Industrial Accelerators – Beyond Transformers and Cyclotrons, More Power

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ABSTRACT

Particle accelerators used in industry require simplicity, versatility, and robustness. To meet these requirements, many industrial accelerators have been based on high voltage transformers or circulating accelerators of modest current. These technology choices lead to limited beam power. Historically, RF cavity-based accelerators for the nation's science community tended to be complex, fragile, and were also often limited in beam power. However, today the requirements of nation's science programs have evolved and accelerators are capable of high beam powers and long running periods with little downtime. Many of these accelerators are now solidly into the megawatt range. Advances in design, materials, and supporting technologies have matured to the point that RF cavity-based accelerators, and especially linear accelerators, are ready to push industrial accelerators into a new high power regime. This presentation will illustrate these new developments and new capabilities to stimulate ideas for new applications.

Keywords: accelerators, high power, industrial

1 ROBUSTNESS VS CUTTING-EDGE

Industrial applications require reliability and simplicity of operation. To be useful in large scale continuous processes, equipment needs to be easy to operate, monitor, and maintain by non-experts. To recover capital investments, the equipment must have significant product throughput. Large technical support staffs and frequent interruptions due to failures of equipment at the edge of technology can be tolerated only for a small subset of very high value products. New robust and cost effective accelerator technology developed for the nation's physics community is ready for technology transfer from labs to industry to answer these challenges.

1.1 Industrial Applications

Accelerators are already in use in many industrial applications. They are used for everything from ion implantations 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 – 700 kW). Figure 1 illustrates these two trends, plotting the energy and power of accelerators used in over 60 applications. 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.

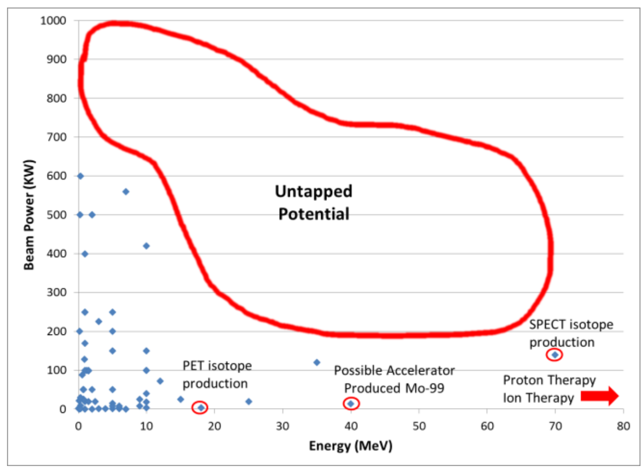

Figure 1. Energy and beam power of industrial and medical accelerators commonly in use today.

Recent examination of new and potentially transformational accelerator technologies lead us to believe that there are several new industrial processes that could benefit from megawatt class accelerators. One example is electron beam flue gas treatment (EBFGT). This uses an electron beam to initiate 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 existence 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 circulating machines such as cyclotrons. Cyclotrons can provide steady continuous wave

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(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. However, these machines are physically very large and it appears that it is difficult to provide long term reliability as voltages approach 1 MV. In practice this has limited the power output of such machines to less than 1 MW. The shielding requirements of large machines have significant impact on the capital cost of industrial installations and therefore limit technology penetration into new areas.

1.2 Accelerators for Physics

The state-of-the-art for cavity based accelerators resides mainly in large government operated science laboratories. Only a handful of these exist. One of the largest is Fermilab where a technical staff of over 600 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 a large number of accumulated particle interactions for experiments that may last several years. In practice this means high reliability for 24/7 operations and more beam power. As rarer particles are investigated, running periods will extend into decades. The rarity of producing the particles of interest requires more and more beam into very high power targets. The increasing complexity of synchronizing a chain of 4 or 5 accelerators each consisting of thousands of active elements and with high beam currents that can easily damage the accelerator requires ever 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 a powerful new set of accelerator tools and technology ready to be applied to new industrial accelerators able to operate at beam powers in the range of 1 – 10 MW.

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 a high-power, high-energy electron source that is both compact and efficient.

1. New surface processing techniques for niobium cavities has improved RF efficiency known as the quality (Q_0) factor. Cavities can be built where only 1 part in 10^{10} of the supplied RF energy is 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 have made it available in large scale applications. Nb_3Sn can operate at 4K as opposed 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. Injection-locked magnetrons to provide phase and amplitude control for radio frequency power delivered to SRF cavities have been developed at Fermilab. 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 these advancements result in more compact, less expensive structures. They can also be incorporated in 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 energies are warranted.

3.1 Mobile Accelerators

Figure 2 illustrates an example of a mobile accelerator application to treat asphalt road surfaces. A 10 MeV electron beam has a range of 3 – 5 cm in asphalt. Such an accelerator could 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 hour shift. The binder is a small fraction of the cost of a road and even a 20 % improvement in road surface lifetime results in a very short payback period.

A similar system can be used for pothole repair on the coldest of winter days. Since the beam energy is delivered deeply into the existing road surface, this eliminates the joint between the old cold and new hot patch material 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.

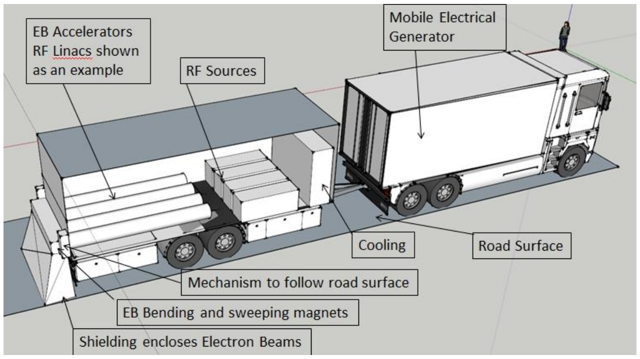

Figure 2. Mobile accelerator for treating asphalt road surface.

Figure 3 illustrates a mobile system for flare gas recovery at the well head. When a new oil well is developed methane gas is frequently produced only during an initial period of 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 long-chain hydrocarbon molecules and at the same time remove hydrogen from methane providing locations for the methane or hydrogen to cap the cracked hydrocarbons resulting in an all liquid lower viscosity product that is more easily transported.

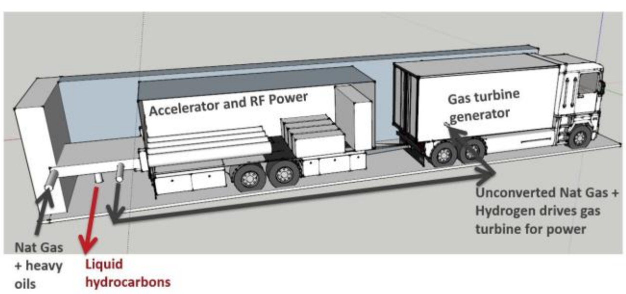

Figure 3. Mobile accelerator for combining flare gas with heavy oils for well-head flare gas recovery.

3.2 Treatment of Flue Gas

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 a small North American company to develop an EBFGT system. Fermilab's partner 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 optimize 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 oxidizing hydroxyl radicals and it simultaneously produces reducing radicals.[2] This makes it a competitive 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 techniques. However, irradiation not only treats biologicals that present techniques target but also has been demonstrated to effectively destroy organic compounds, pharmaceuticals, and other un wanted chemical compounds, therefore increasing its effectiveness for recovery of many industrial waste water streams.

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	
Groundwater	0.48		
Lake or River	0.37		

Table 1: Energy required to produce safe drinking water from various sources. [3]

3.4 Chemical Processes

Most chemical reactions in industry that require breaking difficult chemical bonds are driven by input of heat, pressure, and catalysts. Most thermal energy goes into rotational and vibrational states. In contrast a single ionization interaction from an electron beam can directly break any chemical bond. This makes the concept of accelerator-driven chemistry attractive. For instance, many processes must be conducted in large batches. The demand for the end product 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 jeopardize 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. Quantities 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. 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 maintaining activation rates that are comparable with natural sources. This can further increase the efficiency accelerator driven chemical processes as increasing the beam energy is a cost effective way of increasing beam power for cavity based accelerators.

4 NUCLEAR WASTE

An example of an application not limited to 10 MeV electrons is the treatment of 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 waste have focused on Accelerator Driven Systems (ADS). The ADS concept uses an accelerator to produce a high energy beam directed onto a spallation target. The resulting neutrons push a sub-critical 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 burning very long lived actinides. Accelerators similar to 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 simplify 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 enable the use of normal conducting structures also. These advances result in smaller structures and enable mobile applications of megawatt scale accelerators at reasonable cost.

New applications are now available such the treatment of various wastes. This ranges from treating exhaust gases form carbon burning power plants to the treatment of waste from various industrial processes. Water treatment includes treating wastewater more thoroughly for release into the environment or for immediate reuse.

A new regime of accelerator-driven chemistry is envisioned that utilizes the direct energy deposition of electron beams to facilitate large scale but well controlled chemical reactions.

Finally a new approach to the treatment of nuclear waste is proposed. This approach focuses solely on burning the very long lived actinides and producing end products with lifetimes closer to 100 years. This would give all the nuclear waste products similar lifetimes creating a more uniform and more manageable storage situation. By focusing solely on burning the waste and keeping the amounts of materials in the system small, the regulatory issues may be simplified.

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[3] D. Talbot, "Desalination out of Desperation", MIT Technology Review, December 16, 2014.