Making Room for PIP-II in F-sector

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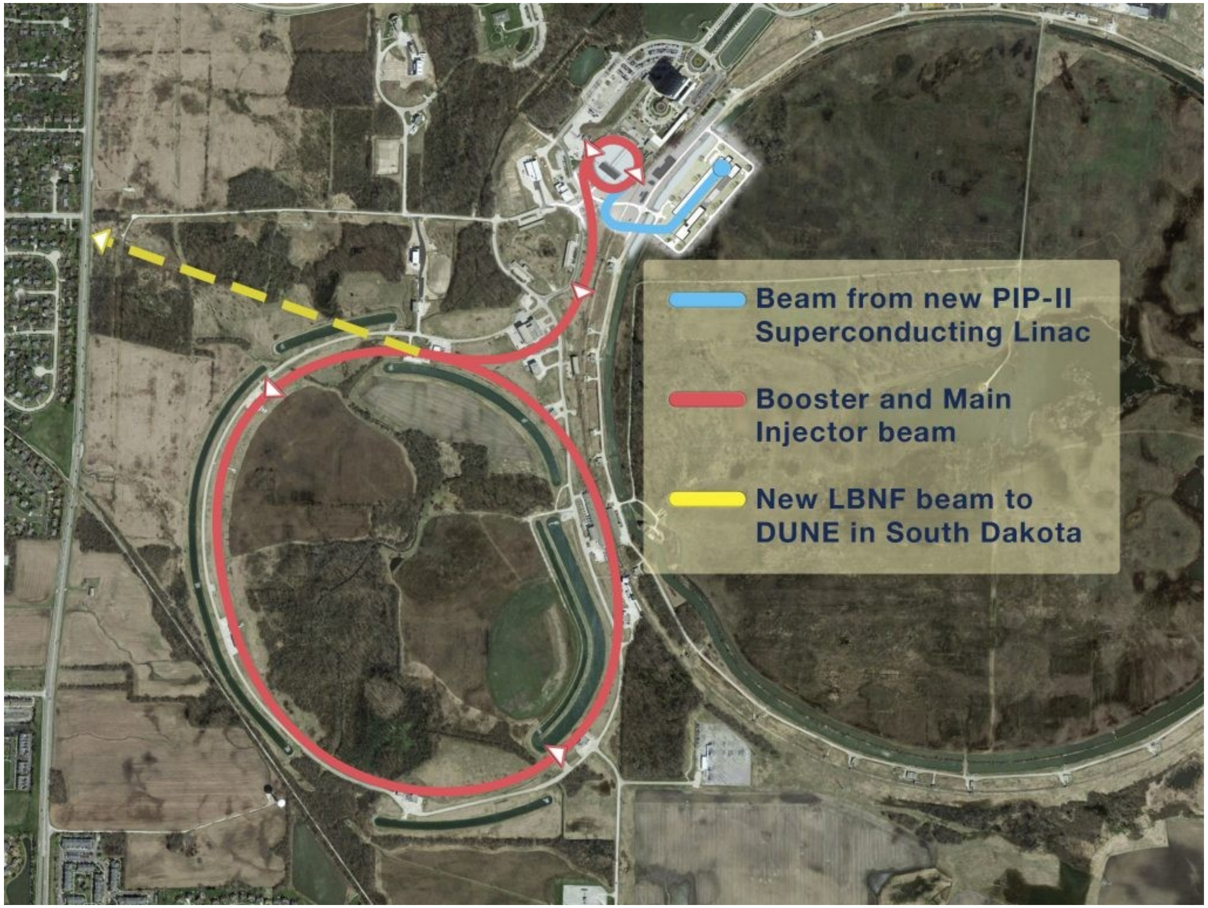
PIP-II Overview

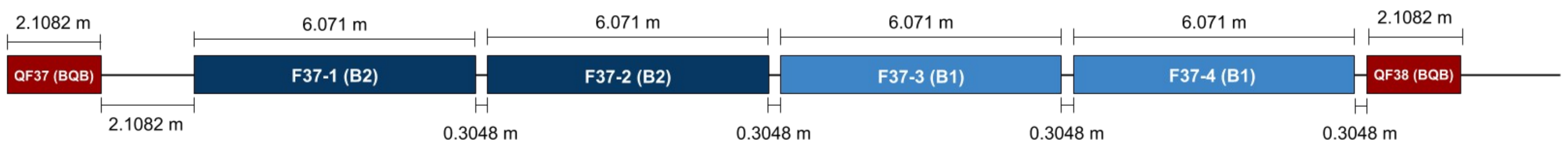
PIP-II beamline will cross the Main Ring at F37 on its way to the Booster. We need to make room in the Main Ring lattice for their magnet moves, etc.



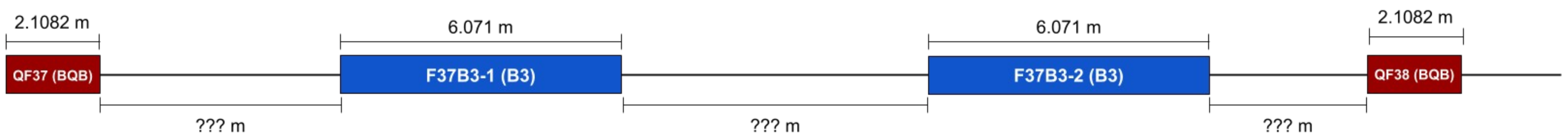
Fermilab

F37 in P3 Beamline

The F37 section of the P3 beamline is a Main Ring half-cell that consists of two Main Ring quadrupoles (BQB) and four Main Ring dipoles (2x B1 and 2x B2).



The goal is to replace the four dipoles with two B3 dipoles to create a space in the middle of the sector for PIP-II. Must work out spacing to ensure effective bend center of the sector is unchanged.

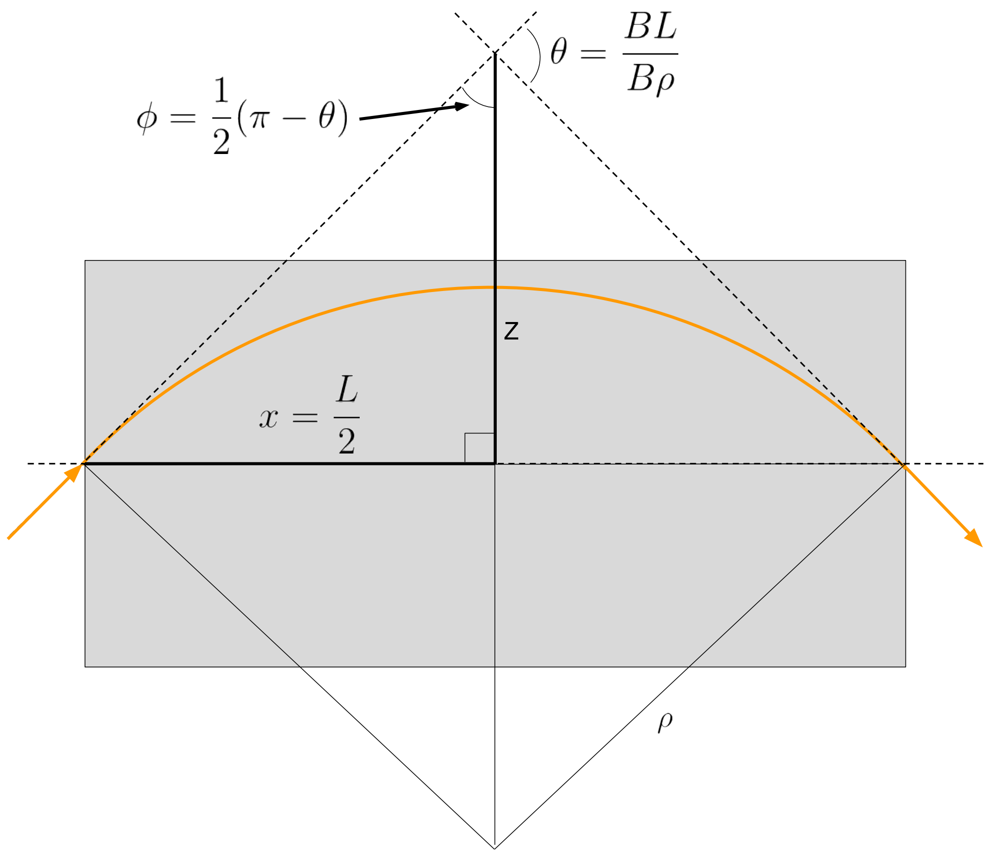


B3 dipoles on HP3DS bus

- B1 (aperture 5” x 1.5” x 240”) and B2 (aperture 4” x 2” x 240”) transfer function: 0.0024 T-m/A.
- B3 (aperture 5” x 3” x 240”) dipoles have the best aperture of each of B1 and B2, but with the same transfer function if the coils are wired in parallel. Wired in series, the transfer function goes up by a factor of two. This lets us wire the B3s into S:HP3DS (1358A) bus and get twice the field.
- Each dipole in P3 beamline bends 8.1178 mrad. Each B3 will therefore bend 16.2356 wired into the same bus with the coils in series.
- For B3 magnets, Dave Harding recommends a maximum RMS current of 775A for series coil configuration. Some B3 magnets have been modified for better cooling; not clear yet which ones.
- Maximum Switchyard ramp duty cycle is 6 second ramp every 45 seconds, i.e. 13.3% duty cycle. So max RMS current is 1358*(0.133)^0.5 = 495.25 A < 775 A.
- Old dipole string: R = 26 mOhm, L = 28.84 mH (source: TM-632)
- String of 2 B3s: R = **82.2 mOhm**, L = 27.188 mH (source: ODM030 TD meas.)
- Power supply load resistance increase is 56.2 mOhm, or ~13.2%. Inductance approx. the same. According to EE Support, this isn’t a problem.

Dipole magnet bend center

To approximate a rectangular bend dipole as a single angular "kick", compute the location of the "bend center", which is the intersection of incoming and outgoing symmetric beam trajectories (enter/exit angles equal).



Coordinates of the bend center with respect to the entrance point of the beam on the upstream face of the magnet:

$$x = \frac{L}{2} \qquad z = \frac{L}{2tan(\frac{1}{2}[\pi - \theta])}$$

For high-energy beam (i.e. large bend radius), y tends to be small.

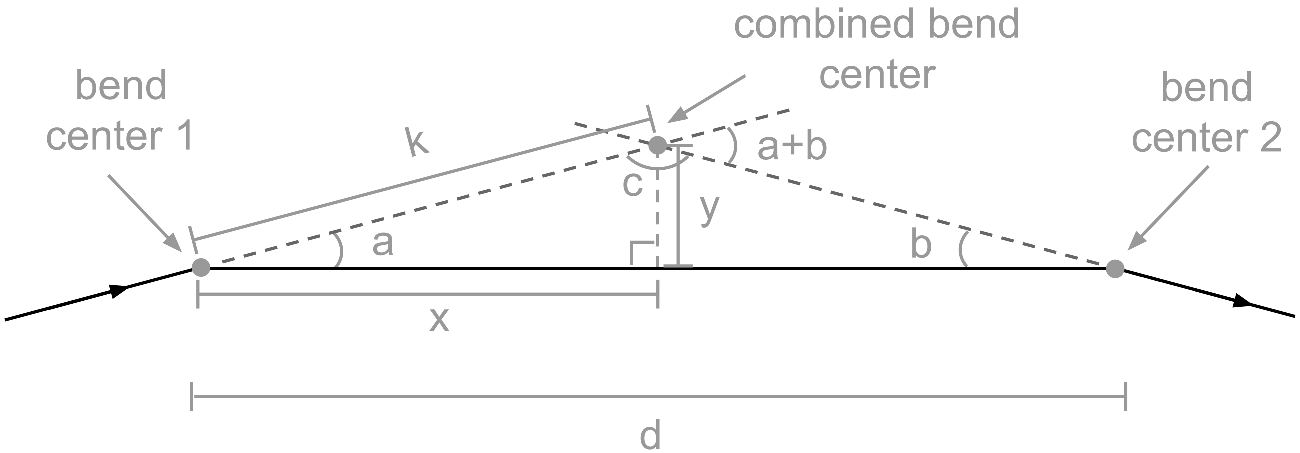
Example: for a Main Ring dipole, z = ~2.5 cm.

Bend center of multiple dipoles

Now each dipole magnet in the half-cell can be described as a simple bend center with an angular kick. Next, combine each magnet pair into a single effective bend center.

$$c = \pi - (a + b)$$

$$\frac{d}{sin(c)} = \frac{k}{sin(b)}$$



Therefore, the net bend center of the two magnets is at (x,y) with respect to the first bend center location:

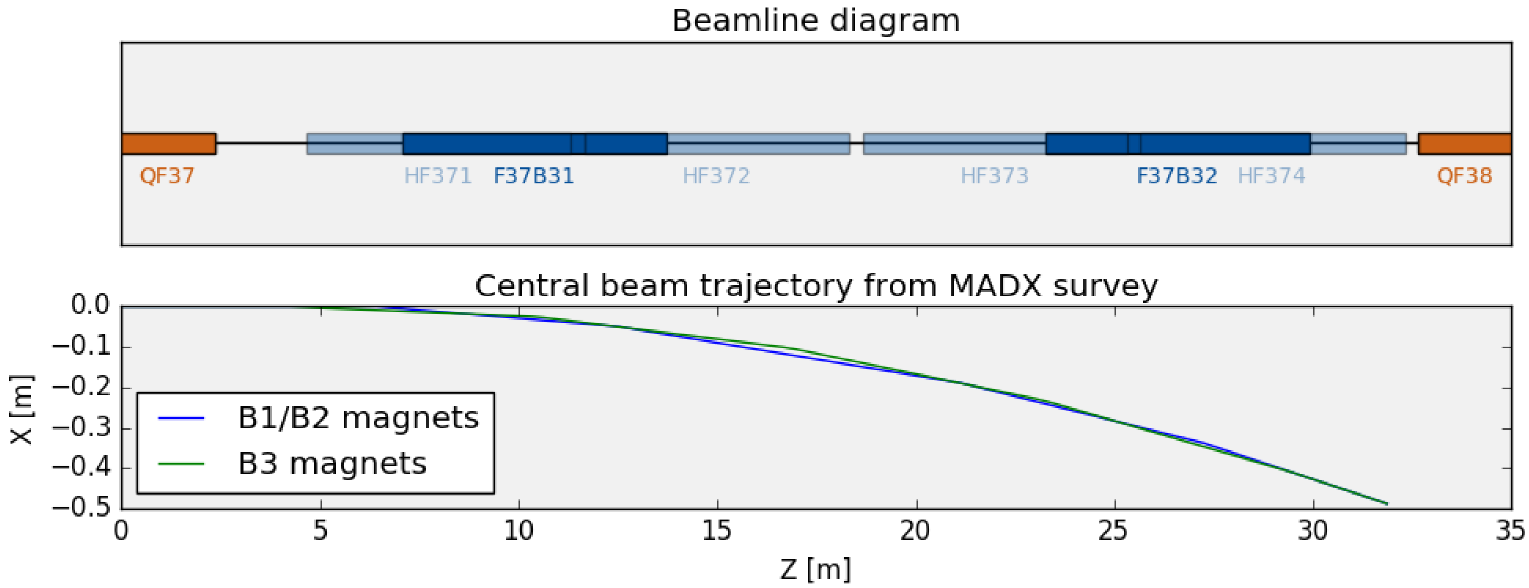
$$x = dsin(a)cos(b)csc(a - b) \qquad y = dsin(a)sin(b)csc(a - b)$$

To convert to the coordinates of the entire string, (x,y) must be rotated through any bend angles between the string’s origin and bend center 1, and translated with respect to the origin as well.

Use MADX to test B3 replacement

First, simply replace the pair of B1s with a single double-strength B3 whose bend center lies on the net bend center of the two original magnets. Do the same for the B2 pair as well. Then move the upstream B3 1m upstream and the downstream B3 1m downstream; this makes more room for PIP-II without affecting the bend center. Compare MADX survey with B3s to that of original B1/B2 configuration to verify beam trajectory unchanged.

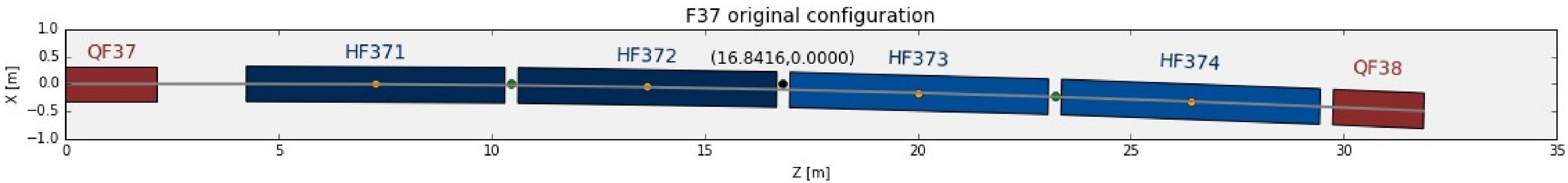
This leaves ~8.68m of free space between downstream end of F37B3-1 and upstream end of F37B3-2. Beam pipe between magnets will be “spool piece”, i.e. easily removed for PIP-II magnet moves.

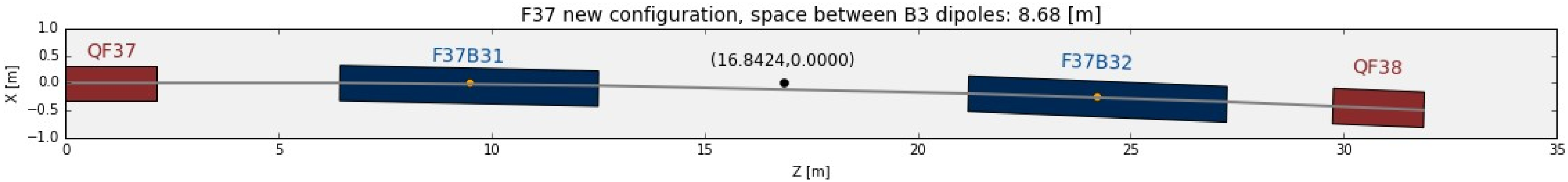


Use MADX to test B3 replacement

These plots show the magnets plotted in an overhead view with bend centers computed and plotted. Orange dot is bend center of individual magnet, green is bend center of B1 and B2 magnet pairs, and black dot is net bend center of the entire string.

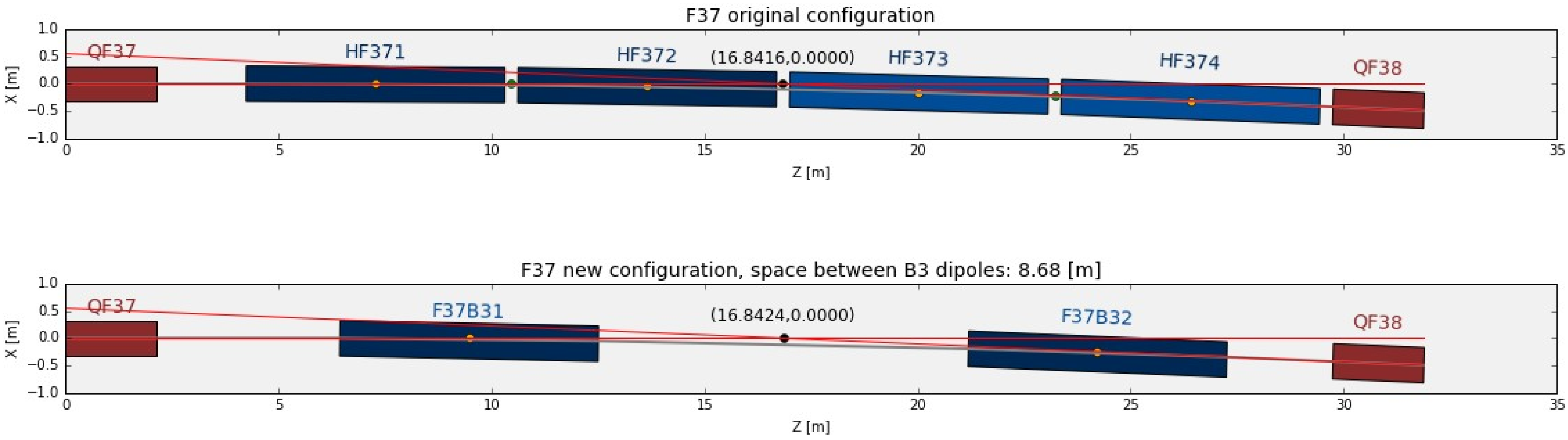
Original configuration is shown first, then replacing B1 and B2 dipole pairs with B3s at their combined bend centers and adjusting the B3s up and downstream by 1m about the combined bend center. Combined bend center in new configuration differs from original by <1mm.





Use MADX to test B3 replacement

As a sanity check, overlay the same plots with (red) lines extending the incoming and outgoing beam trajectories for the entire half-cell to show that the intersection aligns with the computed bend center.



Sagitta correction and distance to wall

The magnet's sagitta is the distance from the magnet center line to the arc of of the beam trajectory. Pictured below, the uncorrected sagitta "s_0" is large enough that the beam only travels through half the magnet's aperture "a". Shifting the magnet normal to the beam path arc (i.e. transverse shift) by $0.5*s_0$ maximizes use of available aperture.

$$s_0 = \rho(1 - cos(\theta))$$

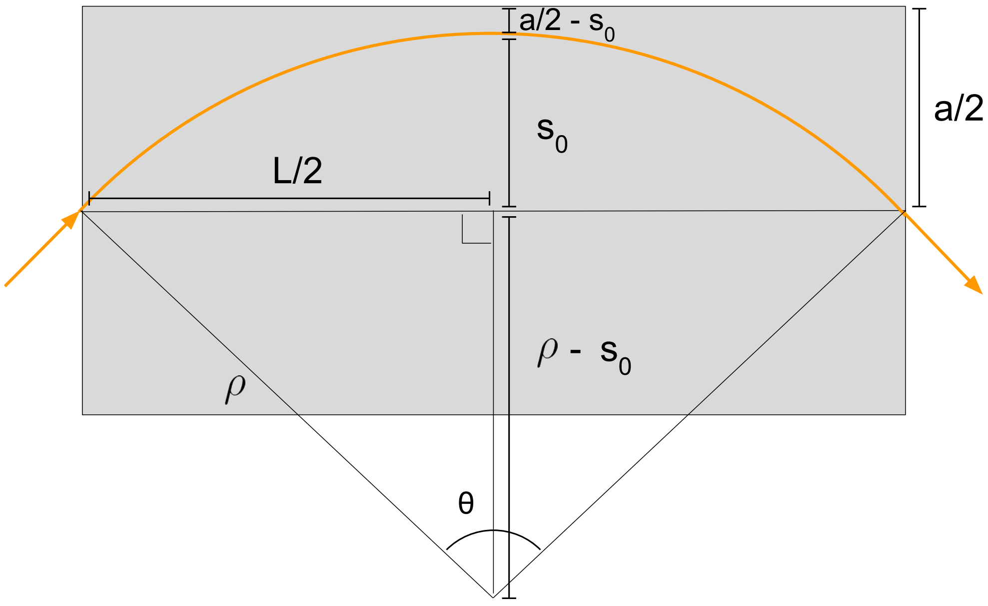
The bend radius is ρ and the bend angle θ, where:

$$\theta = \frac{B[T] * L[m]}{\frac{10}{3}p[GeV/c]}$$

$$\rho = \frac{1}{B[T]}\frac{10}{3}p[GeV/c]$$

So shift magnet toward outside of the beam arc by:

$$\frac{1}{2}\rho(1 - cos(\theta))$$



B3s are about 3.75" wider than B1s/B2s. With sagitta correction, B3s will be about 2.9" closer to the wall than B1s/B2s. I estimate we have about 10" minimum, so this should be fine.

Summary

- Two B3 magnets with coils in series configuration can replace the 2 B1 and 2 B2 dipoles in the P3 beamline at F37. They will be connected to the same HP3DS power supply and bus as the original dipoles. Adjusting B3 magnets away from bend center by 1m each gives a total of ~8.86 m space between the steel of the two magnets for PIP-II without changing the beam path. **Beam trajectory** ✓

- Taking into account sagitta corrections and extra width of B3 magnets, space to enclosure wall will decrease from ~10” to ~7”. **Enclosure space** ✓

- Total load resistance for HP3DS power supply will increase by ~13.2%. Load inductance will not change. **Power supply compatibility** ✓

- Maximum RMS current through B3s is 495.25 A, much less than Tech. Division’s recommended maximum of 775 A for series configuration coils. **Magnet cooling** ✓