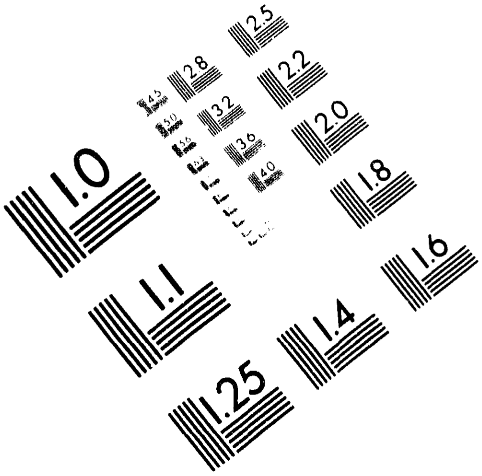

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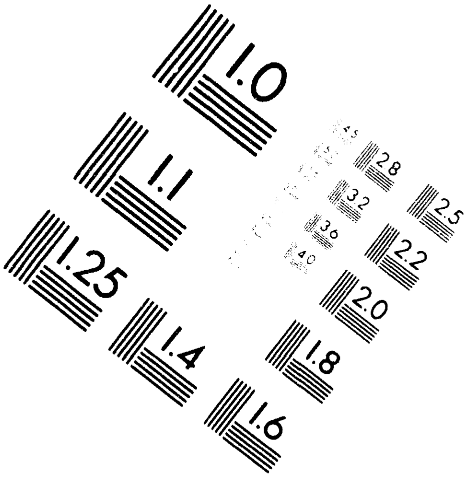

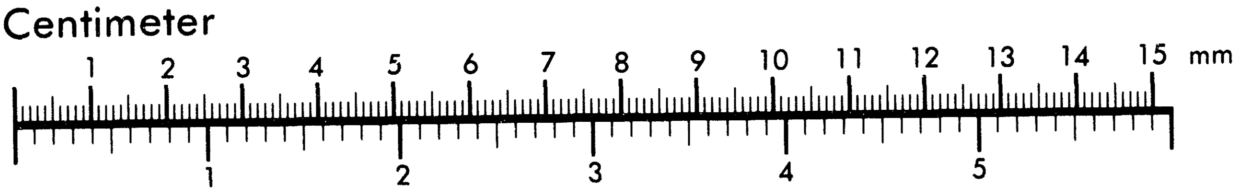

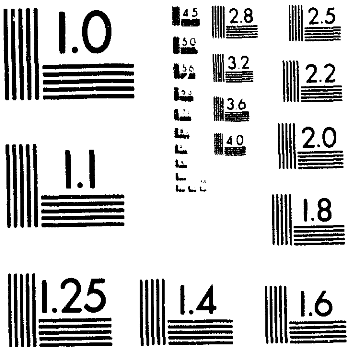

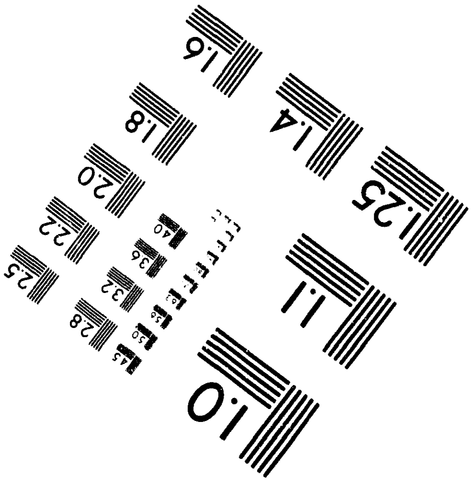

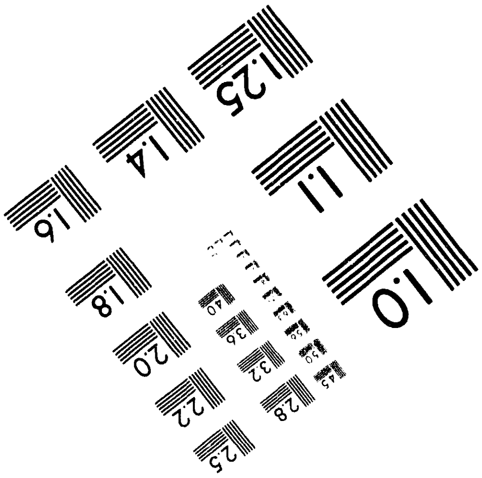

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(ADTT)

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Important Requirements for RF Generators for Accelerator-Driven Transmutation Technologies (ADTT)

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Abstract. All Accelerator-Driven Transmutation applications require very large amounts of RF Power. For example, one version of a Plutonium burning system requires an 800-MeV, 80-mA, proton accelerator running at 100% duty factor. This accelerator requires approximately 110-MW of continuous RF power if one assumes only 10% reserve power for control of the accelerator fields. In fact, to minimize beam spill, the RF controls may need as much as 15 to 20% of reserve power. In addition, unlike an electron accelerator in which the beam is relativistic, a failed RF station can disturb the synchronism of the beam, possibly shutting down the entire accelerator. These issues and more lead to a set of requirements for the RF generators which are stringent, and in some cases, conflicting. In this paper, we will describe the issues and requirements, and outline a plan for RF generator development to meet the needs of the Accelerator-Driven Transmutation Technologies. The key issues which will be discussed include: operating efficiency, operating linearity, effect on the input power grid, bandwidth, gain, reliability, operating voltage, and operating current.

ACCELERATORS NEEDED FOR VARIOUS ADTT OPTIONS

There are many versions of ADTT which require varying amounts of beam current, beam power, and beam energy. The consistent feature in each version is a need for large amounts of continuous (CW) RF power. A selection of some of the options is shown in Table 1.

Table 1. Current, Energy, and RF power for various ADTT options.

Type of Machine	Current (mA)	Energy (MeV)	RF Power (MW-CW)
Commercial Waste Transmuter	250	1600	500
Accelerator Production of Tritium	200	1000	255
Accelerator Based Conversion (ABC) of Pu	80	800	110

It should be noted that the RF power in Table 1 is the amount of power needed for the accelerator, beam acceleration, transport losses, and control. In actuality, because each accelerator module requires a different amount of RF power, the RF generators will in general be capable of providing more power than what is needed in each module. As a result, the purchased RF generation capability will be approximately 40% above the numbers in Table 1. Therefore the range of purchased RF generation capability for the three options listed in Table 1 goes from 155 MW to 360 MW. As a point of reference the largest CW accelerators in the world are CERN in Europe (with 16 MW of CW RF) KEK in Japan (with 38 MW of CW RF). CERN is in the process of upgrading, but even after the upgrade will have 31 MW of installed CW RF power. See Table 2.

In any of the ADTT options, high beam loading is important in order to maximize the operating efficiency. In addition, to achieve the best efficiency, the match of the accelerator to the RF source is very important. A proper match is obtained with two parameters, the coupling of the drive line to the accelerator and the resonant frequency of the accelerator. In essence the coupling loop or iris acts as an impedance transformer to match the impedance of the accelerator (with beam) to the drive line impedance. In addition because the beam is not synchronized with the peak of

Table 2. A Comparison of one ADTT Accelerator with Current Accelerators

Machine	Location	Frequency (MHz)	# of Stations	Peak MW	Duty Factor	First Beam
LAMPF	LANL	805	44	55	12%	1972
LEP	CERN	352	28*	32	cw	1989
TRISTAN	KEK	508	34	38	cw	1986
SLAC	SLAC	2856	247	16000	0.03%	1966
INR-MMFL	Moscow	991	28	130	1%	1990
ABC		**350/700**	**156**	**156**	**cw**	

*by end of 1994

the RF waveform (it is typically 30° before the RF peak), it looks like a reactance to the drive system. The reactance can be eliminated by detuning the cavity (setting the resonant frequency at a frequency different from the drive frequency) so that the cavity presents a compensating reactance to the drive line. The sum of the two reactances then adds to zero. Table 3 shows the result of operation with a properly detuned and matched cavity as well as two other situations which show the effect of incorrect operation. The third column indicates that the tube must be robust. If normal operation is occurring and the beam suddenly stops because of a failure of the injector, the RF generator could see a sudden 3:1 mismatch and a reflected power level of almost 25%. If the tube cannot tolerate this type of condition, costly protection devices such as circulators must be used.

Table 3. Results of Variation of Detuning and Coupling for ABC 800-MeV CCL Cavity*

Parameter	Coupling and Detuning for Full Current	Coupling for Full Current, No Detuning	Coupling and Detuning for Full Current, I=0
Current (A)	0.08	0.08	0
Cavity Power (kW)	299	299	299
Beam Power (kW)	464	464	0
Generator Power (kW)	764	787	393
Reflected Power (kW)	0	23.5	94.1
VSWR	1.0	1.4	2.9
% Power Reflected	0	3	24

*(F=700 MHz, Synchronous Phase =-30°, Beam Loading= 60%

OVERVIEW OF RF GENERATOR PARAMETERS AND IMPACT ON THE ADTT APPLICATIONS

High voltage, operating efficiency (not saturated efficiency), gain, linearity, reliability, lifetime, cooling, ancillary power, robustness, reaction to input power grid, cost, and size are all issues for these applications. Each of the parameters can generally be traded off against one or more other parameters. For instance, the high voltage for a klystron can be reduced by operating the tube at a higher perveance (more current). However, best efficiency is obtained with a low perveance tube. In another example, each klystron can be optimized for output efficiency by varying both the current in the tube and the high voltage so as to run all tubes at constant perveance. That complicates the high voltage system in a very large way. Each klystron would require its own high voltage system. To reduce cost and improve the reliability, we are considering the use of very large AC-DC converters and a high voltage bus for the entire set of RF generators. This allows us to borrow from the electric power industry and use AC-DC converters designed for DC power transmission systems. While this means all RF generators run at the same high voltage, there are important advantages in the lack of system complexity and in the reduced system cost. The primary disadvantage is the need for a HVDC isolation switch.

The Operating Efficiency is a key Issue

The operation of linear beam tubes (e.g. klystron, magnicon, regotron, MBK) must be near saturation in order to minimize the power lost to the collector and to maximize the efficiency. On the other hand. the usual rule-of thumb is that at least 20% excess drive capability is neaded for adequate control response. These two conditions lead to conflicting requirements. The first leads to a decision that all generators will be operated with 10% or less overdrive, and the second that all generators have 20% or more. The ADTT accelerator designs make it very difficult to operate with a very small overdrive capability, simply because the power needed in each station varies throughout the accelerator. Every RF station has a different power level to achieve a specific overdrive percentage. Figure 1 shows the power needed for each module for one ADTT option. The IOT shows promise for excellent operating efficiency in the ADTT applications. Typical efficiencies for the IOT are over 70%, and the degradation in efficiency is only a few percentage points in dropping the output power to 50% of the maximum for the tube.

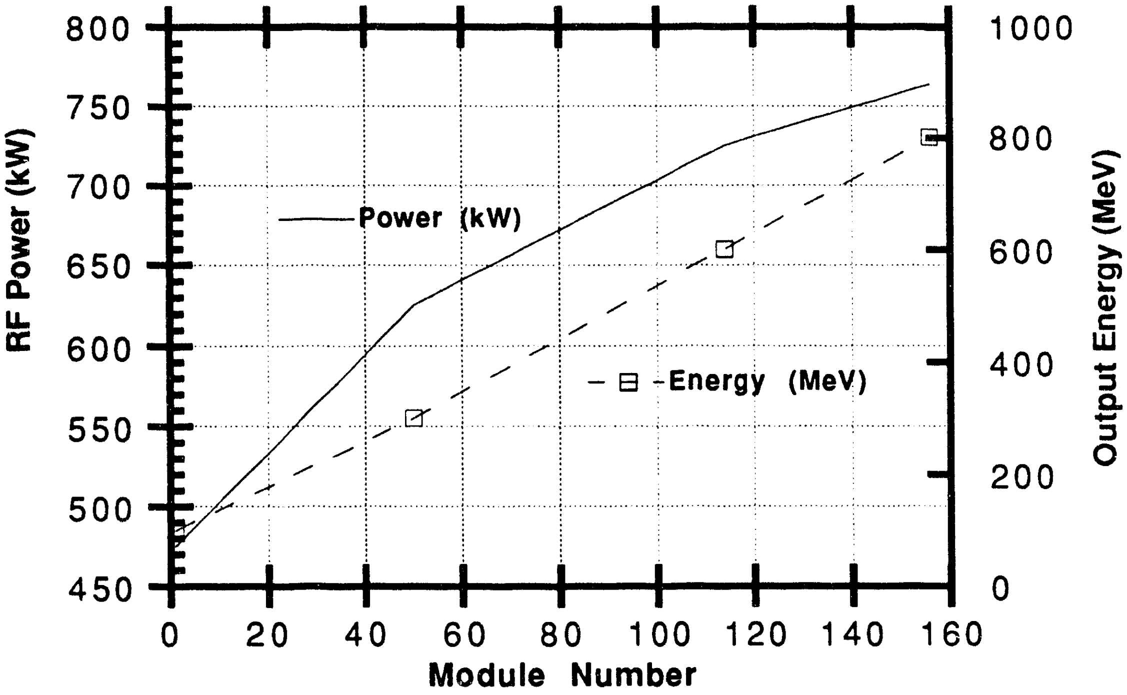

Fig. 1. RF Power and Output Energy versus Module Number for one version of an ABC

Types of RF Generators

There are several types of RF generators in addition to the klystron which can be considered for the ADTT applications. Each of the generators has features which make it attractive for these applications and features which make it unattractive. A short list of some of the leading candidates and a brief comparison is given in Table 4. The klystron is the baseline choice for current ADTT accelerator designs, primarily because of its technological maturity. Almost all RF driven accelerators in use today use klystrons. Other devices look interesting however. One issue which must be considered with any tube choice is the impact on the power grid. If the RF is reduced because of sudden failure of the injector, the power grid could see a large transient- particularly in the high efficiency options such as the IOT or the Depressed Collector Klystron.

Table 4. A Selection of RF Generators appropriate for ADTT Applications

Type	Frequency (MHz)	CW Power (MW)	Efficiency (%)	Maturity
Klystron	352	1.3	67	Very High
IOT	267	0.25	75	Medium
Klystron-(Depressed Collector)	476	1.2	70	Medium
MBK	425	0.1	60	Low
Magnicon	700	>2.0	80	Very Low
Regotron	991	5.0	70	Very Low

Baseline RF Source: The Klystron

The klystron has been the generator of choice for RF accelerators for decades now. It is a very mature device, with long lifetimes (>30,000 hours) and robust operation (especially with the use of a circulator on the output). However, there are negative attributes of the klystron which lead one to at least consider other options. Figure 2 shows a graph of conversion efficiency of a typical klystron versus percent of maximum output power.

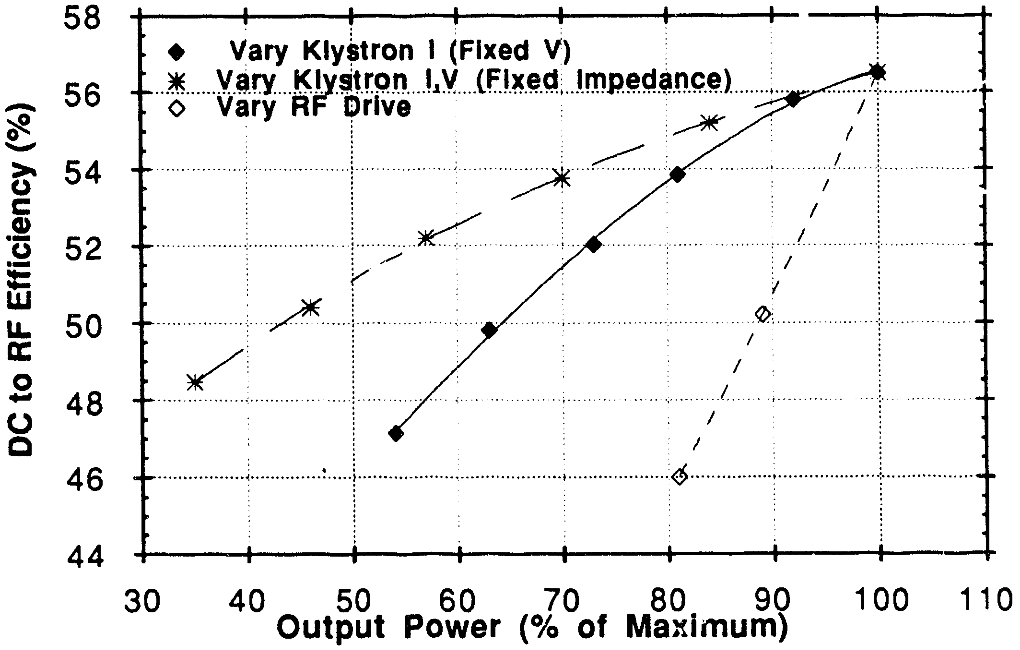

Fig. 2. Measured Output Efficiency of a klystron when output is varied by 3 different methods.

The good efficiency of the klystron (approaching 70% in the best exemples) is achieved only at saturation. The overdrive capability required for the feedback control system reduces the operating efficiency to levels much below the saturated efficiency. If the saturated power level of the klystron is not adjusted somehow and there is no input RF signal or if the input RF signal is small, then most or all of the energy in the klystron electron beam is lost as heat. If the output is varied by changing the RF drive only, the efficiency falls off linearly with output power. Dramatic improvements in the klystron operating efficiency can be made by changing the saturation condition. In one case, by changing the modulating anode voltage, the current in the kystron can be changed. This varies the outut power capability while maintaining the efficiency. This method is used on many accelerators (CERN and LAMPF are two examples). The efficiency can be maintained even higher by varying both the current and the operating voltage in the klystron to maintain constant impedance of the klystron beam.[1] This is much more complicated than just varying the klystron current, and it requires that each klystron have its own high voltage power supply.

Another property of the klystron is that it does exhibit classical saturation. The output power grows more slowly with input power as the level grows until the output achieves a maximum. In addition, while the tube is going into and past saturation, the RF phase is exhibiting large changes. These changes put very large stresses on the feedback control system. [1] Figure 3 shows the amplitude and phase variation of one type of klystron as the tube is driven into and past saturation. At levels well below saturation the gain of the klystron is constant and the loop parameters do not change. Operation near saturation (which is needed to maximize the operating efficiency) makes the setup parameters of the feedback loops very sensitive.

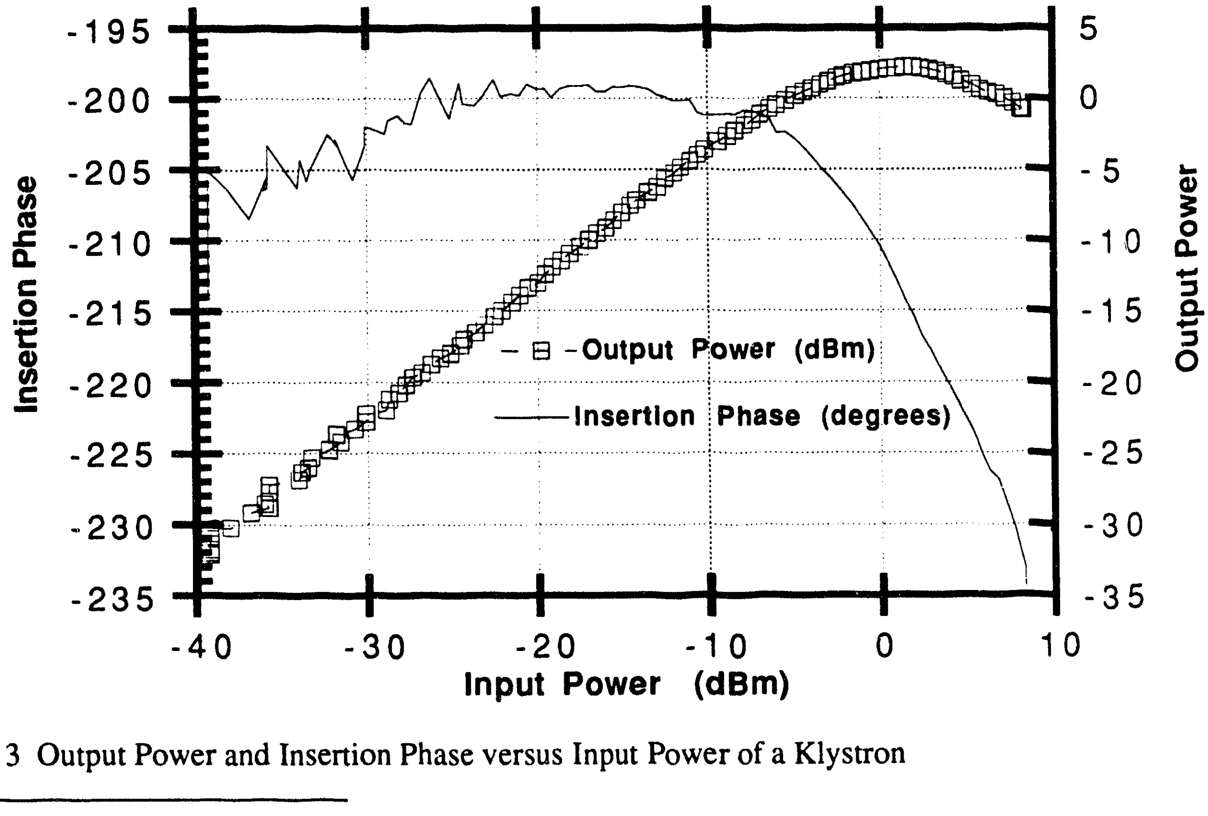

Fig. 3 Output Power and Insertion Phase versus Input Power of a Klystron

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[1] Method first suggested by Robert Symons and Don Laycock of Litton Electron Devices

Near saturation, the loop can be optimized and very little degradation in performance is seen-unless the output power requirements change (even by a small amount). If more power is needed, the loop gain parameters are set too low for optimal performance and the response is sluggish (at best). If less power is needed, the loop gain parameters are set too high and damped oscillations occur. The insertion phase creates corresponding difficulties for the feedback loops because the klystron exhibits large changes near saturation.

AVAILABILITY

Availability is a very important issue for any ADTT application. In all of the applications, the production plant must operate for approximately 75% of a year. This generally means that the accelerator availability must be ≥ 85%. In the energy producing versions of the ADTT, the high availability is coupled with a requirement for minimal shutdowns which might impact the production of power. The availability issues are addressed in other papers at this conference [2,3]. A key point for consideration in availability analysis is the need for all RF systems to be operating in order to have beam. This is unlike high power CW electron linear accelerators. CERN and KEK are both electron machines in which the beam is relativistic. Synchronism with the beam is not lost if one station is not operational. In a proton machine at the 1-GeV energy level, the beam is never completely relativistic. This means that the beam's velocity varies with every new acceleration. In order to maintain synchronism, the beam must see acceleration at every station. However, we have done a beam dynamics analysis that says the accelerating process continues if the RF station failure is above some energy level (> 350 MeV in this particular simulation).

An issue for the availability analysis is the commissioning process. There is often a difficult startup process in which many more tubes fail than when steady state operation is reached. The KEK Tristan project is a good example of this. A plot of the number of failed tubes versus the number of filament operating hours is shown in Figure 4. [4]

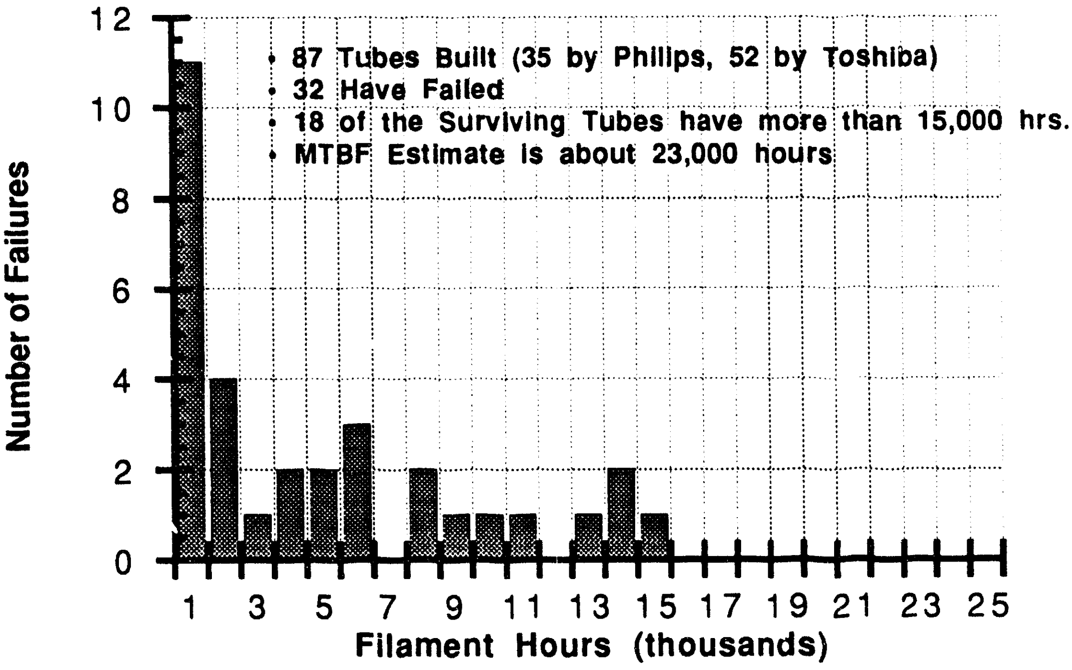

Fig.4. The number of failed klystrons vs. the filament operating hours at the KEK Tristan project

There is a very clear pattern of several early failures with a slowly decreasing failure rate. This is due to manufacuring process development, changes in the machine parameters, infant failures, etc. In order to meet the stringent availability requirements of the ADTT applications, some level of redundancy is probably needed. The important tradeoff that accompanies redundancy is increased cost and (perhaps) complexity.

TUBE DEVELOPMENT PLAN

It should be kept in mind that devlopment of a new high power RF generator can take two or more years, and an additional few years of initial operations are needed to completely solve all initial problems. A few examples will help to illustrate this point.

CERN began its operation with 16 1-MW CW klystrons in 1989. In 1990, 4 of the 16 tubes had to be replaced, and in 1991 another tube had to be replaced. The following year, no tubes were replaced. In those years they had achieved 14,000 hours of operation on the original 11 which had continued to operate successfully.

KEK has had a somewhat similar experience on the Tristan project. This project uses three different CW klystrons at 508.58 MHz. They have Philips klystrons with either 0.8 MW or 1.0 MW output power capability, and they have a Toshiba klystron with 1.2 MW output capability. There are a total of 34 klystrons installed. Figure 4 shows the number of failed tubes versus the filament operating hours.

The final choice for the RF Generator for ADTT applications needs a comprehensive study and design effort. Included in this effort must be: 1) a complete analysis of the tradeoffs, 2) prototyping of several tube options to ensure complete understanding of the tube parameters, and 3) consideration of the feedback control issues. The strict reliability requirements, the large number of generators, and the potential payback in efficiency dictate the need for this design effort.

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