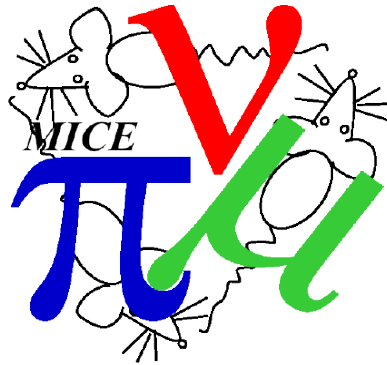


# Effect of Reduced Focus Coil Current on Step IV and Step VI



Chris Rogers,  
ASTeC,  
Rutherford Appleton Laboratory

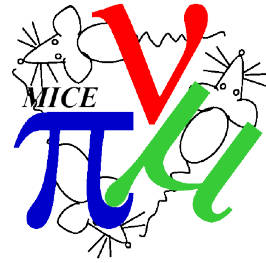


# Overview



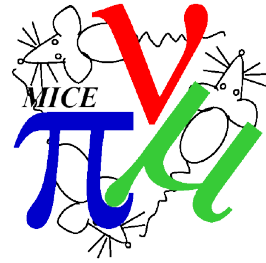
- Focus Coil 1 has not reached nominal currents
  - Stuck at around 200 MeV/c required current
  - Even here, need an operating overhead of order 10%
- If FC can't be fixed; how does this limit the performance of Step IV?
- What about Step VI?
- Caveat:
  - All of this is linear optics
  - Great for getting an idea of the parameter space
  - Not sufficient for redefining MICE baseline
- Propose:
  - If FC current is limited, the limits should be explicitly proposed by FC group
  - Then analysis group proposes new lattice optics/baseline
  - Then verify lattice performance with tracking
  - Then make a decision about FC acceptance criteria

# Optics Routines



- The optics routines used here are available in MAUS release since 0.7.0 or so
  - Usage examples will be in 0.7.4 (currently in trunk)
- Python API to
  - Calculate transfer matrices from arbitrary field maps
  - Transport beam envelopes and particles through the field maps
  - Modify geometry and fields (for optimisation)

# Step IV

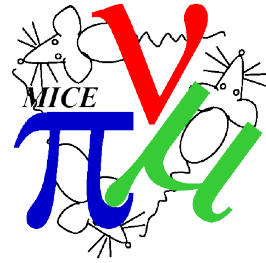


- Step IV has just FC, no coupling coil and no lattice
  - Questions:
    - What beta function can be achieved with reduced FC current?
    - Can we match to this?
- Coil parameters
  - Optimise for matching using Match 2 and Match 1
  - Vary focus coil (+/- 20% of nominal) and look at response
  - End coil and Centre coil is fixed for 4 T field on tracker

Coil Name	Centre z [mm]	Inner radius [mm]	Radial thickness [mm]	Length [mm]	Current Density [A/mm <sup>2</sup> ]
End 2	3201	258	68.2	110	135.18 fixed
Centre	2451	258	22	1294	152.44 fixed
End 1	1701	258	60.9	110.6	127.37 fixed
Match 2	1301	258	30.9	199.5	148.09 maximum
Match 1	861	258	46.2	201.3	145.94 maximum
Focus	205	263	84	210	113.95 nominal

Tab. 1: Coil pack used for simulation of MICE Step IV. The field has odd symmetry about  $z=0$ . (Upstream magnets have opposite polarity).

# Beta function matching

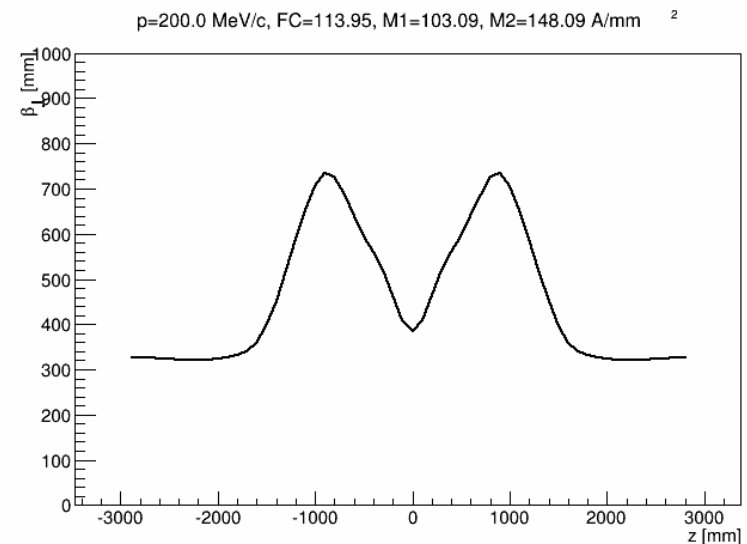
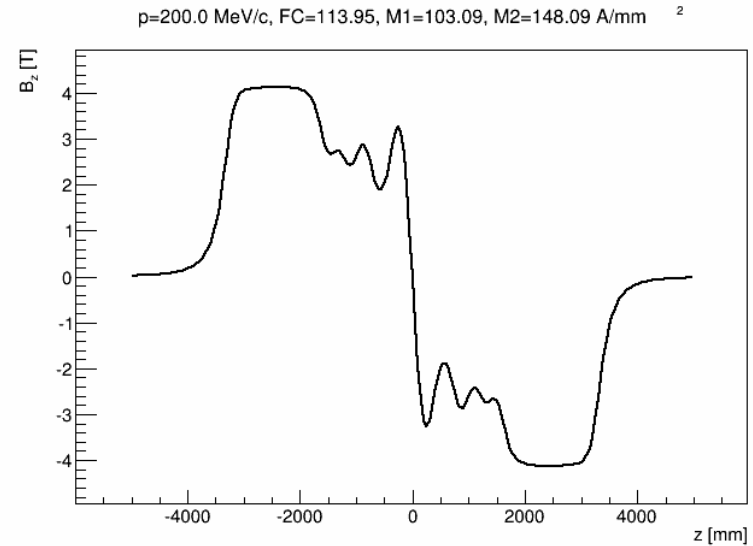


- Standard setting at Step IV is that beta should be symmetric about absorber ( $z=0$ )

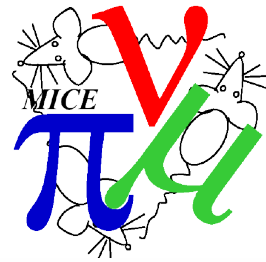
- Require  $d\beta/dz = 0$  at the absorber centre
- Choose  $d\beta/dz = 0$  in the constant solenoid field (analytic solution here)

- Example for 200 MeV/c, with FC current at nominal 113.95 A/mm<sup>2</sup>

- Fix M2
- Scan across M1 looking for  $\alpha = 0$
- Use minuit to do the final selection of M1
- See next slide

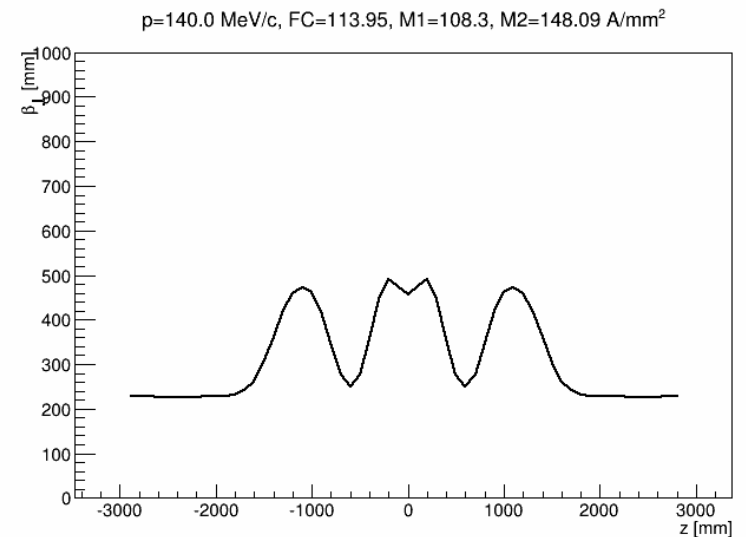
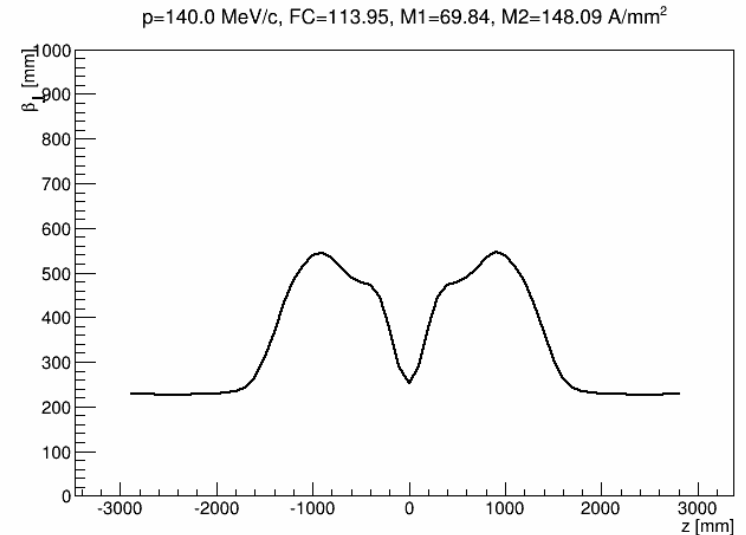


# Solutions to Match Condition

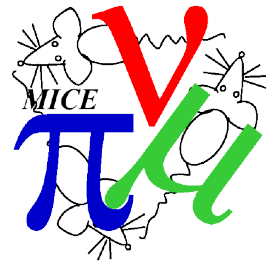


In some cases, there is more than one solution to the match condition for a given M2 current

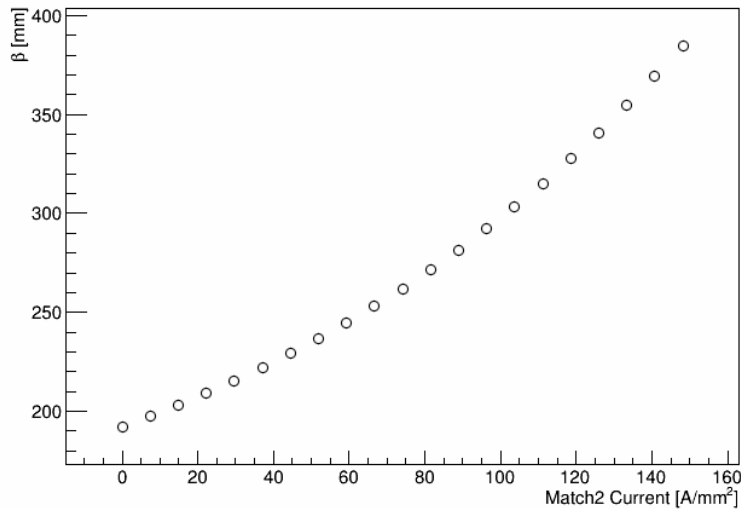
- e.g. at 140 MeV/c case to right
- Means we need to be careful about applying optimisation routines
- Want to find all the possible match conditions...



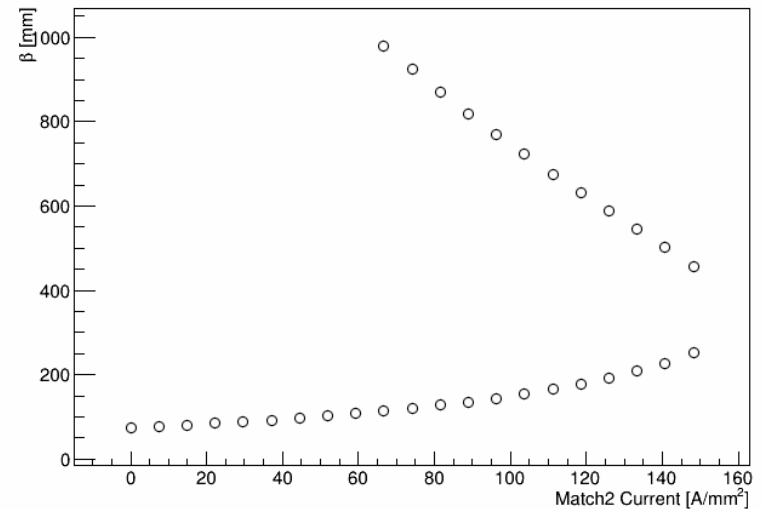
# Scaling M2



Focus Coil=113.95 A/mm<sup>2</sup> Momentum=200.0 MeV/c

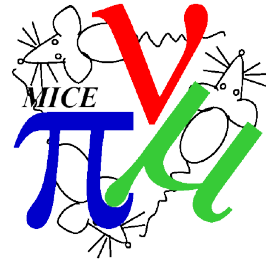


Focus Coil=113.95 A/mm<sup>2</sup> Momentum=140.0 MeV/c

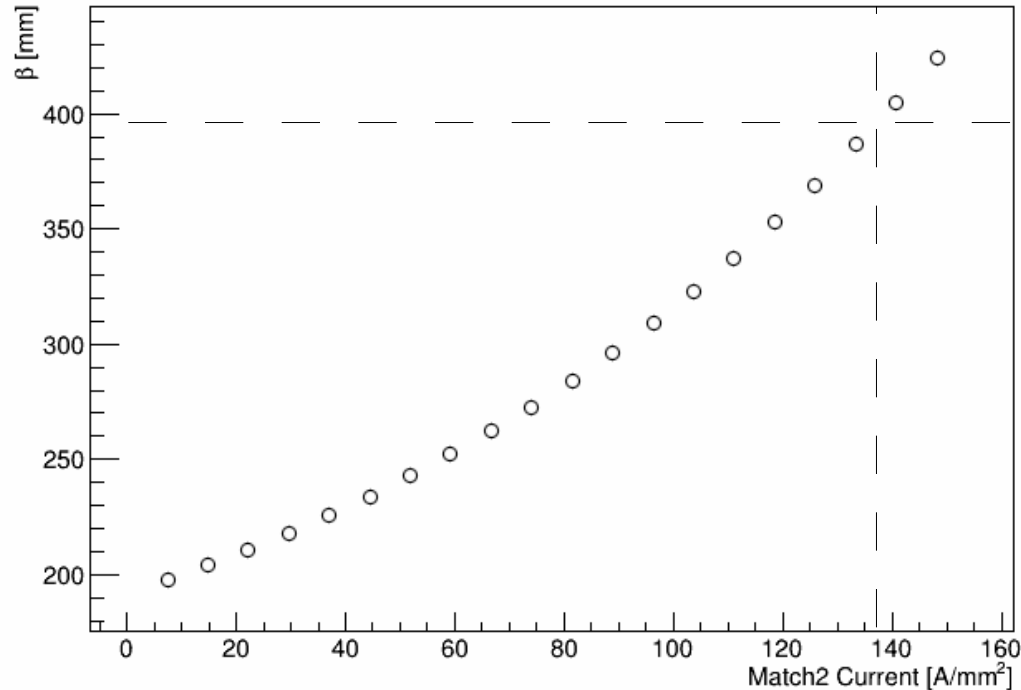


- Fix M2 and let M1 vary freely to find a match
  - As before, scan to find all possible solutions
  - Then optimise to get the best match
- See two families of solutions for  $p = 140$  MeV/c
- Note that there is no solution for beta = 420 mm,  $p = 200$  MeV/c

# Scaling M2 - old coils



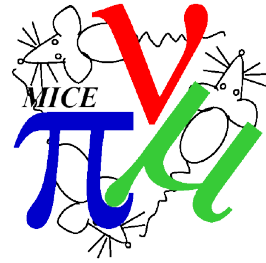
Focus Coil=113.95 A/mm<sup>2</sup> Momentum=200.0 MeV/c



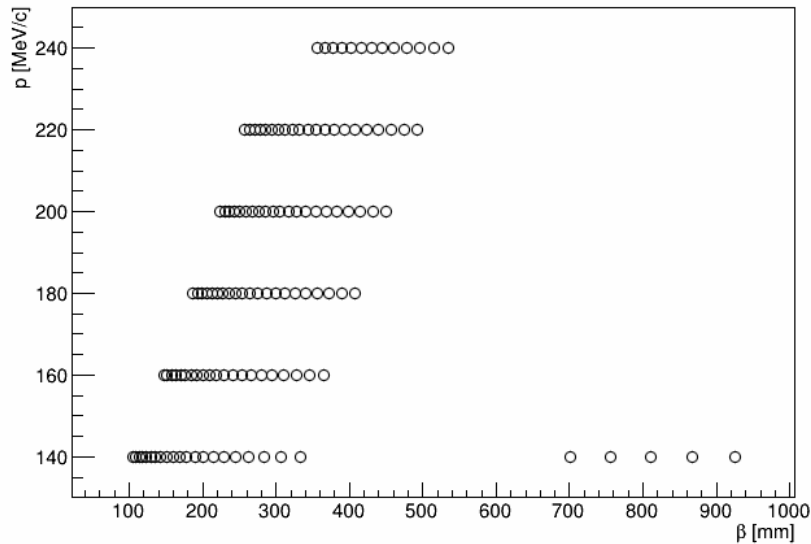
- Really? No solution for baseline?
- Using design coil pack from e.g. MICE Note 244
  - “The Effect of Error Fields due to Hall Shielding on the Performance of MICE”
  - Just manage to get solution for beta = 420 mm
  - Baseline was a little under 400 mm



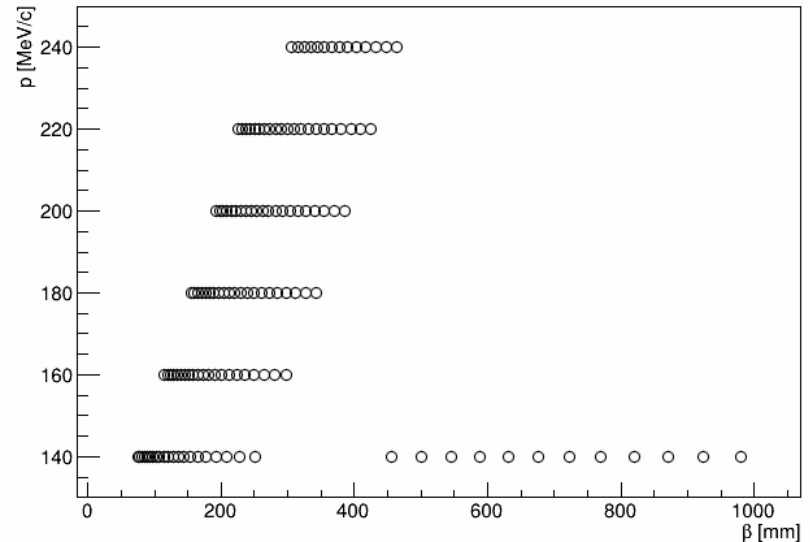
# Matching vs Momentum



FocusCoil 102.555 A/mm<sup>2</sup>



FocusCoil 113.95 A/mm<sup>2</sup>



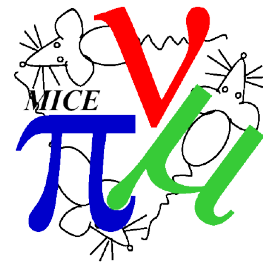
- What is the range of available optics for a given focus coil strength?
  - At 200 MeV/c, 113.95 A/mm<sup>2</sup>, range is - 192 mm to 385 mm
  - At 200 MeV/c 102.55 A/mm<sup>2</sup>, range is - 223 mm to 450 mm
  - At 240 MeV/c, 113.95 A/mm<sup>2</sup>, range is - 306 mm to 463 mm
  - At 240 MeV/c 102.55 A/mm<sup>2</sup>, range is - 356 mm to 535 mm

# Step IV - Conclusions



- Reduced FC current limits accessible range of beta functions
  - Assume FC performance as FC 1
    - e.g.  $J < 102 \text{ A/mm}^2$  with 10 % operating margin
  - Minimum beta function 192 mm  $\rightarrow$  223 mm at 200 MeV/c
  - Minimum beta function 306 mm  $\rightarrow$  356 mm at 240 MeV/c
  - Can still achieve “nominal” beta functions
  - Maximum beta function is unaffected
    - Prefer low FC current for large beta functions

# Step VI

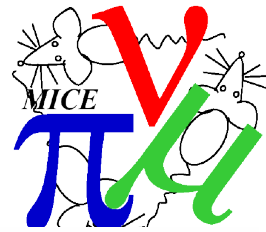


- Consider now Step VI SFoFo lattice only
  - Assume we can match (but see discussion above)
  - Look at how optics scales with Coupling Coil and Focus Coil currents
- Repeat over 2750 mm cell length in flip mode (adjacent cells have opposite polarity)

Coil Name	Centre z [mm]	Inner radius [mm]	Radial thickness [mm]	Length [mm]	Current Density [A/mm <sup>2</sup> ]
Focus	205	263	84	210	113.95 nominal
Coupling	1375	725	116	250	96.21 nominal
Focus	2545	263	84	210	113.95 nominal

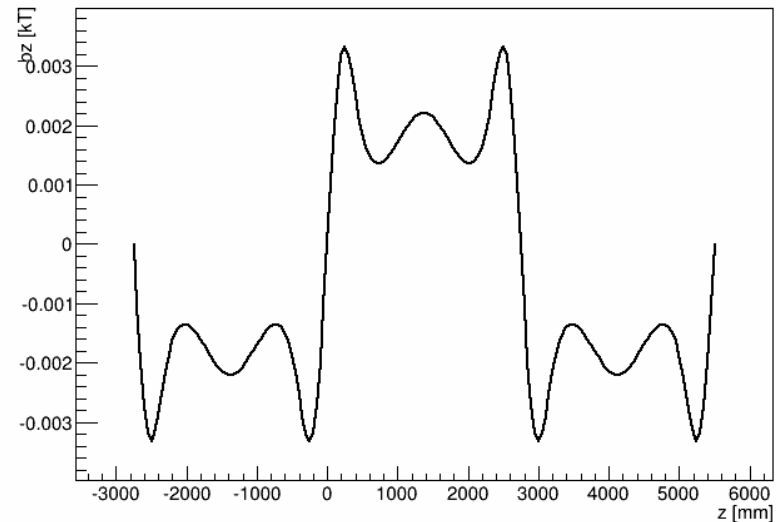
Tab. 2: SFoFo lattice used for simulation of MICE Step VI. The lattice was repeated with a cell period of 2750 mm and adjacent half cells having opposite polarity (i.e. flip mode). 3 half cells were placed on either side of the test cell to ensure correct application of fringe fields.

# Nominal magnets, 200 MeV/c

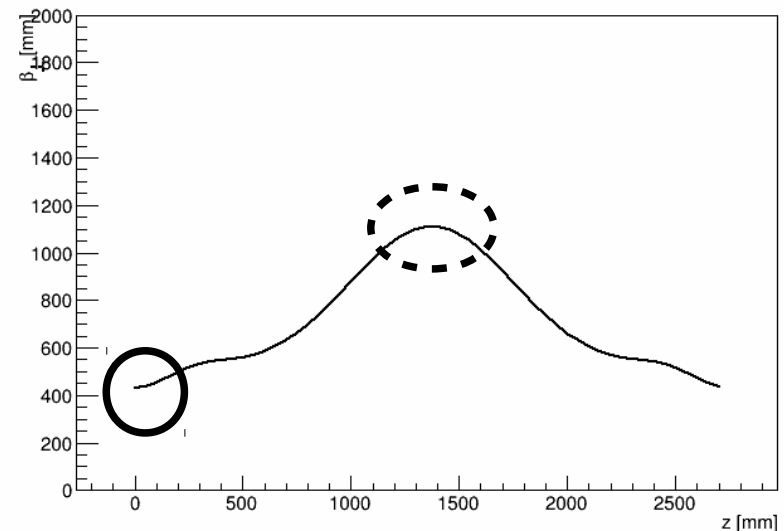


- By way of example
  - $B_z$  as a function of  $z$
  - Beta function for a half cell
- Use Newton Raphson to find the periodic beta function
  - If NR fails for a few different seeds, assume no match exists
    - i.e. resonance
  - Solution is accessible analytically as an eigenvalue problem
  - Resonant condition is also accessible analytically
  - But I find solution numerically
- What is momentum dependence of beta function?
  - At focus (absorber)
  - At anti-focus (scraping aperture)

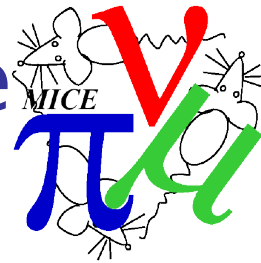
Focus Coil: 113.95 Coupling Coil: 96.21



Focus Coil: 113.95 Coupling Coil: 96.21

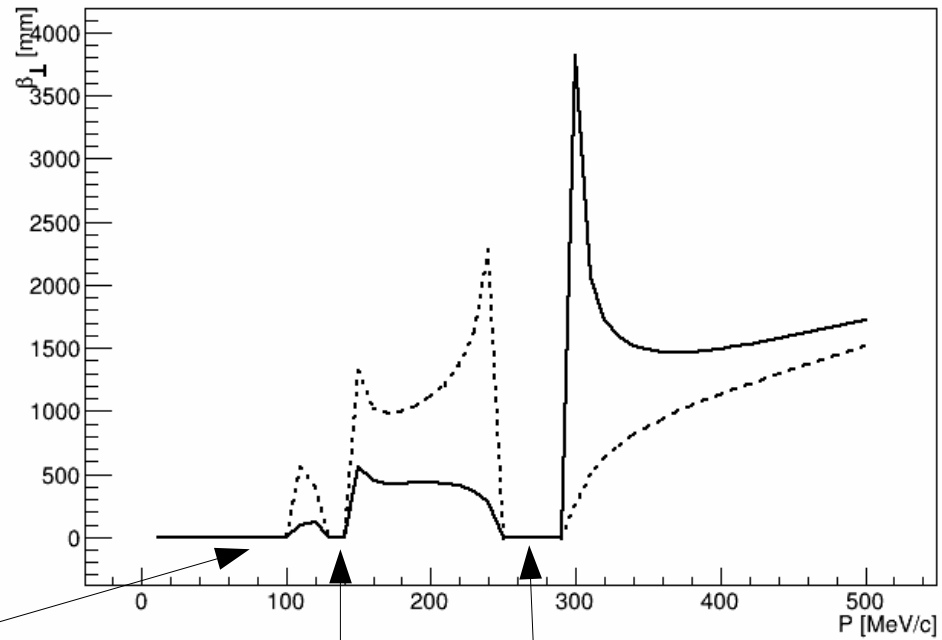


# Nominal magnets, $p$ dependence



- Nice picture of lattice behaviour
  - For e.g. baseline 200 MeV/c lattice
  - MICE working point in  $2\pi - 4\pi$  region
    - Note this is “weird” - most linacs sit in  $< 2\pi$  region
    - NF baseline working point in  $< 2\pi$  region

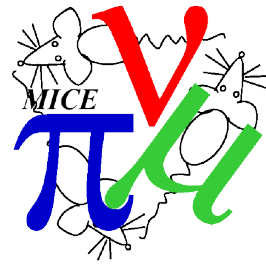
Focus Coil: 113.95 Coupling Coil: 96.21



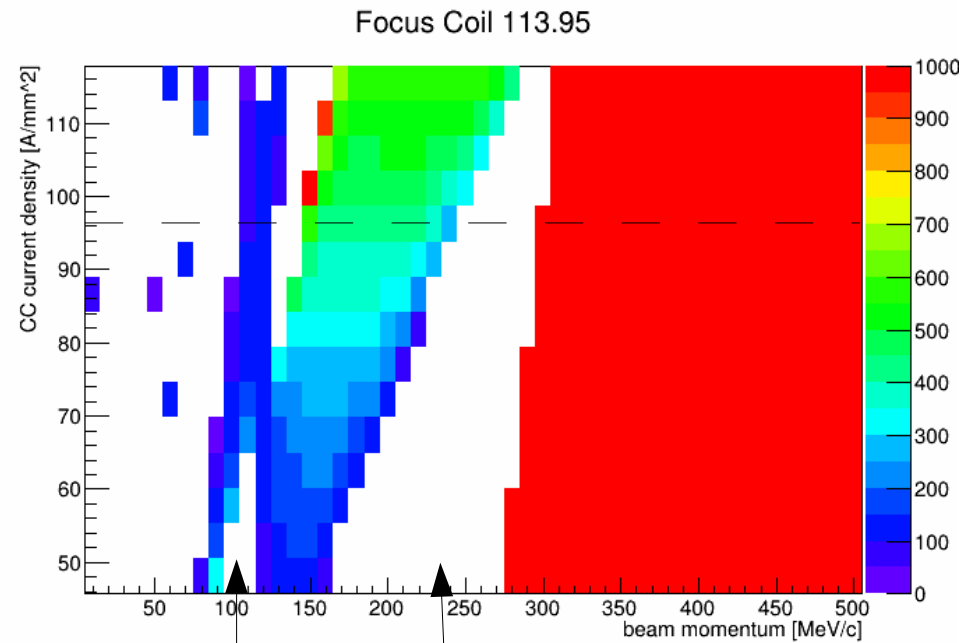
$\geq 6\pi$  resonances

$4\pi$  resonance     $2\pi$  resonance

# Focussing Strength vs CC

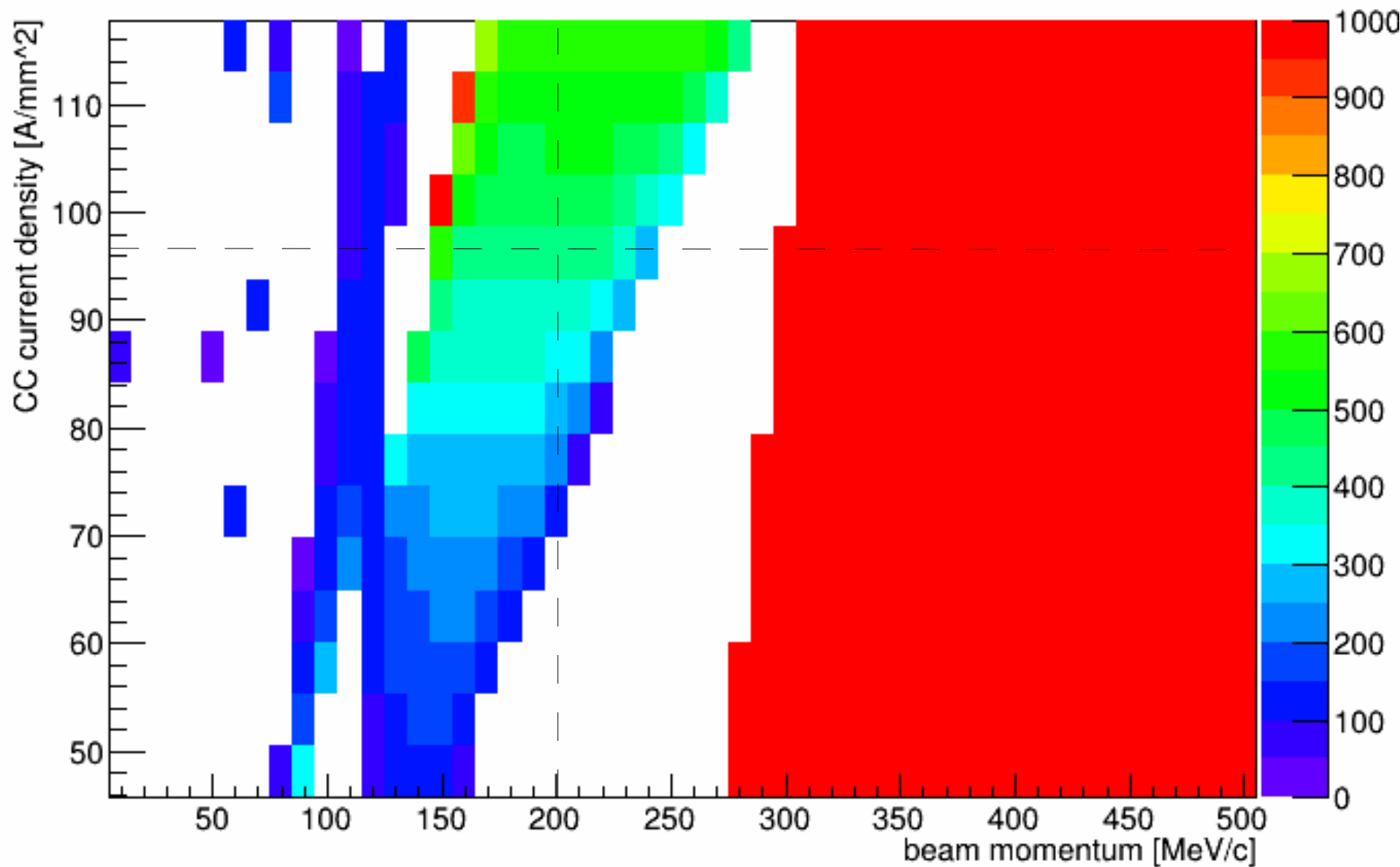


- What happens as CC current is varied?
  - Beta increases
  - Central momentum increases
- Dashed line is MICE baseline
  - i.e. the plot on previous slide
- Consider two more cases
  - FC = 136.74 A/mm<sup>2</sup>
    - 240 MeV/c baseline
  - FC = 102.56 A/mm<sup>2</sup>
    - Possible FC1 working point without further improvement
- Plots on next slides
  - Decide CC working point at 200 MeV/c and 240 MeV/c

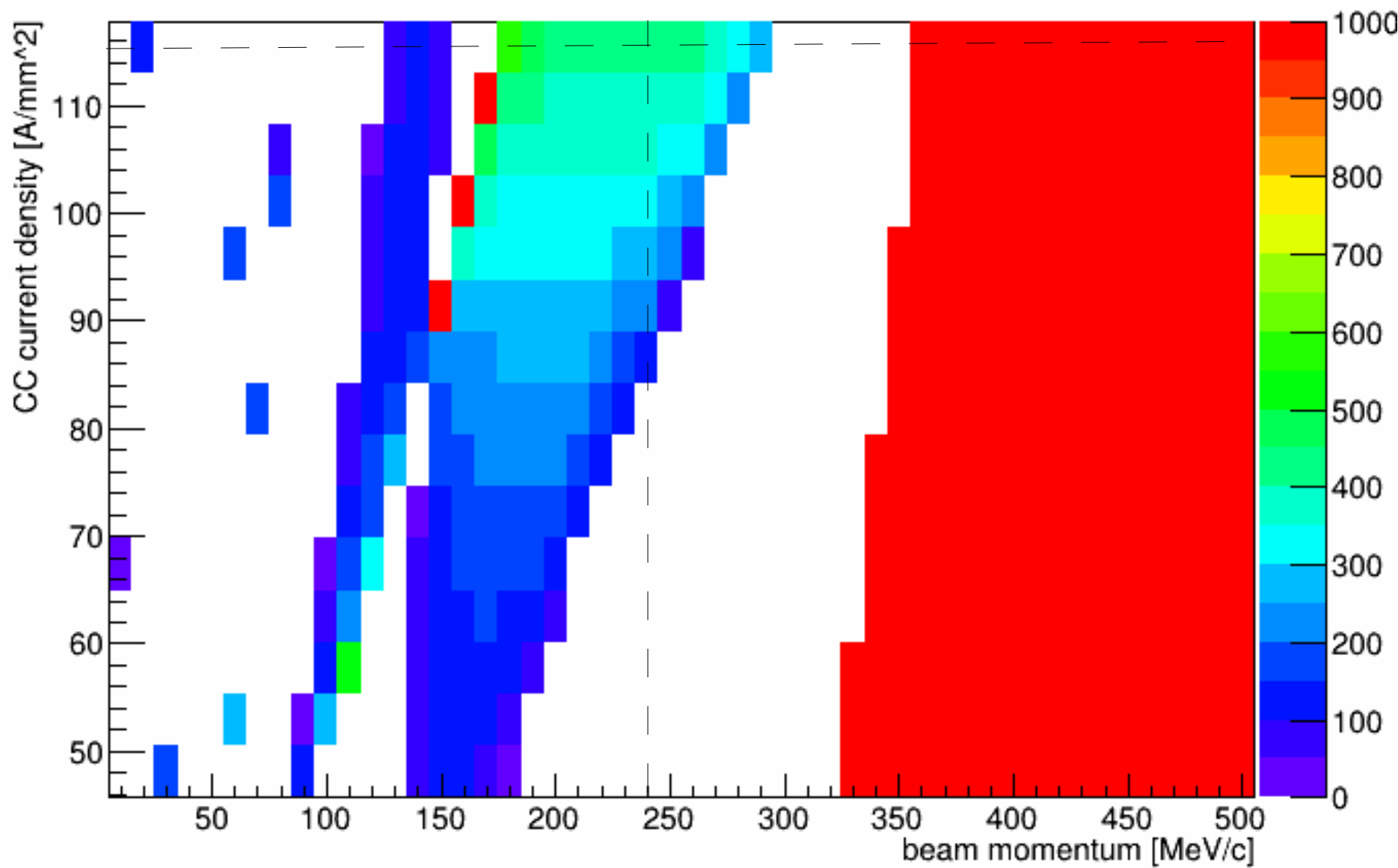


4  $\pi$  resonance    2  $\pi$  resonance

# Focus Coil 113.95

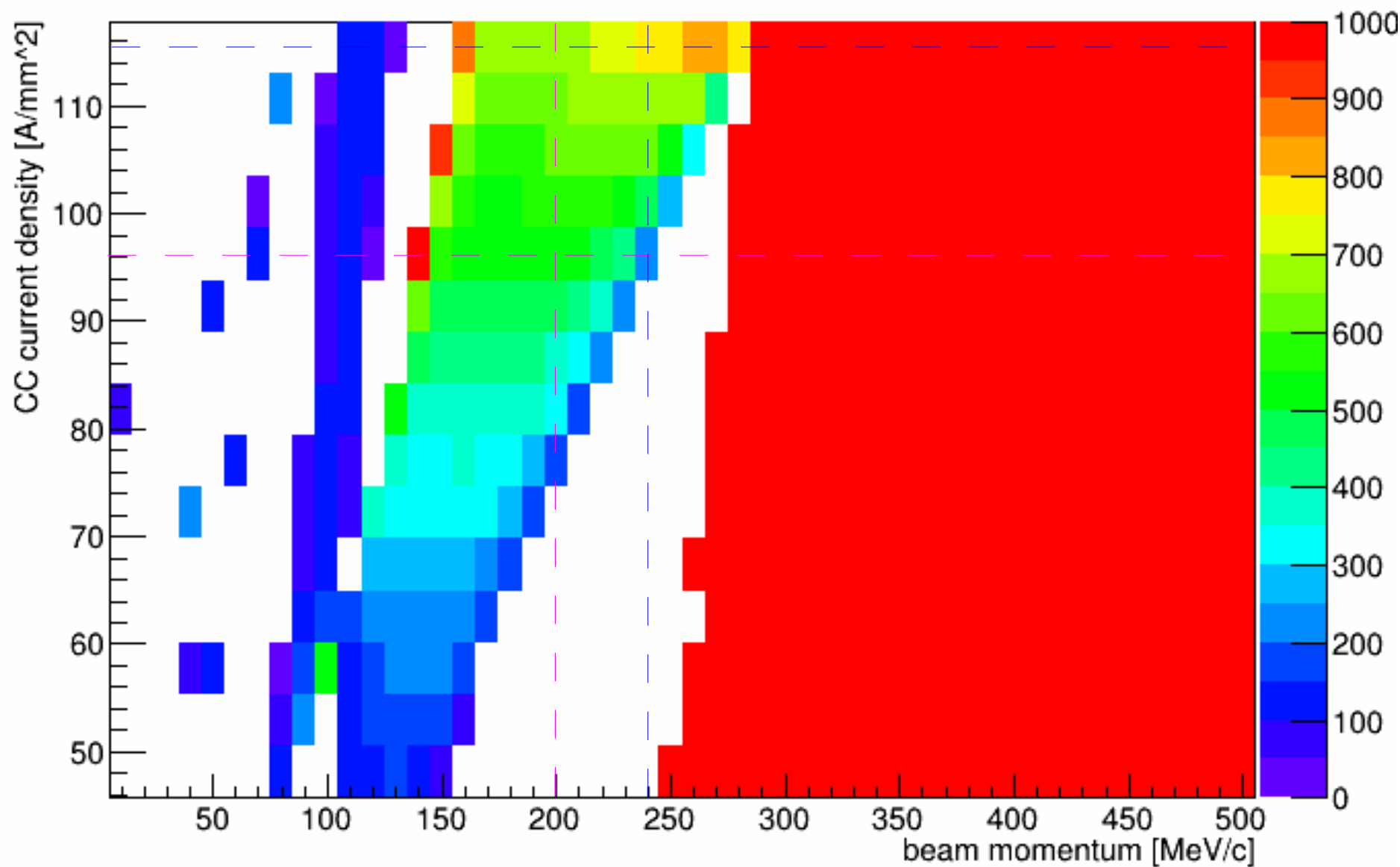


# Focus Coil 136.74

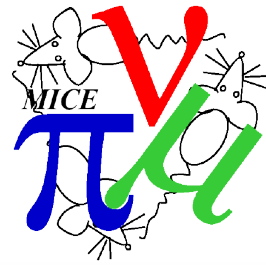




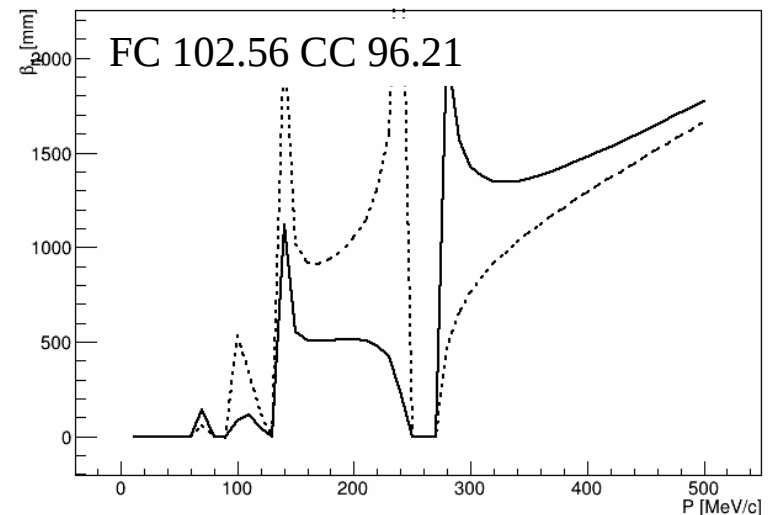
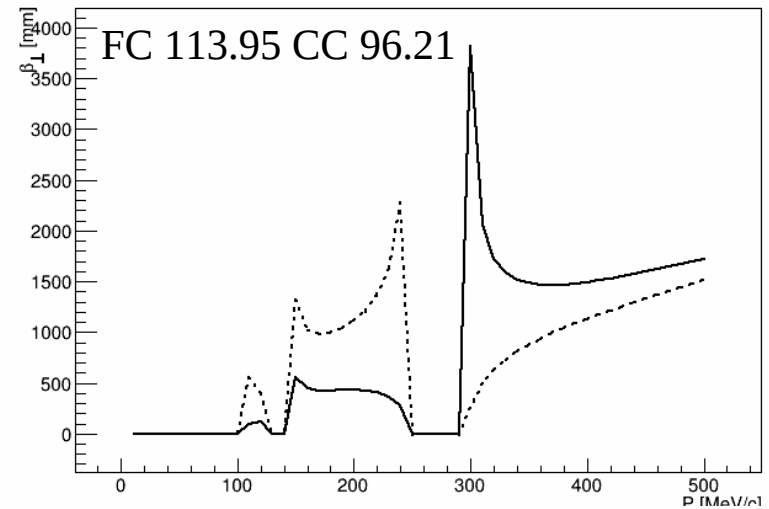
# Focus Coil 102.56



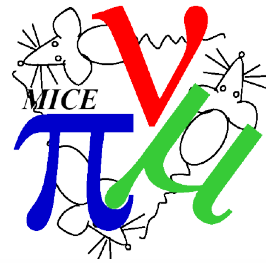
# Response to FC – 200 MeV/c



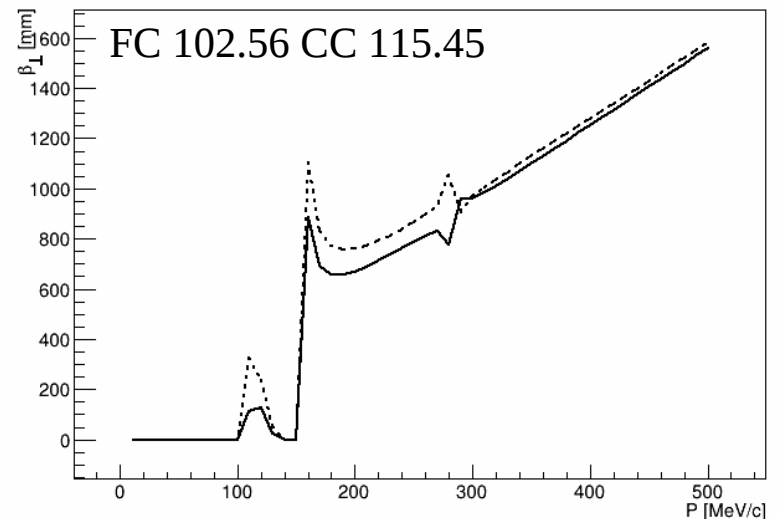
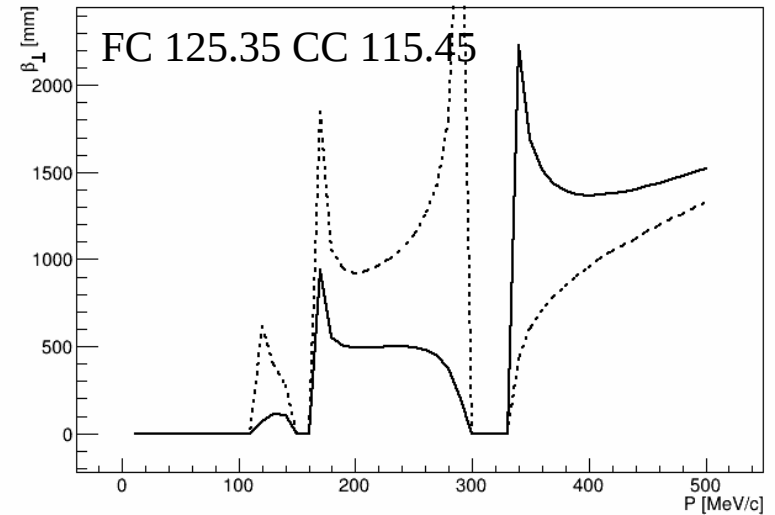
- Assume FC performance as FC 1
  - e.g.  $J < 102 \text{ A/mm}^2$  with 10 % operating margin
  - Beta function 420  $\rightarrow$  500 mm
  - Equilibrium emittance increases by  $\sim 20\%$  (proportional to beta)



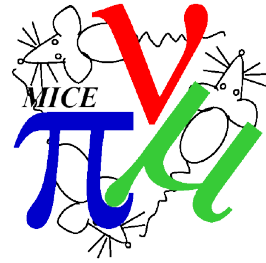
# Response to FC – 240 MeV/c



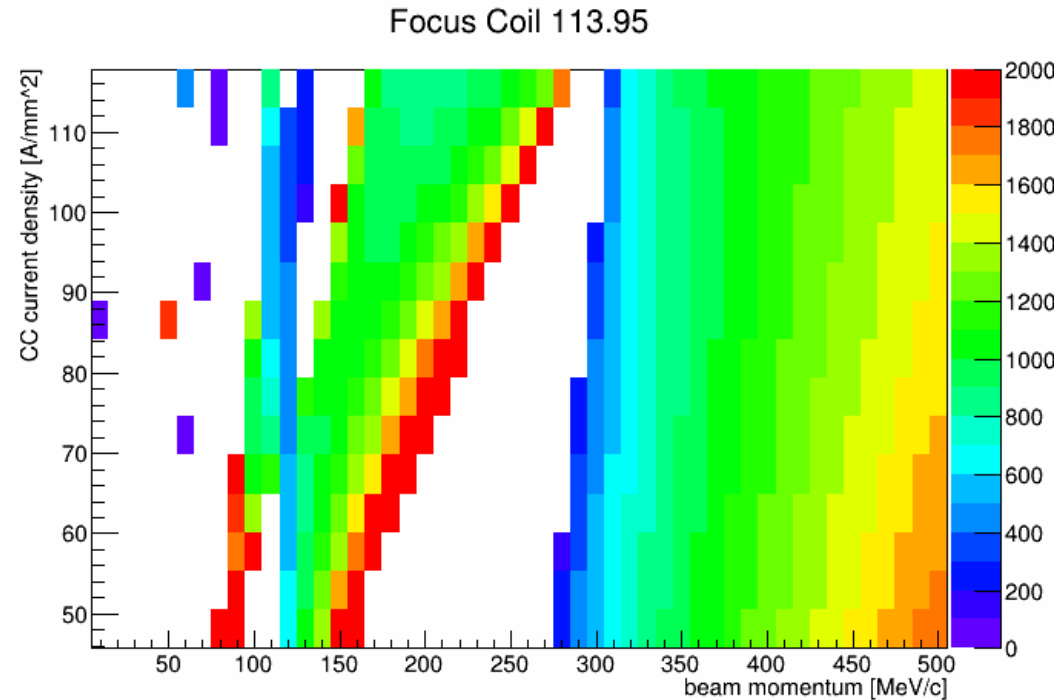
- Assume FC performance as FC 1
  - Beta function  $\sim$  50-100% higher
  - Equilibrium emittance  $\sim$  50-100 % higher
  - Bigger chromatic aberrations
  - Weaker (2pi) resonance
  - Possibly slightly better acceptance
    - Beta at midpoint is lower



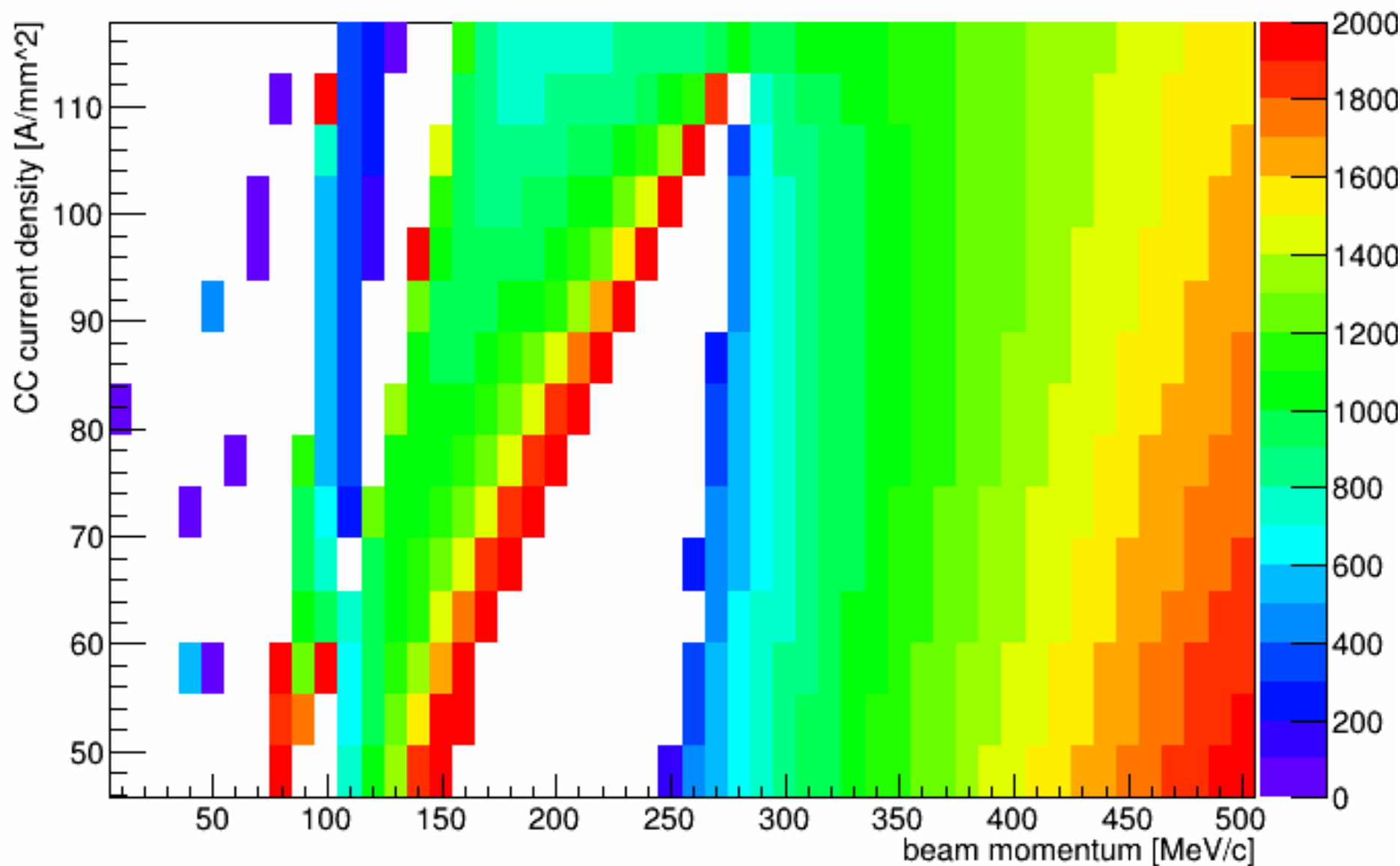
# Acceptance/beta at midpoint



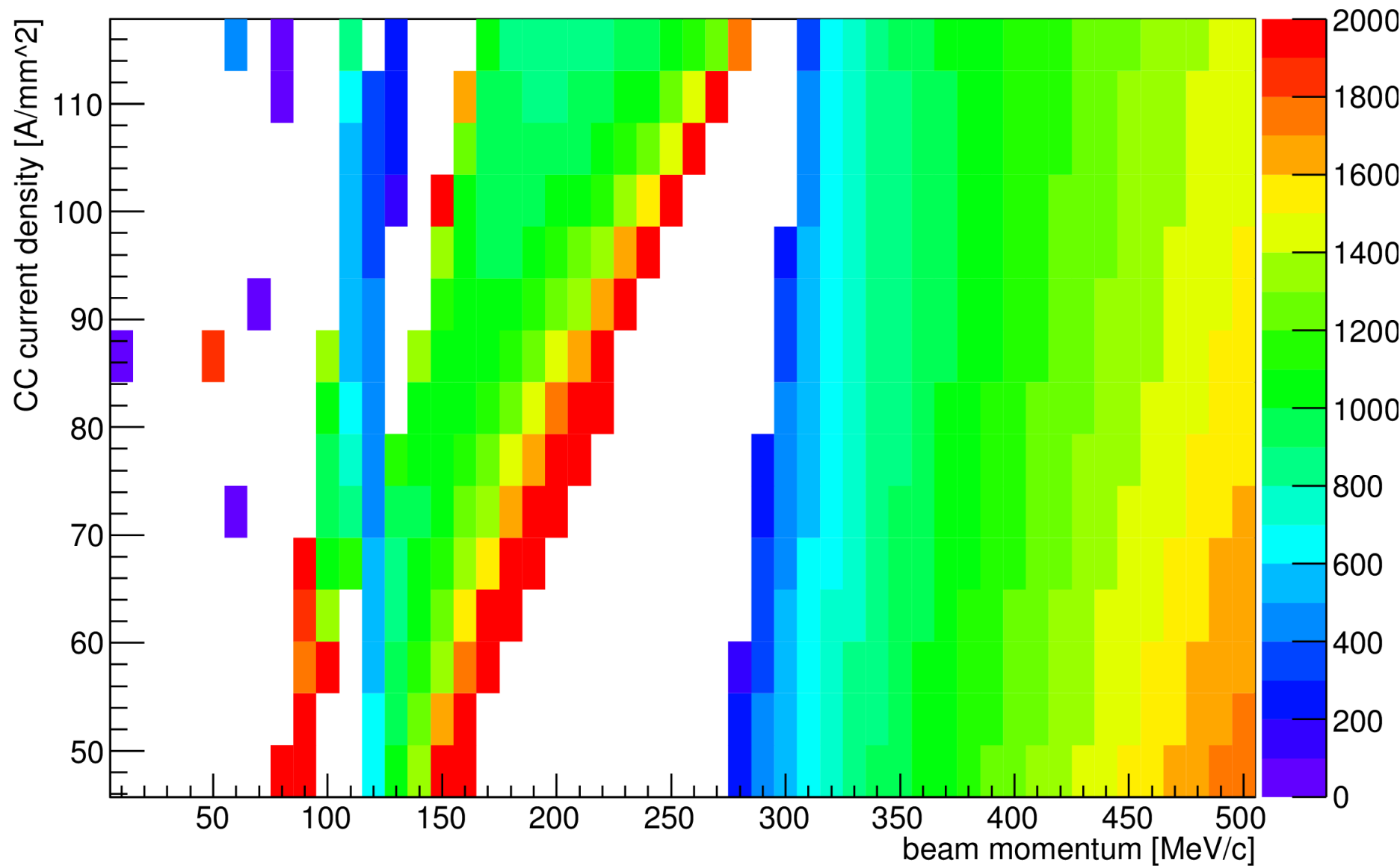
- For interest, we also look at beta at the midpoint
  - Seems largely unaffected by different FC currents
  - (This tells us acceptance is largely unaffected by different FC currents)



# Focus Coil 102.56



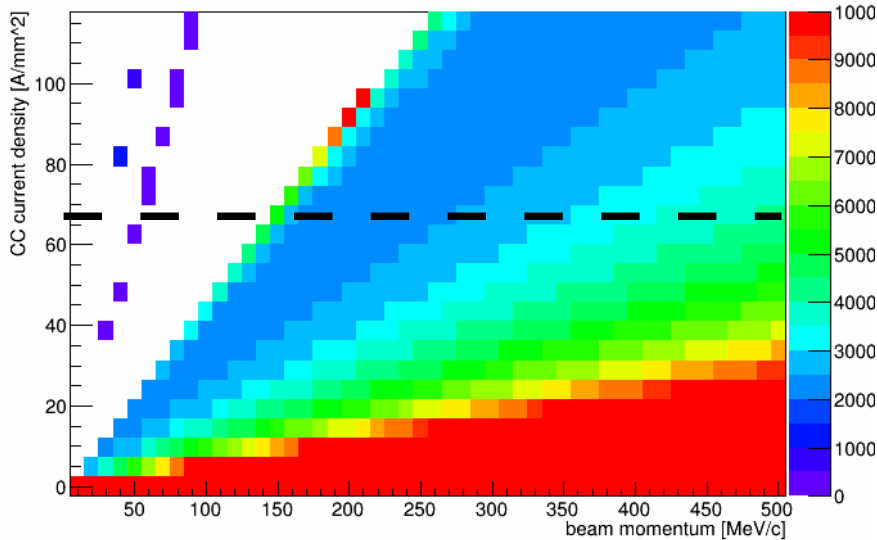
# Focus Coil 113.95



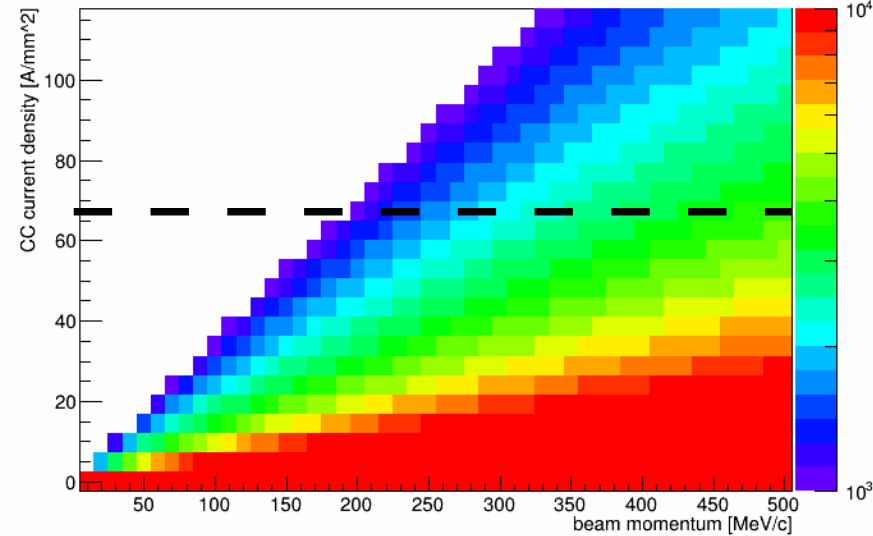
# Addendum - $\phi < 2\pi$



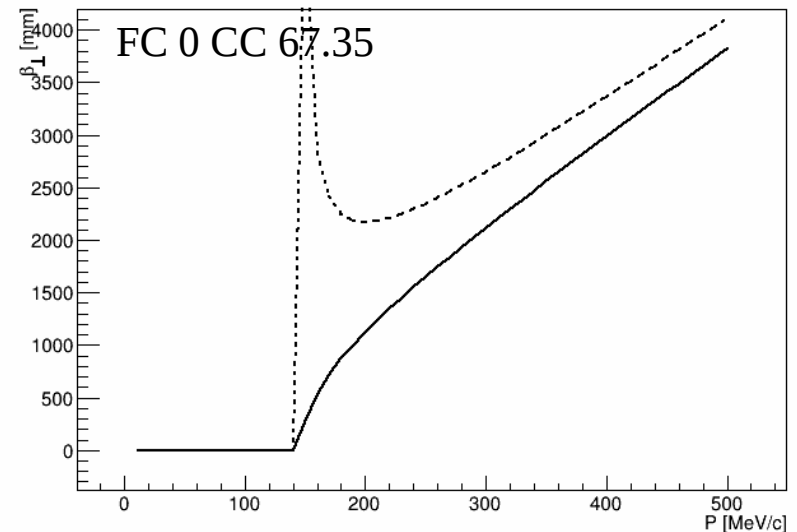
Focus Coil 0.0



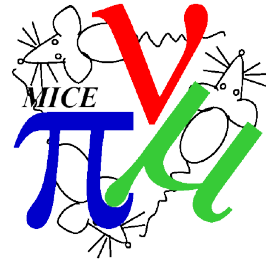
Focus Coil 0.0



- As a matter of interest - can we explore phase advance  $< 2\pi$  regime?
  - Take FC = 0.0
  - Beta  $\sim 1000$  mm
    - Flexible, but acceptance limited for lower CC
  - Potentially matching issue



# Conclusions



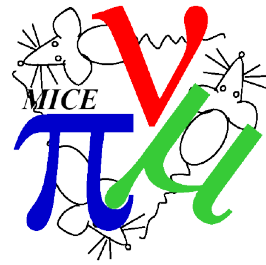
- MICE is certainly still operable with reduced FC
- But physics performance is slightly reduced
  - Lowest beta options are excluded at 140 and 200 MeV/c
  - Baseline (420 mm lattice) is excluded at 240 MeV/c
  - Not clear that match into a 500 mm beta function is ok at 200 MeV/c
- Caveat:
  - All of this is linear optics
  - Great for getting an idea of the parameter space
  - If FC current is limited, limits should be decided by FC group
  - Then analysis group proposes new lattice optics/baseline
  - Then verify lattice performance with tracking
  - Then make a decision about FC acceptance criteria





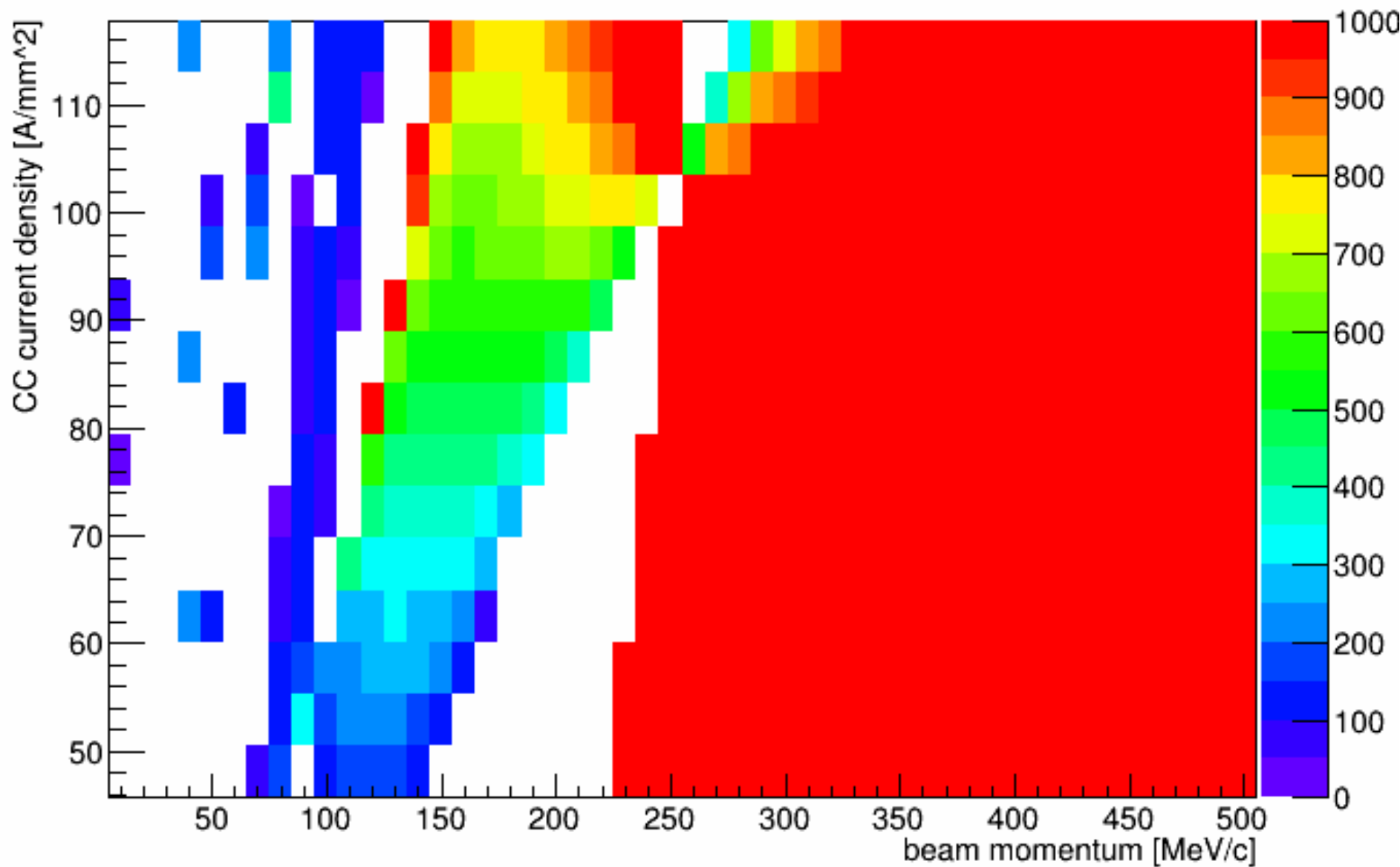
# Appendix

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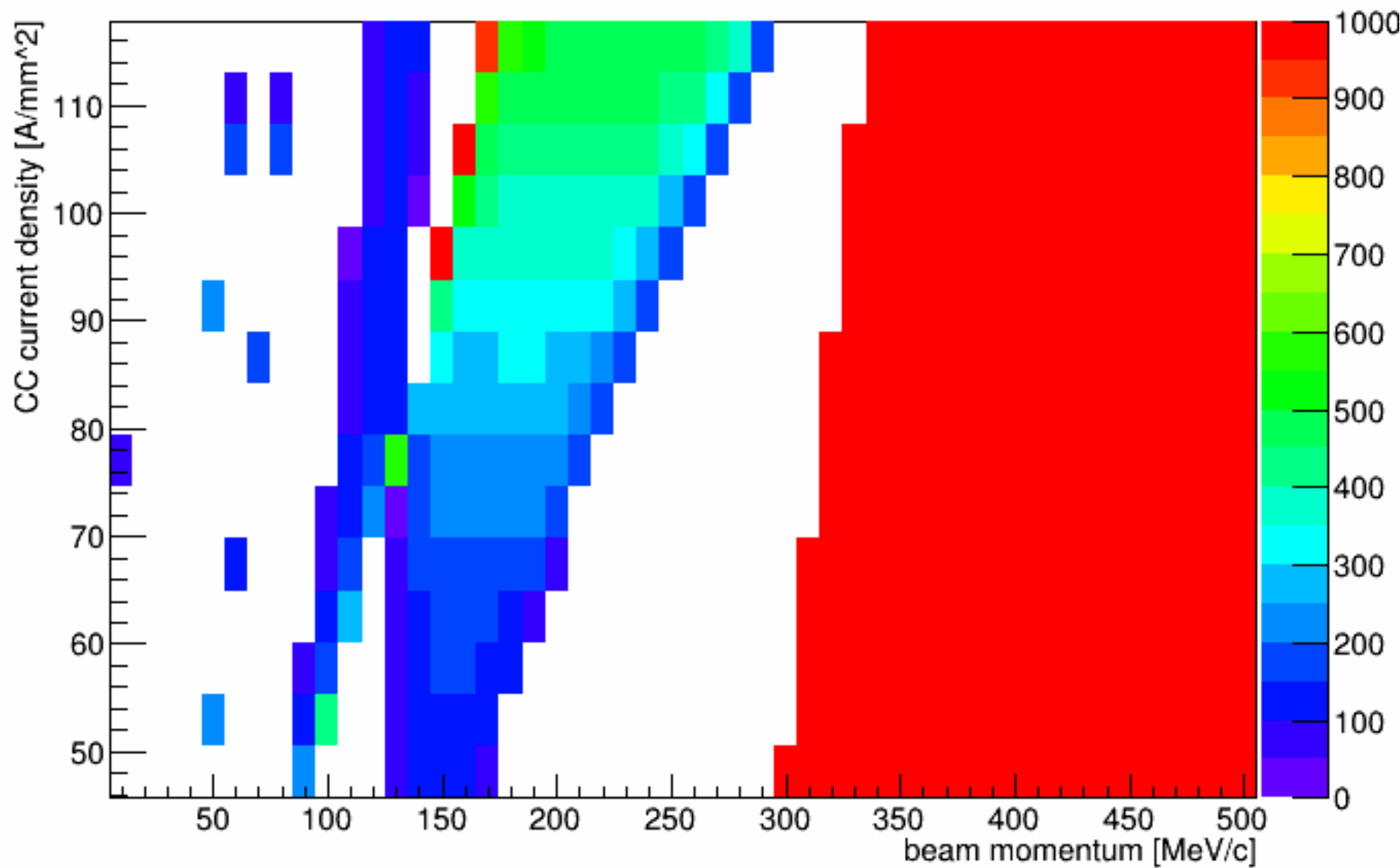


- Extra slides below

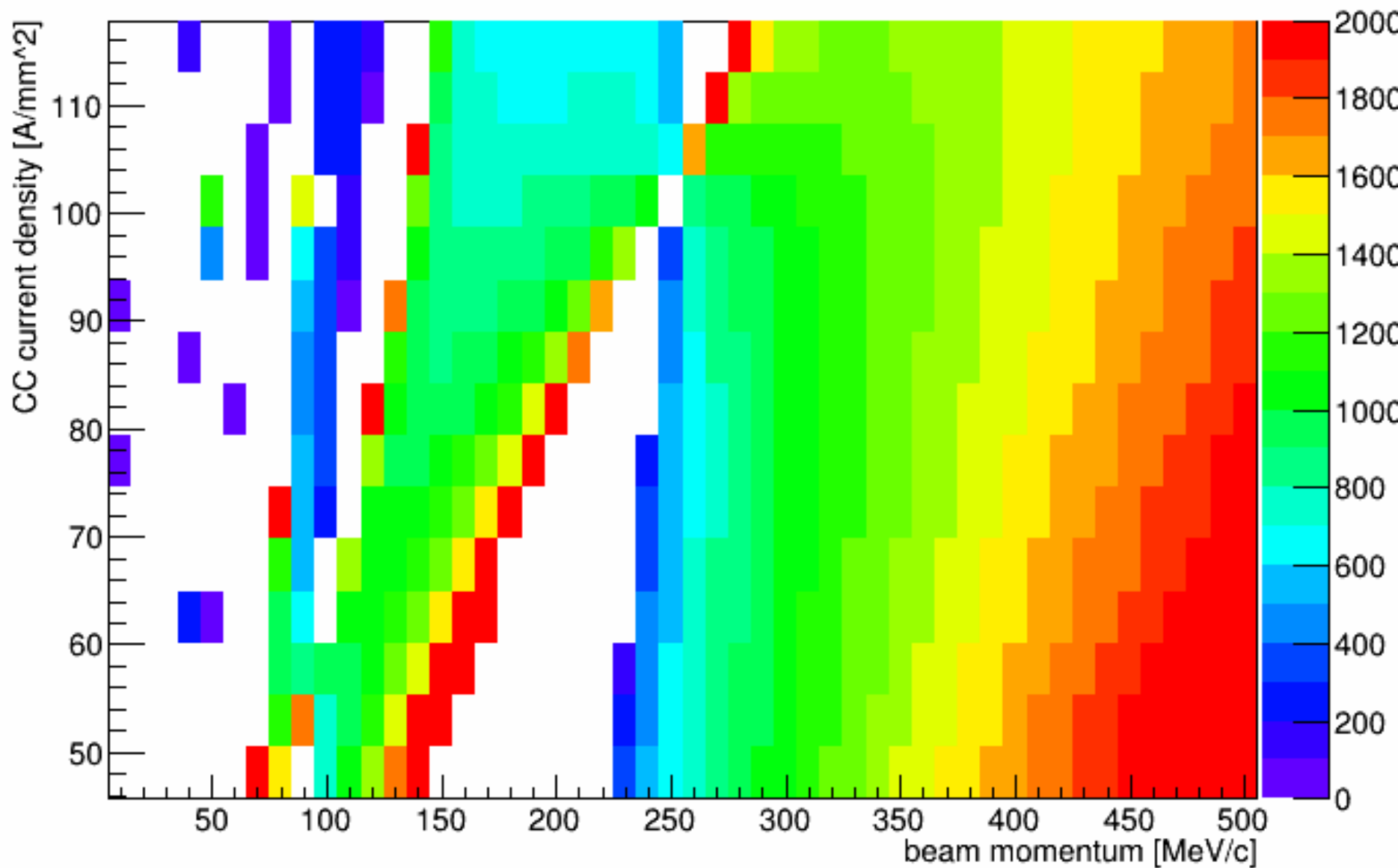
# Focus Coil 91.16



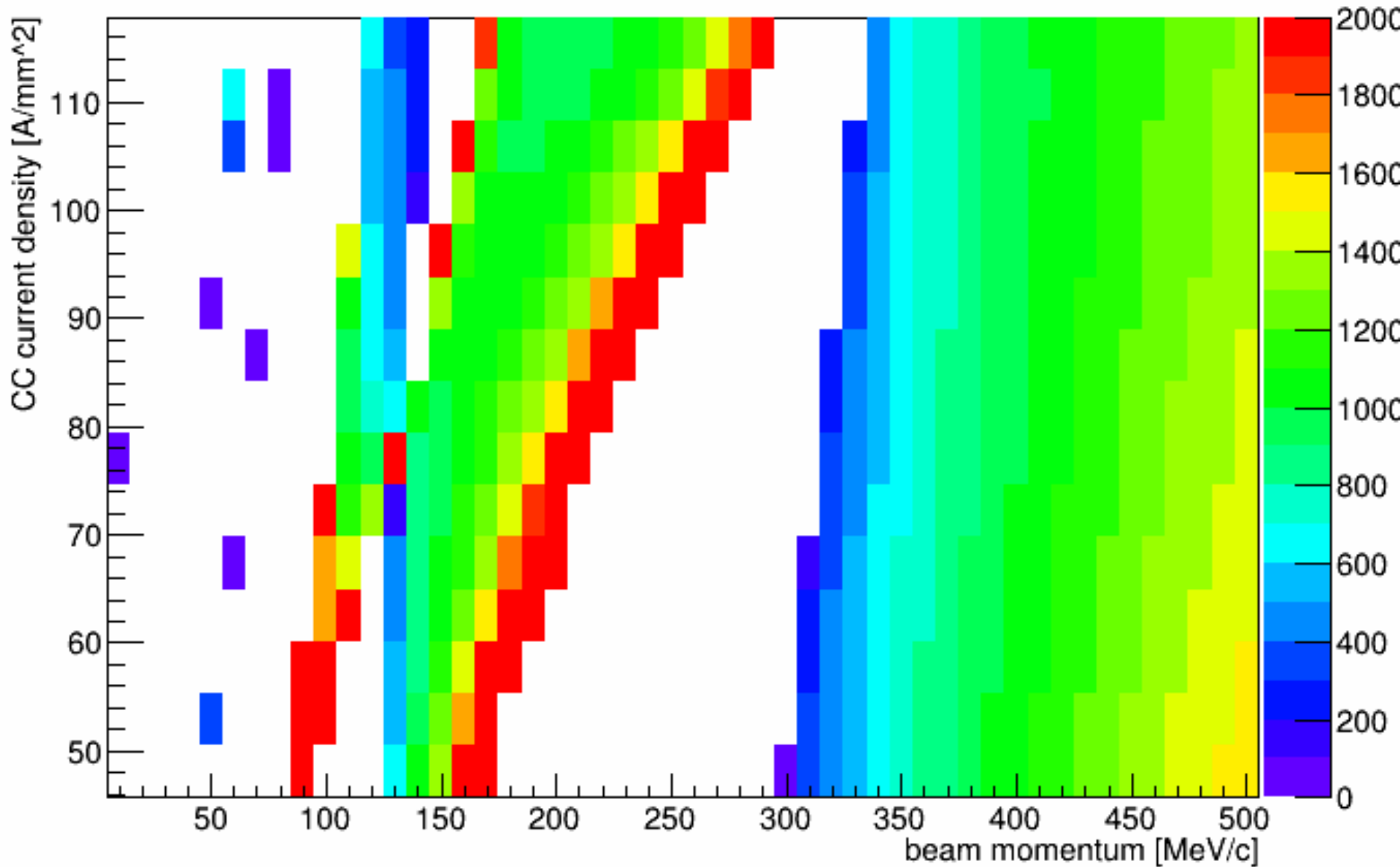
# Focus Coil 125.35



# Focus Coil 91.16



# Focus Coil 125.35



# Focus Coil 136.74

