POWER CONVERSION & VOLTAGE REGULATION FOR ePIC DETECTOR ELECTRONICS

FRIDAY JULY 26th PRESENTATION AT LEHIGH UNIVERSITY
ePIC WORKING GROUP MEETING JULY 2024
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- DC|DC converter options
- Power Distribution
- High-Frequency commercial DC|DC synchronous buck converter rad testing
- CERN DC|DC buck converter & controller & availability
- FE / ASIC & RDO board applications
- CERN tested LDO Linear Regulator testing

ePIC

Brookhaven National Laboratory · Jefferson Lab · U.S. DEPARTMENT OF ENERGY

DC Buck Converter (step-down) Topology

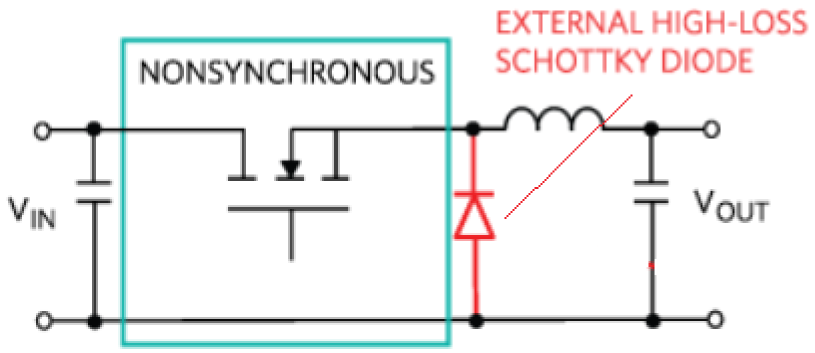


Fig 1. Non-Synchronous Buck Converter

- Older technology typically under 1MHz FSW
- Higher losses (external diode)

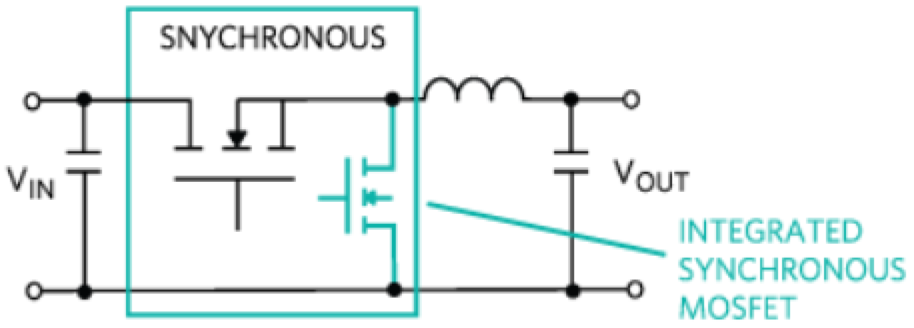


Fig.2 Synchronous Buck Converter

- Integrated rectification inside component package
- FSW typically ~1MHz or greater
- Higher FSW can make use of air-core inductor (< 1uH) which means the part can be used in magnetic field
- Lower rectifier losses
- All devices presented here are Synchronous Type

- **Motivation to explore commercial parts (cost, performance, availability)**
- **Comparisons**

Device (buck converter)	Vin (Vout = 1.2V)	Vout	Iout (80% derated)	Eff.	FSW as tested	Package mm^2	Cost $USD
LTC3626	20V	0.6 – 6V	2.0A	~85% as tested (2.3W)	1.8MHz	12	5.05 (500)
bPOL12V	*10V	0.6 – 5V	3.2A	70% data sheet 75% as tested at 2.0A (3W)	1.5MHz	25	15.00(36)

*Highest voltage recommended for SOA & stability

Device (buck controller)	Vin (Vout = 1.2V)	Vout	Iout (as tested)	Eff.	FSW as tested	Package mm^2	Cost
LTC7890 External GaN FETs	12V can be increased if FSW is lowered	0.8 – 60V	Tested for 12A / channel (2 ch) operate 180° out to reduce EMI	~80% tested 29W	2.0 MHz	36	4.01 (500)
bPOL48V External GaN driver/ FET	15V	0.6 – 24V	Tested at 8A	~78% tested 10W	1.5MHz	25	17.00(36)

Vin / Vout ratio & pulse switch time needs to be observed

Radiation testing criteria:

If commercial parts are tolerant of radiation environment after 10yr operation at full efficiency & machine luminosity…with 3x TID & fluence safety factor => COTS parts can be utilized

CERN bPOL12V & bPOL48V availability

Conversion Stage	Name	Asic Version	Vin	Iout	Technology	Radiation specs	Availability
Stage 1	**bPOL48V**	**V2**	48V	10A	350nm CMOS with High Voltage extension at 80V	TID:50 Mrad SEE:46 MeV/(mg/cm^2) DD:4e14 n/cm2 2.23e14 p/cm2(30MeV)	26k dies in 2022
Stage 2	**bPOL12V**	**V6.1**	12V	4 A	350nm CMOS with High Voltage extension at 25V	TID :150Mrad SEE :45 MeV/(mg/cm^2) DD:4e15n/cm2 1.2e15p/cm2 (30MeV) 2.34e15p/cm2(200MeV)	6k dies in 2021 150k dies in 2022
	FEAST	**V2.3**	12V	4 A	350nm CMOS with High Voltage extension at 80V	TID :150Mrad DD:5e14n/cm2	Obsolete, production ended in 2020

Specifications & Requirements for DC:DC Power regulation

Performance Requirements:

- Efficiency ≥ 70%
- Power Density (power / CM^2) 500mW to 800mW / CM^2
- Low noise/ ripple ≤ 0.5% of VOUT
- Temperature stability 35°C env.
- 1MeV fluence 1E12 n /cm^2 (ePIC upper bound 10yr operation)
- TID 10K rads / year
- Magnet tol. 2 Tesla field

Radiation tolerance if based on worst case upper bound Simulations for 10years of operation

Power Specifications

- VOUT (1.2V, *10V)
- V_{IN} ≥10V
- P_{OUT} 3W – 10W
- I_{OUT} 2.5A – 8A

Power Output & Current are based on cooling and space constraints
*10V if powering bPLO12V from bPOL48V

Disk => 16K channels

64 channel SALSA

4 SALSAs / FEB

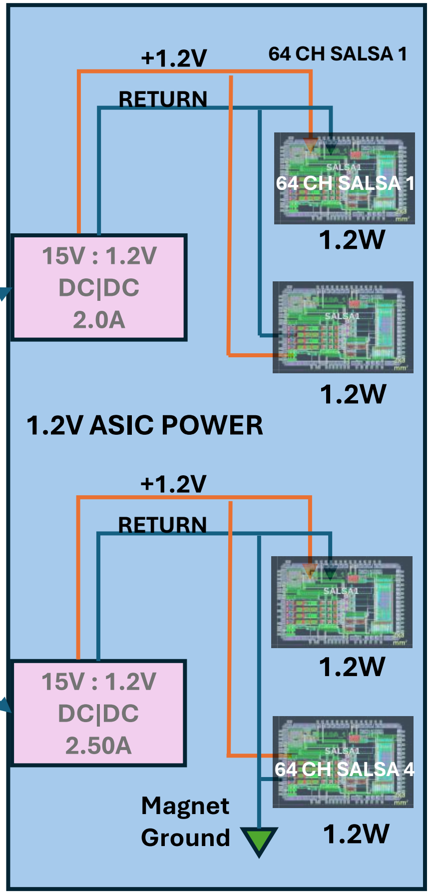
Need to power 63 FEBs

MPGD DISK ASIC FEB POWER REQUIREMENTS

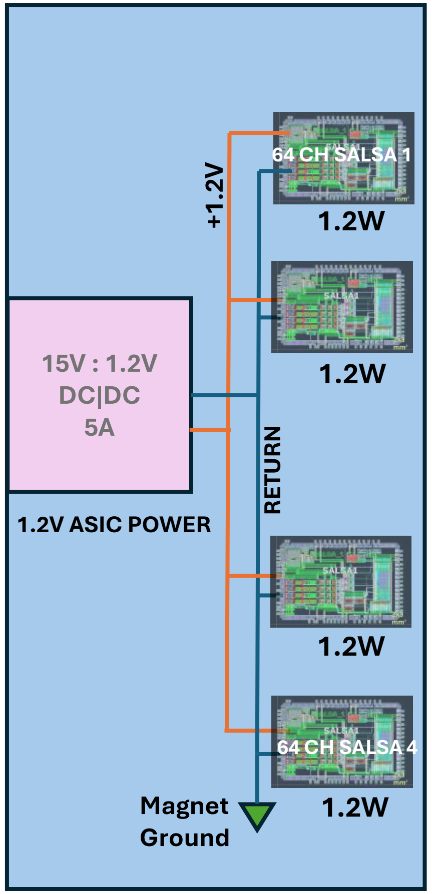
- SALSA: 1W @ 1.2V ≈ 1A (833ma) => 25% margin
- FEB w/ 4x SALSA ASICs ≈ 4A => 4.8W
- Efficiency losses (power in) = 4.8W/ 0.7 ≈ 7W

We could use CERN bPOL12V here but reduce Vin to 10V Lower Vin yields %50 increase in input current (470mA Vs 700mA)

- An option is to use bPLO48V for input regulation & power bPOL12V w/ 10V

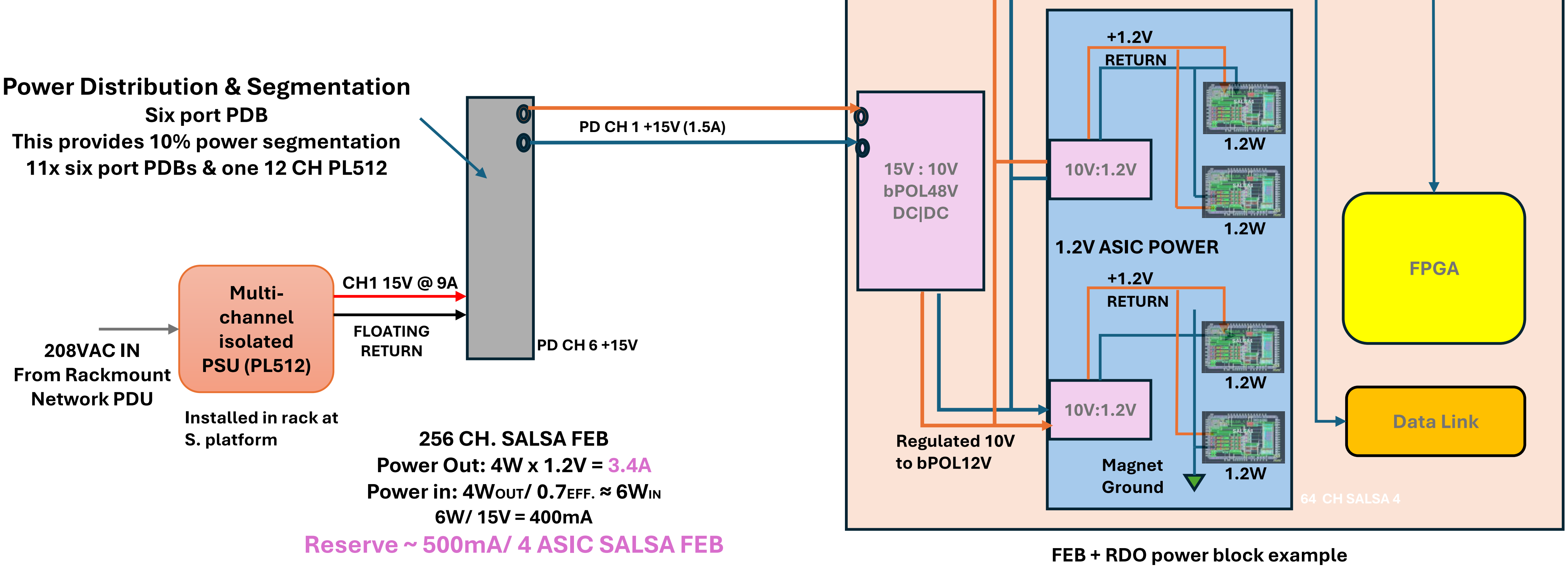


Example with COTS LTC3626 (2.5A)



Example with CERN bPOL48V (10A)

MPGD Trackers
Powering FEB & ASIC Boards
Power distribution from equipment platform to FEBs
Example



FEB + RDO power block example

SALSA ASIC, Sao Paulo University and
CEA IRFU teams

Neutron Fluence & TID at ePIC

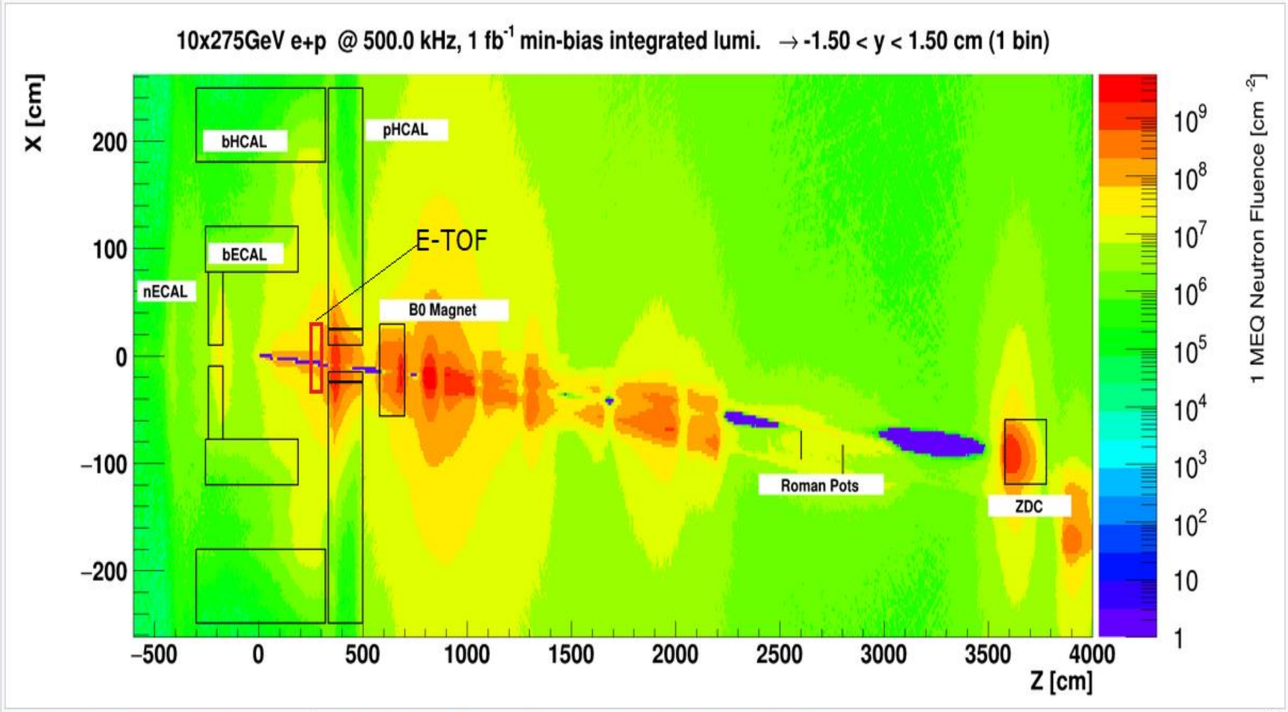
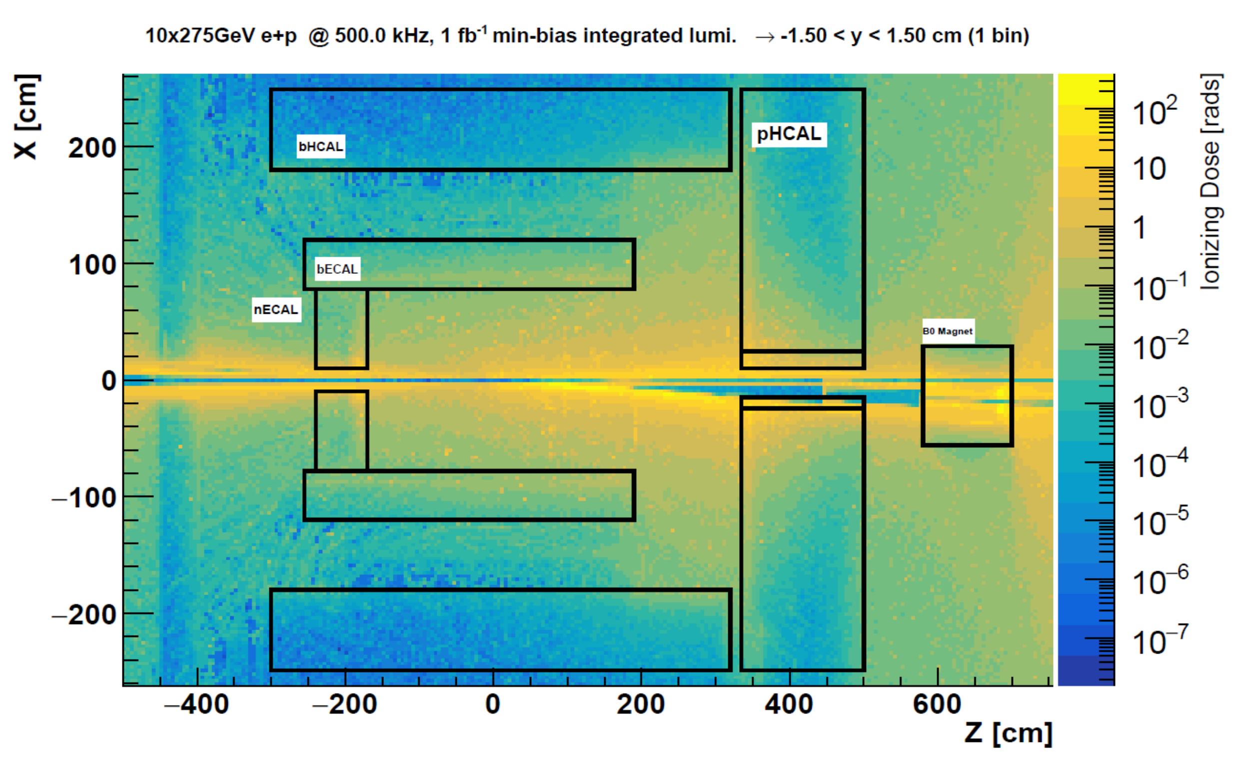


Figure 3: 1 MEQ neutron equivalent fluence per fb⁻¹ for minimum-bias PYTHIA e+p events at 10x275 GeV. ROOT files can be found here.



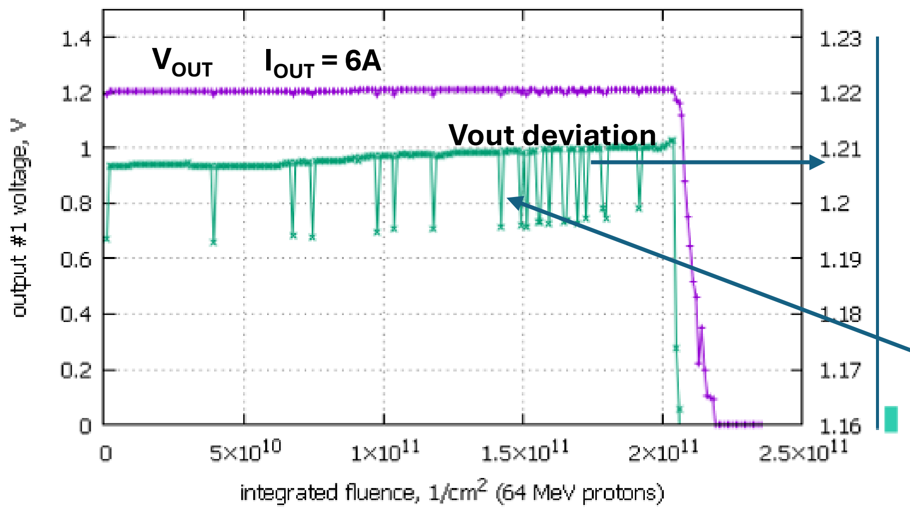
(1MeV equivalent) fluence normalized for 1 fb^{-1}
100 x fb-1 = 1 year. Very conservatively, we can expect an upper bound of 100 fb-1/year at top luminosity => 1E9 x 100 x 10
Worse case (10 years of operation) at insert calorimeters: 1E12 n/sec cm^2
3x safety factor: 3E12 n/sec cm^2

Ionizing dose of 1×10^2 x 100 = 10kRads/ year x 10 years = 100kRads
Safety factor of 3x => 300k rads

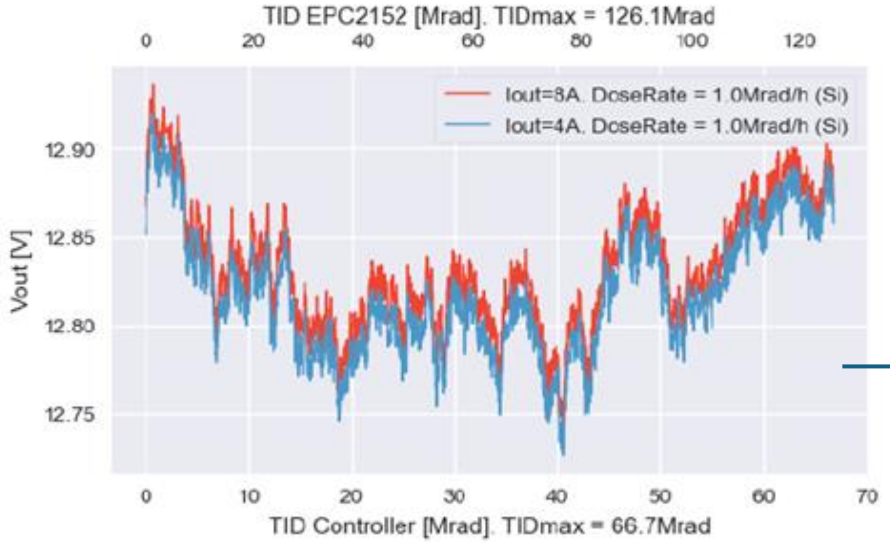
Slides 18-20 backup for proton testing at UC Davis

https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses#Radiation_Doses_and_Fluences_from_10x275_GeV_e+p_minimum-bias_events

MORE RADIATION TESTING BEING DONE ON COMMERCIAL PARTS



LTC7890 Vout Vs neutron fluence @ 25°C



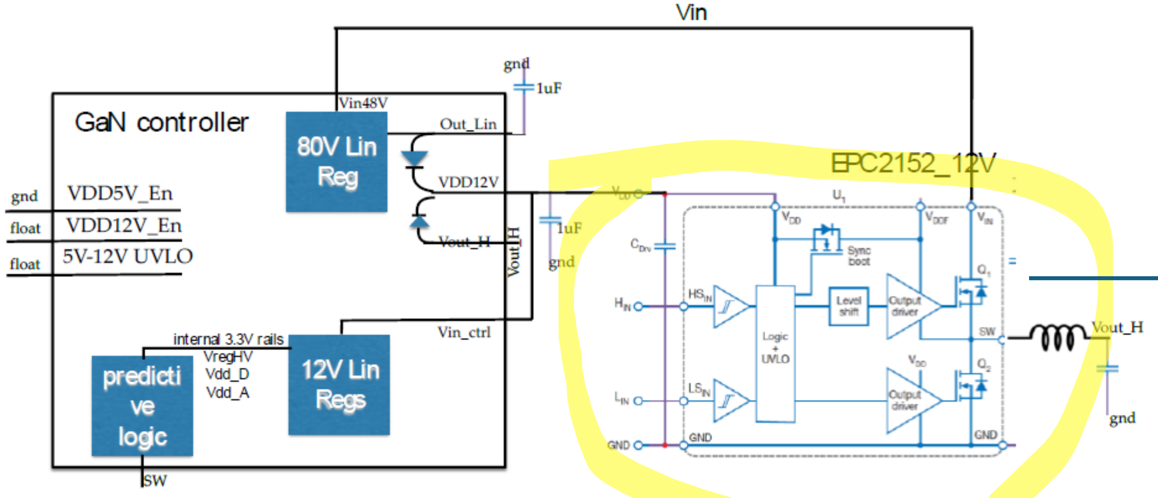
bPOL48V Vout Vs TID @ 30°C

Radiation Type	Testing Notes	Comments
Fast Neutrons	Tested at UC Davis 64MeV proton facility at a flux of 2.5E8/sec cm^2 (45min) Note: this may of given us a higher TID rate that caused early failure. LTC7890 slight Vout deviation: could be SEE	Parts that survived ~ 30% of target fluence of 1.0E12 n/ cm^2 failed at 2.0E11 n/ cm^2 are being considered for further testing. LTC3600 (1.5A) output shorted LTC3626 (2.5A) output shorted LTC7890 (15A) output died…but recovered several hours later. Seems to be 100% now! (possibly annealed displacement damage G.V.)
TID	From our fast neutron test at UC Davis 64MeV beam, simulations indicated the TID < 100k rads	Testing to be done in July BNL gamma ray facility at < 10k rads/ hour
SEE		Single event effects will be studied if parts pass TID testing

The single event effects (SEE) have been evaluated for the controller using heavy ions on the bPOL48V in the Cyclotron Resource Center of UCLouvain. In these tests, the effect on the EPC2152 is negligible, as the range of the heavy ions is not large enough to deposit charge on the sensitive area of the EPC2152. The GaN power stage is being characterized by EPC Co.

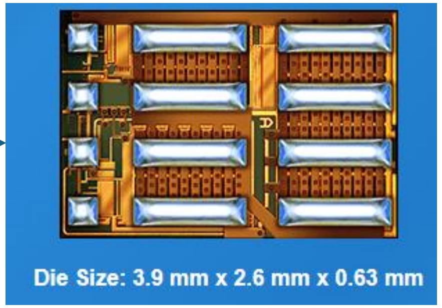
From bPOL48V data sheet

bPOL48V Vs LTC7890 topology difference

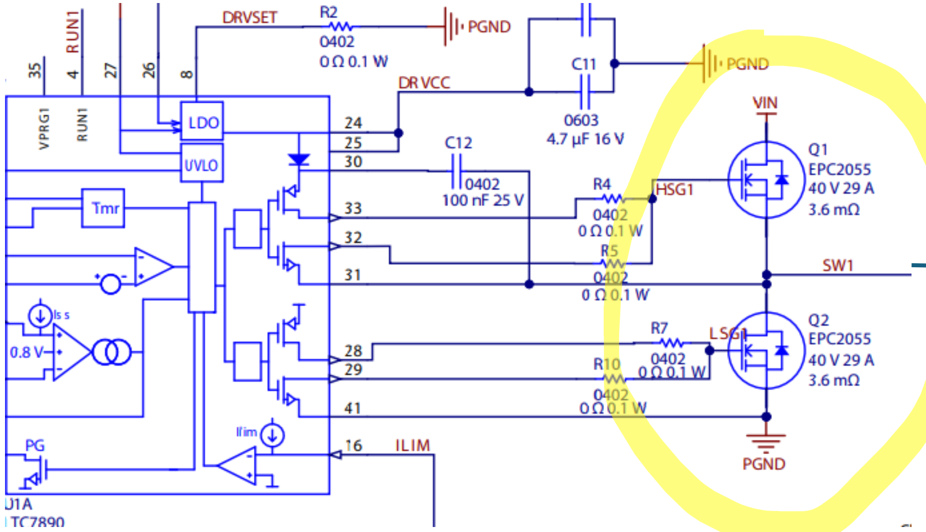


CERN bPOL48V

Driver circuit with GaN FETs

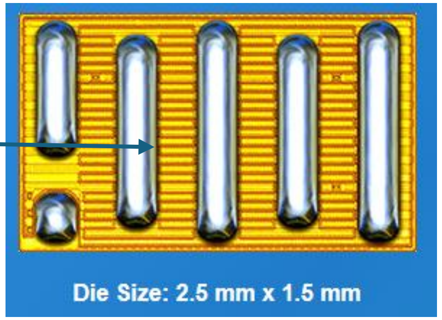


EPC INC. EPC 2152 power output stage driver w/ GaN FET



Analog Devices LTC7890

Just GaN FETs



EPC INC. GaN Power FET

MPGD Neutron Fluence & TID simulations referenced from distance

MPGD layer locations		Maximum EM Radiation dose [krads]	Maximum Hadron radiation dose [krads]	1 MeV neutrons equivalent fluence [cm^{-2}]	1 MeV protons equivalent fluence [cm^{-2}]
Barrel	R = 73 cm	0.3	0.1	2.8×10^{10}	4.2×10^{9}
	R = 55 cm	0.22	0.15	2.7×10^{10}	6.5×10^{9}
Hadron end cap	z = 148 cm	51.2	16.2	1.2×10^{11}	2.3×10^{11}
	z = 163 cm	52.6	14.1	1.1×10^{11}	3.3×10^{11}
Electron end cap	z = -112.5 cm	3.2	0.2	1.3×10^{10}	5.2×10^{8}
	z = -122.5 cm	4.2	0.2	1.4×10^{10}	8.0×10^{9}

TABLE1: e + p minimum-bias event @ 500 kHz event rate for 10 yrs EIC runs with 6 months run time/ yr and 100% efficiency

Layer	Distance cm	TID (k rads)	Fluence n/ sec / cm^2
Barrel	R=73	1.2	8.4E10
Barrel	R=55	1.2	8.4E10
Hadron endcap	Z=148	200	3.6E11
Hadron endcap	Z=163	200	3.3E11
Electron endcap	Z=112.5	10.2	4.0E10
Electron endcap	Z=122.5	13.2	4.2E10

TABLE 2: 1meV n. equivalent fluence & TID from table 1 With added 3x safety factor

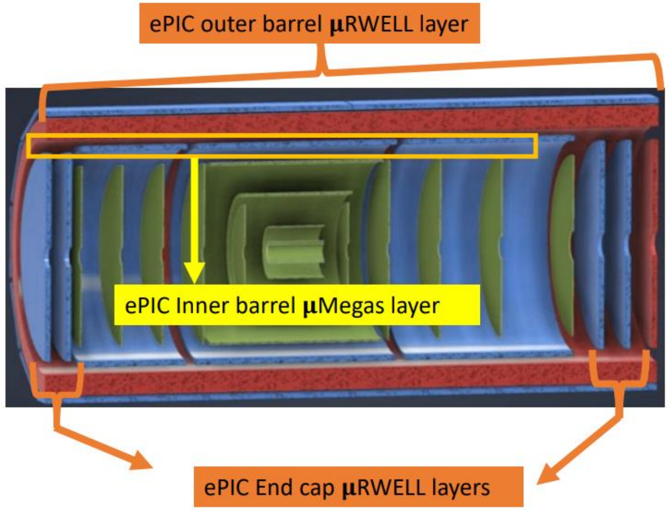


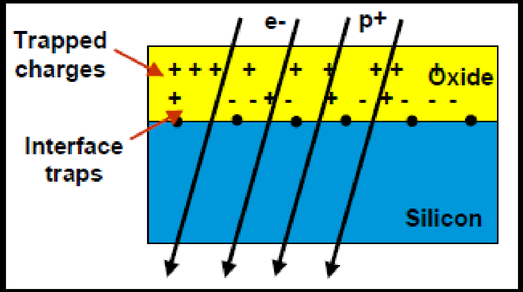
Image from Sourav Tarafdar (Jlab), Vanderbilt U. 2023

https://indico.slac.stanford.edu/event/8288/contributions/7884/attachments/3675/10024/CPAD_11_08_23.pdf

DC:DC converter selection based on rad tolerance & testing at UC Davis 64MeV proton facility

Dose & fluence with added 3x safety factor

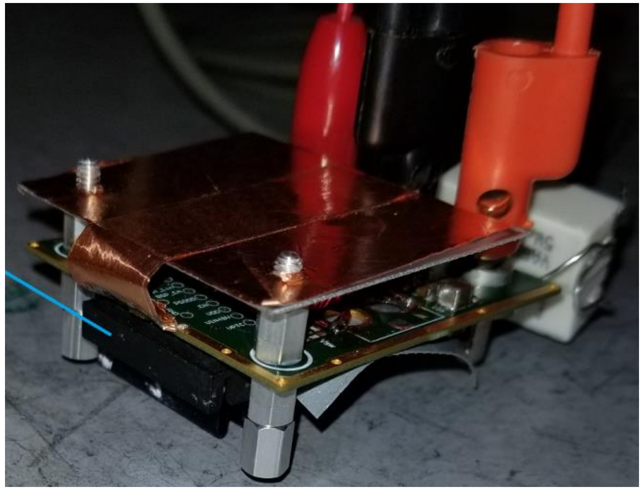
Barrel	TID 1.2K rads	8.4E10 n/sec/cm^2	LTC 3600 LTC 3626 LTC 7890 bPOL12v bPOL48V
Electron Disk	TID 13.2K rads	4.2E10 n/sec/cm^2	LTC 3600 LTC 3626 LTC 7890 bPOL12v bPOL48V
Hadron Disk	TID 200K rads	3.6E11 n/sec/cm^2	bPOL12V bPOL48V



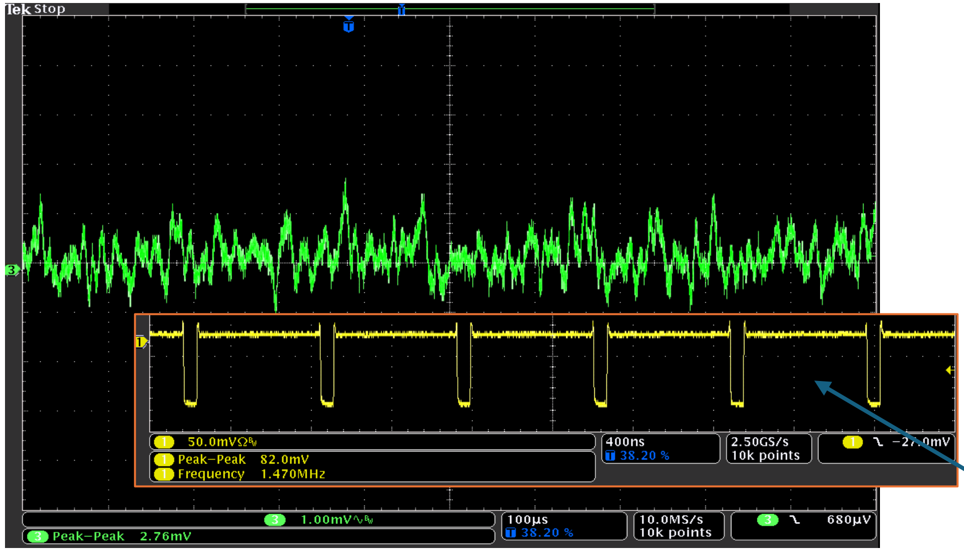
Ionizing effects study on COTS DCDC converters in July at BNL gamma test facility

→ Estimated rad dose on the tested COTS parts => ~10K rads

DC|DC performance testing bPOL48V (bUCK POINT OF LOAD) Vs LTC7890



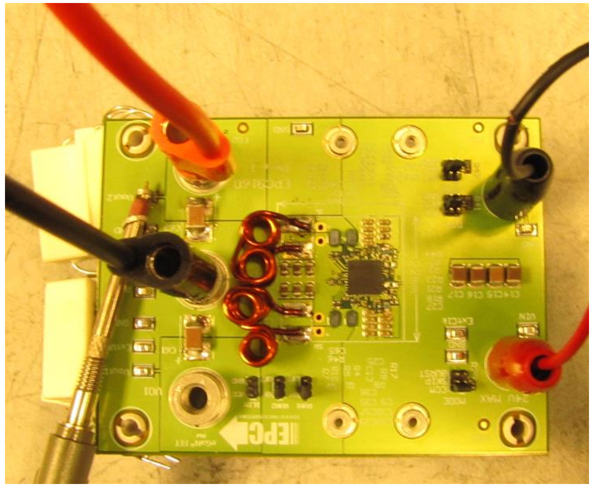
bPOL48V w/ bottom mount heat-sink, 300nH @ 1.5MHz



Vout Noise/ ripple ~3mV (1mV/div) h. 100us

V_{OUT}	1.2V
I_{OUT}	8.2A
V_{IN}	15V
P_{IN}	12.75
P_{OUT}	10.0W
P_{EFF}	78.0%
Noise 1gHz	<0.3%
Ripple 25MHz	<0.3%
On-time	~60ns
Fsw	1.5MHz

EMI (near field) 82.0mV p-p
Measured from bottom of the PCB
50mv/div h.400ns



LTC7890, 270nH @ 2.0MHz FSW

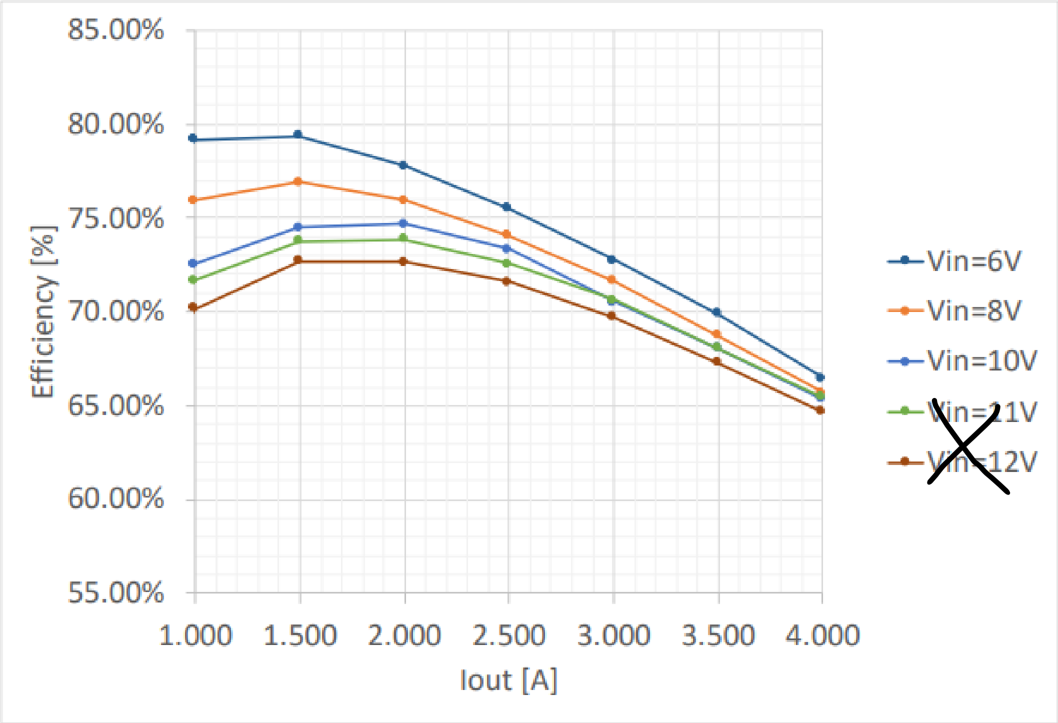
Vout Noise/ ripple ~1.5mV (1mV/div) h.200ns

$V_{OUT\ ch1,\ ch2}$	1.2V, 1.2V
$I_{OUT\ ch1,\ ch2}$	12A, 12A
V_{IN}	12V
P_{IN}	36W
P_{OUT}	28.8W
P_{EFF}	80.0%
Noise 1gHz	<0.3%
Ripple 25MHz	<0.3%
On-time	~60ns
Fsw	2.0MHz

EMI (near field) 118mV p-p
Measured from bottom of the PCB

CERN bPOL12V testing

bPOL12V eval board mounted on test adapter carrier board



Test conditions:

V_{IN}= 10.00V
I_{IN} = 0.4A
V_{OUT} = 1.50V
I_{OUT} = 2.0A
P_{IN} = 4W, P_{OUT} = 3.0W
Noise & Ripple < 0.4% (250MHz, 25MHz)

The measured efficiency with a switching frequency of 1.5MHz and 460nH inductor comes out to ~ %75.0%

Data sheet $P_{EFFICENCY}$ table for 10Vin & 2.0A out ~75.0%

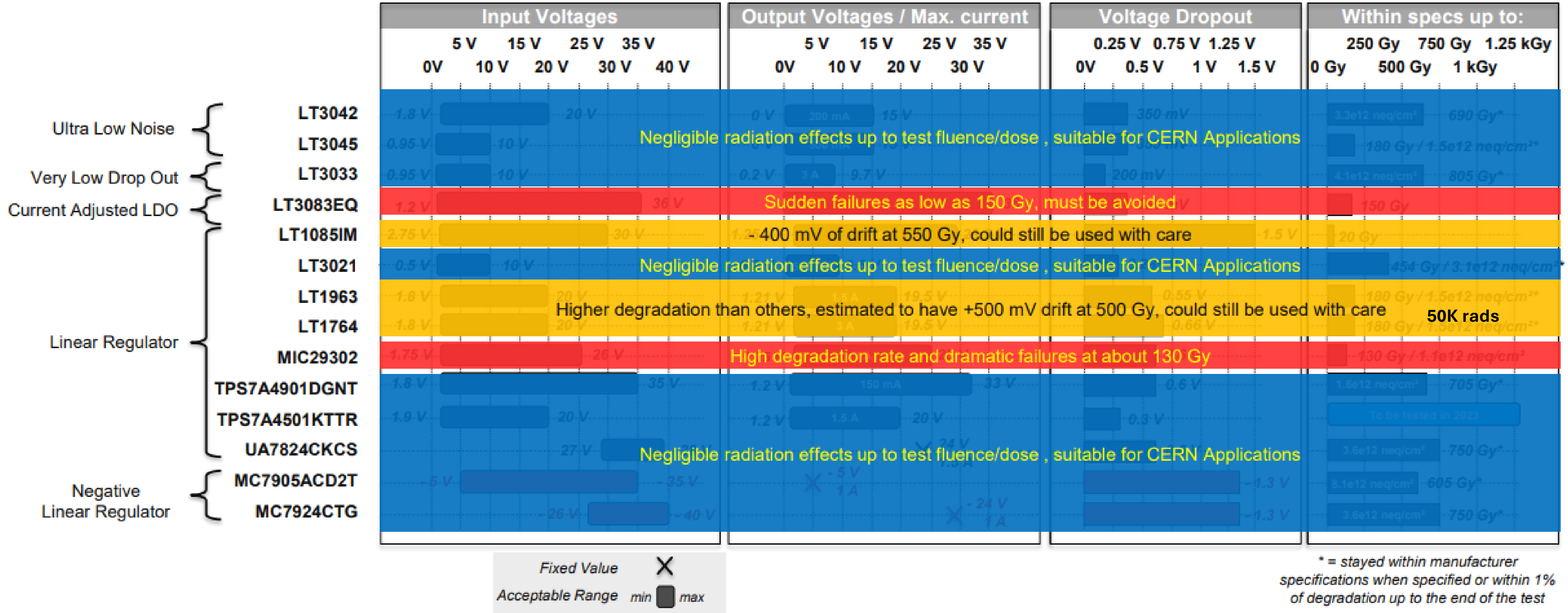
BPOL12V regulator temperature:

I measure ~34 deg C from the devices package (30 degC for inductor) , which is not bad for dissipating almost 3.0W and considering the small area of copper plane on the module. Further improvements in efficiency might be possible by playing with the inductor size and switching frequency...

- More testing to do to optimize FSW and Efficiency
- PCB Layout for > 2.0A output current

CERN Radiation Testing for COTS Linear Regulators

- Are presented only the devices tested in representative LHC radiation environments (i.e. CHARM)



Slide 25 from Rudy Ferraro (CERN CEM group), June 2023

https://indico.cern.ch/event/1295840/contributions/5446495/attachments/2667106/4668570/RADWG%20Voltage%20Regulator%20Final.pdf

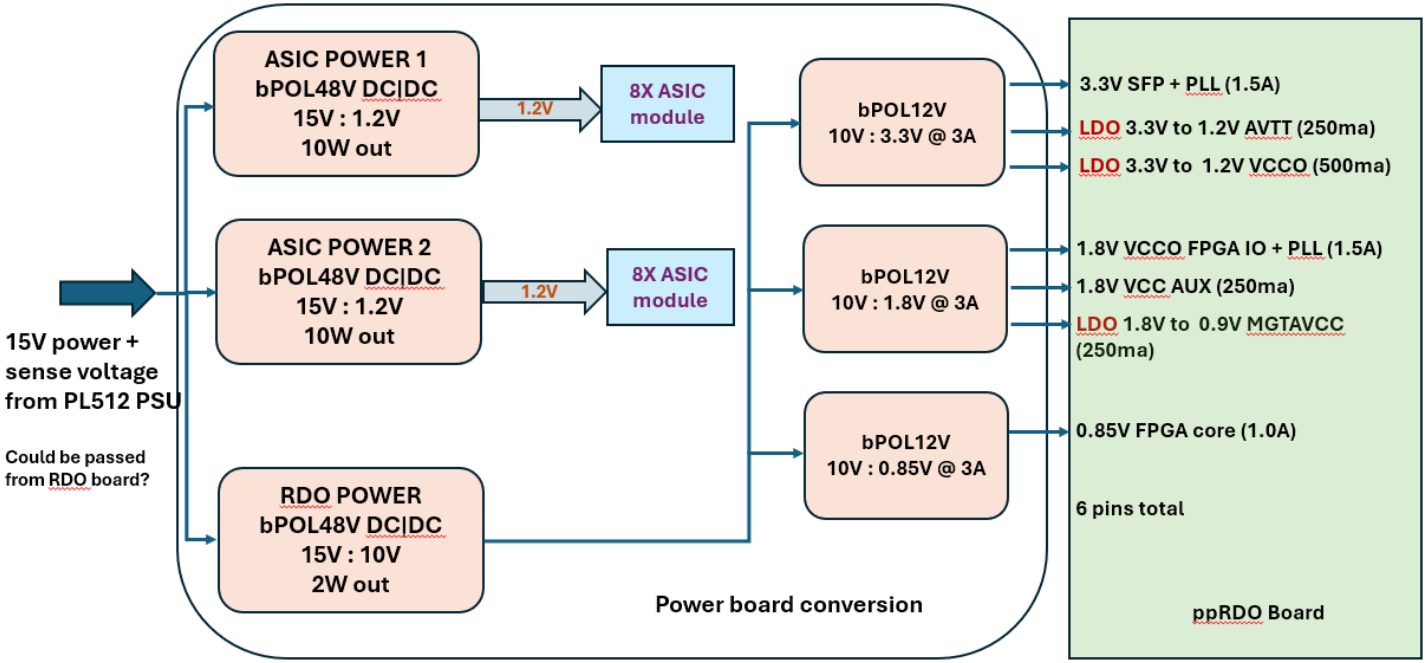
Conclusions

- All tested parts should meet power + noise + efficiency performance specifications for FEBs & RDOs
- CERN bPOL parts will meet radiation requirements at ePIC
- More rad testing is needed for selected COTS parts (candidate parts have not been eliminated yet)
- A good deal of vetting has been done by CERN for radiation effects on linear COTS regulators

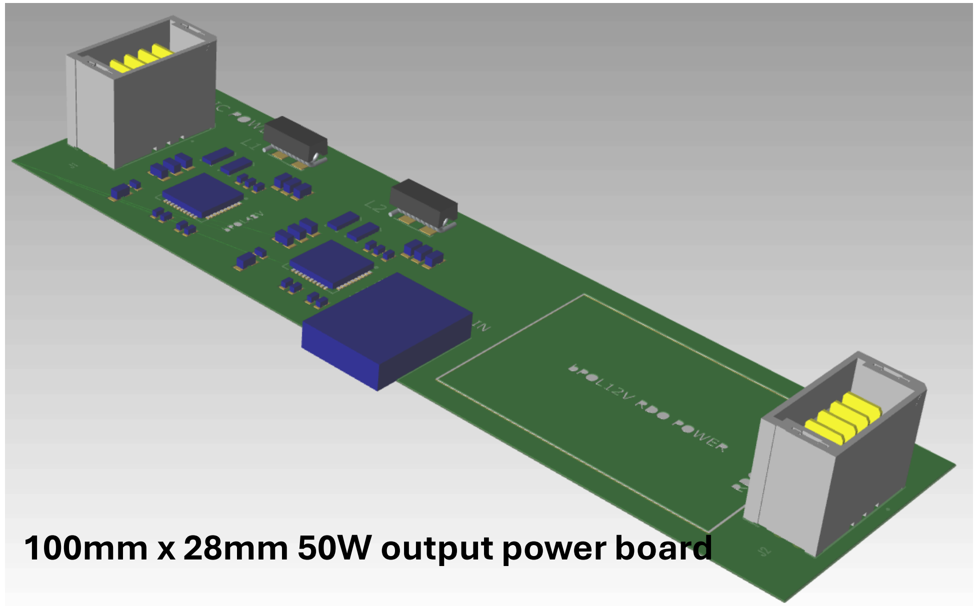
What's Next?

- Continue radiation studies for COTS DC:DC buck converters
- Build prototype power boards
- Power board design for fTOF EICROC FE ASIC Board
- Acceptance testing →
  - Noise / Ripple
  - Regulation
  - Efficiency
  - Temperature & thermal study
  - Reliability & performance stress testing

EICROC FEB ASIC + RDO POWER BOARD EXAMPLE



Preliminary EICROC ASIC+RDO power board flow chart
Optimized for efficiency



100mm x 28mm 50W output power board

Layers: 4x to 6x

2.0 mm thick

Copper Weight: 2oz top/bottom

Heat transfer: Bottom copper w/ gold finish

Thermal compound or sil-pad

mount to plate w/2.0mm screws

Component Mount: Top only

Power Dissipation: ~50W (~75% efficiency) 180mw / cm^2

Boards will range in size based on installed locations

(100x28mm is smallest PCB dimension)

REFERENCES

SALAS ASIC: https://indico.cern.ch/event/1327482/contributions/5692916/attachments/2766588/4819103/SALSA_RD51_20231206.pdf

https://power-distribution.web.cern.ch/ASICS/

https://epc-co.com/epc/products/gan-fets-and-ics/epc2152

https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses#Radiation_Doses_and_Fluences_from_10x275_GeV_e+p_minimum-bias_events

Non Ionizing Energy Loss — Neutron induced displacement damage in silicon

Neutron induced displacement damage in silicon

A. Akkerman et al. / Radiation Physics and Chemistry 62 (2001) 301–310

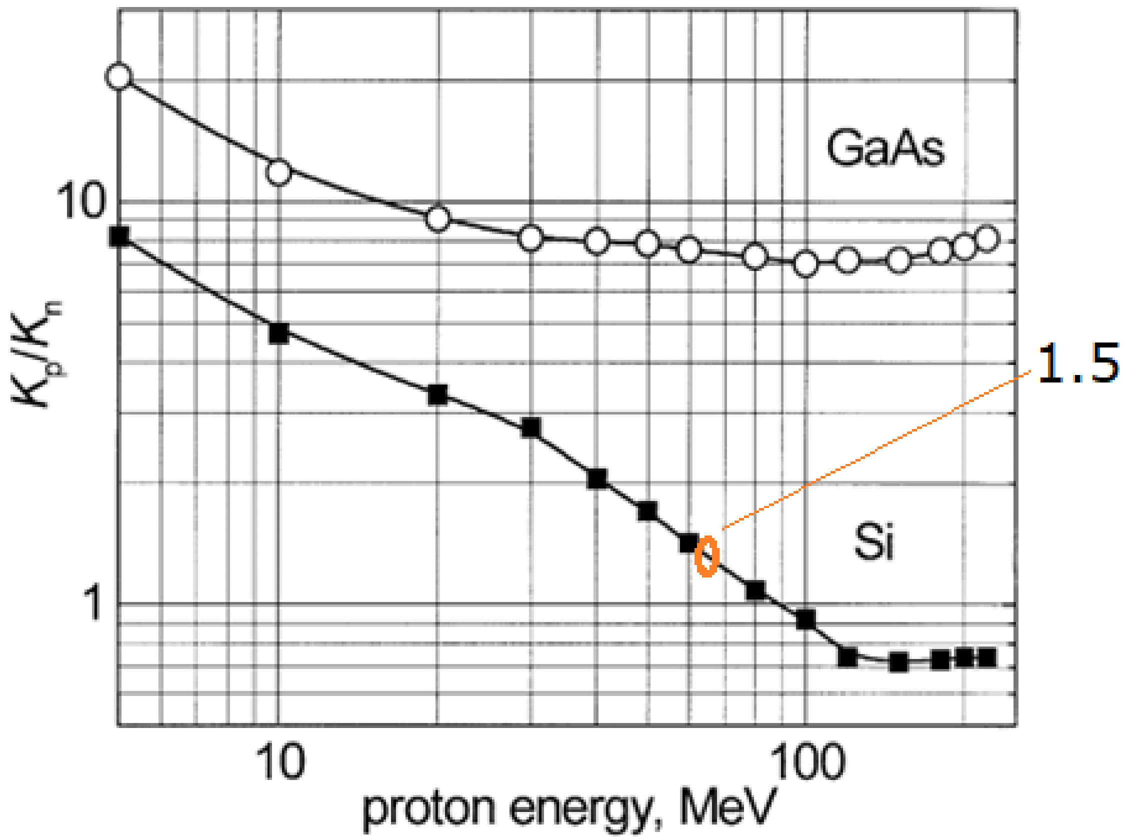


Fig. 6. The relative damage, K_p/K_n, as a function of proton energy where K_n is taken for 1 MeV neutrons.

Ekin [MeV] P	D/(95MeVmb) Huhtinen
6.500E+01	1.580E+00
1.000E+00	3.133E+01

https://rd50.web.cern.ch/niel/protons.pdf

Ekin [MeV] N	D/(95MeVmb) Konobeyev
6.000E+01	1.644E+00
7.000E+01	1.499E+00
6.500E+01	1.572+00 (1.644+1.499)/2 **6.5 not listed so I avg 6.0E+1 & 7.0E+1**
1.050E+00	8.020E-01

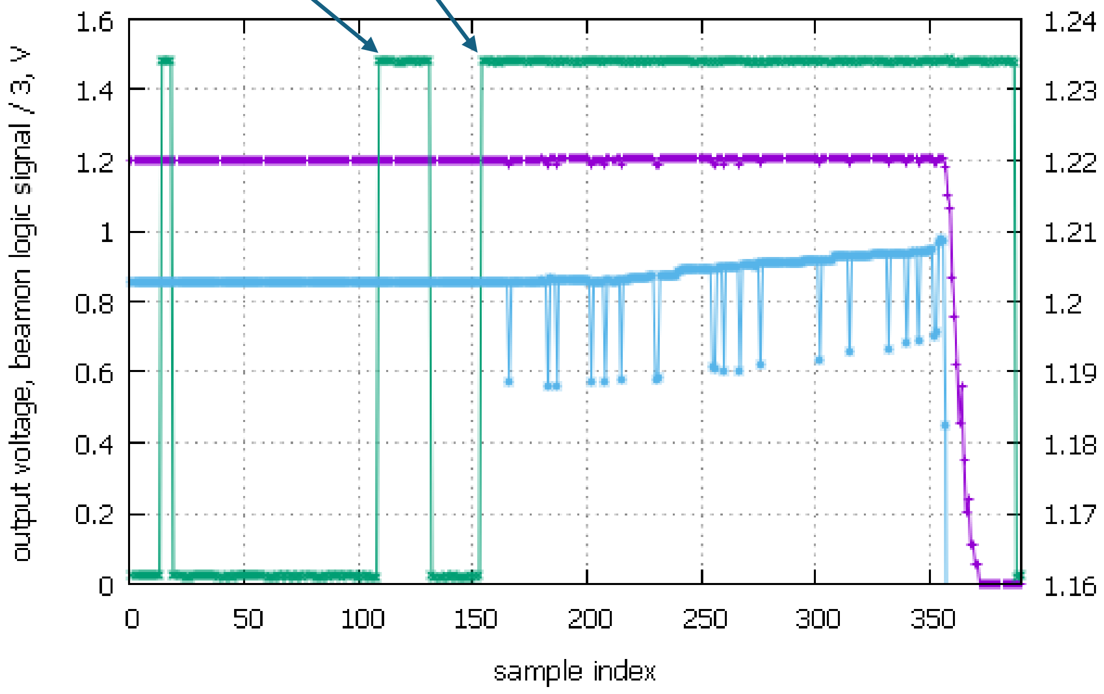
https://rd50.web.cern.ch/niel/neutrons.pdf

Source: https://rd50.web.cern.ch/niel/

LTC7890 Output deviation under 64MeV proton beam

Faraday cup open (t=0) start logging

Beam on, Faraday cup closed



Output deviation

Slight instability (output deviation) observed only when beam is on (Faraday cup open)

Cyclotron configuration setup screen