

HIGH-EFFICIENCY POWER AMPLIFIERS for PARTICLE ACCELERATORS

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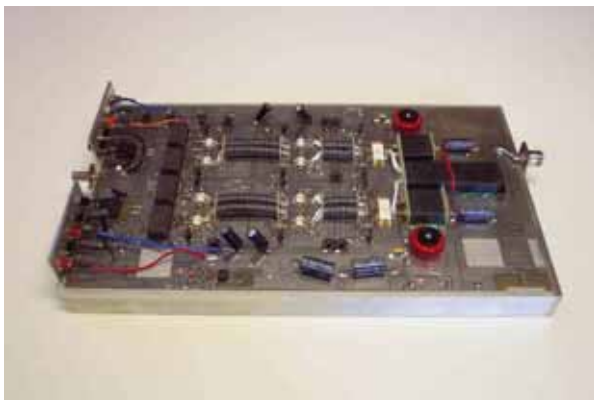
1. GMRR
2. WHY EFFICIENCY ?
3. APPROACH
4. RESULTS
5. BENEFITS

GREEN MOUNTAIN RADIO RESEARCH



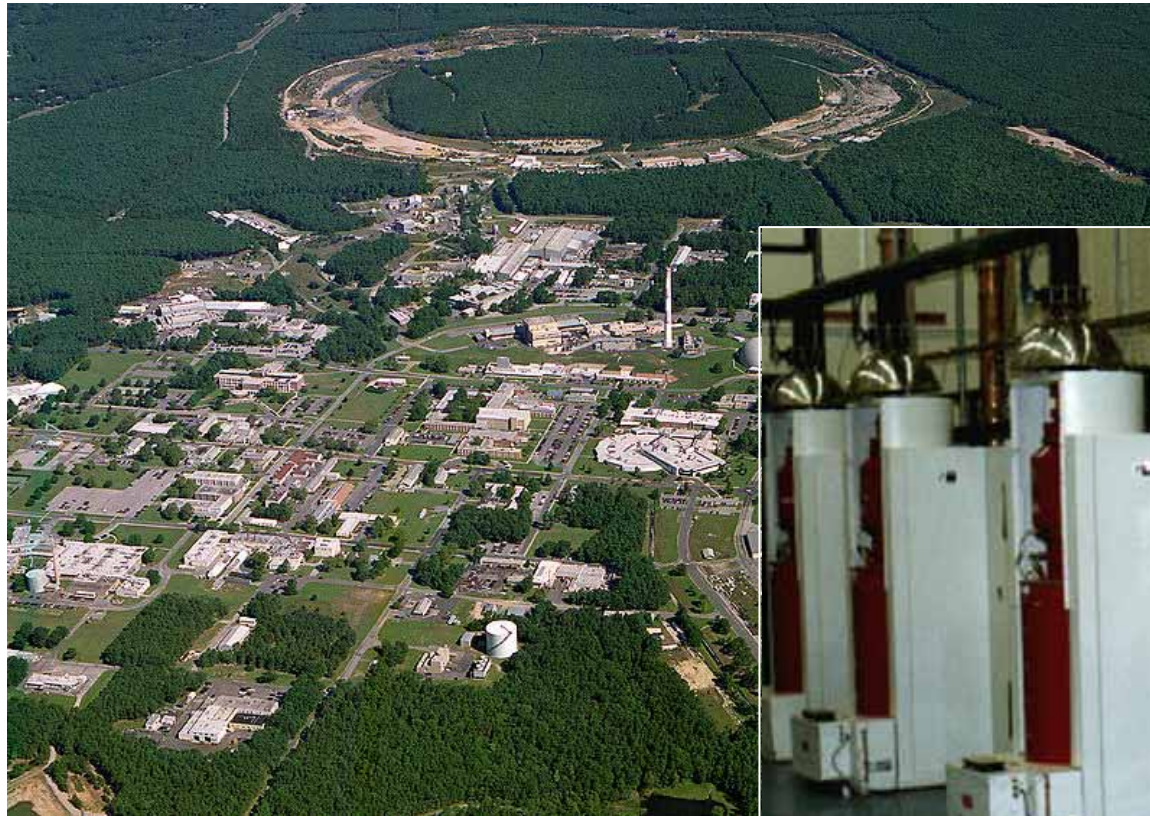
- Small by design
- Focus: R&D
- Full RF lab
- Production by license

GMRR RF POWER AMPLIFIERS



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

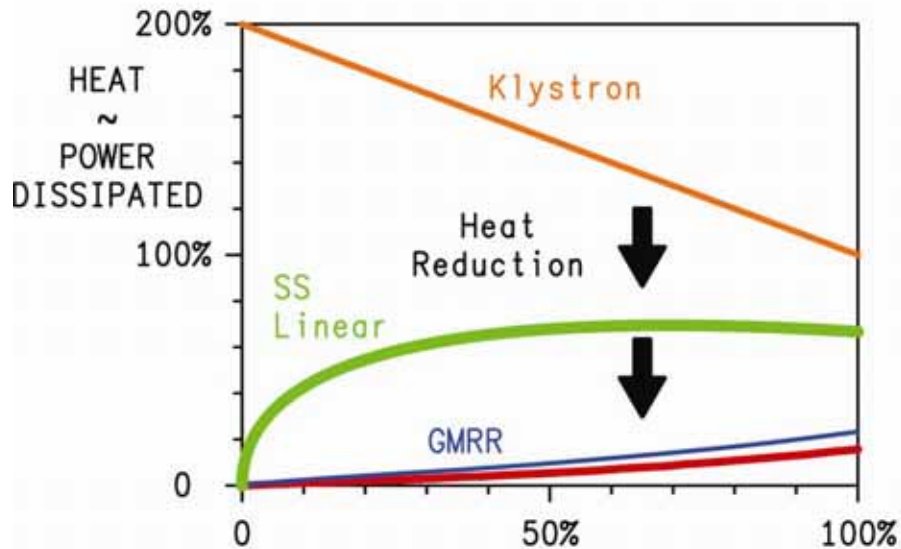
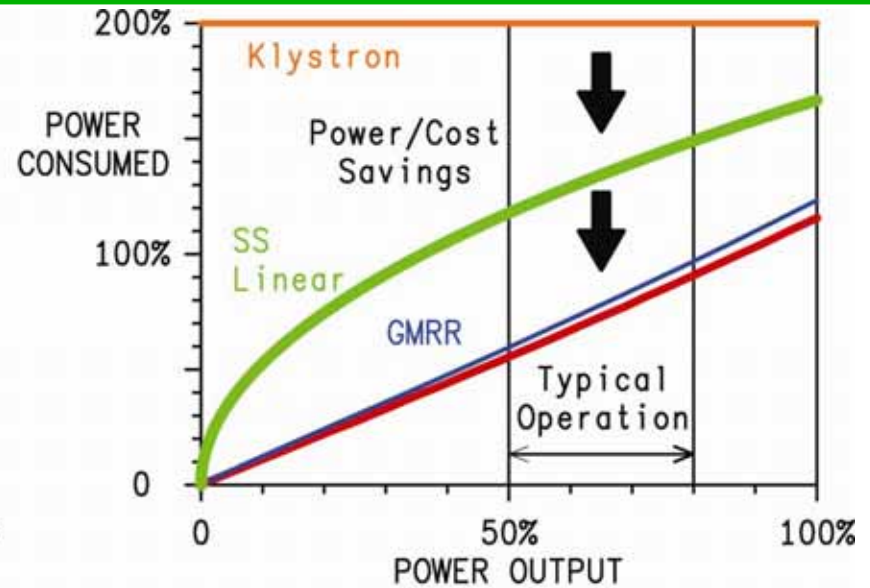
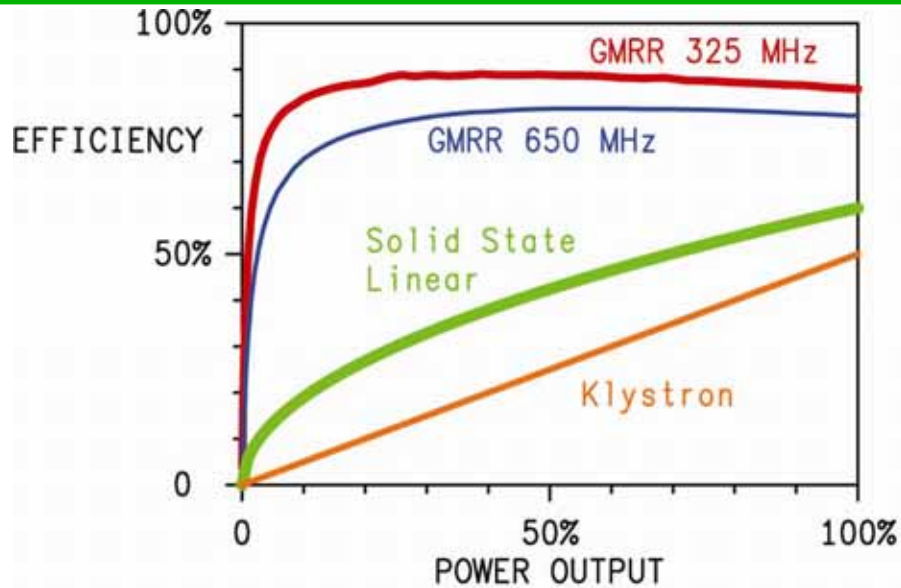
PARTICLE ACCELERATORS



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



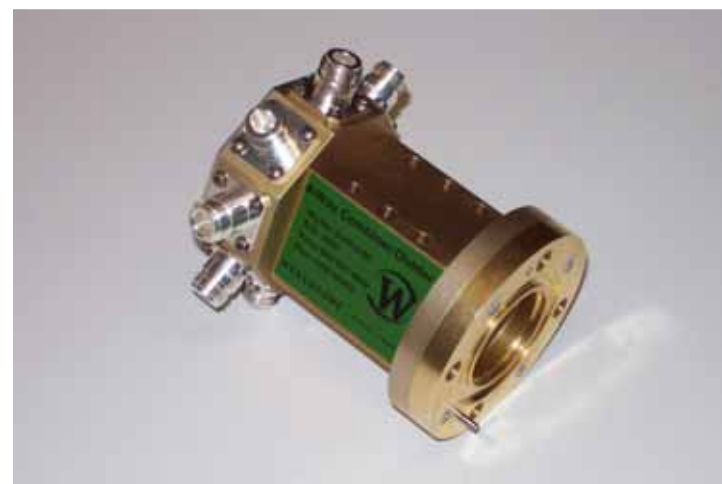
DSP

500-W Combiner

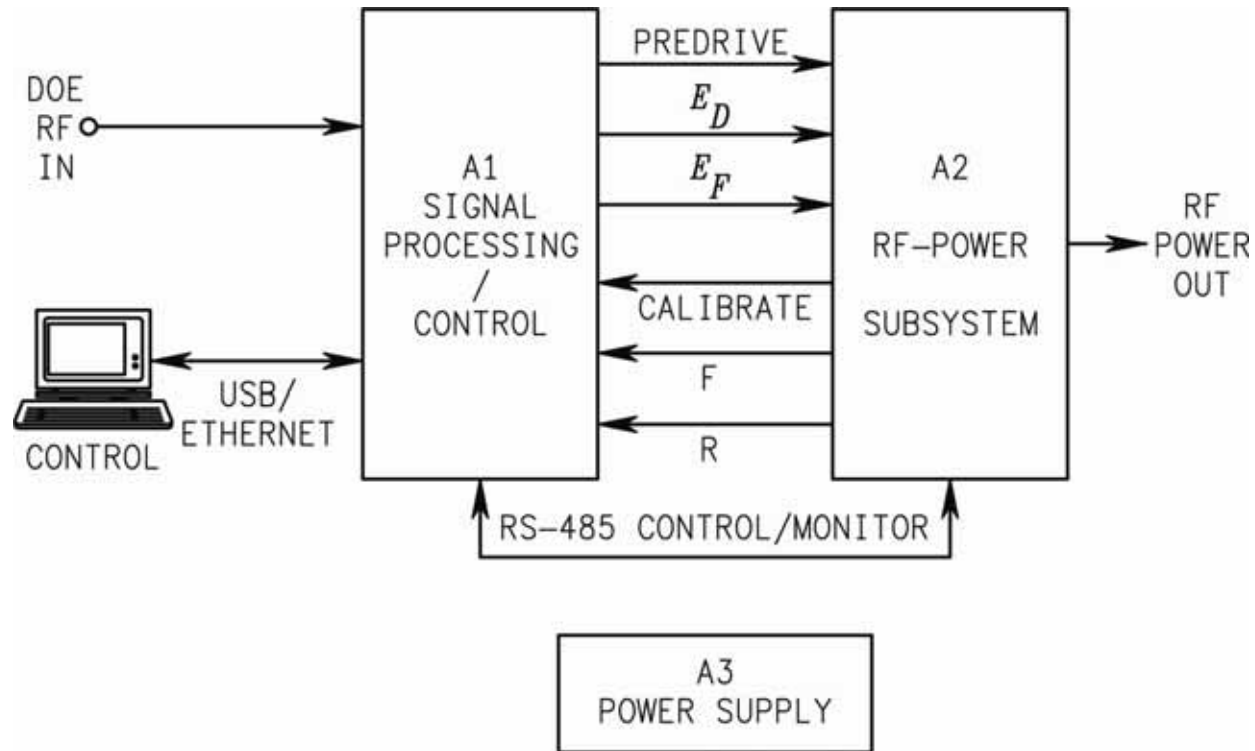
RF PA

Class-S Modulator

Multi-kW Combiner



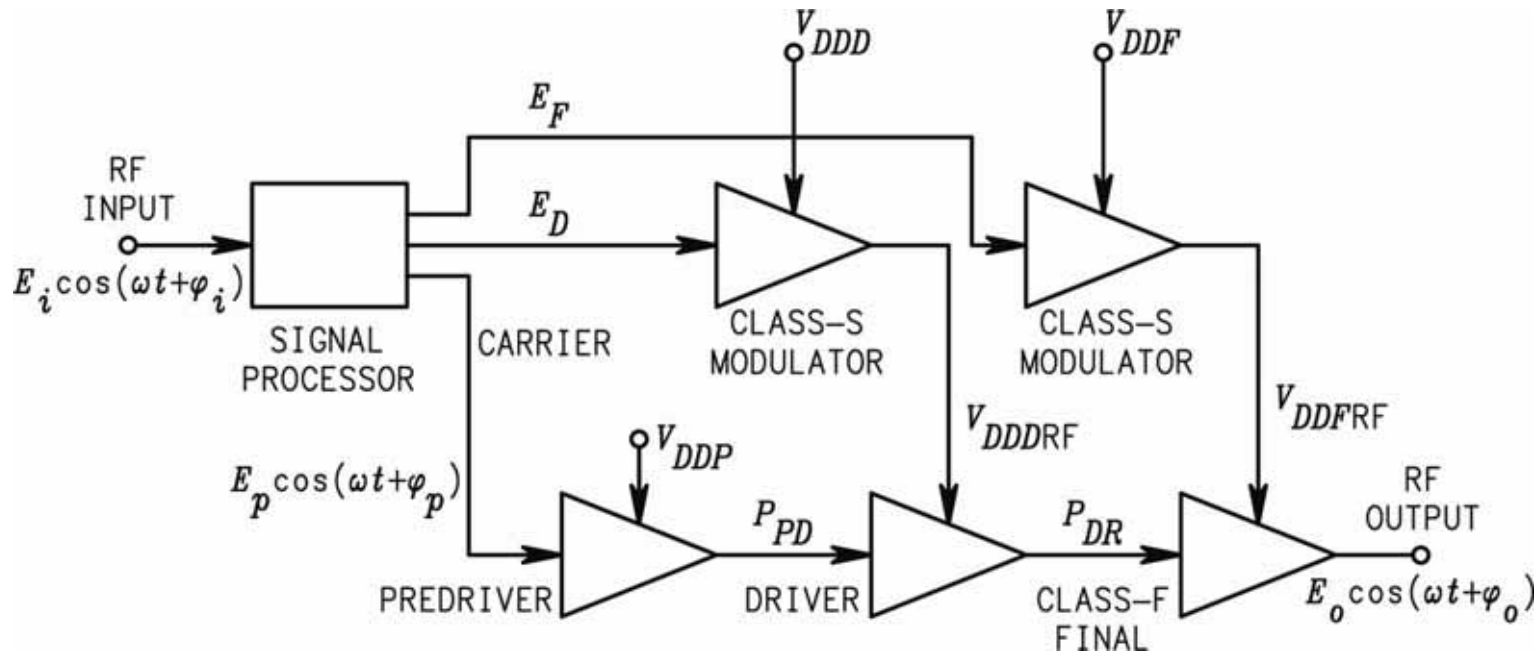
HIGH-EFFICIENCY PA SYSTEM



DSP + HIGH-EFFICIENCY RF PAs

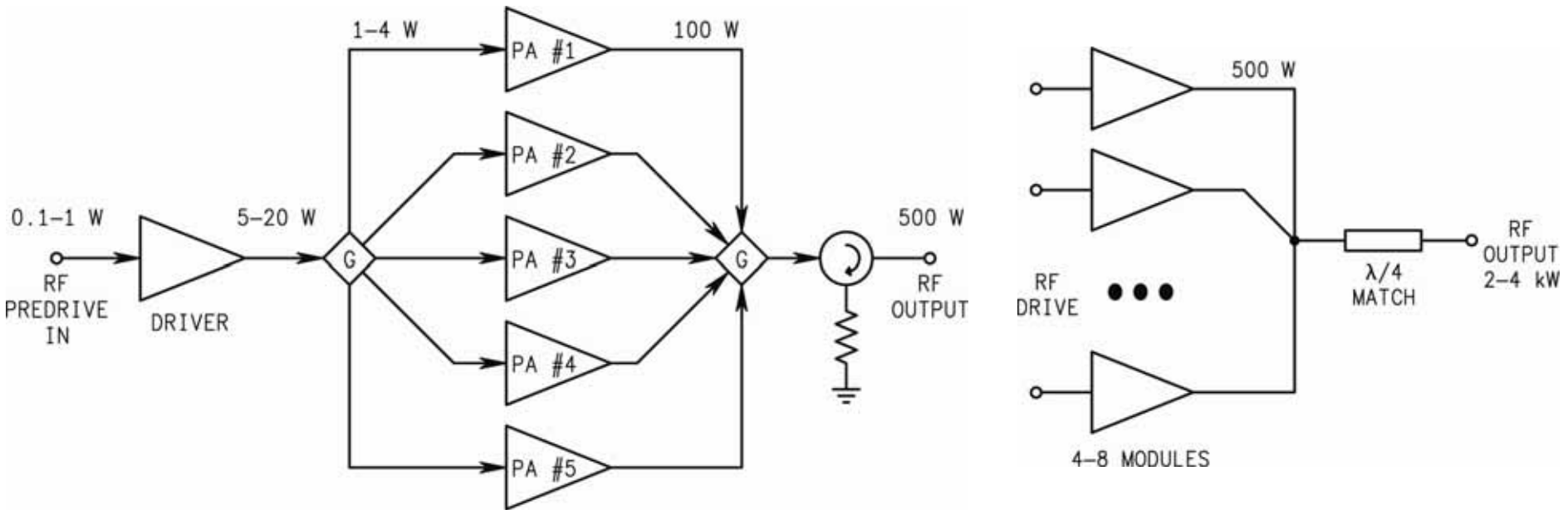
- Max efficiency for given amplitude
- Phase errors corrected
- Control and monitoring

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



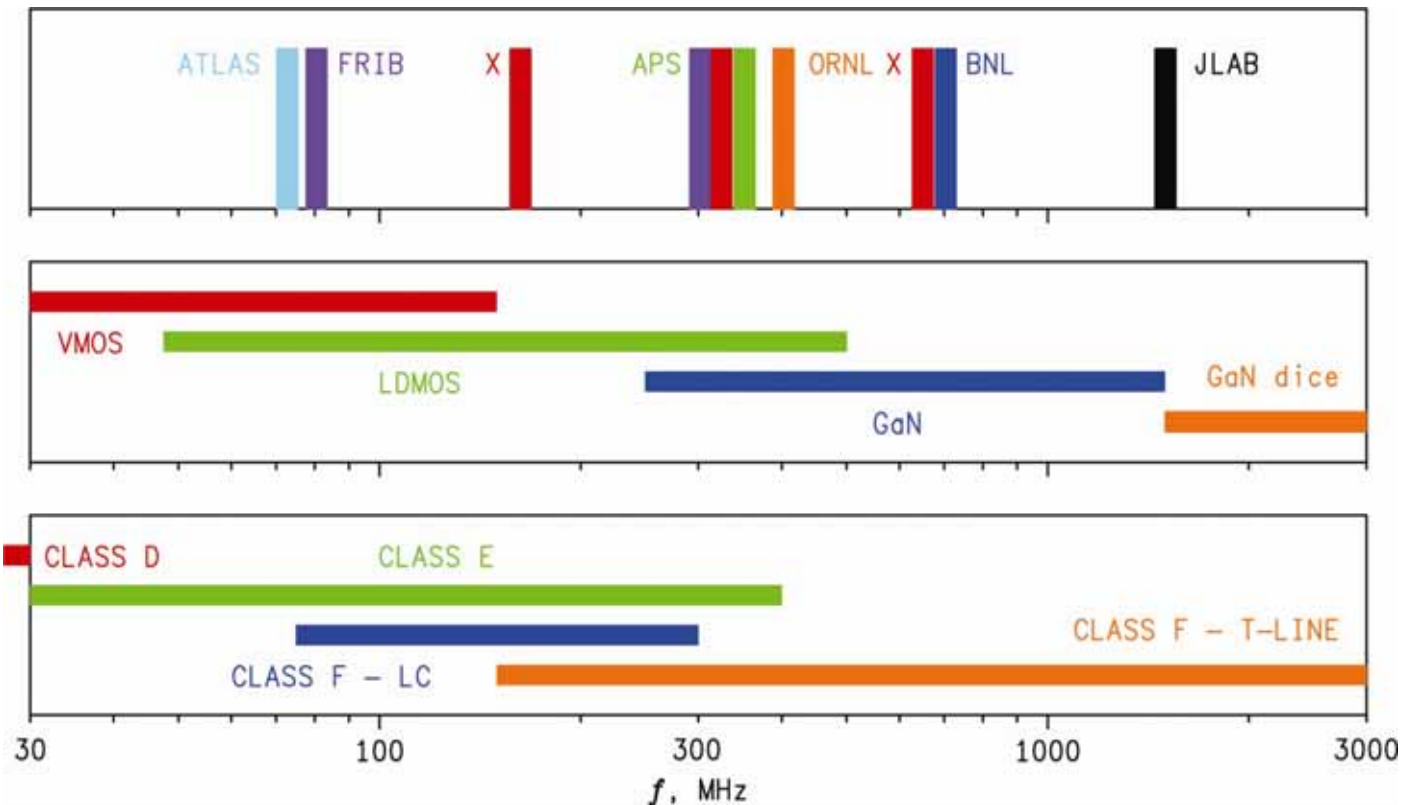
BASIC MODULE

- 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

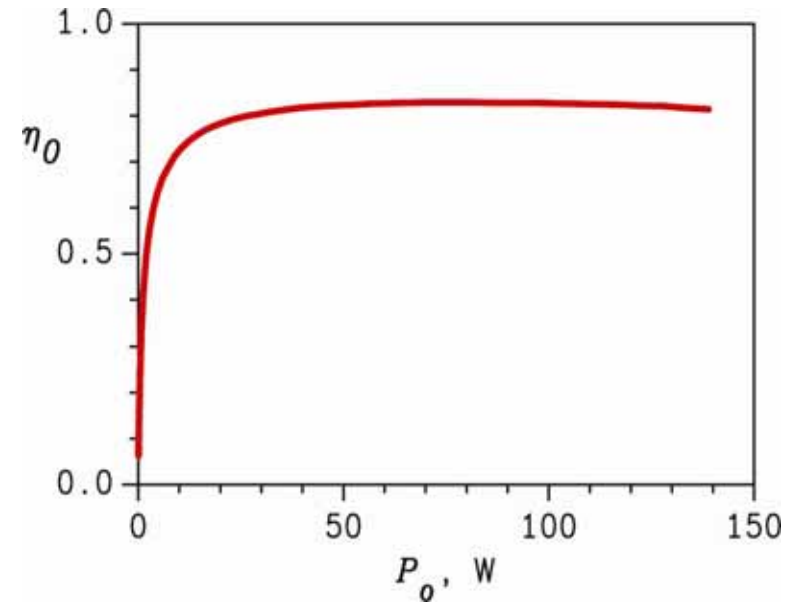


FREQUENCY, MHz	LAB	PA	FET
73-80.5	ANL/FRIB	Class E	VMOS or LDMOS
161 - 162.5	FRIB/X	Class E/F	LDMOS
322 - 402.5	ANL/X/ORNL	Class F	LDMOS or GaN
650 - 704	X/BNL	Class F	GaN

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

COMBINER

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

HIGH-POWER HARDWARE

CIRCULATOR



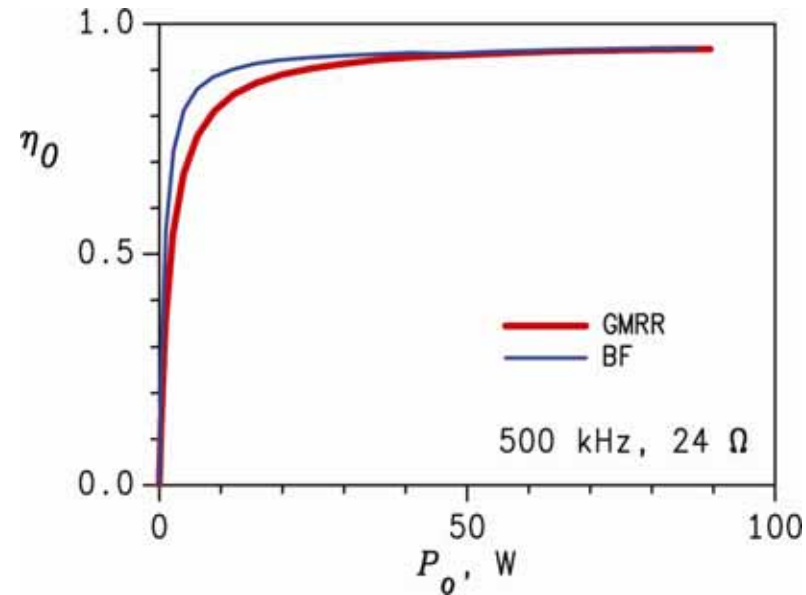
- SWR 1.15
- Loss 0.1 dB
- Isolation 25 dB

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

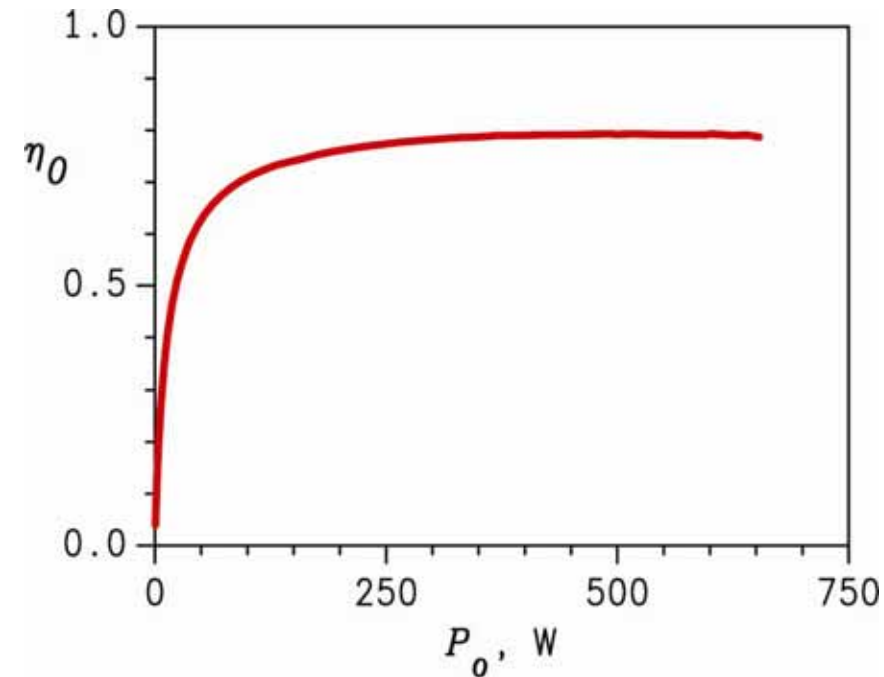
CONTROL/MONITOR BOARDLET



500-W 5-PA MODULE

BRASSBOARD

PERFORMANCE



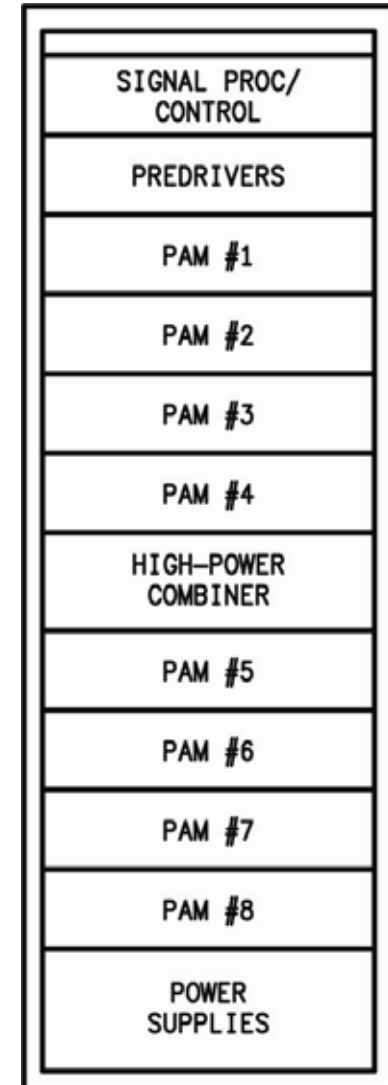
- Efficiency $\geq 79\%$ for 380 - 640 W
- Efficiency $\geq 70\%$ for ≥ 90 W

PACKAGING

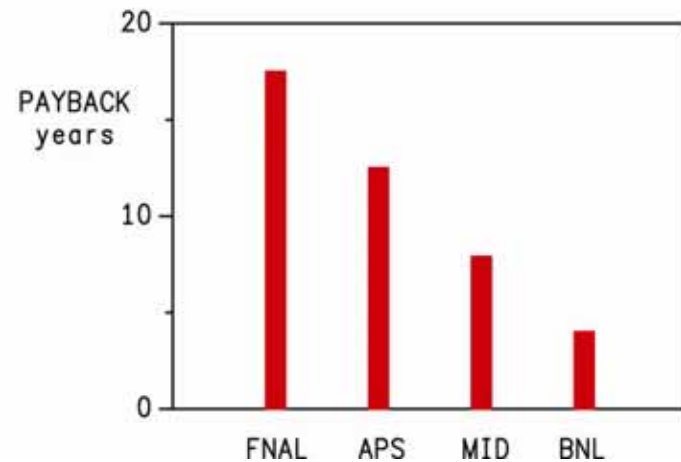
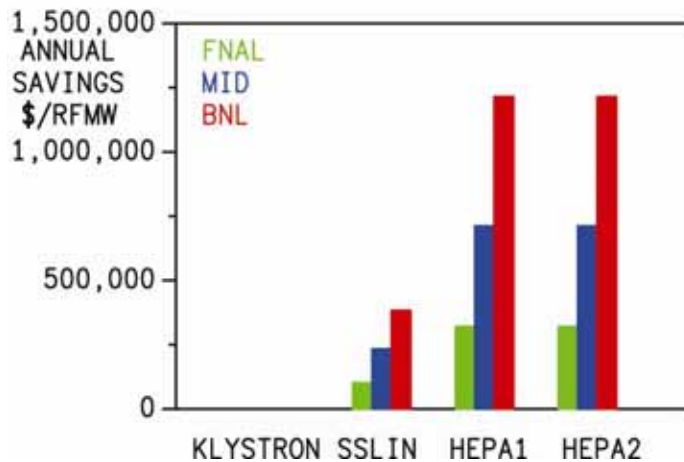
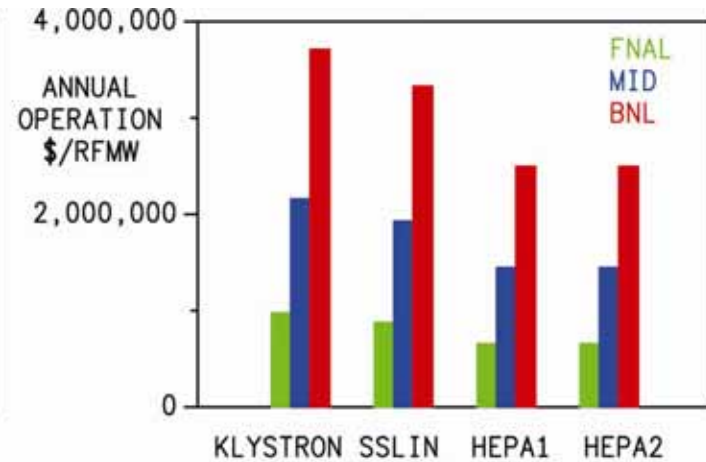
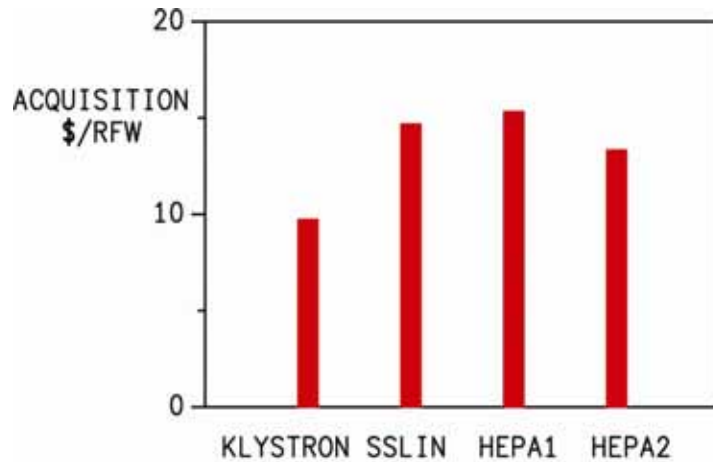
500-W MODULE

- Class-S modulators
- Driver
- Circulator

MULTI-kW UNIT



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?

