

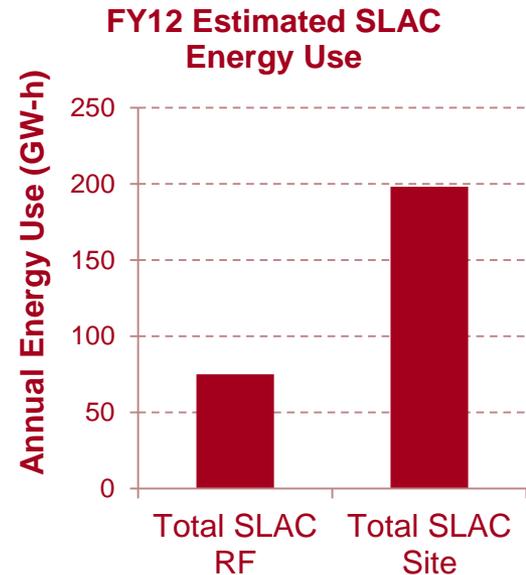
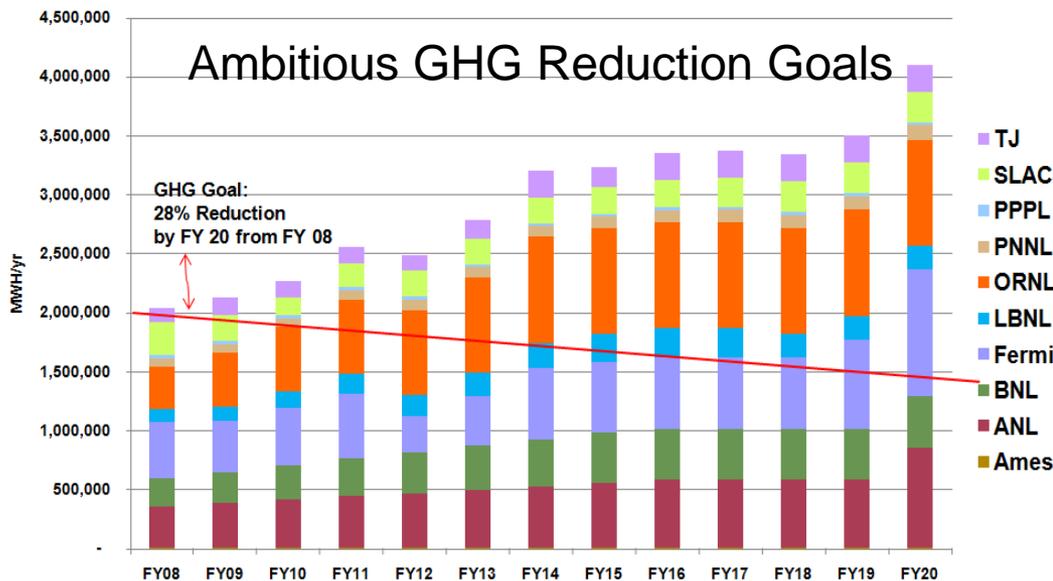
Impact of RF Source Efficiency on RF Accelerator Sustainability

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The HPRF Community Recognizes the Importance of RF Source Efficiency

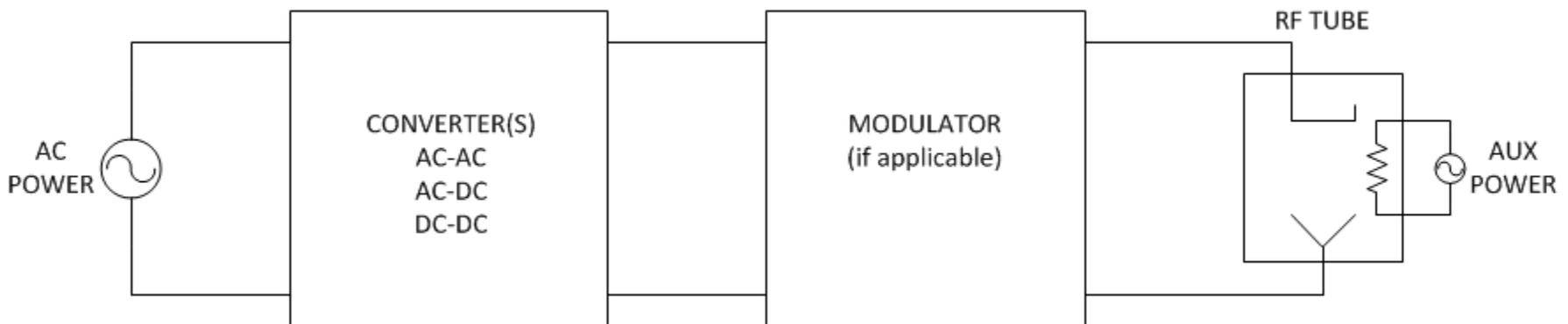
- The ESS “green requirement,” carbon-neutral design goal demands high efficiency RF sources
- CLIC will require high efficiency RF sources to fit within site power capacity
- US Executive Order 13514 Mandates 28% GHG Reduction: FY08 to FY20
- Current DOE complex RF accelerator energy usage is 1 TW-Hr/Yr
 - Projected to *increase* to 1.5 by 2018



Increasing RF efficiency will have a large impact on meeting efficiency mandates

HPRF Source Elements Impacting Efficiency

- RF tube or converter (e.g. klystron)
- Electrical power supply (including modulator in pulsed systems)
- RF drive
 - Typically insignificant for high gain sources (e.g. klystron)
 - May be >10% of total power consumption for low gain sources (e.g. triode)
- Auxiliary power (e.g. heaters, electro-magnets)
 - Typically <5% of total power
- Waste heat removal
 - Secondary evaporative cooling ~0.1 W consumed per W removed
 - Refrigerated cooling ~1 W consumed per W removed



RF source efficiency is the product of the parts

- Power Converters
 - Typically long life
 - Output voltage often fixed, may not readily support a different RF tube
 - High power systems often use unregulated transformer rectifier
 - High efficiency, ~95%
 - Lack of regulation may decrease RF tube efficiency (increased headroom required)
- Modulators
 - Long-life, but may have consumable elements, e.g. thyratron
 - Often fixed voltage and/or current, may use impedance transformer
 - Efficiency can exceed 95%, but may be <50% for short-pulse, high voltage devices

- Several types of converters are used in accelerator applications
 - Klystron
 - IOT
 - Triode/tetrode
 - Solid state amplifier
- RF sources typically have lifetimes less than the desired life of the accelerator
 - Vacuum tube devices are commonly re-built a limited number of times
 - At end of life, sources can be replaced by more efficient upgrades
 - Analogous to replacing incandescent light bulbs with LED bulbs

In general, the RF tube is a HPRF system “consumable”

RF Source Efficiency Improvement Initiative: The Four Program Pillars are Important to DOE

- **Improve sustainability:** replace end-of-life RF sources with more energy efficiency devices and reduce Complex energy consumption
- **Improve RF system performance:** next-generation RF source development will address limitations of current source
- **Support the RF source R&D competency:** supplement base-program demands for this key competency to maintain a strong capability
- **Promote transfer of advanced RF source technology to US Industry:** improve international competitiveness of US manufacturing

Initiative benefits go beyond the needs of individual Labs or programs, to serve the broader needs of the Complex and the Nation.

US DOE Accelerator RF Survey Participants

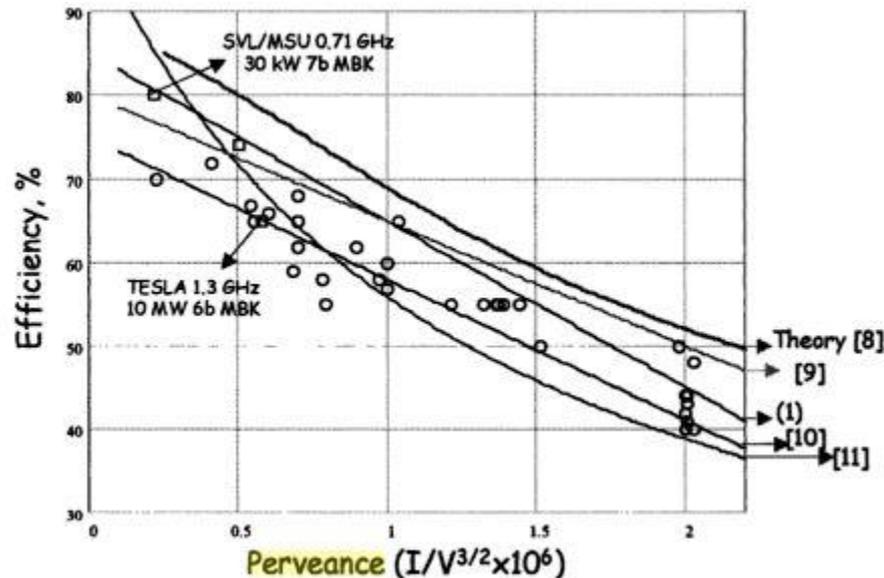
- Argonne National Lab
 - APS & ATLAS: A. Nassiri
- Brookhaven National Lab
 - Collider-Accelerator: V. LoDestro & A. Zaltsman
 - NSLS/NSLS-II: J. Rose
- Fermi National Accelerator Lab
 - Accelerator complex: J. Reid
- SLAC National Accelerator Lab
 - LCLS, FACET, & SPEAR3: C. Burkhart
- Jefferson Lab
 - CEBAF: R. Nelson
- Los Alamos National Lab
 - LANSCE: D. Rees
- Michigan State University
 - FRIB: D. Morris
- Oak Ridge National Lab
 - SNS: M. Crofford
- Lawrence Berkeley National Lab
 - APS: K. Baptiste

Survey Results

- Annual RF source energy consumption and effective efficiency
 - SNS: 59 GW-hr @ 35%
 - FNAL: 75 GW-hr @22%
 - LANSCE: 70 GW-hr @42%
 - APS: 22 GW-hr @34%
 - NSLS-II: 7 GW-hr @ 46%
 - CEBAF: 39 GW-hr @ 27%
 - SLAC linac: 72 GW-hr @ 27%
- Sources with the highest annual energy consumption, complex-wide
 - Y-567B tetrode: >80 GW-hr
 - SLAC 5045 klystron: 72 GW-hr

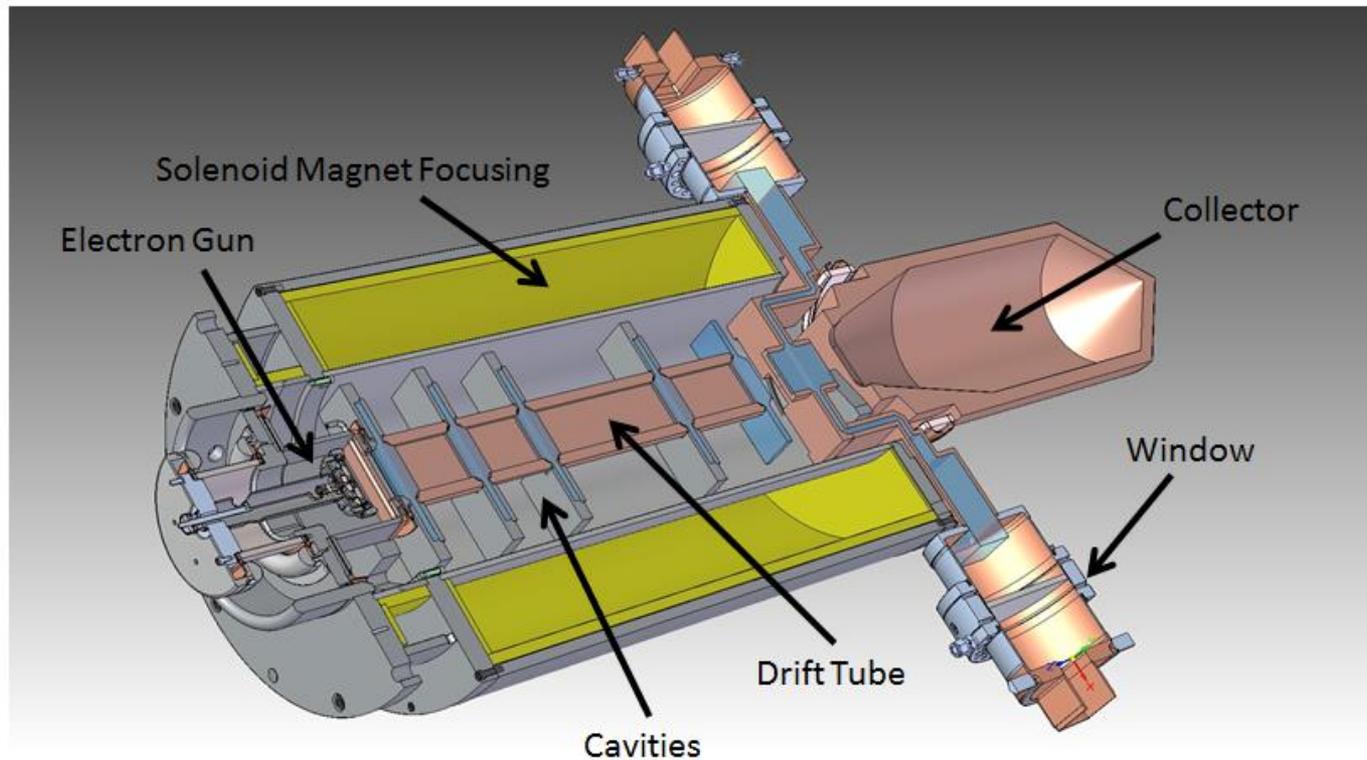
Two Approaches to Increase Klystron Efficiency

- Lower perveance
 - Space-charge de-bunching force increases with perveance
- Energy recovery
 - Space-charge de-bunching force limits extractable energy



Low Perveance Sheet Beam Klystron

Sheet beam klystron for Office of Naval Research FEL Directed Energy Program – 200 kW CW, 2.1 GHz



Very High Efficiency Source Development for New Systems - Matrix Multiple Beam Klystron (MMBK)

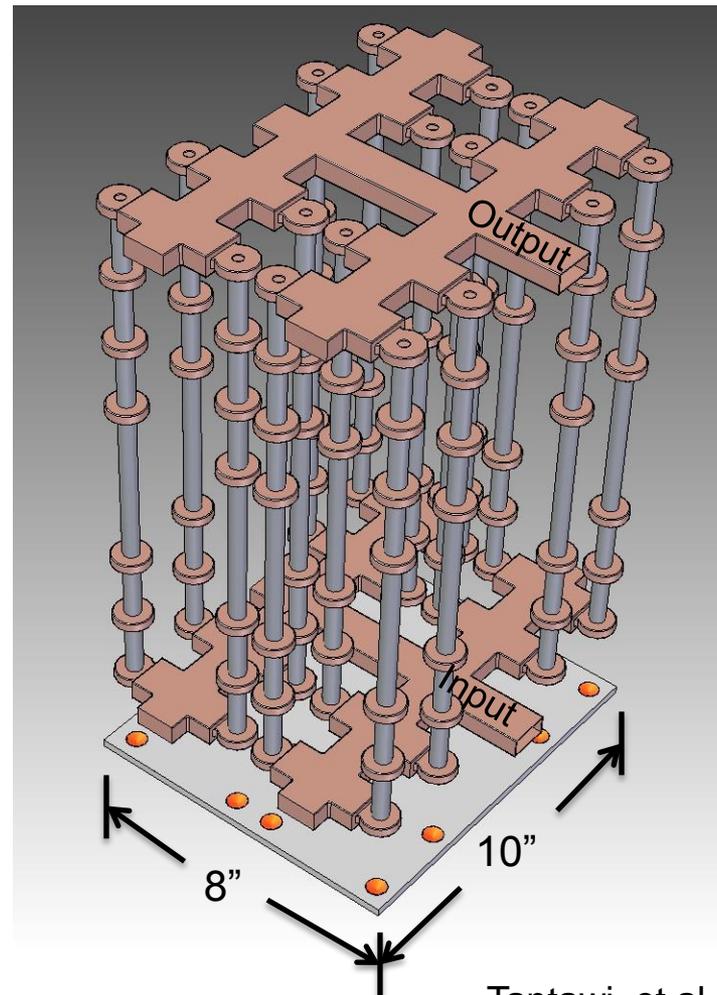
GARD funded study

Goal is very high efficiency klystron (70+%)
scalable design for next generation systems

- Power scales as N^2 where N is number of beams in row/column
- Graceful degradation with individual cathode
Periodic permanent magnet focusing (no DC solenoid)
- Low voltage to eliminate oil
- Novel high current density cathodes with low/no beam convergence to reduce mechanical tolerance sensitivity

With identical modules can take advantage of high production rate economies of scale (not possible with single beam klystrons)

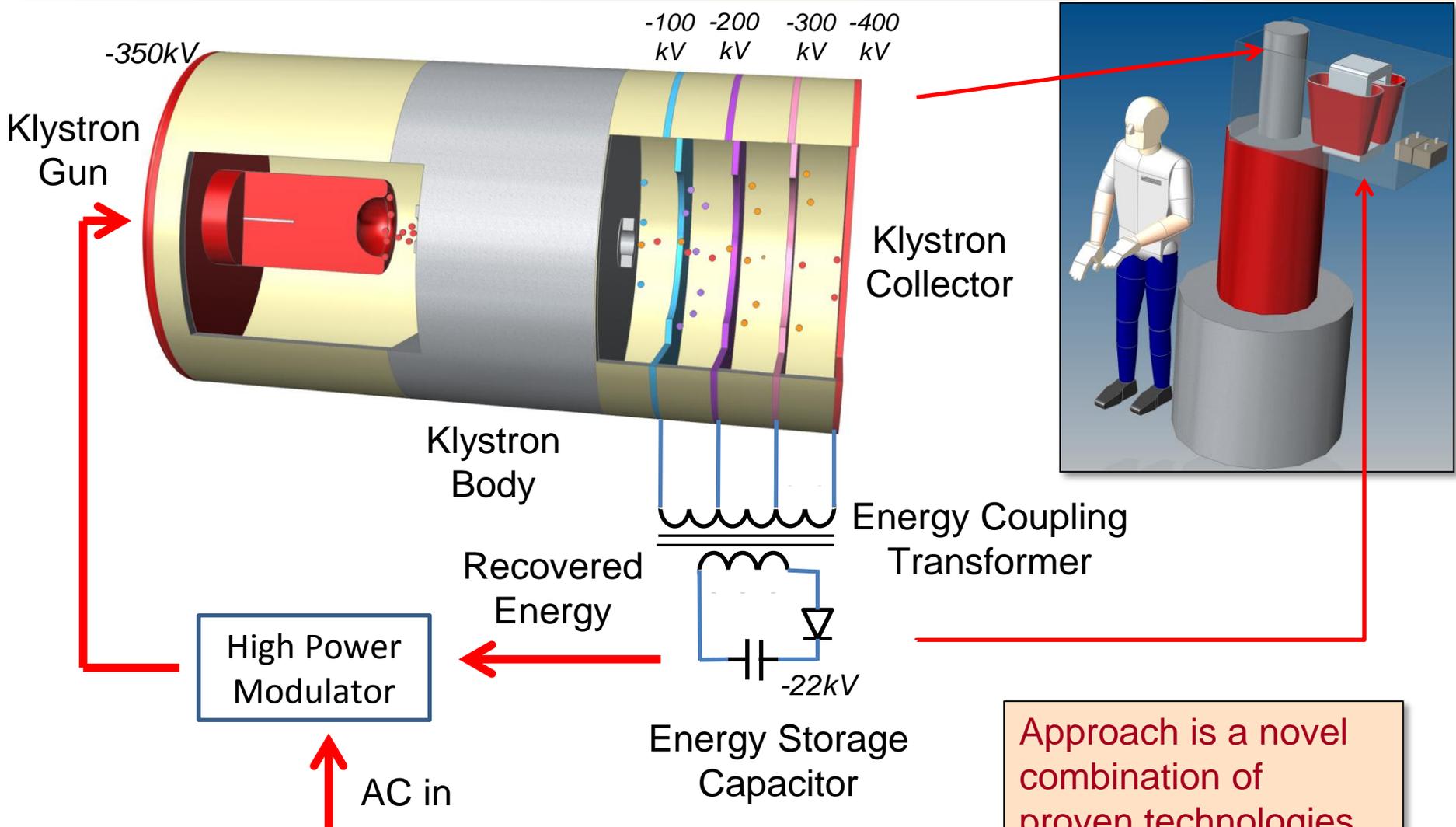
16 Beam 12MW X-Band MMBK



Tantawi, et al

Energy Recovery: Self-Biasing *Pulsed* Depressed Collector

SLAC



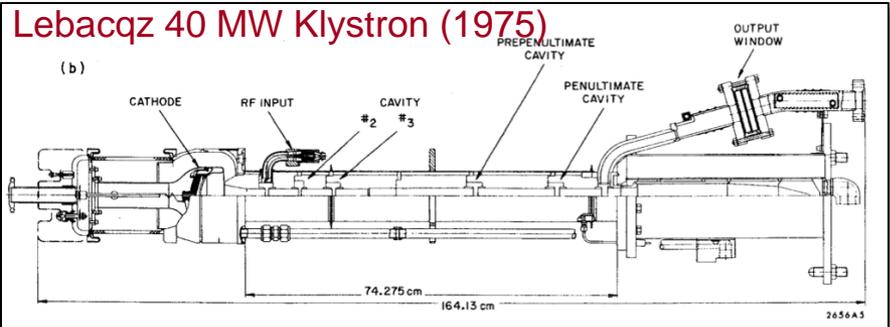
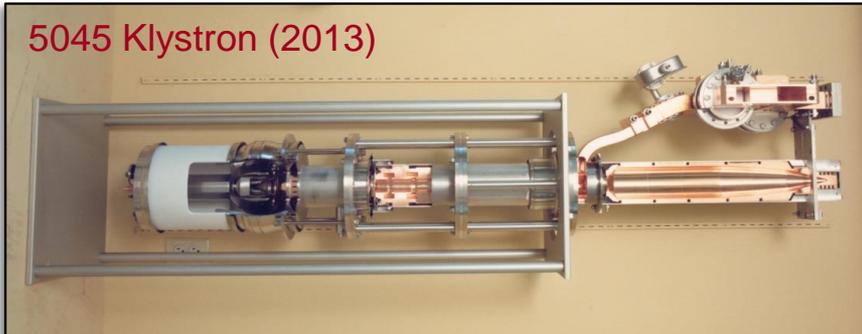
Approach is a novel combination of proven technologies.

Where Do We Get Innovative, High Efficiency RF Sources?

SLAC

- RF tube industry is mature and dominated by a few companies
 - Focus is on profits, minimal research, and risk aversion, little focus on energy efficiency
- 1975 Lebacqz 40 MW klystron is substantially the same as the current 65 MW 5045.
 - Incremental improvements have increased reliability and power
 - Essentially same design, materials, fabrication processes
- Individual programs are challenged to develop a new, high efficiency tube for their needs
- Socket compatibility issues
- **Workshop discussion: how do we overcome these obstacles?**

5045 Klystron (2013)



A microwave tube engineer from the 1960s could step right in and be quite familiar with much of what we do today.

Thank you