ALIGNMENT

- *Alignment* = putting things in the right place
  - With respect to each other
  - With respect to ‘beam axis’
  - Essential for correct operation of cooling channel

- *Survey* = knowing where things are
  - Essential for detectors
    - But their alignment not (so) critical
      - As long as we know where they are

- *Magnets must be aligned*

- *Detectors must be surveyed*

MAGNET ALIGNMENT REVISITED

Subject arose at last CM; some confusion

I have revisited this

Chris Rogers searched the literature:

Four previous studies in MICE notes 64, 77, 202, 229

Some confusion about alignment of trackers and / or spectrometer solenoids

Alignment of the trackers *cannot* affect the emittance of the beam
but can – obviously – affect the measurement of it
must be known well enough

Alignment of S/C magnets can affect:

a) Performance of channel (emittance reduction)
b) Alignment & commissioning studies

Previous studies concentrated on (a); I concentrate on (b)

All documented in MICE note 445

PHYSICS OVERVIEW

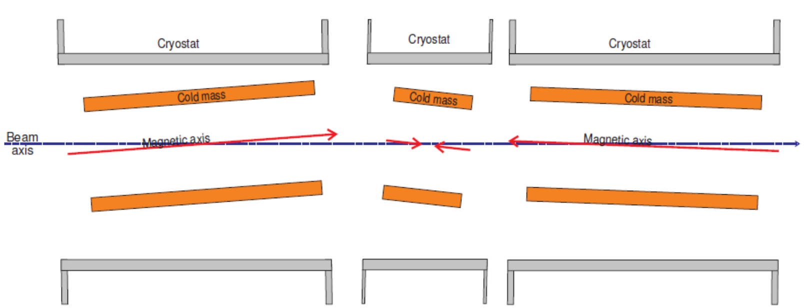
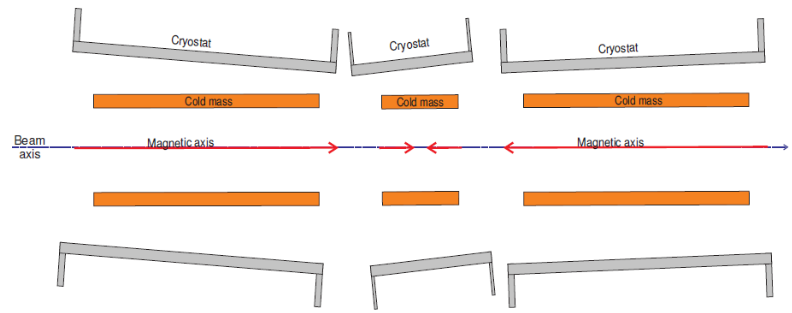


Figure 1: Misaligned modules in Step IV, much exaggerated.



Undesirable **Desirable**

Modules whose magnetic axes are offset & tilted wrt beam axis will give *pt* kicks to muons

Small kicks will move CoG of beam but will not change its emittance : CoG in *x, px,* &c are subtracted

Movement of CoG of beam, especially if momentum dependent, will make alignment & commissioning v. difficult to understand.

PREVIOUS STUDIES

MICE note	Tilt ψ (mr)	Offset d (mm)	Criterion	Comment
64	< 2.4	< 1.8	Reduce 15% $\Delta\epsilon/\epsilon$ to 14%	MC study; tolerances deduced from offsetting only one coil of one FC in Step VI
77	< 6.0 (rms)	3.0 (rms)	$< 0.1\%$ systematic increase in emittance	Extensive MC study of Step VI with random offsets and tilts of coils
202	< 10	< 2	'$< 1\%$ of 10%'	MC study of Step VI; beam started in centre of upstream SS ($z = -4.7$ m) (ψ deduced as $\langle p_t \rangle / p_z = 2/200 = 0.01$)
229	< 1	< 3	1% error on $\Delta\epsilon/\epsilon$	MC study; refers to *tracker* alignment; fields not shifted (?)

Table 1: Summary of previous alignment studies. In all cases the beam was started inside the upstream spectrometer solenoid.

In all cases simulated beam started at ~ mid point of SSU, *inside*

No study considered what happens to a reference muon entering from *outside*

The alignment tolerance was derived as "2mm – 2 mr" from dEps/Eps

EXPLORE WHAT HAPPENS TO REF. MUON

Simple tracking code in magnetic field

3D field model based on Bz on axis
- **gives error fields due to tilted & offset coil**
- **more than adequate for small tilts and paraxial muons**
- **details in MICE note**

Fast to run so I can play with it & get feedback

➔ Plenty of sanity checks

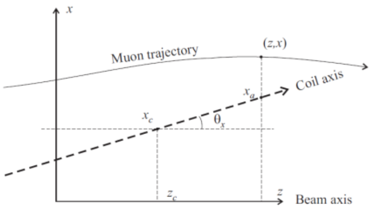


Figure 18: Geometry used for field calculation. Angles and offsets are small. z is the beam axis, θ_x is a small rotation around the y axis.

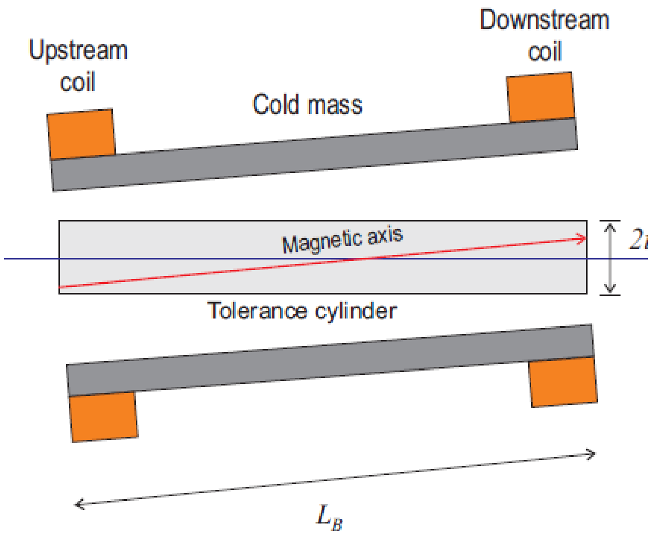
The coils are divided radially into coaxial cylindrical current sheets; all current sheets in a coil have the same tilts and offsets in x and y. In the beamline system the centre of a coil is at (x_c, y_c, z_c) where x_c and y_c are small offsets from zero. The x component of the magnetic field experienced by a muon at (x, y, z) is

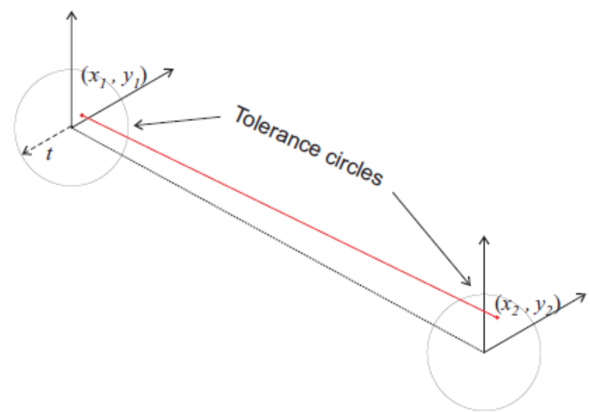
$$B_x = \sum_{\text{sheets}} \left(B_z \theta_x - \frac{(x - x_a)}{2} \frac{\partial B_z}{\partial z} \right)$$

where θ_x is a small rotation around the y axis in the $x - z$ plane and $x_a = x_c + (z - z_c)\theta_x$ is the x coordinate of the axis of the coil at z; the geometry is sketched in figure 18.

B_z is the z component of the field on the axis of a current sheet. The sum is taken over all sheets in all coils. The first term in the expression for B_x is simply the component of the axial field of the sheet resolved in the x direction; the second follows from $\nabla \cdot \mathbf{B} = 0$.

Tolerance Definition





"*x* mm – *y* mr" definition per coil hard to interpret for coils on common bobbin

Practical definition – easy to use / give to surveyors:

Bobbin axis must lie within a *t* mm radius cylinder of beam axis

➔ Translates to circles at ends of modules (flange faces)

Following studies use bobbins rather than individual coils

All for STEP VI 200 MeV/*c* Flip mode, empty channel (*the good old days*)

***Aligned but offset channel*:**

All magnetic axes parallel but offset from beam axis by 2 mm in *x*

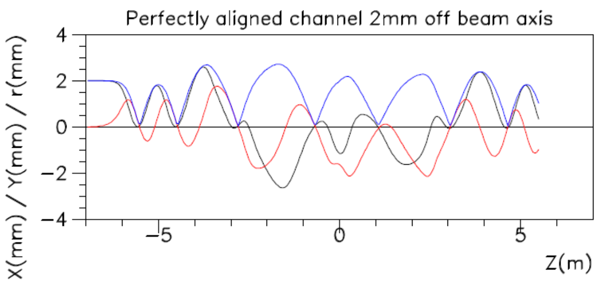
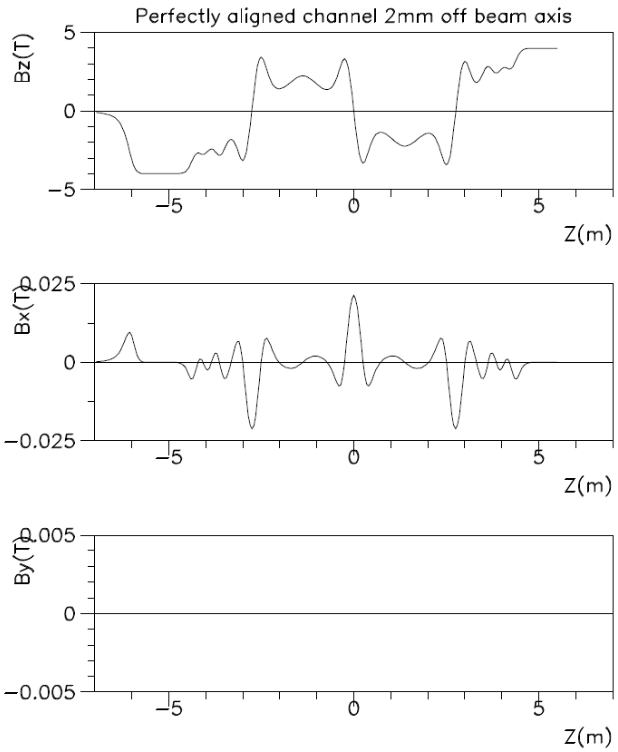
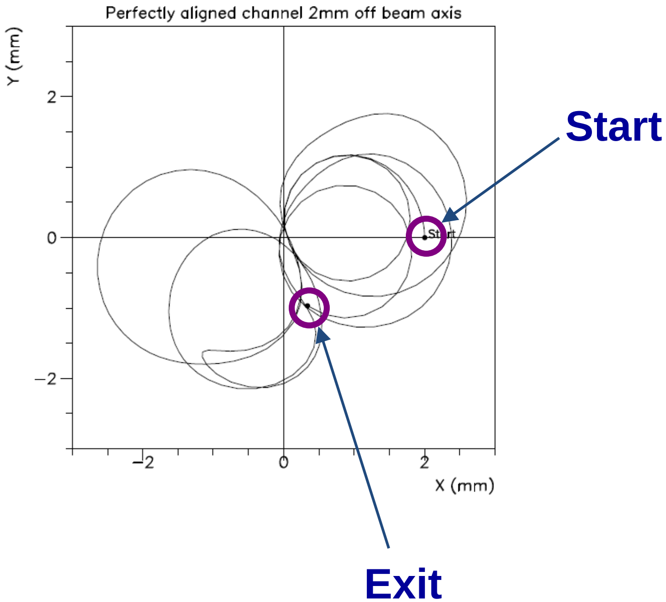


Figure 4: Trajectory of a 200 MeV/c reference muon, x-z (black), y-z (red) and r (blue), for channel axis offset by 2 mm in x.



200 MeV/c



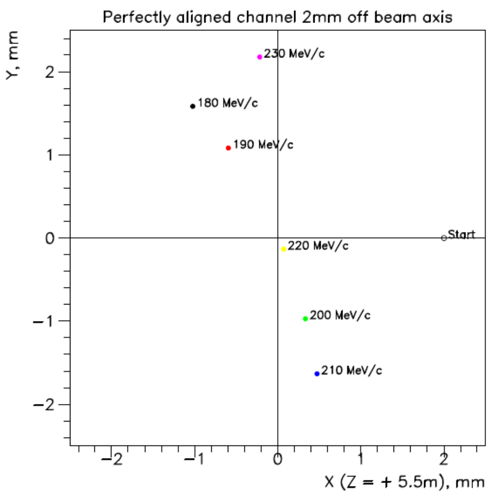
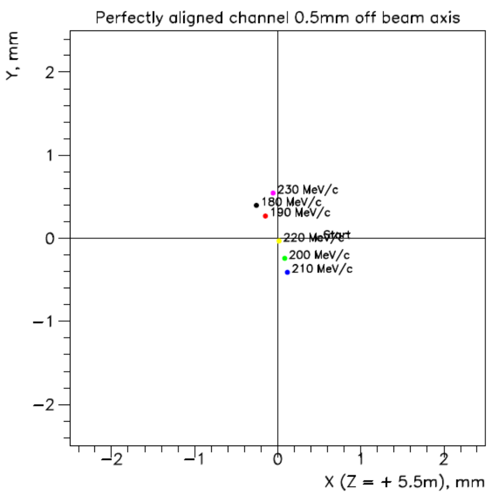


Figure 6: x - y with respect to magnetic axis at z = 5.5 m of reference muons of different momenta for channel axis offset by 2 mm in x.



There is dispersion (expected)

Starting position (z = –7.0 m) is (2,0)

At z = 5.5 m (~ centre SSD) position varies with pz within ~ 2mm radius ➔ "4mm problem"

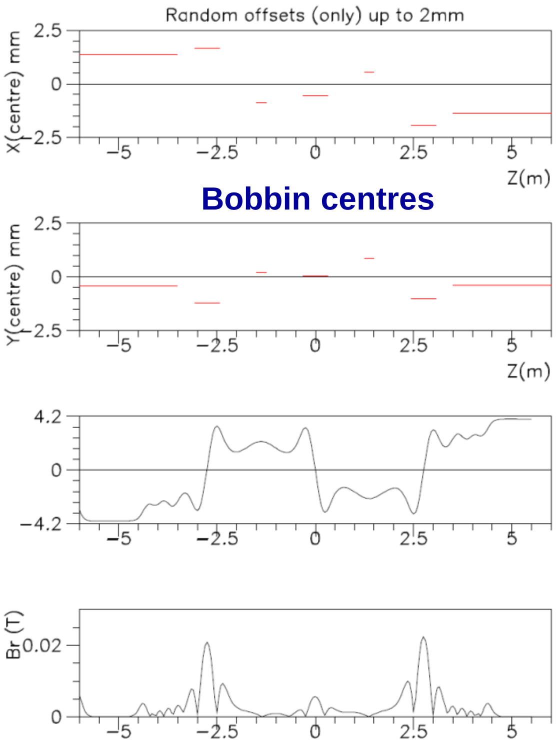
With 0.5 mm common offset problem ~ 1 mm

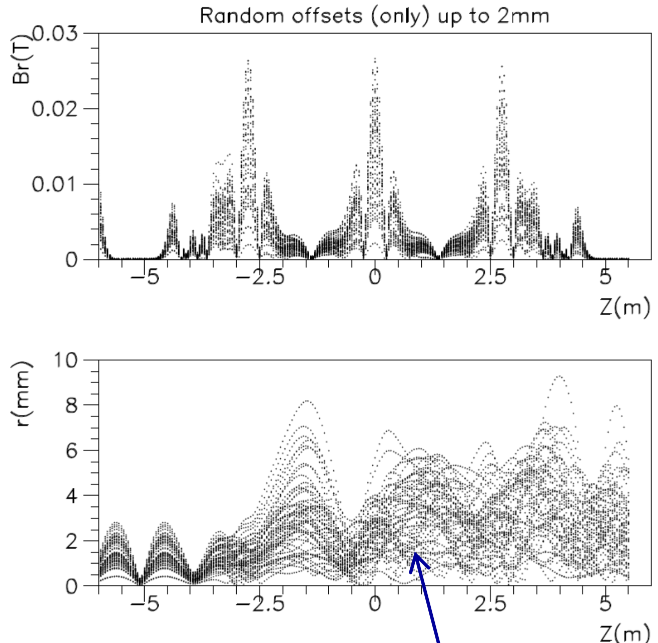
Not unexpected after a few moments thought: muon rotates 8 – 10 times in channel

➔ 2 mm is too much

Random offsets, no tilts

Shift bobbins randomly within *t* = 2mm cylinders, no tilt





Radial B

Radius (mm)

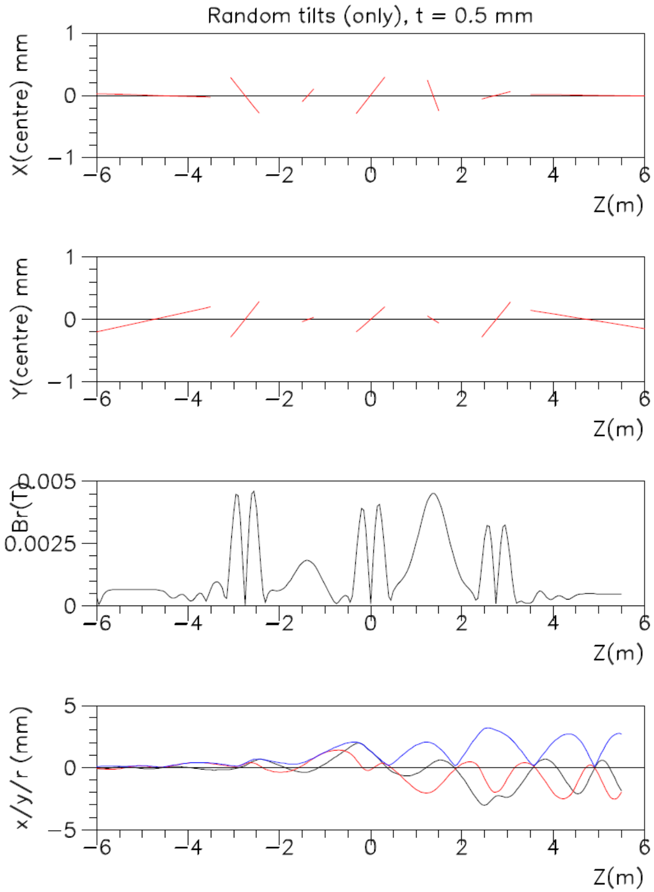
Too much

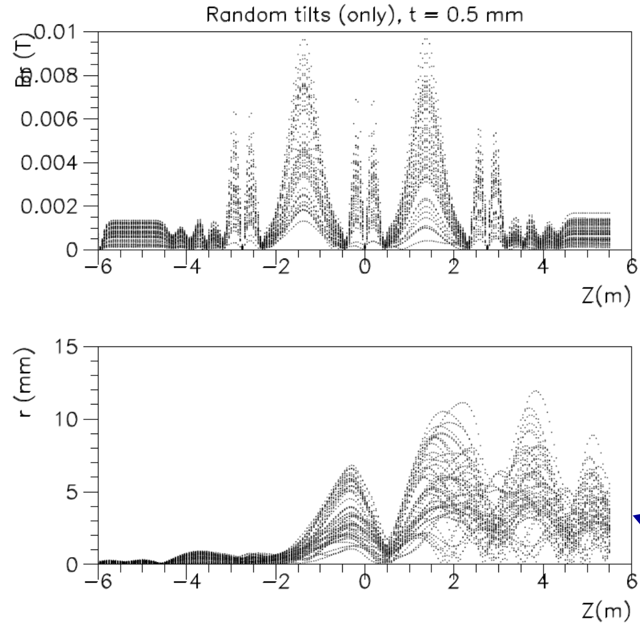
***One* set of offsets**

Reference trajectories for 50 random sets of offsets

Reducing *t* to 0.5 mm reduces spread by ~ 4

Random tilts, *no* offsets, *t* = 0.5 mm





Radial B

Radius (mm)

Too much

***One* set of tilts**

Reference trajectories for 50 random sets of tilts

‘DEMOCRATIC TOLERANCES’

pt kick of misaligned coil is proportional to *NI* ψ

$$\Delta p_t \propto \psi \int B_z dz \simeq \frac{2t_M}{L_B} \sum NI\psi$$

Set module-dependent tolerances, t_M, according to *NI*

Module	$\sum NI$ (M Amp-turns)	L_B (metres)	t_M (rel)	
CC	2.79	0.250	0.286	
FC	4.02	0.620	0.492	Solenoid mode; p_t kicks almost cancel in flip mode, $\sum NI = 0$.
SS	7.98	2.496	1.000	

Table 2: Module-dependent relative tolerances, t_M, with ‘democracy’ (see text).

➔ ~ 3 to 4 x tighter for CCs

Tilts *and* Offsets

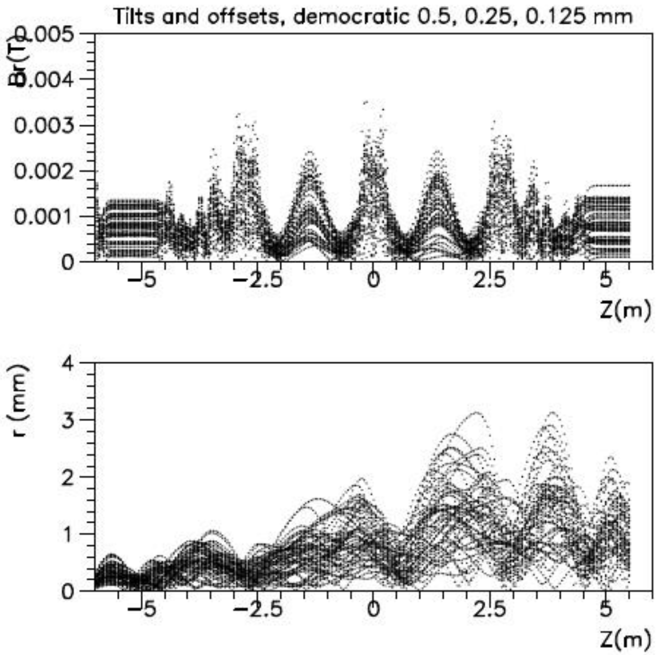


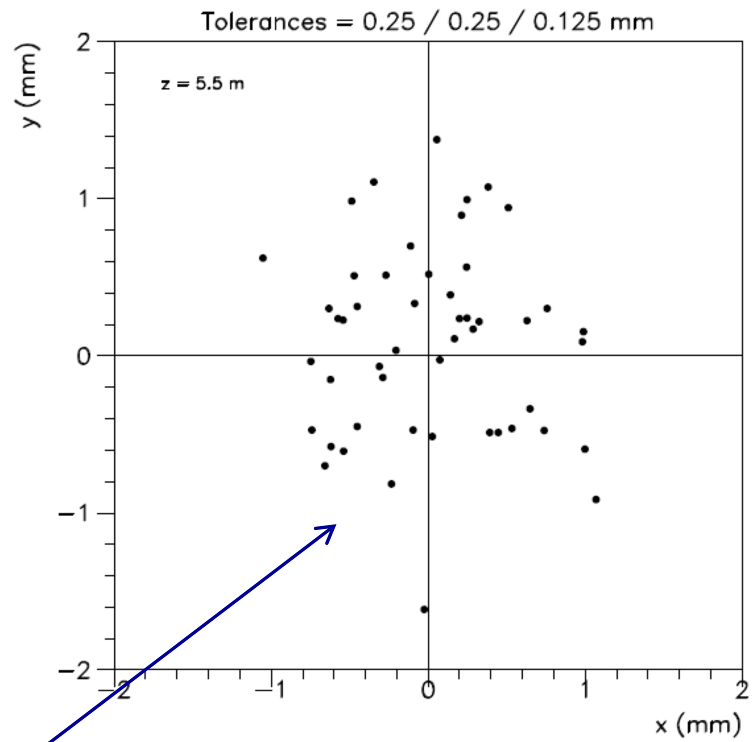
Figure 19: Radial field, B_r and radial displacement, r, from nominal axis of fifty 200 MeV/c reference muons for bobbins randomly tilted and offset with democratic module-dependent tolerances of 0.5 mm (SS), 0.25 mm (FC) and 0.125 mm (CC).

~ Democratic pt kicks

Better

1 – 2 mm offset in SSD

Look at other combinations ➔



CCs must be aligned to < 0.125 mm to be confident that reference muon will be within 1mm of axis in SSD

t_{SS} (mm)	t_{FC} (mm)	t_{CC} (mm)	r_{max} (all z) (mm)	σ_r in SSD (mm)	
2.0	2.0	2.0	39.6	13.4	
0.5	0.5	0.5	11.5	2.91	
0.25	0.25	0.25	5.74	1.45	
0.5	0.5	0.125	3.17	1.04	
0.5	0.25	0.125	3.14	0.94	
0.25	0.25	0.125	2.86	0.80	See figure 20
0.125	0.125	0.125	2.87	0.73	
0.5	0.5	0.0	2.06	0.74	CCs fixed
0.25	0.25	0.125	2.67	0.91	$180 < p_z < 220$ MeV/c

Table 3: Maximum radial displacement in channel, r_{max}, and σ_r, the rms radial displacement of the CoG of a 200 MeV/c beam at the centre of the downstream SS for various combinations of module-dependent alignment tolerances, t_M. The last row is for a beam with a finite flat momentum spread.

80 % probability that ref. muon is within 1 mm of axis in SSD

STEPS IV and V

I haven't studied Steps IV and V *and certainly not Step 3 π / 2*

Tolerances will be somewhat looser: perhaps ~ 0.18 mm for the CC

We shouldn't relax them for STEPS IV and V

Should do the best we can

Ideally:

SS	**0.25 – 0.5 mm**
FC	**0.25 – 0.5 mm**
CC	**0.15 – 0.2 mm**

These fractional mm tolerances will be very hard to achieve

The *magnetic mapping* must be done to at least this level

WHAT IF WE CAN'T ALIGN?

'The software can sort it out' (yeah, right)

It may not be possible to place the magnets in the right places

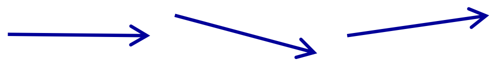
Depends on alignment of magnetic axes & flanges and clearances of flange bolt holes (+/– 2 mm ?)

If so, must survey (i.e. *know)* where the magnetic axes are to similar precision

If they are not known, 'Reverse engineering' from measured position of muons up- and downstream will be very hard:

> **12 parameter fit for STEP IV**
> **20 parameter fit for STEP V**

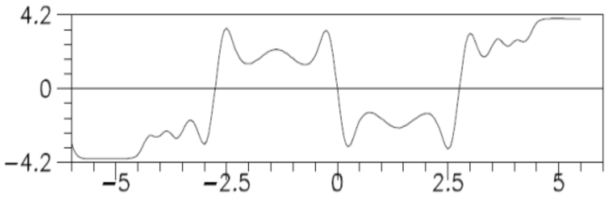
? Self alignment:



-- allow modules to 'float' when first powered

WHAT ABOUT STEP 3 π / 2 ?

- Haven't looked at it
  - Code I wrote not very GP
    - Would take some time to modify



- Off the top of my head:
  - In Steps IV, V, VI muons always see |B| > 2 – 2.5 T
    - muons are confined
  - In Step 3 π / 2 B is low between coils
    - there are (quasi) drifts ~ 700 mm between coils
    - muons at small angles can move off axis
      - Could be more demanding ???
    - Just have to do the best we can at O(0.25mm)