HIGH-EFFICIENCY POWER AMPLIFIERS for PARTICLE ACCELERATORS

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1. GMRR
2. WHY EFFICIENCY ?
3. APPROACH
4. RESULTS
5. BENEFITS
GREEN MOUNTAIN RADIO RESEARCH

• Small by design
• Focus: R&D
• Full RF lab
• Production by license
GMRR RF POWER AMPLIFIERS

- Frequency to 8 GHz
- Power to 4 kW
- High efficiency
- Production-ready
PARTICLE ACCELERATORS

Megawatts of RF power
24/7 operation

Huge utility bills
Limited availability?
EFFICIENCY - WHY?

- Operating cost
- Cooling requirements
- Reliability
GMRR DoE WORK

CONCERNS
• Cost of operation
• Availability of electricity
• Environment
### MAJOR ISSUES AND SOLUTIONS

**POWER CONSUMPTION**
- 24/7 operation
- Megawatts
- Cost

**SOLUTION**
- High-efficiency power amp

**RELIABILITY**
- 24/7 experiments
- Large tube
- Failure = shut-down

**SOLUTION**
- Solid-state power amplifiers
- Multiple modules
- Hot-swap capability

**ADAPTABILITY**
- BNL/PX/APS/ORNL/other

**SOLUTION**
- Common architecture
- Scalable combining
COMPONENTS

DSP
500-W Combiner

RF PA
Multi-kW Combiner

Class-S Modulator
HIGH-EFFICIENCY PA SYSTEM

DSP + HIGH-EFFICIENCY RF PAs

- Max efficiency for given amplitude
- Phase errors corrected
- Control and monitoring
HIGH-EFFICIENCY AMPLIFIER SYSTEM

- High-efficiency RF power amplifiers
- High-efficiency class-S modulators
- Digital signal processor
- High efficiency over wide range of amplitudes
- Excellent amplitude and phase
COMBINING

BASIC MODULE
- 5 PAs
- Hybrid combiner
- 500 - 600 W
- One driver

HIGHER POWER
- 2 - 8 PAs
- Radial combiner
- 1 - 4 kW
- Next stage 8 - 32 kW
CANDIDATE POWER AMPS AND FETS

<table>
<thead>
<tr>
<th>FREQUENCY, MHz</th>
<th>LAB</th>
<th>PA</th>
<th>FET</th>
</tr>
</thead>
<tbody>
<tr>
<td>73-80.5</td>
<td>ANL/FRIB</td>
<td>Class E</td>
<td>VMOS or LDMOS</td>
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<tr>
<td>161 - 162.5</td>
<td>FRIB/X</td>
<td>Class E/F</td>
<td>LDMOS</td>
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<tr>
<td>322 - 402.5</td>
<td>ANL/X/ORNl</td>
<td>Class F</td>
<td>LDMOS or GaN</td>
</tr>
<tr>
<td>650 - 704</td>
<td>X/BNL</td>
<td>Class F</td>
<td>GaN</td>
</tr>
</tbody>
</table>
RF PA DEVELOPMENT

- Experimental evaluation / optimization
- Many different components
RF POWER AMPLIFIER

- Output 120 W
- Efficiency 82%
- Gain 18 dB
- Harmonics < -55 dBc
500-W SPLITTER AND COMBINER

SPLITTER

- SWR: 1.02
- Loss: 0.1 dB (2%)
- Amplitude variation: 0.12 dB rms
- Phase variation: 0.7° rms
- Isolation: > 37 dB

COMBINER
HIGH-POWER HARDWARE

CIRCULATOR

- SWR 1.15
- Loss 0.1 dB
- Isolation 25 dB

COMBINER + DIRECTIONAL COUPLER

- SWR 1.07
- Loss 0.05 dB
- Coupling 40 dB
CLASS-S MODULATOR

- Candidates: 3 MOSFET, 1 GaNFET
- Modulation + Power Switching
- Fly-off: Pending

- Efficiency: 94.5%
- Linearity: < 1% rms error
- Bandwidth: 10 kHz
DSP/CONTROL SYSTEM

ATOM COMPUTER

DIGITAL SIGNAL PROCESSOR

FUNCTIONS

• Sequence power
• Monitor amplifier
• Generate signals

CONTROL/MONITOR BOARDLET
500-W 5-PA MODULE

BRASSBOARD

PERFORMANCE

• Efficiency ≥ 79% for 380 - 640 W
• Efficiency ≥ 70% for ≥ 90 W
PACKAGING

500-W MODULE

- Class-S modulators
- Driver
- Circulator

MULTI-kW UNIT

- SIGNAL PROC/CONTROL
- PREDRIVERS
- PAM #1
- PAM #2
- PAM #3
- PAM #4
- HIGH-POWER COMBINER
- PAM #5
- PAM #6
- PAM #7
- PAM #8
- POWER SUPPLIES
COST SAVINGS

$\$/kWh
0.05 FNAL  0.11 MID
0.07 APS  0.19 BNL

RF POWER
$6/W Klystron
$12/W SSPA
+$2/W GaN

COOLING
$4/W acquisition
$0.5W/W operation
BNL eRHIC PHASE-II GRANT

A. Kick-off meeting

B. Digital signal processor and control
C. PC board
D. 704-MHz PA
E. Combiners

F. Driver
G. Class-S modulator
H. Control
I. Integration

J. Prototype (704 MHz, 1 kW)
K. Presentation and future issues
THANK YOU

QUESTIONS?