JLAB-TN-08-040
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FAQ for Injector Matching

This is a document I compiled some time ago to answer frequently asked question regarding Injector matching and its implication on parity quality beams. Not everything is up-to-date, but I would like to use this space to archive it so the information is not lost. I may update and revise this note in the future.

What is the problem?

"Parity" experiments at CEBAF rely on flipping at 30 hz the polarization of the laser incident on the cathode to induce the same effect on electron polarization (or helicity). As this happens a correlated position change in the laser on the cathode, and thus in the electron beam coming off it, is induced. This "helicity correlated" electron orbit change introduces a systematic error to the effects that the parity experiments set out to measure. Therefore it is our goal to minimize this effect as much as possible.

This problem is attacked on many fronts, involving major work on the laser system, on the cathode, and work that this document is devoted to, namely Injector matching that addresses the electron transport from the cathode to the beginning of the main accelerator[1]. Study in the past few years showed that beam transport for the rest of the CEBAF accelerator does not significantly contribute to this problem.

Transport through the Injector, on the other hand, has been shown to be mainly responsible for the electron part of the problem with helicity-correlated orbits. In a well-behaved transport system, helicity correlated orbit changes as described should undergo amplitude reduction proportional to the square root of the beam momentum. In other words as the electron beam is accelerated, the amplitude of any oscillation originating at the cathode (100 keV in KE) should be "adiabatically damped" by a factor of about 104 when it reaches the typical CEBAF 3-pass energy of 3.6 GeV. Two factors in the Injector, however, can disrupt this theoretical damping:

- We do not have an accurate model of the XY-coupling through the cryo-components (the cryo-unit, **CU**, and the two cryo-modules, **CM**) at such low energy. Consequently the transport through this region is XY-coupled, short of effective correction strategy. The net effect of this is that the apparent oscillation amplitude, as well as beam size, in each plane, is larger than theoretically allowed without XY coupling.

- Independent of XY coupling, again due to the lack of accurate modeling at such low energy, the transport itself can be less than well-behaved. This means the oscillation is "mis-matched" to the optimal transport channel defined by the focusing elements. The consequence of this is also amplification of the oscillation (and beam spot). In theory such amplification can always be arrested downstream before it is too late. In reality however this requires fine tuning of the machine over long range that is not really practiced, or cannot be carried out due to limited accuracy. Very often a locally mismatched transport will "set" the level of oscillation amplitude that cannot be easily brought back down later[2]. The net result of this is, besides blowup in oscillation amplitude, increased sensitivity of the transport leading to poor reproducibility. <u>Purely in terms of blowup of helicity-correlated orbit, this effect is the dominant one</u>.

Numerically, measurements made in the past few years established to very high precision ($<10^{-3}$) the adiabatic damping[3] from 60 MeV to 3.6 GeV, in agreement with the theoretical value of roughly 8. On the other hand, in the worst case, we can see no apparent damping at all in a particular plane from 100 keV to 60 MeV, a missing damping factor of about 13!

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[1] Including the front end of North Linac.

[2] For example, if an <u>otherwise benign</u> XY coupling source or nonlinear field is located in the intervening region where the amplitudes are artificially blown, their effects may not be easily correctible later without extra skew quads or nonlinear elements. For the same reason <u>otherwise benign</u> sources of fluctuation in the intervening region can result in major instability at the end if the matching is not correctly done <u>early and locally</u>.

[3] Quantified by the reduction of the area occupied by ensemble of beam trajectories in the phase space.

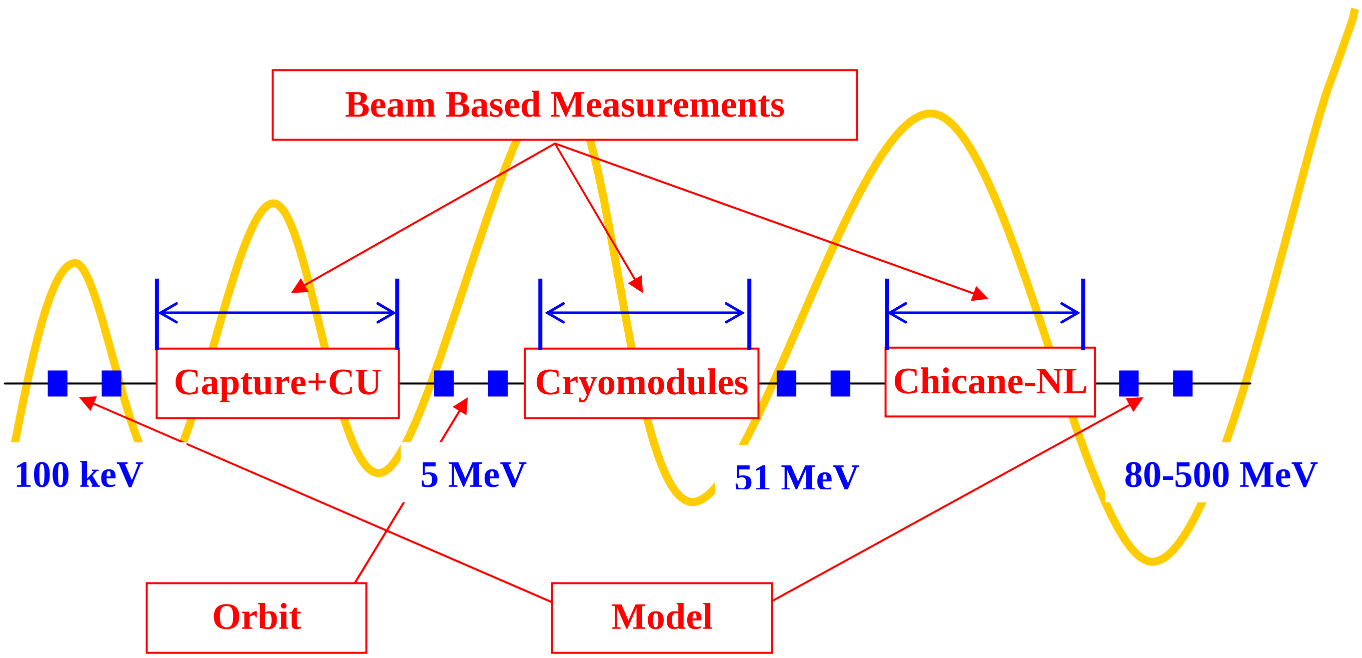
These two problems, although originating from separate sources, are unfortunately intertwined so far as correction strategy is concerned. One cannot talk about fixing one first before the other[4]. Furthermore, due to the gross mismatch, even a slight amount of XY coupling is not something to be glossed over in terms of fixing the coupling. In short, this requires a full 4-dimensional correction of the optics as opposed to the typical 2-dimensional corrections we perform while fixing CEBAF optics.

[4] Actually it was tried but proven unrealistic.

How do we correct the problem through Injector matching?

Since the problem of missing adiabatic damping mainly lies in transport defects in the Injector, effort to recover damping is focused on restoring XY-decoupled and betatron matched optics from the cathode to North Linac. Further attention must be paid to ensuring that this optics provides matched transport for orbits sharing the same phase space characteristics with the helicity-correlated ones.

Since we are dealing with a 4-dimensional problem, in addition to the quadrupoles used for usual betatron matching in the rest of the machine, we also need skew-quads to correct the XY-coupled part of the transport. In a series of measurements performed in 2004 it was shown that the empirically measured transport functions across the questionable sections in the Injector, namely the Capture+Cryo-unit and the two Cryo-modules, were consistent with 4D symplectic transfer matrices[5] to a very high degree. This implies the observed transport defects can be corrected with only quads and skew-quads. The development since has followed this basic premise, and will be lumped under the general title of "Injector Matching".



The few major components of the program of Injector matching can be visualized in the graph above.

- 100 keV: This area poses the biggest obstacle to the entire program, with its inherent difficulty in modeling the transport both in the line itself and when used to provide input for determining the transport through the Capture+Cryo-Unit. The reasons for this are multiple. In particular, we don't have enough BPM's to even cleanly answer the question of whether there is already blowup in the 4D space in this region.

  The trajectories of the PZT in this area display about 60-70% agreement with the model (in the counter-wound solenoid region). This is significantly worse than anywhere else in the machine (other than notorious regions such as the dogleg). Part of this may be attributable to orbit-dependent optics. The aperture restrictions and less-than-desirable modeling of individual elements may play a part too.

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[5] After accounting for adiabatic damping.

- Capture+Cryo-unit (CCU): We mainly need to obtain reliable 4D transfer matrix across this combination[6] using dedicated difference orbit measurements. This in turn depends on the ability to model the transport well enough in both 100 keV and 5 MeV. The former, as mentioned, introduces a nontrivial error bar to this process, while the latter, with only 4 BPM's, relies also critically on good modeling and good performance of all BPM's. Currently a transfer matrix obtained on March 04, 2005 via an extremely elaborate process[7] appears to have been able to explain most (but not all) of the PZT propagation across this combination since then at 50-80% level. This is what we use as part of the basis for Injector matching[8].

  Same as the 100 keV line, this is one of the more vulnerable areas.

- 5 MeV: Significant effort has gone in to fine tune the optical model in this area. As a result with only 4 BPM's (which must all perform) we can rely on its model to provide input to measuring 4D transport across both Capture+CU and the two cryomodules separately with a high degree of confidence[9]. This area however is highly dependent on BPM performance.

- Cryo-Modules (CM): We have been able to get accurate and stable measurements out of either individual Cryo-modules IN03 and IN04, or the combination as a black box.

- 51 (or 60) MeV: This region is important for providing input for characterizing transport across both the CM's and the transition from Chicane into North Linac. It has been reasonably behaved apart from a few question spots.

  - The quads in this region (MQD) have been tested through difference orbit studies with fields ramped up to 800 G (about twice the nominal). However one quad that defies such method, MQD0L06, has been suspected to display an error in online and offline studies.
  - There is no systematic means of ascertaining the energy in this area.
  - The Injection Chicane dipoles may display characteristics not accounted for by the model. This is partly evidenced by the fact that there is dispersion leak out of the Chicane under design optics.

  The bunch-compressing configuration of the Injection Chicane that has been in use for the past few years was recently found to introduce highly singular transport. This adds to the sensitivity in this region and the likelihood of uncontrolled growth in oscillations. We have reverted to the original isochronous configuration during July 2005 startup, which should reduce the sensitivity here considerably.

- Chicane to North Linac (NL): This is the final area in the program that needs be empirically characterized. We know the transport here is not exactly the same as design, while efforts to measure it have been routinely plagued by the highly singular Chicane mentioned above and recently rectified, and at times by the poor NL model due to low end gradient calibration errors. If all these obstacles are cleared, there is no fundamental difficulty keeping this from being accurately measured.

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[6] In the absence of any BPM between the Capture and the Cryo-unit, they can only be lumped together as a black box.

[7] Involving retracting A1/MS/A2 and modifying solenoid strengths.

[8] In contrast, one such matrix measured in 2004 stopped explaining PZT transport when the Capture RF started degrading shortly after.

[9] For example, the measured transfer matrices across the two cryo-modules showed little change over a period of 6 months when the gradients in them remained roughly constant.

The correction strategy is simple: To empirically determine all the "black boxes" above, and work out first order global matching solutions that will eliminate both XY coupling and betatron mismatch (or large singularity). This zeroth order offline solution will then be implemented on line, with additional fine-tuning[10], necessary due to measurement/setting errors, performed under the guidance of real-time tools[11]. More detail will be described under the following question "*Do we have enough degrees of freedom to correct the error in the transport?*"

Do we have enough degrees of freedom (DOF) to correct the error in the transport?

Because it has been demonstrated that the problem we have is a 4D symplectic one, the parameters that we need to control are 10: 3 for each of the uncoupled planes, and 4 cross-plane ones. Since we don't care too much about the betatron phase in this problem, we can drop the 2 phases and end up with 8.

The independent degrees of freedom at our disposal, by symplecticity and if we have sufficient number of quads and skew quads (which we do), are also 10.

Now the real question: We have enough degrees of freedom at our disposal to fix the parameters only in a global sense. In other words if we have a giant and brute force optimization program where we can throw in all 8+ constraints and 10+ control variables and let it grind everything out, we may get some answer, at the expense of neglecting local blowups and other undesirable features in the solution. Also such a solution will be so rigid & un-modular that changing one knob perturbatively would destroy the entire solution, and there is no easy way to move in the solution space on the fly while respecting all constraints. And the fact really is, I don't have such a program that guarantees good usable solutions in a reasonable amount of time.

A more sensible way to do this is to break the system down into modules and take care of different parts at different stages. This decoupled strategy also provides the ability for some simplified empirical manual fine-tuning, since otherwise with the global 10 by 10 solution it would be very difficult to look for increment improvements if the zeroth order solution doesn't work. This is the conceived strategy for the current program, where

- The combination of 5 MeV quads and skew quads corrects coupling and produces a "smooth" transport, although not necessarily betatron matched. This uses 10 independent knobs to control 4 (coupling) parameters, plus qualitatively improve the other 4 (in-plane) parameters.
- The 60 MeV quads are used to perform betatron match into NL. So here 4 independent knobs are used to control 4 already reasonably behaved parameters.

<u>Note in this modular approach we need to look at the DOF count for each module, instead of globally. This is exactly why the upright PZT before the CU becomes critical</u>[12]. If they were not upright before the CU, after the first stage of correction, <u>the independent number of "errors" does not come down from 8 to 4, but stays 8</u>, and I am faced with correcting 8 constraints with only 4 knobs. This is the fundamental reason for demanding that PZT be upright into the CU.

What were past obstacles to this program?

What are the current "road blocks" to this program?

[10] Without undoing XY decoupling.
[11] Mainly the 30 hz PZT and the PZT Zoom Display.
[12] Besides ascertaining the XY decoupling of the 100 keV line.

Where are we in the program?

How bad is the coupling?

Why do we have to use the PZT as guidance?

The 30 hz PZT system was developed by J. Hansknecht by request from the PQB meeting, which identified it as a critical tool for ascertaining proper damping of helicity correlated orbits from the gun to at least the first pass of the main accelerator. It has been demonstrated from online measurements that the effective measurement range can be extended to at least 3 passes, where G0 and HAPPEx have run up to now, and even 5-pass provided adequate statistics is used.

The PZT at the time of the proposal was believed to mimic the phase space characteristics of the helicity-correlated orbits closer than other means. <u>This appeared to be borne out by a comparison made between the helicity correlated orbit data provided by Kaz Nakahara, the G0 PZT, and the accelerator PZT in 2004</u>. The PZT indeed showed close resemblance to the helicity correlated orbit pattern in both the Injector and 3-pass Hall C.

Recent indirect confirmation of this fact came when an Injector matching solution was tested, G0 reported the same overall behavior in the observed helicity correlated orbits in Hall C as was observed of the 30 hz PZT[13].

Is it enough to only improve the transport in the Injector without worrying about the PZT's?

Why do we need to make the PZT's upright before the Cryo-unit?

For XY coupling: This signifies the cancelled rotation (and coupling if any) across the 100 keV region. We don't want this region to impart any XY-correlation into the beam or orbit, especially if we are to fix the coupling downstream, since that will change the projected emittance in the beam/orbit that we cannot undo later[14].

For betatron matching: Inadequate control DOF in 60 MeV if each PZT has 4 independent components.

Is it possible to make the PZT's upright?

Real problem is the 100 keV model.

The real helicity correlated orbit is neither pure X motion nor pure Y motion, so why do we want the X & Y PZT's to be upright?

It has nothing to do with PZT itself, but with making sure the global transport from cathode to 60 MeV is XY decoupled, since after which the machine has mid-plane symmetry. This means if we fix the XY coupling from Capture+CU to 60 MeV, then the transport from cathode to Capture had better be XY decoupled too. But in order to <u>verify</u> that this condition is indeed met, the X PZT must come out along X after the Wien, and the same for Y. In fact this is really only a necessary condition since the PZT only

[13] Riad Suleiman's measurement of March 2005 showed more damped X component and less damped Y component of the helicity correlated orbits, same as observed in the PZT.

[14] This change can be large and in the wrong direction.

represent half the phase space degree of freedom. But as is true with necessary conditions, if the PZT is not upright, we know the cathode-to-capture transport is not decoupled[15].

So what if the PZT's are rotated by an angle by the time they reach 60 MeV?

The problems are two-fold:

- After 5 MeV we don't have cylindrical symmetry any more and would not be able to keep making the PZT's look "rotated".

- A bigger problem is that from 60 MeV onwards we do not have the independent degrees of freedom (DOF) to correct all the components of a rotated PZT system (position and angle for both PZT's in both planes). We can only correct 4 components (for example X, X' from X PZT, and Y, Y' from Y PZT). We lost the opportunity to collapse the 8 DOF into 4 by uncoupling (unrotating, whatever) the 100 keV region. Now we have to <u>rotate the entire accelerator</u> from 60 MeV by the same angle as the PZT rotation to be able to fix them.

Can we rotate the BPM's in 100 keV, or rotate the PZT mirrors, so the PZT <u>appears</u> upright?

If the machine changes all the time, can we ensure the stability & reproducibility of the correction?

The answer is no. If the machine changes (which remains to be quantified) all the time, we cannot ensure the usefulness of the solution.

However, this is not the answer that we should be counting on. There has been a visible trend, with identifiable milestones, in making the machine (injector in particular) more reproducible. In the Injector the following improvements were motivated by this purpose to my limited knowledge:

- Earth field coil
- Various PID locks
- Lens dithering software
- Plan to add BPM at 0I07(?)
- To a degree the PZT itself
- ……(?)

With each milestone the stability does seem to improve. Thus the trend has been to uncover and eliminate sources of non-reproducibility such that a solution will eventually stick. And the correct expectation, in my opinion, is to extrapolate on this trend instead of giving up on it.

Emittance vs transfer matrix

[15] One may want to differentiate between coupling and rotation, which are collectively called "coupling" here. That is OK, but the impact on correctability at 60 MeV from these two are the same.