Motivation and Development of a Compact Superconducting Accelerator for X-ray Medical Device Sterilization

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Motivation for focus on medical device sterilization

Approx 50% of single use medical devices are sterilized with gamma rays from decay of Co-60

- Worldwide, 400 MCi of 600 MCi permitted
- Medical Device industry growing at (at least) 7% per annum
- Cobalt production is behind market demand by 5%
- Sterilization capacity shortages are looming
  - BPSA is aggressively pursuing X-ray by end of 2022
- Radioisotope security concerns
Motivation for focus on medical device sterilization

- Concerns that the industry relies on only two manufacturers
- Capacity has no cushion, 100% full
- In the Bio processing industry (consumables for vaccine and pharmaceutical manufacturing) production could be reduced to 50% by end of 2022 due to lack of sterilization capacity
Motivation for focus on medical device sterilization

- Need more accelerators
- Need the industry and regulators to recognize the equivalency of X-ray with cobalt-sourced gammas
- Need data to support equivalency
  - Team Nablo
  - BPSA data
- Need the data to be shared, non-competitive
Market Situation in 10 years... What if...

In 10 years

What if, Only 40% in ETO, 25% in Gamma and 5% market growth?
→ 35% of 2,400MCi = 840MCi …

~ 280 systems of 3 MCi

What if, Only 35% in ETO, 20% in Gamma and 7% market growth?
→ 45% of 3,000MCi = 1.350MCi …

~ 450 systems of 3 MCi

What if, Only 30% in ETO, 30% in Gamma, 10% other modality and 5% market growth?
→ 25% of 2,400MCi = 600 MCi …

~ 200 systems of 3 MCi

200 to 400 systems over the next 10 years
Accelerator requirements to meet need (X-ray mode)

- Maximize uptime
  - Cobalt is always working, lift mechanisms are simple
- More accelerator suppliers?
- Linac systems need more power to match Rhodotron
  - 300 – 400 kW
- Further optimization of conveyor systems
  - Use all the photons
- Increase allowable energy?
  - Increases Bremsstrahlung efficiency
250 kW Industrial SRF accelerator – under development

- Energy: ~ 10 MeV
- Power: 250 KW
- Turn-key operation
- High reliability
- Low cost
- Small: Cryostat
  - ~ 0.7 m dia
  - ~ 1.5 m long
- Modified existing 650 MHz cavity
- Magnetron RF source and commercial Cryo-cooler
- Modular design scales to MW class industrial applications
- Total weight 3000-5000 lbs \( \rightarrow \) viable for mobile applications
- Mobile platform enables many new applications
- Environmental applications
20 kW prototype

- Cavity support
- Thermal shield
- Conduction cooling links
- Magnetic shield
- Beamline valve
- 1-1/2 cell 650 MHz cavity
Why SRF? Efficiency – the key to economical applications

Accelerator efficiency versus RF source efficiency - 250 kW

- SRF
- Room temp 5% DF
- Rhodotron
- Room temp 25% DF

https://lss.fnal.gov/archive/2020/pub/fermilab-pub-20-369-di-td.pdf
## Efficiency – the key to economical applications

|                           | SRF Nb$_3$Sn | IMPELA      | IMPELA      | RHODOTRON  |
|---------------------------|--------------|-------------|-------------|------------|
| Frequency                 | MHz          | 650         | 1300        | 1300       | 107.5      |
| Length                    | m            | 1.6         | 3.25        | 3.25       | 2          |
| Energy                    | MeV          | 10          | 10          | 10         | 10         |
| Average beam power        | kW           | 250         | 250         | 250        | 250        |
| Duty Factor               | %            | 100         | 5           | 25         | 100        |
| Pulsed beam power         | kW           | 250         | 5000        | 1000       | 250        |
| Power for refrigeration   | kW           | 40          | N/A         | N/A        | N/A        |
| Pulsed Ohmic loss in the linac | kW      | N/A         | 540         | 540        | N/A        |
| Pulsed RF power           | kW           | 250         | 5540        | 1540       | N/A        |
| Average RF power          | kW           | 250         | 277         | 385        | 336        |
| Average Ohmic losses      | kW           | N/A         | 27          | 135        | 86         |
| Beam current              | mA           | 25          | 500         | 100        | 25         |

[1] T. Hhabiboulline, V. Yakovlev, T. Kroc, “Analysis of RF high power sources for 1MW – range, 10 MeV CW industrial accelerator,” FERMILAB-PUB-20-369-DI-TD, May 29, 2020.
[2] J. Ungrin, N.H. Drewell, N.A. Ebrahim, J-P. Labrie, C.B. Lawrence, V.A. Mason, and B.F. White, “IMPELA: AN INDUSTRIAL ACCELERATOR FAMILY,” EPAC 1988, pp. 1515-1517.
[3] Marc Van Lancker, Arnold Herer, Marshall R. Cleland, Yves Jongen, Michel Abs, “The IBA Rhodotron: an industrial high-voltage high-powered electron beam accelerator for polymers radiation processing,” Nuclear Instruments and Methods in Physics Research B 151 (1999) 242-246.
RF Efficiency – the key to economical applications

Accelerator efficiency versus RF source efficiency - 250 kW

Accelerator efficiency, %

0 10 20 30 40 50 60 70 80 90

RF source efficiency, %

0 10 20 30 40 50 60 70 80 90 100

- SRF
- Room temp 5% DF
- Rhodotron
- Room temp 25% DF

https://lss.fnal.gov/archive/2020/pub/fermilab-pub-20-369-di-td.pdf
Efficiency Conundrum

- 0.5/1.0 Mci = 60/120 MW of accelerator beam power
- At 50% efficiency, wasting 60/120 MW
- At 85% efficiency, wasting 10/20 MW

- Solid state RF has tremendous advantages
  - Incremental power
  - Hot switching of power packs

- But low efficiency

- Traditional Power development is waning (knowledge is being lost)
  - Needs revitalization
  - Improve performance
  - Performance needs to outweigh SSRF advantages
Magnetron Power for Accelerators

**PERFORMANCE CHARACTERISTICS**

- **Frequency**: 896, 911, 915, 922, 929 MHz
- **Power Output**: 100 kW
- **Anode Voltage**: 21 kV
- **Anode Current**: 6.5 A
- **Efficiency**: 86 %
Phase & Amplitude Control for Magnetron Driven Accelerators
The program:

1. Use a modern 3D simulation code to understand in detail the beam dynamics of a magnetron.

2. Benchmark the code. This improved and benchmarked code will strengthen the 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. The goal would be to achieve an efficiency of more than 85% with tube lifetime of ~50,000-80,000 hours.
Thank you

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