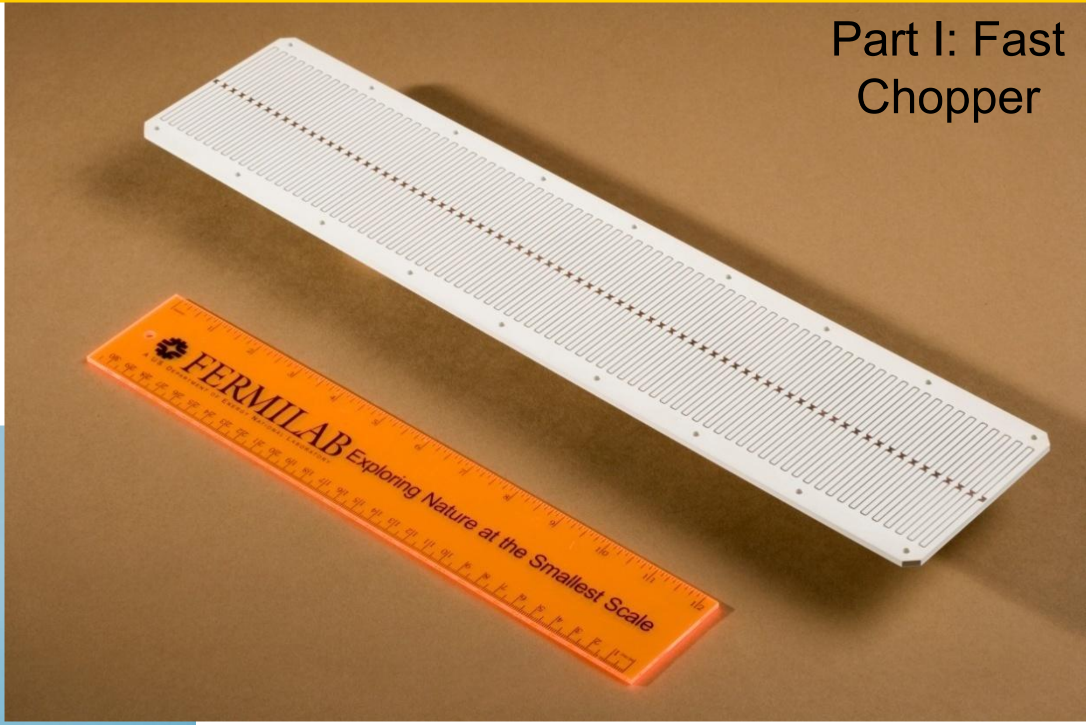
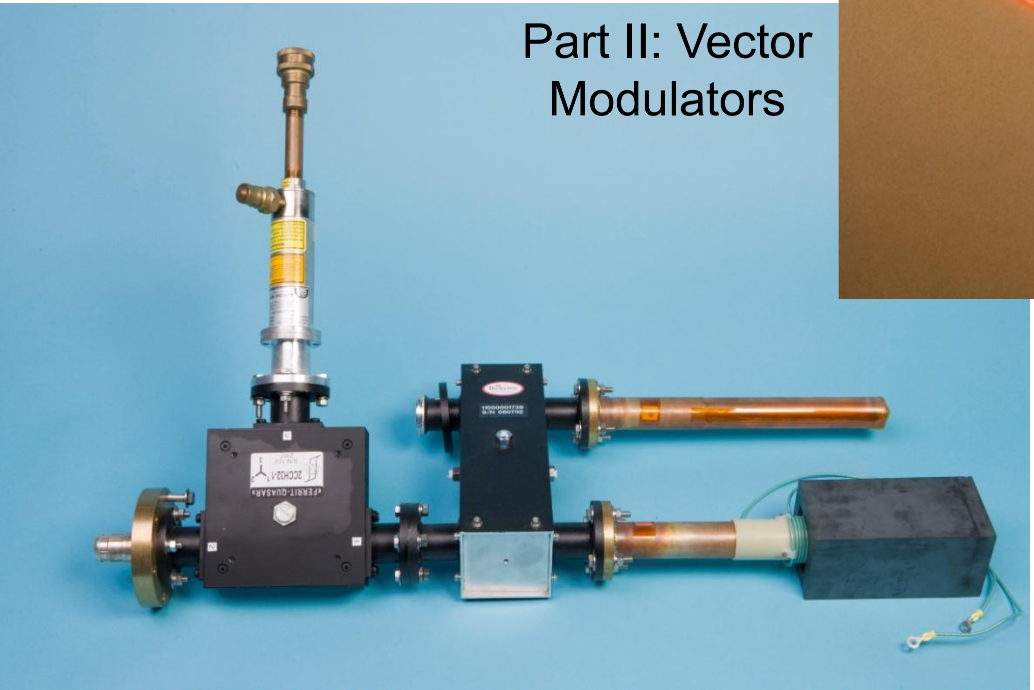
Two Devices for HINS*

Robyn Madrak

Accelerator Physics Center (APC)



Part I: Fast Chopper



Part II: Vector Modulators

*High Intensity Neutrino Source

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

Unique Aspects/Challenges

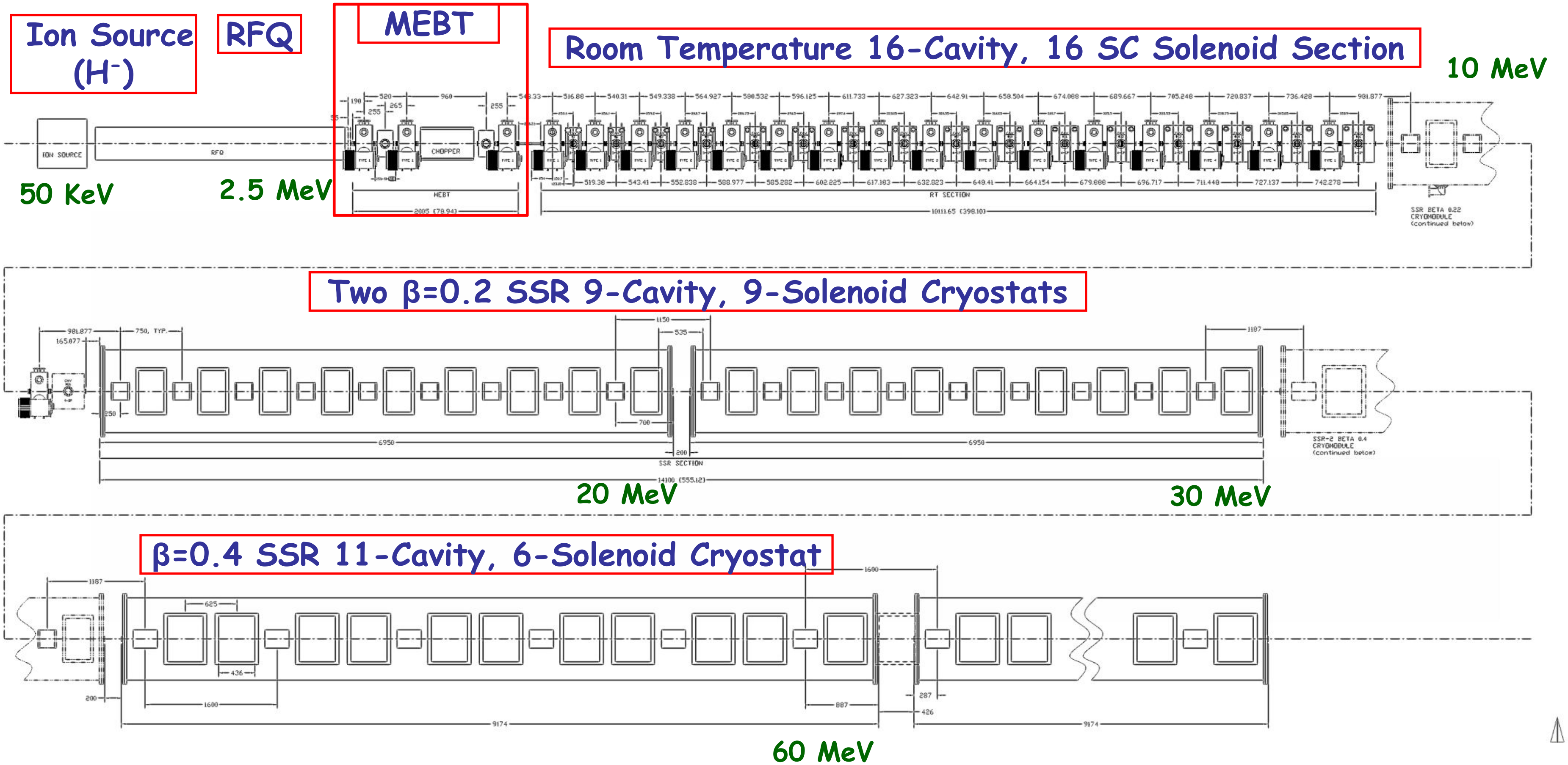
- ***Solenoidal focusing ⇒ cleaner, axisymmetric beam***
- ***Use of SC spoke resonators***
- ***Fast ferrite phase shifters***
  - ***will allow multiple cavities (and RFQ) to be driven by a single 2.5 MW, 325 MHz klystron => cost savings***
- ***Fast Beam Chopper***

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

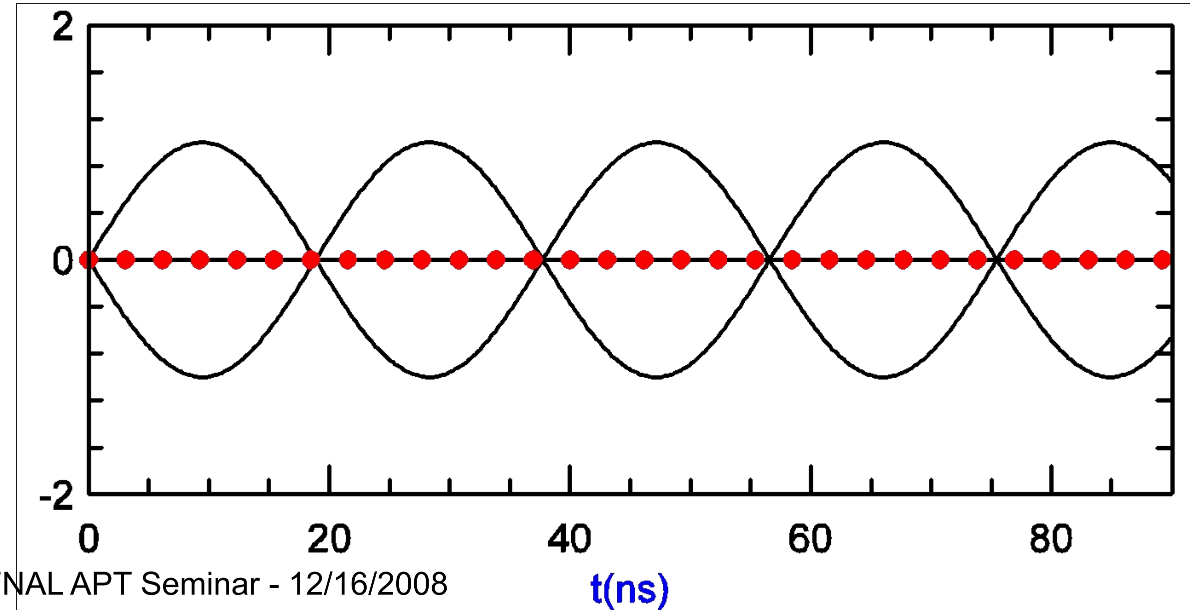
FNAL HINS


Ion Source
(H⁻)
RFQ
MEBT
Room Temperature 16-Cavity, 16 SC Solenoid Section
10 MeV
50 KeV
2.5 MeV
Two β=0.2 SSR 9-Cavity, 9-Solenoid Cryostats
20 MeV
30 MeV
β=0.4 SSR 11-Cavity, 6-Solenoid Cryostat
60 MeV

HINS Chopper – Part I

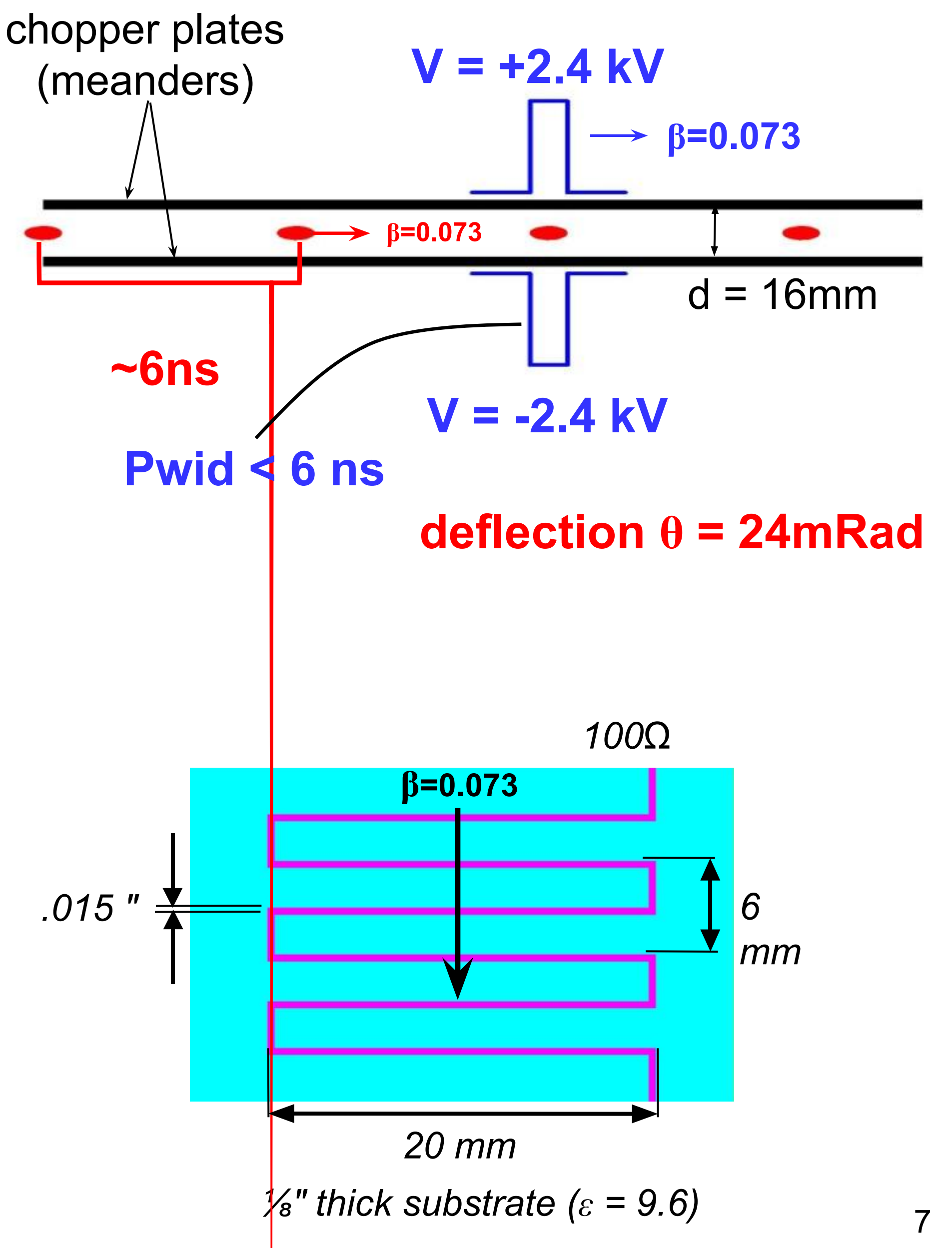
- *Should the HINS be extended to an 8 GeV Linac, output beam would be transferred to Fermilab's Main Injector, with 53 MHz RF frequency*

- ***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 ≠ n G 53***
    - ***⇒ Sometimes chop 1, sometimes 2***

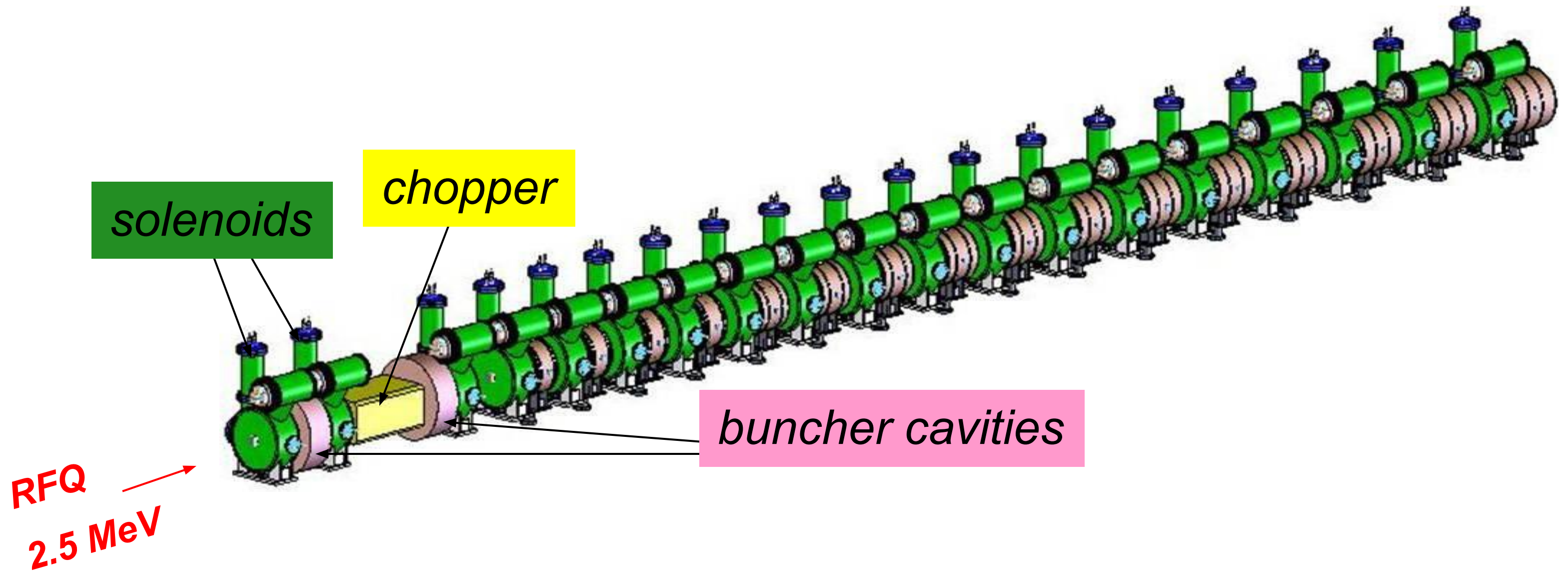


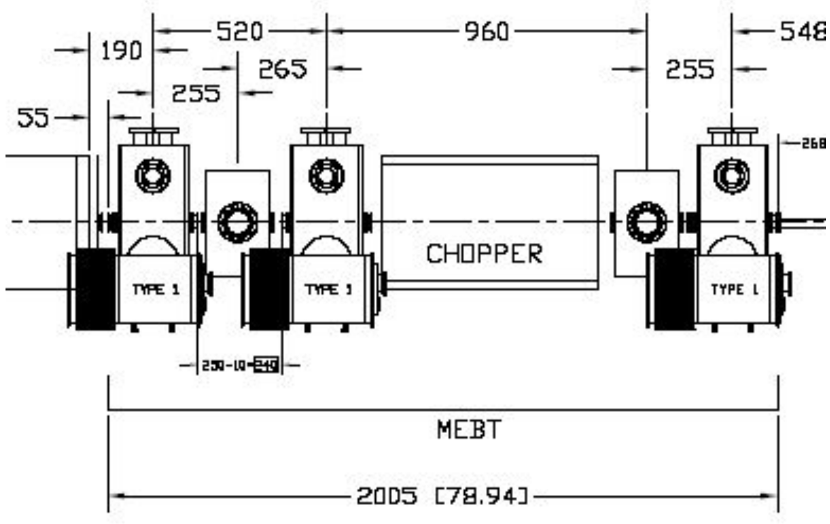
Traveling Wave Chopper Structure

- *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*



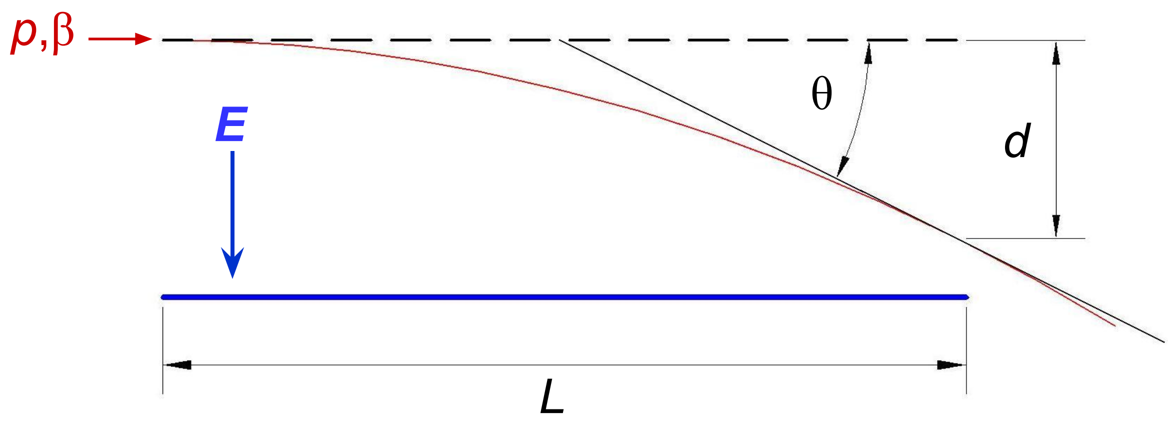
Chopper in MEBT





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

Deflection



length of chopper plates: 50 cm
drift space downstream: 30 cm
plate separation: 16 mm

d [m]= $E\,L^2/2p\beta$ [10^9 Vm/(GeV/c)]

$\theta = \tan^{-1}(EL/p\beta)$

$E = 2 \times (1.9kV)/16mm$
$= 2 \times (C \cdot 2.4\ kV)/16mm$

"coverage factor"

$d(L=50cm) = 6mm$

$\theta(L=50cm) \times 30cm = 7mm$

24mRad

Pulser Development

We need

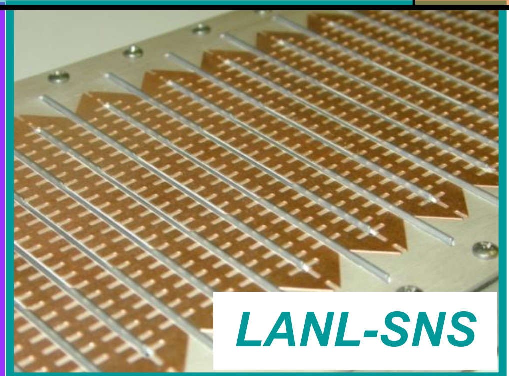
- *Two pulsers to drive the ~50 Ω meanders: +/- 2.4 kV*
- *Max ~5.5 ns pulse width (including rise and fall time)*
- *53 MHz rep rate*
- *burst of 3ms @2.5Hz, or 1ms@10Hz*
- *Programmable pulse width*

(may sometimes chop 1 bunch, sometimes two)

→ ***Specs do not lead to an "obvious" solution***

Similar Choppers

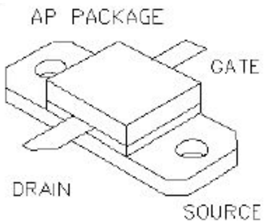
	CERN-SPL	LANL-SNS	RAL/ESS	FNAL HINS
Beam Energy	3 MeV	2.5 MeV	2.5 MeV	2.5 MeV
Electrode Length	2 X 40 cm	35 cm	34 cm	50 cm
Electrode Gap	20 mm	18 mm	14 mm	16 mm
Deflection Angle	5.3 mRad	18 mRad	16 mRad	24 mRad
Electrode Voltage	±0.5 kV	±2.35 kV	±2.2kV	±2.4kV
Pulse Rise Time	< 2ns	10 ns	2 ns	< 2ns
Pulse 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

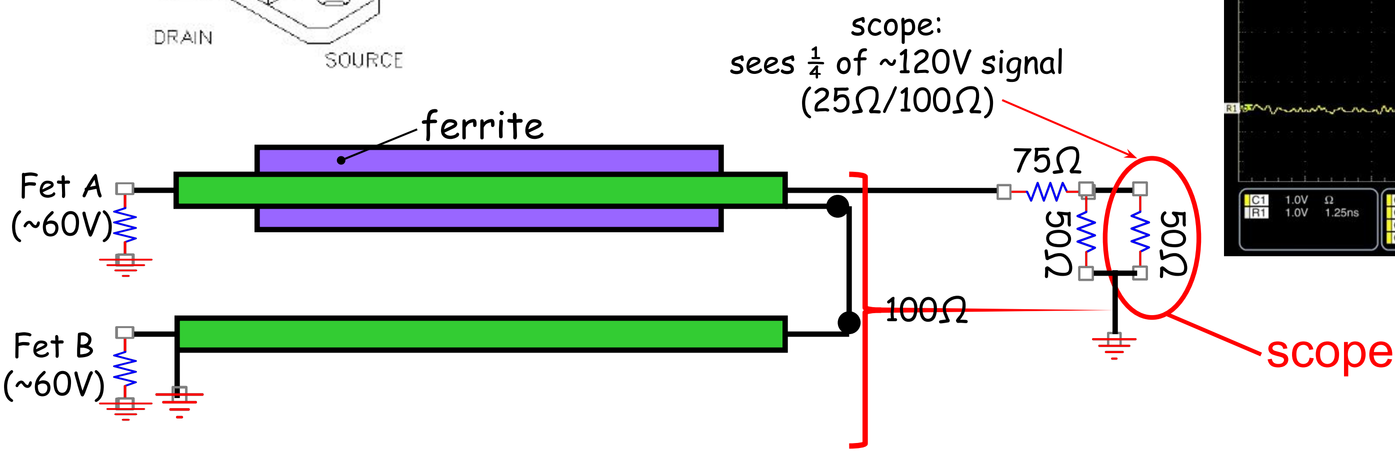


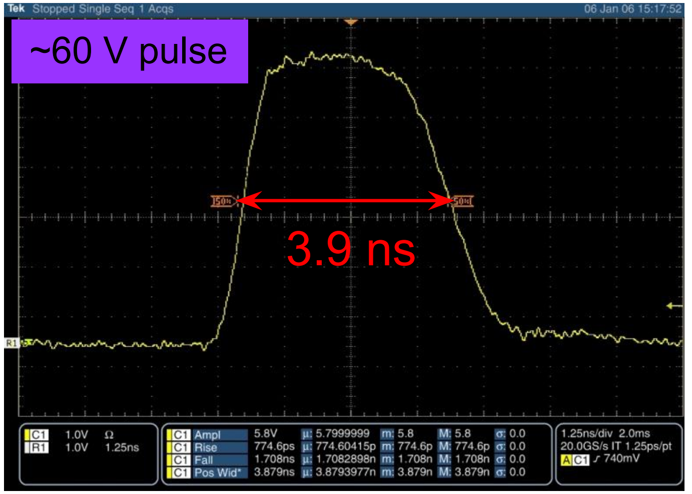
Combining lower voltage pulses?

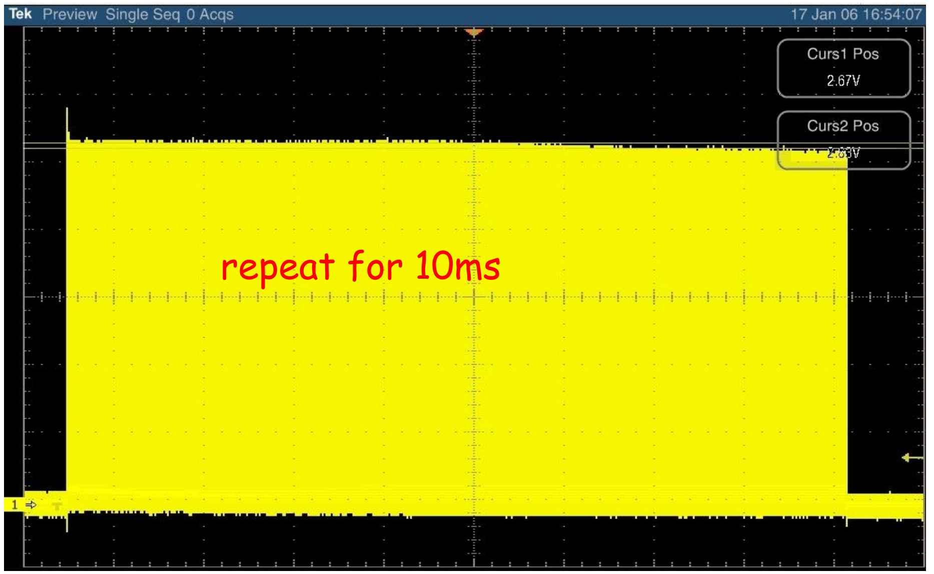
Basic Concept:
Two 60V→50Ω pulses
Combined to
One 120 V→100Ω pulse

Polyfet SP204



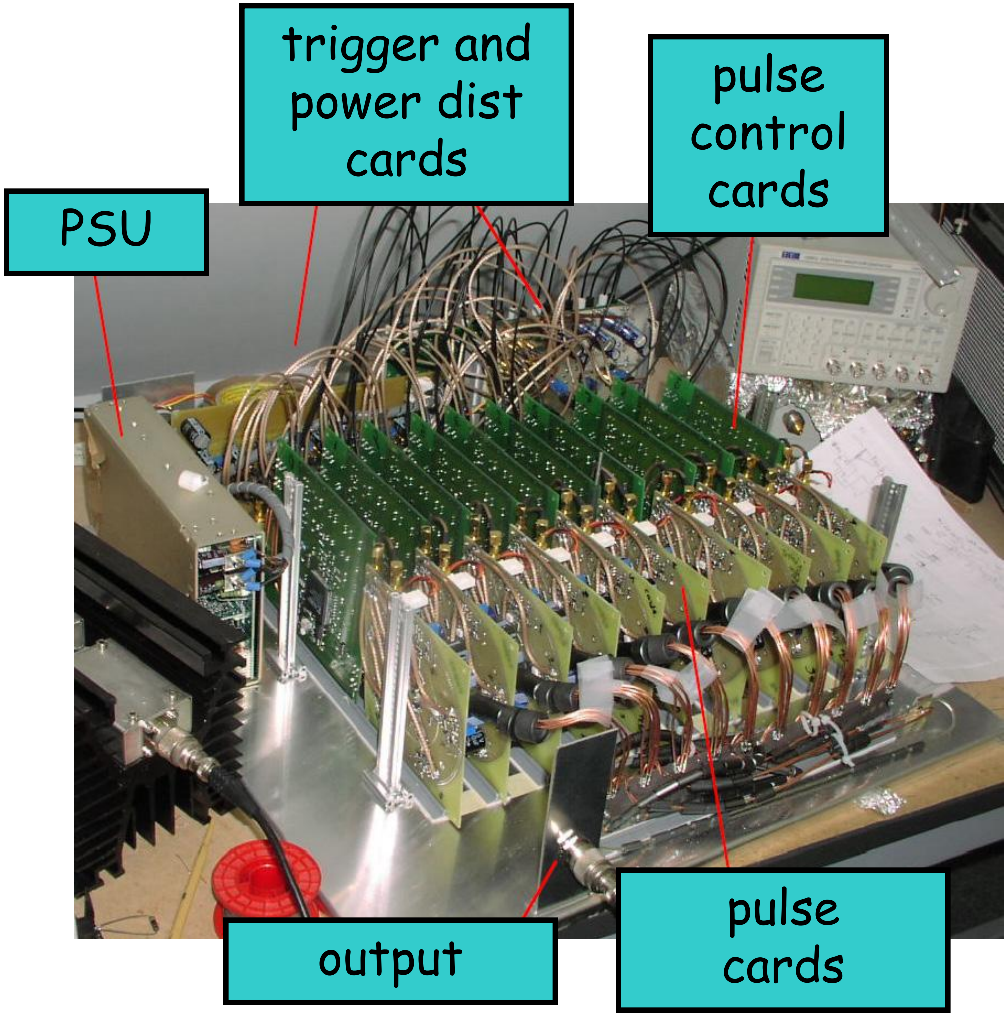




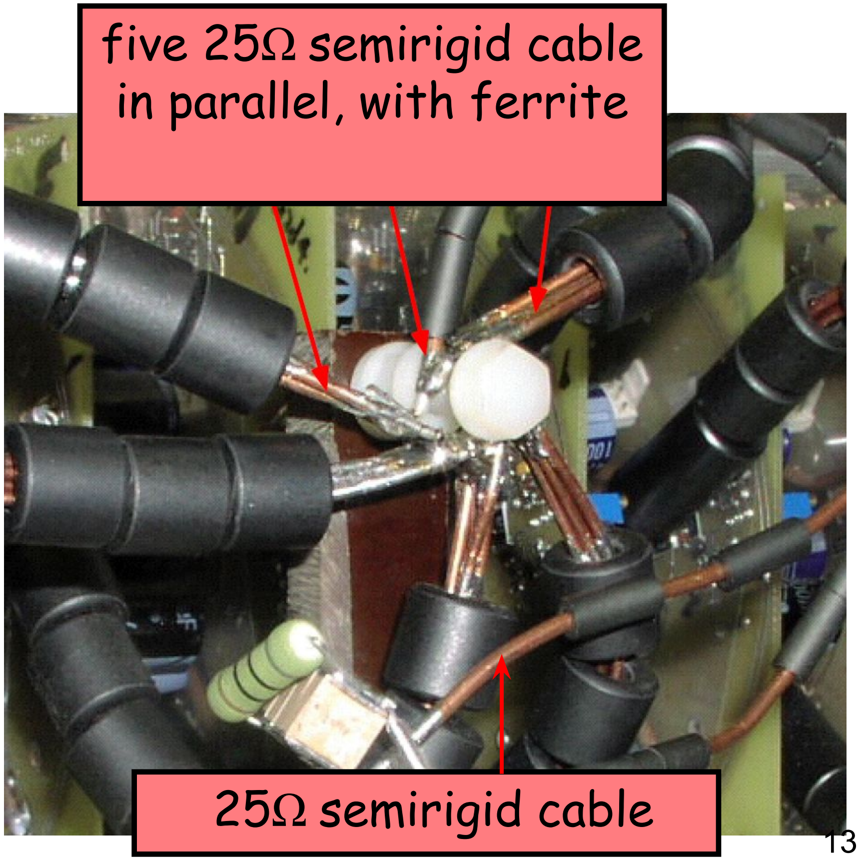


Kentech 500V Pulser

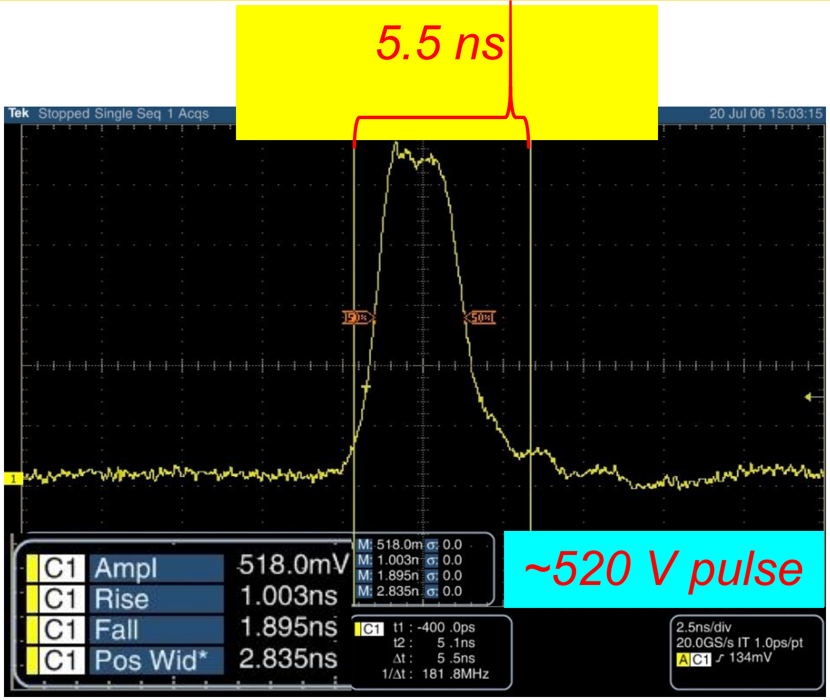
before fully assembled:

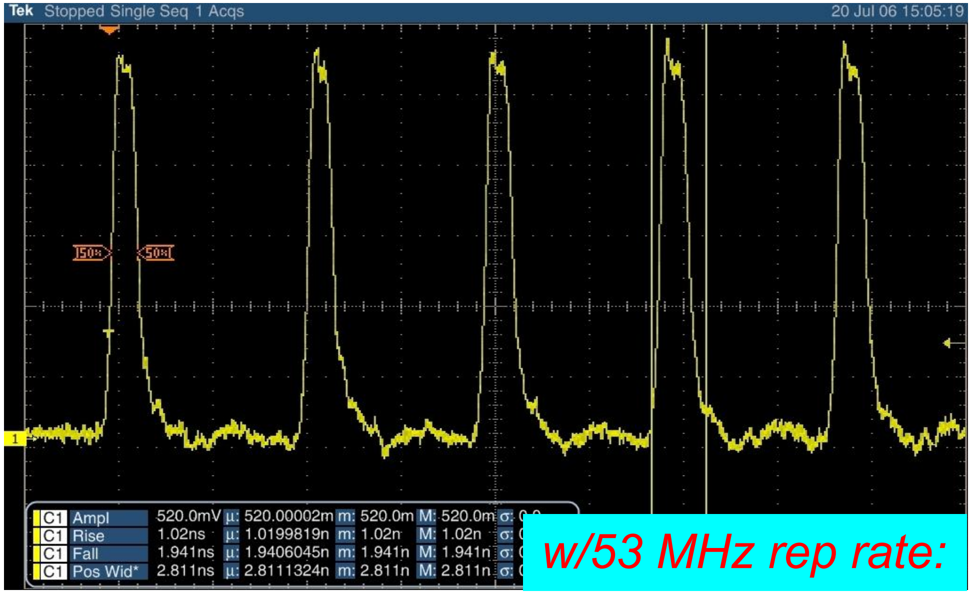


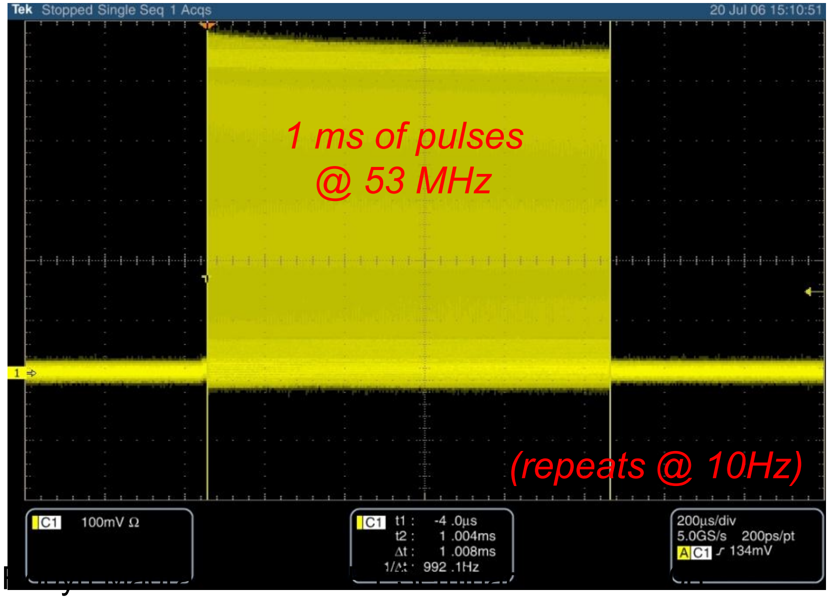
one side of combiner:

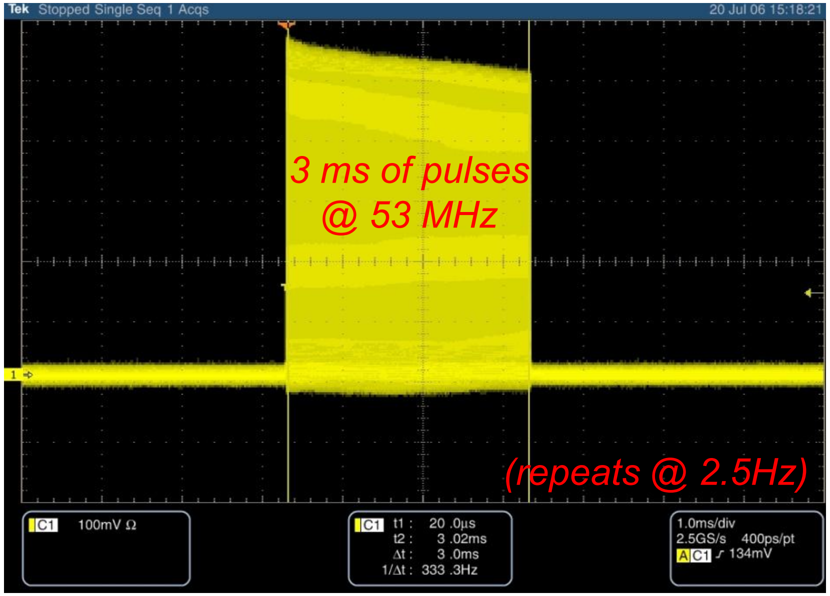


500V Pulser Output

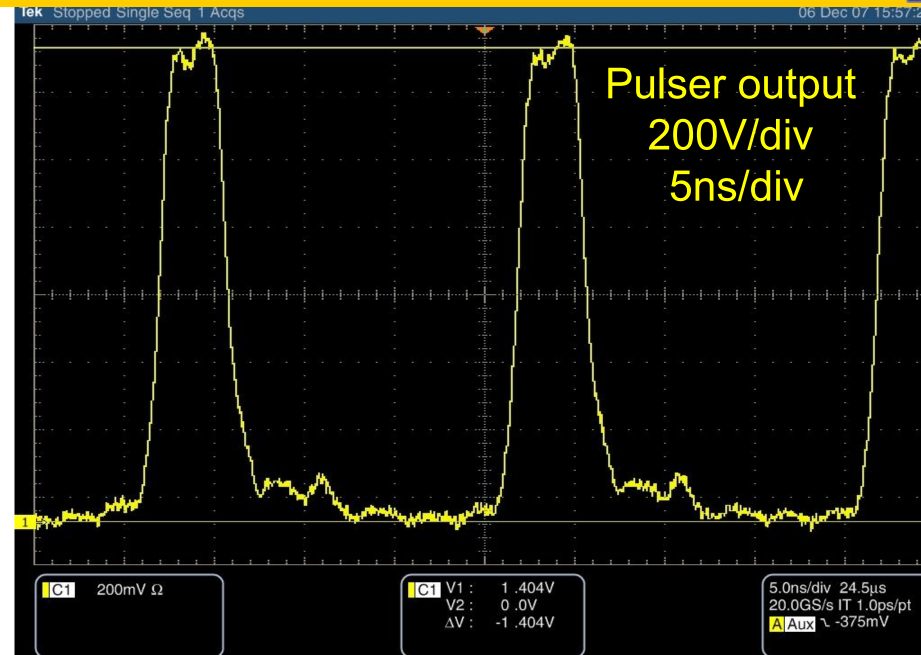


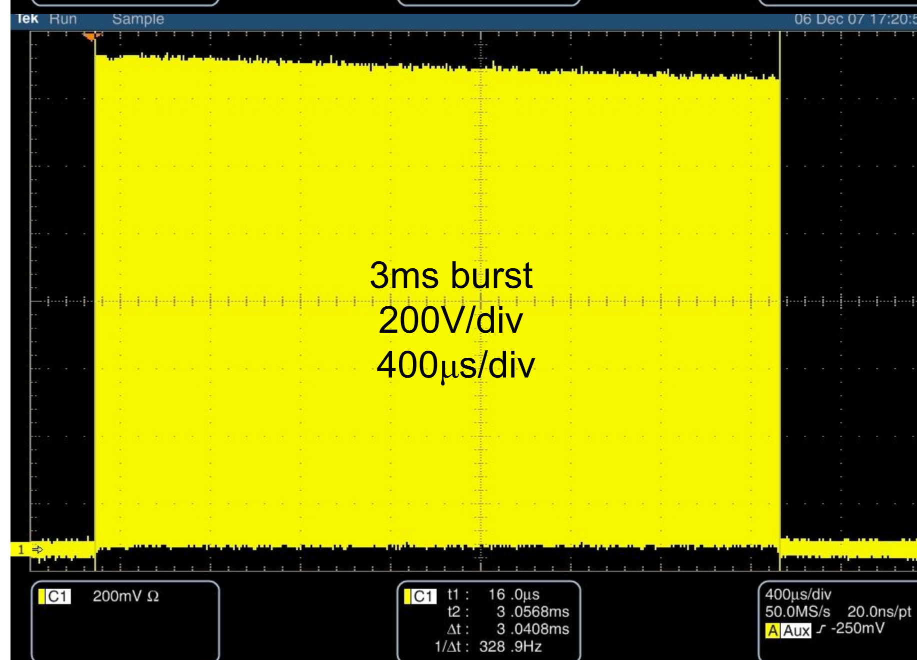






1.2 kV Pulser





Nov '07

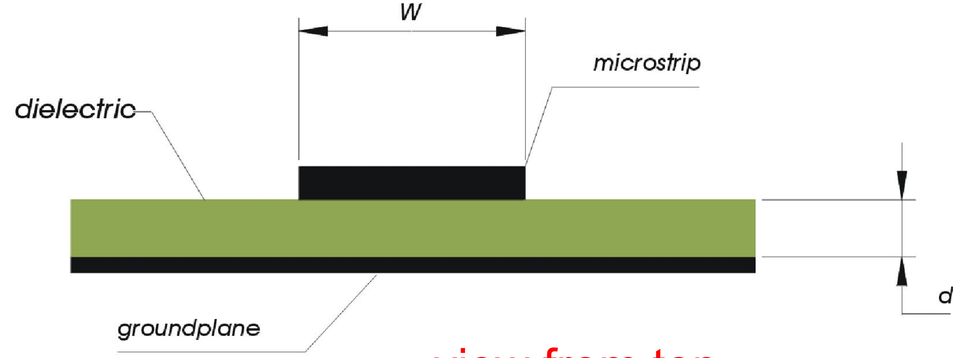
Kentech Pulsers

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

Microstrips in General

phase velocity and impedance are determined by **effective dielectric constant:**

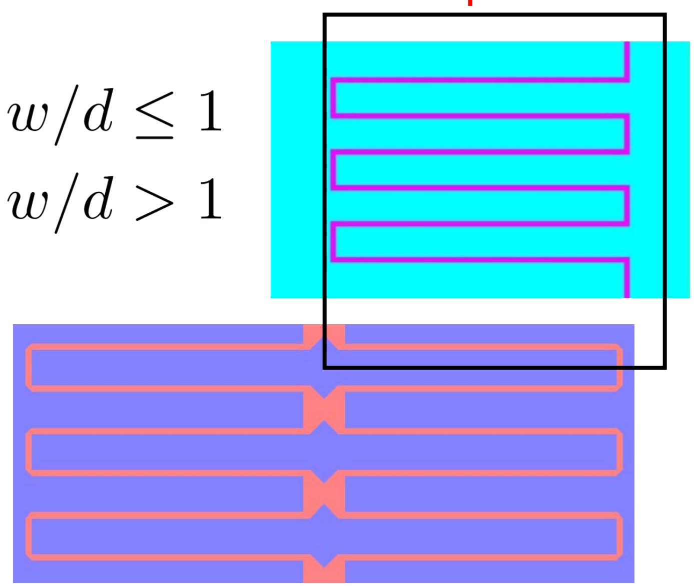
view from end



$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12d/w}}\right)$$

$$v_p = \frac{c}{\sqrt{\varepsilon_e}}$$

view from top



$$Z_0 = \begin{cases} \frac{60}{\sqrt{\varepsilon_e}} \ln\left(\frac{8d}{w} + \frac{w}{4d}\right) & w/d \le 1 \\ \frac{120\pi}{\sqrt{\varepsilon_e}\left[w/d + 1.393 + 0.667\ln(w/d + 1.444)\right]} & w/d > 1 \end{cases}$$

Delay time (β) and Z_0 may be adjusted by

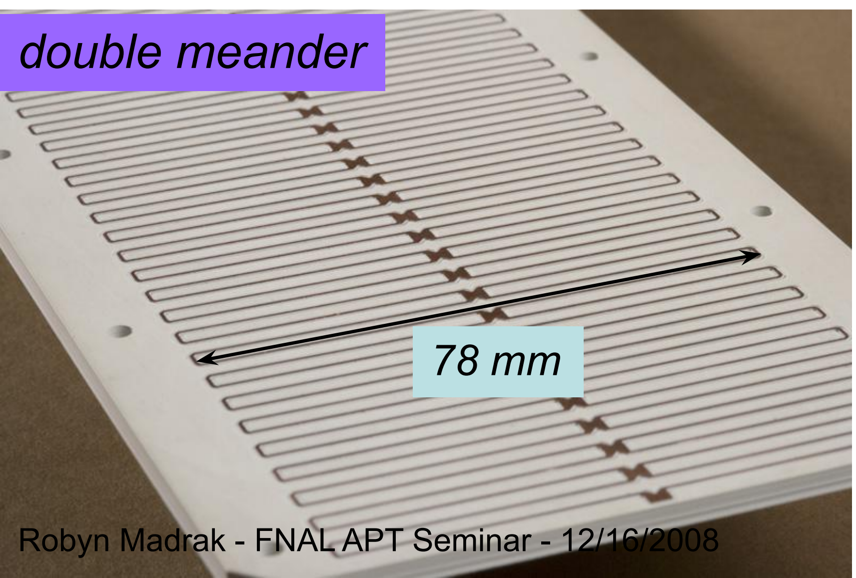
- *Adjusting d, W, and also meander pathlength*
- *Using only one trace or two in parallel*
- *Adding an air gap beneath the dielectric (changes ε_e); can be used to tune β*

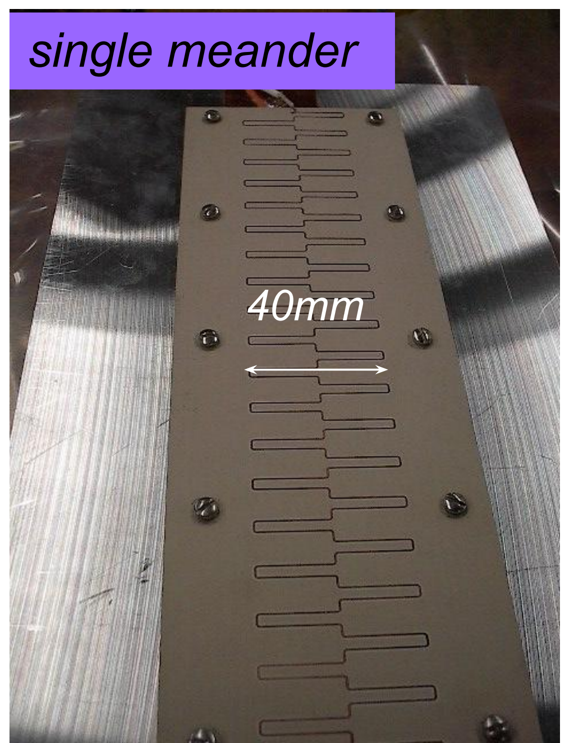
FNAL Fabricated Meanders

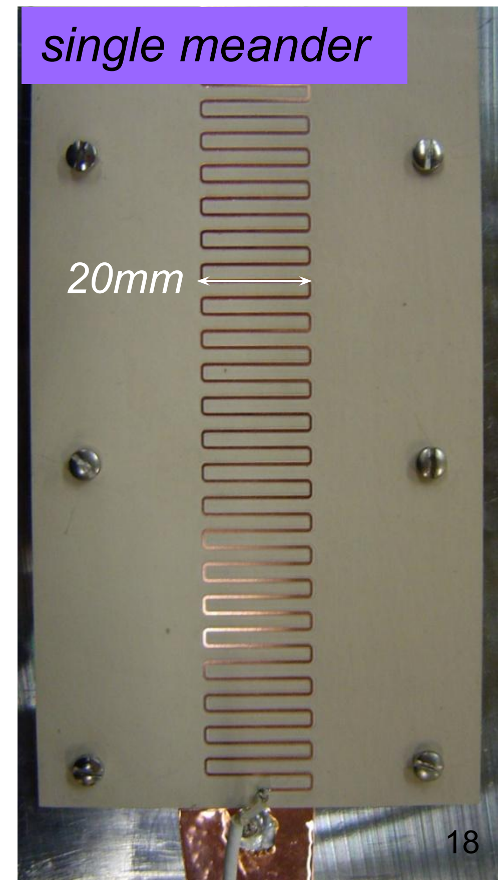
We have pursued the following:

1. *Use double meander design with air gap between meander and ground plane (50Ω w/no gap, 100Ω/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*





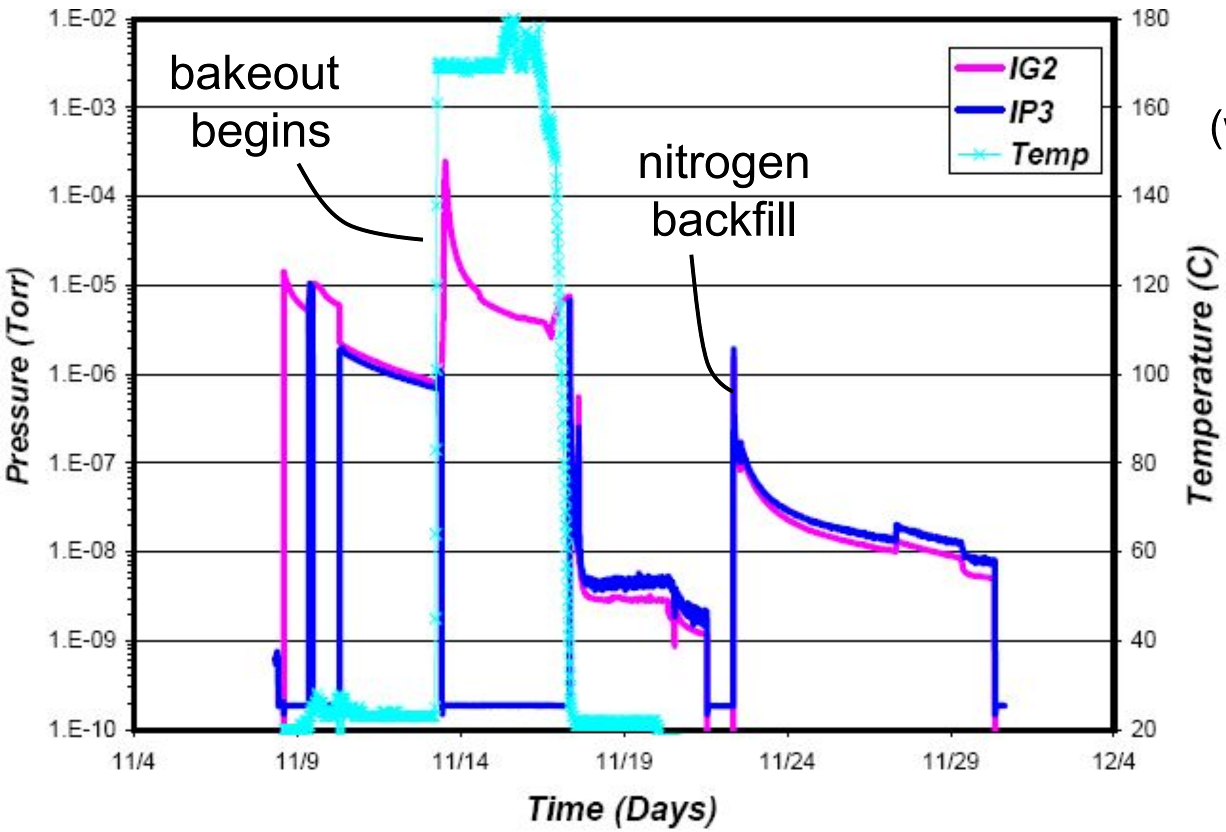


Chopper Meanders

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



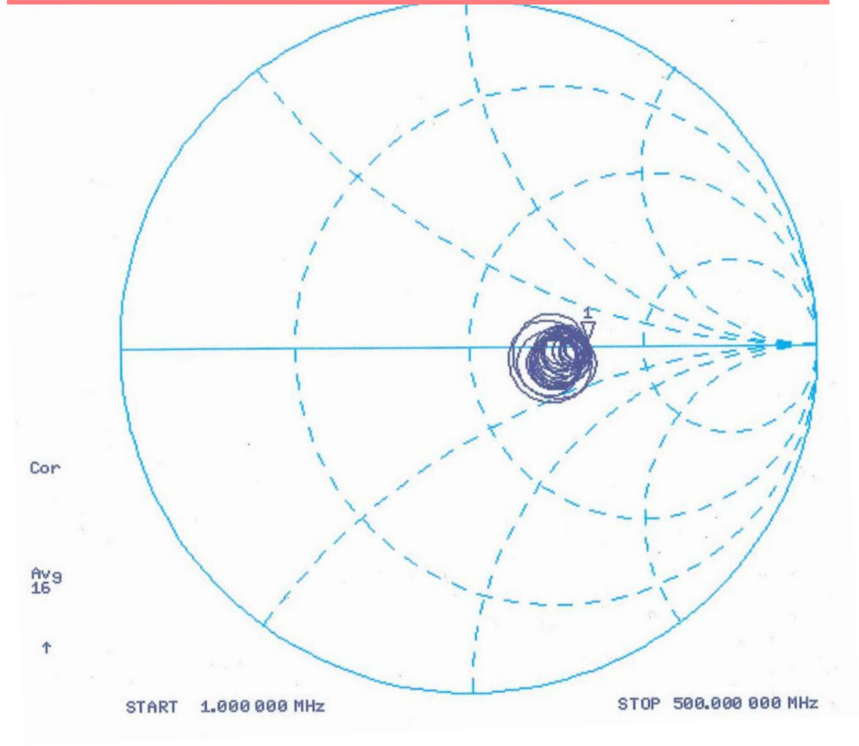
@55C 8E-08 torr
0.63 L/s
(with⅓ final surface area)

Terry Anderson

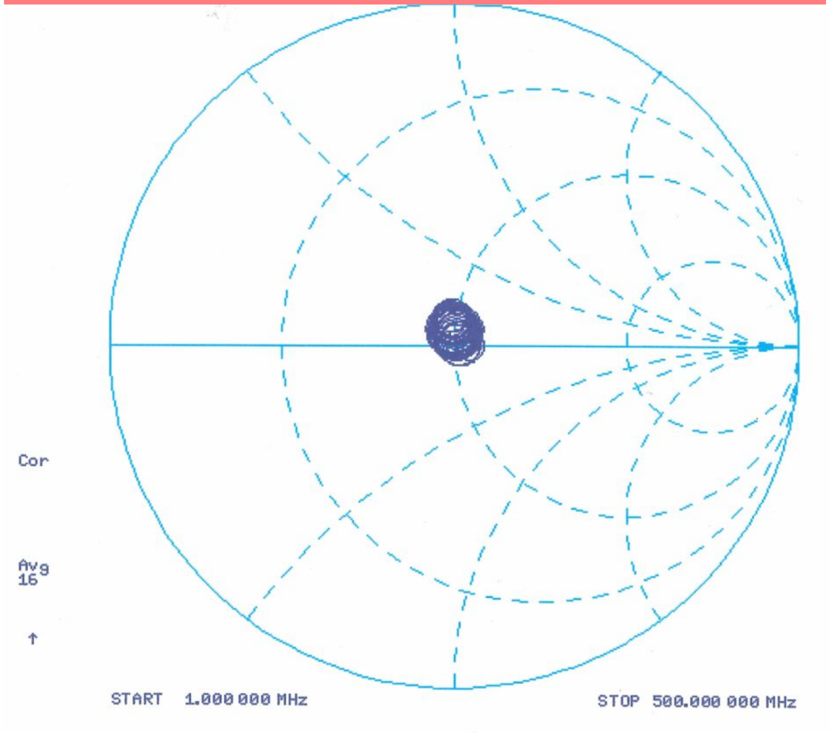
- *Meander traces are generated by routing out traces on Rogers TMM10i, Cu clad*
- *Cheaper, faster than paste/firing/electrochemical deposition*
- *Test indicates acceptable vacuum properties*

Double Meander, Impedance

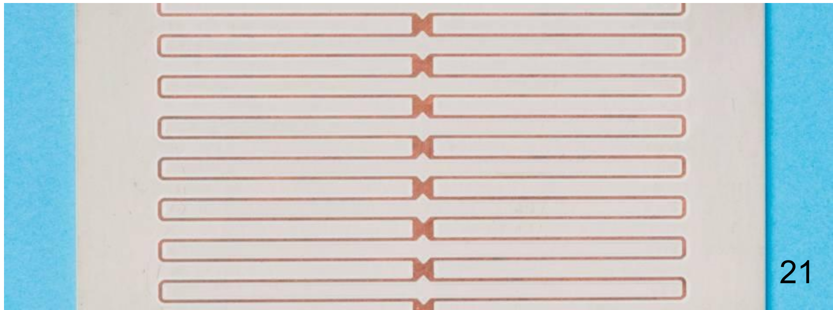
101 Ω: with 0.062" spacers



*55 Ω: with **no** spacers*

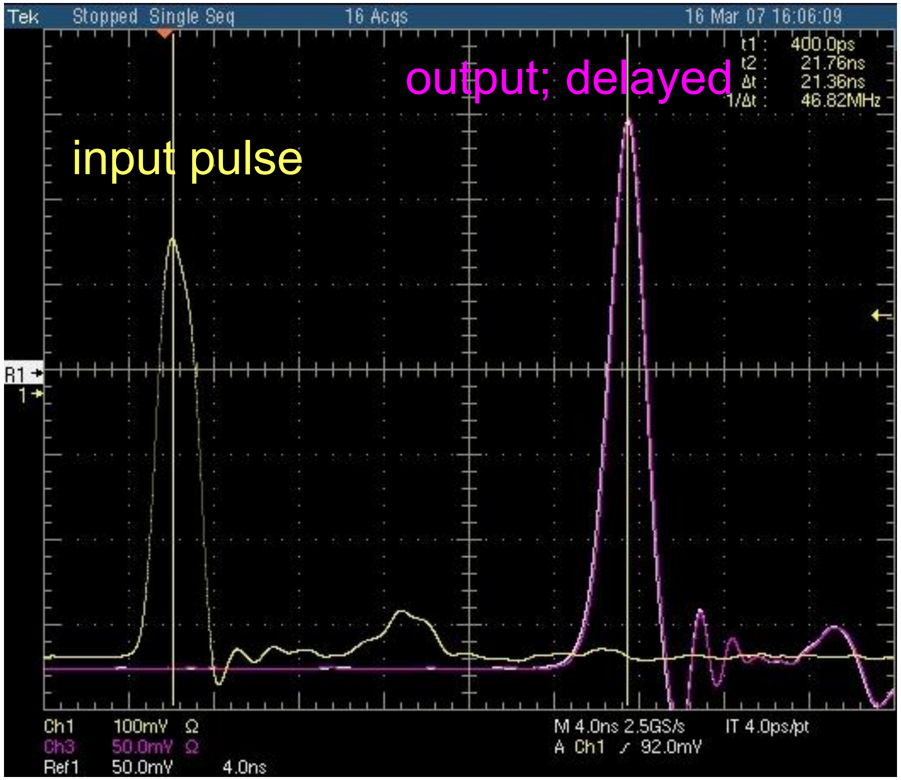


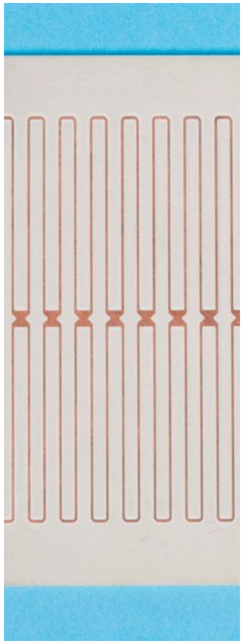
Impedance measurements from 1 – 500 MHz



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*





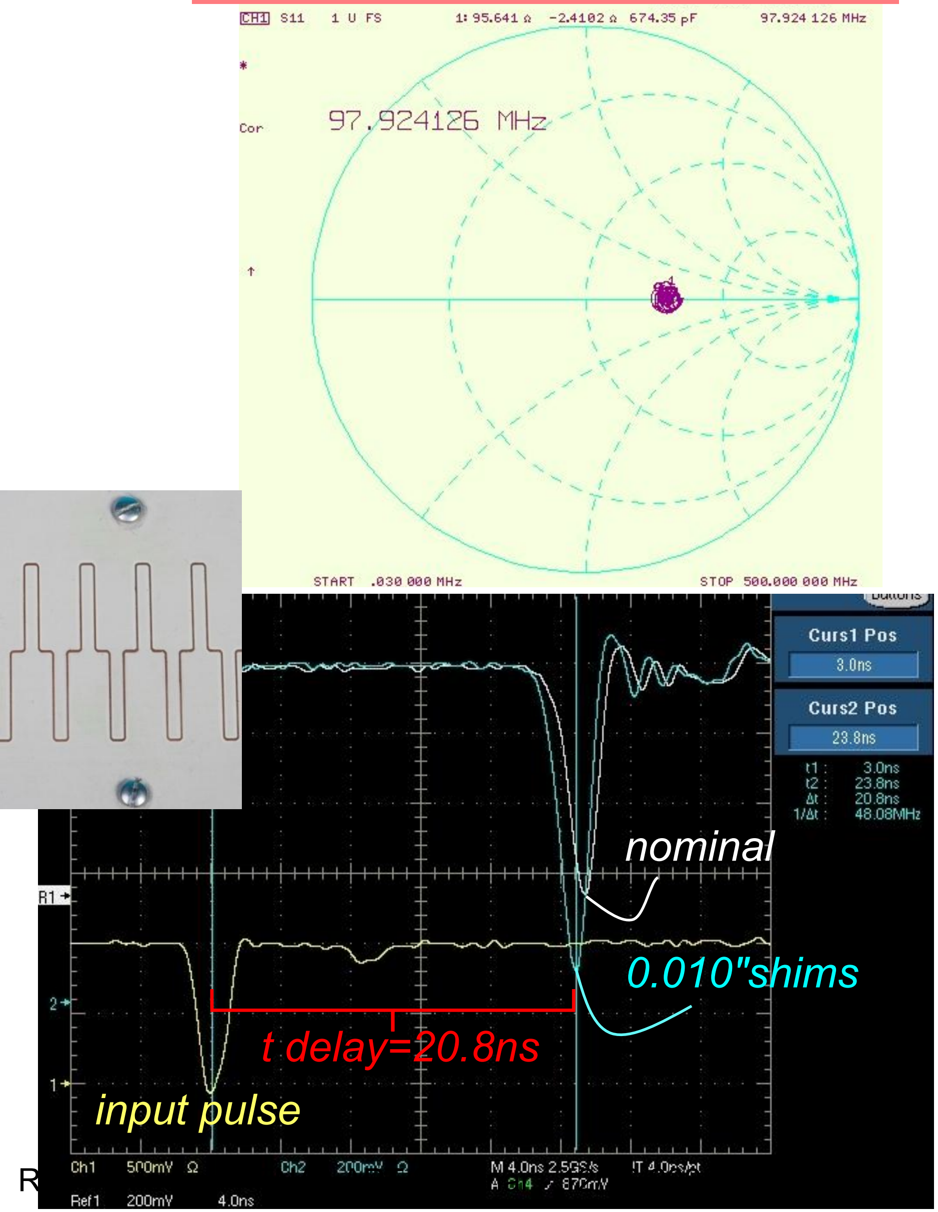
spacing	t delay (ns)	β
0.062''	18.8	0.081
0.040''	21.2	0.072
0	32.3	0.047

~100 Ω

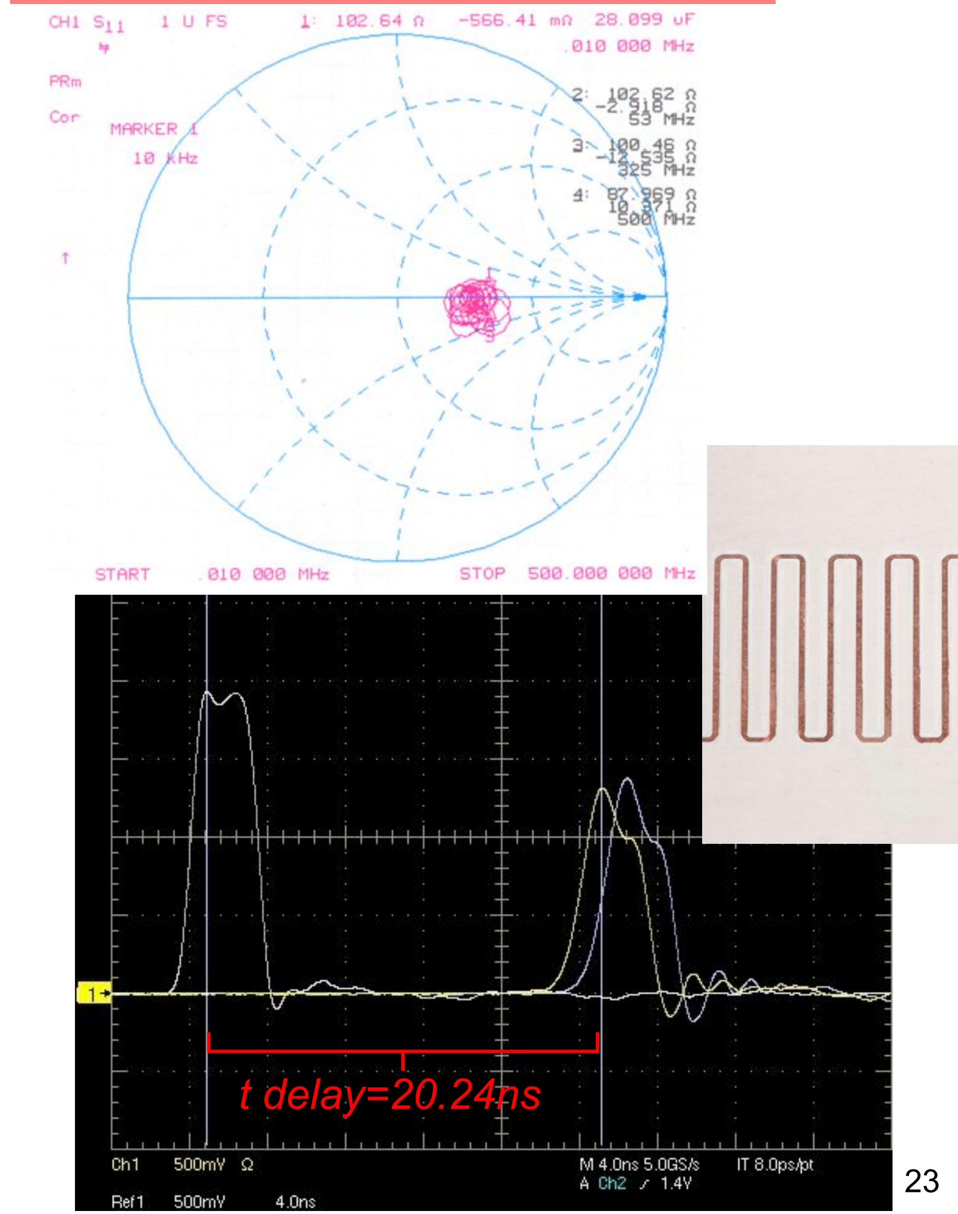
50 Ω

Single Meanders: Impedance and Delay

Meander 1: 95 Ω @~100 MHz

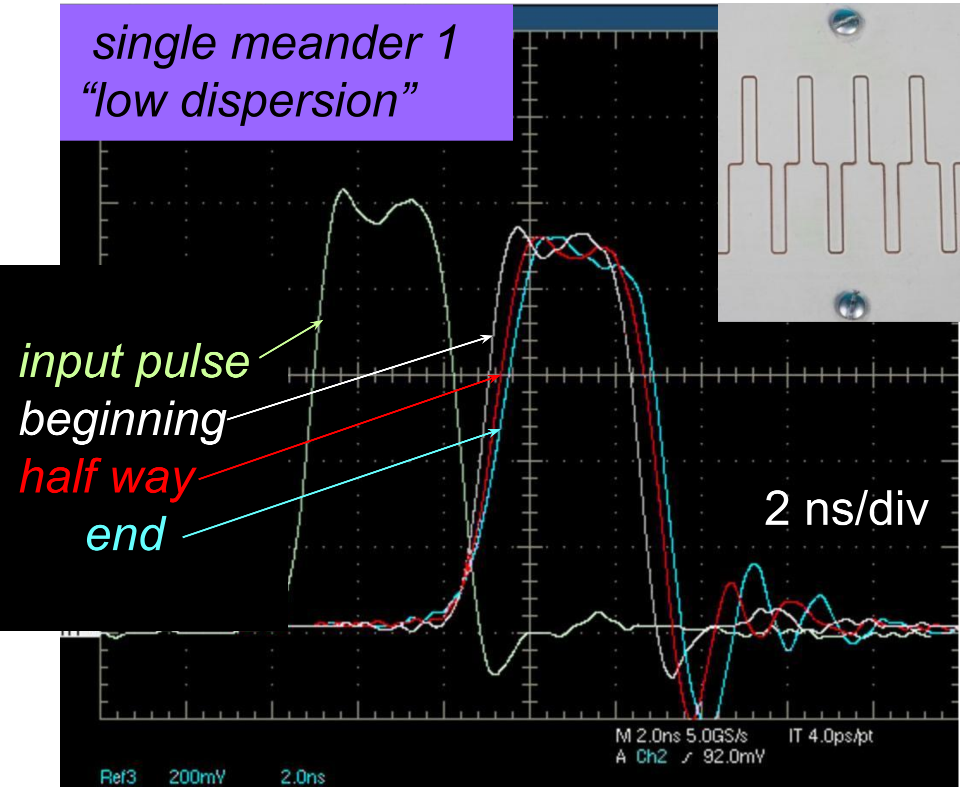


Meander 2: 100.5 Ω @~325 MHz

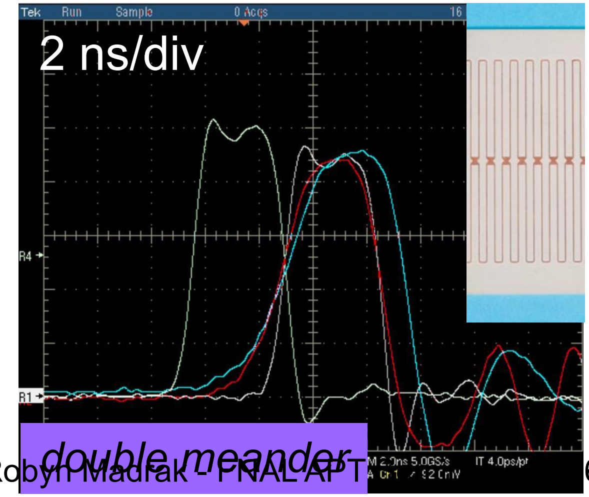


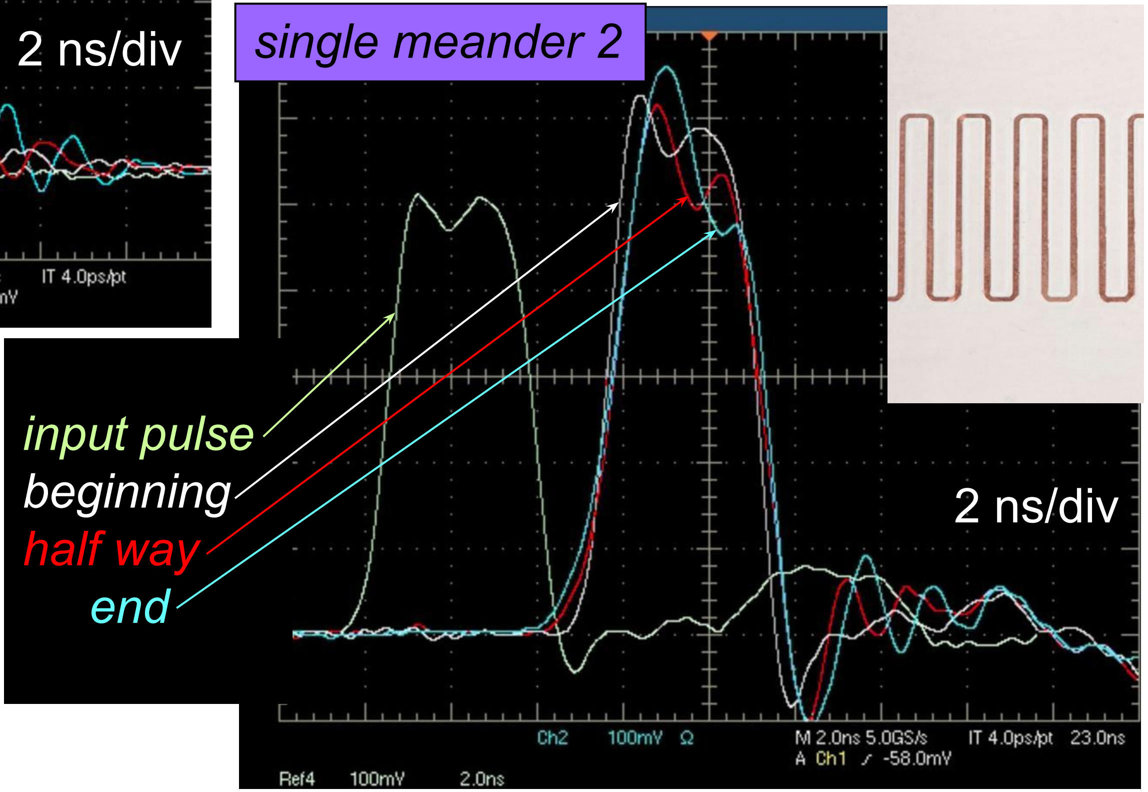
R

Dispersion



- Meanders are 18″ long
- Look at pulse behavior along length using high f scope probe

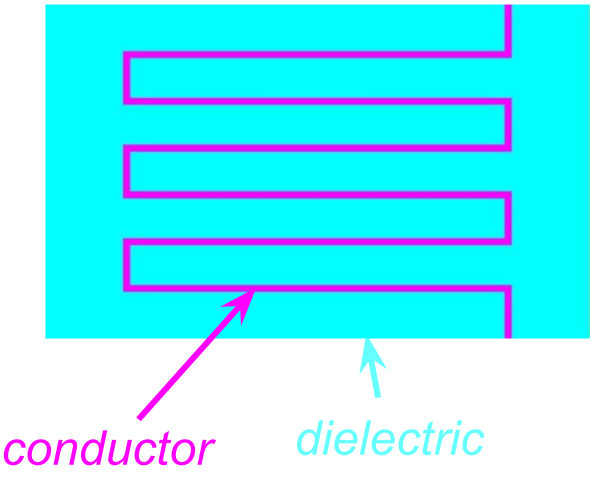


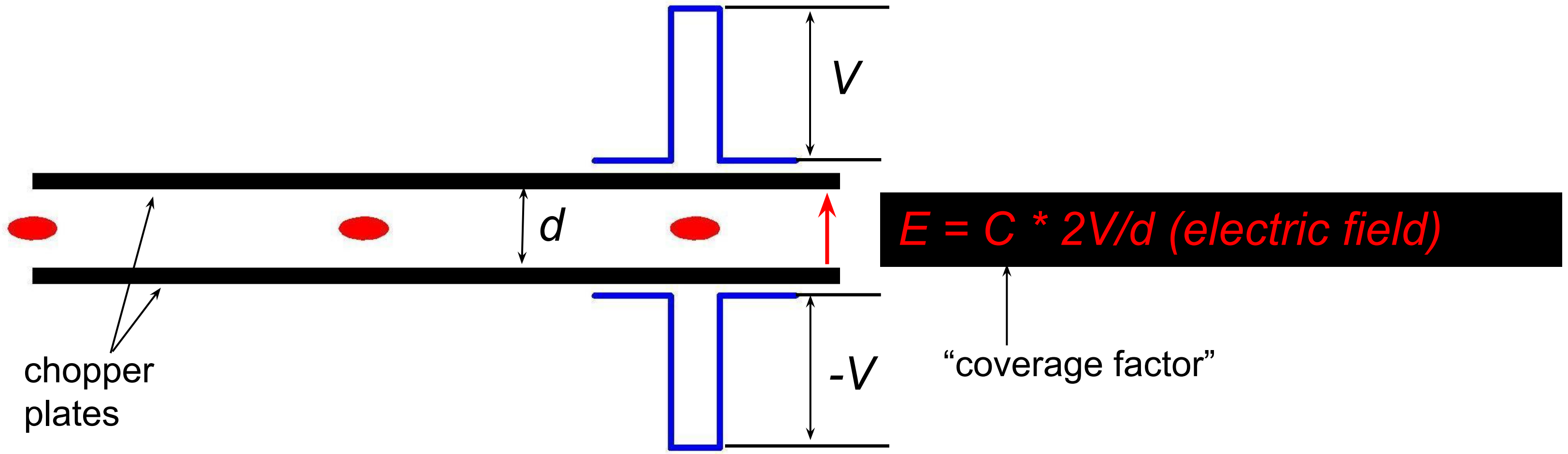


Coverage Factor

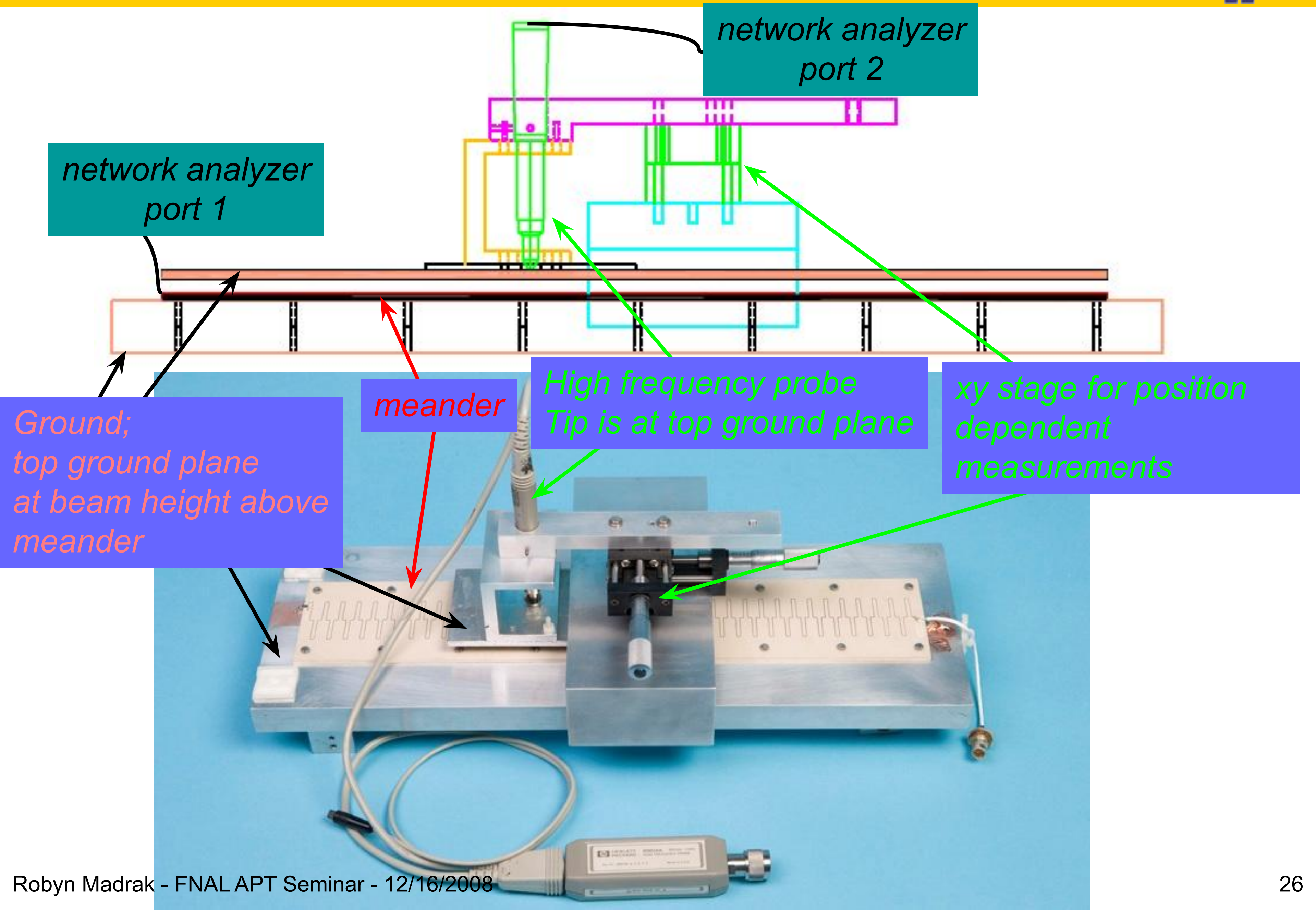
- *The electric field between the chopper plates is less than that for a structure in which the entire surface is conducting*

- *This must be accounted for in the chopper design when determining the voltage needed for the desired kick*



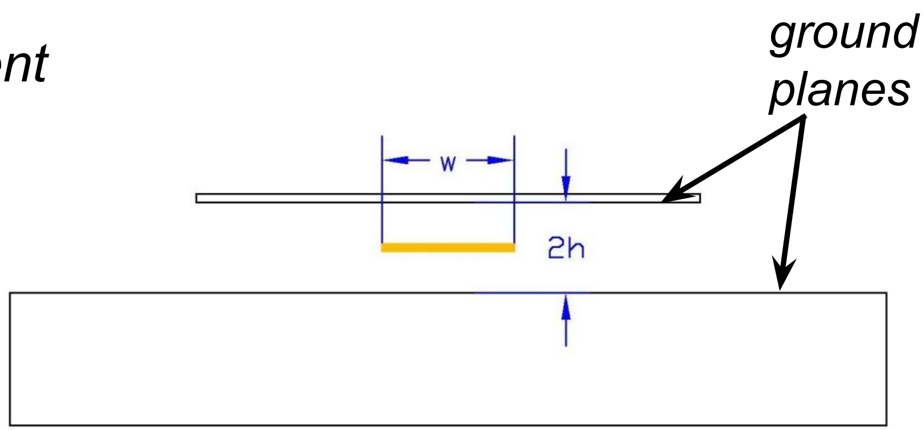


Coverage Factor Measurements



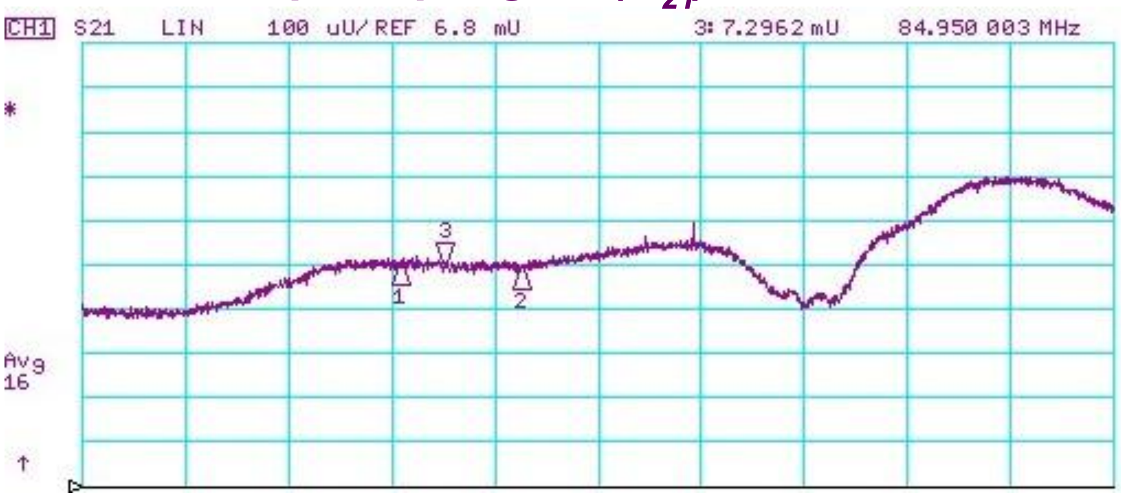
Coverage Factor Normalization

- *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*

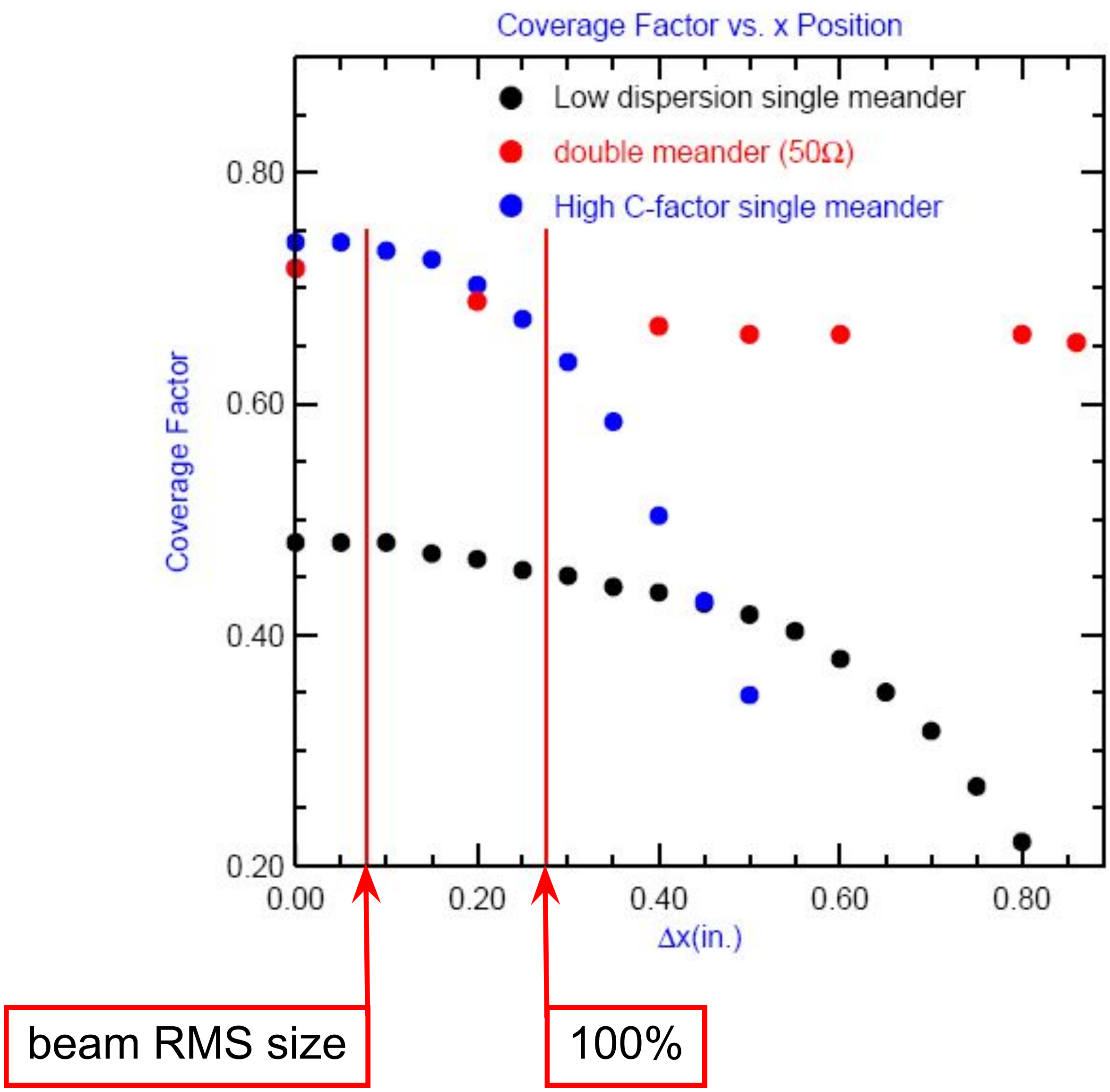
Probe pickup signal (S_{21}), 50 – 150 MHz



All Measured Coverage Factors

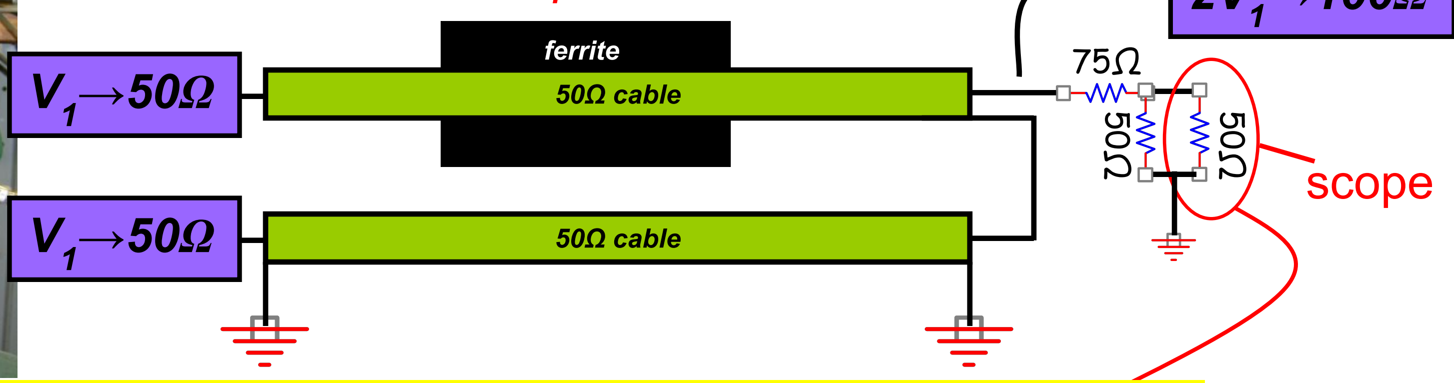
type	Double 50Ω	Double 100Ω	Single 1 (low dispersion)	Single 2 (high coverage)
Coverage factor	71%	87%	48%	74%

Position Dependence



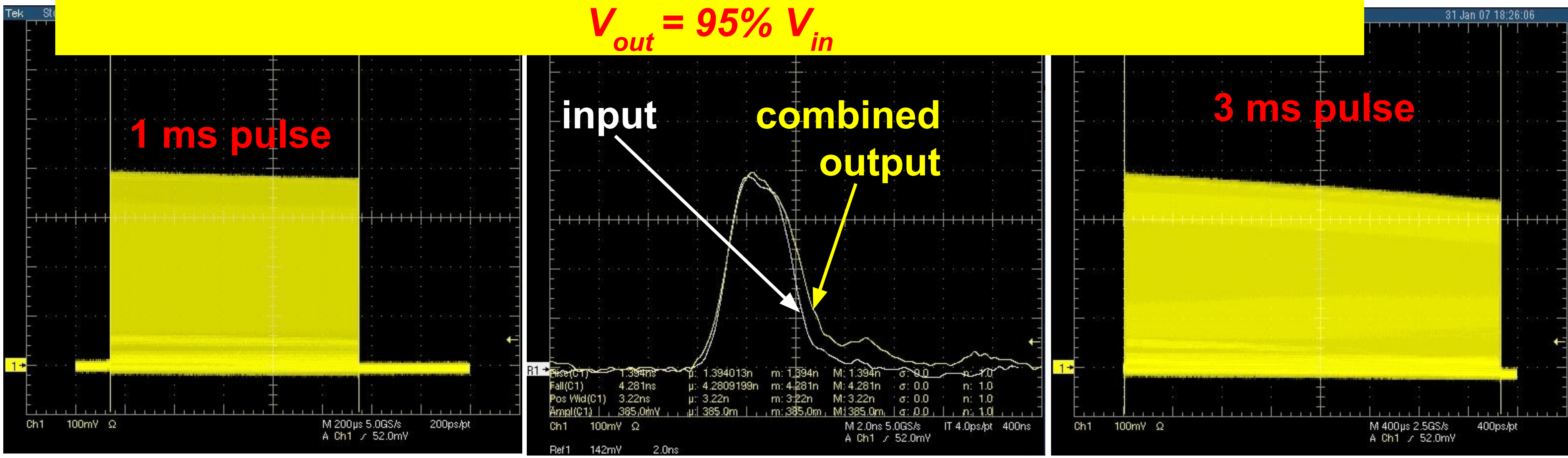
Combiner

- *MN60 ferrite: three 11” OD, 4.5” ID, 1” thick cores*
- *58 turns of ¼" “superflex” cable*



Test combiner by splitting and recombining (using our 500V pulser):

$V_{out} = 95\% \ V_{in}$

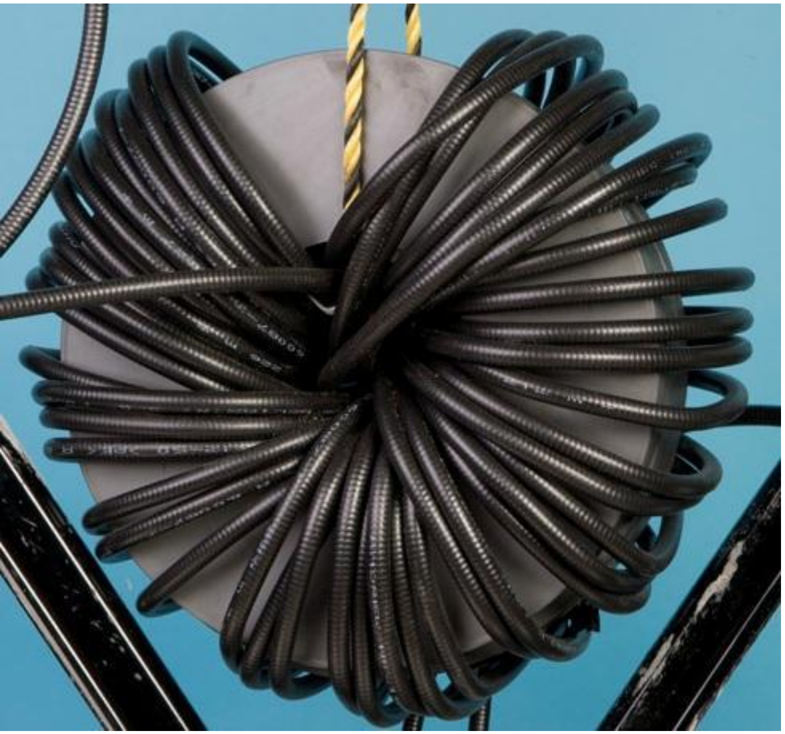


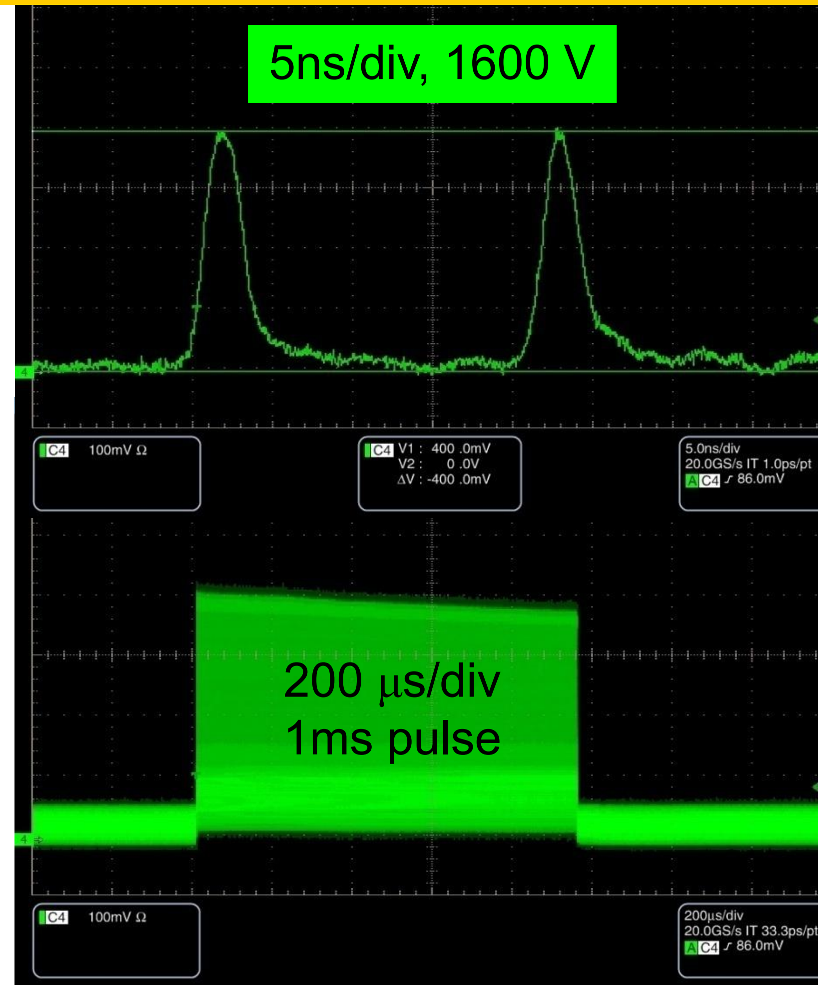
Expect behavior to be better than this:

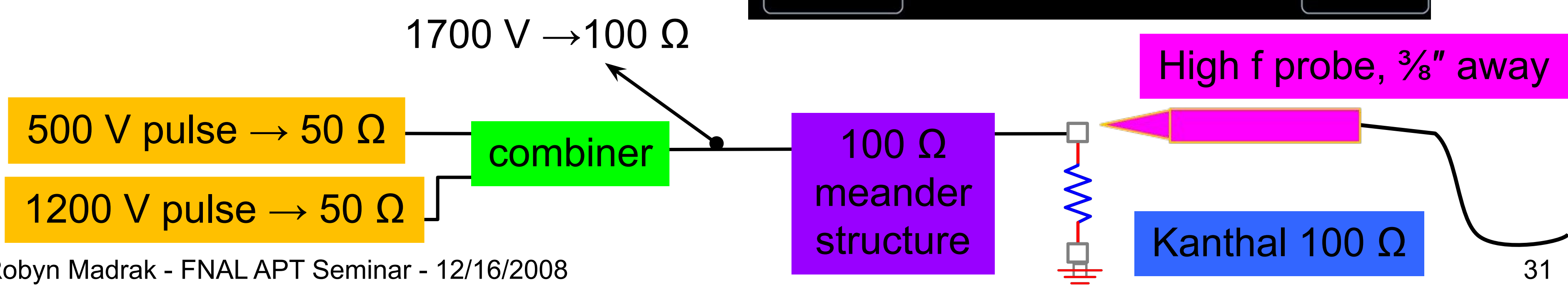
- *currently we have extra unneeded cable length*
- *matching resistors (100Ω to scope 50Ω) add extra inductance*

Combiner Optimized

46 turns of ⅜″ superflex around
five 1″ MN60 cores







Heating in Meander

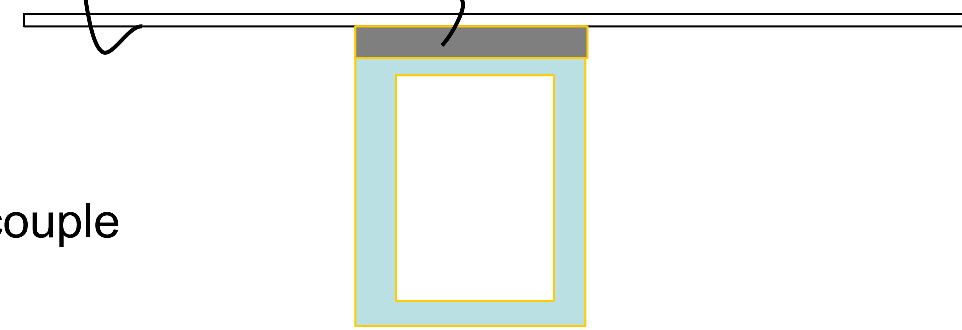
Current in meander will be 2.4 kV/100 Ω = 24 A

Need to test heat/current handling capacity

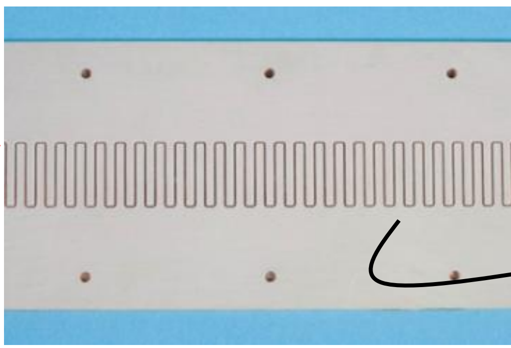
Use 1ms/3ms pulses: $(24A)^2 \times ⅓ \times 5.3 = I^2_{test} \Rightarrow I_{test} = 32$ A

(24A)² = actual pulsed current; ⅓ = chopping DF; 5.3 = Skin depth factor

Minimal heat sinking:
Meander sits on SS stand (not clamped)



50 A →



thermocouple

Equilibrium Temperature	1ms, 10 Hz, 50A	1ms, 10Hz, 41 A	3ms, 2 Hz, 50 A
T (near trace)	83 C	58 C	44C
T (on trace)			65C

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

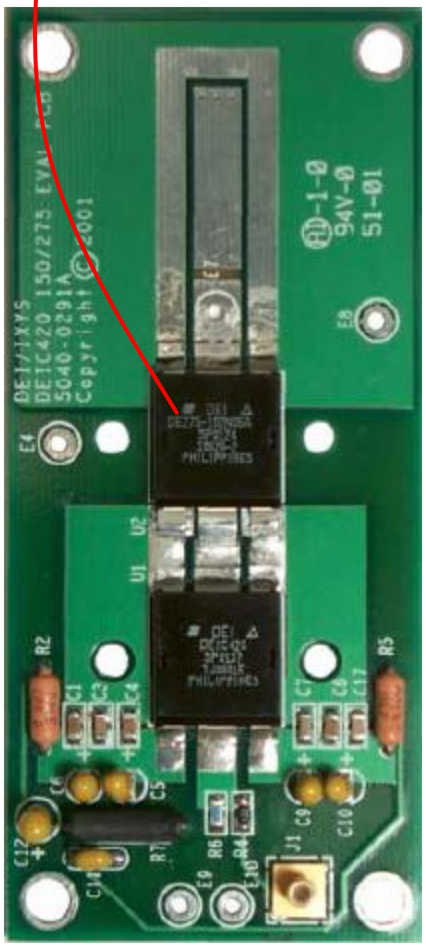
- Realized these could be used for notching in the 750 keV line:
  create a notch for booster kicker rise time
  (minimize losses)

- This effort was begun initially in collaboration with Doug Moehs
  (first attempt was chopping in the source)

Combining three DEI FETs

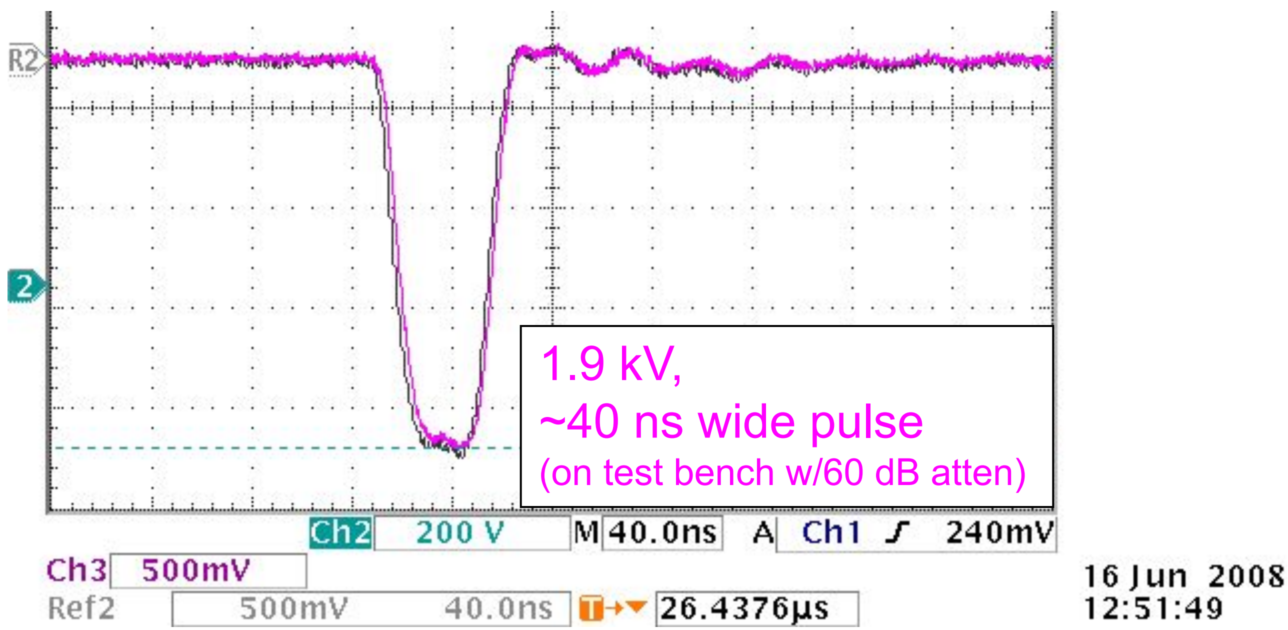
DE375-102N10A
RF Power MOSFET

V_{DSS}	=	1000 V
I_{D25}	=	10 A
$R_{DS(on)}$	=	1.2 Ω
P_{DC}	=	940 W



from DEI/IXYS RF

- Use the same scheme as HINS pulser, combining three ~1kV → 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*



Notching Plates in 750 keV line (H^-)

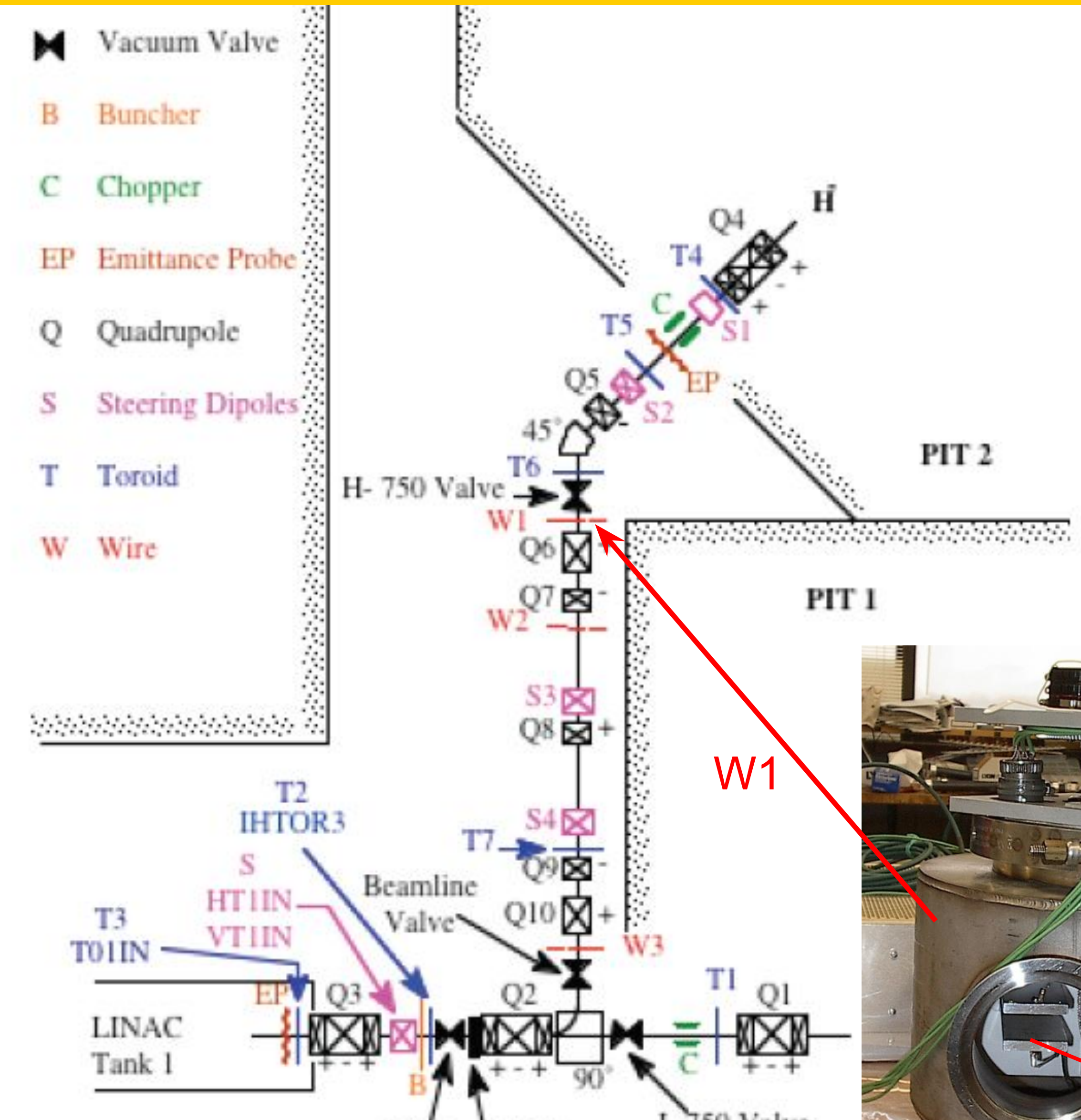
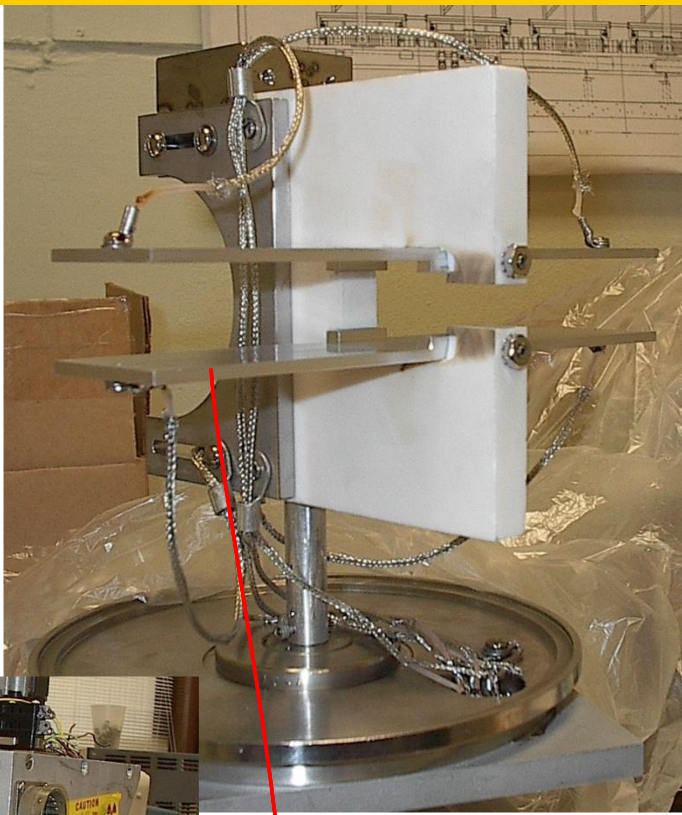


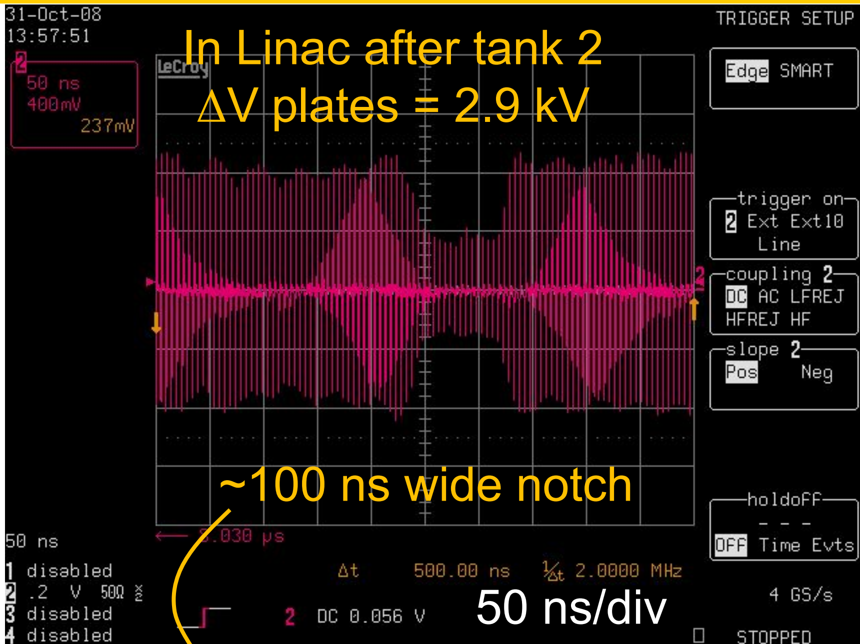
Fig. 3-1
750 KeV Transport
Line Layout

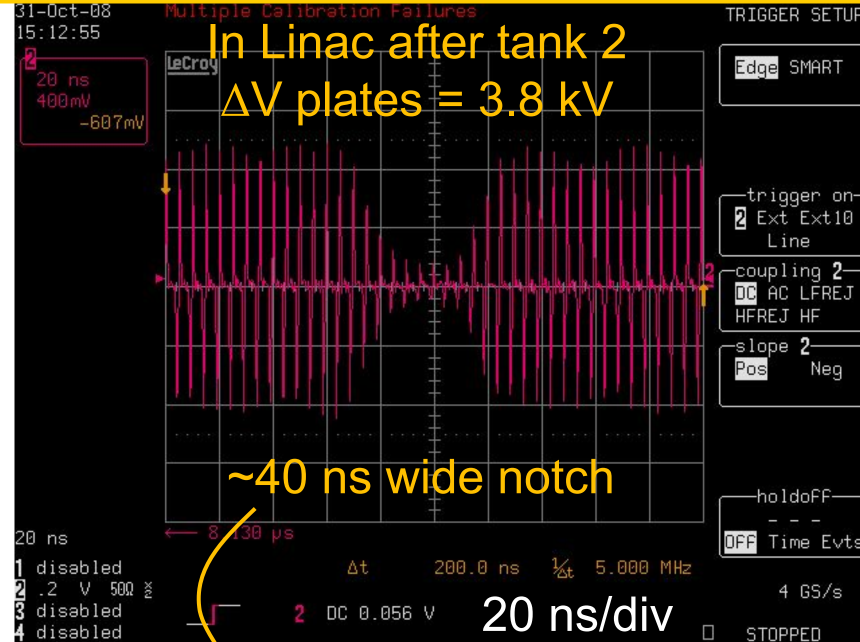
W1

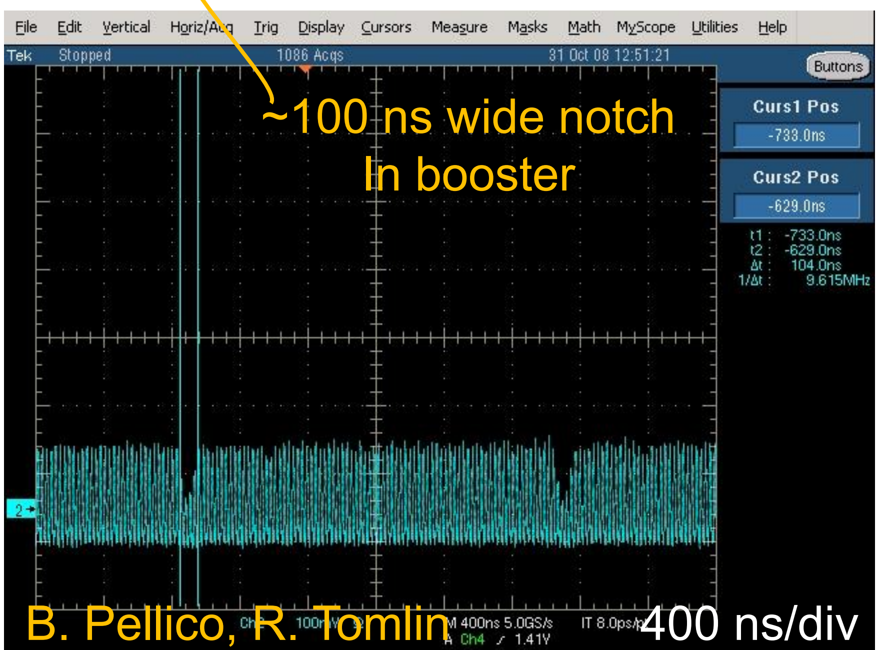


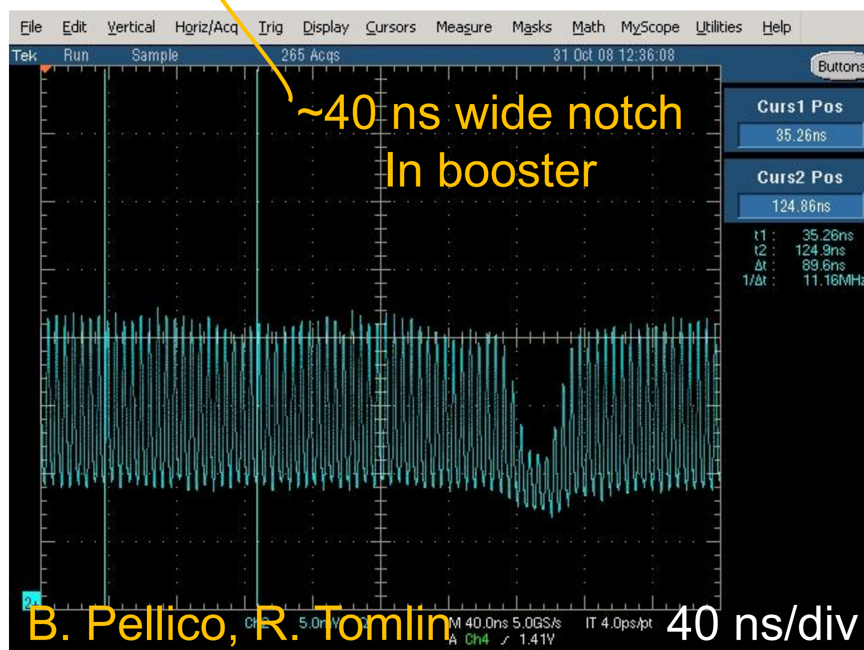
Plates: 0.9″ spacing

Notching Study



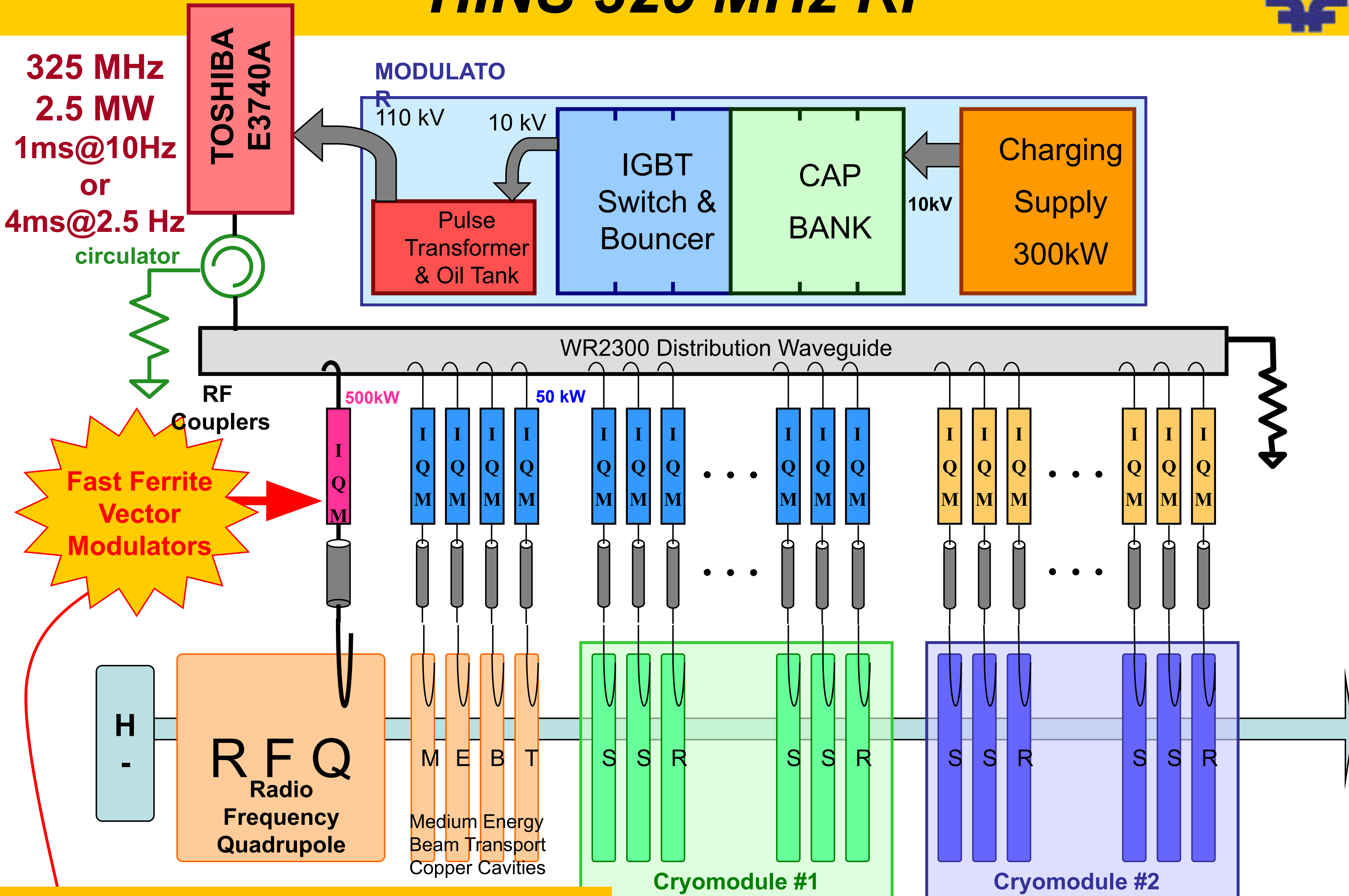






Part II – Vector Modulators

HINS 325 MHz RF



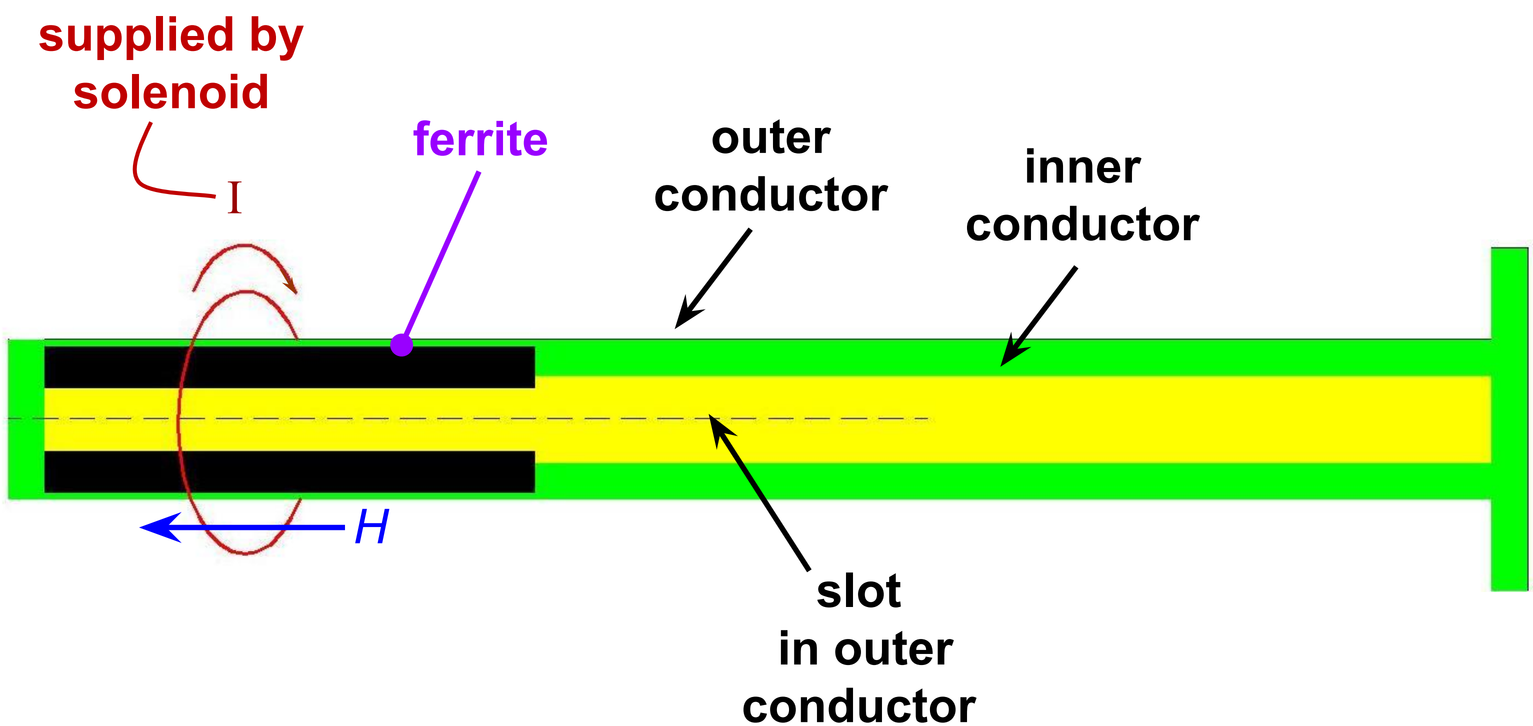
independent phase and amplitude control in each cavity

How it Works

In a coaxial line filled with some dielectric (ε,μ)

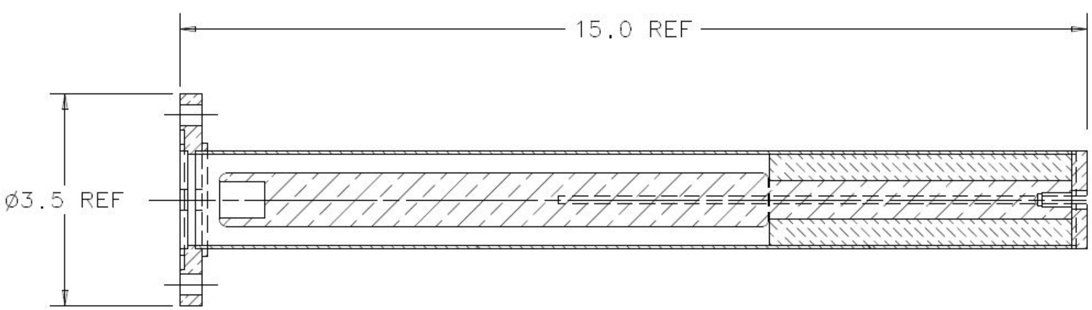
$v = c/\sqrt{\varepsilon\mu}$

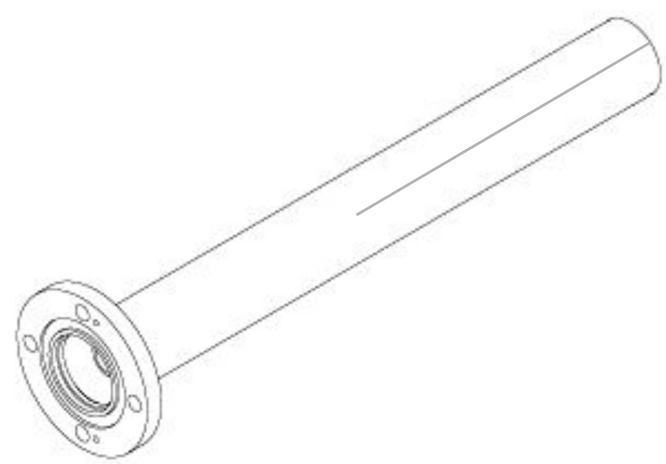
We vary μ and thus v and phase by varying H applied to the ferrite.



Fermilab’s Ferrite Phase Shifter

- *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 Al doped Yttrium Iron Garnet (YIG) – TCI Ceramics AL-400*
- *Required rate: 1º/μs*
- *Power Rating: ~50kW (Room Temp Cavities) or ~500kW (RFQ)*





Vector Modulator:

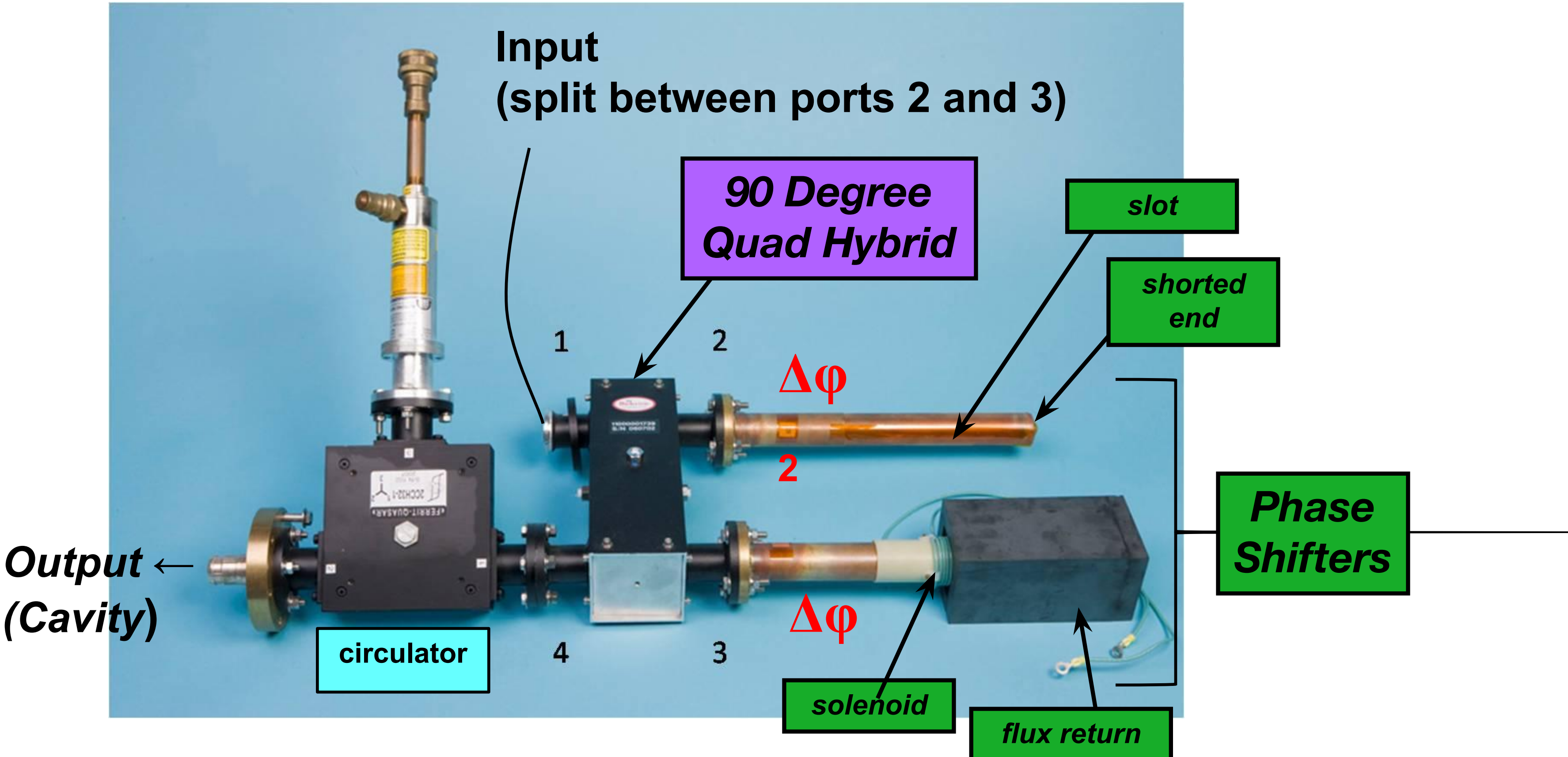
Modulates phase and amplitude independently:

With $\Delta\Phi = (\Delta\varphi_2 - \Delta\varphi_3)/2$

$\Phi = (\Delta\varphi_2 + \Delta\varphi_3)/2$

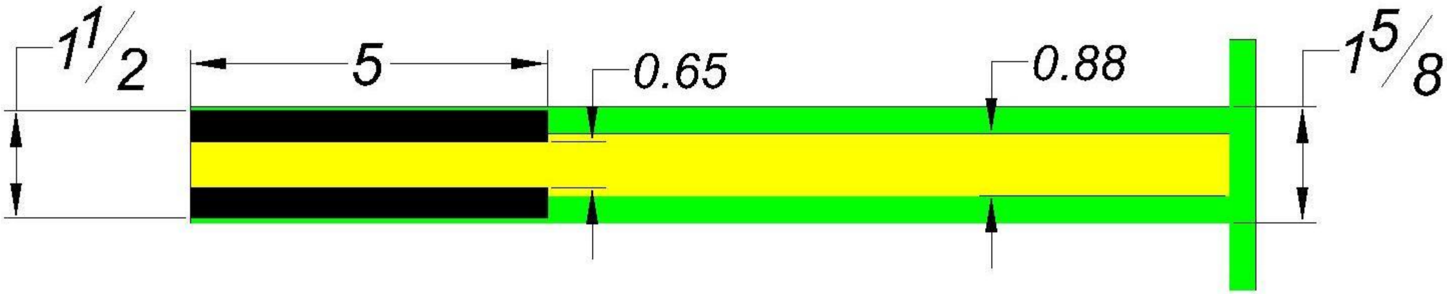
Output power ~ $\cos^2(\Delta\Phi)$

Phase shift ~ $\Phi + 3\Pi/2$

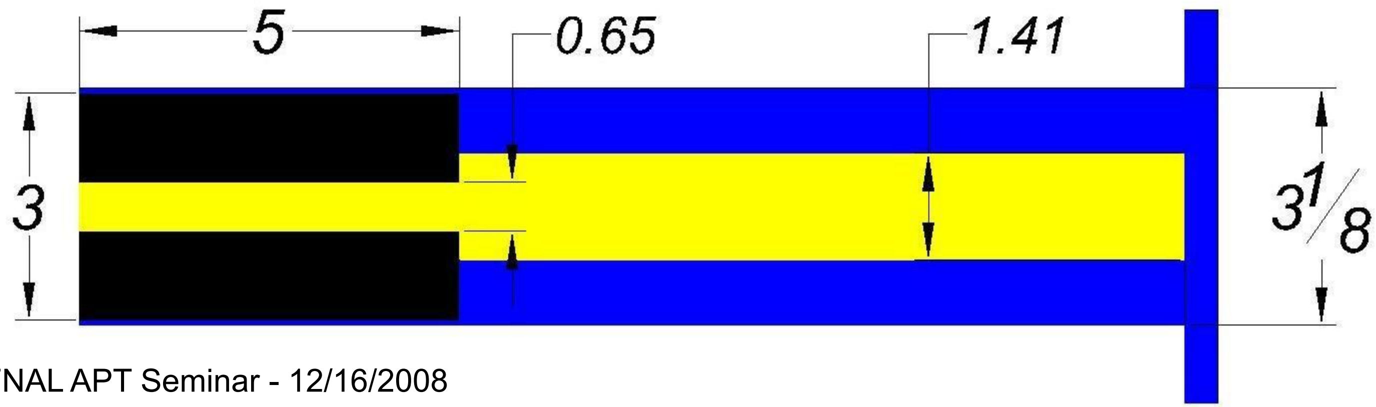


Two Phase Shifter Types

- ***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

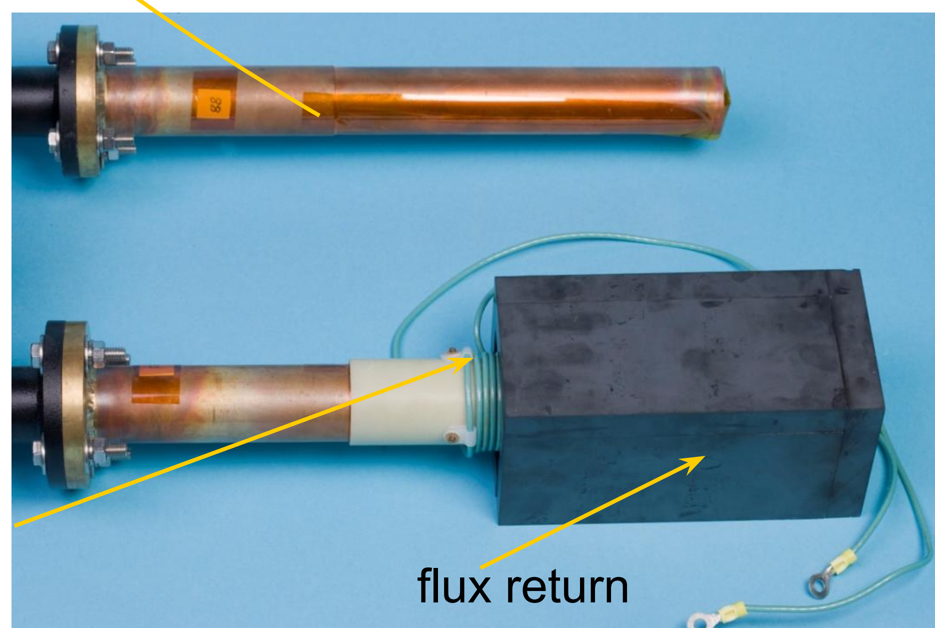


Shifter Design Details

- 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)



solenoid
(12 awg wire around G10)

Other VM Parts

hybrid for 1⅝ vm: Dielectric

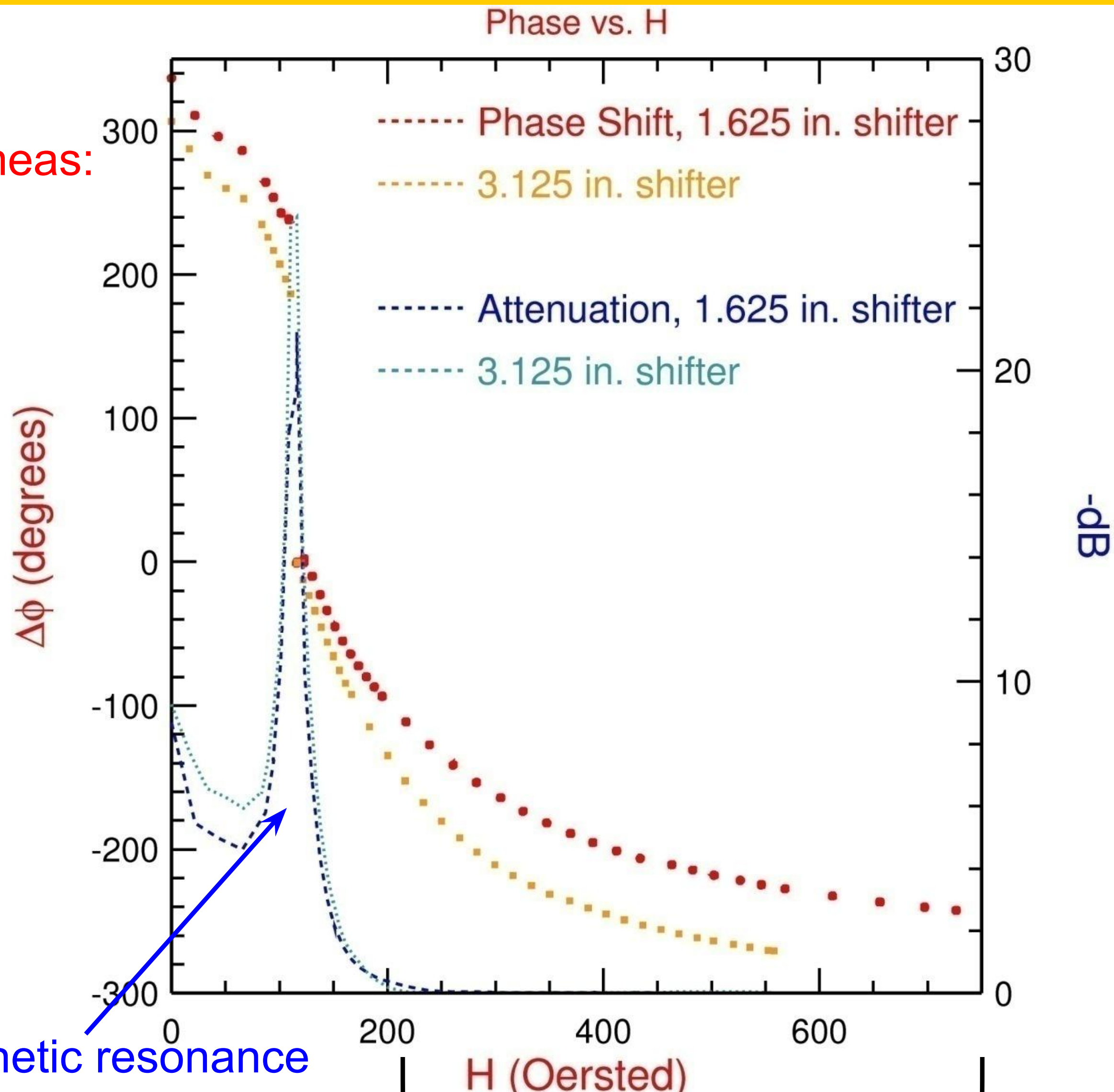
circulator for 1⅝ vm:
Ferrit-Quasar

circulator load:
5kw CW
water cooled
Altronics

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

Phase vs. Applied Field

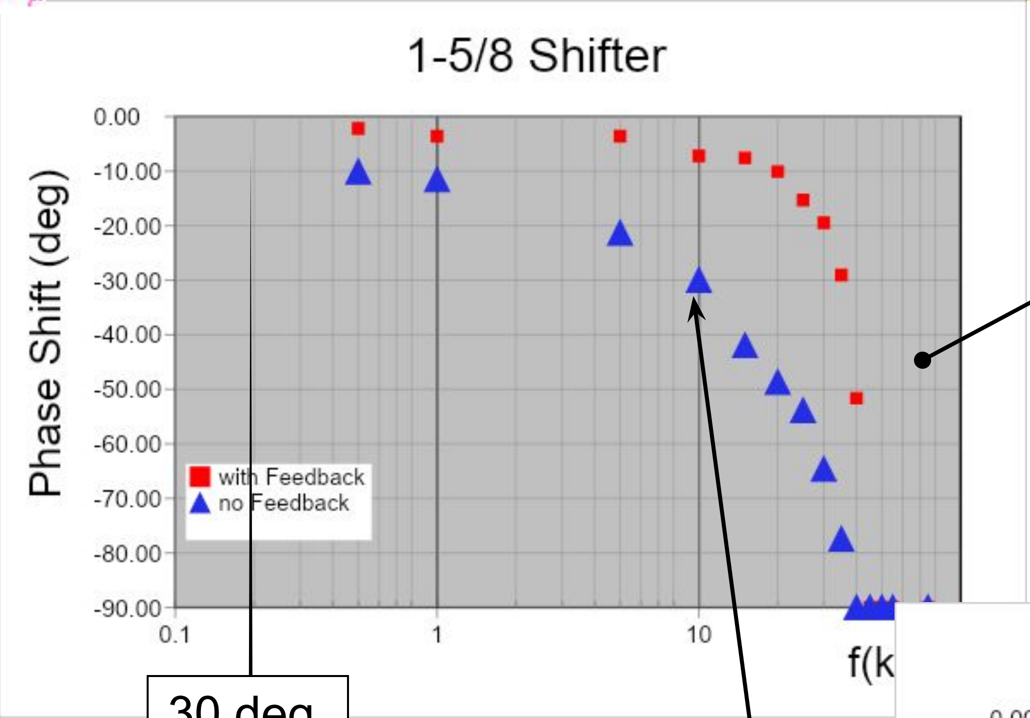
325 MHz
Low Power meas:



Gyromagnetic resonance (lossy) @ 2.8 MHz/Oe

useful phase shift range ~120 deg. (loss < -0.2 dB)

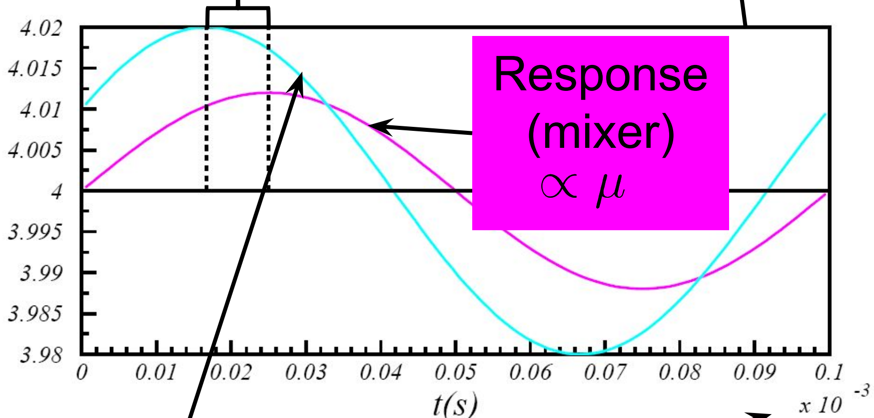
Small Signal Frequency Response



Open loop bandwidth: 15 kHz

- ***> 35 kHz w/feedback***

30 deg.

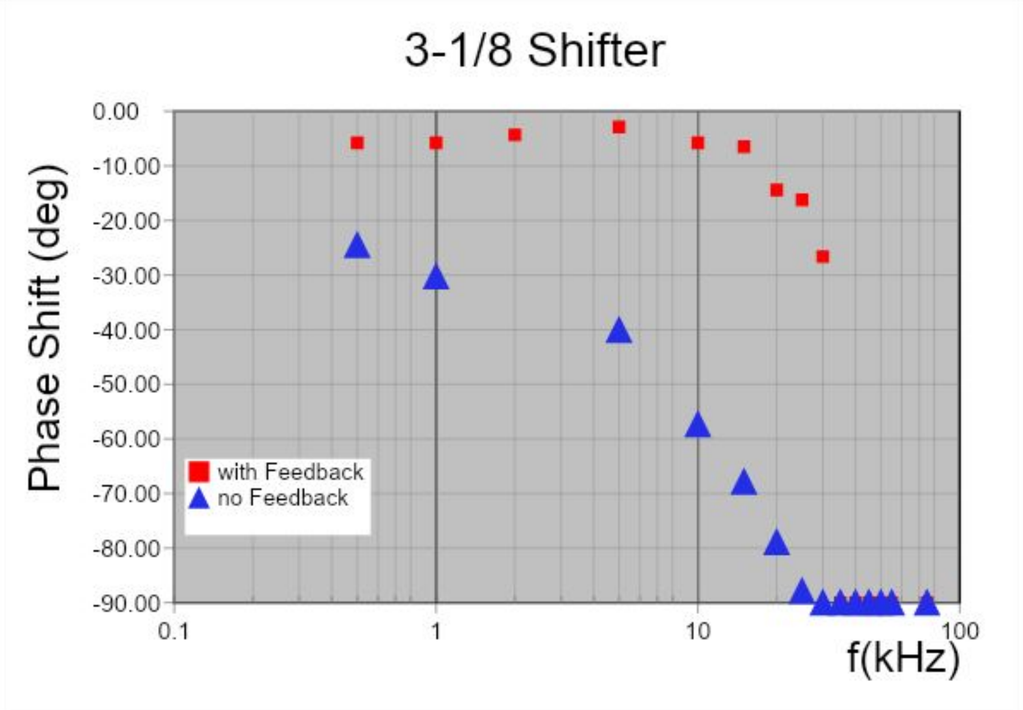


Response (mixer) $\propto \mu$

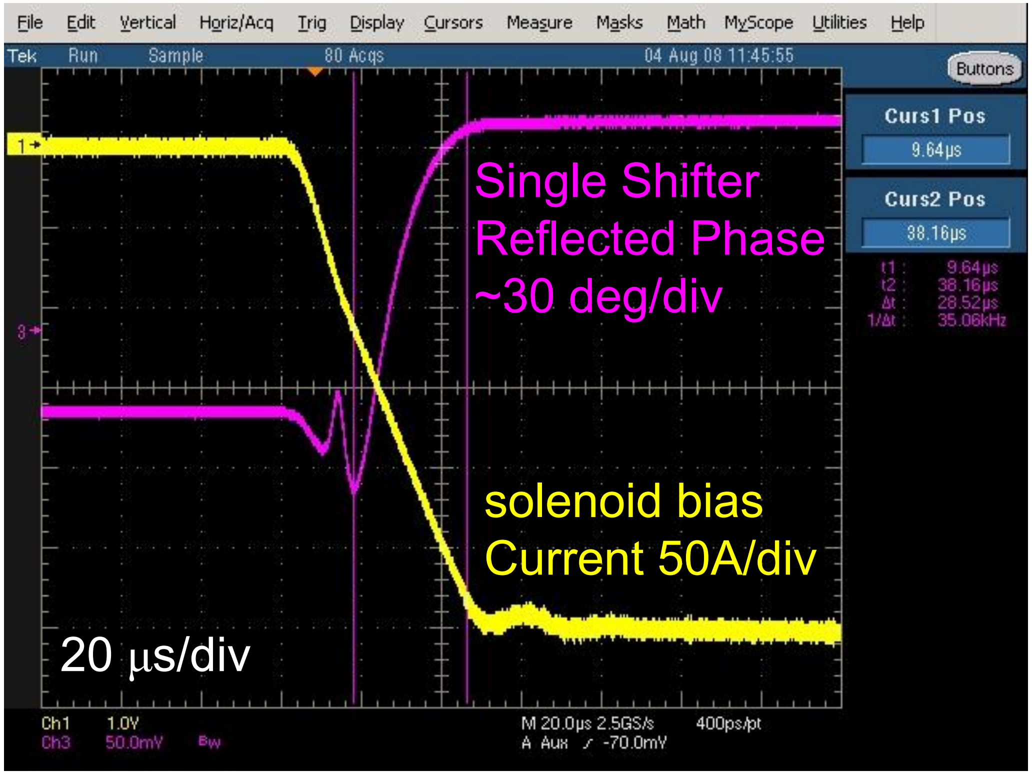
solenoid I

<u>Program, 10 kHz</u>

0.1 ms



Slew Rate

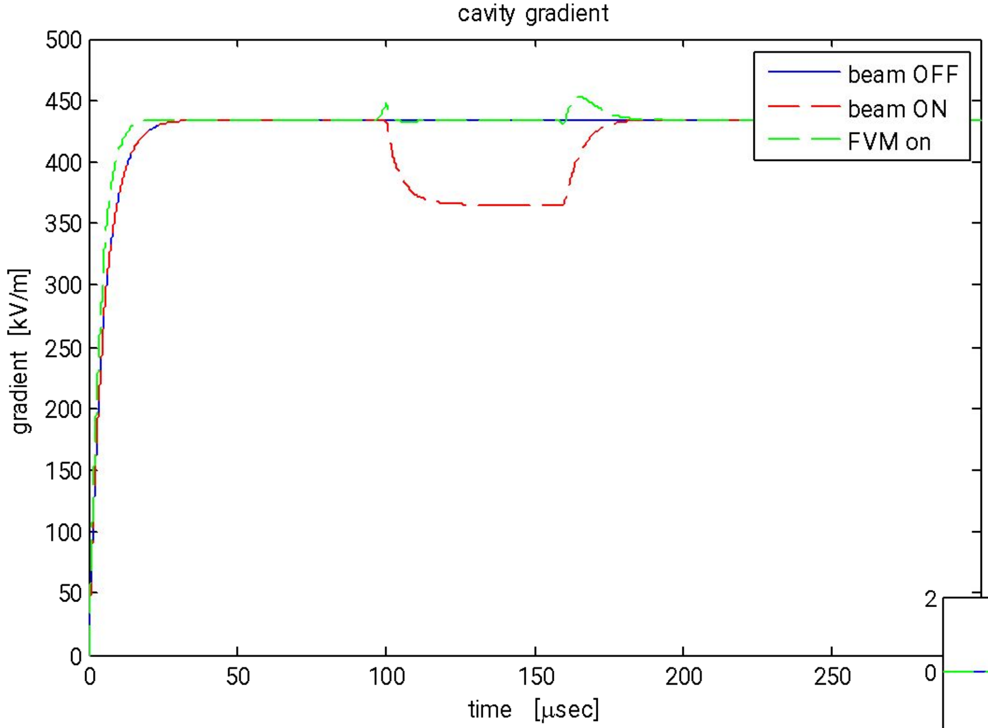


Phase Shifter Slew Rate:
(above resonance)
6 deg/µs

Current risetime limited by supply output, solenoid inductance

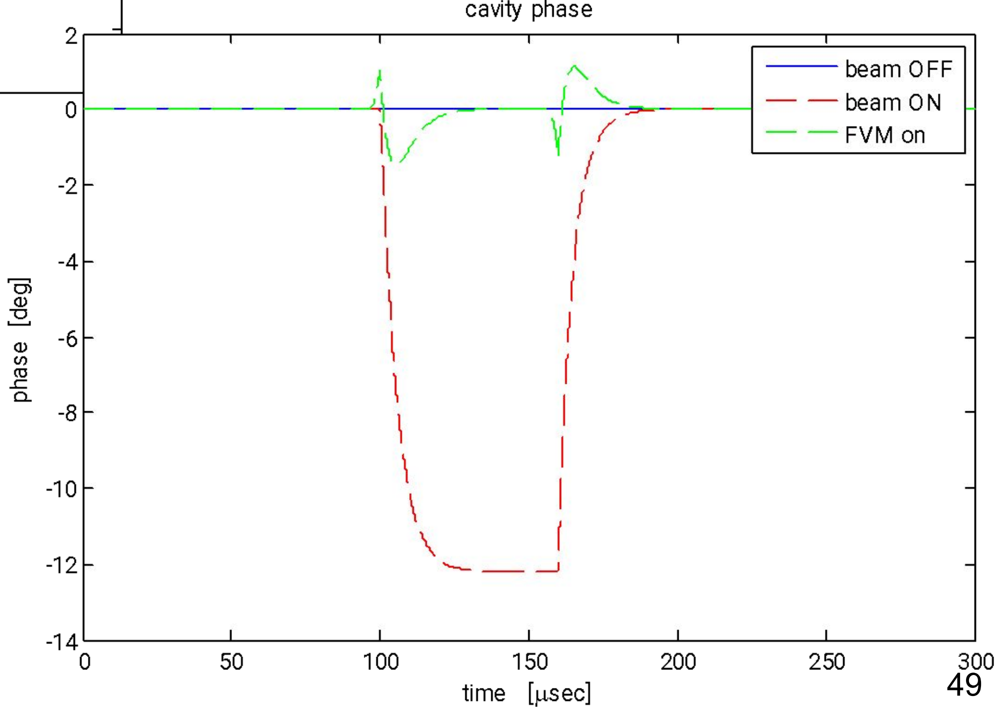
Fast 300A power supply thanks to Brad Claypool, Steve Hays, Howie Pfeffer

Beam Loading - Simulation



Results courtesy
Julien Branlard

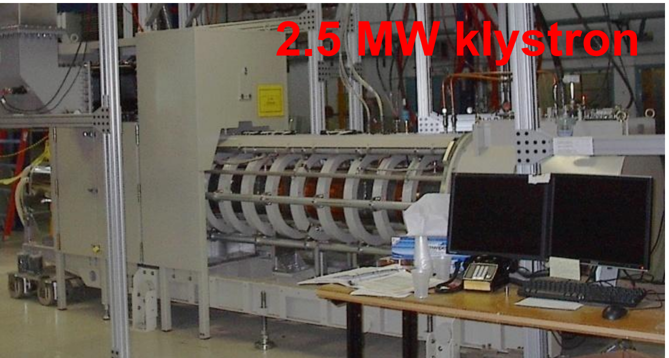
Cavity 6

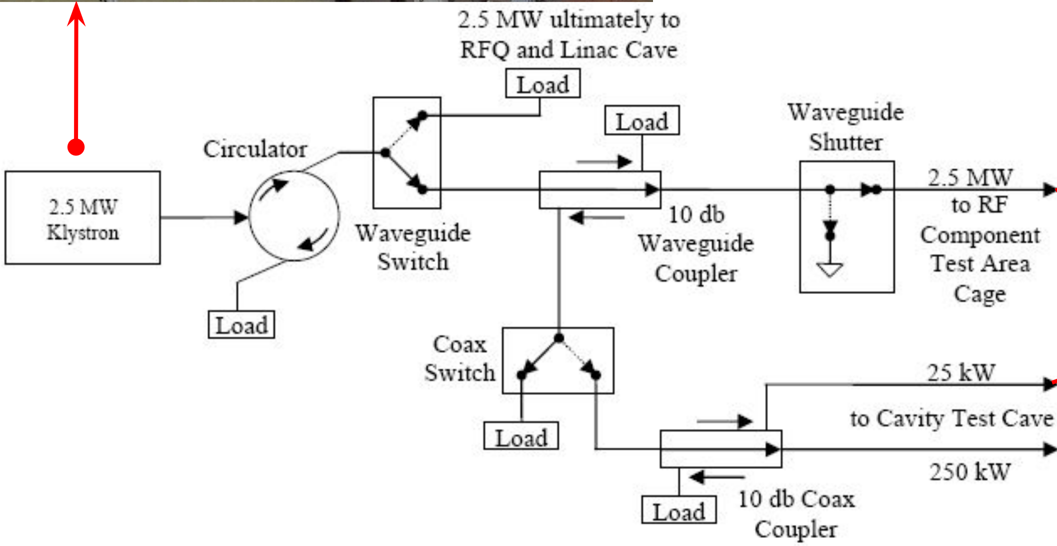


Starting and stopping the compensation 4 usec prior to beam arrival time

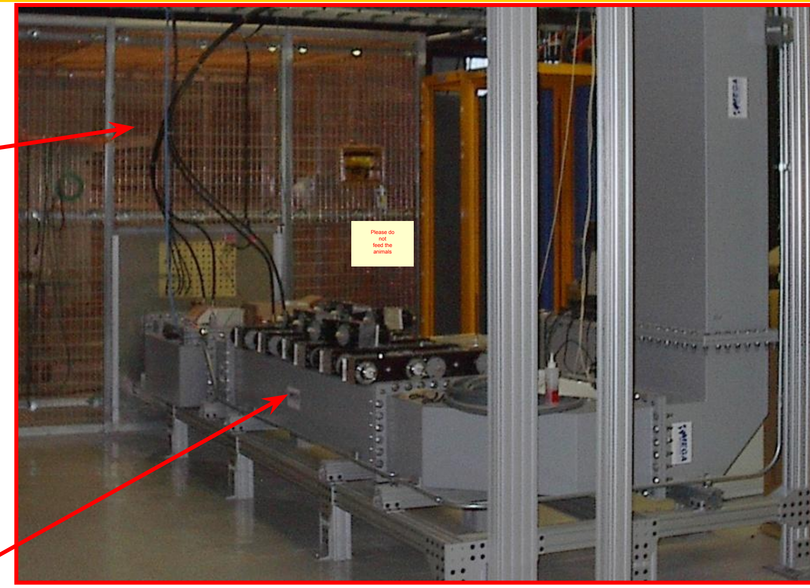
Beam current 26 mA
phiS = -45 deg

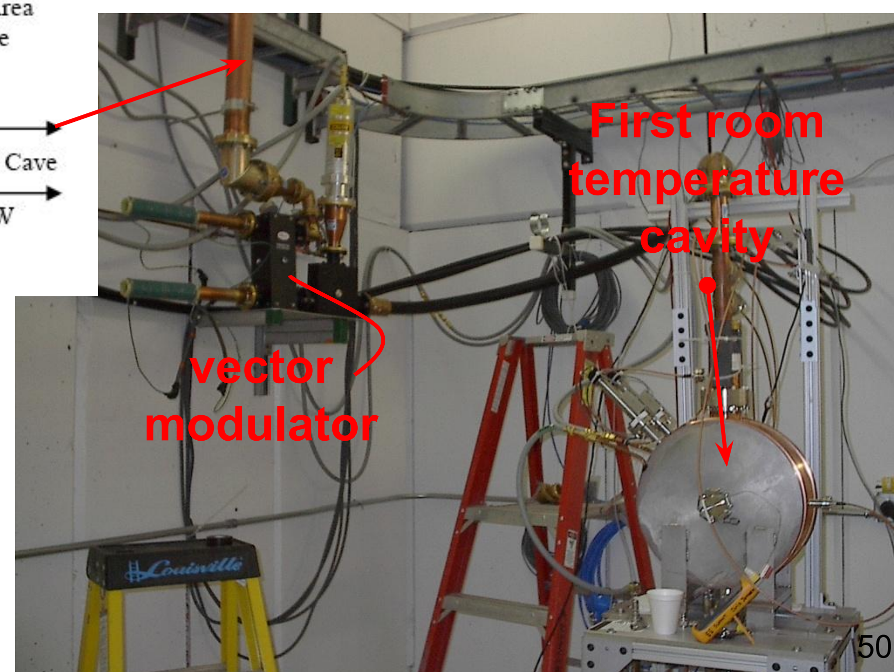
Meson Building Test Facilities



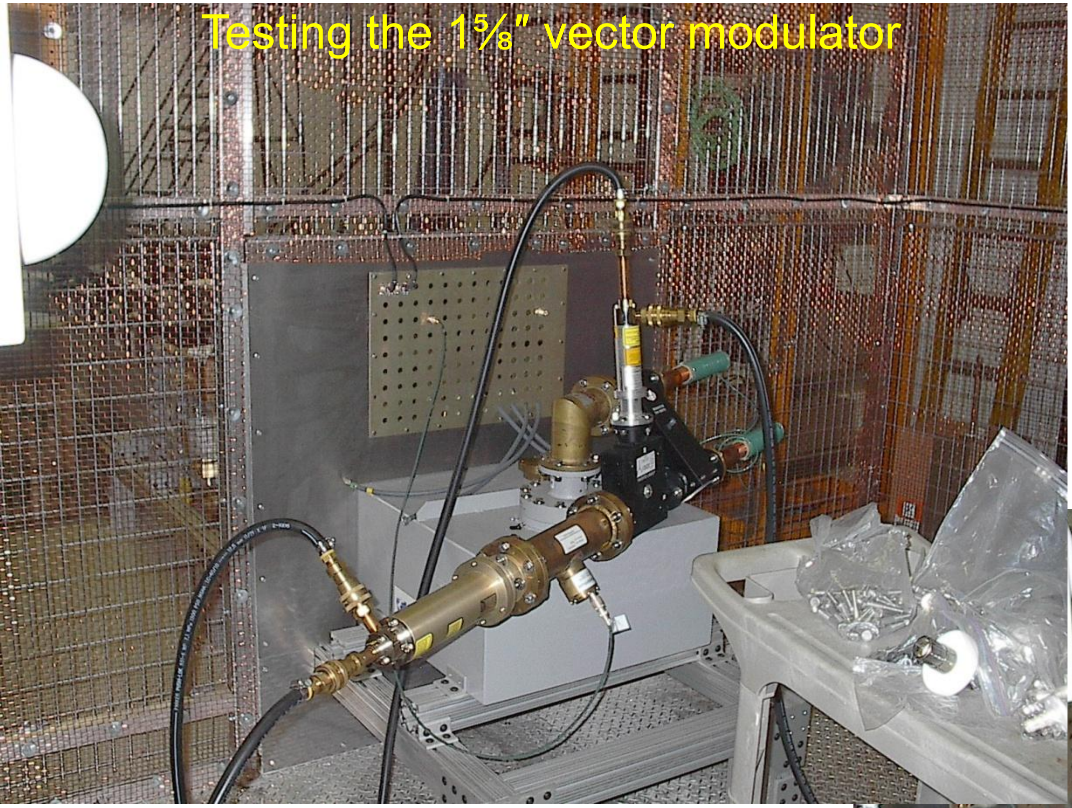


325 MHz
RF Test Cage





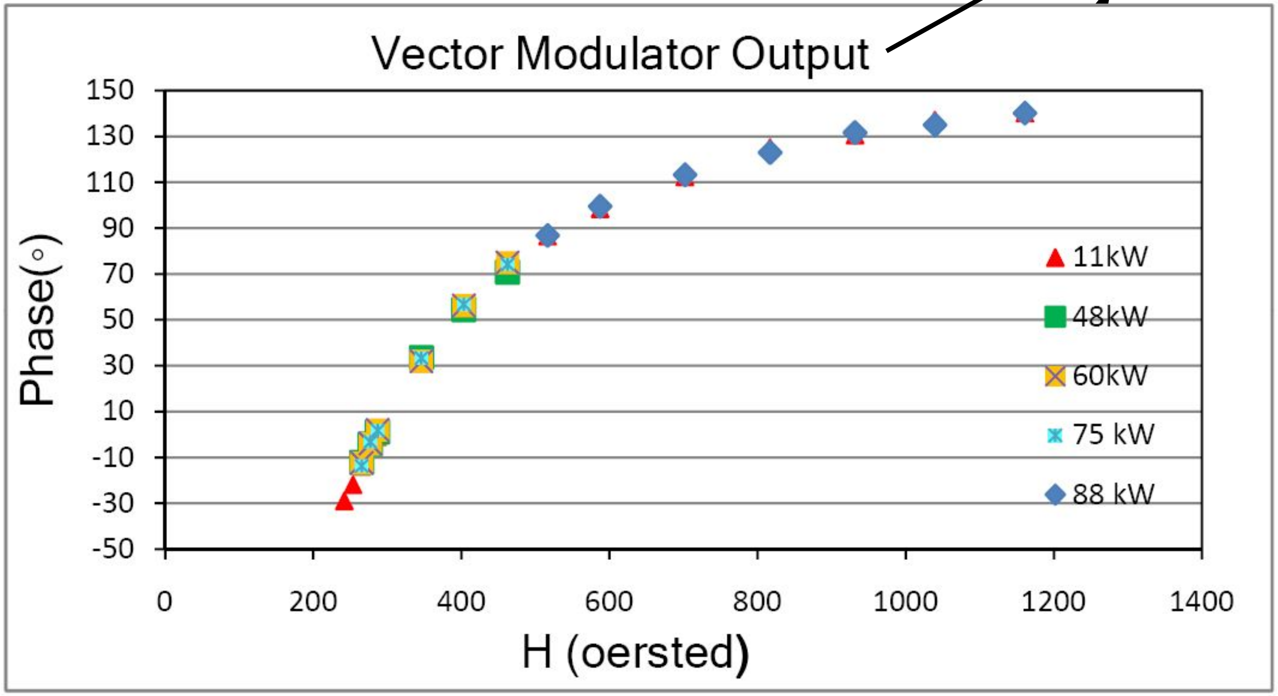
Meson Building Test Facilities



Power Capabilities

here, both shifters' solenoids driven by one power supply
$(\Delta\varphi_1 = \Delta\varphi_2)$

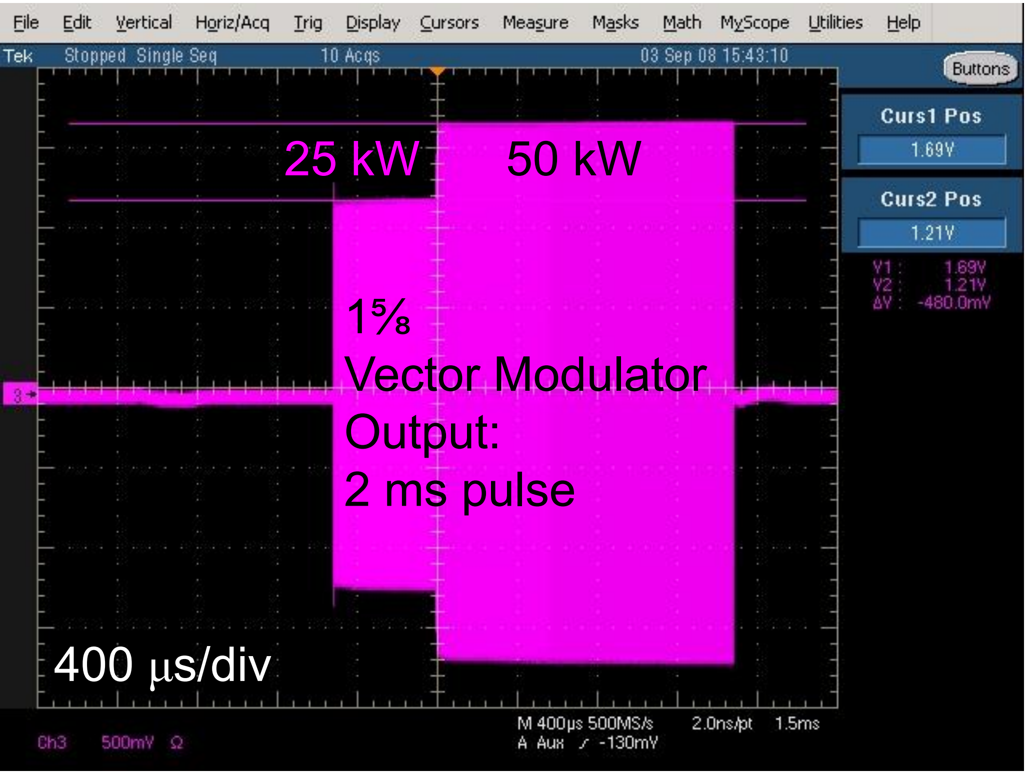
phase ~ $(\Delta\varphi_1 + \Delta\varphi_2)/2$



Power Capabilities

1⅝ 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 1⅝" 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)"

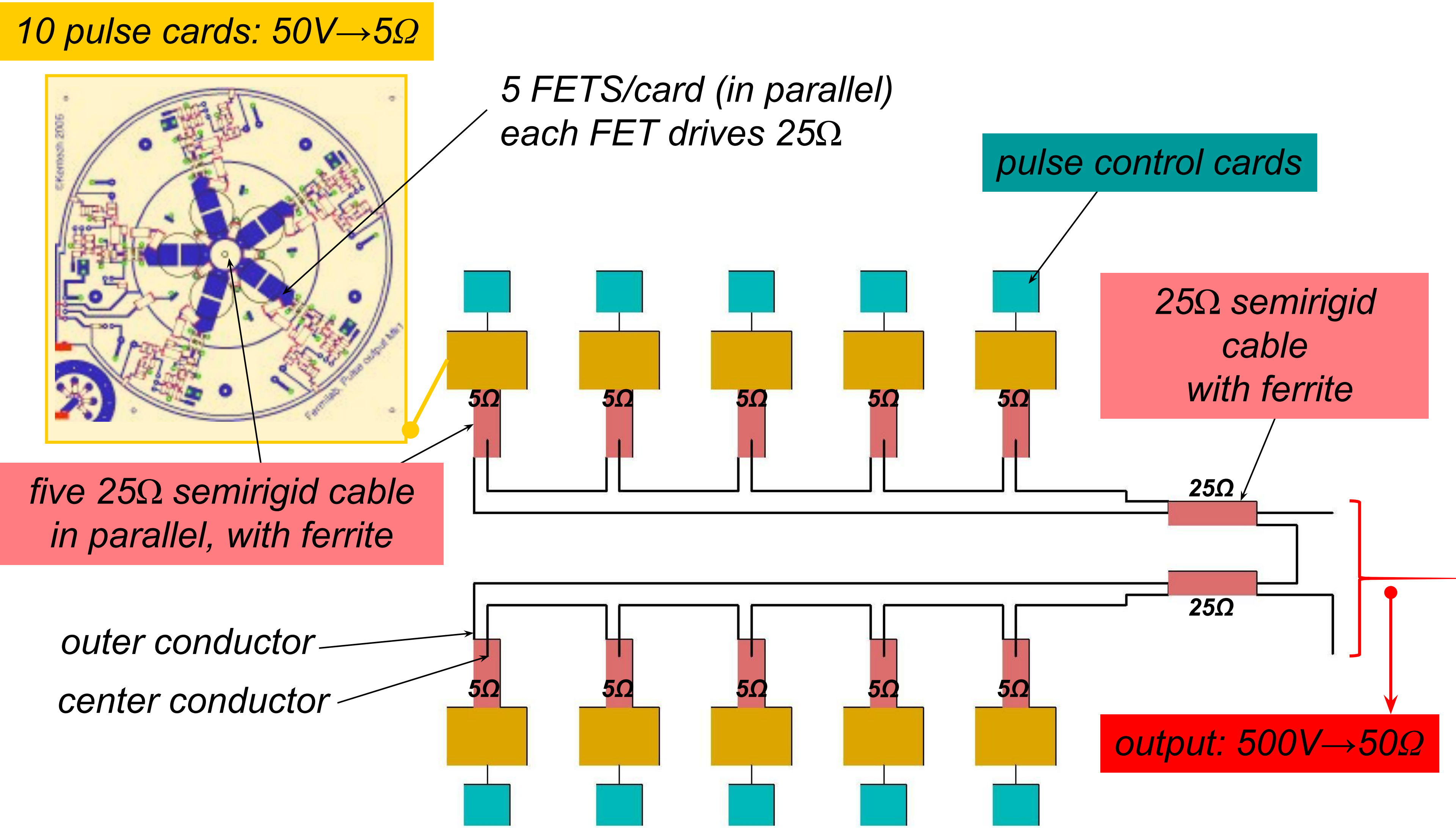
Conclusions

- ***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***

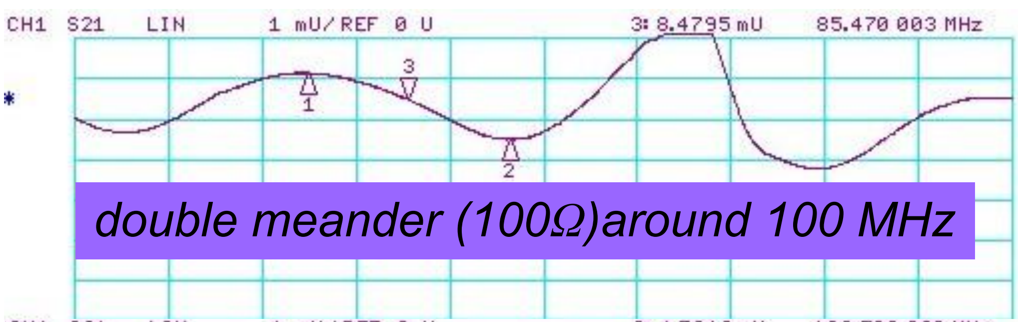
Backup Slides

Kentech 500V Prototype Pulser Scheme

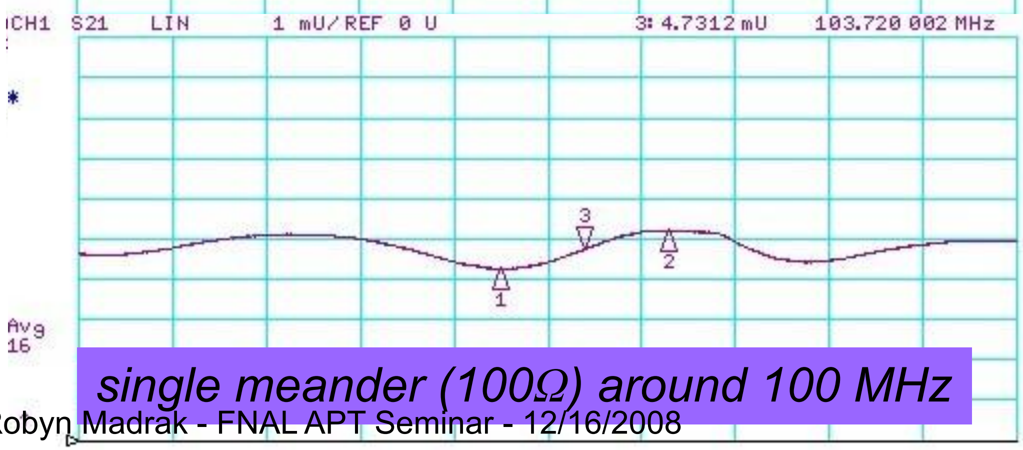


Coverage Factor, Meanders

single meander signal to 500 MHz



double meander (100Ω)around 100 MHz



single meander (100Ω) around 100 MHz

Which gives:*

type	c
double	87%
Single 1	48%

**Relative to normalization measurement;*
After correcting for impedance difference and reflected power

Heating in Meander

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

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

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

Estimate I factor for RF losses @ 100 MHz(skin depth): 2.6 in/√f = 6.6 μm

Skin depth factor = 35μm/6.6μm = 5.3

$(24A)^2 \times \frac{1}{3} \times 5.3 = I^2_{test} \Rightarrow I_{test} = 32\ A$

actual pulsed current — chopping DF — Skin depth factor

- Or -

- Measure power spectrum of pulses; normalize to $(2.4kV)^2/100\ \Omega \times \frac{1}{3} \times 0.01 = 192W$

low power, spectrum analyzer

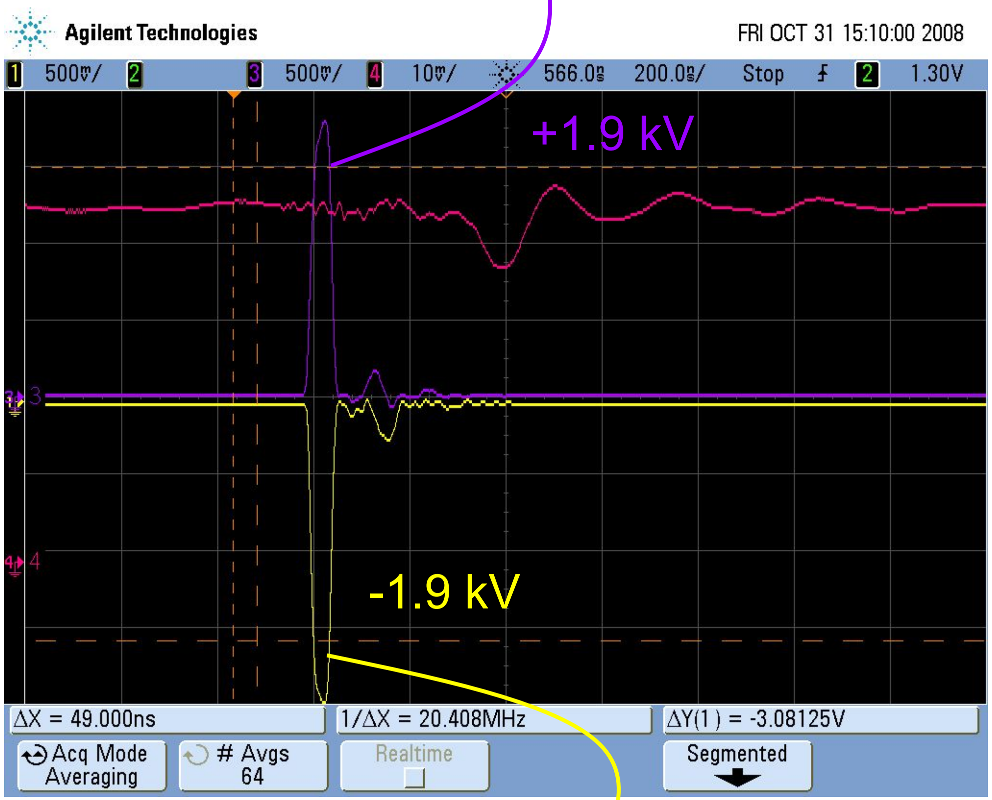
actual pulsed power — chopping DF — DF (1ms @ 10Hz)

- Convolute with S_{21} thru meander; this give Pdiss = 46 W
- $I^2_{test} \times DF_{test} \times 2.7\ \Omega = 46W \Rightarrow I_{test} = 41\ A$

⇒ With safety factor, test at 50 A

Notching Study

+ pulse → top plate → 60 dB → scope 50 ohms

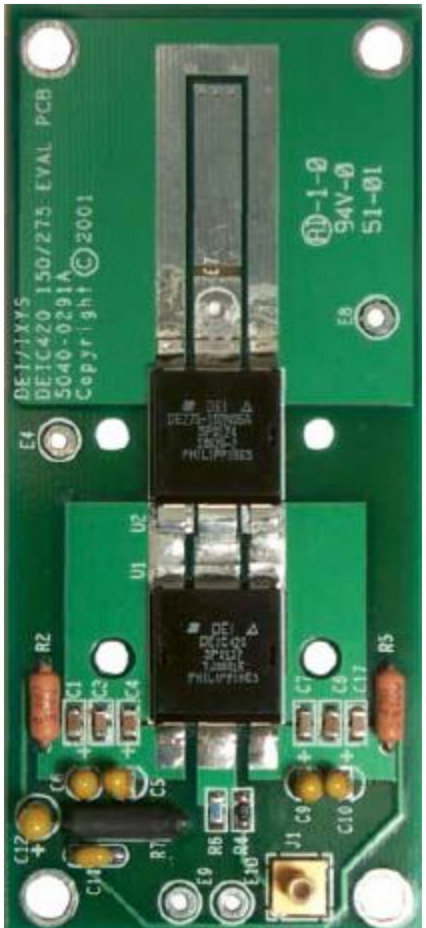


- pulse → bottom plate → 60 dB → scope 50 ohms

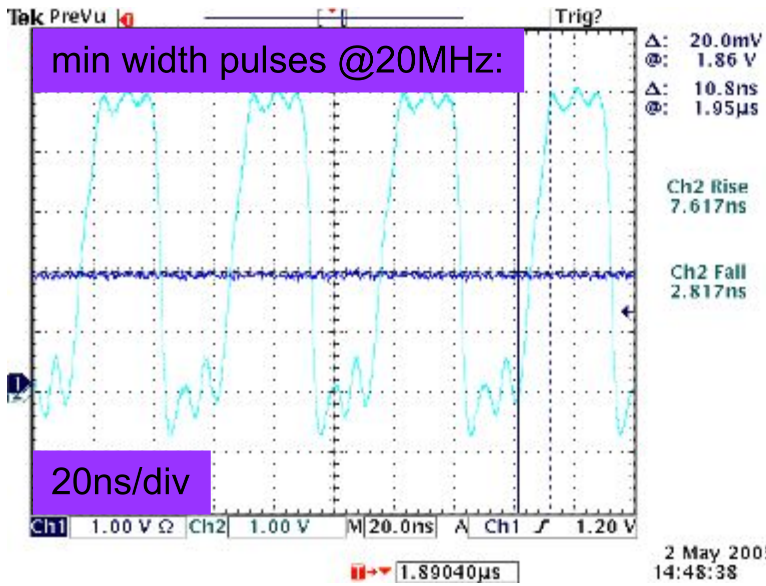
Using one or two single power switches:

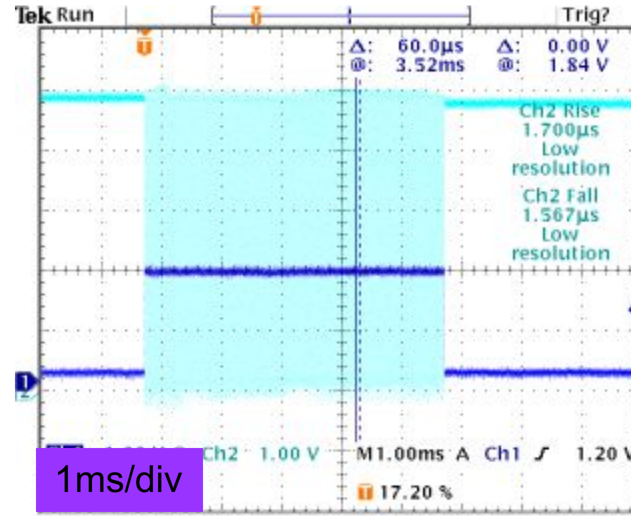
DE375-102N10A
RF Power MOSFET

V_{DSS}	=	1000 V
I_{D25}	=	10 A
$R_{DS(on)}$	=	1.2 Ω
P_{DC}	=	940 W



from DEI/IXYS RF

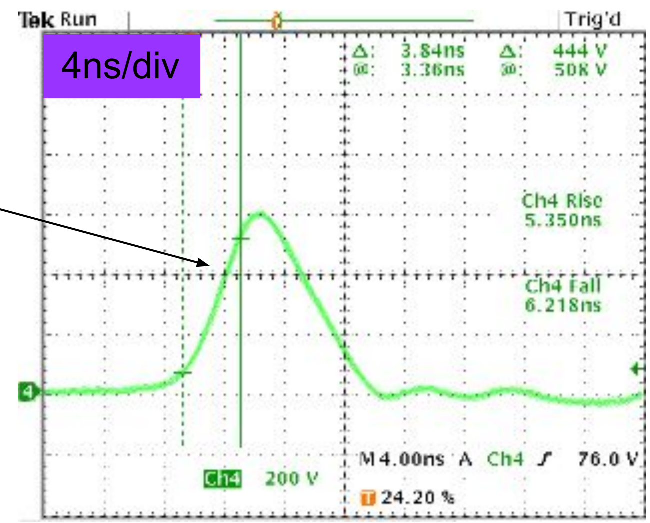




→ *cannot get to a narrow enough pulse …*

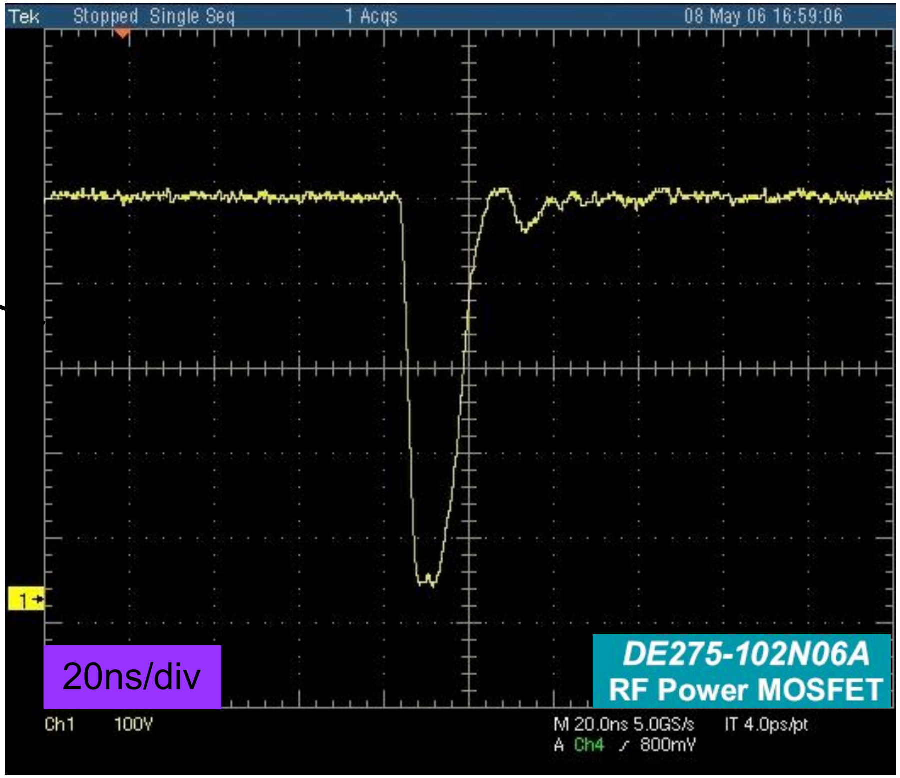
With two switches:

Pulses are narrower, but
Still not narrow enough



Using one or two single power switches:

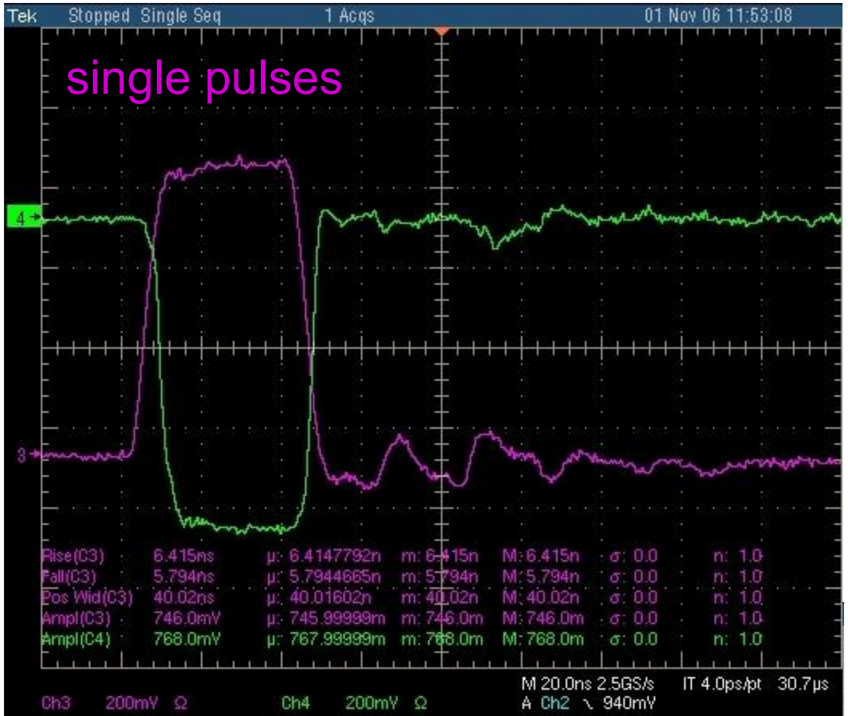
With a slightly lower current version of the switch:

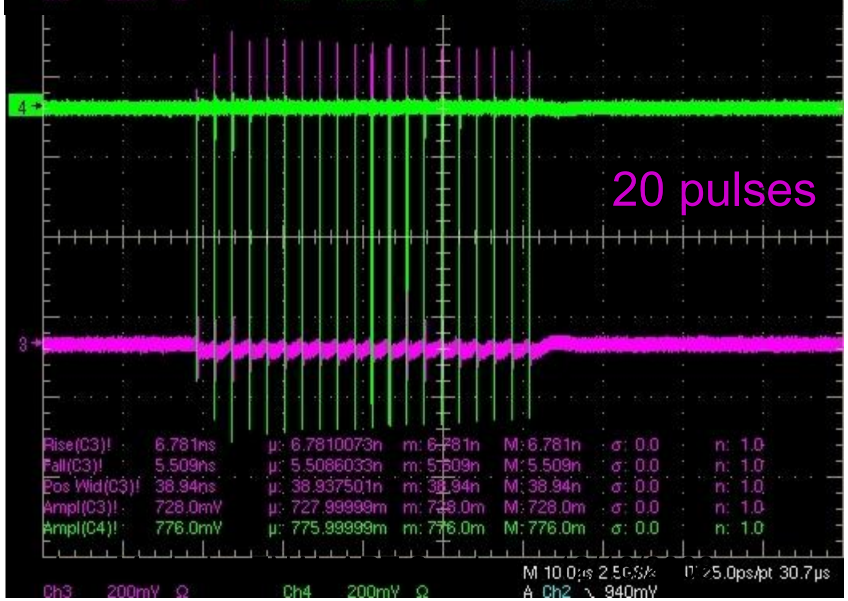


- The DEI FETS *can* be used to make a very narrow pulse by charging cable in the drain

- 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*