Muon Collider Task Force

- Formed in July'06 by FNAL Director:
  - "... the Muon Collider represents a possible long term path for extending the energy frontier in lepton collisions beyond 1 TeV..."
  - MCTF formed "...to develop a plan for an advanced R&D program aimed at the technologies required to support the long term prospects of a Muon Collider..."
  - leaders: S.Geer and V.Shiltsev
  - requested for Sept'2006: "...a report outlining a plan for developing the Muon Collider concept based on recent ideas in the realm of ionization cooling, and an associated cooling R&D plan that can be implemented starting in FY2007"

MCTF Report (https://mctf.fnal.gov)

- MCTF formed:
  - FNAL(35 people), Muons Inc (5), BNL (6), LBNL(4), JLAB (5), ANL (1)
- MCTF Proposal deliv'd in Sep'07 includes plan for:
  - Collider design studies and 6D cooling theory and simulations (Theorists)
  - 6D cooling and other experiments with 100's MeV p/muon beams at Muon Test Area . (Experimental)
  - Design and development of Helical Cooling Channel magnets, "50T" solenoids, MC dipoles (Magnet program)
- MCTF activities are complementary to NFMCC
- Pending request for AARD support from DOE…

MCTF R&D Proposal

1. **Collider Design and Simulations to establish the muon cooling requirements.** We will take a fresh look at the overall Muon Collider scheme. In addition to establishing the ionization cooling requirements, we will also identify the remaining muon source and collider design and performance issues.
2. **Component Development:** We will develop and bench test the components needed for the 6D cooling channel.
3. **Beam Tests and Experiments**: We will perform beam tests of the components. For that we will build a proton beam line for high-intensity tests of LiH absorbers* and pressurized RF cavities. Later, we will design and build a muon production, collection and transport system. 250-300 MeV/c muons will be used in the 6D ionization cooling demonstration experiment.

*Moved to collaboration

FY07

a) Initial design report for a 1.5 TeV low emittance muon collider;
b) MTA high power proton beam implementation plan;
c) HTS material studies report and development plan for a very high-field solenoid for muon cooling;
d) HCC design and utility report, decision to prototype;

FY08:

a) Pressurized RF cavity and absorber tests in the MTA with high-intensity proton beam;
b) Development and installation of muon target, transport line and diagnostics in MTA;
c) HTS insert built and tested at 15T and test report;
d) HCC and matching sections design finished, prototypes built;

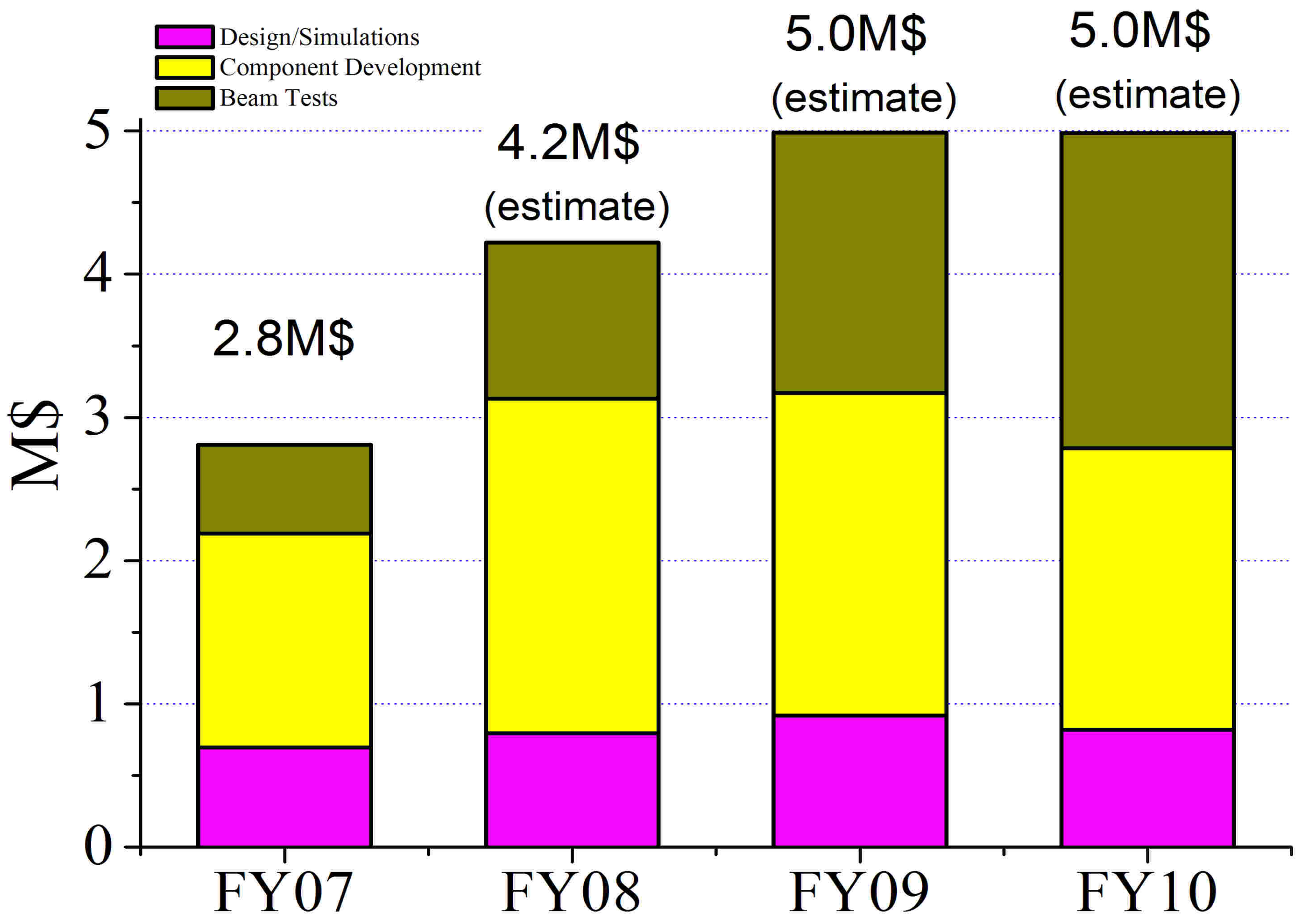
FY09:

a) Muon beam commissioned, start of muon diagnostics tests;
b) HCC magnets construction starts;
c) High Field HTSC solenoid engineering design finished;

FY10:

a) HCC magnets competed and 6D cooling experiment starts;
b) high-field HTSC solenoid prototype built.
c) Muon Collider cooling channel report

MCTF Report (https://mctf.fnal.gov)



- Current FY07 guidance: 750k$ total (p-line and MTA exp)
- FY08 guidance: 2.2M$ M&S + 3.9M$ SWF

PPENDIX A: BUDGET REQUEST SUMMARY

TASK NO.	DESCRIPTION OF WORK:	FY07 k$	FY08 (est) k$	FY09 (est) k$	FY10 (est) k$
01	**COLLIDER DESIGN AND SIMULATIONS**	***695***	***795***	***920***	***820***
1.1	1.5TeV Muon Collider studies				
	M&S	*10*	*10*	*10*	*10*
	SWF[1]	*250*	*300*	*350*	*400*
1.2	6D Cooling Simulations				
	M&S	*10*	*10*	*10*	*10*
	SWF	*350*	*400*	*500*	*350*
1.3	Collider Magnet Specs				
	M&S	*0*	*0*	*0*	*0*
	SWF	*75*	*75*	*50*	*50*
02	**COLLIDER COMPONENT DEVELOPMENT**	**1495**	**2355**	**2260**	**1965**
2.1	HCC Magnet Design and Prototyping				
	M&S[2]	*160*	*540*	*260*	*0*
	SWF	*250*	*270*	*270*	*75*
2.2	HTS High Field Solenoid				
	M&S	*350*	*380*	*780*	*940*
	SWF	*245*	*525*	*525*	*525*
2.3	Collider Magnet Design				
	M&S	*75*	*110*	*110*	*110*
	SWF	*200*	*315*	*315*	*315*
2.4	Absorber Development				
	M&S	*65*	*65*	*0*	*0*
	SWF	*150*	*150*	*0*	*0*
03	**EXPERIMENTAL BEAM TESTS**	**620**	**1095**	**1820**	**2200**
3.1	Muon 6D Cooling Test				
	M&S	*50*	*370*	*1300*	*1600*
	SWF	*400*	*520*	*520*	*600*
3.2	High Power Absorber Test[3]				
	M&S	*65*	*65*	*0*	*0*
	SWF	*65*	*65*	*0*	*0*
3.3	Pressurized RF Beam Tests				
	M&S	*0*	*0*	*0*	*0*
	SWF	*40*	*75*	*0*	*0*
	TOTAL:	**2810**	**4245**	**5000**	**4985**

[1] SWF rates used: 150k$/FTE of engineers and postdocs, 200k$/FTE of scientists
[2] 30% contingency is included in all M&S estimates
[3] In FY07, most of MTA proton beam line cost of 515k$ to be covered from ongoing program funds

APPENDIX B: FY07 BUDGET BREAKDOWN BY INSTITUTION

		FNAL	**BNL**	**LBNL**
TASK NO.	DESCRIPTION OF WORK:	k$	k$	k$
01	**COLLIDER DESIGN AND SIMULATIONS**	***695***	***0***	***0***
	M&S	*20*	*0*	*0*
	SWF	*675*	*0*	*0*
02	**COLLIDER COMPONENT DEVELOPMENT**	**940**	**280**	**275**
	M&S	*425*	*150*	*75*
	SWF	*515*	*130*	*200*
03	**EXPERIMENTAL BEAM TESTS**	**620**	**0**	**0**
	M&S	*115*	*0*	*0*
	SWF	*505*	*0*	*0*
	TOTAL:	**2255**	**280**	**275**

A look at progress to date

Task 01

Muon Collider ring optics design

Y.Alexahin & E.Gianfelice-Wendt

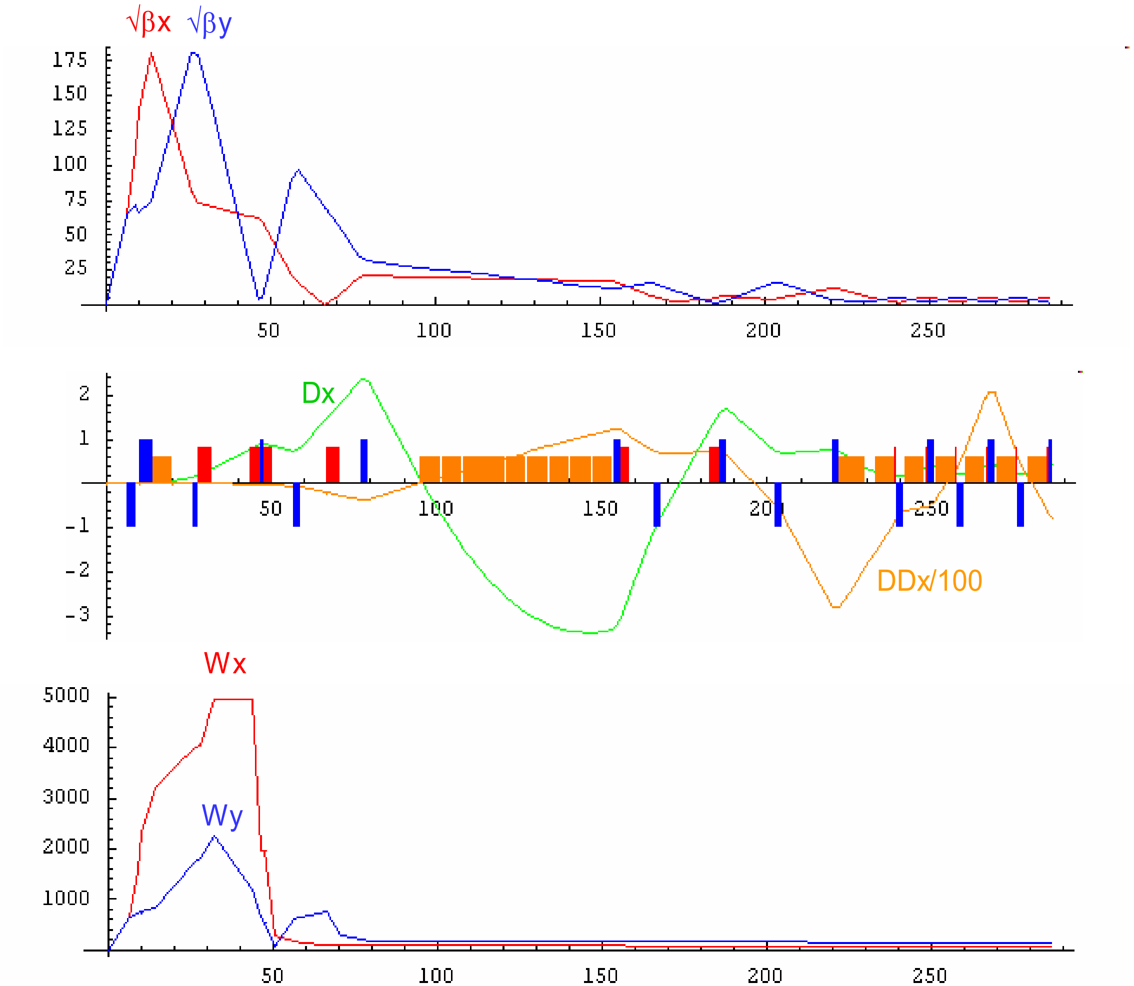
(FNAL)

Muon Collider Parameters

- **Low emittance option** - just a beautiful dream so far
- **High emittance option** - cautiously optimistic, reflects the latest results

	Low Emitt.	*High Emitt.*
Energy (TeV)	0.75+0.75 (γ=7098.4)	
Average Luminosity (1e34/cm^2/s)	2.7	2
Average bending field (T)	10	6
Mean radius (m)	361.4	500
Number of IPs	4	2
P-driver rep.rate (Hz)	65	60
Beam-beam parameter/IP, ξ	0.052	0.1
$\beta*$ (cm)	0.5	1
Bunch length (cm), σ_z	0.5	1
Number of bunches/beam, n_b	10	1
Number of muons/bunch (1e11), N_μ	1	11.3
Norm.transverse emittance (μm), $\varepsilon_{\perp N}$	2.1	12.3
Energy spread (%)	1	0.2
Norm.longitudinal emittance (m), $\varepsilon_{\|\|N}$	0.35	0.14
Total RF voltage (GV) at 800MHz	$406.6 \times 10^3\alpha_c$	$5.6\times 10^3\alpha_c$
RF bucket height (%)	23.9	2.4
Synchrotron tune	$0.723 \times 10^3\alpha_c$	$0.1\times 10^3\alpha_c$

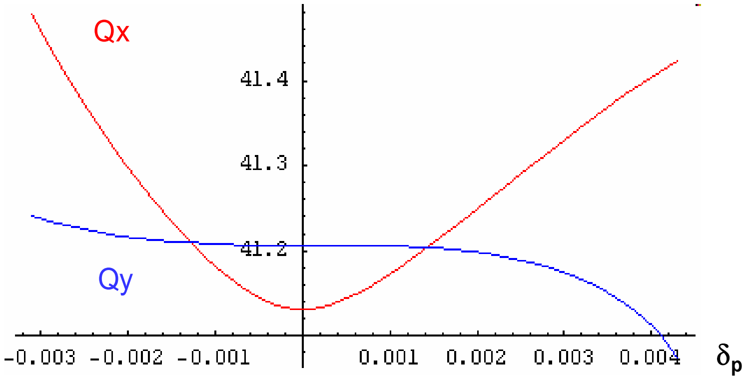
“Quad First” @6.5m MC Lattice Design



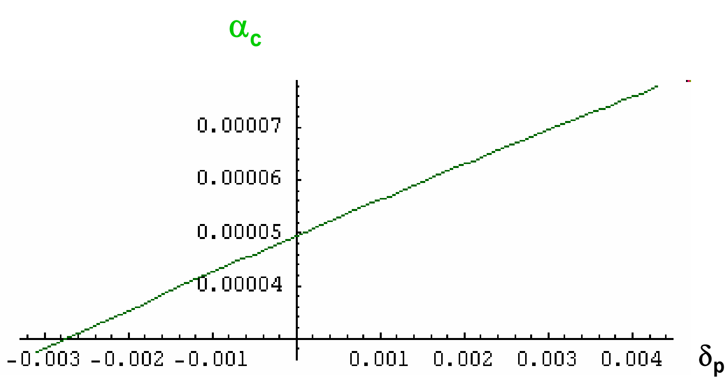
IR, negative dispersion and matching sections

"Quad First" MC Lattice Properties

No octupoles



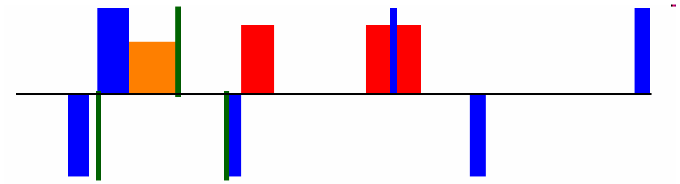

```
Second order chromaticity:
Q1''     = 102511.04779854
Q2''     =    366.54867056
Normalized anharmonicities:
dQ1/dE1 =  0.55557395E+08
dQ1/dE2 =  0.20800890E+09
dQ2/dE2 =  0.58845415E+08
```



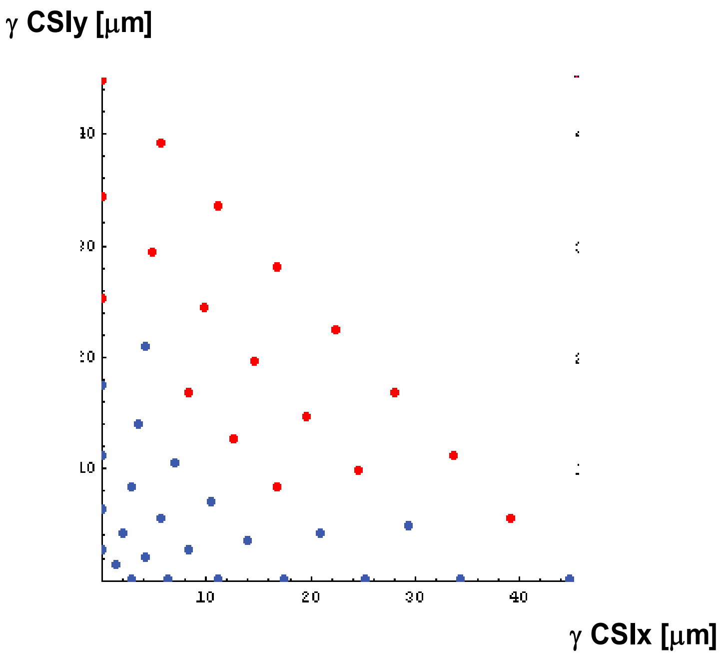
Huge cross-detuning makes dynamic aperture virtually vanishing – octupoles necessary

“Quad First” MC Lattice Properties

With octupoles (shown in green)



```
Second order chromaticity:
Q1''    = 102517.98582532
Q2''    =   1127.89764247
Normalized anharmonicities:
dQ1/dE1 =  0.65239168E+08
dQ1/dE2 =  0.47761742E+08
dQ2/dE2 =  0.37233974E+08
```



Dynamic aperture with ~ optimum octupole strength still is not sufficient for the high-emittance option: <1.5σ for $\varepsilon_{\perp N}$=12.5 μm (marginally O.K. for the low-emittance option)

How to Improve the DA?

- Retreat to $\beta*$ 2-3cm (not interesting)
- Move quads closer to the IP? – actually does not help
- Increase dispersion @ IR sextupoles!

This can be done by placing a dipole between the IP and the first quad. The arguments pro:

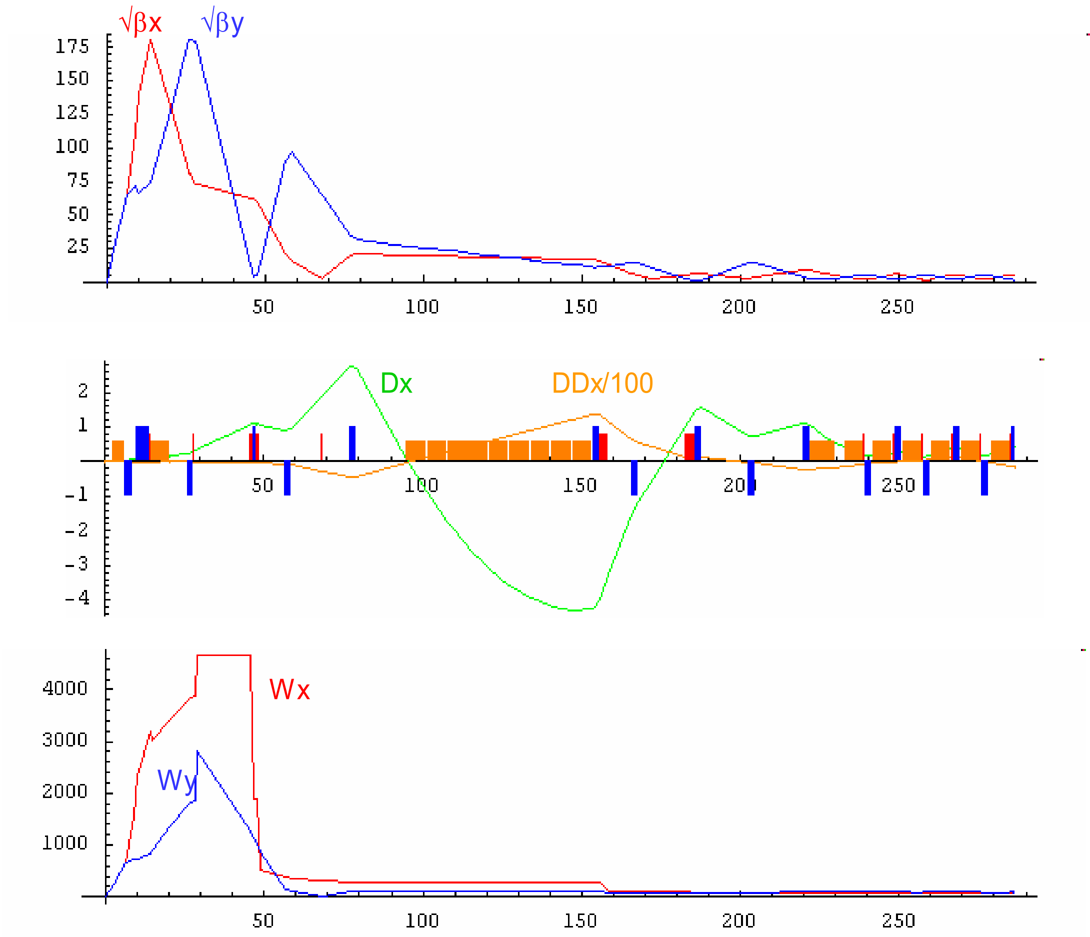
- the requirement of 6.5m stay-clear was obtained for twice higher energy and bunch intensity
- the dipole itself will protect the detector from the most dangerous sources of backgrounds: decay electrons and Bethe-Heitler muons

The arguments contra:

- 250 Gev decay electrons will produce hard synchrotron radiation in the dipole field

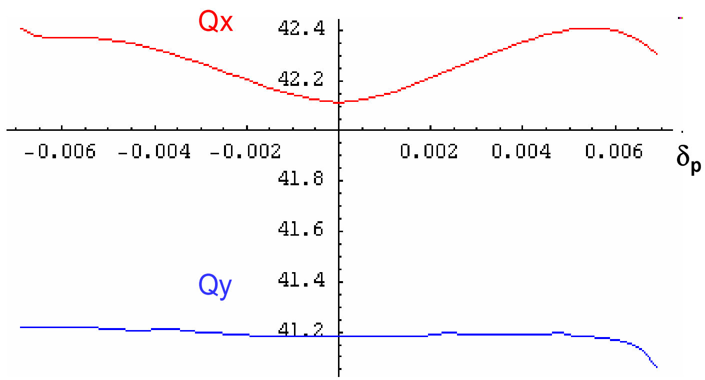
But first of all let us see what improvement in the DA it promises

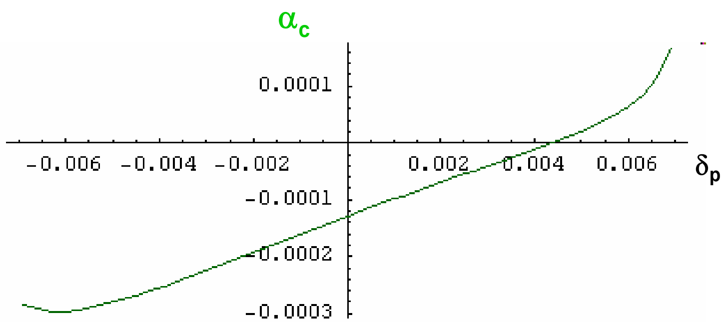
“Dipole First” MC Lattice Design Option



IR, negative dispersion and matching sections, octupoles not shown (there is one more at maximum |Dx| to control 2nd order chromaticity).

"Dipole First" MC Lattice Properties





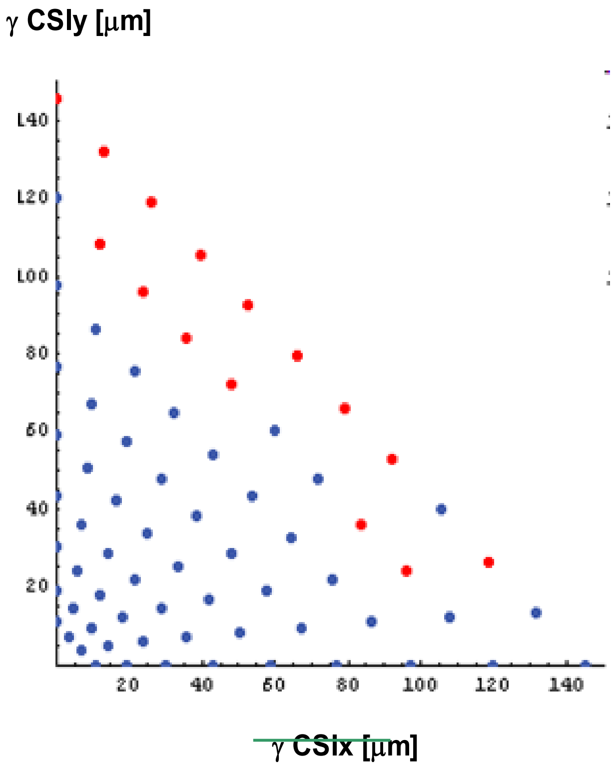

```
Second order chromaticity:
Q1''     =  67698.83542578
Q2''     =   1860.74134081
Normalized anharmonicities:
dQ1/dE1 =  0.43575747E+08
dQ1/dE2 =  0.16659793E+08
dQ2/dE2 =  0.14651033E+08
```

Owing to larger dispersion at IR sextupoles the requires sextupole gradient became lower reducing 2nd order effects.

Also, in this version 2nd order dispersion was corrected with sextupoles in the matching section.

Momentum acceptance of ± 0.7% is O.K. for the high-emittance option (not for the low)

"Dipole First" MC Lattice Properties



The 1024 turns DA is only marginally sufficient for the high-emittance option: ~3σ for $\varepsilon_{\perp N}$=12.5 μm (O.K. for the low)

- The "dipole first" option gives a hope to obtain the required DA (by further optimization) with β∗=1cm
- It is not clear, however, if the synchrotron radiation from a dipole so close to the IP would be tolerable.
- To proceed further to a realistic design a close collaboration with the detector, energy deposition and magnet technology groups is a must.
- We estimate the time necessary for backgrounds evaluation and shielding design as ~ 2 FTE.

Task 02
MCTF Magnet Effort

- Support specific magnet projects for 6D Cooling Demonstration
  - Helical Cooling Channels and Matching Sections*
- Longer Term Magnet R&D
  - "50 T" Solenoid*
  - Next generation Helical Solenoid (future Muons Inc SBIR)
  - Collider and IR magnets?
  - Provide Coordination for Muon Magnet Program for Fermilab Muon Experiments
  - Interface with AP and Detector groups
  - Coordinate activities with other magnet laboratories (BNL, FNAL, LBNL, NHMFL, Muons Inc.)

***Called out in MCTF charge and primary R&D focus**

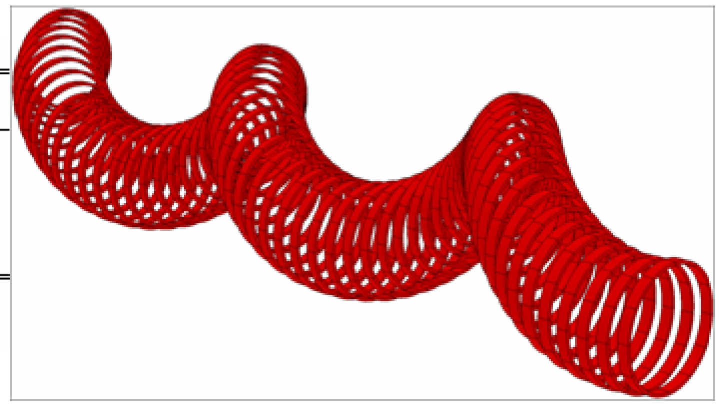
Helical Cooling Channel

The solenoid consists of a number of ring coils shifted in the transverse plane such that the coil centers follow the helical beam orbit. The current in the rings changes along the channel to obtain the longitudinal field gradients.

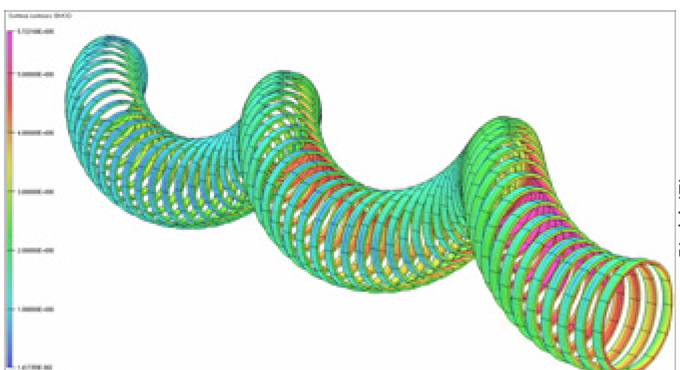
Parameters of Small Bore Cooling Channel

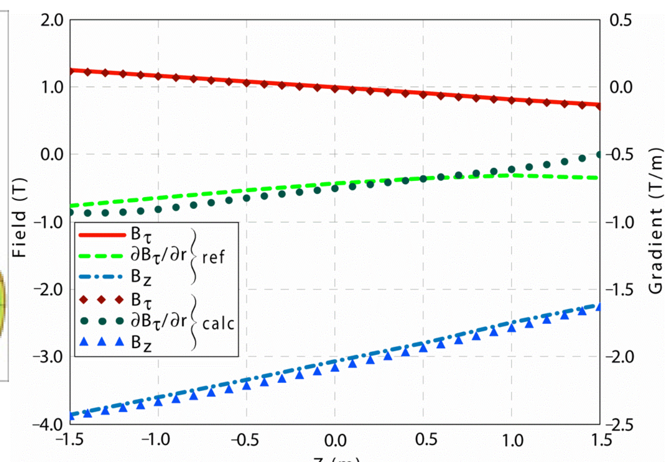
Parameter	Unit	Value
Inner radius	m	0.28
Radial thickness	mm	15.00
Operating current density†	A/mm^2	346.4
Operating peak field	T	5.72
Quench peak field‡ at 4.2 K	T	7.38
Operating stored energy	MJ	4.42

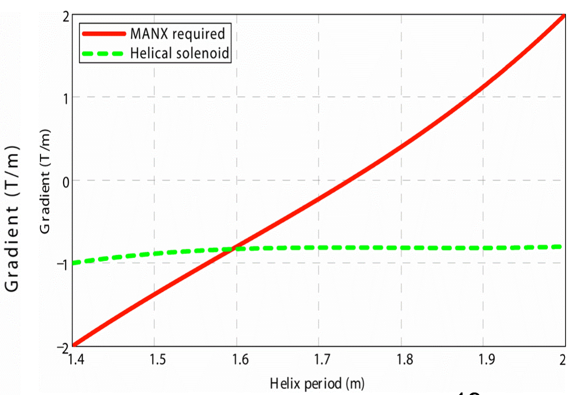
†Calculated as the total current over the total conductor cross-section.
‡Calculated assuming that the non-Cu fraction of superconductor spans 30% of the total conductor area.

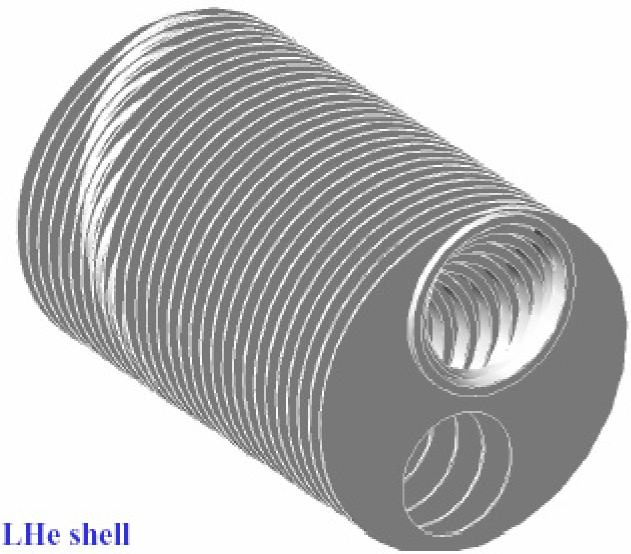


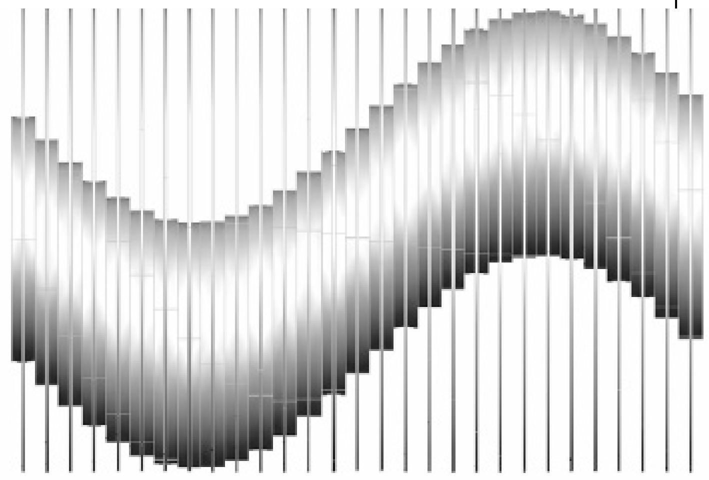
One can see that the optimum gradient for the helical solenoid is -0.8 T/m, corresponding to a period of 1.6 m.

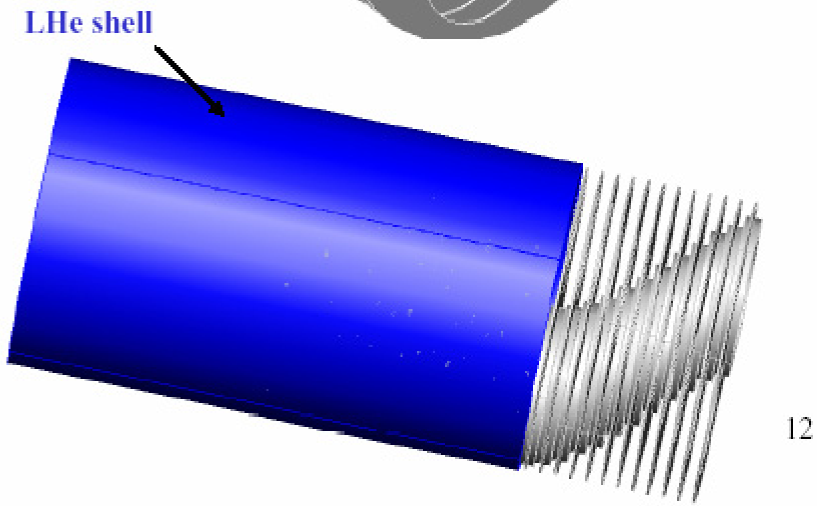












1. The cold mass assembled by 12.4° rotation of each coil assembly around axis Z
2. Technological holes used to splice cables of neigboring coil sections
3. 29 coils form 1.6 m period
4. LHe vessel has longitudinal keys with angular step 12.4 ° to protect coils from rotation under Lorentz forces torques

V. Kashikhin

Superconducting Coil Test

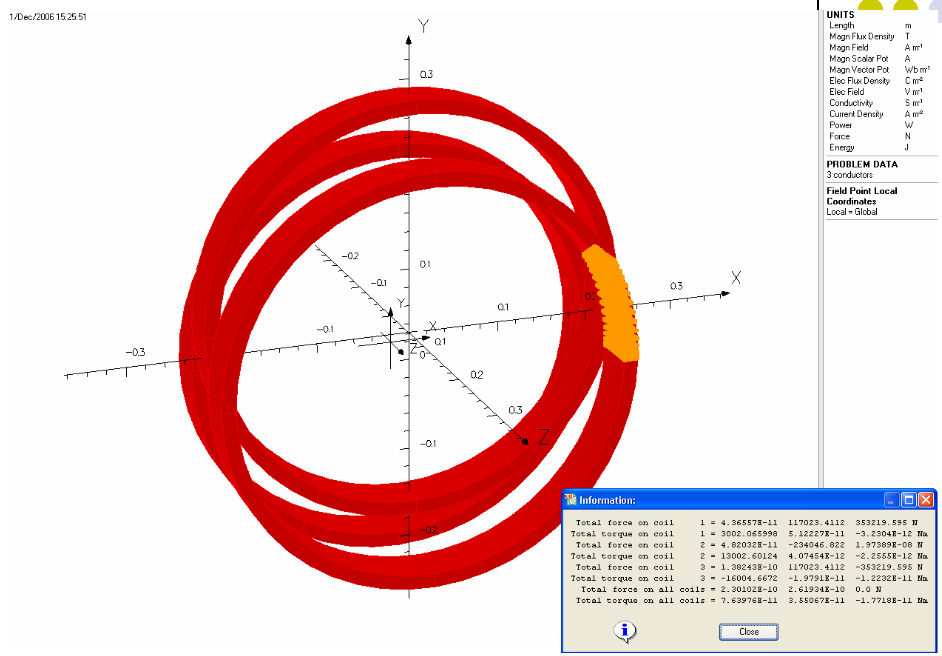
Proposal to build 3 coil section of Helical Cooling Channel, then test coils in Fermilab Vertical Magnet Test Facility

Purpose:

-Develop Engineering Design for HCC rings and magnet mechanical support structure

-Develop in situ magnetic measuring system for field characterization and field stability

-Create "coil test facility" which can be used for studying powering and quench protection and error conditions i.e. tests that might be risky to perform on the full scale magnet. Later, production coils can be qualified in this structure prior to final assembly



Helical Solenoid Forces

Section N	Fx, kN	Fy, kN	Fz, kN
1	-185	-63	304
36	74	-11	-8
73	-49	18	-81

Coils shifted 55.5 mm in radial direction, Frmax=196 kN

“50 T” Solenoid

- Proposed for end of cooling channel for final emittances. General high field solenoid R&D essential for muon cooling!
- “50 T” DC, 30 mm aperture, 1-2 m length
- Superconducting for manageable power reqs
  - HTS or HTS/Nb_3Sn/NbTi hybrid
- Beyond present capabilities (has never been attempted)
  - Proposals to built 25-30 T HTS solenoids
  - Conceptual design studies performed with Muons Inc. in collaboration with BNL.

Interest in HTS for high field solenoids

- High field solenoids are crucial for muon cooling. HTS very attractive but will require real support and collaboration with the conductor companies as well as collaboration with other labs and sciences. 30 T solenoid for NMR for medical for instance. We need work here.
- Conceptual design of 50 T solenoid ongoing, Kahn/ Muons Inc. and Palmer/Gupta at BNL **See EPAC06 WEPLS108**

- **NHMFL has developed 5 T HTS insert, for 25T solenoids**
- **Muons Inc has pending SBIR's on HTS application to magnet design**
- **Fermilab, BNL and LBNL experience on conductor and small coils**
- **"2212 day" workshop organized by Tollestrup & Larbalestier November 6, 2006**

2007-8 R&D on HTS for high field solenoids

- Evaluation of HTS Materials
  - BSCCO 2212 wires/cable
  - We have requested samples of BSCCO and YBCO tapes from conductor vendors
- Mechanical/electrical probe design and construction
  - Tensile strain
  - Field orientations
- HTS coil insert designs
  - 1-5 T insert(s) suitable for SC R&D lab 16 T or 17 T Teslatron
- Investigate possible collaborations/cooperations between FNAL, NHMFL, BNL & Muons Inc.…to develop long term strategy

Muon Test Area (MTA): Task 03.
Beam Tests and Experiments.

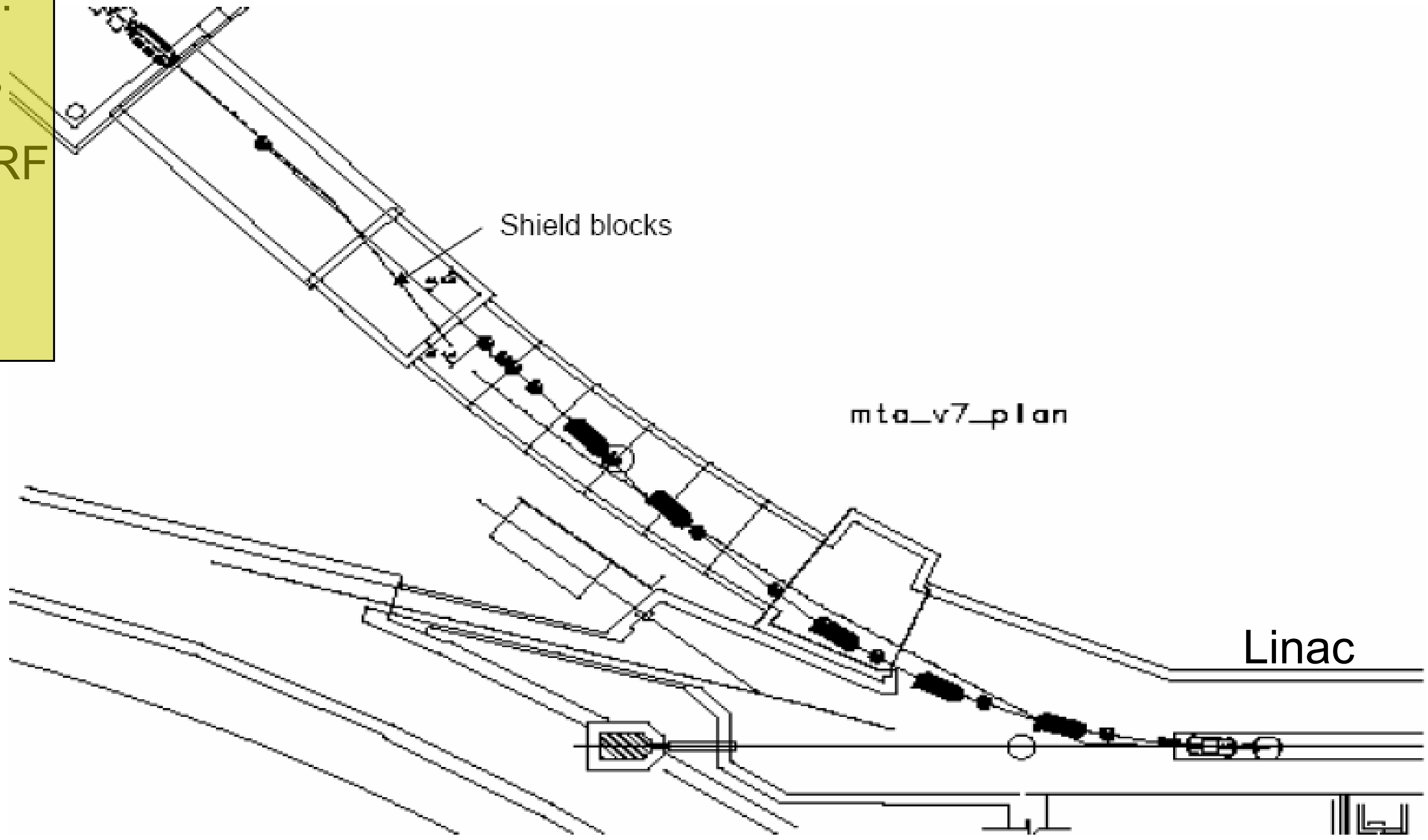
400 MevProton-beamline to MTA (Carol Johnstone)

Test Area for:

Thin wndows

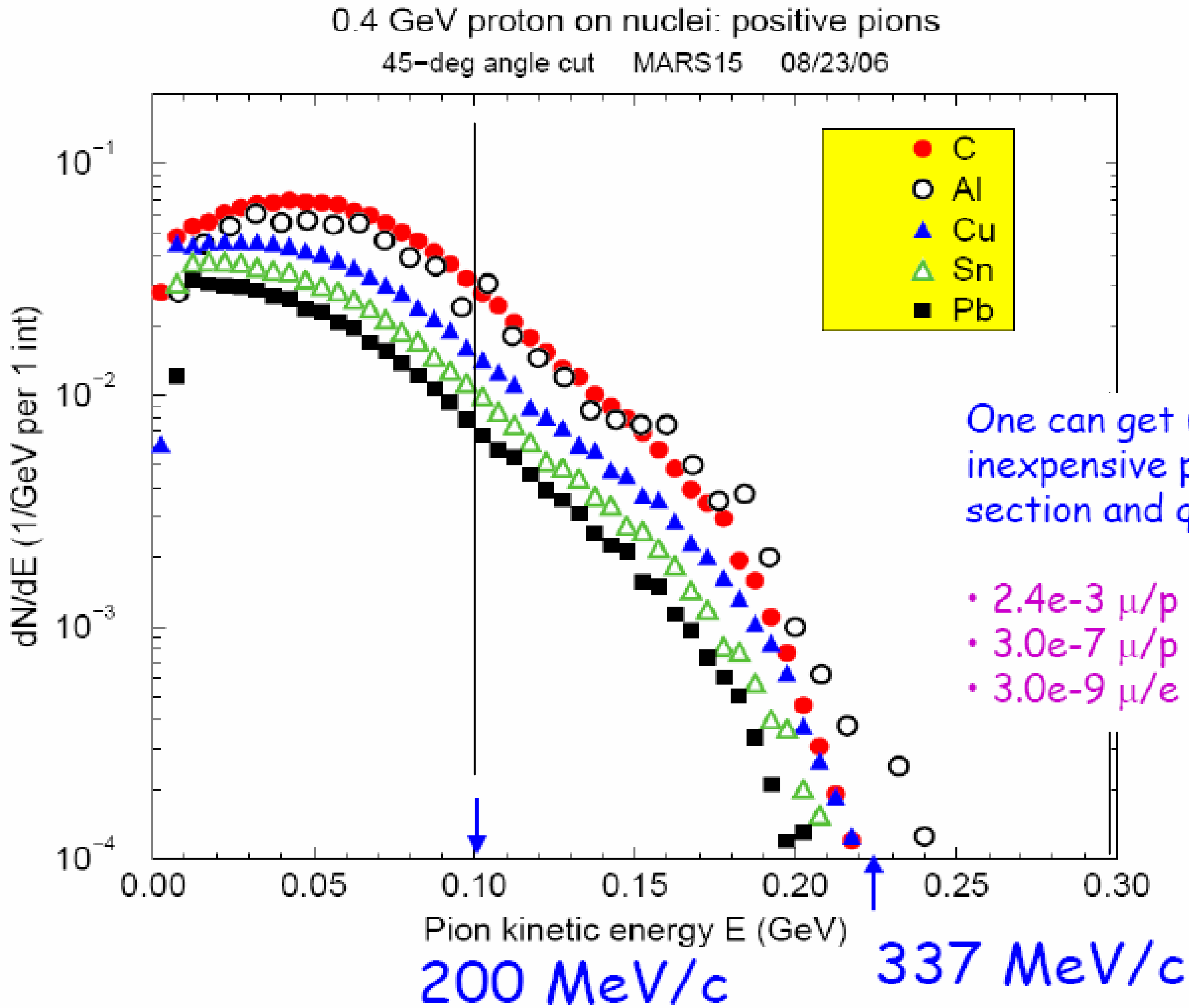
Hi Pressure RF cavities

LiH absorber



Muon test beam At MTA

Yield of muon+ with 400 MeV Protons



MARS Calculation

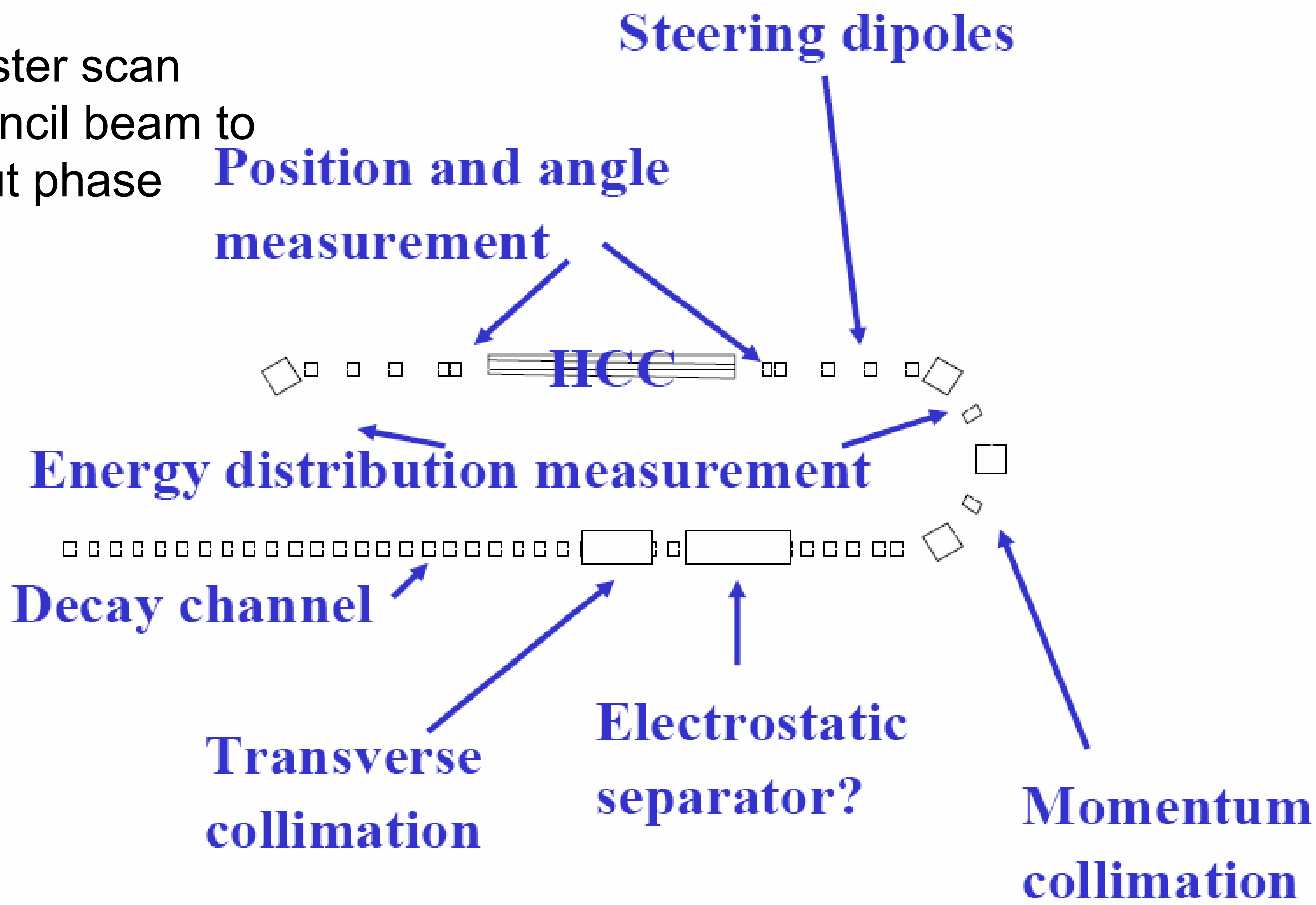
One can get usable (test) muon beams with simple inexpensive production target, capturing/matching section and quadrupole-based decay channel:

- 2.4e-3 μ/p with 8-GeV protons from Booster
- 3.0e-7 μ/p with 0.4-GeV protons at MTA
- 3.0e-9 μ/e with 0.75-GeV electrons at ILCTA

Overall scheme (Janssen)

Muon test beam at MTA and cooling tests for an HCC

Use raster scan with pencil beam to map out phase space.

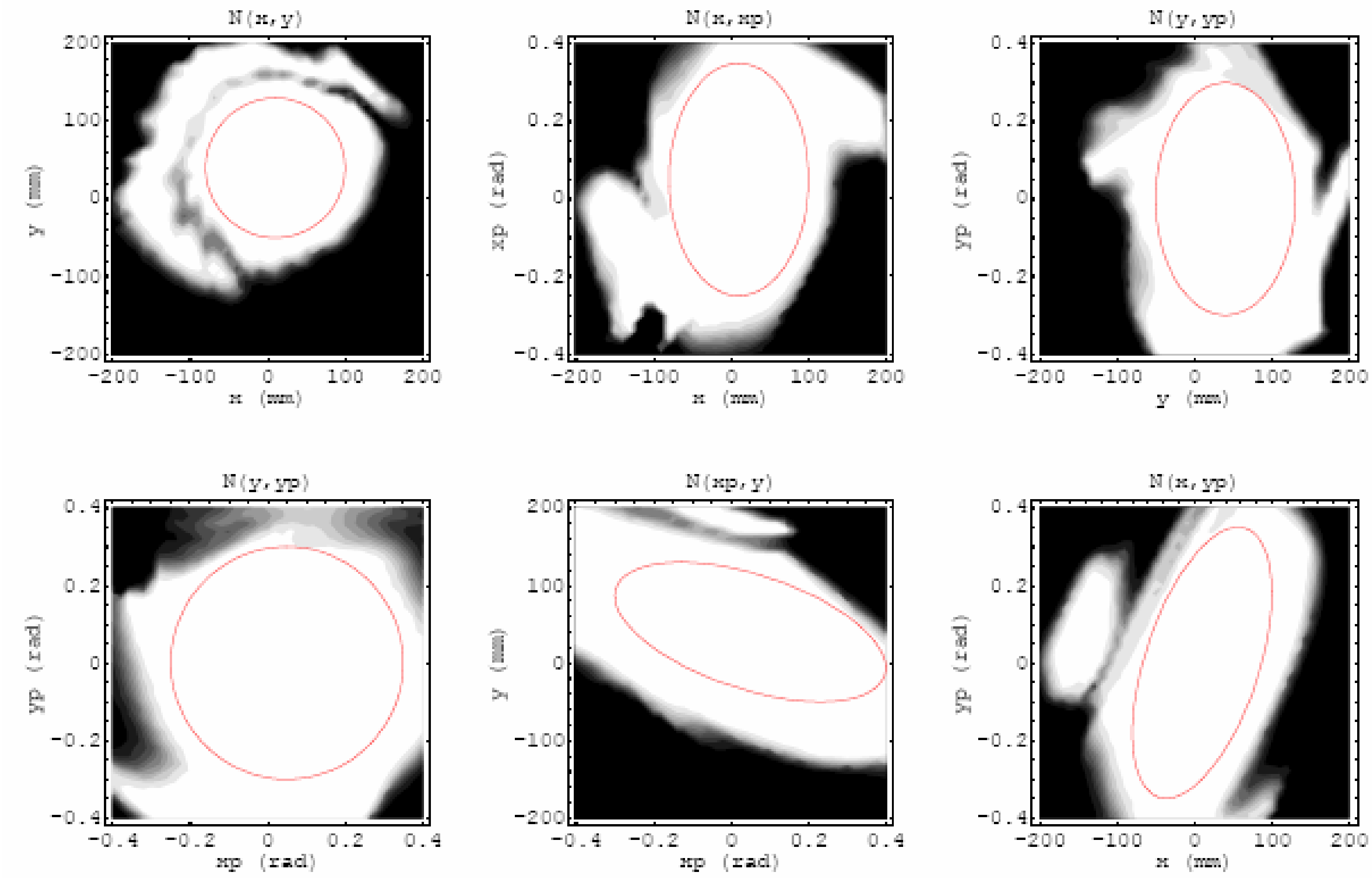


HCC + Beam simulation

- Launch a beam of zero 6D emittance.
  - Used 1000 particles per beamlet
- Scan the initial parameter space (x,x',y,y',p)
  - 2D planes (e.g. x and y, while x'=y'=0, $p=p_{ref}$)
  - 41 * 41 points, ~15h on single CPU
- Record transmission, average coordinates at output (x,p_x,y,p_y,t,p_z) and covariance matrix of beam.
- All this done by PERL scripts calling G4BL under linux.

Results: Transmission

Red ellipses are eye guides



Note angular momentum

What will we get for the buck? 07 08 09+

Cooling &MC Design

Conceptual Design:
- -Optics collider
- -Beam-beam in Coll
- -Final mcool/Li?/res?
- -Main mcool/inj/extr
- -Injection/rad Coll
- -Racetrack
- -20GeV beam mnpl
- -source/transport

Cooling:
- -realistic modeling
- -simul 6DHCC exper
- -radiation/diagn/RF
- -inj/extr/transport
- -error sensitivity

Experimental R&D

MTA studies:
- -build MTA p-line
- -beam dump
- -MTA infrastructure
- -200/800 cavity test
- -absorber LH,He/LiH

6DMANX@MTA:
- -design work
- -m-product'n/capture
- -m-transport/match
- -m-diagnostics
- -HCC cryo/PSs/QPS
- -beam dump/radiation
- -windows
- -absorber system

Magnet R&D

HCC:
- -design
- -prototype/testing
- -fabrication/test

Hi T Solenoid:
- -material research
- -insert design
- -insert fabricat/test
- -solenoid design
- -prototype/test

12T Dipole:
- -specs
- -design
- -prototype/test

APC: Muon Collider Department

- Mission:
  - The group leads an AARD program at Fermilab to develop, in collaboration with the NFMCC, Muons Inc., BNL, and LBNL, the Muon Collider concept. The focus of the R&D is, within a few years, to develop a practical design for a low emittance Muon Collider; design, prototype and bench test a complete set of components needed for 6D cooling channel, and carry out 6D cooling demonstration experiment with beam of muons.
- People and collaborators:
  - S.Geer (MCTF co-leader) to head the MC Dept.
  - A.Jansson, A.Bross – lead experimental groups
  - Yu.Alexahin, M.Lamm – lead Theory, MAG parts of MCTF
  - Muons Inc, BNL, LBNL, TJNAF, IIT, NIU, UIUC, UC