Muon Synchrotron Acceleration

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Neutrino Factory
Muon Collider

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Guiding Principles

- High injection γ due to low muon mass plus cool muons
  $\longrightarrow$ small magnets ramping with a few thousand volts.

- Ameliorate eddy current and hysteresis losses in magnets.
  Thin grain oriented silicon steel laminations.
  Stainless steel cooling tubes for water and thin copper wire.
  Conductor in use for new ISIS choke. Made by Trench Ltd.

- Exploit the 4% duty cycle.
  25x lower losses than continuous operation.
  96% of the time energy just sits in the capacitor banks.
  Intermittent LC Circuit, not continuous offset White Circuit.

- Muon survival is reasonable in a fast ramping synchrotron.

- Power can be go into cavities fast enough (need 3x ILC).

- Goal: 1.5 TeV collider with moderate acceleration cost.
  See PAC07 arXiv:0707.0302 for details.

Grain Oriented 3% Silicon Steel EI Transformer Laminations

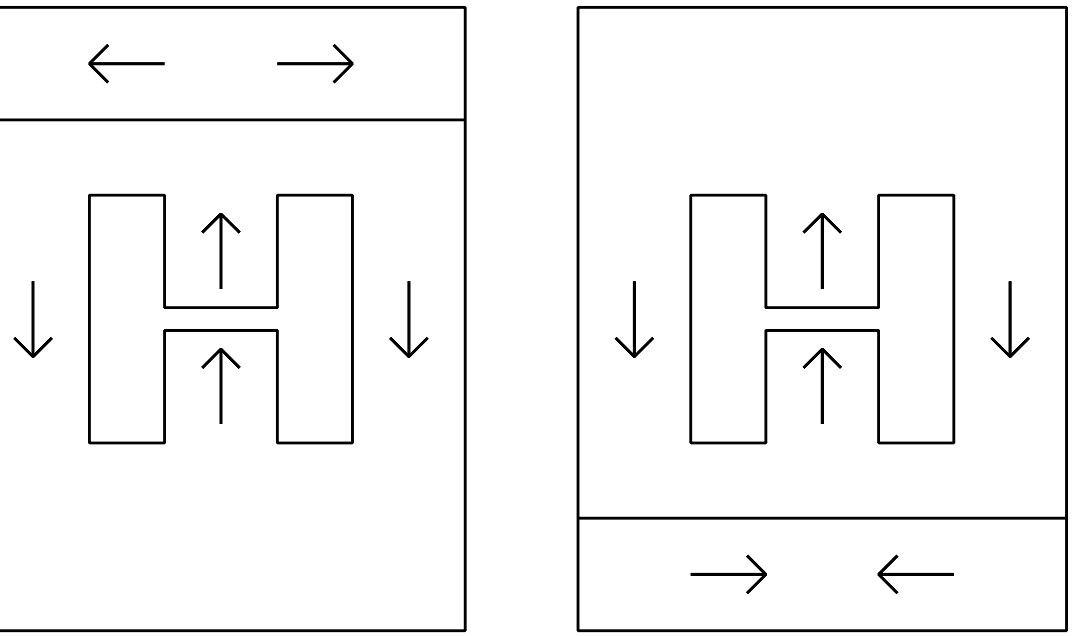


Table 1: Resistivity (ρ), coercivity (H_c), and permeability (μ) of steels. Higher resistivity lowers eddy current losses. Low coercivity minimizes hysteresis losses. Grain oriented 3% silicon steel has a far higher permeability parallel ($\|$) to than perpendicular ($\perp$) to its rolling direction and permits minimal energy ($B^2/2\mu$) storage, as compared to low carbon steel at 1.8 T.

Steel	ρ(nΩ-m)	H_c(A/m)	μ(1.0 T)	μ(1.5 T)	μ(1.8 T)
.0025% Carbon	100	80	$4400\mu_0$	$1700\mu_0$	$240\mu_0$
Oriented ($\|$) Si	470	8	$40000\mu_0$	$30000\mu_0$	$3000\mu_0$
Oriented ($\perp$) Si	470		$4000\mu_0$	$1000\mu_0$	

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

- Practice Dipole. We put a slot in a \$20 "EI" transformer.
  And reached 1.6 Tesla in the slot with DC current.
  F. W. Bell 4048 Hall Probe good to 2% at up to 3000 Hz.

- Now assembling dipole with 46 x 46 x 1.5 mm gap
  Thomas-Skinner 3-phase transformer 11-mil "EI" laminations
  SuPer-Orthosil grain oriented 3% Si steel. $\mu = 3000\mu_0$ @ 1.8T
  We have now "slotted" all laminations with our wire EDM.
  Winding coils with 12 gauge copper magnet wire. D = 2 mm.
  Exploring stainless steel water cooling tubing as used at RAL

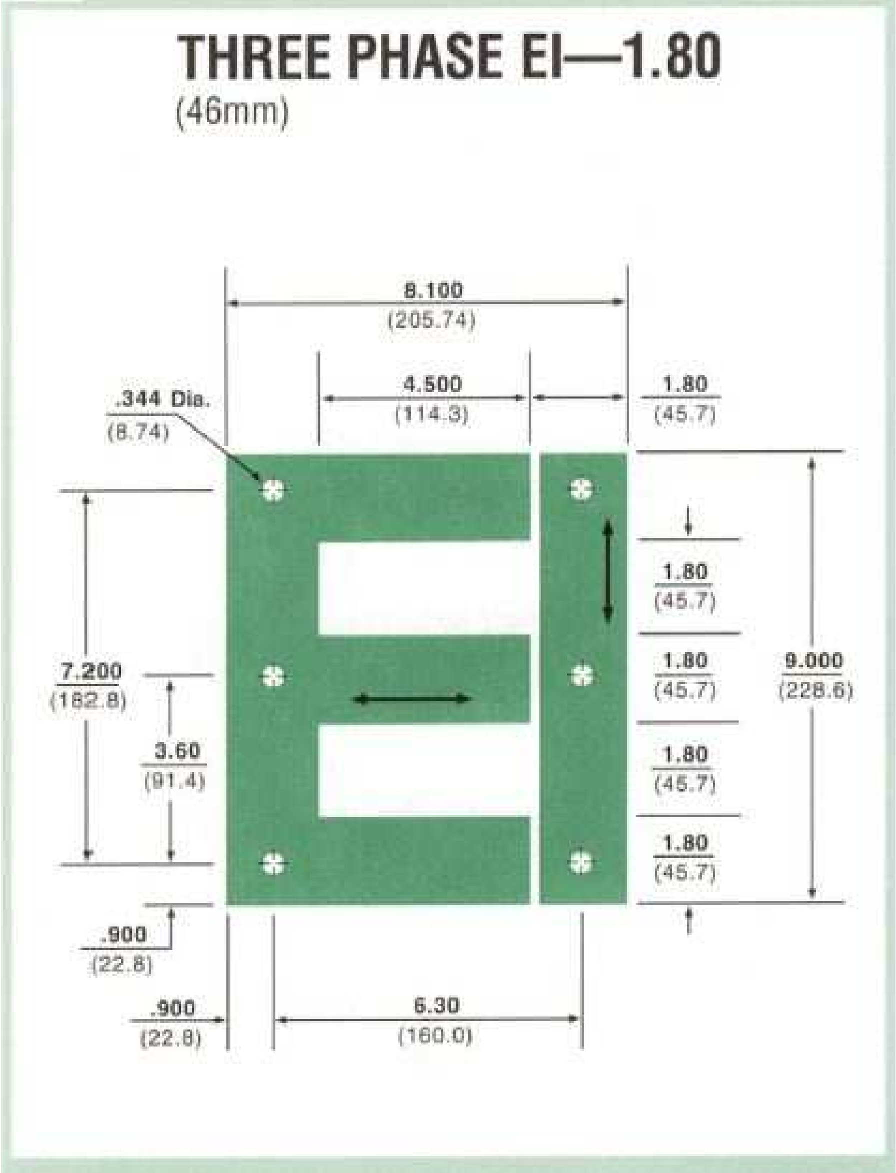
- LC circuit with capacitor and IGBT switch. $f = 1/2\pi\sqrt{LC}$
  $1.5 \times 46 \times 46$ mm bore, N=40; $I = B\,h/\mu_0 N$ = 54A
  W = $\int \frac{B^2}{2\mu_0} d\tau = .5\,LI^2 = .5\,CV^2$; V = $2\pi B f N w \ell$ = 400V
  Polypropylene Capacitor: Cornell Dubilier 52μF, 1400V, 60A
  TENNELEC TC 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

Power Supply Parts and Costs

Part Description	Manufacturer	Cost
Polypropylene Capacitor: 52μF, 1400V, 60A	Cornell Dubilier	\$62
1200V, 600A IGBT Switch	Powerex	\$166
IGBT Gate Driver	Powerex	\$43

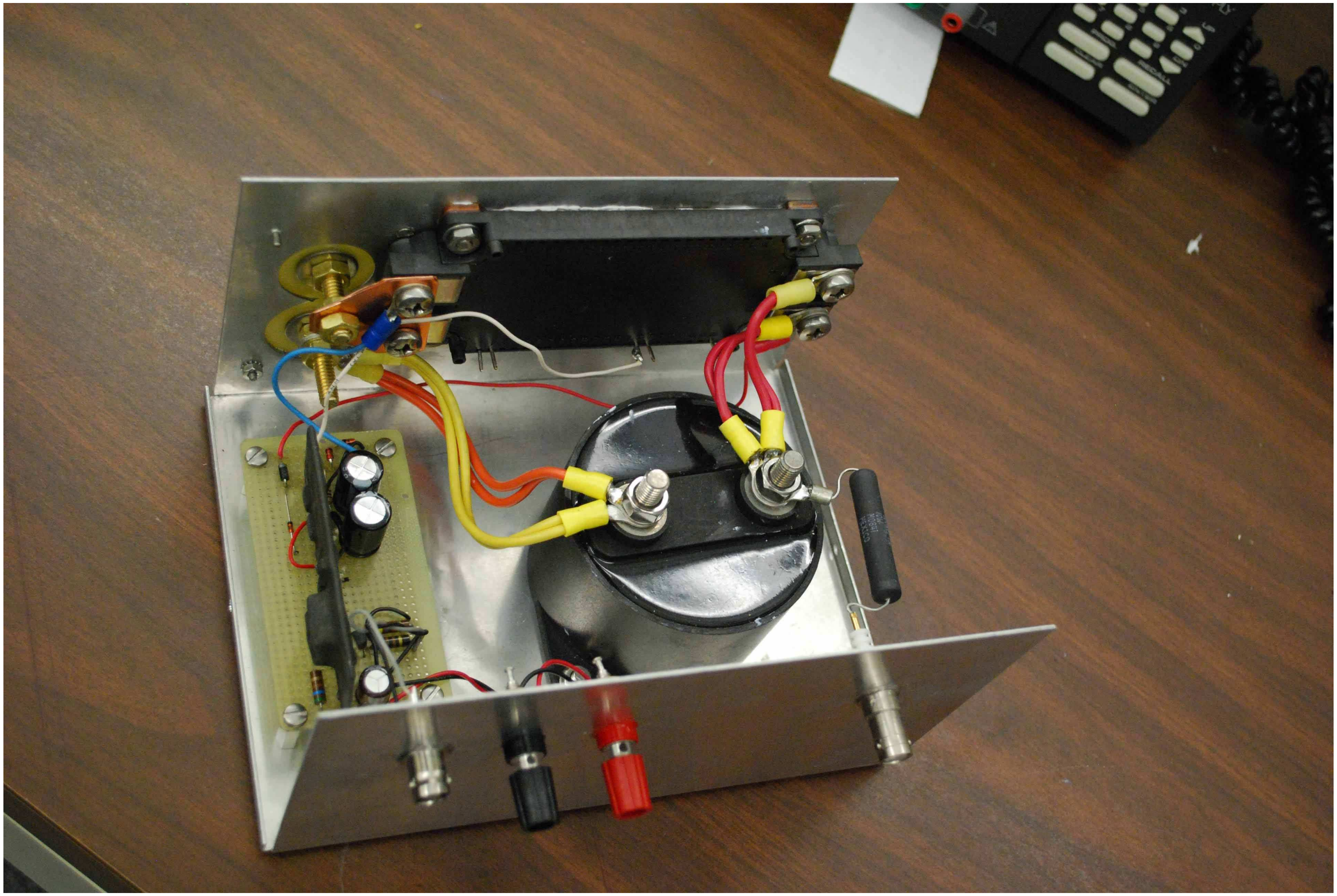
- **Vendor: Digi-Key.**

"EI" Silicon Steel Lamination Set, $11/kilogram



- A slot in the center leg to turns a transformer into a dipole.

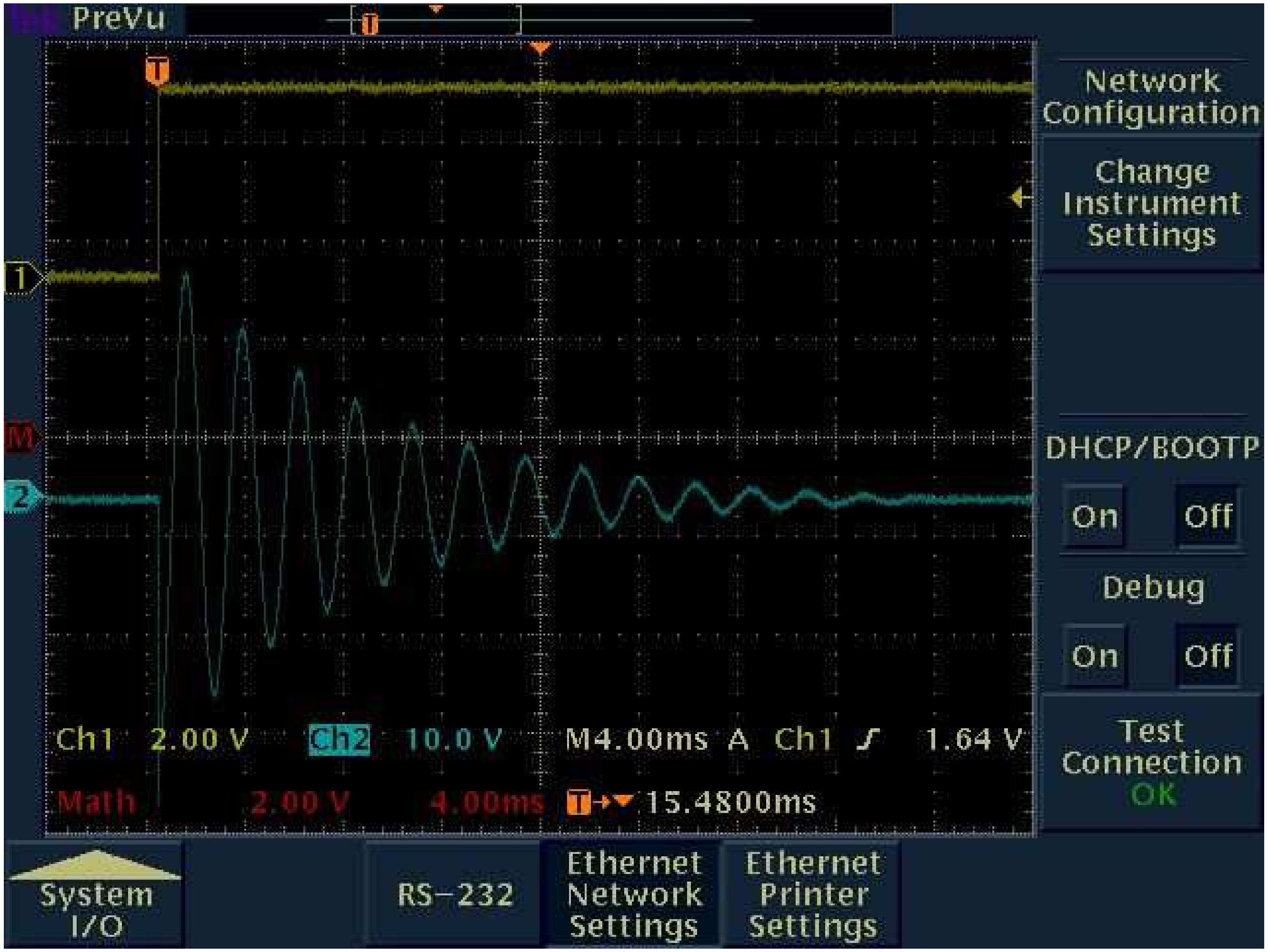
IGBT Switch, IGBT Gate Driver, and Capacitor



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

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

- Tektronics TDS3054B 500 MHz Oscilloscope



- 2.2 mH, 0.36 Ω air core inductor coil. Vendor: Parts Express
  14 gauge copper wire, 94 mm coil diameter

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

Summary

- A small prototype 400 Hz 1.8T dipole is in progress.
- 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 silicon steel laminations. Get to 1.8T!
  Stainless steel cooling tubes for water and thin copper wire.
- Exploit the 4% duty cycle.
  25x lower losses than continuous operation.
  96% of the time energy just sits in the capacitor banks.
- Muon survival is reasonable in a fast ramping synchrotron.
- Power can be go into SRF cavities fast enough (need 3x ILC)
- Goal: 1.5 TeV collider with moderate acceleration cost.
- Partial list of things to do
  Build on Alex Bogacz's OPTIM lattice simulation.
  Continue investigation of transverse beam pipe impedance.
  Lamination punching accuracy for small gaps.