Beam Optics for Parity Experiments

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Electron beam optics in the injector, accelerator, and transport lines to the experimental halls has a significant impact on helicity-correlated beam properties observed in parity-violation experiments.

Efforts are underway in the accelerator division at Jefferson Lab to optimize electron beam transport for parity experiments. The work is still in progress, but the developments could play an important role in achieving helicity-correlated beam parameter goals for upcoming experiments.

Helicity-correlated position/angle requirements at JLAB

Experiment	Date	Run averaged HC position difference	Run averaged HC angle difference
G^0	2/04-5/04	< 20 nm	< 2 nrad
HAPPEX II/He	6/04	< 2 nm	< 2 nrad

- G^0 achieved these specifications in its recent run using intensity and position feedback devices on the laser table
- HAPPEX may benefit from improvements in "adiabatic damping" and the newly developed "phase trombone"
- Future experiments will have somewhat more stringent requirements, so continued work on the accelerator side will be important in addition to the laser efforts (Pockels cell work, feedback, improved GaAs "analyzing powers")

Introduction to Linear Beam Optics

Linear beam optics: describes motion of beam particles in the vicinity of the nominal beam trajectory

Assumptions:

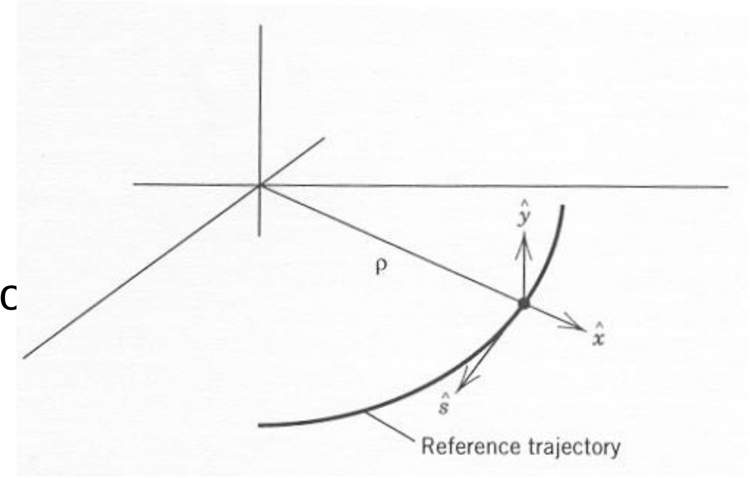
- Particle motions are paraxial (inclination angles are small)
- Magnetic restoring forces are
  - constant (dipole for beam steering)
  - linearly increasing with displacement from ideal trajectory (quadrupole for beam focusing)

Particle orbits described by vector:

$$\mathbf{x} = [x, x', y, y']$$

where x, y $=$ displacement from nominal trajectory

x', y' $=$ inclination angles relative to nominal trajecto



Introduction to Linear Beam Optics, continued

Linear equations of motion for particle traveling through magnetic structure of accelerator:

$$\boxed{\begin{aligned} x''(s) + \left(\frac{1}{R^2(s)} - k(s) \right) x(s) &= 0 \\ y''(s) + k(s)\, y(s) &= 0 \end{aligned}}$$

$$\text{where } \frac{1}{R} = \frac{e}{p} B_{y0} \quad \text{(dipole, beam steering)}$$

$$k = \frac{e}{p} \frac{dB_y}{dx} \quad \text{(quadrupole)}$$

Both equations are of the form:

$$\boxed{\begin{gathered} x''(s) + K(s)\, x(s) \;=\; 0 \\ \text{(Hill's equation of motion)} \end{gathered}}$$

Introduction to Linear Beam Optics, continued

Solution for transverse oscillation about nominal orbit:
"betatron oscillation":

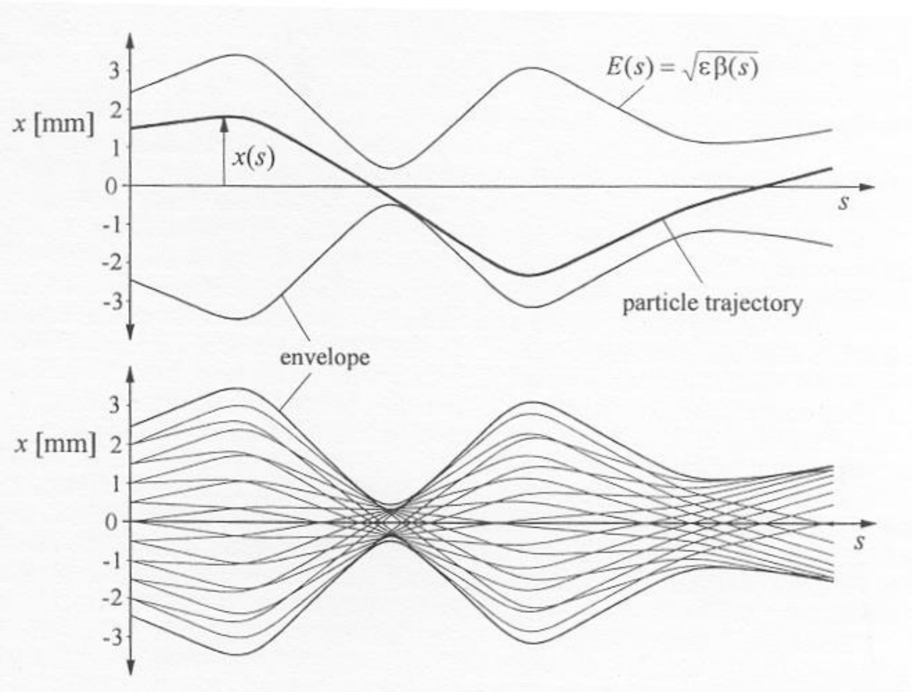
$$\boxed{x(s) \quad = \quad \sqrt{\varepsilon}\ \sqrt{\beta(s)}\ \cos[\Psi(s)+\phi]}$$

where ε = emittance

$\beta(s)$ = beta function (or amplitude function)

$\Psi(s)$ = betatron phase advance $= \int_0^s \frac{d\sigma}{\beta(\sigma)}$

ϕ = launch phase

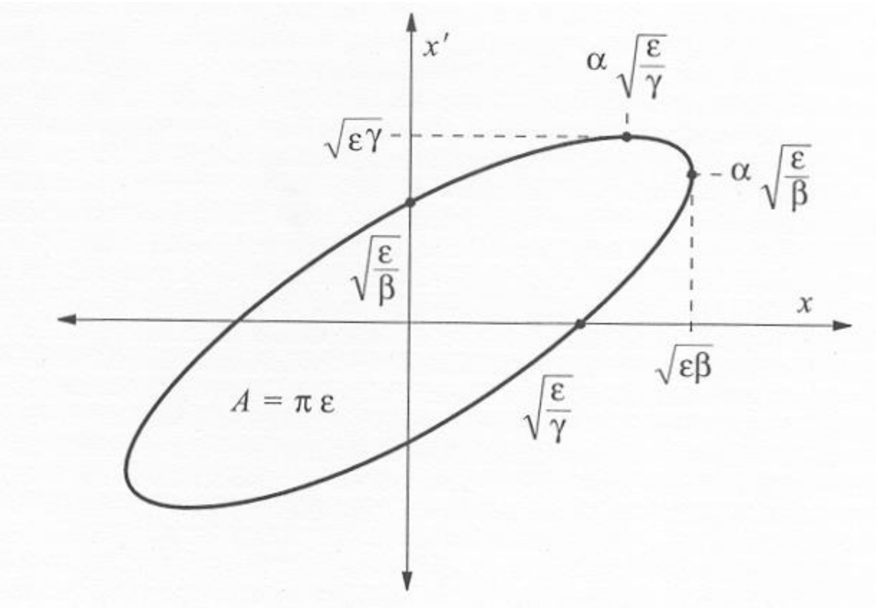


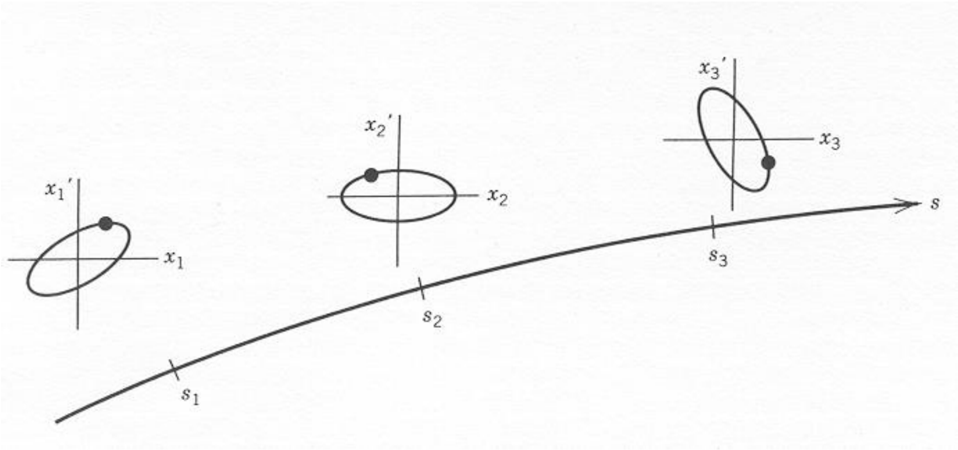
Phase Space Ellipse Description of Particle Motion

The solutions for x and x' can be combined in the equation of the "phase-space" ellipse in the x - x' plane:

$$\boxed{\gamma(s)\, x^2(s) + 2\,\alpha(s)\, x(s)\, x'(s) + \beta(s)\, x'^2\,(s) = \varepsilon}$$

where α, β, γ are the Twiss parameters





Adiabatic Damping of Betatron Oscillations

In the case where the particle momentum is a slowly varying function of longitudinal position in accelerator, we have:

$$x''(s)+\left(\frac{p'}{p}\right)x'(s)+K(s)\,x(s)=0$$

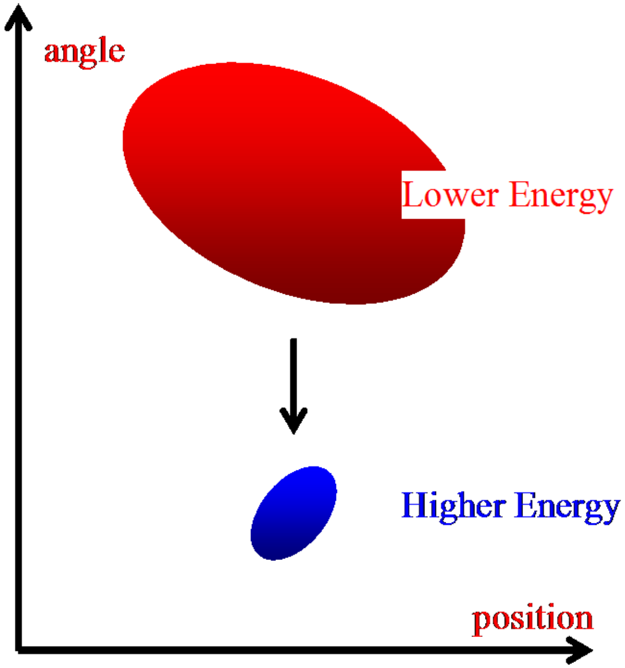
$$x(s)\quad=\quad\sqrt{\varepsilon}\;\sqrt{\beta(s)}\left(\frac{p_0}{p}\right)^{1/2}\cos\left[\Psi(s)+\phi\right]$$

→ Amplitude of betatron oscillation is damped as the beam energy is adiabatically increased

From injection energy = 100 keV
to typical hall energy ~ 3 GeV,

maximum expected adiabatic damping →

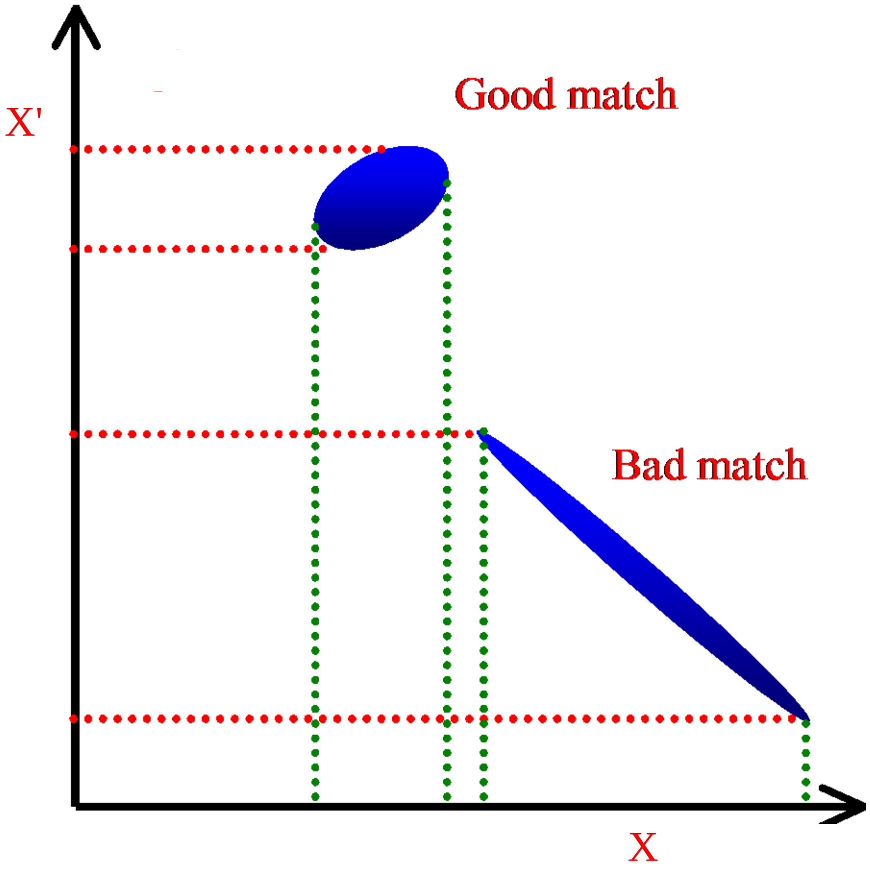
$$\sqrt{\frac{3\,\mathrm{GeV}}{335\,\mathrm{keV}}}\approx 95$$

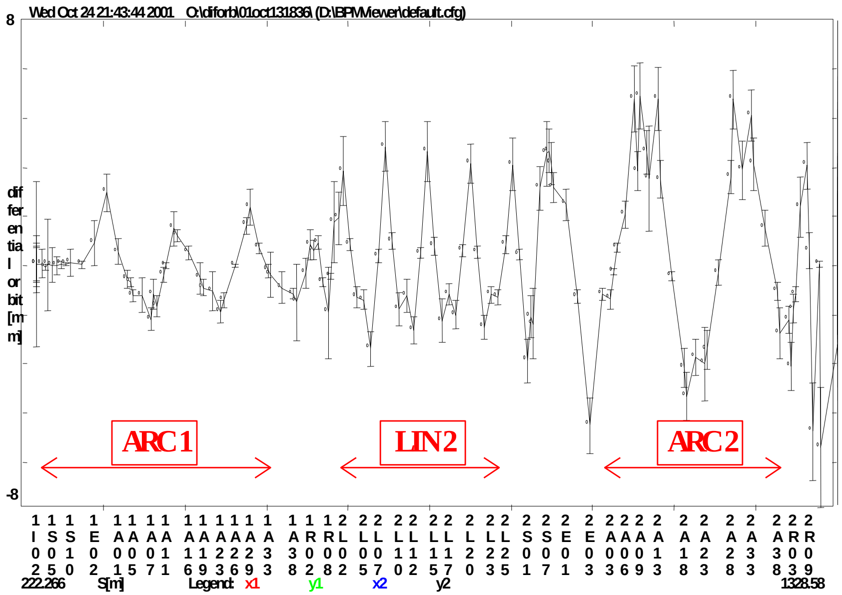


What could go wrong? go wrong? go wrong? go wrong?

Full adiabatic damping is usually not achieved because of:

- Mismatched beamline (not "betatron" matched)
  - due to deviations in magnetic elements from design
  - unaccounted for focusing forces from rf couplers at cavities (important at low beam energies in injector)



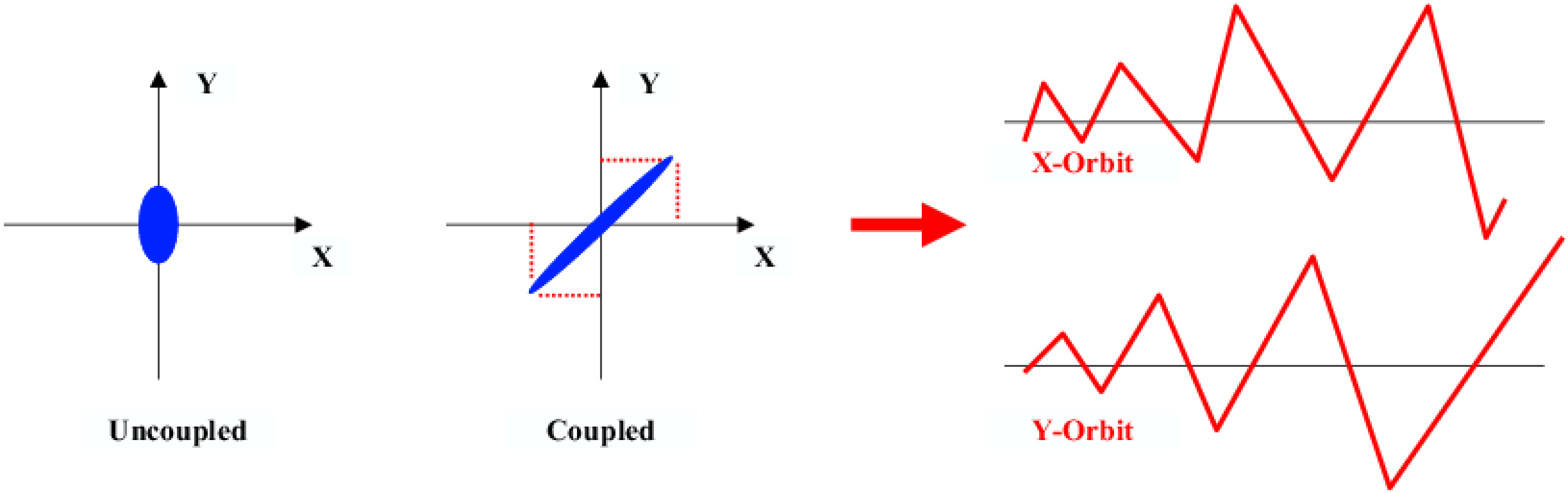


go wrong? go wrong? go wrong? go wrong?

Imperfect Adiabatic Damping, continued

X-Y coupling can also cause phase-space ellipse "stretching" and resulting orbit "blow-up". Caused by:

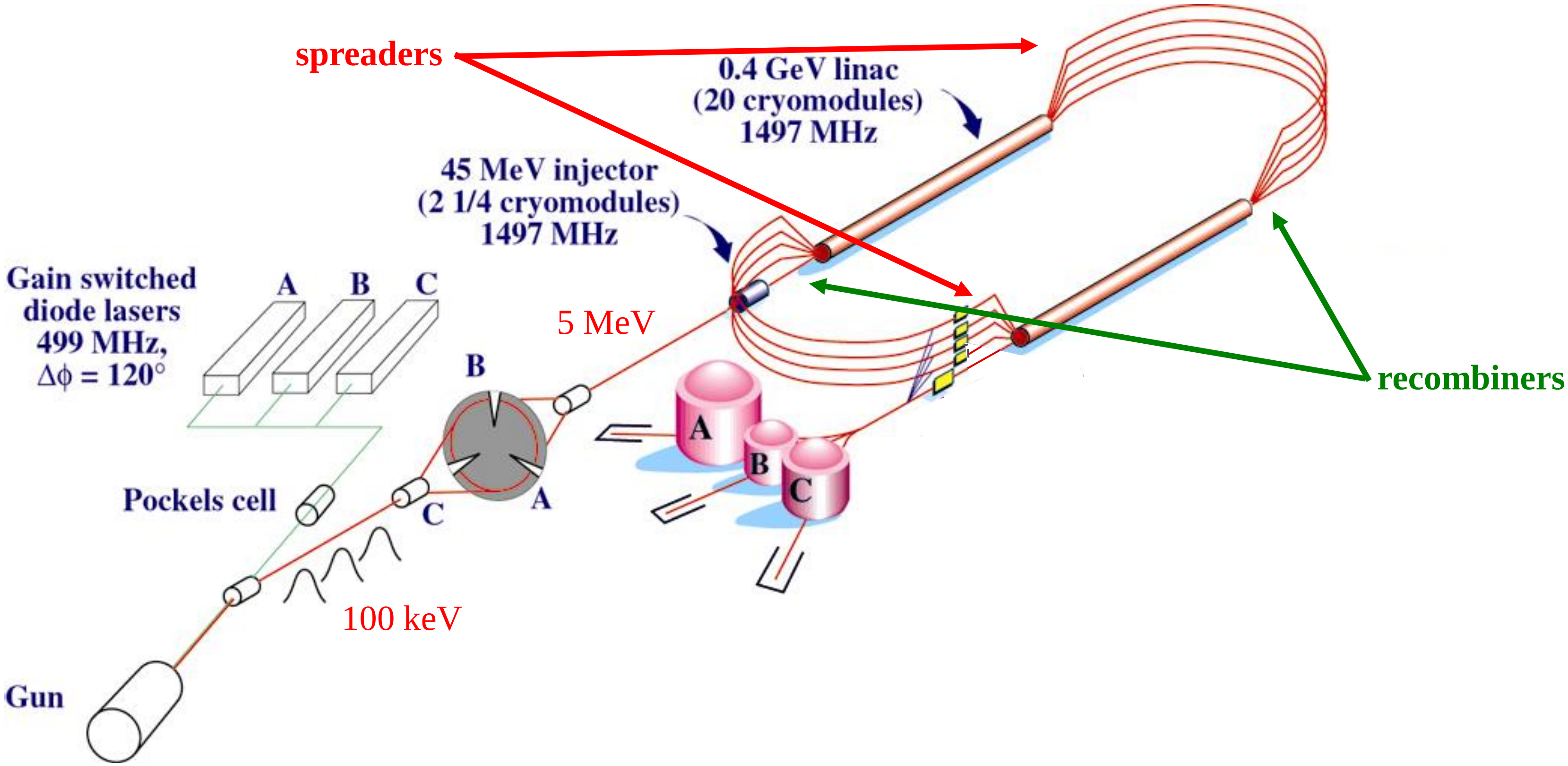
- Rotated (skew) quadrupoles (due to unintentional misalignments)
- rf couplers at cavities (important in the linacs)



Note: (deliberate) skew quads can be used to correct for X-Y couplings and linear magnetic imperfections

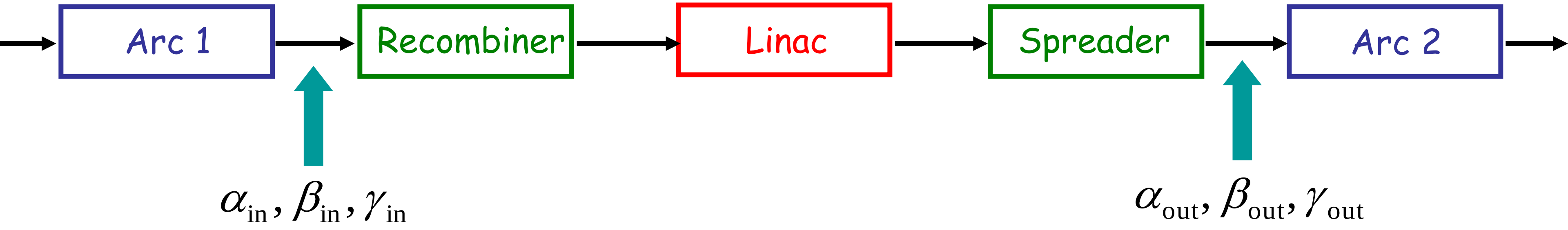
- Skew quads are currently installed in the linacs and are being installed in the injector

CEBAF Accelerator



Both HAPPEX and G^0 have capability to readout and do helicity-correlated analysis on beam positions using BPMs at:
100 keV, 5 MeV, 45 MeV, and in their respective arcs and halls.

Betatron Matching Procedure in CEBAF



Arc 1
Recombiner
Linac
Spreader
Arc 2

$\alpha_{\text{in}}, \beta_{\text{in}}, \gamma_{\text{in}}$

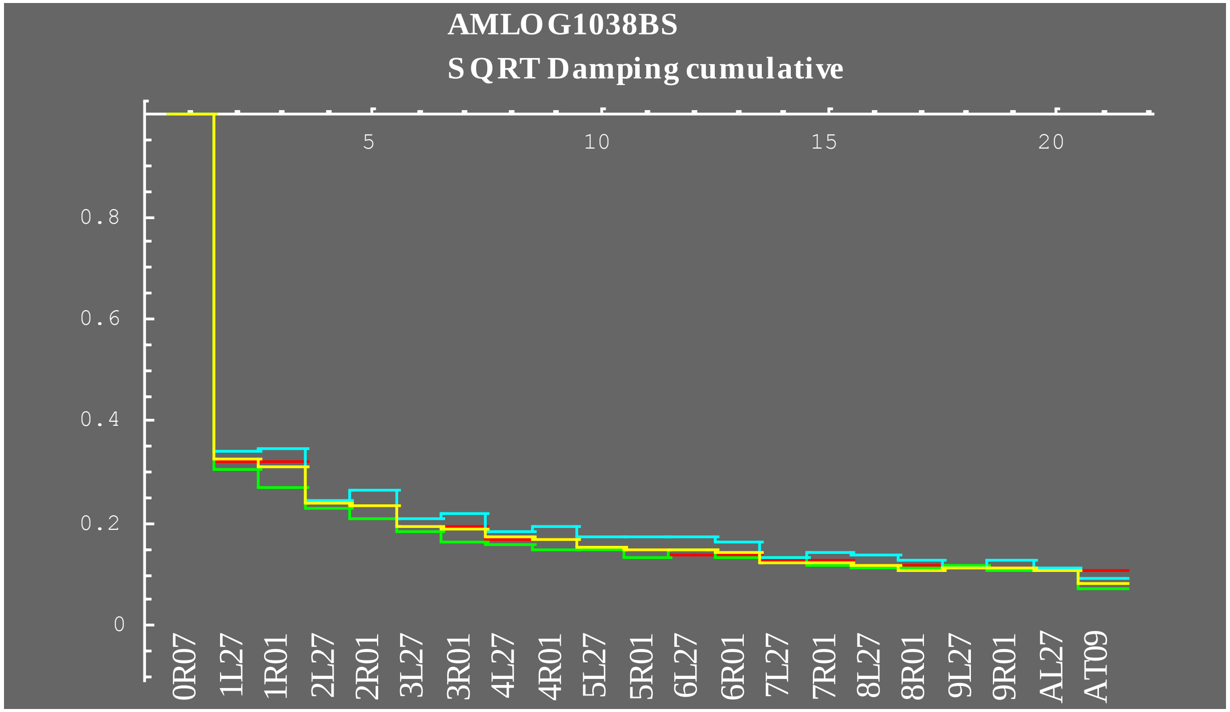
$\alpha_{\text{out}}, \beta_{\text{out}}, \gamma_{\text{out}}$

There is a standard working procedure developed by Yu-Chiu Chao for matching from 45 MeV to high energy.

1. For each pass through the Linac, acquire difference orbit data (FOPT)
2. Interpret the difference orbit data using the well-modeled arcs to extract the TWISS parameters at the input and output of the mismatched sections.
3. Adjust quadrupole magnets in the recombiner and spreader regions to force the outgoing TWISS functions to match the design (assuming the incoming TWISS functions are at the design value)
4. Follow this procedure pass by pass to ensure that the TWISS parameters at the exit of the machine match the design.

This procedure uses a few quadrupole magnets to correct for all cumulative errors in a given pass.

Results From the Betatron Matching Procedure



Measured amplitude damping (01/31/03)

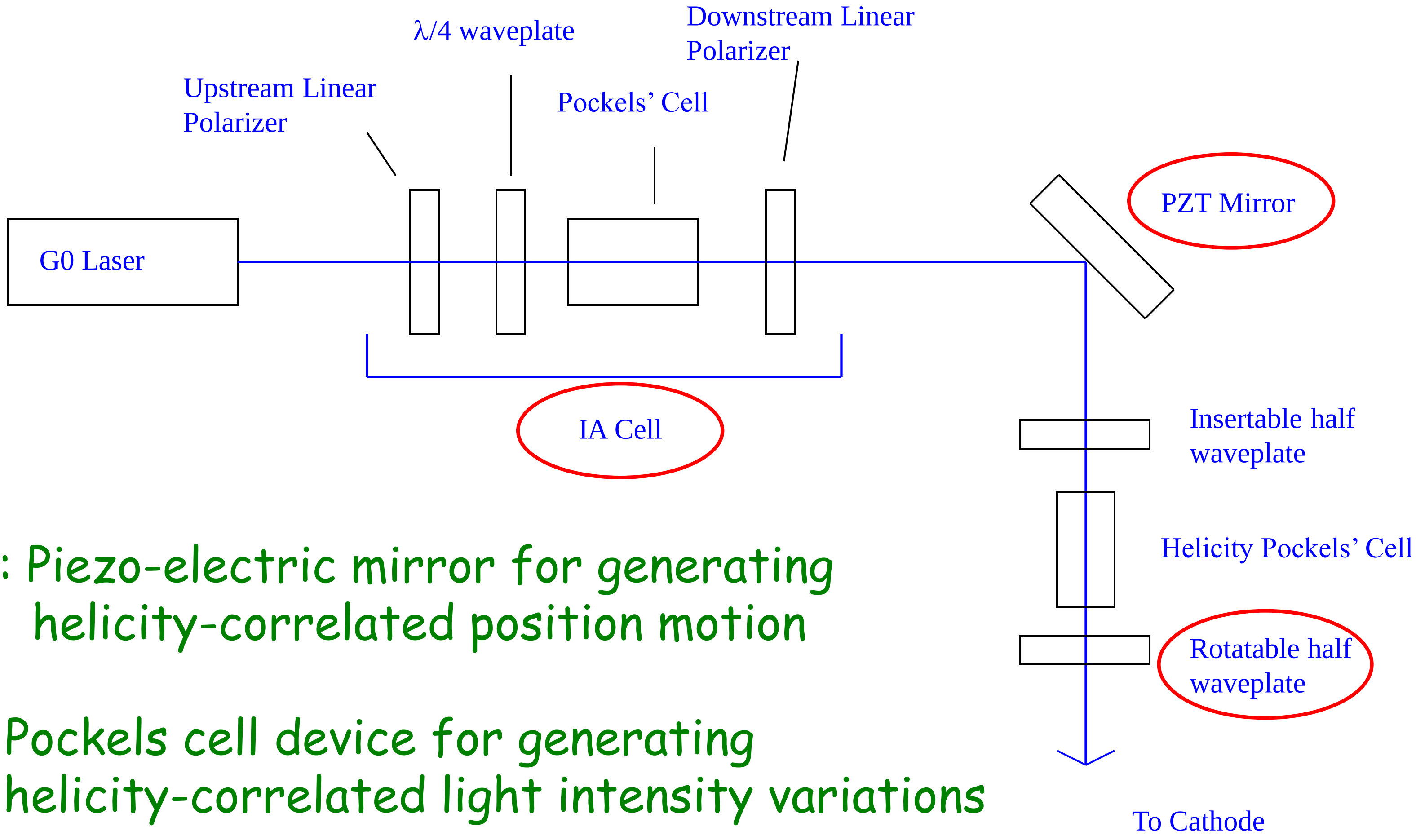
from 55 MeV to 5 GeV

red: theory
yellow: measured

Observed damping agrees with expectation →

$$\boxed{\sqrt{\frac{5\,\mathrm{GeV}}{55\,\mathrm{MeV}}} \approx 9.5}$$

Laser Table Devices used for Helicity-Correlation Control

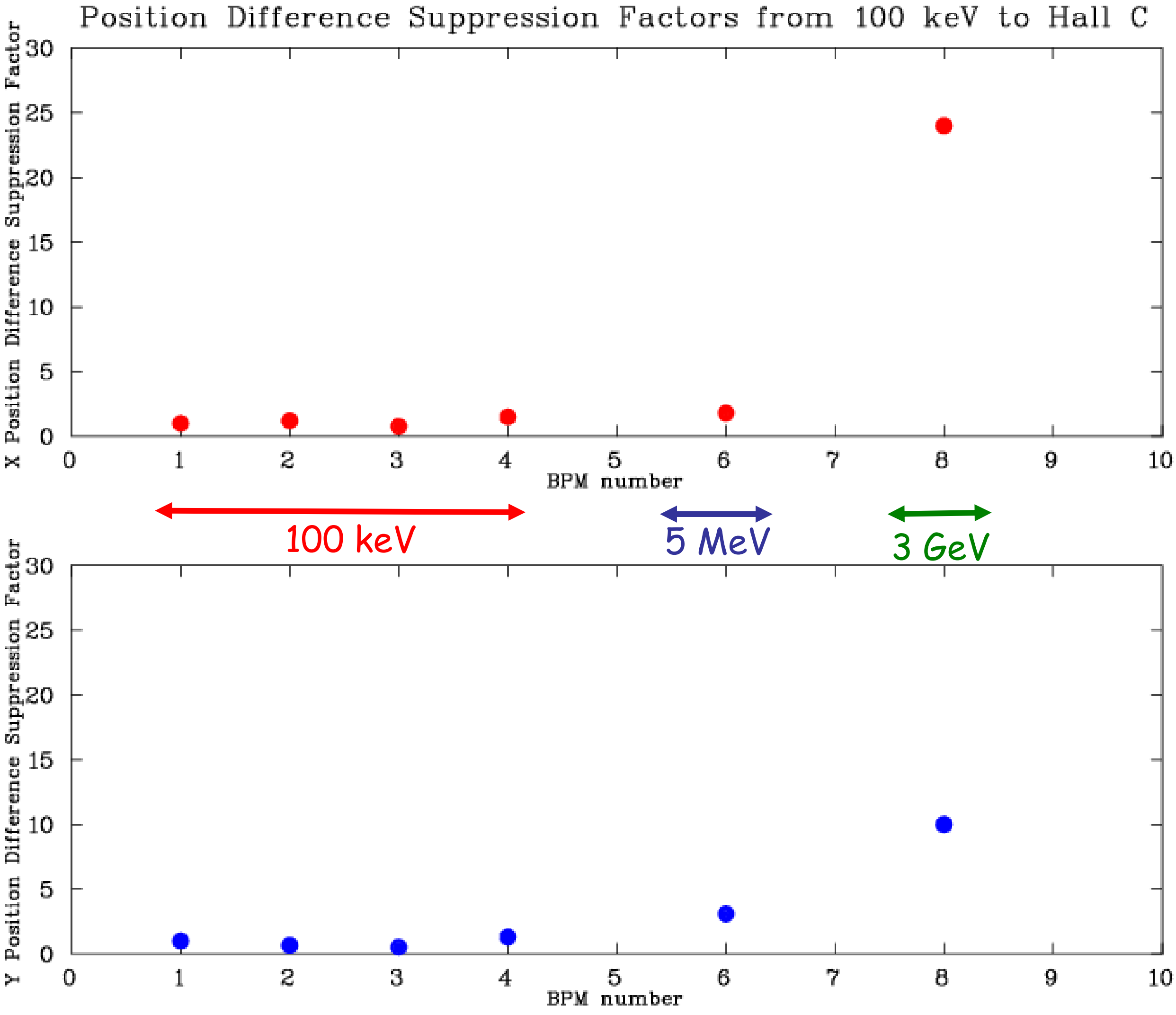


1. PZT: Piezo-electric mirror for generating helicity-correlated position motion

2. IA: Pockels cell device for generating helicity-correlated light intensity variations

3. RHWP: rotating half-wave plate for minimizing intensity and position differences resulting from interaction of imperfectly polarized laser light with strained GaAs crystal

G^0 results on "adiabatic damping" from PZT scans



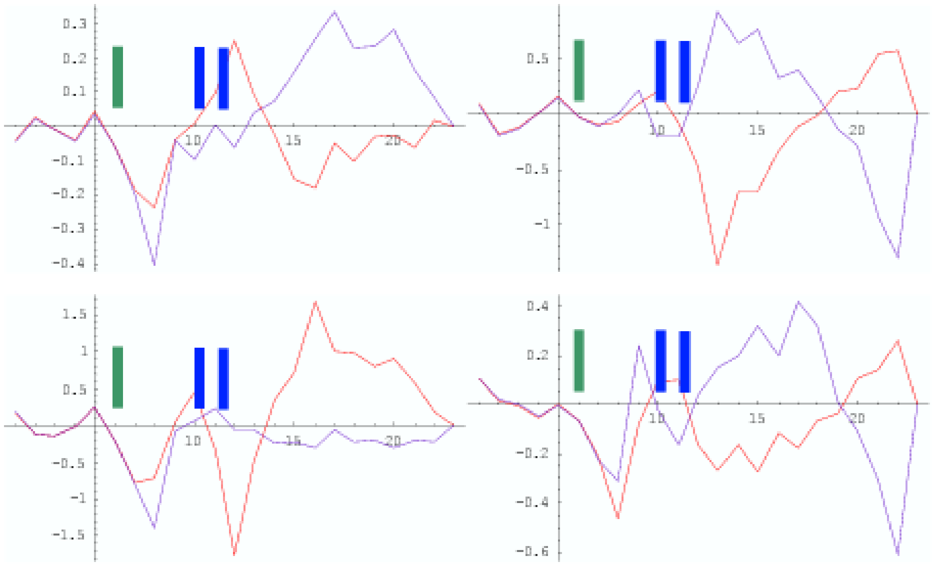
Total observed damping from 100 keV to 3 GeV:
x ~ 24, y~ 10
Most of damping comes from 5 MeV → 3 GeV region

Prospects for Improvement on Adiabatic Damping in Injector

Adiabatic damping from 60 MeV → 3 GeV appears okay;
missing damping is in the injector region (100 keV → 60 MeV)

Recent work (Y. Chao) has used the "30 Hz PZT" to look at difference orbits in the CEBAF injector.

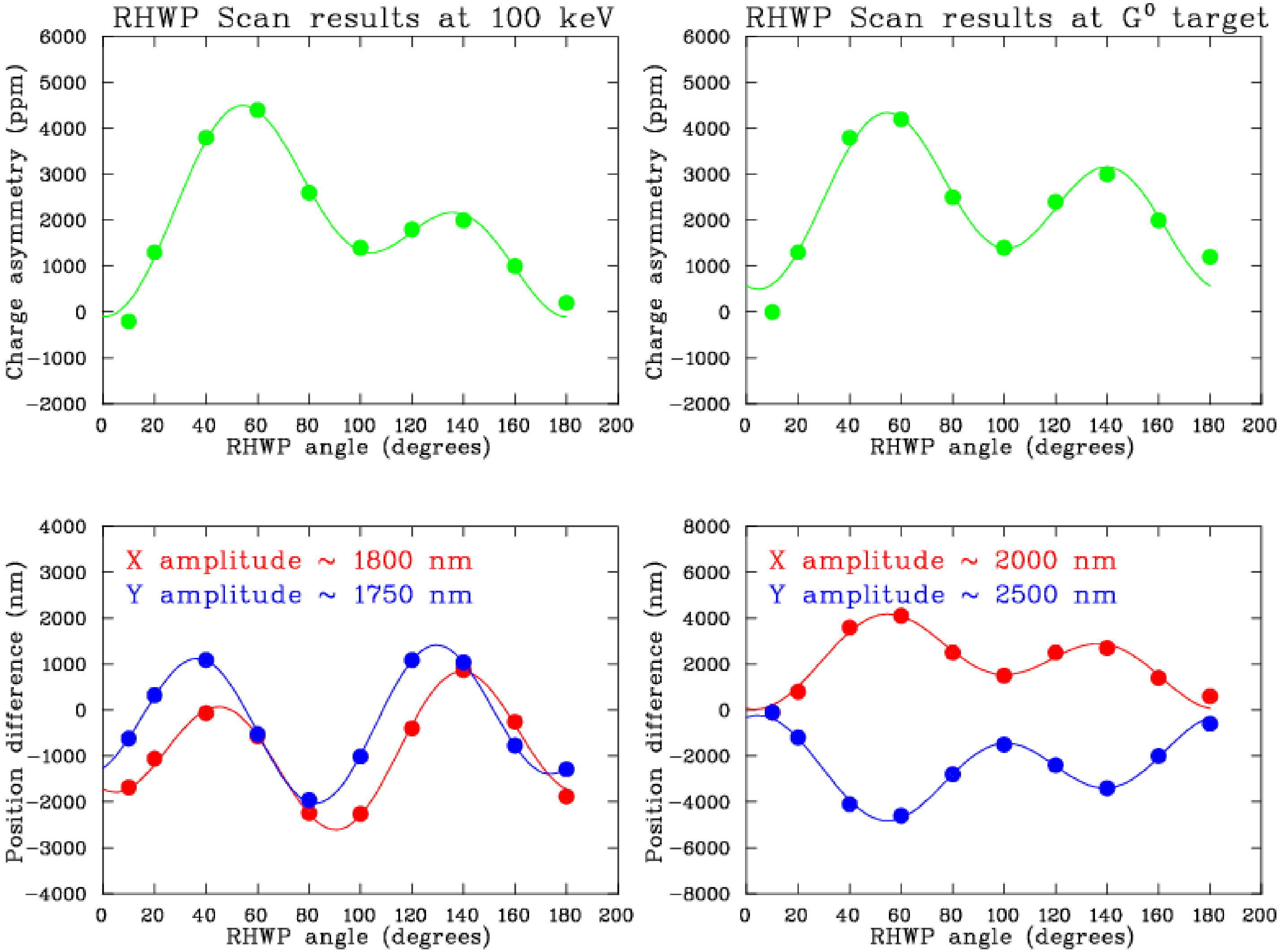
PZT orbits (spot displacement on cathode) in the Injector (times $\sqrt{P}$)



Green: Cryo-Unit **Blue: Cryo-Modules**

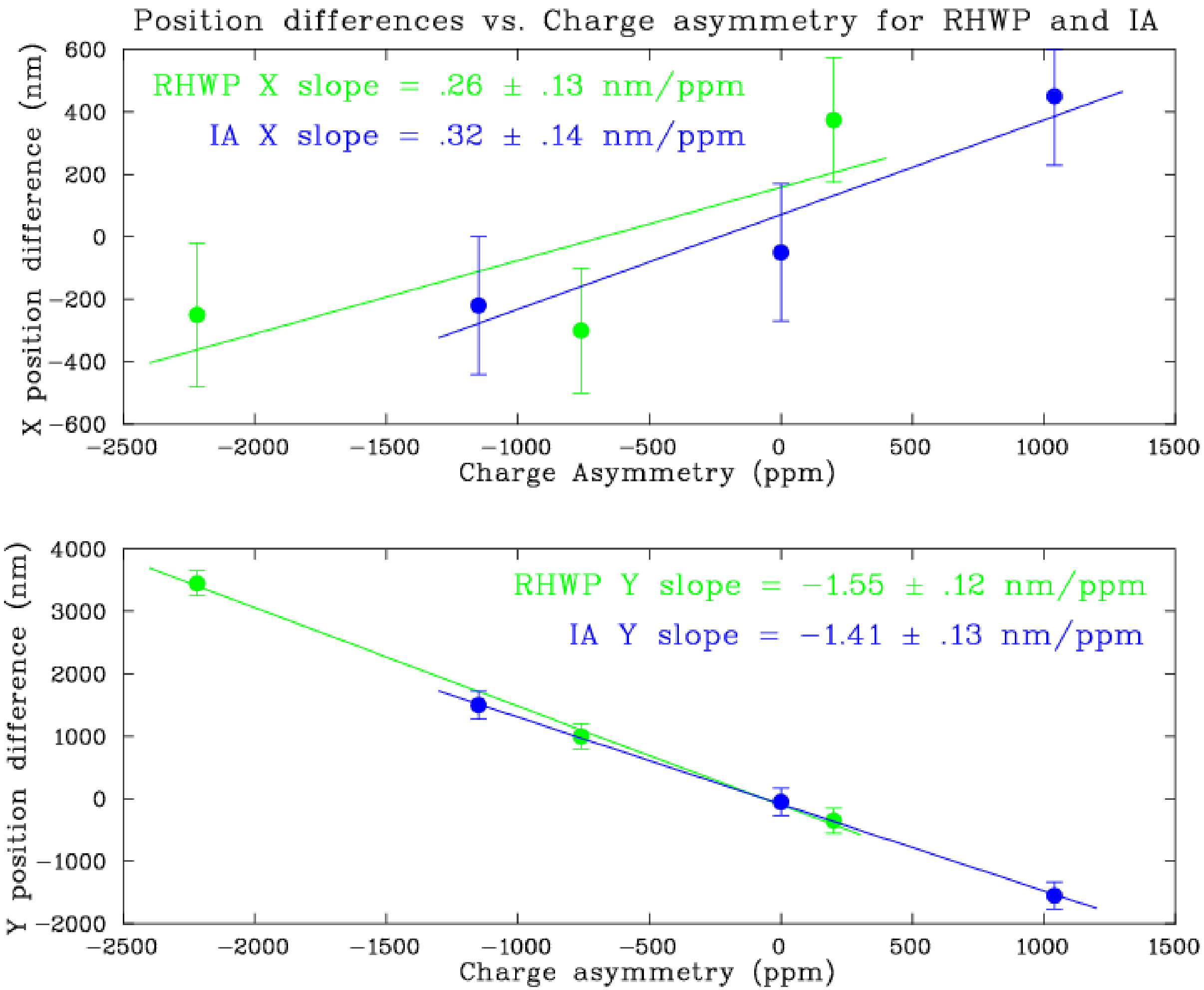
Conclusion: Adiabatic damping is in fact happening in the injector; the apparent large position amplitudes are coming from "orbit blow-up" due to betatron mismatches at the accelerating cavities. The mismatches are due to unaccounted for focusing from the rf couplers on the cavities.
A solution is being implemented with skew quads for compensation.

G^0 results on "adiabatic damping" from RHWP scan



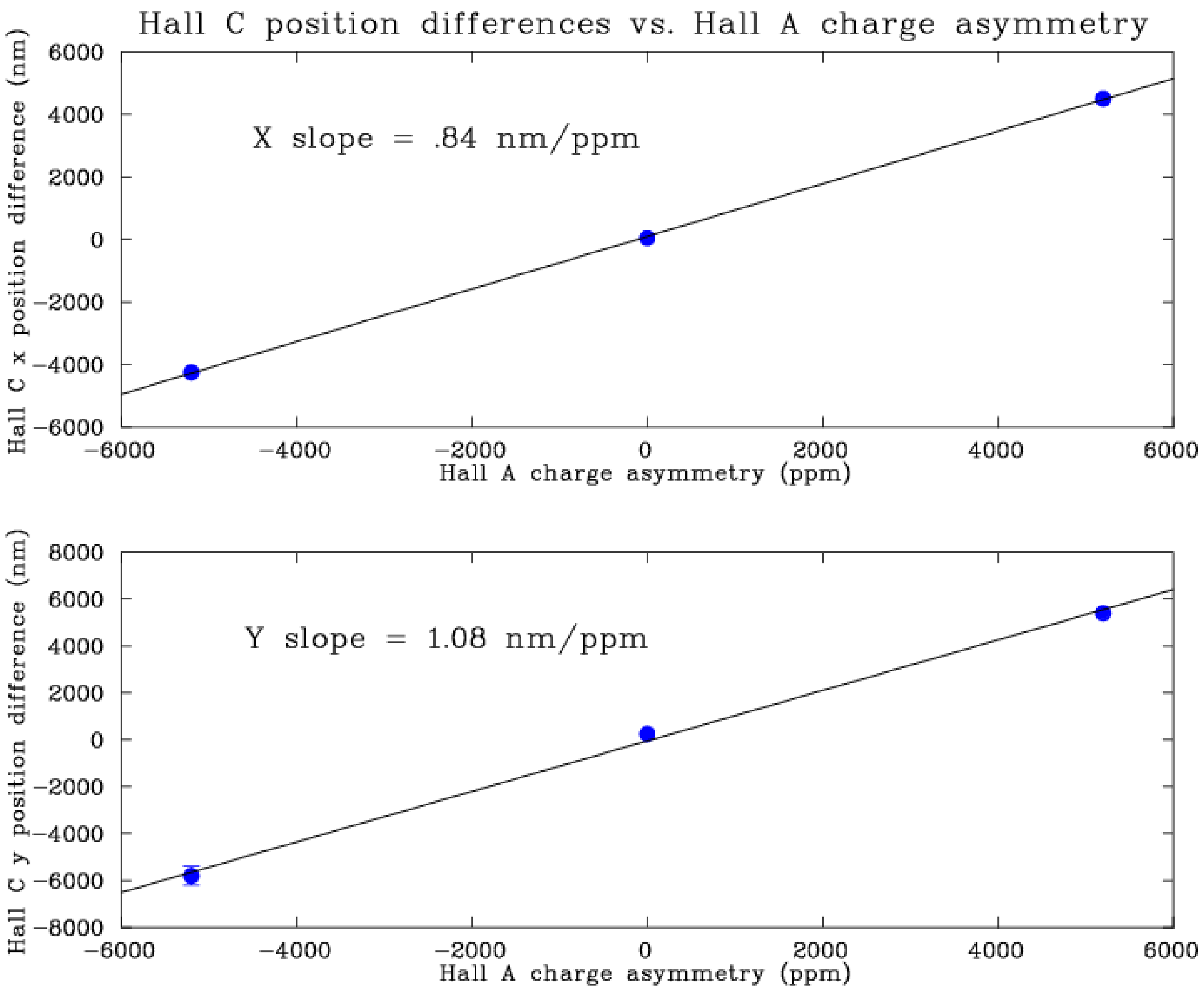
There appears to be no damping at all in the position differences induced by the RHWP (rotating halfwave plate).

Position differences in hall correlated with charge asymmetries



The position differences in the hall seem to be correlated with the charge asymmetry, independent of how the charge asymmetry is generated.

Correlation between Hall C position differences and Hall A charge asymmetry (Hall A ~ 100 μ A, Hall C ~ 20 μA)



A similar correlation is seen with the Hall A beam, which occurs at least 2 nsec different in time than the Hall C beam.

Varying beam optics in Hall C - impact on PZT slopes

During G^0 , the effectiveness of PZTy often got very small; a quick "recovery" was done by varying the furthest downstream y-quadrupole magnet. An example is:

Before change:

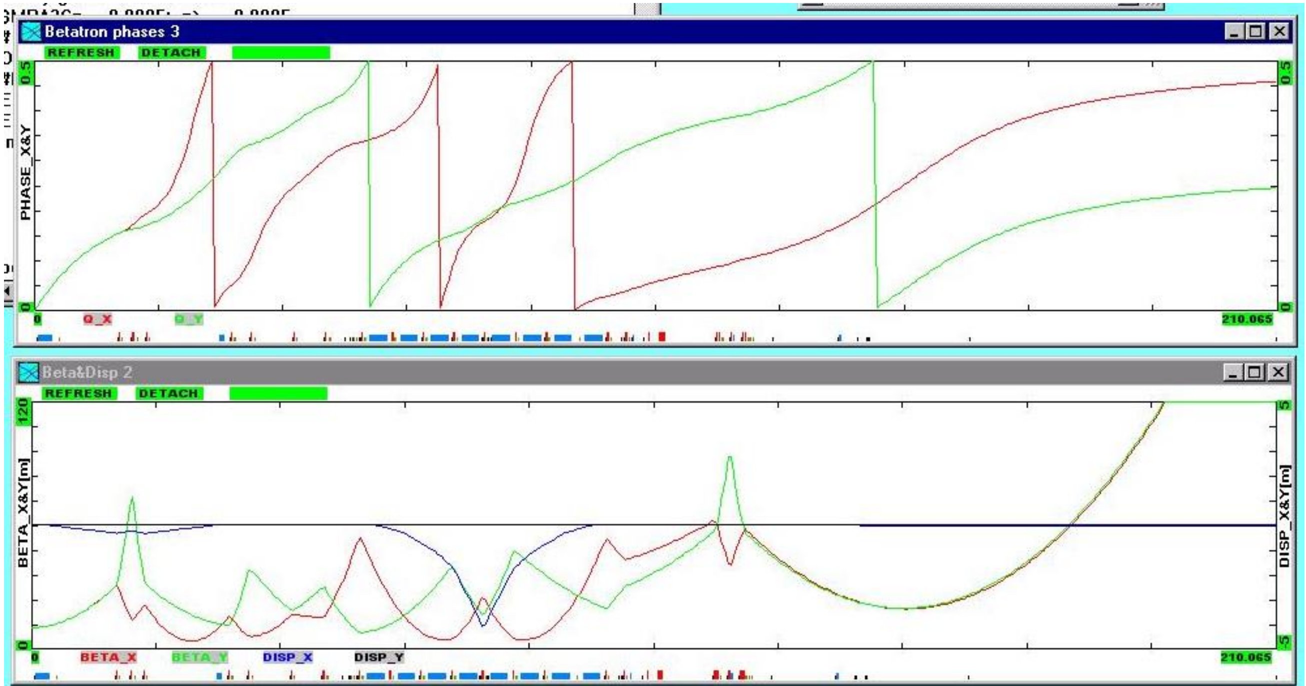
dX_PZTX = 397 +/- 31 nm/V dY_PZTX = -141 +- 30 nm/V

dX_PZTY = -42 +/- 28 nm/V **dY_PZTY = 37 +/- 26 nm/V**

After change:

dX_PZTX = 238 +/- 31 nm/V dY_PZTY = -123 +/- 50 nm/v

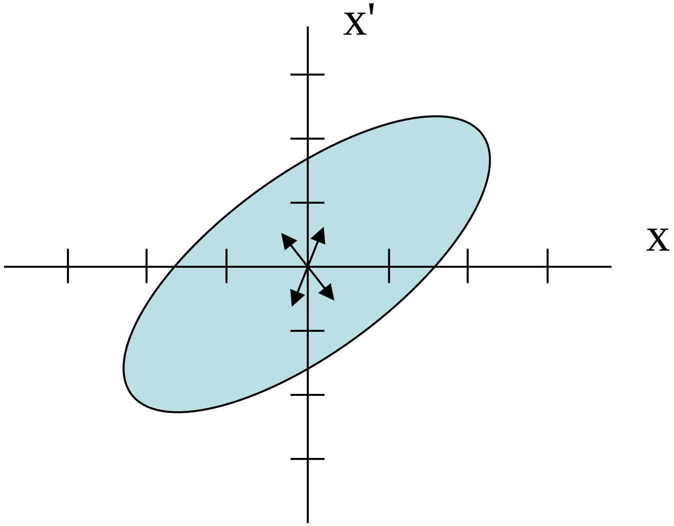
dX_ PZTY = -60 +/ 30 nm/V **dY_PZTY = -267 +/- 46 nm/V**



Phase Trombone

- New development during current HAPPEX run (Alex Bogacz, Kent Paschke)

- Goal: vary betatron phase while preserving the shape and orientation of the phase space ellipse
  - implemented with eight existing quads at the beginning of the Hall A arc
  - Allows for independent betatron phase control in horizontal and vertical planes
- Uses:
  - Allows one to trade off position and angle differences
  - Periodic phase changes can be used to randomize or reverse the sign of position differences

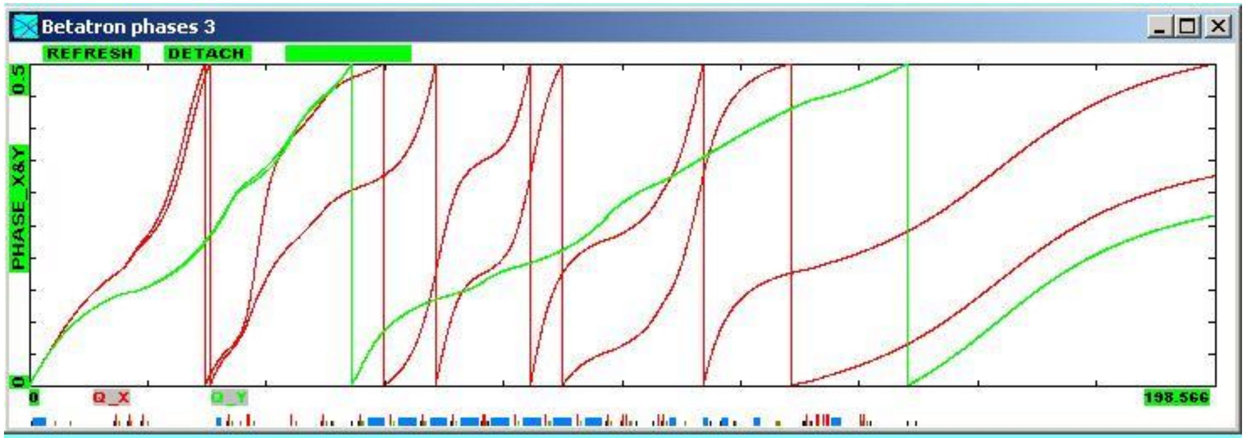


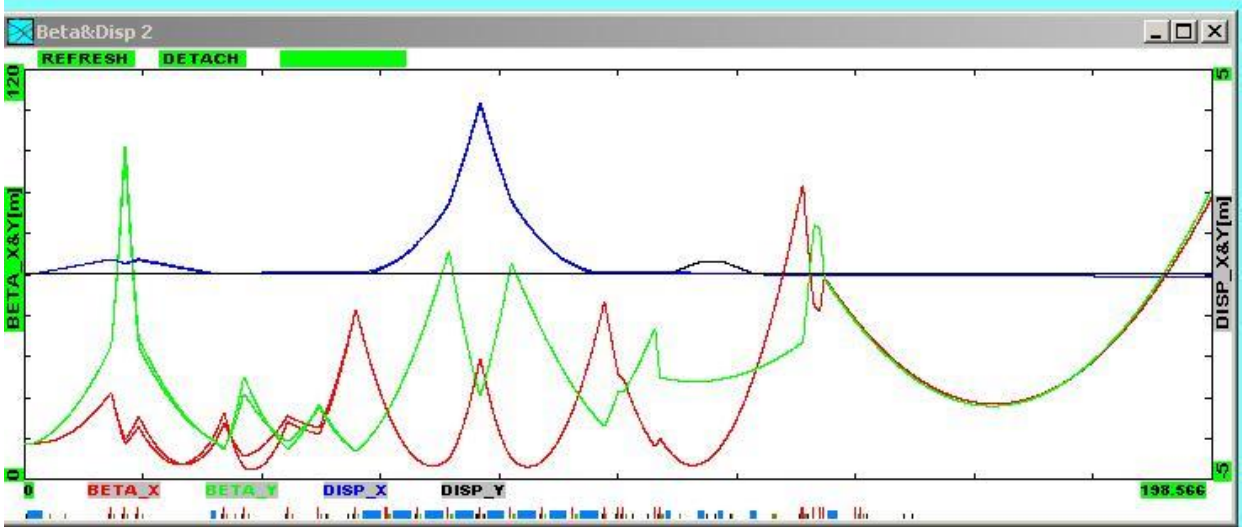
Phase Trombone, Hall A Beam Transport Calculations

Constraints:

- Preserve beam size at the location of the Compton polarimeter
- Preserve large dispersion at center of arc
- Preserve ability to independently vary spot size at target

while varying betatron phase advance independently in horizontal and vertical over the range ±$\pi/2$

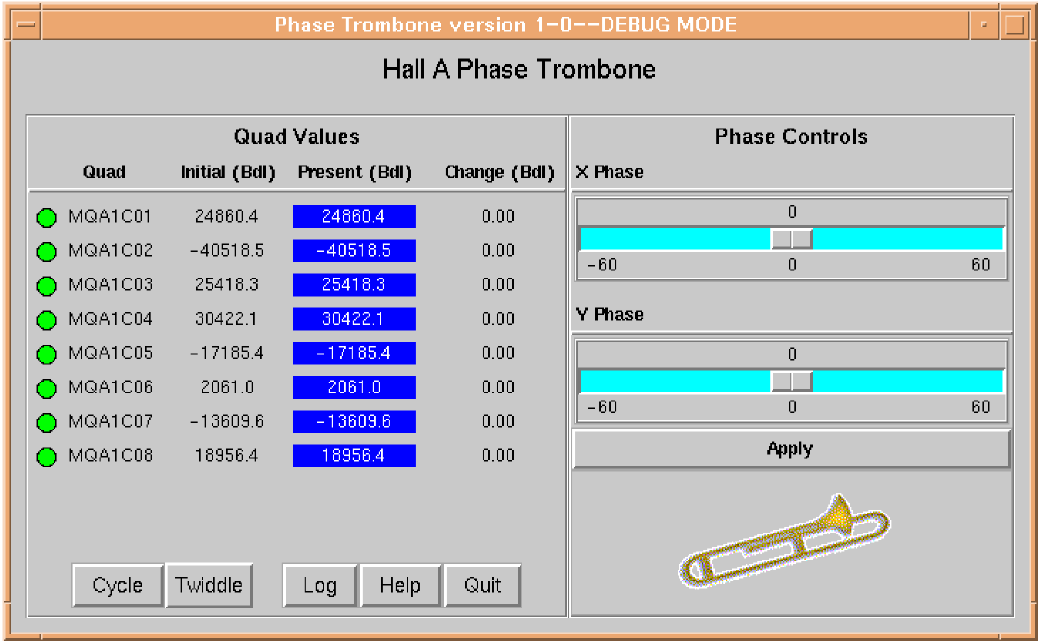




Example:

- horizontal betatron phase advanced by 60° while vertical stays fixed
- beta function changed slightly at beginning of arc ("bump") but unchanged throughout rest of Hall A line

PhaseTrombone, Preliminary Results from First Test in Hall A



Hall A Phase Trombone

Quad Values

	Quad	Initial (Bdl)	Present (Bdl)	Change (Bdl)
●	MQA1C01	24860.4	24860.4	0.00
●	MQA1C02	-40518.5	-40518.5	0.00
●	MQA1C03	25418.3	25418.3	0.00
●	MQA1C04	30422.1	30422.1	0.00
●	MQA1C05	-17185.4	-17185.4	0.00
●	MQA1C06	2061.0	2061.0	0.00
●	MQA1C07	-13609.6	-13609.6	0.00
●	MQA1C08	18956.4	18956.4	0.00

Phase Controls

X Phase: 0 (-60 0 60)

Y Phase: 0 (-60 0 60)

Phase Trombone Setpoint ($\Delta\theta_x$, $\Delta\theta_y$)	Δx (μm) ± 0.3 μm	Δy (μm) ± 0.3 μm	$\Delta\theta_x$(μrad) ± 0.01 μrad	$\Delta\theta_y$ (μrad) ± 0.02 μrad
(0°,0°)	2.9	2.0	-0.08	-0.19
(30°,0°)	2.7	1.2	-0.07	-0.22
(-30°,0°)	2.8	3.2	-0.07	-0.16
(30°,30°)	1.0	1.2	-0.12	-0.21

Conclusions and Outlook

1. Adiabatic damping in helicity-correlated position differences has been observed at Jefferson Lab. The full damping from 60 MeV to high energies has been obtained, while further work in the injector region is in progress to obtain the damping in the 100 keV to 60 MeV region.

2. A possible complication in reduction of position differences is the observed correlation between charge asymmetries and position differences. The physical mechanism for this correlation is not yet clear.

3. A new development, the phase trombone, is being pursued by the HAPPEX collaboration in Hall A. It will allow for trade-off in position and angle differences and possibly the ability to reverse the sign of the position differences.