# R&D Needs and Priorities

R. B. Palmer (BNL)

Collaboration Meeting

BNL March 20 2008

# Needed Design and Simulation

An incomplete list of things we sometimes forget

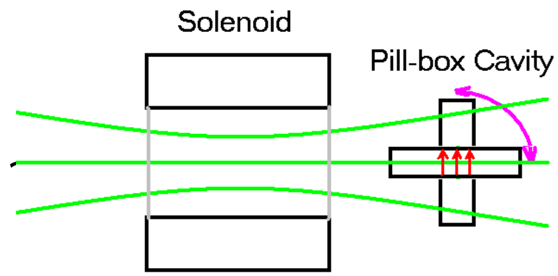
- Proton Driver and Buncher design (8 and 56 GeV)
- Vacuum rf studies
  - Calculate gain and loss from 77 deg rf
- Design and simulate separation of charges
- Design bunch merge (Low or High Energy)
- Slava's PIC (still no lattice realization) ***
- Look at alternatives to 50 T for final cooling
  - Slava's REMEX (still no lattice realization) ***
  - REMEX with wedges in a low k helix inside a high field solenoid
  - Potato slicer
- Simulate longitudinal and transverse space charge
- Calculate neutrino radiation, including hot spots from straight sections
- Re-evaluate detector shielding with LHC technology and "dipole first" lattice

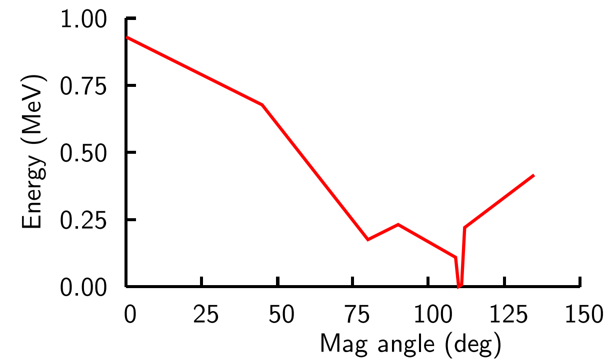
# Ongoing and Planned Hardware R&D

- MICE
  - Transverse cooling with re-acceleration
  - Earlier 6D cooling without re-acceleration ??
- Liquid hydrogen absorber R&D
- Button Studies in 805 MHz cavity
  - Dependencies on materials and surface treatments
- Tests of 201 MHz cavity in magnetic fields
  - 300 Gauss (done)
  - 1 T (started)
  - 3 T (when coupling coil arrives)
- Test gas cavity in beam
  - For Large Emittance parameters: initial charge in one train (12 bunches)=$3\ 10^{13}$
  - Low emittance calls for less charge, but based on optimistic assumptions

.

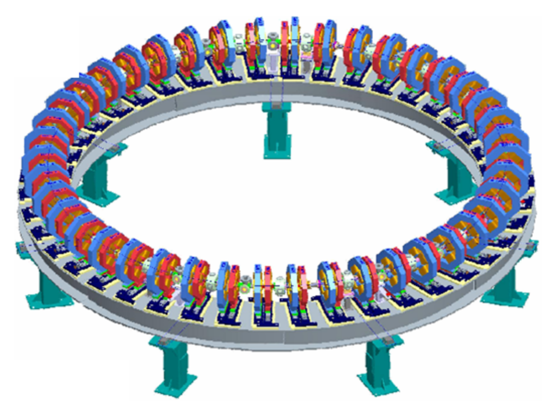
- Current 805 pillbox cavity with B at different angles
  Note that just 0 and 90 degrees may not
  define the problem
  more angles are needed




- Construction of coils for HCC (without rf)

- Electron model of muon FFAG (EMMA)
  - Designed for Neutrino Factory application
  - Not essentially part of Muon Collider acceleration, although nit could be used for acceleration at energies too low for pulsed synchrotrons

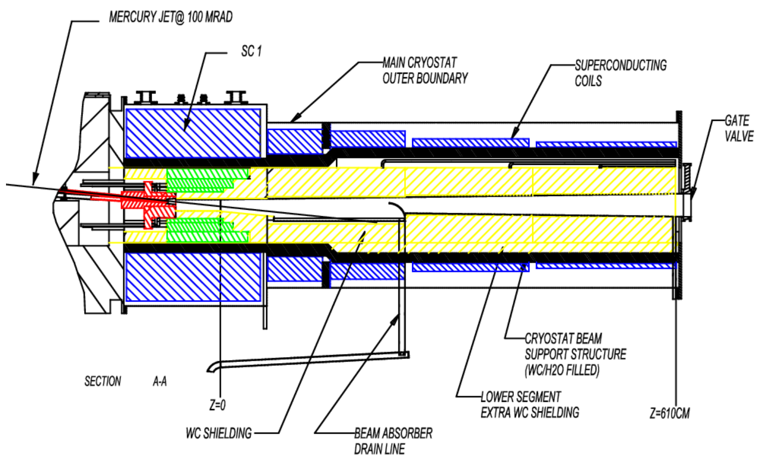


# Needed New Hardware R&D

## For target and Capture

- Studies of Hg jet entering the magnet
  The jet seen in MERIT was more extended in the vertical direction (and presumably narrower in depth) than simple magnetic field effects predicted. This could be from magneto-hydrodynamics in the plumbing that needs study.

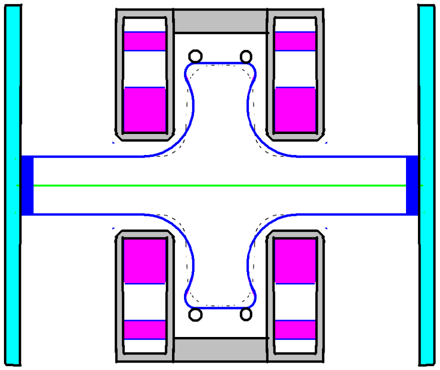
- Build 20 T hybrid magnet and integrated Hg jet
  The 20 T hybrid is n ot a standard magnet and a prototype will eventually be needed




## rf Studies

- Commission development of rf power sources
  In particular a 201 MHz Klystron could greatly reduce the cost of low frequency rf power

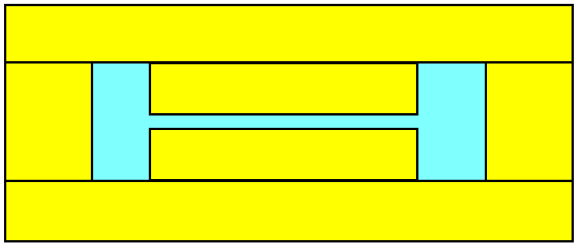
- Open cavity experiment with coils in irises
  When the iris surface follows the magnetic field lines then dark current are constrained to the surface. giving "magnetic insulation". This should allow higher gradients, with higher fields, instead of the reverse



  The experiment could include test in Lab G magnet and with high pressure gas, but these will significantly complicate its design

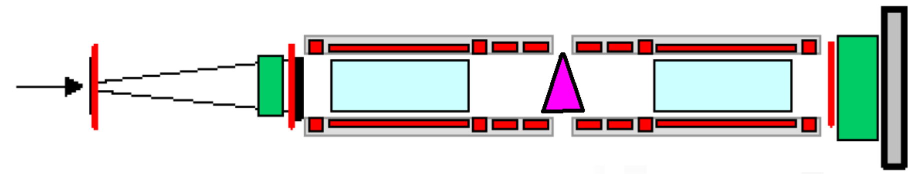
- Test 201 MHz cavity with coils in irises
  To do this right requires a new cavity and coils and would be expensive hopefully we can learn what is needed from the current tests and the above 805 MHz experiment

- Test 201 MHz gas filled cavity.
  We need this to know the frequency dependence of the plateaux breakdown fields. The cavity does not have to be large if a small gap is used

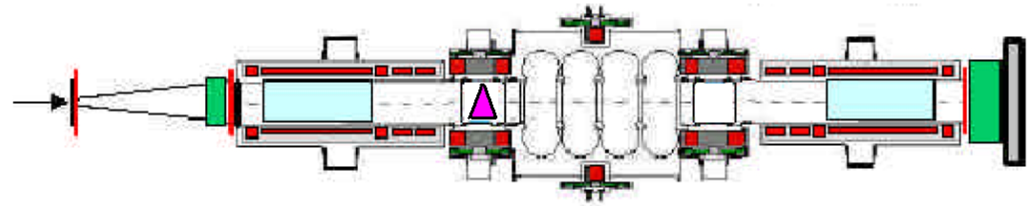


For 6D cooling

- Demonstrate 6D cooling without acceleration using a wedge at MICE
  Tracks can be selected off line to represent a beam with dispersion at the wedge absorber. Reconstruction of emittances before and after the LiH or polyethylene wedge will show 6D cooling



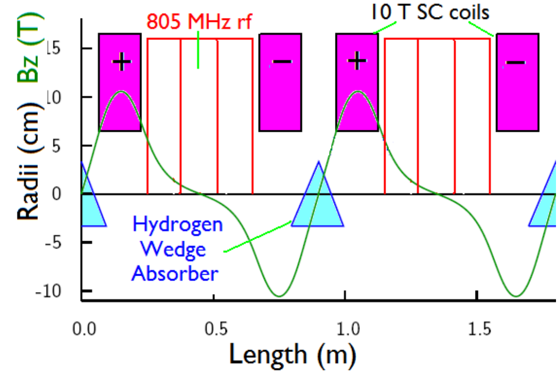
  Later re-acceleration can be included



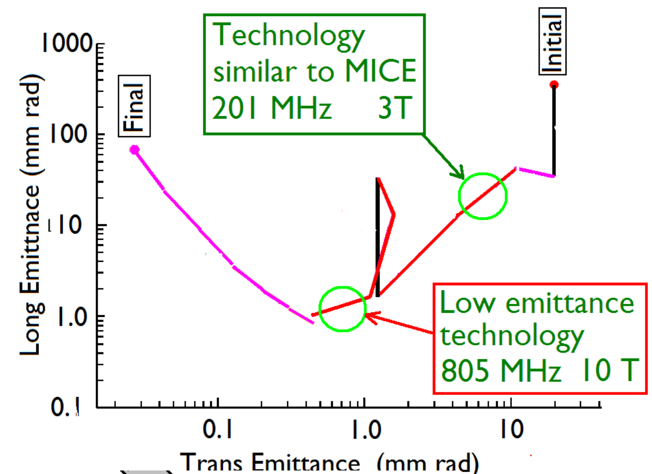
- Construct liquid hydrogen Wedge (large, small or both?)
  The Guggenheim, Yuri's PIC and REMEX lattices all need wedges. Hydrogen is the prefered material, at least in some of these. Various design concepts have been suggested and need study and test.

- R&D program on small Nb3SN solenoids with fields in the 10-17 T range using technology similar to that used in LBNL and other Nb3Sn accelerator magnets This would develop magnets needed for the 6D cooling down to 400 (pi mm mrad) for the high emittance solution, or lower for Yuri's scenario or PIC. It could reasonably be funded using generic accelerator magnet funds if P5 and DoE encouraged it.

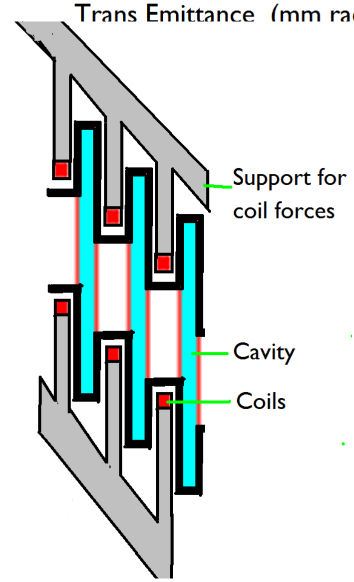
- Build a short section of 6D cooling to $\leq$ 400 (pi mm mrad), including rf
  This would demonstrate the integration of Nb3Sn solenoids, 805 MHz rf, and a small hydrogen wedge




- Demonstrate 6D cooling to low trans emittance
  This represents a test of integrated cooling components at emittances quite different from the current MICE. The MICE detectors could not measure these emittances, so this involves significant changes and significant cost

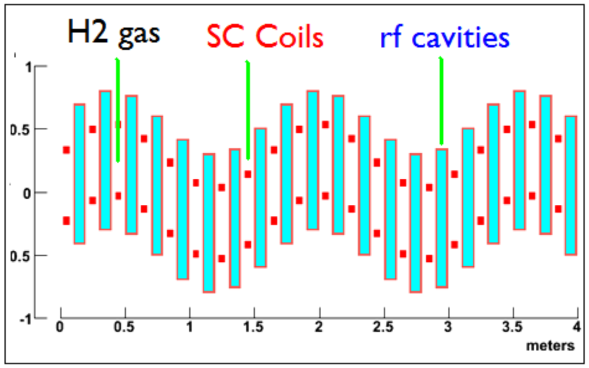



- Build a short length of HCC with rf and high pressure hydrogen gas and thin windows
  Addressing the two serious questions for HCC:
  - How to integrate the rf
  - Satisfying a safety committee with high pressure hydrogen with thin windows



- Demonstrate 6D cooling without rf using HCC
  This would be expensive, though less than MICE
  if tested at RAL because the beam and infrastructure exists
  But this does not address the HCC viability questions

- Demonstrate 6D cooling using HCC
  This would be a real demonstration
  of the HCC technology



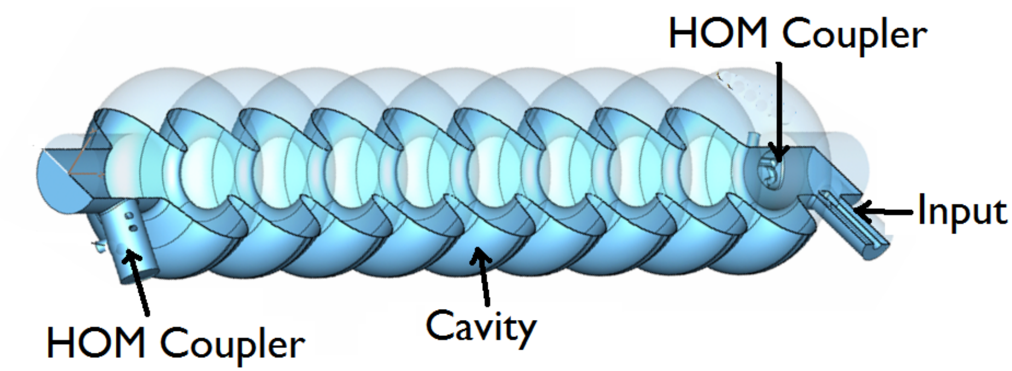

For final effective reverse emittance exchange

- Studies of HTS to reduce power of 50 T magnets

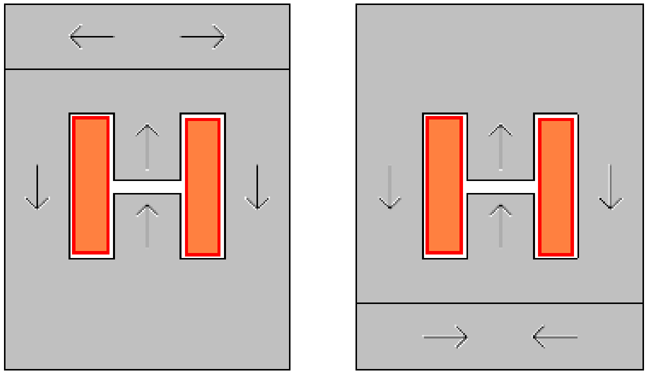
## For Acceleration

- Re-start 201 MHz superconducting rf work
  This is not obviously relevant to a Muon Collider, the acceleration would be done with 1.3 GHz SC cavities

- Build 1.3 GHz SC structure with strong HOM damping
  Certainly needed for the high emittance scheme (Yakovlev)

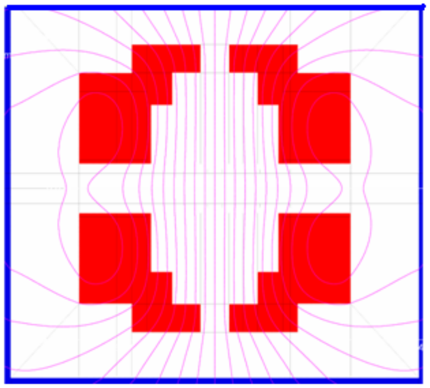



- Build model of pulsed synchrotron magnet
  Step 1 is to build a 30 cm section to demonstrate low losses and field quality. Later a full length magnet should be tested, addressing freedom from the higher Voltage breakdown



For collider ring

- Prototype of "open mid-plane" Collider Ring Magnet
  Design for 16 T with Nb3Sn
  Such a high field magnet decreases the
  ring diameter and raises the luminosity
  But will need significant development



- Build very high gradient quads for collider ring

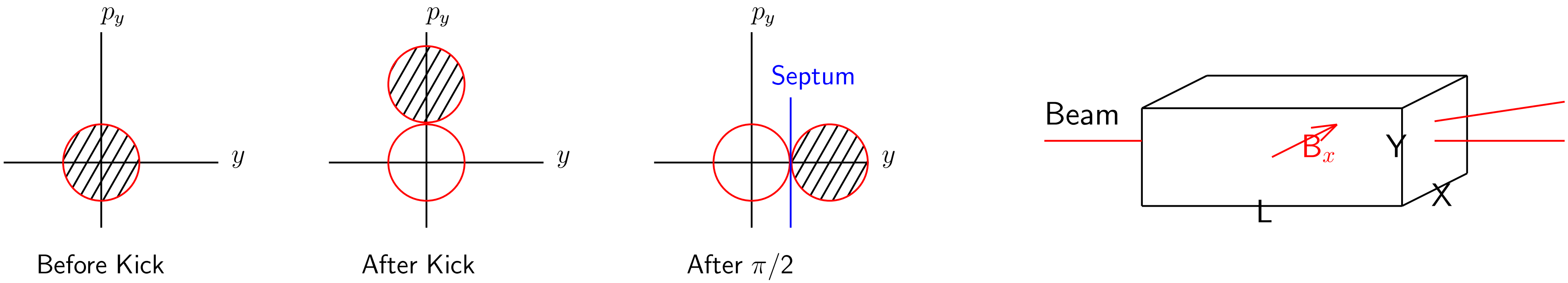
$$\mathcal{L} \propto n_{\rm turns}\, f_{\rm bunch}\, \frac{N_\mu^2}{\sigma_\perp^2} \qquad \Delta\nu \propto \frac{N_\mu}{\epsilon_\perp}$$

$$\mathcal{L} \propto B_{\rm ring}\, P_{\rm beam}\, \Delta\nu\, \frac{1}{\beta^*}$$

Stronger quadrupoles allow lower beta. Higher gradients require higher current densities Nb3Sn gives higher $j$ than NbTi Probably because of the greater temp margin If so, HTS should give even higher $j$s and higher gradients This is beyond the time scale for LARP, but would be of interest to many

- Kicker R&D for Neutrino Factory

  The minimum required kick to insert or extract a beam:




$$f_\sigma = \frac{\mathrm{Ap}}{\sigma} \qquad \mu = \mathrm{inf} \qquad F = \frac{Y}{X} \qquad U = F \left( \frac{m_\mu^2 \; 8 \; f_\sigma^4 \; R}{\mu_o \; c^2} \right) \quad \frac{\epsilon_n^2}{L}$$

  – $\nu$ factory $\epsilon_n \gg$ other $\epsilon_n$'s

    3,000 pi mm mrad (acc=30,000) vs. 300 pi mm mrad for p bar

  – $\nu$ factory Joules $\gg$ other kickers

    1000 J vs. 10 J

  – Need for R&D

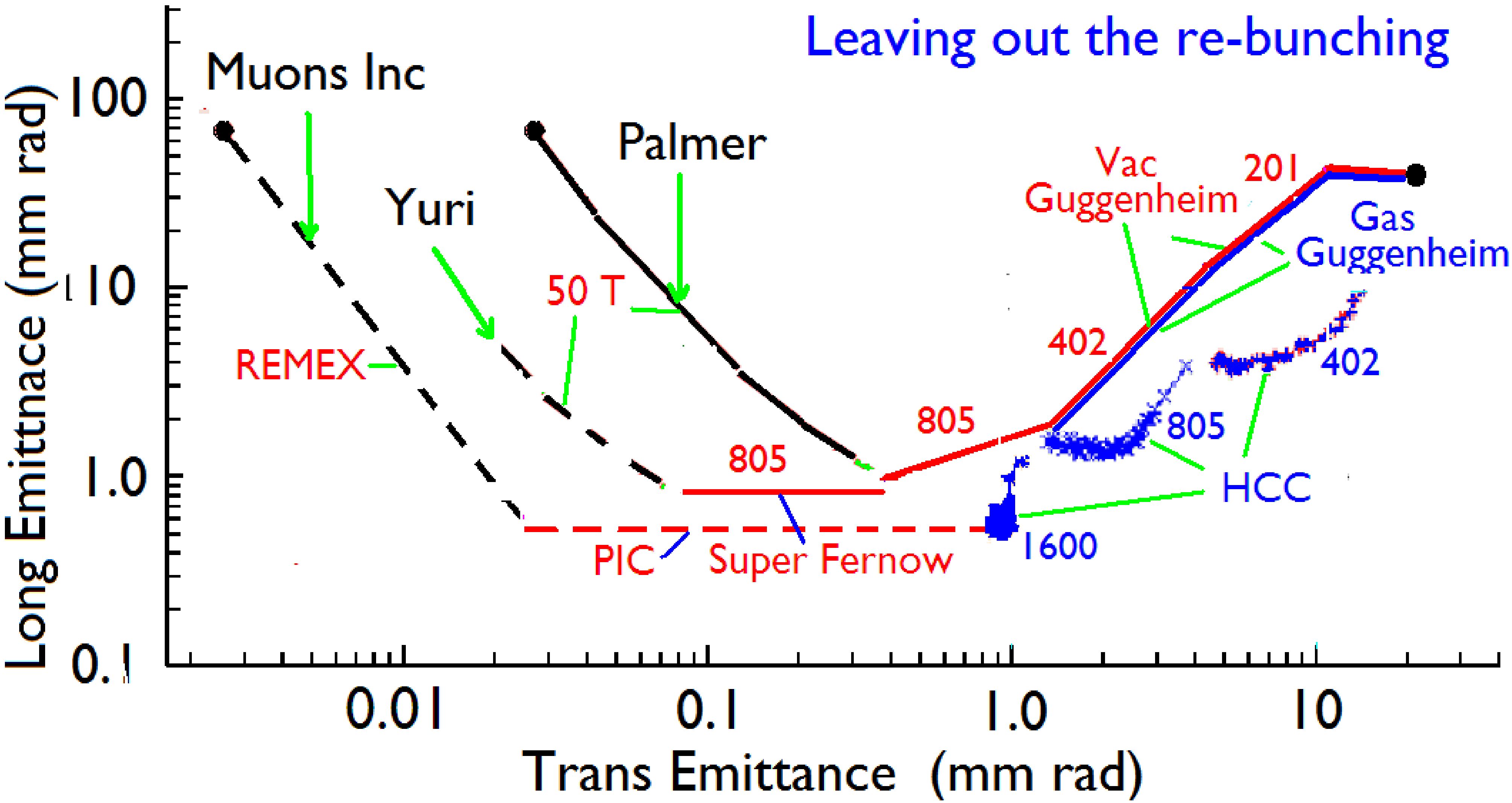
  – Not a problem for Collider because $\epsilon_\perp$ is small

    25 pi mm mrad vs. 300 pi mm mrad p bar

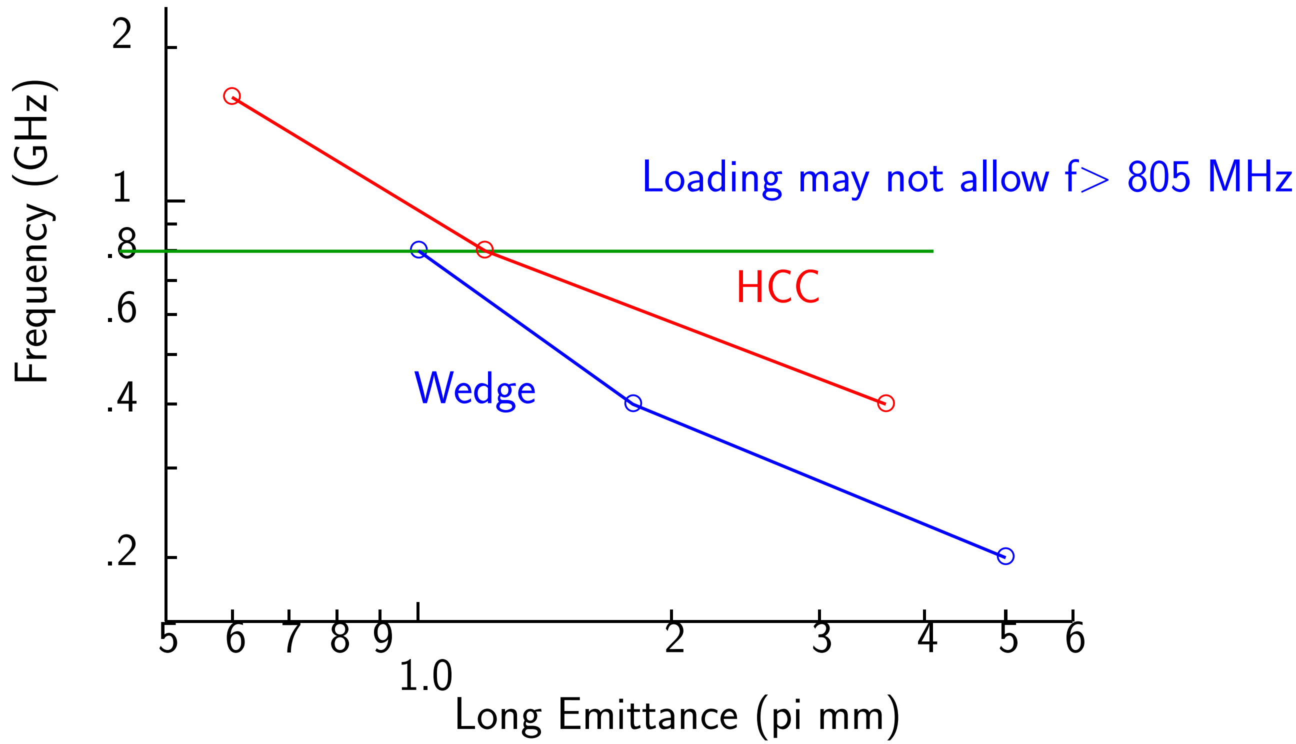
- Low Energy Neutrino Factory Large volume Detector Magnet

  Needed only for a low energy neutrino factory, added for completeness

# Look again at the overall system



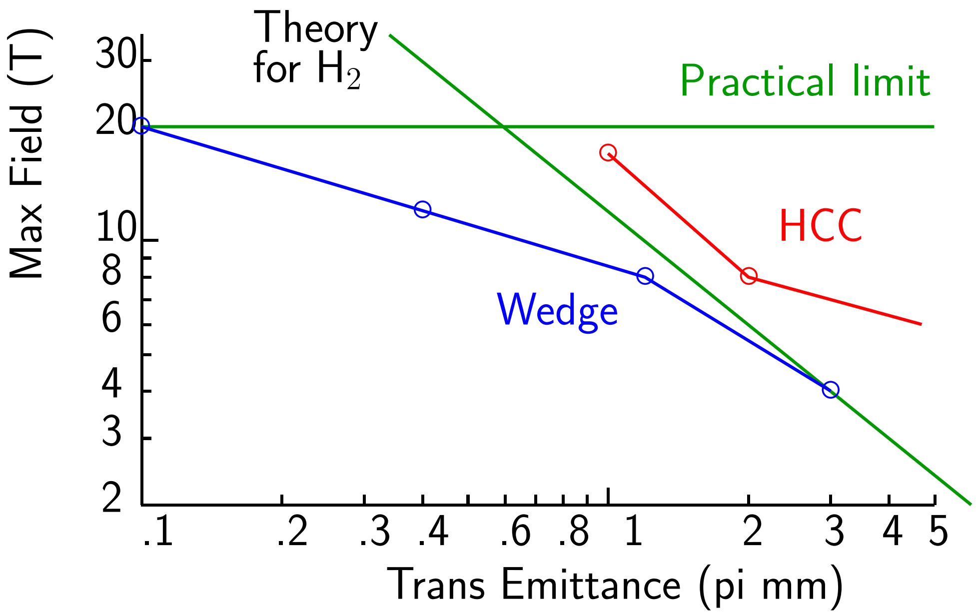
# Dependencies on Frequency




- With fixed emittance exchange, longitudinal cooling is to a fixed dp/p
- Higher frequencies cool to lower longitudianl emittance
- But beam loading of the rf probably limits rf to 805 MHz or lower

- Not clear why Guggenheims get somewhat lower long emittance for same f

# Dependencies on Peak Field




$$\epsilon_\perp = \frac{C\ \beta_\perp}{J_\perp}$$

$$\beta_\perp = \frac{6.66\ p}{< B >}$$

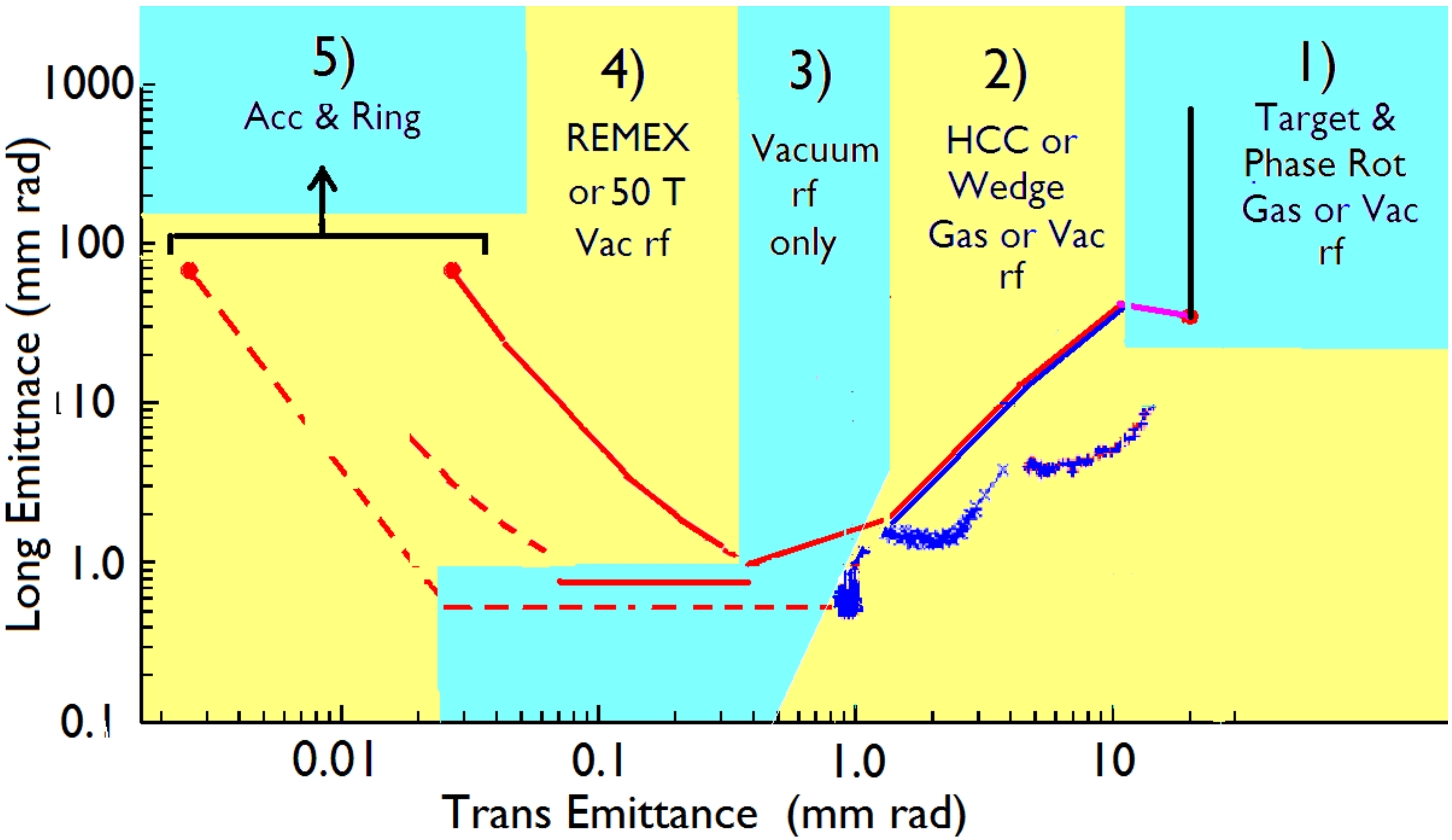
$$\text{if} \quad B_{\max} \approx 1.5\ < B >$$

$$\epsilon_\perp = \frac{6.66\ C\ p}{< B >\ \ J} \approx \frac{8}{B_{\max}}\ \text{(mm)}$$

- Lattices with gas must get their low betas from high average fields
  - When the need for dispersion is included, current density considerations limit the maximum practical fields to about 20 T
    $\rightarrow\ \epsilon_\perp > 0.8\ (\pi$ mm)
- Lattices without gas, using wedges, can use focus to get lower betas and $\epsilon_\perp$
- 50 T is a special case where no dispersion is required and momentum can be low, allowing higher fields and cooling to low $\epsilon_\perp$ but rising $\epsilon_\parallel$

# Scores (N)

- Divide system into 5 sub-systems
- Add 1 to the 'score' $N$ for each subsystem application for each of Low emittance and normal emittance systems
- Add 1 for any sub-system if also needed for a Neutrino Factory



# Priorities

WARNING What follows is VERY subjective and crude

I estimate the 'costs' ($C$) of each R&D activity in Millions of dollars per year
These are supposed to include overhead and associated instrumentation and controls

I define a Quality $\quad \mathrm{Q} = \mathrm{N} - 2\ \mathrm{C}$

If $Q$ is positive its Q is printed in red These are the 'high priority' items

If $Q$ is negative I print it in blue

# Needed R&D

| | cost M$ /yr | 1 tgt NF | 1 rot MC | 2 6D HCC | 2 (1) Vac | 3 6D L | 3 (2) H | 4 rev L | 4 exch H | 5 acc NF | 5 ring MC | score | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Study effects on Hg jet entering magnet | 1/4 | 1 | 2 | | | | | | | | | 3 | 2.5 |
| 20 T capture solenoid | 2 | 1 | 2 | | | | | | | | | 3 | -1 |
| 200 MHz rf power sources | 1 | 1 | 2 | 1 | 1 | | | | | | | 5 | 3 |
| 805 MHz open cavity experiment | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | 9 | 7 |
| 201 MHz cavity with coils in irises | 1 | 1 | 2 | 1 | 1 | | | | | | | 5 | 3 |
| 201 MHz gas filled cavity | 1/4 | 1 | 2 | 1 | 1 | | | | | | | 5 | 4.5 |
| Construct liquid hydrogen wedge | 1/2 | | | | 1 | 1 | 1 | | | | | 3 | 2 |
| 6D cooling in MICE | 1/4 | | | | 1 | 1 | 1 | | | | | 3 | 2.5 |
| Small Nb3Sn solenoid R&D | 1 | | | | | 1 | 1 | | | | | 2 | 0 |
| Section of low $\epsilon_\perp$ 6D cool | 1 | | | | | 1 | 1 | | | | | 3 | 1 |
| 6D cooling to $\epsilon_\perp \leq$ 400 $(\pi\ 10^{-6}$ m) | 4 | | | | | 1 | 1 | | | | | 2 | -6 |
| Short length of HCC with rf | 1 | | | 1 | | | | | | | | 1 | -1 |
| 6D cooling without acceleration in HCC | 2 | | | 1 | | | | | | | | 1 | -3 |
| 6D cooling with acceleration in HCC | 4 | | | 1 | | | | | | | | 1 | -7 |
| HTS for 50 T magnets | 1 | | | | | | | 1 | 1 | | | 2 | 0 |
| Re-start 201 MHz superconducting rf | 1 | | | | | | | | | 1 | | 1 | -1 |
| 1.3 GHz SC rf with mode damping | 1 | | | | | | | | | | 2 | 2 | 0 |
| Magnetic field on 201 MHz SC rf | 1/2 | | | | | | | | | 1 | 2 | 3 | 2 |
| Pulsed synchrotron magnet | 1/4 | | | | | | | | | | 2 | 2 | 1 |
| Open mid-plane Collider Magnet | 2 | | | | | | | | | | 2 | 2 | -2 |
| Very High gradient quads for IP | 1 | | | | | | | | | | 2 | 2 | 0 |
| Kicker Studies | 1 | | | | | | | | | 1 | | 1 | -1 |
| Neutrino detector magnet | 1 | | | | | | | | | 1 | | 1 | -1 |
| TOTAL | 28 | | | | | | | | | | | | |

| Ordered List | cost M$ /yr | scor | Q | $\Sigma$cost M$ /yr |
|---|---|---|---|---|
| 805 MHz open cavity experiment | 1 | 9 | 7 | 1 |
| 201 MHz gas filled cavity | 1/4 | 5 | 4.5 | 1.25 |
| 200 MHz rf power sources | 1 | 5 | 3 | 2.25 |
| 201 MHz cavity with coils in irises | 1 | 5 | 3 | 3.25 |
| 6D cooling in MICE | 1/4 | 3 | 2.5 | 3.5 |
| Study effects on Hg jet entering magnet | 1/4 | 3 | 2.5 | 3.75 |
| Construct liquid hydrogen wedge | 1/2 | 3 | 2 | 4.25 |
| Magnetic field on 201 MHz SC rf | 1/2 | 3 | 2 | 4.75 |
| Section of low $\epsilon_\perp$ 6D cool | 1 | 3 | 1 | 5.75 |
| Pulsed synchrotron magnet | 1/4 | 2 | 1 | 6 |
| Small Nb3Sn solenoid R&D | 1 | 2 | 0 | 7 |
| Very High gradient quads for IP | 1 | 2 | 0 | 8 |
| HTS for 50 T magnets | 1 | 2 | 0 | 9 |
| 1.3 GHz SC rf with mode damping | 1 | 2 | 0 | 10 |
| Kicker Studies | 1 | 2 | -1 | 11 |
| Neutrino detector magnet | 1 | 1 | -1 | 12 |
| Re-start 201 MHz superconducting rf | 1 | 1 | -1 | 13 |
| Short length of HCC with rf | 1 | 1 | -1 | 14 |
| 20 T capture solenoid | 2 | 3 | -1 | 16 |
| Open mid-plane Collider Magnet | 2 | 2 | -2 | 18 |
| 6D cooling without acceleration in HCC | 2 | 1 | -3 | 20 |
| 6D cooling to $\epsilon_\perp \leq$ 400 $(\pi\ 10^{-6}$ m) | 4 | 2 | -6 | 24 |
| 6D cooling with acceleration in HCC | 4 | 1 | -7 | 28 |

# Conclusion

- The lowest priority items are the 3 possible cooling experiments
- If we choose one cooling experiment (with acceleration) we have a total of 22 M\$/yr plus $\approx$ 10 M\$/yr needed for simulation, thus requiring $\approx$32 M\$/year. More than requested at p5.
- If we drop all cooling demonstrations and consentrate on the component work, then the total comes down to 18 M\$/yr which is starting to be more reasonable

  The cooling experiments are very expensive, and component testing will tell us almost all we need to know

  MICE can soon demonstrate 6D cooling without re-acceleration. Later, replacing a hydrogen absorber with a wedge, it can do it with re-acceleration. Doing the same thing another way is nice, but not a high priority
- The 10 "High priority" items (positive Q) cost 7 M\$ per year
- The highest priority item is an Open Cavity experiment

  because vacuum acceleration is needed in all scenarios in most sub-systems, and it is not excessively expensive
- My estimates are very very rough, but I doubt they are underestimates
- One could do everything and do them infinitely slowly. This would be a mistake.

# Appendix: R&D Underway or soon, with Qs

| | cost M$ /yr | 1 tgt NF | 1 rot MC | 2 6D HCC | 2 (1) Vac | 3 6D L | 3 (2) H | 4 rev L | 4 exch H | 5 acc NF | 5 ring MC | score | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MICE | 4 | | | 1 | 2 | 1 | 1 | | | | | 5 | -3 |
| 805 Button study | 1/2 | 1 | 2 | | 1 | 1 | 1 | 1 | | | | 7 | 6 |
| 805 pillbox with B at angles | 1/4 | 1 | 2 | | 1 | 1 | 1 | 1 | | | | 7 | 6.5 |
| 201 MHz cavity in magnetic fields | 1 | 1 | 2 | | 1 | | | | | | | 4 | 2 |
| Gas cavity in beam | 1 | 1 | 2 | 1 | 1 | | | | | | | 5 | 3 |
| HCC coils | 1 | | | 2 | | | | | | | | 2 | 0 |
| EMMA | 3 | | | | | | | | | 1 | 1 | 2 | -4 |
| TOTAL | 11 | | | | | | | | | | | | |