SRF AND COMPACT ACCELERATORS FOR INDUSTRY AND SOCIETY

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Despite their powerful impact on Science, most accelerators are used for other purposes

- About 30,000 accelerators are in use world wide
  - Sales of accelerators > $ 2 B /yr and growing
  - Accelerators touch over $ 500B/yr in products
  - Major Impact on our economy, health, and well being

Some Products:

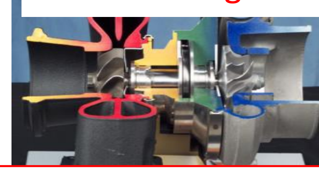
Radial Tires & heat resistant wire

Manufacturing: Electron beam welding

Aircraft

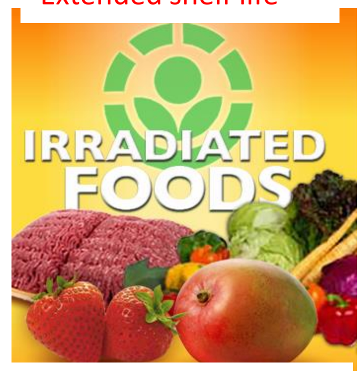
Fuel injectors

Turbo chargers



Food

Extended shelf life



Shrink wrap and electron beam printing

Medicine:
- Cancer treatment
- Sterilization
- Implants

NO SRF based industrial accelerators in production

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Many Future Industrial Accelerator Applications are envisioned. Some examples:

Sector		Opportunities
Energy and Environment	e^- →	• Upgrade of heavy oils with electron beams
	e^- →	• Gas to liquids conversion and flare gas recovery
	e^- →	• Waste water and sludge treatment
	e^- →	• Flue gas treatment (SOx, NOx removal)
		• Accelerator driven power plants
		• Nuclear waste destruction
Industrial		• Next generation semiconductor fabrication (FEL's)
	e^- →	• Improved Highway construction (extended life)
		• Materials: new surface properties
		• Industrial isotopes as wear indicators
	e^- →	• Improved food preservation and safety
	e^- →	• Catalyze chemical reactions to save energy/time
Medical		• Accelerator-driven medical isotope production (Mo99)
		• Heavy ion beam cancer therapy
Safeguards and Security	e^- →	• Non-invasive and stand-off inspection

- Some of these applications may create entirely new industries (large!)
- Most require: High average beam power industrial accelerators

Low energy (< 10 MeV), high power electron accelerators appears to be broad need where SRF might play a role… so I will focus on that for this talk.

Considerations for Industrial Accelerators

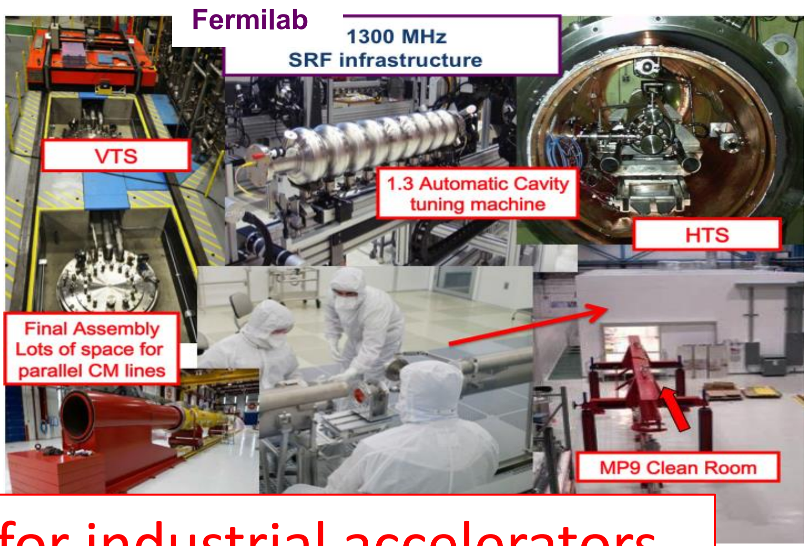
- The whole idea of using an accelerator must make financial sense (its not enough that it works technically)
- Accelerator capital and operating costs both matter
  - So do facility costs (shielded enclosures, infrastructure, etc)
  - Size matters, smaller is better.
- Must be robust and simple to operate & maintain
- Downtime is expensive ➔ reliable
- Accelerators must be matched to the task… often industry needs a “blow torch” not a “surgical laser”

SRF has now become the "technology of choice" for big science accelerators

- Why? SRF cavities enables high gradients and Q_0
  - limits construction costs
  - a large fraction of the input RF power goes into beam power
  - CW operation lowers the cost of RF power (ave power = peak power)

- SRF is now used for essentially every new large science accelerator requiring high power beams *(e.g. CBEAF, SNS, FLASH… XFEL, LCLS-II, ESS, PIP-II, FRIB, RAON, ILC, etc)*

- These projects have driven large international efforts on SRF R&D
- Extensive infra: DESY, FNAL, JLAB, Cornell, China, India, Korea, etc
- SRF is judged by review committees to be a "credible" technology on which to base ~$ 1B class science projects



But interestingly not currently credible for industrial accelerators

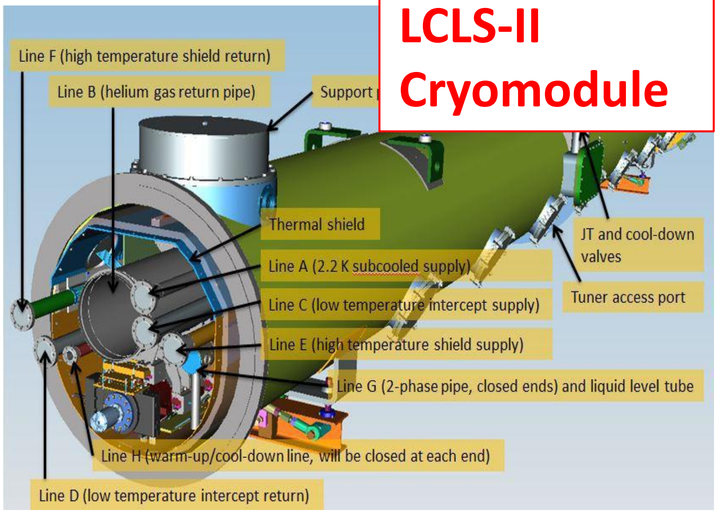
SRF based accelerators are not attractive to industry

- Why? Because current designs are complex
  - Experts required for both operations and maintenance
  - Many external systems needed
  - Complex construction (can't easily buy one!)
    - e.g. Chemistry, HPR, clean rooms, RF power systems, LLRF, cryogenic systems, gas and liquid cryogen storage, electrical and water cooling infrastructure, safety systems, etc)
  - Need complete turn-key solutions

- Cryogenics is particularly problematic!
  - Losses in SRF cavities are small, but they take place at low temperature (4 K or even 2 K) where the Carnot efficiency is poor
  - Leads to complex cryomodules and large complex cryogenic refrigerators for current big science accelerators

Current: SRF “science” accelerators are large and complex

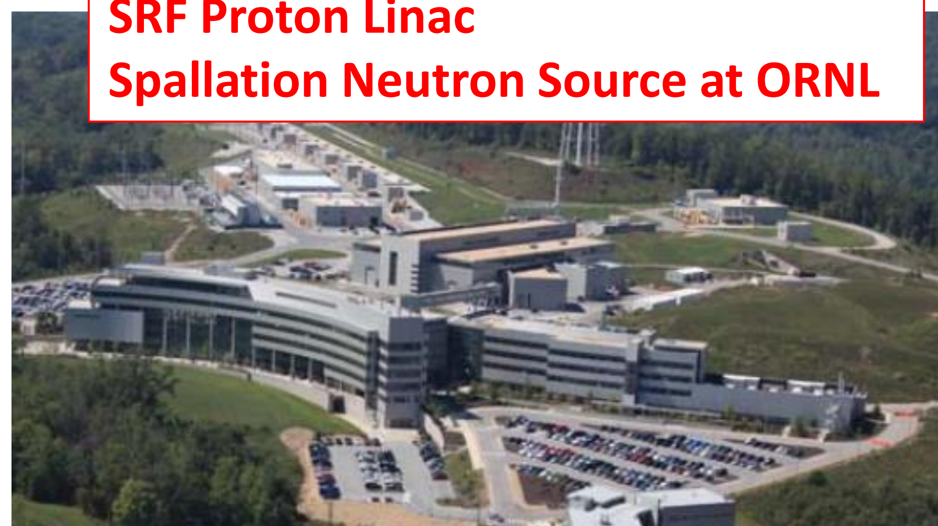
LCLS-II Cryomodule



FNAL FAST 50 MeV injector and ILC cryomodule

CBEAF CW electron linac 2 K cryoplant

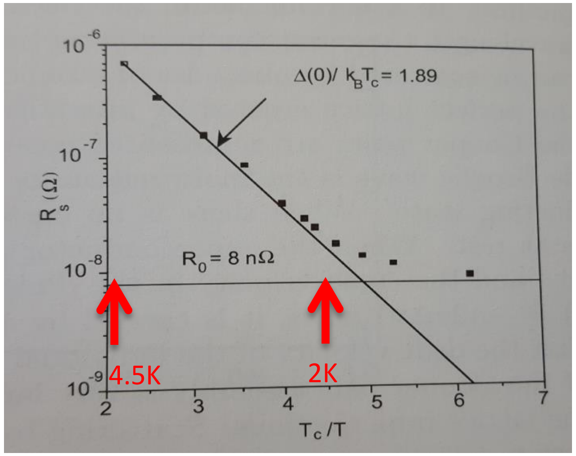
SRF Proton Linac Spallation Neutron Source at ORNL



If complexity is driven by cryogenics… What can be done?

- SRF cavities have losses at cryogenic temperatures that depend on frequency, temperature, gradient, and surface processing

$$P_{loss} = \underbrace{\alpha \;\; \omega^{2} \exp -(T/Tc)}_{R_{BCS}} + R_{residual}$$



Padamsee, pg 74

- The BCS term dominates at 4K for pure Nb cavities in the past this has driven the choice of low temperature operation and/or low frequency cavities
- Even with low frequency cavities and 4 K operation, attempts to date to make an industrial SRF accelerators have resulted in much of the complexity of a big science machine

Implications of low frequency choice

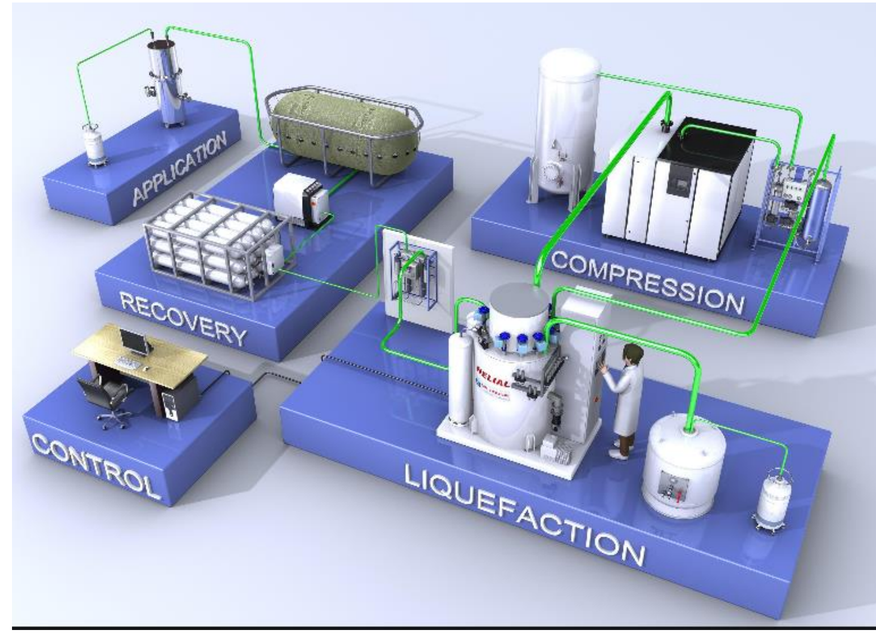
Niowave has been a pioneer
350 Mhz, 3 accel gaps

1.3 GHz produced by Niowave for FNAL

9 accel gaps ~35 MeV

- Low frequency cavities are physically larger ➔ higher capital costs vs higher freq elliptical cavities
- But… in the past, operating higher frequency Nb cavities with CW RF at any reasonable gradient at 4K➔
  - very high cryogenic losses ➔ refrigerators with 100's of watts capacity
  - Even "small accelerators" need complex cryo systems.
- Can we imagine a "simple" higher frequency SRF industrial accelerator ?

Even “small” 4K cryogenic plants are complex



- Lots of ancillary equipment beyond the refrigerator cold box
- Compressors, He Gas storage tanks, LHe & LN2 storage dewars, purification package, cooling water, controls, etc.
- Fermilab operated ~ 30 such systems over 25 yrs in a semi-industrial environment. Lots of experts & maintenance required !
- <u>Showstopper</u> for many industrial applications

Can SRF accelerators be attractive to industry ?

An assertion:

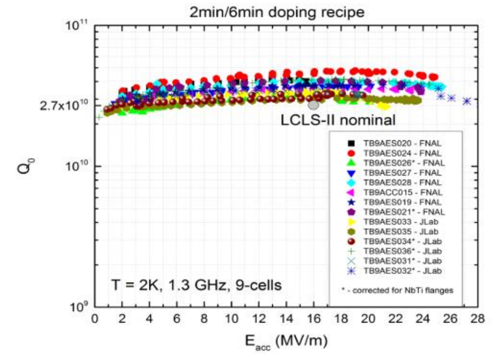
- Recent technology advances in SRF now make plausible to construct dramatically simplified compact, efficient, lightweight SRF electron linacs
  - capable of 10's or even 100's of kW ave beam power @~ 10 MeV
  - able to operate with high duty factors e.g. Continuous Wave (CW)
- I will describe one specific vision for such a device, but it should be understood that we are suggesting an approach to creating an entirely new class of SRF based accelerators
- Such accelerators could find widespread use in industry, medicine, environmental, & security applications …
  - including replacing powerful Co^{60} sources that now represent significant security risks (use in "dirty" bombs)

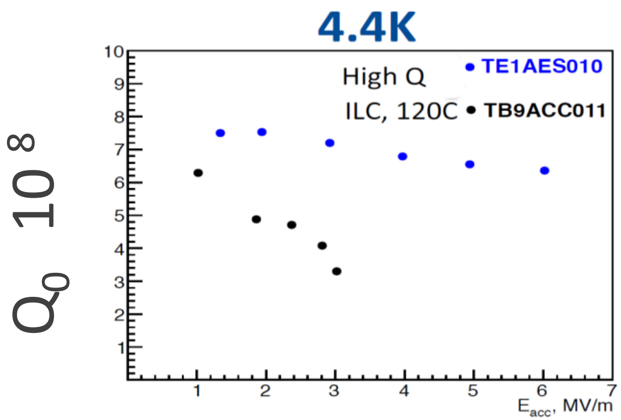
Why has this not been done before?

The approach integrates six recent technical advances

1) N doping ➔ Factors of 3-4 improvements in Q_0 at 2 K

- LCLS-II 9-cells ➔ Ave $Q_0 > 3 \times 10^{10}$ at 2 K, 16 MV/m
- Big savings for LCLS-II …
- But… N-doping also helps at 4 K!





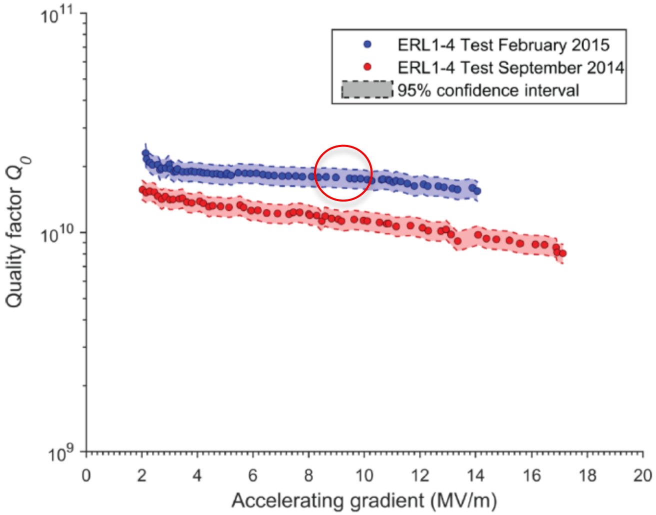
N doped 1.3 GHz cavity (blue) has a much slower Q_0 fall off with gradient vs a standard ILC, 120C baked cavity (black)

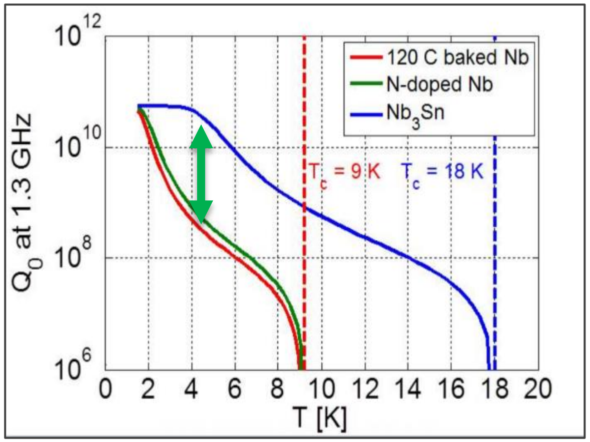
An area for more research/optimization !

- Without optimization a 1.3 GHz 9-cell elliptical cavity can accelerate electrons to ~7 MeV at 5% duty factor using ~ 3.5 W of refrigeration
  - Game changer! A compact 7 MeV SRF accelerator cooled with a commercial 5 W @ 4 K cryo-cooler! (ave power = a few kW)
  - We know how to do this today

2) Nb Cavities coated a higher Tc superconductor*:

- Cornell has demonstrated that a 1.3 GHz, 1-cell Nb cavity coated with Nb_3Sn can be operated with quality factors ~ 2 x 10^{10} at 4.2 K with gradients ~10 MeV/m (e.g. Dan Hall's talk Tues)





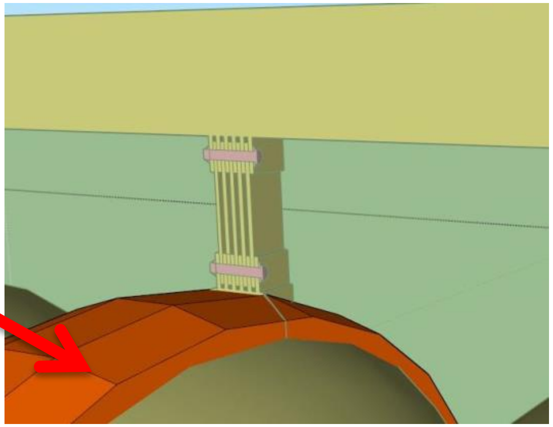
Nb_3Sn ➔ factor of >20 higher Q_0 at 4 K vs pure Nb!

- A Nb_3Sn coated 9-cell cavity operated with CW RF at 10 MeV/m @ 4.2K has cryogenic losses ~ 3.5 W
  - Again in range for a commercial 5 W cryo-cooler
- Clearly a lot of work needs to be done to develop a robust Nb_3Sn 9-cell process, but this seems likely to work (ie plausible)

* D.L. Hally, M. Liepe, J.T. Maniscalco, S. Posen "RECENT STUDIES ON THE CURRENT LIMITATIONS OF STATE-OF-THE-ART Nb3Sn CAVITIES" IPAC15, WEPTY074 (2015)

3) Conduction Cooled Cavities:

- With small enough losses conduction cooling* is plausible
  - Dramatically simplifies cryomodule: NO liquid Helium, pressure vessels, piping, pressure reliefs, safe under vacuum fault, etc.
  - Dramatically simplifies external systems: NO "open" He gas or liquid storage, no purification systems, cryo-cooler replaces LHe refrigerators (very reliable and simple)
  - For cavity heat loads < 5 W: the cavity and cryo-cooler can be connected with high purity Aluminum ➔ < 0.5 K temp rise from cryocooler tip to cavity
  - FNAL demonstrated a cond cooled SC quad
  - Received DOE Accel stewardship award
    - FNAL-PAVAC working on additive process to add high purity aluminum ring to cavity
  - Plausible?... Needs to be demonstrated!



*FNAL patent pending

Commercial cryo-coolers are now better & cheaper!

4K GM-JT CRYOCOOLER SERIES

Performance Specifications

Model Number	CG304SC	CG308SC	CG310SC
3rd Stage Capacity* Watts @ 4.3 K (50/60 Hz)	1.0/1.2	3.0/3.5	4.2/5.0
Electrical Supply 50/60 Hz	3 phase, 200 V		
Power Consumption 50/60 Hz	4.5/5.4	5.1/6.4	5.1/6.4
Cooling Water L/min. (gal./min.)	5.5-6.5 (1.5-1.7)	8.0-10.0 (2.1-2.6)	8.0-10.0 (2.1-2.6)
Refrigeration Unit Weight kg (lbs.)	18.0 (39.7)	35.0 (77.2)	50.0 (110.2)
Compressor Weight kg (lbs.)	205 (452)	220 (485)	220 (485)
Maintenance Hours	10,000		

Standard Scope of Supply

- V304SC, V308SC or V316SC Cold Head
- U304CWA or U308CWA Compressor
- Helium Vapor Gauge (with CG308SC and CG310SC models)
- Hydrogen Vapor Gauge
- 6 m (20 ft.) Helium Gas Lines
- 6 m (20 ft.) Valve Motor Cable
- Tool Kit

- Commercial 5 W@ 4 K systems available (e.g Sumitomo)
- Simple, turnkey operation; highly reliable (light… < 600 lbs)
- Widely used for hospital MRI magnets, He recovery systems

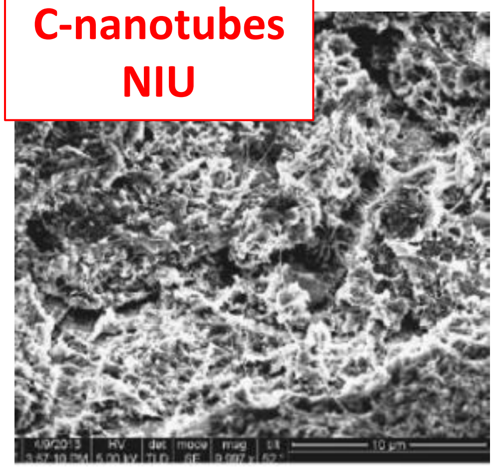
4) New RF power technology (magnetrons!):

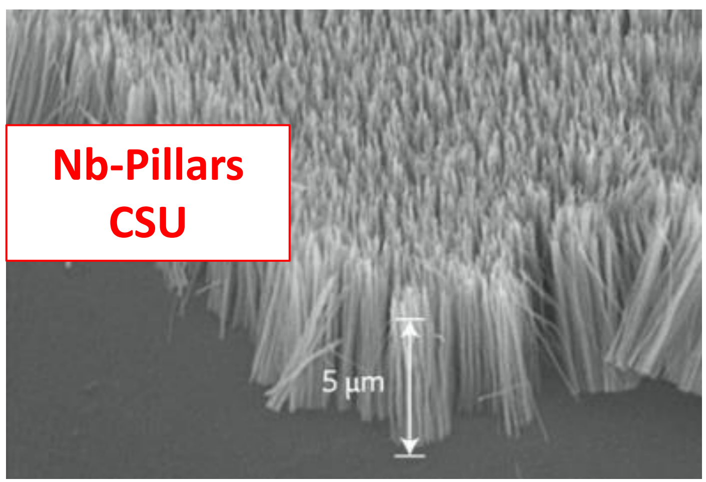
- Injection locked magnetron with excellent phase and amplitude control have been demonstrated* when driving a narrow band load (SRF cavity @ 2.45 GHz)
  - Dynamic range of 30 dB, amplitude stability of 0.3% r.m.s, and phase stability of 0.26 degrees r.m.s.
- Magnetrons can drop the cost of RF power substantially
  - ~$ 10 /watt for solid state or tubes to ~ $ 2-3/ Watt
  - High efficiencies > 80% possible (~ factor of 4-5 cost reduction)
  - FNAL is part of $ 1 M Phase II DOE SBIR with Calabazas Creek/CPI to develop a 1.3 GHz 60 KW CW injection locked magnetron. (ready to test in ~18 months)
- Allows accelerators with multiple cavities driven by multiple magnetrons locked to a common frequency

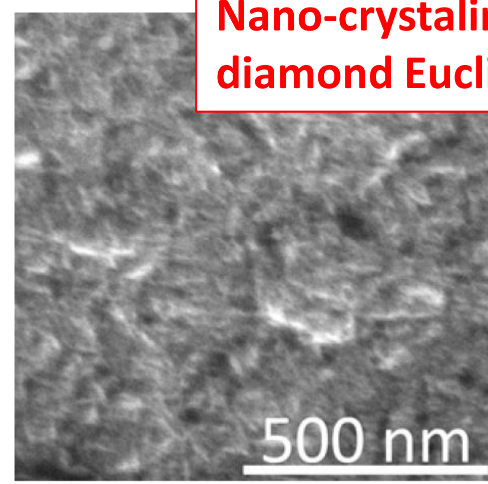
* Fermilab patent pending:

5) Compact, integrated electron guns: (several approaches)

- Field Emission Cathodes : Examples: under development by Colorado State, Northern Illinois University, and Euclid
  - Promising because they are simple and have low heat leak
  - Various technologies: Carbon nano-tubes, Nb pillars, nano-diamonds
  - A key requirement is that the electron gun must not contaminate the interior of a high Q_0 cavity

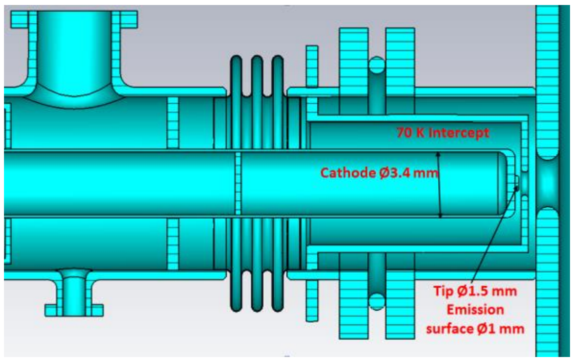


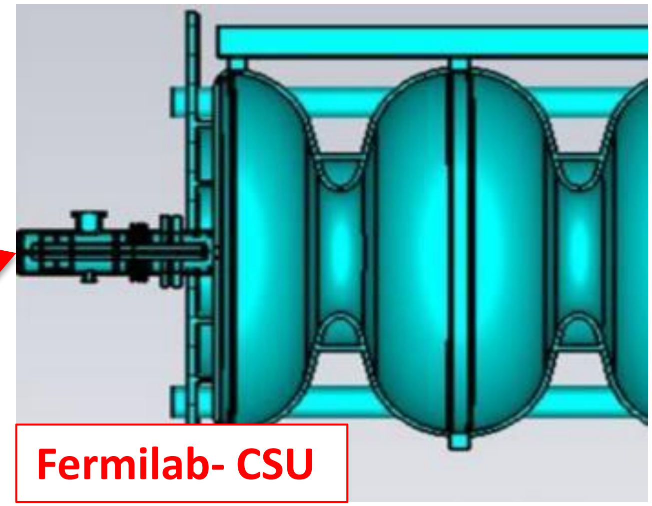




5) Compact, integrated electron guns (cont)

- Building on work at Berlin, BNL, etc, Fermilab and CSU are studying integration of the electron gun directly on to the end of a multi-cell 1.3 GHz cavity (creating an 8.5 cell version) and feasibility of a thermionic gun.

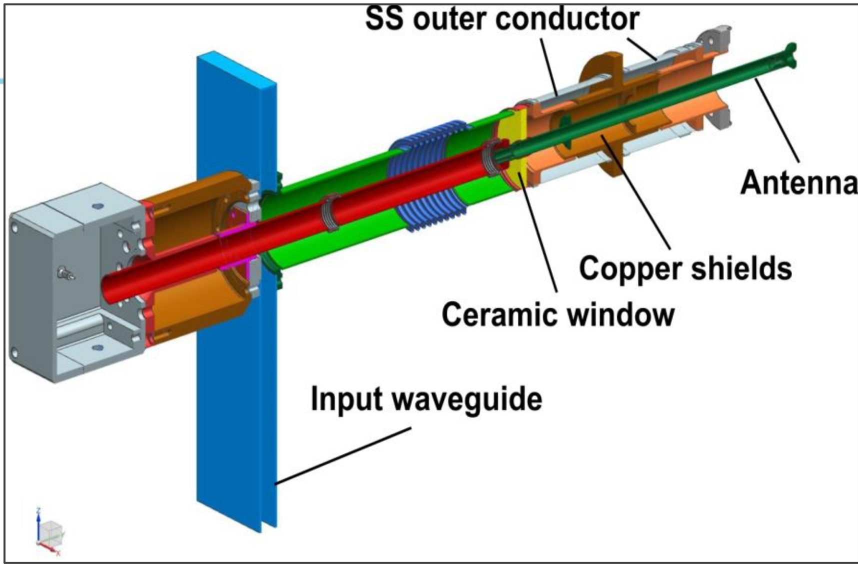




- Thermionic gun requirements
  - Low thermal load…3 W input ➔< 0.1 W estimated into 4 K cavity
  - Need excellent beam transmission to achieve low beam loss to cold surfaces (e.g. 50 kW * 10^{-5} = 0.5 W)
  - Simulation indicates a 3rd harmonic RF gun can do this
  - Plausible? Need to validate simulations with high Q_0 single cell gun cavities, then full 8.5 cell cavities

6) Low Heat Leak Couplers :

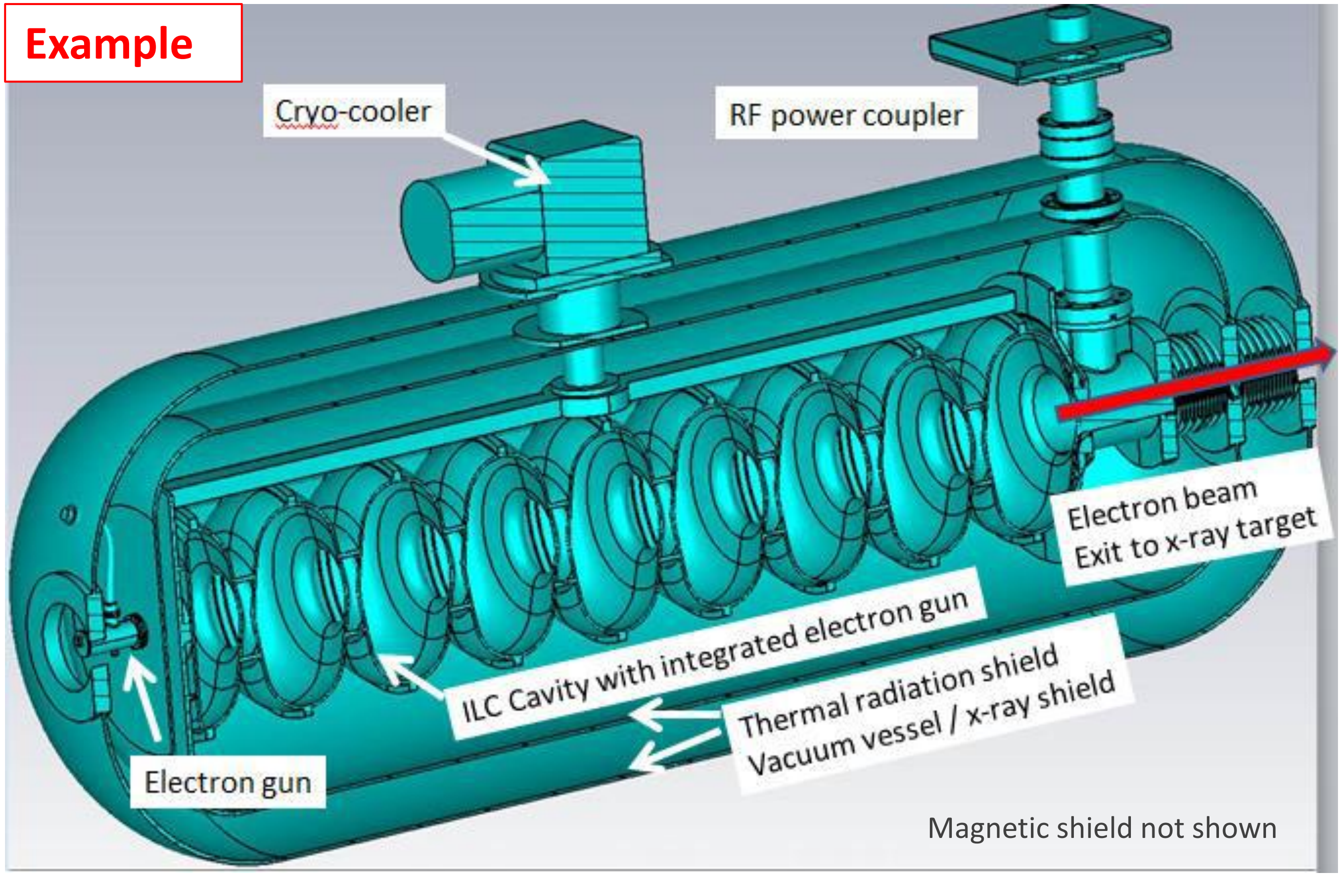
- Fermilab and Euclid have developed a novel very low heat-leak fundamental RF power coupler*



- Electro-magnetic design is such that eliminates the need for copper plated tubes & bellows connecting room temperature to 4 K
- Dynamic heating in copper shield is largely removed at ~ 60 K
- For 20 KW, static and dynamic loss @ 4.5 K is < 0.5 W
- Eliminates copper plating, a major failure mode for many existing coupler designs
- Recent DOE Acc stewardship award to Euclid-FNAL

*patent pending,

Integrating these ideas one can create a design for simple industrial SRF based accelerator



- ~ 10 MeV
- 5→50 KW
  Nb→ Nb_3Sn
- Cryostat
  - ~ 0.5 m dia
  - ~ 1.5 m long
- Cooled by cryo-cooler
- RF power = magnetron
- Simple, rugged design*
- Total weight < 3000 lbs → mobile apps.

- Industry, mobile, or security applications
- Goal: Simple, turnkey operation, low cost
- An example of a future SRF industrial accelerator

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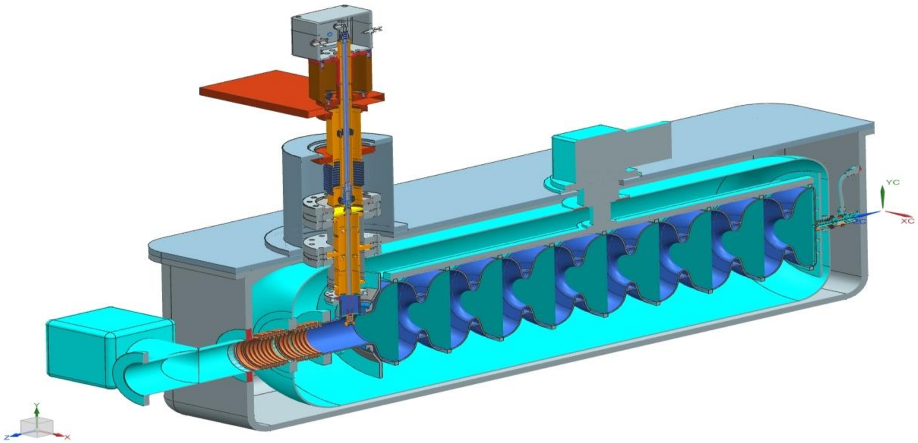
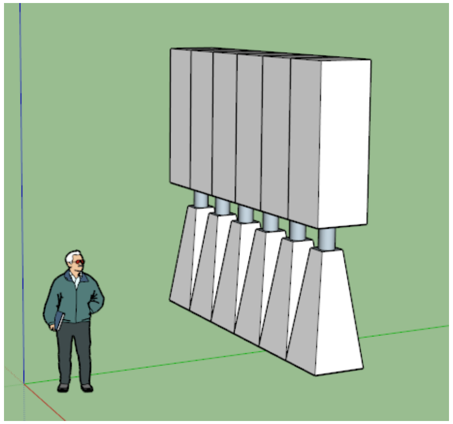
* FNAL patent pending

Variations on this theme



Rectangular cryostats
Operates in any orientation



enables “arrays” e.g. 6 x 50 KW
for industrial applications like cross-linking, food irradiation, security and cargo scanning

- Higher beam power:
  - While less compact 5-cell 650 MHz cavities have lower dynamic RF heating and twice the aperture
  - Refinery, water/sludge, EBFGT, etc need MW !
- Higher beam energy…multiple cavities in series
  - Isotope creation, FEL’s, etc
  - Requires tuners, RF freq, phase, amp control

Summary

- Many future accelerator applications can benefit from the high wall plug power efficiencies possible with SRF
- Advances in SRF technology now make it possible to envision simple, compact, high average beam power SRF based industrial accelerators
  - Nb_3Sn development, cryocoolers, conduction cooling, and cheaper RF sources all are key areas of development
- SRF industrial accelerators when fully developed will likely find broad use in new industrial, medical, environmental remediation, and security applications
- It seems likely that industrial SRF linacs will become a reality in the next decade … this may alter the focus of our R&D which thus far has been aimed at big science accelerators

Acknowledgements

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extras

Does Conduction cooling work?
Recent FNAL conduction cooled SC quad via cryo-cooler

- FNAL recently demonstrated conduction cooling via high purity Aluminum to successfully cool and operate a superconducting Quadrupole magnet with a cryo-cooler (1.5 Watt) … funded as part of the ILC R&D program
- Very simple… very clean… worked well! (0.6 Watt load)
- Note lack of plumbing, pressure reliefs, u-tubes… etc.

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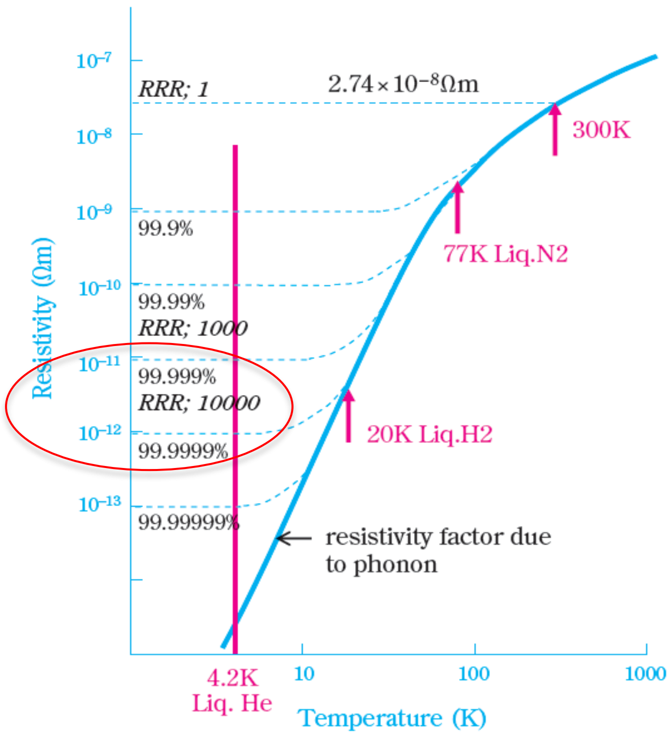
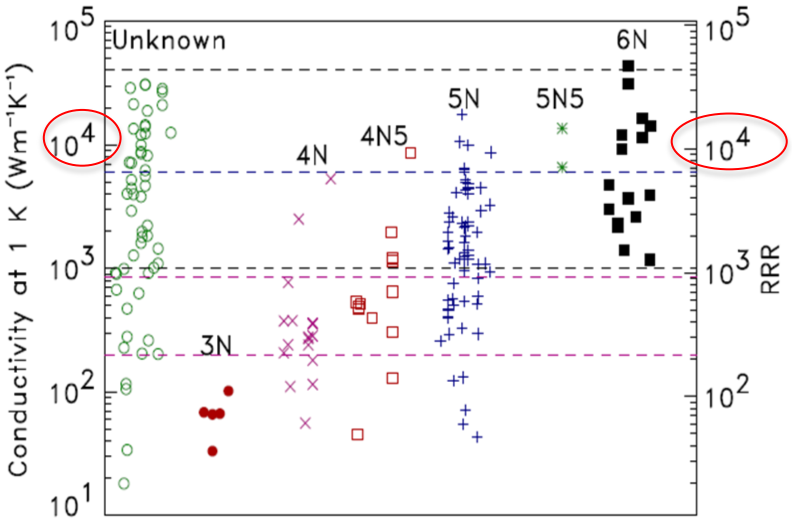
Thermal conductivity of High Purity Aluminum

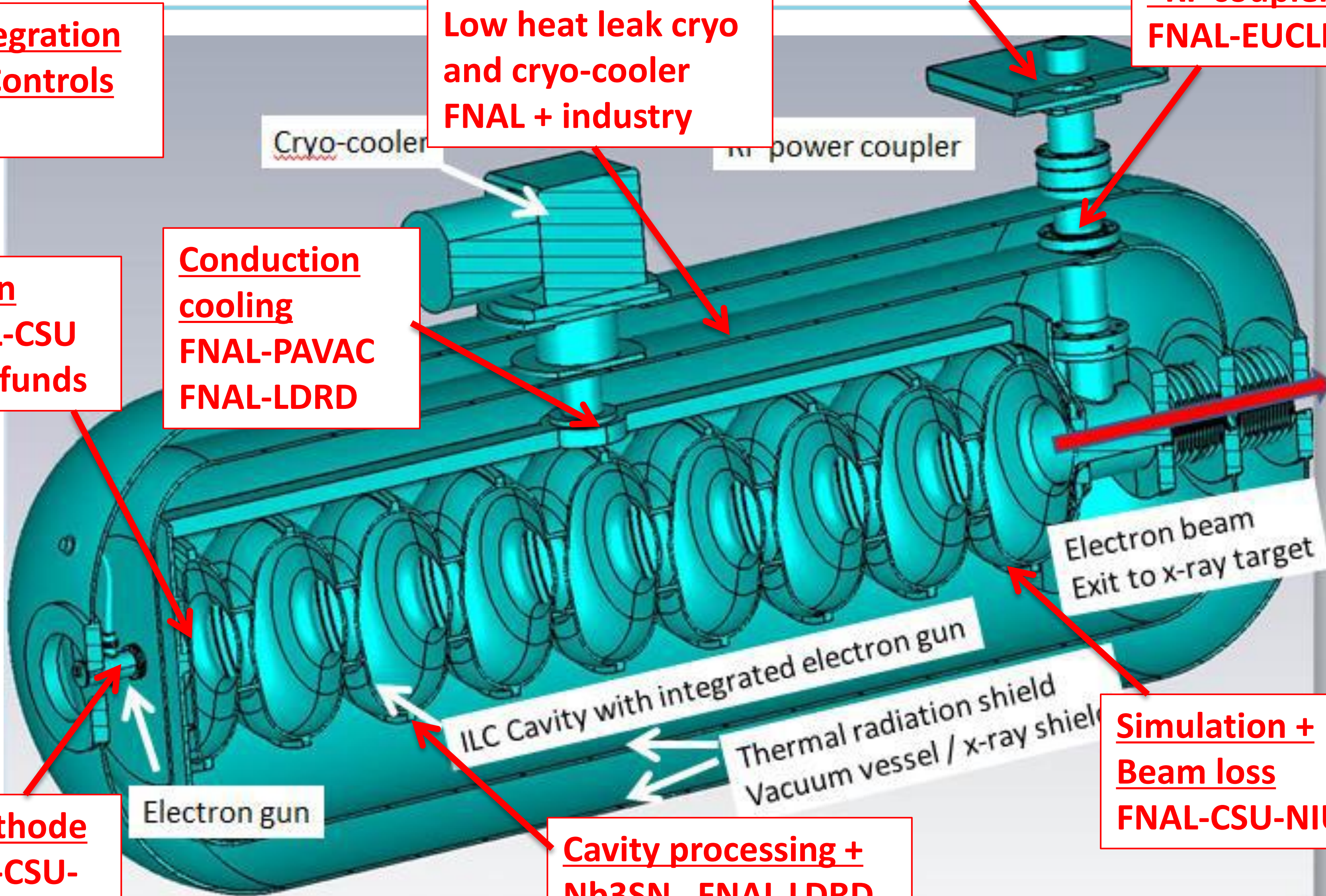




See Adam L Woodcraft, Cryogenics 45(9) 626-636 (2005))

- 5N5 is available commercially

Technology Road Map



Magnetron RF
FNAL-Calabazas

RF coupler
FNAL-EUCLID

Integration & Controls
All

Low heat leak cryo and cryo-cooler
FNAL + industry

Conduction cooling
FNAL-PAVAC
FNAL-LDRD

E-Gun
FNAL-CSU
URA funds

Simulation + Beam loss
FNAL-CSU-NIU

FE Cathode
FNAL-CSU-NIU

Cavity processing + Nb3SN **FNAL LDRD**

We have the ideal place to work on this !

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