

ABSTRACT

Superconducting technology has significantly advanced the capabilities of particle accelerators, facilitating higher beam-power operations for fundamental research at a comparatively lower cost. However, the conventional implementation of superconducting technology introduces complexities in the form of cryogenic plants, cryogenic distribution systems and substantial construction and operational cost. In response to these challenges, recent research efforts at Fermilab have been dedicated to the development of a cryogen-free, conduction-cooled Nb3Sn-based superconducting technology. This paper outlines the beam optics design of a 20-kW conduction-cooled compact superconducting accelerator for medical sterilization. The paper reviews both the physics and practical constraints associated with high beam-power operation within the context of industrial applications. The focus is on providing insights into the potential of this innovative technology to overcome existing challenges and pave the way for more accessible and efficient industrial particle accelerators.

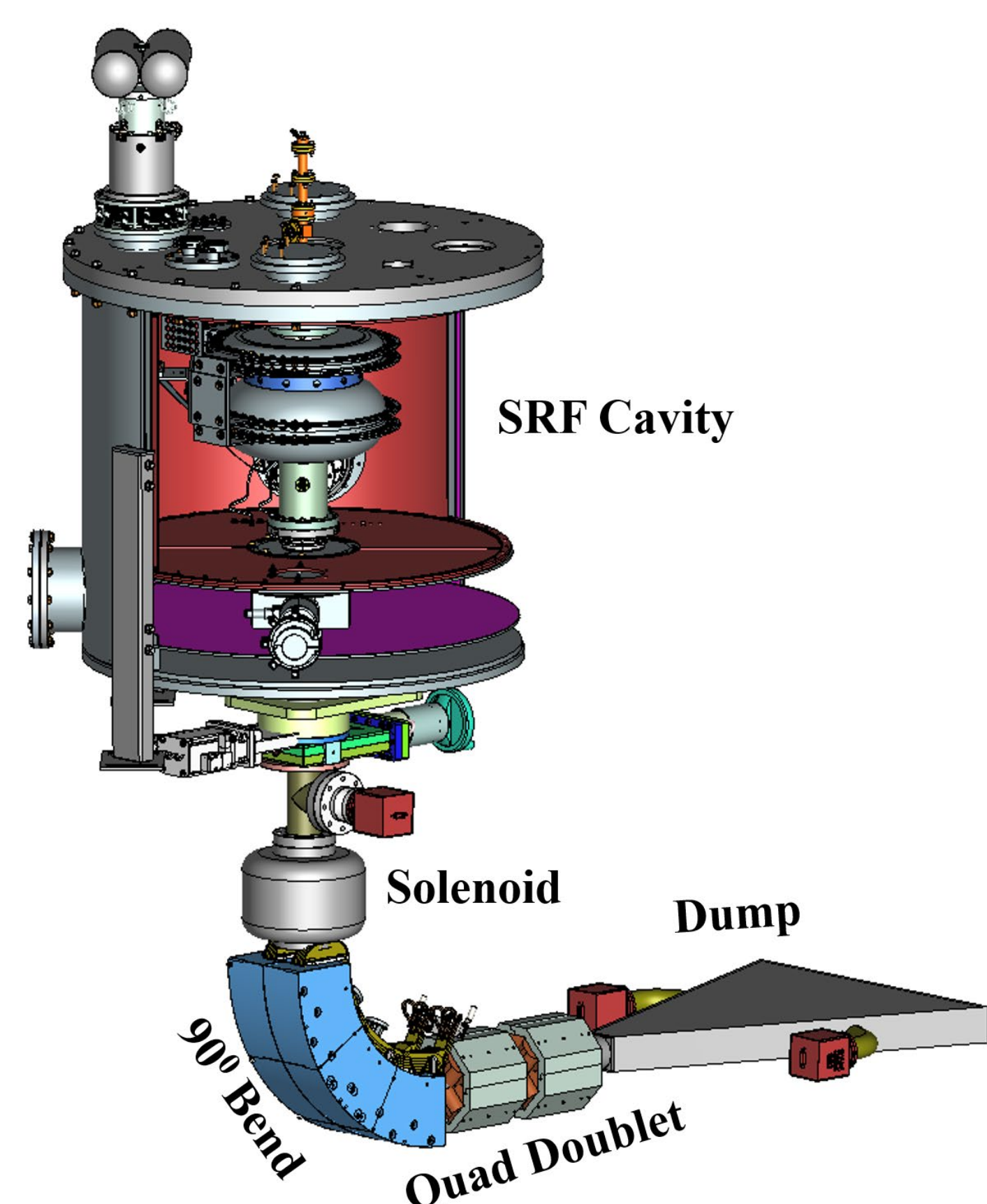
MOTIVATION

- ❖ The Superconducting Radio Frequency (SRF) accelerating structures provide higher accelerating fields with minimal power dissipation, making them highly energy-efficient and capable of delivering significant energy-gains.
- ❖ Despite these advantages, SRF technology has not fully adopted in the commercial sectors. This is primarily due to several pragmatic hurdles associated with conventional SRF accelerators, including:
 - The significant initial capital investment required to establish an SRF facility.
 - Comparatively a larger footprint of the overall infrastructure.
 - Complexity of routine operation and maintenance associated with cumbersome systems such as cryo-plant and cryogenic distribution.
 - Need for highly skilled personnel to manage and maintain the facility.
- ❖ To overcome these challenges, recent research and development efforts at Fermilab have been focused on developing enabling technologies to simplify and reduce the construction and operational cost of SRF particle accelerators for a variety of energy and environmental applications including but not limited to medical sterilization.

20-KW PROTOTYPE SRF ACCELERATOR

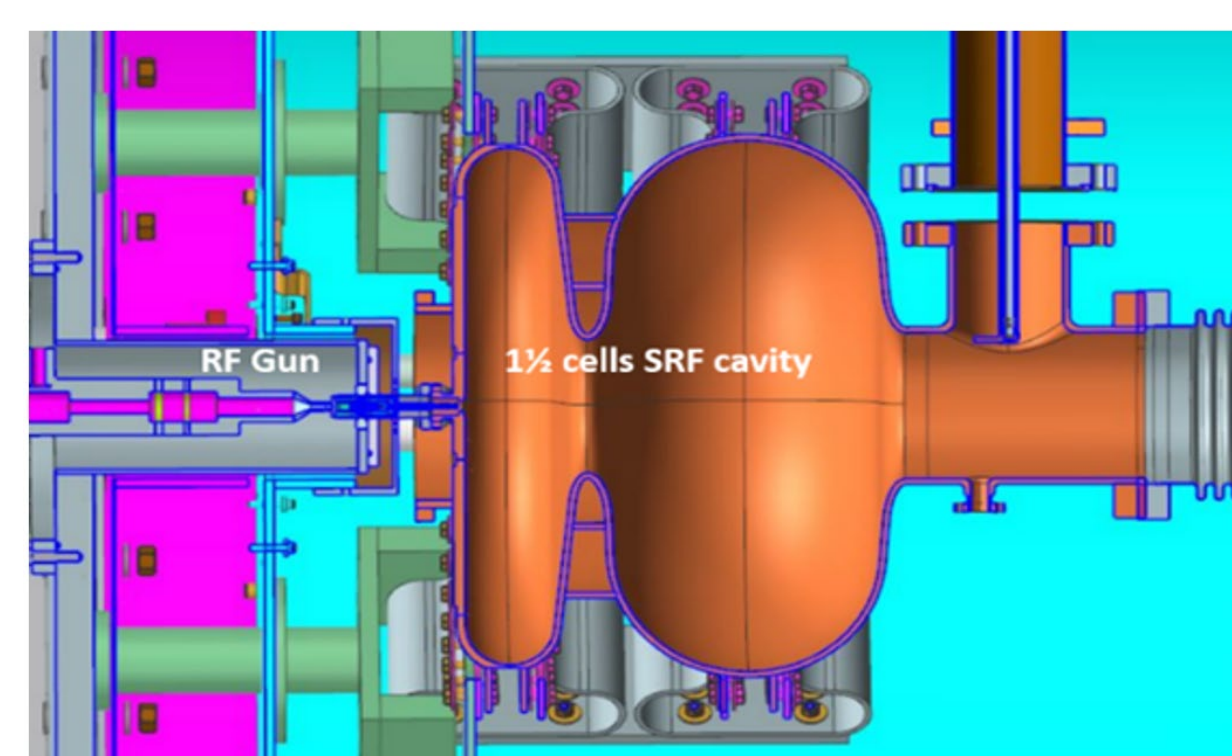
- ❖ Fermilab has been working to develop a prototype cryogen-free, conduction cooled Nb3Sn based, 20 kW, Continuous Wave (CW), electron SRF accelerator.
- ❖ Nb3Sn coated cavities significantly reduce cryogenic losses and allow for operation at higher temperature (i.e., 4. K vs 2.0 K). This, in turn, enables the replacement of complex cryogen-based cooling systems with commercially available cryocoolers, resulting in a smaller infrastructure footprint, highly reliable and simplified superconducting operation with minimal expert's involvement.
- ❖ The prototype SRF accelerator is designed to deliver 12.5 mA beam current at 1.6 MeV in CW regime.
- ❖ It represents a significant milestone in establishing the feasibility of beam accelerating using conduction cooled Nb3Sn SRF technology. A successful demonstration will set the stage for building a full-scale, high power SRF accelerator facility, aimed at providing megacurie-level capabilities as a replacement for Cobalt-60 (Co-60) irradiation facilities.

BEAMLINE AND MAJOR COMPONENTS



- ❖ Key components are organized in three major sections: (a) Integrated electron gun, (b) SRF section and (c) Beam Delivery System (BDS).

1. Integrated Electron Gun



- ❖ An internal injection scheme is preferred due to its compact design. An RF gun with a thermionic gridded cathode is directly integrated into SRF cavity.
- ❖ It is developed for continuous operation over 25 years, with a material evaporation rate of less than 0.5 nm per year to minimize the risk of contaminating the SRF cavity.
- ❖ Its design is optimized to operate at 350V RF voltage and approximately 300V DC bias voltage in CW mode to generate short, clean bunches of peak current of 12.5 mA without tail particles, which is crucial for maintaining a low current interception in the SRF cavity, well below 1W.
- ❖ Engineering design of the gun is optimized to limit its contribution to SRF cavity thermal load below 0.5 W.

2. SRF Section

- ❖ The accelerator employs a 1.5 cell, 650 MHz, Nb3Sn-coated, niobium SRF cavity. Table 1 represents key RF parameters of the cavity.

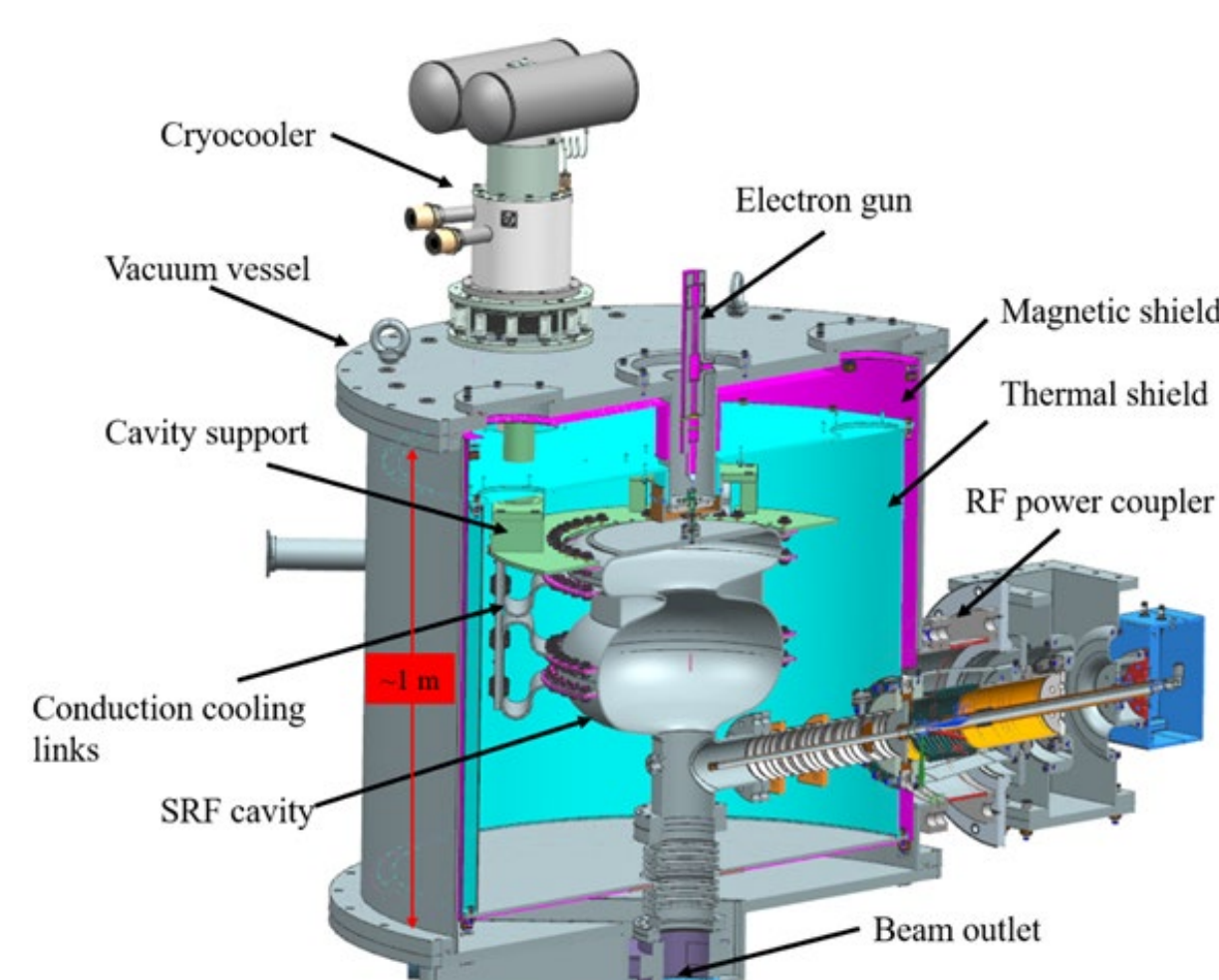


Table 1: RF parameters of 1.5 cells SRF cavity

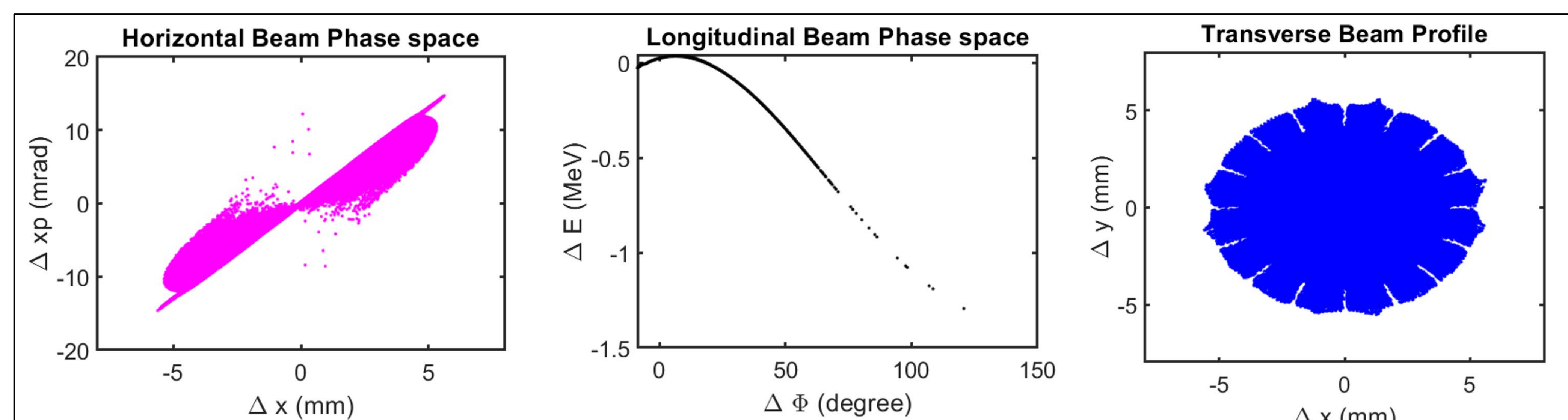
Parameters	Magnitude	Unit
Frequency	650	MHz
Voltage Gain	1.6	MV
R/Q	178	Ω
G factor	197	Ω
Peak surface Electric Field	16.5	MV/m
Peak surface magnetic Field	23.8	mT
Power dissipation	1.46	W

3. Beam Delivery System

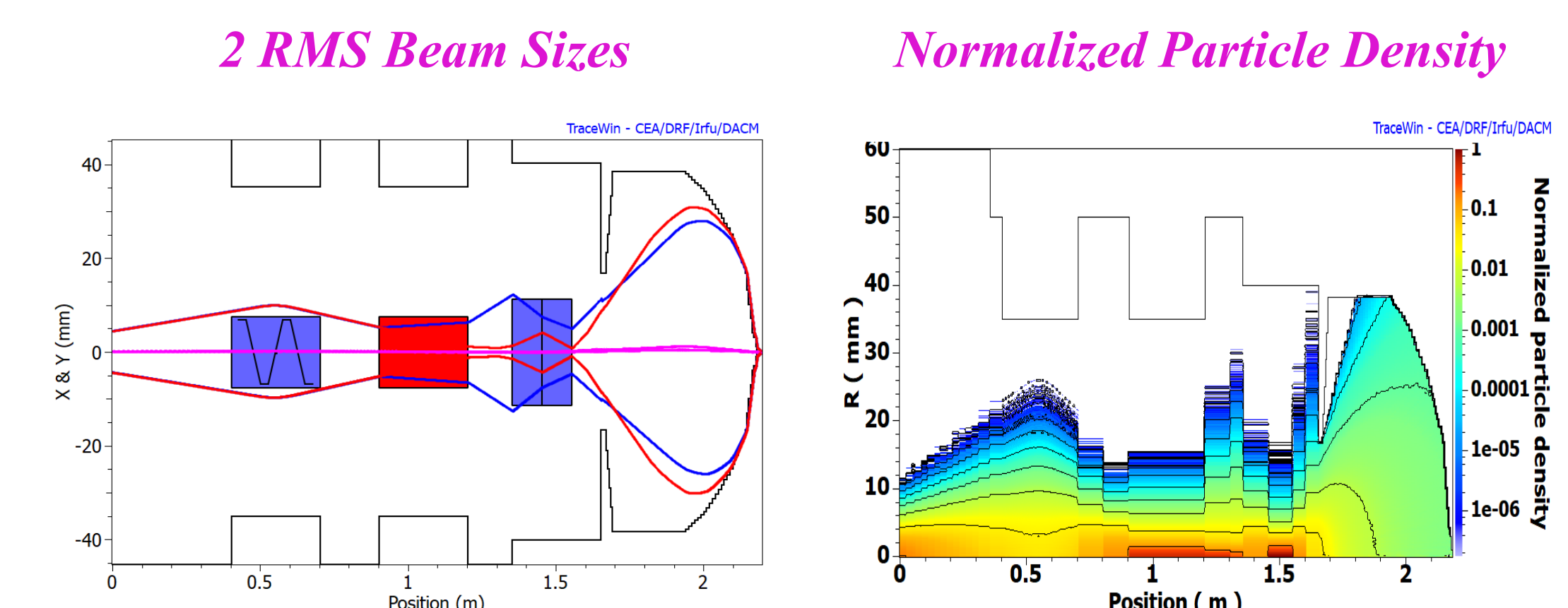
- ❖ The beam delivery system is designed to safely deposit 20 kW beam to a collector (dump), minimize uncontrolled beam loss during transport and prevent backscattered particles from reaching the SRF section.
- ❖ In addition to optical elements, it includes Beam Position Monitors and Current Monitors.

BEAM OPTICS DESIGN

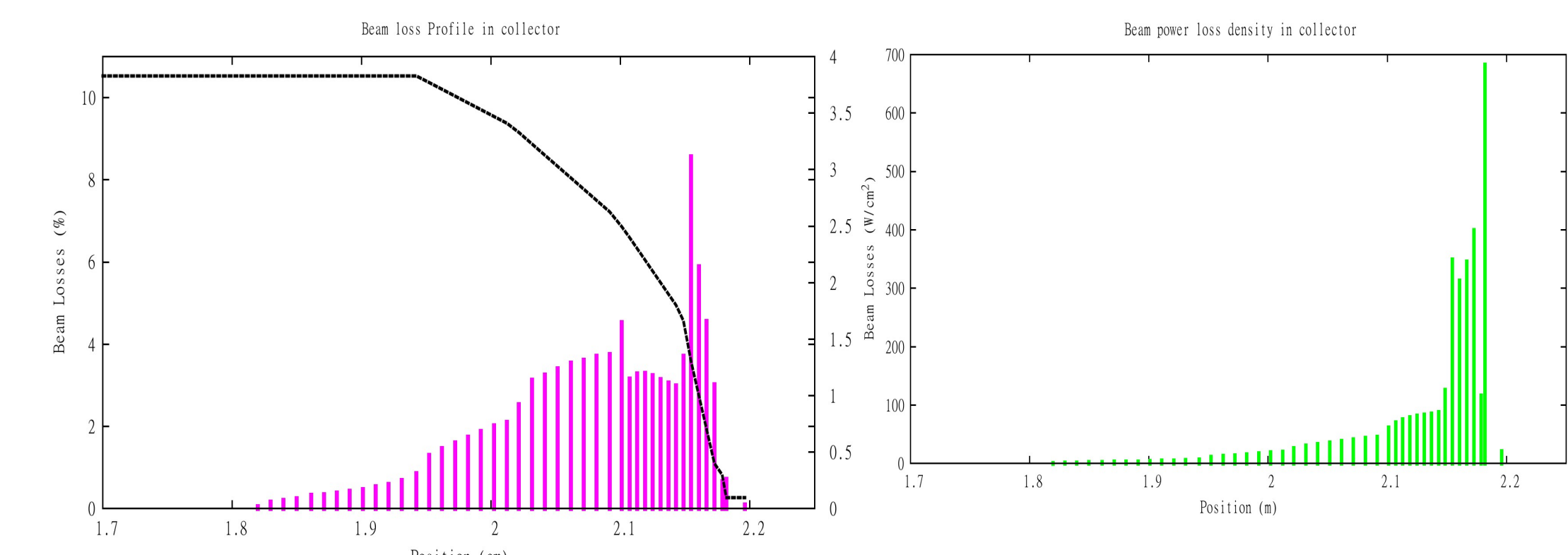
- ❖ The beam optics design was conducted in two stages. The first stage focused on optimizing the beam optics through the integrated gun and accelerating cavity, utilizing the beam dynamics simulation code MICHELLE.
- ❖ Optimization resulted in the following outcomes: (a) compact beam bunches with minimal tail particles and low energy spread, (b) absence of particles between bunches, and (c) no beam loss at the surface of the cavity.
- ❖ In the second stage, this distribution is used to design the beam delivery system with the TRACEWIN.



BEAM SIMULATION STUDIES IN BDS



Beam Loss Profile and Power Density Deposition Profile in Collector



OUTLOOK

As we advance towards completing 20 kW prototype SRF accelerator's construction, several key milestones are approaching. The fabrication of critical components, including the electron gun and the 1.5-cell, 650 MHz cavity, is nearly complete, with the cavity currently undergoing Nb3Sn coating. The shielding of the accelerator cave has been completed. Looking ahead, our next steps will involve rigorous testing of electron gun and SRF cavity to ensure that operational performance meets design specifications. Successful integration and performance validation of the accelerator will pave the way for exploring its applications in medical sterilization. This will also provide valuable insights into scaling up the technology and addressing potential challenges in broader implementation.