Industrial Accelerators – Beyond Transformers and Cyclotrons, More Power

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ABSTRACT

Equipment used in industrial applications to deliver large amounts of energy requires simplicity, versatility, robustness and always – more power. To meet the first three of these requirements, "high power" industrial accelerators have been based on transformers or cyclotrons, but have limitations on the power that they can produce. In contrast, RF cavity-based accelerators developed for the nation's physics community have been complex, fragile, and also limited in power. However, today physics programs have evolved into needing accelerators with industrial-type requirements – long running periods, with little downtime, simpler operations. And now these accelerators are truly high power; solidly into the megawatt range. Advances in design, materials, and supporting technologies have matured to the point that RF cavity-based accelerators are ready to push industrial accelerators to the next level. We will illustrate these new developments and new capabilities to stimulate ideas for new applications.

Keywords: accelerators, high power, industrial

1 ROBUSTNESS VS CUTTING-EDGE

Energy delivery in industrial applications requires reliability and simplicity of operation. Large support staffs and frequent interuptions for maintenance and reapir of equipment at the edge of technology can only be tolerated for very high value products. In order to be useful in large scale continuous processes, equipment needs to be easy to operate, monitor, maintain and have large capacity. The cavity-based accelerators developed for the nation's physics community are ready to answer that challenge and apply this technology to new areas.

1.1 Industrial Applications

Accelerators are already in use in many industrial applications. They are used for everytrhing from ion implantation to materials processing and irradiation to radionuclide production and more. Most of these accelerators have one of two characteristics. They can be high energy – 10s of MeV, but low power – less than 100 kW, or they can be low energy – less than 10 MeV, and of modest power, 100 – 1000 kW. Figure 1 illustrates these two trends by plotting the energy and power of accelerators used in over 60 applicatkions. Relatively untouched are applications for high energy and modest power, the center of the graph, or low to medium energy but high power of over 1 MW.

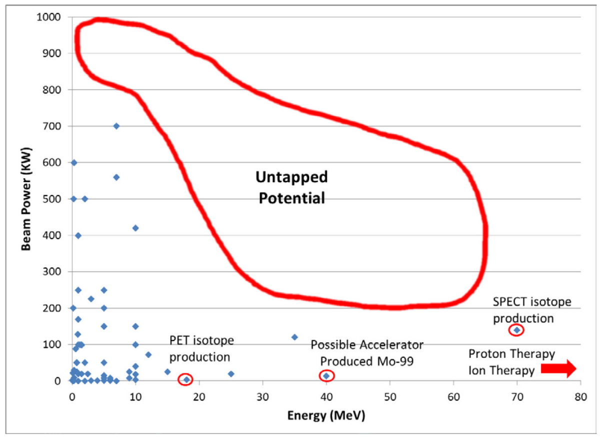

Figure 1. Energy and beam power of industrial and medical accelerators commonly in use today.

There have been a few attenpts to push accelerators in this direction. One example is electron beam flue gas treatment (EBFGT). This uses an electron beam to intiate chemical reactions between ammonia and the sulfur and nitrogen oxides in the flue gas of carbon burning power plants. The byproducts of these reactions are ammonia sulfate and nitrate fertilizers. The process has been in existance since the 1980s. However, industrial scale applications have been small and intermittent. A 2011 review of the state of EBFGT stated that "… the reliability of such big machines is still regarded as not satisfactory…"[1]

The need for robustness and reliability has historically pointed to DC accelerators and cyclotrons. Cyclotrons can provide steady continuopus wave (CW) beams at energies ranging from hundreds of keV to tens of MeV. But their current output is generally low, micro-amps or possibly a few milliamps. Therefore, the actual beam power produced is modest. Transformer-based DC accelerators can produce higher currents, even a few amps. But it appears that it is

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difficult to provide long term reliability at voltages approaching 1 MV. This limits the power output to less than 1 MW.

1.2 Accelerators for Physics

The state-of-the-art for cavity based accelerators resides in the world's physics laboratories. At each one, dozens of operators, technicians, engineers, and physicists design, develop, built, commission, and operate the latest, most advanced accelerators. While reliability is required, periodic and frequently long maintenance and development times are scheduled, which has historically mitigated some need for robustness. In recent years however, the nature of the physics being pursued has changed with the focus becoming – more power. As rarer particles are investigated, running periods extend into multiple year runs. The rarity of poducing the particles of interest requires dumping more and more beam into high power targets. The increasing complexity of synchronizing a chain of 4 or 5 accelerators with high beam currents requires increased automation. Procedures that once required many hours of intense concentration by a dozen operators and physicists are now initiated by the click of a mouse.

The end result is that today's accelerator technology is ready to be applied to new areas of industrial processes. A new power range, 1 – 10 MW is now achievable.

2 RECENT DEVELOPMENTS

Megawatt scale accelerators are possible with both normal conducting copper cavities and superconducting radio-frequency (SRF) cavities.

Numerous advances have been developed in recent years to make SRF more applicable to industrial settings. Five advances in particular, when integrated into a single design, create high-power, high-energy electron source that is both compact and efficient.

1. New surface processing techniques for niobium cavities has improved RF efficieciency, the quality (Q_0) factor.Cavities can be built where only 1 part in 10^{10} of the supplied RF energy gets turned into heat to be removed by the cooling system. The rest of the energy is transferred to the beam.
2. Advances in the processing of Nb_3Sn allow this material to be used, Nb_3Sn can operate at 4K as oppesed to 1.2K for pure niobium cavities.
3. These first two advances reduce the dynamic heating of the cavities. Expensive cryogenic systems can be eliminated and smaller, less expensive cryocoolers can be used instead.
4. A new Fermilab development is the use of injection-locked magnetrons to provide phase and amplitude control for SRF cavities. Use of this magnetron system is expected to reduce the capital cost by a factor of 5 and yet provide efficiencies of 80%.
5. Cold, field-emission electron cathodes will result in smaller electron sources and remove the necessity of warm elements in SRF systems.

All of thes advancements result in more compact, less expensive structures. They can be designed even for mobile applications of megawatt-range accelerators.

3 POTENTIAL APPLICATIONS

The new areas for accelerator applications can be distinguished by either the nature of the process to be addressed or by the manner in which the technology is applied. Most cases that we present focus on electron beams with energies of 10 MeV or below. Doing so eliminates issues of radioactivation. However, there are also applications where higher enegies are warranted.

3.1 Mobile Accelerators

Figure 2 illustrates an example of a mobile accelerator application to treat aspalt road surfaces. A 10 MeV electron beam has a range of 3 – 5 cm in asphalt. It can be used in-situ to improve the cross linking of the asphalt binder providing improved resiliency to the road surface and increasing the lifetime. The 1.4 MW SRF system shown can treat 2 lane miles per 8 hr shift. The binder is a small fraction of the cost of a road and a 20 % improvement in road surface lifetime results in a very short payback period.

A similar system can be used for pothole repair. Since the energy is delivered directly into the target material, the egdes of the existing road surface can be efficiently heated. This eliminates the cold joint between the old and new materials resulting in a more durable repair. Applying this technology requires looking beyond initial costs and instead looking at total life-cycle costs. Doing so can result in significant long-term cost savings.

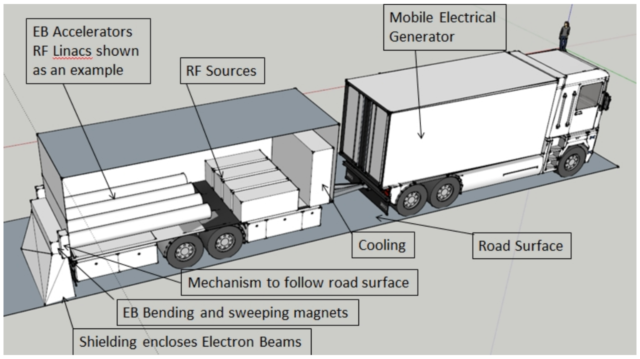

Figure 2. Mobile accelerator for treating asphalt road surface.

Figure 3 illustrares a mobile system for flare gas recovery at the well head. When a new oil well is developed methane gas is frequently produced but only for a short period compared to the life of the well. It is frequently not economical to provide pipeline connections for both the liquid and gaseous products leading to millions of BTUs being burned off, increasing CO_2 production with no benefit. An electron beam in a mobile system can crack the liquid molecules providing locations for the methane to cap resulting in an all liquid product stream that can then be piped. By using a mobile system, the euqipment can be moved to new locations once the initial methane production has subsided.

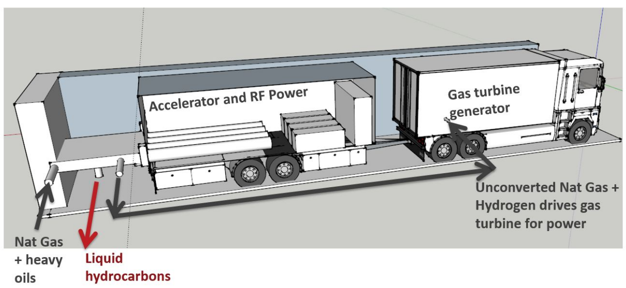

Figure 3. Mobile accelerator for combining flare gas with heavy oils for well-head flare gas recovery.

3.2 Flue Gas Treatment

We have previously mentioned electron beam flue gas treatment (EBFGT) as an example of the application of large accelerators. In order to provide a robust turn-key solution, Fermilab has teamed with PAVAC Industries to develop an EBFGT system. PAVAC is a supplier of turn-key electron beam welders and so has the experience required to produce equipment with simple control systems suitable for the industrial environment. Fermilab has the experience to optimise the design of a normal conducting copper linac to provide the beam power required. Together they plan to build a demonstration facility that can be used to examine the many parameters that have confounded previous applications. The resulting system will be simple to operate and able to respond to the many carbon fuels used in power generation.

3.3 Wastewater Treatment

The current drought on the US west coast brings the subject of water treatment into particular focus. An electron beam is the most efficient process for generating oxydizing hydroxyl radicals. It simultaneously produces reducing radicals.[ref] This makes it a competative process for treating water from various sources, expanding the number of potential sources for water. Either previously unusable sources or reuse of wastewater is now feasible. Table 1 lists the energy required to provide water from various sources. The energy requirements for irradiation of wastewater are comparable to that of current wastewater treatment tecbiques. However, irradiation not only treats biologicals that present techniques treat but also organic compounds, pharmaceuticals, and other chemical compounds, therefor increasing its potential source inflows.

Energy Required	**kWh/m^3**		
	Low	**High**	
Water Desalination	2.58	8.5	
Wastewater Reuse	1	2.5	
Wastewater Irradiation	0.75	1.5	2 kGy 40 – 80 % eff.
Wastewater Treatment	0.62	0.87	
Grounwater	0.48		
Lake or River	0.37		

Table 1: Energy required to produce safe drinking water from various sources. [2]

3.4 Chemical Processes

The electrons in an accelerated beam are able to directly ionize many atoms or molecules (~2.5×10^4 per 1 MeV electron). This makes the concept of accelerator-driven chemistry attractive. For instance, processes that presently must be conducted in large batches are all-or-nothing. The demand must be large enough to warrant the large quantities or the end product must be stable and valuable enough to warrant storage of much of the product. Disruptions in the process can jeaprodize the entire batch. With an accelerator driven chemical process, the amount of material undergoing the reaction at any given time can be greatly reduced. Batch processes can be converted to continuous processes. Qantities on hand at any given time can be reduced. Disruptions risk the loss of smaller quantities of product.

We stated previously that most applications of electron beams were limited to less than 10 MeV. This is because, above 10 MeV some elements produce photoneutrons which can lead to activation of components or the materials being processed. However, careful design of reaction vessels and attention to the composition of the reactants may allow higher energies while maintinaing activation rates that are copmarable with natural sources. This can further increase the efficiency accelerator driven chemical processes.

4 NUCLEAR WASTE

An example of an application not limited to 10 MeV electrons is the treatment on nuclear waste. The materials are already radioactive and the reactions to be initiated require proton beams of GeV range energies.

Current proposals for dealing with nuclear watse have focused on Accelerator Driven Systems (ADS). This concept uses an accelerator to produce a high energy beam directed onto a spallation target. The resulting neutrons push a sub-crtical reactor into the critical range only while the accelerator is on. This has been proposed for both energy generation in addition to nuclear waste treatment.

Another possibility is to focus solely on the treatment of nuclear waste and specifically on the very long lived actinides. Accelerators similar to the SNS at Oak Ridge or the proposed PIP-II at Fermilab have the beam power and energy to potentially bypass the need for a spallation source and the corresponding need for design and optimization of the target-blanket assembly. Designing the system to minimize the amount of fissile material present in the target area and removing the desire to co-produce power could greatly simplfy the regulatory requirements. Directly fissioning the actinide isotopes to produce short lived byproducts would eliminate the need for long term storage solutions.

5 SUMMARY

Despite the many uses of accelerator technology prevalent today, there are new areas of application that are ready to be explored. Transformational, technological advances mean superconducting RF is available for industrial applications. These advances reduce the size and cost of accelerating structures. New control technology for both RF and overall system control greatly simplify control systems allowing the development of turn-key systems. Similar advances

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