FFAG Cell Candidate February 2017

Stephen Brooks 2017-Feb-23 CBETA machine note #9

1. Summary

The magnets for the CBETA "First Girder" have been ordered on the basis of the FFAG cell given in note [CBETA001]. However, detailed dynamics studies of this cell have shown the 42MeV energy is close to a $Q_x+2Q_y=1$ cell resonance [CBETA007]. The cell intended for the final CBETA machine was therefore retuned to avoid this resonance. The changes are summarised below.

Magnet	Parameter	Old value	New value
QF	Quadrupole (T/m)	-11.5	-11.2
BD	Dipole at centre (T)	-0.311	-0.309
BD	Quadrupole (T/m)	11	10.7

As previously, the values in the table above are average values – that is, integrated fields as measured from a single magnet on a rotating coil, divided by the magnet nominal length. Thus, the new magnets can also be specified by their integrated fields given in the table below.

Magnet name	Integrated dipole (T.m)	Integrated quadrupole (T)
QF	0	-1.49296
BD	-0.0376053	1.30219

The lengths of the magnets have stayed the same as before (QF=133.3mm, BD=121.7mm).

The cell geometry is now arranged around a "block-and-straight" design that will be described in other documentation, but the drift lengths are to a good approximation the same. The magnet design will be finalised soon and described in another note.

This cell may or may not be the final CBETA cell, but is intended as our current best working point for further studies to confirm its suitability.

2. Changes to the Tunes

This change to the magnet strengths affects the cell tunes in the way shown in the table below. All calculations were done with the Muon1 code using a soft-edged field model falling as 0.5+0.5*tanh(z/2.5cm) at each end of each magnet.

Total Energy (MeV)	Old Q_x	New Q_x	Old Q_y	New Q_y
150	0.102835	0.100854	0.039079	0.036222
114	0.126853	0.124162	0.068072	0.064874
78	0.182031	0.178065	0.128300	0.124370
42	0.383192	0.366829	0.301829	0.291162

The main change was to reduce the 42MeV tunes enough to avoid the $Q_x+2Q_y=1$ cell resonance. The old cell had $Q_x+2Q_y=0.98685$ and the new cell has $Q_x+2Q_y=0.94915$, which studies by Scott Berg have

shown to be a comfortable distance from the resonance, in the sense that it is similar to the distances from other resonances that bound the working region.

3. Changes to the Orbit Excursions

Generally speaking, when the cell geometry is held constant, lowering the highest tune or increasing the lowest tune in a non-scaling FFAG cell increases the orbit excursion. Our maximum orbit excursion is in the QF magnet and the table below shows how the minimum and maximum local x values in the QF magnet have changed.

Cell Version	Local x_{min} in QF (mm)	Local x_{max} in QF (mm)	Distance from 2.75" ID vacuum pipe (mm)
Old (first girder)	-21.744	21.474	13.181
New (February 2017)	-22.696	22.755	12.170

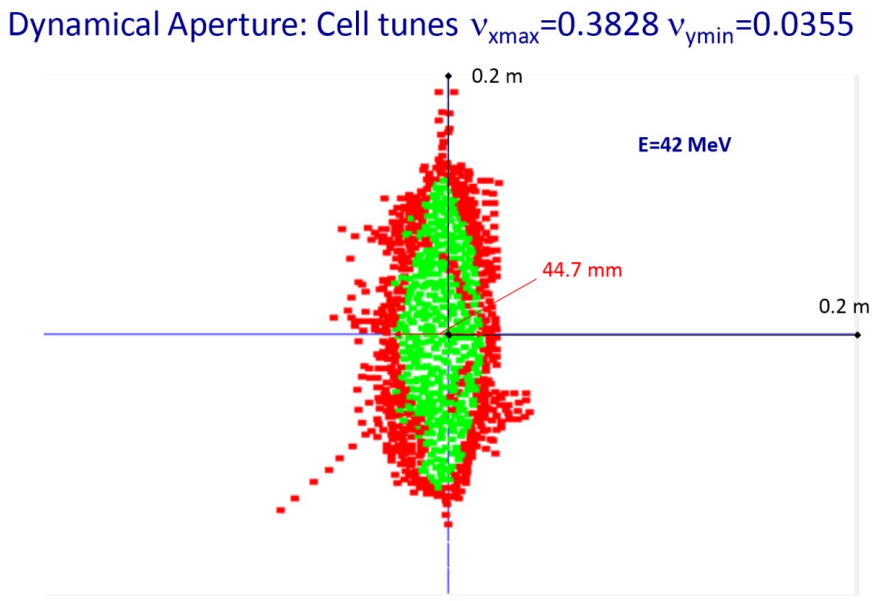
The new cell has ~1mm less clearance but still, in this field model, more than the 12mm required by the original CBETA specification.

4. Dynamic Aperture Code Issues

This resonance initially only appeared in Francois Meot's Zgoubi tracking code, which tries particles of gradually greater amplitudes until it finds a loss.

Scott Berg initially did not see it, but found that making the particle loss condition stricter, to eliminate particles whose amplitude had doubled from the starting amplitude, rather than waiting for the amplitude to tend to infinity, showed the resonance.

Stephen Brooks did not see the resonance at all in Muon1's dynamic aperture study, which used the real beam pipe as the loss condition. However, the Muon1 study counted the entire area of the transmitted beam region as the figure of merit for a given working point. The problem with this became clear when Dejan Trbojevic did a dynamic aperture study in MADX-PTC, resulting in the plot below.



Some of the losses (red) are at smaller amplitudes enclosed inside the overall accepted region. So, the Muon1 study counted the entire green area and did not see the losses at low amplitudes that actually dictate the safe amplitudes for beams. It is planned to rerun the Muon1 study with an updated dynamic aperture definition at a later date.

5. Appendix: Parameter Space Explored

Some other combinations of gradients and tunes were tried before settling on this combination. In the spreadsheet below, the two gradients were varied without changing the BD central dipole and the maximum (42MeV horizontal) and minimum (150MeV vertical) tunes were noted, as well as the orbit ranges and likely distance to the beam pipe.

QFQ	BDQ	Qmax	Qmin	QF xmin	QF xmax	QF halfran	To 2.75" ID pipe (Yulir	Muon1, soft-edge field model, fringe=2.5cm				
-11.5	11	0.382737	0.039005	-0.02188	0.021619	0.021749	0.013176	First girder lattice (my "v3.2")				
-10.8	10.4	0.348768	0.036904	-0.02453	0.023633	0.02408	0.010845	Bringing the tune down to the old 0.34x value (for iron)				
-10.7	10.4	0.344048	0.040445	-0.02501	0.024526	0.02477	0.010155					
-10.8	10.3	0.349375	0.03196	-0.02445	0.023014	0.023732	0.011193					
-10.7	10.3	0.344641	0.035967	-0.02493	0.02386	0.024396	0.010529					
"Compromise" parameters												
-11.1	10.6	0.362611	0.035073	-0.0233	0.022398	0.022849	0.012076	Stephen's suggestion after talking to Chris				
Towards Scott's suggestion (nux(42)=0.3712, nuy(150)=0.0357)												
-11.2	10.7	0.367343	0.036078	-0.02293	0.022199	0.022566	0.012359	<-- Scott actually prefers this one, Stephen has no problem with it				
-11.3	10.8	0.372263	0.037068	-0.02257	0.022002	0.022288	0.012637					
-11.3	10.7	0.372878	0.032145	-0.02252	0.021473	0.021995	0.01293					
Deltas												
0.1	0	-0.00554	0.003933	-0.00042	0.000726	0.000571	-0.00057	det	-2.48303E-05	inverse	-198.27	158.4112
0	0.1	-0.00061	0.004923	-5.6E-05	0.000529	0.000292	-0.00029				-24.7681	222.913
Required change		-0.00168	0.003555									
0.024464	0.052666											
-11.2755	10.75267	0.371165	0.035754	-0.02265	0.021926	0.022287	0.012638	Bringing the low tune down doesn't seem to have any advantage				

Low tunes were initially tried that emulated the 0.34x cell tune of the iron lattice, but these produced orbit excursions that were too large. A compromise was found that retained the 12mm clearance and finally Scott Berg suggested going even higher in tune as this gave an operating point that had some flexibility to jump over a resonance if the linac energy was varied, as a fallback.