TUNING THE BEAM: A PHYSICS PERSPECTIVE ON BEAM DIAGNOSTIC INSTRUMENTATION *

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ABSTRACT

In a nutshell, the role of a beam diagnostic measurement is to provide information needed to get a particle beam from Point A (injection point) to Point B (a target) in a useable condition, with 'useable' meaning the right energy and size and with acceptable losses. Specifications and performance requirements of diagnostics are based on the physics of the particle beam to be measured, with typical customers of beam parameter measurements being the accelerator operators and accelerator physicists. This tutorial will be a physics-oriented discussion of the interplay between tuning evolutions and the beam diagnostics systems that support the machine tune. This will include the differences between developing a tune and maintaining a tune, among other things. Practical longitudinal and transverse tuning issues and techniques from a variety of proton and electron machines will also be discussed.

MOTIVATION

This is intended to be an 'end-user perspective', with the view that the accelerator operator and accelerator physicist are the primary users of beam diagnostic instrumentation. This is also intended to be a comparison of machines, not just a "LANSCE" talk. If this works, it will trace my experiences in going from an experimenter to an accelerator physicist to supervising operators to supervising beam diagnostic instrumentation personnel.

WHO IS THE TUNER?

To begin a discussion of this nature, one first must ask what is meant by a 'physics perspective'. As I struggled with this question, the first thing that I realized was that to understand such a perspective, one must begin by understanding the user.

Is there such a thing as a typical accelerator physicist? Of course not. However, there are certain commonalities. Let us start out with education. The education of most accelerator physicists comes from a couple of different areas. The first area is, of course, formal education and/or training in accelerator physics. This, actually, is not a common thing to find, at least in my experience. I performed an informal poll of my colleagues at and beyond the Los Alamos Neutron Science Center (LANSCE), which is where I work, and found a decided lopsidedness to the origins of many of the physicists there. Jeff Kolski is a graduate student from Indiana University working on his thesis performing studies of our Proton Storage Ring (PSR). So, he is developing the background one might expect from an 'accelerator physicist'; accelerator physics. Yuri Batygin, new to our Operations Physics Team, is also formally trained in accelerator physicst in the former USSR.

Now let's look at the other end of the scale, starting with me. I came from a background of accelerator-based atomic physics. Several of my colleagues, such as Larry Rybarcyk, Rod McCrady, Chandra Pillai, Glen Johns, and Thomas Spickermann all were experimental nuclear and/or particle physicists. Many of us landed at some point in our careers here at the accelerator to do experimental physics and eventually ended up moving over into the operation, design and modeling of accelerators. I have had numerous conversations where one of us would point to an area and make a comment about the first experiment we were involved in here.

The next question is "what, if anything, does this mean?" One thing that it means is that the odds are against the average physics graduate student walking into a physics program that has accelerator physics as a subject area.

That is not surprising. I did an informal search for physics programs that included accelerator physics and found fewer than ten institutions in the US that offered programs of various types in fields of accelerator physics or beam physics. This is compared to institutions that number in the rough range of three hundred or so that offer graduate studies in physics.

The next question that can be asked is about the other major brand of accelerator tuner, the accelerator operator. Operators come from a different mold than the physicist does, typically. So, where does the typical operator come from? This question is as least as machine dependent as the first one. At LANSCE, many of the operators have a background of having served in the Navy's Nuclear Power School. This is the school that trains sailors and civilians for shipboard nuclear power plant operation and maintenance of naval nuclear ships and submarines. These 'navy Nukes' have several of the qualities needed for accelerator operation. They have experience with large, complex systems. They, in fact, have experience with large, complex systems that will kill you if you do not pay attention to what you're doing. They have experience with radiological environments. They have strong technical backgrounds.

LANSCE has also had some success with hiring operators with backgrounds in nuclear power plant operation. Another area that LANL has explored has been 'local talent'. What has been done is to go out and find qualified candidates who are in a local electrical/mechanical technician program and have them do an apprenticeship at the accelerator.

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Not surprisingly, another common area that operators come from is physics. Many accelerators, such as Fermilab and Jefferson Lab, look to physics BA/BS recipients as potential operators. These operators also have a strong technical background and a basic understanding of the physics behind the machine.

REQUIREMENTS

The next question one might ask to get a better understanding of a physics perspective is “what does the typical tuner want?” This question is asked from the perspective of what one wants in beam diagnostic instrumentation. The first thing that the tuner wants is to get what could be referred to as reliable measurements. This means that the equipment works, the results are trustworthy, and the measurements are timely. The term ‘timely’ is pretty open to interpretation, but if one is spending most of the time waiting for the diagnostics system to go through an evolution of obtaining and displaying data, then that is where there is usually a problem.

There is a relationship between the person who knows what the equipment does and how it works and the person who understands the information it generates. Do the tuners care about the details of the equipment functionality? Generally, yes. Keep in mind the typical tuner has a technical background and is the sort of person who dismantled the first VCR player the family owned to see how it worked. So, part of the process of developing confidence in the results the equipment is providing is to understand what is going on to get the data. This history that the typical tuner has can be used to the advantage of everyone.

WHAT DO WE NEED TO KNOW?

Physically, we need the beam to get from point A (which is usually a source or injector system) to point B (which is typically a target) in the right condition. What is meant by the right condition? There are a number of things to consider. First, where is the beam within the beam pipe? This is the zeroth order part of the transverse tune. Next is the beam focusing the way that it should and at the points in the transport that it should? This gets us into looking at the phase distribution of the beam with this aspect being the transverse distribution. Next, what is the beam energy and how well is it being bunched? This gets us into the other aspects of the distribution of the beam, which is the longitudinal distribution. Other parameters that we need to know about are things like beam intensity and how well the beam is being transmitted along the accelerator or transport. The other parameter that has to be kept in mind is basically how all of these aspects of the beam are related to each other.

TRANSVERSE TUNING

This can be generally referred to as the “keep it between the ditches” part of the tune. The beam needs to be bent by the right amount at the right locations. Even with benders, corrector or steering magnets need to be strategically placed. In addition, other elements, such as quadrupole magnets, will have an impact on the steering of the beam. The other part to this is proper focusing of the beam.

One may ask one’s self, “what can possibly go wrong?” as far as transverse tuning goes. Mis-steered beam will create havoc in a number of ways, including creating spill and transmission problems all the way to damaging equipment. Looking at Figure 1, one can see a dark spot in the center of the picture which is a hole in the beam pipe. In this case, an issue with the accelerating structure and run permit system upstream of this area allowed beam that was roughly 89 MeV into a bender magnet set for 100-MeV beam.

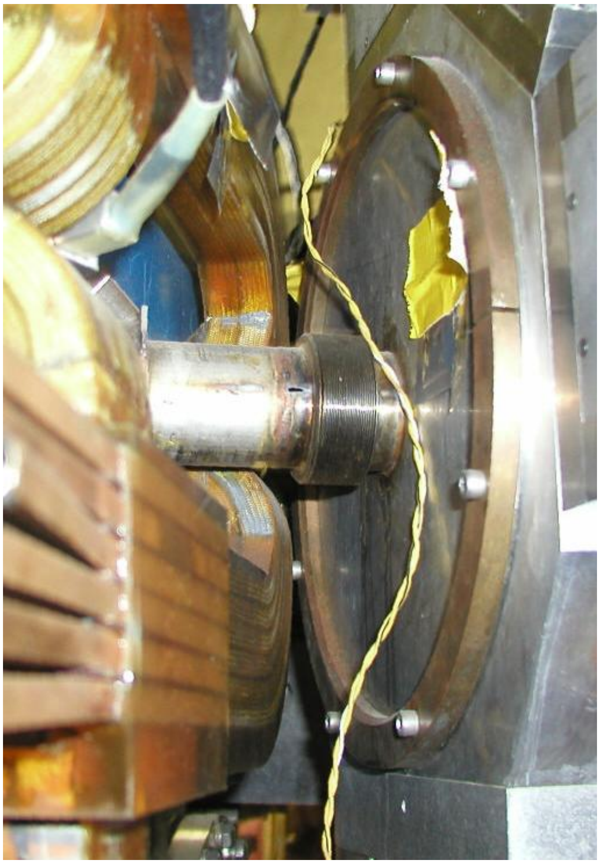


Figure 1. The dark spot in the center is a hole created by an 89-MeV proton beam in a beam pipe in the Transition Region of the LANSCE accelerator.

TRANSVERSE DEVICES

There are a number of transverse devices that are commonly used for diagnosing the beam. Examples include wire scanners and harps. These provide interesting information to the tuner in the form of showing what a cross section of the beam looks like. One can quickly and easily see how Gaussian the beam looks. Another device commonly used is a phosphorescent screen. These screens are straightforward but they usually cannot handle full beam currents. Also, unless one is digitizing the image and analyzing it, one can only get qualitative information from it. There is also a plethora of different devices intended for directly producing the emittance of the beam. Another type of transverse device is any one of a variety of beam position monitor. These have the characteristic of primarily measuring the position of the centroid of the beam, without necessarily showing information about the cross-sectional profile of the beam the way a diagnostic like a wire scanner can.

So what are we doing with this information? We are interested in the emmitance because it needs to be within certain values or the beam will expand too much for reasonable transmission. We also need to confirm that it is going to focus properly at the locations that we want it to focus at. The sort of locations we are interested in are areas like the center of a beam buncher or chopper, and so on. Also, the beam needs to have the proper characteristics at injection points of accelerating structures.

PARTICLE PARAMETERS

The primary thing that a tuner is concerned with is the particles that make up the beam. Table 1 shows some typical numbers of particles in each bunch or macropulse for a variety of different machines. The thing to notice here is that the number of particles in a bunch is huge. Numbers are typically between 10^9 and 10^14.

Facility	# of Particles per bunch/macropulse
LANSCE	5.9e13 H+ 3.3e13 H-
SNS	1.6e14
ISIS	2.5e13
APS	2.3e12
ALS	4.16e9
LHC	1.1e11

Table 1. Typical numbers of particles per bunch or macropulse at a sampling of facilities.

Why does this matter? Because, given the ability to do so, the tuner would try to understand the machine better by knowing what each and every particle is doing in each of six coordinates in its phase space. The six coordinates that make up this vector quantity are the horizontal and vertical positions of the particle, the angle of the particle's trajectory with respect to the horizontal and vertical axes, the particle's momentum, and phase.

Not surprisingly, this cannot be done easily. There are simulation codes in use that make use of macroparticles to simulate groups of individual particles and these codes can handle number such as 10^5 macroparticles. Figure 2 shows what a simulation of the LANSCE low-energy beam transport using the Beampath code looks like.

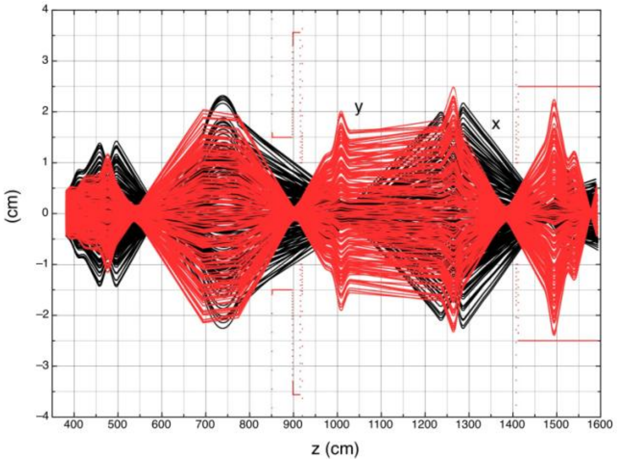


Figure 2. Beampath simulation of the LANSCE low-energy beam transport. The red paths are the vertical plane and the black paths are the horizontal plane. Courtesy of Yuri Batygin.

One thing that needs to be pointed out with this type of simulation is that it is time-intensive. It is not conducive to tuning a beam line in real time, despite that fact that it creates a simulation that might come closer to the real thing than a standard envelope calculation.

As a result, many beam simulation tools use beam envelope calculations for real-time tuning. These tools can take information from actual emittance measurements and do a reasonable job of predicting the transport of the beam, assuming the details of the transport are known reasonably well. Thus the emittance ellipse becomes an important tool in the process of tuning a beam line. Instead of looking at individual particles or macroparticles, we look at the integral of different parts of the phase distribution of the group of particles. This is where the beam envelope concept comes in. Transversely, we look at what the envelope of the position and angle of the beam looks like. The area of this envelope is what is referred to as the emittance of that part of the distribution. Figure 3 shows an example of such an emittance ellipse. From it, one can see relevant parameters for one axis, namely the x-axis in this case, with x representing the position of the particles and x' representing the angle the particles are traveling with respect to the x-axis. Various parameters of the ellipse are also called out such as the maximum extent in the x and x' axes, the x and x' intercepts. These values are described in terms of the emittance (ε) as well as the so-called Twiss parameters

(α, β, and γ). These will be discussed more later and are the characteristics of the envelope emittance ellipse that can be determined from the measurements and used to predict the action of the beam.

Emittance is the area of the beam ellipse and as such has units of distance times angle. Typical units used are mm times mrad. But there are numerous ways to express this quantity. Since the rad is a dimensionless quantity, it can be left off and simply implies. As a result, one can see emittance expressed as µm. Table 2 shows some emittance values from a sampling of different machines.

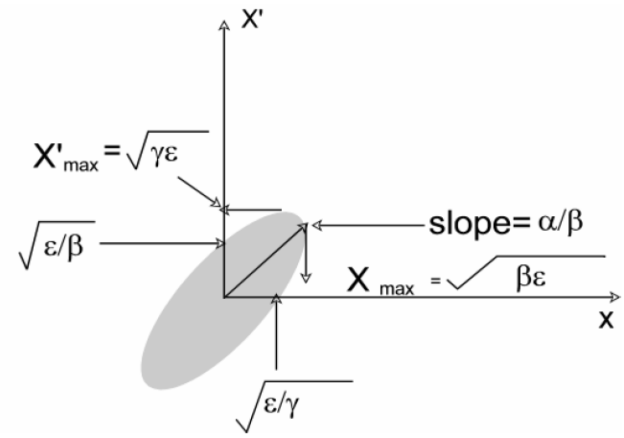


Figure 3. An example of an emittance ellipse.

Facility	Emittance	Normalized Emittance
APS	2.5 nm-rad	
ISIS Source		.2 π mm mrad
ALS	6.8E-9 m*rad	10/0.7 µm
SRC Aladdin	40 π nm rad	
SLC		50/8 µm
SPS-LHC		3 µm/3.5 µm
LANSCE (750 keV)	5 π mm mrad	.2 π mm mrad
LANSCE (800 MeV)	.2 πmm mrad	.3 π mm mrad

Table 2. Emittance measurements from a sampling of machines. Notice the variety of ways of reporting the emittance units.

One can see that there are various ways of reporting emittance, starting with natural emittance vs. normalized emittance and going into different units (µm rad, mm mrad, etc.), which can lend itself to confusion on what the relative sizes of emittance at different machines are. It is also worth pointing out that there is a wide spread in the size of the particle beams at different facilities, which covers several orders of magnitude. Storage ring colliders such as PEO-II, KEKB and LEP often have rms spot sizes between 100 to 200 µm horizontally and just a few µm vertically. Sizes in some of the linear colliders such as NLC or TESLA get down into the range of a few hundred nm horizontally and a few nm vertically. High intensity proton machines such as SNS or LANSCE can have rms spot sizes up to a couple of mm.

TWISS PARAMETERS

It has been mentioned that the beam envelope can be described by an ellipse. The details of how this is derived are available in any one of a number of accelerator physics texts. The equation is that of an ellipse in phase space for either of the transverse planes:

$$\gamma x^2 + \alpha x x' + \beta x'^2 = \varepsilon \qquad \text{Eq. 1}$$

The important thing to note is the information one can extract from the different Twiss parameters. The beam size is the square root of β times the emittance. Similarly, the beam spread is the square root of γ times the emittance. α gives insight into whether the beam is converging, diverging, or columnar. It is worth quoting Minty and Zimmermann [1] at this point; "Thus, the actual values of β, α and γ can be deduced from the measured beam distribution. It is a challenge to the accelerator physicist to make them coincide with their design values."

Having an understanding of what the elements of the equation means is one thing, but another useful thing to know is what the size and shape of the emittance ellipse implies qualitatively. For our first example, in Figure 4 one sees two ellipses, one of which is vertical and one horizontal. The vertical orientation means there is not much spread in the x position, but quite a bit in the x' position. This is a beam at a focal point. Inversely, a horizontal spread indicates a wide beam that is columnar.

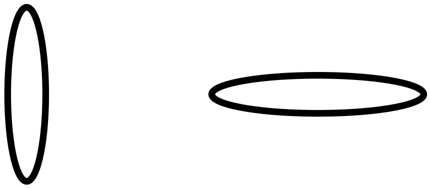


Figure 4. Emittance ellipses for a focused beam and a columnar beam.

Most emittance measurements show an ellipse at an angle (see Figure 5). In such a case, the beam is neither focused or columnar, but somewhere in between. It is important for the tuner to get an intuitive feel for what is going on in such a case, because one can quickly determine what is going on. Another point to note is that often the emittance ellipse will not be a nice, geometrically simple ellipse. This is the case when non-linear forces have had an effect on the particle beam. An example of such a distribution is shown in Figure 6.

Figure 5. Emittance ellipses for a beam that is focusing and one that is diverging.

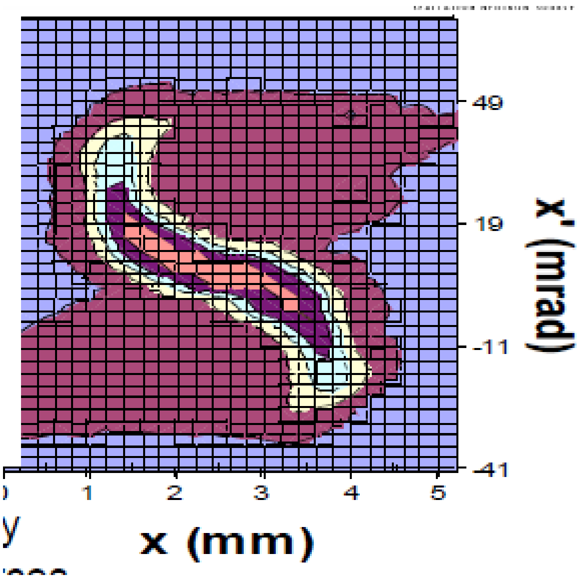
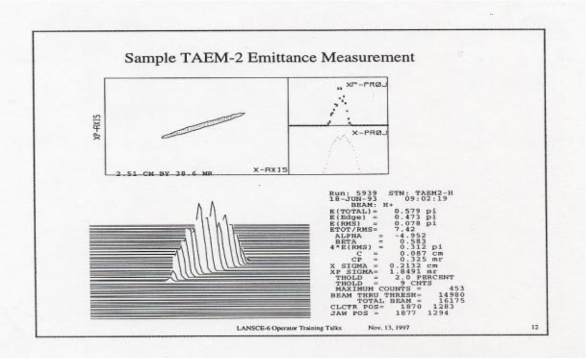


Figure 6. Measured emittance at SNS [2].

The color-coded emittance graph as seen in Figure 6 is one way to graphically represent the emittance ellipse. Another way is shown in Figure 7.



Sample TAEM-2 Emittance Measurement

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Run: 5939   STN: TAEM2-H
18-JUN-93       09:02:19
    BEAM: H+
E(TOTAL)=     0.579 pi
E(Edge) =     0.473 pi
E(RMS)  =     0.078 pi
ETOT/RMS=     7.42
 ALPHA    =  -4.952
 BETA     =   0.583
4*E(RMS)  =   0.312 pi
    C     =   0.087 cm
    CP    =   0.325 mr
X SIGMA =  0.2132 cm
XP SIGMA=  1.8491 mr
 THOLD   =   2.0 PERCENT
 THOLD   =    9 CNTS
 MAXIMUM COUNTS =      453
BEAM THRU THRESH=    14980
     TOTAL BEAM =    16175
CLCTR POS=   1870  1283
JAW POS =    1877  1294
```

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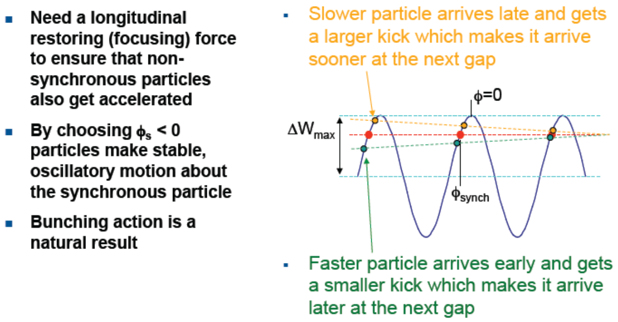
Figure 7. Sample output of the Emittance Replay program from LANSCE.

The reason that some amount of effort has been expended in going over a general description of the emittance is because the quantities associated with it are at the heart of what the person tuning the beam is trying to understand. Basically, we try to understand what the distribution of the particles in phase space is doing. Further, and very importantly, this is a dynamic process. As one looks through texts and presentations, the emittance is presented as a graph and it lends itself towards being interpreted as a static measurement when, in fact, it is a snapshot of what the beam is doing at a very particular moment and place.

LONGITUDINAL TUNING

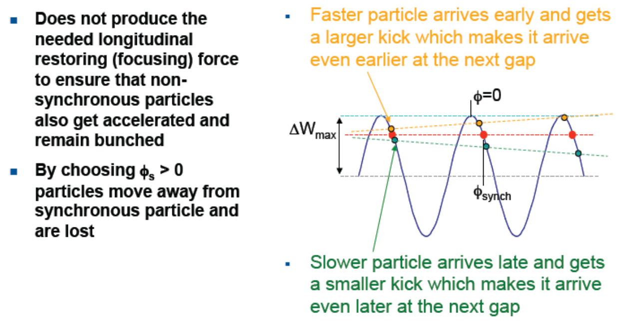
The next important concept related to the particle distribution is the longitudinal component. Most of what we have discussed until now is about understanding how the bunch of particles is distributed within the beam pipe. The other important aspect is how to measure the acceleration of the beam and know that it is reaching the right energy and is staying together longitudinally while doing it. Accelerators are radio-frequency (RF) devices and as such, we need to understand how the bunch of particles needs to interact with the RF. In general, the particles need to see the RF field when the field will stably accelerate the particles. Not all particles will be at this point for synchronous acceleration. Some will be a bit too fast and some too slow. By picking the synchronous phase to be less than zero, the slower and faster particles will naturally tend towards being bunched. Figures 8 and 9 show this requirement to get the particle bunch properly phased with the RF.



- **Need a longitudinal restoring (focusing) force to ensure that non-synchronous particles also get accelerated**
- **By choosing $\phi_s < 0$ particles make stable, oscillatory motion about the synchronous particle**
- **Bunching action is a natural result**

- Slower particle arrives late and gets a larger kick which makes it arrive sooner at the next gap
- Faster particle arrives early and gets a smaller kick which makes it arrive later at the next gap

Figure 8. Choosing ϕs such that the motion about the synchronous particle is stable. Courtesy of Larry Rybarcyk.



- **Does not produce the needed longitudinal restoring (focusing) force to ensure that non-synchronous particles also get accelerated and remain bunched**
- **By choosing $\phi_s > 0$ particles move away from synchronous particle and are lost**

- Faster particle arrives early and gets a larger kick which makes it arrive even earlier at the next gap
- Slower particle arrives late and gets a smaller kick which makes it arrive even later at the next gap

Figure 8. Choosing ϕs such that the motion about the synchronous particle is not stable. Courtesy of Larry Rybarcyk.

To maintain the stable motion of the beam, longitudinally it needs to be within a phase space region bounded by what is generally referred to as the separatrix, or more colloquially, the "fish". The separatrix is a nice graphical way to show where the areas are in which the particles will exhibit stable motion (meaning they will continue to accelerate) and which particles will "get lost". This means they don't get accelerated properly and eventually become spill of some sort. This relationship is shown graphically in Figure 9.

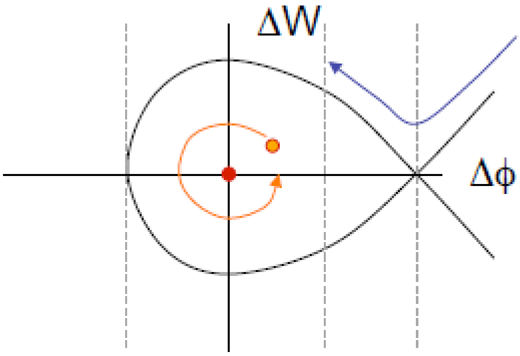
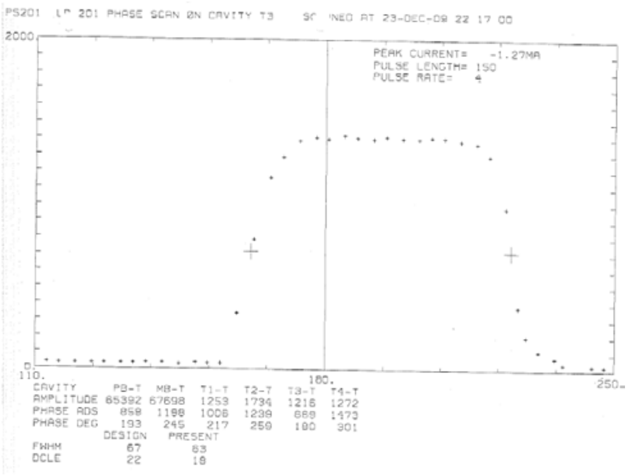


Figure 9. Examples of stable and unstable motion within phase space. Courtesy of Larry Rybarcyk.

MEASURING THE LONGITUDINAL TUNE

How this tune gets measured is dependent on the machine and energy level. A common method used at a number of machines is the absorber and collector technique. Here, a device, usually a slab of metal whose thickness is designed to completely absorb particles below a certain energy, is placed in the beam. A collector, such as a Faraday cup, is placed behind the absorber and measures the amount of beam current getting through the collector. By scanning though the RF phase of the accelerating structure, one can plot out the results and see the optimal RF phase setting. Figure 10 shows an example from LANSCE, but the technique is comparable at other machines.



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PS201  L  201 PHASE SCAN ON CAVITY T3     SC  NED AT 23-DEC-09 22 17 00
PEAK CURRENT=    -1.27MA
PULSE LENGTH= 150
PULSE RATE=    4
CAVITY      PB-T  MB-T   T1-T  T2-T  T3-T  T4-T
AMPLITUDE  65392 67698   1253  1734  1216  1272
PHASE ADS    858  1188   1006  1239   689  1473
PHASE DEG    193   245    217   259   180   301
          DESIGN    PRESENT
FWHM         67        83
DCLE         22        18
```

Figure 10. Example of a phase scan of Module 2 at LANSCE.

Another common procedure for longitudinal tuning as the particles get up to higher energies is the Delta-T scan. In this procedure, beam position monitors between accelerating cavities measure the difference of the phase of the beam between the RF accelerating field being on and off. The measurements from the two devices are then compared to the design and appropriate adjustments to the phase and amplitude can then be made to optimize the settings [3].

INDIRECT TUNING - SPILL

Up to this point we have looked at issues around getting the beam to do what we want it to. Now we will mention what happens when it is doing what we do not want it to do. Most machines have some method of detecting the particles that have "gotten lost". Either they have fallen out of the longitudinal bucket, scraped on something, etc. These particles eventually hit something and the result will send out secondary radiation such as gamma rays that can be detected. This is called spill. Spill detectors are often either scintillation material or ionization chambers. I mention this because minimizing spill is a part of the tuning process and a discussion of it gets us into the realm of what is the relation between setting up a tune and maintaining a tune. After an acceptable tune is established using instrumentation for determining the emittance and acceleration of the beam, the tune typically needs to be optimized. At LANSCE, this usually involves a lot of "tweaking" of accelerator elements to improve certain beam parameters. These parameters are most often the beam transmission and the spill levels. The optimization of the beam parameters is where the tune maintenance skills of the accelerator operators often come into play. Figure 11 shows the spill monitoring of the LANSCE linac for a well-established tune.

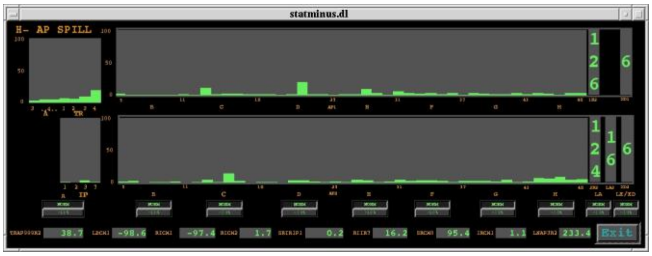

Figure 11. Linac spill monitors for the LANSCE accelerator.

THE CONTROL ROOM

The control room is worth mentioning because in many ways it is the human-machine interface for a tuner. Furthermore, the control room has evolved over the decades in some interesting ways. Figure 12 shows a series of control rooms over the decades.

Figure 12. Controls rooms from A) the 88-inch cyclotron, B) the Advanced Light Source, C) the Advanced Photon Source, and D) the Large Hadron Collider.

CONCLUDING REMARKS

Physicists care about the phase distribution of the particles in the accelerator beam, both transversely and longitudinally. This is what we want the instrumentation to tell us.

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[2] M. Stockli, “Emittances, Straight and Simple: their Usefulness and their Limitations”, LANL Seminar, February 28, 2008.

[3] K. Crandall and D. Swenson, “Side Coupled Linac Turn-on Problem”, MP-3-98, February 9, 1970.