Two Devices for HINS* Robyn Madrak Accelerator Physics Center (APC)

Part II: Vector

Modulators





HINS - Purpose



- 60 MeV Linac under construction at Fermilab's meson building
- R&D Linac which will demonstrate novel technologies used for the first time
- Technical feasibility proof of (front end) for 8 GeV Linac, Project X, etc.

High intensity proton source for neutrino physics/ muon storage ring experiments





- Solenoidal focusing ⇒ cleaner, axisymmetric beam
- Use of SC spoke resonators
- Fast ferrite phase shifters

 will allow multiple cavities (and RFQ) to be driven by
 a single 2.5 MW, 325 MHz klystron => cost savings
- Fast Beam Chopper

Parameters



RF Frequency	325 MHz
Particles/ Pulse	37.5* E13
Pulse Length	3/1 msec
Average Pulse Current	~20 mA
Pulse Rep. Rate	2.5/10 Hz
Chopping : 700 ns MI abort gap MI bunch structure	~6% @ 89KHz ≤33% @ 53MHz

* full un-chopped 3 msec pulse at klystron-limited 20 mA

FNAL HINS









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HINS Chopper – Part I



- Should the HINS be extended to an 8 GeV Linac, output beam would be transferred to Fermilab's Main Injector, with 53 MHz RF frequency
- HINS Linac Bunches are spaced by 325 MHz (3.1ns)
 - In MI, RF frequency is ~53 MHz (~19ns)
 - Don't want bunches in the 53 MHz separatrix
 ⇒ Chop out ~1 of every 6 bunches
 - Additional complication: $325 \neq n G 53$

⇒ Sometimes chop 1, sometimes 2



Traveling Wave Chopper Structure



- beam is deflected by traveling pulse (electric field)
- β(beam)=0.073 => must slow down pulse

□Use traveling wave "meander"
structure:

- 50 cm long
- 16 mm between chopper plates
- 2.4 kV per plate
- deflection of 6mm at end of plates



Chopper in MEBT

length of chopper plates: 50 cm drift space downstream: 30 cm

Deflection

length of chopper plates:50 cmdrift space downstream:30 cmplate separation:16 mm

 $d \text{ [m]} = E L^2/2p\beta \qquad [10^9 \text{ Vm/(GeV/c)}] \qquad E = 2 X (1.9kV)/16mm \\ = 2 X (C \cdot 2.4 kV)/16mm \\ \text{"coverage factor"}$

d(L=50cm) = 6mm $\theta(L=50cm)X30cm = 7mm$

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Pulser Development

We need

- Two pulsers to drive the ~50 Ω meanders: +/- 2.4 kV
- Max ~5.5 ns pulse width (including rise and fall time)
- 53 MHz rep rate
- burst of 3ms @2.5Hz, or 1ms@10Hz
- Programmable pulse width (may sometimes chop 1 bunch, sometimes two)

\rightarrow Specs do not lead to an "obvious" solution

Similar Choppers

	CERN-SPL	LANL-SNS	RAL/ESS	FNAL HINS
Beam Energy	3 MeV	2.5 MeV	2.5 MeV	2.5 MeV
Electrode Length	2 X 40 cm	35 cm	34 cm	50 cm
Electrode Gap	20 mm	18 mm	14 mm	16 mm
Deflection Angle	5.3 mRad	18 mRad	16 mRad	24 mRad
Electrode Voltage	±0.5 kV	±2.35 kV	±2.2kV	±2.4kV
Pulse Rise Time	< 2ns	10 ns	2 ns	< 2ns
Pulse Duration	min 8ns	300 ns	12 ns	< 5.5 ns
Pulse Rep Rate	44MHz	1 MHz	2.4 MHz	53 MHz
Bunch Frequency	352 MHz	402.5 MHz	280 MHz	325 MHz
Burst Duration	0.6 ms	945 ns	1.5 ms	3ms, 1ms
Burst Rep Rate	50 Hz	60 Hz	25 Hz	2.5, 10 Hz
Chop Description	3/8 bunches	On 300,off 645 ns		1 or 2/6 bunches

Combining lower voltage pulses?

Kentech 500V Pulser

before fully assembled:

one side of combiner:

five 25 Ω semirigid cable in parallel, with ferrite

 25Ω semirigid cable

500V Pulser Output

1.2 kV Pulser

70, AoN

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Kentech Pulsers

- 500 V Pulser was a success
- Subsequent 1.2 kV pulser was a success
- Plan: two $(1.2kV \rightarrow 50\Omega)$ into one $(2.4kV \rightarrow 100\Omega)$ output
- This requires a combiner and a meander with 100Ω impedance

Microstrips in General

- Using only one trace or two in parallel
- Adding an air gap beneath the dielectric (changes ε_{e}); can be used to tune β

FNAL Fabricated Meanders

We have pursued the following:

- 1. Use double meander design with air gap between meander and ground plane $(50\Omega \text{ w/no gap}, 100\Omega/\text{w gap})$
- 2. Using single meander
- Material: Rogers TMM10i, Cu clad;
 ε =9.8, 18" long (46 cm)
- Meander is formed by
 routing out traces

Chopper Meanders

Important Aspects

- 1. Material: Outgassing?
- 2. Impedance (avoid reflections)
- 3. Delay time (match beam β)
- 4. Pulse Behavior along length (dispersion)
- 5. Coverage Factor

Meander Substrate

- Meander traces are generated by routing out traces on Rogers TMM10i, Cu clad
- Cheaper, faster than paste/firing/electrochemical deposition
- Test indicates acceptable vacuum properties

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Double Meander, Impedance

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Impedance measurements from 1 – 500 MHz

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Double Meander, Delay

- Want β = 0.073 to match beam speed
- Measure pulse delay in meander: _____
- Varying distance between meander and ground plane shows sensitivity

spacing	t delay (ns)	β	
0.062"	18.8	0.081	
0.040"	21.2	0.072	
0	32.3	0.047] – 50 Ω

Single Meanders: Impedance and Delay

Dispersion

Coverage Factor

- The electric field between the chopper plates is less than that for a structure in which the entire surface is conducting
- This must be accounted for in the chopper design when determining the voltage needed for the desired kick

Coverage Factor Measurements

Coverage Factor Normalization

ground

planes

2h

- Normalize to stripline with wide trace •
- Use geometry for 50Ω convenient
- For striplines • $Z = 120\pi^{2}/8(\ln^{2} + \pi w/4h)^{*}$
- Use w = 25mm, 2h = 16mm •
- * R. Collin, Foundations of Microwave Engineering

Probe pickup signal (S_{21}), 50 – 150 MHz

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All Measured Coverage Factors

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type	Double 50Ω	Double 100Ω	Single 1 (low dispersion)	Single 2 (high coverage)
Coverage factor	71%	87%	48%	74%

Position Dependence

Combiner

Expect behavior to be better than this:

• currently we have extra unneeded cable length

• matching resistors (100 Ω to scope 50 Ω) add extra inductance

Combiner Optimized

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500 V pulse \rightarrow 50 Ω

1200 V pulse \rightarrow 50 Ω

1700 V \rightarrow 100 Ω

combiner

Heating in Meander

Current in meander will be 2.4 kV/100 Ω = 24 A

Need to test heat/current handling capacity

Fuses @ 180A, 3ms pulse

Chopper: Summary

We have built prototypes for the necessary components for the chopper: the pulser, meander structures, and combiner

- The prototype pulsers from Kentech performed to specs; For a complete chopper system we need 3 more
- We have built a combiner suited for combining these fast pulses
- We have explored different layouts for the chopper plates (meander structures). The higher coverage factor single meander is the best candidate.
- For more details, see proceedings of Linac'08 :

R. Madrak et al., "A Fast Chopper for the Fermilab High Intensity Neutrino Source (HINS)"

Aside: Application of Chopper R&D to the current accelerator

- Initially explored the option of using a few fast, 1 kV FETs from DEI for Chopper pulser
- Realized these could be used for notching in the 750 keV line: create a notch for booster kicker rise time (minimize losses)
- This effort was begun initially in collaboration with Doug Moehs (first attempt was chopping in the source)

Combining three DEI FETs

from DEI/IXYS RF

- •Use the same scheme as HINS pulser, combining three ~1kV \rightarrow 16.7 Ω signals (x 30 = 50 Ω)
- ~40ns pulses 2.2μs spacing
- Burst of 15 pulses, repeat at 15 Hz
- Two pulsers: ±1.9kV

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Notching Plates in 750 keV line (H⁻)

Notching Study

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Part II – Vector Modulators

HINS 325 MHz RF

control in each cavity

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How it Works

In a coaxial line filled with some dielectric (ϵ,μ) v = c/ $\sqrt{\epsilon\mu}$ We vary μ and thus v and phase by varying H applied to the ferrite.

Fermilab's Ferrite Phase Shifter

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- Operates in full reflection mode (end is shorted)
- Use solenoid along with shifters: phase of reflected wave determined by μ of ferrite (μ depends upon applied H Field)
- Ferrite is AI doped Yttrium Iron Garnet (YIG) TCI Ceramics AL-400
- Required rate: 1% µs
- Power Rating: ~50kW (Room Temp Cavities) or ~500kW (RFQ)

Vector Modulator:

Modulates phase and amplitude independently:

With $\Delta \Phi = (\Delta \phi_2 - \Delta \phi_3)/2$ $\Phi = (\Delta \phi_2 + \Delta \phi_3)/2$ Output power ~ $\cos^2(\Delta \Phi)$ Phase shift ~ $\Phi + 3\Pi/2$

Two Phase Shifter Types

• For Cavities (~75 kW): 1.5" OD X 0.65" ID X 5" long garnet

• For RFQ (~500 kW): 3" OD X 0.65" ID X 5" long garnet

Shifter Design Details

solenoid (12 awg wire around G10)

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 Center conductor: shrink fit during assembly

• Use quarter wave matching section (for 50Ω)

• Outer conductor has 0.020" slot (length = 9") to reduce eddy currents (gives faster response)

Other VM Parts

hybrid for 1% vm: Dielectric

circulator for 1⁵⁄₃ vm: Ferrit-Quasar

6 "hybrid for RFQ vm: MCI Filled with SF_6 to prevent sparking

circulator load: 5kw CW water cooled Altronics

Phase vs. Applied Field

Small Signal Frequency Response

αµ

Slew Rate

Phase Shifter Slew Rate: (above resonance) 6 deg/µs

Current risetime limited by supply output, solenoid inductance

Fast 300A power supply thanks to Brad Claypool, Steve Hays, Howie Pfeffer

Beam Loading - Simulation

Meson Building Test Facilities

Meson Building Test Facilities

Power Capabilities

here, both shifters' solenoids driven by one power supply $(\Delta \phi_1 = \Delta \phi_2)$

Power Capabilities

1⁵/₈ VM for cavities:

- good to >75 kW
- Shifters alone could be used in a 200 kW VM if used with oil in ferrite part of coax line (higher power quad hybrid & circulator would be needed)

RFQ VM

- Shifters and Hybrid filled with SF6: Good to > 500 kW
- Current hybrid is 6"
- Stripline "500 kW" Circulator failed: Getting a new one from Ferrite

Vector Modulators: Summary

- The 1⁵/₈" vector modulators can operate well up to 75 kW (more than needed for the RT cavities)
- The RFQ vector modulator elements:
 - phase shifters good to ~600 kW
 - hybrid good to ~600 kW
 - initial circulator failed; new Ferrite™ model on order

•The speed of the response for the cavity shifters is 6X as fast as the original spec

• bandwidth > 35 kHz for a first attempt at feedback

• For more details, see proceedings of Linac'08 :

R. Madrak and D. Wildman, "High Power 325 MHz Vector Modulators for the Fermilab High Intensity Neutrino Source (HINS)"

Conclusions

- HINS is a key part of Fermilab's Accelerator R&D program, and likely a key part of its future physics program
- We have demonstrated the workability of two of its more challenging components

Backup Slides

Kentech 500V Prototype Pulser Scheme

10 pulse cards: $50V \rightarrow 5\Omega$

Coverage Factor, Meanders

single meander signal to 500 MHz CH2 S21 LIN 500 uU/REF 2 mU 1: 4.6130 mU 10.000 000 MHz 500 uUnits/div CH2 Markers 2: 4.7735 mU 50.0000 MHz 1 million 3: 4.7236 mU 100.000 MHz 4: 4.9061 mU 200.000 MHz Av9 5: 3.5820 mU 500.000 MHz 1 STOP 500.000 000 MHz START 010 000 MHz CH1 S21 LIN 1 mU/REF 0 U 3: 8.4795 mU 85.470 003 MHz 3 4 double meander (100 Ω)around 100 MHz ICH1 LIN 1 mU/REF 0 U 3: 4.7312 mU 103.720 002 MHz S21

3

4

Av9 16

*Relative to normalization 2 measurement; single meander (100Ω) around 100 MHz Robyn Madrak - FNAL APT Seminar - 12/16/2008

Which gives*:

type	С
double	87%
Single 1	48%

After correcting for impedance difference and reflected power 58

Heating in Meander

Final Pulse: 2.4 kV \rightarrow Z= 100 Ω , 1ms@10Hz or 3ms@2.5Hz, Chop \leq 30%

Meander Traces: 70 μ m thick, R(DC) = 2.7 Ω

Don't have 2.4 kV pulser, use test pulse of 1 or 3ms (low freq)

 \Rightarrow With safety factor, test at 50 A

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Notching Study

Using one or two single power switches:

M4.00ns A Ch4 J 76.0 V

1 24.20 %

Ch4 200 V

Using one or two single power switches:

With a slightly lower current

- The DEI FETS *can* be used to make a very narrow pulse by charging cable in the drain
- But in this case we cannot attain the desired 53 MHz rep rate

DEI FETS for H⁻ Source

- DEI FETS were useful for beam notching in H⁻ source for the current linac
- ~40ns pulses 2.2μs spacing
- Burst of 15 pulses, repeat at 15 Hz
- Two pulsers: ±800V

