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Progress in RF Controls at SNS

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Oct. 21, 2007

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OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

SNS Linac RF Control

Abstract

The Spallation Neutron Source uses a digital low-level RF control system (LLRF) on all of the 92 klystrons and 4 triode RF power amplifiers throughout its linac. The installation and commissioning of the LLRF began in 2004. It successfully supported beam commissioning during 2005-2006, and has continued to support subsequent neutron production and the beam power ramp-up to the current record of 180 kW. To date, the LLRF system has proved very reliable and easy to operate. Furthermore, the design of the digital hardware and software has demonstrated the required flexibility, allowing for the continual addition of new functionalities to meet the needs rising from operation. A sufficient quantity of spare hardware has been produced for long-term operation support. The planned power upgrade project will require production of an additional quantity of hardware, and this production is underway. This preparation has raised the issue of parts sourcing. By its nature, SNS RF control is a continuously-evolving project. It is anticipated that the current effort of beam power ramp-up to 1.4 MW will pose more challenges to RF controls during the next few years.

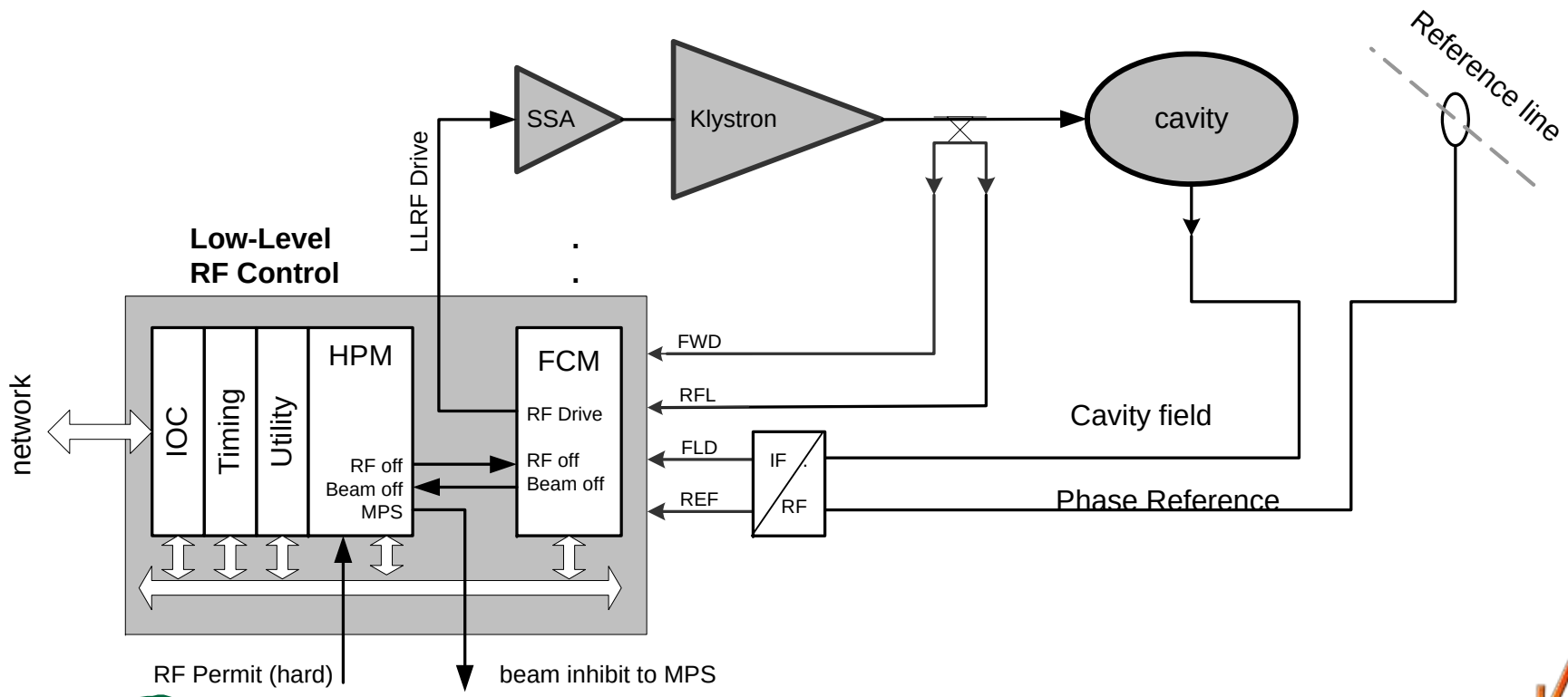
SNS Linac RF Control / overview / basic configuration for each system

Each LLRF system consists of

- Field Control Module (FCM)
- High-power Protection Module (HPM),
- Support cards: Timing,
- Utility card, and (I/O control) card.

The functionalities include:

Cavity field regulation, rf/cavity protections, support of various linac operation modes



Overview / 96 systems total deployed throughout Linac

Installation team

Mark Crofford

Jeff Ball,

Taylor Davidson

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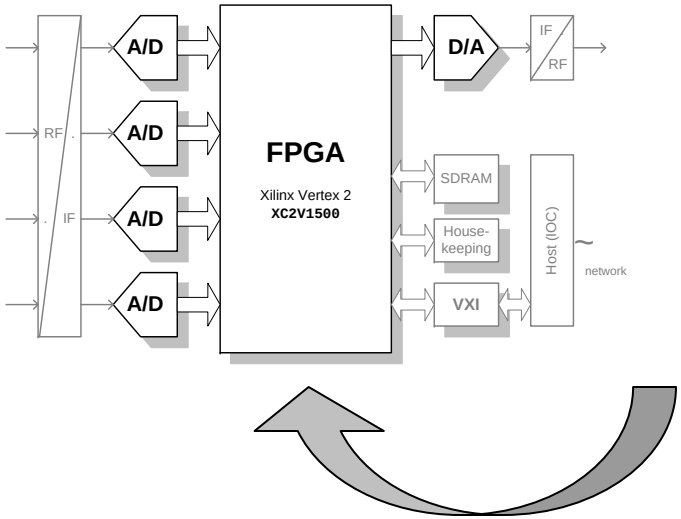
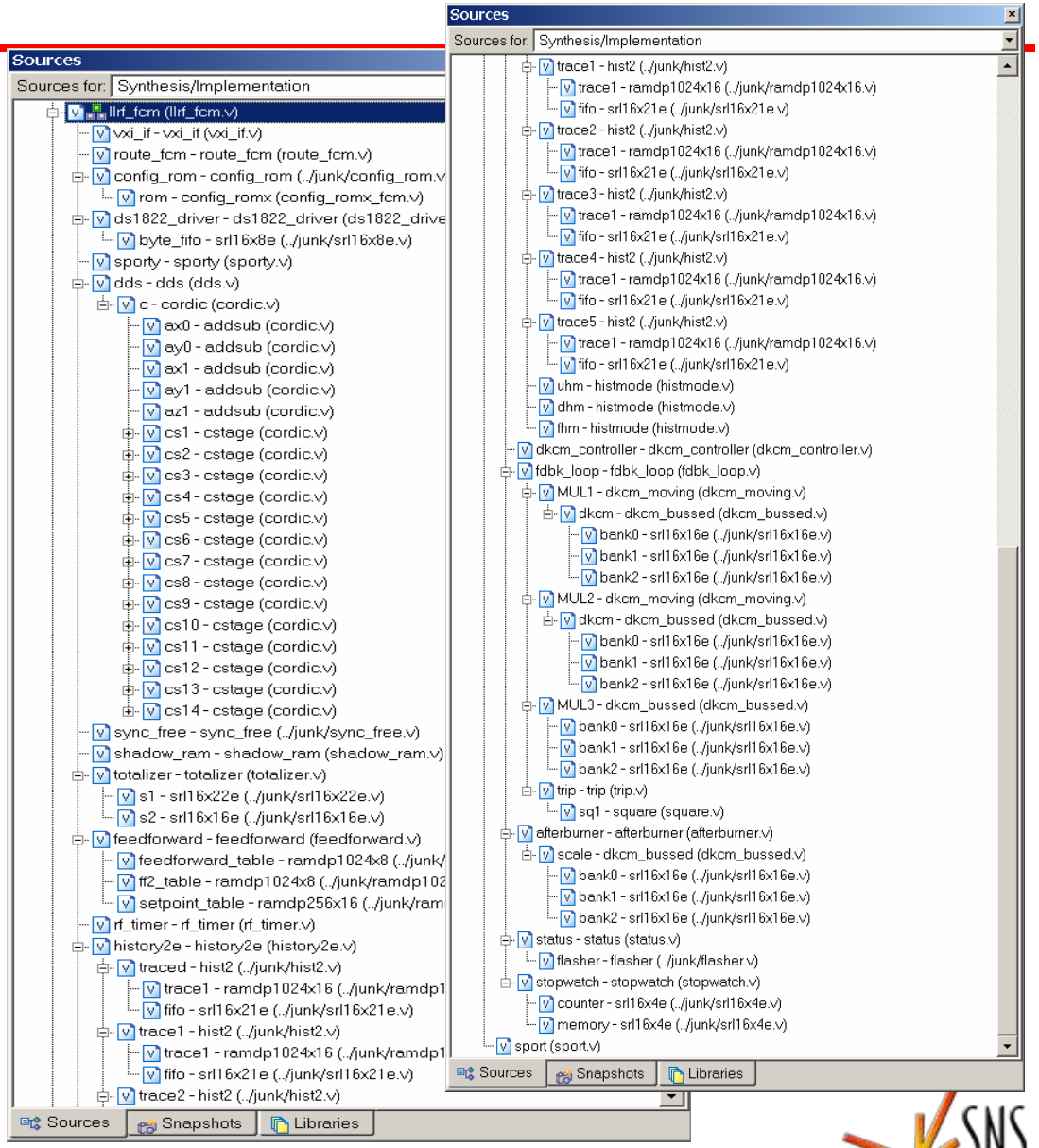
Overview / hardware design

HDL design is in Verilog

- 30 handwritten modules
- 16 machine generated modules Machine, including top-level net-list.





Overview / hardware development/CVS under Eclipse

C/C++ - Compare fdbk_loop.v 1.12 and 1.11 - Eclipse SDK

File Edit Refactor Navigate Search Project CVS Window Help

C/C++ Pr... Navigator

RAMB4_S8_S8.v 1.5
SRL16E.v 1.5 (ASCII -l
afterburner.v 1.5 (ASCI
afterdemux.v 1.5 (ASC
bram.pl 1.4 (ASCII -kk
bram2.pl 1.4 (ASCII -kk
config_cruncher 1.4 (A
config_rom.v 1.5 (ASCI
config_rom_fcm.make 1
config_rom_interim.make
config_rom_mebt.make
cordic.v 1.5 (ASCII -kk
dds.v 1.5 (ASCII -kkv)
dkcm_bussed.v 1.5 (A
dkcm_controller.v 1.5 (
dkcm_moving.v 1.5 (A
ds1822_driver.v 1.5 (A
ds2401_driver.v 1.5 (A
fdbk_loop.v 1.12 (ASCI
feedforward.v 1.9 (ASC
flasher.v 1.5 (ASCII -kk
hist2.v 1.5 (ASCII -kkv
histmode.v 1.5 (ASCII
history2e.v 1.8 (ASCII
intercon.pl 1.4 (ASCII -
llrf.rules.make 1.4 (ASC
llrf_config.v 1.5 (ASCII
llrf_fcm.ucf 1.4 (ASCII
llrf_interim.ucf 1.4 (ASC
llrf_mebt.ucf 1.4 (ASCI
loc.sh 1.4 (ASCII -kkv)
mult_bussed.v 1.5 (AS
mult_controller.v 1.5 (A
mult_moving.v 1.5 (AS

Compare fdbk_loop.v 1.12 and 1.11

Text Compare

Repository file: fdbk_loop.v 1.12

```
                    {e4[12:0], 3'b000} : {e4[15]
wire [15:0] e4_ls5  = ((e4[15:10]==6'b000000) | (e
                    {e4[10:0], 5'b00000} : {e4[1
// wire [15:0] e4_int     = int_scale_sc ? e4_shif
wire [15:0] e4_shift   = int_scale_sc[1] ? e4_ls5
wire [15:0] e4_int     = int_scale_sc[0] ? e4_shif
wire [13:0] fdbk_err_wide = {integrate_out[20], in

// arithmetic saturation from 14 bits down to 13 b
wire [11:0] fdbk_err = ((fdbk_err_wide[13:12]==2'b
    fdbk_err_wide[12:1] : {fdbk_err_wide[13],{11{-
always @(posedge clk40) fdbk_err_out <= fdbk_err;

wire [11:0] peak_err_narrow;
trip trip(
    .clk(clk40), .inval(e2[10:2]), .trip_thresh(tr
    .gate(trip_gate), .reset( trip_reset ),
    .tripped(err_tripped), .peak_val(peak_err_narr
        );
assign peak_err = {peak_err_narrow, 4'b0};

// gauging for output magnitude
wire [11:0] peak_out_narrow;
trip clip(
        .clk(clk40), .inval(fdbk_err[11:3]), .trip
        .gate(feedback_on), .reset( trip_reset ),
        .tripped(out_clipped), .peak_val(peak_out_
         );
assign peak_out = {peak_out_narrow, 4'b0};

endmodule
```

Repository file: fdbk_loop.v 1.11

```
//  ff_pipe <= feedforward_data;
    ff_pipe <= ff_data_sat;      // hma:
    integrate_input <= {ff_pipe,5'b0} + (corrupte
end
// Combine low-latency linear feedback with the i
// Saturation and sign extension are claimed vali
// wire [13:0] fdbk_err_wide = {integrate_out[20]

wire [15:0] e4_ls3  = ((e4[15:12]==4'b0000) | (e4
                    {e4[12:0], 3'b000} : {e4[15
wire [15:0] e4_ls5  = ((e4[15:10]==6'b000000) | (
                    {e4[10:0], 5'b00000} : {e4[
// wire [15:0] e4_int     = int_scale_sc ? e4_shi
wire [15:0] e4_shift   = int_scale_sc[1] ? e4_ls5
wire [15:0] e4_int     = int_scale_sc[0] ? e4_shi
wire [13:0] fdbk_err_wide = {integrate_out[20], i

// arithmetic saturation from 14 bits down to 13
wire [11:0] fdbk_err = ((fdbk_err_wide[13:12]==2'
    fdbk_err_wide[12:1] : {fdbk_err_wide[13],{11{
always @(posedge clk40) fdbk_err_out <= fdbk_err;

wire [11:0] peak_err_narrow;
trip trip(
    .clk(clk40), .inval(e2[10:2]), .trip_thresh(t
    .gate(trip_gate), .reset( trip_reset ),
    .tripped(err_tripped), .peak_val(peak_err_nar
);
assign peak_err = {peak_err_narrow, 4'b0};

endmodule
```

Problems Console History

fdbk_loop.v

Revision	Tags	Revision Time	Comment
Previous			
*1.12		2/14/07 12:13 PM	firmware with output clipping

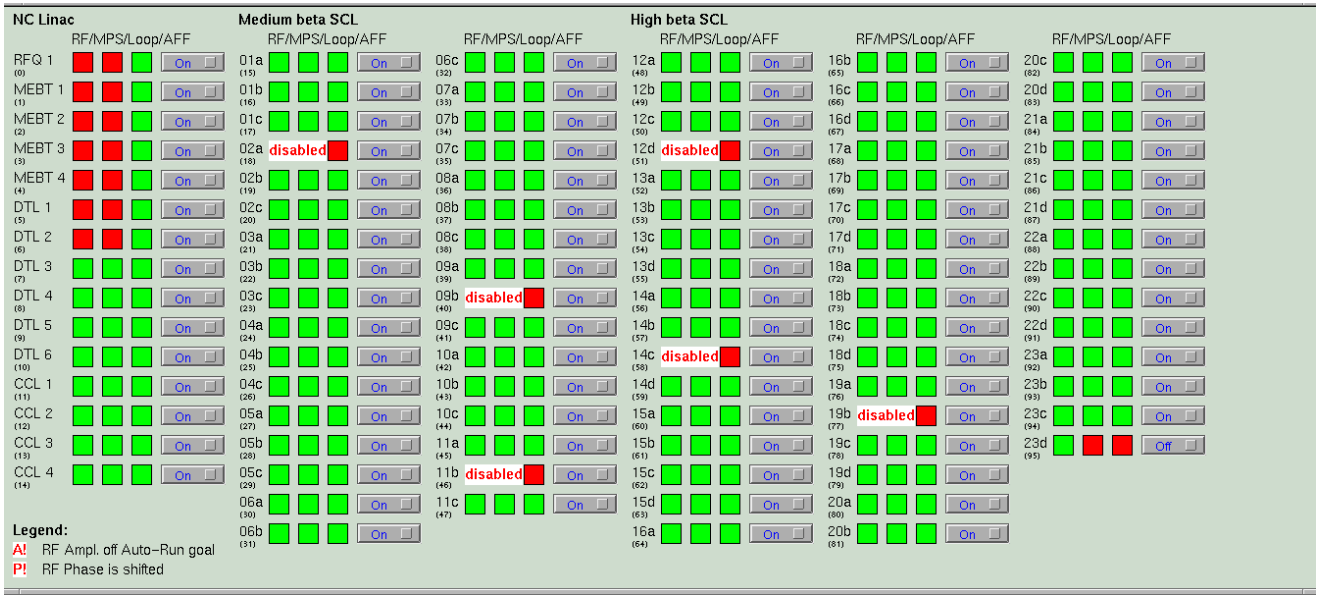
Overview / software multiplicity

96 SNS LLRF Systems, handled by ~50 front-ends

- As different as warm vs. super-conducting cavities

One source base for all of them

- Differences handled by configuration settings
- If possible, startup files and overview displays script-generated from central system info.



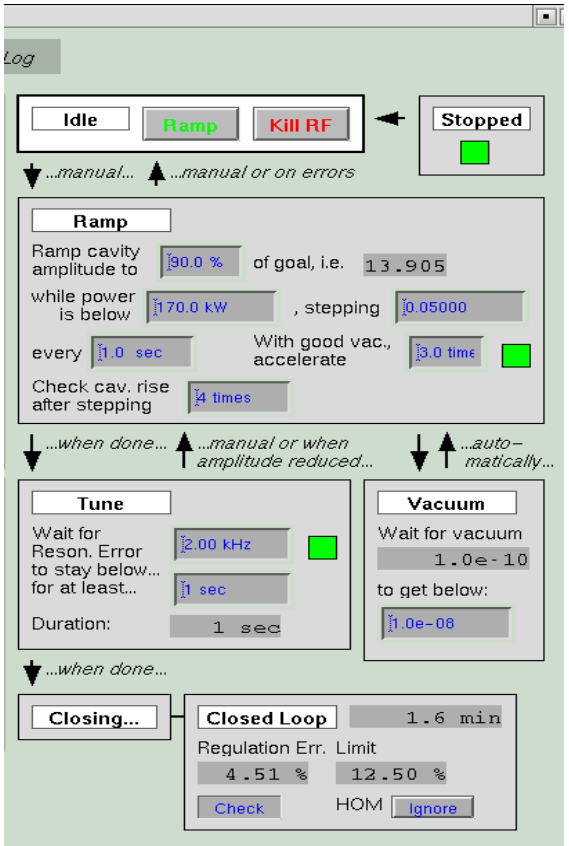
Overview / Software / Automated operations

Operators screen displays all the control and administrative information important to the operation, and hosts some of the automated operation sequences

Such as

- Auto-run
- Loop close/open
- Warm-up mode
- rf pulse width setting
- Etc.

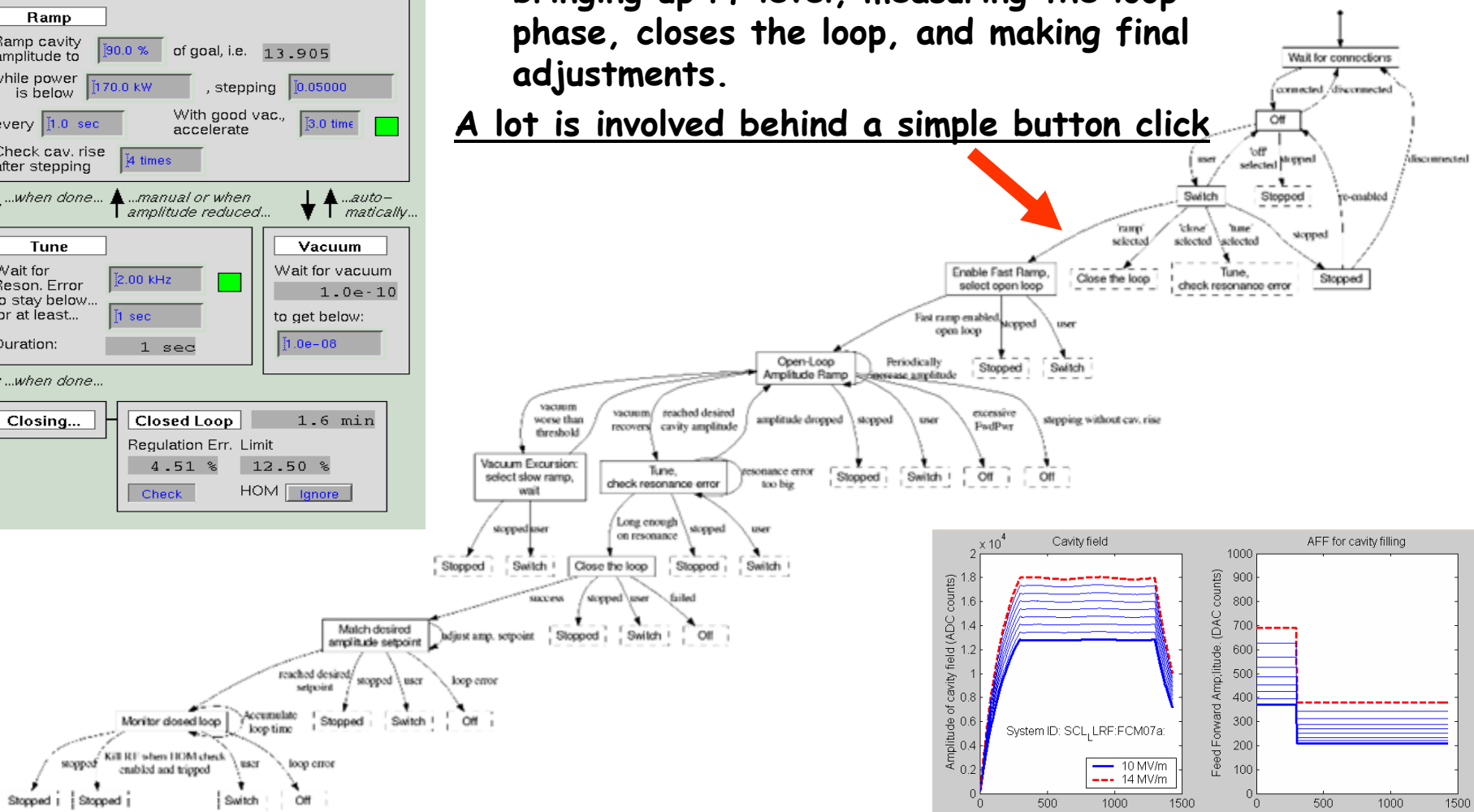
Overview / software / automation



An example of automation sequencer:

RF turn-on ("Auto-Run") - The automated procedure comprises checking conditions, bringing up rf level, measuring the loop phase, closes the loop, and making final adjustments.

<u>A lot is involved behind a simple button click</u>

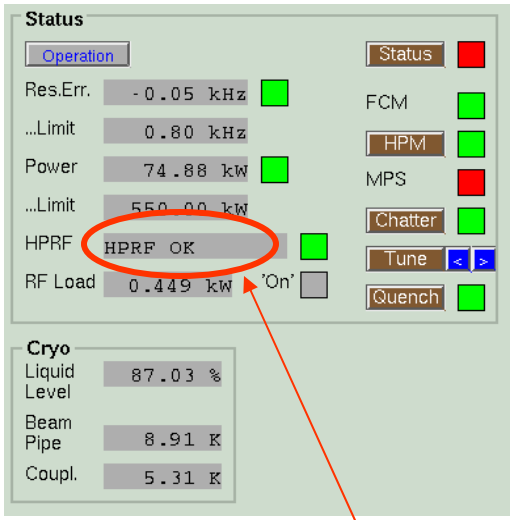


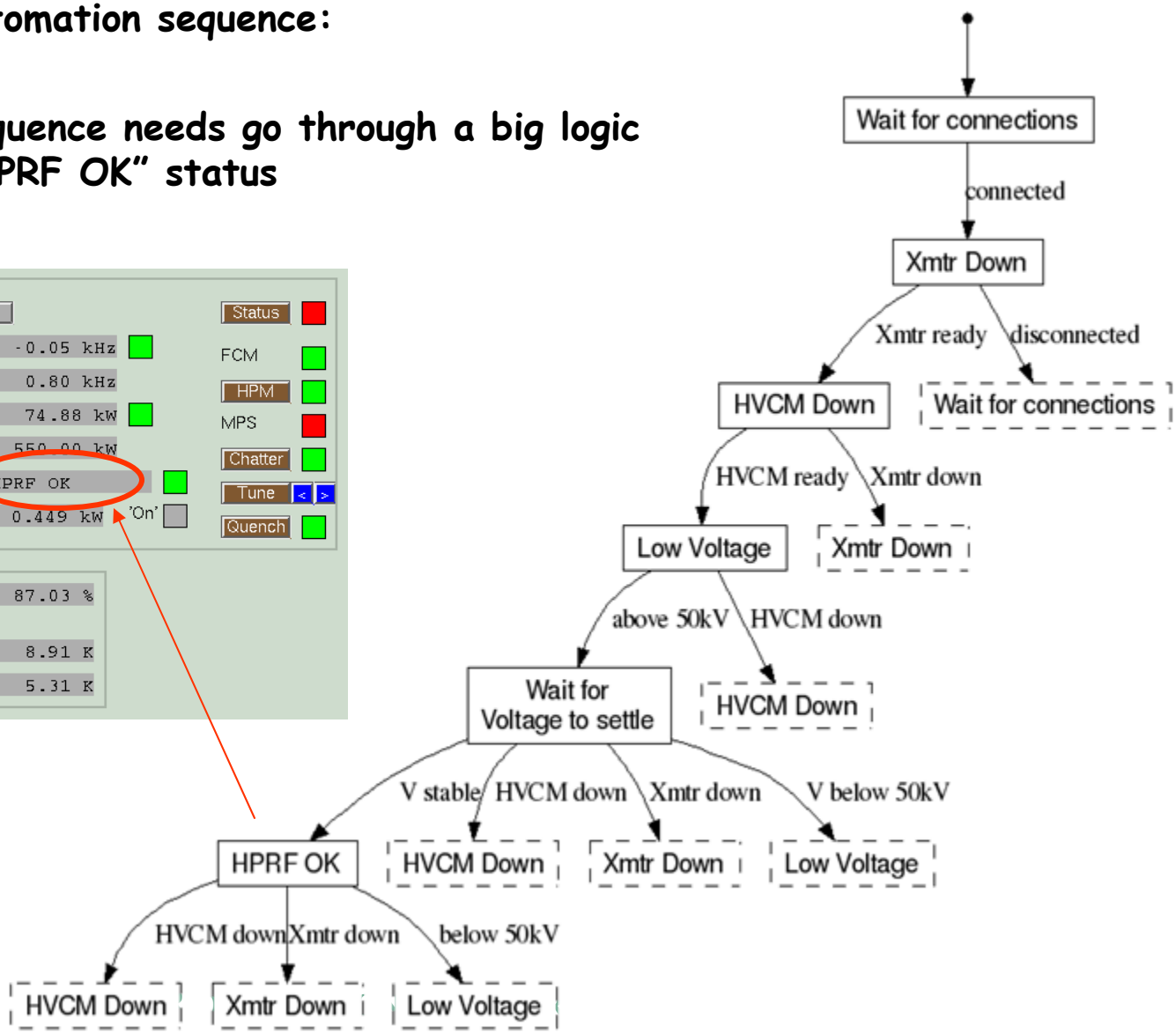
Overview / software / automation

Another example of automation sequence:

High-Power RF check

The software check sequence needs go through a big logic tree for giving a "HPRF OK" status





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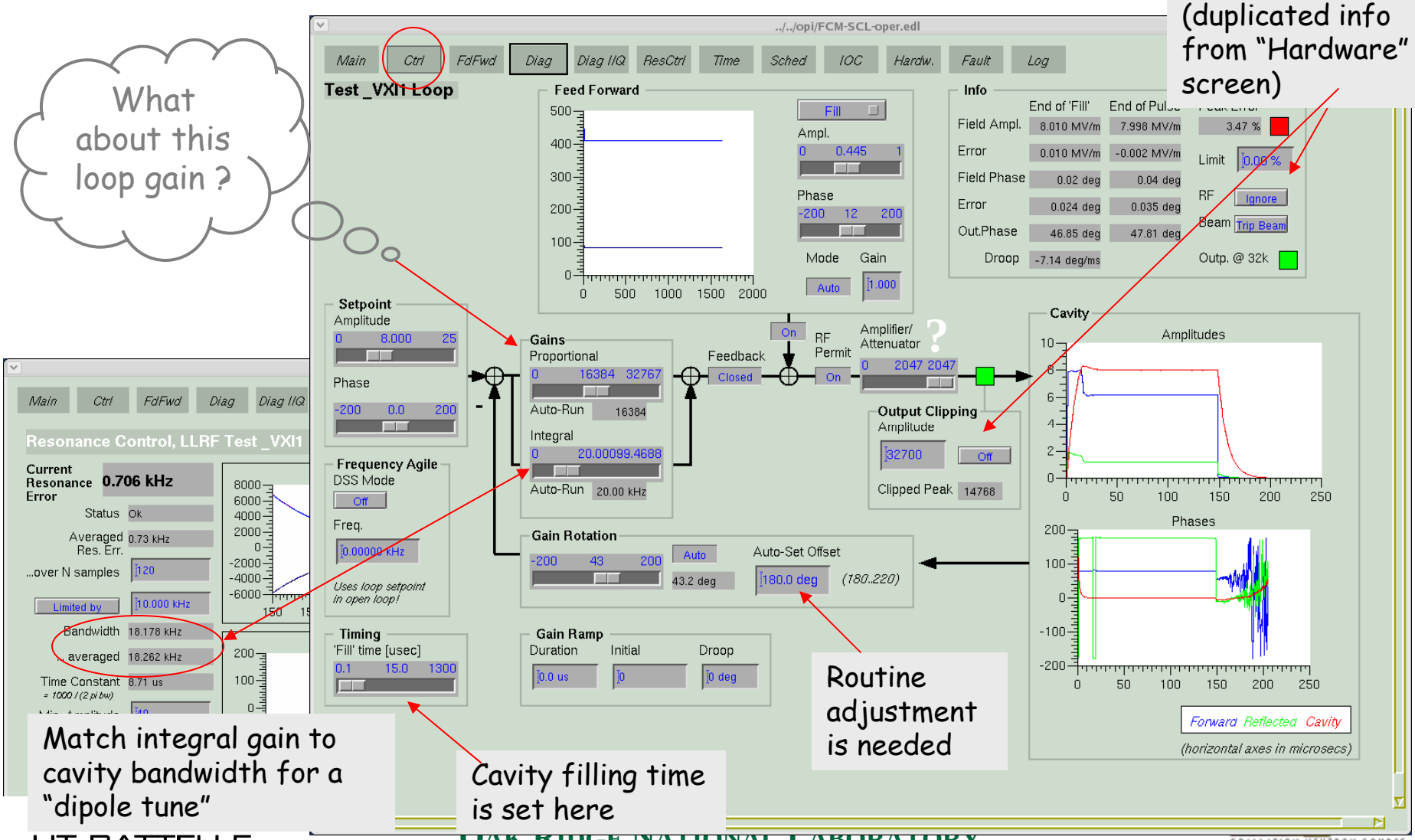
Overview / software / GUI support

Expert control screens facilitate study and troubleshooting

What about this loop gain ?

Interlock configuration

(duplicated info from "Hardware" screen)



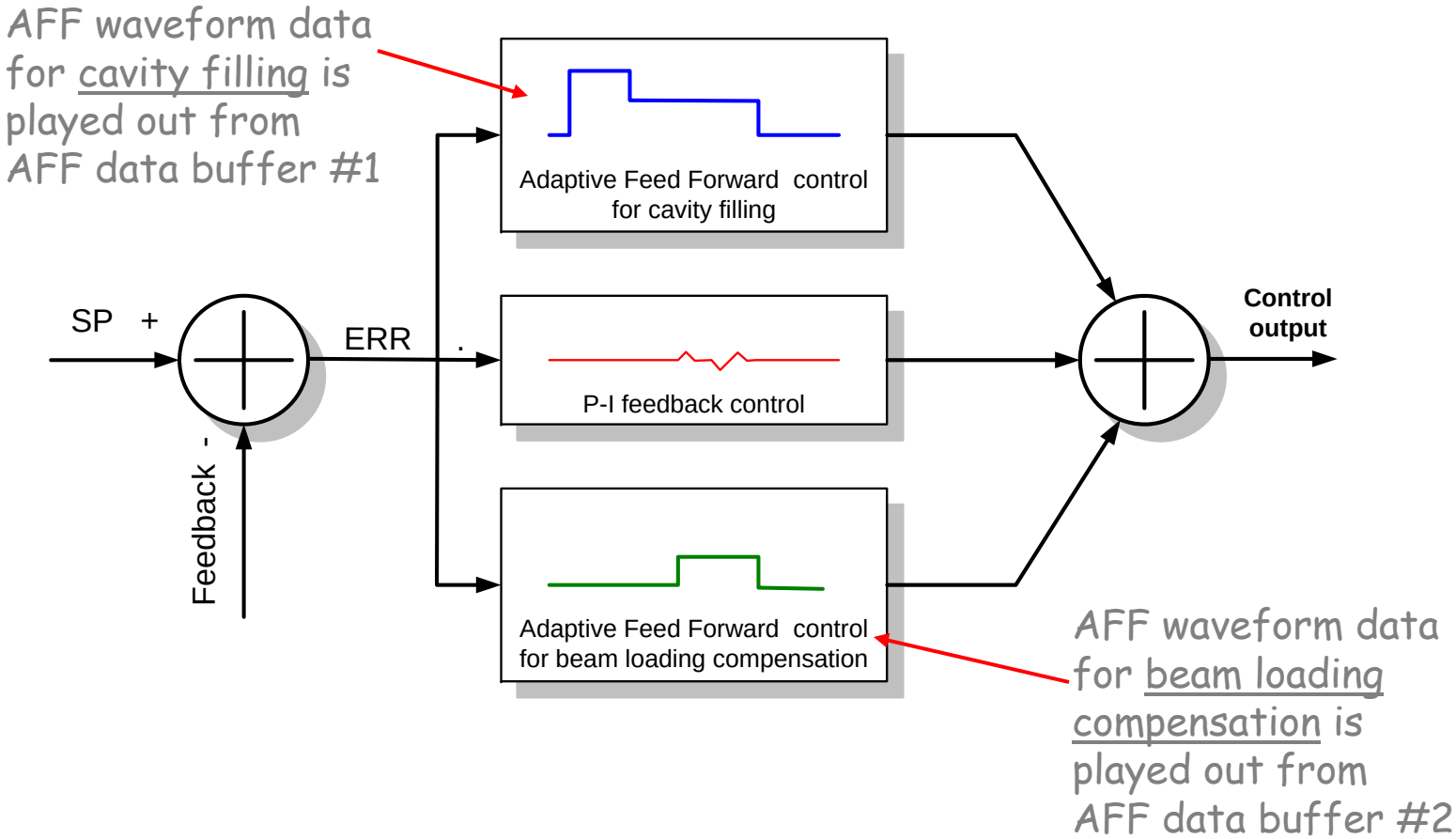
Routine adjustment is needed

Match integral gain to cavity bandwidth for a "dipole tune"

Cavity filling time is set here

Overview / RF control scheme

SNS Linac rf control employs a combined control of an Adaptive Feed Forward (AFF) for cavity filling, a real-time feedback for field regulation, and another AFF for beam loading compensation



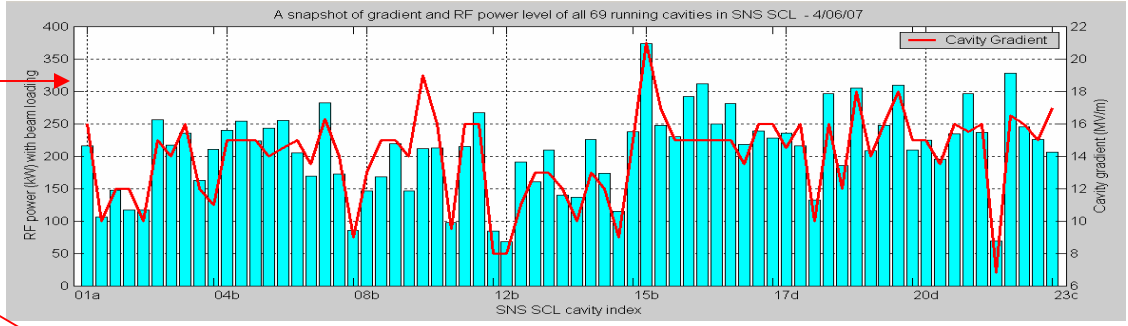
Commissioning results/ SCL cavity field control

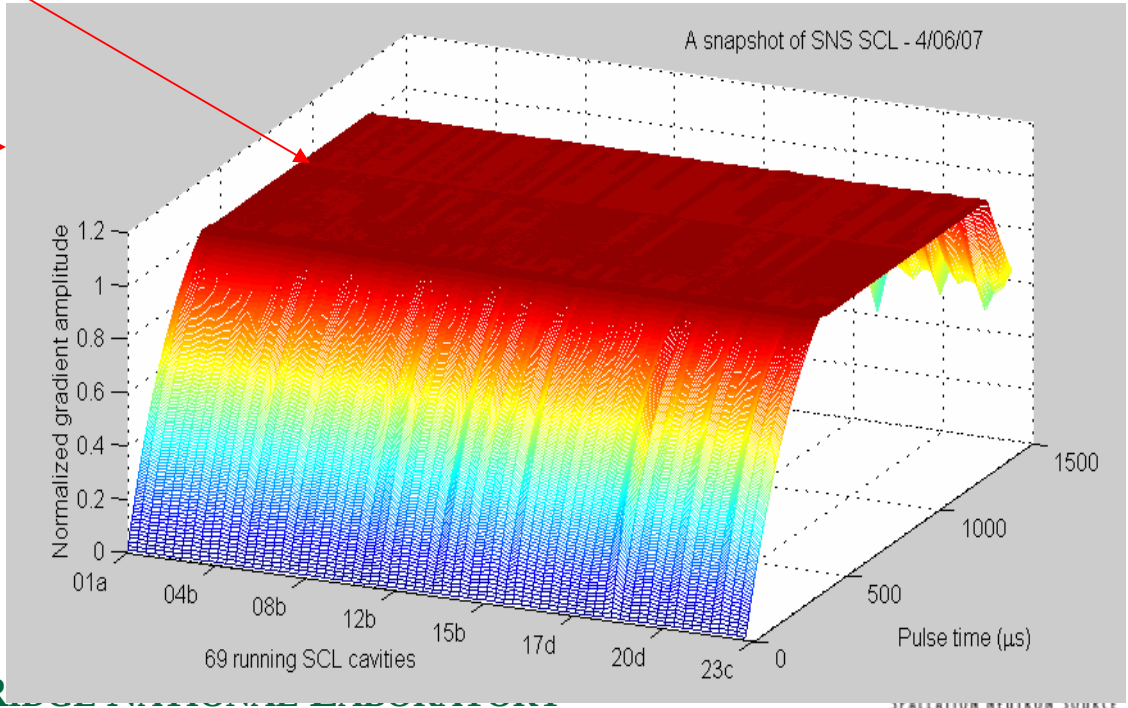
The combined control scheme has produced a stable and nearly an identical field waveform in every cavity across SCL.

The current running gradient and power across SNS Linac

The crest line is the transient of beam loading (peak error ~1%)

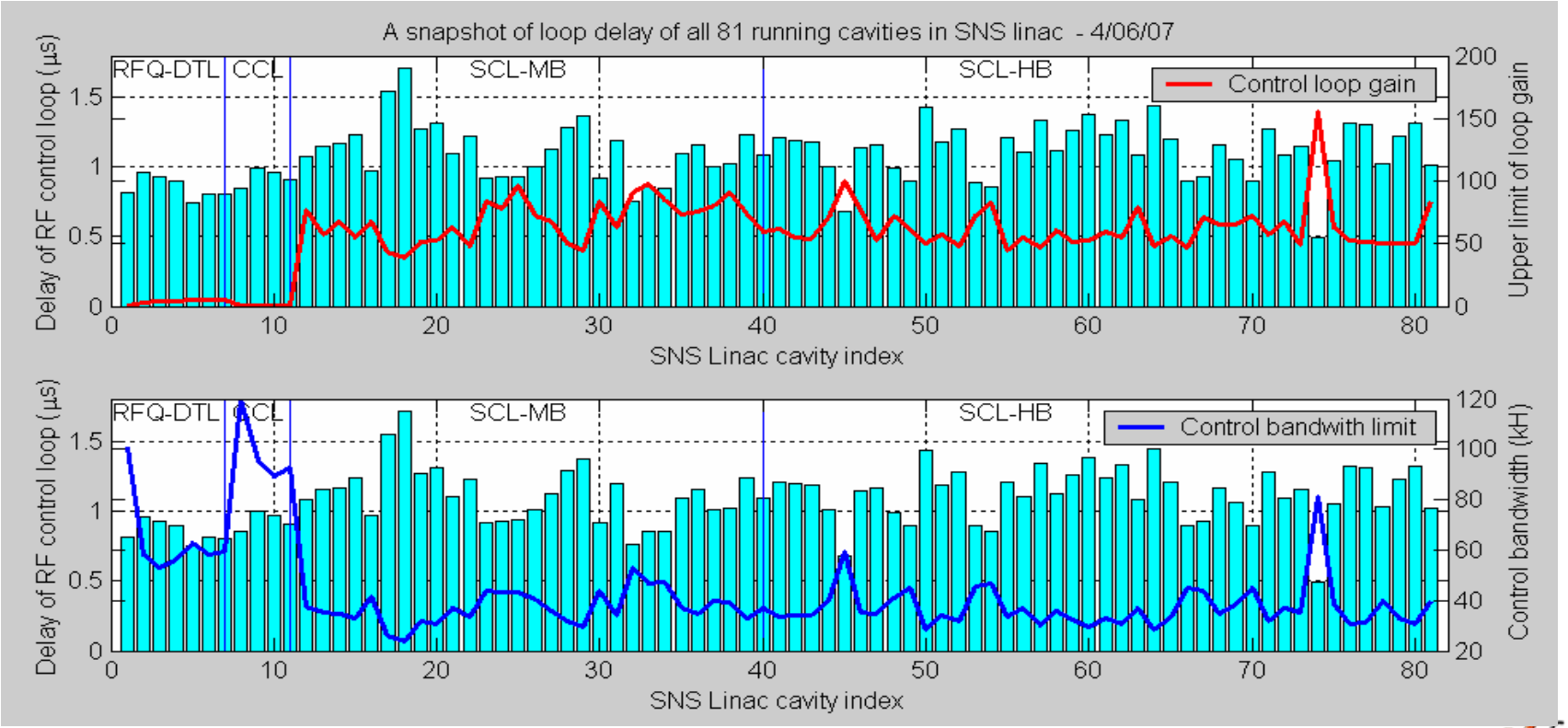
An stack-view of the actual cavity rf waveform (amplitude normalized) of all SC cavities in operation (with 400us, 12mA avg. beam current running). <u>A consistent field profile in all cavities across SCL has been achieved</u>.





Commissioning result / loop delay limited control performance

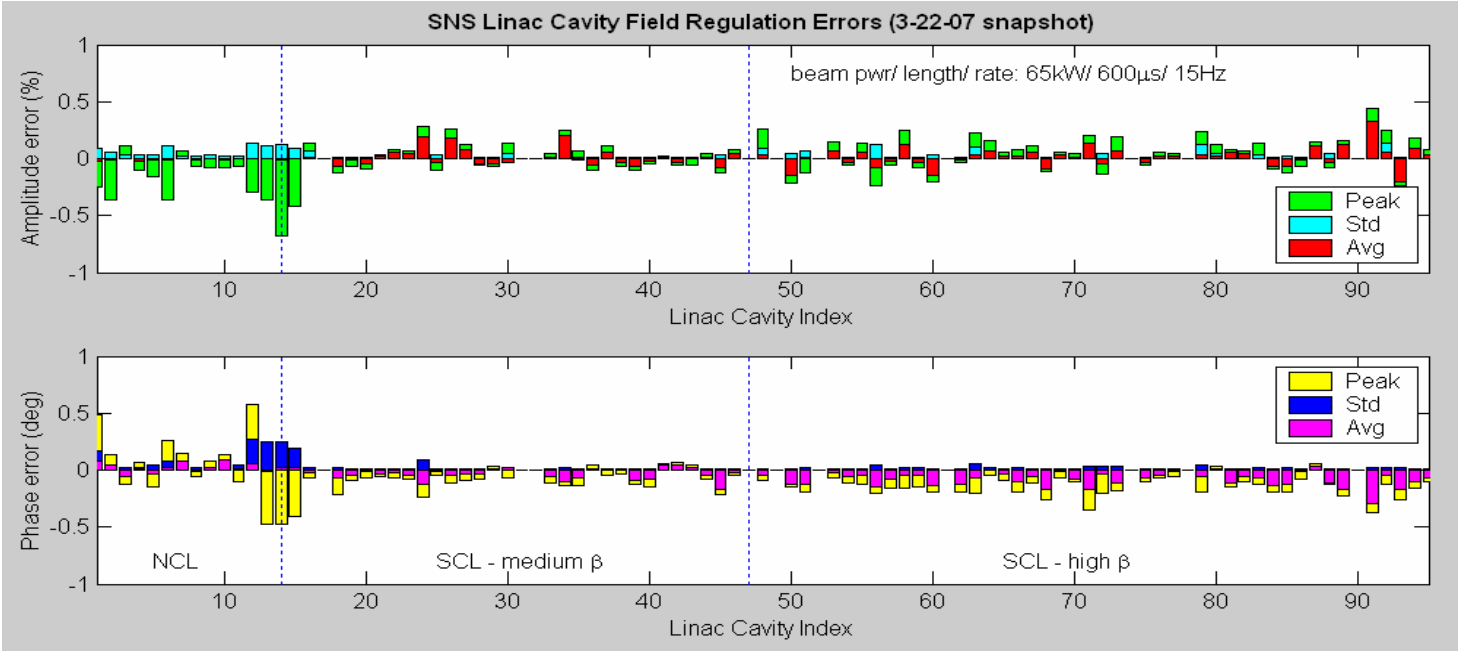
Measured loop delay of running cavities in the Linac, and the calculated limits set by the delay on the maximum usable real-time feedback control gain and the achievable control bandwidth. (typically G_{max}~50, and BW_{max}~40 kHz for SCL)



Operation performance / cavity field control errors

LLRF has steadily supported the operation of neutron production and beam power ramp-up to today's record of 183 kW

- Up to today's beam current level of ~30 mA (chopped), 30 Hz.
- Field regulation typically under 1%, 1 degree.



A snapshot of rf error across Linac (April, 2007)

beam condition: 65kW (12mA avg./600μs/15Hz

Commissioning and operation / reliabilities

Hardware reliability from 2004 to present

- LLRF hardware generally has been very reliable. The hardware failure rate was between 10~14% at beginning, and has largely come down since.
- Most of the operation difficulties have been in false tripping, possibly as result of the EMI emission from other failing equipment in the Linac gallery.

Hardware	Failure rate	Note
Field Control Module (**FCM**)	14% 13 out of total 96 units failed	Most of the failure occurred in the initial operation.
High-Power Protection Module (**HPM**)	10% 10 out of the total 96 units were removed	7 of the 10 damaged units have been repaired.

Software ?

- Bugs are resulted from less than 100% simulation (firmware), but mostly from conflicting, confusing and changing requirements (such as interlock schemes).
- IOC uptime issue: VxWorks network kernel often hangs up in response to network glitches. A good news is that the LLRF hardware is basically fault-safe when that happens..

Continual development

Further development continues since the commissioning.

The development for new functionalities has been mainly driven by the needs from operation.

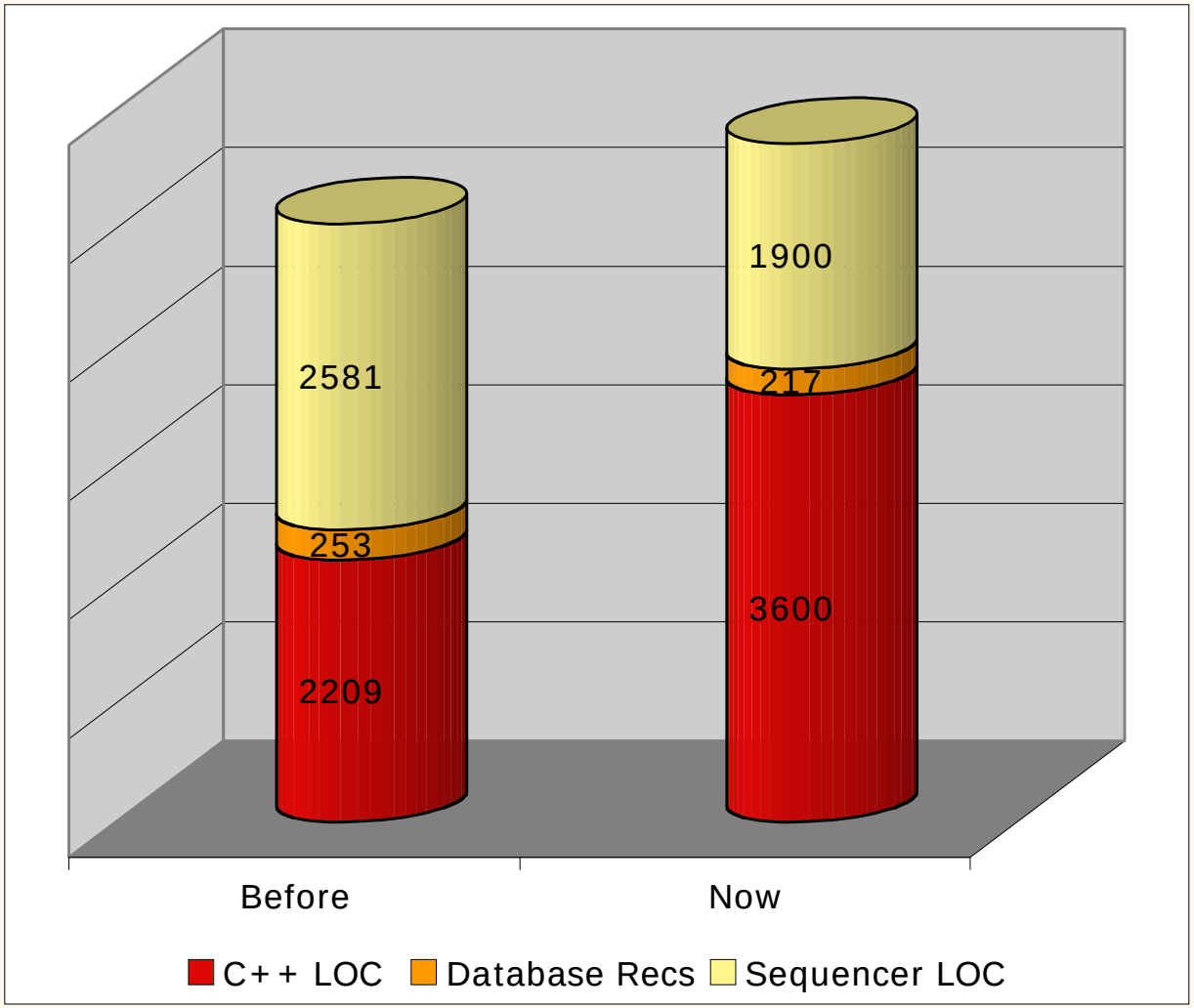
some instances;

- **Software upgrade for better performance, support for new features**
- **Beam pulse blanking**
- **Pulse-to-pulse real-time rf phase reverse**
- **5/6 pi mode instability suppression.**

Continual development / examples

K. Kasemir

- **Latest software upgrade**
- **Improve performance of tested algorithms by converting Sequencer (State Machine) code and Database Records to C++**



K. Kasemir

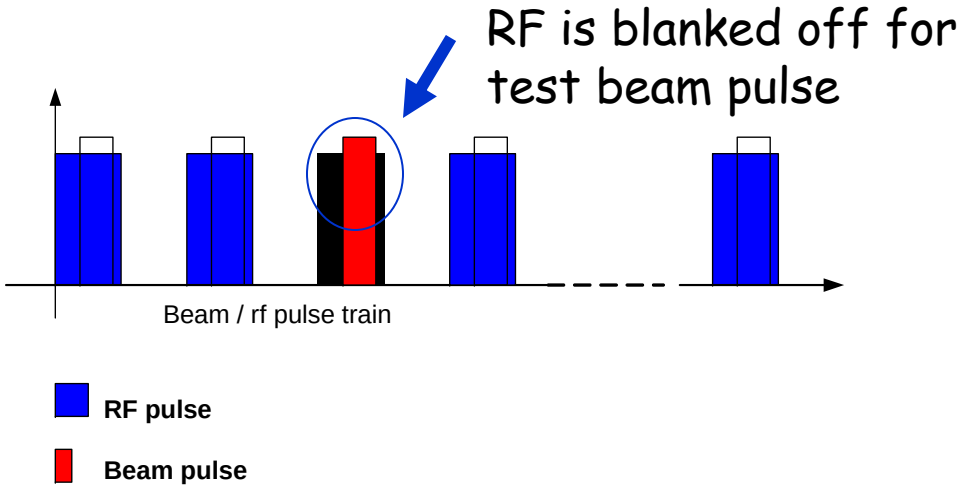
New Features

- **Better control over scheduling**
- **Processed at up to 20Hz *(was: less than 2Hz):***
  - **Amplitude+phase during 'fill' time**
  - **Phase tracking of reference line**
  - **Adaptive Feed-Forward**
- **History of processed waveforms**
  - **Last 60 pulses, up to fault or manual stop**
  - **Saved in Matlab file**
- **Detect output saturation**

Continual development / new features for special operation needs

Eg.(1) : Beam Blanking

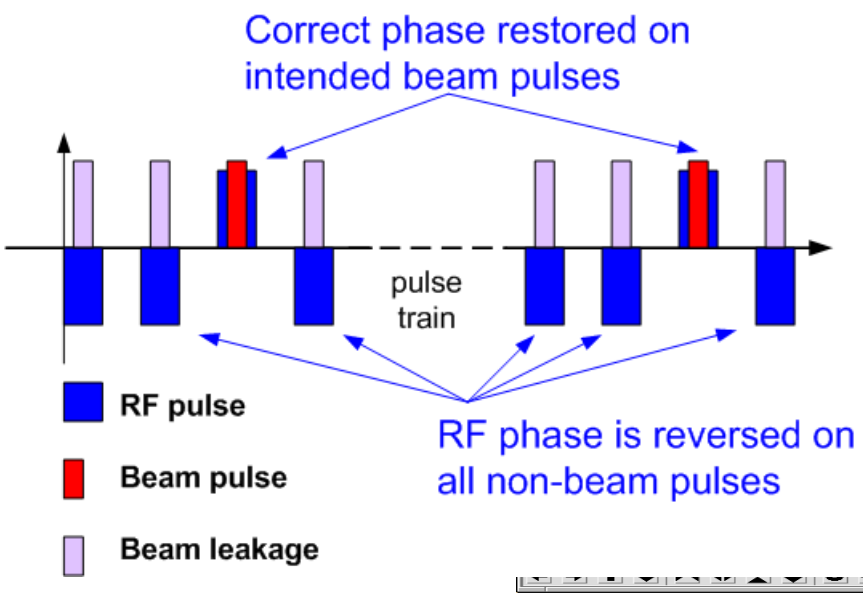
- Turns off RF for the test beam pulse (1 Hz beam pulse rate).
- Without having to turn off rf entirely (29 Hz rf pulse rate),
- without changing heat loading too much.
- Speeds up Lianc rf tuning process significantly . The time is reduced from shifts to hours for all 96 cavities), provides a possibility of implementing an automated Linac tuning.

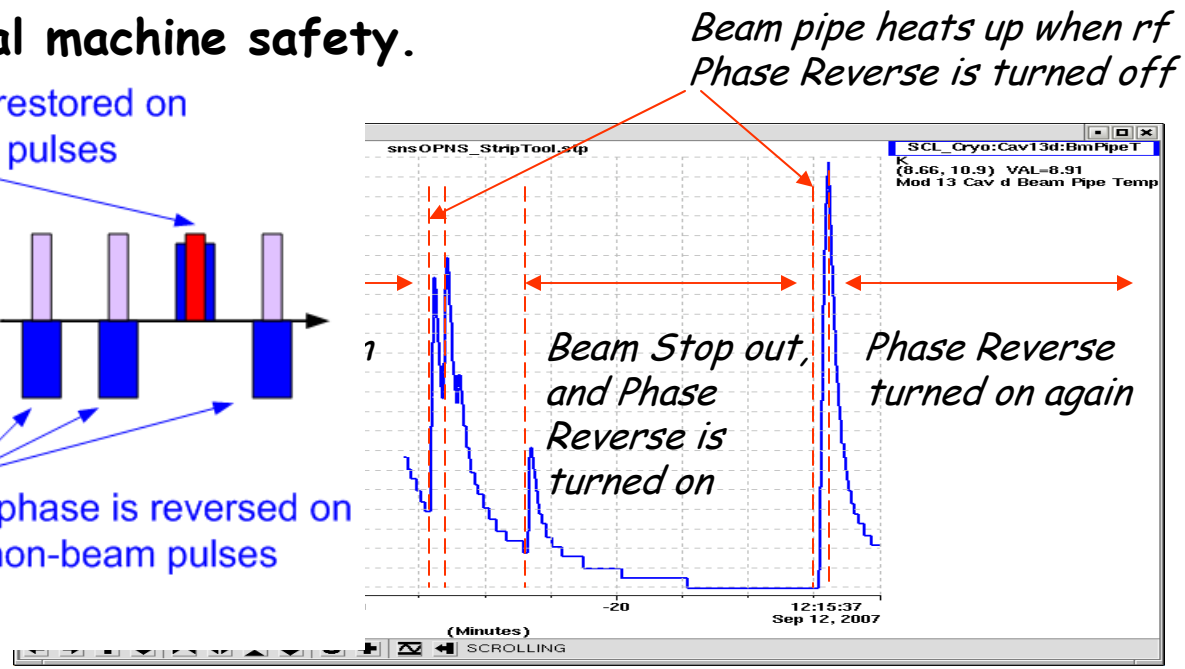


Continual development / new features for special operation needs

Eg. (2): rf phase flipping for blocking ion source leakage

- Real-time reverse rf phase on all rf pulse with no beam, and restore the correct phase on the beam rf pulses.
- This function is turned on only on DTL-1
- Prevents the heating of downstream SCL beam pipe due to the leakage of the ion source.
- Provides additional machine safety.



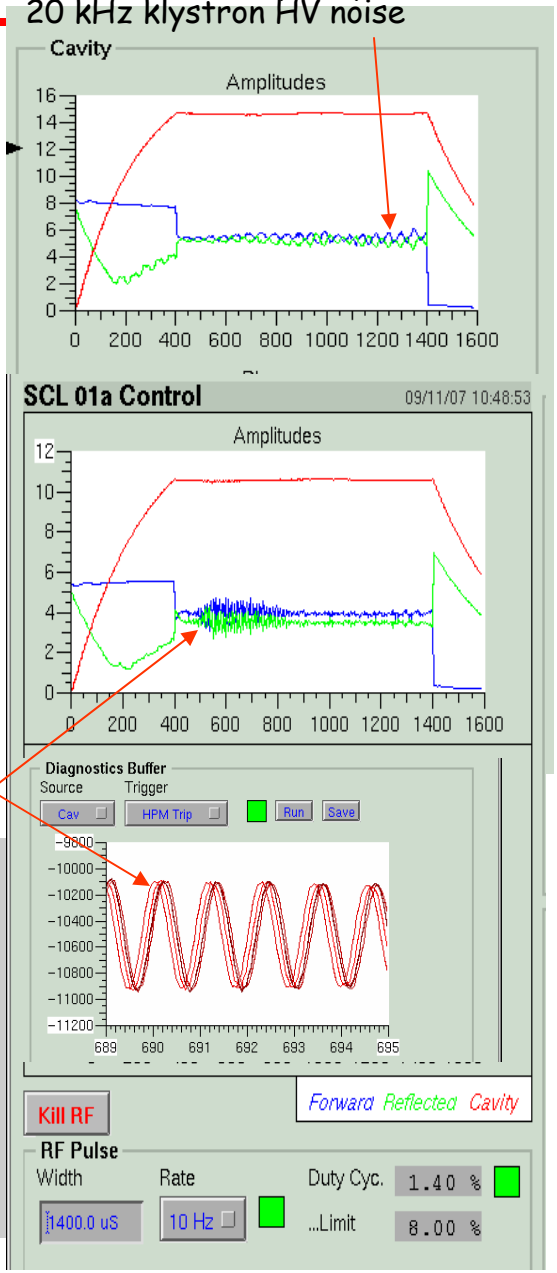


Continual development / currently under test

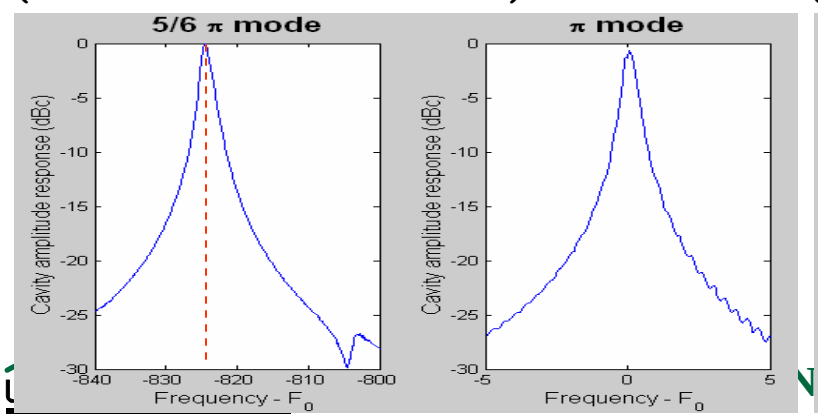
Suppressing 5/6 pi mode instability (1)

- The exist of cavity π and 5/6π mode frequency pass-band and loop delay τ creates a necessary condition for loop instability to occur at either or both frequencies, depending on the given delay τ and the loop gain used.
- Use a compromised loop phase compensation and lower gain can make both modes stable, resulting
  - reduced stability phase margin.
  - reduced control performance (what we have now)

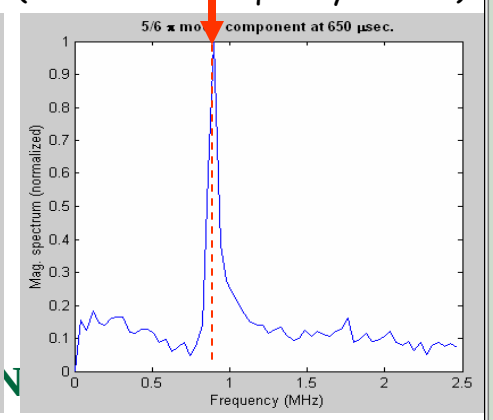
π Mode instability coupled with 20 kHz klystron HV noise



Swept (open loop) cavity frequency response (5/6π mode at ~-825 kHz offset)



excited 5/6π frequency (~-900 kHz frequency offset)



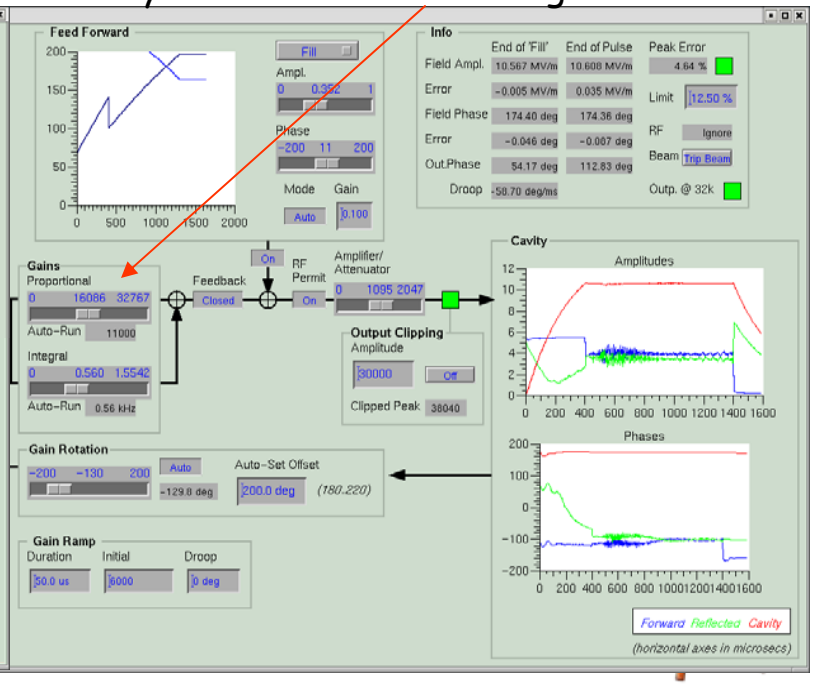
Continual development / currently under test

Suppressing 5/6 pi mode instability (2)

- Insert a term $[1+(-1)^n \cdot z^{-2n}]$ in the forward transfer function to place a zero at ~900 kHz and to cancel the 5/6 π mode cavity pole,
- An initial test has shown this zero-pole cancellation scheme works well, improved stability and performance.
- More study is needed for a full implementation.

900kHz reject filter on, allowing use of a much higher gain without causing instability.

for comparison, 900kHz reject filter off instability starts at a moderate gain



Current activities / follow-up production of LLRF hardware

Hardware productions

- Previous production yields have been good,
- 2nd follow-up production for additional 50 sets of hardware is underway,
- Experience in preparation is a key factor for the successful productions (Davidson, Crofford, DeBaca)
  - parts selection and sourcing
  - Kitting
  - coordination/communication with vendors

Production run	Qty	Yield (FCM)
Initial production (04, for installation)	125	VXI motherboard : ~90%, Digital Front End dautherboard: > 99% RF Output daughterboard: ~ 80%
1st Follow-up (05, spares)	25	VXI MB and DFE : 100% RFO: ~90%
2nd follow-up	50	TBD Have found obsolete parts from "grey market", no chip migration is necessary at this time.

Future plans

In summery, top priority is the support for achieving the goal of 1.4MW beam power, and ultimately 2 MW (PUP)

- Improving control algorithms to maintain the performance and stability with increasing nonlinearity (klystron gain compression)
- Study the need for implementing klystron linearizing loop for improving the control and klystron power utilization.
  (Experience and ideas are welcomed)
- Complete the 2nd follow-up hardware production (Davidson, Crofford, , Jones, Ball)
- Development of the new ring LLRF (currently under test) (Hardek, Crofford, Ma, Piller).
- Improvement of reference system (Piller)

Acknowledgement

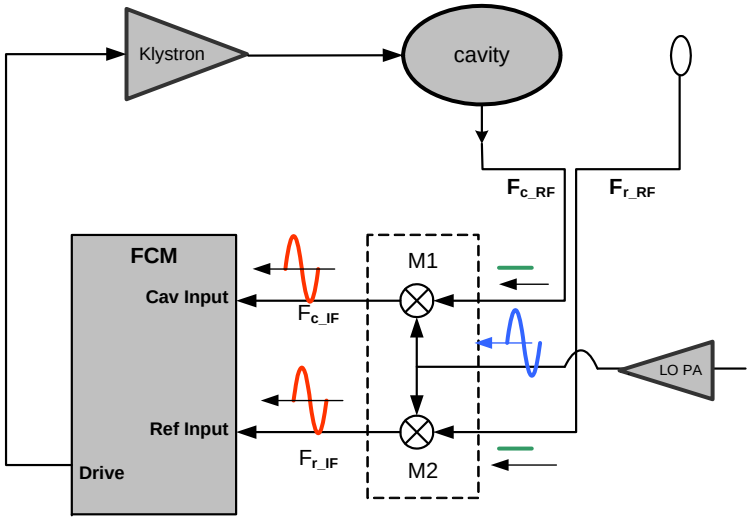
Many people from ORNL, LBNL, and LANL collaboration contributed to the success of SNS LLRF system development. The continual improvement , and more importantly, the operation support have being carried out by the LLRF team members, including

Jeff Ball, Mark Champion (FNAL), Mark Crofford, Taylor Davidson, Tom Hardek, Kay Kasemir, Hengjie Ma (BNL), Chip Piller

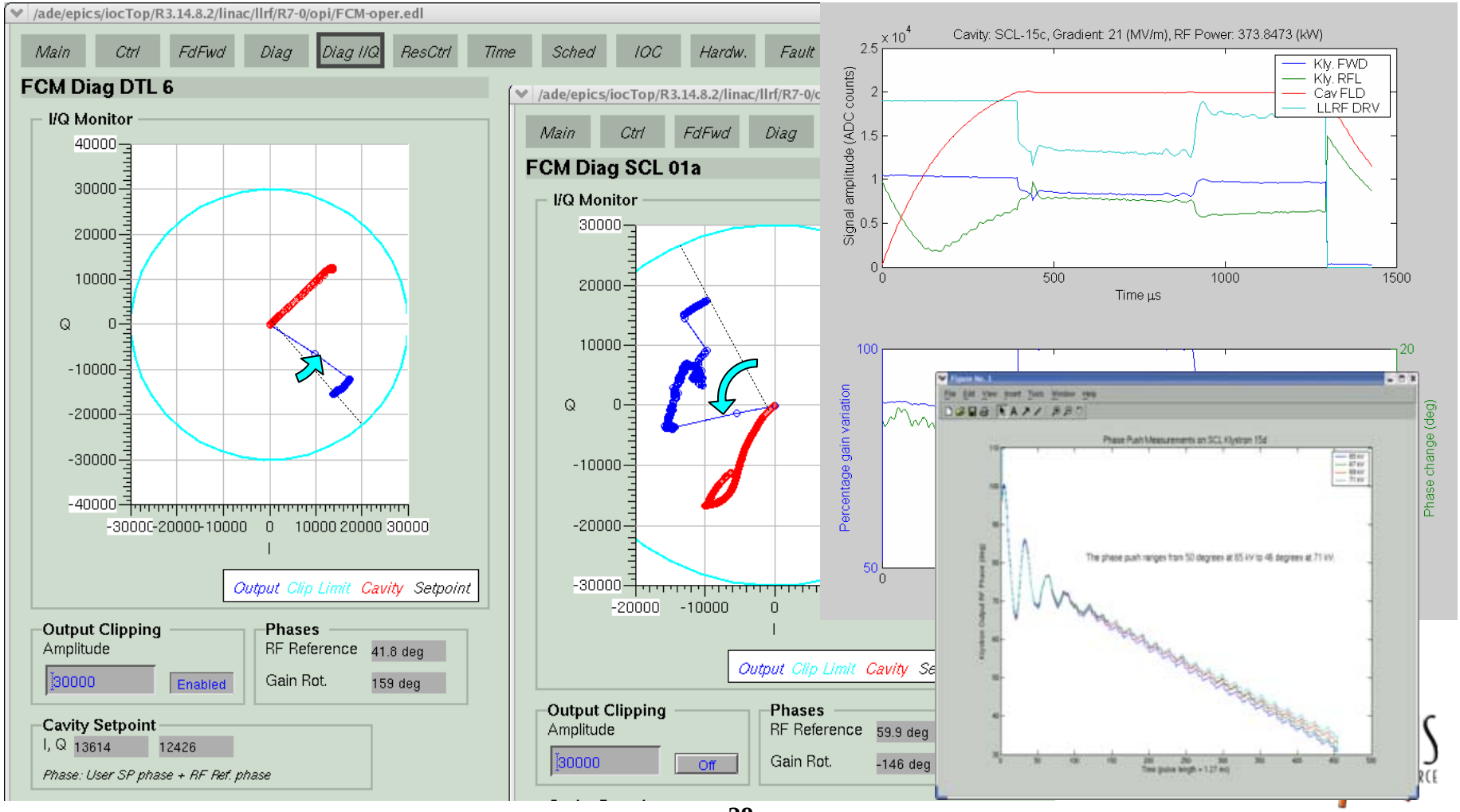
Backup slide / reference system

Reference monitoring

- Concern:
  - LO level amplitude-modulates the cavity field signal,
  - LO level change is outside of the feedback loop, and therefore caused error in the cavity signal amplitude cannot be corrected by the loop,
- Improvement: monitoring of LO level at both the source (MO) and service ends (each LLRF). The measured change is then used in SP compensations.



Backup slide / dynamic loop phase error and klystron gain compression

Phase margin of feedback control stability is reduced due to

- HPRF phase droop and Lorentz force detuning takes away phase margin.
- Klystron saturation pushes LLRF into nonlinear operation