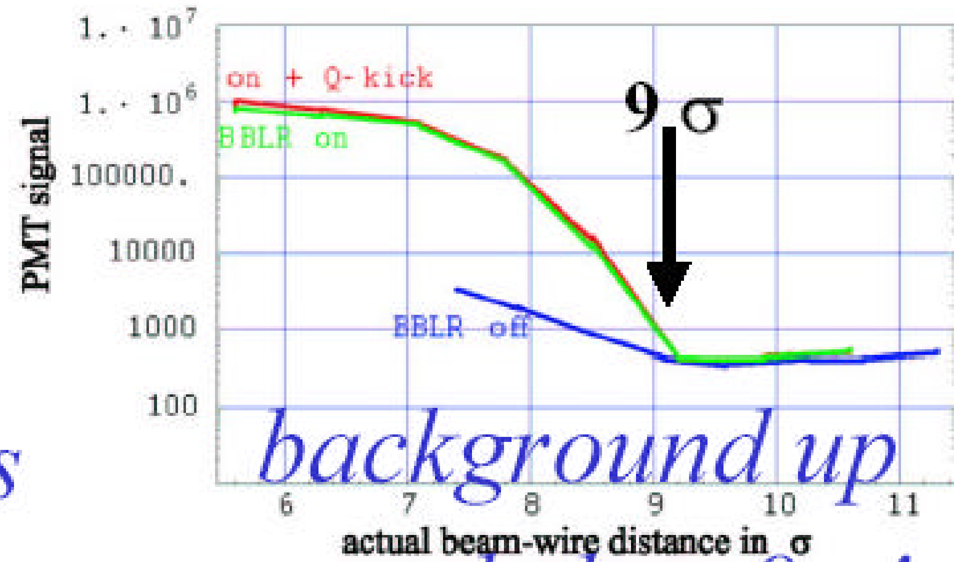
$$B_0 = \frac{\mu_0}{2\pi}\frac{I_W}{\langle r_W\rangle} \quad (5)$$

$$R_{ref} = \langle r_W\rangle = \frac{1}{N_W}\sum_j r_j \quad (6)$$

Each wire creates normal and skew multipoles to all orders.

preliminary evidence for diffusion vs. beam-wire distance in SPS

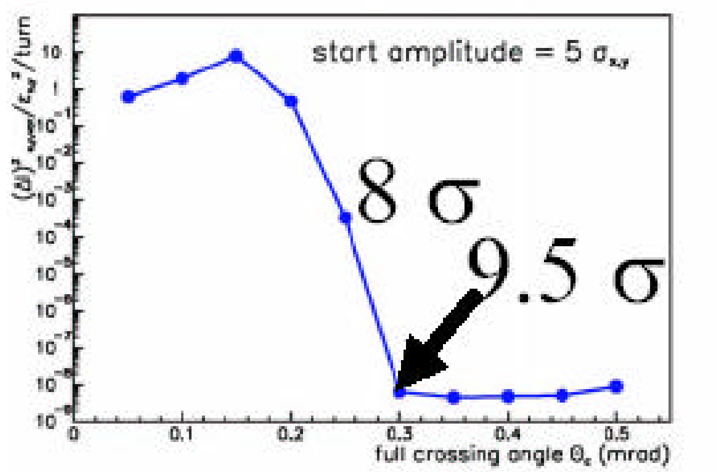




logarithmic scales! *below 9σ!*

F. Zimmermann

compare with LHC simulation:



SPS Wire Parameters

J.P. Koutchouk

Materials	Cu OFHC, Al_2O_3, stainless steel	m
Active length	2* 0.6	m
Outer/Inner diameters	2.54 (r=1.25σ)/1.54	mm
Intensity	0 to 267	A
Current density	81	A/mm^2
Power	760	W
Water flow	0.36	l/mn
Pressure drop	2.5	bar
Max Pressure	4+2.5=6.5	bar
Pressure of service	60	bar

SPS Wire Design

J. Kerby

Recent tests w/ Single Wire in SPS successful

(the proposed 'next step design from CERN shown here)

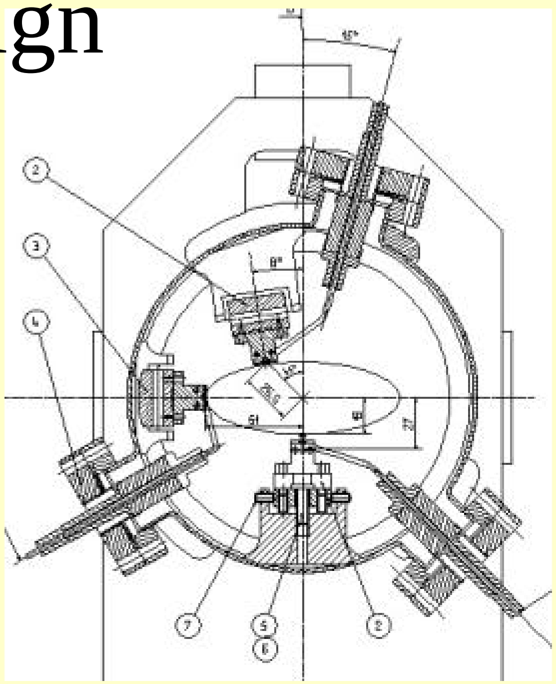
For further optimization effort is needed on:

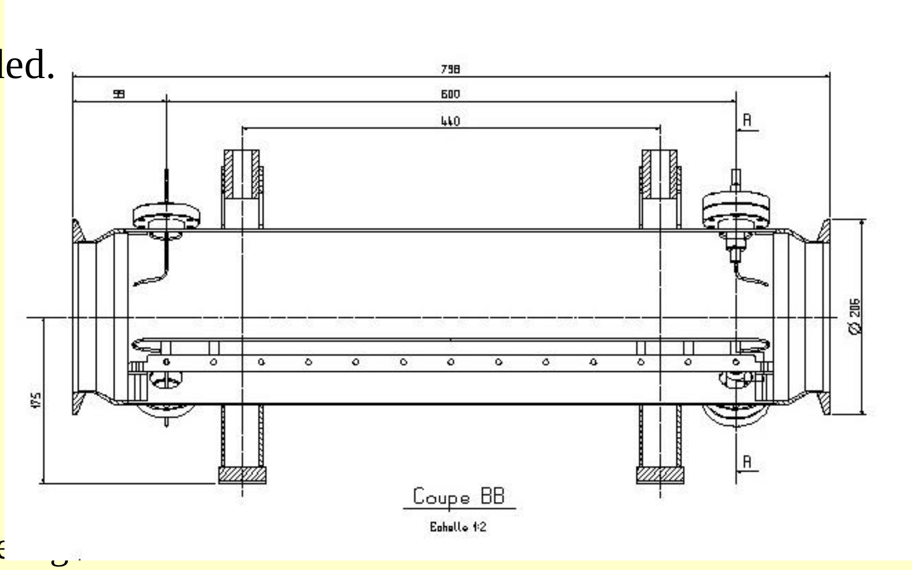
•Mechanical design, overall size, number of wires, and interfaces w/ remainder of machine

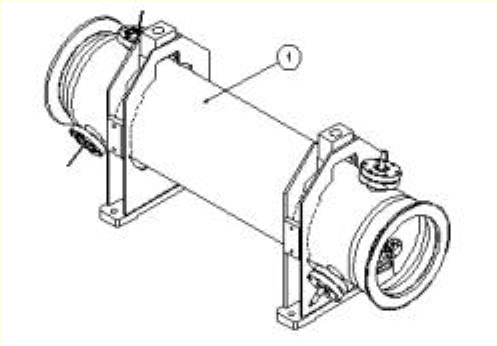
•RF / impedance matching

•Possibly cooling, though SPS unit (water cooled) was successful

•Investigation of moveable wire systems, as needed.





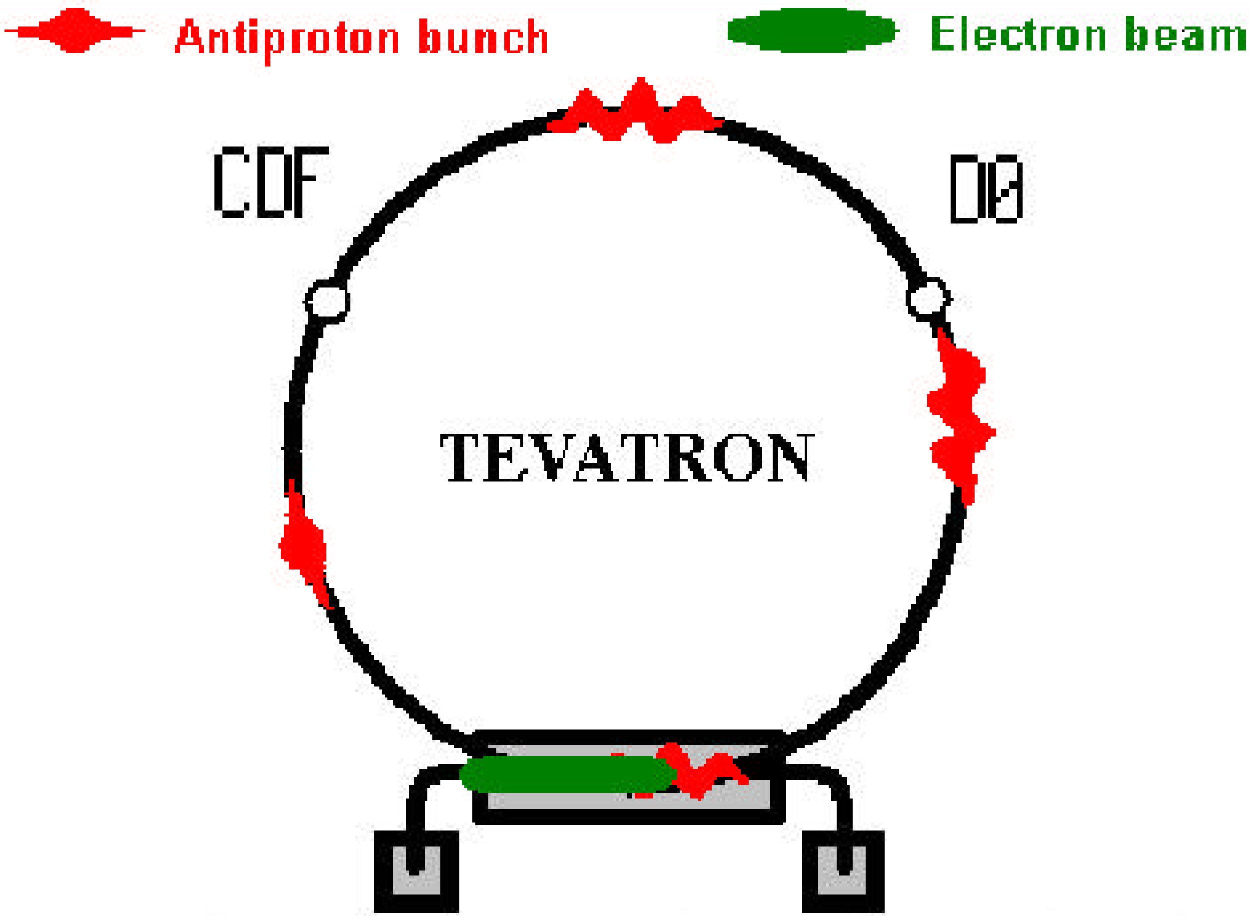


Tevatron Wire Summary

- With 1 wire at each location, tune shifts and resonances depend sensitively on the azimuthal position of wires.
- 1 wire at each location cannot compensate the main 7th order resonances
- Robust compensation and need to adapt to changes in the helix require multiple wires

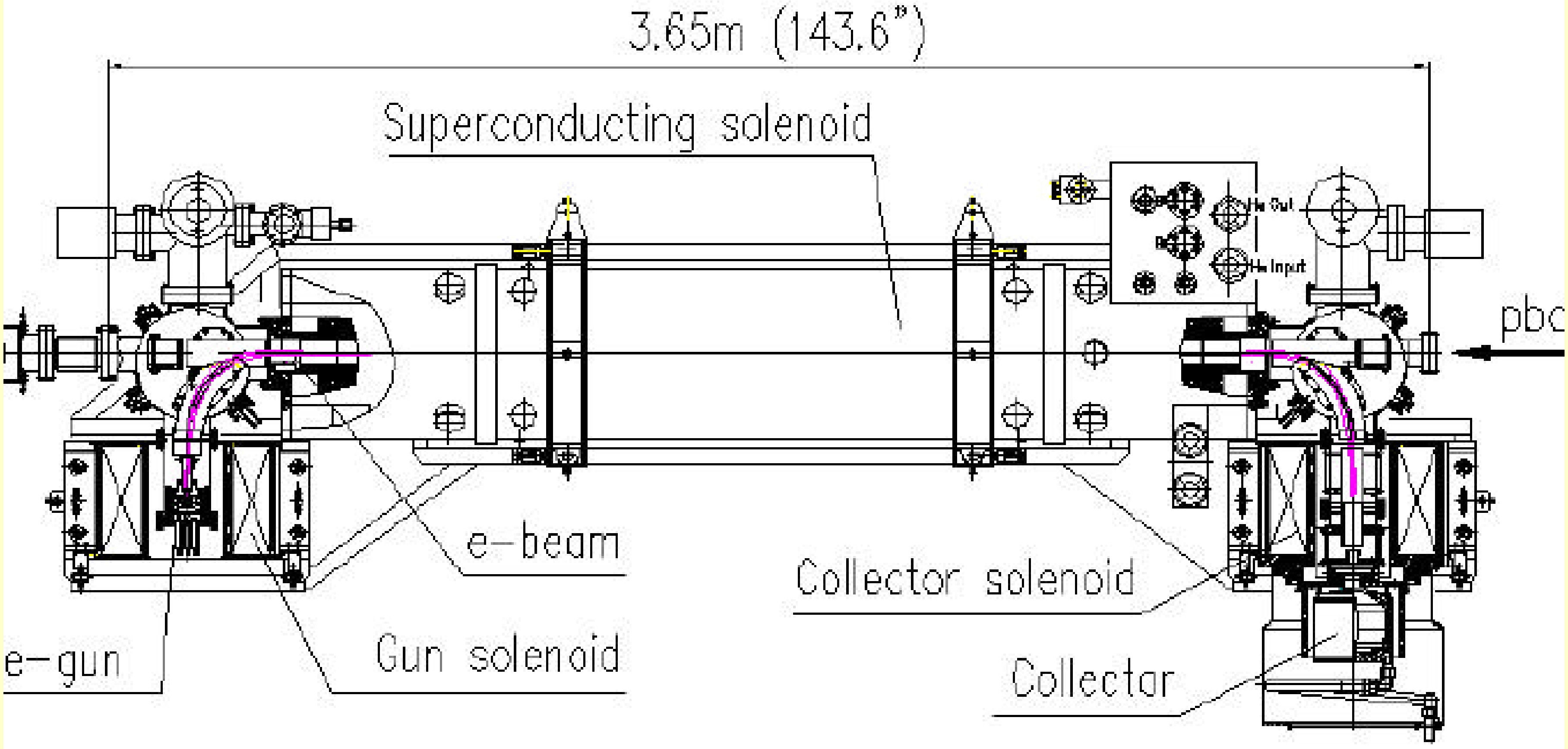
  Exact number to be determined by beam physics and engineering constraints.
- Studies in progress to determine if multi-wire compensation works in principle.

Original Idea Was…

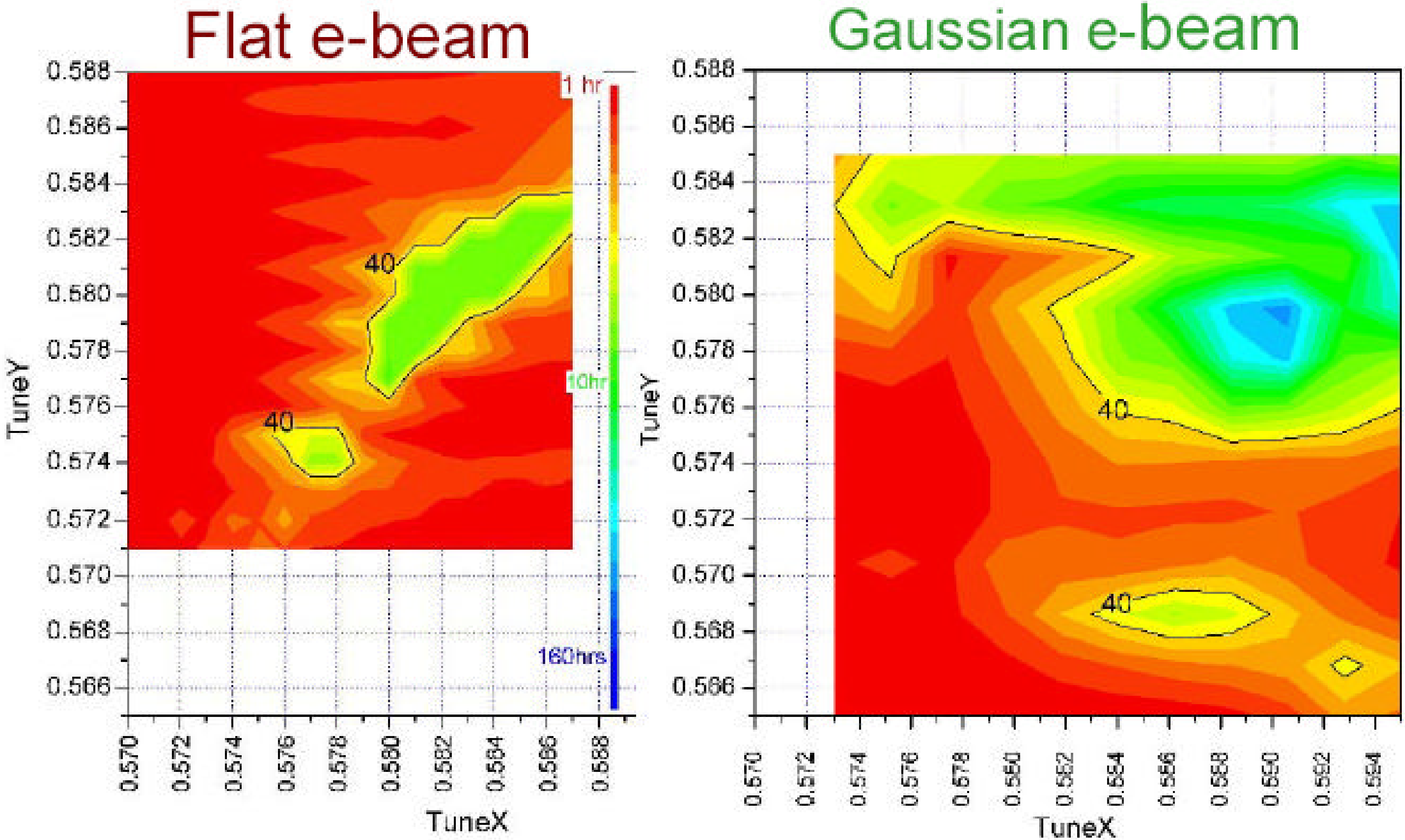


"…to compensate (in average) space charge forces of positevely charged protons acting on antiprotons in the Tevatron by interaction with a negative charge of a low energy high-current electron beam " (1997)

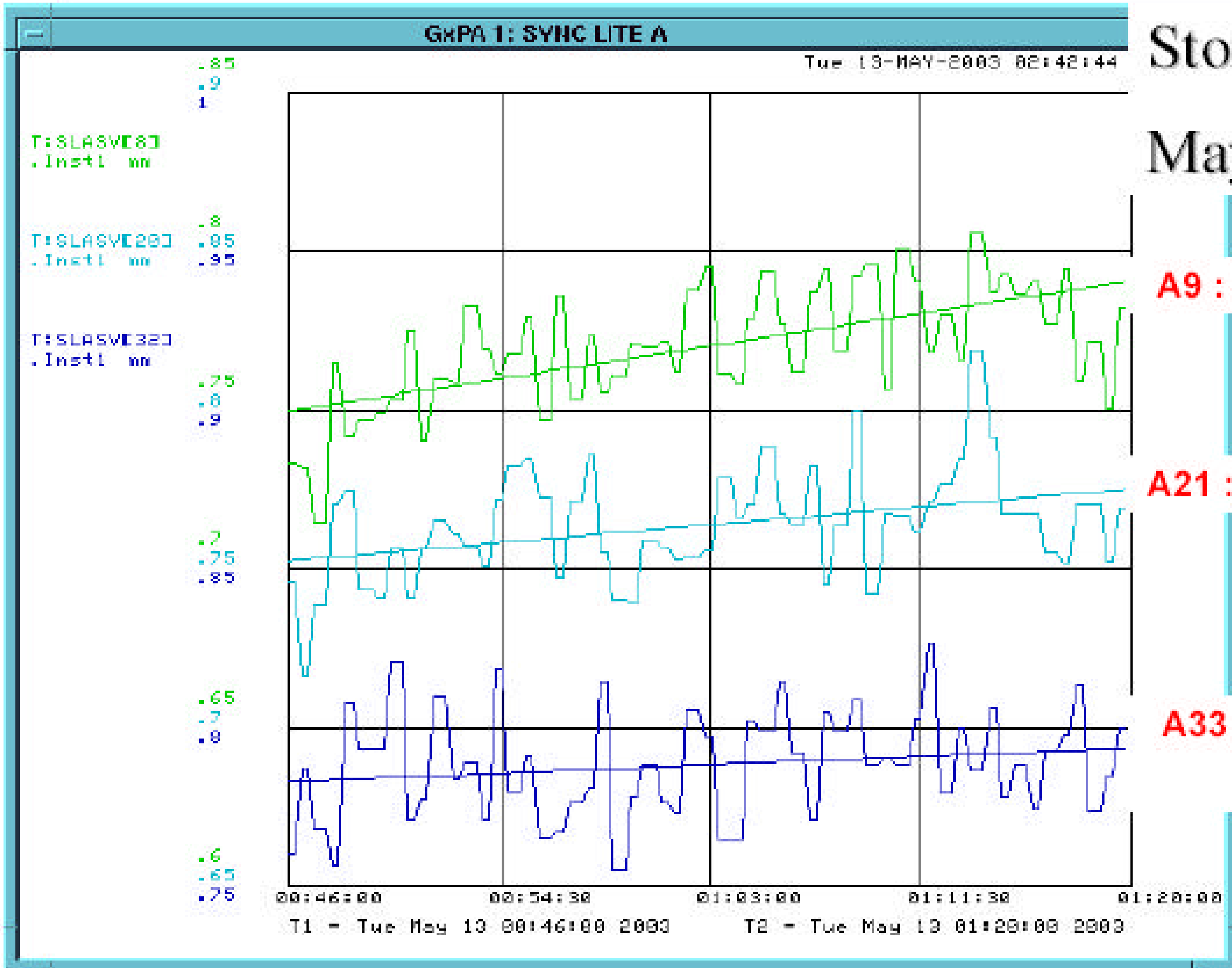
TEL-1: installed Mar.1, 2001



Lifetime vs WP with dQ_{TEL}~0.004



Pbar V-Sizes 34 min after p-pbar collisions initiated



Store #2540

May 12, '03

A9 : 4.1 • •mm mrad/hr

A21 : 2.2 • •mm mrad/hr

A33 : 1 • •mm mrad/hr

-TEL on it

TEL Summary

- Status:
  - max dQ~0.009 tuneshift achieved
  - p(bar) lifetime deterioration proved to be due non-linear beam-beam force due to e-beam edges ("soft collimator")
  - after installation of Gaussian e-gun, p-beam lifetime of ~160hrs has been achieved (compare with 40 hrs in stores)
  - TEL was used in several stores recently and we've got first indications of successful beam-beam compensation : vertical emittance growth rate was reduced for pbar bunch #33 early in store #2540
- Work to do:
  - continue to explore BBC at 150, ramp, LB for both pbar and p
  - improve diagnostics (TEL BPM, Pbar Schottky tunemeter, etc)
  - wider e-beam
  - better beam current and position stabilization
  - the second TEL is under construction but the BBC is not the major motivation (← spare for the DC beam removal)
  - new HV pulser (~ 15kV instead of 7kV, shorter pulse)