Bench Test Results of a Helical Microstrip Line Chopper

Project X Technical Meeting
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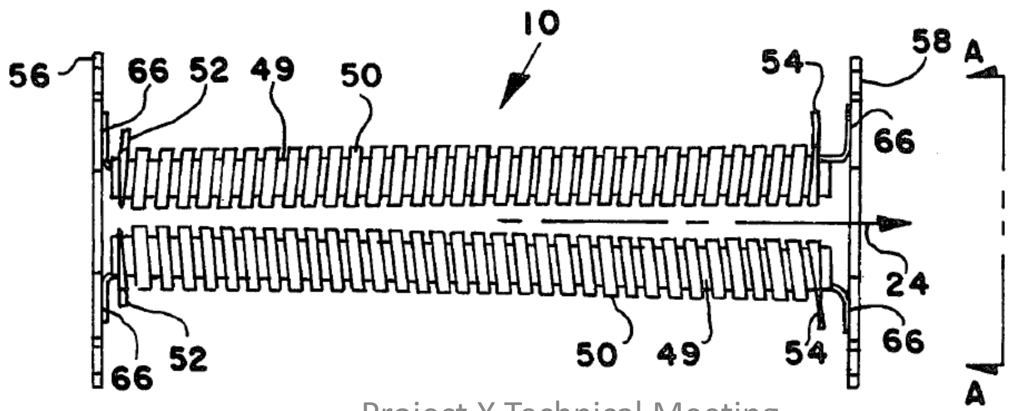
Topics to be discussed

- Measurement results of two Helical Chopper prototypes
- Design issues related to power dissipation of this high rep rate and duty factor chopper
    - In the driver circuit
    - The resistive termination of any traveling wave type deflector

Other helical deflectors

- Main motivation of this effort was to examine the virtues of previously built traveling wave helical type electrostatic deflectors
- LAMPF 750 KeV proton injector traveling wave deflector (1975)
  - Dual rectangular helix 1 meter long
  - 5 ns pulse width
  - Prototyped and tested, but never installed. (Allegedly something “similar” was installed)
- Tektronix 1 GHz analog bandwidth oscilloscope, model 7104
  - Helical strips for both vertical and horizontal electrostatic deflection.
  - Driven differentially, having 3 GHz bandwidth



Design parameters and tests performed

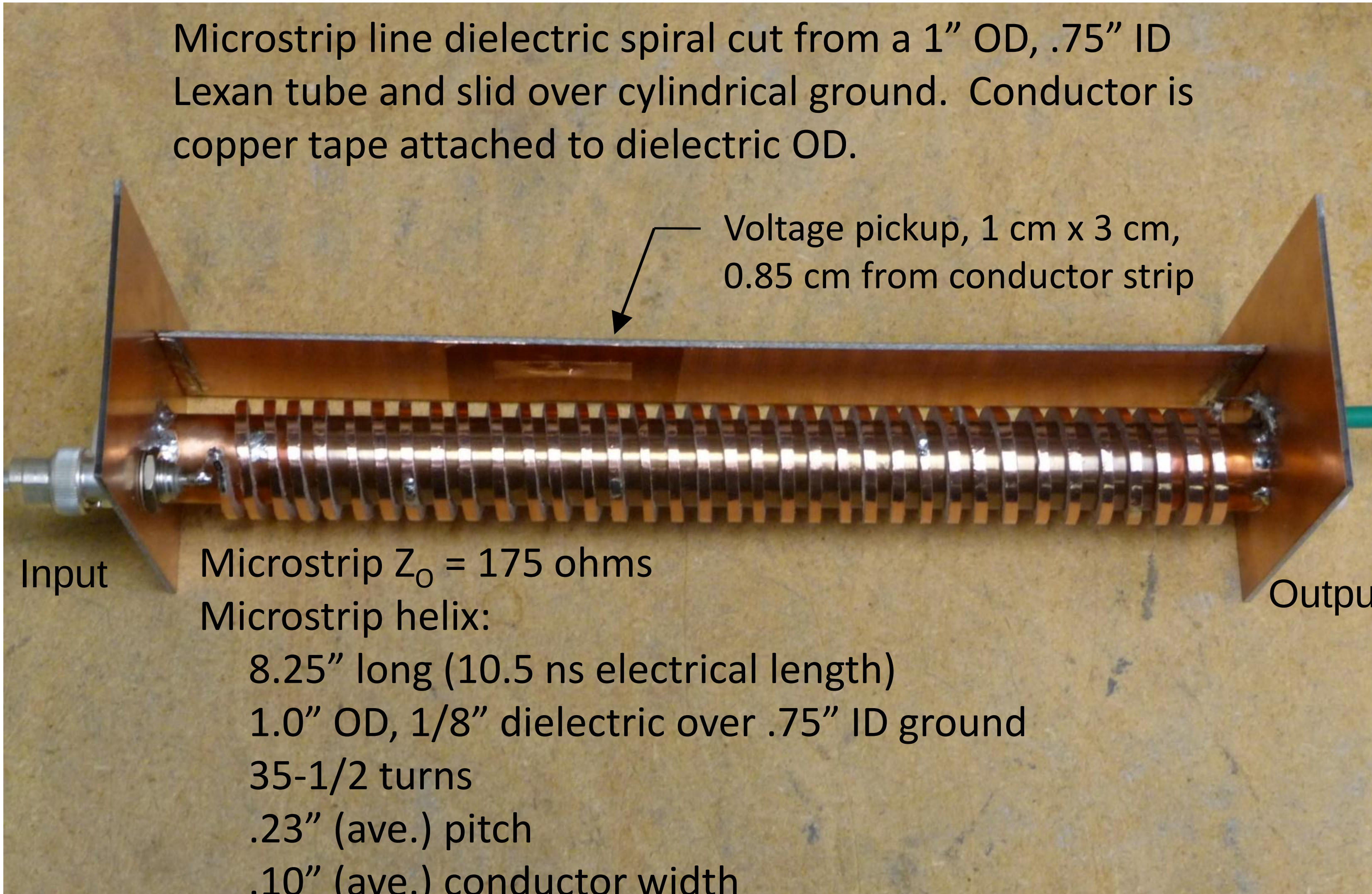
- Chopper parameters
  - two microstrip helixes on opposite sides of the beam
  - The two helixes are driven differentially and terminated into their characteristic impedance
  - The characteristic impedance approaching 300 Ohms
  - The traveling wave pulse velocity is matched to beam beta 0.073
- Helical pitch is

$$pitch = .073 * cir * c / v$$

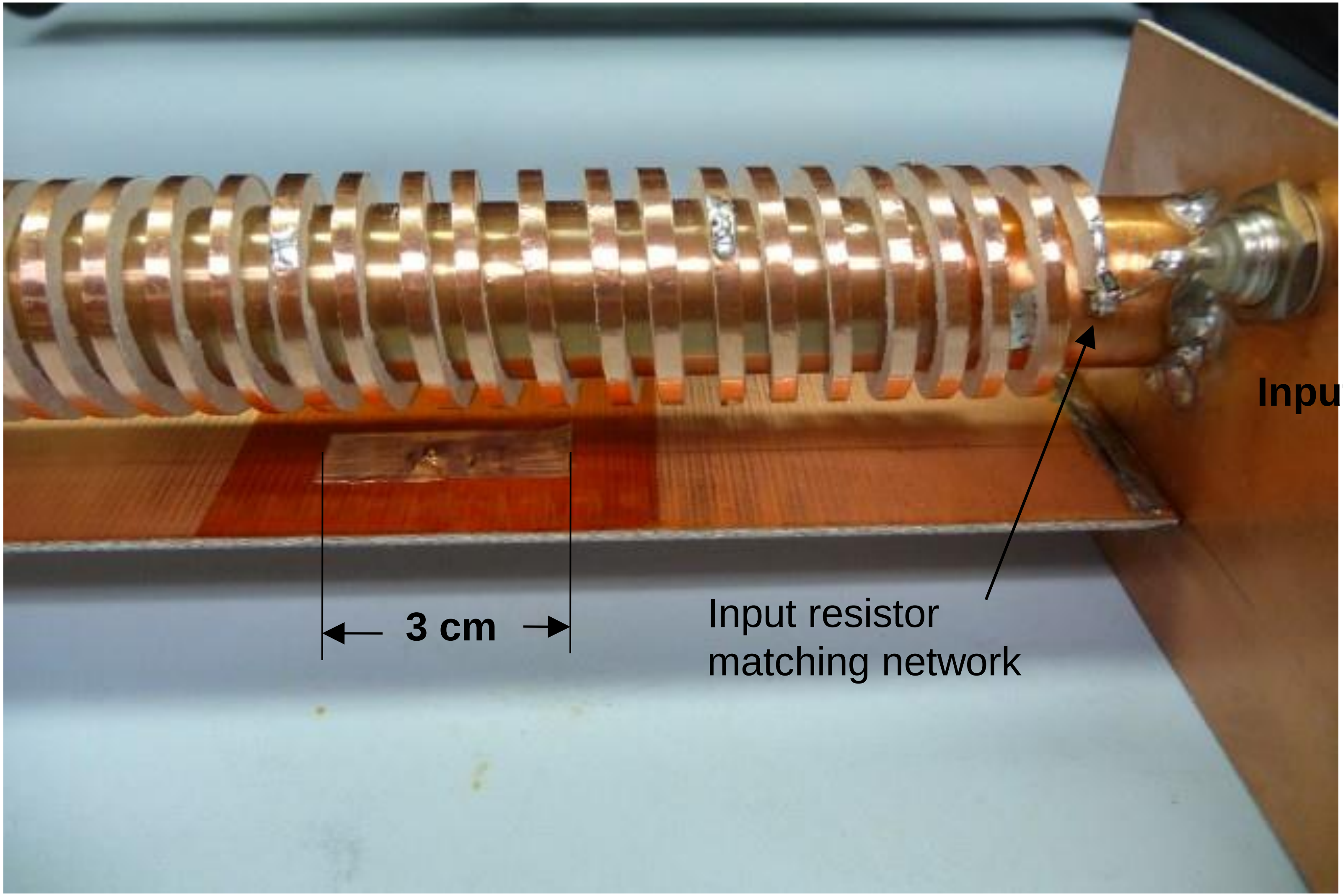
Where: cir is conductor circumference,
c is speed of light,
v is strip line propagation speed

- Tests performed
  - TDR measured characteristic impedance and electrical length
  - Evaluate the strip line output signal (through-voltage) for
    - Ripple/overshoot
    - Rise time
  - Determine the E-field "fill factor" of the helical geometry

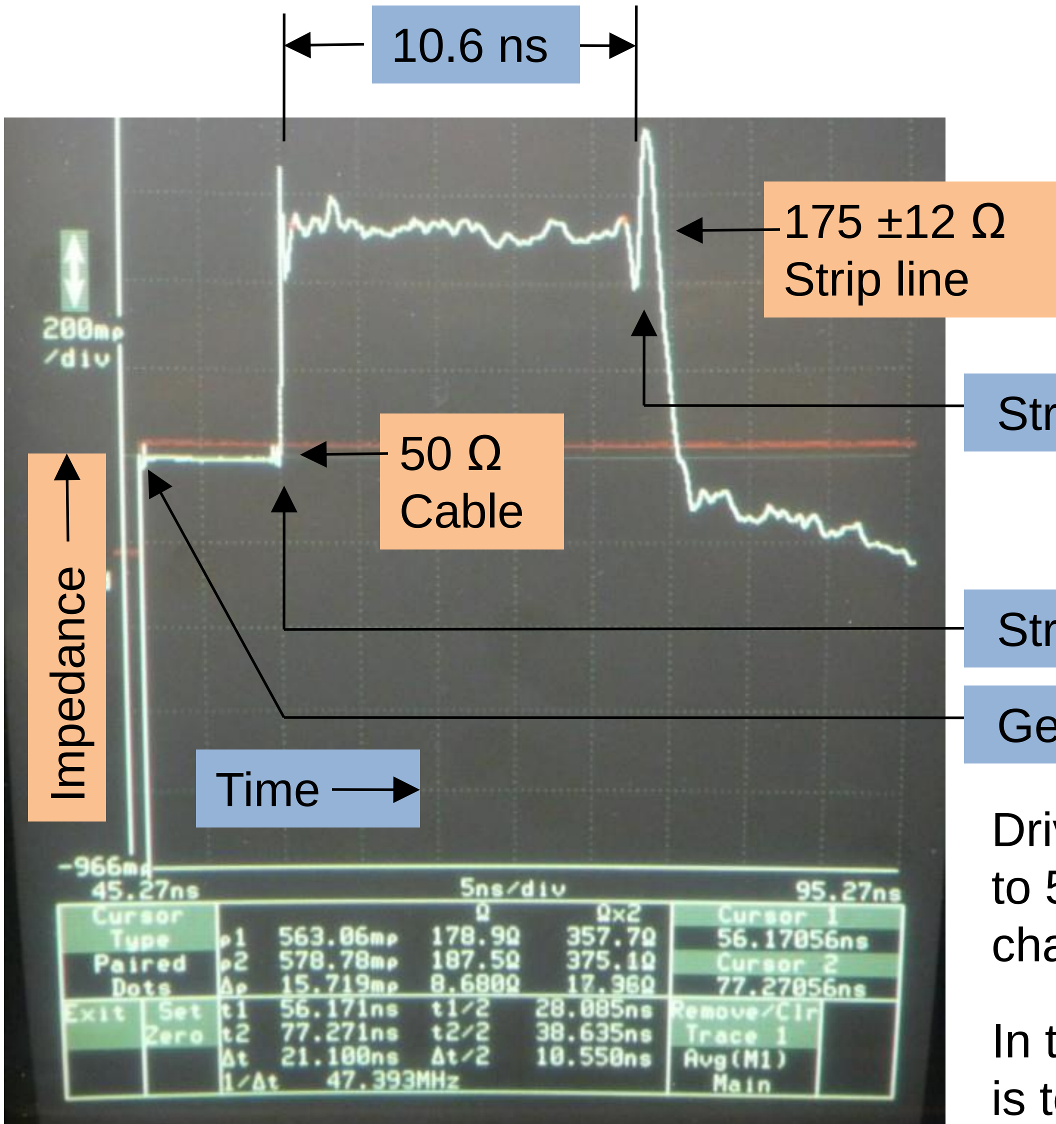
First prototype: 21 cm helical microstrip line



Zoomed in view



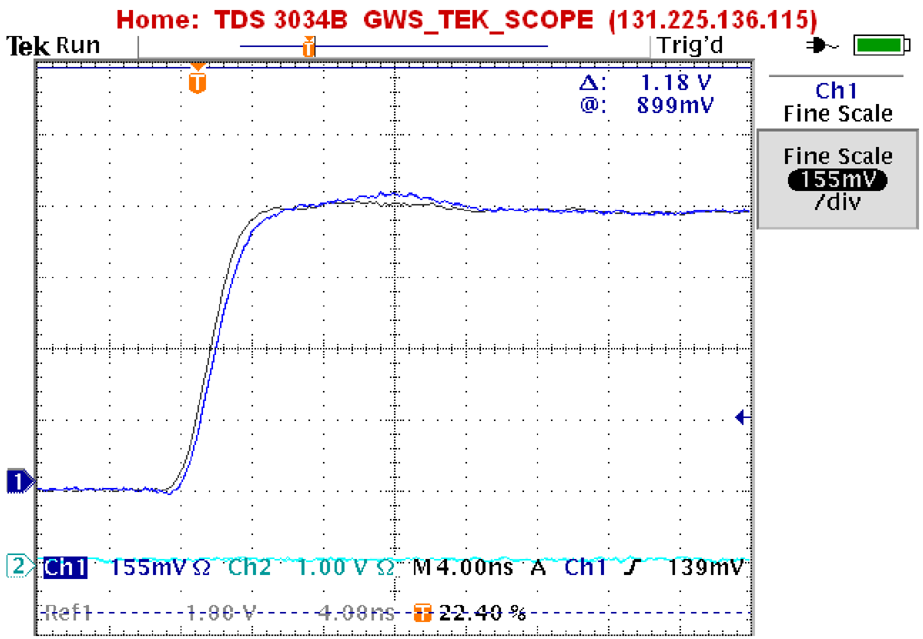
TDR measurement



Driving the strip line unmatched to 50 Ω reveals the strip line characteristic impedance.

In this measurement, the strip line is terminated into 50 Ω.

Through-voltage from "slow" rise time generator



Blue trace:
through –voltage scaled to match generator output amplitude

Black trace:
generator output signal (driven directly into the scope)

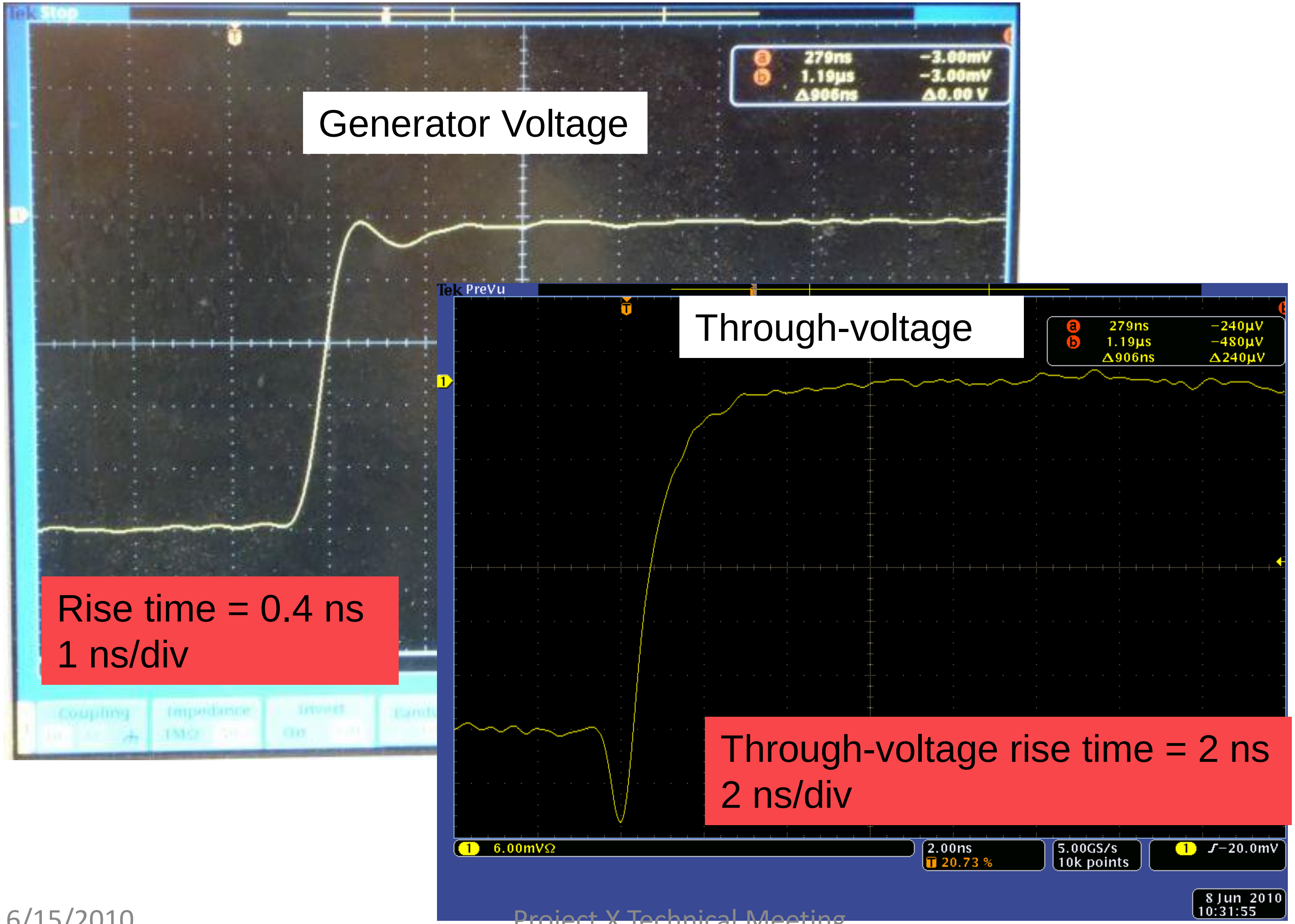
Generator rise time (Tg) (10-90%) = 3.0 ns

Through –voltage rise time (Ttv) (10-90%) = 3.6 ns

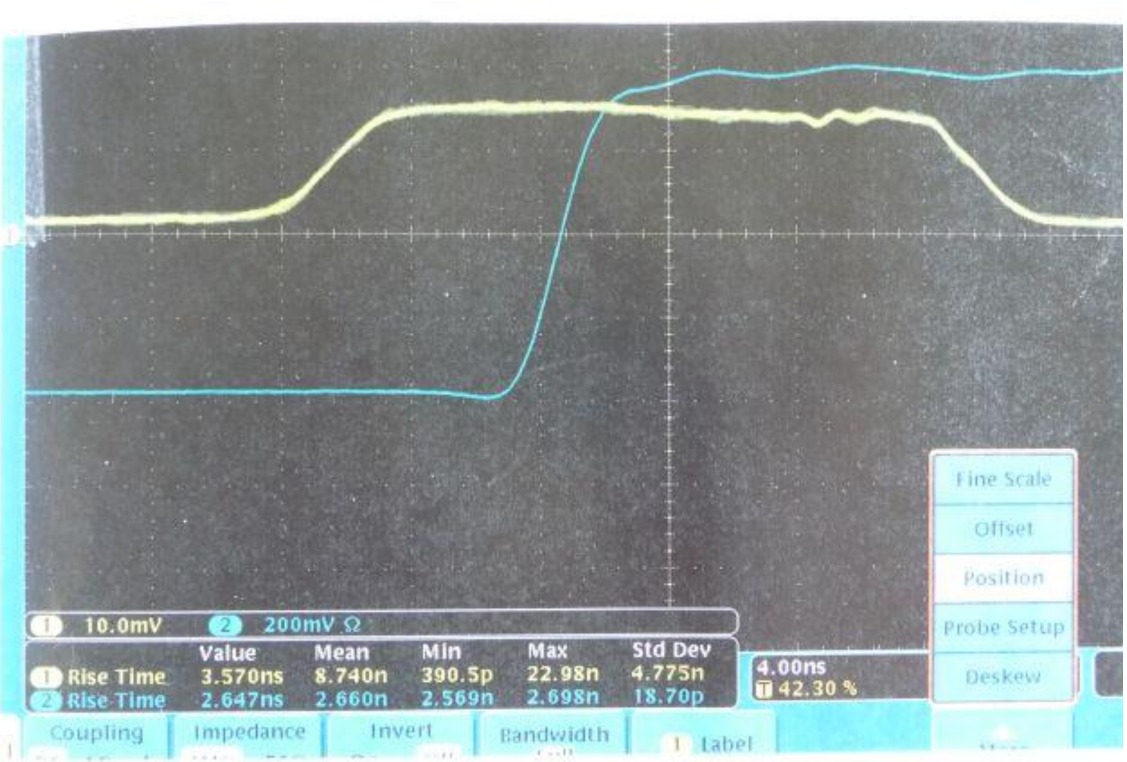
Microstrip line rise time, calculated = $\sqrt{Ttv^2 - Tg^2} = 2\ ns$

Microstrip line is impedance matched to 50 Ohms at the input and output ("L" network on the input and a series resistor at the output)

Through-voltage from a fast generator



E-field pickup voltage



Through-voltage
200mV/div

Voltage pickup
10mV/div

Generator output rise time,
10-90% = 2.5 ns

Measured voltage on the pickup: 13 mVpp
Voltage on the strip line: 2.71 Vpp

E-field measurement

- From 1 cm x 3 cm voltage pickup electrode located a distance at the presumed beam center:
  - Pickup location is .85 cm from the conductor
  - E-field calculated from voltage measurement:

$$E_p = \frac{D}{\epsilon} = \frac{C \cdot V}{\epsilon \cdot A}$$

$$= 294\ (\mathrm{V/m})$$

where: C = 60 pF measured pickup cap.,
V = 13.1 mV measured on the pickup,
A = 3 cm^2
$\epsilon = 8.85\times10^{-12}$ F/m

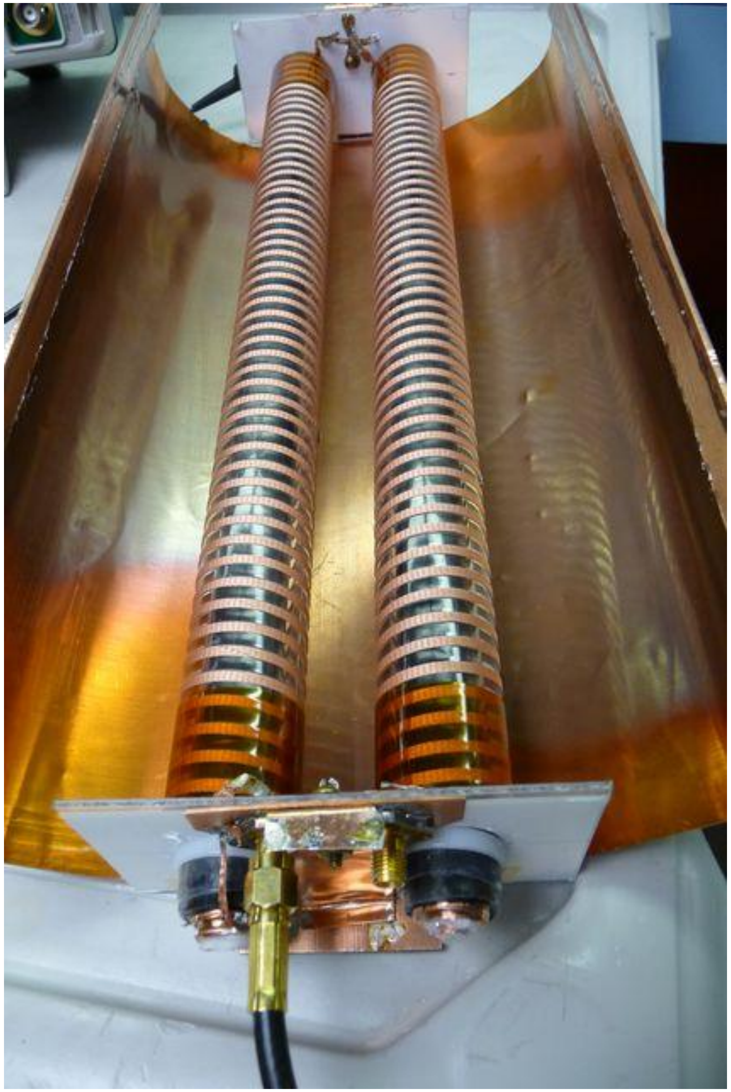
  - Maximum possible E-field at the beam center:

$$\mathrm{E_m} = \frac{2.71\ \mathrm{V}}{.85\ \mathrm{cm}} = 318\ (\mathrm{V/m})$$

where 2.71 V is voltage on the plates.

$$\frac{E_p}{E_m} = .92$$

Second prototype: dual 30 cm helical microstrip line



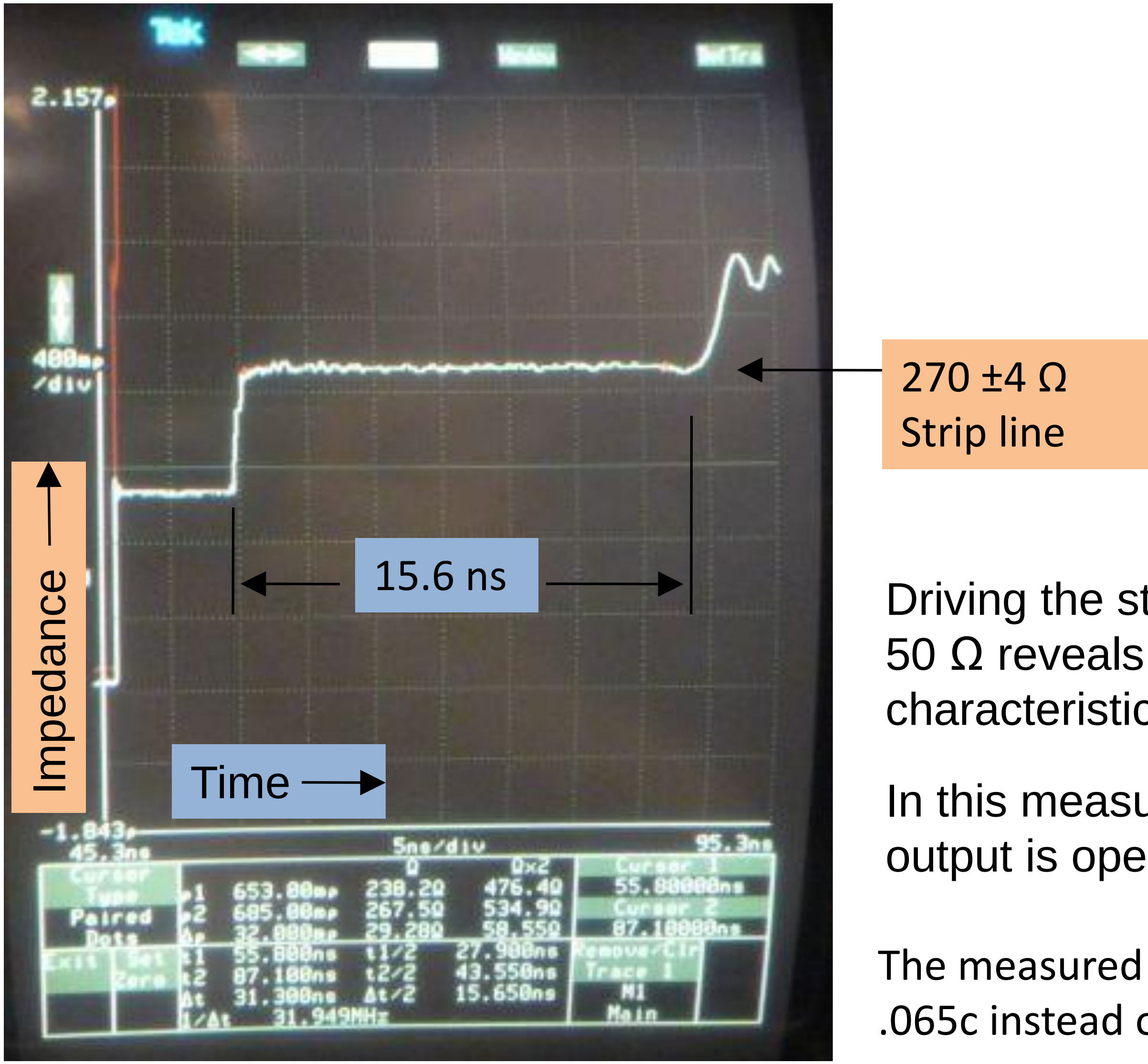
First attempt with this prototype was to duplicate the 7104 oscilloscope construction in which ground surrounded the helixes. The results were undesirable and not presented here.

This construction has a cylindrical ground down the center of both helixes.
Conductor wound around 1” OD Lexan tube.

Tube length:	12” (30 cm)
Conductor width:	.10”
Conductor spiral pitch:	.23” (4½ turns/in.)
Ground return:	.54” dia. inside each spiral coil
Tube separation:	1.5 cm between tube surfaces
Microstrip impedance:	270 Ohm each coil.

Each microstrip line is matched to 50 Ohm at input and output (“L” network on the input and a series resistor at the output).

TDR measurement

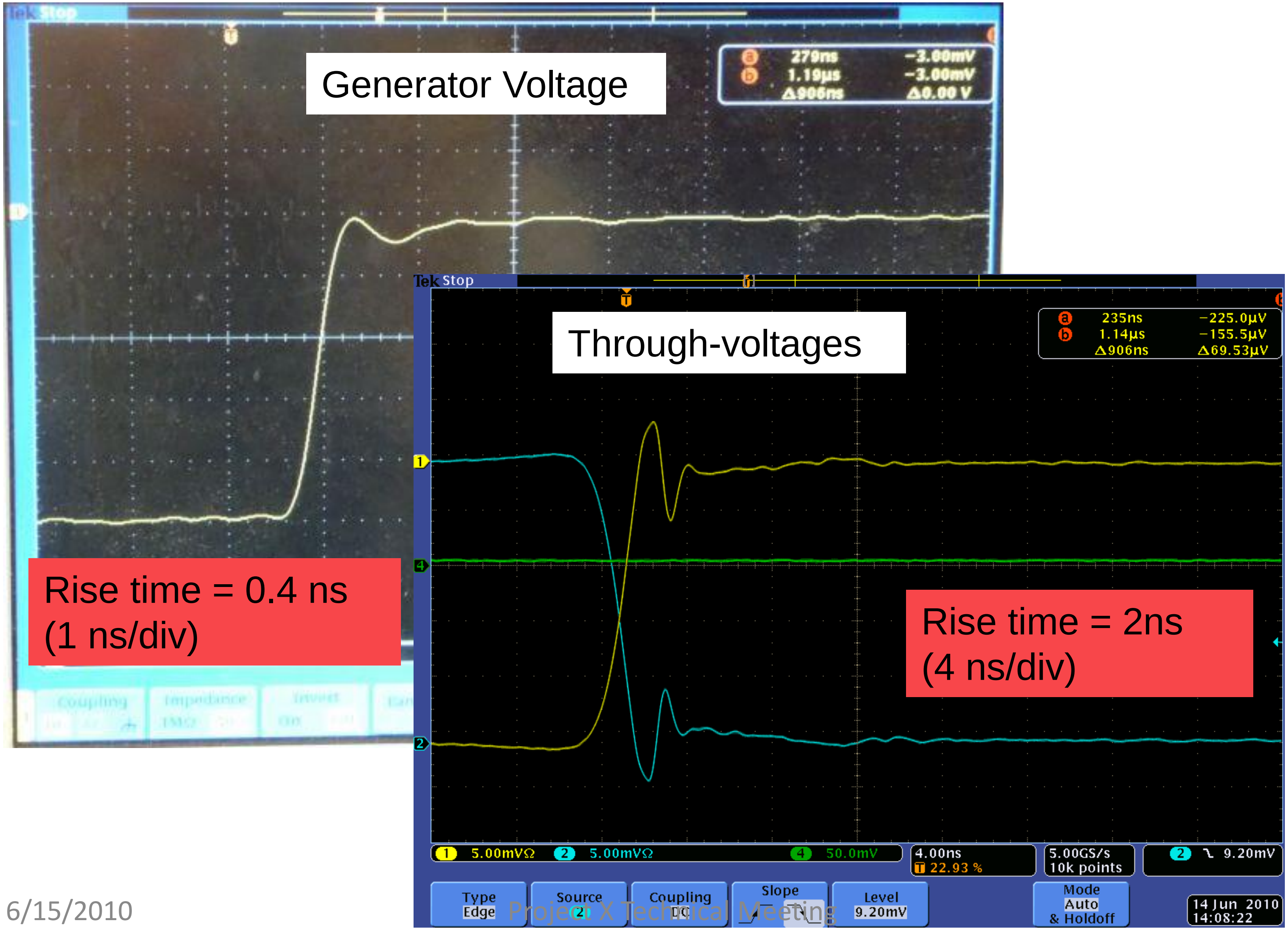


Driving the strip line unmatched to 50 Ω reveals the strip line characteristic impedance.

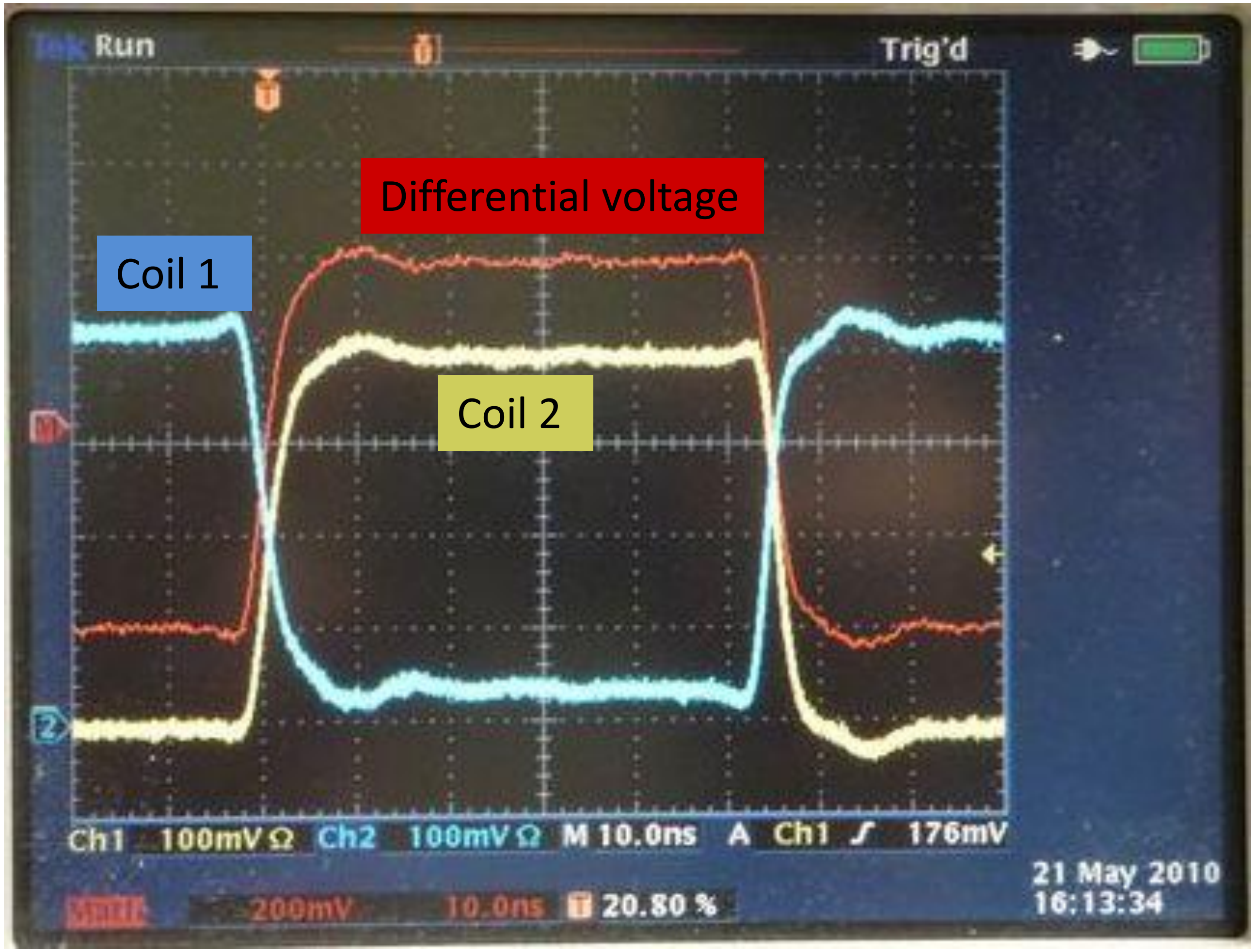
In this measurement, the strip line output is open circuited.

The measured traveling wave velocity is .065c instead of the desired .073c.

Differential through-voltage (.4 ns rise time source)



Differential through-voltage (3 ns rise time source)



Displayed at 10 ns/div

Generator rise time is 3 ns

Helical Kicker Study Conclusions

- The helical traveling wave deflector is a proven technology used for fast electrostatic kicking
- The helical chopper provides:
  - A continuous structure without internal reflections
    - Benefits rise time and kicker length
  - A high characteristic impedance
    - substantially reduces power in the kicker and termination
  - More kick per watt from the drive amplifier
- Results from the first prototypes warrant further investigation of the helical design approach

Chopper driver power design issues

- Show the various switching rates and duty factors for 162 MHz beam
  - Switching rep rate determines power dissipated in the driver for a given drive voltage
  - The average duty factor determines the I^2R loss in the chopper's termination resistor (and conductor).
- The sources of power dissipated in the driver
  - I^2R loss
  - Transition switching loss
  - Internal C_{ds} switching loss

Chopper switching rates (162 MHz beam)

Kaon	μ2E	other	Peak Rep Rate	Ave Duty Factor
20-30 MHz	.5-1 MHz*	80-300 MHz	(MHz)	
√	√	√	60	.23
√	√		20	.86
√		√	60	.25
	√	√	80	.32
√			20	.88
	√		1	.90
		√	80	.33
			DC	1.0

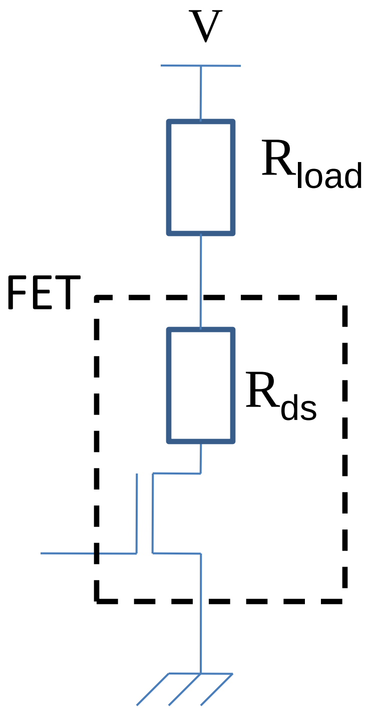
* 100 ns burst of bunches

Note: the average rep rate nearly equals to the peak rate

Power loss sources

- Driver I^2R conduction losses

$$P_w = \left(\frac{V}{R_{load}}\right)^2 R_{ds} \bullet DF \quad \text{(W)}$$



Example

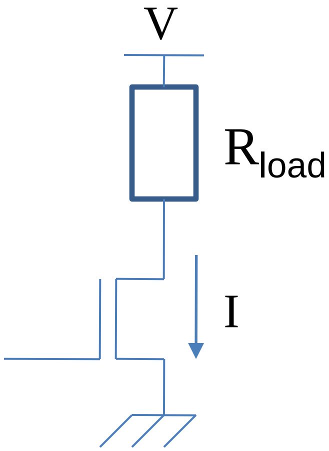
- V = 200 V
- R_{load} = 50 Ω
- R_{ds} = 1.6 Ω
- DF = .90
- ➢ P_w = 23 W

Power loss sources (cont.)

- Driver loss due to transitioning

$$P_{tran} = 2 \times f_{sw}\left(\int_0^{trf} V_{rf}(t) I_{rf}(t) dt\right) \quad \text{(W)}$$

  - Assuming rise time equals fall time
  - And where: $$I_{rf}(t) = \frac{V - V_{rf}(t)}{R_{load}} \quad \text{(A)}$$



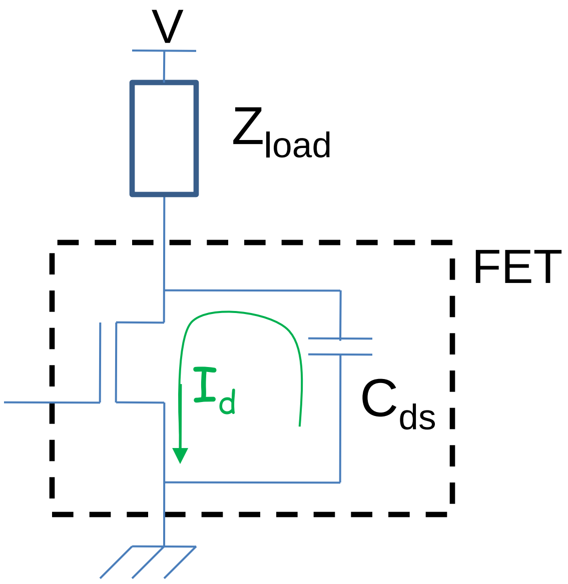
Example

- Tr = Tf = 1.5 ns (10-90%)
- V = 200 V
- f_{sw} = 80 MHz
- Z_{load} = 50 Ω
- ➢ P_{tr} = 40 W (calculating for an exponential transition)

Power loss sources (cont.)

- Driver internal switching loss due to discharging C_{ds}

$$P_{inl} = \frac{1}{2} C_{ds} V^2 \bullet f_{sw} \quad \text{(W)}$$



I_d is C_{ds} discharge current

Example

- C_{ds} = 140 pF
- V = 200 V
- f_{sw} = 80 MHz

➢ P_{inl} = 224 W

200 V is used for design example

Power dissipation summery

- Driver power dominated by internal switching losses as a function of voltage – not termination resistance
  - Assume 200 V drive
  - 50 Ω termination:
    224 + 40 + 23 = 287 W
  - 200 Ω termination:
    - 224 + 10 + 6 = 240 W
- This power level is not insignificant – for this transistor.
- Suggestion:
  Consider two separate choppers to lower switching rates
  - One chops out Muon conv.
  - One chops out Kaons
  - Either one can chop out Mu2e

- Termination resistor dissipation for each helix
  - Assume 200 V drive
  - 50 Ω at .90 duty factor:
    $.9(200)^2 / 50 = 720$ W
  - 200 Ω at .90 duty factor:
    $.9(200)^2 / 200 = 180$ W
- Higher characteristic impedance will reduce I^2R loss in the chopper
- Conclusion:
  Design strip line for as high an impedance as practically allowed by dispersion

Where we go from here

- Build and test prototype(s) to determine the best geometry
  - Non-circular geometries allow for use of air (vacuum) as the dielectric and, thus, minimum dispersion
  - Determine effects of dielectric spacers
- Use modeling to assist in the design
  - E-field shape in the region of the beam various helical geometries
  - Determine fill factors for various strip width, pitch and circumferences
- Determine the maximum feasible length for a spiral microstrip line
- Pursue the design of a 200 V, fast, driver circuit
- Target a chopper for 162 MHz beam—first—to demonstrate a working system

The end

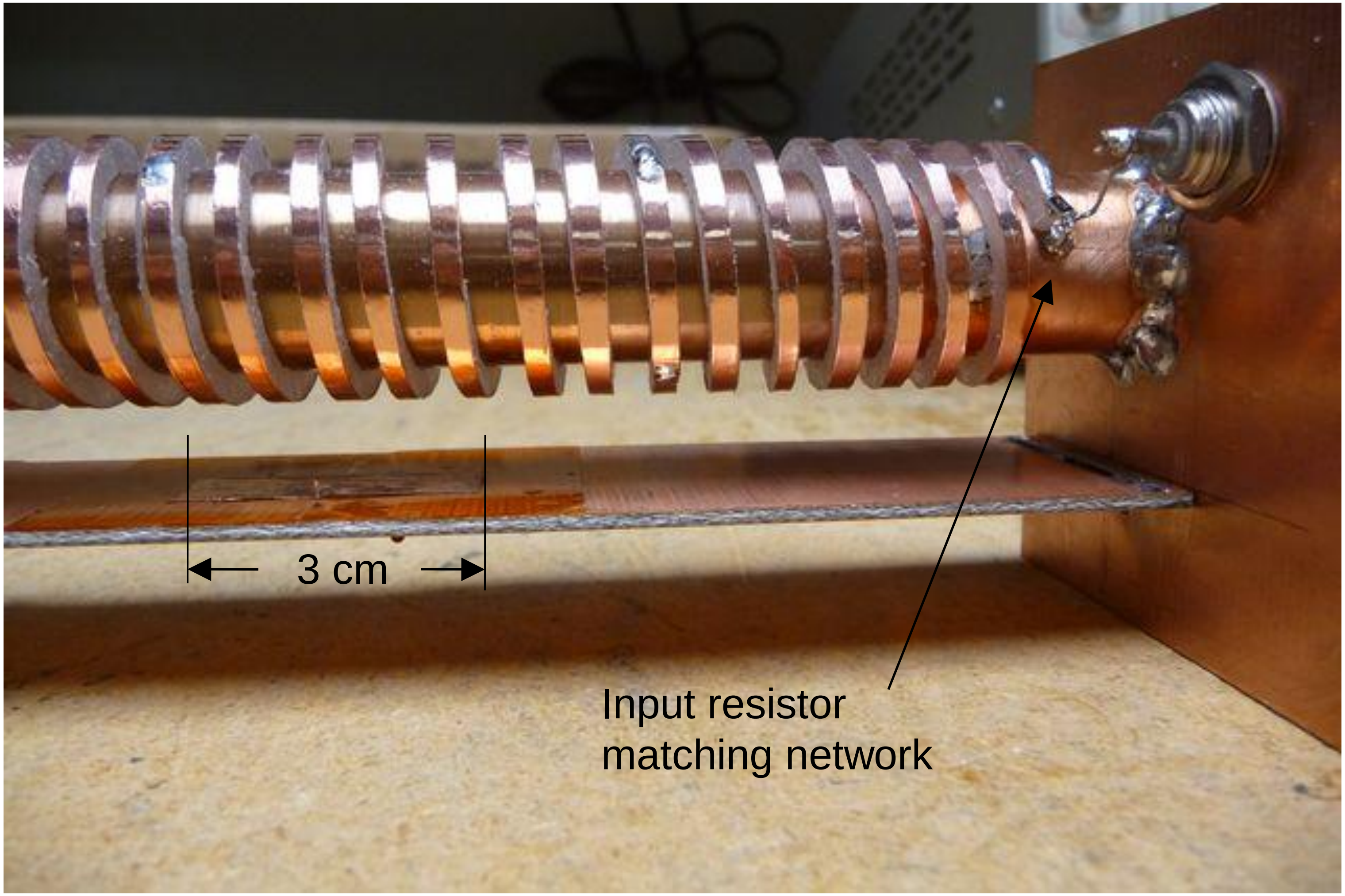
Omit-------Chopper system design issues

- Show the switching rates for the chopper system
- Power dissipated in the driver
  - Internal switching loss
  - Transition switching loss
  - I^2R loss
- Explain why switching rate is an issue
  - Emphasize drive FET power switching losses.
  - Give Joules/pulse and an example.
- Show effect of two kickers
- Show the issues that are different between 162 and 325MHz

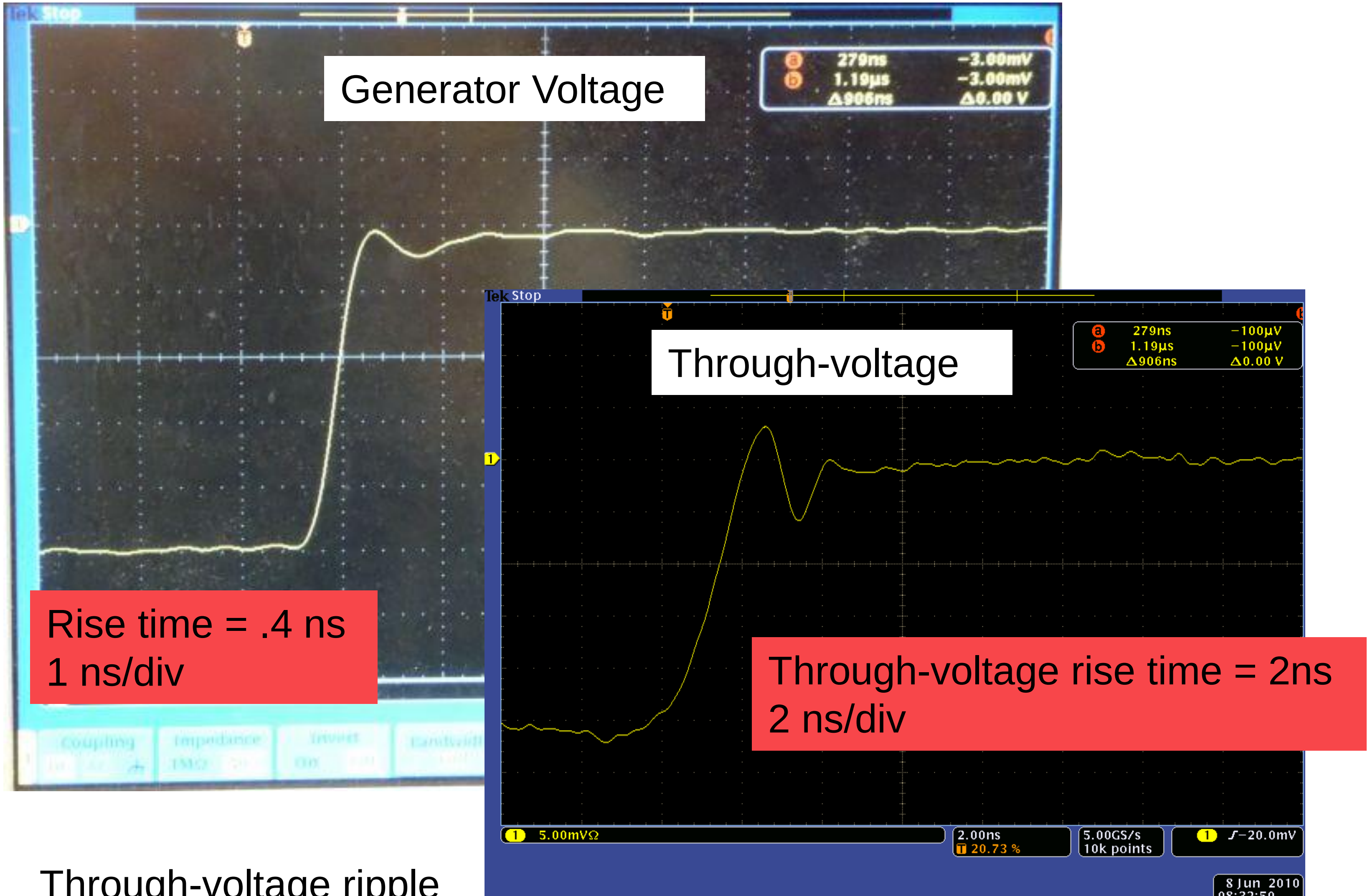
Acknowledgements

- Acknowledge constructive conversations and cooperative efforts from a number of people in various departments:
  - Manfred Wendt
  - Milorad Popovic
  - Ding sun
  - Dave Wildman
  - Dan Wolff

Zoomed in view



Through-voltage measurement



Through-voltage ripple
Is likely due to either interwinding capacitive coupling or ground bounce.