SRF accelerators for industrial applications

GARD RF Roadmap Update - SRF Meeting

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Why SRF is attractive to industry?

Disclaimer:
Industry = Users, not Vendors!

RadiaBeam

- Vast majority of the current industrial applications are served by conventional normal-conducting accelerators
  - Often developed many decades ago
  - Can be very expensive (>$5M for 100kW)
  - Poor wall plug efficiency ~10%
- SRF accelerators promise some attractive properties:
  - RF power losses into cryogenic environment can be of the order of Watts
  - Cryogenic losses are much more expensive to manage
  - c.w. lower-frequency power sources tend to be cheaper per Watt of average power
- With a proper balance of beam power + RF / cryogenic power costs, SRF can be much more cost-efficient than NCRF accelerators:
  - Typically, when very high beam power (100s kW to MWs) is needed

$$P_{RF} = \frac{V^2}{R \cdot L} + V \cdot I;$$

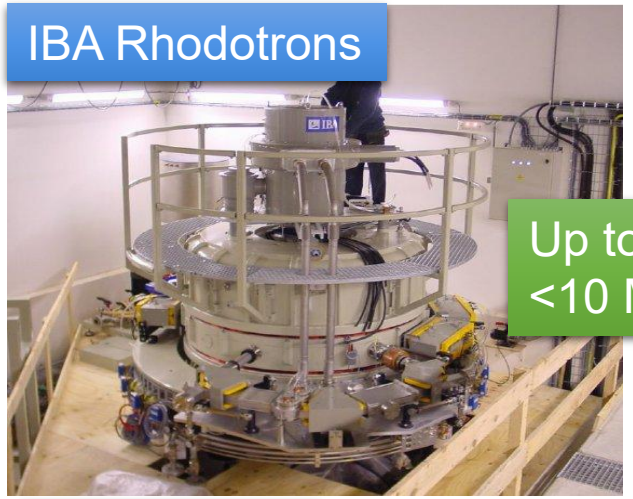
but

$$V \cdot I \sim \$7/W$$

$$\frac{V^2}{R \cdot L} \sim \$20{,}000/W$$

doesn't scale with beam current!

IBA Rhodotrons

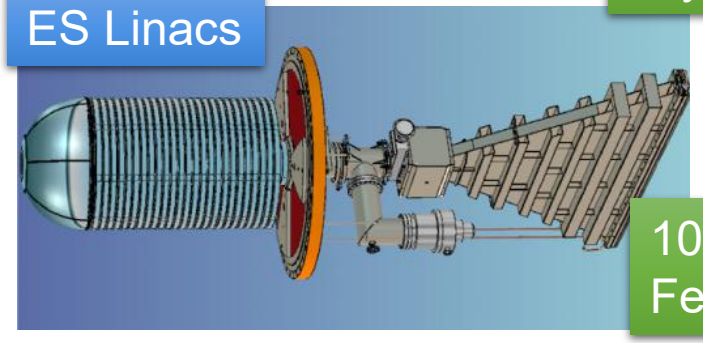


Up to 700 kW, <10 MeV

RF Linacs

100+ kW, any energy

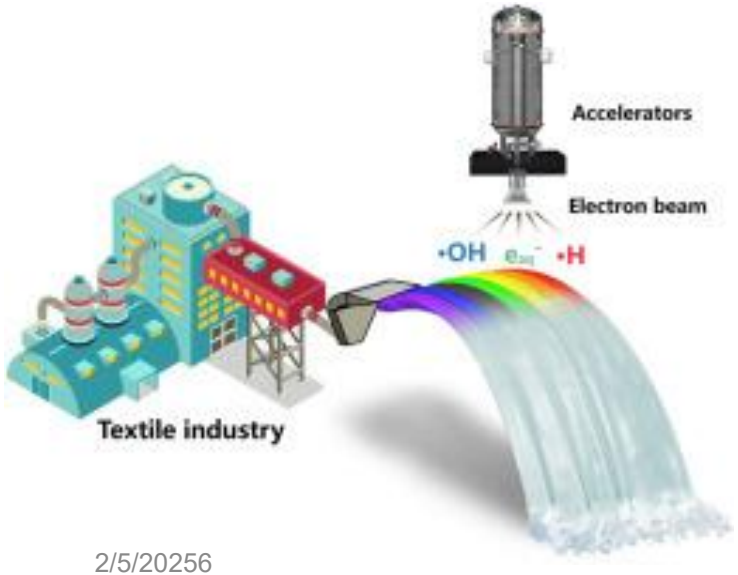
ES Linacs

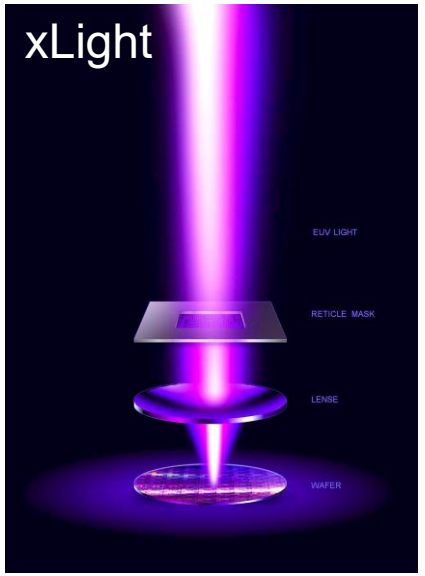


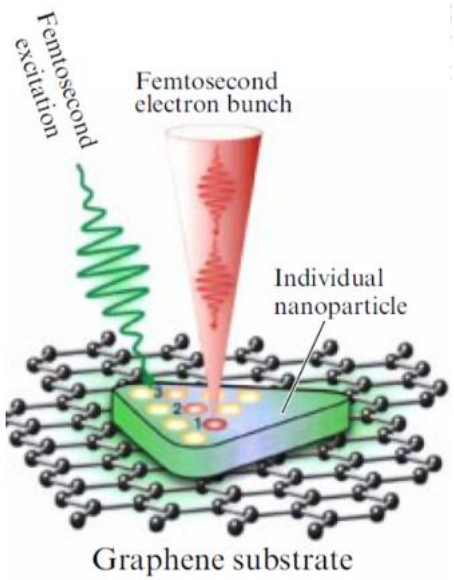
100+ kW, Few MeV

Potential applications for SRF accelerators

- There are several emerging applications that require cost-efficient high-power *electron* accelerators:
  - **Environmental applications.** 5-10 MeV 100-1000 kW beams can used to kill pathogens or destroy chemicals in food, water, flu gases etc.
  - **Accelerator Driven Systems**. 50-150 MeV 1MW beams can be used to generate neutron flux in modular sub-critical reactors or radioisotope production.
- Other emerging applications:
  - **EUV lithography**. GeV electron beams can be used to generate nm-wave EUV light for chip fabrication.
  - **Ultrafast Electron Microscopy**. SRF guns can generate c.w. high-brightness MeV beams for high-resolution imaging.







Commercial challenges

- Current market for high-power (100+ kW) applications is small
  - Few dozens of systems per year
  - Few **paying** customers
- MW-class applications market is still emerging
  - Regulation hurdles
  - Non-accelerator alternatives (gamma-sources, chemicals, non-ADS reactors)
  - NCRF alternatives (rhodotrons, RF linacs, ES linacs)
- 100+ kW "dressed" accelerator can cost $7M or higher
  - But it can be purchased right now and is a proven technology
- 1MW SRF linac ***may*** cost $5-15M, but
  - These numbers only exist on paper
    - Even at $15M for 1 MW SRF linac could be competitive
  - Public perception that SRF is very expensive and complex
  - No operational proof-of-principle prototype yet

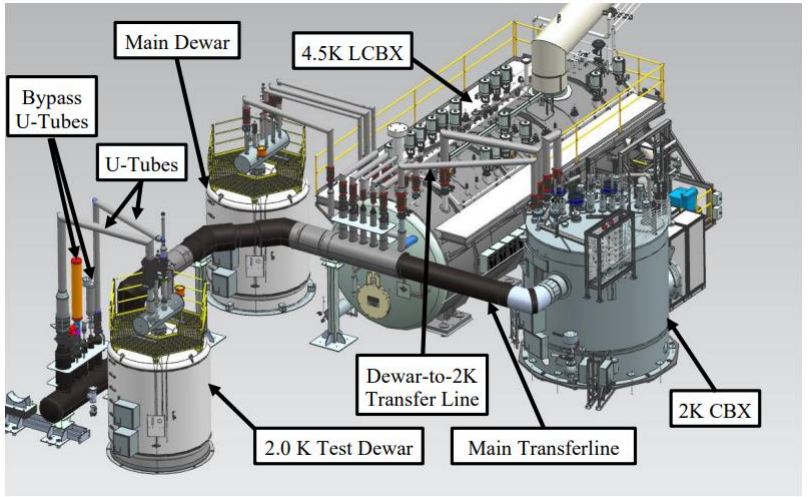
Table 7: Capital cost (unit: k$) of the 1 MW, 10 MeV SRF accelerator.

Total	**5,134**
1 MW RF Power Source	**3,200**
Cryomodule	**1,554**
Cryocoolers w/ He Compressors	492
650MHz Nb_3Sn Cavity	402
RF Couplers	282
Vacuum Vessel	100
Beamline (HOM, Bellows, Valves)	104
Auxiliary Hardware (Chillers, Pumps)	93
Magnetic Shield	65
Thermal Shield	16
Electron Injector	**217**
Beam Delivery System	**125**
Beam Diagnostics & Controls	**38**

Technological challenges

- In the past decade “industrial” SRF made a huge jump from a “No-go” technology to “This might work” state
- Enabling technologies:
  - New materials (***Nb_3Sn***) reduce the losses by an order of magnitude
  - Compact Liquid-He-free ***cryocoolers*** with high power capacity (2-10 W)
  - Low-loss cryomodules based on ***conduction cooling***
  - **RF power sources** (magnetrons, solid-state) with high efficiency (>50%) and low cost per Watt (<$3-7/W)
- Technological risks (from an industry viewpoint):
  - **Reliability and serviceability**
    - Industrial accelerators are operated by technicians, not PhDs
    - If SRF linac breaks how long would it take to repair it?
  - **Beam loss management**
    - Even a few W (0.0001%) of beam loss in the cavity region can be critical for activation, heating, or quench risk.
    - Acceleration of 1 MW c.w. beam from cathode to the delivery system can be very challenging
      (1A+ emission, lossless injection, HOMs, BBUs, beam windows etc.)
  - **Challenging fabrication**
    - Very few Nb cavity vendors, long lead time
    - Nb3Sn coating is a very complex and delicate process
    - Vendor hesitation to step into SRF business
      (high initial investments, unstable demand, unflexible infrastructure)

From this:



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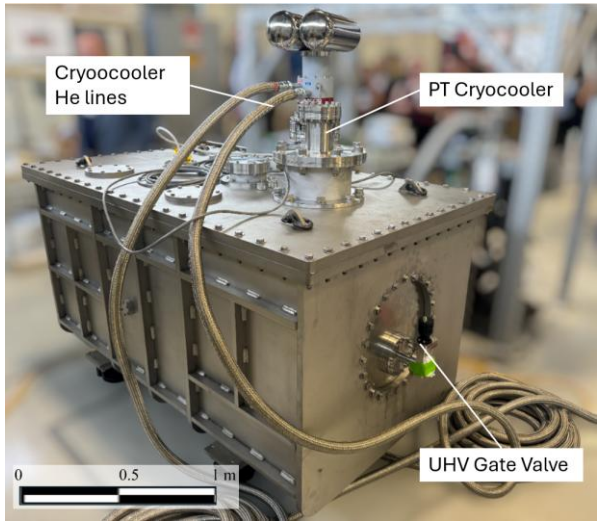

Notable industrial SRF linac developments

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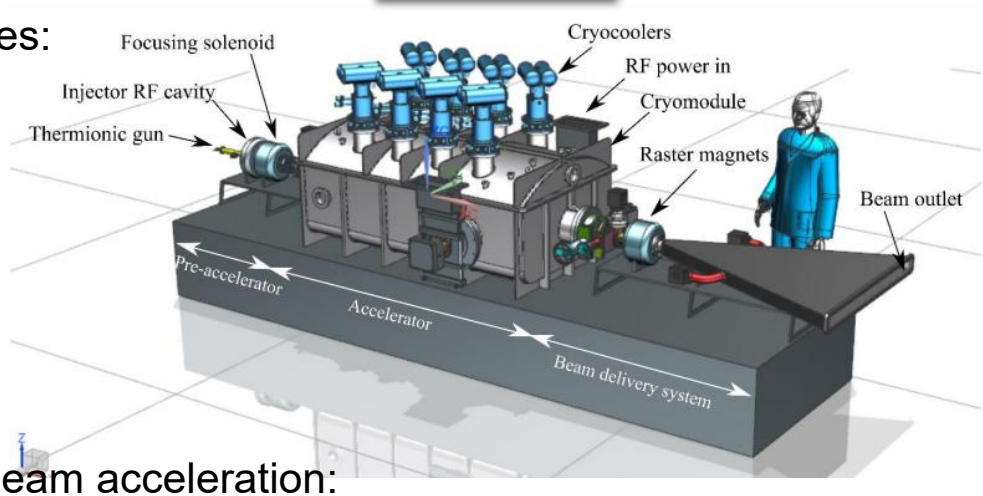
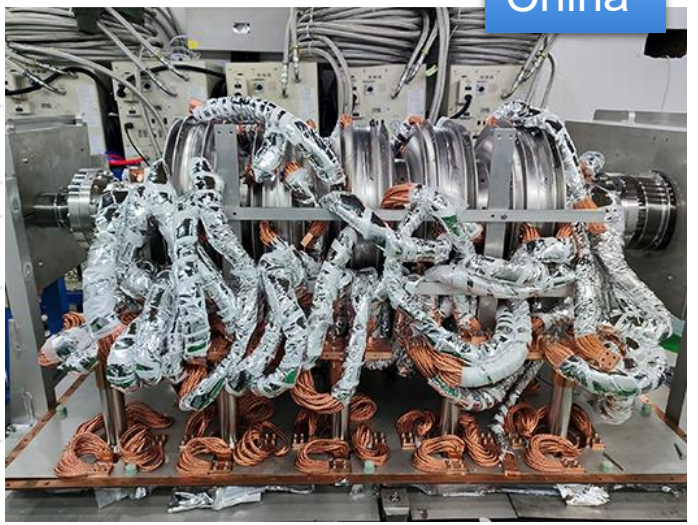
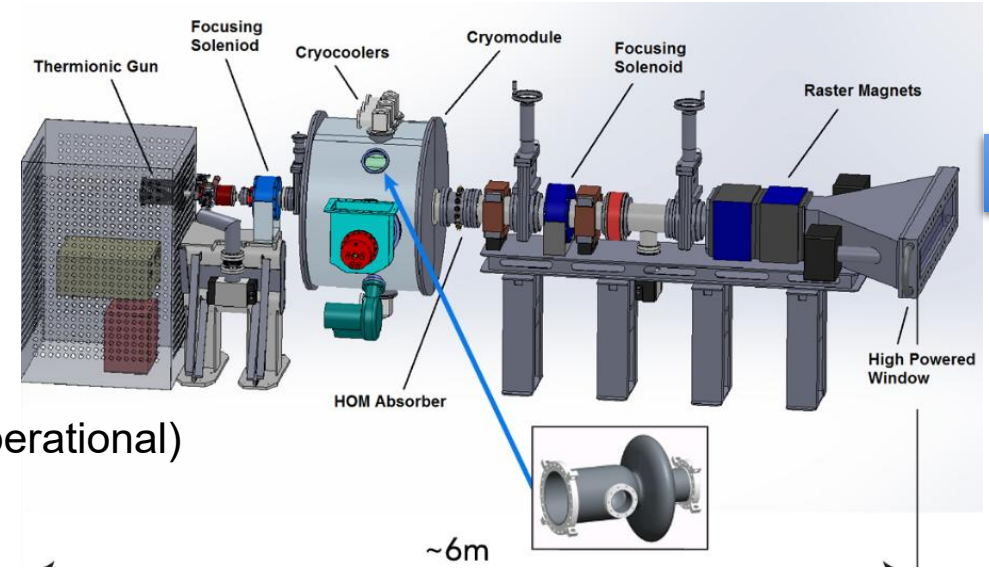
- Fermilab is developing several prototypes:
  - 650 MHz, 10 MeV, 1 MW,
  - 650 MHz, 1.6 MeV, 20 kW
  - 1.3 GHz, 10 MeV, 20 kW
- Jlab is developing a prototype:
  - 915 MHz, 1 MeV, 1 MW
  - Magnetron-powered
- IMP, China has demonstrated the first beam acceleration:
  - 650 MHz, 4.6 MeV × 100 mA (2 μs beam pulses)
  - >50% beam loss!
    - 2 μs × 20 Hz x 460 kW = 20 W
- Yet to be demonstrated:
  - Low-loss injection
  - Full power acceleration
  - Beam delivery system
  - Wall plug efficiency, reliability, costs (both capital and operational)

Fermilab



China





JLab

Required R&D and Summary

RadiaBeam

- Most of the commercial industrial applications are served by normal-conducting accelerators
- SRF accelerators can be attractive and commercially competitive when c.w. high-power beams are required:
  - The market for such applications is still emerging
  - Strong competition from the existing accelerators and non-accelerator alternatives
- The following R&D is required for industry adoption :

Mandatory:

  - Demonstration of high-power operation, reliability, robustness and real costs
  - Beam injection / extraction systems development

Wish-list:

  - Higher-efficiency / lower-price cryocoolers to enable lower power applications
  - Solid-state RF amplifiers with 70% <$3/W costs, or magnetron combination to MW level

Future:

  - Technology transfer and mass-production of SRF cavities