TRIUMF LLRF Control

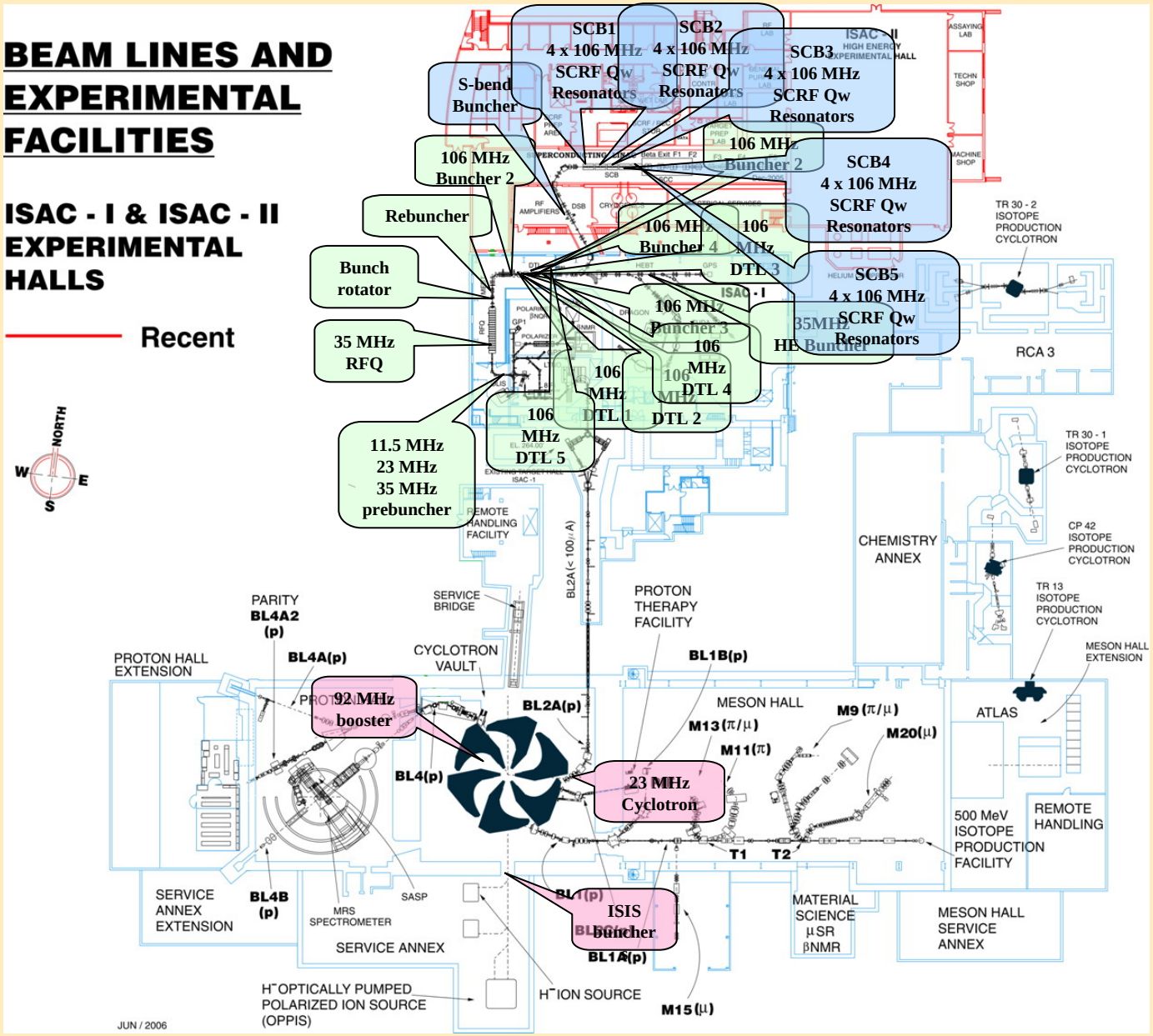
K. Fong, M. Laverty and Q.W. Zheng,

TRIUMF

BEAM LINES AND EXPERIMENTAL FACILITIES

ISAC - I & ISAC - II EXPERIMENTAL HALLS

Recent



TRIUMF Cyclotron, ISAC I and ISAC II
RF System

CW Normal conducting, multi-frequencies system

- Non-resonant and resonant structures:
  - Strip Line (prebuncher)
  - Lumped elements (bunch rotators)
  - Dee resonator (cyclotron)
  - Spiral $\lambda/4$ resonators (bunchers)
  - DTLs
  - RFQ
- 7 frequencies – 6, 11, 23, 35, 47, 92, 106 MHz
- Q ranges from 1 to 5000.

CW Superconducting rf system (ISAC II)

Red denotes under construction

- 3 frequencies –70.7, 106, 141 MHz
- 48 RF cavities – 8 low β, 20 medium β, and 20 high β cavities.
- $\lambda/4$ resonators.
- $Q_{ul} \sim 10^9$.
- Operate with coupling coefficient $\beta \sim 200$, $Q_l \sim 5\times10^6$.

LLRF Controls in TRIUMF

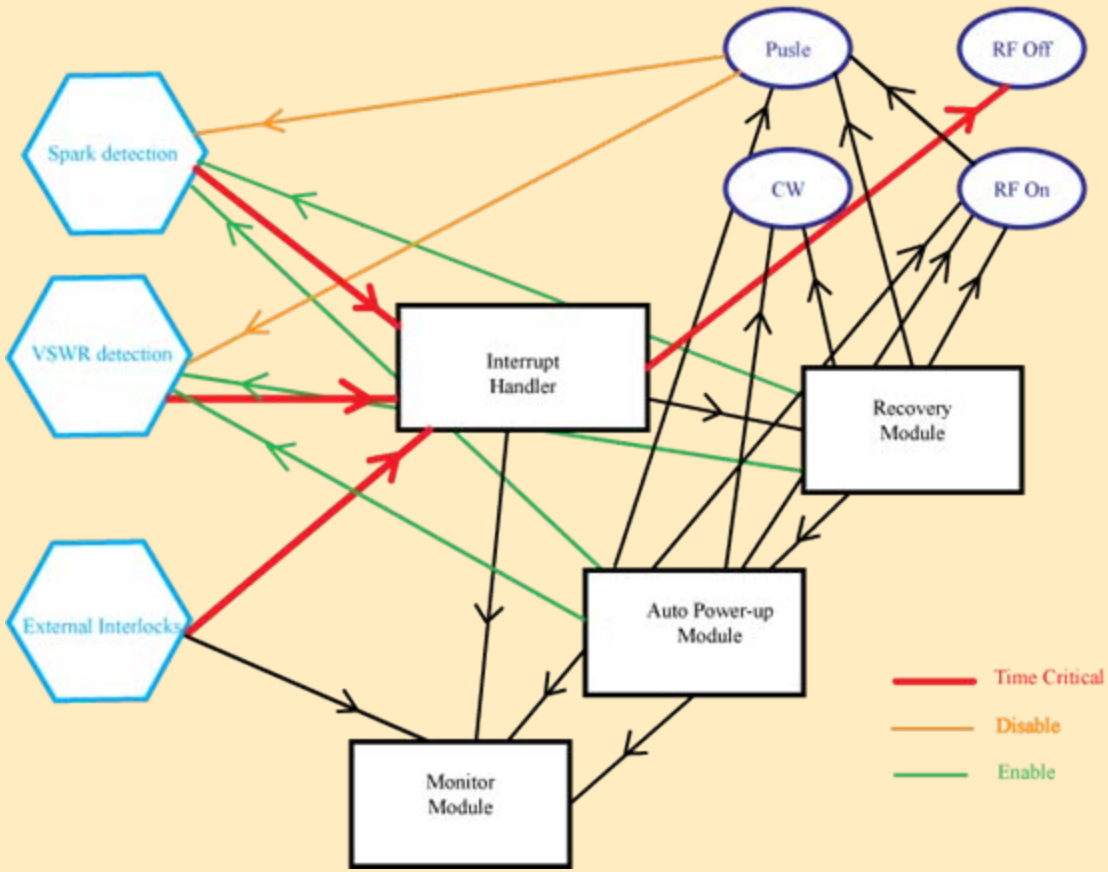
Blue denotes topics included in this talk

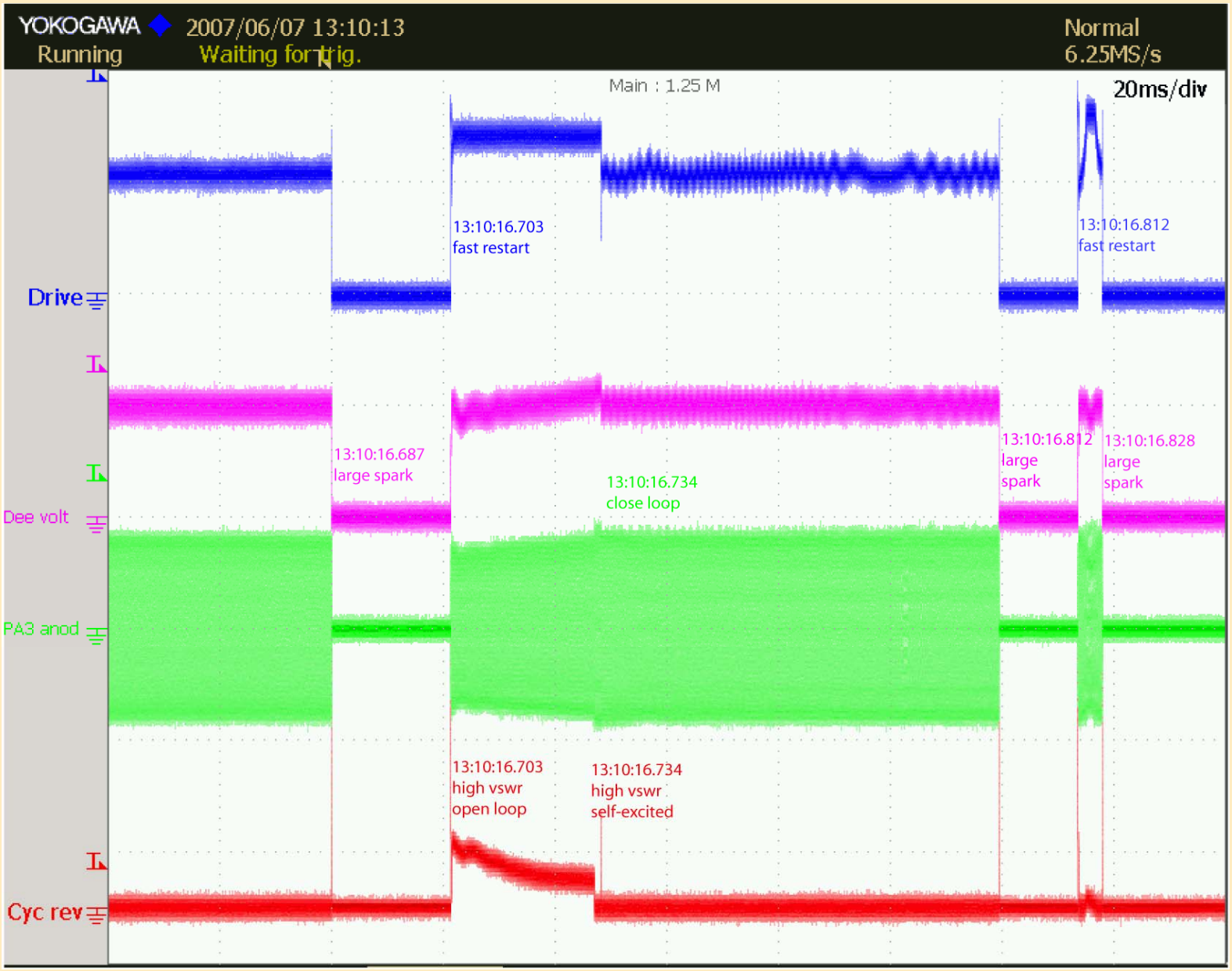
- Cyclotron
  - Commissioned in 1975. LLRF upgrade in 1994
    - VXI, DSP
  - CPU upgrade in 2006 – multi-threading
- Cyclotron Booster
  - Commissioned in 1990. LLRF upgrade in 2003.
  - Investigate AM-PM instability causing limit cycle oscillation
  - Replaced I/Q modulator with Amplitude/Phase modulator
- ISAC 1
  - Commissioned in 2001.
  - Upgrade to EPICS softioc – in progress
- ISAC 2
  - Commissioned in 2005.
  - Adaptive (Self-tuning regulator) control for cavity resonance control
  - VSCS – sliding surface controller for frequency acquisition
  - Alignment and Suppression of phase noise
- Remote Monitor of status
  - JSON response string

23 MHz Cyclotron CPU upgrade

- 1990 vintage 386 Radisys embedded CPU
- MSDOS – single task only.
- During 2006, main and spare MFM hard drives showing signs of failure.
- December 2006 - Replaced by Rackmount 2GHz Pentium and Firewire slot 0 controller.
  - Advantage of non-embedded PC:
    - RAID 1 (Mirrored drives)
    - Independent power supplies for CPU and VXI mainframe.
    - Supports for PCI devices
    - Cheaper + Easier further upgrade
- Major software revision
  - Different operating system – Preemptive multi-tasking and multi-threading
  - Different VXI driver.
- Concurrent programming
  - Preventing Race conditions
    - Critical Sections
- Increase Responsiveness- Interrupt driven asynchronous calls are assigned different priorities. Time critical calls are assigned highest priority.
  - Highest priority – Exception handling.
    - Spark detect
    - VSWR detect
    - Safety interlock
  - High priority – Operator interface.
  - Normal priority – scheduled tasks (read/write Status).

23 MHz Cyclotron Multithreading Modules




YOKOGAWA
2007/06/07 13:10:13
Running
Waiting for trig.
Normal
6.25MS/s
Main : 1.25 M
20ms/div
13:10:16.703
fast restart
13:10:16.812
fast restart
Drive
13:10:16.687
large spark
13:10:16.734
close loop
13:10:16.812
large
spark
13:10:16.828
large
spark
Dee volt
PA3 anod
13:10:16.703
high vswr
open loop
13:10:16.734
high vswr
self-excited
Cyc rev

92 MHz RF Booster Control

Booster AM-PM instability

- Booster control “upgraded” from Amplitude/Phase modulator to I/Q modulator in 2003.
- Booster operation stable @ 90 kV
- Booster operation intermittently unstable @ 100kV
- On to the long road to investigate this instability…
  - Booster located inside operational cyclotron
  - Extremely short time allotted for investigation.
  - Problem is intermittent.
- Clues
  - replaced system is stable.
  - System is stable when Q loop is opened

AM-PM Instability

The output power of **I/Q modulator** is given by

$$P = P_0\left(1+q^2\right) \qquad q = \frac{V_q}{V_i}$$

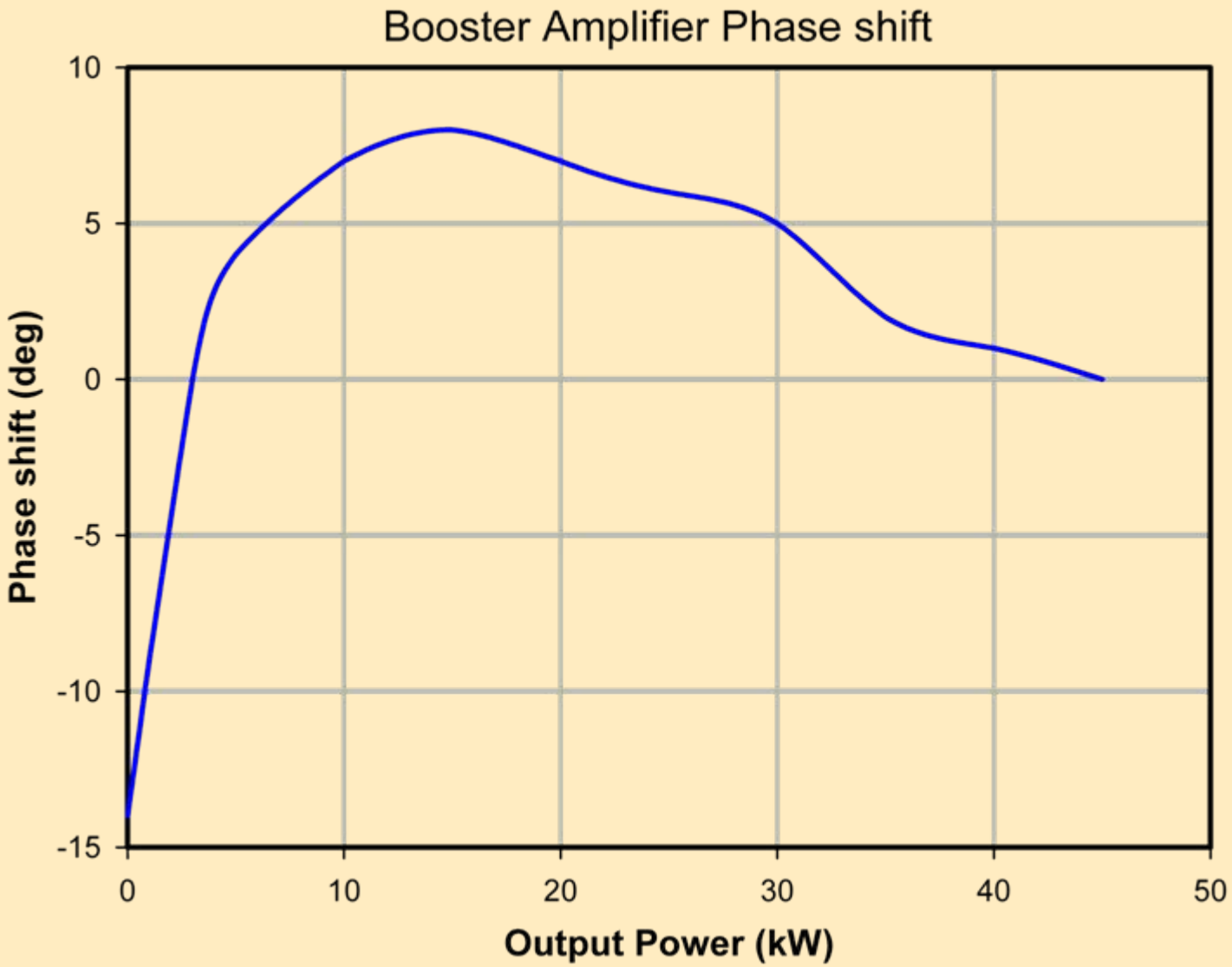
The phase of the voltage at the cavity output is

$$\theta = \tan^{-1} q + \frac{\partial\theta}{\partial P}_{P=P_0}(P-P_0) + \tan^{-1}\delta$$

where $\frac{\partial\theta}{\partial p}$ is the phase shift dependence on power. The first term is due to the modulator, the second term is due to the amplifier phase shift and the third term is due to detuning of the cavity.

A solution for $\theta = 0$ does not exist when

$$8P_0\frac{\partial\theta}{\partial P}\Delta\omega > \omega_{bw}$$


Booster Amplifier Phase shift
Phase shift (deg)
10
5
0
-5
-10
-15
0
10
20
30
40
50
Output Power (kW)

AM-PM Instability

In the booster, $\frac{\partial\theta}{\partial P} \approx -4^o \frac{\pi}{180^o} \frac{1}{10kW}$

$$P_0 = 45kW$$

Therefore, stability limit at

$$2.51\Delta\omega < \omega_{bw} \qquad \text{or} \qquad \Delta\omega < 0.4\omega_{bw}$$

Actually, things go bad before this limit is reached.

$$\begin{bmatrix} 1 & \delta \\ -\delta & 1 \end{bmatrix} \begin{bmatrix} V_i \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_i \\ v_q \end{bmatrix}$$

$$\begin{bmatrix} 1 & \delta \\ -\delta & 1 \end{bmatrix} \begin{bmatrix} V_i \\ V_q \end{bmatrix} = \begin{bmatrix} 1 & -0.31q^2 \\ 0.31q^2 & 1 \end{bmatrix} \begin{bmatrix} v_i \\ v_q \end{bmatrix}$$

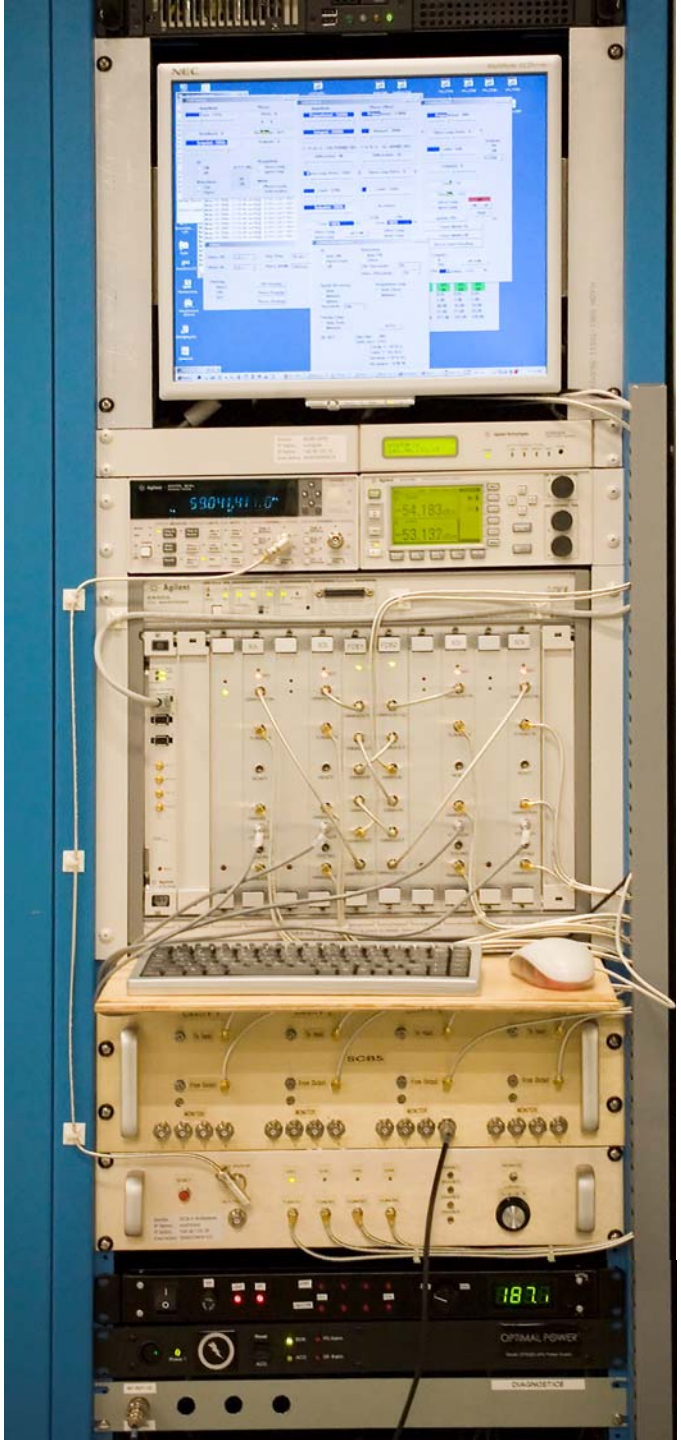
So if I/Q demodulator is used, there is a large amount of cross-talk between the 2 channels. The system went into cross-talk induced oscillation.

AM-PM Instability

- Instability limit ~ 4 kHz
- Cyclotron frequency swing ~ 20 kHz -> booster swing ~ 80 kHz
- The I/Q modulators are replaced by Amplitude/Phase modulators.
- The I/Q demodulator are replaced by Amplitude/Phase detectors.
- The booster LLRF control becomes stable.

ISAC 2 Superconducting Cavities

- 1st beam through 20 cavities – spring 2006
- 1st experiment completed - May 2007



Supervisory PC

Local operator
GUI

Ethernet-GPIB controller

Frequency, Power meter

4 controllers
&
Frequency Distribution

Rf deck

Rf multiplexer

Tuner Motor controller

Controls

Vacuum & cryogenics

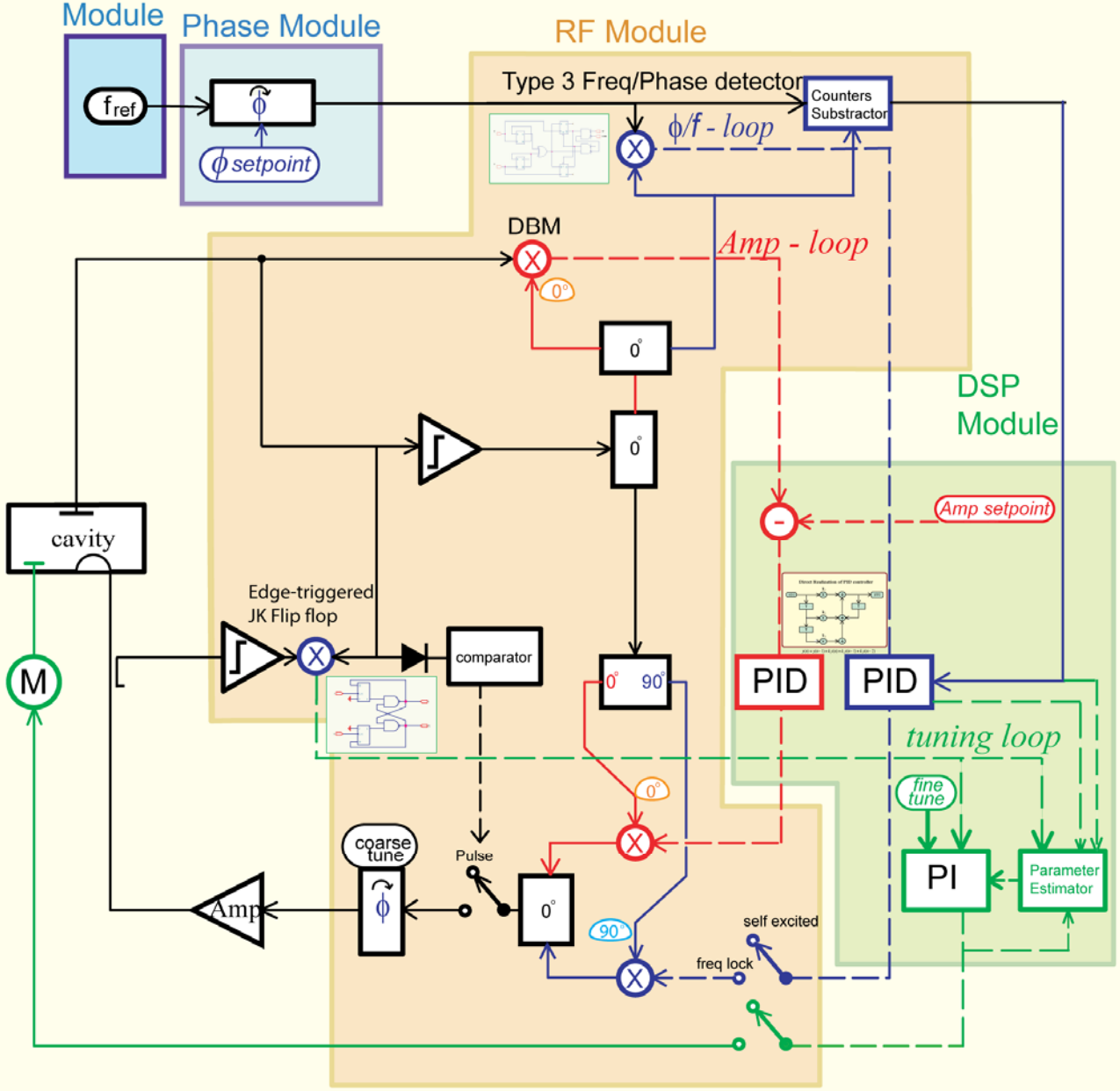
SC Solenoid supply

Tuner Amplifier

Rf Control

Rf Amplifier

ISAC II RF Control Block Diagram



Requirements for Tuner Control

•Keep cavity resonant frequency the same as reference frequency
•After initial power up in self-excited mode, the difference between the self-excited frequency and the reference frequency can be several kHz.
•The tuner must move the self-excited frequency to within 4 Hz of the reference frequency
•After phase-locking the self-excited frequency to the reference frequency, the tuner continually adjusts the cavity against cavity deformation due to helium pressure fluctuation.

Adaptive Tuner Control -Variable Structure Control

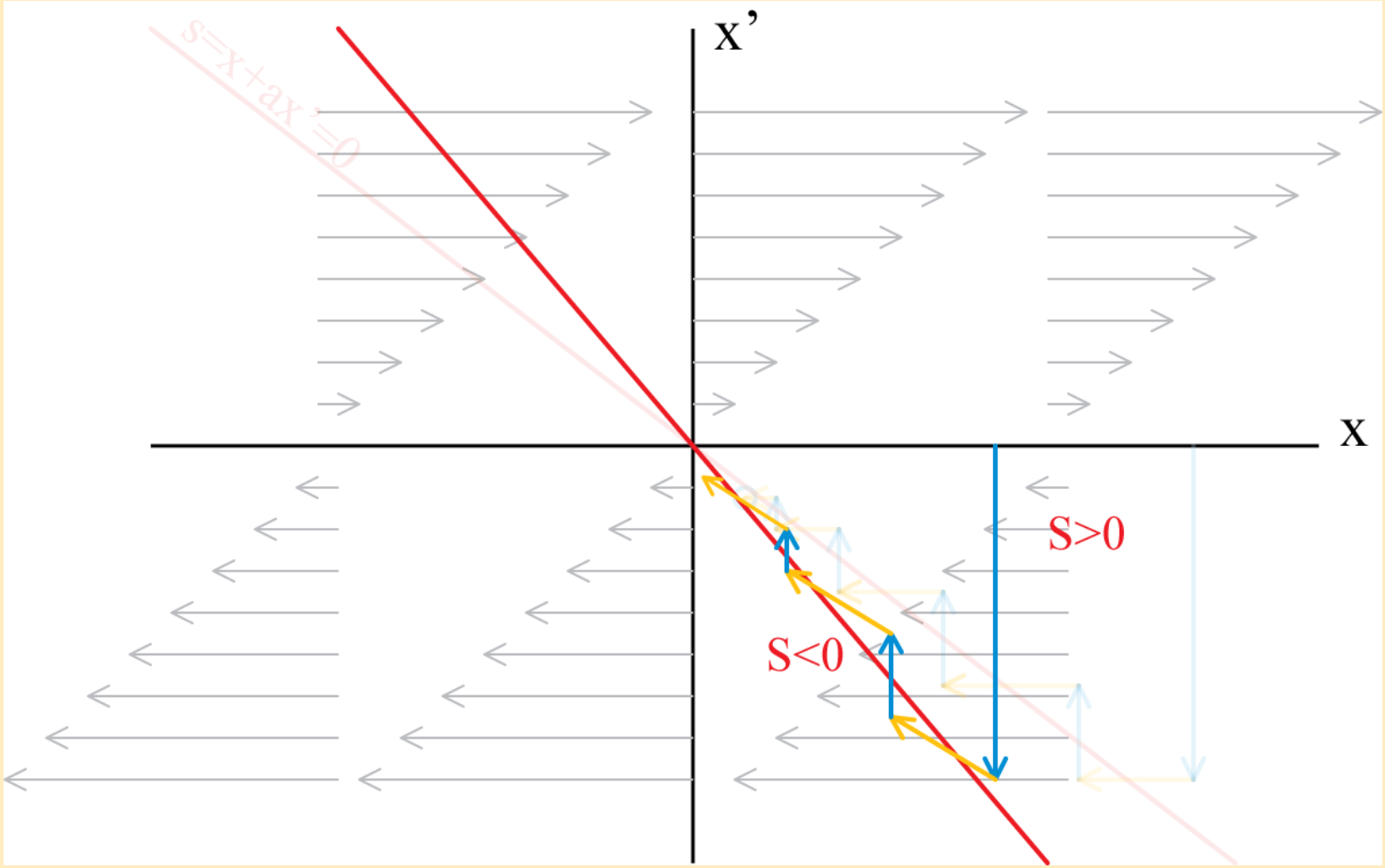
- Tuner control can most benefit from adaptive control.
- Tuner control operates in 2 modes
  - Acquisition
    - The self-excited frequency is different from the reference frequency.
    - The tuner is moved to reduce the difference in frequencies.
    - Large amount of tuner movement is required to bring the self-excited frequency to the reference frequency.
    - Tuner-generated microphonics is not important.
  - Tracking
    - The self-excited frequency is phase-locked to the reference frequency.
    - The tuner is in a feedback loop to minimize the RF power
    - Only small tuner movement is required.
    - Tuner generated microphonics can adversely affect the performance of the accelerator.

Acquisition Phase

- Frequency difference can be several kHz at the start of the acquisition phase.
- Frequency difference must be less than 4 Hz at the end of acquisition phase.
- High data latency
  - FPGA Frequency counter reads frequency difference every 1 second.
- Discontinuous feedback loop control of tuner – nonlinear response
- Uses Sliding mode controller
  - Robust control
  - Nonlinear feedback
  - The switch function is $s = x + a\dot{x}$
  - To reduce the chattering phenomenon of the sliding mode control the sign function is replaced with a continuous approximation.

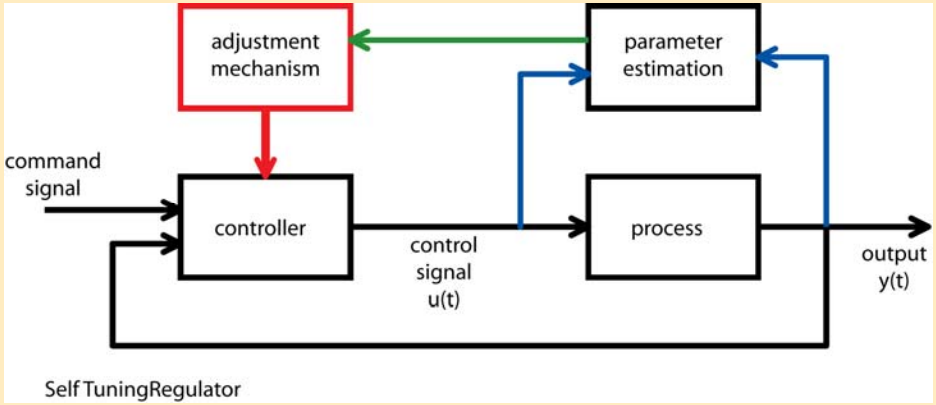
$$u = -x - K\frac{s}{|s| + \delta}$$

Phase space of tuner movement under sliding mode control

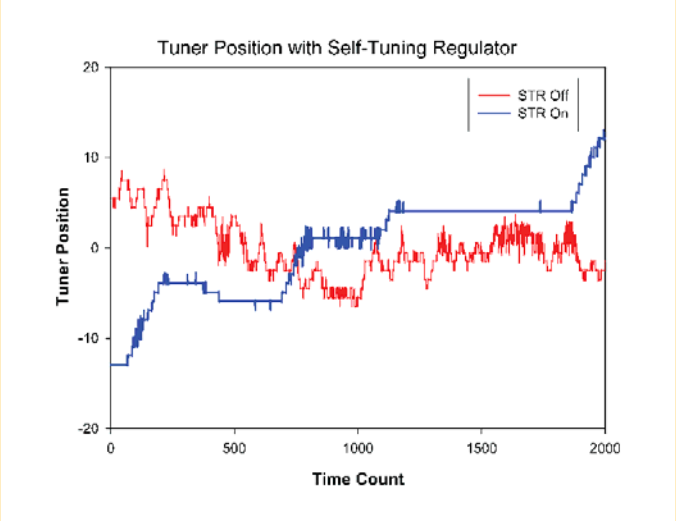


Tracking Phase

- Tuning signal contaminated with noise
- Minimize tuner drive to reduce further excitation of noise
- Adaptive control - Self Tuning Regulator

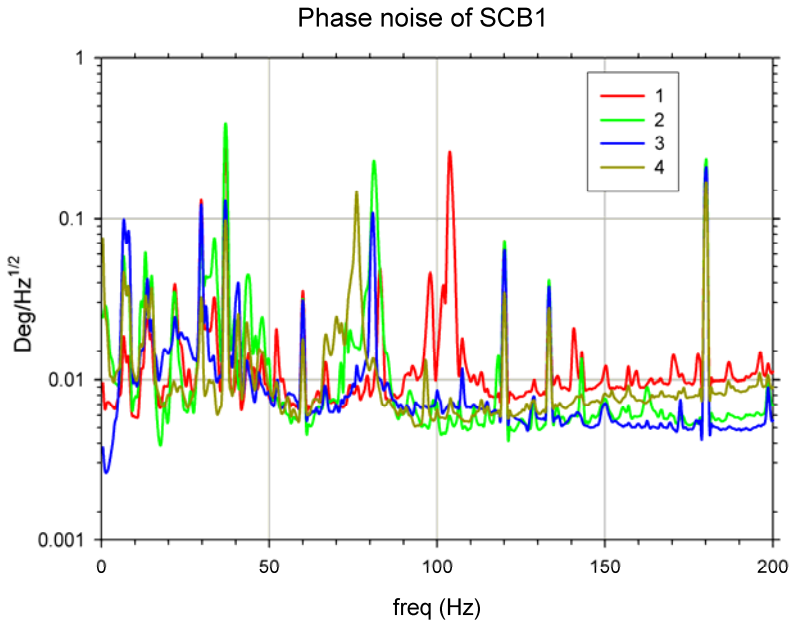


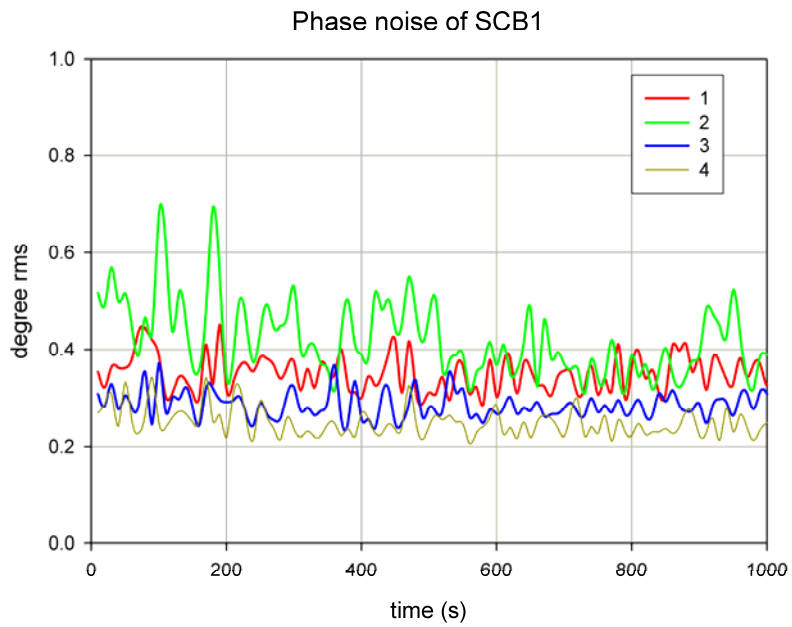
$$J = \lim_{N\to\infty} \frac{1}{N} \sum_{k=1}^{N} E\left[y(t)^2 + \rho u(t)^2\right]$$



ISAC 2 Alignment and Phase noise

- Alignment of phase delay affects cross talk in both self-excited and driven operation.
- Although alignment can be set accurately manually, the alignment can change due to component aging and thermal effects.
- Phase delay is the combined effects of cavity tuning and transmission line (cable + amplifier) delay.
  - Cavity tuning is controlled by tuner
  - Transmission line delay is controller by phase shifter, either internal or external.
- Needs to isolate these effects online to allow retuning.
- A series of theoretical and experimental studies have been done to isolate these effects.
- The time average of the cross error product between amplitude and phase is a monotonic function of transmission line + amplifier phase delay.
- There will be in a poster on Wednesday Afternoon, titled "Effect of Misalignment on Phase Noise in Superconducting Cavities", presented by Q. Zheng.


Phase noise of SCB1
1
2
3
4
1
0.1
0.01
0.001
Deg/Hz^1/2
0
50
100
150
200
freq (Hz)


Phase noise of SCB1
1
2
3
4
1.0
0.8
0.6
0.4
0.2
0.0
degree rms
0
200
400
600
800
1000
time (s)

Remote Communications

- Central Control
  - SDLC (Synchronous Data Link Control) link
    - Cyclotrons
  - TCP (Transmission Control Protocol) servers
    - ISAC (Isotope Separator and Accelerator) 1
      - Converting to EPICS
  - EPICS (Experimental Physics and Industrial Control System)
    - ISAC 2
- Remote Status Monitoring
  - Back door to controller status
    - Alternative to and Independent of EPICS
  - UDP (User Datagram Protocol) server in controller
    - XML (Extensible Markup Language)
    - JSON (JavaScript Object Notation)
  - Tomcat HTTP (HyperText Transfer Procotol) Server
    - MAC Server OS X
    - Dual ethernet ports
    - JSP (JavaServer Pages)
    - AJAX (Asynchronous Javascript and XML) - live update

Comparison between XML and JSON

- Example of Amplitude Setpoint and Readback

```
<Cyclotron>
  <Amplitude>
    <Setpoint>
      100.0
    </Setpoint>
    <Readback>
      100.1
    </Readback>
  </Amplitude>
</Cyclotron>
```

- Document-oriented
- Text-based
- Position-independent
- High overhead
- Not well suited to data-interchange
  - Does not match data model of most languages

- Example of Amplitude Setpoint and Readback

```
{ "Cyclotron":
  { "Amplitude":
    { "Setpoint":100.0
      "Readback":100.1
    }
  }
}
```

- Object-oriented
- Text-based
- Position-independent
- Low overhead
- Well suited to data-interchange
  - Match data model of Javascript

Comparison between XML and JSON

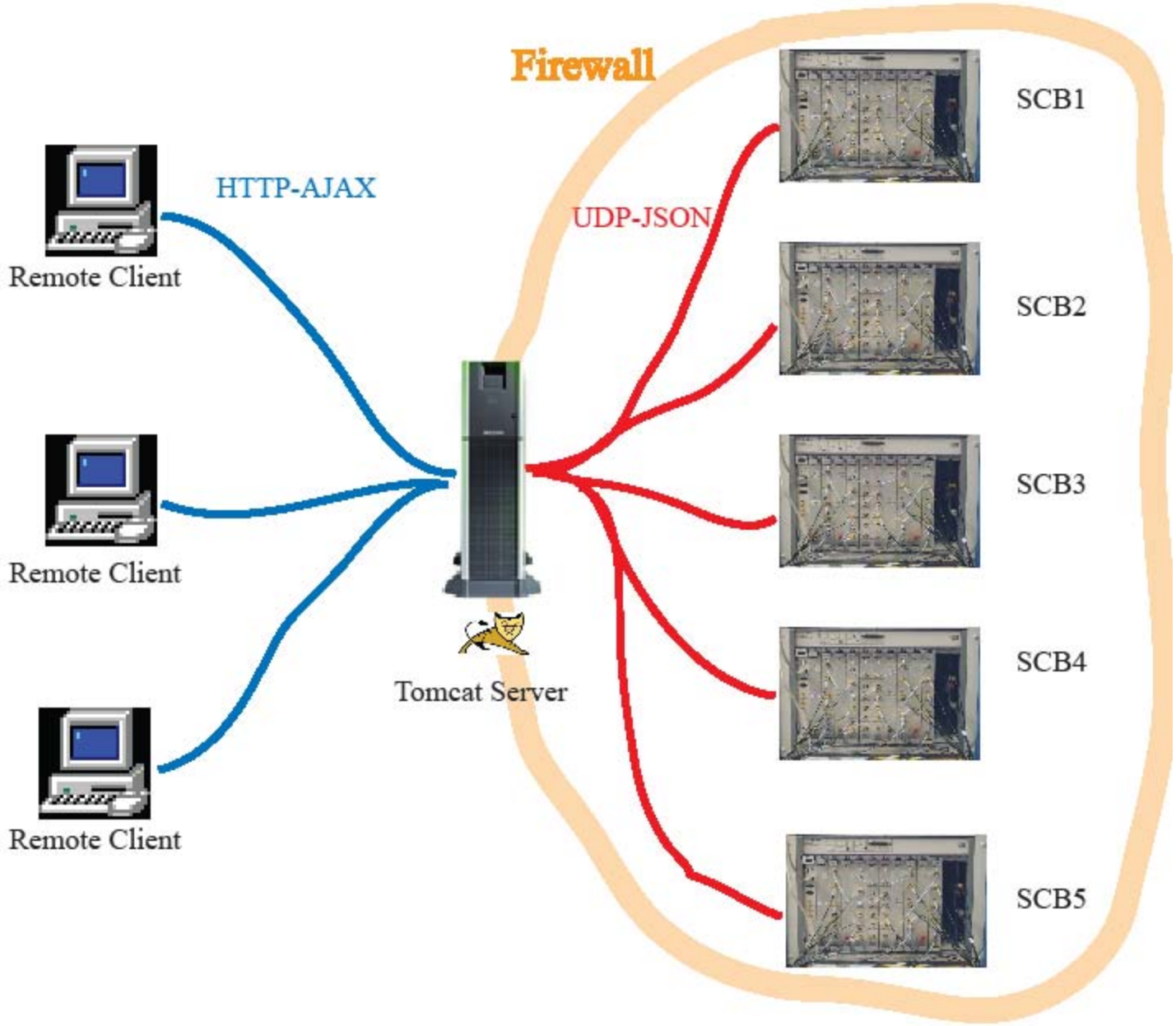
Examples of parsing the previous documents

XML

```
DOMParser parser = new DOMParser();
parser.parse(req.responseXML);
Document document = parser.getDocument();
Element cyclotron =
        document.getElementsByTagName(“cyclotron")[0];
Element amplitude =
        cyclotron.getElementsByTagName(“amplitude”)[0];
Element setpoint =
        amplitude.getElementsByTagName(“setpoint”)[0];
Int x = setpoint.getNodeValue());
Element readback =
        amplitude.getElementsByTagName(“readback”)[0];
Int y = readback.getNodeValue());
```

JSON

```
json = eval('(' + response.responseText + ')');
X=json.cyclotron.amplitude.setpoint.value;
Y=json.cyclotron.amplitude.readback.value;
```


Firewall
HTTP-AJAX
UDP-JSON
Remote Client
Remote Client
Remote Client
Tomcat Server
SCB1
SCB2
SCB3
SCB4
SCB5

MAIN RF Control STATUS - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://xserve01a.triumf.ca:8080/mainrf/index.html

Getting Started Latest Headlines GM2GPX

MAIN_RF V1.30 Complied at 14:40:04 Jul 4 2007 (mainrfvxi.triumf.ca:1550)
last update: Oct-11 2007 14:25:42
RF: ON CW Driven State : 2
Freq Syn = 23059336 **Freq Counter** = 23059335.99 **Δf:** 0.01

	Amplitude	Phase	Tuner
proportional	13500	200	2000
integral	180	20	500
differential	5	300	100
setpoint	94.00	0.00	10.00
readback	95.00	-3.14	119.00
drive limit	521	602	800
drive	457	501.96	549.02
ε	15	577	0

Interlock Status

No FastTrip
Control Enable
Amplifier OK
Interface Power OK
VSWR FastTrip OK
last trip:
Oct-10 2007 10:46:58
VSWR fast trip

Spark summary since : Oct-11 2007 09:00:00

Level	0	Oct-11 2007 07:12:28
Large	0	Oct-11 2007 07:12:31
Medium	0	Oct-11 2007 07:12:31
Small	0	Oct-01 2007 14:50:54
ADC	0	Oct-11 2007 06:03:33
Out of Driven	0	Oct-07 2007 07:58:32
Clustering	0	

Program running since Oct-01 2007 14:50:55

◉ **Update** ○ **HOLD**

Powered by TOMCAT The Apache Software Foundation http://www.apache.org/

Log of mainrfvxi.triumf.ca:1550
Current time : Oct-11 2007 14:25:42

Oct-11 2007 07:12:28.529 ModemThread->Fast Restart...
Oct-11 2007 07:12:28.654 ModemThread->Voltage < 10kV. # 3. Fault Count=3
Oct-11 2007 07:12:28.669 MonitorException 1:**** Cluster = 16. Voltage < 10 kV. Code = -3
Oct-11 2007 07:12:28.669 MonitorException 2:***RF Off.
Oct-11 2007 07:12:28.779 MonitorException 3:**Pulse Restart @ 190
Oct-11 2007 07:12:28.826 Auto Sequence: CW Self Excited. Drive=194
Oct-11 2007 07:12:29.091 MODEM_DEVICE - Spark Trip Armed.
Oct-11 2007 07:12:31.685 Modem Thread->Large Spark. # 51. Fault Count=1
Oct-11 2007 07:12:31.701 ModemThread->Fast Restart...
Oct-11 2007 07:12:31.779 ModemThread->Medium Spark. # 1.
Oct-11 2007 07:12:31.873 Auto Sequence: Amplitude closed loop regulation. Error = -496, Drive=400.
Oct-11 2007 07:12:31.904 Auto Sequence: VSWR Trip Armed.
Oct-11 2007 07:12:32.044 MODEM_DEVICE - Spark Trip Armed.
Oct-11 2007 07:12:51.685 SDLC->DSP::sp_write 0, value=900.00,0x05ca
Oct-11 2007 07:13:07.310 SDLC->DSP::sp_write 0, value=910.00,0x05da
Oct-11 2007 07:13:10.123 SDLC->DSP::sp_write 0, value=920.00,0x05ea
Oct-11 2007 07:13:34.810 SDLC->DSP::sp_write 0, value=930.00,0x05fa
Oct-11 2007 07:13:36.998 SDLC->DSP::sp_write 0, value=940.00,0x060a
Oct-11 2007 07:14:14.810 SDLC:Request to Driven - Ref=23059442, Cav=23060361.37
Oct-11 2007 07:14:28.951 MonitorThread: Driven @ 23059442
Oct-11 2007 07:14:28.982 Auto Sequence: Tuning loop closed.
Oct-11 2007 07:14:29.013 MonitorThread: RF Ready.
Oct-11 2007 09:00:00.127 Spark Status...
Oct-11 2007 09:00:00.142 Level: 3
Oct-11 2007 09:00:00.142 Large: 51
Oct-11 2007 09:00:00.142 Medium: 1
Oct-11 2007 09:00:00.142 Small: 0
Oct-11 2007 09:00:00.142 ADC: 3
Oct-11 2007 09:00:00.142 Out of Driven: 10
Oct-11 2007 09:00:00.142 Spark count cleared.

Powered by TOMCAT The Apache Software Foundation http://www.apache.org/

Done

Summary 2005-2007

- All controllers now rackmount PCs running 32-bits multitasking OS
- VXI mainframe + firewire slot 0 controller
- Instability in booster resolved
- Adaptive controls in ISAC 2 resonance controls
- Developed alignment strategy, phase noise reduction is continuing