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Title: High-speed electrical measurements and experimental challenges

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High-speed electrical measurements and experimental challenges

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Outline of material

- Plasma experiments are hard
- Case study: measuring voltage in DARHT-1
- System response or transfer functions
- Unifying diagnostics and cross-calibration of instruments
- Summary

Do you really need to do all this work?

- Much of this talk is about achieving precision to ~1%. Why?!
- Is a complicated analysis/model warranted if a simple one describes the data?
- Distinguishing between theories sometimes demands accuracy and precision
- Theory and experiment should challenge each other

There are very few* perfect plasma diagnostics

*Probably none

- Almost never directly measure the quantity of interest:
  - Density: cannot “weigh” plasma or count particles
  - Temperature: single number describes distribution of energies
  - Potential: particle distribution responds to materials

- Complementary techniques reduce overall uncertainties by making different assumptions

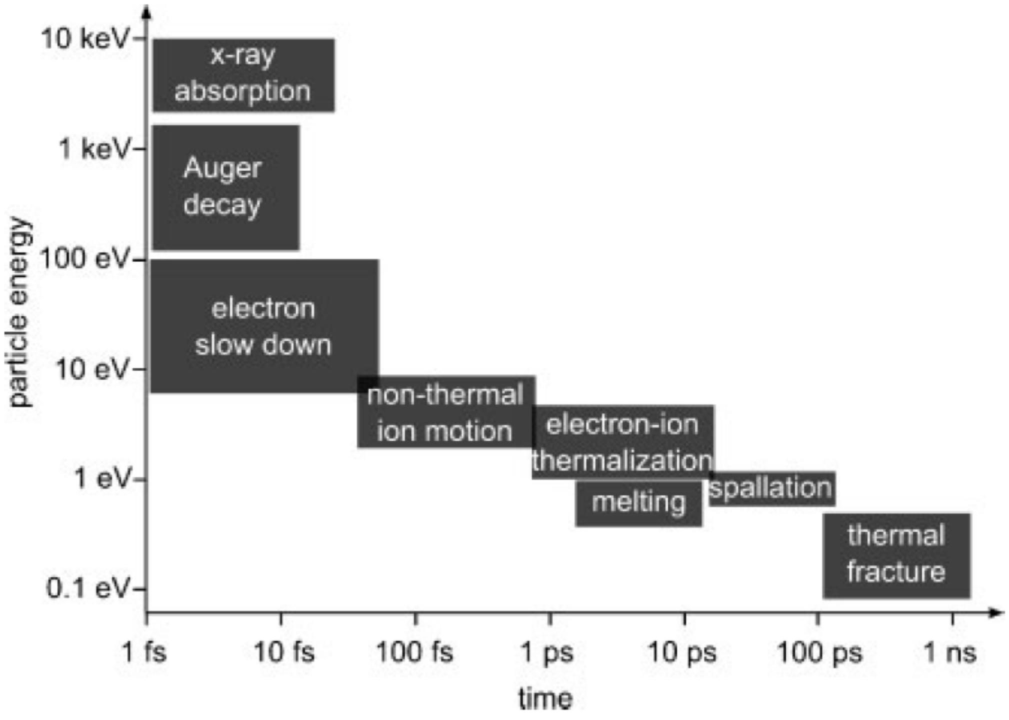
How do you define "fast" or "high-speed"?

- 1s? 1ms? 1us? 1ns? 1ps?

- Often depends on the field or community and phenomena

Plasma experiments span many orders of magnitude in time

- Magnetic fusion wall evolution: 1-2 years
- High-Z, ~1eV plasma expansion: ~1us
- X-ray interactions with matter: ~10 fs



S. Hau-Riege, *High-Intensity X-Rays – Interaction with Matter*, Wiley-VCH, 2001.

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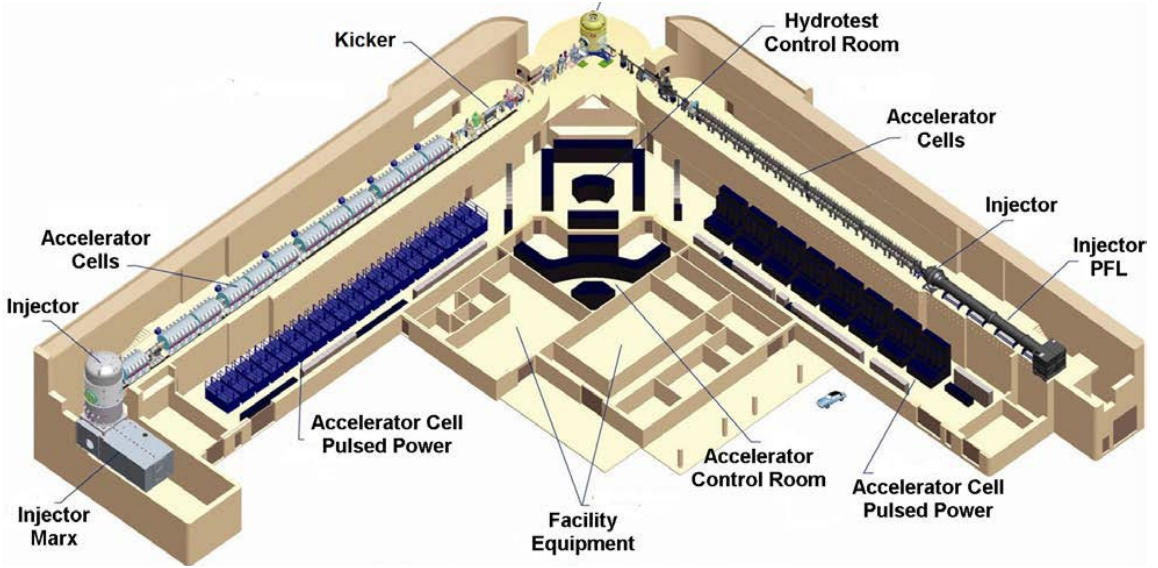
Dual-Axis Radiograph Hydrodynamic Test (DARHT)

- Uses intense, relativistic electron beams for flash x-ray radiography
- Flash x-ray experiments achieve spatial resolution with short pulses
  - Resolution~1mm
  - Velocity~10km/s
  - t_{pulse}~100ns
- X-ray dose ~ $IxV^{2.8}$ and small spot requires stable beam



C. Ekdahl, "Contemporary electron accelerators for flash radiograph", LA-UR-13-23845.

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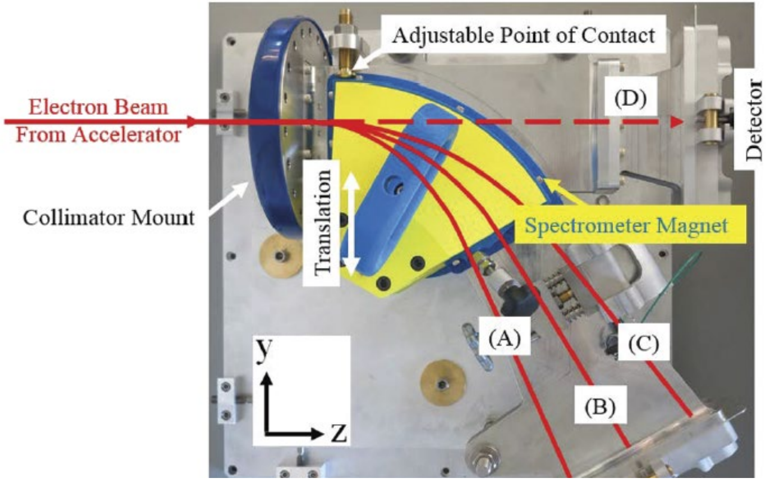
Assume you have wrapped it in foil and loaded up on ferrites…

- Electromagnetic interference (EMI) is often associated with transient, high-power experiments
- Ground loops, shielding and other aspects of good experimental hygiene are real concerns
- **Even if** you eliminate such signals, what can happen in high-speed experiments?

Magnetic spectrometer separates particles by energy (velocity)

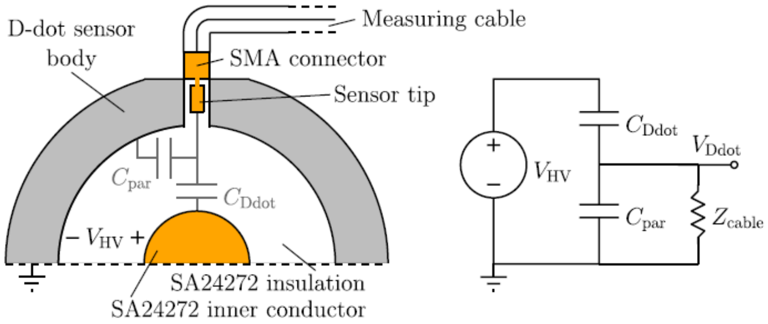
- Charged particles deflected in magnetic field
- E-beam bremsstrahlung lights up scintillator
  - Recorded with streak camera for time resolution
  - Can also expose x-ray film for permanent records
- Calibrated at low energy with heavy, negative ions



T.J. Burris-Mog, *et al.*, *Rev. Sci. Instrum.* **89** (2018) 073303.

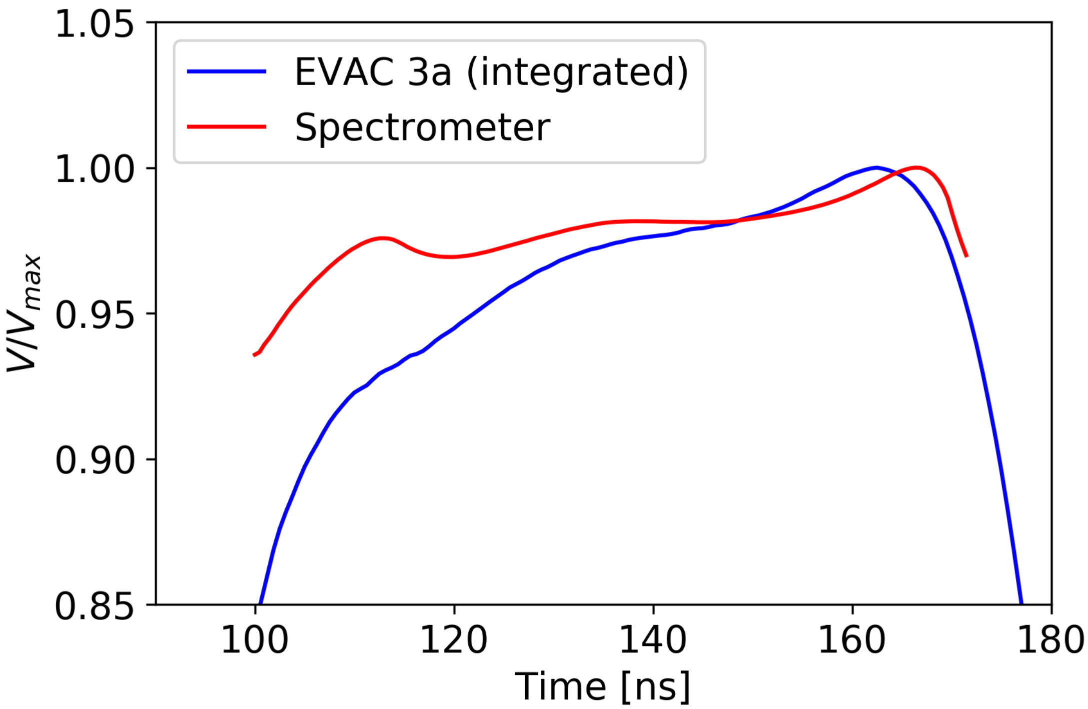
E-dot sensors are simple capacitive pickup probes

- Voltage divider circuit
- Sensitive to dV/dt
- Analog or digital integration gives V(t)

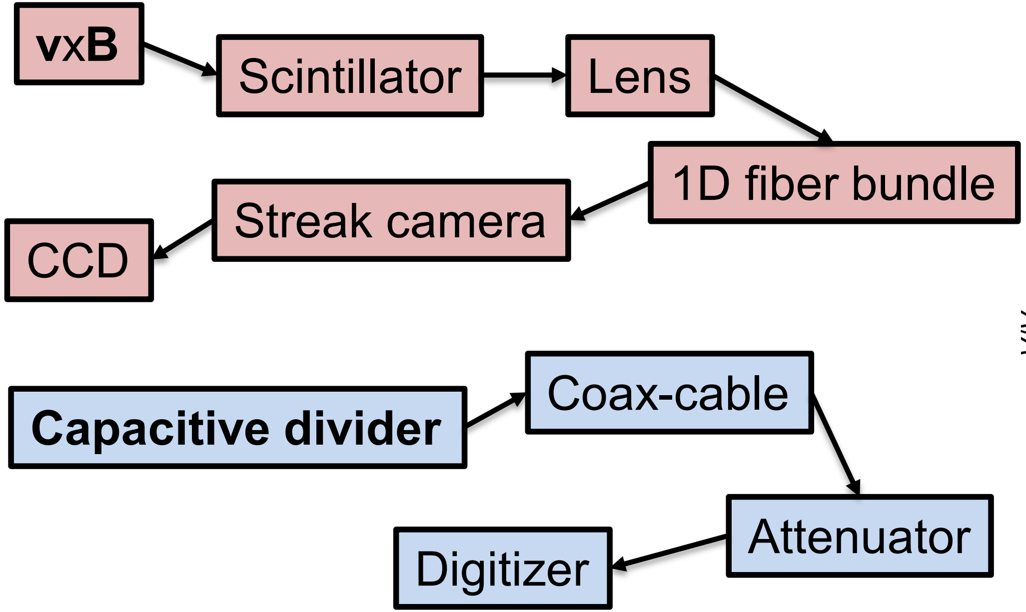


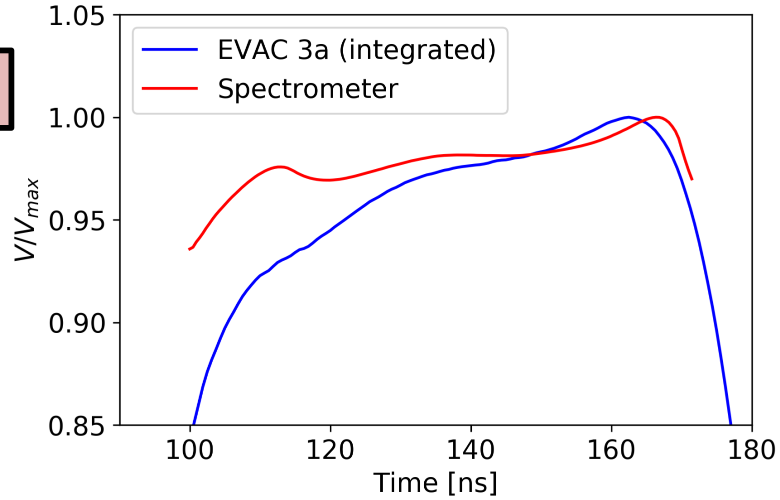
T. Huiskamp, *et al.*, *IEEE Sensors Journal* **16** (2016) 3792.

Which diagnostic is right?



Which diagnostic is right?





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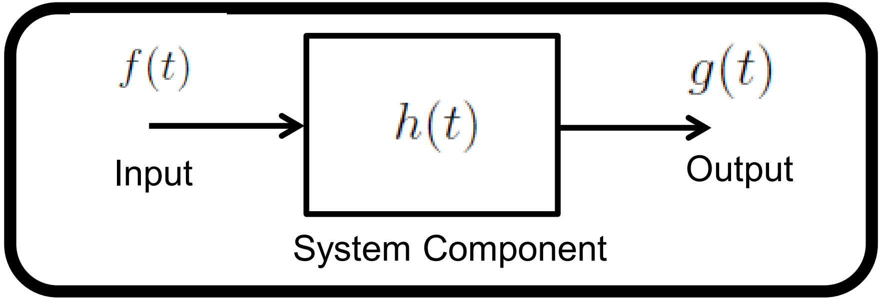
Transfer functions dictate transformation of inputs to outputs

- System response models link processes together
- Series connected systems convolve signals
- System identification is the process of determining the transfer function

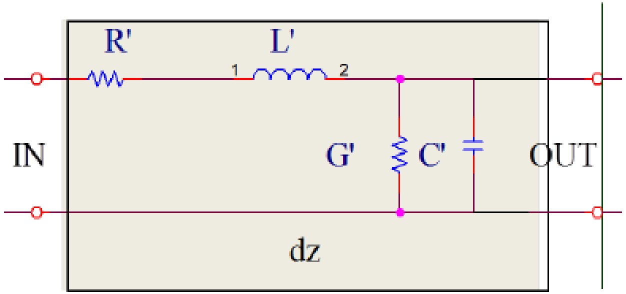


Time Domain

$$g(t) = (f \star h)(t) = \int_{-\infty}^{+\infty} f(\tau)h(t-\tau)\mathrm{d}\tau$$

Lossy- (real world) transmission lines add frequency-dependent losses

- Ideal transmission lines feature purely reactive elements
- Lossy-lines include series resistance and parallel conductance
- General solution has real and imaginary components
  - Attenuation coeff. (real)
  - Phase shift coeff. (imag.)



Q. Shi, Trans. Sys. Signals & Dev. V7 (2012) 311.

$$\frac{\partial u}{\partial x} = -Ri - L\frac{\partial i}{\partial t}$$

$$\frac{\partial i}{\partial x} = -Gu - C\frac{\partial u}{\partial t}$$

$$\frac{d^2\bar{U}}{dx^2} = (R + Lj\omega)(G + Cj\omega)\bar{U}$$

$$\bar{U} = A_1 e^{-\gamma x} + A_2 e^{+\gamma x}$$

$$\gamma = \sqrt{(R + Lj\omega)(G + Cj\omega)} = \alpha(\omega) + j\beta(\omega)$$

$$u(x,t) = C_1 e^{-\alpha x}\sin(\omega t - \beta x + \theta_1) + C_2 e^{\alpha x}\sin(\omega t - \beta x + \theta_2)$$

Cable design can be used to derive lossy-transmission line parameters

- This is an old problem…
  - Schelkunoff of Bell Labs wrote up solution in 1934
  - Q. Shi is a recent usage (2012)
- Model solves EM field inside cables including skin effect
- R, L, G, C values determined from solution of inner and outer conductors

$$\eta = \sqrt{\frac{j\omega\mu_0}{\sigma}} \qquad \gamma_c = \sqrt{j\omega\sigma\mu_0}$$

Inner conductor impedance

$$Z_a'(\omega) = \frac{\eta}{2\pi a}\left[\frac{I_0(\gamma_c a)}{I_1(\gamma_c a)}\right]$$

Cable resistance/inductance per unit length

$$R' = \mathrm{Re}\left[Z_a'(\omega) + Z_b'(\omega)\right]$$

$$L' = \mathrm{Im}\left[Z_a'(\omega) + Z_b'(\omega)\right]\frac{1}{\omega} + \frac{\mu_0}{2\pi}\ln\left(\frac{b}{a}\right)$$

Aside: sometimes you run out of numbers

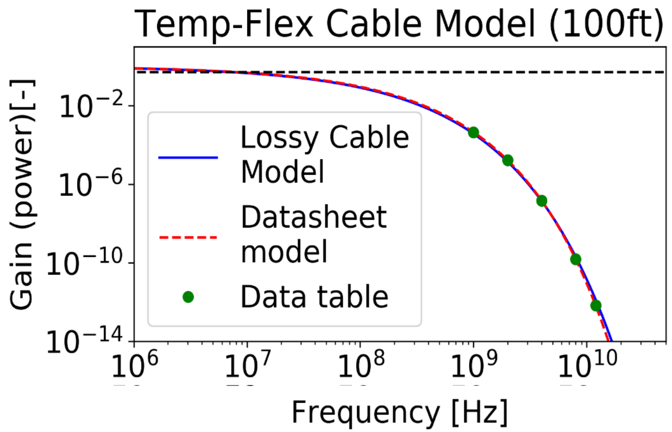
- Many computer programs will complain if you try to calculate exp(+400)
- Bessel functions can be simplified for large arguments
- Be aware of this type of problem and check for
  - Simplifications
  - Accuracy of simplifications

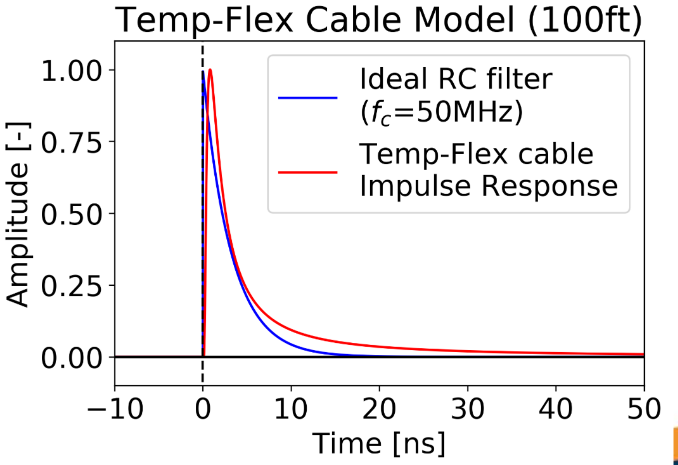
$$\eta = \sqrt{\frac{j\omega\mu_0}{\sigma}} \qquad \gamma_c = \sqrt{j\omega\sigma\mu_0}$$

$$Z_a'(\omega) = \frac{\eta}{2\pi a}\left[\frac{I_0(\gamma_c a)}{I_1(\gamma_c a)}\right]$$

Example cable used to check theory

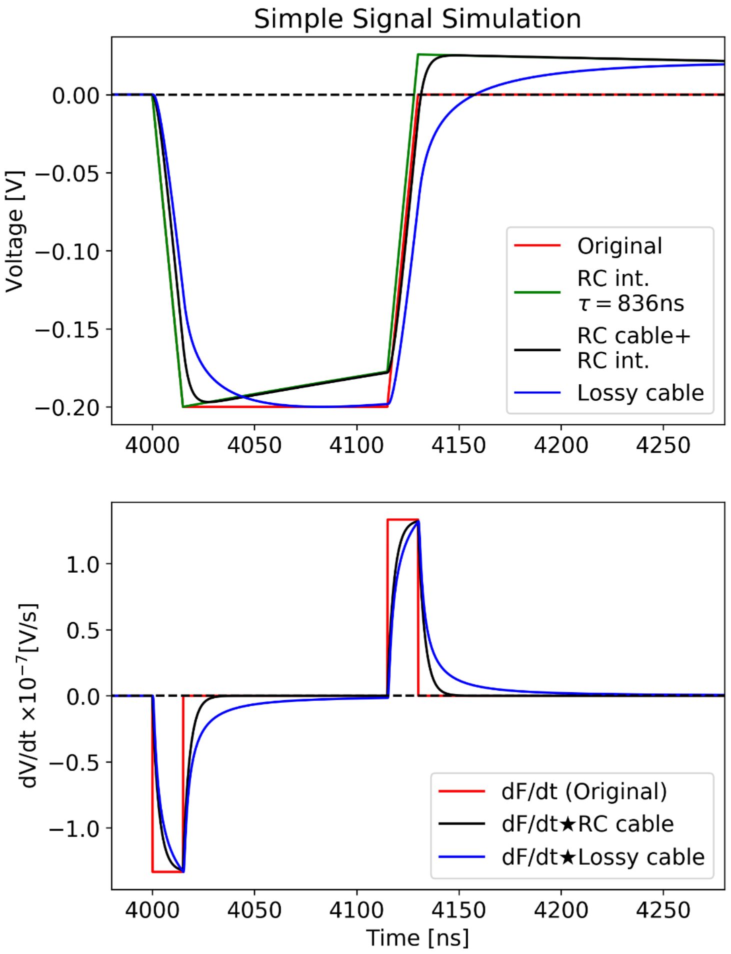
- “Ultra-low loss microwave cable” used for first comparison
- Cable geometry in, lossy cable parameters out
- Inverse Fourier Transform of cable model yields impulse response function





Realistic cable changes the character of the signal

- Consider trapezoidal pulse with three models:
  - RC integrators, pseudo-ideal cable,
  - vs. lossy cable
- Long tail of lossy-cable is key feature
- Signal droop vs. growth can drastically courses of action!

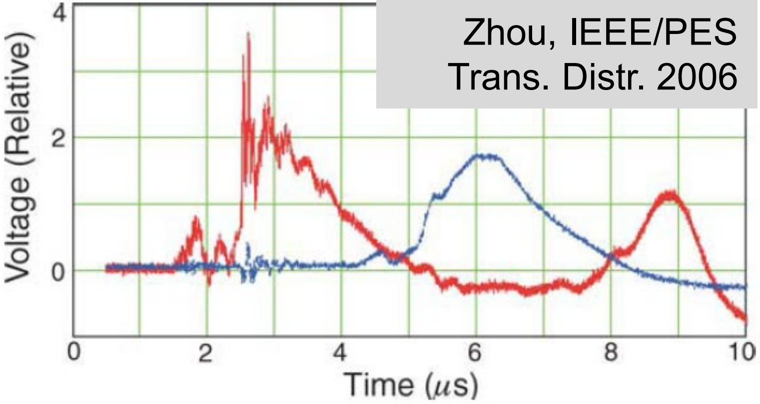


Literature shows common methods to characterize cables

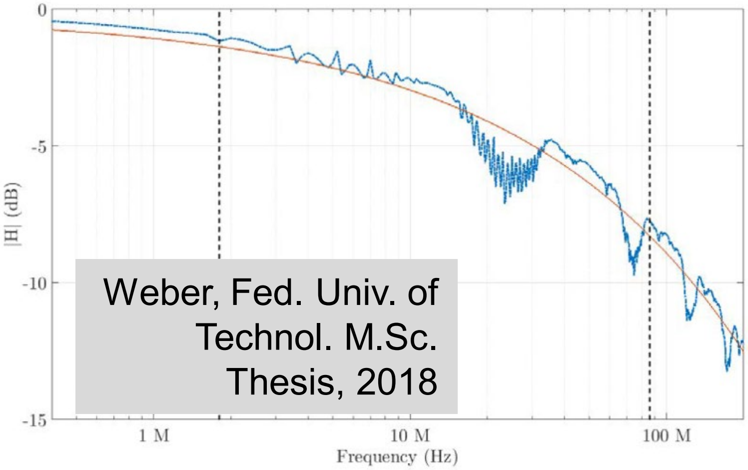
- Zhou used HV pulser as excitation (30 MHz, IEEE/PES Trans. Distr. 2006)

- Chengxiao used sampling o-scope (100ns rise, ACM Int. Conf. Robot. Contr. Autom. 2017)

- Weber utilized time and freq. domain techniques (M.Sc. Thesis, Fed. Univ. of Technol. Curitiba, Brazil 2018)



Zhou, IEEE/PES Trans. Distr. 2006

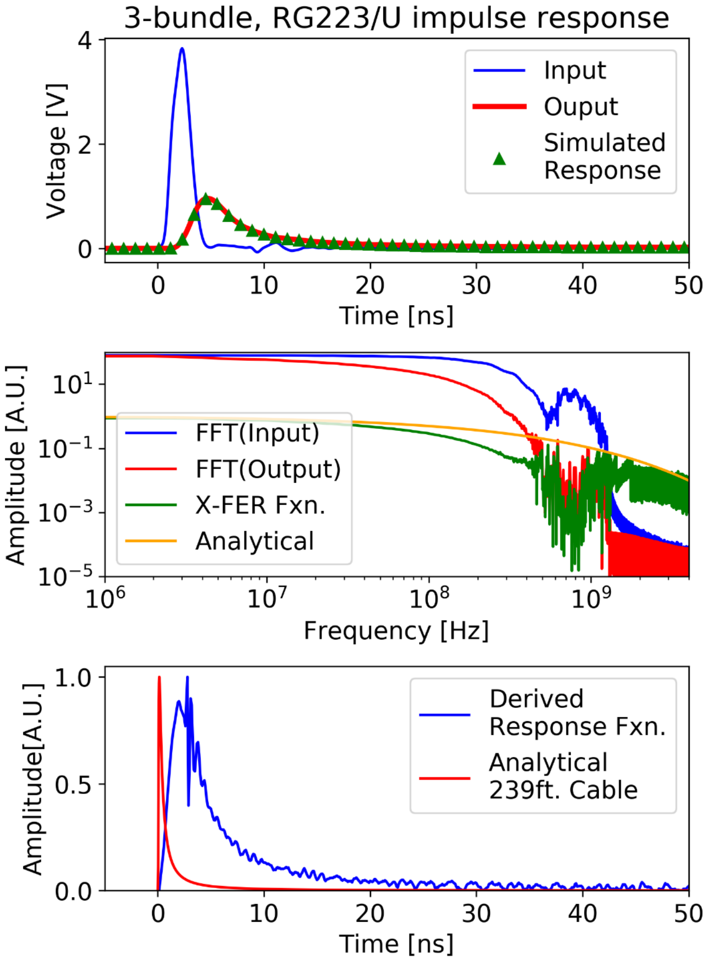


Weber, Fed. Univ. of Technol. M.Sc. Thesis, 2018

Figure 30 - Frequency response of the channel under analysis, in dB.

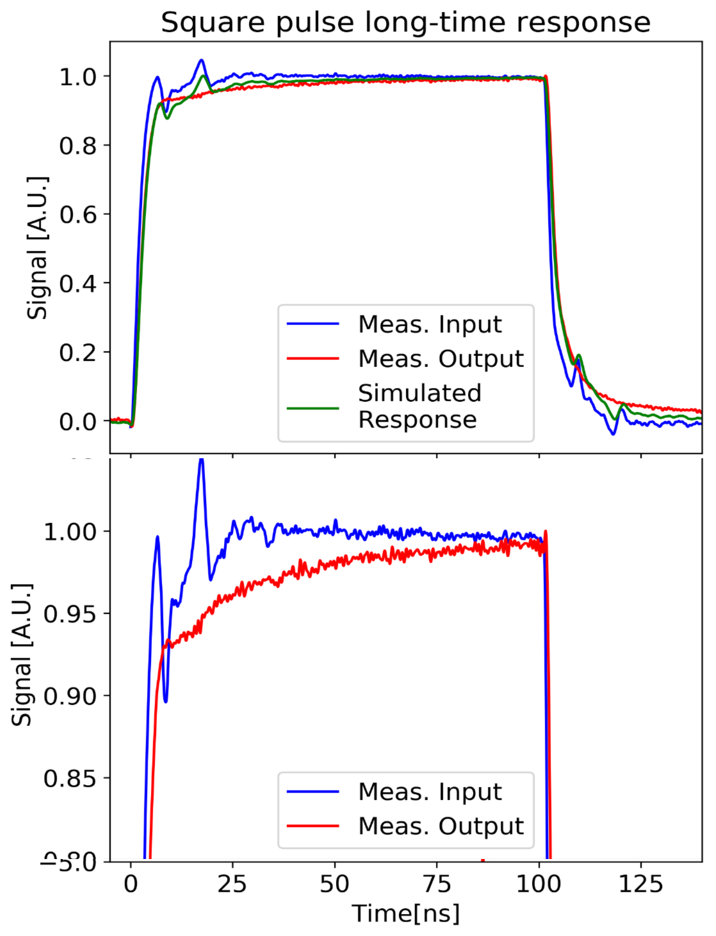
Analysis process tested on lossy-cable

- Data-sheet geometry used to create analytical cable
- DG 645 + Lecroy 8108A used for excitation and measurement
- Analytical model used to clamp transfer function



Lossy-cable model indicated in raw measurements

- Step response indicates long-period response
- Impulse response gives frequency response up to 500MHz, but significant noise
- Quick initial response with long tail indicative of loss-cable model



Working in Fourier space simplifies system identification process

- Fourier (or Laplace) space converts convolution integral to multiplication

$$F(\omega) = \mathcal{F}[f(t)] \qquad f(t) = \mathcal{F}^{-1}[F(\omega)]$$

- Division of input and output signals yields transfer function

$$\mathcal{F}[f \star h] = \mathcal{F}[f] \times \mathcal{F}[h] = F(\omega) \times H(\omega)$$

- Ideal transfer function is Dirac delta (i.e. constant response at all frequencies)

$$H(\omega) = \frac{F(\omega)}{G(\omega)}$$

In the real world, noise ruins many "simple" deconvolution processes

- In a noise-free world, Fourier-space operations work fine
- With noise, inverse transform often diminishes to zero while noise remains constant (white)

$$g = \mathbf{A} f^{(0)} + w$$

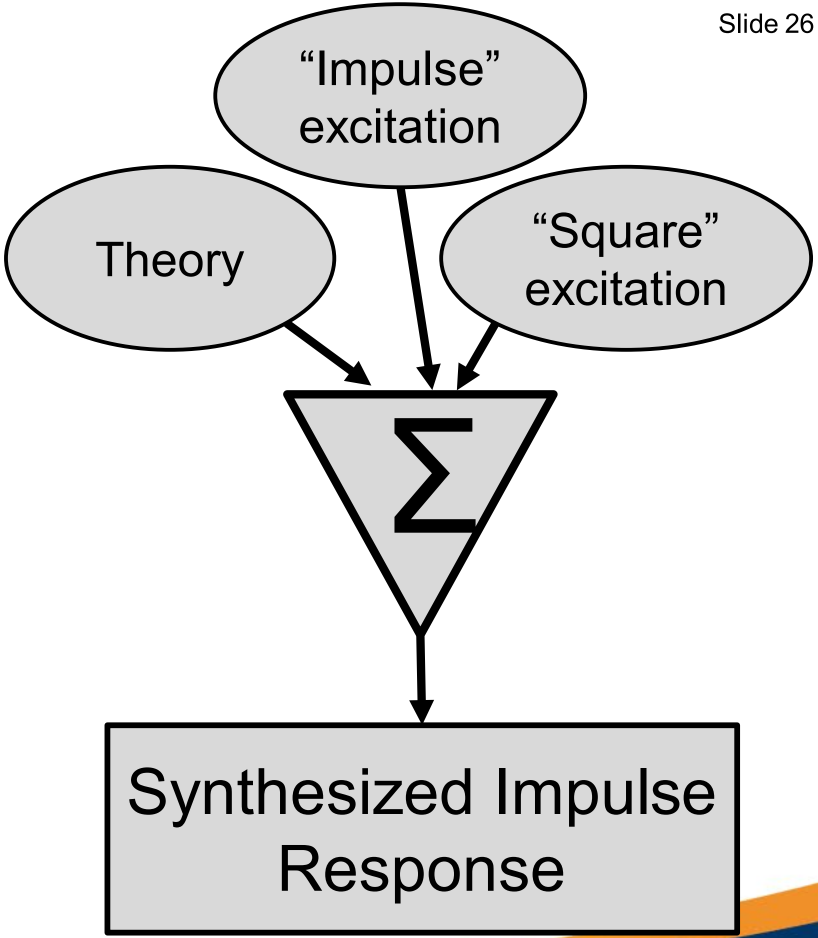
$$\hat{f}(\omega) = \frac{\hat{g}(\omega)}{\hat{K}(\omega)}$$ **No noise!**

$$\hat{f}(\omega) = \hat{f}^{(0)} + \frac{\hat{w}(\omega)}{\hat{K}(\omega)}$$

Oh No!

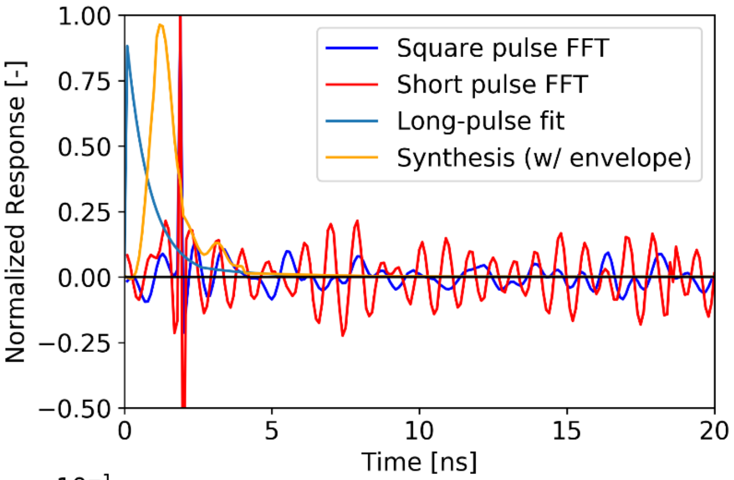
Three sources of information used to develop transfer fxn

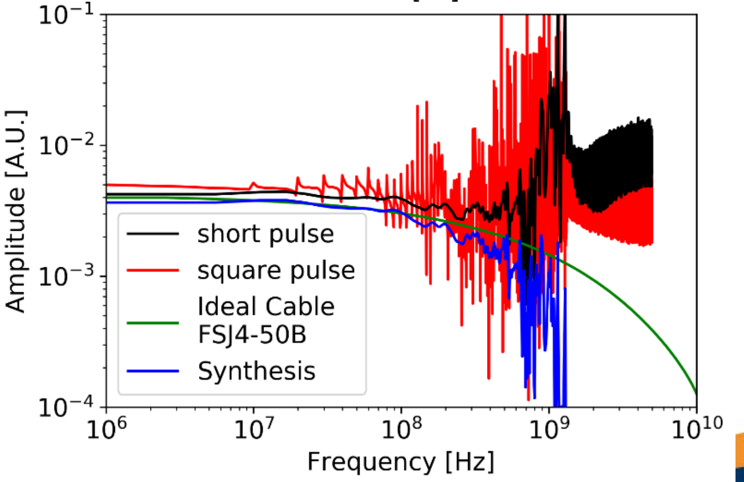
- Theory indicates unipolar function with “ideal cable” limit
- Impulse response yields early time information
- Square pulse yields late-time information



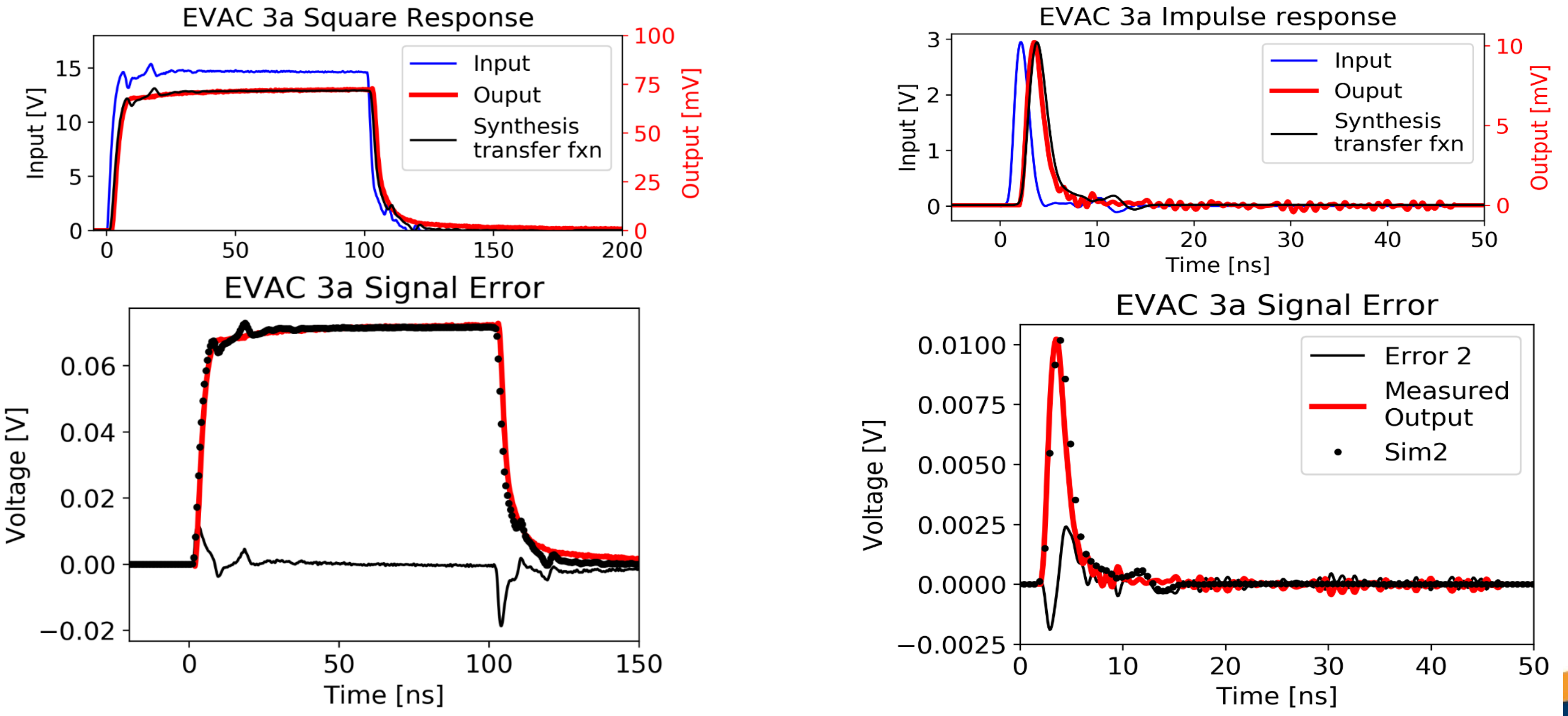
Presence of noise obvious in simple inversion attempts

- Short pulse with theory envelope results in early time
- Square pulse model eliminates late oscillations
- Tanh weighting function transitions between two models





Synthesized impulse response reproduces (most of) the measured outputs



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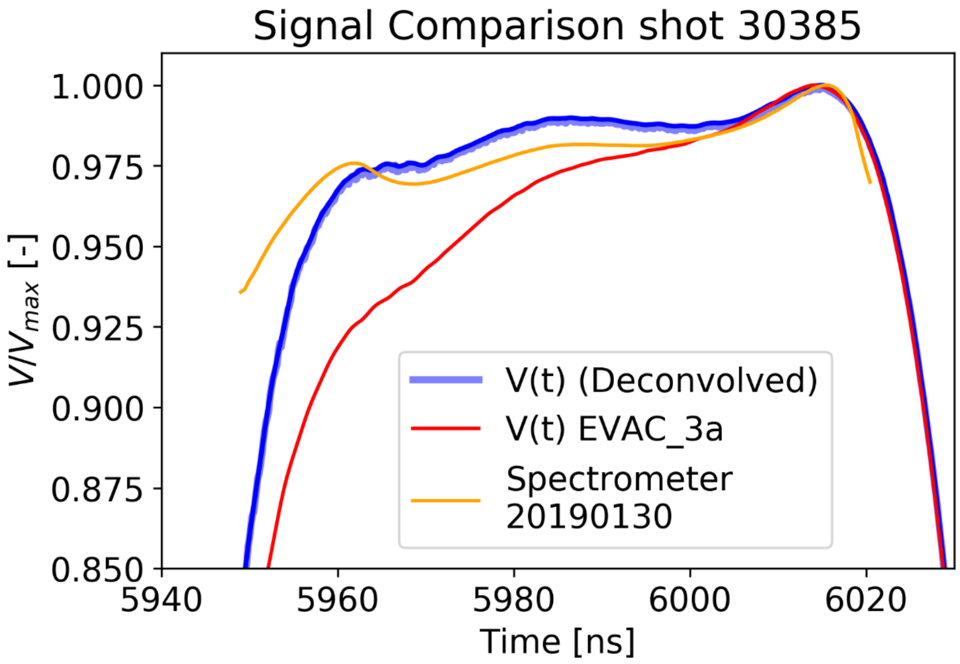
Mathematics for deconvolution relatively straightforward with this xfer function

- E-dot signal up-sampled to include high-frequency components
- Deconvolution performed in frequency domain
- IFFT result is smoothed with moving Gaussian average

Deconvolution recovers most of the signal from the spectrometer

- Signals again normalized to 1.0 for comparison
- Xfer function only derived from "calibration" shots
- Synthesis is "kludgy", but it's "good enough"



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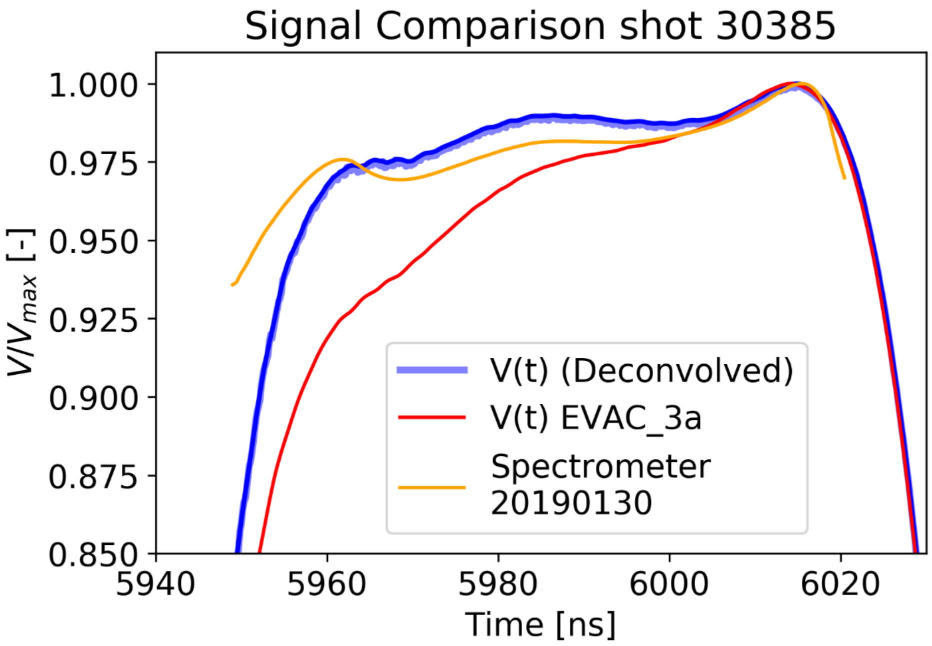
Cross-calibration or independent calibrations?

- In an ideal world: independent calibrations yield identical results
- Don’t always have necessary equipment, time, or forethought to do this
- Instead, can choose to cross-calibration the diagnostics

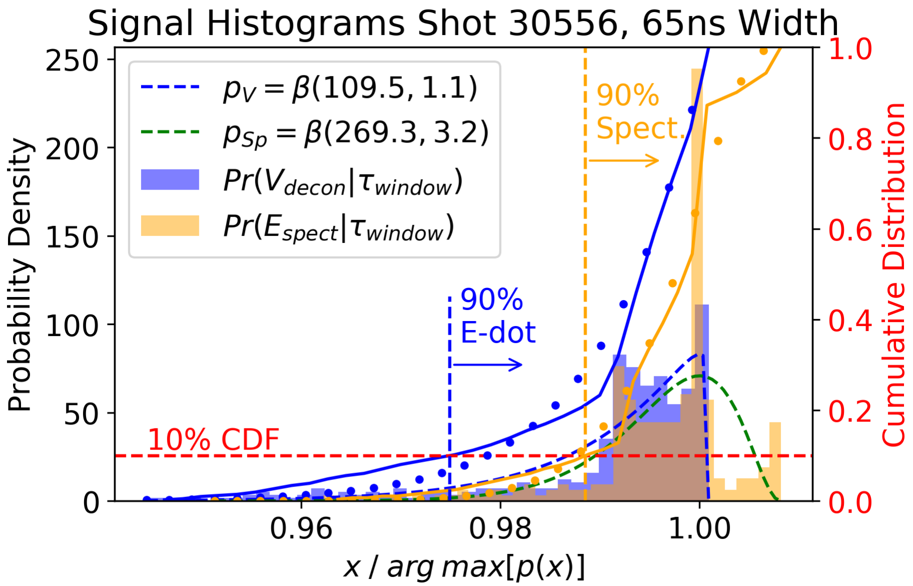
Caveat Emptor: linear least-squares carries assumptions about the data

- Previous calibrations used V_{max} and E_{max}
- Least-squares assumes data normally distributed (and *one* known perfectly)
- Is it true? (can you tell already?)

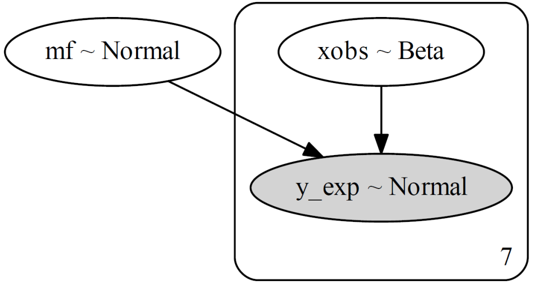


With a single-point model: data are NOT normally distributed!

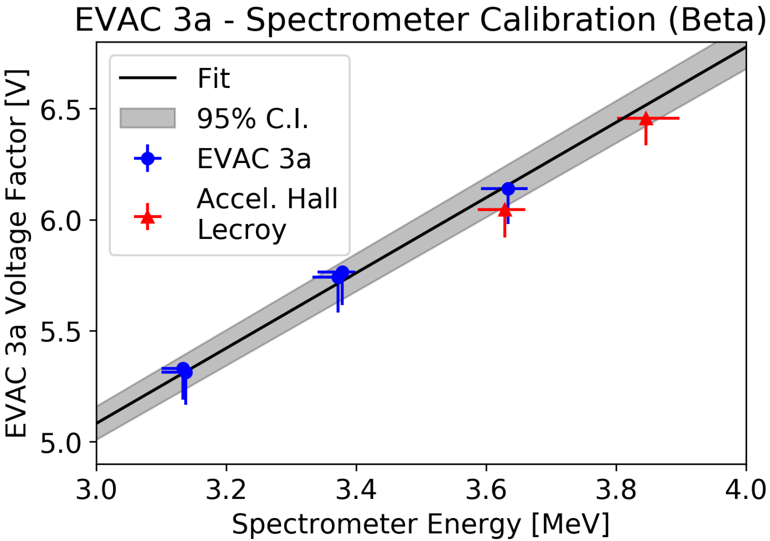
- Data at flattop are limited to maximum value
  - Normal distributions extend smoothly out
  - Most likely value does not coincide with the max
- Beta distribution can give fixed range distribution
  - Can be sampled by Markov-Chain Monte-Carlo algorithms
  - Alpha and beta parameters determined by mean, mode, and maximum of data sets



Calibration with beta model yields reasonable results



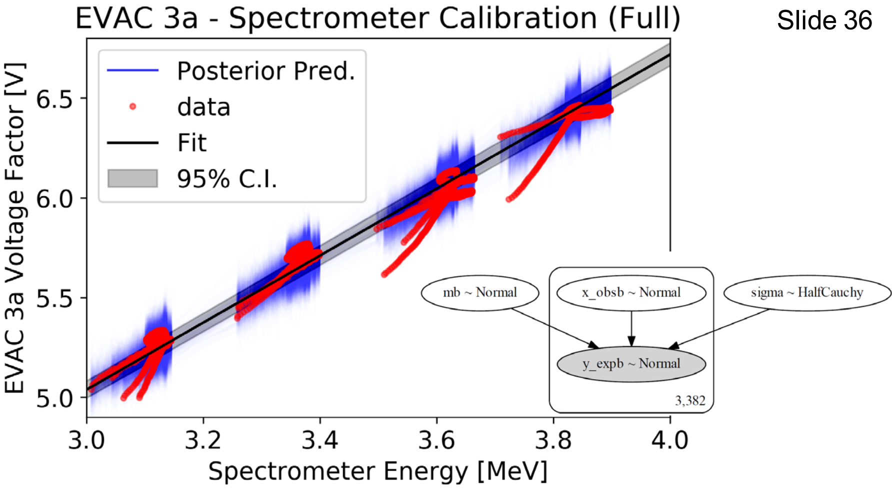
- Single calibration constant found
  - Intercept set to zero
  - Spectrometer data follows Beta distribution
  - Observations normally distributed with variance equal to observed

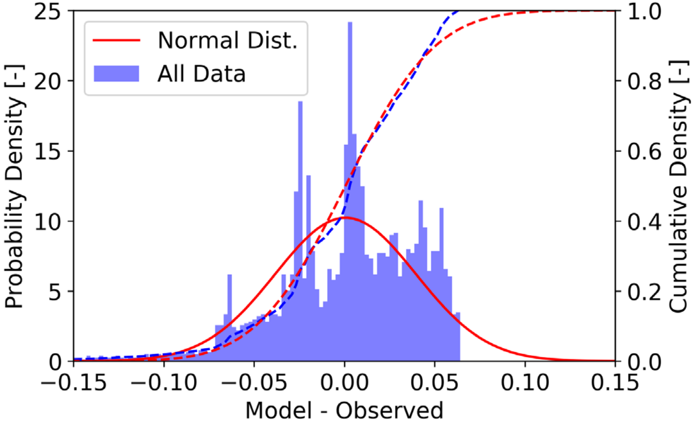


- Result with **seven data points** at right (1.5% variation in 95% Confidence Interval)

Using all data points, find smaller uncertainty

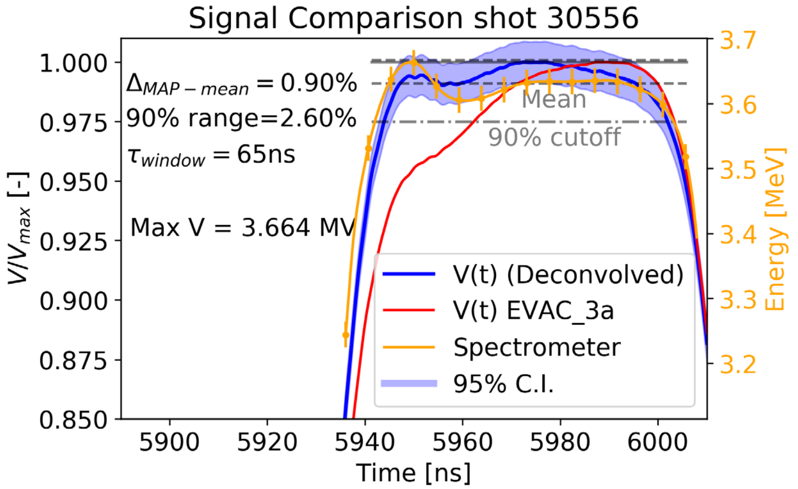
- Larger number of observations (~3400 vs. 7)
  - Normally distributed variables assumed
  - Compare CDFs of data and Gaussian
- Result with **seven shots** yields improved precision (~0.86% variation in 95% Confidence Interval)

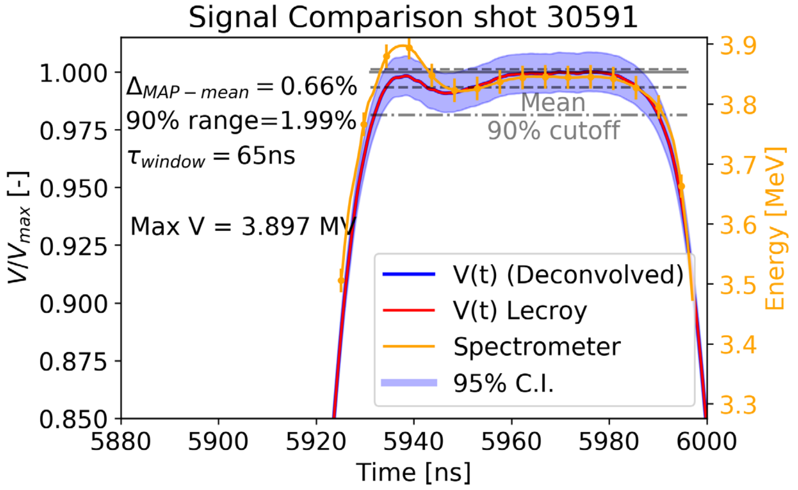




Results give good agreement with spectrometer

- E-dot signal now consistent with spectrometer to within uncertainty (of **both** instruments)
- Can, in principle, use E-dot instead of time-intensive spectrometer





Which calibration process is correct?

- What do you think? Beta model or total data set?
- More computational horsepower was needed for the full data set, but resulting confidence interval is tighter. Do you believe it?
- Assumed distributions are present in both analyses. Were either correct?
- In the end, stating your assumptions, displaying the results, and drawing reasonable conclusions are what peers review

Words of wisdom:

- “All models are wrong, but some are useful.” –George Box

Some suggested readings

- M. Bertero and P. Boccacci, *Introduction to Inverse Problems in Imaging*, IoP publishing, 1998. (overview of issues and strategies with ill-posed problems)

- D. Sivia and J. Skilling, *Data Analysis: A Bayesian Tutorial*, Oxford Univ. Press, 2006. (includes great discussion of least squares)

- A. Gelman, *et al.*, *Bayesian Data Analysis*, Chapman and Hall/CRC Press, 2013. (more theoretical basis for Bayesian analysis methods)

- N.C. Barford, *Experimental Measurements: Precision, Error and Truth*, Wiley, 1985. (traditional, “frequentist” approach, very practical)

More suggested readings for your specific diagnostic method:

"Why waste 2 hours in the library when you can spend 6 months recreating someone else's result?"

Anonymous

Summary

- Diagnostics are hard, even ones that haven't touched a plasma yet!
- Injector voltage on DARHT-1 is a case study in keeping track of the entire diagnostic chain
  - System response functions were the key to recovering precision in the diagnostic
- Cross-calibration methods and models compared, **you are not only modeling the experiment, you are also modeling the data!**

Acknowledgements

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