Superconducting Accelerators for High-Power X-ray production

Thomas K Kroc, PhD
Virtual Technical Meeting on the Recent Development of Radiation Generators for Industrial Applications
29 September 2021
Fermi National Accelerator Laboratory

- National Laboratory: Funded by the Department of Energy (OHEP)
- Mission: High Energy Physics Research (Discovery Science)
- To carry out that mission Fermilab designs, builds, & operates: High Energy, High Power (MW), High reliability Accelerators
- 6800 acre (2750 ha) site, ~$360M/yr budget, Staff of 1700, > 2200 users
- 350 Accelerator Scientists and Engineers + 300 technical staff (+ANL)
- Largest collection of Accelerator Experts in the world
- Broad skills in accelerator design, simulation, fabrication, integration & test
- Also well versed in industry/university partnerships
Scientists and engineers at IARC work side by side with industrial partners to research and develop breakthroughs in accelerator science and technology and translate them into applications for the nation’s health, wealth and security.
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 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
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 → 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

Fermilab
Integrated electron gun – no LEBT

300 K

70 K

70 K intercept to gun assembly

4 K
**Nb$_3$Sn – Raises the critical temperature, $T_c$**

- Sn vapor evaporated onto Nb cavity surface, Sn reacts with Nb to form Nb$_3$Sn at elevated temperatures
- Reasons for choosing vapor diffusion:
  - **Only process** shown to produce Nb$_3$Sn SRF cavities with high $Q_0$ at $E_{acc} > 1$ MV/m
  - Extremely close match of **thermal expansion coefficient**: avoid delamination
  - High temperatures $\sim 1100$ C: low $T_c$ Nb-Sn phases not thermodynamically stable
  - Strict control of impurities – **no copper involved**
  - Can achieve very **clean grain boundaries**
  - Relatively **smooth surface** to avoid field enhancement

*SEM images of Nb$_3$Sn film coated on Nb: a) surface, b) cross section*

*Close match of CTE between Nb and Nb$_3$Sn for strong bond at cryogenic temperatures*
**Challenge of Closed Structure**

- Sn vapor flow is below viscous regime – line-of-sight is a factor
- High performance coatings in complex 9-cell cavity give hope for 1.5 cell

Good performance already: 9-cell 1.3 GHz, open on **both** sides

This project: 1.5-cell 650 MHz, open on **one** side

https://www.pfeiffer-vacuum.com/en/know-how/introduction-to-vacuum-technology/fundamentals/types-of-flow/
What is a conduction-cooled SRF cavity?

- SRF cavities require cooling near 4 Kelvin to operate in the superconducting state. The cooling is traditionally provided by liquid helium.
- The 20 kW accelerator will be the first ever to use an SRF cavity without liquid helium.
- Cavity is cooled *via* thermal conduction using:
  - High thermal conductivity link
  - Mechanical 4 K cryocoolers
Characterization of link thermal conductor

5N purity aluminum is chosen as the thermal link material

Setup for measuring 4 K thermal conductivity, contact resistance

4 mm thick Al plate

4 K cryocooler

R = 1.0” (~45°)

Torque (75 in-lb)

Indium foil (4 mils)

Sensors

Al (N5) plate #2

X6

X5

X4

X3

Al (N5) plate #1

X2

X1

Heater

Thermal conductivity found to be near the lower band of 5N, no deterioration from bending

R.C. Dhuley et al., IEEE Trans. Appl. Supercond., 2019. https://doi.org/10.1109/TASC.2019.2901252

J. Thompson and R.C. Dhuley, 2019. https://doi.org/10.2172/1546003
Thermal link design for the 1.5-cell cavity

2 x cryocooler mounting pads

5N aluminum thermal link

FEA verification of thermal link performance
Specifications for the 1.5-cell cavity

Target for NNSA

20 kW prototype:

\[ E_{\text{acc}} \approx 7 \text{ MV/m} \]

\[ Q_0 \approx 1 \times 10^{10} \]
# 1.5-cell cavity expected heat load

| Heat load at ~5 Kelvin                                      | Value [W] |
|-------------------------------------------------------------|-----------|
| RF dissipation in cavity (with $Q_0 = 1e10$)                | 1.46      |
| Gun static heat leak                                        | 0.08      |
| Cathode radiation to cavity (temp = 1373 K)                 | 0.22      |
| Conduction through cavity supports                          | 0.1       |
| Conduction through outlet beam pipe                         | 0.1       |
| Thermal radiation to cavity from thermal shield             | 0.1       |
| Thermal radiation to cavity through beam pipe window        | 0.24      |
| Beam loss ($1e-6$ of 20 kW = 0.02 W)                        | 0.02      |
| Coupler static + dynamic at 20 kW cw                        | 1.0       |
| **Total**                                                    | **3.5**   |
### Estimated heat loads to ~50 K

| Heat source                                              | Heat load (W) |
|----------------------------------------------------------|---------------|
| Radiation and residual gas conduction                    | 5.6           |
| Gun static heat leak                                     | 0.4           |
| Conduction through cavity supports                       | 3.0           |
| Cold to warm transition bellows                          | 6.2           |
| Coupler static + dynamic at 20 kW CW                     | 5.0           |
| **Total**                                                | **20.2**      |
200 kW, 7.5 MeV 1st Article
RF Design
Efficiency – the key to economical applications

Accelerator efficiency versus RF source efficiency

- SRF
- 5% DF
- 25% DF
- Room Temp
Magnetron Power for Accelerators

PERFORMANCE CHARACTERISTICS

| Property         | Value         |
|------------------|--------------|
| Frequency        | 963, 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
Magnetron Performance Improvement Program

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 [12].

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