Wide Band-Gap Semiconductor Amplifiers for Plasma Heating and Control

GAMOW Kickoff Meeting
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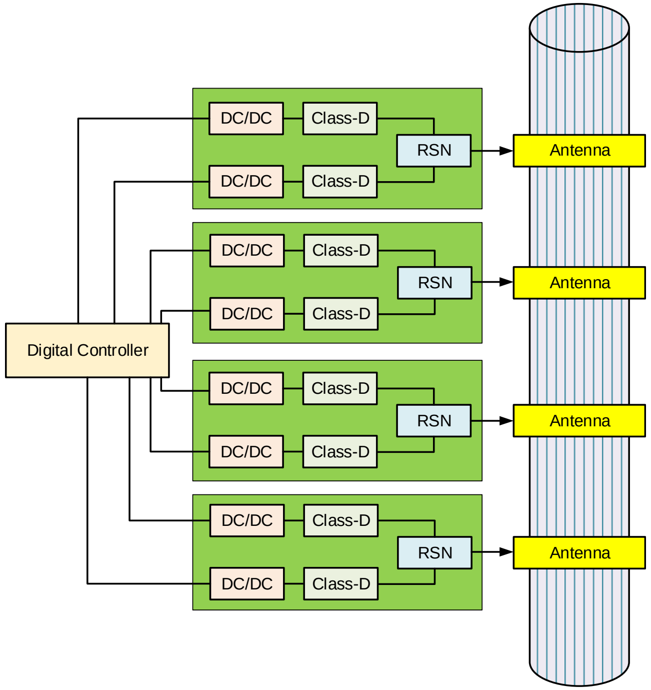
Team members and roles

- Princeton Fusion Systems
- Overall lead organization
  - Pulse generator design
  - Control amplifier design
- Princeton University
- Wave generator design
  - Support all power electronic design
- National Renewable Energy Laboratory
- Thermal design for all boards
- UnitedSiC
- Wide Band-Gap SiC cascodes for the power electronics

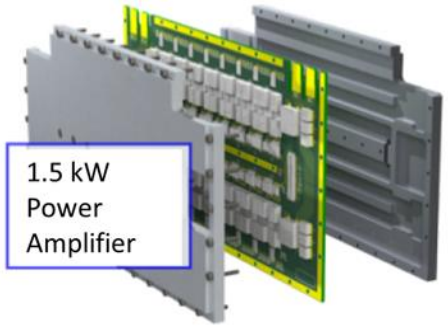
High-level motivation, innovation, and goals of the project

- Power electronics are a critical part of fusion reactors
  - Plasma heating
  - Plasma feedback control
  - Support functions
- Requirements
  - High efficiency
  - Compact
  - Produce lowest possible thermal loads
  - Low cost
- Identify all applications of power electronics for fusion
  - Include existing fusion machines and new fusion machines under development by ARPA-E and commercial companies
- Design and build prototype boards for both wave heating and pulse generation that are high efficiency, compact and low-cost
- Use 2 kV SiC cascodes to implement the boards
- Implement high efficiency thermal control

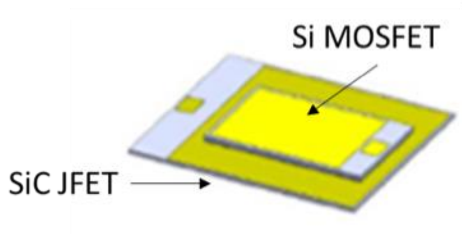
Key Technologies



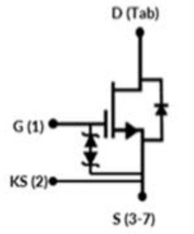
Digitally controlled amplifier array (PU)



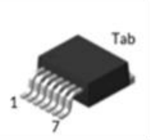
High power density electronics (NREL)



UnitedSiC 4th Gen. SiC Stack-Cascode Technology

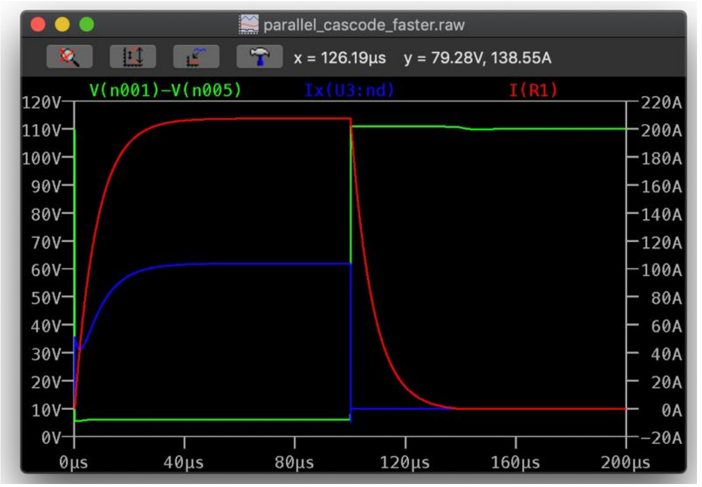


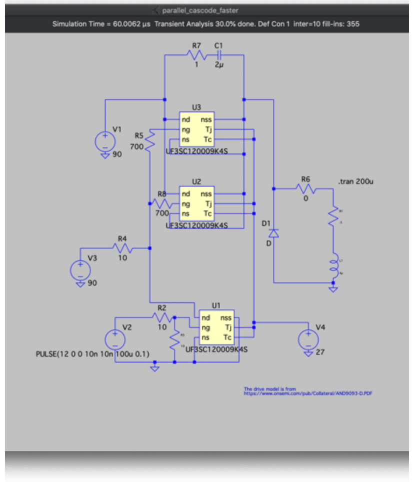
Normally-Off FET



2kV/65mOhm Discrete Switch

2 kV Cascodes United SiC





High efficiency pulse generators (PFS)

Identification of Power Requirements

- Heating
- Plasma control
- Heat to power conversion systems
- Superconducting coil cooling
  - It can take 6 months to cool down superconducting coils so a failure is very costly
- Neutral beam heating power supplies
- Discussed requirements with Dr. Steven Cowley of PPPL
  - Stellarators (ideally) only need a start-up pulse
  - Tokamaks have numerous systems requiring high reliability power sources
  - Will talk to the designer of the TFTR power system and other experts
- Zoom meeting scheduled with Tokamak Energy

Major Tasks, Milestones, Risks, and Desired project outcomes

- M 1.2 Fusion industry survey
- M 2.2 Cascode design
- M 3.1- M 3.4 Board design
- M 4.1 Thermal control demonstration
- M 5.1 - M 6.2 Integrate thermal and board design

- M 1.2 - Comprehensive study of power electronics for fusion reactors
  - Will be useful for this project and all fusion projects
  - Other vendors will benefit
  - Help guide board requirements
- M 2.2 - 2 kV Cascodes
  - Wide industry applicability
- M 3.1- M 3.4 High power board prototypes
- M 4.1 High power thermal control
- M 5.1 - M 6.2 Prototype boards for fusion application testing

Risk Mitigation

- SiC may not produce sufficient power density at desired frequencies
  - In discussions with GaN providers
- The added cost and complexity of combining small boards may make them less cost-effective at very high power
  - The optimal combination of per device power and number of boards will be determined
  - Closed loop control should allow for larger numbers of boards
    - Includes fault detection
  - Can build higher power SiC devices using different geometries
  - Cooling may limit board density
- Turnkey boards may not be attractive to fusion power companies
  - License the core technology
  - Build custom solutions

Metrics

Switch	Voltage Rating	$R_{ds,on}$ (mW)	C_{oss} (pF, @1000V)	Recommende Gate Drive	Gate Charge (nC)	Package
State-of-Art A	1700V	80	105	+20V on -10V/+25V	120	Thru-Hole
State-of-Art B	1700V	45	171	+20V on -10V/+25V	188	Thru-Hole
UnitedSiC UJ4SC20065l (proposed)	2000V	65	65	+10-12V on +/- 20V max	27	SMT

Table 1: Performance matric for SiC devices

Quantity	Value
Input Voltage (DC)	500V
Input Current (DC)	3A
Power Rating	1.5kW
Switching Frequency	6.78 - 13.56 MHz
PCB Area	10cm x 10cm
Targeted Efficiency	90%
SiC Device	UF3C170400K3S

Table 2: Performance Metric for CW Drive

	Present State of the Art	Ultimate Target	To be achieved in this project
Switching Transistors	1700 V R_{ds} 90 m, C_{oss} 171 pF	2000 V 30 m C_{oss} 58 pF 100 A	2000 V 30 m C_{oss} 58 pF 100 A
Power Amplifiers	2 kW/board 20% efficient	10 kW/board 90% efficient	1.5 kW/board 80% efficient
Control Amplifiers	Thyristor based 20% efficient	SiC based 90% efficient	SiC based 80% efficient
Fast pulse	Ignitron, 4 year lifetime	SiC based, $>$ 50 year lifetime	SiC based, $>$ 50 year lifetime
Cost Metric	$1000/kW	$8/kW	$20/kW

Table 3: Impact on fusion machines

T2M and Aspirational Follow-on Plans

- An example
  - 500 kW needed for PFRC
  - For PFRC that would be $500K for power electronics for heating
  - Additional savings due to simplified installation, etc.
  - Because multiple boards are used, the system is failure tolerant and increases the availability of a fusion power power lowering the LCOE
- Replacing failure prone items like ignitrons will lower costs
- Would also support systems for magnetic cooling
  - A failed magnet could shut down a fusion machine for a year
- Test & deployment plans/aspirations
  - Spherical tokamaks
  - Compact tokamaks
  - Stellarators
  - Mirrors
  - Pulsed machines
- Heating, control, other power electronics
- Produce prototype boards for selected concepts
  - Provide to customers for testing
- PFS and UnitedSiC are commercial entities and will commercialize the boards and semiconductor devices