A New Digital Low-Level RF Control System for Cyclotrons

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science & technology
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NRF
National Research Foundation
iThemba LABS
Laboratory for Accelerator Based Sciences

Outline

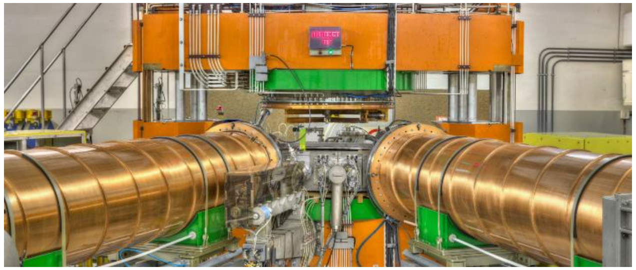
- Overview of RF and Cyclotron systems at iThemba LABS
- Overview of previous RF Control Systems
- Methodology of design
- Detailed description of the New RF Control System

RF and Cyclotron Systems

SSC

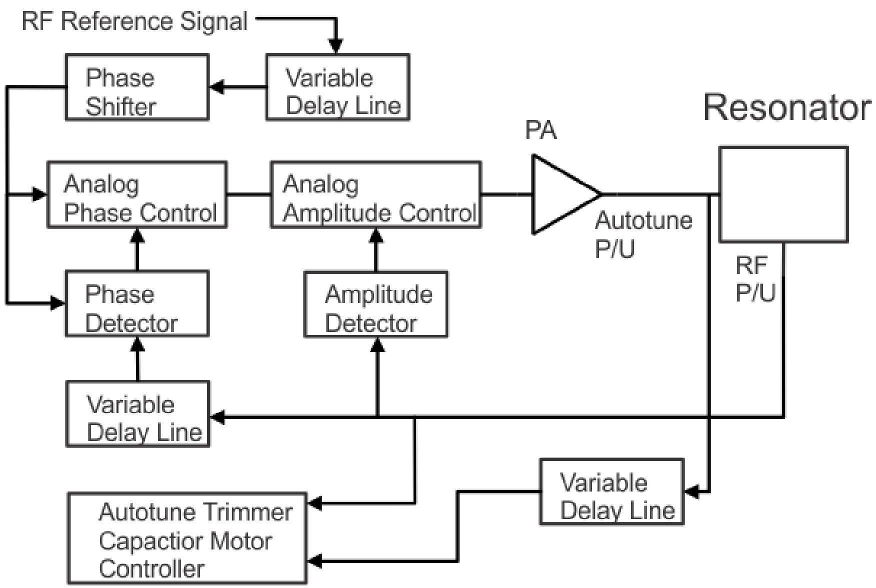
SPC1

SPC2



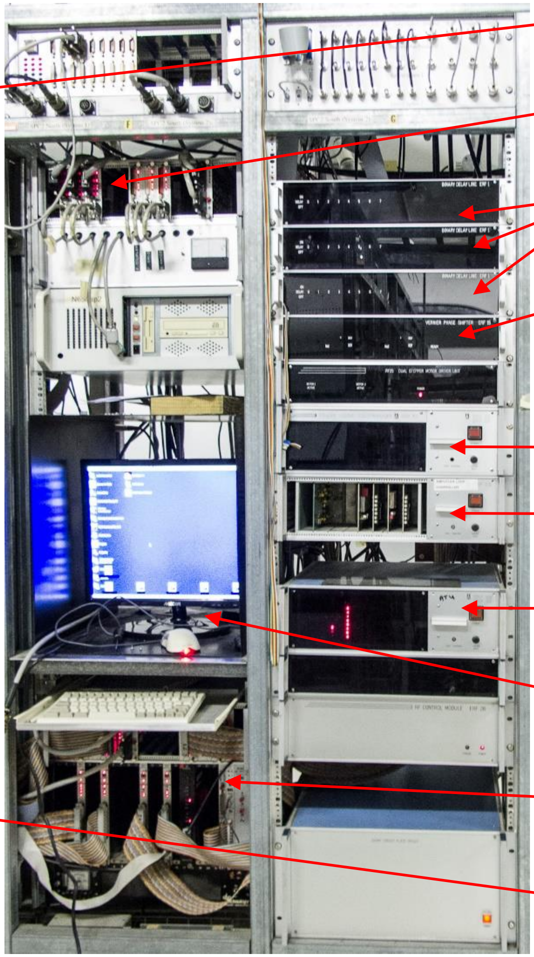
- 2 injector Cyclotrons
- K=8 SPC1 with an internal ion source
- K=8 SPC2 with an external ion source
- K=200 SSC
- Various buncher systems
- In total 13 RF systems
- Fixed and variable frequency systems
- Wide frequency range from 8 to 81 MHz
- Wide power range from 50 W to 150 KW

Previous Control System Block Diagram



- Primarily analogue control system
- Dated, utilizes 30 year old technology
- PROF180 processor with bubble memory
- Terminal display interface
- Software interface upgrade but it runs on OS2
- All the terminals have failed and have been replaced with software emulators

Elements of the Previous Control System



Prof180 Terminal Interface

Motion Control

Variable delay lines

Phase Shifter

Phase Controller

Amplitude Controller

Autotune Controller

OS/2 PC

CAMAC Controller

Software Terminal Emulator

Methodology of Design

- Goal: to replace 30 year old analog control system with a generic digital low-level RF control system over frequency range 5 to 100MHz
- Performed an extensive market analysis
- Several advances in technology demonstrated that it is possible to design a DLLRF
- FPGA based system is an excellent platform for design as we can implement state-of-the-art techniques such as Direct Digital Synthesis and I/Q Demodulation
- Set out to achieve 0.01% Amplitude and 0.01° Phase stability
- Along the way it became clear there were several important design decisions to make

Methodology of Design

- When evaluating DACs and ADCs must consider: Max sample rate, SNR, ENOB and SFDR
- 16 bit high-speed DACs exist
- True 16 bit high-speed ADCs over full frequency range don't exist: limited by max sample rate, SNR and ENOB.
- Final Solution: Use an FPGA to perform DDS and generate RF and LO signals
- Use heterodyning approach, mix RF pickup signal to IF
- Sample IF with ADC that meets SNR, ENOB, and SFDR and minimizes delay
- Perform I/Q demodulation in FPGA and use information to close the loop

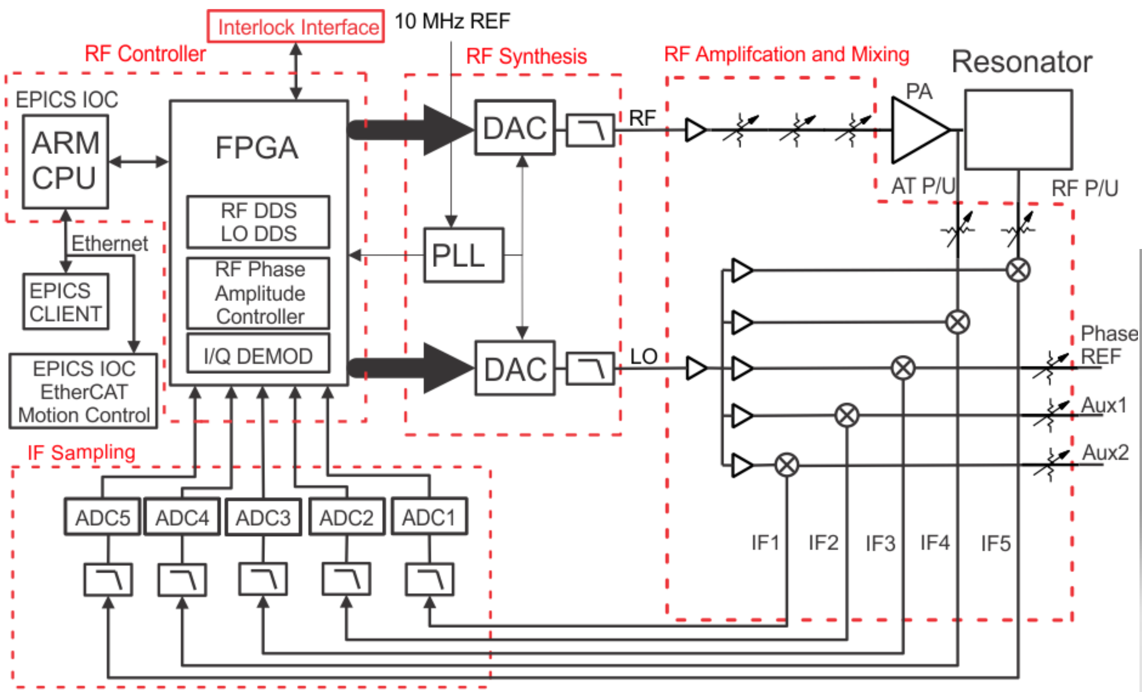
New Digital Low-Level RF Control System

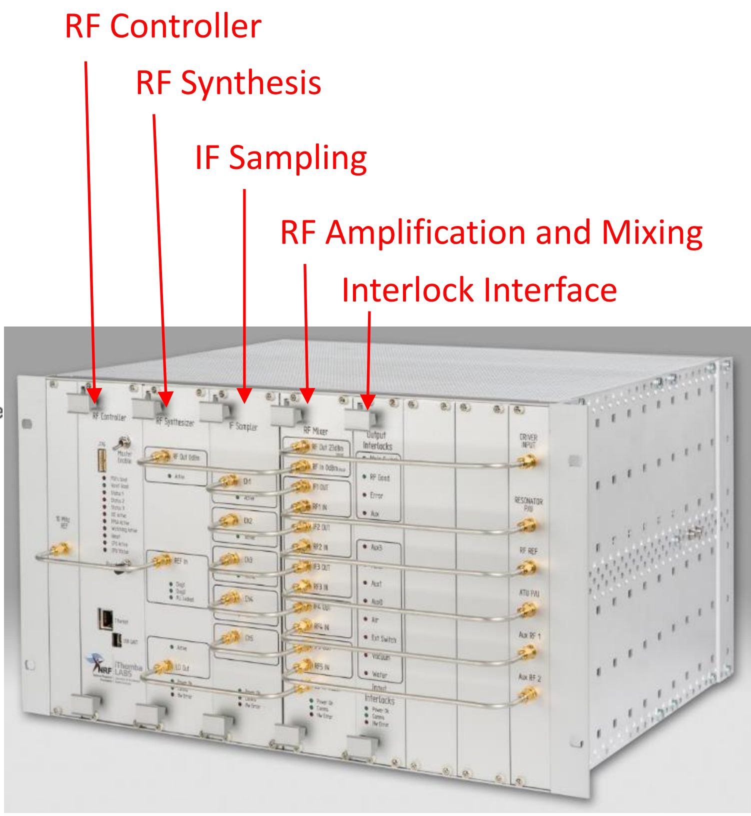
- Modular Design
- All RF signals are easily accessible from the front
- Digitally programmable
- 16 bit Amplitude resolution
- Operates between 5 and 100 MHz
- Programmable in steps of 1 μHz
- Phase resolution in steps of 0.0001º
- EPICS based

Designed for Maintainability

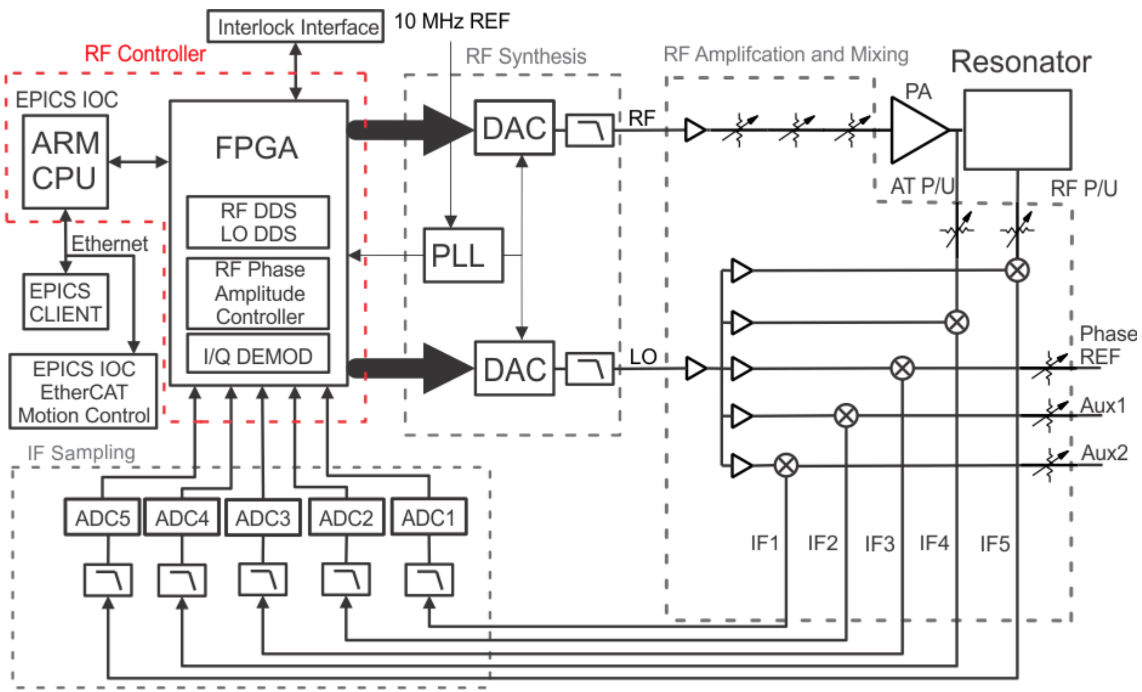
- All system modules are easily removed
- N-Type connectors to RF systems
- All RF signals are easily accessible from the front
- Power supplies are easily accessible from the rear

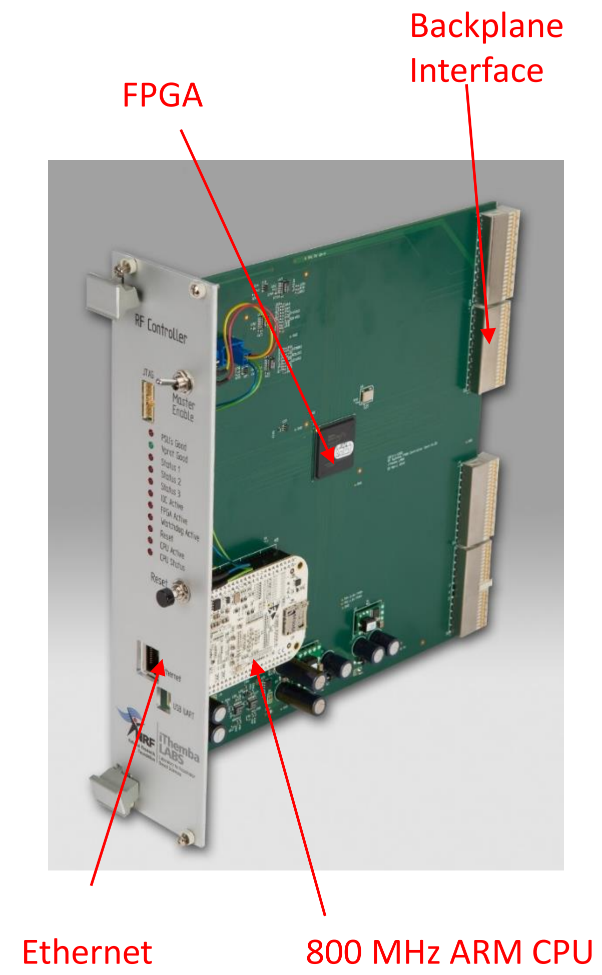
System Modules



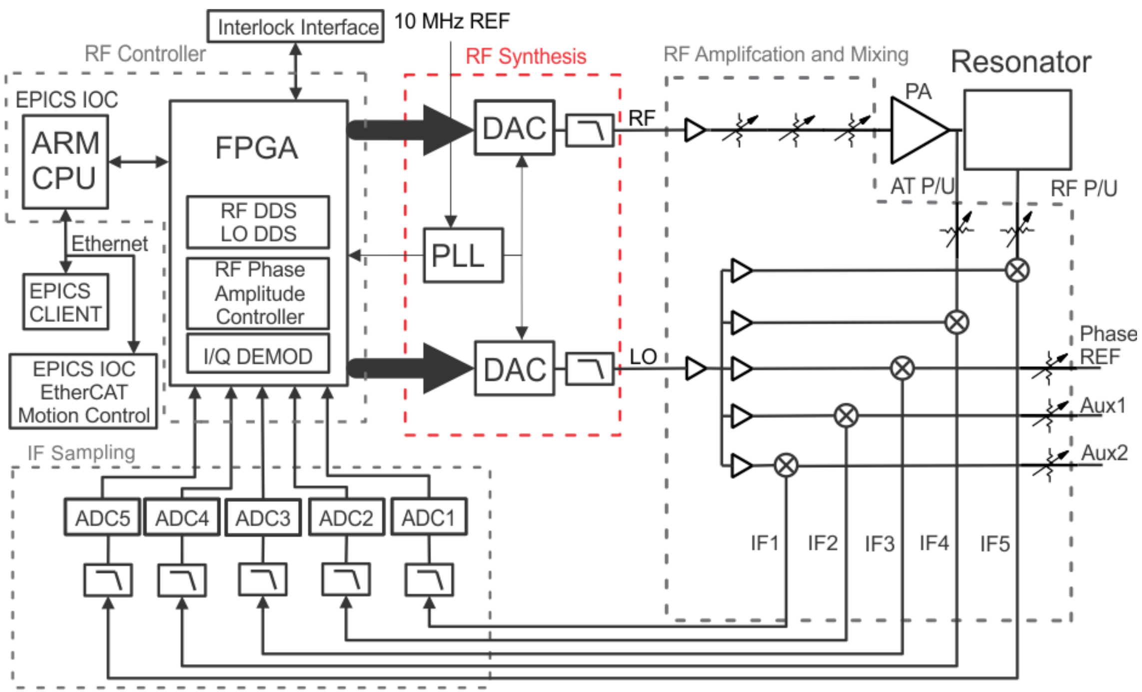


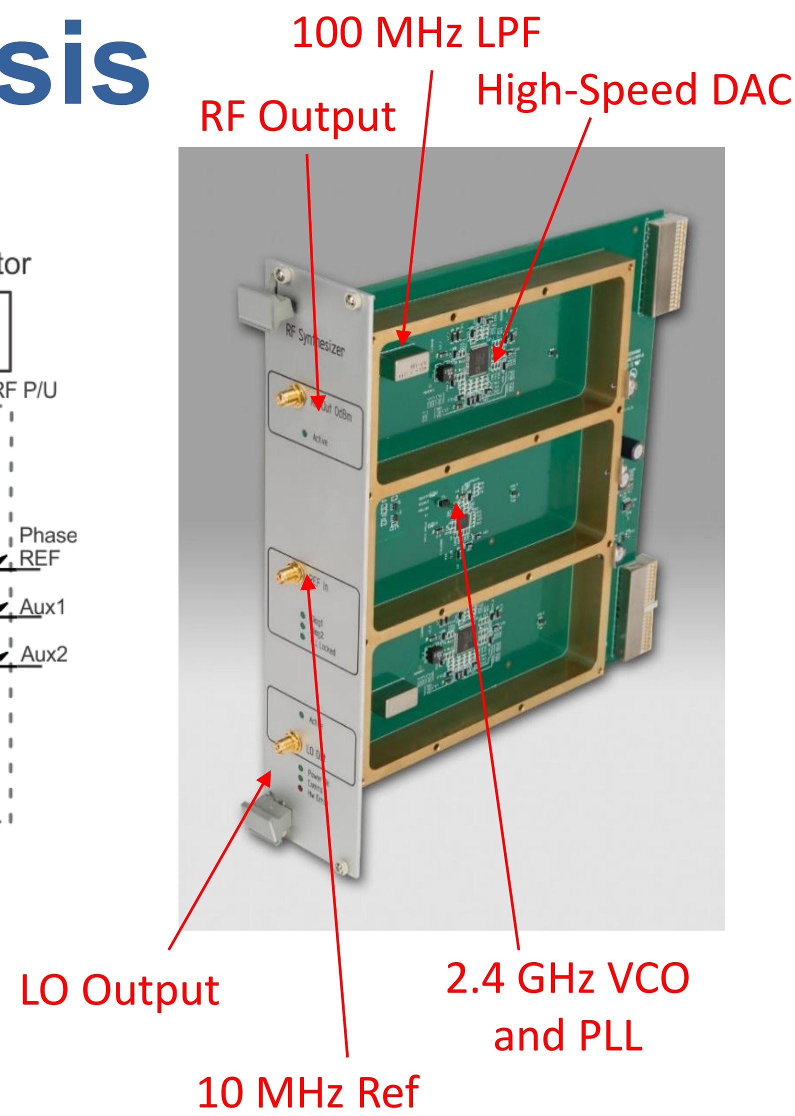
RF Controller



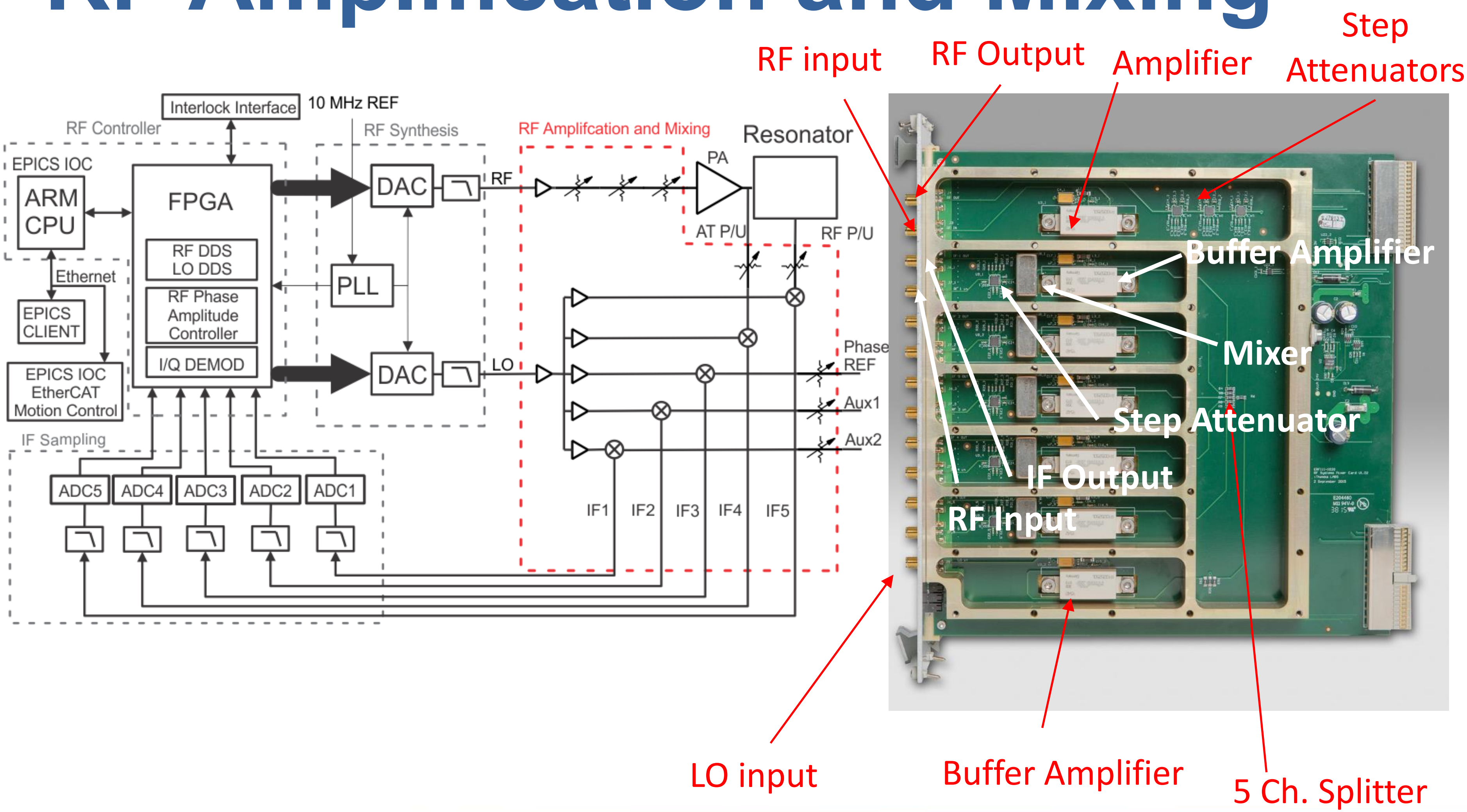


RF Synthesis

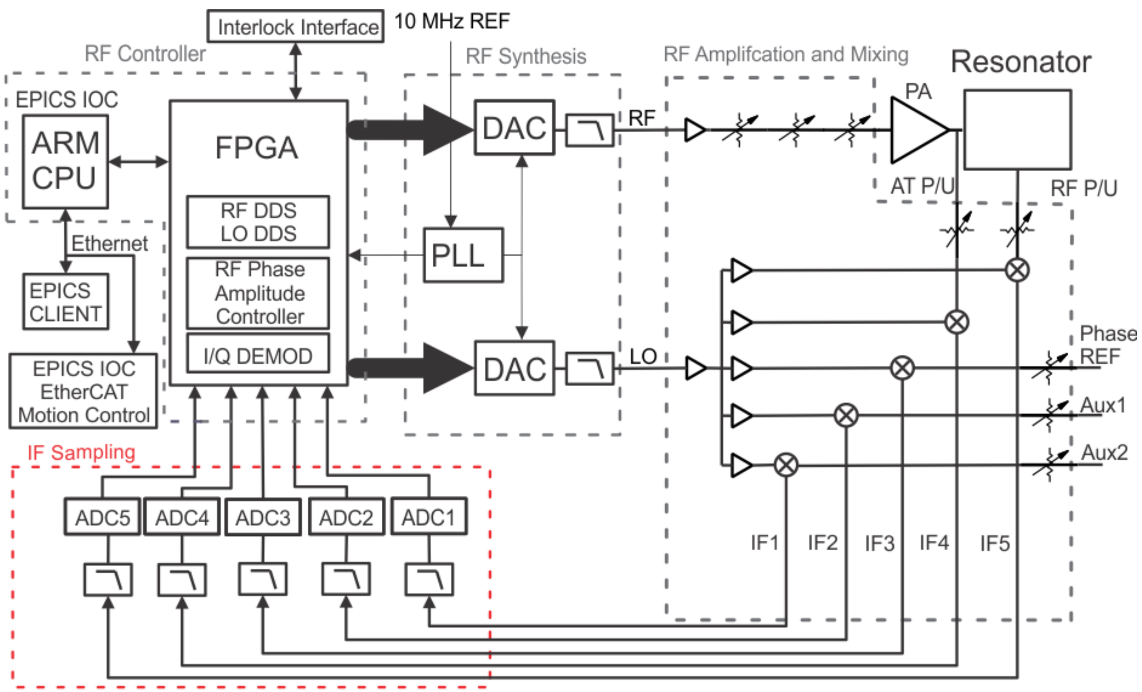




RF Amplification and Mixing



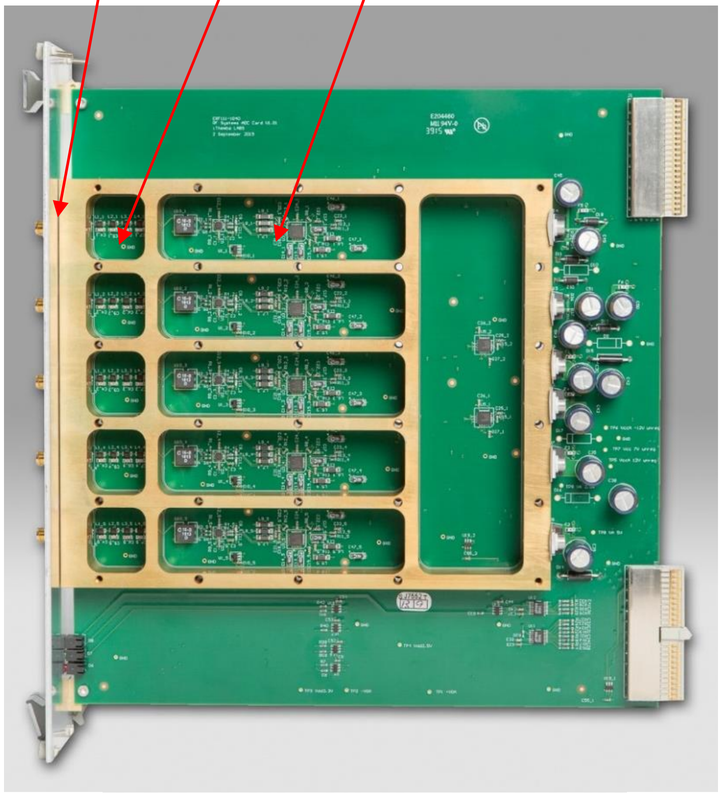
IF Sampling



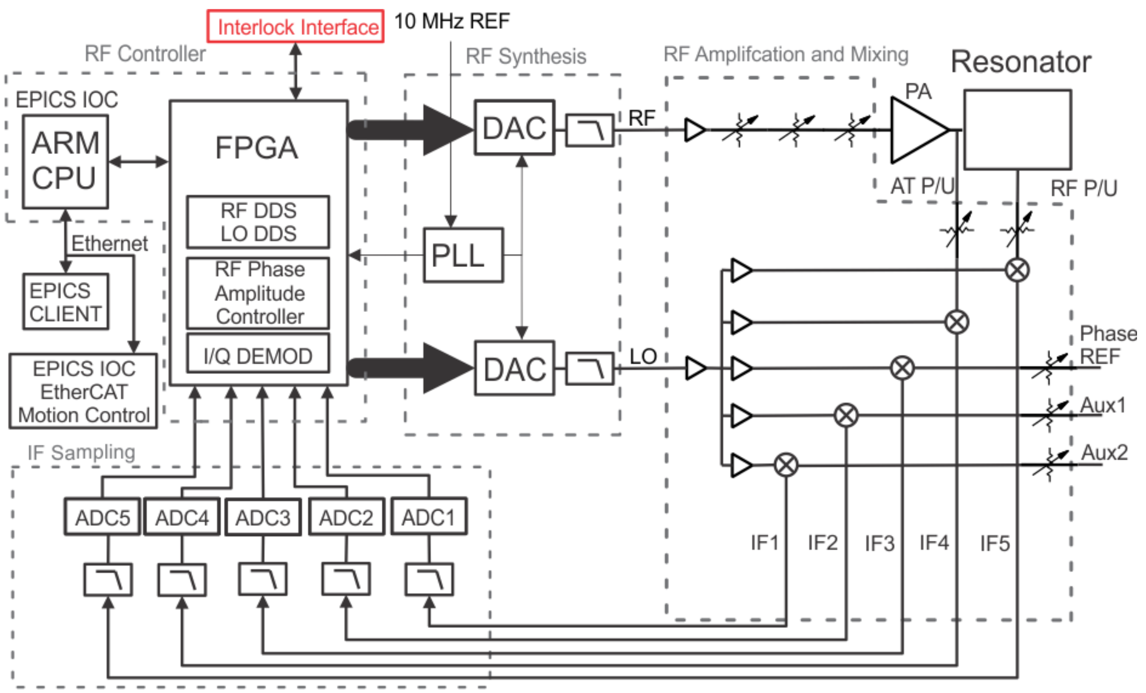
Low-pass filter

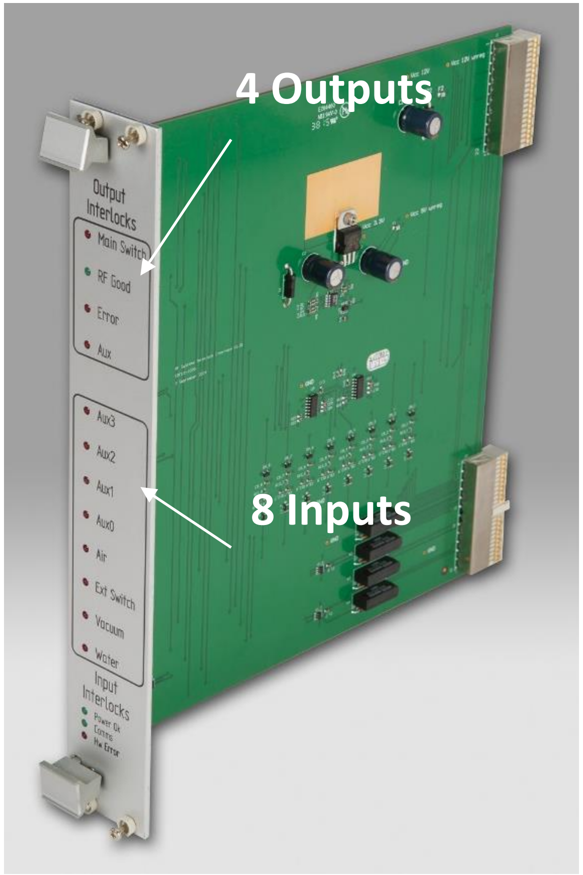
CH1 Input

10 MHz SAR ADC

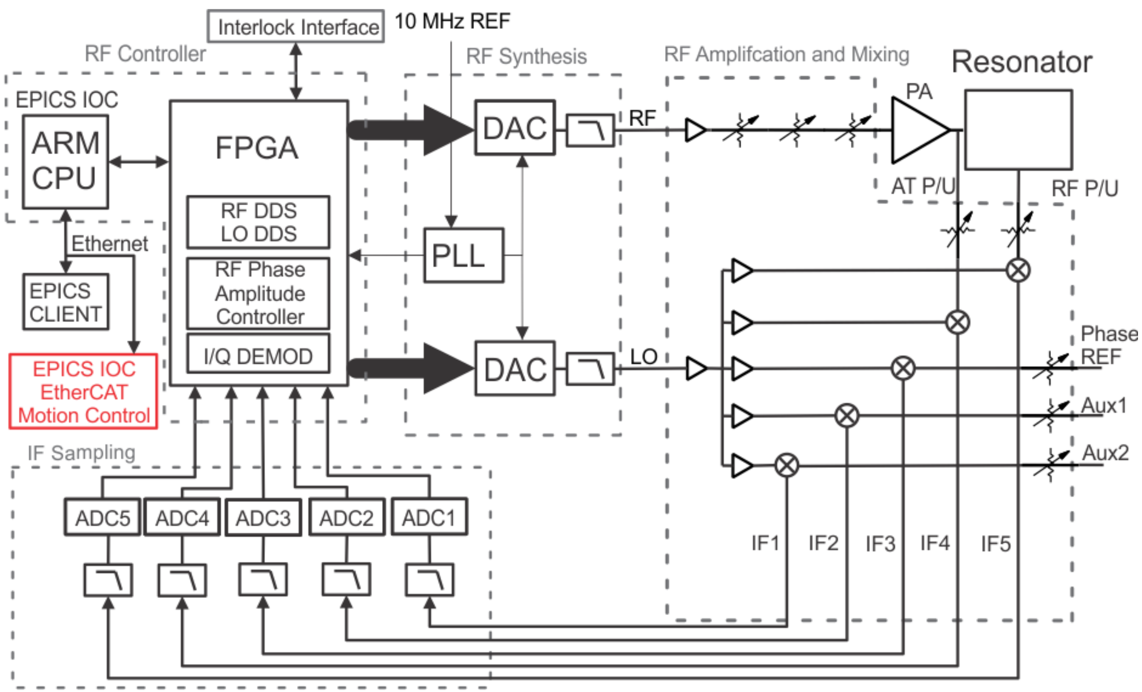


Interlock Interface





RF Motion Control



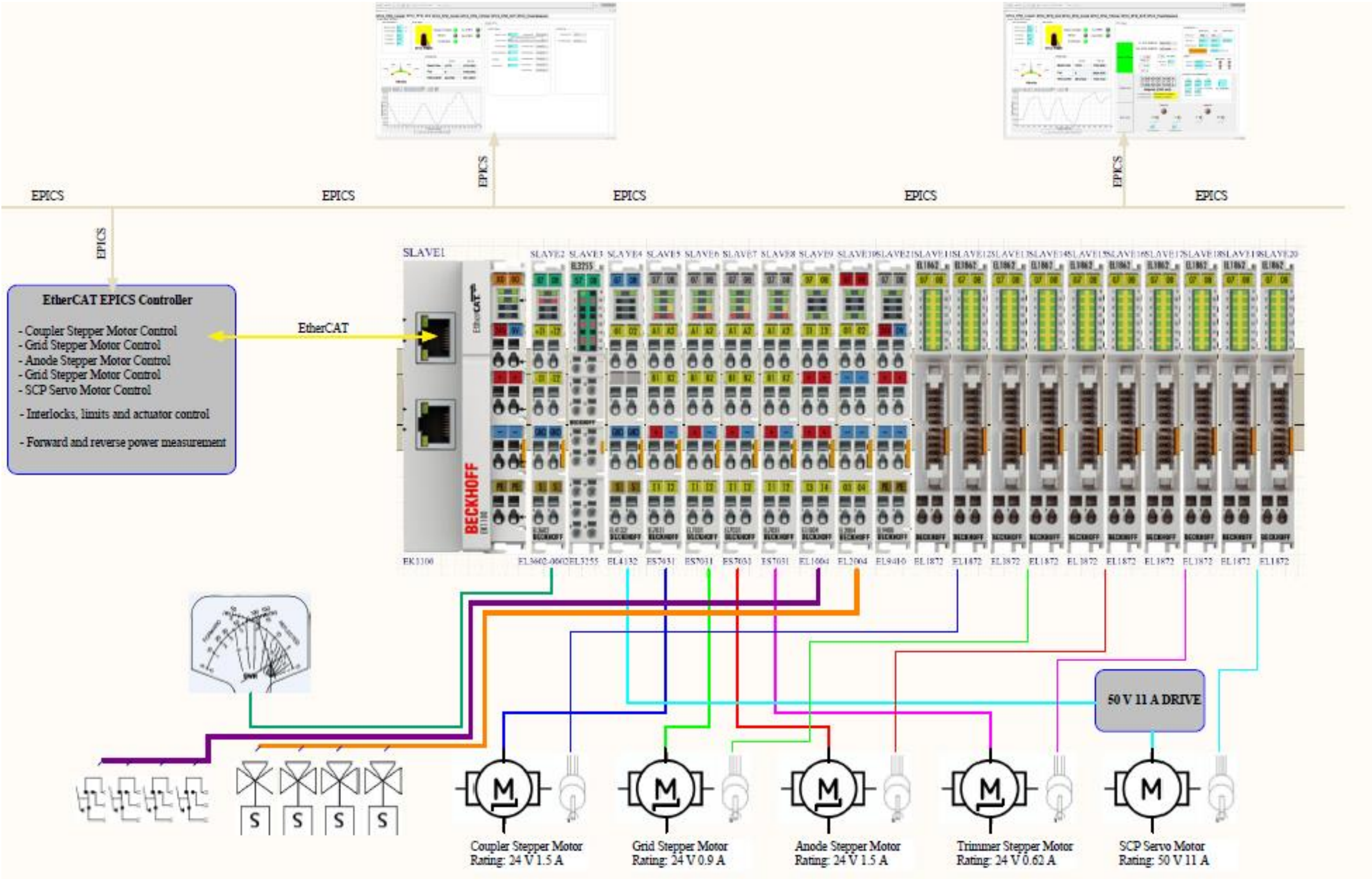
- Needed a solution for control of the physical motion of the tuneable elements
- We could have done it in house
- However this is time consuming and requires specialised manpower
- Could we do it with off-the-shelf systems?

Solution

- Beckhoff EtherCAT Terminals
- Real-time industrial solution, available for 25 years
- 1,000 distributed I/Os in 30 µs
- Built on EPICS EtherCAT interface developed by Diamond Light Source
- Fully integrated stepper motor controller, DC motor controller, analog input and output, and digital input and output terminals

EtherCAT Technology Group

Block Diagram Motion Control



Complete Solution

iThemba LABS

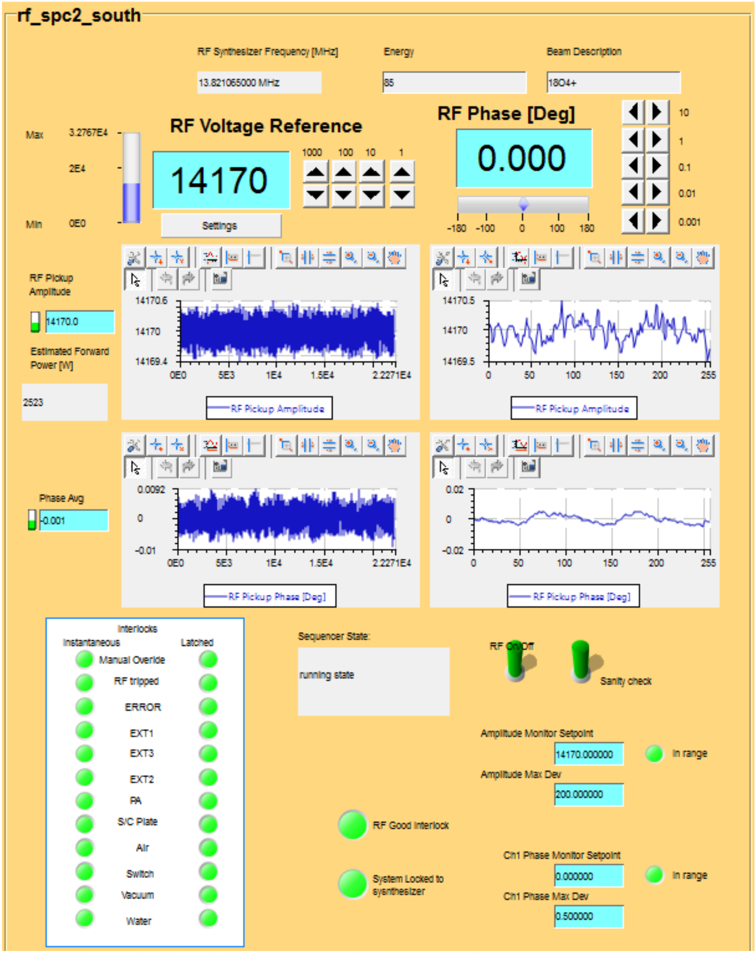
&

Beckhoff

RF Control

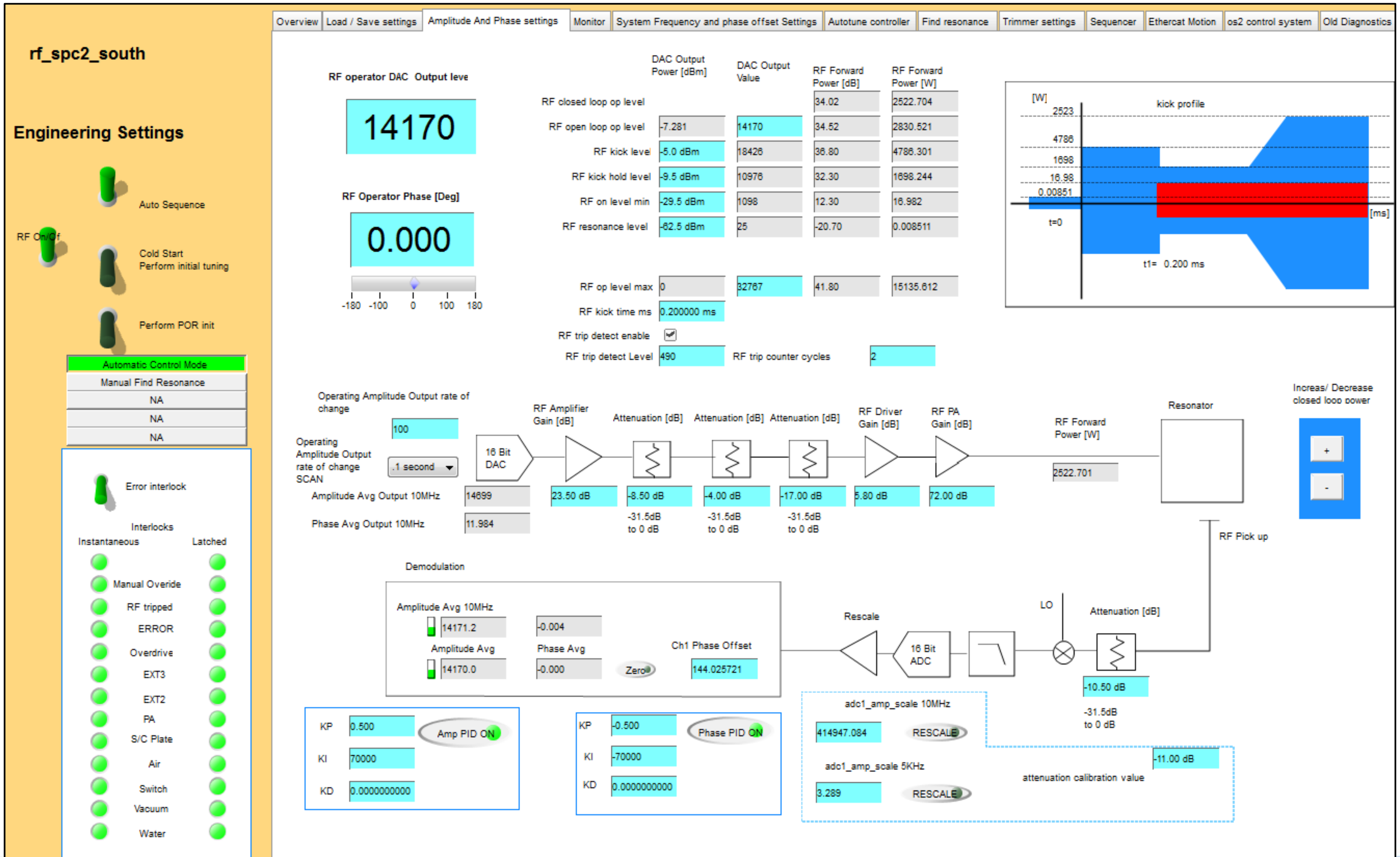
Power amplifier, anode,
grid, trimmer, coupling capacitor
and short circuit plate control

Operator User interface



- Allows operator to set RF amplitude and phase setpoints
- Real-time display of 10ms and up to 100s of RF amplitude and phase information
- All RF system interlocks are displayed

Engineering Control Parameters



- Multi-tabbed user interface
- Adjust kick and ramp profiles
- Signal chains are modelled schematically
- Set values of attenuators transmit and receive chain
- Adjust the PID parameters

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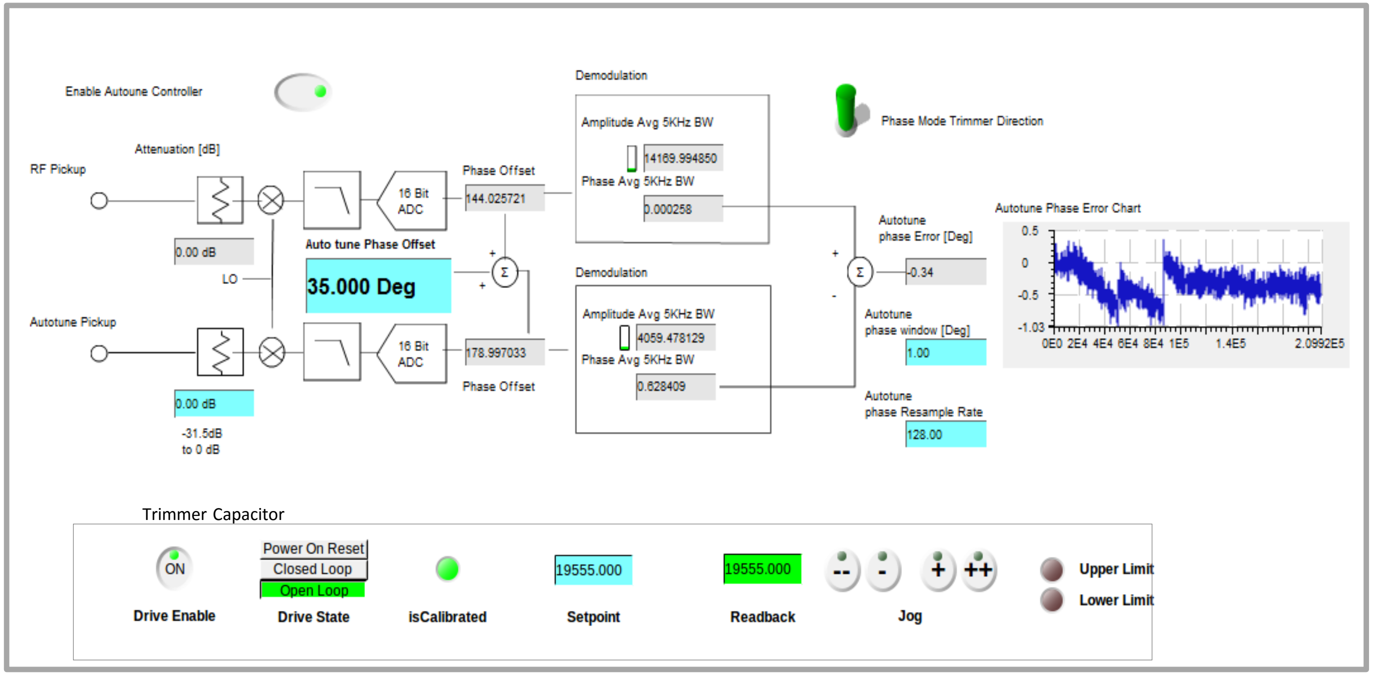
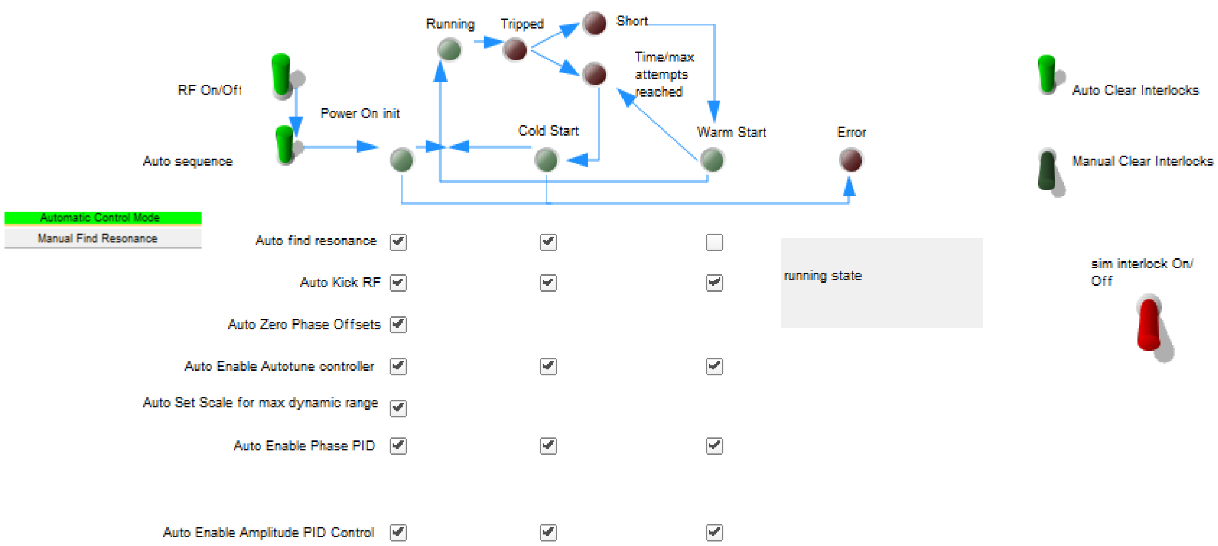
Auto-tune Control

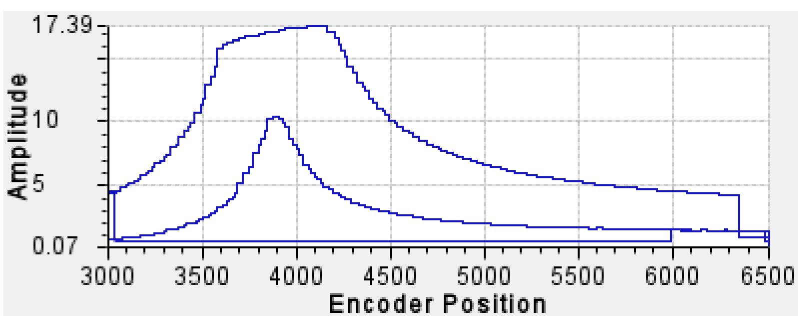


- Auto–tune control of the trimmer capacitor is performed through EPICS- EtherCAT interface
- Need Auto-tune to minimize the RF reflected power
- Setup the phase offset between the RF pickup and auto-tune pickup.
- If the phase drifts outside the phase window the system jogs the trimmer capacitor motor until it is with in range

Automatic Sequence Control



- An SNL Sequencer program was used to automate the system
- Can operate in manual/automatic configuration mode
- In manual config , the user can adjust parameters, find resonance and switch on the system manually
- In automatic config, the system can perform a power on reset, find resonance, and resume from cold or warm start state.



RF pickup amplitude vs encoder position during a search for resonance

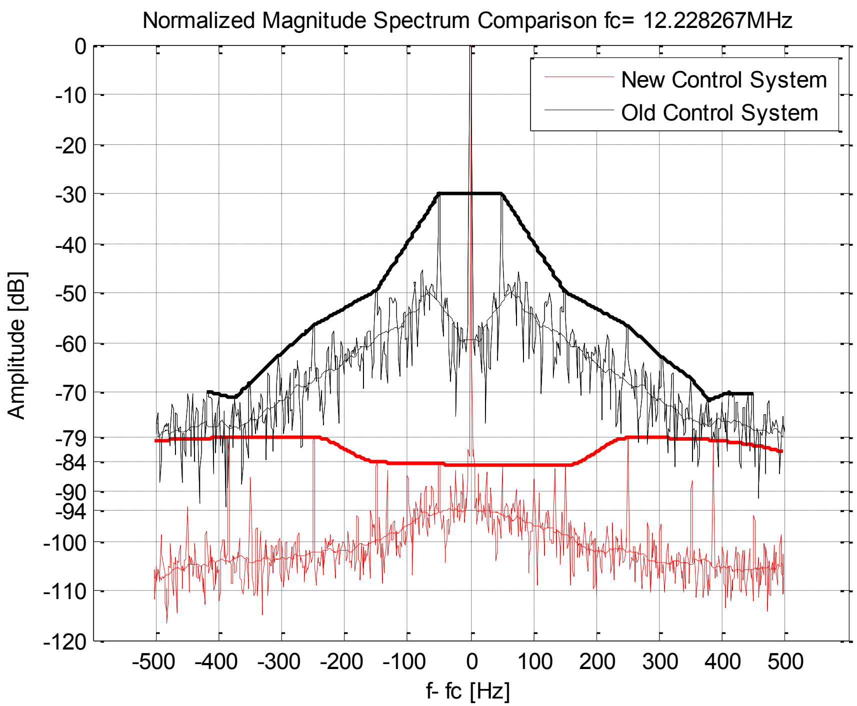
Operational History

	Date	Frequency [MHz]	Power [KW]	Particle	Energy [MeV]
1	2015/02/06	13.312675	4.4	$^{40}Ar^{7+}$	175
2	2015/02/13	26.000000	21.3	H^{+}	200
3	2015/02/20	26.000000	21.3	H^{+}	200
4	2015/02/27	26.000000	21.3	H^{+}	200
5	2015/03/05	12.083549	2.8	$^{40}Ar^{6+}$	144
6	2015/03/06	12.083549	2.8	$^{40}Ar^{6+}$	144
7	2015/03/13	14.468056	3.7	$^{4}He^{2+}$	200
8	2015/03/20	14.468056	3.7	$^{4}He^{2+}$	200
9	2015/03/21	14.468056	3.7	$^{4}He^{2+}$	200
10	2015/03/27	14.468056	3.7	$^{4}He^{2+}$	200
11	2015/04/03	14.468056	3.7	$^{4}He^{2+}$	200
12	2015/04/10	14.468056	3.7	$^{4}He^{2+}$	200
13	2015/04/17	14.468056	3.7	$^{4}He^{2+}$	200
14	2015/04/24	11.896349	3.5	$^{86}Kr^{12+}$	300
15	2015/05/01	11.896349	3.5	$^{86}Kr^{12+}$	300
16	2015/05/08	11.896349	3.5	$^{86}Kr^{12+}$	300
17	2015/05/15	14.468056	3.7	$^{4}He^{2+}$	200
18	2015/05/22	15.376543	5	$^{14}N^{3+}$	82
19	2015/05/29	15.322345	6.3	$^{16}O^{3+}$	93
20	2015/06/05	14.568634	5	$^{16}O^{3+}$	84
21	2015/06/12	14.221051	3.1	$^{22}Ne^{5+}$	110
22	2015/06/26	26.000000	21.3	H^{+}	200
23	2015/07/03	14.468056	3.7	$^{4}He^{2+}$	200
24	2015/07/10	25.962188	16.2	$^{4}He^{2+}$	68
25	2015/07/17	25.398046	14.9	$^{4}He^{2+}$	65
26	2015/09/04	11.379999	4.2	$^{4}He^{2+}$	120
27	2015/09/11	11.379999	4.2	$^{4}He^{2+}$	120
28	2015/09/25	13.740135	3.1	$^{18}O^{4+}$	84
29	2015/11/06	12.080335	2.3	$^{20}Ne^{4+}$	72
30	2015/11/13	25.655769	9	$^{3}He^{2+}$	50
31	2015/11/20	26.000645	8.8	$^{3}He^{1+}$	51.4
32	2015/11/27	26.000000	21.3	H^{+}	200
33	2016/02/05	13.821065	3	$^{18}O^{4+}$	85
34	2016/02/12	13.821065	3	$^{18}O^{4+}$	85

	Date	Frequency [MHz]	Power [KW]	Particle	Energy [MeV]
35	2016/02/19	24.024688	9.6	$^{4}He^{2+}$	58
36	2016/02/26	24.819700	10.7	$^{4}He^{2+}$	62
37	2016/03/04	24.819700	10.7	$^{4}He^{2+}$	62
38	2016/03/18	11.701959	2.9	$^{40}Ar^{6+}$	135
39	2016/03/24	12.285665	2.1	$^{36}Ar^{7+}$	134
40	2016/03/31	12.285665	2.1	$^{36}Ar^{7+}$	134
41	2016/04/14	12.285665	2.1	$^{36}Ar^{7+}$	134
42	2016/04/21	12.285665	2.1	$^{36}Ar^{7+}$	134
43	2016/04/28	12.228267	3.0	$^{32}S^{5+}$	118
44	2016/05/05	12.228267	3.0	$^{32}S^{5+}$	118
45	2016/05/13	25.962180	16.6	$^{4}He^{2+}$	68
46	2016/05/20	25.999920	17.9	H^{+}	200
47	2016/05/27	19.664119	4.4	H^{+}	100
48	2016/06/01	19.664119	4.4	H^{+}	100
49	2016/06/08	19.664119	4.5	H^{+}	100
50	2016/06/17	25.655769	8.8	$^{3}He^{2+}$	50
51	2016/06/30	25.655769	9.0	$^{3}He^{2+}$	50
52	2016/07/08	25.655769	9.3	$^{3}He^{2+}$	50

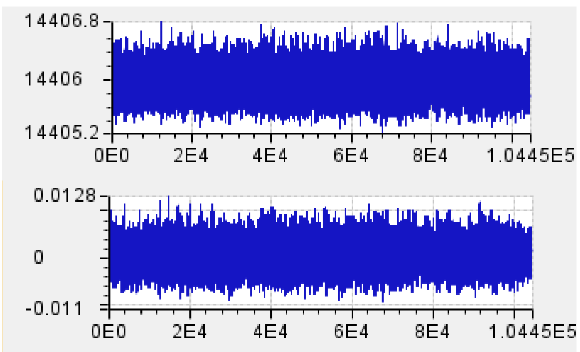
- 3 prototypes
- Commissioned on SPC2 November 2014
- 52 energy changes in 2015/2016
- No callouts
- No breakdowns

Comparison of Old and New system



	Old	New
f_c	12.228267 MHz	12.228267 MHz
Power	2.6 kW	2.6 kW
SFDR	30 dB	84 dB below 150 Hz, 79 dB above 150 Hz

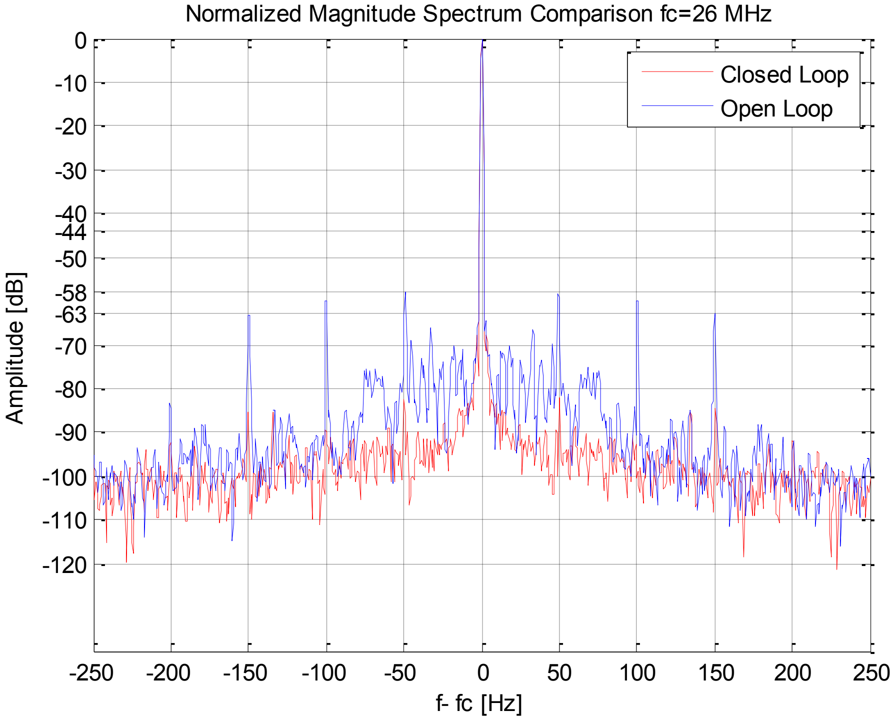
Amplitude and Phase Read Back of New System, Fs=2.5kHz



Amplitude Reference Setpoint: 14406

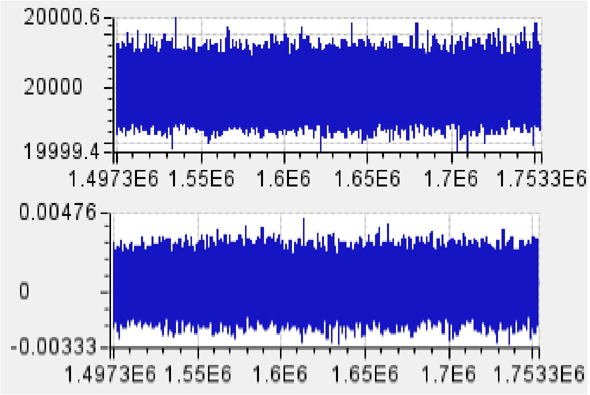
Phase Setpoint: 0 °

Best Performance



f_c	26 MHz
Power	12 kW
Open-loop SFDR	58 dB
Closed-loop SFDR	> 80 dB
Closed-loop Amplitude Stability	Better than 0.01%
Closed-loop Phase Stability	Better than 0.01 °

Amplitude and Phase Read Back of New System, Fs=2.5kHz



Amplitude Reference Setpoint: 20000

Phase Setpoint: 0 °

Final Production

- Manufactured 35 systems
- Completely assembled 10 systems
- Enough spare parts
- Enough systems to meet existing collaboration commitments

Conclusion

- Successfully designed a generic DLLRF control system
- Can achieve RF amplitude and phase stability of better than 0.01% and 0.01° respectively
- Operational reliability has been demonstrated
- Manufacturability and reproducibility has also been demonstrated
- Incorporation of EPICS EtherCAT-based motion control enables the system to be easily deployed at other facilities

Thank you