Fast Ramping 750 GeV Muon Synchrotron Dipoles

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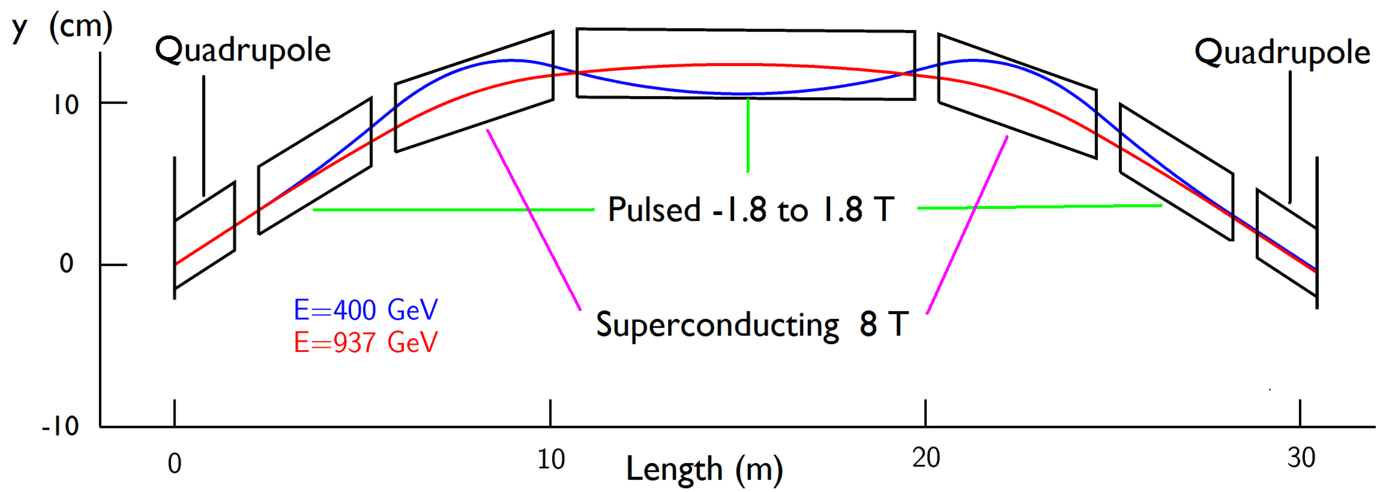
Muon Acceleration Program (MAP)

19 Aug 2011   Fermilab, Batavia, IL
Friday 1:00 MAP Meeting

Muon Acceleration to 750 GeV in the Tevatron Tunnel

- Cool muons plus high injection γ due to low muon mass $\longrightarrow$ small magnets ramping with a few thousand volts.
- Ameliorate eddy current and hysteresis losses in magnets. Thin grain oriented 3% silicon steel laminations. Low $B^2/2\mu$ Stainless steel cooling tubes for water and thin copper wire. Conductor in use for new ISIS choke. Made by Trench Ltd.
- Exploit 4% duty cycle. Energy usually sits in capacitor banks. Muon survival is reasonable in a fast ramping synchrotron. Power can be go into cavities fast enough (need 3x ILC).
- Interleave 400 Hz ramping & fixed superconducting dipoles.



- 1.5 TeV $\mu^+\mu^-$ collider. D. Summers et al., arXiv:0707.0302

Prototype 400 Hz, 1.8T, 46 mm Long Dipole Magnet

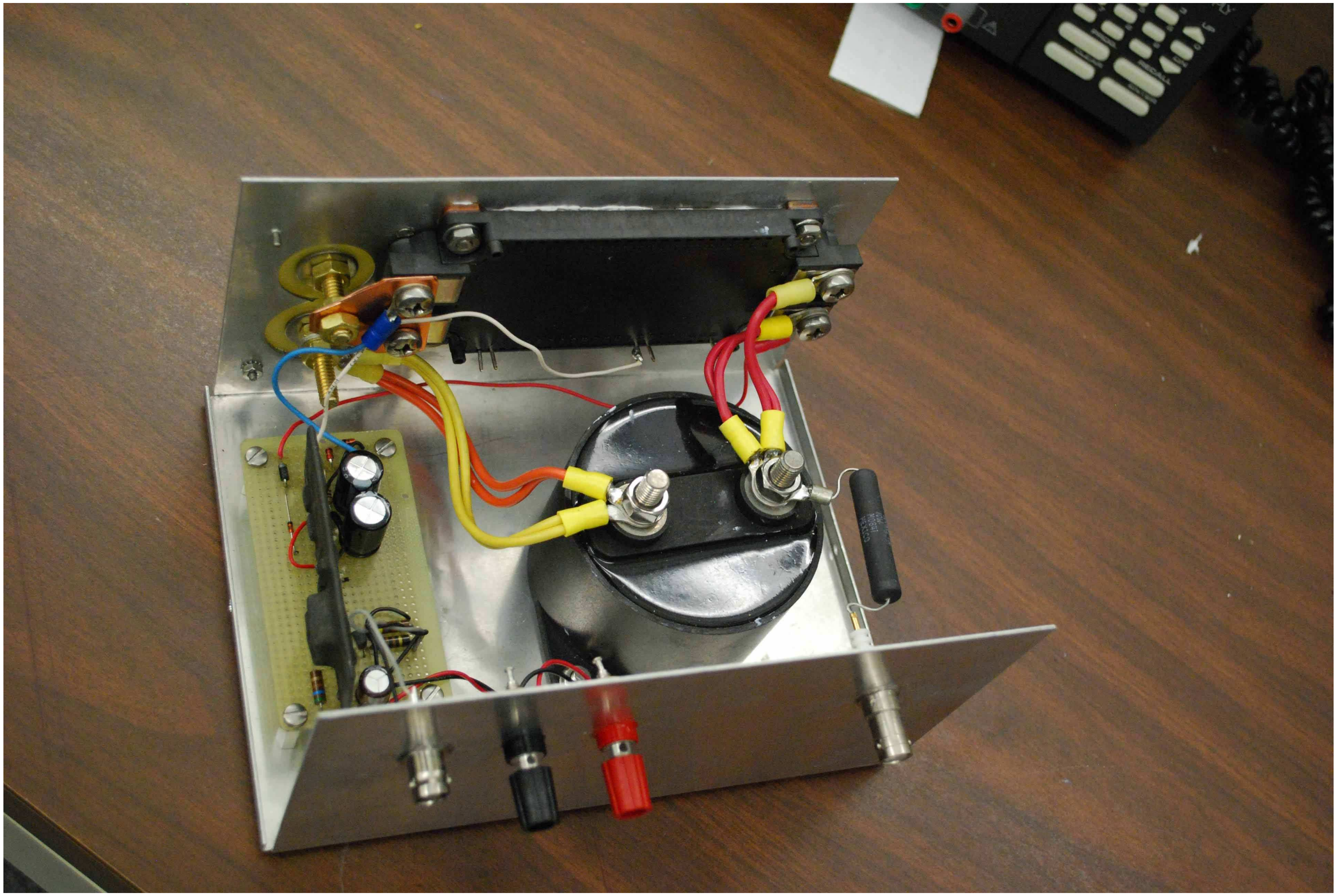
- **Have built dipole with 46 x 46 x 1.5 mm gap**
  Thomas-Skinner 3-phase transformer 11-mil "EI" laminations
  SuPer-Orthosil grain oriented Si steel. $\mu = 14000\mu_0$ @ 1.8T
  "Slotted" all laminations with our wire EDM.
  Wound coils with 12 gauge copper magnet wire. D = 2 mm.

- **LC circuit with capacitor and IGBT switch. $f = 1/2\pi\sqrt{LC}$**
  1.5×46×46 mm bore, N=40; $I = B\,h/\mu_0 N$ = 54A
  W = $\int \frac{B^2}{2\mu_0} d\tau = \frac{LI^2}{2} = \frac{CV^2}{2} = 4.1$ J; V = $2\pi B f N w \ell$ = 400V

- **Parts**
  Polypropylene Capacitor: Cornell Dubilier 52μF, 1400V, 60A
  TENNELEC TC 952 HV Supply for topping off capacitor.
  IGBT switch: Powerex CM600HX-24A, 1200V, 600A
  IGBT Gate Drive: Powerex VLA500-01 (5V pulse control)
  Berkeley Nucleonics BNC 8010 NIM Pulse Generator
  F. W. Bell 4048 Hall Probe good to 2% up to 3000 Hz AC.

- **Rough Cost of a Power Supply**
  Capacitors: $5/joule. Choke: $3/joule. Switch: $1000/MW

IGBT Switch, IGBT Gate Driver, and Capacitor



- **Many thanks to Sten Hansen and Ken Bourkland for advice.**

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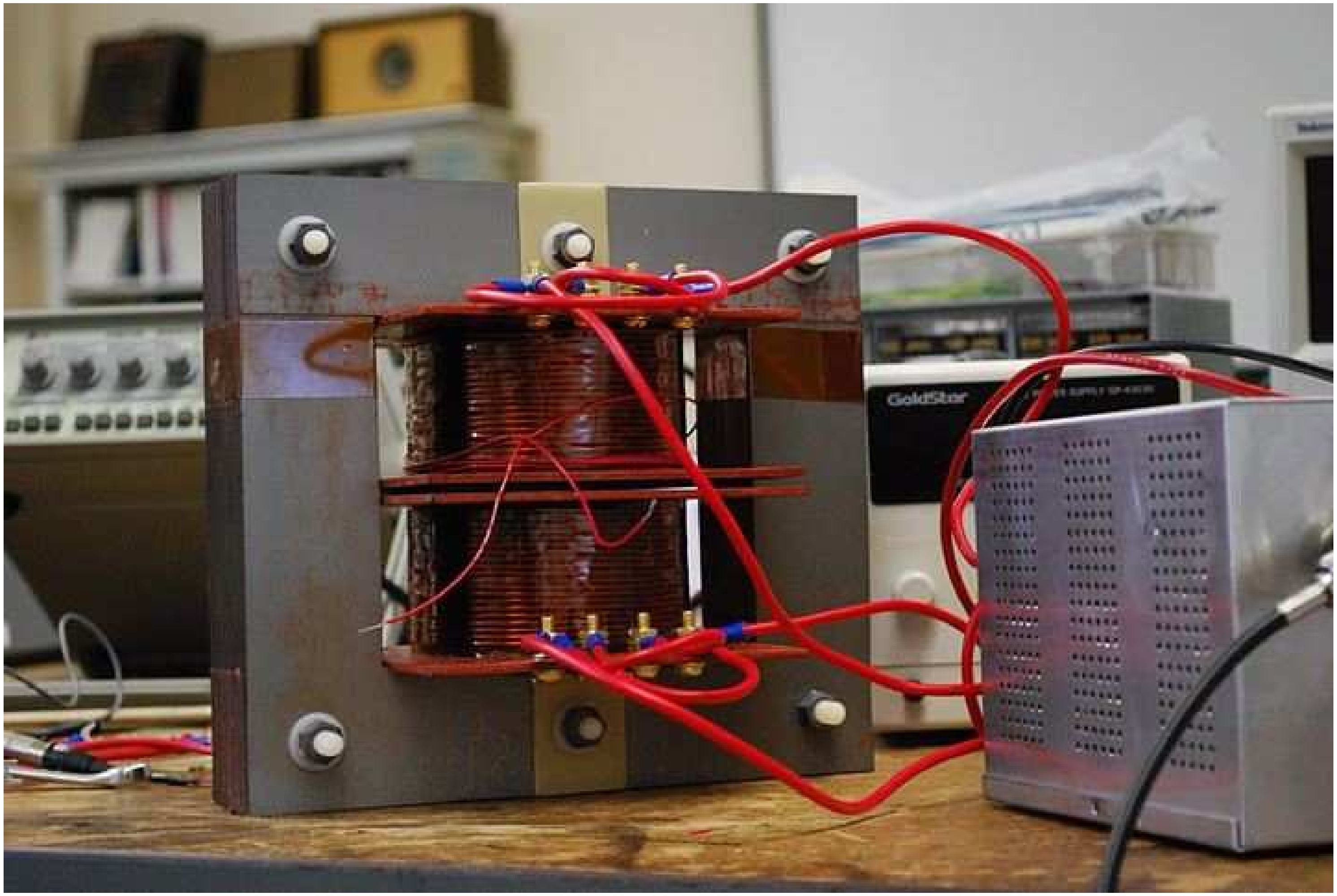
Grain Oriented Silicon Steel Dipole Prototype



- 1.5 x 46 x 46 mm gap, “EI” Laminations

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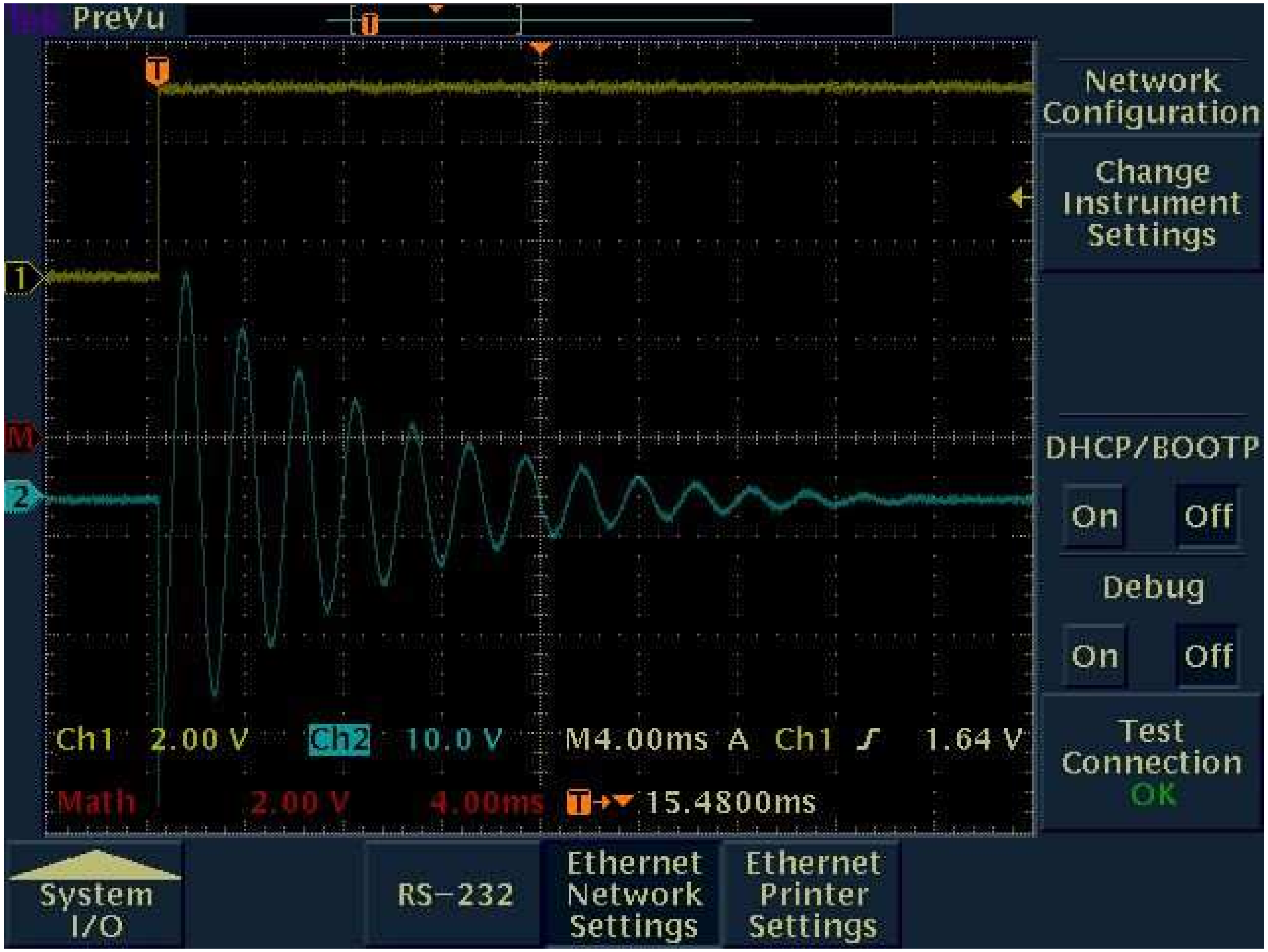
IGBT power supply test: 400 Hz, 400V, 50 Amps

- **Tektronics TDS3054B 500 MHz Oscilloscope**



- **Results: LC circuit should ring for twice the time.
  Magnet only goes to 1.5 Telsa DC. Saturated T joint?**

Grain Oriented Silicon Steel Relative Permeabilities

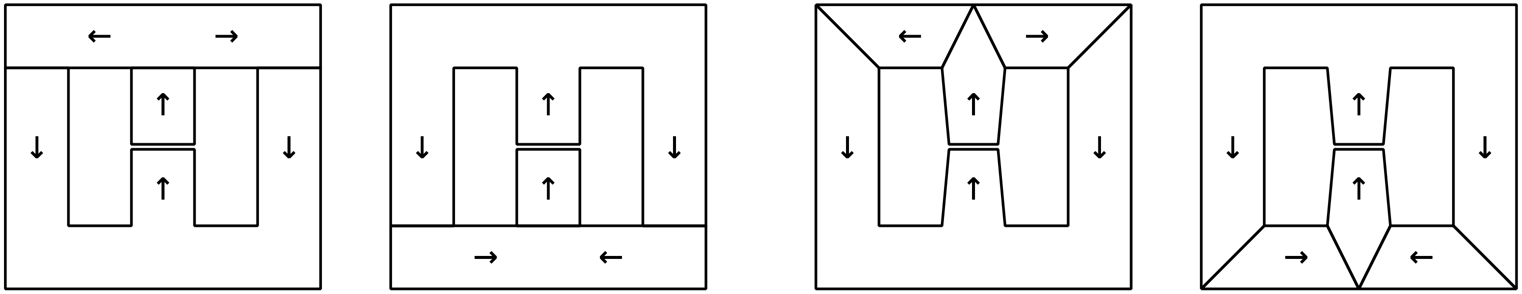
	0.1 T	0.5 T	0.7 T	1.0 T	1.3 T	1.5 T	1.7 T	1.8 T	1.9 T	2.0 T
0^o	29000	40000	46000	50000	49000	48000	30000	14000	6000	180
10^o	8000	13000	14000	14000	14000	10000	3000			
20^o	3500	7000	9800	11000	9000	2100				
55^o	700	3400	3800	1100	540					
90^o	660	2400	3300	4300	2300	320	120	80	60	50
Steel	1500	4000	4700	4100	3300	1900	600	290	160	90
NOSS	2600	5700	5400	3600	1600	350	210	95	50	
Fe Co		12000	14000	17000	16000	15000	13000	9000	8000	6000
Dy										

Table 1: Relative permeability (μ/μ_0) for HiB 3% grain oriented silicon steel as a function of magnetic field (Tesla) and angle. The minimum at 1.3 T and 55^o comes from the long diagonal (111) of the steel crystal. For comparison, (μ/μ_0) of four other ferromagnetic materials are shown in the bottom half of the table.

	Material	$\rho(\mu\Omega - \mathrm{cm})$	H_c(Oersteds)
	Grain Oriented Silicon Steel	46	0.09
Steel	0.0025% ultra low carbon LHC steel	10	0.8
NOSS	non-oriented 3% silicon steel	46	0.7
Fe Co	Hiperco 50A (2 V : 49 Fe : 49 Co)	24	1.0
Dy	Dysprosium at T = 70K	50	

Try Mitred Joints with Grain Oriented Silicon Steel

- Good magnetic properties only in the grain direction. Look at the construction of large 3 phase transformers. Avoid T-joint saturation with some kind of 45^o mitre. Mitred laminations from Pacific Laser Laminations.



- **Need software** simulation with BH curves at many angles!
  2D: $\nabla \times H = \nabla \times \frac{\nabla \times A}{\mu(B,\theta)} = J$, $\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} - \frac{1}{\mu}\frac{\partial \mu}{\partial x}\frac{\partial A}{\partial x} - \frac{1}{\mu}\frac{\partial \mu}{\partial y}\frac{\partial A}{\partial y} = -\mu J$
  $J = J_z$, $\nabla \cdot A = 0$, $A = A_z$, $B_x = -\frac{\partial A}{\partial y}$, $B_y = -\frac{\partial A}{\partial x}$, $\theta = \text{atan}(\frac{B_y}{B_x})$
  Solve on a mesh, then iterate with new $\mu(B,\theta)$ in FEMM

- Opera-2D: BHDATA enters 5 to 50 BH pairs into a table. BHX, BHY: anisotropic components of non-linear μ. Can fudge μ_{90^o} to correct μ_{10^o} in Opera2D elliptical model.
  $\mu_{90^o}(120 \rightarrow 520) \Rightarrow \mu_{10^o}(690 \rightarrow 3000)$ $\mu_\theta = [(\frac{\cos\theta}{\mu_{0^o}})^2 + (\frac{\sin\theta}{\mu_{90^o}})^2]^{-0.5}$

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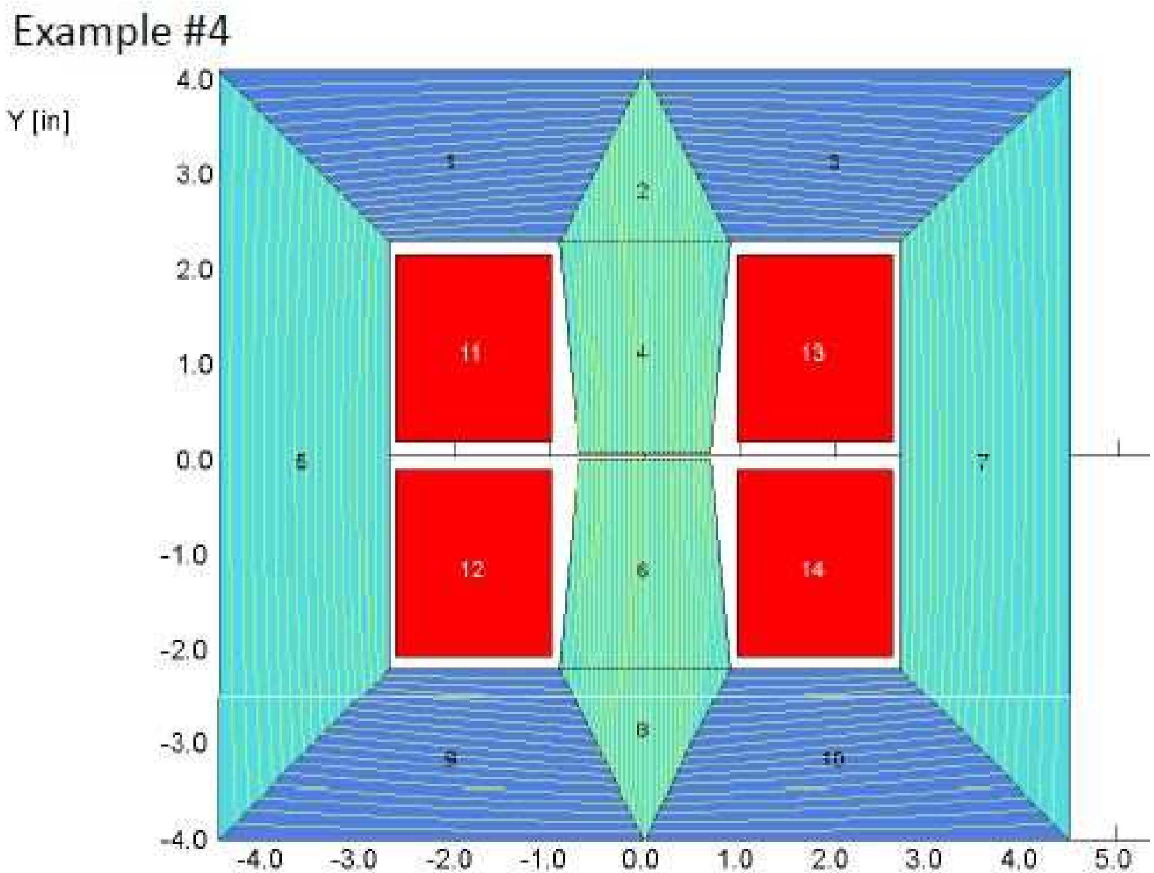
OPERA-2D Simulation of a Dipole with Mitred Joints

- **Simulation of Grain Orieneted Silicon Steel**
  OPERA-2D elliptical approximation: $\mu(55^o)$ 5$\times$ too good.
  Elliptical approximation: Only two angles can be correct.
  Mauricio de Lima Lopes, mllopes@fnal.gov



Measuring Magnetic Fields. Hall probes and coils.

- **Our F. W. Bell 4048 Hall Probe measures DC and AC fields. It does not measure pulsed magnetic fields.**
- **Have been testing a small coil read out by an oscilloscope. Calibrate with magnet at 60 Hz where Bell Hall probe works.**
- **Now have newer F. W. Bell Hall 5180 with DSP & peak hold.**
  5180: USB, 0.045" $\perp$ probe, 100K/s data $\longrightarrow$ BNC, $1325.
  7030: RS-232, 3D $\frac{5}{16}$" probe, 50K/s data $\longrightarrow$ 3 BNC, $10925.

Measuring Magnetic Fields. Epstein Frame results.

- **Measuring BH curves in 3cm x 30cm lamination strips.**
  FNAL Main Injector: Epstein Frame, Hysteresigraph 5500

- **0.011” AK Steel TRAN-COR H-1 grain oriented silicon steel**
  T C Metal Co., Los Angeles
  Pacfic Laser Laminations, West Chicago
  Many thanks to Rob Riley and John Zweibohmer, FNAL

1 Oersted	17000 gauss	$\mu/\mu_0 = 17000$
2 Oersted	18100 gauss	$\mu/\mu_0 = 9000$
10 Oersted	19580 gauss	$\mu/\mu_0 = 1950$
25 Oersted	20030 gauss	$\mu/\mu_0 = 807$

- **Conclusion: μ is large and $B^2/2\mu$ is small.**

Transverse beam pipe impedance (Thanks to Bill Ng)

- $Z_1^{\perp} = [\mathrm{sgn}(\omega) + j] 2cR/(b^3 \sigma_c \delta_c \omega) = 742\,\mathrm{M\Omega/m}$
- Take ring radius R = 1000 meters.
  Take beam pipe radius b = 6mm. Resistive wall impedance.
  σ_c is the conductivity of copper
  beam revolution frequency, f = 47.7 kHz
  f $= \omega/2\pi$
  skin depth $= \delta_c = \sqrt{2/(|\omega|\mu\sigma_c)}$
- Transverse coupled bunch instability is the most serious.
  Driven mostly by the first negative betatron sideband
- Growth rate $= 1/\tau = [eMI_b\,\omega_0\beta_y/(4\pi\beta E_0)]\,ReZ_1^{\perp}F$
- I_b is average current. 2×10^{12} muons/bunch, M = 1 bunch
  E_0 is the muon energy. Use 150 GeV average.
  β_y = 99 meters = vertical betatron function
  Form Factor = F = 0.8 for a short bunch
- Growth rate is 333 orbits. 60 to 400 GeV ring has 43 orbits.
  b = 6mm is double the size of the PAC07 b = 3mm size
  M = 1. Higher order sidebands may give helpful cancellations

References

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[2] Zhiguang Cheng *et al.*, "Analysis and Measurements of Iron Loss and Flux Inside Silicon Steel Laminations," IEEE Trans. Magnetics **45** (2009) 1222.

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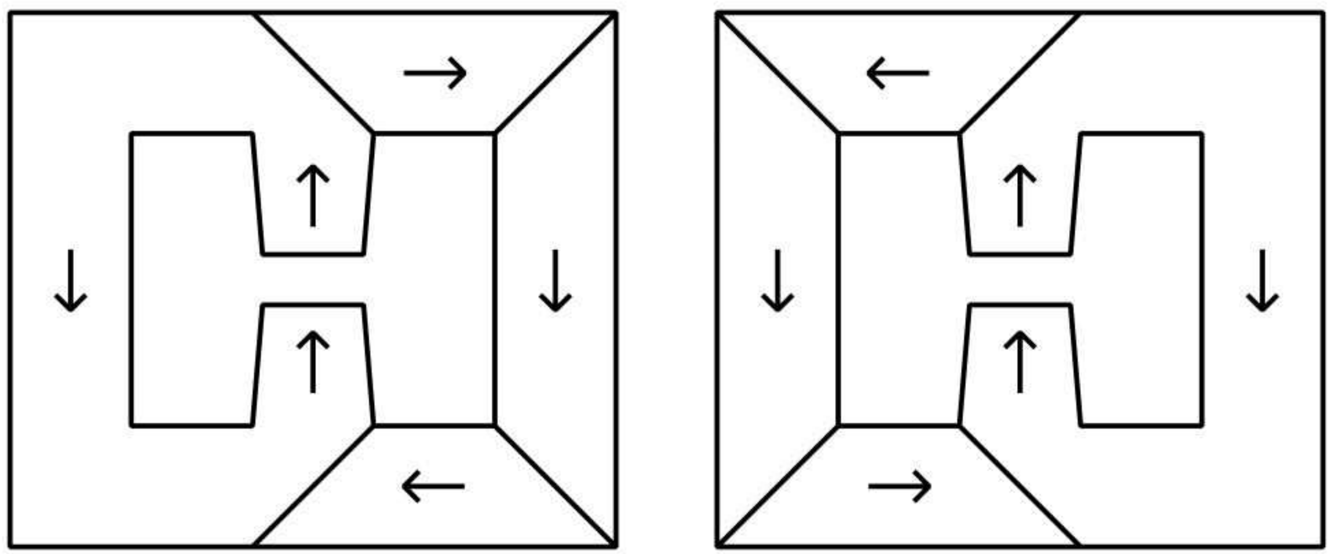
Larger Prototype 400 Hz Dipole with mitred joints

- **Larger 12mm gap.**
  Larger gap allows slipping coils into a more rigid "C" dipole.
  Up to a meter long.
  Power supply with a multiple IGBT array.



Muon Acceleration Summary

- Synchrotrons are a lot less expensive than racetracks
- 400 Hz, 1.8 T dipole prototype is in progress.
  Mitred laminations from Pacific Laser Laminations in hand.
  Need to see how well the magnetic flux circuit works.
- Al Garren and Scott Berg are working on interleaved lattice.
  What magnet errors can be tolerated? Gap is small.
  Hexapole fields in beam pipe.