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Analysis of RF high power sources for 1MW – range, 10 MeV CW industrial accelerator.

A study submitted to NNSA performed by
Fermi National Accelerator Laboratory

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Executive Summary

Cobalt-60 is the dominant source of ionizing radiation for sterilizing products in the $200B/year medical device industry. Security and accessibility concerns around this radioactive material - sourced from countries including Russia and China - present national security and economic risks. There is a continued national urgency to replace such high-risk sources with low-risk alternatives such as electron or x-ray beams driven by accelerators. While e-beam sources have been in use for many years, they still represent a small portion of the market. X-ray sources are becoming economical alternatives. Meeting the processing capacity required to replace Co-60 requires a step-change in the capability, efficiency, and overall operating cost of electron accelerators to make adoption feasible. The radiofrequency (RF) power that drives accelerating cavities represents significant capital and operating costs for these accelerators. For accelerator-based systems to be a viable alternative for these applications, RF systems must be economical to manufacture, deploy, and operate.

The first phase of this two-phased project for NNSA included investigation into the current usage of various RF sources. This drew on experience at Fermilab and conversations with RF source manufacturers and users. This document describes a comparison of RF sources to determine their suitability for powering accelerator cavities for improved economy of operation. The interplay of efficiencies of the various components of an accelerator system are examined for normal conducting and superconducting systems. The document illustrates how compact superconducting accelerators with inexpensive RF sources provide optimal economy for producing electron beams.

The RF sources that we consider in detail are Inductive Output Tubes (IOTs), Solid-State Amplifiers (SSAs), and Magnetrons, which are generically referred to as ‘tubes’. These tubes are compared at three operational frequencies, 650 MHz, 915 MHz, and 1.3 GHz. Work to date on Fermilab’s Compact Superconducting RF (CSRF) design has focused on 650 MHz as a result of optimization of the super conducting cavity size and frequency, to minimize heat production, and the cooling capacity of cryocoolers; the enabling concepts of the CSRF design. However, there are no commercially available magnetrons at this frequency. The use of magnetrons to power the CSRF accelerator is a complimentary feature to its enabling technologies, increasing its efficiency and economy. Magnetrons are commercially available at 915 MHz due to their use in the process heating industry. A primary purpose of this study is to evaluate whether that availability is sufficient to promote a shift in effort to that frequency. The final frequency, 1.3 GHz, is considered due to its use in High Energy Physics (HEP) applications such as the LCLS-II.

Section 1 evaluates all the elements of an RF system that strongly contribute to the system efficiency. The efficiency of systems using superconductivity is dominated by the efficiency of the RF source. The efficiency of room temperature or normal conducting systems is dominated by the ratio of the energy used to accelerate the beam vs the energy dissipated in the cavity itself, which is qualitatively referred to as the beam loading.

Section 2 examines the general requirements of an RF system. It looks at single cavity and multi cavity systems in both normal conducting and superconducting regimes at all three frequencies. A summary table lists the pros and cons of each choice.

Section 3 looks at specific features of IOTs, SSAs, and magnetrons as RF sources. It describes the state of development of each and how that impacts their use in an accelerator system.

Presently, there is some level of investigation of the performance of commercially available 915 MHz tubes looking at their suitability for powering accelerating cavities. While we have determined that our efforts should remain focused on system integration at 650 MHz, Section 4 describes a development plan to address a fundamental deficiency of magnetrons, their short lifetime compared to the other sources. In our conversations we have heard that present magnetron tube lifetime is approximately 8,000 hours but can be as short as 2,000 or as long as 15,000 hours. The goal of the development plan would be to achieve an efficiency of more than 85% with tube lifetime of ~50,000-80,000 hours. It should be noted that magnetrons are very inexpensive. The cost of frequent replacement is probably not a significant factor if they were to be incorporated into an accelerator system. Rather, the unpredictability, and its impact on process continuity, is of greater concern.

Section 5 summarizes this report and presents our conclusions.

The selection of an RF source is the last remaining component of Fermilab's CSRF design. Its impact on the overall design depends on its successful integration with all the other components of the CSRF. While we have been eager to proceed with the development of a magnetron RF source, the preliminary efforts of this project have led us to conclude that a more pressing need is to demonstrate the viability of superconducting accelerating technology as a concept at 650 MHz for medical device sterilization. Since thermal losses in the SRF cavity will double if the frequency is increased from 650 to 915 MHz, the data provided by a CSRF demonstration will determine if it is feasible to scale our superconducting cavities to 915 MHz.

To that end, the second phase of this project will develop a digital design of a 200 kW, 7.5 MeV, 650 MHz electron beam accelerator along with beam delivery and x-ray conversion systems. This design will be the basis for the production of a complete first article once funding is available.

1. Introduction

Various types of high-power, Continuous Wave (CW, 100% duty factor) RF sources are available to power industrial accelerators. In this section we will examine their areas of applicability and their effect on the system efficiency. Typical sources include:

- Tetrode & Diacrode;
- Inductive Output Tube (IOTs);
- Klystron;
- Magnetron;
- Solid-State Amplifier (SSA)

The power and frequency range for these RF sources operating in the CW regime are shown in Table 1 below.

	Freq. range, MHz	Power, kW	Efficiency, %	Gain, dB (see sidebar in Section 3)
Tetrodes & Diacrodes	Up to 400 MHz	2000 (110 MHz) 60 (400 MHz)	Up to 70	3-15
IOT	Up to 1300 MHz	150 (704 MHz) 30 (1300 MHz)	Up to 70	20-25
Klystron	Up to 1300 MHz	2000 (200 MHz) 352 (1300 MHz)	60-70	45-55
Magnetron	Up to ~ 1.5 GHz	300 (915 MHz)	85-90	N/A
SSA	Up to 1300 MHz	Up to 1 MW	Up to 60	40-50

Table 1 Comparison of possible RF power sources for accelerator systems.

The overall efficiency of industrial accelerators, η_{acc}, is determined by the following factors [1.3]:

- Efficiency $\eta_{AC\rightarrow DC}$ of the conversion from AC to DC; typically, the efficiency of transformers and rectifiers is higher than 95%;
- Efficiency of the RF source $\eta_{DC\rightarrow RF}$ including additional power for the gun heater and electromagnets for vacuum tubes (this power is typically small compared to other parameters);
- The need for equipment cooling. A chiller adds additional power overhead ξ_{chill} ~ 15% of the power dissipated in the tube;
- Input power determined by the tube gain K (in dB); the input power is ~0.001-5% of the output RF power, depending on the tube type.
- Transmission line efficiency η_{trans}; for industrial linacs, where the RF source is typically placed next to the accelerator, it is close to 100%;
- Accelerator cavity efficiency $\eta_{RF\rightarrow beam}$; for SRF linac operated in the CW regime it may be close to 100% if the cavity is matched to the line. Note that in a pulsed regime, $\eta_{RF\rightarrow beam}$ is smaller because of the filling time, RF source timing off-set, the modulator off-set, etc.;
- Efficiency of the electron injector η_{inj},

- Efficiency of the cavity cryogenic cooling η_{cooler}, which in turn is determined by the RF losses P_{loss} in the cavity and cooling efficiency. For cryo-plant (2K) it is about 1-1.3x10^{-3}, for cryo-cooler (~ 4 K) it is 1-1.5x10^{-4}.

The energy consumption diagram for CW accelerator is shown in Figure 1.

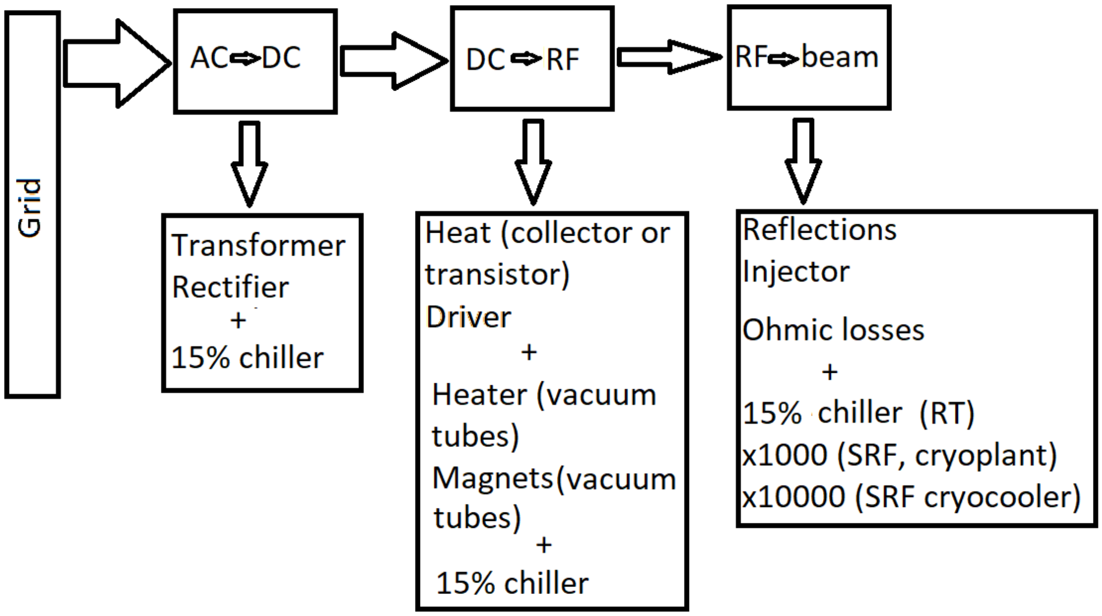


Figure 1. Power consumption diagram for CW accelerator.

The total accelerator system efficiency may be calculated using the following formula:

$$\eta_{acc}^{-1} = 1 + \left({1}/{\eta_{\mathrm{RF}\rightarrow\mathrm{beam}}} - 1\right)(1+\xi_{chill}) + \\ + \frac{\left[\left(\frac{1}{\eta_{DC\rightarrow RF}} - 1\right)(1+\xi_{chill}) + (1-\eta_{trans}) + \frac{1}{\eta_{DC\rightarrow RF}}\left(\frac{1}{\eta_{AC\rightarrow DC}} - 1\right) + 10^{-0.1K}\right]}{(\eta_{acc}\eta_{trans})} \\ + \frac{P_{inj}\left(\frac{1}{\eta_{inj}} - 1\right)}{P_{beam}} + \frac{P_{loss}}{P_{beam}\eta_{cooler}}$$

The overall efficiency of an industrial accelerator is determined to a high degree by the efficiency of RF sources, especially for SRF accelerators. If we consider 650 MHz, 10 MeV, 250 KW linac based on the Nb_3Sn technology, we may expect the unloaded quality factor Q_0 of up to 3x10^{10} at 5-6 MeV/m at 4.5 K, and R/Q of up to 670 Ohm/m. It means that for a cavity length of ~1.6 m, the total surface Ohmic loss is 3 W. If the cryo-cooler efficiency is $\gtrsim 10^{-4}$, the total power necessary for the cooling system is $\lesssim$ 40 kW. If one assumes that the power necessary to excite the RF source is small and that the losses in the electron injector are small, the formula is simplified:

$$\eta_{acc}^{-1} = 1 + \left(\frac{1}{\eta_{DC\rightarrow RF}} - 1\right)(1+\xi_{chill}) + \frac{1}{\eta_{DC\rightarrow RF}}\left(\frac{1}{\eta_{AC\rightarrow DC}} - 1\right) + \frac{P_{loss}}{P_{beam}\eta_{cooler}}$$

In this case, the overall efficiency of the complete CSRF system is determined by the efficiency of the RF source as shown in Figure 2.

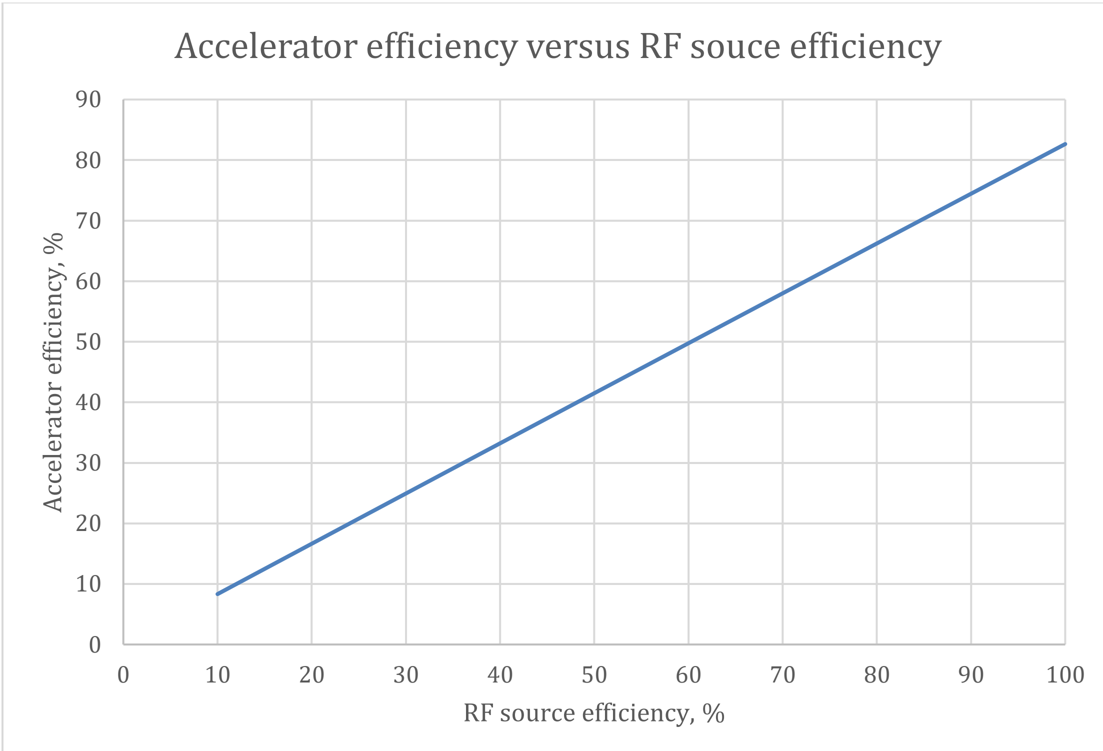


Figure 2: Total efficiency η_{acc} of the 10 MeV, 250 kW CWSRF accelerator versus RF source efficiency $\eta_{DC\rightarrow RF}$.

The overall accelerator efficiency ηacc for the parameters stated above is ~83% for the ideal RF source and depends almost linearly on the RF source efficiency. A "conventional" RF source (IOT, SSA) typically has efficiency less than 70%, and therefore, the overall efficiency of the accelerator is below 60%. If the RF source efficiency is significantly higher than 90%, the total system efficiency remains at its theoretical maximum, see Fig. 2.

There is recognition in the accelerator community of the benefit of developing a new generation of high-efficiency RF sources, see [1.1]. A special program, High Efficiency International Klystron Activity (HEIKA), devoted to development of high-efficient klystron (efficiency $\eta_{DC\rightarrow RF}$ higher than 90%) has begun at CERN [1.2].

Note that the magnetron does not need "input" power if the magnetron operates in injection-locked mode for a one-cavity accelerator. It only needs a locking signal which can be provided by a small amount of reflected power from the cavity. If the magnetron is used for a multi-cavity linac and each cavity is fed by a separate magnetron, the locking signal must be provided by an external driver. A circulator is used to direct the drive wave to the magnetron, the magnetron output power to the cavity, and the forward wave from the cavity to the load. In this case, one may define the "gain" for the magnetron, i.e., $K=10\log(P_{magnetron}/P_{driver})$, where $P_{magnetron}$ is the magnetron output power, and P_{driver} is power of the driver necessary to provide necessary locking signal. Typically, the "gain", K, for magnetrons is about ~15 dB, or the input power must be about 3% of the output power.

2. General Requirements

In this section we will examine the requirements of the individual elements of the RF system depending on the type of RF source chosen.

a. The common parameters that we will consider are that of a superconducting (SC) CW industrial linac having the power of 250 kW and the output energy of 7.5 or 10 MeV (for X-rays or electron beams, respectively). In this case, the acceleration efficiency $\eta_{RF\rightarrow beam}$ is close to 100%. We assume that the RF source is perfectly matched to the linac – for an IOT or SSA, or has the relevant coupling providing operation in the injection-locked mode for a magnetron. The RF source will require a power overhead of approximately 50 kW for a total system power requirement of 300 kW. We consider only magnetrons [2.1], IOTs [2.2] and SSAs [2.3].

b. We will not consider tetrodes and diacrodes, because they operate at low frequencies, below 400 Hz, which is impractical for SC linacs. The diameter of the accelerating cavity is directly proportional to the cavity frequency, which is about ¾ of the wavelength for an elliptical cavity. Large cavities increase the size of the system and have more surface area that must be treated by surface coatings which increases the difficulty of the coating process. Alternatives to elliptical cavities are multi-spoke SRF cavities which have a diameter of about half of wavelength but they are not as effective as elliptical cavities when relative electron velocity β is close to 1 [2.4] such as for accelerating electrons to 10 MeV.

c. We will not consider klystrons. The power of a >300 kW klystron requires a klystron beam voltage greater than 60 kV, which then requires a large oil tank - see, for example, 300 kW, 1.3 GHz CPI klystron VKL-7967A [2.5]. A Multi-Beam Klystron (MBK) having significantly lower beam voltage could be an option, but it is complicated and therefore, expensive [2.6]. There are no high-power CW MBKs available from industry. Another disadvantage for klystrons is that, in contrast to IOTs, magnetrons, and SSAs, the klystron efficiency $\eta_{DC\rightarrow RF}$ depends strongly on the output power. This would not allow variable output power which may be desirable for industrial applications.

d. Next we consider a single cavity linac which allows the use of a single RF source. Fast and precise phase and amplitude control is not required. Here we chose a simple built-in electron source based on a gridded RF gun (see section 2.g below). The accelerator schematic for the amplifier (IOT, SSA) option is shown in Figure 3. The RF system operates in the self-excitation mode, no mechanical tuners (step-motor and piezo) are necessary. The magnetron option is shown in Figure 4. It is very similar, but contains a reflector in the transmission line, which provides the locking signal for the magnetron. On the other hand, it does not need the components for the feedback line – phase shifter, attenuator, directional coupler.

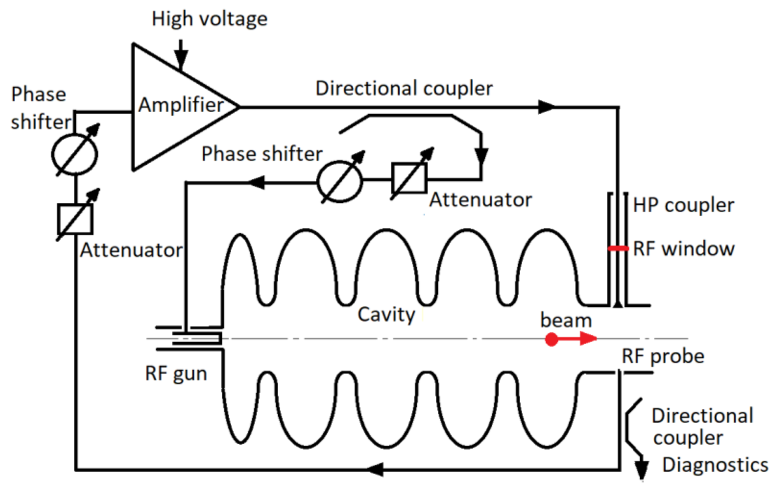


Figure 3. A single-cavity accelerator with an “internal” built-in injector (see 2.g) operating in the self-excitation mode. The RF gun is fed by the same amplifier, the directional coupler provides the necessary power from the main feed line. The signal from the cavity RF probe is used in the feedback loop.

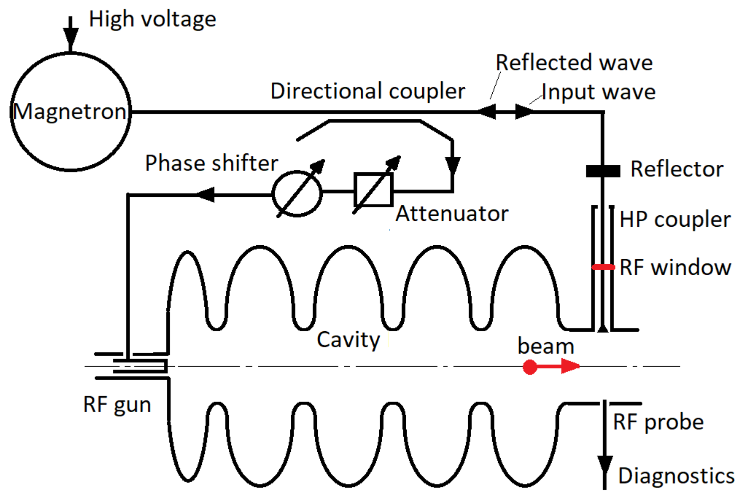


Figure 4. A magnetron option of a single-cavity accelerator with an “internal” built-in injector (see 2.g). The RF source is also fed by the magnetron, the directional coupler provides the necessary power from the main transmission line. The reflector between the High-Power coupler and the magnetron provides the necessary locking signal.

e. In contrast to a single cavity linac, multi-cavity industrial linacs need individual precise RF field phasing in each cavity, which in turn needs a Low Level RF control system (LLRF). Extra RF power for control of up to 15% may be necessary. This does not exclude magnetron sources because it is possible to control magnetron phase and amplitude [2.7, 2.8]. However, a multi-cavity option requires mechanical cavity tuners, which increases expense and decreases reliability: the tuners are vulnerable and fragile devises. The tuner may contain a coarse tuner having a step-motor as an actuator and fine tuner having piezo actuator. For high-power linacs, a fine tuner may be not necessary. The multi-cavity linac layout is shown in Figure 5. The remainder of this analysis will be on a single cavity linac.

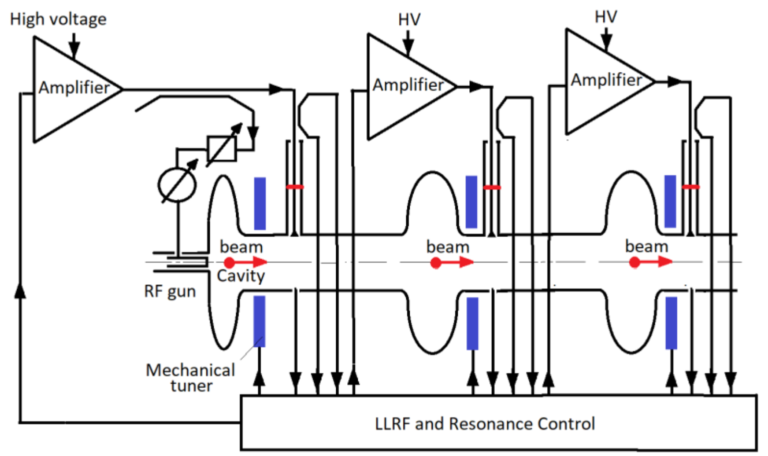


Figure 5. Multi-cavity option of the SRF linac with the built-in RF injector in the first cavity. Each cavity is fed by separate RF source (amplifier or magnetron) and has a mechanical tuner.

f. Three operating frequencies will be considered: 650 MHz, 915 MHz and 1300 MHz. The single cavity linac will contain 5 cells for 650 MHZ, 7 cells for 915 MHz and 9 cells for 1300 MHz.

g. A very stringent requirement exists for superconducting cavities: the beam current striking the SC cavity (beam loss) should not deposit more than 1 W of energy, or a beam loss fraction of about 4e-6. External electron sources (Figure 6), providing short bunches at considerably high energy (relative to internal electron sources), make it easier to meet this requirement. This may make it easier to utilize a 915 MHz source and take advantage of their commercial availability. However, this places stringent performance requirements on the injector; very short intense bunches, very precise and clean, without tails. Therefore, the beam energy exiting the source is greater than in an integrated source, most probably a few hundred keV compared to tens of keV.

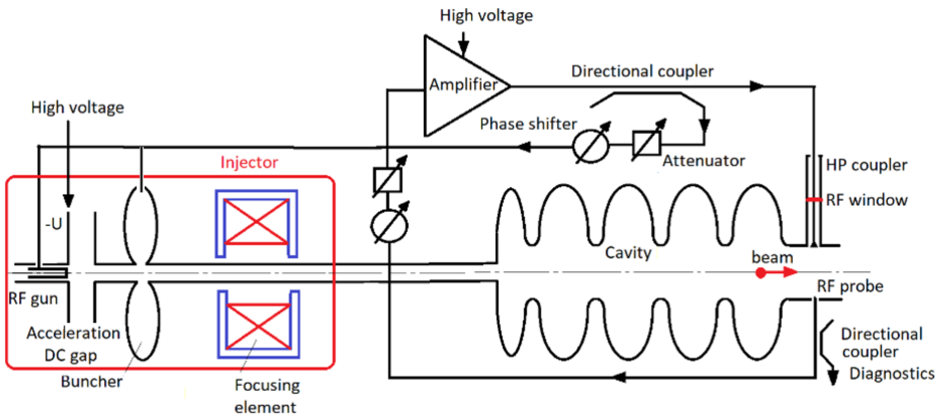


Figure 6. One-cavity option of the SRF linac with the external RF injector. The Injector has a gridded RF gun, acceleration DC gap, a bunching cavity (probably, excited by the beam), and focusing element (solenoid). The RF gun may be fed from the same amplifier.

The power consumed by this injector may be of the order of 10 kW. It needs a focusing and bunching system and a HV source. In this case the cost and size of this injector may be significant. In addition, significant R&D would be required. On the other hand, an integrated, inexpensive RF injector (“internal injector”) requires larger apertures in the accelerating cavity to reduce beam loss, which may limit the operation frequency (the aperture decreases as the frequency increases). Note that internal injector systems are widely used in industrial accelerators.

h. A critical feature of the compact SRF design is the use of Nb_3Sn, which enables operation at >4 K with the cryo-cooler. The coating process is simplified by minimizing the number of cells in order to provide a good coating quality. Note that the first cell in most designs is shorter than the rest. This will necessitate additional R&D to ensure quality Nb_3Sn coating of the short cell. In this case, the larger cavity size and apertures argue in favor of lower frequencies such as 650 MHz for “internal injection”.

i. Because the acceleration efficiency in this case is very high, the total linac efficiency is determined by efficiency of the RF source. Hence, the efficiency of the RF source should be as high as possible. Modern magnetrons provide efficiency $\eta_{DC\rightarrow RF}$ of 80-85%; IOT – up to 70 %, SSA - ~50%.

j. Our target cost for a production system is $3/W. This dictates a cost for the RF to be <1-3 $/W. Magnetrons may provide this; IOT and SSA are more expensive, ~10 $/W.

k. To meet the expectations of an accelerator for industrial use that minimizes maintenance needs, the ideal RF source lifetime should be not less than 80,000 hours, which provides operation of 10 years without a tube change. IOTs and SSAs provide this life span; the magnetrons have poor longevity, ~8,000 hours and should be improved (Section 4 proposes a program to improve the lifetime to 50,000 – 80,000 hours). The cost of frequent replacement is probably not a significant factor for business. Rather, the unpredictability, and its impact on process continuity is of greater concern.

l. The power output of an industrial linac should be adjustable. All the sources considered here – IOT, SSA and magnetrons – provide this. The magnetron power adjustment is provided by operating in the subcritical injection locked mode. Note that efficiency of these RF sources does not depend strongly of the output power (SSA requires careful design to accomplish this, IOT has this feature intrinsically).

m. All the considered RF sources need DC voltage sources and therefore, rectifiers. The magnetron and IOT operate at the voltage of ~20 kV.

n. The SSA at this power has much larger footprint compared to the magnetron and IOT, see for example, [2.3].

All these considerations are compared in Table 2:

	650 MHz	915 MHz	1300 MHz
Magnetron	**Pros:** • High efficiency, >80%; • Low cost, 1-2 $/W; • Best for the beam optics; **Cons:** • Poor longevity, <8,000h, Tube R&D is needed to improve; • Are not available, R&D is needed	**Pros:** • High efficiency, >80%; • Low cost, 1-2 $/W; • Available; **Cons:** • Poor longevity, <8,000h, Tube R&D is needed to improve; • Beam optics poorer than 650 MHz, linac R&D is needed	**Pros:** • High efficiency, >80% • Low cost, 1-2 $/W **Cons:** • Poor longevity, <8,000h, Tube R&D is needed to improve; • Are not available, R&D is needed; • Beam optics poorer than 650 and 915 MHz, linac R&D is needed
IOT	**Pros:** • High efficiency, >70%; • Best for the beam optics; • Good longevity **Cons:** • Tube R&D is needed for this frequency; • High cost, ~10 $/W	**Pros:** • High efficiency, >70%; Good longevity; **Cons:** • Tube R&D is needed for this frequency; • High cost, ~10 $/W • Beam optics poorer than 650 MHz, linac R&D needed	**Pros:** • High efficiency, >70% • Good longevity; **Cons:** • Tube R&D is needed for this frequency; • High cost, ~10 $/W • Beam optics poorer than 650 and 915 MHz, linac R&D is needed

SSA	**Pros:** • Best for the beam optics; • Good longevity **Cons:** • R&D is needed to improve efficiency • Large footprint; • High cost, ~10 $/W	**Pros:** • Good longevity; **Cons:** • R&D is needed to improve efficiency • Large footprint • Beam optics poorer than 650 MHz, linac R&D is needed; • High cost, ~10 $/W	**Pros:** • Good longevity **Cons:** • R&D is needed to improve efficiency • Large footprint • Beam optics poorer than 650 and 915 MHz, linac R&D is needed; • High cost, ~10 $/W

Table 2 Pros and Cons of Magnetrons, IOTs, and solid state amplifiers (SSA) at all three frequencies.

Note that none of these RF sources are presently available for these parameters and operation regimes except the 915 MHz magnetron. The most promising RF source may be a magnetron, because it promises the required parameters and operation regimes at the lowest cost. However, the magnetron requires some minimal development to improve it precision and additional R&D to improve the tube lifetime.

Superconducting RF versus Room Temperature (or Normal Conducting):

We now compare the SRF option considered above and a room temperature (RT) option, i.e., 10 MeV, 250 kW copper accelerator. As an example, we may take a well-optimized RT standing-wave cavity having the following parameters [3.7]:

Operating frequency	325 MHz
R/Q	340.8 Ω
R_{sh}	14.05 MΩ
Unloaded cavity quality factor	41200
Cavity aperture	70 mm
Cavity length	309 mm

In Figure 7 the acceleration efficiency $\eta_{RF \rightarrow beam}$ is shown for a geometrically similar acceleration structure operating in CW regime at 915 MHz versus the structure length L. Note, that the acceleration efficiency may be improved for a RT linac if it operates in a pulsed regime with a lower duty factor; in this case the beam loading will be higher, and the relative Ohmic loss will be smaller resulting in higher acceleration efficiency. However, in this case, the instantaneous power of the pulsed RF will be higher, and the instantaneous beam current will be higher also. In contrast, RT copper structures can tolerate more beam loss than conduction - cooled SRF structures.

The Radio Frequency (RF) energy in an accelerating cavity is dissipated in two ways. Some of the energy is used to maintain the resonance in the cavity by resupplying the energy that is lost due to resistance in the surface of the cavity. The rest of the energy is used to accelerate the beam. The fraction of energy used for the beam is referred to as the "beam Loading." Because superconducting materials offer little electrical resistance to the currents in the surface of the cavity, almost all of the RF energy can be used to accelerate the beam. Therefore, SRF cavities are almost 100% beam loaded.

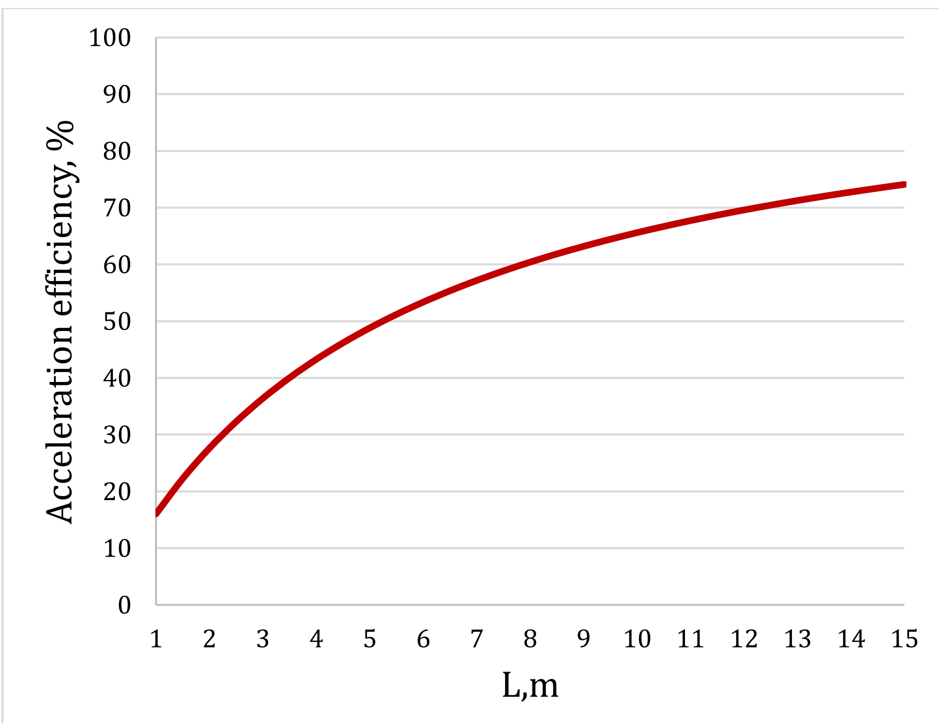


Figure 7: The acceleration efficiency $\eta_{RF \rightarrow beam}$ versus the structure length L. The structure is geometrically similar to one considered in Ref [3.7], see the Table above, and operates in CW regime at 915 MHz.

The acceleration efficiency $\eta_{RF\rightarrow beam}$ for selected values of this structure length at different duty factors (DF), 20% and 100%, is shown below.

Length ↓ DF→	100%	20%
5 m	49%	83%
10 m	65%	91%
15 m	74%	94%

Lower acceleration gradients give higher efficiency. For CW operation (100% duty factor) of the RT structure, a long structure, more than 10 m, is required to get reasonable efficiency, $\eta_{RF\rightarrow beam}$ ~ 65%. This is not practical for industrial applications. Lowering the duty factor (DF) to 20% allows 83% efficiency $\eta_{RF\rightarrow beam}$ for 5 m - long structure. In Figure 8, a total accelerator efficiency η_{acc} as a function of RF source efficiency $\eta_{DC\rightarrow RF}$ is shown for three cases:

- SRF linac operating in CW regime at 650 MHz, L=1.6m;
- RT linac operating in CW regime at 915 MHz, L=10 m;
- RT linac operating at DF=20% at 915 MHz, L=5 m.

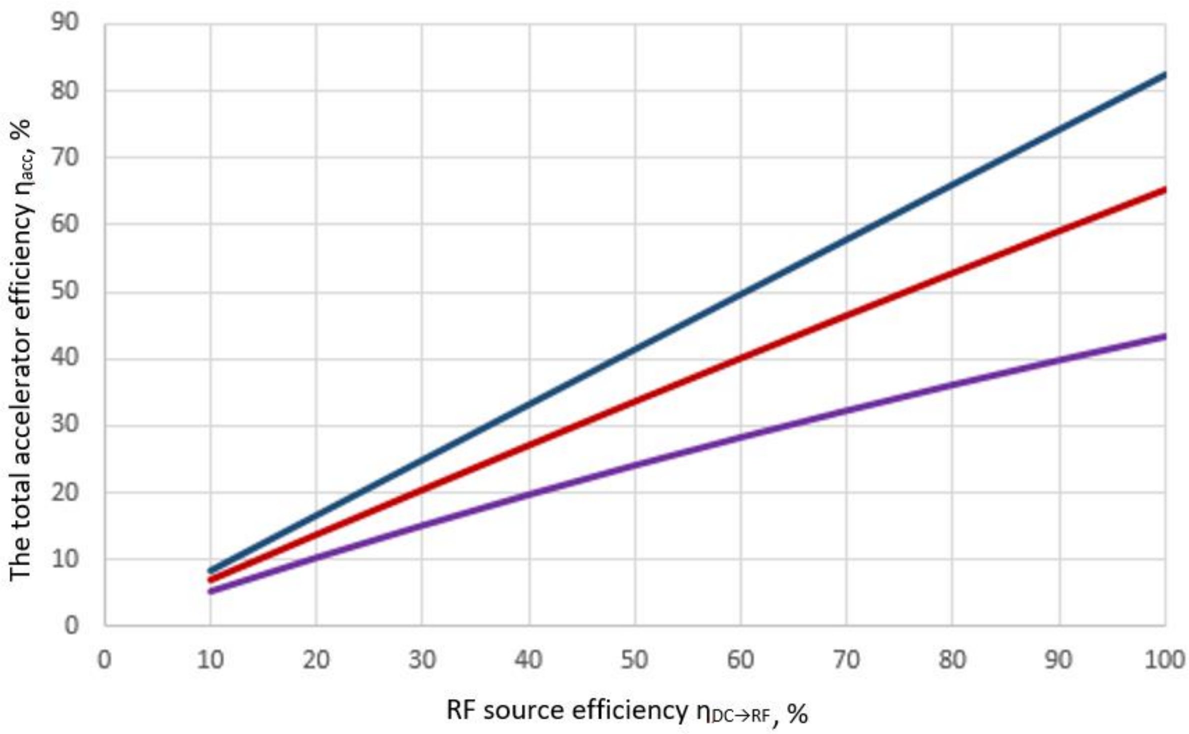


Figure 8: The total accelerator efficiency η_{acc} versus the RF source efficiency $\eta_{DC\rightarrow RF}$: SRF linac (blue), pulsed RT linac (red) and CW RT linac (purple).

In Figure 9 the total RT accelerator efficiency is shown versus acceleration efficiency for the case where the RF source efficiency is 90%. One can see that in order to reach the same total efficiency η_{acc} as SRF linac, or 74% (see Fig. 8) the acceleration efficiency $\eta_{RF\rightarrow beam}$ should be about 92%.

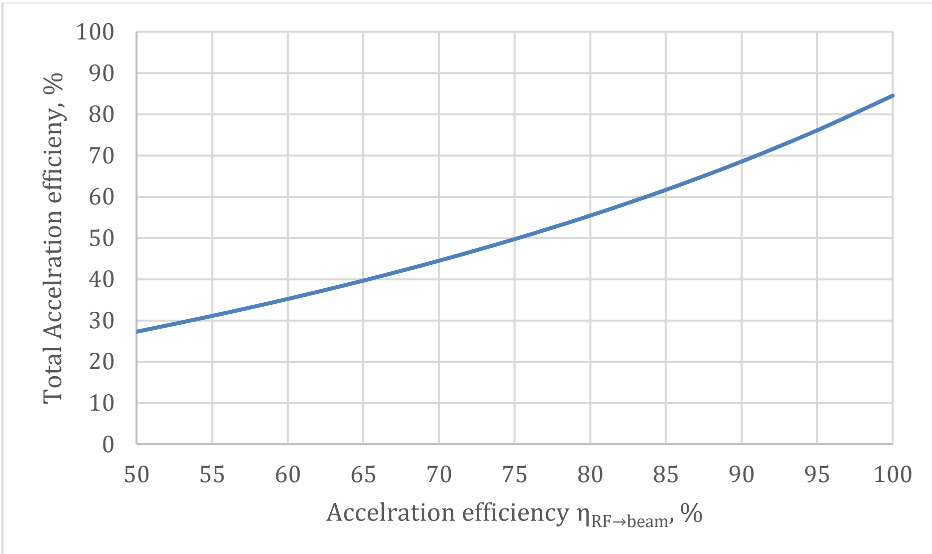


Figure 9: Total accelerator efficiency η_{acc} versus acceleration efficiency $\eta_{RF\rightarrow beam}$ for RF efficiency $\eta_{DC\rightarrow RF}$ of 90%

One can see that at a linac energy of 10 MeV, SRF is definitely more efficient and more compact than RT linac, even if RT linac is operated in the pulsed regime. At lower beam voltage, at high power, the situation is different. The wall losses are inversed proportional to the length of accelerator and proportional to the beam voltage squared. For lower beam voltage it is possible to decrease the linac length, keeping the surface loss density below ~5 W/cm2 which is acceptable for water cooling. For the optimized RT structure considered in ref. [3.7], it limits the acceleration gradient to ~1.5 MeV/m. If one considers the overall accelerator efficiency η_{acc} of >75% and "the goal" RF efficiency $\eta_{DC\rightarrow RF}$ of 90%, the length of the RT and SRF linacs versus the beam voltage at the linac power of 250 kW is shown in Figure 10. Note that the length of the SRF linac is determined by using a reasonable acceleration gradient, ~ 6 MeV/m, when Q_0 is higher than $3x10^{10}$.

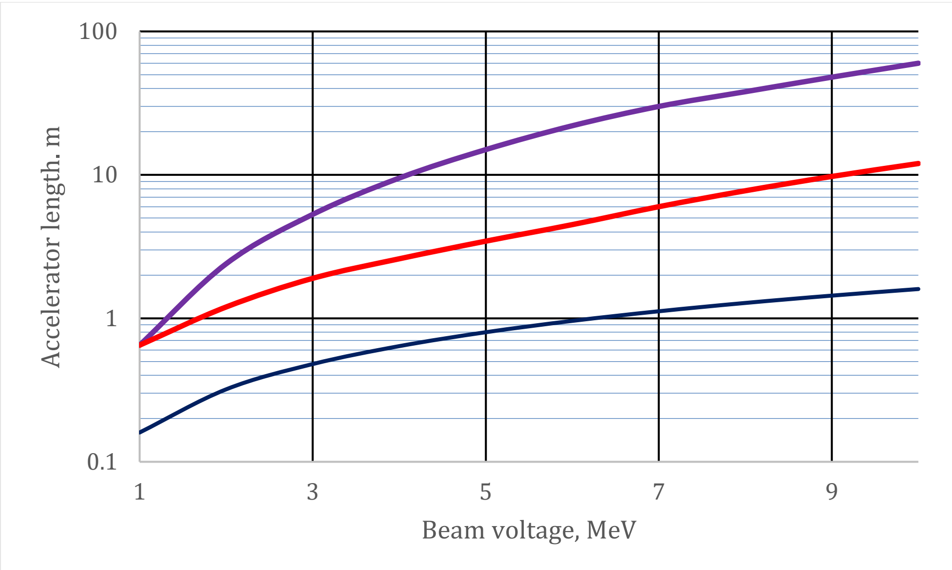


Figure 10. The linac acceleration structure length versus the beam voltage for the total accelerator efficiency ηacc ≥75% at the “goal” efficiency of the RF source $\eta_{DC\rightarrow RF}$ of 90% for RT CW 915 MHz accelerator (pink), RT pulsed accelerator having 20 % duty cycle (red), and SRF CW accelerator (blue). The beam power is 250 kW.

One can see that for low beam voltage, the length of the RT linac may be acceptable, but at beam voltages above ~4-5 MeV the length of the RT linac is substantial, > 20 m compared to SRF linac having the length <1.6 m. Of course, it is possible to pass the beam through the acceleration cavities many times (see, for example [2.9], where the concept of a RHODOTRON™ is considered. However, for high power this accelerator has limitations caused by beam loss in the 180° dipole magnets).

3. Details of an RF Station

The necessary components of a RF station are different for a single-cavity linac than for a multi-cavity linac. For the multi-cavity linac, fine amplitude and phase control is necessary to provide synchronous acceleration in the accelerator cavities fed by separate RF source. This is necessary to compensate for detuning of the cavity due to microphonics. In this case, coarse tuners are necessary for each cavity (see 2e. above). For a single cavity linac, the RF system is much simpler, because it operates in a self-excited mode and does not need phase control (see 2d. above). However, amplitude control may be necessary for variable output energy of the electron beam.

An RF station has the following components, common for all sources that we are considering, see Figures 3 and 4:

- RF source;
- AC transformer from the grid voltage to the voltage necessary for the RF source (high voltage for vacuum tubes and low voltage for SSA);

- Rectifier;
- High-power directional coupler to feed the RF gun resonator;
- High-power RF load;
- High-power transmission line;
- Matching elements (3-stub tuner, etc.);
- The driver (for IOT and SSA, for the magnetron it is not necessary);
- The current source for the tube focusing magnets (for IOT);
- Low-power components (attenuators, phase shifters, probes, directional couplers, loads, heater source for vacuum tubes, etc.);
- Cooling system for the RF source and the coupler;
- Control and diagnostic system;
- Bias source for the High-Power input coupler;
- Rack.

Highlights of an IOT RF station:

The IOT-based 250-300 kW CW RF station provides the following benefits [3.1]:

- High reliability;
- Compact size: 1 m x 1 m;
- Weight, about 50 kg;
- Efficiency $\eta_{DC\rightarrow RF}$: > 65%;
- DC power supply ≥30 kV;
- Gain: 22-24 dB
- Lifetime: about 50 k hours.

Gain is a measure of the amplification, in this case, of the power between the input and output of an amplifier expressed in logarithmic terms.
A gain of 20 dB is a factor of 10 amplification.
23 dB = 200
37 dB = 5,000
Because a magnetron does not require an external input, its gain is not defined.

A disadvantage of an IOT is its low gain; however, solid state drivers are commercially available to provide the required power of a few kW. The IOT-based 250-300 kW RF station needs a 1-2 kW driver. An example of the high-power IOT is CPI/Eimac (Varian/Eimac) 2KDW250PA, the so called “Chalk River Tube”, which provides 250 kW CW output power at 267 MHz with $\eta_{DC\rightarrow RF}$ = 73 % efficiency [3.2], see Fig. 11.

Figure 11: 250 kW CW, 267 MHz “Chalk River” IOT.

In order to increase the output power and reduce the tube size, a multi-beam IOT (MBIOT) has been developed. An example of a high-power MBIOT is the 350 MHz, 200 kW, CW tube developed by CPI, LLC and Calabazas Creek, Inc for the Advanced Photon Source [3.3]. The advantage of the MBIOT includes the high operating efficiency $\eta_{DC \rightarrow RF}$ of 70% and the dramatically reduced size.

The 350 MHz MBIOT uses seven electron beams driven by a coaxial input cavity. The RF power in the input cavity modulates the grid voltage of the guns, resulting in a pulsed emission of electrons during each positive phase of the RF cycle. This provides a bunched beam from the cathode that provides the high efficiency operation. A single output cavity converts the beam power to RF power which is extracted through a coaxial waveguide. A 3D solid model image of the MBIOT is shown in Figure 11 with a representative image of six-foot person and a sliced view showing the internal structure. This demonstrates the compactness of the MBIOT [3.1].

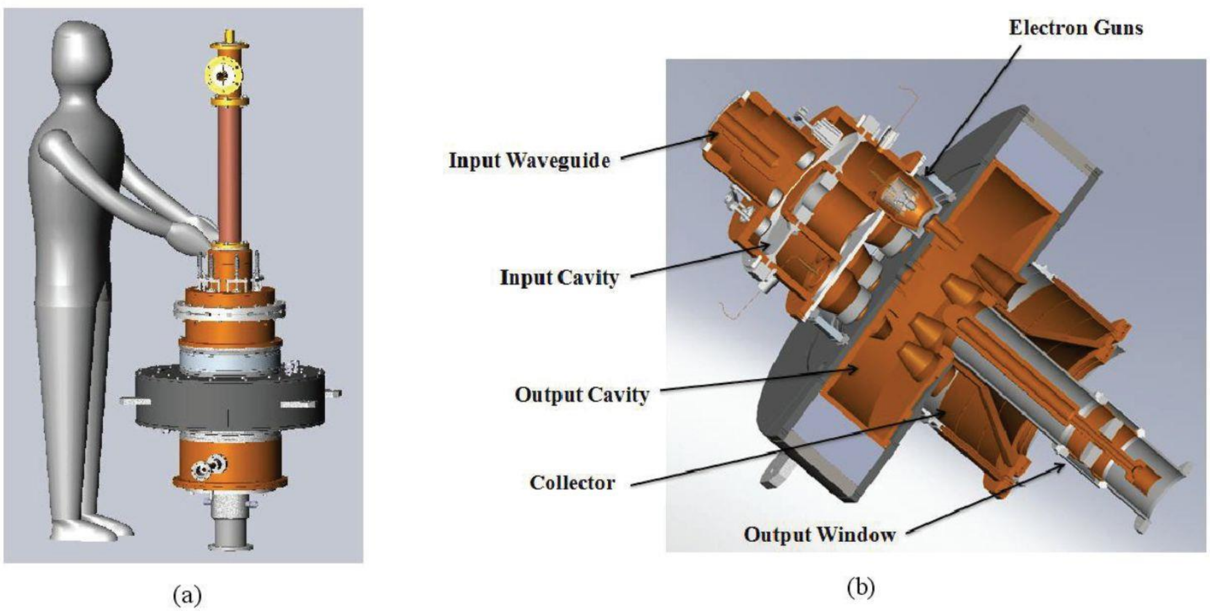
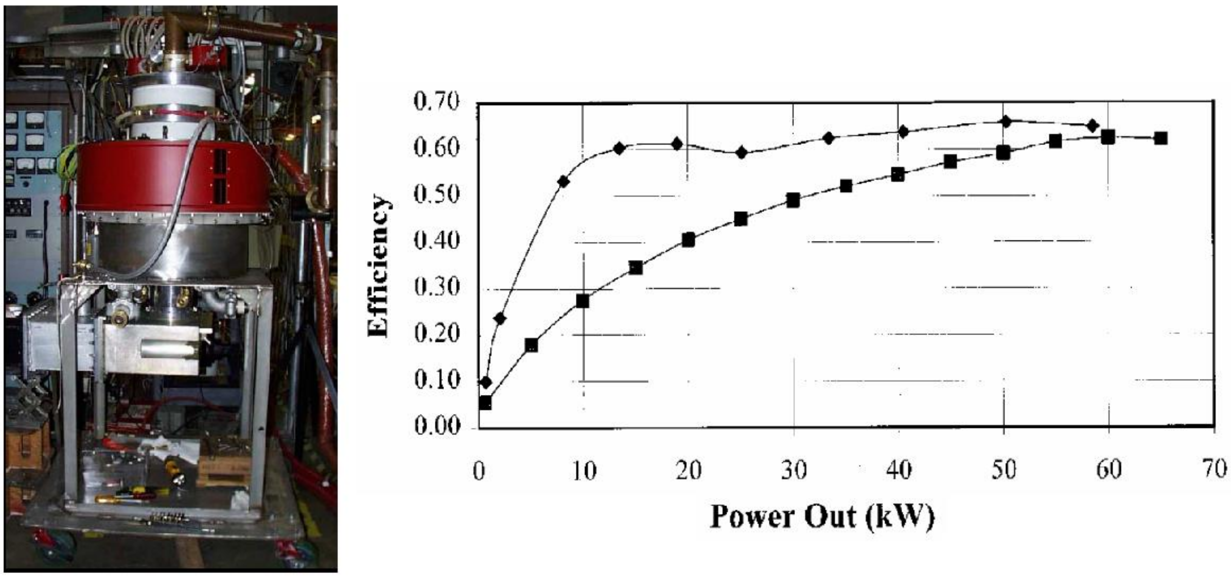


Figure 12: Solid models of 350 MHz MBIOT with six-foot-tall human figure (a) and sliced view (b).

The tube operation parameters are shown in the Table:

Parameter	**Value**
Frequency	350 MHz
Beam voltage	30 kV
Beam current	9.5 A
Efficiency $\eta_{DC \rightarrow RF}$	70%
RF output power	200 kW CW
Gain	23 dB
Number of beams	7

An MBIOT can produce over 1 MW of power. An example is the 1.2 MW, 704 MHz MBIOT developed by CPI for Accelerator Production of Tritium (APT) [3.3], see Figure 13a. The efficiency of an IOT, η_{RF} , does not depend on the output power at high power. In the Figure 13 the IOT efficiency is shown versus the output power for CPI 1.2 MW tube [3.3]. One can see that the tube efficiency is the same for the output power >75% of the maximal, see Figure 13b, lower curve. For the IOT with depressed collector the efficiency is even higher, and it is the same for the output power >25%, see 13.b, upper curve. This provides the ability to alter the linac power without losing much accelerator efficiency.



a) b)

Figure 13: 1.3 MW CW, 704 MHz CPI MBIOT (a); Efficiency vs. Output Power for a standard IOT (lower curve) and IOT with depressed collector (upper curve).

Possibilities exist for further improvement in IOT efficiency

- Operation in a deep “C” regime, using a multi-frequency RF gun providing short bunches;
- Use of a multi-stage depressed collector;
- Use of a multi-harmonic output cavity, where the modes at higher harmonics are not coupled to the output port.
- All these means altogether.

Further development of these ideas would involve detailed simulation efforts using modern 3D RF gun codes like MICHELLE [3.4].

Note that high power MBIOT for the frequencies of $\lesssim$1 GHz is a proven technology.

Highlights of a Solid-State Amplifier RF station:

CW Solid-State Amplifiers (SSA) for the power of 250-300 MW for the frequencies <1 GHz have the following features [3.1]:

- 50-60 modules of 5 kW each that are combined;
- High reliability due to use of circulators and hybrid couplers;
- Efficiency $\eta_{DC\rightarrow RF}$: 65%;

- Distributed power supply 50 V, >1000 A (low voltage, high current);
- Gain: 37 dB;
- Driver not needed;
- Lifetime: about 50 k hours.

The main disadvantage of an SSA for this power level is its large size, ~ 20 m^2 [3.1] which limits application of this RF source for industrial application, especially for portable accelerators. SSA amplifiers have not been developed for frequencies above ~ 700 MHz. Schematic of an SSA module [3.1] is shown in Figure 14.

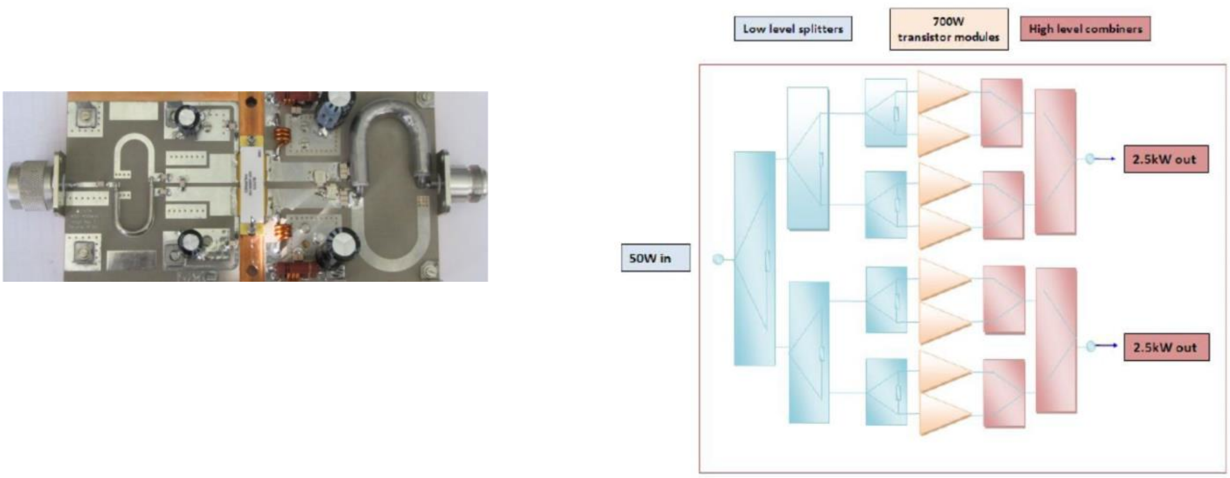


Figure 14. Example of schematic of the 5 kW, 325 MHz module of a Solid-State Amplifier [3.1].

An example of the concept and entire 150 MHz CW, 352 MHz Solid State Amplifier for SOLEIL are shown in Figure 15 [3.5]. One hundred twenty-eight 650 W RF modules are combined to get 75 kW power. Two 75 kW modules provide 150 kW. The overall efficiency $\eta_{DC\rightarrow RF}$ =55%.

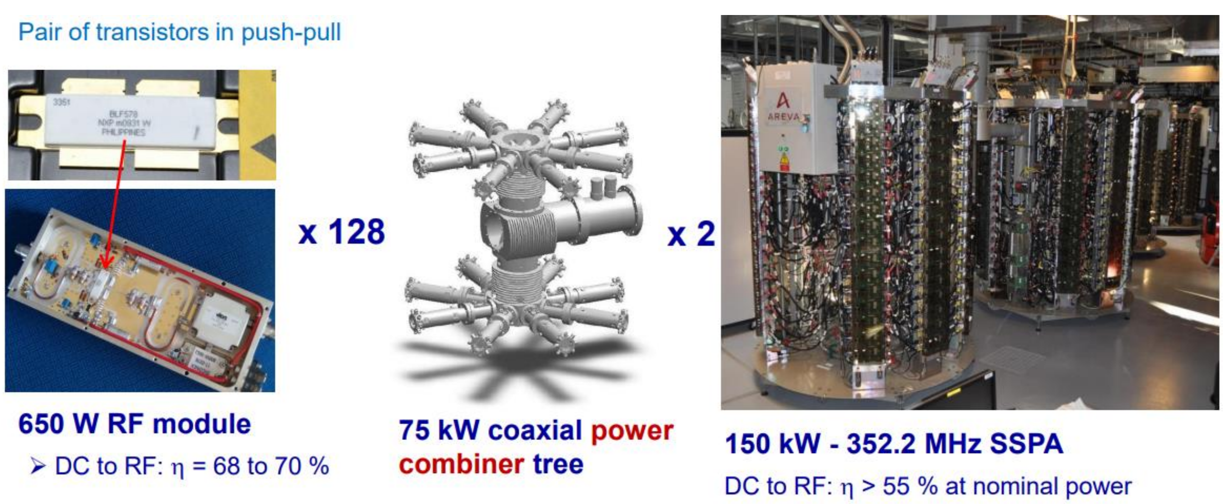


Figure 15. SSA amplifier for SOLEIL

The SSA amplifiers in the power range of hundred kW CW have been developed for the frequencies up to 500 MHz. No examples greater than 20 kW have been developed for frequencies above 1 GHz. Additional R&D is required [3.5]. Another serious issue for SSA is comparatively high cost. In the Table 3 below [3.1] for RF sources used in the European Spallation Source one can see that SSA RF cost is more than 2 times higher than for IOT:

Component	**Tetrode** (k€)	**Klystron** (k€)	**IOT** (k€)	**Solid State Amplifier** (k€)
Driver Tube	38	300	313	1000
Required Accessories	150	20	20	820
Power Supply	135	600	200	Incl in Accy's
Preamplifier	125	NA	13	NA
Total System	450	900	850	1850

Table 3: Capital cost comparison (in k€) of traditional RF power sources. Note: Total is not exact sum due to values being representative.

Highlights of a Magnetron-based RF station:

A magnetron-based 250-300 kW CW RF station for the three frequencies has the following parameters:

- Very compact size: ~ <0.5 m x 0.5 m;
- Weight about <10 kg;
- High efficiency $\eta_{DC\rightarrow RF}$: > 80 %;
- DC power supply ≥30 kV;
- Driver not needed;
- Low cost.

Presently, a major disadvantage of high-power CW magnetrons is low life span, ~ 8,000 hours. There are many 100 kW CW magnetrons available form industry in the frequencies 896, 915, 922, 929 MHz with the efficiency up to 88% from CPI LLC, L3 Technologies, Richardson Electronics and other vendors. All of them are very compact, having diameter <15 cm and length <40 cm, see Figure 16. Table 4 lists the component costs of a magnetron system. The values in parentheses illustrate the additional gains that can be achieved by improving tube lifetime.

Component	**Magnetron** (k$)
Driver Tube	11 (110*)
Required Accessories	10
Power Supply	100
Preamplifier	NA
Total System	121 (231*)

Table 4: Capital cost of a magnetron system to be compared to Table 3. (* value in parentheses accounts for shorter lifetime, and therefore more frequent replacement of tubes, compared to the other sources)

PERFORMANCE CHARACTERISTICS

Frequency	896, 911, 915, 922, 929 MHz
Power Output	100 kW
Anode Voltage	21 kV
Anode Current	6.5 A
Efficiency	86 %

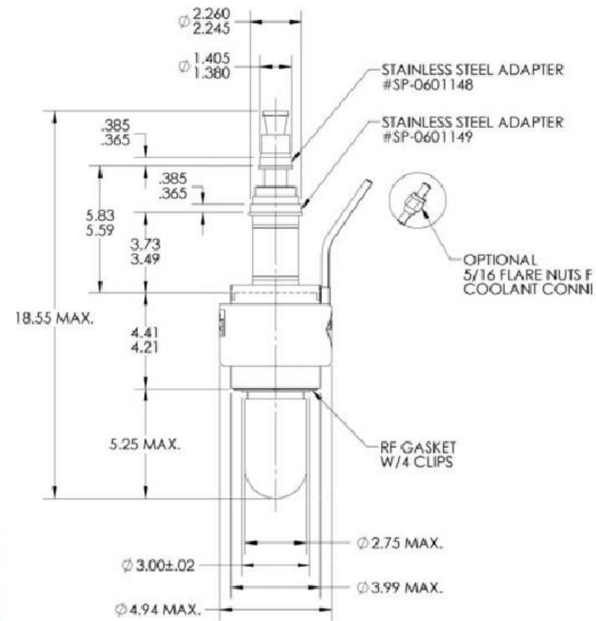


Figure 16. L3 Technologies CWM-100 100 kW magnetron, dimensions and parameters.

An example of a high-power magnetron operating in our power and frequency range is CWM-300L, a 300 kW CW, 915 MHz magnetron developed by California Tube Laboratory (CTL) [2.1]. This tube has efficiency $\eta_{DC \to RF}$ of about 90%. Parameters are shown in the Table:

Parameter	Value
Frequency	915 MHz
Beam voltage	32 kV
Beam current	10 A
Efficiency $\eta_{DC \to RF}$	90%
RF output power	300 kW CW

The sketches of this tube are shown in Figure 17.

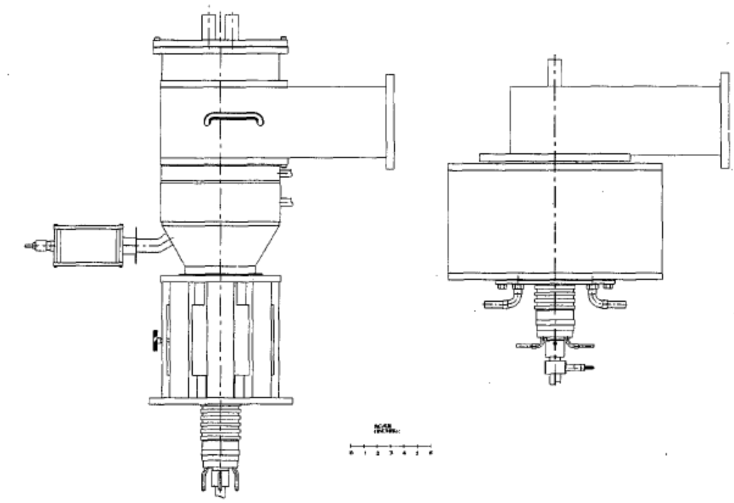


Figure 17: Final (left) vs. Experimental (right) versions of the CTL CWM-300L.

The Hartree voltage determines the range of operation of a magnetron. It is dependent on the magnetic field of an external electromagnet or permanent magnet applied to the magnetron.

The magnetron may be used for one-cavity linac as it shown in Figure 4. The magnetron may operate below the Hartree voltage, but in this case a larger locking signal reflected from the acceleration structure is required. Note that operation in injection-locked mode below the Hartree voltage allows modulation of the output power. The magnetron option does not need a driver, nor low power components like attenuator and phase shifter. The remaining components are the same as for IOT – based RF station, except that the high voltage source needs to provide the voltage modulation. This is not necessary for IOT; the output power may be altered using an attenuator in the low-power circuit.

4. Proposal for Magnetron Performance Improvement

According to Sections 1 and 2, a major issue that may inhibit the use of magnetrons for industrial accelerators is its low life span. Magnetron tubes are inexpensive, so the cost of replacement is probably not a concern. It does not appear that the process heating industry (drying wallboard and lumber) is troubled by this very much. For an industry such as medical device sterilization, the concern would be process interruption on a frequent and irregular basis. Longer lifetime and a more dependable mean-time-to-failure may be necessary for adoption of this power source. The main reasons for the present state of tube lifetime are:

- Anode sputtering of the cathode material;
- Cathode bombardment by backward electrons.

General measures which may be taken to address these issues are:

- Active vacuum pumping of the magnetron;
- Electron dynamics optimization.

Attention to electron dynamics may also improve the magnetron efficiency. Our recent investigations show [4.1, 4.2] that magnetron efficiency may be improved together with lifetime extension by operating in a sub-critical operation regime with a larger locking signal as noted in section 3.
While we have concluded that our next efforts should be focused on completing the integration of a complete CSRF system, we have outlined a program to address these issues of magnetron lifetime and efficiency.

The program:

1. Use the modern 3D simulation code, MICHELLE [4.3], to understand in detail the beam dynamics of a magnetron. This will allow self-consistent beam modeling of the electron flow in a magnetron in 3D RF and DC magnetic field in presence of the space-charge limited current emission. The emission model will need to be modified to take into account tangential DC magnetic fields on the cathode. This model has been developed and tested for high-power electron guns for electron cooling [4.4] and should be implemented in MICHELLE. The code should be modified also to simulate the transient processes of tube excitation and operation regimes – like it has been done for IOT modeling [4.5]. This effort would involve a partnership with Leidos (former SAIC), the developer of the MICHELLE code.
2. Next, the code will need to be benchmarked with the collaboration of a company with experience in high-power magnetron development. The partner would need to provide drawings of an existing well-measured magnetron, which would be simulated using the modified MICHELLE code. This improved and benchmarked code will strengthen the national RF industry allowing better designs of the magnetron for different applications – scientific, industrial, civil, and military.
3. Finally, it would be possible to optimize the magnetron design to improve its longevity and efficiency and optimize various operation regimes. Different options could be explored, like 2D harmonic cavities, different types of cathodes including the newly developed Nanocomposite Scandate Tungsten cathodes [4.6].

The goal would be to achieve an efficiency of more than 85% with tube lifetime of ~50,000-80,000 hours.

5. Conclusion

The initial phase of this project included an investigation into the current usage of the various RF sources. We drew on experience at Fermilab and conversations with RF source manufacturers and users. Much of the usage of RF power occurs in the broadcast media industry, and it is a strong driver of the technology that is prevalent today. We learned of the historical transition from vacuum tubes, to klystrons, to IOTs, and now to solid state sources. We learned of the impact of the process drying industry, which does not require precise narrow-band power sources, on the prevalence of 915 MHz for magnetron sources. The historical transition from classical sources such as klystrons and the niche market for 915 MHz magnetrons makes them desirable for use as a source for a compact SRF accelerator at first glance. However, accelerator physics scaling favors lower frequency. Thermal losses increase as the square of the frequency at SRF temperatures. Therefore, increasing the cavity frequency from 650 to 915 MHz will double the thermal losses. These reasons make 650 MHz attractive compared to 915 MHz from an SRF accelerator system perspective.

Further analysis for this report supports the choice of superconducting RF vs normal conducting systems. By using SRF, the efficiency of the accelerating structure is great enough that the system efficiency is driven by that of the RF source. SRF also provides a more compact design compared to room temperature machines.

Magnetrons are a very attractive RF source because they are simple and inexpensive and are themselves compact compared to IOTs and SSAs. The efficiency of magnetrons matches well with the efficiency of SRF accelerating cavities leading to an efficient complete system. Addressing the issue of precision and poor lifetime of magnetron tubes is not expected to greatly increase the production cost of the tubes.

The choice of 650 MHz for the CSRF was made as the achievable balance between heat generated due to RF induced heating, beam loss dependence on aperture size, physical size of components, and the cooling capacity of available cryocoolers. This frequency provides operating margins that increase certainty that a system that integrates all the technologies of the CSRF design will be successful.

In summary, an RF magnetron source is just one critical component of the entire accelerator system. Given that high-power RF magnetron development is still at an early development stage for both 650 MHz and 915 MHz, the most valuable question, at this time, is not RF cost economics (operating expense) but the thermal budget (technology risk) of the system. The demonstration of a prototype based on SRF technology with an off-the-shelf RF source is the optimal path that will provide the NNSA with the information necessary to evaluate its technology options for medical device sterilization. Once this has been proven by an actual operating system, we will have the knowledge necessary to evaluate whether the concept can be scaled to other frequencies.

The final phase of this project will develop a digital design of a CW, 200 kW CSRF systems optimized for x-ray medical device sterilization application at 650 MHz.

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