Computer Lab: Intro to madx, Lattices and Dispersion

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This lab uses the program `madx`, a standard tool for accelerator lattice design developed over many years by CERN scientists and collaborators. It is available for many different operating systems and is still in active development. Extensive (likely even overwhelming) documentation is located at `http://madx.web.cern.ch` under the "Documentation" link in the left sidebar and shortcuts, including some "tutorials".

Some of the early part of this writeup is based on a set of slides at `http://accelerators.org.au/indico/getFile.py/access?contribId=13&resId=7&materialId=slides&confId=4` from Ken Peach, who inherited and modified them in order from Suzie Sheehy, Ted Wilson, and Volker Ziemann. Some other excellent slides that I will show in class are at `http://indico.cern.ch/event/286275/contributions/651708/attachments/531417/732835/juas.pdf` from Guido Sterbini at the Jan 2014 JUAS school. Why be original when you can liberally "borrow" what works?

There are *many* other codes available for beamline design, particle tracking, electromagnetic field calculations, plasma calculations, and other diverse areas of research in accelerator physics. madx does some things extremely well (particularly optics design and matching), and some things reasonably well (tracking or pushing particles through magnets like in large accelerators). There are some things it does not do very well though:

- Acceleration and tracking simultaneously. (esme and BLonD are better longitudinal dynamics engines.)
- Not very good approximations for large excursions, particularly large δ as found in FFAGs.
- Tracking through spatial descriptions of measured magnetic fields ("field maps": elegant and zgoubi are better at this).
- Very complicated magnet geometries (where field maps are usually better descriptions than multipole coefficients anyway).

It is likely that you have been exposed to some already and will be exposed to many more over the course of your career. A list of some common codes and links to further indices are at `https://en.wikipedia.org/wiki/Accelerator_physics_codes`.

Good practice in USPAS labs is to create a directory on the desktop with the class name and a unique identifier, and to work within that directory. That will nicely partition partition your work from other classes sharing the lab while still making it easily accessible. You can also put this directory on a USB memory stick if you have one; it will make it easier for you to move to different computers in the lab.

1. A Toy FODO cell

   (a) Download the RHIC FODO lattice madx file from `http://www.toddsatogata.net/2017-USPAS/lab/fodo.madx` to your working directory. Open this file in a text editor. Lines that begin with `//` or `!` are comments and *all statements must end with a semicolon.* You will see several sections, including some precursor information; beam, element, and lattice definitions; and actions. madx also lets you input commands from other files with the `call file='filename';` statement. madx is mostly case-**in**sensitive.

   (b) The element and lattice definition sections both have some interesting features. The `K1` in the quadrupole definitions is the linear focusing (the 1 stands for first order) K value, so the focal length of each quadrupole is $f = 1/(K1\,L)$. The quadrupoles are split in half so we can easily calculate twiss parameters at their centers. The drift is also sliced up into sections so the twiss plots show the beta function curves more clearly rather than linearly interpolating the plots between distant points. The lattice definition also uses a nice shorthand in madx for repeated occurrences of an element.

   (c) Type `madx` in the terminal command line, then at the prompt type

   `call, file=fodo.madx;`

   You can hit a carriage return at the various prompts when madx displays lattice functions. You may have to hit "q" in the plot window to move forward to the next plot. When the prompt returns at the end, type

   `exit;` or `quit;` or

   to exit from the program. You will also see that madx has written the files `madx.ps` (containing both plots), and `fodo.dat` (containing twiss parameters at the magnets).

   (d) By default the `MATCH` command adjusted the incoming $\beta_{x,y}$ and $\alpha_{x,y}$ parameters until their behavior moving through the lattice was periodic; it did not change any magnet strengths.

   (e) Open and print the `madx.ps` lattice function plots. You can fiddle with the initial conditions of $\beta_{x,y}$ in the first plot (such as moving them closer to or further from the periodic conditions found by MATCH) and re-run madx to see how the first plot changes. Try figuring out how you adjust their slope by changing $\alpha_{x,y}$ in the TWISS command from the madx documentation. The second plot is after a `MATCH` command that adjusts the initial twiss parameters until their transport is periodic through this lattice so it will usually rematch whatever you throw at it. Remember that $\beta_{x,y} > 0$ but $\alpha_{x,y}$ can be positive or negative.

2. The RHIC FODO cell

   (a) There are design parameters for the RHIC arc FODO main arc optics in a document at the class website, `http://www.toddsatogata.net/2017-USPAS/lab/rhicdm.pdf`. These are taken from the full RHIC configuration manual located at `http://www.bnl.gov/cad/accelerator/docs/pdf/RHICConfManual.pdf`.

   (b) Download the RHIC FODO lattice madx file from `http://www.toddsatogata.net/2017-USPAS/lab/rhicfodo.madx` to your working directory. You will see sev-

eral sections again, including some precursor information; beam, element, and lattice definitions; and actions.

(c) Type `madx` in the terminal command line, then at the prompt type

```
call, file=rhicfodo.madx;
```

You can hit a carriage return at the various prompts when madx displays lattice functions. When the prompt returns at the end, type

```
exit;
```

to exit from the program. You will also see that madx has written the files `rhicfodo.ps` (containing both plots), `rhicfodo1.twi` (containing ascii twiss parameters from the unmatched FODO cell), and `rhicfodo2.twi` (containing raw ascii twiss parameters for the matched FODO cell).

(d) Open and print the `rhicfodo.ps` lattice function plots, and compare them to the RHIC design optics. (Note that the RHIC design optics plot actually plots $\beta_{x,y}^{1/2}$.) You can fiddle with the initial conditions of the beta functions in the first plot and re-run madx to see how the first plot changes. The second plot is after a `MATCH` command that adjusts the initial twiss parameters until their transport is periodic through this lattice so it will usually rematch whatever you throw at it. Remember that $\beta_{x,y} > 0$!

Q1 (2 pts): Why is β_y(max) smaller than β_x(max) in the matched cell? How would you change magnet strengths to make them equal?

Q2: (2 pts) Find the phase advance per cell from numbers in the `rhicfodo2.twi` matched twiss file and compare to the design values of $2\pi\times0.224$ horizontal and $2\pi\times0.237$ vertical. Is this lattice overfocused or underfocused compared to design?

Q3: (3 pts) Given the FODO lattice parameters, do the β_x(min), β_x(max), η_x(min), and η_x(max) agree with equations (6.5-6) and (6.25, 6.27) in Conte/MacKay?

Q4: (3 pts) For IBS suppression, we have decided to change the phase advance per cell to 120 degrees in each plane. How much stronger do we need to make the quadrupoles? What happens to the periodic beta functions and dispersion? The reduced periodic dispersion is what limits the coupling between longitudinal and transverse motion and makes this an "IBS suppression" lattice.

Q5: (4 pts) Return to the original RHIC lattice, and vary the quadrupole strengths to explore the limits of the FODO lattice stability. Are your observations consistent with the necktie diagram for FODO stability, Figure 6.1 in Conte/MacKay?

3. Quadrupole error in a periodic lattice

(a) Download the RHIC FODO10 lattice madx file from `http://www.toddsatogata.net/2017-USPAS/lab/rhicfodo10.madx` to your working directory. Run madx to see how it's a pretty, symmetric lattice, and have a look at the madx file itself.

Q6 (3 pts): Lower the QDH5 magnet strength by 10% — this will change only this magnet in the regular lattice. Note that the beta functions now alternate up and down — you have broken the lattice symmetry. What is the lattice periodicity now? Can you fix this by increasing a different quadrupole strength to compensate?

Q7 (4 pts): For a single 10% error in this lattice, calculate the change in the quadrupole strength ΔKL and the peak $\Delta\beta_x(s)/\beta_x(s)$:

$$\frac{\Delta\beta_x(s)}{\beta_x(s)} = \frac{1}{2\sin(2\pi Q_x)}(\Delta KL)\beta_x(s_{\text{quad}}) \tag{0.1}$$

This is the beta wave from a single quadrupole error located at s_{quad} with beta function $\beta_x(s_{\text{quad}})$. Is this calculation consistent with what you observe?

4. Dispersion suppressors insertion

   (a) Download the RHIC FODO10 lattice madx file from `http://www.toddsatogata.net/2017-USPAS/lab/rhicfodo10d.madx` to your working directory. Run madx to see how it's a pretty, symmetric lattice, and have a look at the madx file itself. This is the ten-cell lattice, except that some dipoles have been removed in four cells to make a straight section. Note that the beta functions have hardly changed, but the dispersion has become an absolute mess.

Q8 (4 points): We want the dispersion to be zero through the straight, and the normal FODO dispersion through the rest of the arcs. Adjust the cells next to the straight to become dispersion suppressors such that you have the regular lattice dispersion in the cells at the edge of the plot, and zero dispersion through the straight section. Remember that the best way to make a dispersion suppressor is to watch eta and eta' as they enter and exit the area where you want the dispersion to be zero and flat.