Amplifiers for CLIC Drive Beam Phase Correction

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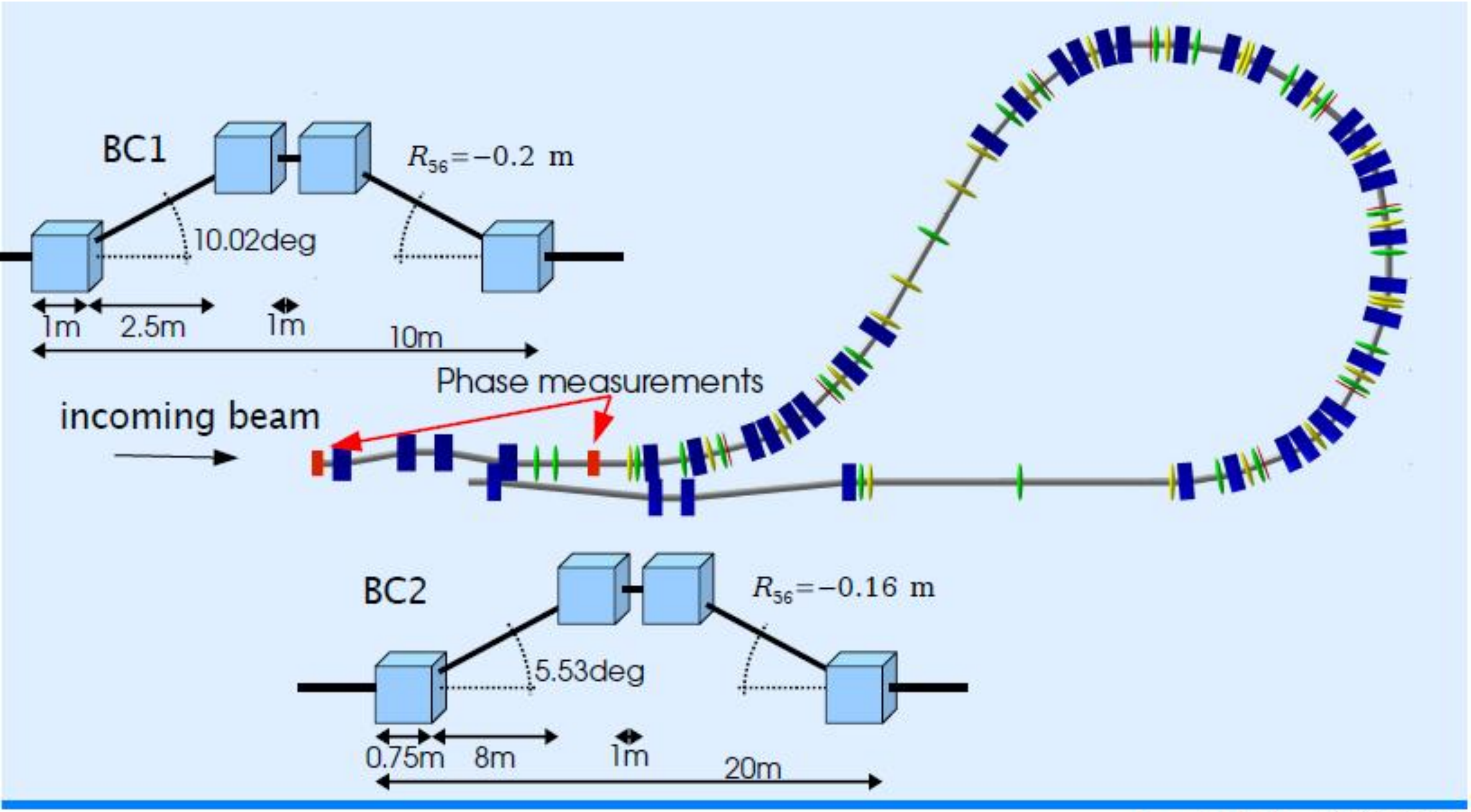
for Colin Perry

Reminder of phase feed-forward concept



Frank Stulle, 13.08.2009

Requirements & Assumptions - 1

Based on discussion in *August 2009*, we assumed:

***Speed:* 10ns**

- we shared the bandwidth limitation equally between kicker and amplifier
    - kicker active length is limited to 1.1m
- split amplifier bandwidth equally between amplifier modules and combining system
    - each needs a 70MHz bandwidth

***Kickers:* stripline kickers, 20mm clear aperture, 1m long**

- ~120 ohm impedance, balanced
    - each connected to amplifier with pair of coaxial cables
- fit maximum possible total length of kickers for minimum total power required
    - this means 4 at each bend (3, slightly longer, might be better)

***Deflection:* +/-720μrad at each bend**

- divided over 4 kickers = +/-180μrad at each

***Amplifier architecture:* modular, MOSFET**

- standard solution for fast, high-power amplifiers
- output from many low power modules have to be combined
- output voltage has to be stepped-up to provide the kV needed by the kicker
- the *very low* duty factor required (0.002%) is very unusual
    - it allows extremely high power densities and (relatively) low cost
- *note:* MOSFETs have almost entirely superceded bipolar transistors in this role

A Preliminary System Concept

It can be done – but looks very expensive. This is what we came up with:

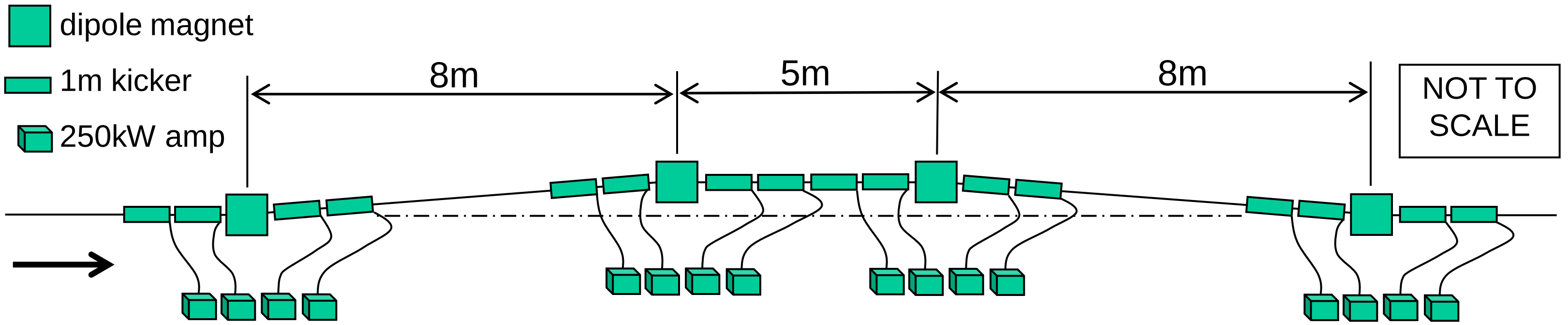
- 4 kickers at each bend
- 250kW peak power amplifier to each kicker
- 256 amplifier modules in each amplifier
- 1.2kW output each amplifier module (1kW after losses in combining etc)

- ***amplifier size:* 60 x 60 x 30cm** (=100 litres) min (double that is more comfortable)
- ***amplifier cost:* £75K per 250kW amplifier** (£300 per kW delivered to kicker)

****** This is all very very approximate ******

  - it makes no allowance for technological progress
  - no single dominant cost, so estimates very rough until details worked out
  - very dependent on high-volume costs: we have no sound basis for these

- 16 amplifiers & kickers / drive beam, 768 amplifiers total, 200MW total peak power
- ***SYSTEM COST:* £60M** (perhaps +/-£30M)

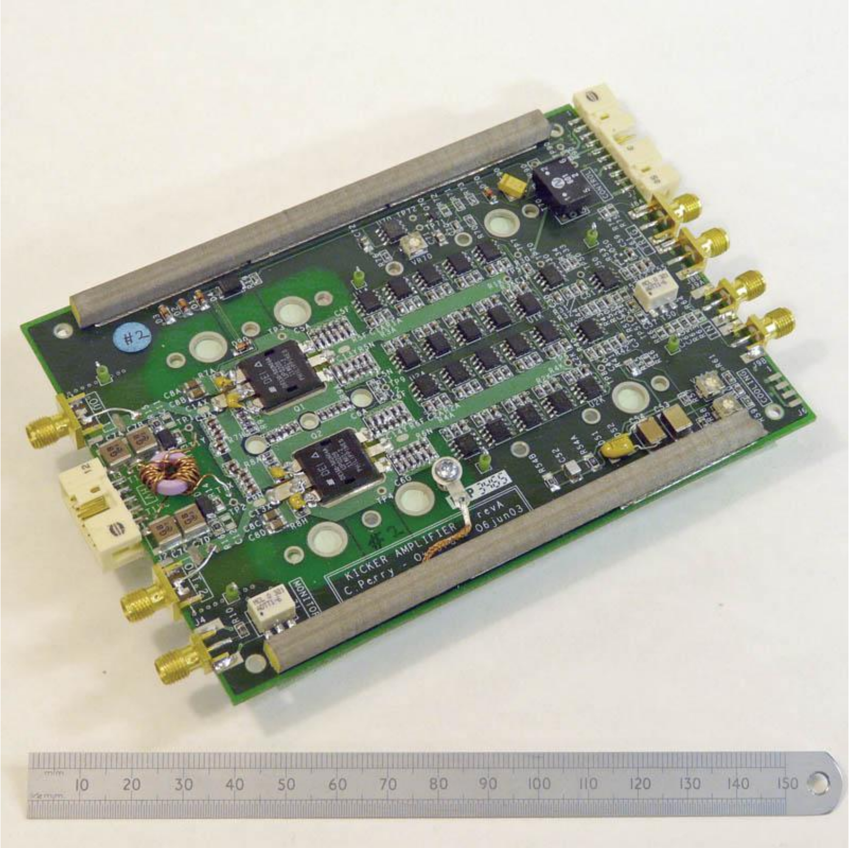


Technicalities – Amplifier Modules – 1

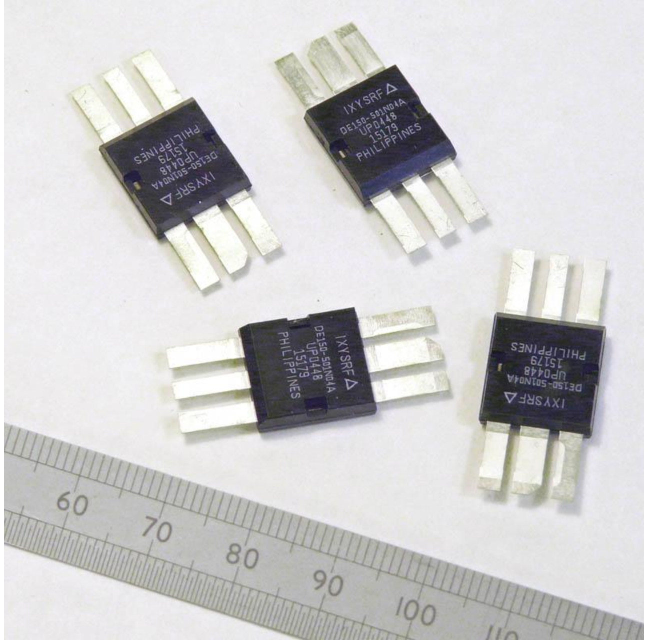
Module power is a matter of cost and size

- sweet spot looks today to be 1 to 2kW peak for 100MHz module bandwidth

- we are forced to low voltage, low impedance operation, and transforming the output



⮙ 2kW peak output
10ns amplifier module



⮘ typical fast, high voltage MOSFETs
(DE150-501N)

Technicalities – Amplifier Modules – 2

1)	Polyfet	LR301	Dual	LDMOS	28V	0.6kW	0.15ns	
2)	Polyfet	SX501	Dual	VDMOS	28V	0.7kW	0.2ns	
3)	**Freescale**	**MRF6VP11***	**Dual**	**LDMOS**	**50V**	**1.5kW**	**0.2ns**	**$170 @ 150**
4)	Polyfet	SR746	Dual	VDMOS	50V	0.6kW	0.3ns	
5)	IxysRF	IXZ215N12L	Single	HV	55V	0.6kW	0.4ns	2 x $32 @ 50
6)	IxysRF	IXZ210N50L	Single	HV	100V	1.0kW	0.8ns	2 x $18 @ 50
7)	IxysRF	IXZ318N50	Single	HV	100V	2.0kW	1.0ns	2 x $35 @ 25
8)	IxysRF	IXZ210N50L	Single	HV	200V	1.0kW	0.8ns	
9)	IxysRF	IXZ318N50	Single	HV	200V	4.0kW	1.6ns	2 x $35 @ 25
10)	IxysRF	DE150-501N	Single	HV	220V	1.3kW	1.3ns	2 x $28 @ 50

Examples of possible MOSFETs and output stages based on them

- table gives supply voltage, peak output power, & a speed ‘figure of merit’

- RF MOSFETs (1-4) tend to be expensive, low power, but fast

- HV MOSFETs (5-10) tend to be cheaper, higher power, but slower

- technically, #3 is the most attractive

- HV MOSFETs on 100V *may* be possible, but lower speed makes more demands on rest of system

- #10 is one we have used in two amplifier designs

Technicalities – Transformation and Combining

The ~50V at the MOSFETs is a long way from the >2.5kV needed at kicker
- a lot of voltage step-up is needed & will have to be obtained in a series of stages

Standard RF combiners can't be used
- they can't give the bandwidth & they are too expensive

This is not trivial:
- we need a high upper frequency limit
- we need a good low frequency response: this is unusual
- we need good efficiency per stage
- first stage has to be small and cheap
- last stage has to handle high peak power and voltage

We use transmission-line transformers to step-up impedance and voltage
- voltage ratios of 1:3 or 1:4
- impedance transformation is from ~3 to 6 ohms to ~50 to 100 ohms (differential)
- higher ratios cannot give the bandwidth needed

Combining is by parallelling outputs
- typically, 16 at the higher impedance level to give 1 at the lower
- this does not have the isolation and protection from faults of 'proper' combiners
- passive protection (~10% power loss) serves to prevent faults propagating
- a redundant fuse-based disconnect system isolates failed amplifier modules

System Issues

The obvious point of ***cost*** has been mentioned. Here are other importants issues that have been addressed in this scheme:

Size - seems reasonable. But allowing a little more space may significantly reduce costs.

Power consumption - low enough to not give cooling problems nor significant electricity costs. Power stages would be enabled for at most 5us per bunch train.
- rough estimate: 500W per 250kW amplifier

Reliability - does not push things to their limit: saving money but impairing reliability is not acceptable

Fault tolerance - allows for modules failing without damaging others: it would continue to operate with a proportionate reduction in power

Self-diagnosis - system includes built-in test, and reporting of faults

Ease of maintenance - most faults require only plugging-in new small modules.
Note: very dense packaging tends to make this harder

Response correction - uncorrected response will *not* be sufficiently clean and accurate (many small reflections, non-linearities etc). Response would be continously tested between bunch trains, and digital correction applied at input.

Changed Requirements

In *Febuary 2010* we learned requirements had changed somewhat:

- required kick angle at each bend was reduced to +/-375 μrad
    - this would have reduced power per kicker to 66kW peak
    - much more reasonable than the previous 250kW

- but energy spread of beam & dispersion of chicane increased kicker aperture
    - 0.5% rms energy spread, 1m dispersion
    - adds 5mm rms spread to beam width in middle section
    - to accept up to 4σ in energy, extra 40mm aperture needed
    - allowing for beam deflection and a finite beam size, need 50mm aperture
    - brings power back up to 410kW peak

- allowing any sort of margin brings this to 600kW
    - eg for a slightly higher energy spread than assumed

Later it was indicated that full kick would not be essential at full bandwidth

- this may prove a useful dispensation, but doesn't have a radical effect

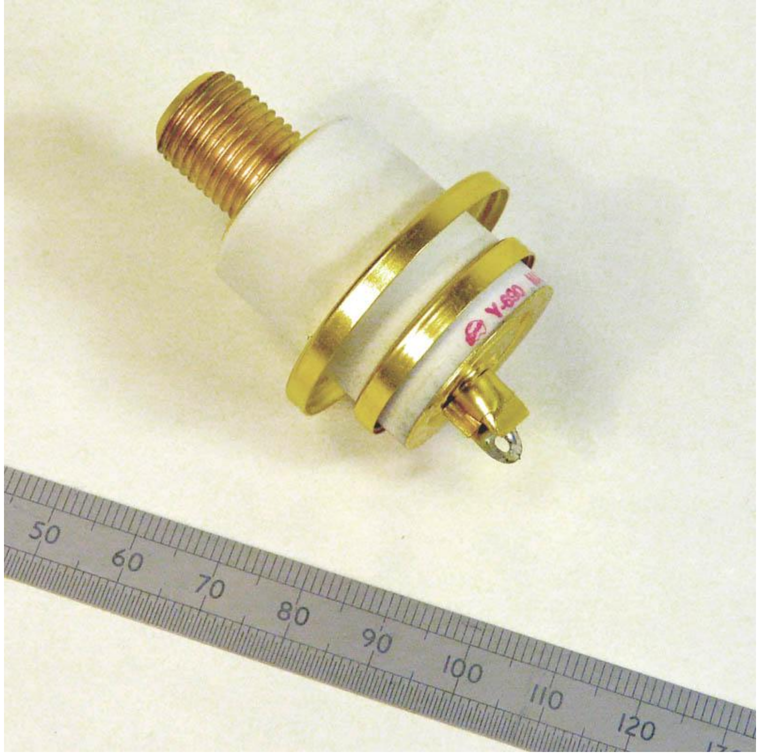
A Technology Option: Vacuum Tubes - 1

Vacuum tubes should not be discounted.
- capable of high peak powers
- capable of the high voltages needed to drive kickers directly.

Y690 planar triode looks useable
- factory confirms it will remain available
- multiple tubes can provide high powers

We have a conceptual design for a 500kW peak power amplifier:
- 7 tubes with plates in parallel drive each kicker strip
- each tube has its own MOSFET driver
- believe we have a solution to critical problem of protecting driver from flashover
- could fit in 30 x 20 x 15cm (+50% for power supplies etc): total 14 litres
- cost: maybe around £40K

(We have used the tube. We only got 5kW peak, 40MHz from one, but should be able to push this to 35kW, 65MHz)



⮙ Y690 Planar Triode

A Technology Option: Vacuum Tubes - 2

Another possiblity – the 3CPX10,000U7 pulse-rated triode

- this was suggested by an Eimac engineer

- it should remain available

- it is a large, transmitting type tube

- CPI would make a special with reduced cooling fins

- pair ought to do 500kW peak with 100MHz _output stage_ bandwidth (perhaps even 750kW or so...)

- attractive as an output stage, _but I don't yet see how to drive them_

- might be hard to get _overall_ bandwidth better than 60MHz

- amplifier would be larger than with Y690s: perhaps 45 x 30 x 30cm

▲ 4CX5000 – similar to the 3CPX10,000U7 but a bit taller and slimmer

Engineering Improvements

Better, cheaper parts (esp MOSFETs) by the time system has to enter production

- gains likely to be modest

Engineering for high-volume manufacture

- get modules smaller & simpler than I assumed
- design for automated assembly

Volume purchasing

- I've *no idea* how parts costs fall in 100K+ quantities...

Special MOSFETs

- standard parts are in expensive & bulky high-power packages
- RF types are made and tested to meet demanding RF test specifications
- we need neither
- an existing die, packaged & tested to our requirements, *might* save costs

Driver ASIC

- an analog ASIC for the driver part of module could reduce size and cost
- feasible but difficult: analog ASICs are hard...

Exploit reduced drive requirement at high frequencies?

- *may* permit higher voltage, higher power, & cheaper output stages to be used
- not a safe assumption until fully worked out and demonstrated
- might offer a factor of 2 to 3 saving

Note: compound amplifiers (separate HF & LF parts) don't seem feasible

Kicker Improvements

Optimized use of kickers – *probably worthwhile*
- required aperture varies between the kickers
- reducing aperture when possible reduces drive power
- modular amplifier allows configuration for different powers

Best compromise might be:
- halve the gap on kickers at first and last dipoles, and fit 2 kickers not 4
- keep drive power to each kicker the same
- saves 25% in amplifiers (number and total power) & reduces overall length

Caution: responses of kickers must match – easiest if kickers & amps are identical

Improved kicker design – *probably too difficult*
- stripline kickers are inefficient when aperture needed is longer across B
- ferrite yokes can confine magnetic field energy to useful region
- modest gain (factor of 2 in power?), but looks difficult and expensive

Separate fast and slow kickers – *doesn't seem to work out*
- exploit reduced kick required at high speeds
- separate fast (stripline) and slow (ferrite) kickers with their own amplifiers
- sound in principle, doesn't seem to work out in this case

Kicker with integrated drive amplifiers – *not meant seriously!*
Radical solution (impractical for CLIC): kicker with short sectional ferrite yokes slipped over ceramic beampipe. Each yoke has its own integrated driver. This can be a lot more efficient...

The Future – System Design

In designing the drive beam phase correction system, bear in mind that:

- amplifier system cost will be **very** large

- it will be **very** sensitive to:
    - maximum kick angle
    - kicker aperture

- power and cost go roughly as the square of each of these factors

- requiring a conservative specification can be **very** expensive
    - eg fully correcting for more of the time
    - going from '2σ' to '3σ' (95% to 99.7% of the time) more than doubles the cost

- any reduction in initial drive beam phase errors will be enormously valuable

Note: the increased kicker aperture required by dispersion is a major cost driver.
And were there to be incoming dispersion in the opposite sense:
- maximum beam size would be reduced
- smaller aperture kickers could be used
- drive power needed would be decreased
- all the kicker/amplifier systems made identical with no loss of efficiency.

The Future – Engineering Validation

It would be important to validate the basic concepts of the amplifier system.

amplifier output stage:

- can we actually get the predicted performance?

combining system:

- can we do this reliably?
- can we do it the final power levels needed?
- can we get adequate frequency response?

transformers and associated ferrites:

- will they work well enough?
- what are the detailed properties of the ferrites?
- how big and how expensive will they end up?

size and cost:

- push an amplifier module to a more-or-less finished design
- that would set an upper bound on size and cost
- amplifier module will dominate system cost

system concepts:

- functional test of a small-scale system would be an appropriate next stage
- eg: 16 amplifier modules and one combining stage, driving a kicker

The Future – The Vacuum Tube Alternative

Finally, a plea...

The modular, solid-state amplifier system is very attractive. But not simple, and not cheap

Vacuum tube amplifiers *may* be able to provide high powers at considerably lower cost

If the drive power requirement increase any further, they may be the only affordable solution

But this is not a standard vacuum-tube application: there are several practical issues that may turn out to be show-stoppers

So without some real development work, they will not be available as an option

There would be a real advantage in working on vacuum-tube amplifiers in parallel with solid-state designs