High Precision Magnetic Field Measurements of Fast Pulsed Magnets

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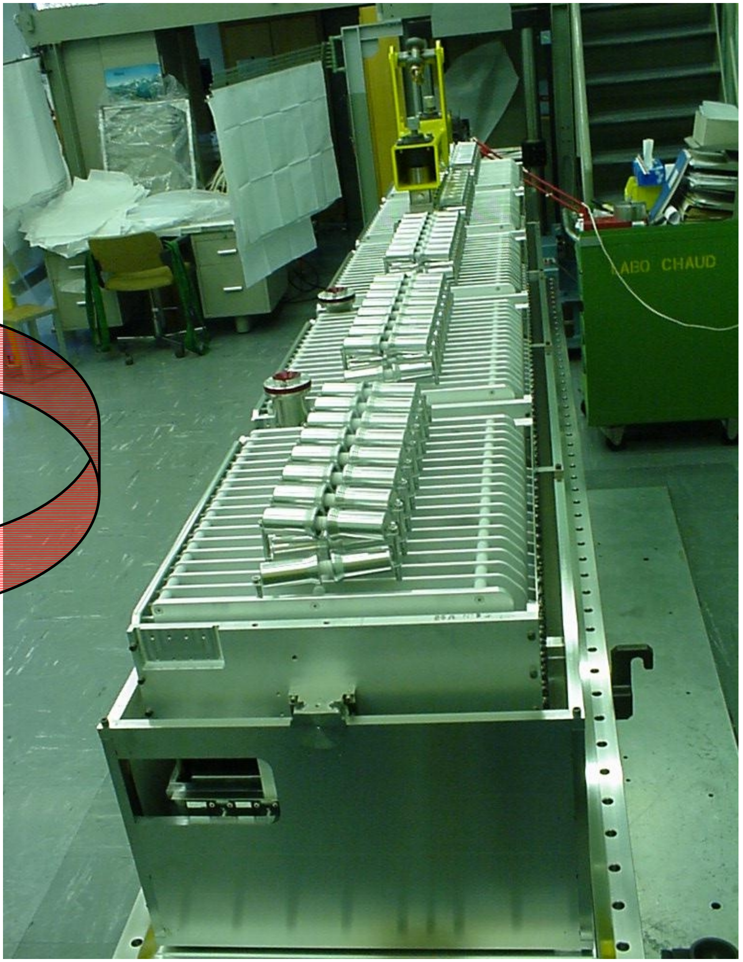
Fast Pulsed Magnets

- ***Fast*** pulsed magnets are used for extracting or injecting particles
  - » ***Fast*** = rise times as fast as 150 ns
  - » ***But 'long'*** = flat top of several μs
  - » allowed field ripple < 1 %

Hard to measure simultaneously, with the same device

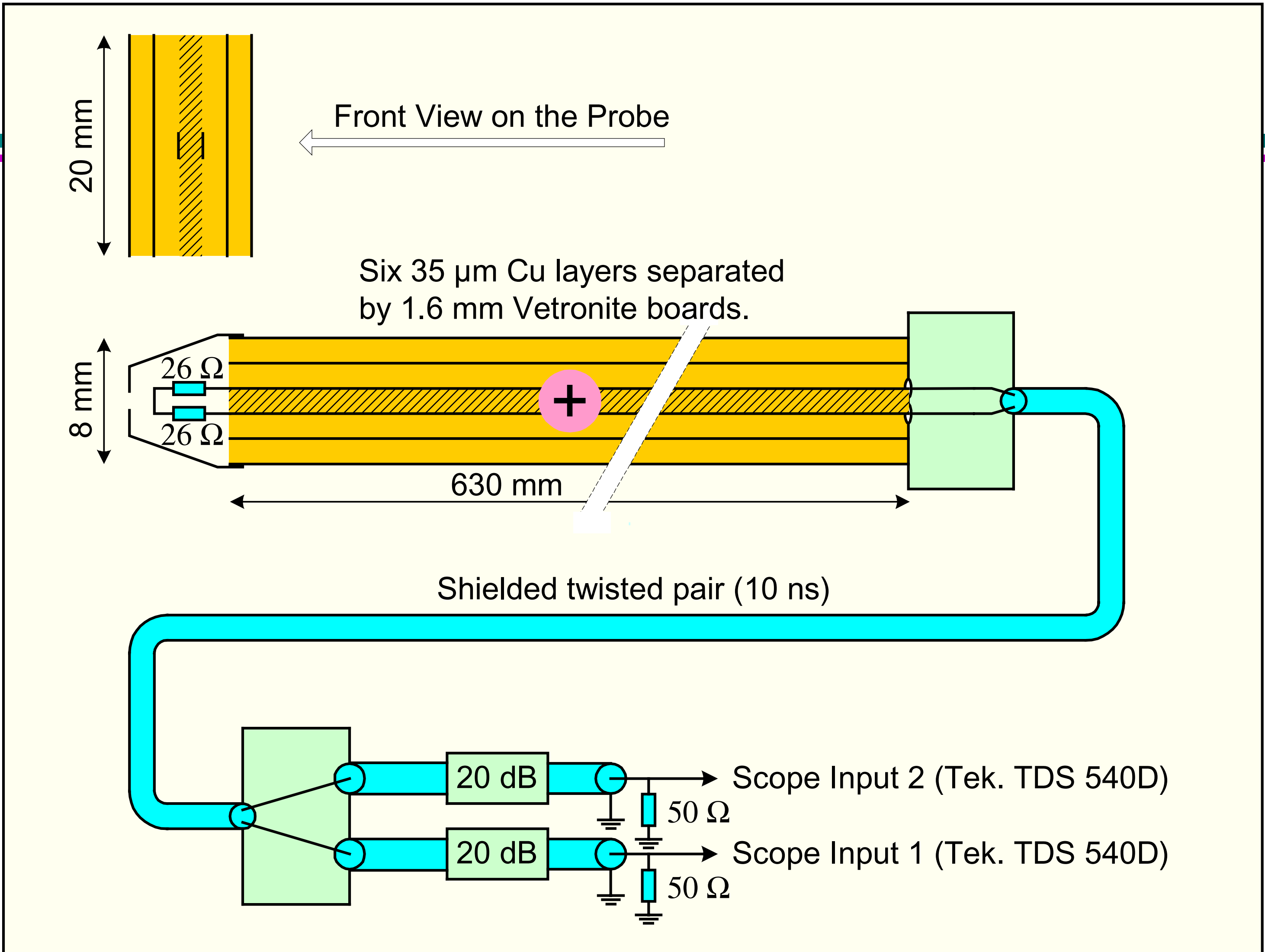


- Transmission line type magnet with terminating resistor

Field Measurements

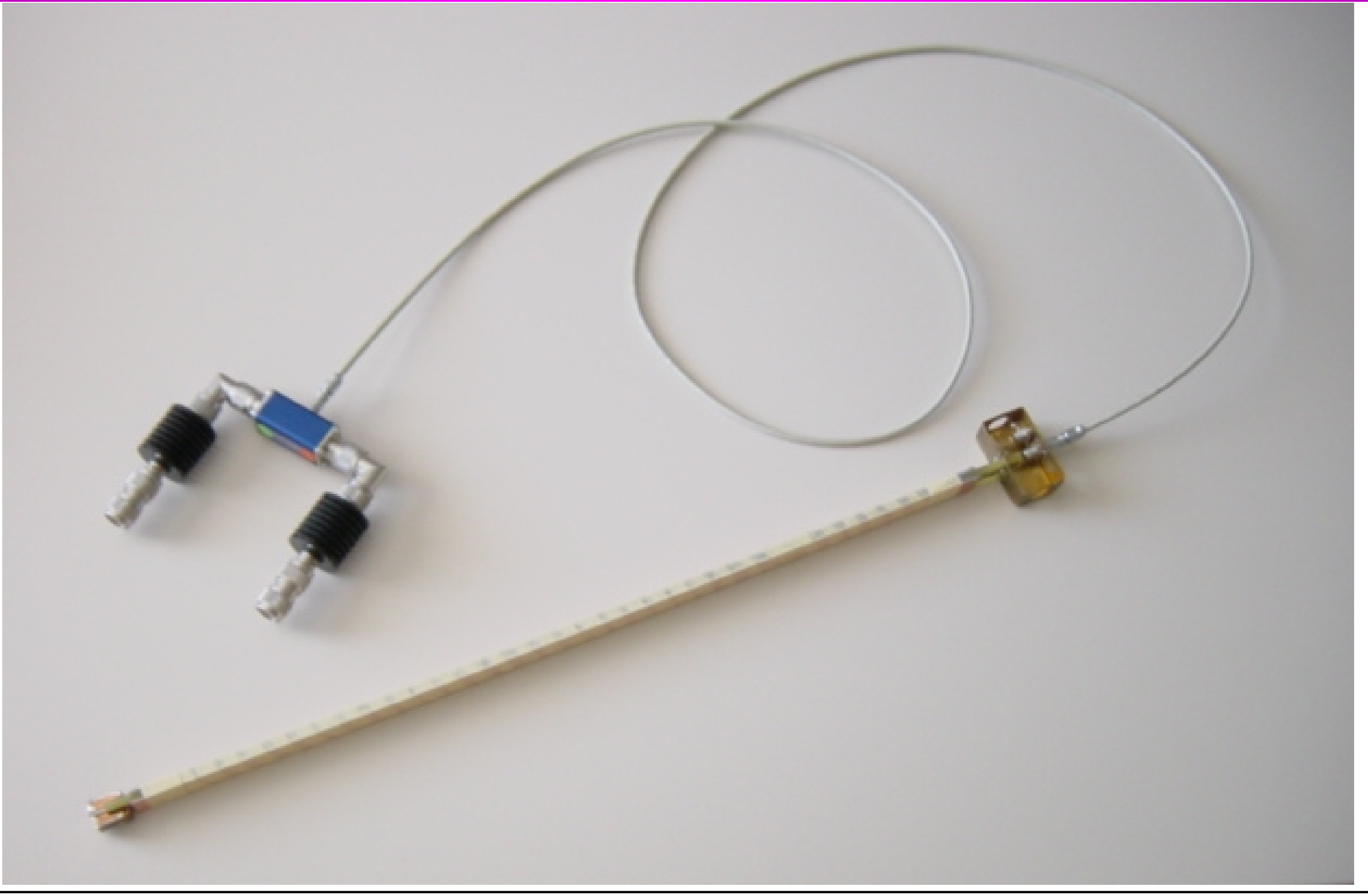
- Interested in **time** behaviour, not in field maps
- Standard: look at signal from the ***terminating resistor***
  - » no information on rise time
  - » signal is filtered by the resistor
- ***Inductive probe:*** can be used in laboratory but not under machine conditions
  - » only ***direct*** measurement of the field
  - » problem is capacitive noise, can be screened
- ***Capacitive probe:*** can be used in the machine as well
  - » use that $B = \quad (U_{\mathbf{entrance}} - K(t) \cdot U_{\mathbf{exit}})\, dt$
  - » need very precise measurements, errors integrate in the time

Inductive Probe, Schematic

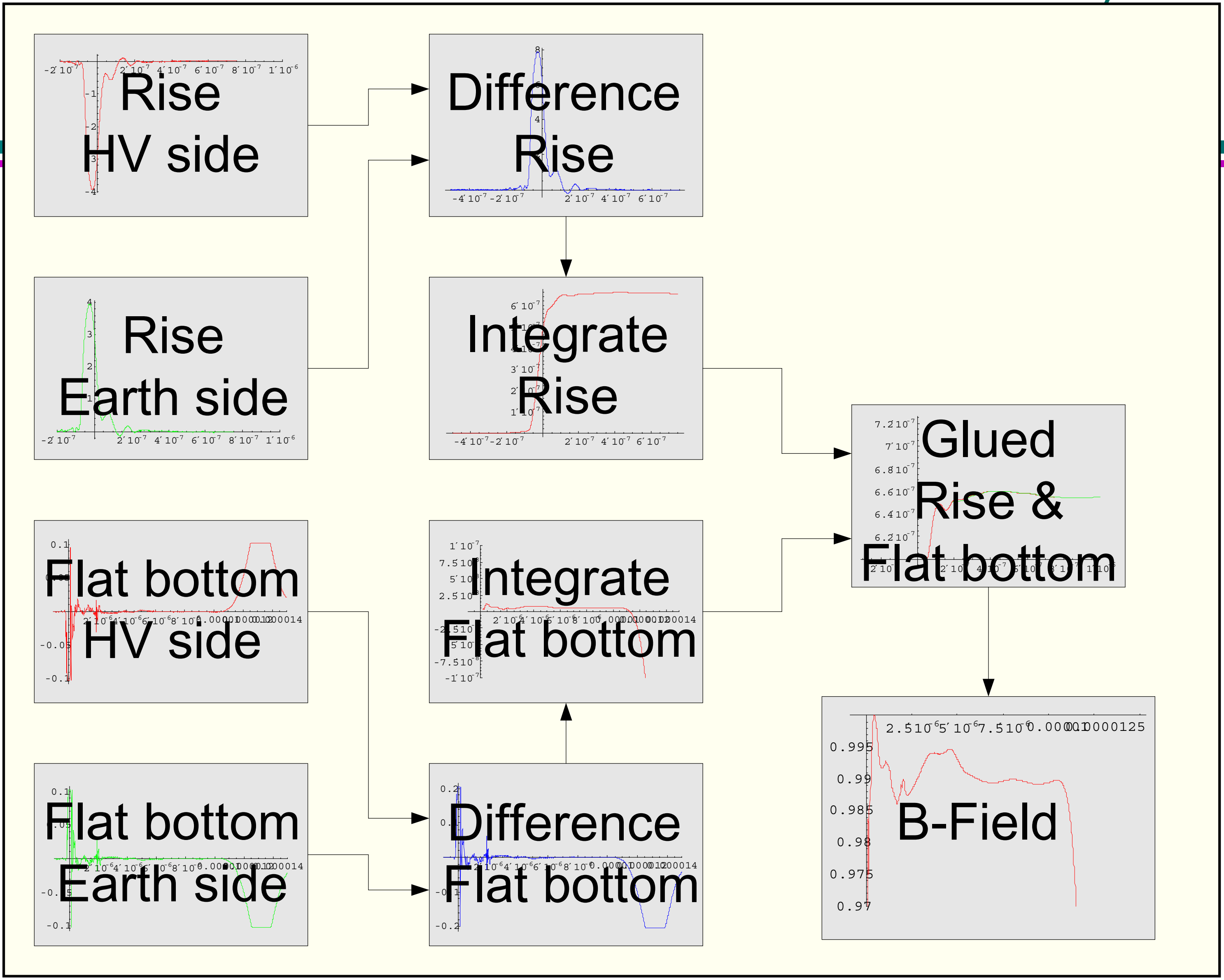


Inductive Field Probe for Kicker Magnets

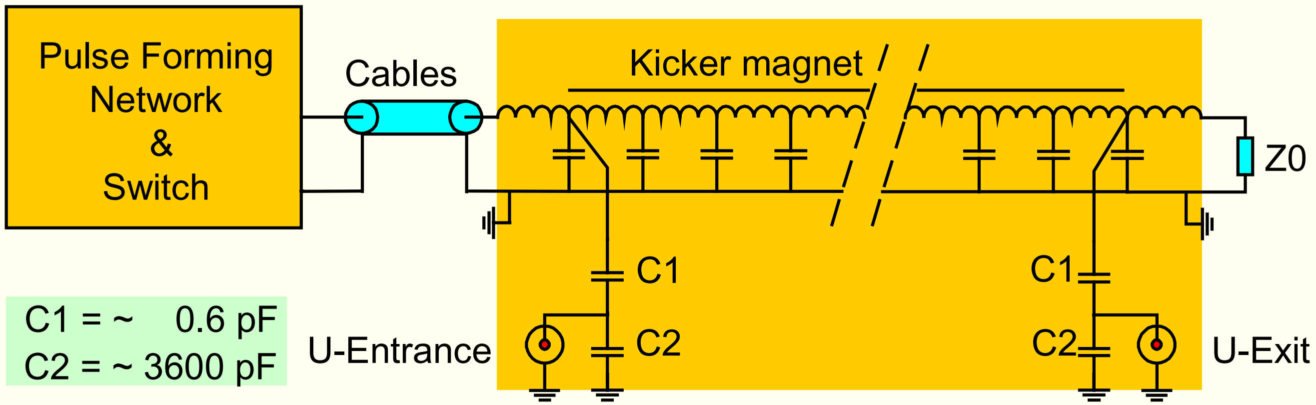
Inductive Probe



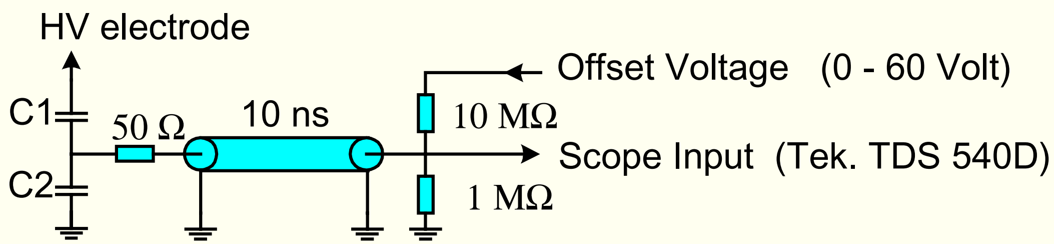
Inductive Probe: Data Analyses



Capacitive Probe: Principal

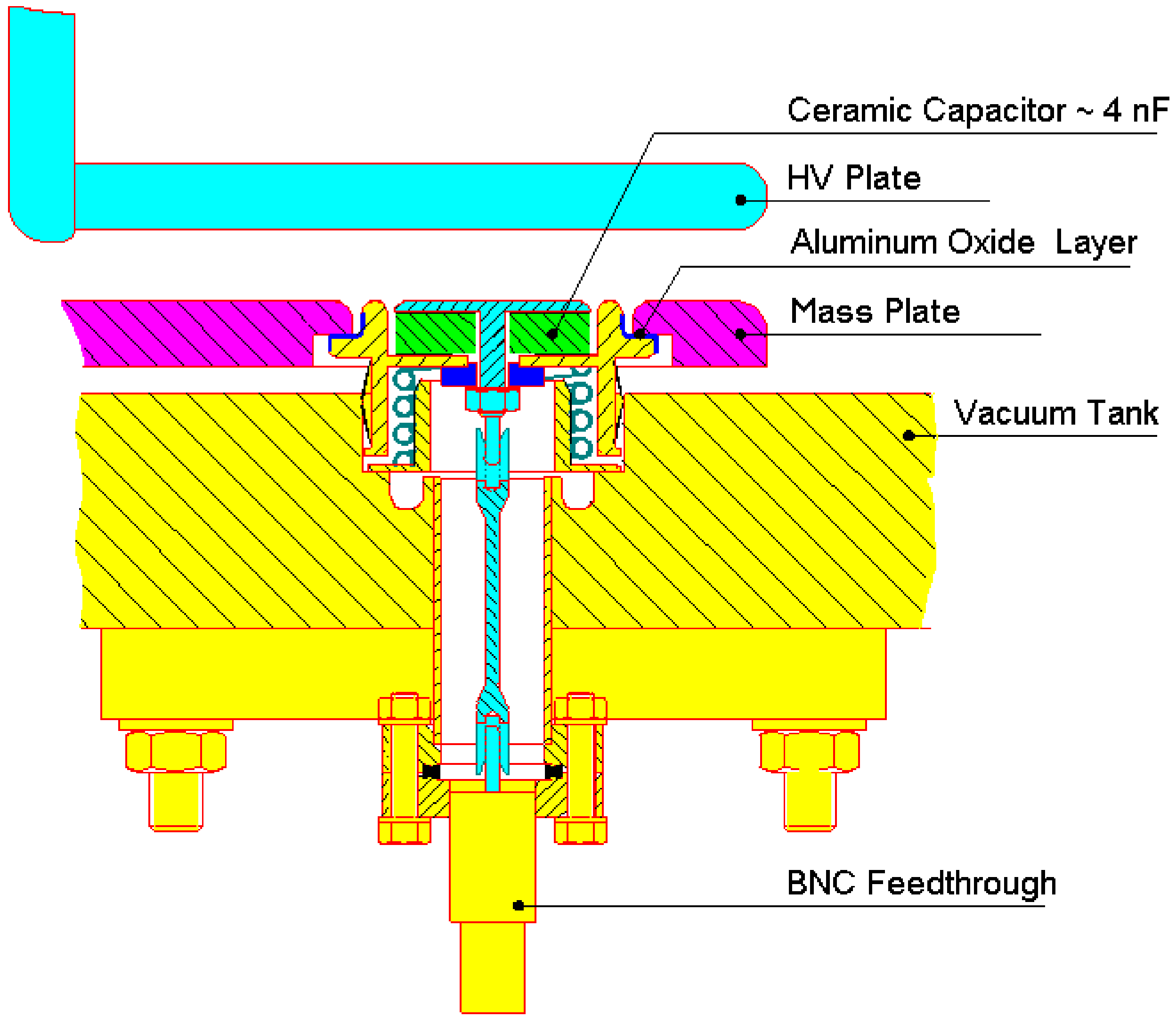


Kicker Magnet with Capacitive Pick-ups



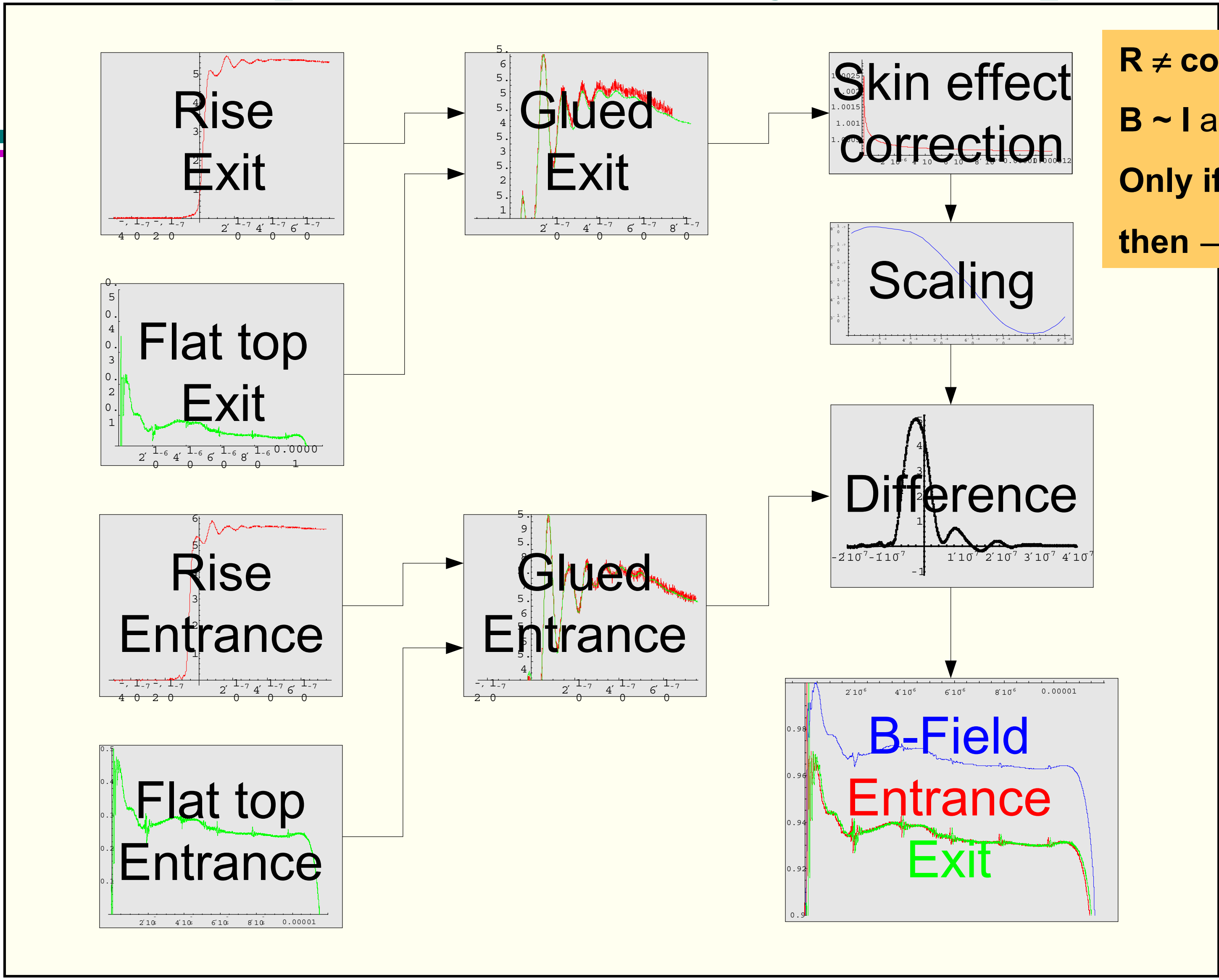
Measurement circuit

Capacitive Probe, Mechanical



Capacitive Pick-up SPS Injection Kicker Magnets

Principal Data Analyses Capa Probe



R ≠ constant

B ~ I and **U = I R**

Only if R = constant

then → B ~ Δ U

Capacitive Probe: Skin Depth Correction

- The surface impedance of a plane conductor, for the case of an applied unit-step voltage, is :

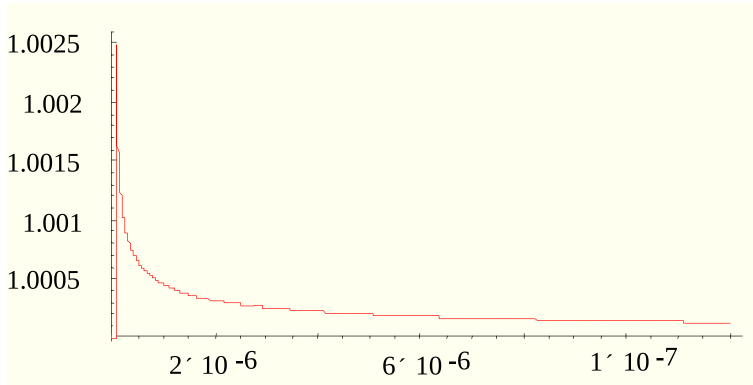
$$z(t) = \frac{l}{w} \cdot \sqrt{\frac{\pi \cdot \mu_o}{4 \cdot \sigma} \cdot \frac{1}{t}} \quad [\Omega]$$

- Summing up of the surface impedances of all cells along the HV conductor results, for t > delmag, in:

$$z(t) = fid \cdot \frac{Lmag}{n} \cdot \frac{1}{W} \cdot \sqrt{\frac{\pi \cdot \mu_o}{4 \cdot \sigma}} \cdot \sum_{i=1}^{n} \sqrt{\frac{1}{(t - delmag) + (i - \frac{1}{2}) \cdot \frac{delmag}{n}}} \quad [\Omega]$$

- For a correctly terminated magnet with its characteristic impedance z_o the exit voltage must be corrected by the factor:

$$K(t) = 1 + \frac{z(t)}{z_o}$$



Parameters

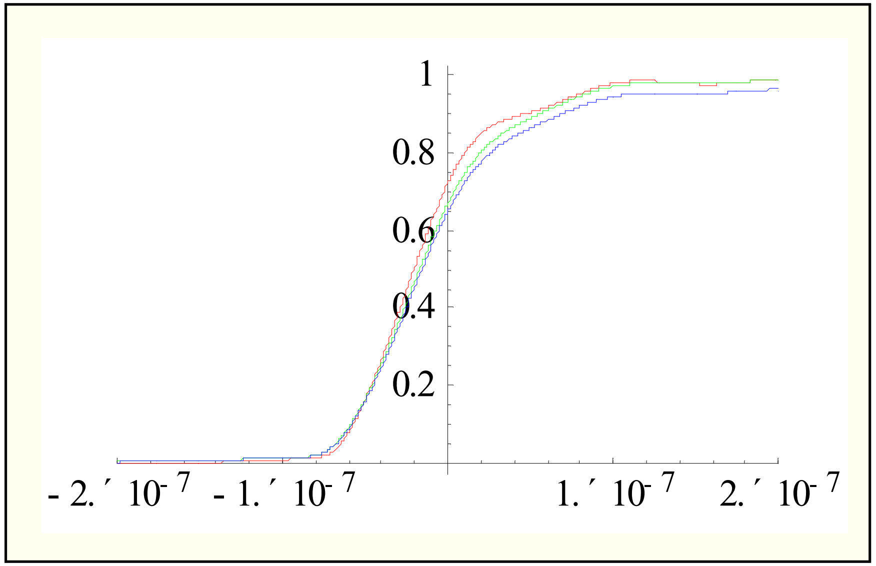
- *Lmag*	= total length of HV conductor
- *n*	= number of cells (used: n = 17)
- *W*	= width of the HV conductor
- *delmag*	= delay of the magnet
- *fid*	= a multiplication factor (used: *fid* = $2\sqrt{2}$)
- σ	= conductivity (used: stainless steel)
- μ_o	= permeability of free space

Capacitive Probe: Measurement & Data Analyses

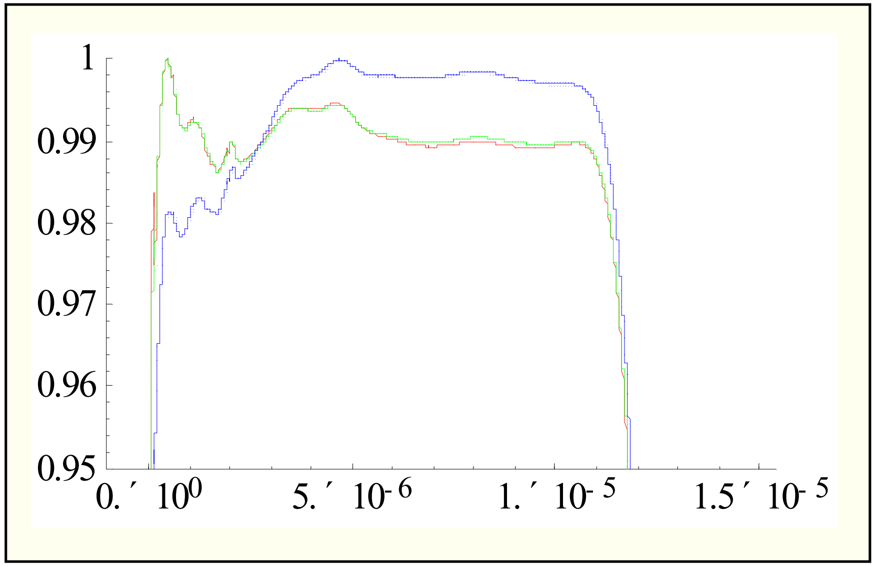
- Difficulty with the analysis is that errors accumulate due to integration process, need very precise measurements:
  - » Measurement is very sensitive to earth loops, need good mass connections
  - » quantification errors due to limited resolution of the equipment
- Resulting B-field in time should be parallel to direct voltage measurements in the flat part of the pulse verification of the measurement without having the inductive probe results

Comparison Inductive and Capacitive Probe Results

Rise time of magnetic field



Flat top of magnetic field



- Inductive probe
- Capacitive probe without skin depth correction
- Capacitive probe with skin depth correction

Conclusions

- An inductive probe and capacitive probe have been developed to measure fast pulsed magnetic fields.
- Inductive probe = direct measurement of the field you want
  - » Shield for capacitive pick-up. Careful probe design
- Capacitive probe more complicated but can be used in situ
  - » Is also a diagnostic of the powering equipment, Pulse Forming Networks
  - » location of breakdown in a magnet can be determined
  - » a skin depth correction has to be made to the capacitive measurement at the exit of the magnet
  - » care should be taken to avoid earth loops
- Both measurement agree very well within the required tolerance