I_c Testing — Standard Operating Procedure

April 2025

Contents

1 Overview

This document contains the information necessary to take critical current measurements of HTS tape samples using the Keysight N6972A current source and Keysight 34420A nanovoltmeter. The manuals for these are linked here and here respectively. While these are useful resources for further tuning the equipment, the aim is for everything here to be self-contained.

We will explain the basic operation procedure of the current source and voltmeter and describe how these are to be connected to a sample of interest. Taking measurements using an existing Labview VI is detailed with guidance on how to design new measurement scripts for other experiments.

2 Equipment List

2.1 Current Source — Keysight N6972A

The N6972A power source is capable of delivering 2 kW with a maximum current of 50 A and maximum voltage of 40 V. Annotated diagrams of the front and rear panels are shown below.

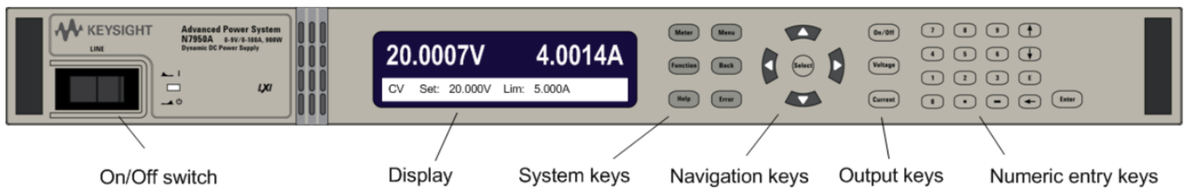


Figure 2.1: Front Panel of N6972A [1]

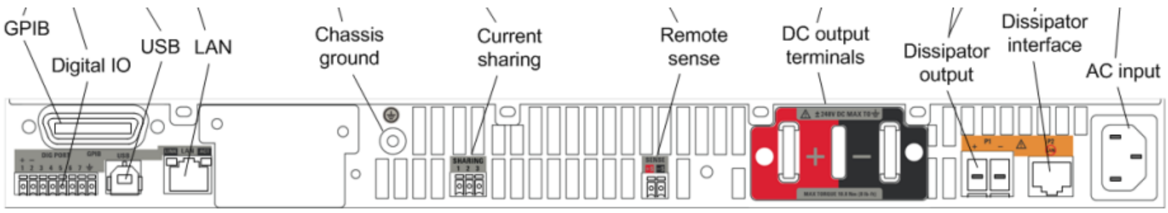


Figure 2.2: Front Panel of N6972A [1]

1. Connecting to Mains

   The N6972A requires a 15A AC input. A '20A in → 15A out' conversion box must be used to connect the source to the mains supply.

2. Manual Operation

   While the source is to be mainly operated remotely using a Labview VI, the front panel display is useful for monitoring the instantaneous delivered current and voltage. Manual operation mode however is useful to test if a connected circuit is indeed closed. To switch between manually delivering a current or voltage, use **Menu → Output → Current/Voltage Priority Mode**. Failsafe current and voltage limits can be set directly using the front panel, or more easily, adjusted through a Labview VI.

3. Connection to Computer

   Use the USB terminal visible on the rear panel for remote operation with a computer.

2.2 Voltmeter — Keysight 34420A

The 34420A nanovoltmeter is capable of measuring voltage signals from two channels.

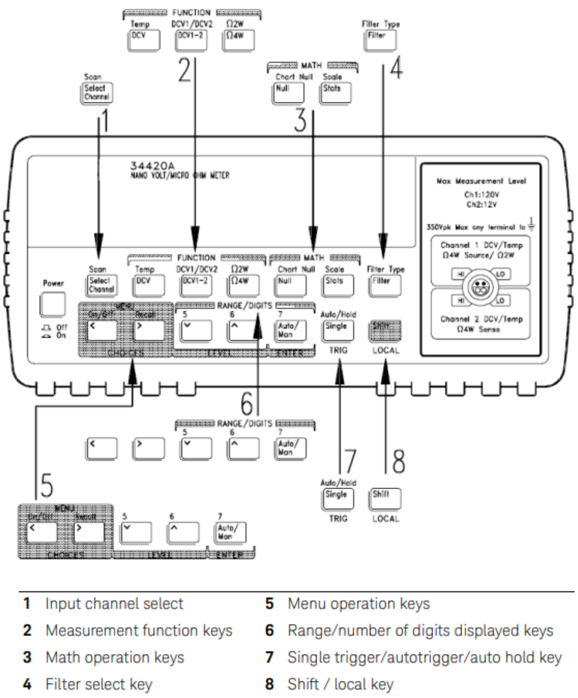
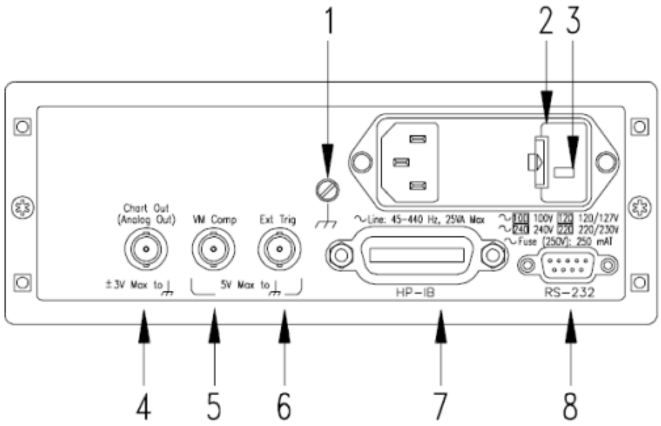


Figure 2.3: Front Panel of 34420A [1]



1	Chassis ground	**5**	Voltmeter complete output terminal
2	Power-line fuse-holder assembly	**6**	External trigger input terminal
3	Power-line voltage setting	**7**	GPIB (IEEE-488) interface connector
4	Chart recorder output terminal (Analog out)	**8**	RS-232 interface connector

Figure 2.4: Rear Panel of 34420A [1]

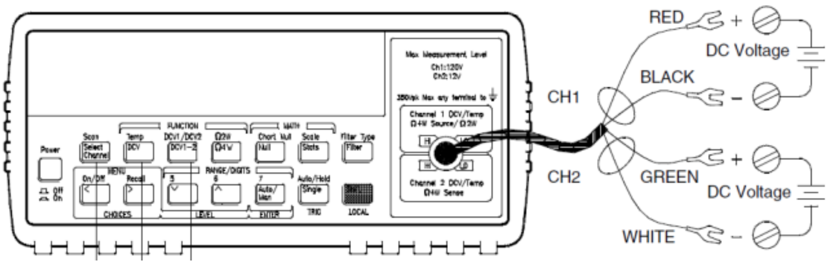


Figure 2.5: Provided cable to connect two voltage channels

1. Manual Operation

   Operating the voltmeter manually is useful to verify whether a connected circuit is closed and can also be used to get an indication of the critical current in the absence of a working Labview VI. Use the **Local** button to toggle between remote and local operation and use the **Select Channel** button to alternate between both channels.

2. Filters

3. Connection to a Computer

   Use the RS-232 interface connector for remote operation with a computer.

2.3 Voltage Taps

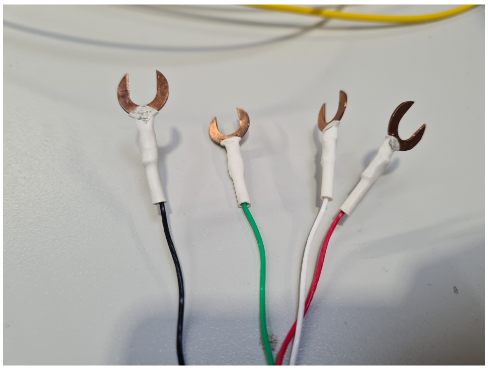
1. Voltage channel wires

   Use enamel-coated copper wire to make a twisted pair for the greatest noise reduction in the measured signal.

2. Connection to Voltmeter

   To connect a voltage signal to the nanovoltmeter, it is recommended to use an intermediate connector as in the figure below. This fastens the wires and voltmeter connectors together decreasing the amount of noise in the measured signal. A small piece of wood with through holes drilled a few cm apart can be used in a pinch, with the wire and connector being fastened using a screw

(a) Intermediate connector between copper plate and channel



(b) Voltmeter channel connectors

and nut. Other modes of connection without proper fastening like crocodile clips have previously resulted in much greater signal noise. Minimise the distance between the Hi and Lo connectors to avoid any inductive loops.

2.4 Current Connection

1. HTS tape

   If connecting voltage taps across a section of HTS tape, minimise the size of any potential inductive loops formed at the tape. Voltage wires should run parallel to the tape section as shown in the figure below to achieve this.

2.5 Loading Effect

When connecting the current source to a sample, an increase in the measured voltage across the sample was observed on the nanovoltmeter. This was observed independent of whether the current source was turn on or off. The voltage offset measured was often between 100 uV to 1000 uV and varied whenever the source was disconnected and reconnected. If just a power law is fit to the voltage-current curves measured, this effect will confound the fitted I_c. It is recommended that either a DC offset is added to the fitting model, or the offset is subtracted from each measurement live as data is being obtained.

3 Labview Interface

3.1 Drivers

To use the Labview VIs for the current source and voltmeter, the appropriate drivers for your Labview version must be downloaded from the NI website. The most recent driver available should be compatible with any Labview versions released after it. The driver landing pages can be found at:

1. Keysight N6972A Labview Driver
2. Keysight 34420A Labview Driver

Zip files of the drivers used in the following VI explanations can be found in the same repository as this SOP.

3.2 Useful VIs

When setting up the current and voltmeters for remote operation, there are a number of high-level VIs that can be used. To find the VIs for each device on Labview, use **Functions Pallete** → **Instrument I/O** → **Instr Drivers** → **Agilent 34420/Agilent N6900 N7900 Series**. Listed below are the basic VIs necessary to perform I_c tests.

Table 1: Useful Voltmeter VIs

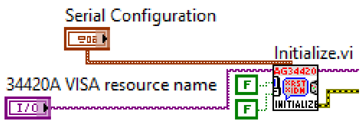
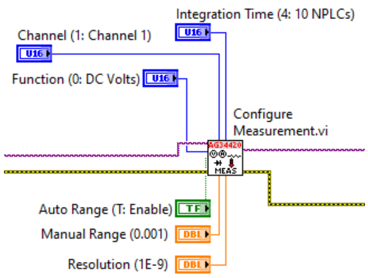
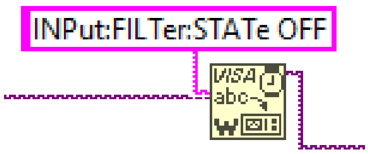
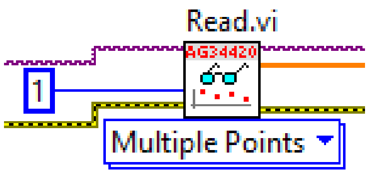
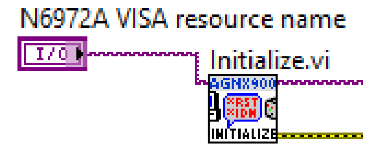
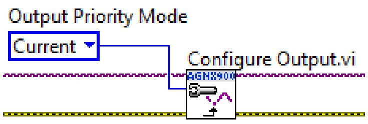
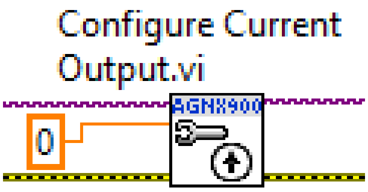
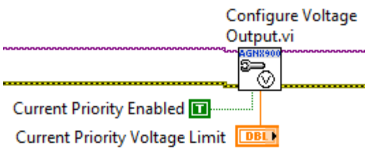
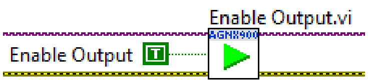
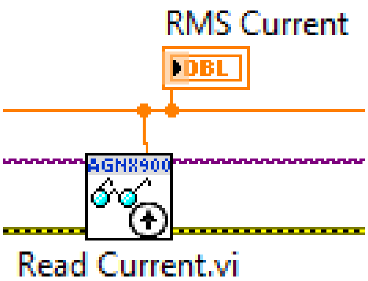
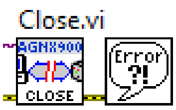
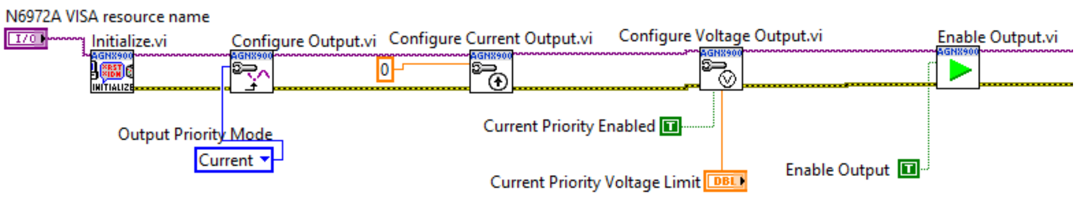
VI Name	Image	Description
Initialize.vi		This VI should be used to load the voltmeter into Labview. For normal usage, controls for each of the inputs should be created with all of the default values selected.
Configure Measurement.vi		This VI allows the setup of measured voltage range, resolution etc.. The 'Auto Range' input is usually sufficient for the voltage ranges measured in a standard I_c test. If 'Auto Range' is not sufficient, the 'Manual Range' and 'Resolution' inputs are partially dependent on each other, only allowing measurement for certain pairs of values. For more information, see to be completed. The initial channel to measure from can be selected here.
VISA Write		For more specific commands for which there exists no specific high-level VI, a 'VISA Write' VI can be used to directly pass arguments to the meter. The above code block is necessary after using Initialize.vi and Configure Measurement.vi. We will explain directly writing to a device without using a VI in section to be completed
Read (Multiple Points).vi		When given an integer number n of measurements to read, this VI reads n voltage values and returns them as an array of double precisions numbers.
Close.vi		Ends the remote operation of the voltmeter, to be used at the end of an I_c measurement script.

Table 2: Useful Current Source VIs

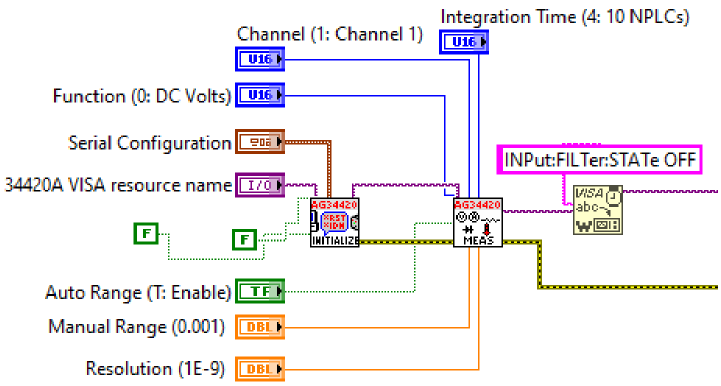
VI Name	Image	Description
Initialize.vi		Loading in current source into Labview.
Configure Output.vi		Setting up the Keysight N6972A as a current source, not a voltage source.
Configure Output Current.vi		Manually setting the current output value.
Configure Voltage Output.vi		Although we will not be setting a voltage for the source to output, we still use the corresponding VI to set a maximum voltage threshold for the current source.
Enable Output.vi		Turns the current source on, at which time the current set using 'Configure Output Current.vi' will be delivered.
Read Current.vi		Read instantaneous current supplied
Close.vi		Close remote operation of current source

4 Existing I_c testing VI

Within this repository, in the to be completed VI, there is a complete ic testing VI. The default setup for the current source and voltmeter in this VI is pictured below:



(a) Setting up current source



(b) Setting up nanovoltmeter

The basic measurement script executes the following:

1. Configure both the current source and nanovoltmeter for data collection
2. Given the presence of a DC voltage offset when the current source is connected to a sample, we measure the voltage across the taps when the current is 0 A. The average voltage measured from 10 data points is then subtracted from every subsequent voltage measured with the current source active. While this is strictly not necessary as we can add a DC offset into the curve fitting model, already subtracting it at this point allows us to use a simple power law fit. In some cases, fitting an I_c curve with a DC offset and resistive contribution term to noisy data can lead to a negative resistance value which is non-physical. It is generally preferable to just fit a power law to avoid this.
3. Loop

Algorithm 1 I_c Testing Loop

$i \leftarrow 0$
$v \leftarrow$ Read (Multiple Points).vi
while $(v \leq v_{MAX}) \wedge (i \leq i_{MAX})$ **do**
  $v \leftarrow$ Read (Multiple Points).vi
  Record i, v values in tdms file
  if $i \geq$ i threshold 1 **then**
    $i_{INC} \leftarrow$i increment 2
  else
    $i_{INC} \leftarrow$i increment 1
  if $v \geq$ v threshold **then**
    $i_{INC} \leftarrow$i increment above µV threshold
  $i \leftarrow i + i_{ENC}$
  WAIT 1 s

4. Wait a specific amount of time. If desired, take temperature measurements from the Pt100 at specified intervals.

5. Fit the extended power law ic relationship, $V = (\frac{I}{I_c})^n + I \times R + V_0$, to the obtained data. Log both the I_c and n value in the tdms file.
6. Set current source to 0 A and close remote operation of both devices.

4.1 Output tdms file

Data from an experimental run is stored in three groups: Measured Data, Temperature Data, and Aggregated Data. **All data is stored as strings.**

Table 3: tdms File groups and channels

Group	Channels	Description
Measured Data	**Date** **Time** **Run Number** **Temperature (K)** **Voltage (uV/cm)** **Current (A)**	Stores data collected during each I_c test, including the voltage, current, and Pt100 Temperature (if desired).
Temperature Data	**Date** **Time** **Run Number** **Test Active?** **Temperature (K)**	Stores temperature data in between each I_c test, collected at specified time intervals.
Aggregated Data	**Date** **Time** **Run Number** **Ic (A)** **n value**	Stores the fitted I_c and n values from each I_c test.

5 Data Analysis

In *'Data Analysis.vi'*, a script has been written to analyse tdms files from one or more experimental runs. This file is set up to automatically read data from two previous sets of data collection, found in the folders 'Xray runs' and 'Further Tests'. See *'Data Analysis VI — Annotated'* for an explanation of each of the plots in *'Data Analysis.vi'*. An explanation of how to use this VI is in *'READ_ME.txt'*.

In the process of writing *'Data Analysis.vi'*, several helper VIs have been written, stored in the *'Helper VIs'* folder. If you would like to write your own VI to analyse data, these will be extremely useful to use. An explanation of the most useful of them is presented below.

Table 4: Name and Description of useful Helper VIs

Helper VI Name	Description
CtoK	Convert array of temperatures in °C to °K.
KtoC	Convert array of temperatures in °K to °C.
Power Law Model VI	Function object storing the standard $V = (\frac{I}{I_c})^n$ model. Used for curve fitting.
Extended Model VI	Function object storing the extended $V = (\frac{I}{I_c})^n + I \times R + V_0$ model. Used for curve fitting.
datetimearray_to_reltime	Converts a pair of date and time arrays into relative time doubles. **Extremely Useful!**
curvefit_usingmodel	Fits a desired function to an array of input X and Y values. Initial parameters and parameter bounds are to be specified.
NEWTempInterpolate	Given arrays of I_c and corresponding measurement temperatures in °C, calculates the temperature changes that would entirely explain the I_c variation.

References

[1] current manual `https://keysight-docs.s3-us-west-2.amazonaws.com/keysight-pdfs/N7977A/Advanced+Power+System+N6900+_+N7900+Series+-+Op.pdf`

[2] voltmeter manual `https://xdevs.com/doc/HP_Agilent_Keysight/34420A/34420_SM_Ed3.pdf`