RF Power Sources for XFELs and ERLs

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RF Source Choices

- Frequency
  - L-band
  - S-band
  - C-band
  - X-band
- Modes of operation
  - Pulse
    - Short /Long
  - CW
- Devices
  - Tetrode (low-frequency, < 500 MHz)
  - Diacrode (low-frequency, <500 MHz)
  - Klystron
    - Conventional (Pulsed/CW)
    - MBK
    - SBK
  - IOT
  - Solid-state RF amplifier

Vacuum tube technology

Facilities Survey - XFELs

Project	Electron Beam Energy (GeV)	RF frequency	Type	Location
LCLS (operational)	13.4	2.856 GHz	Pulsed NC	USA
FLASH (operational)	1.2	1.3 GHz	Pulsed, SC	Germany
Eu-XFEL (const. Phase)	17.5 (20)	1.3 GHz	Pulsed SC	Germany
FERMI@ELETRA (operational)	1.8	3 GHz	Pulse NC	Italy
SCSS: RIKEN/SPring8 (operational)	8	5.7 GHz	Pulsed NC	Japan
NLS (proposal)	2.25	1.3 GHz	CW, SC	UK
NGLS (proposal)	2.4	1.3 GHz	CW, SC	USA
Swiss FEL@PSI (proposal)	5.8 GeV	5.7 GHz	Pulsed, NC	Switzerland
XFEL@PAL (proposal)	6 - 10	2.856 GHz/(5.7 GHz)	Pulsed, NC	S. Korea
SPARX	2.6	2.856 GHz/(5.7 GHz)	Pulsed, NC	Italy
SINAP/Shanghai (proposal)	6.4	5.7 GHz	Pulsed, NC	China
Max-lab (proposal)	3.4 GeV	2.856 GHz	Pulsed, NC	Sweden
WiFEL (proposal)	2.2 GeV	1.3/1.5 GHz	CW,SC	USA

L-band : 5, S-band: 5, C-band: 2(2)

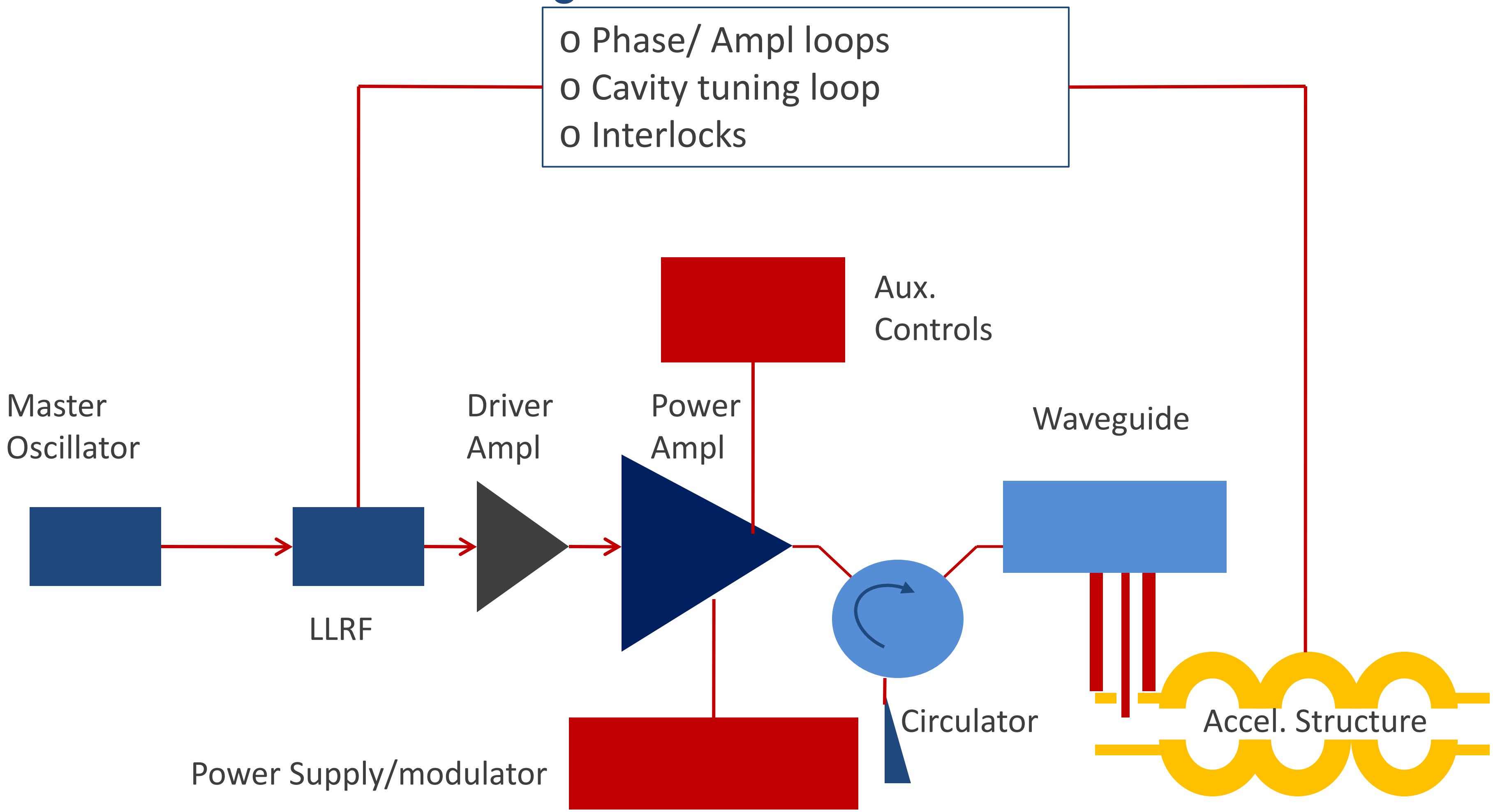
Facilities Survey - ERLs

Project	Electron Beam Energy (MeV)	Frequency	Type	Location
JLAB (operational)	120	1.497 GHz	CW, SC	USA
Cornell (proposal)*	5000	1.3 GHz	CW, SC	USA
KEK (proposal)*	5000	1.3 GHz	CW, SC	Japan
HZB (proposal)*	100	1.3 GHz	CW,SC	Germany
Budker Institute (operational)	98	180 MHz	CW, NC	Russia
ALICE (operational)	28MeV?	1.3 GHz	CW, SC	UK
BNL (R&D, const. Phase)	20	700 MHz	CW, SC	USA
PKU (under construction)	30	1.3 GHz	CW, SC	China
FZR-Dresden (operational)	40	1.3 GHz	CW, SC	Germany
JLAMP (proposal)	600	1.3 GHz	CW, SC	USA
FSU (proposal)	60	1.497 GHz	CW, SC	USA
Arc-en-Ciel (proposal)	1000	1.3 GHz	CW, SC	France

*Ongoing R&D

L-band: 10, VHF: 1, UHF: 1

RF Transmitter Configuration



Problematic for high current machines

Small for SC cavities
Large for NC cavities

~ 20 to 30%

~ 15 to 20%

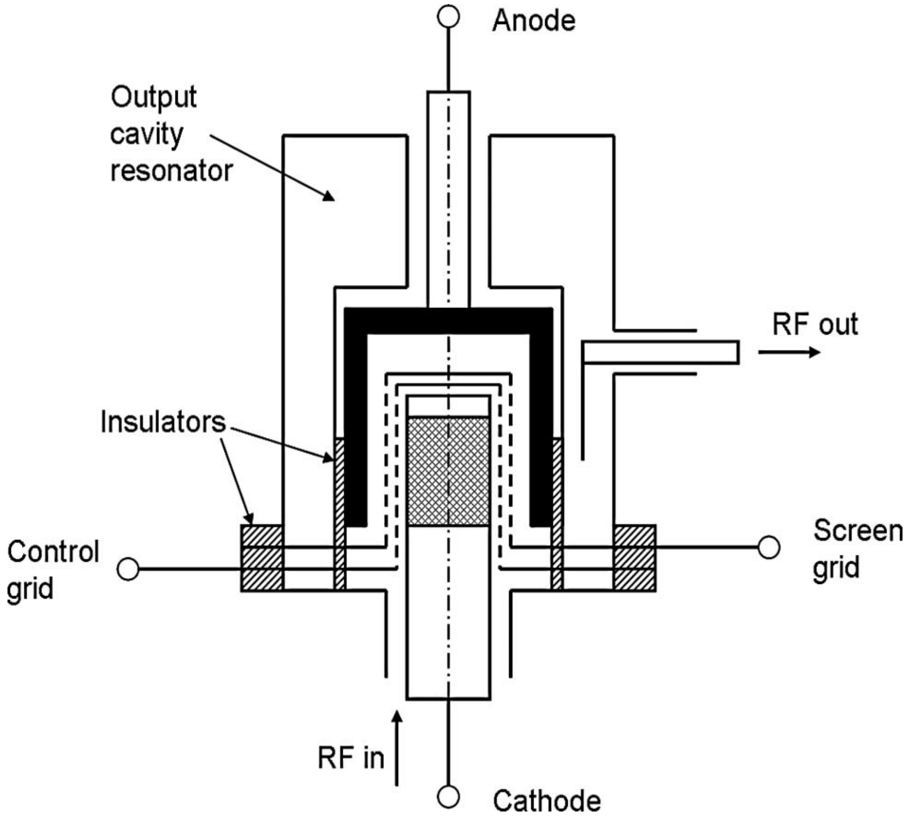
$$P_{RF} = P_{beam\ loading} + P_{cav\ loss} + P_{wg\ loss} + P_{overhead}$$

Performance Requirements

- Choice of frequency
  - In most cases accelerators are designed based on available rf sources
- Power level
  - Machine-specific
    - Pulse versus CW
- Gain
- Efficiency (wall-plug to RF)
  - It is more important for large machines
    - Potential cost savings
- Stability
  - Phase and amplitude
    - XFELs are very demanding
      - Phase jitter: ~0.01 deg. and voltage ripple ~0.01%
  - RF system reliability/availability
    - Beam availability (extremely important to facility users)
    - MTBF (extended periods of beam uptime with minimum interruption)
- Cost
  - Capital (appreciable portion of the total accelerator cost)
  - Running (efficiency is key for large facilities/ long-term operation)
  - Repair and maintenance
  - Footprint (impact on tunnel and building cost)

Tetrode

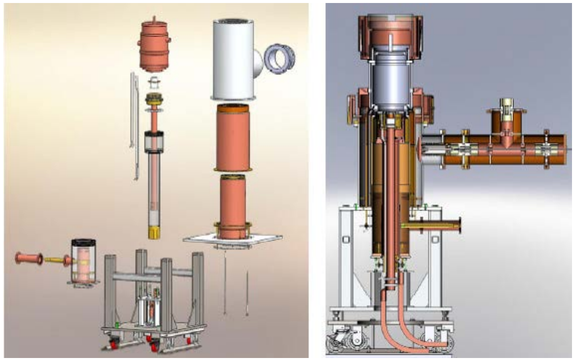
- Vacuum tube based on electron beam intensity modulation
- Typical parameters:
  - Frequency : 30 – 400 MHz (VHF band)
    - Finite electron drift time limits the achievable gain at much higher frequencies
  - Output power:
    - 10 kW to 2 MW CW or average
    - More in pulsed mode



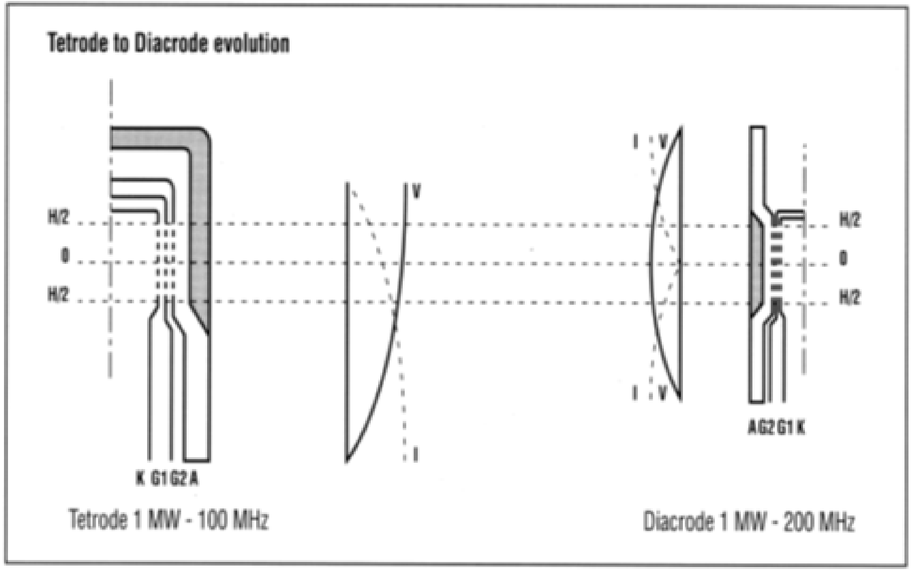
Diacrode

- Its symmetric geometry is optimized to couple to a $\lambda/2$ coaxial resonator
- Coaxial line between anode and screen grid is extended to a SC.
- Double-ended tetrode configuration allows to tune the device in ½-wave length
  - Maximum RF voltage in the middle of active part rather than at the top
- Smaller reactive current flow and much smaller power dissipation in the screen grid compared to tetrode
- It achieves twice the frequency × power product than a conventional tetrode
  - Frequency : 200 MHz
  - Output power:
    - 1MW CW, 4.5 MW with 500 μsec pulse, 1%duty cycle 1%duty cycle

Thales Diacrode TH628

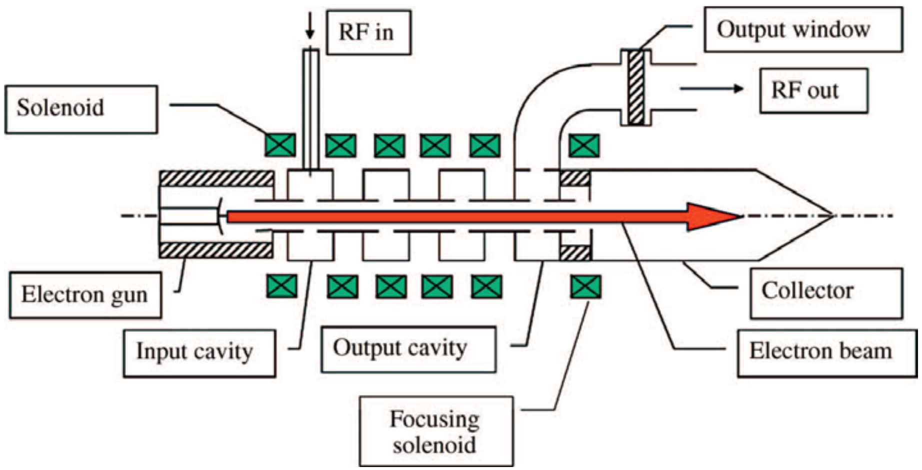


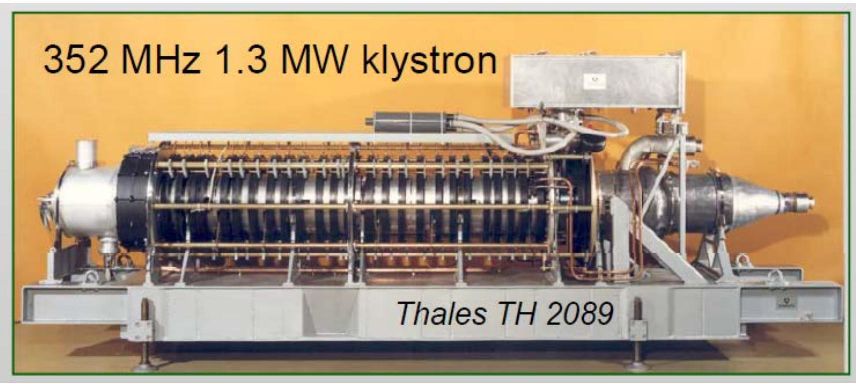
LANSCE diacrode based on 3.2 MW power amplifier



Klystron - CW

- Velocity modulation with input cavity
- Drift space and several cavities to achieve bunching
  - It is highly efficient DC to RF conversion
- High gain
- CW klystrons typically have a modulating anode for
  - Gain control
  - RF drive power in saturation
  - High efficiency operation
    - Over large dynamic range
  - Drawback: anode modulation has a low BW
    - ~10 Hz
- Frequencies
  - 300 MHz - 30 GHz
- Power
  - 60 kW/500 MHz (small accelerators) CW mode
  - ~1 MW / 300 MHz, 500 MHz, 700 MHz (larger accelerators) CW mode

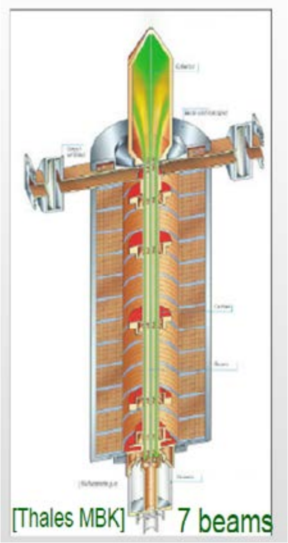


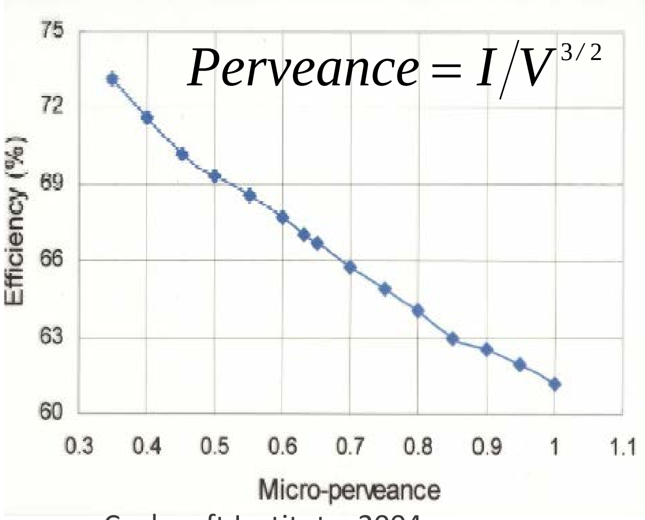


Klystron - Pulsed

- S-band
  - High peak power ~ 30 MW – 50 MW
  - Short pulse, less than 10 μsec
  - All are based SLAC-developed technology
- MBK (CPI, Toshiba, Thales)
  - Designed for high efficiency
  - Low beam perveance to maximize efficiency
    - 45% to 65%
  - High-power and longer pulses
    - 10 MW, 1.5 msec at low high-voltage: 120 kV
- PPM klystrons
  - SLAC X-band 75 MW PPMK
    - Significant saving , 80 MW focus supply
- SBK
  - Produce very high power at a relatively low voltage but high efficiency
    - A single beam is extended in one dimension and the current is increased by having a wider beam
    - An SBK, at higher frequencies can be fabricated with very few vacuum parts
    - One drawback: it may require overmoded cavities and must be operated at a frequency free from interference from neighboring cavity modes

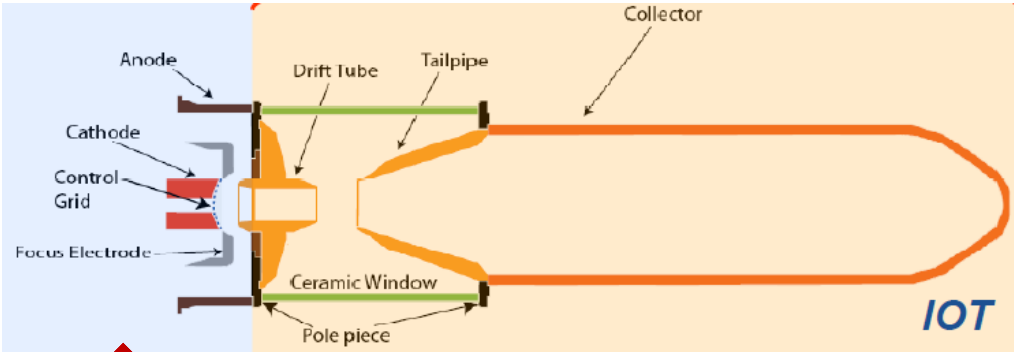
Toshiba S-band Klystron

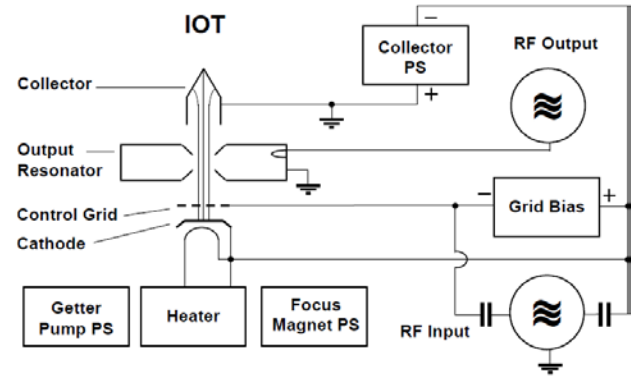




Cockcroft Institute, 2004

Inductive Output Tubes (IOT) - Klystrodes





As a tetrode

As a klystron

- Intensity modulation of DC beam by control grid
- TV IOT
  - 460 MHz – 860 MHz / ~60 kW
- IOT developed by CPI and Thales
  - 470 MHz – 760 MHz / 80 kW CW
  - High efficiency (70%) but with intrinsic low gain (20 -25 dB)
- L-band IOT for XFELs and ERLs
  - 16 to 20 kW CW, efficiency 55 to 65% (CPI, E2V, Thales)
- Main advantages of IOTs
  - Higher efficiency
  - Less A/P sensitivity to HV ripples
  - More economical

TV-IOT from E2V

TV –IOT from CPI

Solid-State RF Amplifiers

- Solid-state power amplifiers for use at high frequencies employ transistor with wide band-gap semiconductor materials, Si, GaAs, GaN, Sic, and diamond.
- It is claimed that SSA are more reliable than their vacuum-tube counterparts by a factor of 2.5
- Because many transistors are operated in parallel, the failure of on has negligible effect on output power
- Other advantages claimed: high stability, low maintenance, absence of warm-up time

Manufacturer	Freescale			TriQuint		TriQuint
Material	Si			GaN		GaAs
Frequency	350 MHz	700 MHz	1300 MHz	3 GHz	12 GHz	6 GHz
Mean RF power	1000W	125W	230W	90 W	50W	15 W
Operating voltage	50V	50V		28V	30V	8V
Gain	22 dB	19dB	20 dB	15 dB	9 dB	10dB
Max. junction temperature	200 °C	200 °C	200 °C	200 °C	200 °C	150 °C

- SOLEIL synchrotron uses 726 315-W, 352-MHz modules to combine the outputs from four 50kW towers to generate a total of 180kW
- ESRF uses 128 650-W,352-MHz modules to generate a 75kW. Two 75kW towers are combined to produce a total of 150 kW for each booster synchrotron rf cavity

Solid-State RF Amplifiers

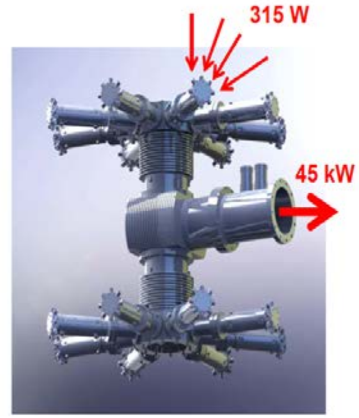
SOLEIL SR RF Implementation

T. Ruan, Soleil


315 W power module


28 V 600 W DC/DC converter


10 x power combiner



160 way power combiner (AREVA)


180 kW 350 MHz solid state amplifier, each column 45 kW (Soleil)

ESRF Booster RF Implementation

75 kW tower →

- 128 RF modules
- Coaxial combiner tree with λ/4 transformers

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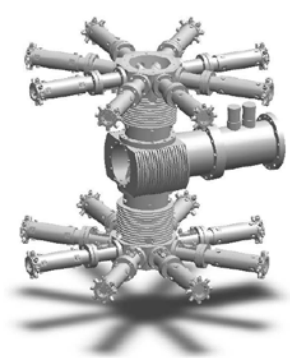
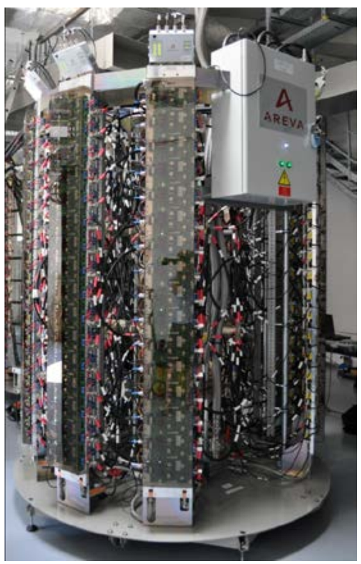
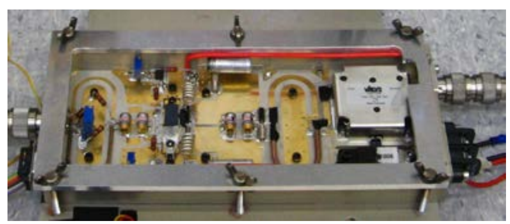




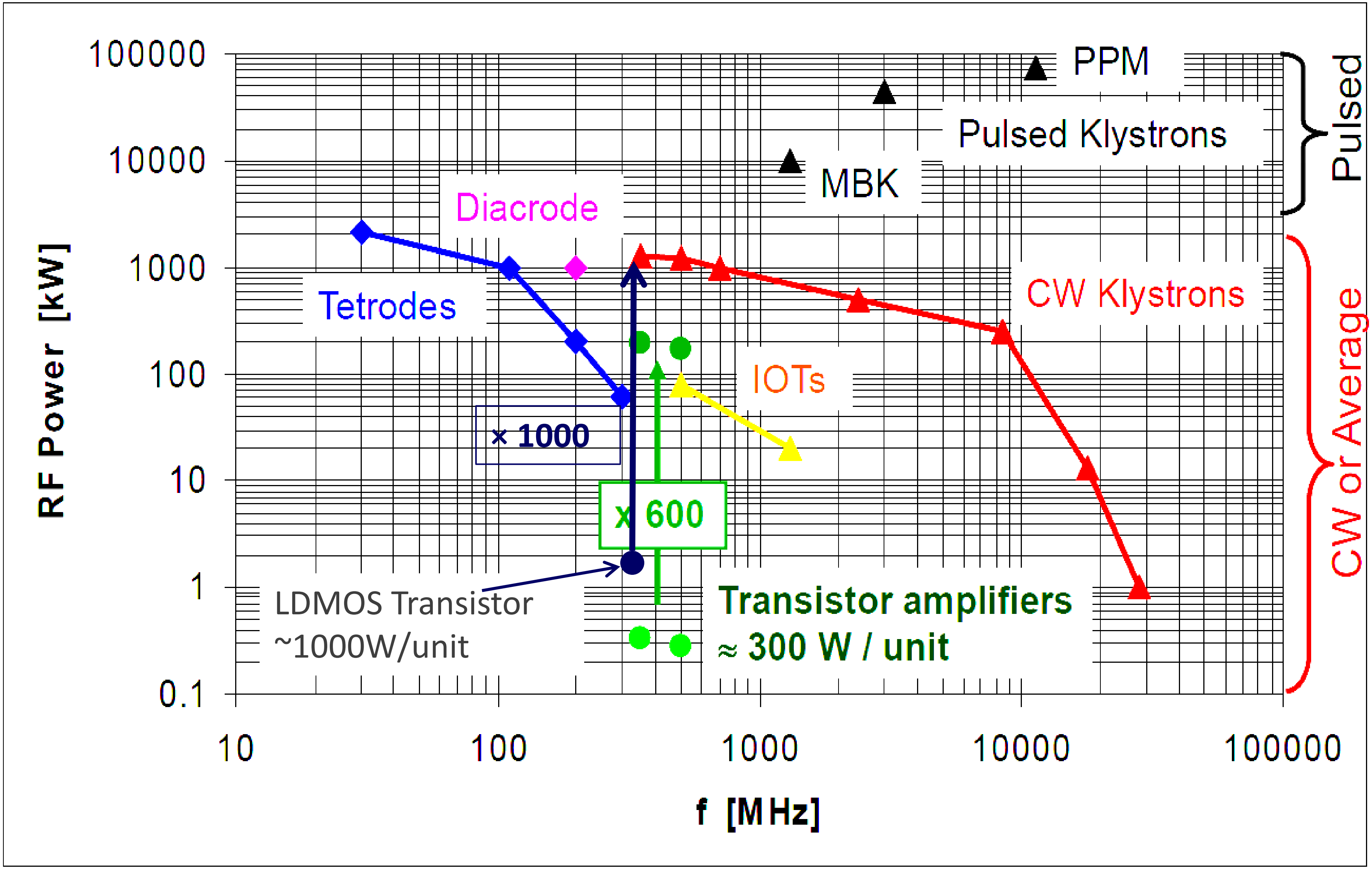


A 650W , 352.2 MHz module Developed by SOLEIL using 6th Gen. LDMOSFET.

Initially $\eta \approx$ 59 %
It degradation after 1000 h run test → **$\eta \approx$ 57 %**
(still above spec)

J. Jacob, ESRF

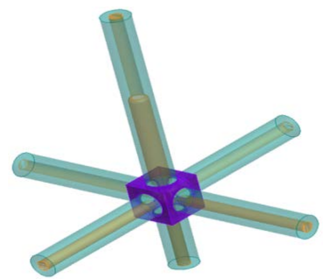
RF Power Sources - Summary

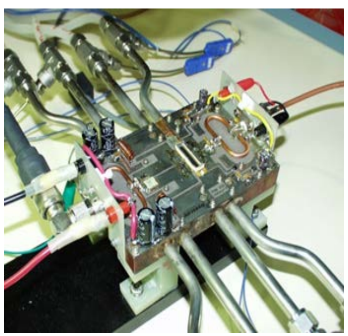


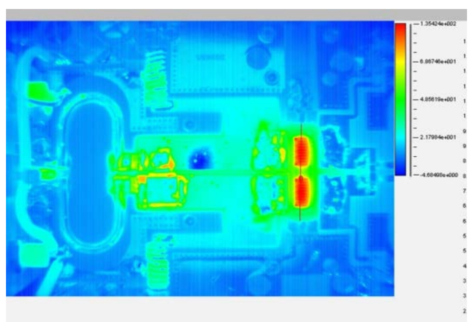
J. Jacob (ESRF)
A. Nassiri (ANL)

Solid-state RF amplifier development at ANL

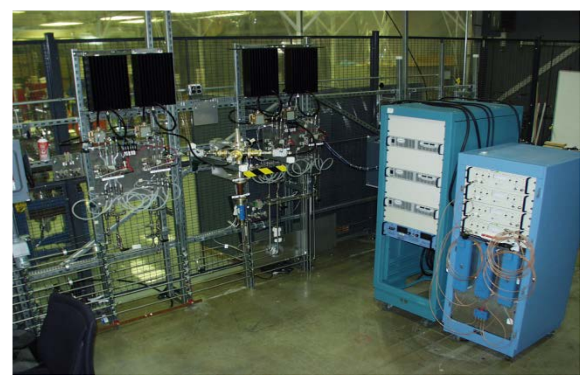
- In 2009, we started a small-scale D&D project to demonstrate feasibility of a 352MHZ 4-kW CW combined solid-state amplifier system
  - Determine practical output power limit from a single device
  - Evaluate thermal performance
  - Develop a baseline design for a 200kW system
- We successfully demonstrated 1kW CW @352 MHz using the latest LDMOS transistor by Freescale.
- We successfully demonstrated 4kW CW 352 MHz using ¼-λ design using standard 1-5/8” EIA coaxial hardware.
- Looking ahead, complete conceptual design of potential combining networks for a 352-MHz/200kW CW rf amplifier system.







Max. temperature: 136 °C @1kW output



Concluding Remarks

- Compact and modular RF amplifiers are more suited for XFELs and ERLs operating at L-band frequencies or below.
- The use of IOTs is on the rise for accelerators. It provides high efficiency and it has intrinsic lower phase noise compared to klystrons. It is an alternative to klystrons for L-band CW XFEL and ERL.
- Looking ahead, solid-state amplifiers could be serious contenders. Semiconductor industries are making significant progress developing next generation devices using innovative approach which will benefit accelerators development
  - A wide rage of frequencies
  - High power modules
  - Power combining schemes to produce 100's of kW
  - Highly modular systems
  - Industrial mass production
- Solid-state sources can compete with tubes at the lower frequencies and power levels. The outlook for higher-frequency, higher-power solid-state rf sources is promising but with many technical challenges.
- Pulsed systems require multi-MW RF power. Klystrons are still the best option. Currently there are no reliable alternatives to high-power klystrons above 1.3 GHz
  - IOTs power combining is not a reliable and cost-effect alternative at this time.