In Situ Testing of EHT Integrators on a Tokamak

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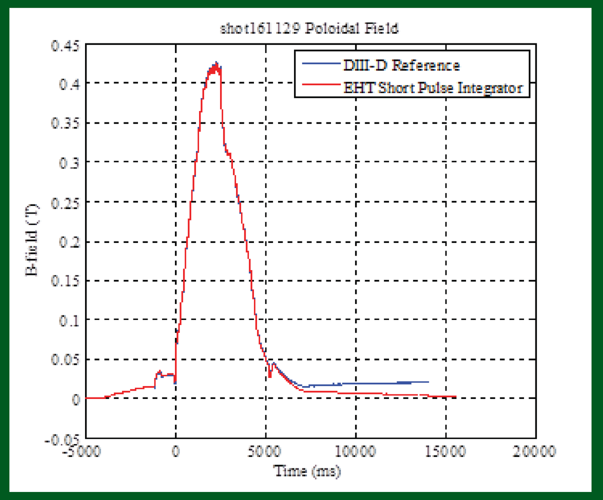
Introduction

EHT has developed three analog integrators for magnetic field diagnostics: a short-pulse integrator, a high dynamic range short-pulse integrator, and a long-pulse integrator. The short-pulse integrator is an off-the-shelf solution for experiments that need a high-gain and stability integrator. The high dynamic range integrator allows for improved resolution (bit-depth) for short-pulse experiments. The long-pulse integrator presently is the only known integrator that meets the specifications for ITER.

Previously the short-pulse integrator has been successfully tested on a Validation Platform Experiment. Here we present the results of testing all three integrators at DIII-D.

Short Pulse Integrator

EHT integrators were tested at DIII-D with three different diagnostics: the poloidal field, saddle loop, and Rogowski coil. The EHT integrator performance was comparable to the DIII-D integrators. The EHT integrators were gated on well before the toroidal field is turned on so the full temporal profile can be measured, while the DIII-D integrators are actively switched into their measurment circuit just prior to the plasma pulse to avoid excessive drift and noise injection.



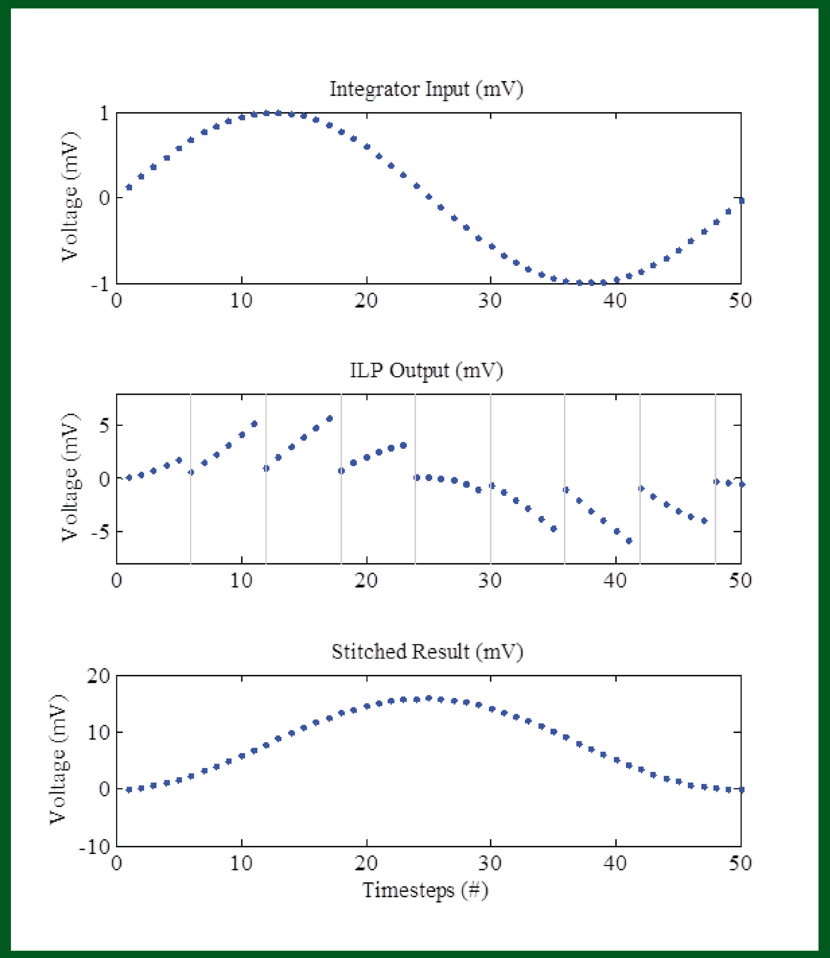
DIII-D vs EHT Poloidal Field measurement.

Integrator Operation:

In long pulse and/or high dynamic range operation, the EHT integrator utilizes a fast digital reset to rapidly re-zero the integrator. The reset period is short compared to the integrator drift timescale, which allows the EHT integrator to remain stable for long periods of time (> 1000 s). As a result, the raw integrator data must be processed prior to utilization.

The figure shows a simulated sine wave input (top). The middle plot shows the simulated output of the EHT integrator with the re-zero periods highlighed with vertical lines. Note that each data set during a reset period starts at zero. The simulated raw data is stitched back together (bottom) to form the expected cosine wave.

The data processing can be accomplished in real time using an FPGA or by post-processing.



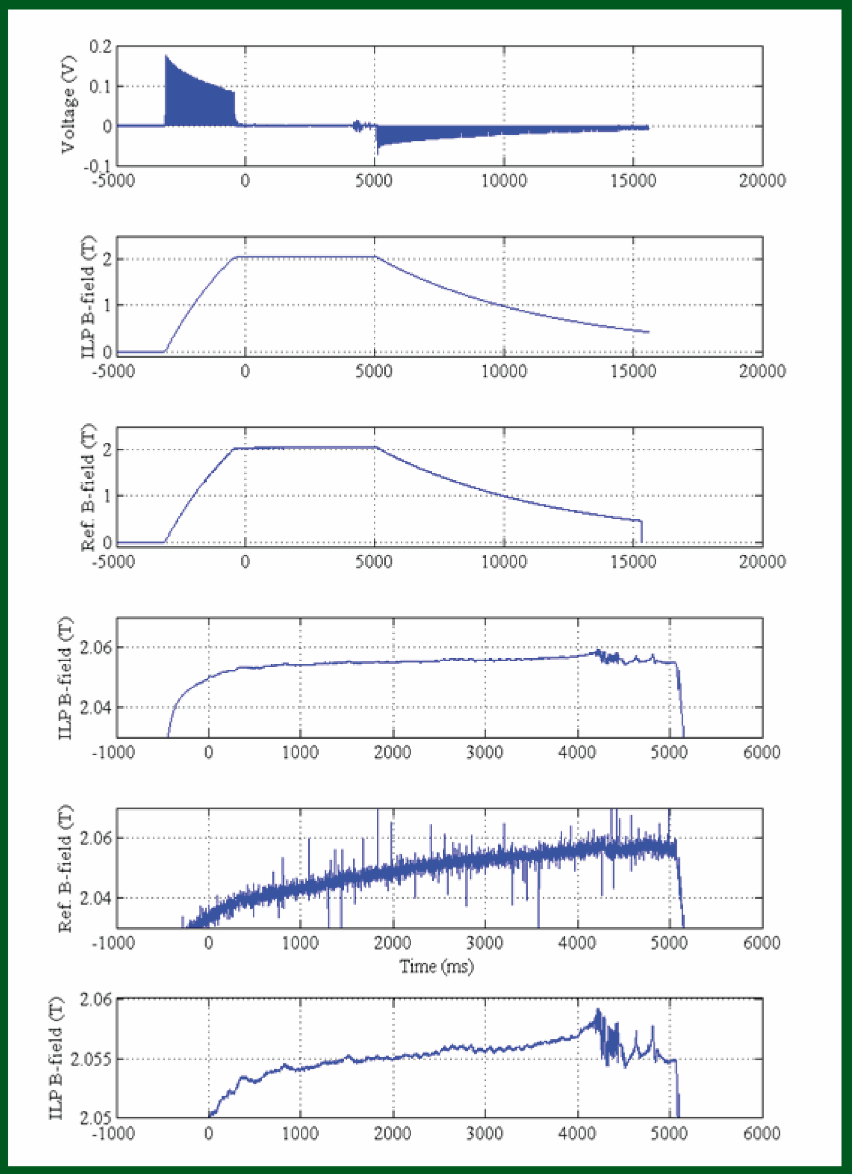
Simulated integrator input (top), raw integrator output (middle), and stiched data (bottom).

High Dynamic Range Integrator

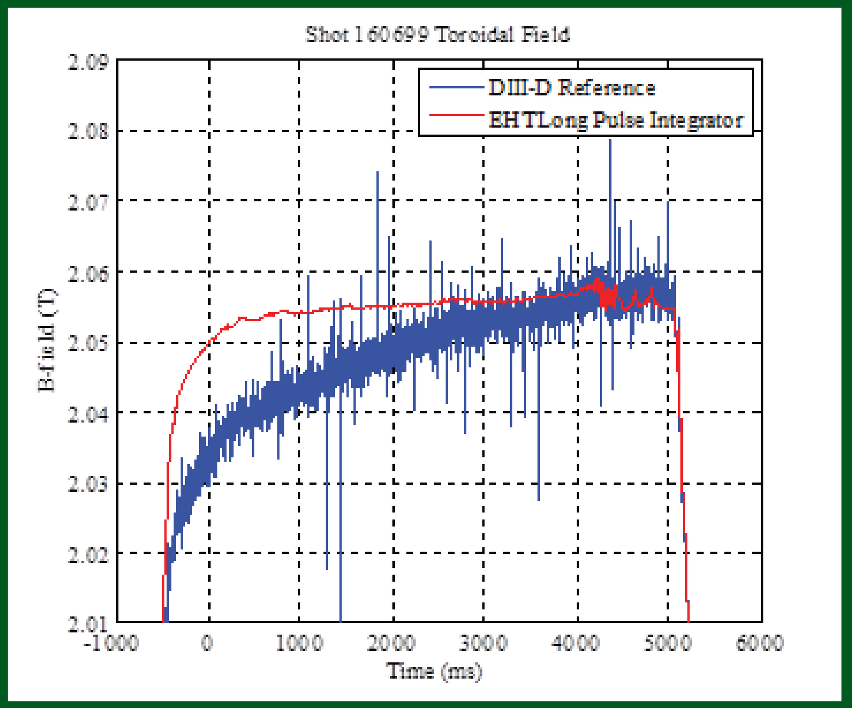
The output of an integrator is recorded by a digitizer, which has a specified input voltage range and bit depth (resolution). For example, a typical DAQ might have an input range of ±1 V and 16 bits of resolution (meaning it can ideally resolve the input data in 31 µV increments). With a standard integrator, these 16 bits of resolution are all the user gets for their output signal.

In contrast, the full range of the DAQ can be filled in a single re-zero period with the EHT integrator. For example, a 10 second linearly ramping signal obtained with a standard integrator and DAQ might have 16 bits of resolution, but if it is recorded with the EHT integrator re-zeroing at 10 Hz, there will be an extra factor of 100 in voltage resolution, or roughly an extra 7 bits of resolution.

This high dynamic range technique was tested on a toroidal magnetic field coil at DIII-D. The figure shows the EHT integrator (ILP) data prior to stitching, and the EHT integrator data post stitching, the DIII-D toroidal field reference. The next three plots show a detailed view of the flat top of both the EHT integrator (ILP) and DIII-D integrator, which highlights the difference in resolved signal. The EHT integrator can resolve features that are lost in the bit noise of the DIII-D integrator and increases the dynamic range by about 100.


Comparison of the EHT long pulse integrator vs DIII-D integrator. Dynamic range enhancement

This is result is highlighted by overlaying the ILP8 data (red) and reference data (blue). The overall amplitude and profile of the magnetic field differs between the plots because they were obtained using different locations for the measurement coils, but the increased resolution of the EHT signal is clearly evident.

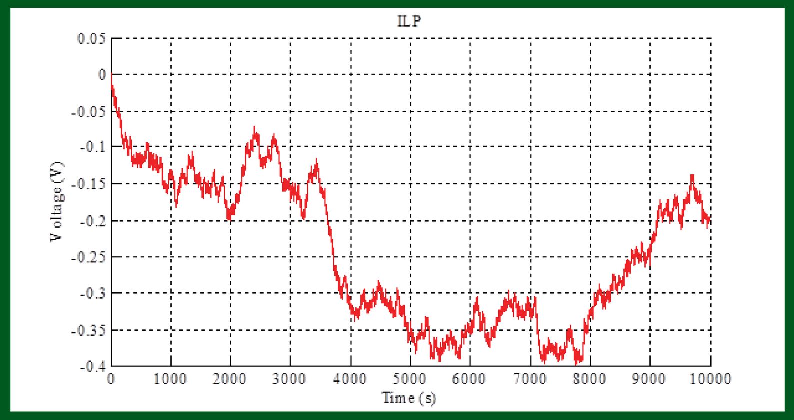


Overlay of EHT vs DIII-D integrator data showing increase dynamic range of the EHT long pulse integrator.is seen using the EHT integrator.

For short pulse experiments (several milliseconds), faster re-zeroing is necessary to provide this benefit.

Long Pulse Integrator

Long pulse drift testing was conducted at DIII-D. The EHT integrator (2 ms RC) was connected to the toroidal field diagnostic and monitored for 10^5 s while DIII-D was not in operation. The measured drift was 0.3 V over 10^5 s and the figure of merit was $6x10^{-8}$ V-s/s. This figure of merit is just within the ITER specification of $7x10^{-8}$ V-s/s (over a 1 hour period). On the bench the EHT integrator had figure of merit in the 10^{-9} V-s/s range. Drift performance can be improved with shorter RC times, which can be accomplished with a shorter re-zeroing period.


EHT integrator 10,000 second drift data while connected to DIII-D toroidal field dignostic.

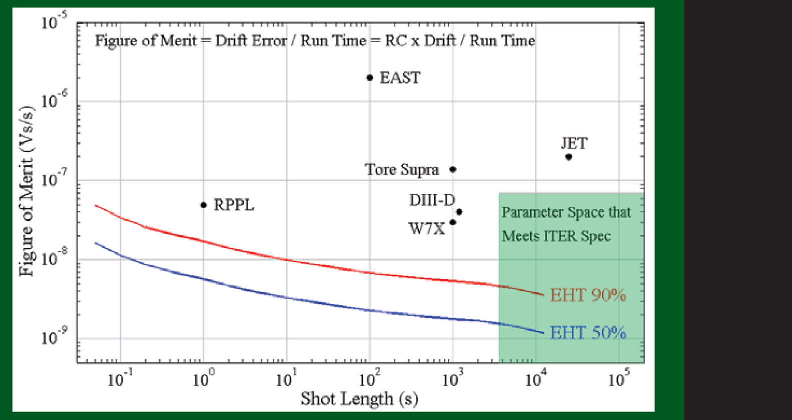


Figure of merit comparison of different integrators and ITER spec.

The figure above (right) shows the ITER drift specification (green), as well as the results reported from integrator testing by other groups. The red and blue curves show the figure of merit of the EHT long pulse integrators at the 50% (blue) and 90% (red) confidence levels. The EHT long pulse integrator is the only integrator that meets the ITER specifications.

Summary

EHT has developed a short pulse integrator, relevant for validation platform experiments and many tokamaks; long pulse integrator, relevant for burning plasma experiments like ITER; and a high dynamic range integrator, relevant for precision measurement of short pulse experiments. The characteristics of each integrator are summarized in the table below.

	Short Pulse	Long Pulse
Number of channels	16	8
Bandwidth	5 MHz	5 MHz
Drift error	< 10^{-7} V-s for 1 s	< 5 × 10^{-5} V-s for 3600 s
Gain (RC time constant)	1 µs to 100 ms	1 µs to 100 ms
Input impedance	50 Ω to 100 kΩ	50 Ω to 100 kΩ
Low output impedance	50 Ω	50 Ω
Stable operating time	10 s	---------
Input connectors	RJ45	RJ45
Output connectors	BNC, RJ45, VHDCI	BNC, RJ45, VHDCI


Left: Front (Left) and back (Right) panels of the EHT integrator short pulse.

Acknowledgments:

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Further Information:

For more information on the EHT Integrator or switching power supplies please visit our website (http://www.eagleharbortech.com) or email us.