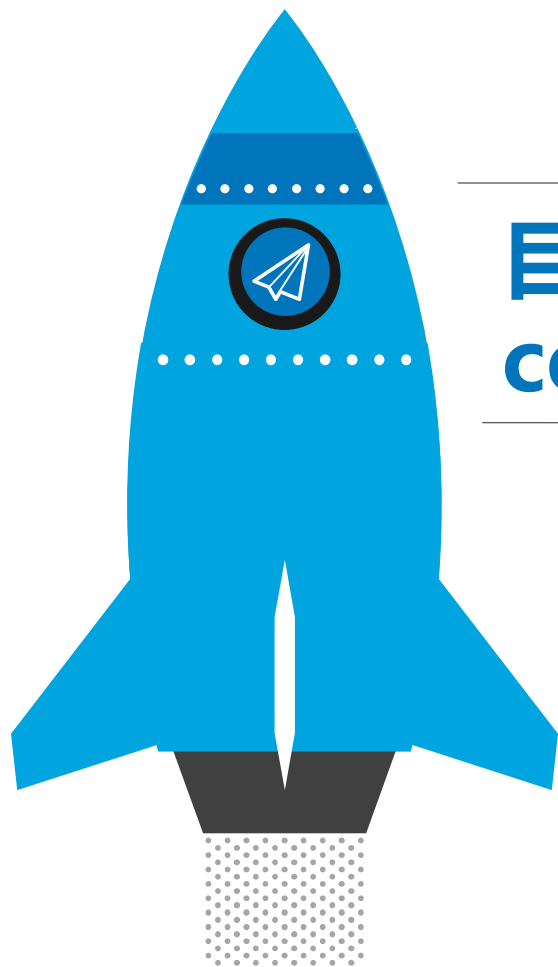


基于GaN的抗辐射低噪声DC/DC BUCK型电压转换器研究

王夏雨 阳卫名 贾渊升 王佳

西北工业大学

jwang@nwpu.edu.cn



目录

content

一、探测器供电系统

二、STCF电源需求

三、抗辐射DC/DC芯片设计

四、总结



ATLAS barrel detector (Power cable: Red)



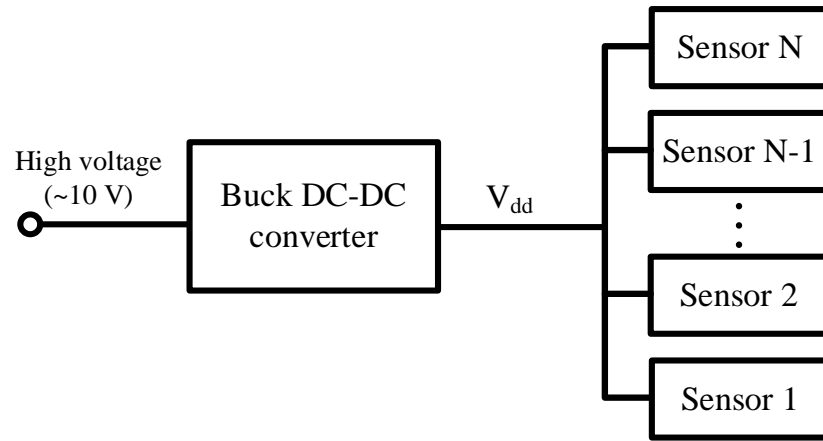
独立供电的缺点

- 电源效率低
- 电源/地线上压降大
- 物质量大
- 线缆安装空间大
- ...

Figure 9.19: Cable tray showing low voltage cables and distribution boxes on CalFrame.

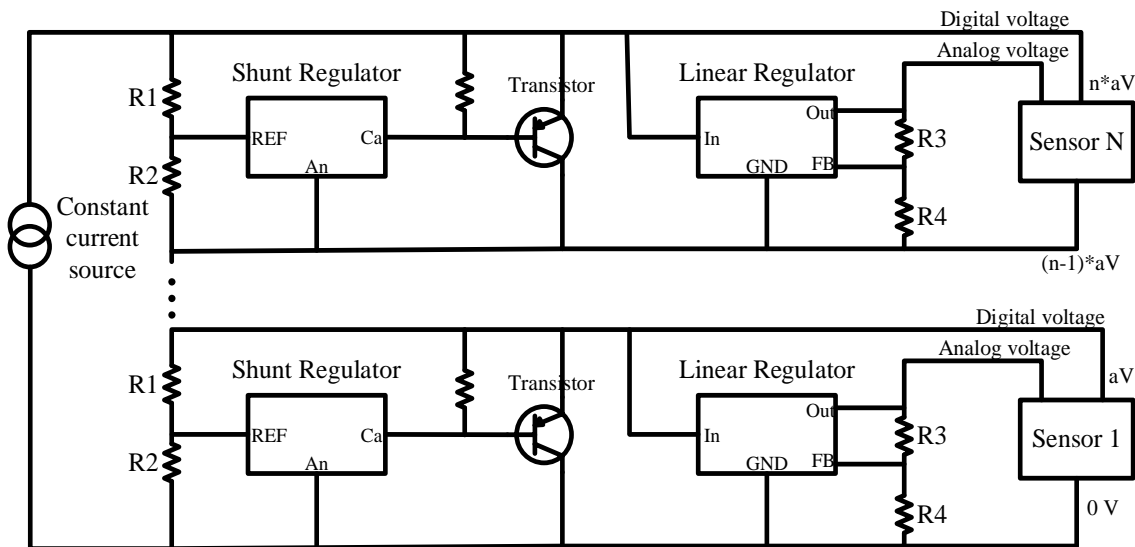
并联供电 VS 串联供电

- Parallel powering with DC-DC converter VS Serial powering



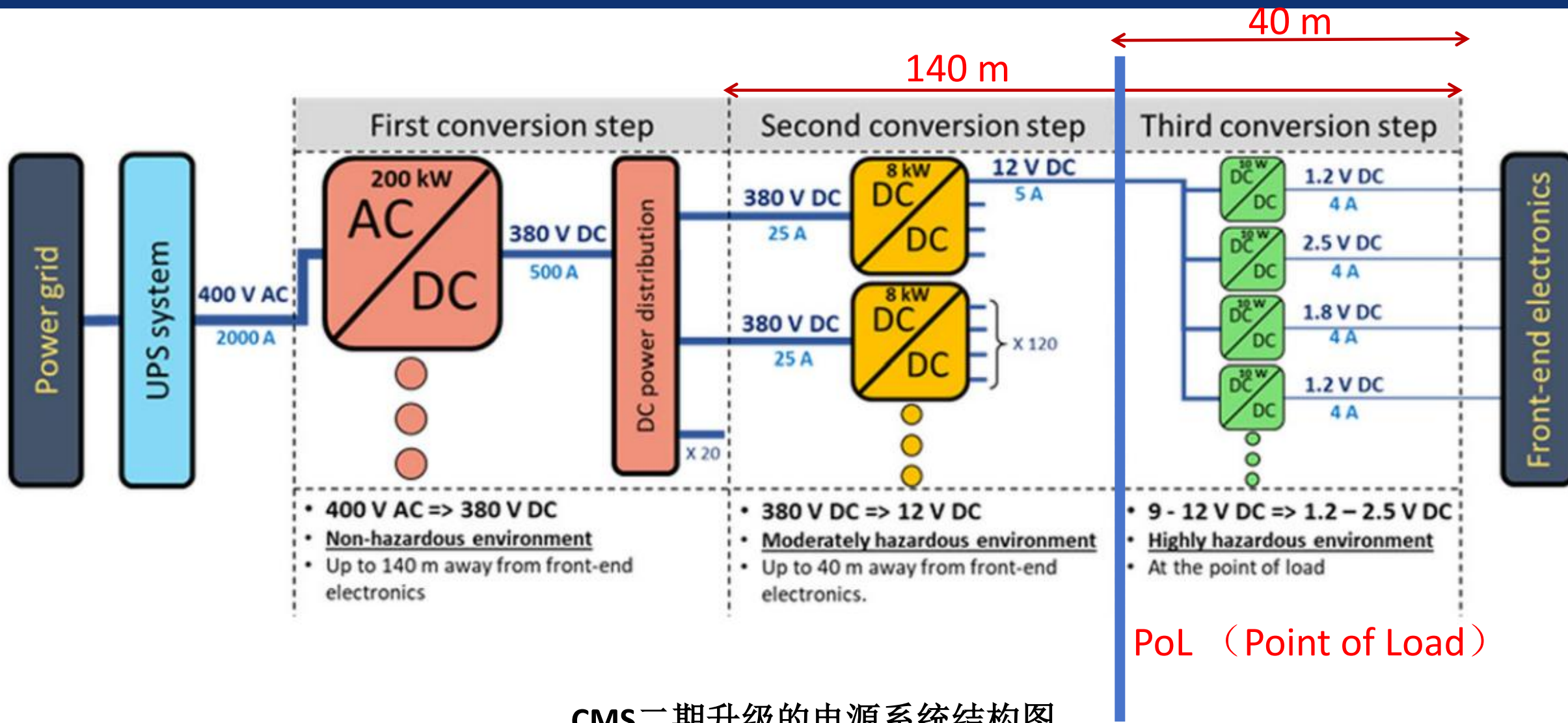
Parallel powering

- ✓ Compatible with the conventional power system
- ✓ Few changes of readout circuit or sensor required
- ✓ High reliability
- ✓ Unnecessary on-chip regulator -> less die area
- ✗ Noisy ripple voltage
- ✗ Large-area air-core inductor
- ✗ EMI



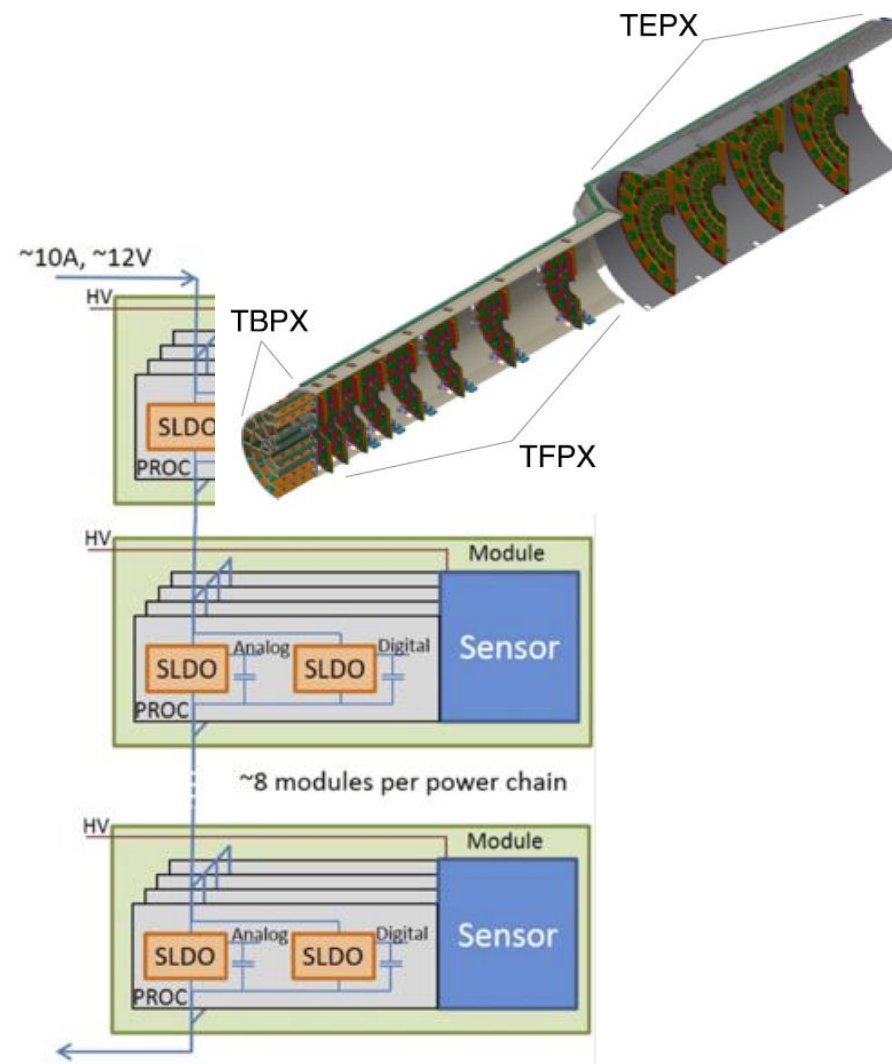
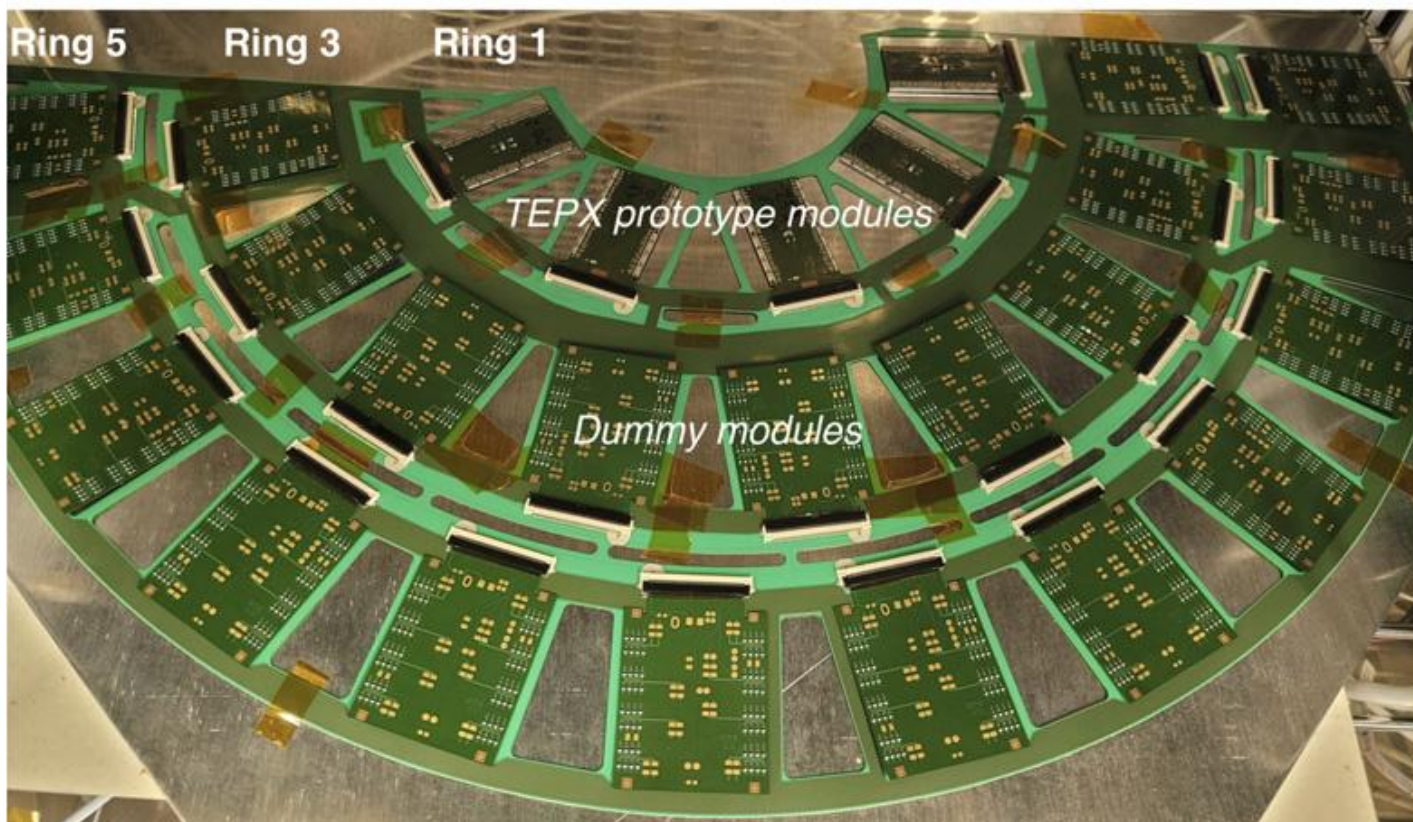
Serial powering

- ✓ Less cable mass
- ✓ Higher power efficiency, more suitable for large current load
- ✓ Low noise
- ✓ Unrequired Magnetic components
- ✗ Many changes with the old power system
- ✗ Lower reliability
- ✗ Different ground potential -> AC-coupled output, not suitable for stitching chips, very high bias voltage of sensors
- ✗ "Larger" threshold current required to switch on shunt regulator
- ✗ Consistency of shunt regulator and LDO



CMS二期升级的电源系统结构图

Tracker Endcap Pixel (TEPX) 的串联供电



STCF探测器电源需求



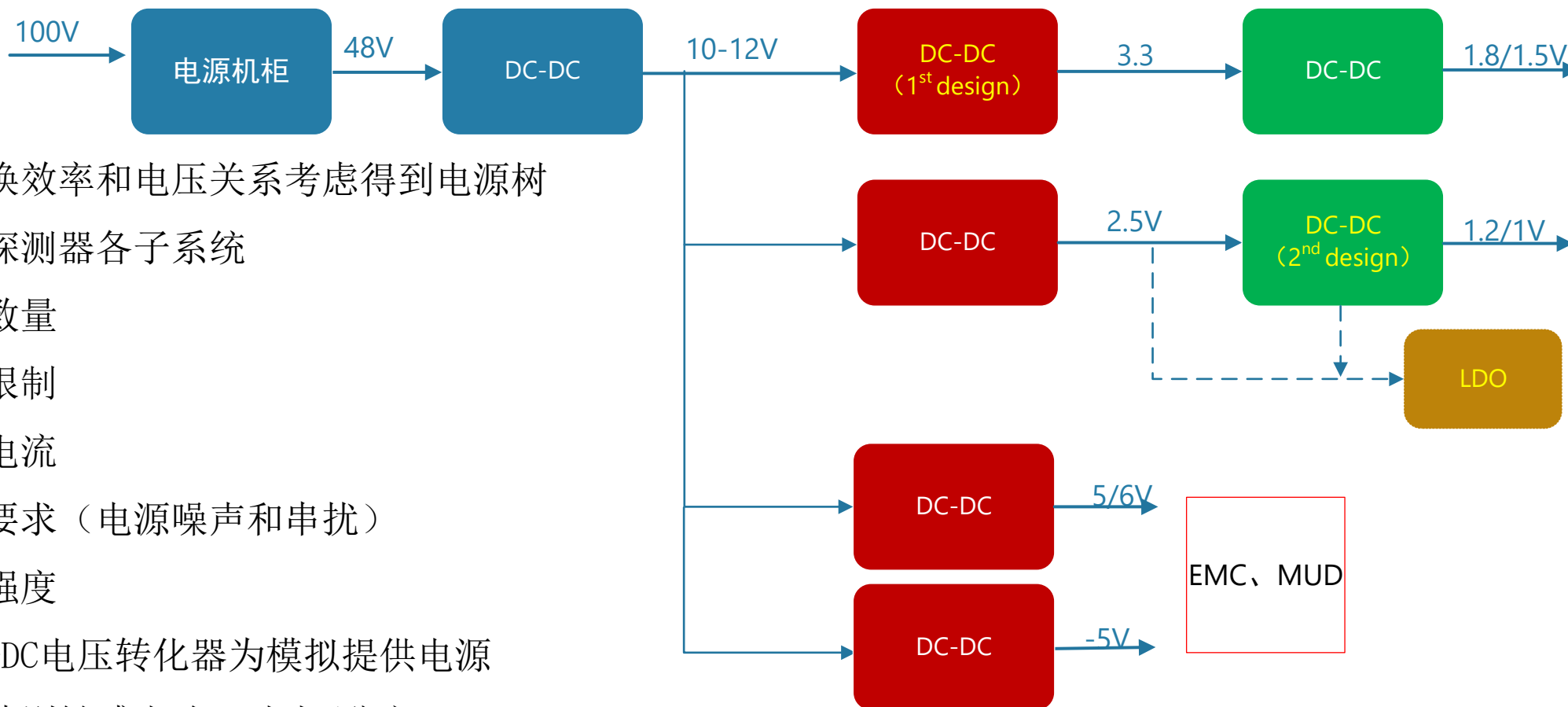
供电电压	子系统	单板电流组成	单板总电流
1.0 V (数字)	EMC	10	10 A
	MDC	4	4 A
	MUD	2 + 4	6 A
1.2 V (数字)	MAPS内/外层FEE	1.02 * 3	3.06 A
	MAPS中层FEE	1.02 * 4	4.08 A
	μRWELL	2.94 + 1.02 * 6	9.06 A
	D-TOF	1.5 * 18	27 A
	MUD	2.4 + 4	6.4 A
	MAPS FEE	2.94	2.94 A
	μRWELL	2.94	2.94 A
	RICH	2.94	2.94 A
1.8 V (数字)	RICH	0.68 * 57	38.76 A
	MDC	1.12	1.12 A
	MUD	0.6 + 1	1.6 A
2.5 V (数字)	μRWELL	0.26 + 0.07 * 6	0.68
	EMC	8	8 A
	MDC	0.16 * 4 + 0.8	1.44 A
	MUD	0.2	0.2 A
3.3 V (数字)	MAPS内层Stave	0.01 * 10	0.1 A
	MAPS中层Stave	0.01 * 27	0.27 A
	MAPS外层Stave	0.01 * 88	0.88 A
	MAPS内/外层FEE	0.08 * 3	0.24 A
	MAPS中层FEE	0.08 * 4	0.32 A
	MAPS FEE	0.1	0.1 A
	μRWELL	0.1	0.1 A
	RICH	0.12 * 57 + 0.08	6.92 A
	D-TOF	0.3 * 18*2	10.8 A
	EMC	8	8 A
	MDC	0.62 + 0.08	0.7 A
	MUD	0.2 + 1.2	1.4 A

数字：DC-DC转换器、模拟：LDO

供电电压	子系统	单板电流组成	单板总电流
1.2 V (模拟)	μRWELL	2.18	2.18 A
	D-TOF	0.4 * 18	7.2 A
	MDC	0.68 * 4	2.72 A
1.5 V (模拟)	D-TOF	0.32 * 18	5.76 A
1.8 V (模拟)	MAPS内层Stave	0.46 * 10	4.6 A
	MAPS中层Stave	0.46 * 27	12 A
	MAPS外层Stave	0.46 * 88	39.2 A
	RICH	0.68 * 57	38.76 A
2.5 V (模拟)	MUD	0.008 * 16	0.128 A
± 5 V (模拟)	EMC	1	1 A
6 V (模拟)	MUD	0.02 * 16	0.32 A

优先设计：1.2/1.5/1.8V (LDO)
1/1.2/1.8/3.3V (DC-DC电压转换器)

探测器电源系统结构（总体）



- 从电源转换效率和电压关系考虑得到电源树
- 仍需考虑探测器各子系统
 - 布线数量
 - 空间限制
 - 负载电流
 - 噪声要求（电源噪声和串扰）
 - 辐射强度
- 直接用DC-DC电压转化器为模拟提供电源
 - 噪声特别敏感电路：片上/分立LDO

短期

- 12/3.3V, 3.3/1.2 DC/DC
- 片上LDO MAPS (TowerJZ)

远期

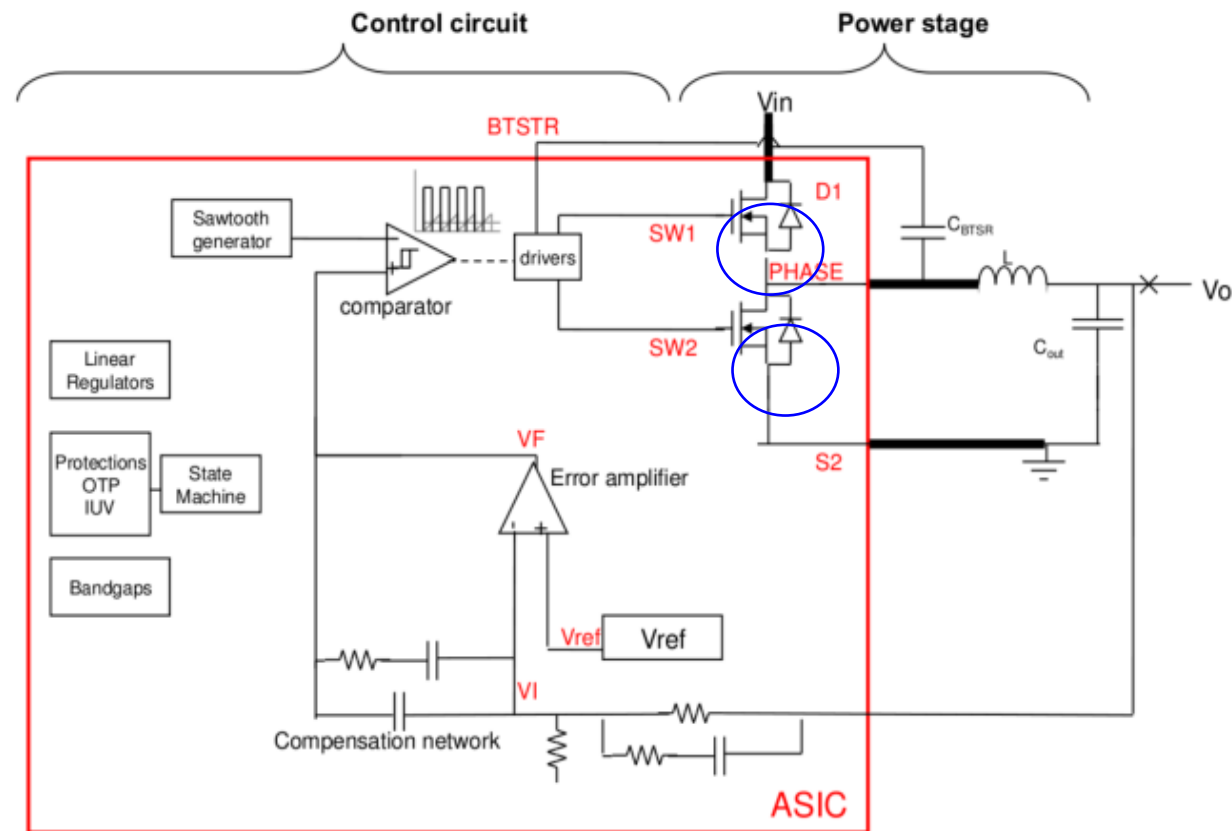
- 补齐DC/DC
- 片外LDO（模拟）1.2、1.5、1.8

抗辐射DC/DC芯片



❖ 设计指标

Parameter	Value
Input voltage	12-10 V
Output voltage	1.8/1.2 V (adjustable)
Output current	<10 A
Output ripple voltage	<10 mV
power efficiency	>80%
Power module size	<30x20x6.7mm ³
TID	0.6 Mrad/year
Magnetic field	3T
Switching frequency	1-3 MHz



基于GaN功率管设计

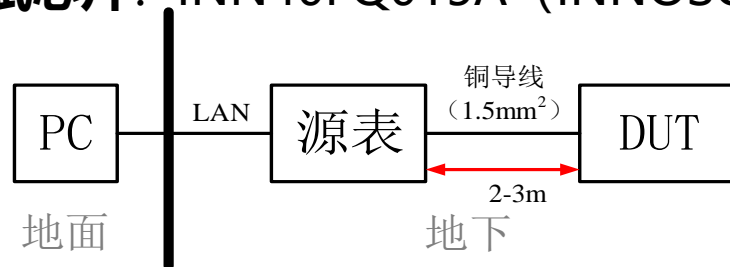
- 高开关速度
- 低功率损耗
- 强抗辐射能力
- 低导通电阻

更适合大输出电流应用!

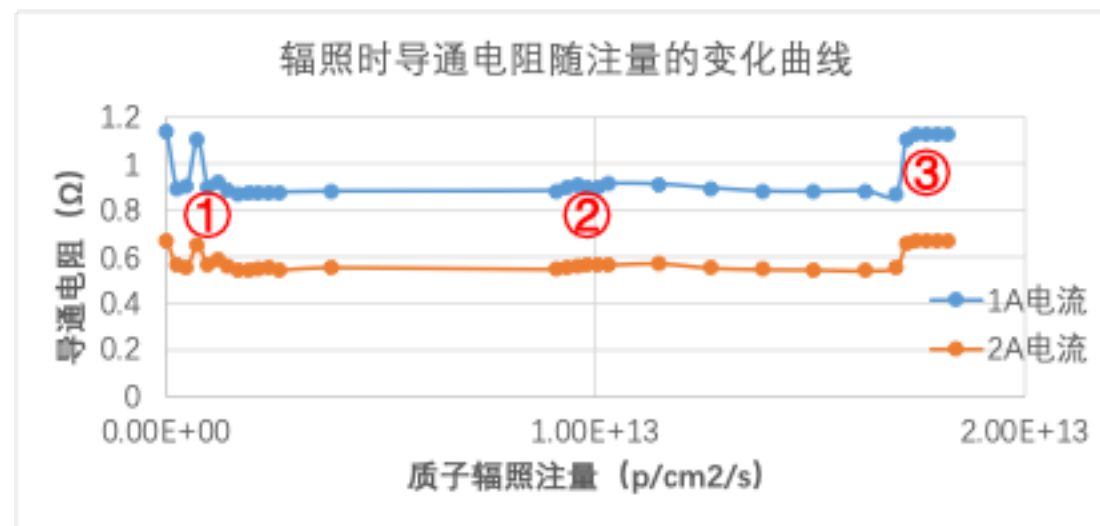
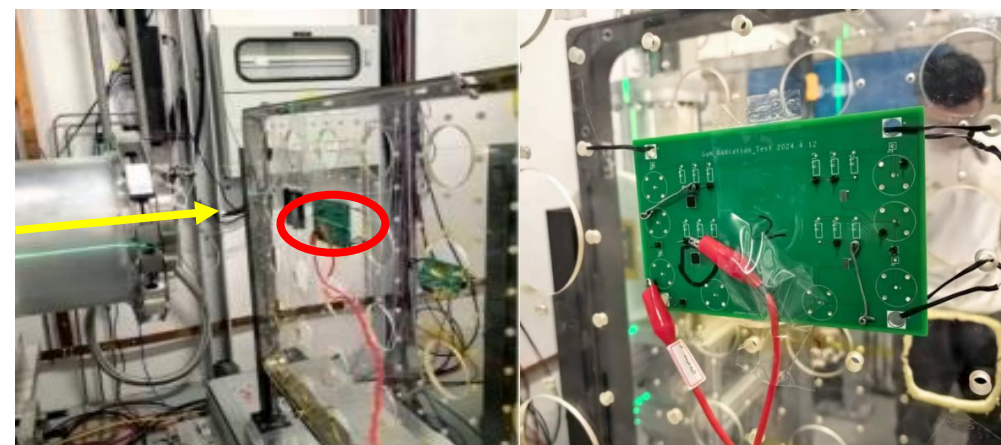
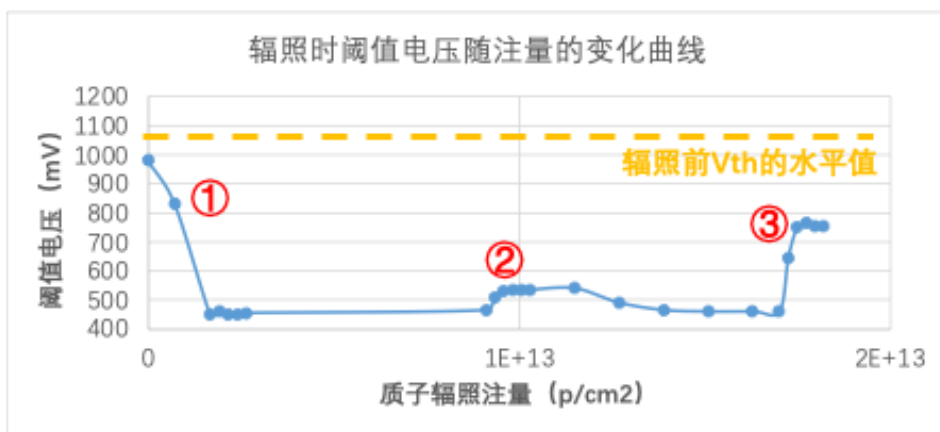
❖ 在CSNS开展GaN功率管的辐照测试

❖ 用于DC-DC的开关管

测试芯片: INN40FQ015A (INNOSCIENCE)

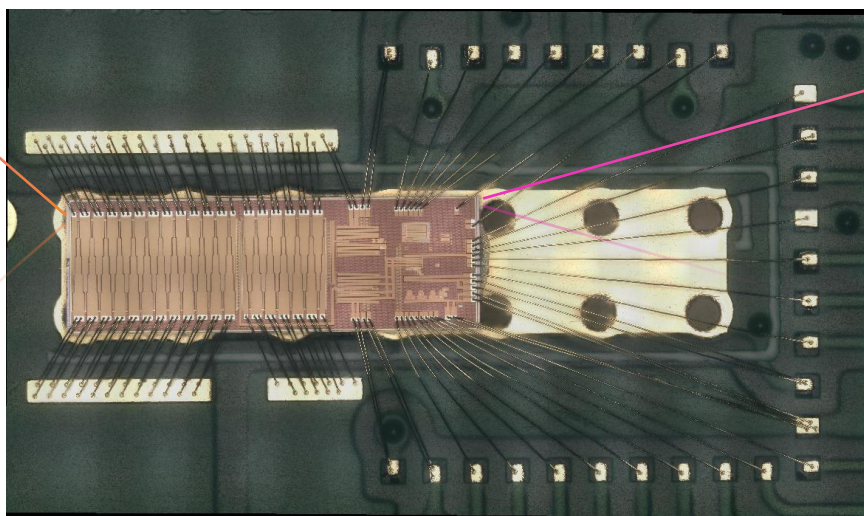
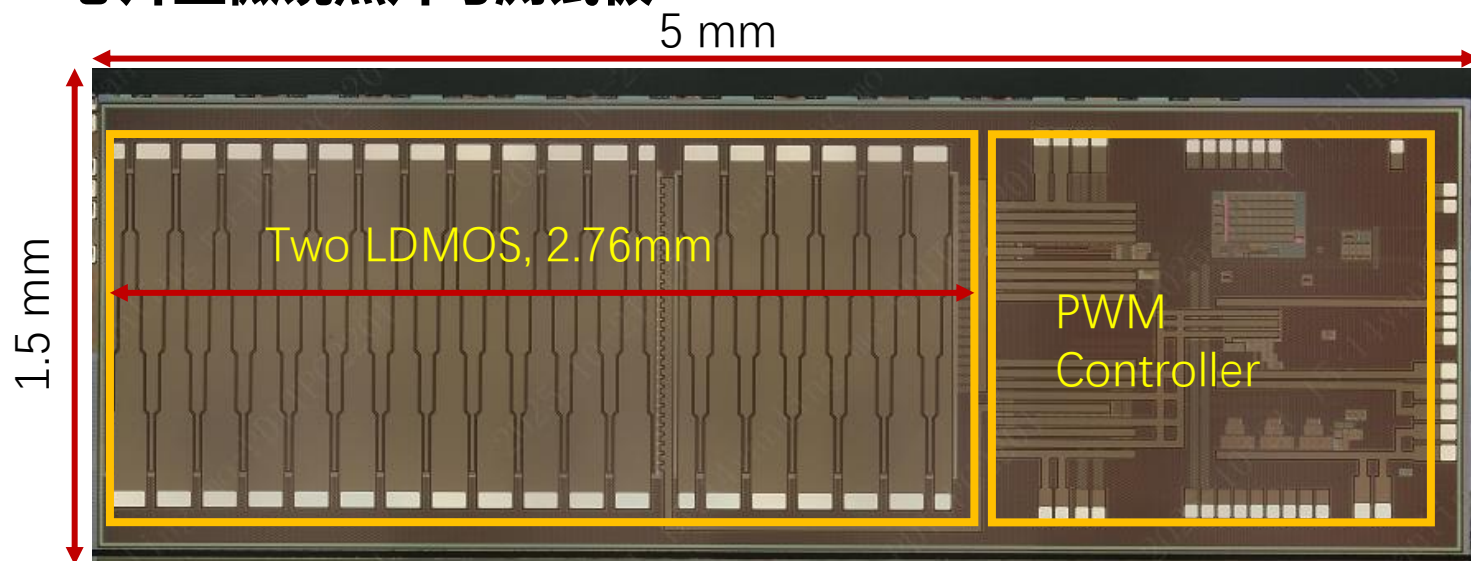


在线辐照测试实验装置示意图

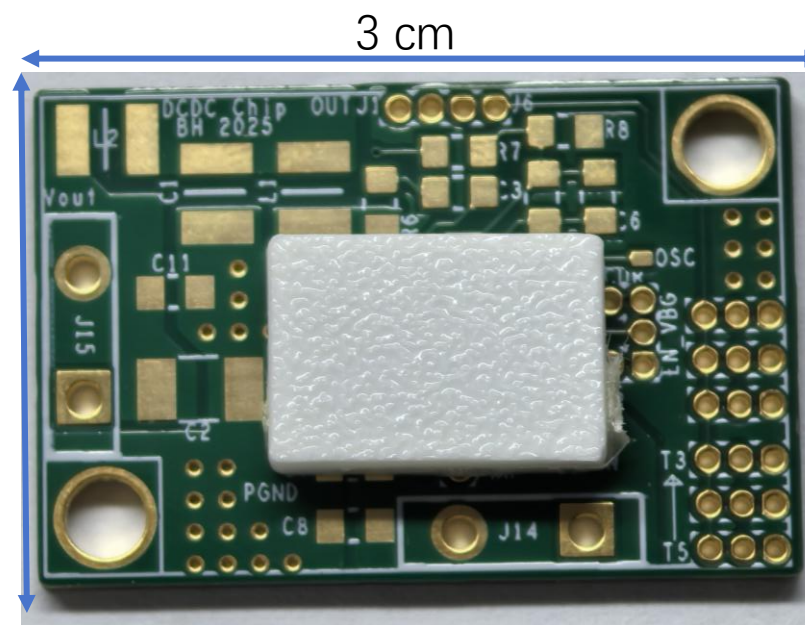


该国产GaN功率管可以耐 1.7×10^{13} 注量@80MeV

❖ 芯片显微镜照片与测试板

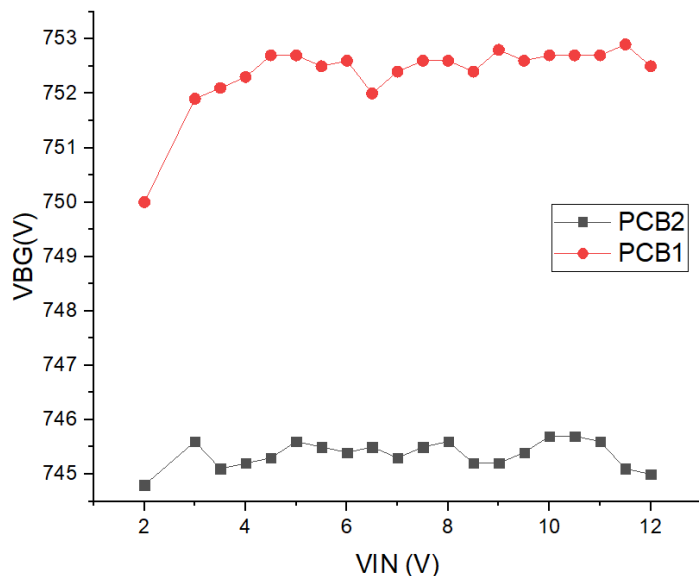


- 180nm 高中低压混合BCD国产商用工艺
- 增大焊盘尺寸 → 提高电流能力
- 2025.4投片

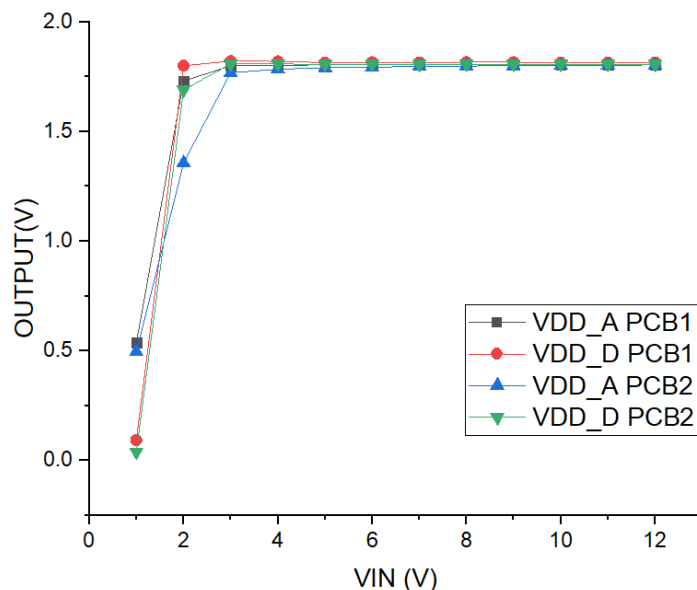


测试板照片

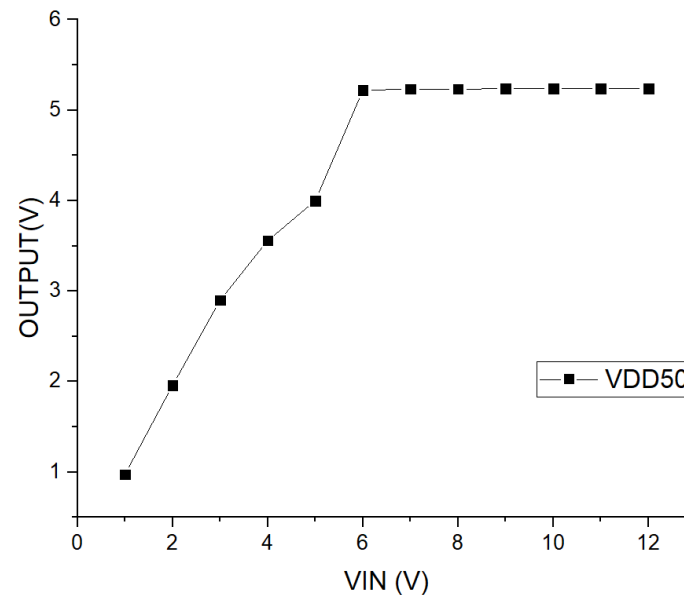
关键模块测试结果 (电压基准源和内部LDO)



基准电压源测试(750mV)



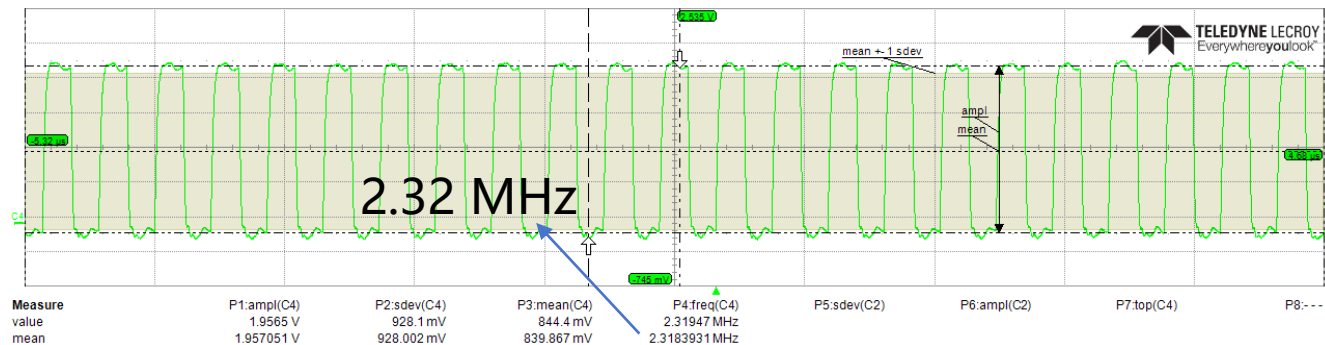
内部数字/模拟电路供电LDO测试(1.8V)



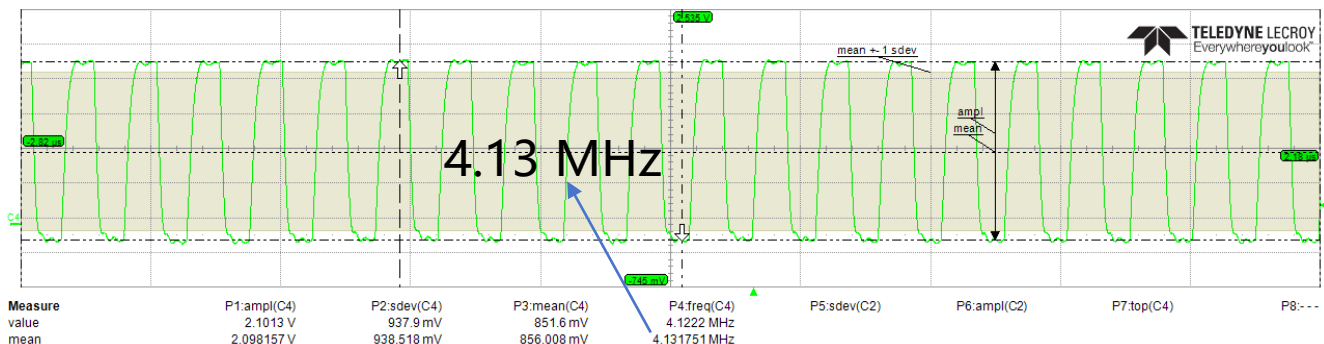
驱动电路供电LDO测试(5V)

- 基准电压源和内部LDO均正常工作，能够输出稳定电压。
- 由于工艺偏差影响，基准电压源在不同芯片间存在差异，但是可以通过寄存器微调满足要求。

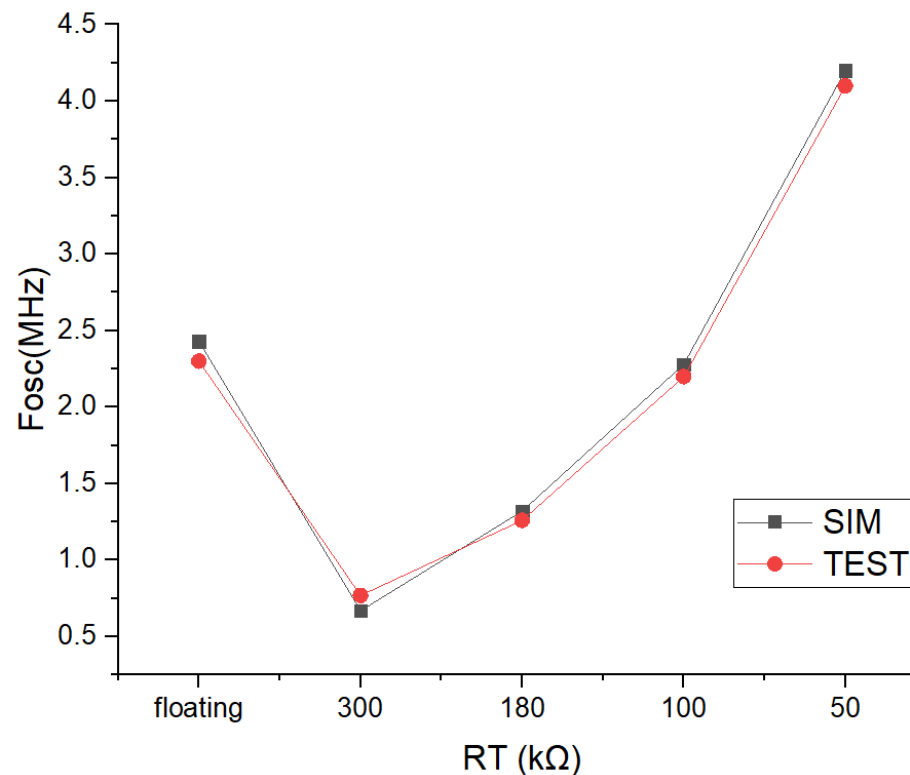
关键模块测试结果 (振荡器)



频率调节端RT悬空，内部产生固定振荡频率



可通过RT端电阻调节振荡频率@ RT=50kΩ



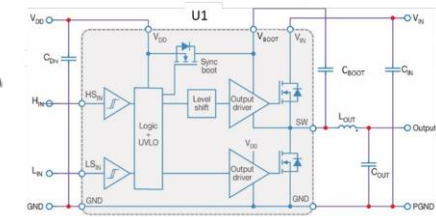
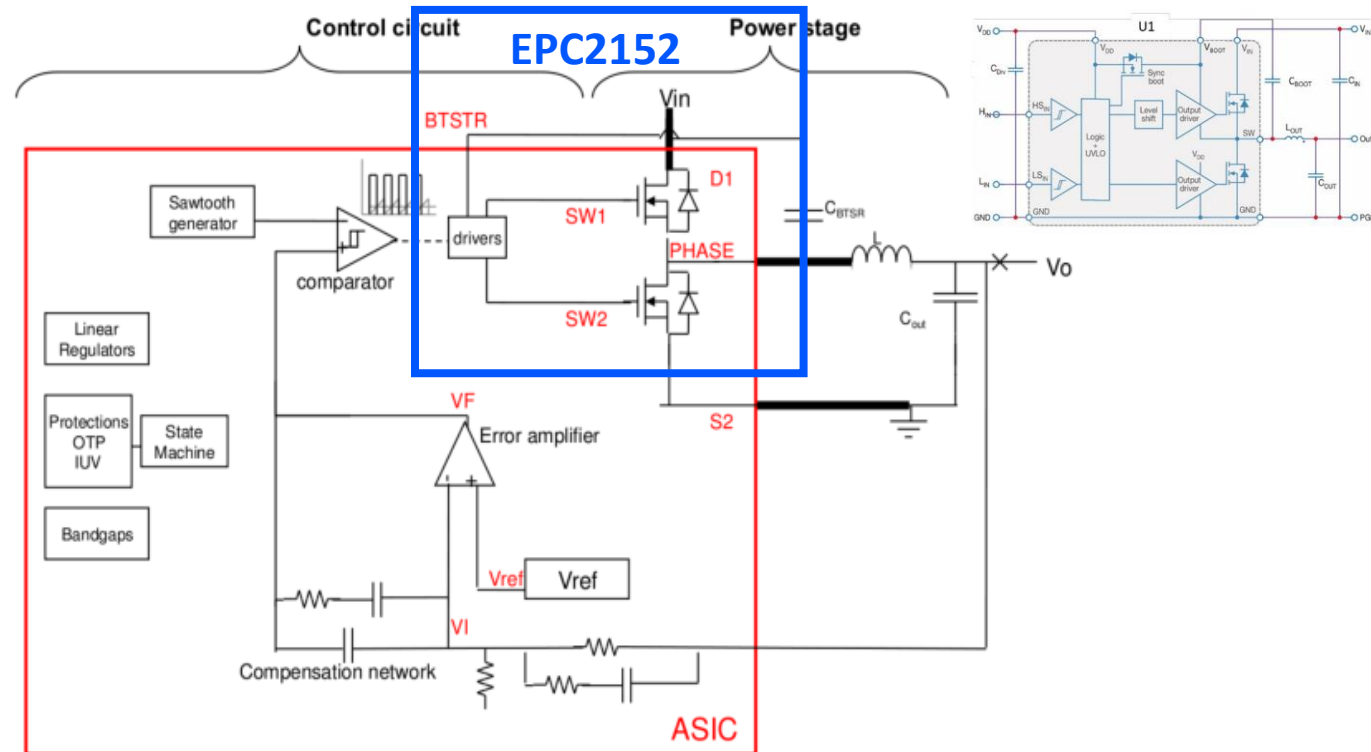
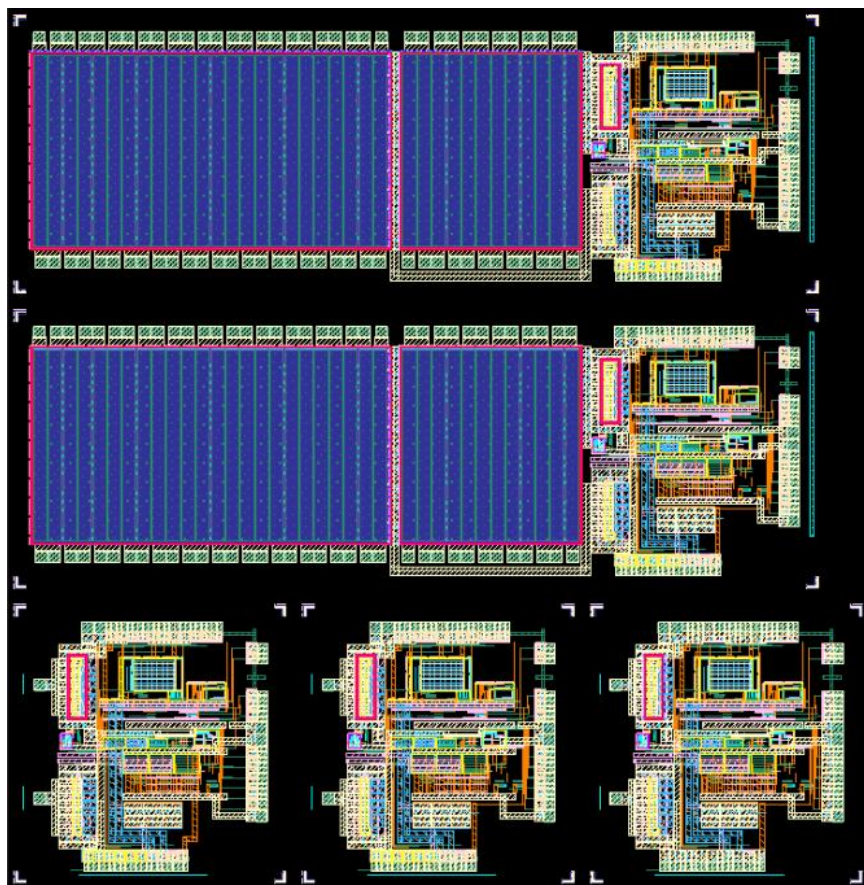
振荡频率 VS RT 测试结果

振荡频率可调且与设计结果一致。

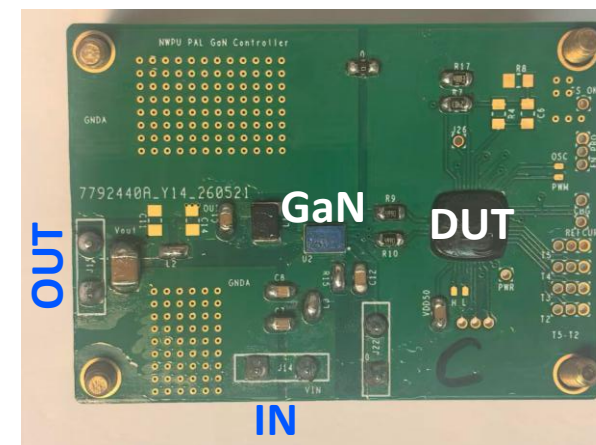
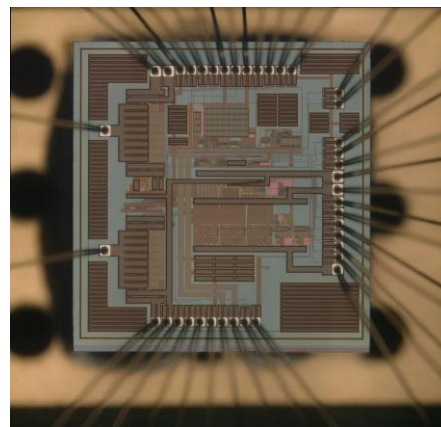
抗辐射DC/DC芯片



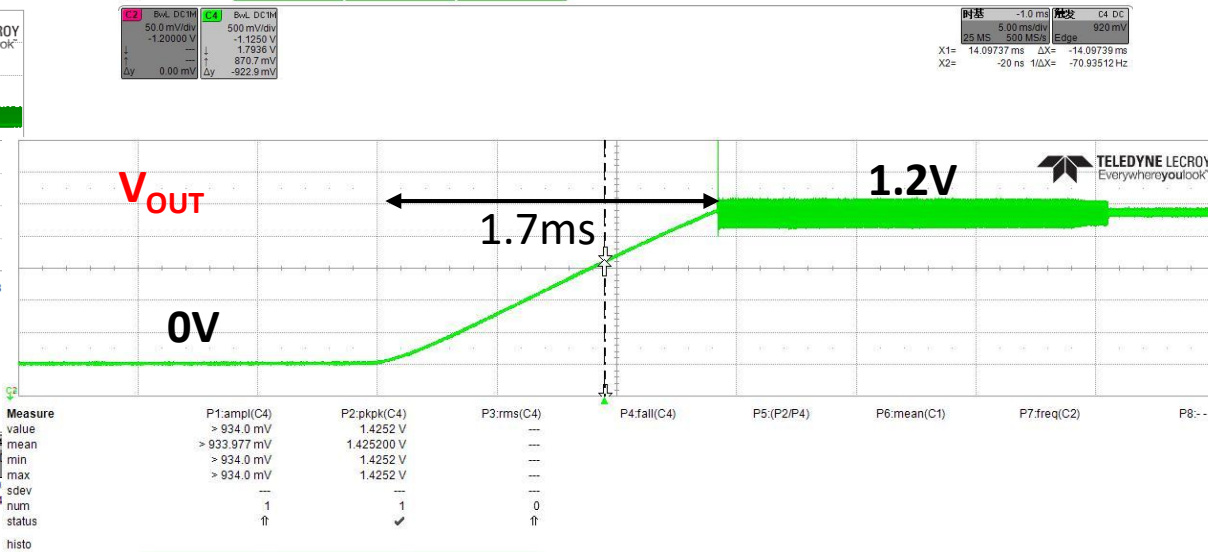
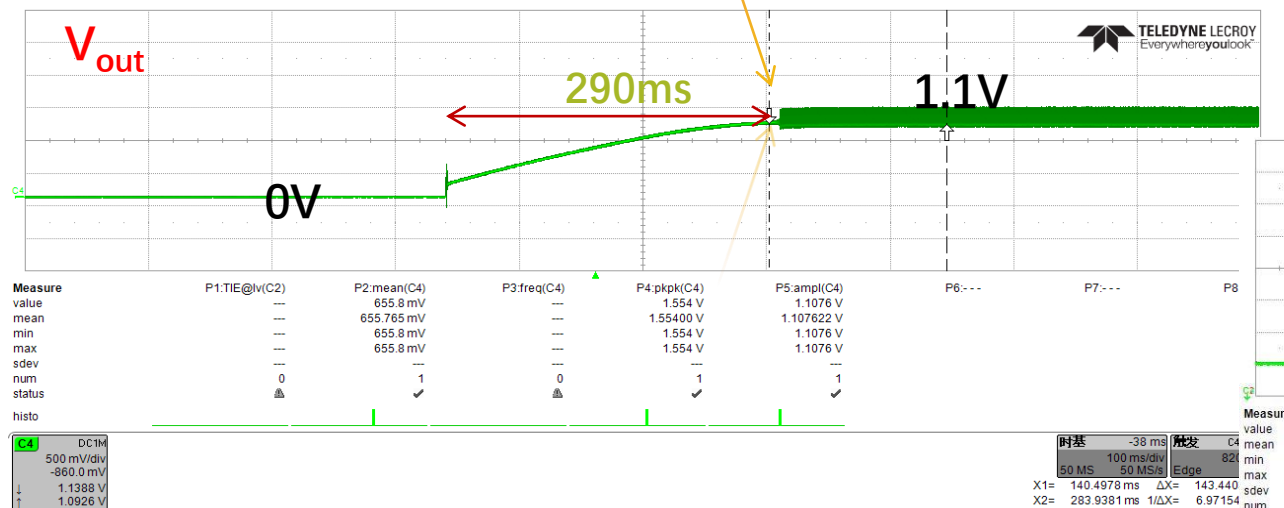
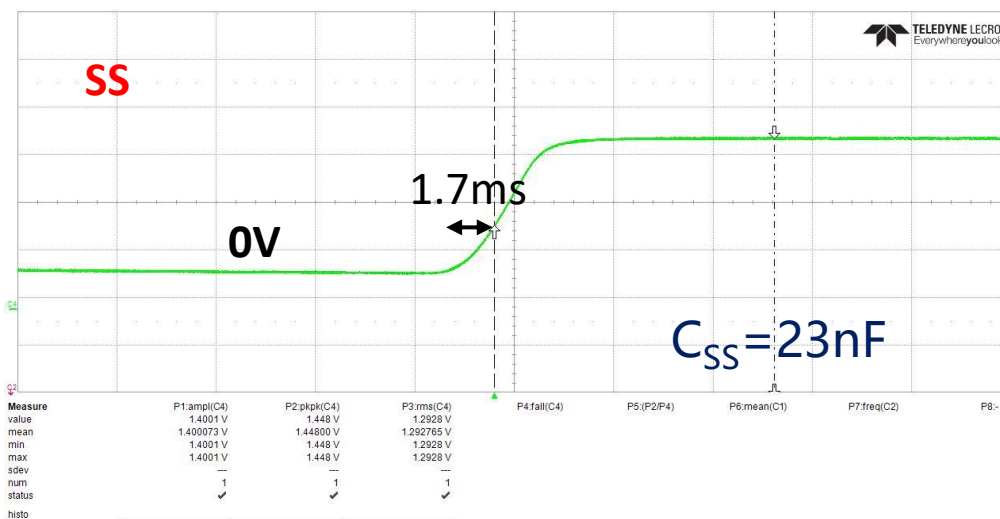
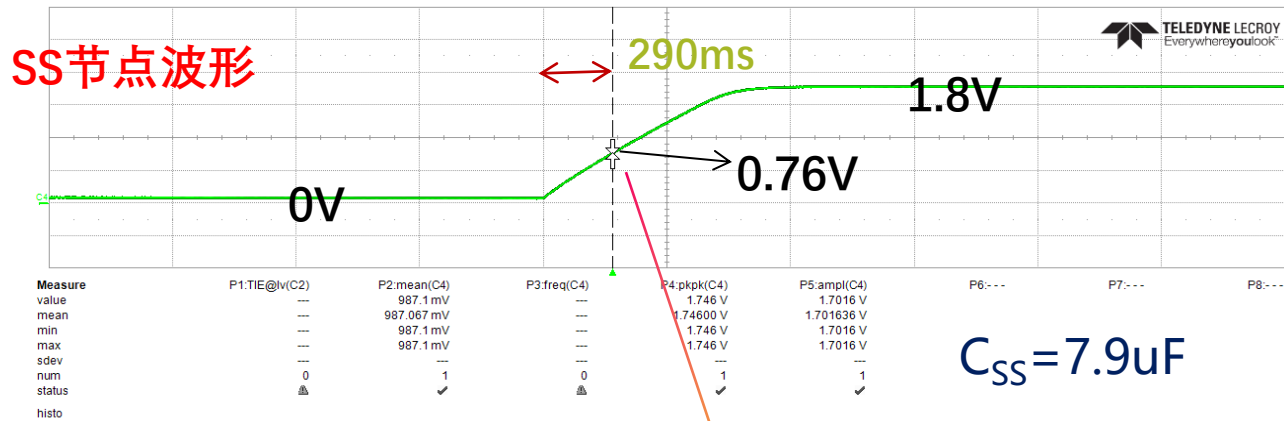
❖ 2026年1月流片班车



➤ 控制器和外置GaN功率管测试



软启动测试结果



- 软启动电压SS在大于0.76V后开始快速启动，软启动时间为290ms@ $C_{SS} = 7.9\mu F$ ，1.7ms@ $C_{SS} = 23nF$
- 软启动时间可通过 C_{SS} 调节，与仿真结果一致。

稳态工作测试波形

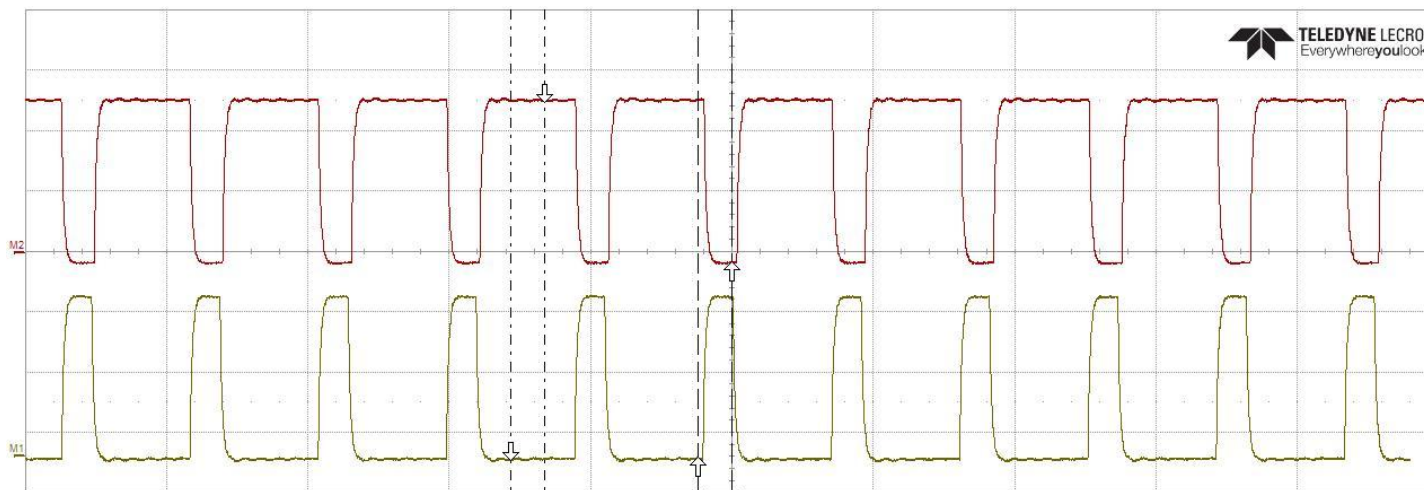


下管驱动电压

SW_L

上管驱动电压

SW_H

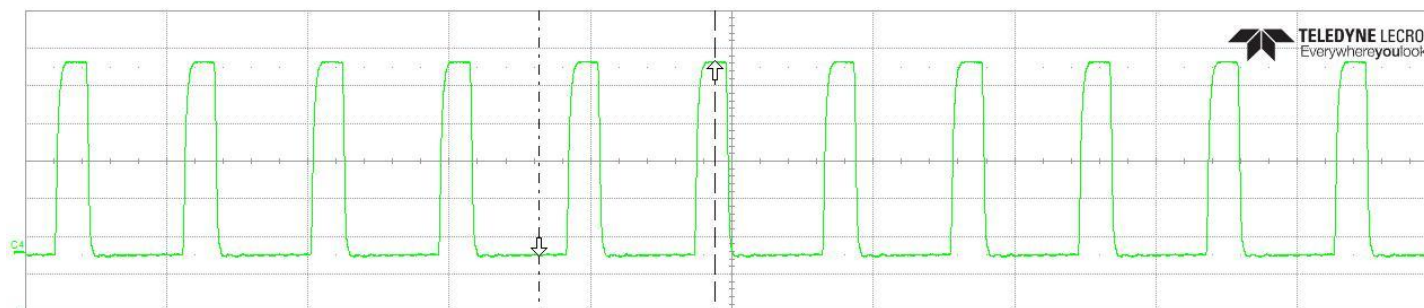


M1	M2
2.00 V/div	2.00 V/div
500 ns/div	500 ns/div
-107.5 mV	5.0163 V
-64.0 mV	-331.8 mV
Δy 43.5 mV	Δy -5.3480 V

时基	触发	C2 DC
20 ns	500 ns/div	1.44 V
12.5 kS	2.5 GS/s	Edge
X1= -682 ns	ΔX= 660.8 ns	
X2= -20.8 ns	1/ΔX= 1.513 MHz	

电感输入电压

PHASE



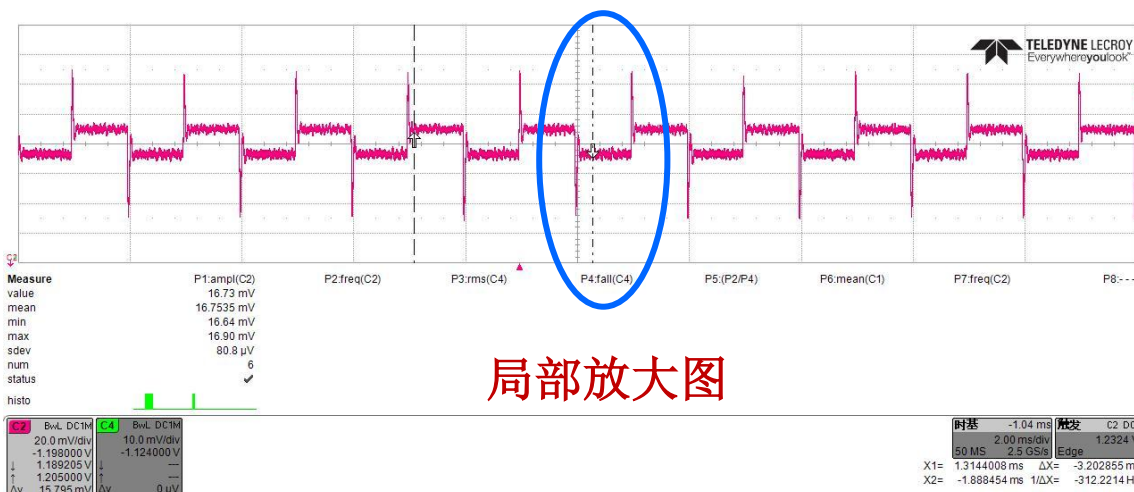
Measure	P1:ampl(C2)	P2:freq(C2)	P3:ampl(C4)	P4:fall(C4)	P5:(P2/P4)	P6:mean(C1)	P7:freq(C2)	P8:---
value	3.27 mV	28.7169 MHz	5.1204 V					
mean	3.2711 mV	23.705970 MHz	5.120406 V					
min	3.27 mV	4.3575 MHz	5.1204 V					
max	3.27 mV	48.9468 MHz	5.1204 V					
sdev		10.752168 MHz						
num	1	75	1					
status	✔	✔	✔					
histo								

C4	BwL DC1M
1.00 V/div	
-2.4400 V	
-59.3 mV	
5.0666 V	
Δy 5.1259 V	

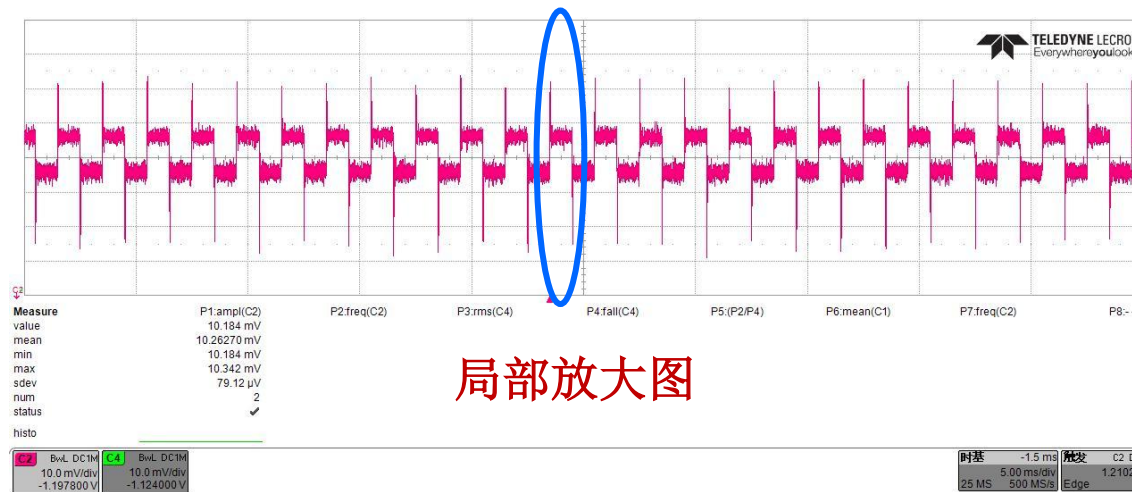
时基	触发	C4 DC
-120.00 μs	500 ns/div	2.83 V
12.5 kS	2.5 GS/s	Edge
X1= 119.317 μs	ΔX= 623.2 ns	
X2= 119.940 μs	1/ΔX= 1.60 MHz	

- 稳态波形与仿真相符
- 工作频率可由外挂电阻调节

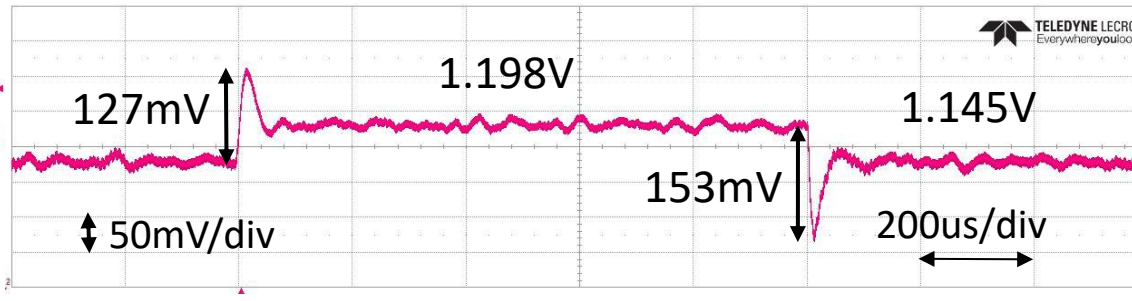
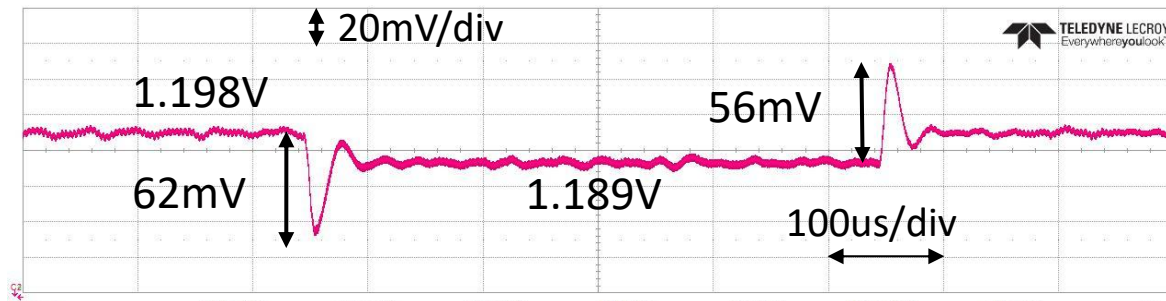
负载电流变化，瞬态响应测试结果



局部放大图



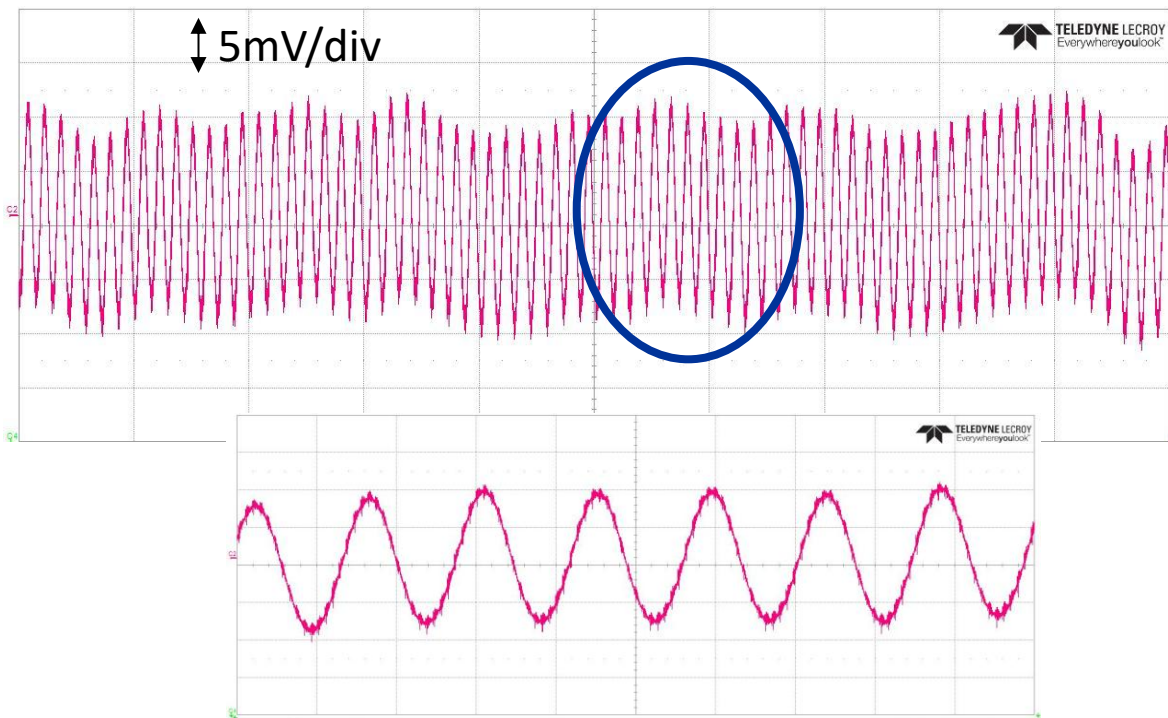
局部放大图



- load: 0A \rightarrow 1A @ SR=1A/us
- over/under shoot=56mV、62mV
- settling time: 46us、63us

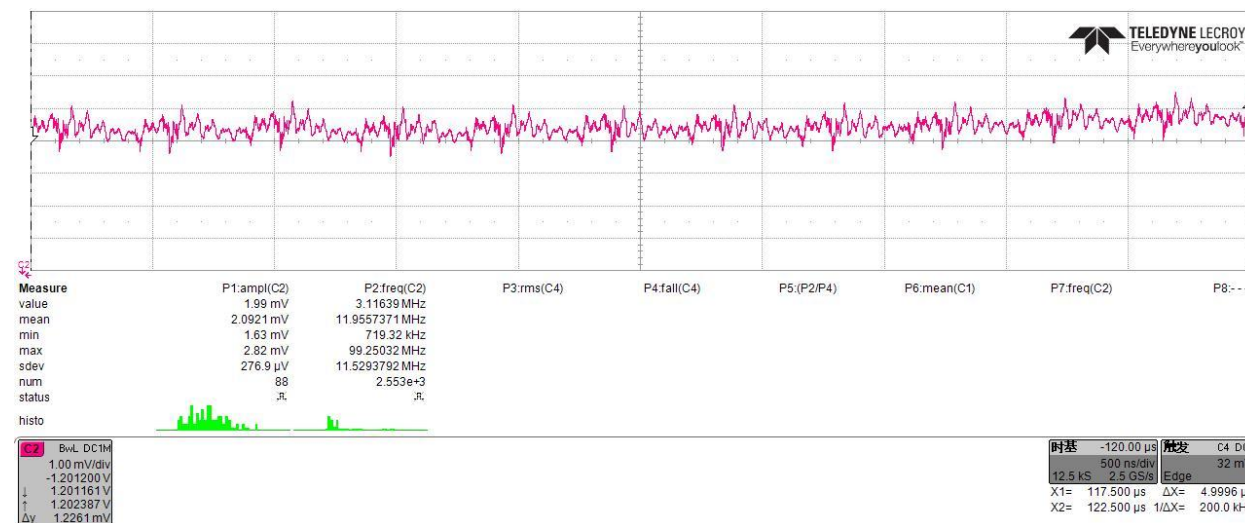
- load: 0A \rightarrow 5A @ SR=1A/us
- over/under shoot=127mV、153mV
- settling time: 72us、90us

电压转换器输出电压



➤ 纹波电压 18mV @ 2MHz

经过 π 滤波后

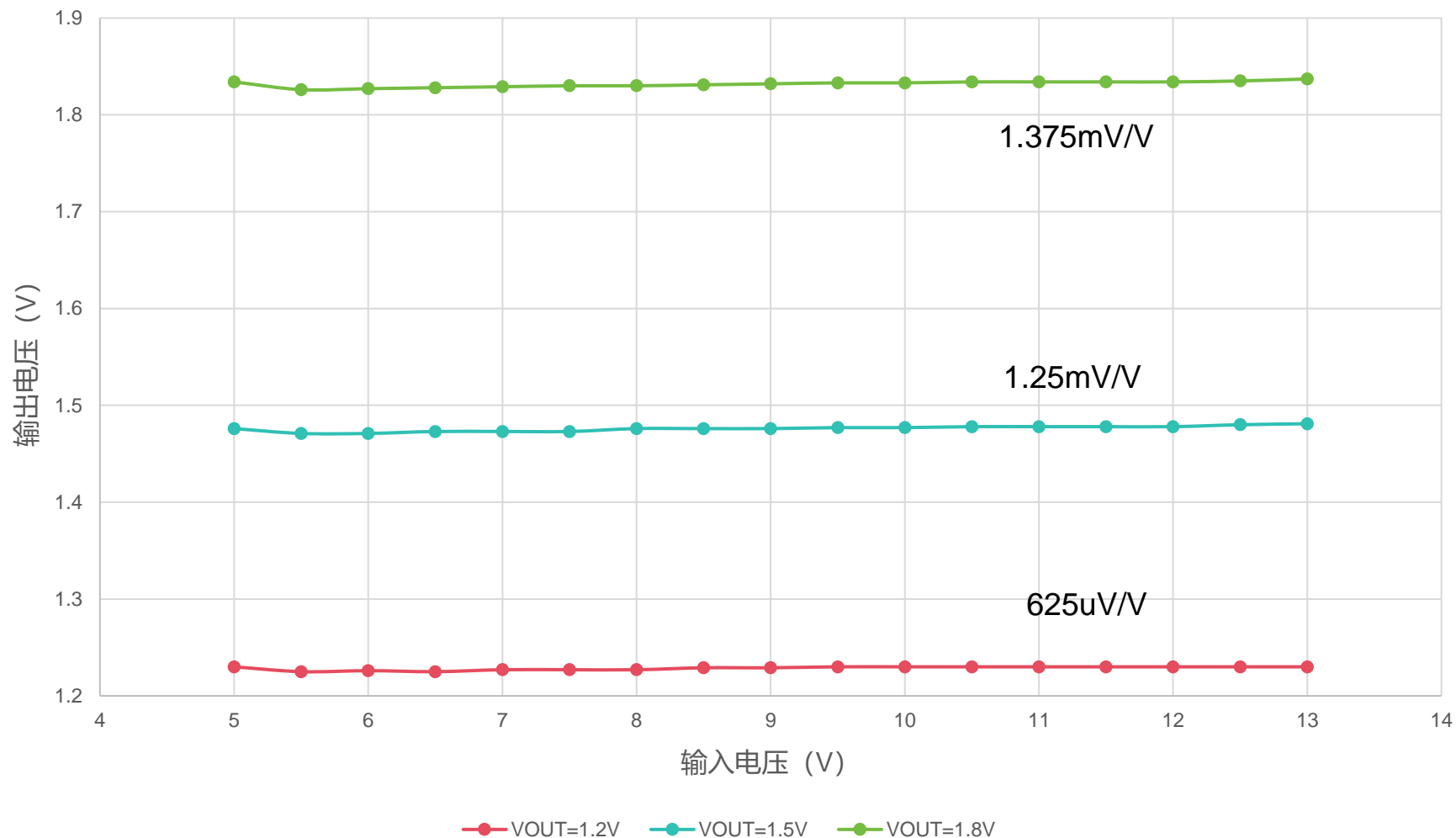


➤ 纹波电压 < 2mV @ 2MHz

稳压性能测试——Vout VS Vin



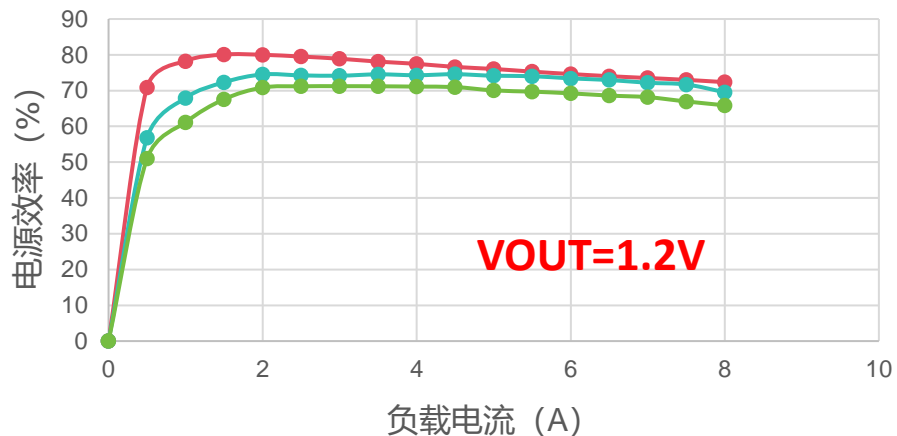
不同输出电压下输入输出转换曲线



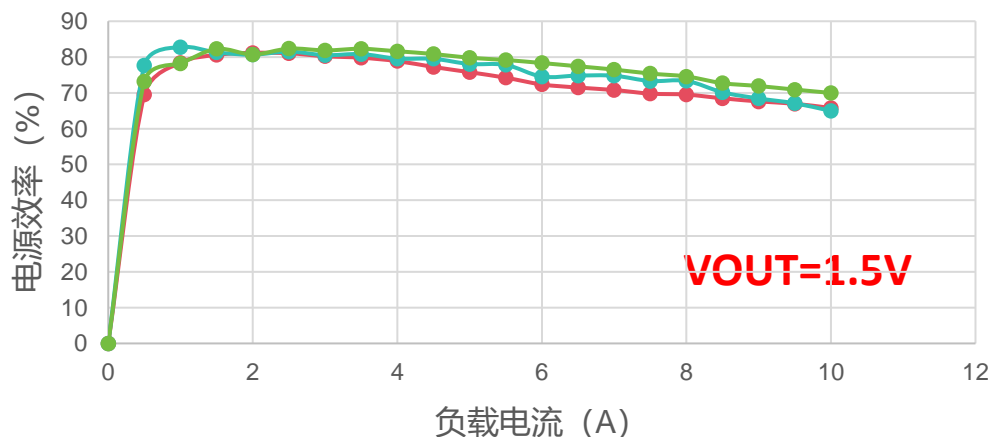
电源效率测试结果



开关频率: 2 MHz 不同输入电压下电源效率

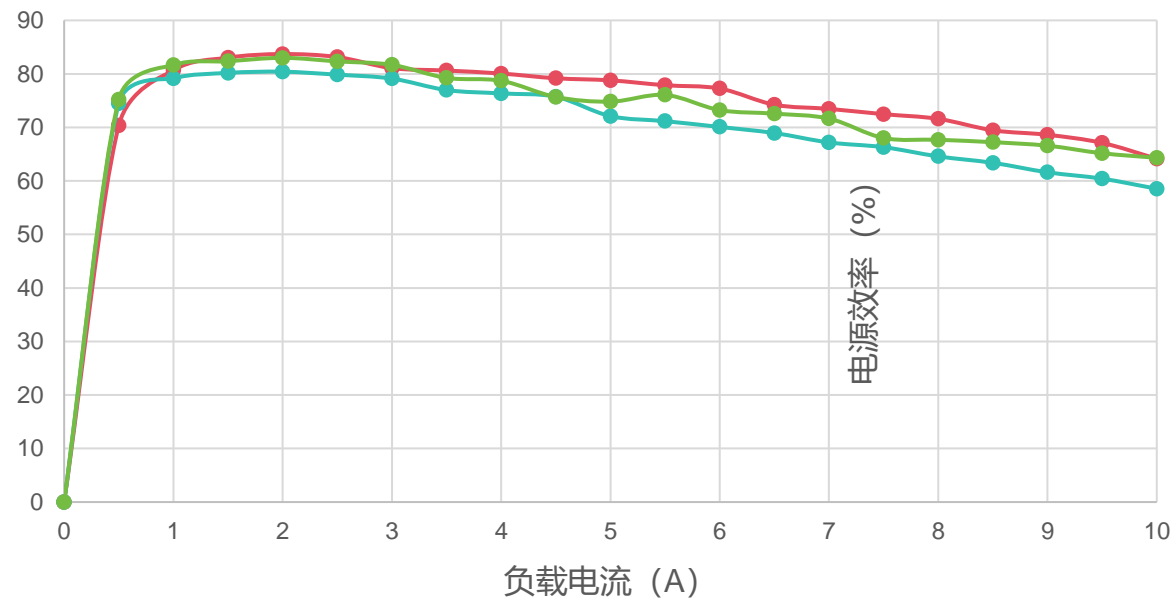


不同输入电压下电源效率



VOUT=1.2V, Vin=12V

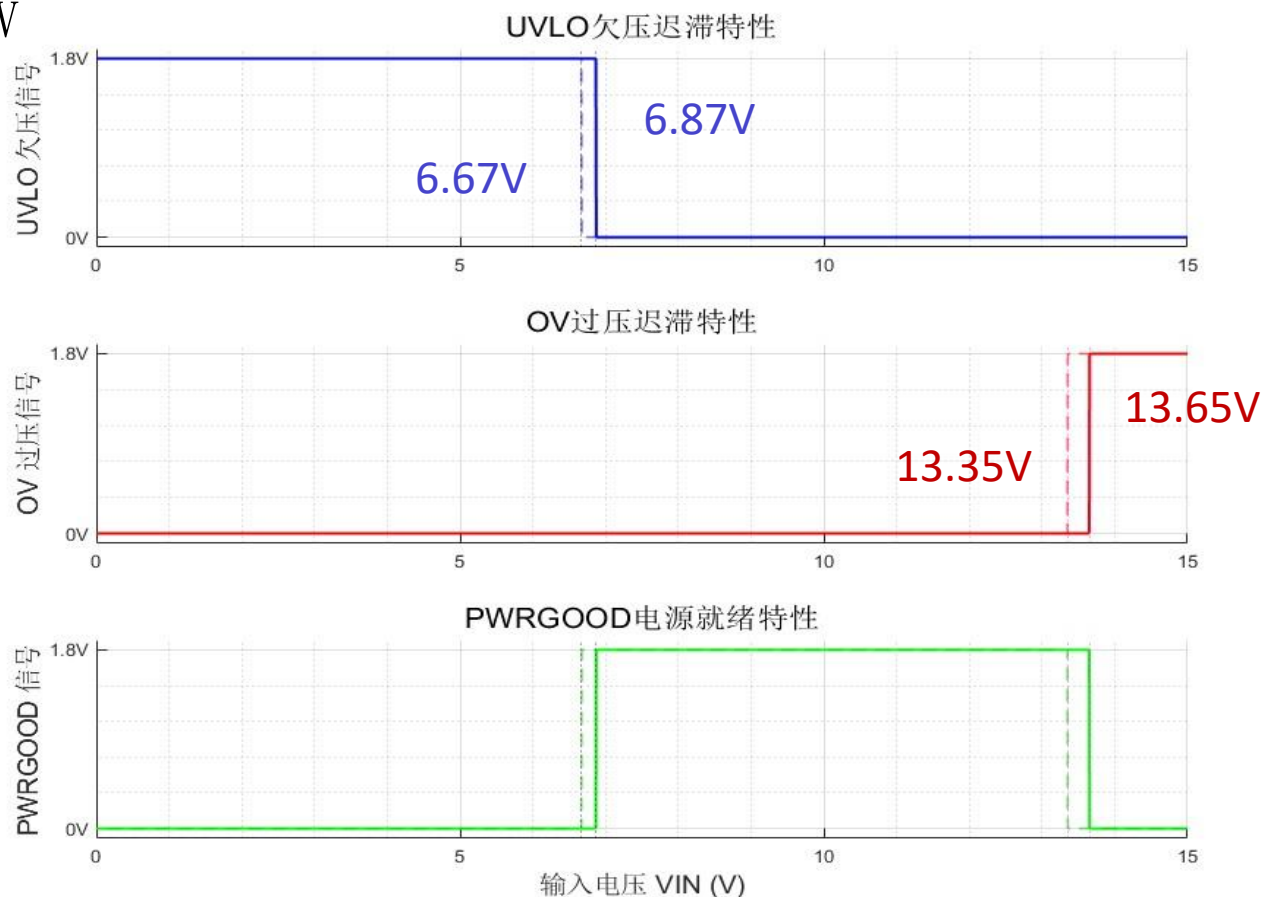
不同工作频率下电源效率



Frequency=1.1MHz Frequency=2.8MHz Frequency=1.9MHz

- ✓ 欠压电路工作正常，迟滞范围6.87-6.67V
- ✓ 过压保护工作正常，迟滞范围13.35-13.65V
- ✓ PWRGOOD: 正常输出电压时指示高电平
- 测试中暂未触发过温保护

UVLO/OV/PWRGOOD 迟滞特性曲线 (本次测试未触发热保护)



- 完成了DC/DC原型芯片的设计和优化，达到了设计指标。
- 继续完成基于内置功率管的芯片测试
- 下一步将进行芯片的抗辐照实验
- 完成大电流LDO的流片

Thanks for your attention!