Electro-Magnetic Variably Polarizing Undulator Power Supply System

ASD Seminar 3/18/2011

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Abstract

- A new beamline providing circularly polarized x-rays that will cover photon energies from 250 eV to 2.5 keV is under development at the APS. Because of the unique requirements of the electromagnetic variably polarizing undulator (EMVPU) constructed for this beamline, a new power supply system (PSS) design is required. The undulator will contain sixteen sets of electromagnetic coils -- two main, two quasi-periodic, and twelve correctors. The undulator will incorporate variable polarization control and reduction of the magnetic fields at so-called quasi-periodic pole locations for the purpose of suppressing the higher-order radiation harmonics. The challenges met in the power supply system design for the project will be discussed.

EMVPU Selected Parameters (M.Jaski)

General	Period	12.5	cm
	Gap	10.5	mm
	Periods per device (including end poles)	38	Periods
Horizontal Linear Polarization	Minimum Photon Energy	250	eV
	Required vertical effective field	4510	Gauss
	Current density in the copper conductor[2]	4.7	A/mm^2
	Current	47.6	A
	Turns per coil[1]	62	turns
	Ampere-turns[1, 2]	2951	Ampere-turns
	Watts per coil[1, 2]	44.9	Watts
	Total number of coils	152	Each
	Total power[2]	6630	Watts
	Maximum temperature of coils	100	°C
Vertical Linear Polarization	Minimum Photon Energy	440	eV
	Required horizontal effective field	3310	Gauss
	Current density in the copper conductor[2]	4.9	A/mm^2
	Current	50.3	A
	Turns per coil[1]	46	turns
	Ampere-turns[1, 2]	2314	Ampere-turns
	Watts per coil[1, 2]	40.2	Watts
	Total number of coils	304	Each
	Total power[2]	11,868	Watts
	Maximum temperature of coils	100	°C
Circular Polarization	Minimum Photon Energy	440	eV
	Required horizontal and vertical effective field	2340	Gauss
	Current at vertical effective field	20.7	A
	Current at horizontal effective field	34.2	A

[1]End coils are smaller

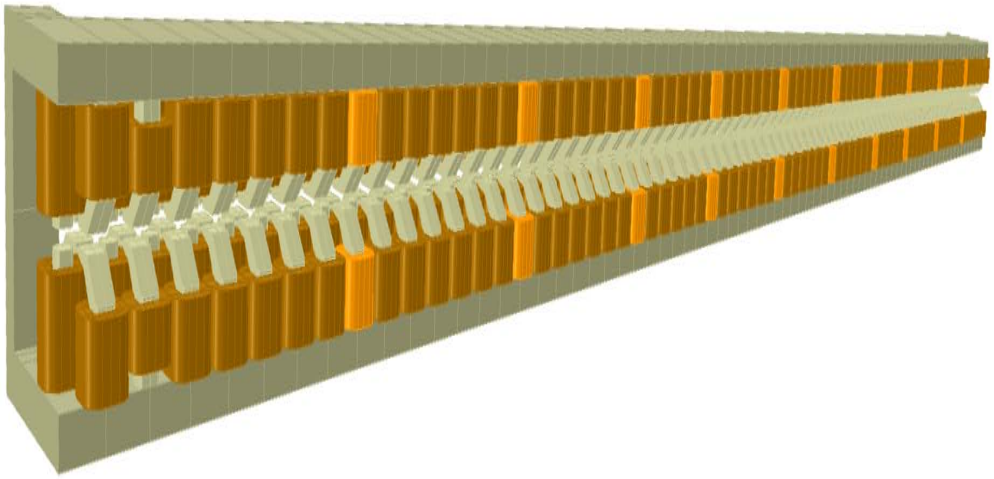
[2]At the required effective field

Main Coils Power Supplies Requirements

Bx: Total number of poles: 76
Number of Bxqp poles: 16 to 22

By: Total number of poles: 76
Number of Byqp poles: 16 to 22

It may be desirable to size the large Bx and By power supplies to run all 76 poles.



Summary:

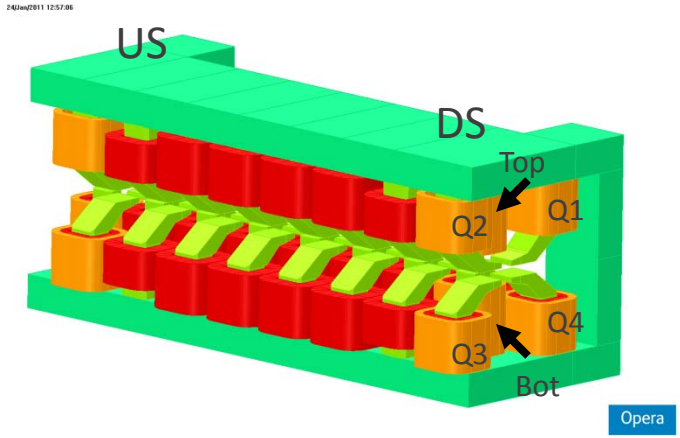
Bx main power supply	@76 poles	50.26 A max	11874 W max (desirable)
	@54 poles		8338 W max
	@60 poles		9303 W max
Bx QP power supply	@22 poles	50.26 A max	3536 W max
	@16 poles		2571 W
By main power supply	@76 poles	47.54 A max	6788 W max (desirable)
	@54 poles		4811 W max
	@60 poles		5350 W max
By QP power supply	@22 poles	47.54 A max	1978 W max
	@16 poles		1438 W

Initial requirements:
Bx Coils 50.3 A max ~8500 W max
Bx quasi-periodic coil 50.3 A max
~3500 W max
By Coil 47.6 A max
~4800 W max
By quasi-periodic coils 47.6 A max
~2000 W max

Trim Coils (Correctors) Power Supplies Requirements

To specify the required parameters for the final device, a four period prototype of the EMVPU was built and tested

Since the undulator has nonlinearities, especially during transients, and the fields are very sensitive to misalignment, the system has to be improved to correct all measurable EMVPU perturbations. Each end of the undulator has 6 trim coils for steering the electron beam.

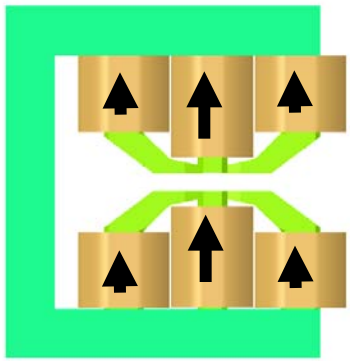


Based on the calculation and test results of the EMVPU prototype, the following numbers were specified:

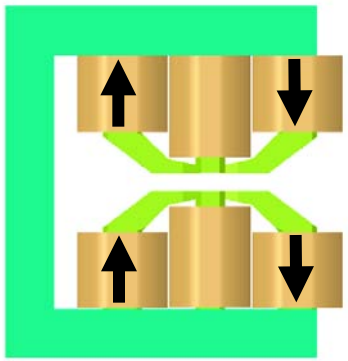
- Top and Bottom corrector coils:
  - 5.5 A max/45 W max
- Quadrants:
  - 5.84 A max/40 W max

1. US top
2. US btm
3. US Q1
4. US Q2
5. US Q3
6. US Q4
7. DS top
8. DS btm
9. DS Q1
10. DS Q2
11. DS Q3
12. DS Q4

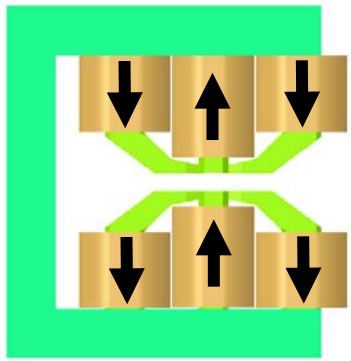
End Coil Multi-pole Field Configurations (M.Jaski)



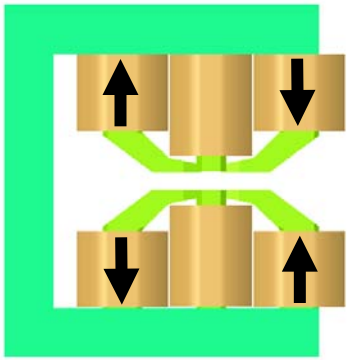
Normal Dipole



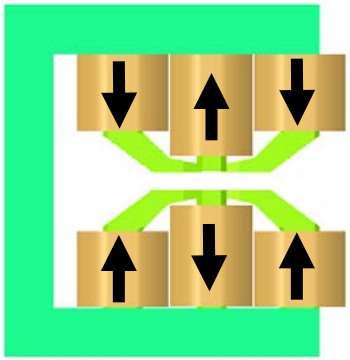
Normal Quadrupole



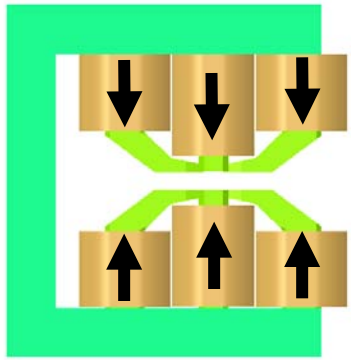
Normal Sextupole



Skew Dipole



Skew Quadrupole



Skew Octupole

Depending on the current flow in these six coils, the corrector can be configured as either normal or skew corrector magnet - dipole, quadrupole, sextupole, or octupole.

Magnet Interlocks

- Monitoring temperature and other interlocks condition of the device:
  - Water flow
  - 16 thermocouples (one thermocouple on a coil for each power supply)
  - 16 thermal switches (two switches on each coil in parallel, NC, 110°C shut off) .
    - Readback: Each switch or all 16 in series?
- Two fans with programmable turn on/off condition

Summary Interlocks

- The following interlocks will shut down the power supplies and give indication in the local control panel and via the remote control line:
  - AC input over-current
  - AC input voltage failure
  - DC output over-current
  - DC output over-voltage
  - Over-temperature on power components
  - Over-temperature on magnets
  - Cooling water failure
  - Cabinet door open
  - Power components failure
  - Three external interlock inputs, with normally closed contacts

Other Requirements for the EMVPU Power Supply System

- Synchronization from multiple sources:
  - Internal timer
  - Storage Ring Timing System trigger
  - User's trigger
- Programming output currents for routine procedures, like
  - Degaussing:
    - Should be run every time the beam turns off.
    - Long and short method
  - Ramping profiles for
    - Soft Start
    - Soft Shutdown
    - Programmable slew rate

EMVPU Power Supplies System

Main coil power supplies

Bx

By

Bxqp

Byqp

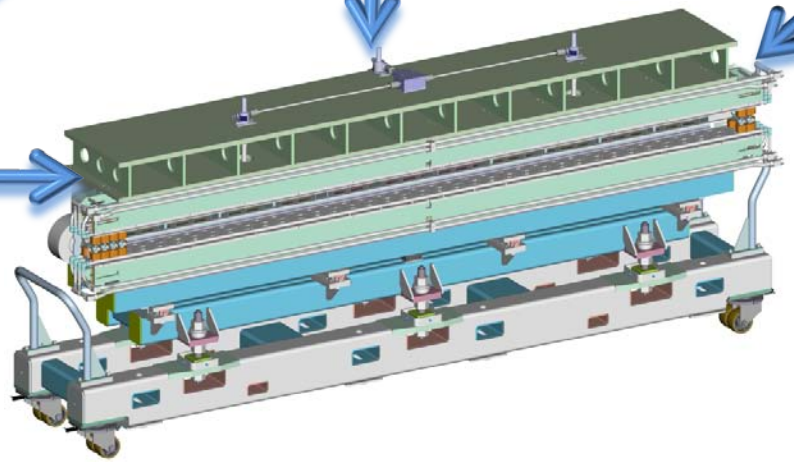
Ethernet
EPICS
SR Timing System

PSS Controller

Correctors' PS crate

Interlocks

IGBT
Polarity
Switch



$DS_{q1..q4}, Ds_{top}, DS_{bot}$

$US_{q1..q4}, Us_{top}, US_{bot}$

Bx and By 15kW Power Supplies Specification

Selected Output Parameters:
Max. output current : 66A
Max. output voltage : 250V
Ramp time : From 0 to 100%, max 100 ms
Temperature stability : 0.02%/°C
Load Regulation (CV and CC) : 0.075%
Vout and Iout programming accuracy: ±0.5% of output voltage/current
Vout and Iout programming resolution: ±0.02% of full scale
Ripple noise RMS (5Hz-1MHz): 12mV
Noise p-p (<20MHz): 80mV

Regulation:
Max.line regulation (0.01% (cv) 0.05% (cc)
Max.load regulation 0.015% + 5mV (cv), 0.1% (cc)

•Interface Options
• Isolated Analog Program/Monitor 0-5V & 0-10V User Selectable
•IS420 - 4-20mA
• USB
• LAN - LXI Certified

Mechanical
Size: 19" W x 3U (5.25") H x 25.5" D
Weight: 97lbs/43kg

Protection:

•OVP type: Inverter shutdown, Manual reset by On/Off or by OUT button
•OVP response time: < than 10ms
•OCP type : constant current
•Short circuit protection
•Over-temperature protection: Shutdown when internal temperature exceeds safe operating levels

AC Input
AC mains input : 480 V ± 10%, 60 Hz, 3 phase and Ground.
•Input current 27A@full rated output power.
•Efficiency at 100% load: 88% min
•Input protection: Line fuse
•Phase imbalance: <=5%

Bxqp and Byqp 5kW Power Supplies Specification

Selected Output Parameters:
Max. output current : 65A
Max. output voltage : 80V
Ramp time : From 0 to 100%, max 100 ms
Temperature stability : 0.02%/°C
Load Regulation (CV and CC) : 0.075%
Vout and Iout programming accuracy: ±0.1% of output voltage/current
Vout and Iout programming resolution: ±0.012% of full scale
Ripple noise RMS (5Hz-1MHz): 12mV
Noise p-p (<20MHz): 80mV

Regulation:
Max.line regulation (0.01% (cv) 0.05% (cc)
Max.load regulation 0.015% + 5mV (cv), 0.1% (cc)

•Interface Options
• Isolated Analog Program/Monitor 0-5V & 0-10V User Selectable
•IS420 - 4-20mA
• USB
• LAN - LXI Certified

Programming
0-5V, 0-10V User Selectable via DIP Switch, LAN-LXI, RS-232/RS-485
Parallel Master/Slave setting reports total current of up to four like supplies connected in parallel

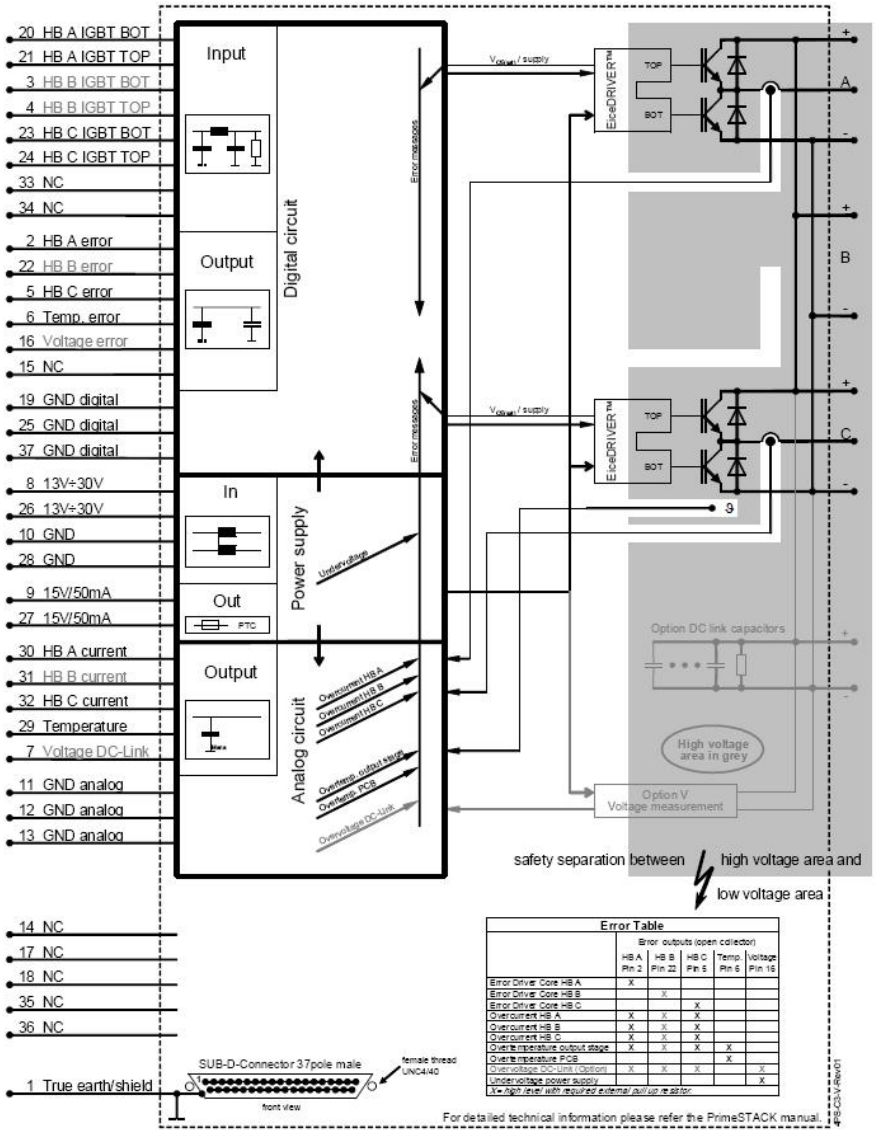
Protection:

•OVP type: Inverter shutdown, Manual reset by On/Off or by OUT button
•OVP response time: < than 10ms
•OCP type : constant current
•Short circuit protection
•Over-temperature protection: Shutdown when internal temperature exceeds safe operating levels

AC Input
Three phase 208VAC
170-265VAC 47-63 Hz, with active PFC
PF=0.94, Imax=21.5A

Mechanical
Size: 19" W x 2U (3.5") H x 17" D
Weight: 36lbs/16kg

IGBT Polarity Switch

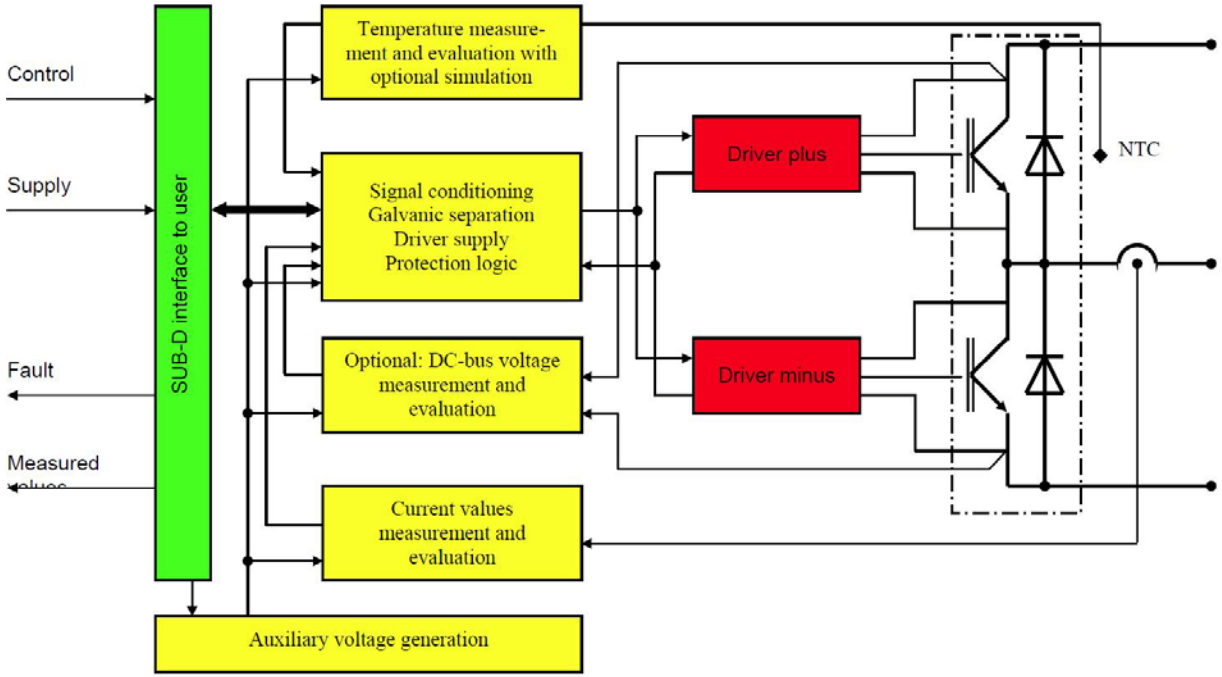


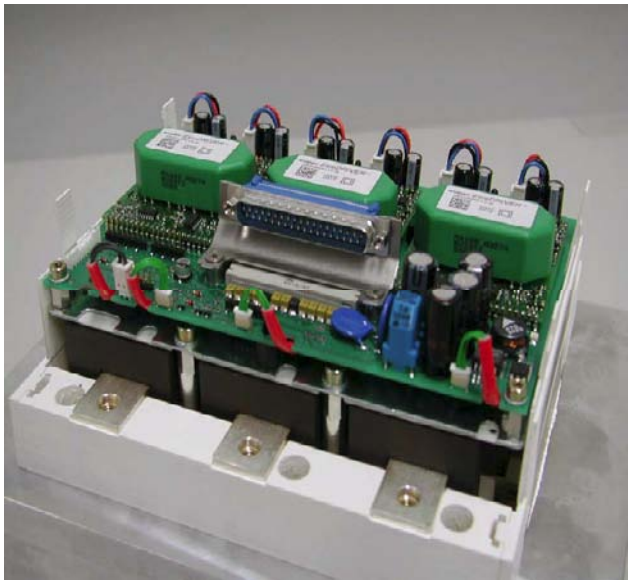
DC Link			min	typ	max	units
Voltage		V_{DC}		370	400	V

Unit 2 AC			min	typ	max	units
Voltage	depending on controller	V_{Unit2}		230		V_{RMS}
Continuous current	V_{Unit2} = 230V_{RMS}, V_{DC} = 370V, T_{inlet} = 40°C, $T_J \leq$ 125°C, f_{Unit2} = 50Hz, f_{sw2} = 5000Hz, cos(phi) = 0,85	I_{Unit2}			300	A_{RMS}
Continuous current overload cap.	T_{inlet} = 40°C, for overload capability 150% for 60s			215		A_{RMS}
Short time current	T_{inlet} = 40°C, 10s, every 180s, initial load = 264A_{RMS}	I_{Unit2}			330	A_{RMS}
DC current	no rotating field, T_{inlet} = 40°C	$I_{Unit2\ DC}$			172,0	A_{av}
Overcurrent shutdown	within 15µs			625		A_{peak}
Switching frequency		f_{sw2}			20000	Hz
Power losses	V_{Unit2} = 230V, V_{DC} = 340V, T_{inlet} = 40°C, $T_J \leq$ 125°C, f_{Unit2} = 50Hz, f_{sw2} = 5000Hz, cos(phi) = 0,85, I_{Unit2} = 300A_{RMS}	P_{loss2}		1160		W
Power factor		$cos(phi)_{Unit2}$	-1,00		1,00	

General data				min	typ	max	units
Power losses (PCB)			$P_{loss\ aux}$			t.b.d.	W
EMC test	according to IEC61800-3 at named interfaces	power	V_{Burst}		2		kV
		control	V_{Burst}		1		kV
		aux (24V)	V_{Surge}		1		kV
Insulation management is designed for			V_{Line}		230		V_{RMS}
Insulation test voltage	according to EN50178, f = 50Hz, t = 60s		V_{isol}		1,8		kV_{RMS}

IGBT Polarity Switch



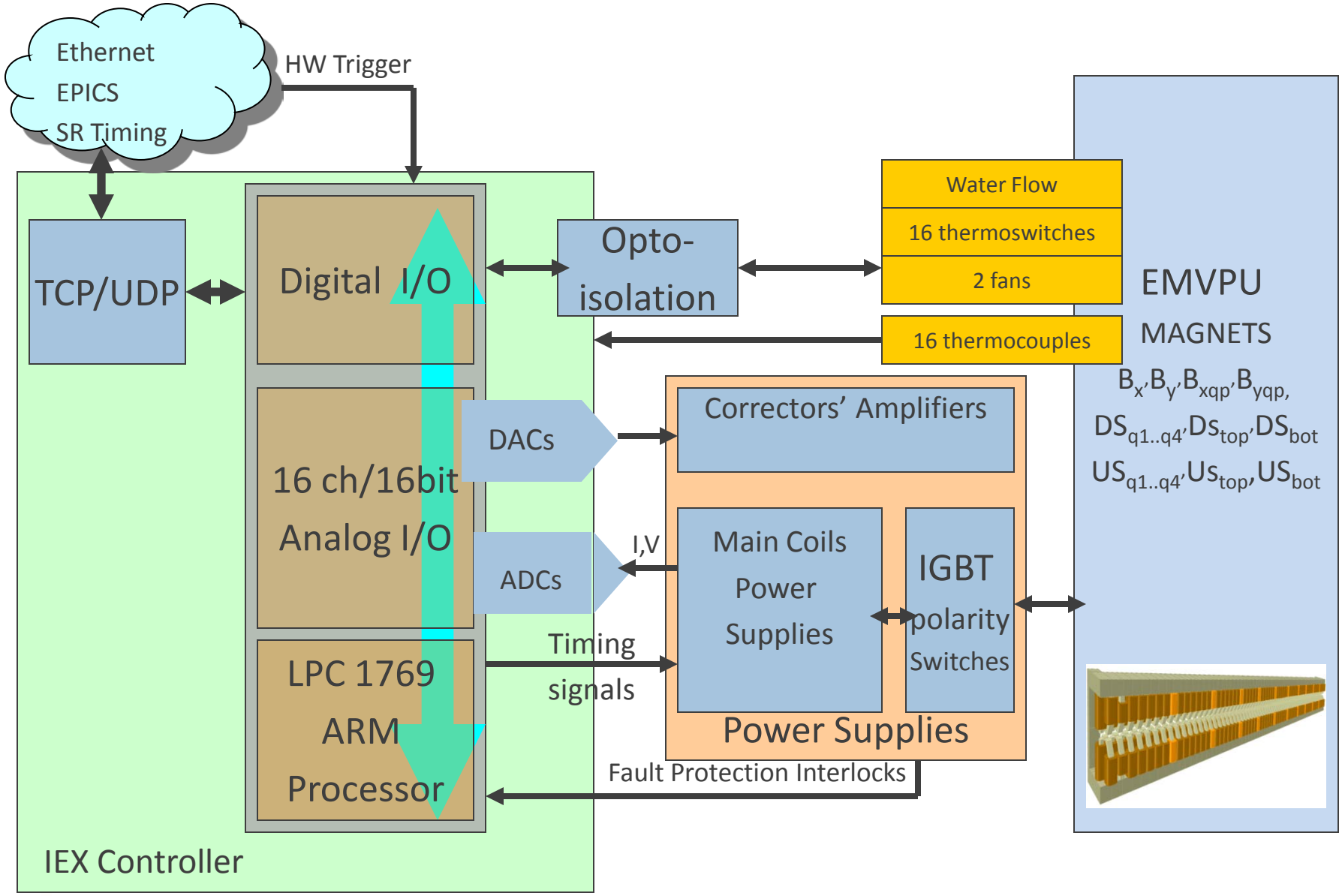


12 Correctors Power Amplifiers Crate (MCOR)

1.0 SPECIFICATIONS

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
DC Mains Input Range		20		50	V
Output Polarity			bipolar		
Nominal Output Current Range		0		12	A
Maximum Fault Current				15	A
Output Compliance Voltage			DC mains X 90%		V
Power Dissipation of Module at full current				20 (30A8)	W
Load Capacitance range (for stable operation)		0		50	uF
Output short circuit duration:					
	line to line		continuous		sec
	line to ground		continuous (driver shuts down)		sec
Transfer Ratio:			1.00V = 2.00A		
	Error (at 25°C ambient, 12A)			0.1	%
	Vs. temperature (10 to 25°C)		15		ppm/°C
	Vs. temperature (25 to 50°C)		7		ppm/°C
	Vs. time				ppm/mo.
	PSRR (DC-60Hz, 1V change)		84		dB
	Nonlinearity		0.025		%
Initial Offset:			480		uA
RMS Output Current Noise (w/ 6mH+5 ohm load):					
	DC-200 kHz (0A)		0.01		% of F.S.
	DC-200 kHz (12A)		0.01		% of F.S.
RMS Injected Noise (into HVDC busbar):					
	DC-200 kHz		20		mV
RMS Common-Mode Noise (output to GND):					
	DC-200 kHz		120		mV
Small Signal Bandwidth (w/ 6mH+5 ohm load):					
	3 dB, 0.5 % FS signal			1.5	kHz
Slew Rate	0 to 5 A, 70VDC mains			2.5	A / ms
Settling Time	1%, for a 5A step		12		mS
Operating Temperature Range (for spec'd accuracy)		15		65	°C

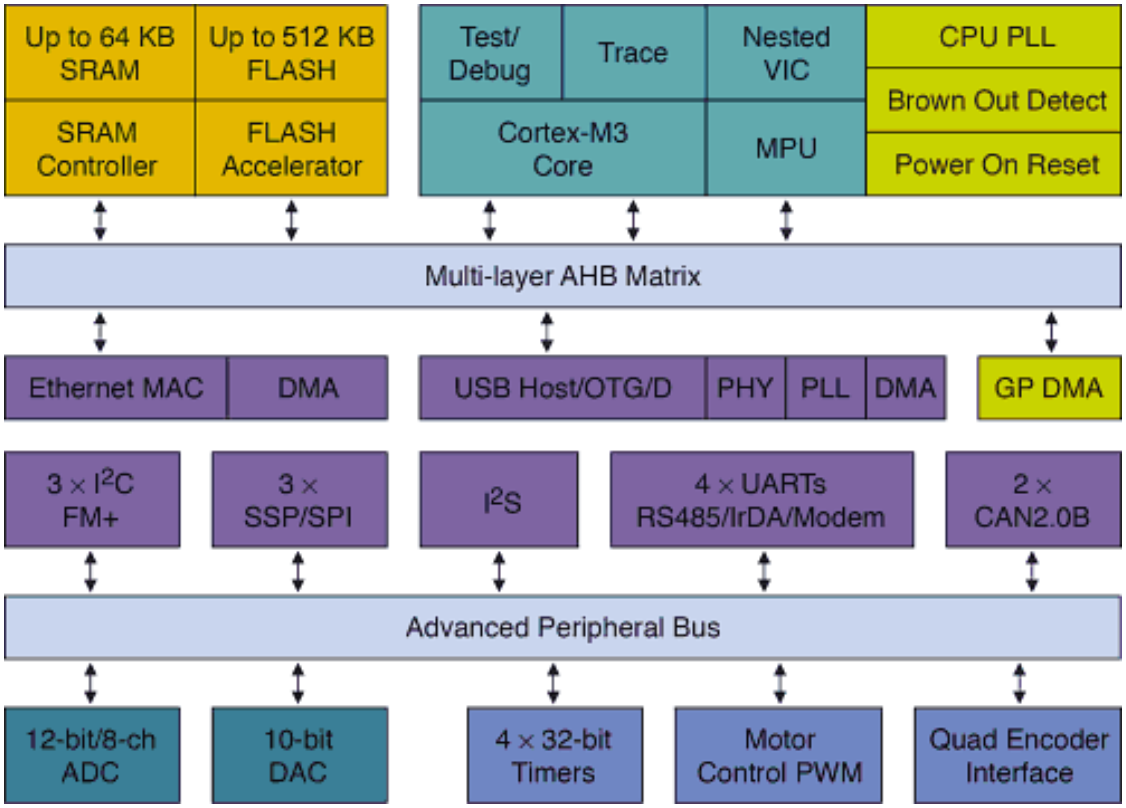
PSS Controller connections



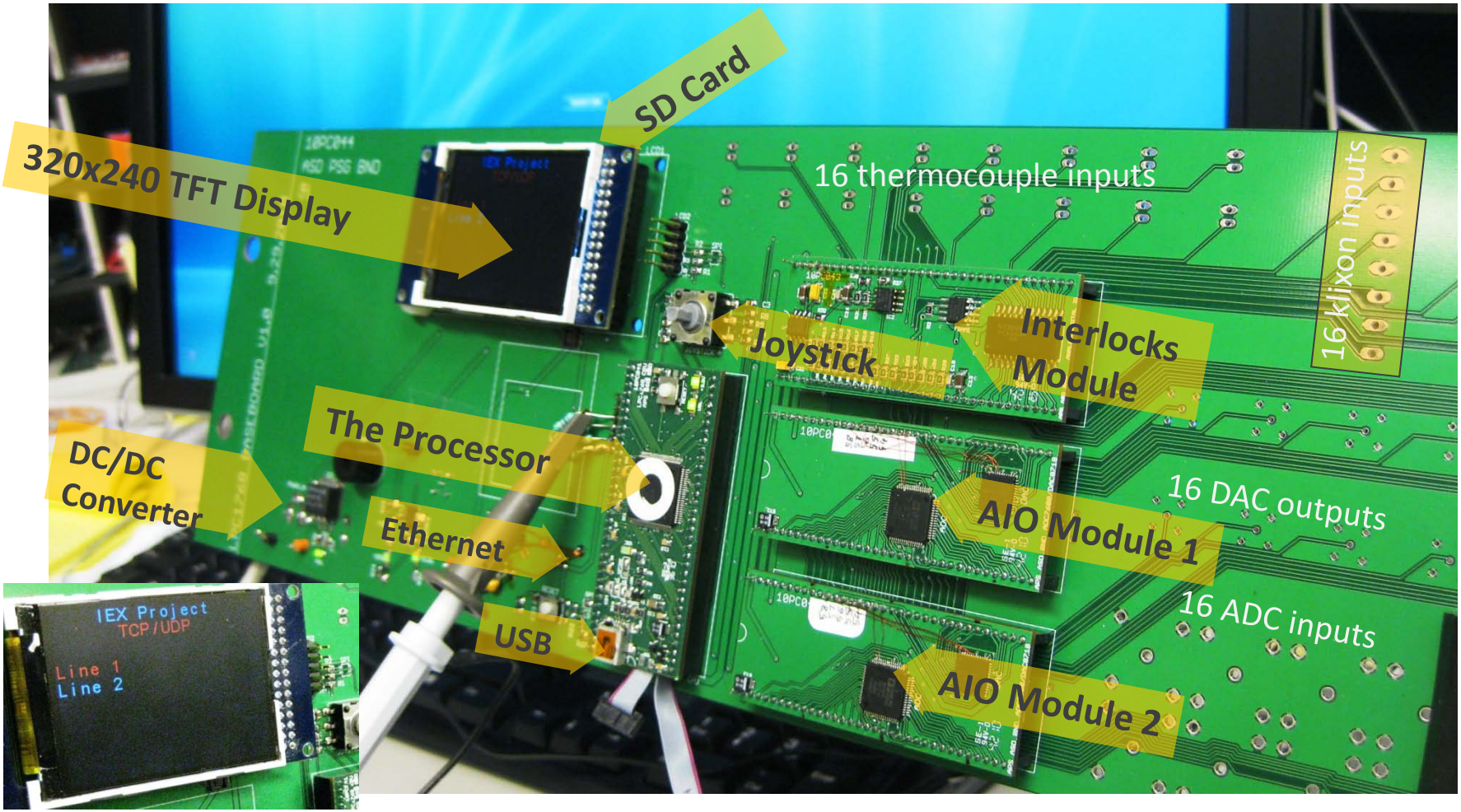
The heart of the PSS Controller –uP Module

ARM-based PSS Controller The PCB has 68-pin DIP connector that can be plugged in a socket of a baseboard. It uses a standard JTAG connector for programming and debugging the program. An extended pinout allows exploiting of all features of the processor. The Keil µVision4 IDE is used for programming the embedded module. The IDE combines project management, source code editing, program debugging, and complete simulation in one powerful environment. The RealView Real-Time Library including RTX Kernel, Flash File System, and TCP/IP Protocol Suite was also utilized.

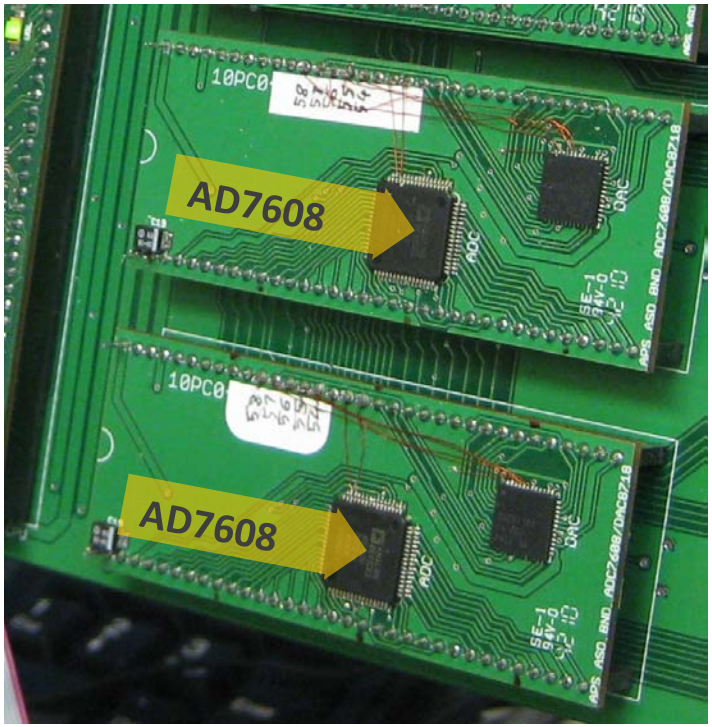
32-bit 120MHz LPC1769 Cortex M3 ARM uController

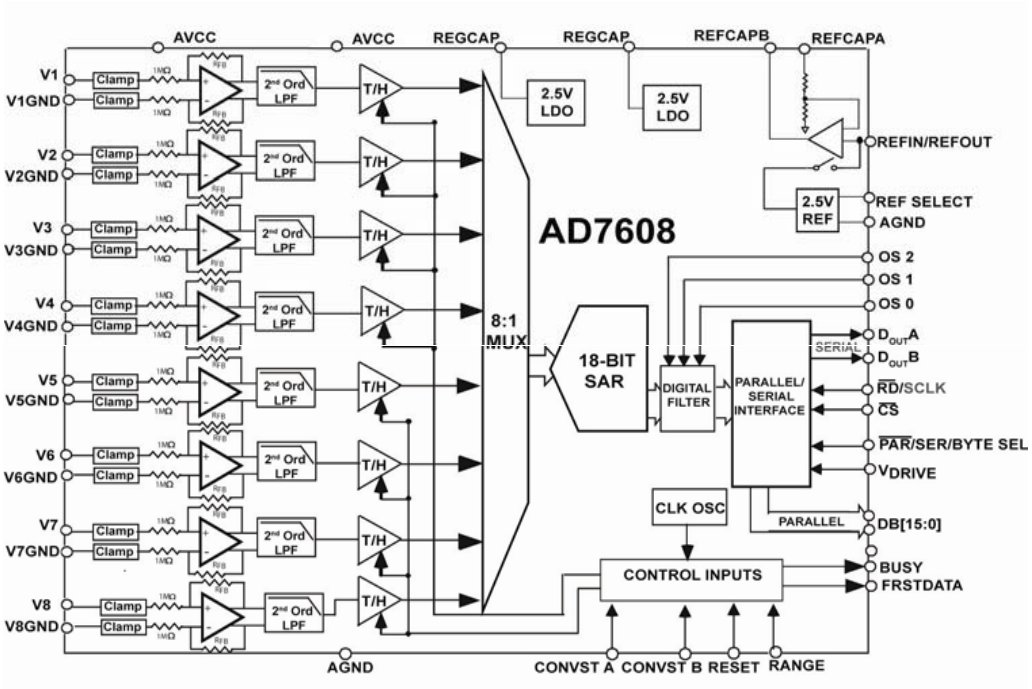


Baseboard and Full Set of Modules Built for IEX Project Development



Analog IO Module: Octal 18/16-bit AD7608/AD8606 ADC

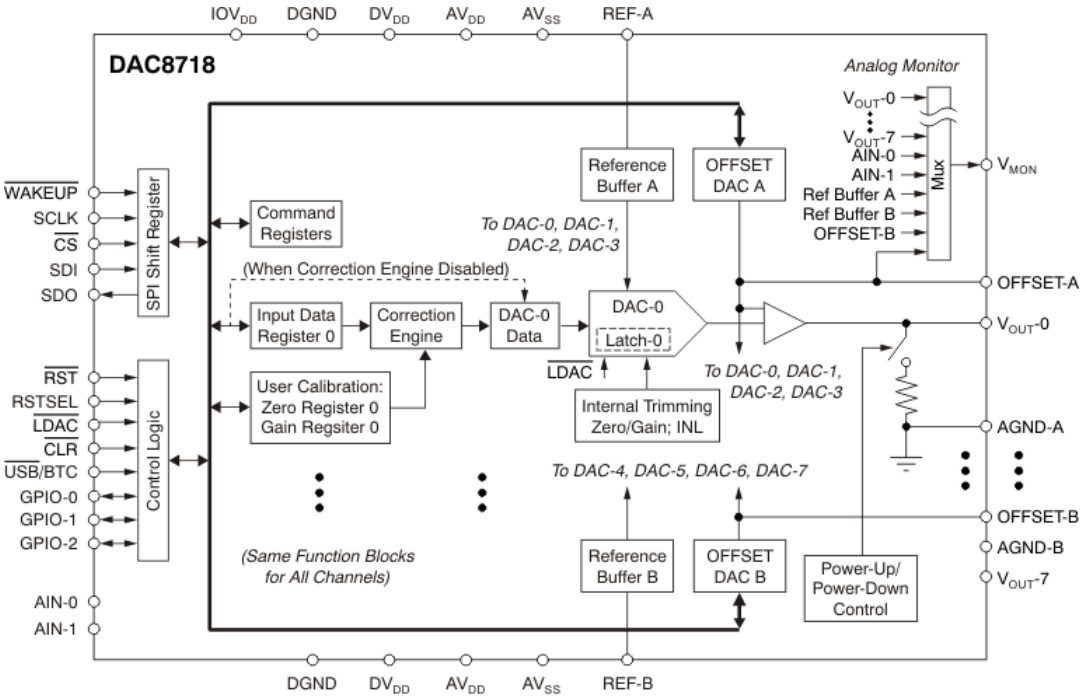




This fully integrated device with remarkable parameters facilitates building of a high resolution data acquisition system.

- 8 Simultaneously Sampled Inputs
- True bipolar analog input ranges: ±10 V, ±5 V
- Single 5V Analog Supply, 2.3V to +5V V_{DRIVE}
- 2nd Order Anti-alias Analog Filter
- Over-sampling capability with digital filter, e.g. 96dB SNR at 50 ksps
- Fast throughput rate: 200 kSPS for all channels 90dB SNR at 200ksps

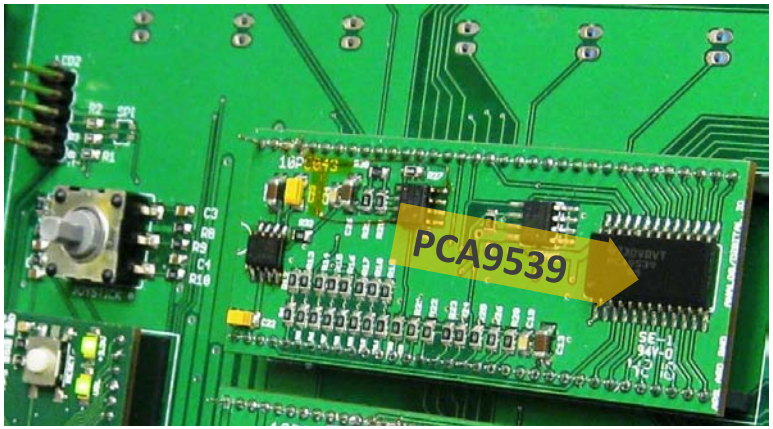
Analog IO Module: Octal 16-bit DAC (DAC8718)

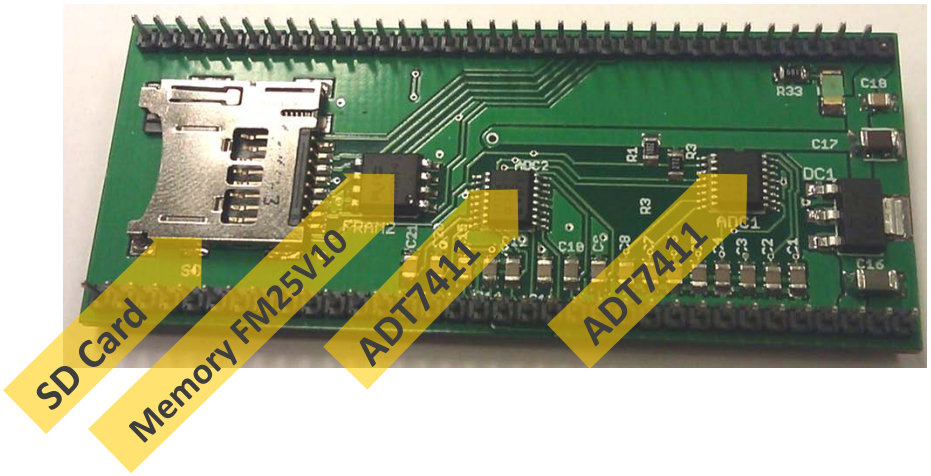


Eight 16-bit channels
Bipolar Output: ±2V to ±16.5V; Unipolar Output: 0V to +33V
Flexible System Calibration:
- Before User Calibration: ±10 LSB Max
- After User Calibration: ±1 LSB

Settling Time: 15µs
Channel Monitor Output
Programmable Gain and Offset
SPI: Up to 50MHz

Digital IO Module: Isolated I2C with ADT7411 and PCA9539





Two ADT7411:
- 16 Analog Channels for T/D Conversion with 0.25^{0}C resolution
- Generates HW Interrupt when preset window limits are exceeded
- Fast I2C Bus

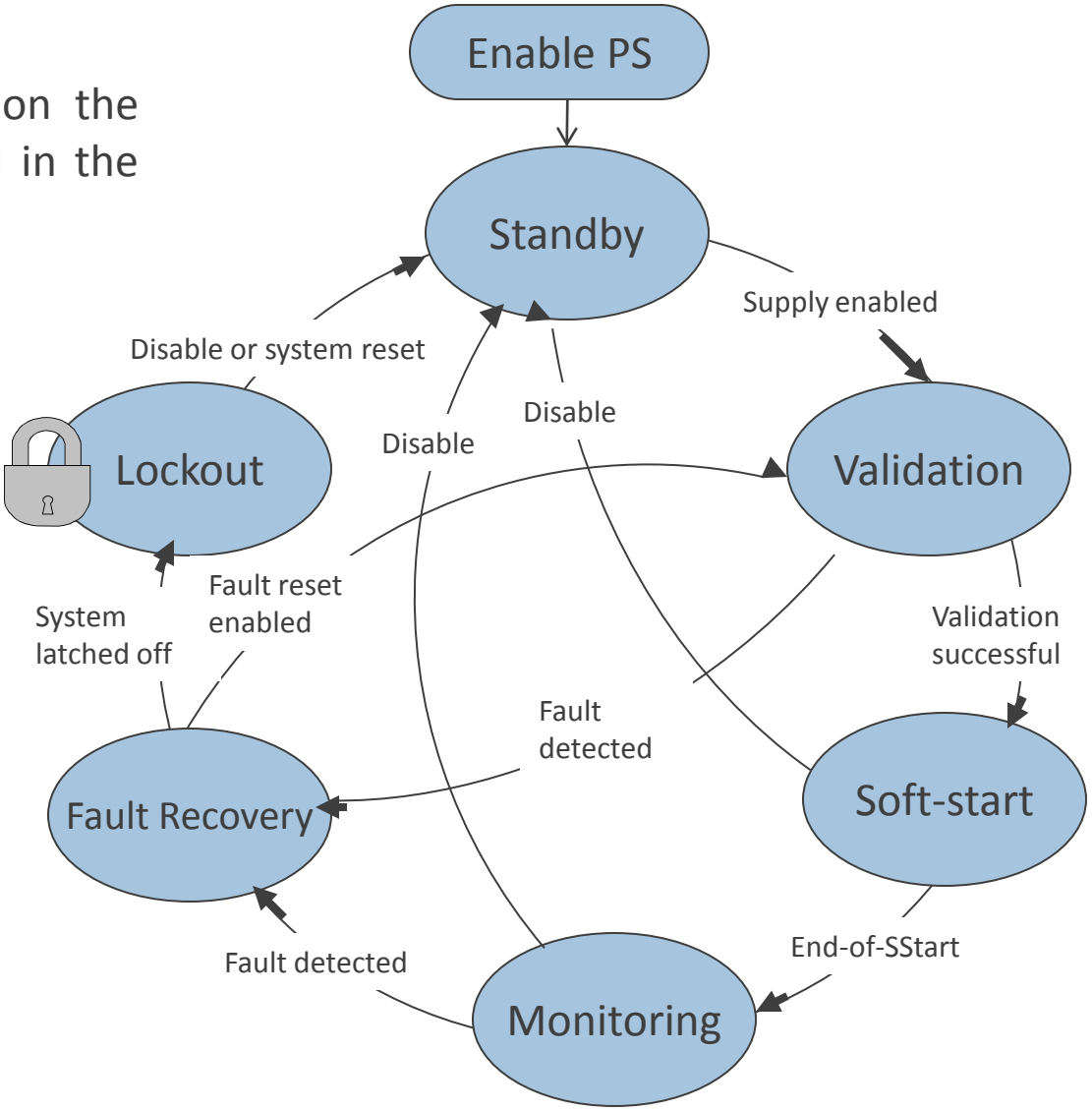
PCA9539:
- 16-channel I2C to Parallel Port Expander
- Latched Outputs With High-Current Drive
- Open-Drain Active-Low Interrupt Output
- 400-kHz Fast I2C Bus

FM25V10: 1M bit Ferroelectric Nonvolatile RAM
- Organized as 128K x 8 bits
- High Endurance 100 Trillion (1e14) Read/Writes
- 10 Year Data Retention
- Up to 40 MHz SPI

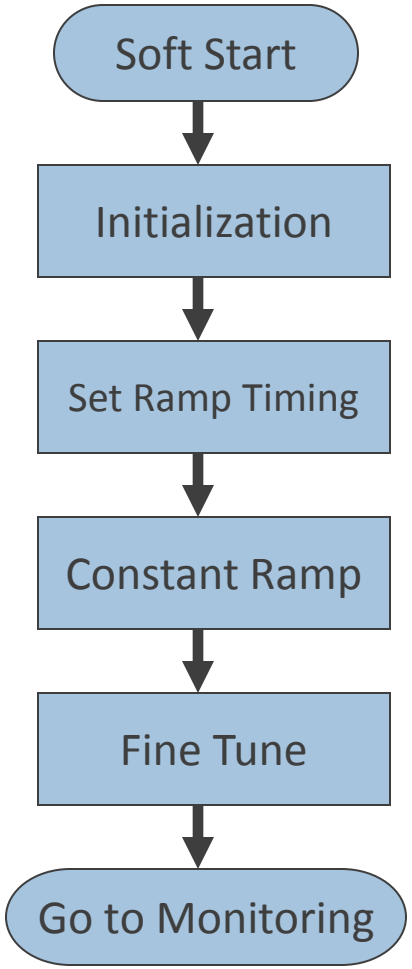
microSD Card:
Both FM25V10 and microSD card will be used for keeping pre-fault taken data for a fault analysis

PS high-level state diagram

All functional blocks shown on the diagram will be implemented in the EMVPU controller firmware.



Soft Start Algorithm



The soft start algorithm generates a fixed slew rate output current while maintaining closed-loop control and full system fault protection.

Set Ramp Parameters: Δ_{time} and $\Delta_{current}$

I_{out} ramped up to a value just below set point at a rate determined by timer

Increase the output current at a lower rate to a setpoint.

The Firmware

- To facilitate the firmware design C++ Classes were developed for all of the major components :
  - AD7608 A/D Converter
  - DAC8718 D/A Converter
  - ADT7411 T/D Converter
  - LM75 and LM83 thermo-sensors
  - PCA9539 16-bit Digital IO Expander
  - LCD TFT Display
- Communication with asynDriver was tested over:
  - Telnet
  - TCP
  - UDP
- Building of a set of high-level commands for communication with EPICS over asynDriver was started

```
/* IEX Library - spiDAC
 *  bderiy
 */

#include "SpiDAC.h"

#include "mbed.h"

using namespace mbed;



void SpiDAC::command(int value) {
    _spi.write(value & 0xFF);
}

void SpiDAC::data(int value) {
        _spi.write(value>>8);
        _spi.write(value&0xFF);
}

void SpiDAC::_select() {
    _cs = 0;
}

void SpiDAC::_deselect() {
    _cs = 0;
}
void SpiDAC::write(int reg, int value){
    _cs = 0;
    _spi.write(reg & 0xFF);
    _spi.write(value>>8);
    _spi.write(value&0xFF);
    _cs = 1;
}

void SpiDAC::init(){
int i;
    write(DAC_CONF,0x8000);
    write(DAC_MON,0x08000);
    write(DAC_SPImode,0x0000);
    for (i=0;i<8;i++){
    write(Gain+i, 0x8000);
    }
}

/*****************************************************************************/

SpiDAC::SpiDAC(PinName mosi, PinName miso, PinName clk, PinName cs, PinName
    : _spi(mosi, miso, clk)
    , _clr(clr)
    , _cs(cs) {
```

Next Steps:

- Finalize procurement:
  - Two TDK-Lambda PS for quasi-periodic coils + 1 spare(~$4,000x3=~$12,000)
  - Correctors' crate + Raw PS (~$50,000)
  - Four IGBT Switching Assemblies +1 spare ($1,225x5=$6,125)
  - ….PCB, machine shop, and other components (~$20,000)
- Convert the Development Set of Modules into final layout(6U VME-form factor board), manufacture, assemble, and test
- Complete the firmware design (soft start, soft shutdown, degaussing, programmable ramp, synchronization with multiple triggers etc…)
- Complete software interface with EPICS (asynDriver)
- Build the User's EPICS Screens - Controls Group?
- Energy-to-Current Conversion – Input from Roger?
- $I_{corr} = f(B_x, B_y, B_{xqp}, B_{yqp}, \ldots)$ – Input from Roger, Louis?

Conclusion

- The development of a new beamline providing circularly polarized x-rays at the APS has progressed from testing the prototype to building the final system. Major details of the new power supply system designed for this electromagnetic undulator were discussed in this presentation.

Thank you