Depressed collector option for HE 50 MW X-band klystron

Jeff Neilson, Mark Kemp, Brandon Weatherford – SLAC

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Overview

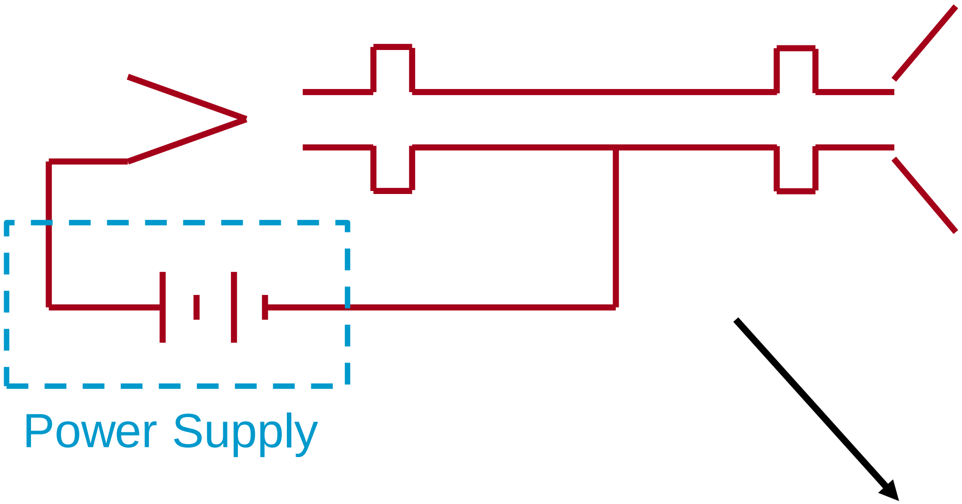
- Pulsed depressed collector technology
- Current programs
- Application to HEX
- Conclusions

High Efficiency Retrofit Program for S-Band Source at SLAC

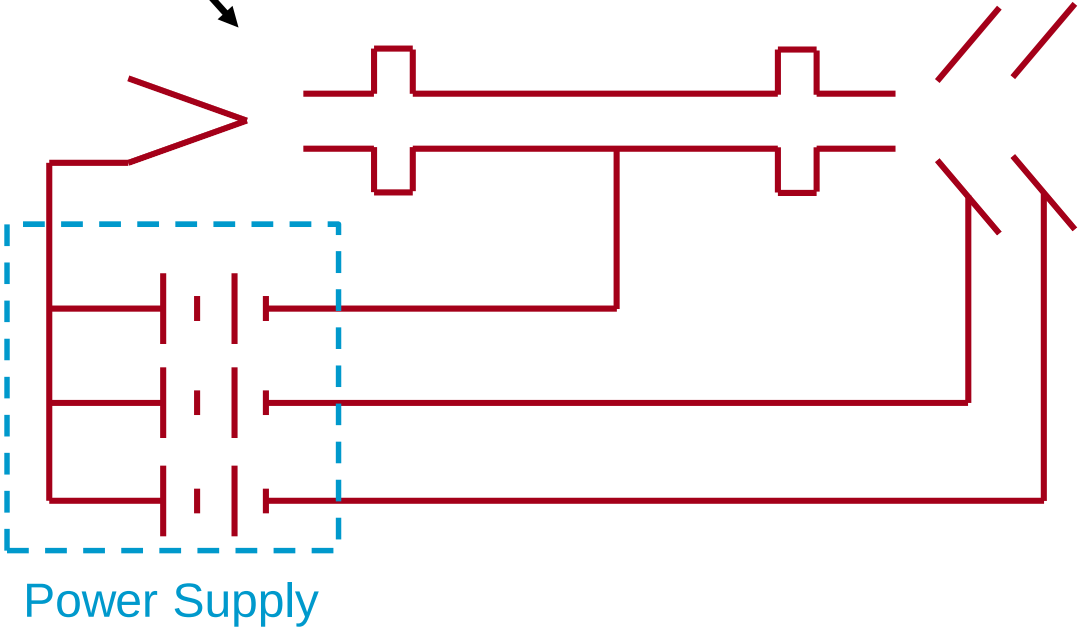
Two programs to upgrade efficiency and power of 65MW S-Band 5045 tubes used in SLAC LCLS

- Redesign of 5045 interaction circuit to increase rf output power via increase in efficiency using high efficiency bunching technique Bunch-Align-Collect (BAC)
- Increase system efficiency by recovery of energy in spent beam of klystron (depressed collector)
- Both approaches constrained to be “plug-compatible”

Conventional Depressed Collector Power Supply

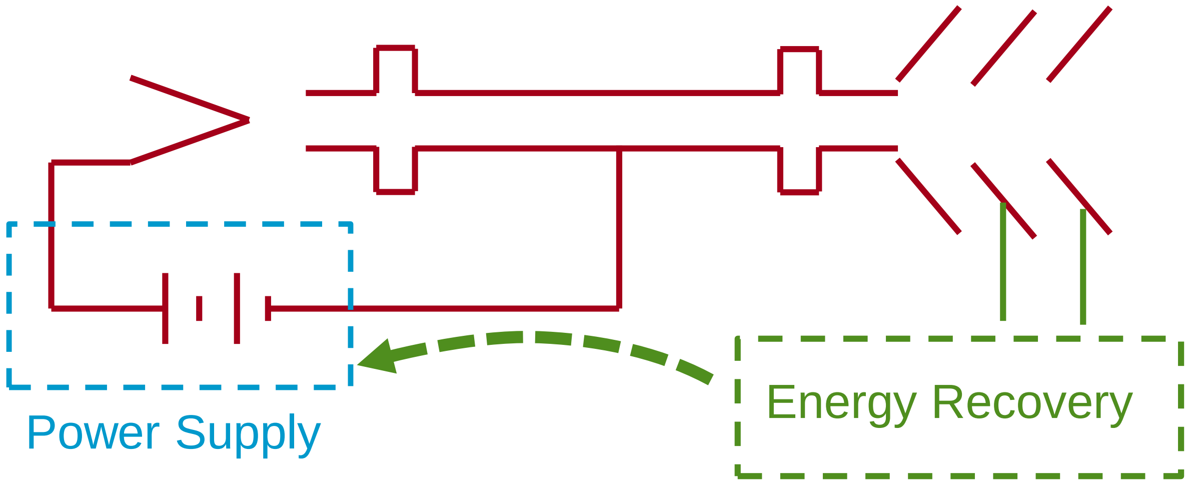


In the conventional approach to depressed collectors, the power supply must be replaced with one appropriate for multiple collector stages



Upgrading existing systems is very expensive

Feed-forward energy recovery scheme

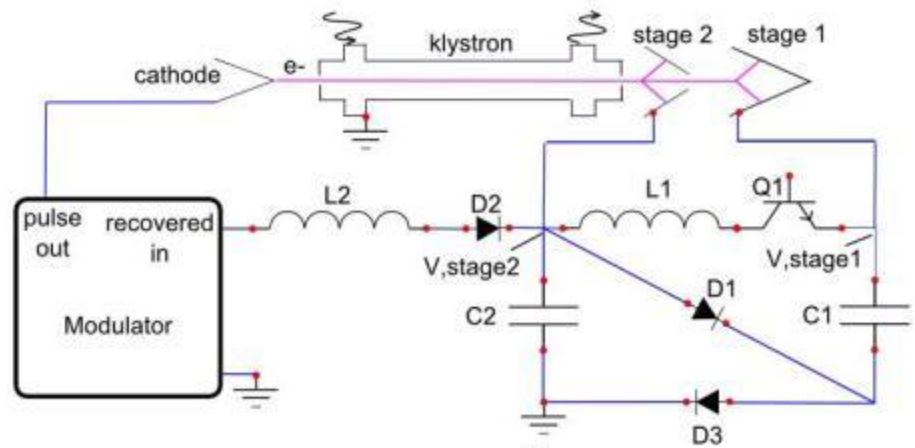


Ideal Characteristics for “drop-in” retrofit for use of depressed collectors for increased efficiency :

- Existing infrastructure is re-used so power supply remains the same
- Energy is recovered by a separate component, and returned to the DC supply
- Energy recovery is completely passive

An “Inverse” Marx Energy Recovery Modulator

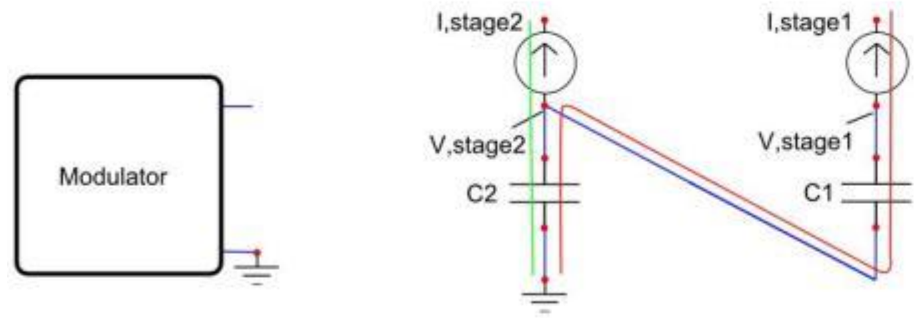
- Capacitors charge in series, and discharge in parallel
- Each cell pre-charged to a voltage
  - The initial voltage at a tap is the number of cells below that tap times the pre-charge voltage



(a)

During pulse

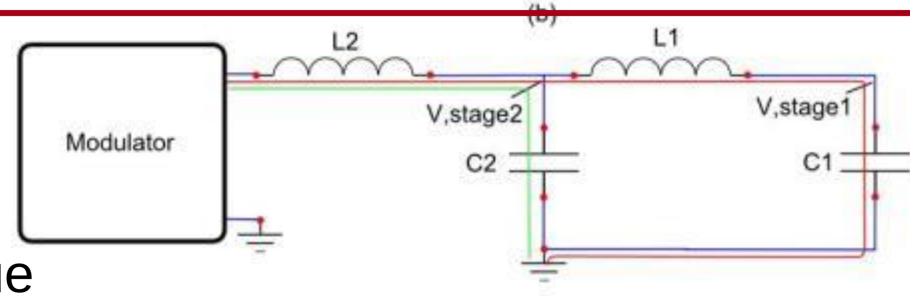
- Voltage rises in response to current to stage, and capacitance



(b)

In-between pulses

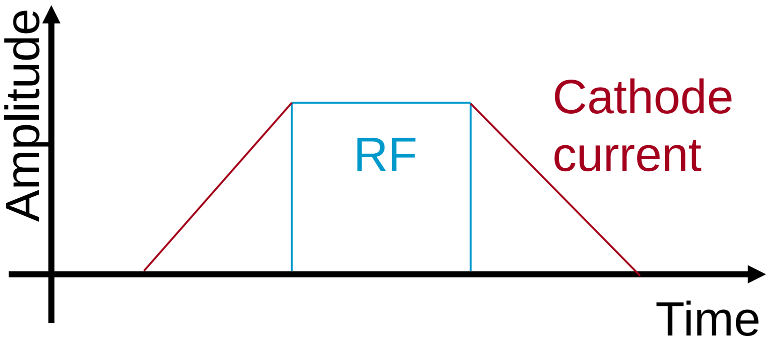
- CLC resonant structure transfers energy in capacitors to modulator
- Voltages re-settle to pre-charge value



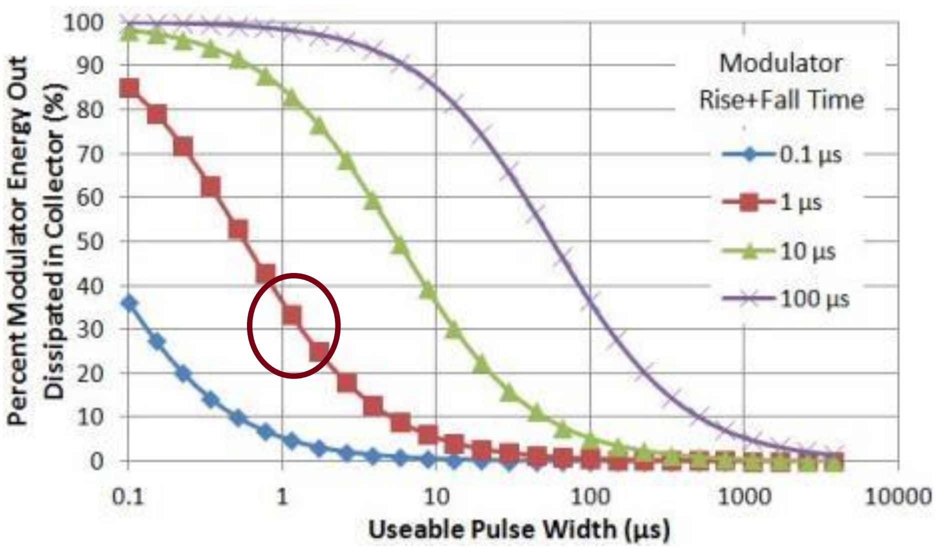
(c)

Ability to Recover Rise and Fall of Pulse

RF is applied when the cathode current is flat

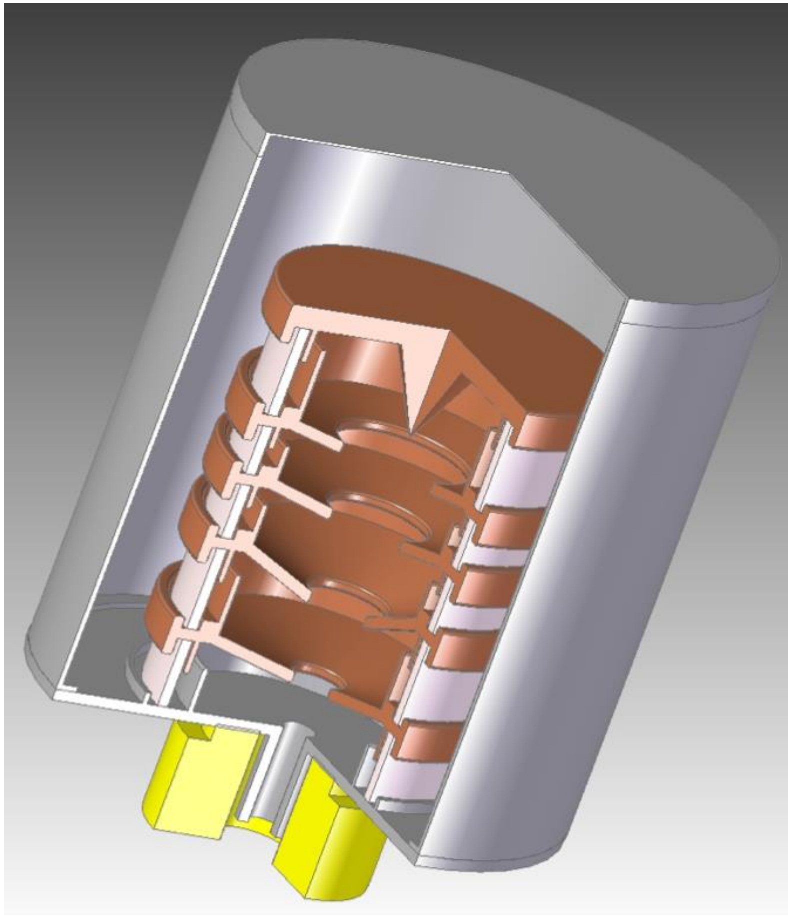


Energy wasted in collector during rise and fall times

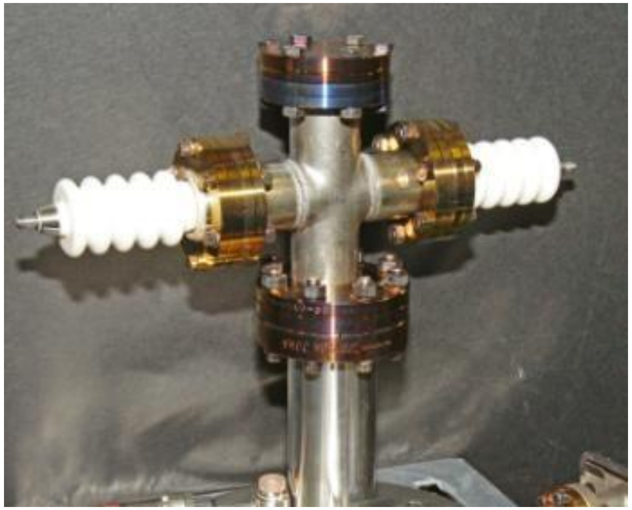


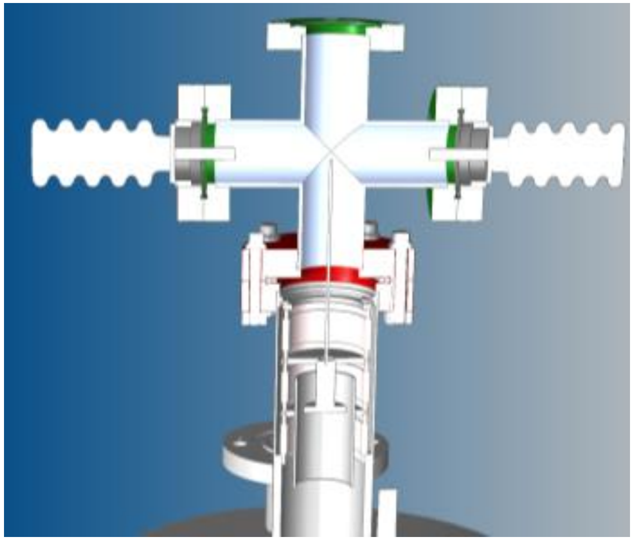
- A key advantages of a depressed collector for pulsed klystrons is the ability to recover energy during the rise and fall time
- Even for well designed modulators with short rise and fall, large fractions of the energy supplied to the beam are wasted
- With proper energy recovery, could relax modulator rise and fall constraints, potential cost savings

Test Results and Current Programs



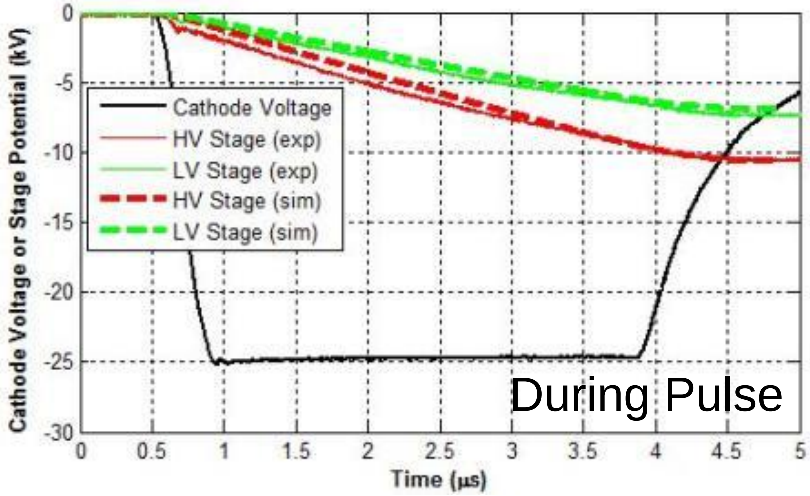
Sub-booster Demonstration (S band, 65 kW, 25 kV tube)



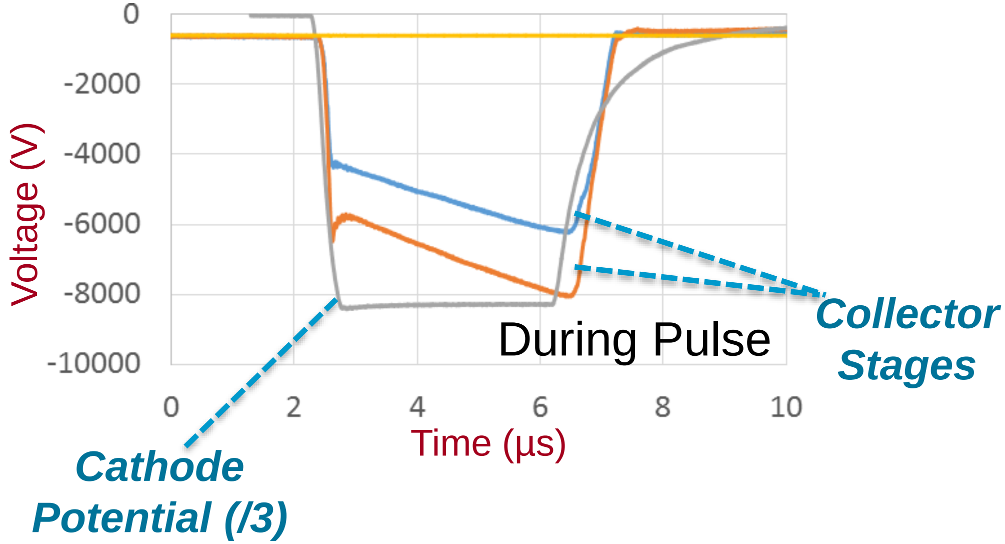


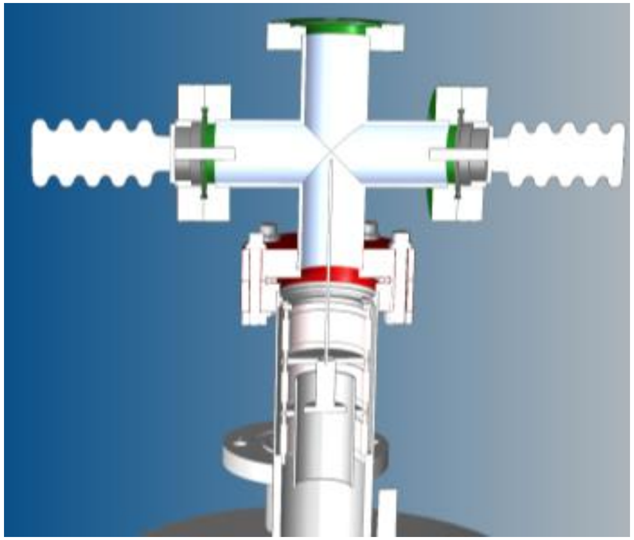
Sub-booster Demonstration
Comparison of Simulation to Experiment

Without pre-bias applied:



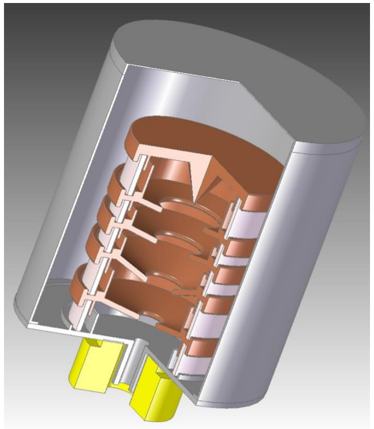
Capacitors pre-charged:





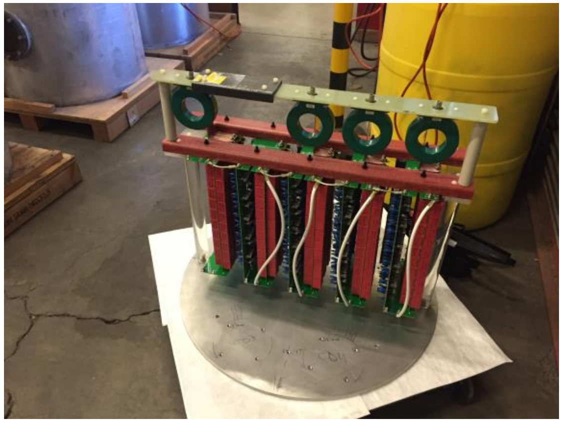
Current Testing at SLAC

- First test of multi-stage depressed collector with energy recovery between pulses has just been started
- Collaboration between SLAC and CPI
- Four stage collector on modified VKS-8262 tube (2.856 GHz, 5.5 MW peak, 6 us, 180 Hz, 45% efficiency)
- Collector predicted to improve total efficiency to 65%



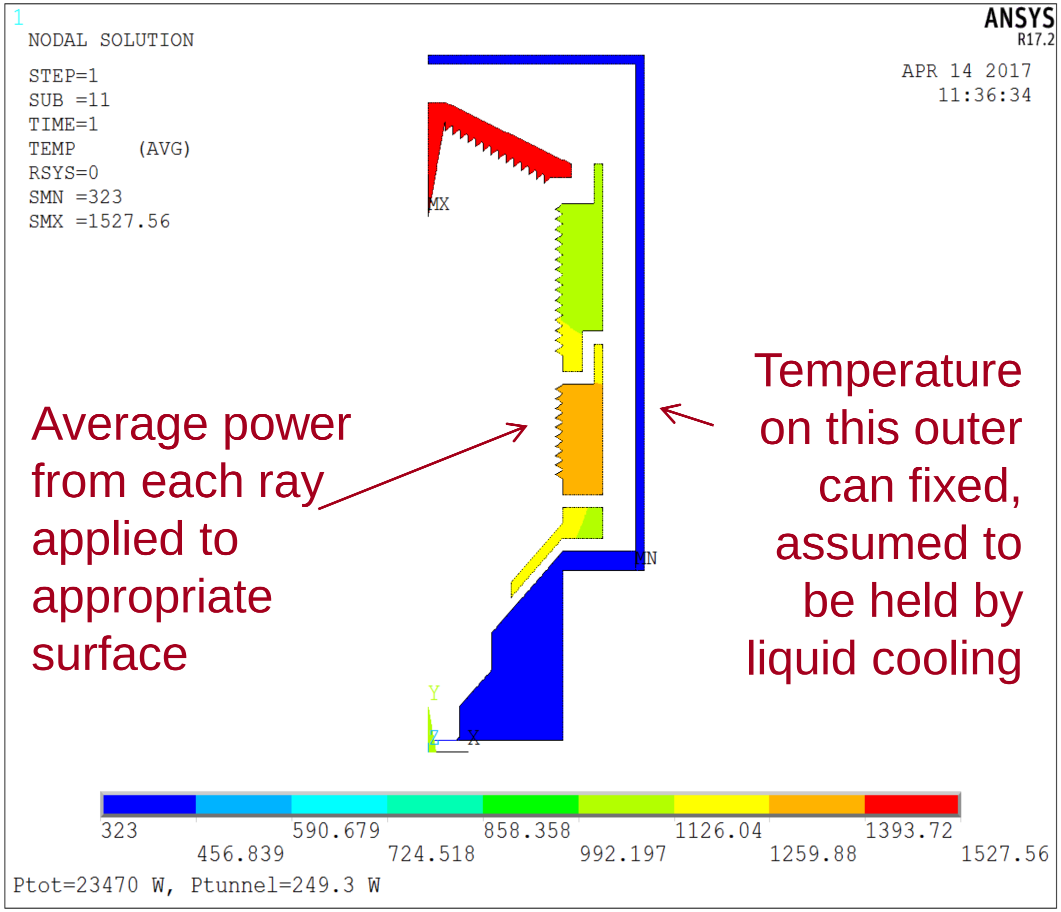
Depressed Collector on VKS-8262

“Inverse” Marx power recovery module

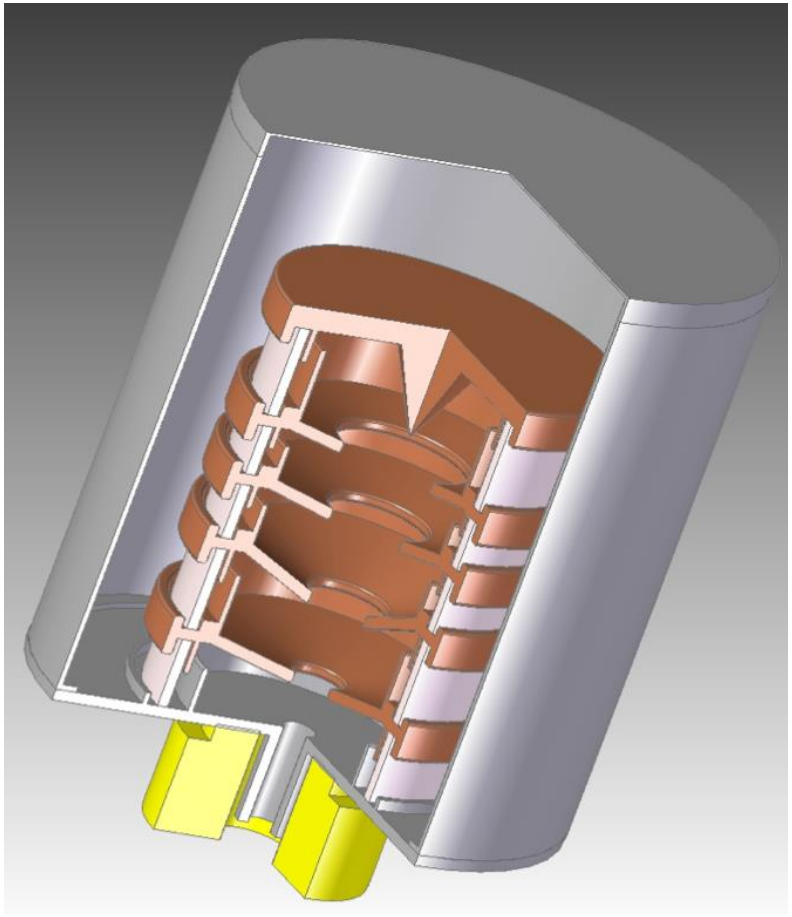


Program for 5045 Test

- Will use radiation cooling with isotropic graphite surfaces
  - Collector efficiency 53 %
  - Total efficiency = 68%
  - Include three generations of secondaries
- Test in late 2017



Application to HEX Klystron



Efficiency Gain Estimate for HEX

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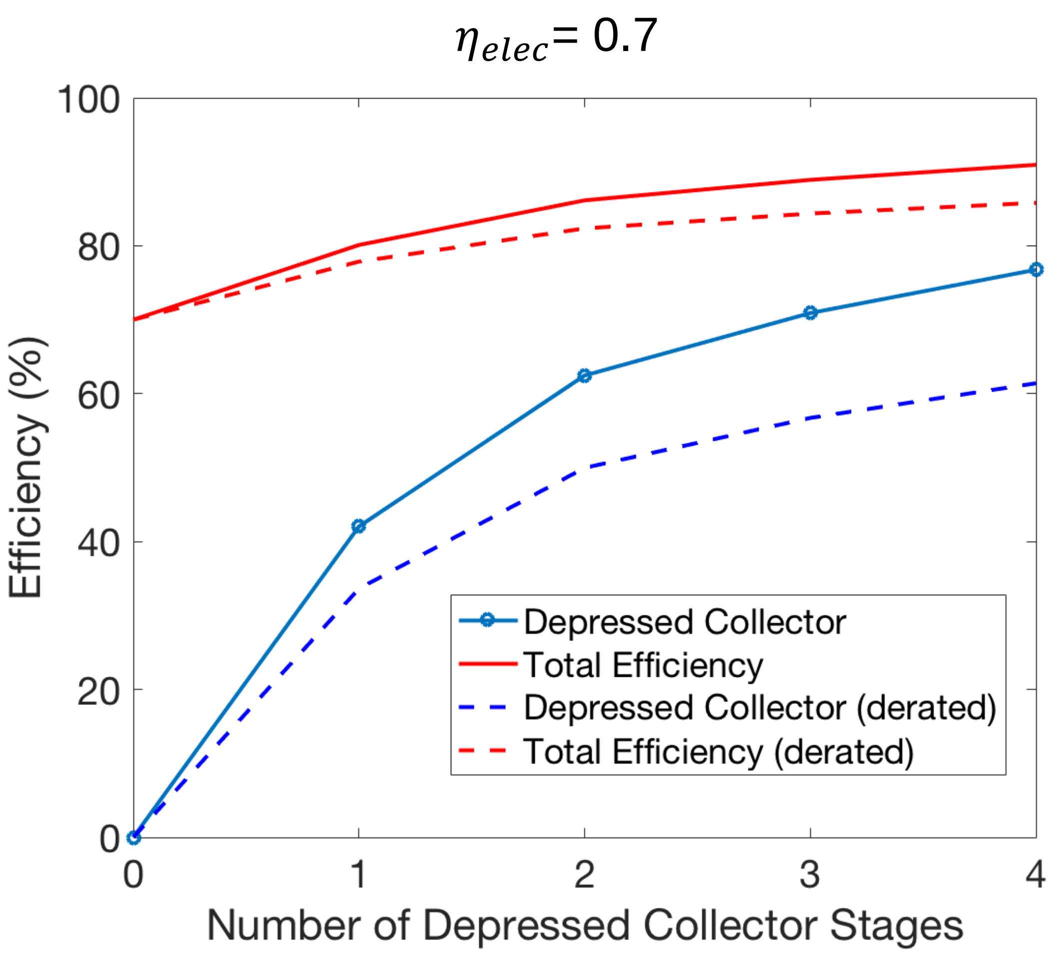
- Theoretical upper limit for collector recovery efficiency ($\eta_{collector}$) obtained using spent beam data from HEX circuit design
- Total system efficiency given by

$$\frac{\eta_{elec}}{1 - \eta_{collector}(1 - \eta_{elec})}$$

Using circuit efficiency (η_{elec}) value of 0.7 from circuit efficiency calculations



Rough Power Savings Estimate

- Assume 50MW peak rf power, duty cycle 0.01%
- Average power savings per tube is 1kW for increase in efficiency from 70->80%
- Capturing the 30% energy loss in rise/fall time at 60% efficiency saves 2kW per tube
- For recent CLIC concept, 5000 tubes with operation time of 5000 hours/year:
  5000 tubes X 5000 hours X 3 kW X 50 Euro/MW hour
  => 3.8M Euro/year
- Calculation doesn't include savings from reduction in cooling costs, power plan acquisition cost, modulator cost reduction
- System efficiency
  - 0.7 modulator X 0.7 tube efficiency => 0.5
  - (0.7 / (1 – 0.6(1 - 0.7)) X 0.8 tube efficiency => 0.68

Conclusions

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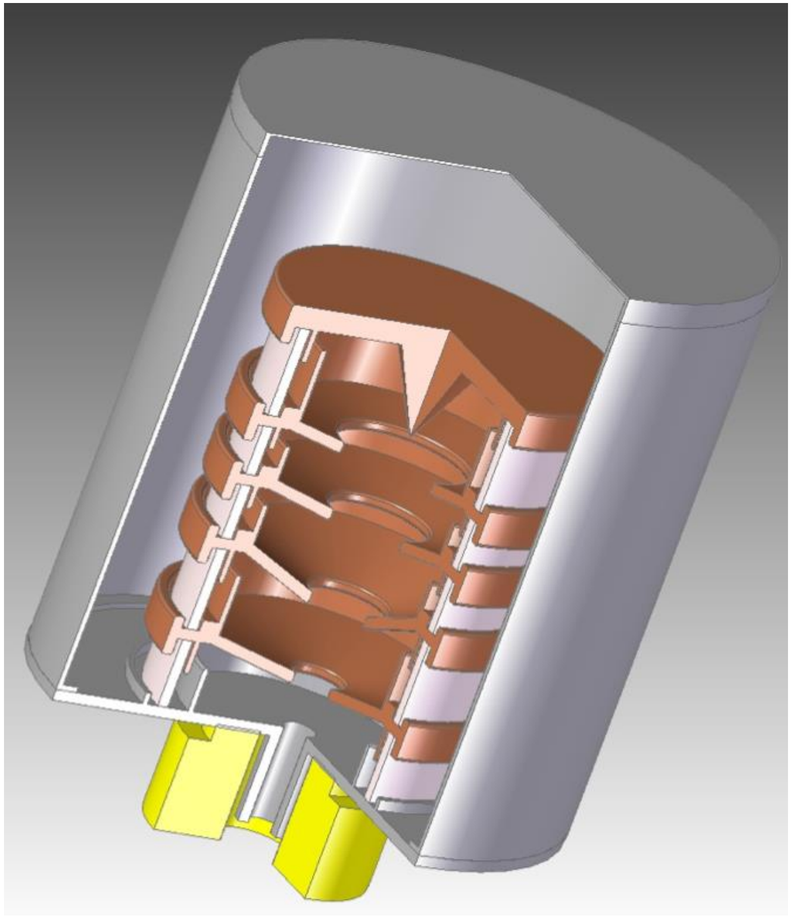
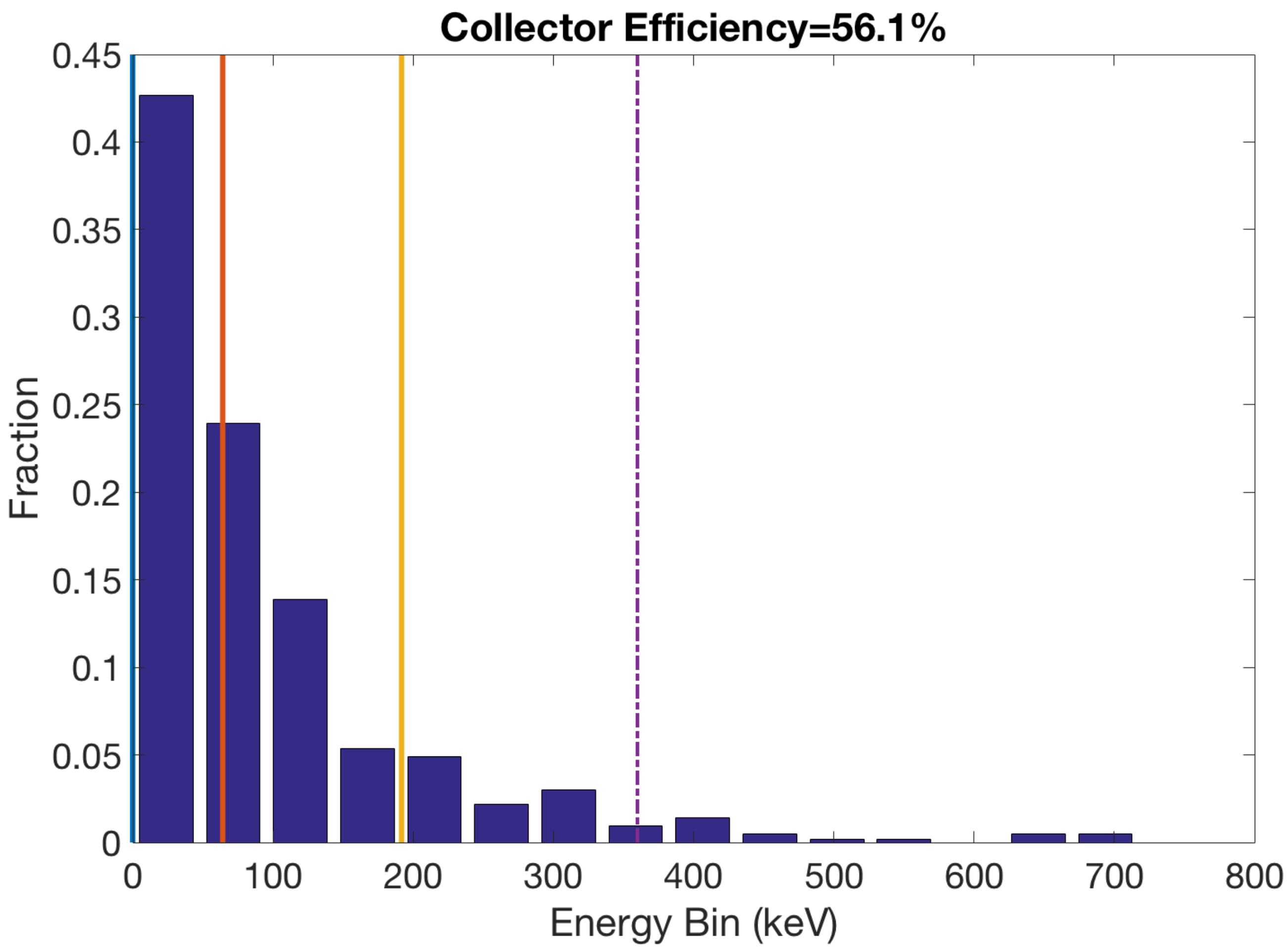
- Pulsed depressed collector technology particularly useful for retrofitting low efficiency (<50%) existing systems
- Use of depressed collector for HEX klystron likely to provide 80% tube efficiency
- Because of HEX high tube efficiency, largest gains result from recovery of pulse rise/fall time power loss

Backup Slides



Depressed Collector



The Effect of Collector Efficiency on Overall Efficiency

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Claimed correct relation:

$$\eta_{overall} = \frac{P_{rf,out}}{P_{beam,in} - P_{recovered}} \rightarrow \eta_{overall} = \frac{\eta_{rf}}{1 - \eta_{col}(1 - \eta_{rf})}$$

Claimed incorrect relation:

"If I have a 50% klystron, and a 50% efficient collector, half of the wasted energy is recovered, so I have a 75% efficient system"

$$\eta_{overall} = \frac{P_{rf,out} + P_{recovered}}{P_{beam,in}} \qquad \eta_{overall} = \eta_{rf} + \eta_{col}(1 - \eta_{rf})$$

- Say, with a 50% RF efficiency, and a 50% collector efficiency, the expected system efficiency would be 75%
- With 10W beam power in and 5W RF out, 5W*0.5=2.5W would be recovered and 2.5W would be wasted.
    - To produce 5W of RF out, how much net power is input to the system?
    - 5 W (for RF out) plus 2.5 W (wasted in collector) is 7.5W total input to the system
    - System efficiency = RF Pout/Pin = 5W/7.5W = 66%