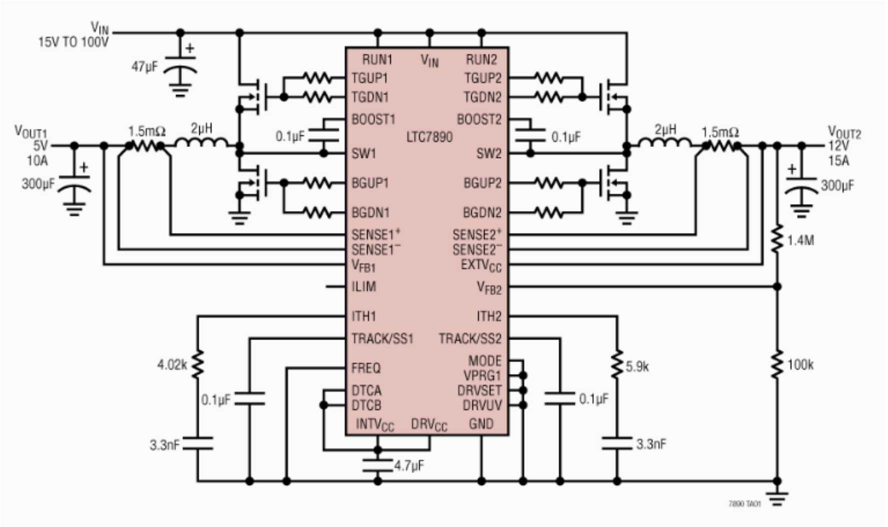
DC Buck Converter Testing for powering RDOs + Front End ASIC Boards

Tim Camarda for Brookhaven National Lab Electronics Group, FEB 2024

Presented here are 4x synchronous buck converters. Since these are of the synchronous high-efficiency type, no external rectifier diodes are required.

- High power 100W (Analog Devices LTC789 & CERN bPOL48V)
- Mid Power 25W (MPS MPQ8626)
- Low power 10W (CERN bPOL12V) Limited Availability



LTC 7890 Synchronous "Buck" converter, Analog Devices

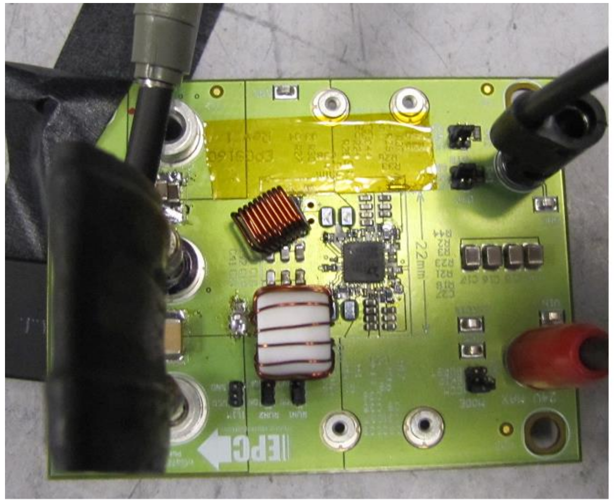
Criteria

- operate in a 2 Tesla or greater field
- withstand radiation exposure similar to STAR experiment (*from Hadron side of ePIC*)
- low ripple & noise <0.5%$_{RIPPLE}$, ≤1.0%$_{NOISE}$)
- Load regulation ≤1.5%
- efficiency ≥ 65% (depending on power output)
- mitigate EMI (radiated & conducted)
- compact size (high power density)
- operates in 35°C environment with minimal derating
- Rugged (test power cycling, T°C environment, TID etc.…)
- Input power delivered over cable of several meters (20 meters) from PSU at rack to DC|DC regulator

Testing specifications & measurements:

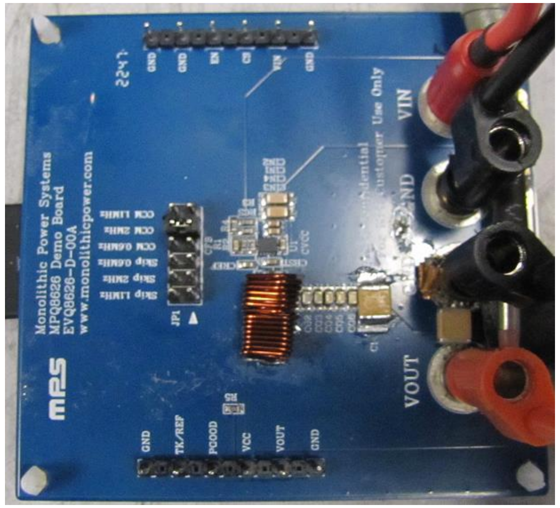
- 1.2Vout, Up to (7W) *Typical ASIC PWR rail requirement*
- Ripple + Noise
- Efficiency
- Regulation
- Temperature
- 2.0meter cable length (Power$_{IN}$)

Synchronous buck "step-down" converter evaluation circuits under test



Analog Devices LT7890, 2channel 100W DC buck converter, External GaNi rad tolerant

CERN bPOL48V2.1, 1channel 100W DC buck converter, High rad tolerant



MPS MPQ8626 25W DC buck converter

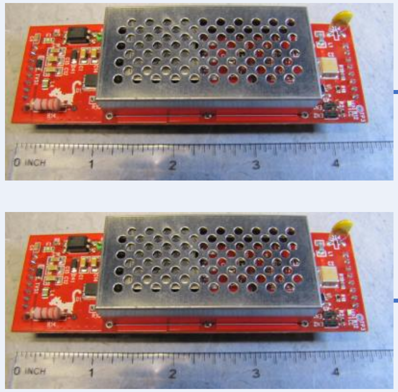
CERN bPOL12V 10W DC buck converter, high rad tolerant
Availability? Need to purchase from stockpile

NOTE: Output power determined from practical implementations

Topology is used extensively in detector electronics
Here is example of Powering the STGC Detector @ STAR

STAR ELECTRONICS

Turned DEP crates into
Custom 2kW LV power bin x2

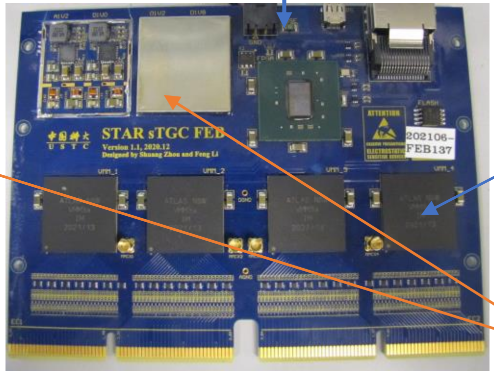


Custom 30W LV power
module (12V @2.5A_{OUT}) x 126

Come detectors will require a combination of switching converters and Linear LDO regulators (See Tonko's E-TOF example)

18-meter LV cable to detector electronics
2 pair 18AWG (1 pair to each board)
1A/ feed (sourced 10V) 1W
>70% P_{EFF}

STGC RDO



STGC FEB

ATLAS VMM ASIC x 4

CERN "FEAST" DC|DC buck converters
(similar specs to bPOL12V)

Inductors used for bPOL48V, MPQ8626 & LT7890 testing

Allied Part Number*	Inductance (nh)	Tolerance	Q Typ.	Test Freq. (MHz)	SRF Min. (GHz)	DCR Max. (mΩ)	Irms (A)
SQAC2929-331N_-RC	330	G, J	180	50	.66	12.5	4.7
SQAC2929-501N_-RC	500	G, J	180	50	.50	16.5	4.3

Measured T_{IND}°C is well below operating tmp, hence we are well within I_{RMS} rating of inductor

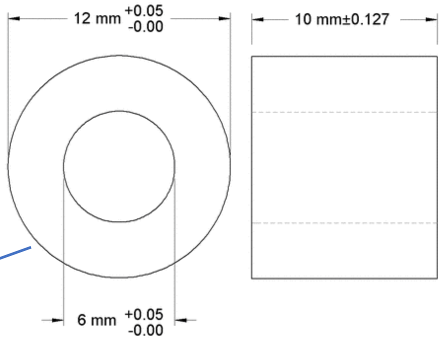
Electrical

Impedance range: 330nH to 500nH
Tolerance: available in 2% and 5%
Test Frequency: 400MHz
Operating Temp: -40°C to +125°C

Inductor for bPOL12V testing (I_{RMS} 2.5A)

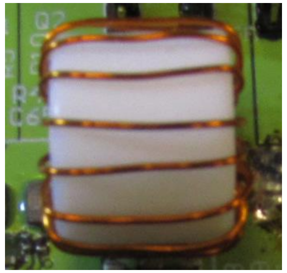
Part number	Inductance (nH) ±5%	Q min	DCR max (mΩ)
132-17L	460	66 @ 25 MHz	22.5

Ran a little hot in 3W testing of bPOL12V but should be below saturation current



Air-core toroid form made from a plastic sleeve bearing. Larger than needed, but easier to wind by hand

Custom Toroid



- 220nH
- No Data other than inductance based on windings & toroid dimensions.
- Used as *proof of concept*. DCR @ test F_{sw} & Q value will need to be measured as testing with toroids continues
- *Toroid benefit: Uniform flux & inherent EMI shielding properties.*

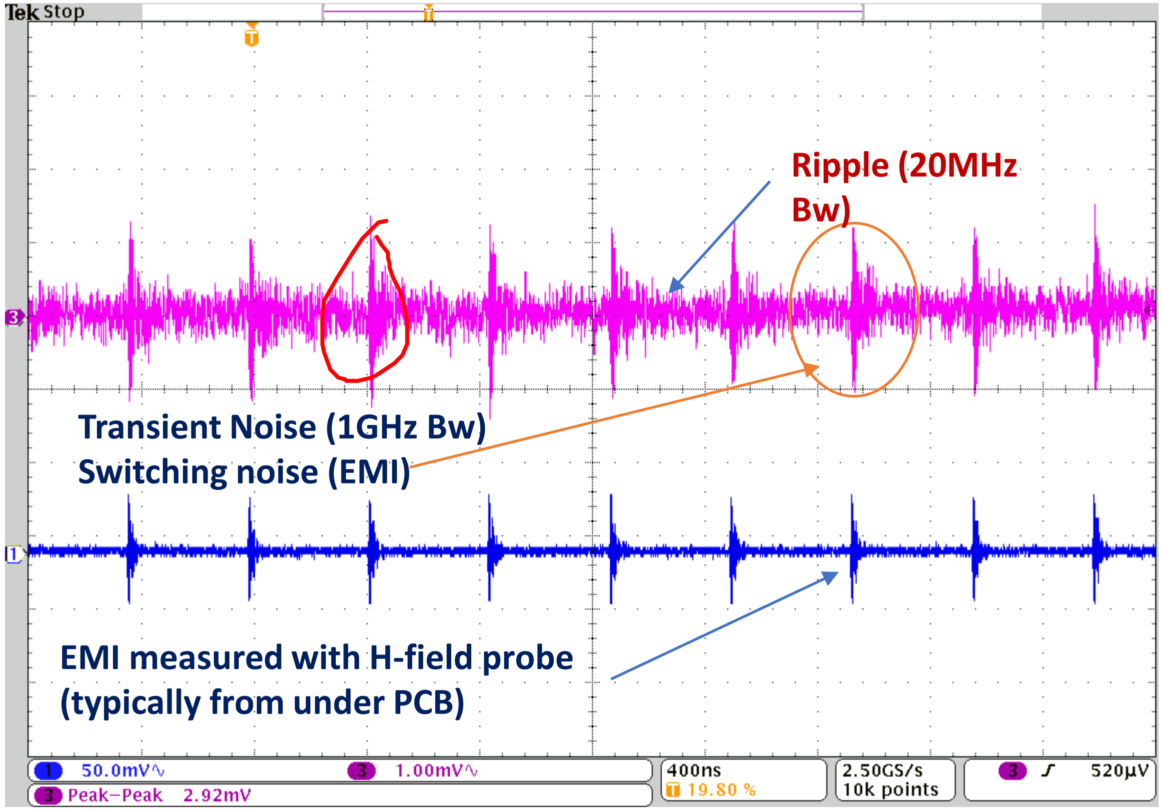
Optimizing inductor value

- ✓ **Core permeability (air) no core losses but higher winding losses**
- **Need to find optimal inductor…**
  1. **Fsw (higher Fsw will increase DC & ripple losses)**
  2. **Loss Factor = R/ (2pi*f*L) &**
  3. **Q factor: Q = (2pi*f*L)/ R**
  4. **INDUCTOR-LOSS & IRIPPLE-LOSS**

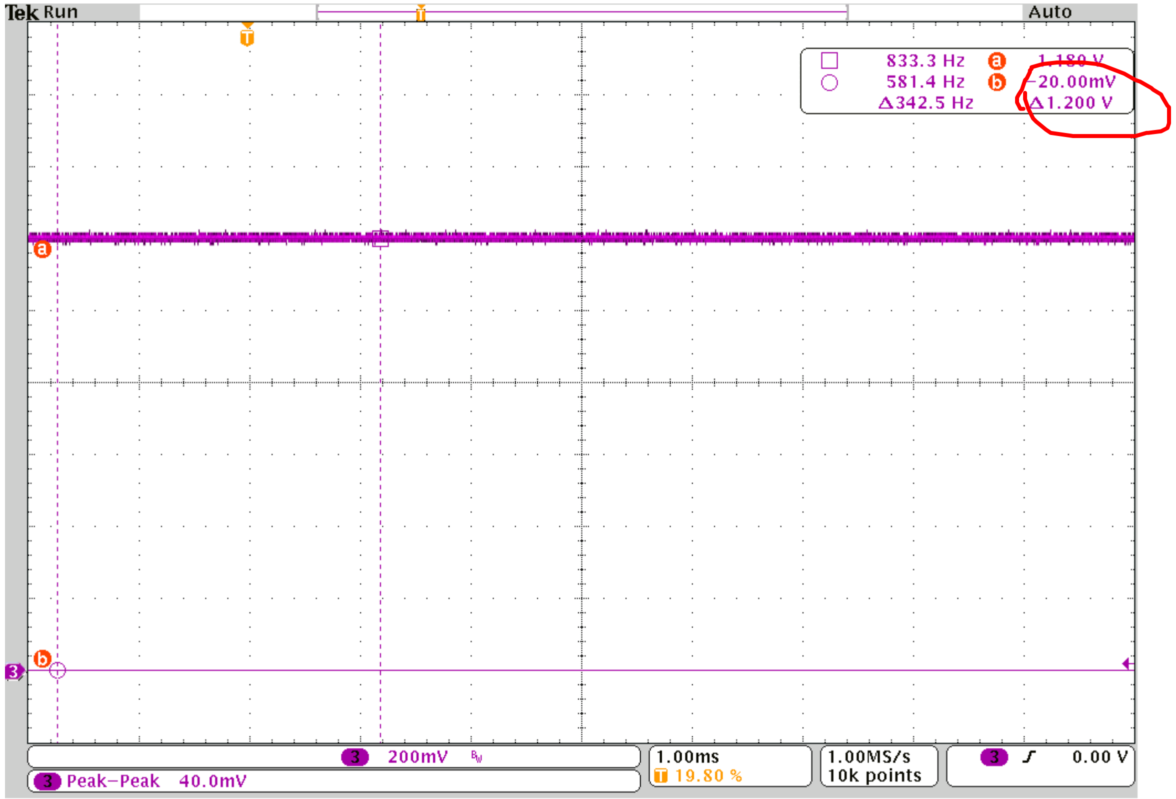
Example with 330nH @ 2MHz (2.5) 3W

$$P_{inductor} = I_{OUT}^2 x DCR$$

$I^2 * R = (2.5)^2 * 12.5E-3 = 0.08W$



Ripple & Noise measurements (MPQ8626 example)



DC output & stability (No oscillations observed)

Test Parameters:

- 1.2Vout, 6A (7W)
- 1.2Vout, 2.5A (3W)
- Ripple + Noise
- DC stability
- Efficiency
- Regulation
- Temperature

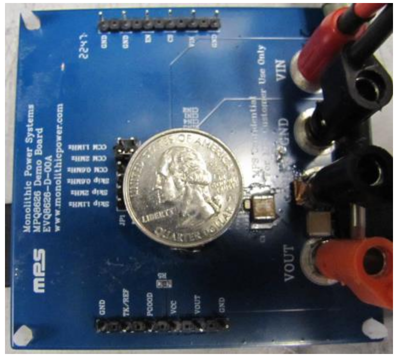
Test conditions:

≥ Vin:	$+12V_{IN}$ or +24Vin **(10Vin for bPOL12V)**
Ambient:	~21°C
Ripple Bw:	20_{MHZ}
Noise Bw:	1_{GHz} (EMI)
Power INPUT, cable length:	2.0_{meters}
Load:	Resistive

Noise testing criteria

Brookhaven National Laboratory

ePIC



DC|DC buck converter testing w/ MPQ8626 @3W

Modifications:

•500nH air-core inductor PN: SQA2929-501

•47uF ceramic output decoupling

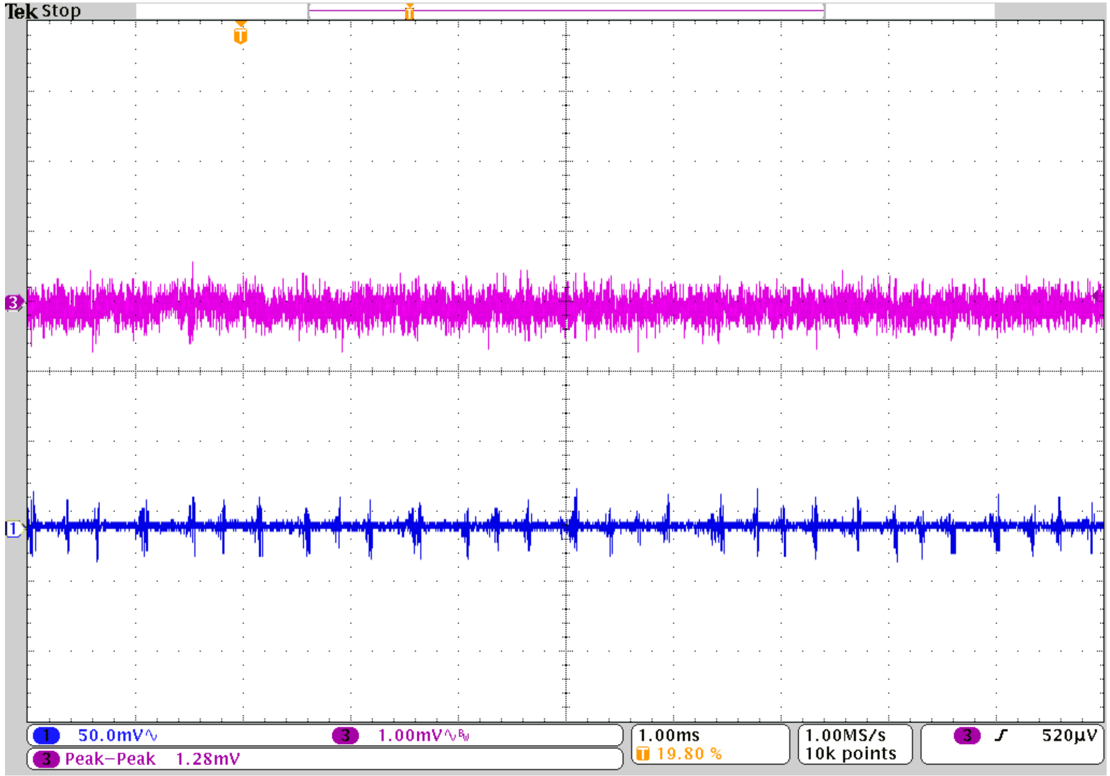
MPS MPQ8626

Basic data sheet features:

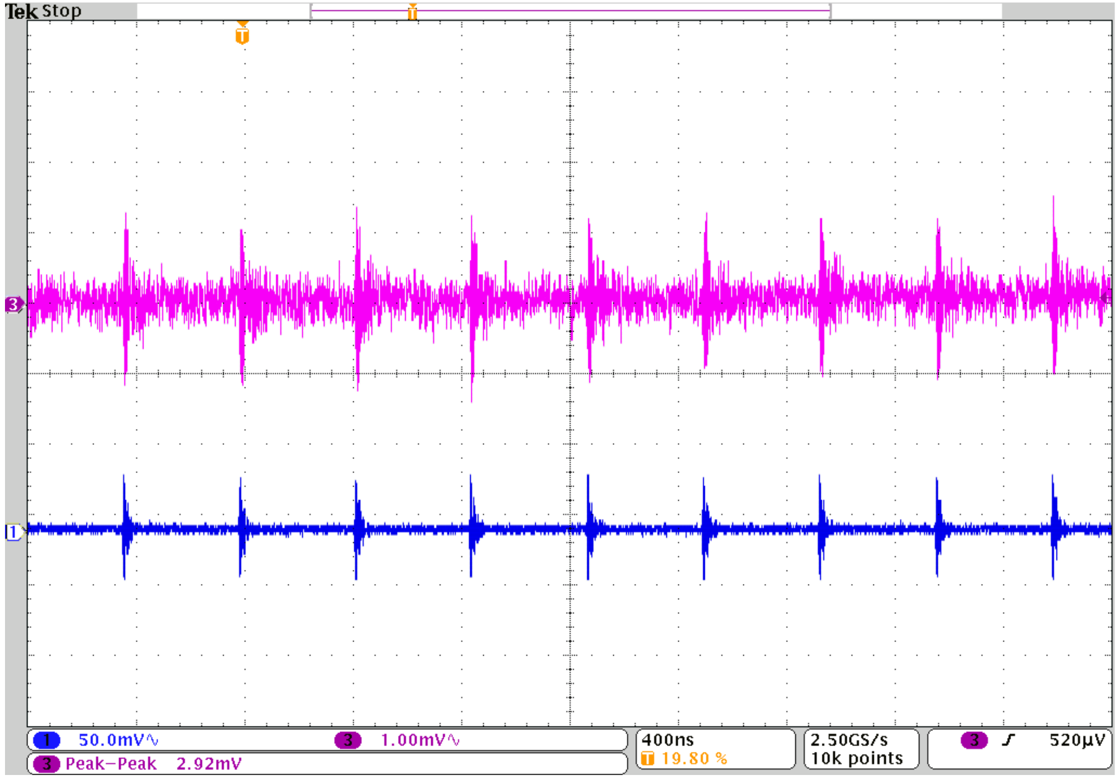
- **V_{IN} 4V- 16V**
- **V_{OUT} 0.6V - 6V**
- **I_{OUT} 8A**
- **Chip Package 6.0mm²**
- **0°C to +70°C (Vref stable)**
- **(TJ)... -40°C to +125°C**

Test Results

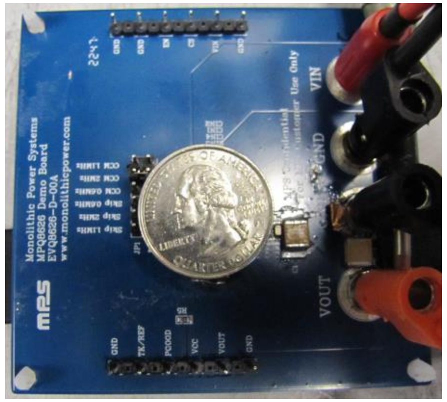
- **V_{IN} = 12V**
- **$1.2V_{out}$ with 2.5A load 3W**
- **ripple <0.11%**
- **noise < 0.3%**
- **load regulation: <1.0%**
- **P_{EFF}: > 83.0%**
- **Fsw = 2.0MHz**
- **T_{8626} 32°C, T_{IND} 30°C**



MPQ 8626 3W out ch3 ripple (20MHz Bw), ch1 EMI probe under PCB



MPQ 8626 3W out ch3 noise (1GHz Bw), ch1 EMI probe under PCB



DC|DC buck converter testing w/ MPQ8626 @7W

Modifications:

•500nH air-core inductor PN: SQA2929-501
•47uF ceramic output decoupling

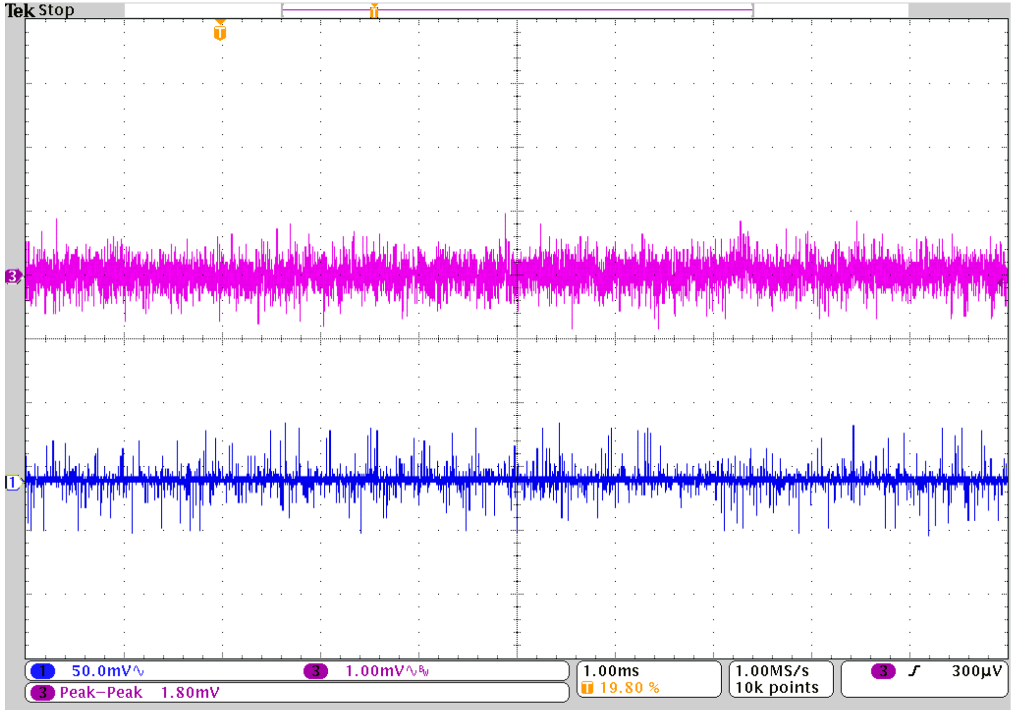
MPS MPQ8626

Basic data sheet features:

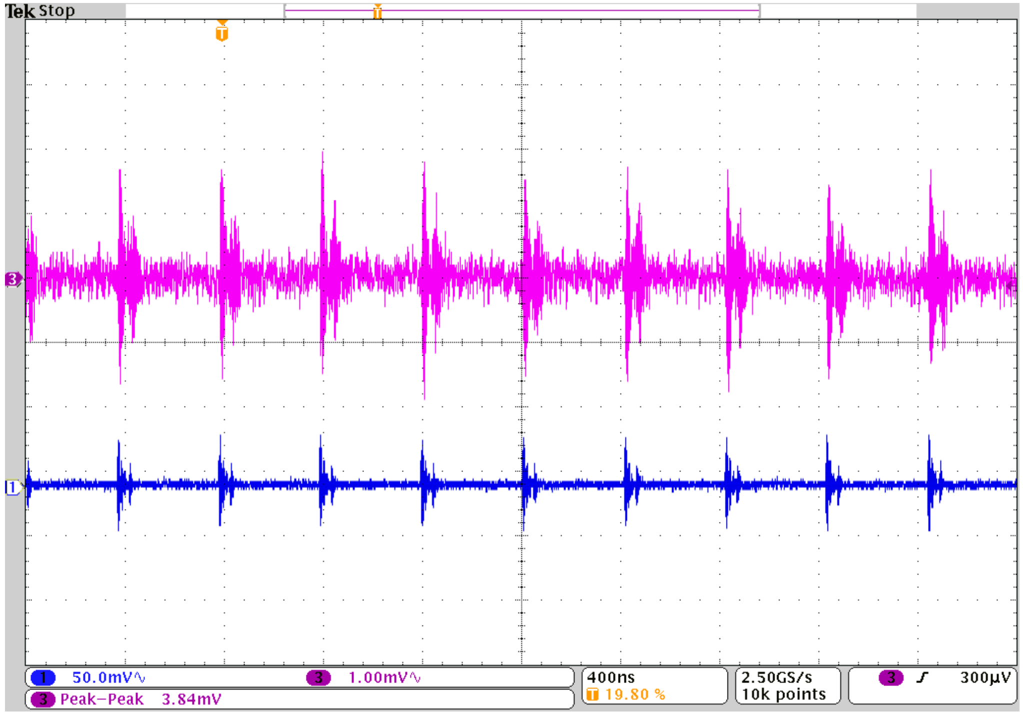
- V_{IN} 4V- 16V
- V_{OUT} 0.6V - 6V
- I_{OUT} 8A
- Chip Package 6.0mm²
- 0°C to +70°C (Vref stable)
- (TJ)... -40°C to +125°C

Test Results

- V_{IN} = 12V
- $1.2V_{out}$ with 6.0A load 7.2W
- ripple <0.20%
- noise < 0.35%
- load regulation: <1.5%
- P_{EFF}: > 80.0%
- Fsw = 2.0MHz
- T_{8626} 50°C, T_{IND} 40°C



MPQ 8626 3W out ch3 ripple (20MHz Bw), ch1 EMI probe under PCB



MPQ 8626 3W out ch3 noise (1GHz Bw), ch1 EMI probe under PCB

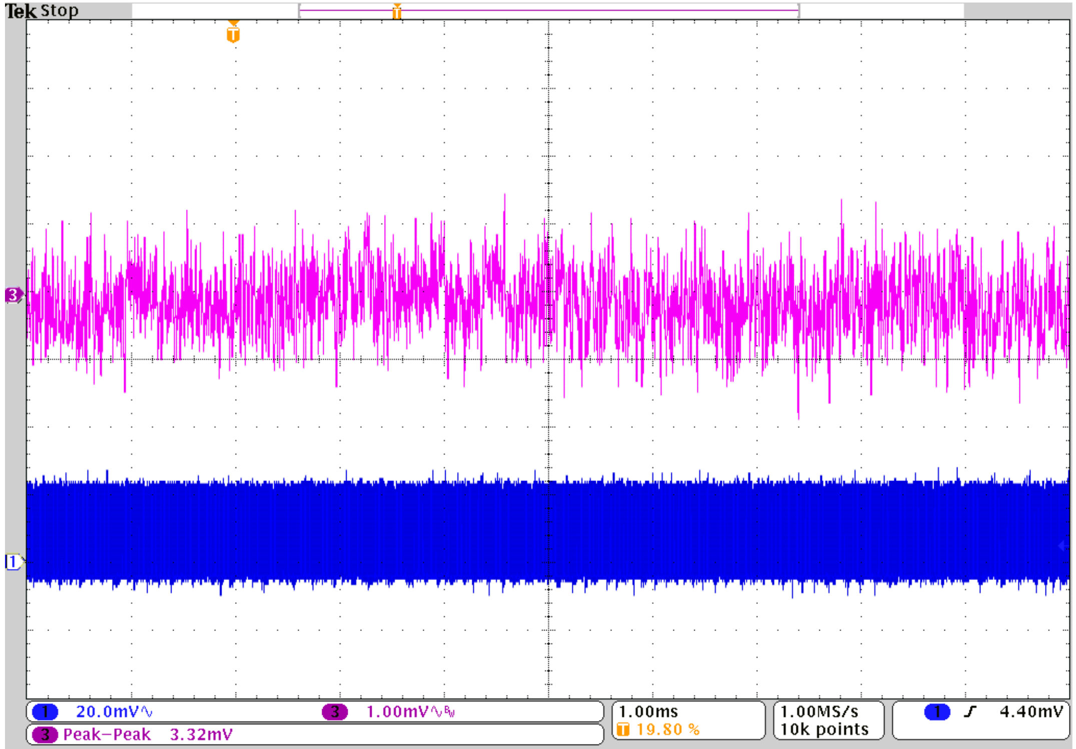
DC|DC buck converter testing w/ bPOL12V @3W

BPOL12V evaluation testing

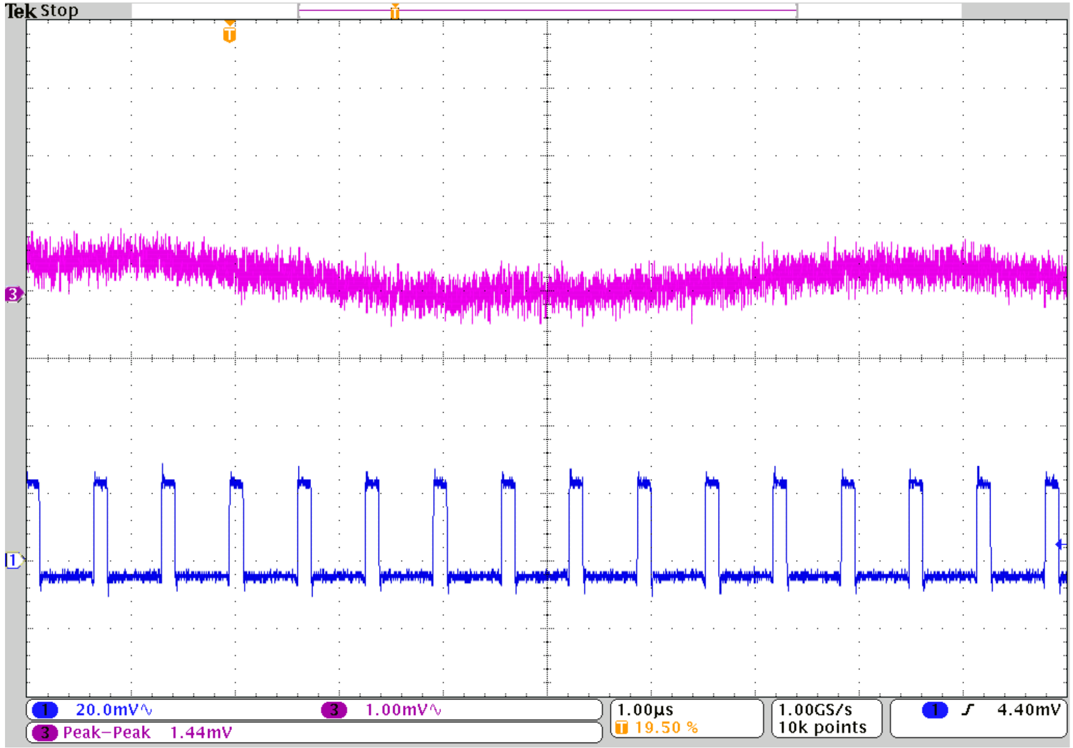
Modifications:
- 47uf decoupling on carrier PCB
- 460nH PN: 132-17L

bPOL12V
Basic data sheet features:
- V_{IN} 6V- 12V
- V_{OUT} 0.6V - 5V
- I_{OUT} 4A
- Chip Package 30.25mm^2
- (TJ)… 0°C to +120°C

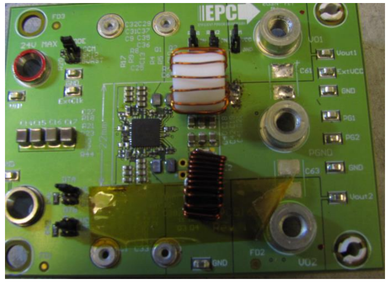
Test Results
- V_{IN} = 12V
- 1.2V_{out} with 2.5A load 3W
- ripple < 0.30%
- noise < 0.15% unusual to be < ripple!
- load regulation: <1.0%
- P_{EFF} 63% (>70% @ 2.25W)
- F_{SW} 1.5MHz
- T_{CHIP} 32°C, T_{IND} 75°C



bPOL12V 3W out ch3 ripple (20MHz Bw), ch EMI probe near inductor



bPOL12V 3W out ch3 noise (1GHz Bw), ch1 EMI probe near inductor



DC|DC buck converter testing w/ LTC 7890 @7W (Vo 2)

Modifications:

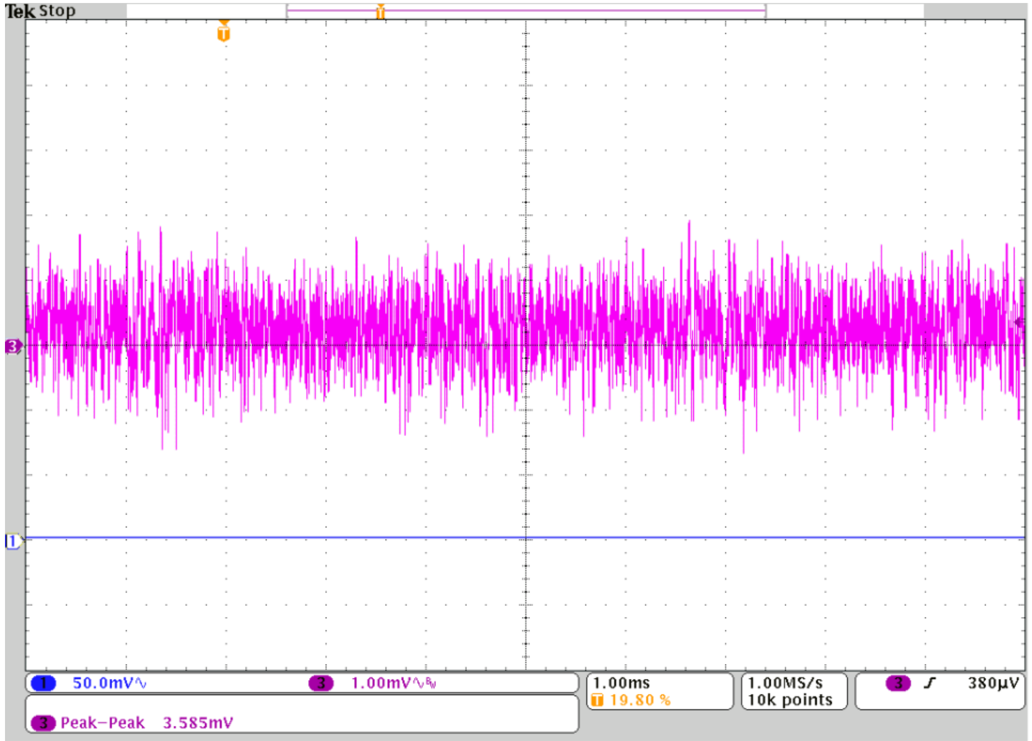
•CH1 Custom 220nH toroid
•CH2 330nH air-core inductor PN: SQA2929-501
•47uF ceramic output decoupling
•4.7Ω gate resistor (*reduce sw noise*)
•Continuous mode sw

Basic data sheet features:

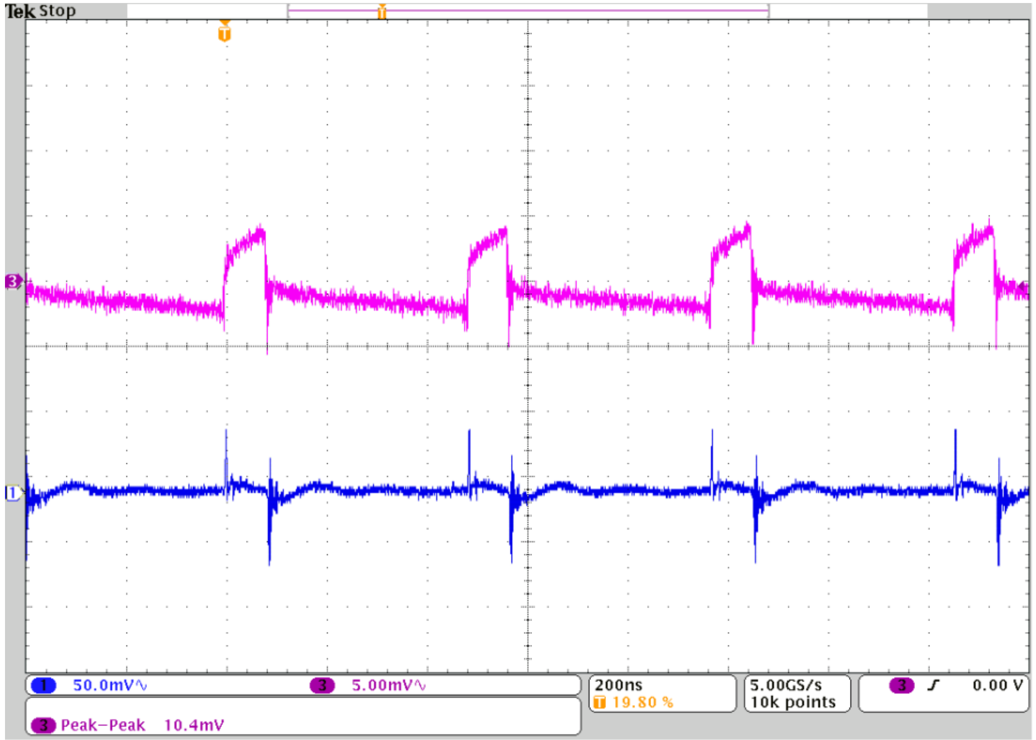
- V_{IN} 4V- 100V
- V_{OUT} 0.8V - 60V
- $I_{OUT\ /CH}$ 15A
- Package 6.0mm²
- 0°C to +70°C (Vref stable)
- TJ = −40°C to +150°C (TA = 25°C)
- Use w/ GaN FET

Test Results

- **V_{IN} = 12V**
- **1.2V_{out} with 6.0A load 7.2W**
- **ripple <0.30%**
- **noise <1.0%**
- **load regulation: <1.0%**
- **P_{EFF}: > 75.0%**
- **Fsw = 2.0MHz**
- **T_{7890} 43°C, T_{IND} 46°C, T_{FET} 42°C**

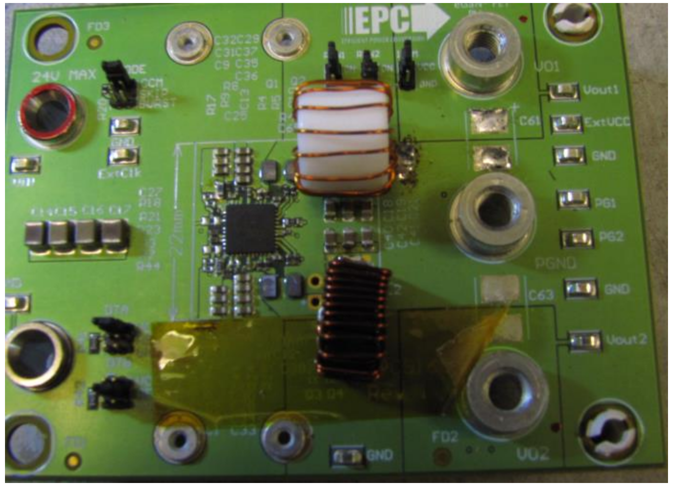


LTC 7890 7W $V_{OUT\ 2}$ ch3 ripple (20MHz Bw), ch1 EMI not connected

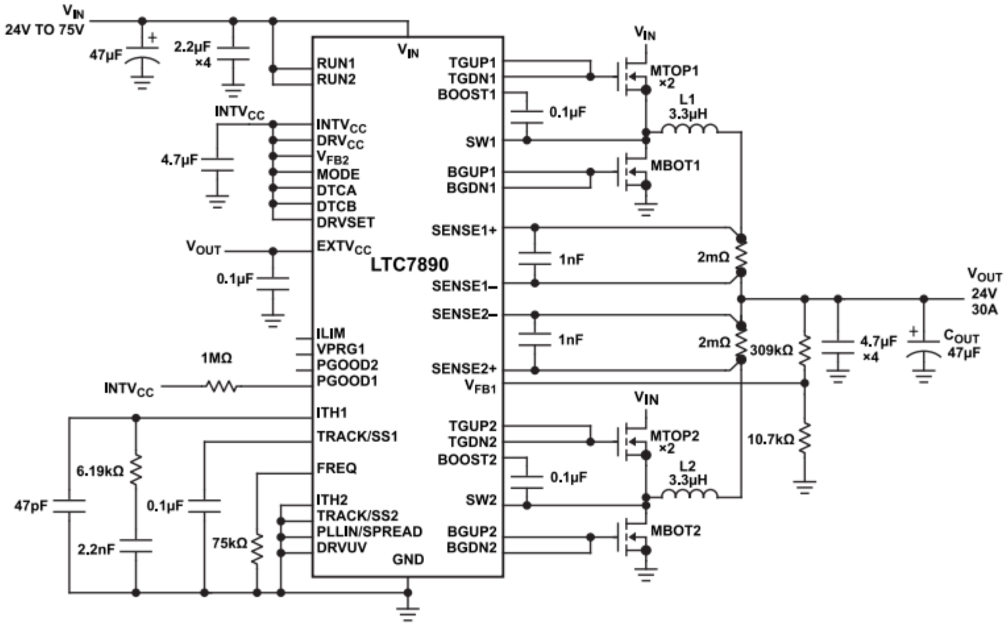


LTC7890 7W V_{out2} ch3 noise (1GHz Bw), ch1 EMI probe under PCB

NOTE: similar noise & ripple with custom toroid but w/ lower P_{EFF} of 60.0%



LT7890 MORE POWER!

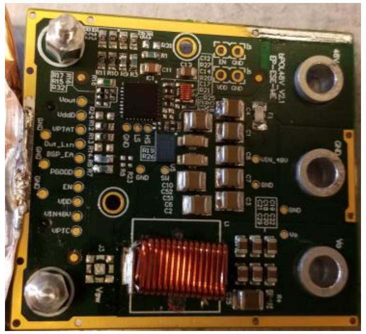


Running LT7890 with Vout1 + Vout2 in parallel, 30A!

As some detectors such as the TOF and dRICH will be quite power demanding from the LV system…a high power & efficient DC regulator is needed.

Vout 1 & Vout 2 of LT7890 can be run in parallel, which doubles the output current. Or we run them as separate channels and split the power between the ASICs.

DC|DC buck converter testing w/ bPOL48V @7W

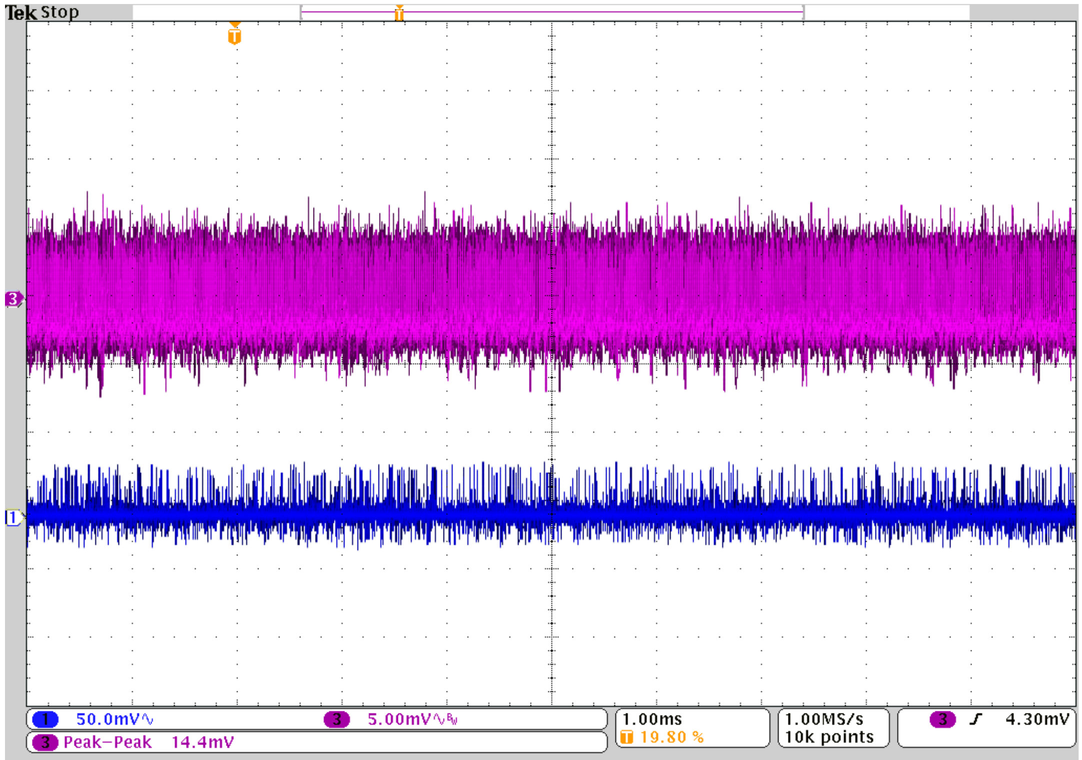


Modifications:
- 500nH air-core inductor PN: SQA2929-501

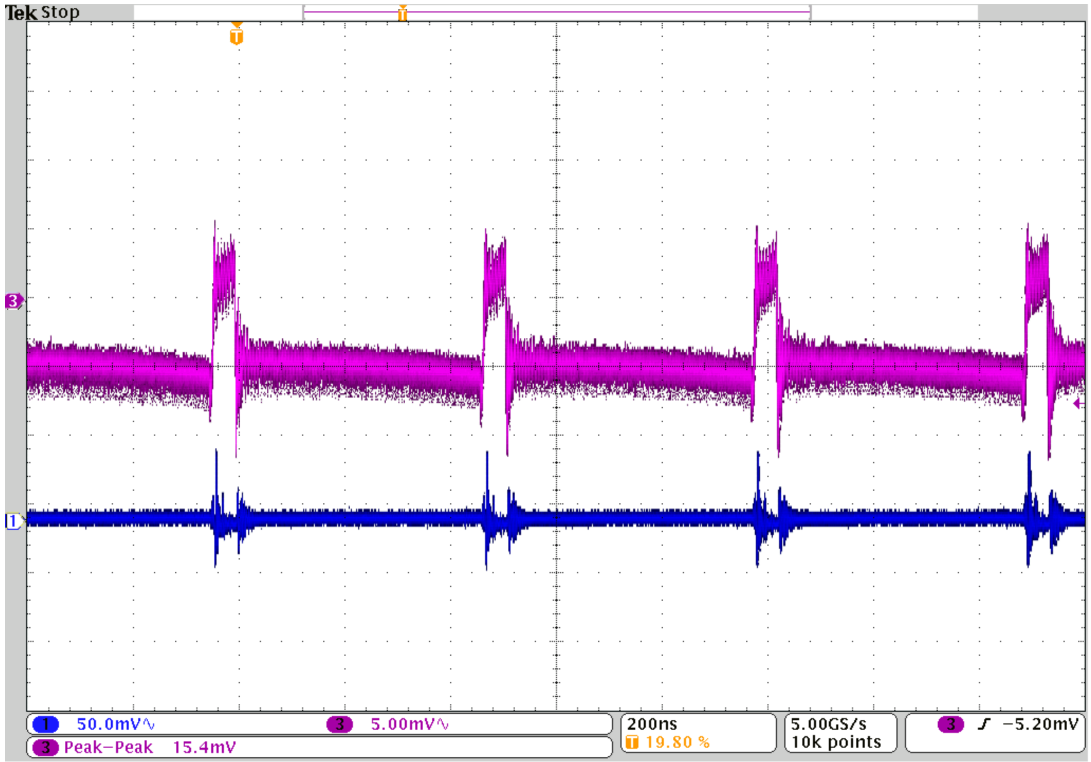
Basic Data sheet features

•V_{IN} 17V - 48V
•V_{OUT} 0.6V - 24V
•I_{OUT} 10A
•Chip Package 30.25mm^2
•TID 50Mrad
30MeV proton beam
4e14 n/cm2
2.23e14 p/cm2

Test Results
- V_{IN} = 24V
- Fsw = 2.0MHz
- ripple <1.3% (fig.7)
- noise <1.3% (fig.8)
- load regulation <1.0%
- P_{EFF}: > 64.0%
- T_{CHIP} 54°C, T_{FET} 56°C, T_{IND} 50°C



bPOL48V2.1 7W out, ch3 ripple (20MHz Bw), ch EMI probe near inductor



bPOL48V2.1 7W out, ch3 noise (1GHz Bw), ch1 EMI probe near inductor

DC|DC step-down converters under consideration, comparison table (data sheet specs)

Attribute	bPOL12V	LT3600	MPQ 8626	bPOL48V	LTC7890	Comments
V_{IN}	6V – 11V	4 V - 15 V	4V – 16V	17V – 48V	4V – 100V	Typica supply options (5V, 12V, 24V,48V)
V_{OUT}	0.6 – 5V	0 - VIN-0.34	0.6V – 6.0V	0.6V – 24V	0.8V – 60V	
I_{OUT}	4A	1.5 A	6A	10A	15A	
Power output	10W	5W	25W	120W	100W/ ch	
Load Regulation	0.5%	0.5%	0.5%	<1.0%	0.5%	
Chip package size	$30.25_{mm}{}^2$	$9.0_{mm}{}^2$	$6.0_{mm}{}^2$	$30.25_{mm}{}^2$	$42.25_{mm}{}^2$	
Typical circuit real estate	$450.0_{mm}{}^2$	$210_{mm}{}^2$	$400_{mm}{}^2$	$1,600_{mm}{}^2$	$1,225_{mm}{}^2$	L x W, Circuit height above PCB should be ~10.0mm, mostly dependent on inductor & shield height.
Power density Based on circuit size	22.0_{mW}/ mm^2	24_{mW}/mm^2	60_{mW}/mm^2	75.0_{mW} / mm^2	100_{mW}/ mm^2	
Output channels	1x	1x	1x	1x	2x	
$P_{EFFICIENCY}$	>70%	85%	>80%	>80%	>80%	
~no. of support components	25	16	26	30	40 (2 channel)	Vendor application/ eval circuits
Switching device	Internal	internal	internal	External GaN	External GaN	COTS GaN FET is rad tolerant
TID rad hardness	150_{MRAD}	TBD	[1]TBD	50_{MRAD}	[1]TBD	(1) GaN switching FET is rad tolerant…but rad tolerance of LTC7890 will need to be evaluated.
magnetic tolerance	4.0_{TESLA}	[2] $>2.0_{TESLA}$	[2] $>2.0_{TESLA}$	40K Gauss	[2] $>2.0_{TESLA}$	(2) In practice, the high Tesla field will have negligible effect on air-core inductors. CERN mag field data comes from actual test
Input controls	Enable/SD	Enable/SD	Enable/SD	Enable/ SD	Enable/ SD	
Output monitoring	P_{GOOD}, $T_{°C}$	P_{GOOD}	P_{GOOD}	P_{GOOD}, $T_{°C}$, $UV_{LOLCKOUT}$	P_{GOOD}	
F_{SW}	$1.0 – 3_{MHz}$	$0.2 – 4.0_{MHz}$	$0.6 – 2.0_{MHz}$	$0.5 – 3_{MHz}$	$0.1 – 3_{MHz}$	Configurable
Cost	$15.00/ piece	$4.39/ 1k	$2.10/ 1k	$30.00/ piece	$7.32 / 10	

DC|DC step-down converters under consideration, comparison table (Test data)

Attribute	bPOL12V	LT3600	MPQ8626	MPQ8626	bPOL48V	[1]LTC7890	Comments
V_{IN}	10V	15V	12V	12V	24V	12V	
V_{OUT}	1.5V	1.8V	1.2V	1.2V	3.3V	1.2V $_{/CH}$	
I_{OUT}	1.9A	1.0A	2.5A	6.0A	4.7A	6.0A $_{/CH}$	(1) each channel
P_{OUT}	2.85W	1.85W	3W	7.2W	15.5W	7.2W $_{/CH}$	
Load Regulation	<0.5%	1.0% (0 to 1.5A)	<1.0%	<1.5%	<1.0%	<1.0%	
circuit real estate	450.0$_{mm}{}^2$	290mm^2	400mm^2	400mm^2	1,600$_{mm}{}^2$	1,225$_{mm}{}^2$	
Power density FROM AIR-CORE IND TESTING	5.0$_{mW}$/ mm^2	6.2$_{mW}$ /mm^2	7.5$_{mW}$ /mm^2	18$_{mW}$ /mm^2	10$_{mW}$ / mm^2	12$_{mw}$ /mm^2	
$P_{EFFICIENCY}$	>70%	76%	>80.0%	>80.0%	>80%	>75%	
T° c $_{PCB}$	34	No data	32	43	50	44	
noise, ripple	<0.40%, <0.40%	[2]ND/ <2.3% (40.0mvp-p)	<0.35%, 0.11%	<0.40%, <0.2%	<0.40%, <0.4%	<1.0%, <0.35%	(2) G.V. ripple on LTC3600 eval board is certainly suboptimal / improvable
F_{SW}	1.5$_{MHZ}$	2.3$_{MHz}$	2.0$_{MHz}$	2.0$_{MHZ}$	2.0$_{MHZ}$	2.0$_{MHZ}$	

- **Best evaluation will be in actual use w/ prototype electronics**
- Some specs should be derived directly from the ASIC & Sensor technology that is being used
  - General power requirements
  - Space constraints
  - Cooling limitations
  - Load regulation
  - Cable drive length (from distribution board to FEB)
  - Consider feed cable size from electronics platform
  - ASIC ripple and noise specifications (SNR?)

Things to do!

- Build prototype DC|DC power boards
- PCB & regulator circuit footprint constraints (power density size)
- Further mitigate switching/ EMI noise
- Cooling considerations

Related links & information

Wei Li (Rice University) ETOF electronics
https://indico.bnl.gov/event/17336/contributions/68692/attachments/43571/73398/EIC_TOFPIDWG_ETOFLayoutv3_09192022.pdf

Tonko Ljubicic (Rice University) ETOF powering scheme for ASIC + FEB + RDO
https://indico.cern.ch/event/1242308/attachments/2747264/4780641/20231109%20Seminar%20EP-ESE.pdf

S. Michelis, G. Ripamonti F. Faccio, P. Antoszczuk, M. Besirli, A. Cristiano (bPOL12V history) CERN
https://indico.cern.ch/event/1242308/attachments/2747264/4780641/20231109%20Seminar%20EP-ESE.pdf

List of RAD tested devices: List curtesy of Tullio Grassi, University of Maryland
https://twiki.cern.ch/twiki/pub/Main/EpicSH/Rad_list.pdf

FEAST 10W DC Buck converter, CERN
https://espace.cern.ch/project-DCDC-new/Shared%20Documents/FEAST%20datasheet.pdf

LT7890 DC buck converter, Linear Tech.
https://www.analog.com/media/en/technical-documentation/data-sheets/ltc7890.pdf

MPQ8626 DC buck converter, MPS
https://www.monolithicpower.com/en/documentview/productdocument/index/version/2/document_type/Datasheet/lang/en/sku/MPQ8626GD-Z/document_id/4379/

ePIC Detector power requirements & RDO cooling, BNL
https://brookhavenlab-my.sharepoint.com/:p:/g/personal/dcacace_bnl_gov/ERoe2RD1aL5HhZbBoMdVI6wBhI2t5LXgRf0Jz2nVieYrDw?CID=29C363F8-4098-45A5-8258-5C08D4DF6E60&wdLOR=c27CA0BC5-C97C-4D89-81E5-5A351197CAFE