S&T Lessons Learned – the Good, the Bad and the Ugly

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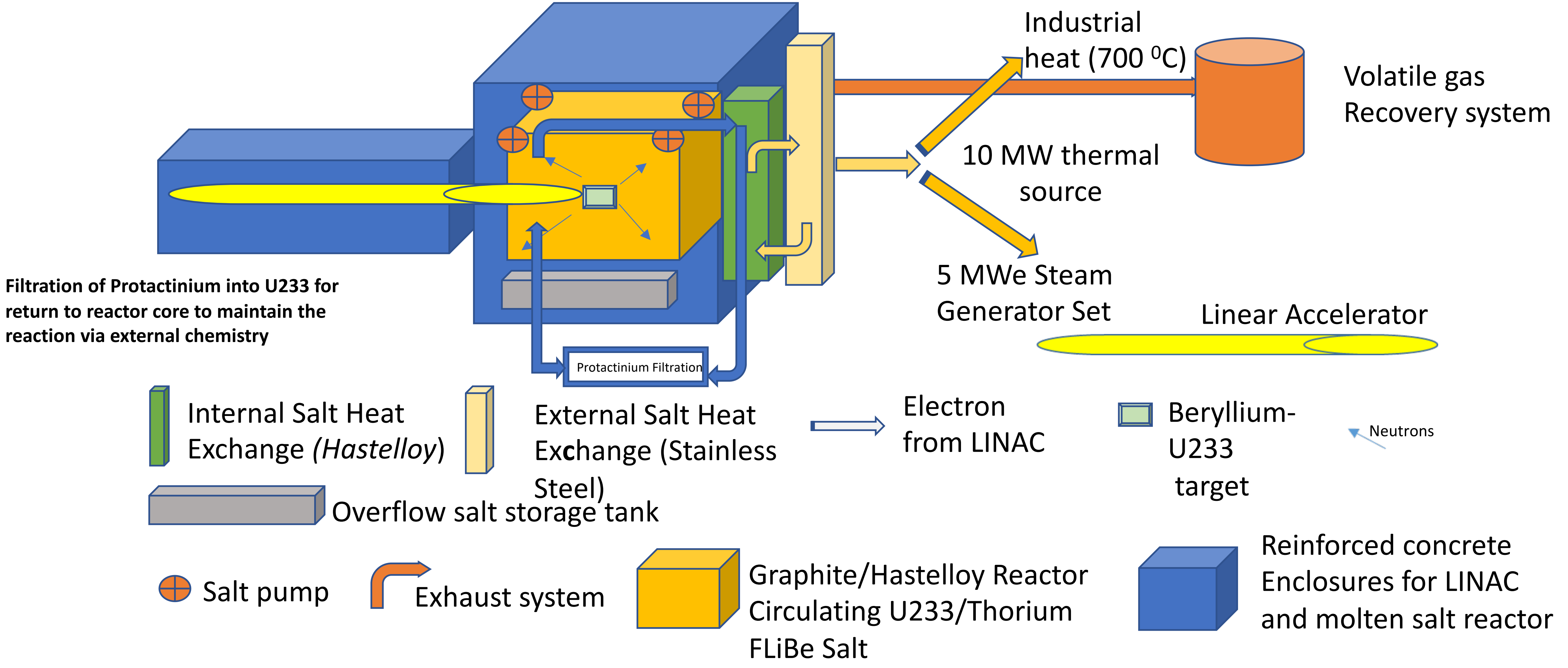
Overview

- Accelerator based green energy ASMR with Thorium
- SRF Niobium-Hydrogen Issue Path Forward
- S&T Lessons Learned 1974 – 1992
- S&T Lessons Learned 1992 – 2002
- S&T Lessons Learned 2002 – 2022

Advanced Subcritical Micro Reactor (ASMR) – 10 MWt/5 MWe
Low Cost, Incremental Power Route to a Zero Carbon Future



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ASMR's Unique Aspects

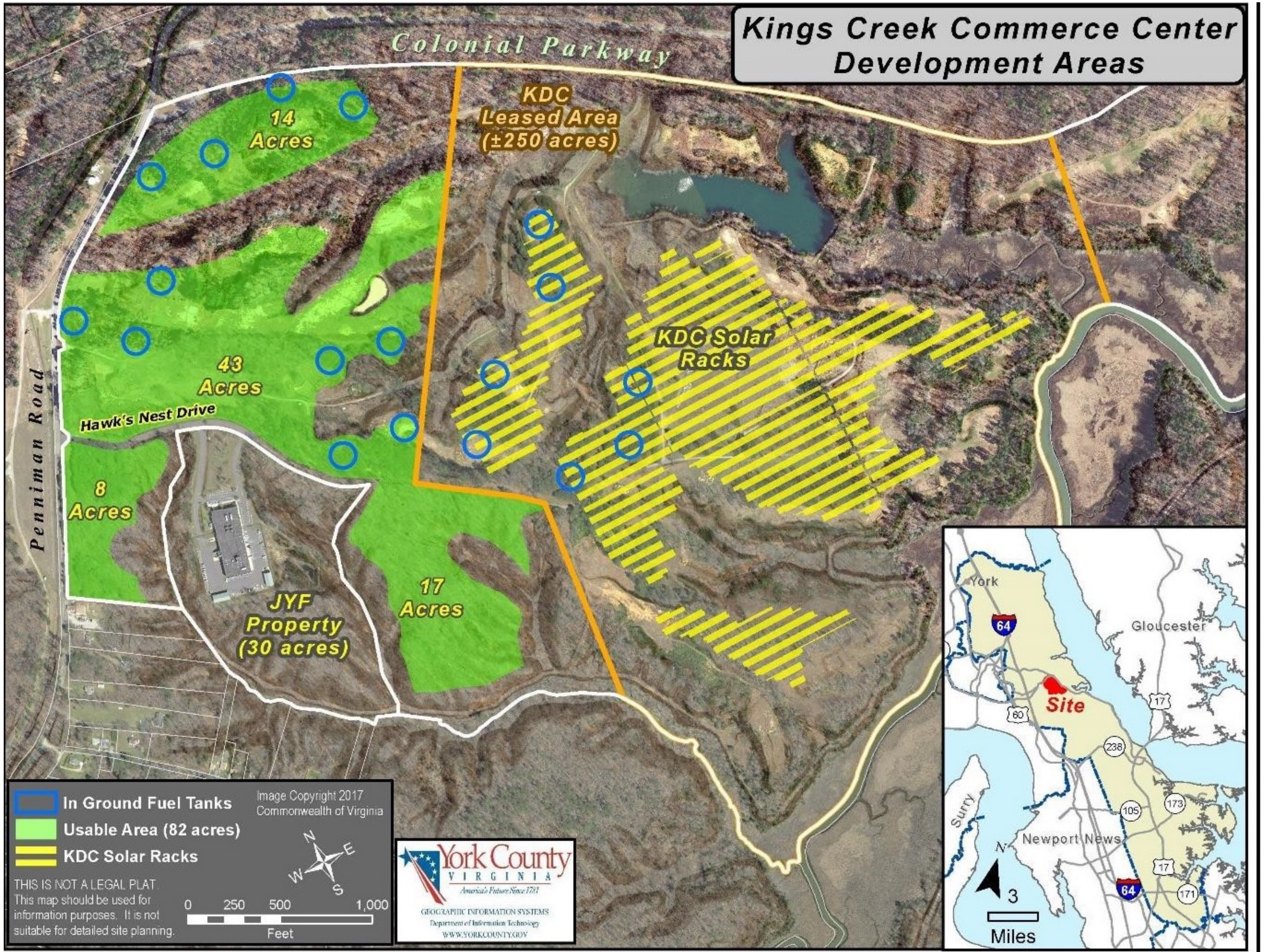
- Divorce from minor actinides by disassociating with ^{235}U & ^{238}U
- Reduce/remove concerns regarding nuclear proliferation & low waste
- Serve as backup generators to renewables
- Usher in much needed Hydrogen Economy
- Serve as high temperature heat sources for industrial processes
- Highly economical, ultra clean, super safe and distributed source

Declining Coal - Enthroning Nuclear - Fizzling out Gas -
Enabling Renewables – Pathway to Zero Carbon

We propose to build an Advanced Subcritical MSR ^{233}U & ^{232}Th breeder-burner in equilibrium Micro-Reactor (ASMR) R&D Center under a PPP in Yorktown,

These micro-reactor's linacs have dual use for the production of ^{225}Actinium for medical applications

VA ASMR site identified



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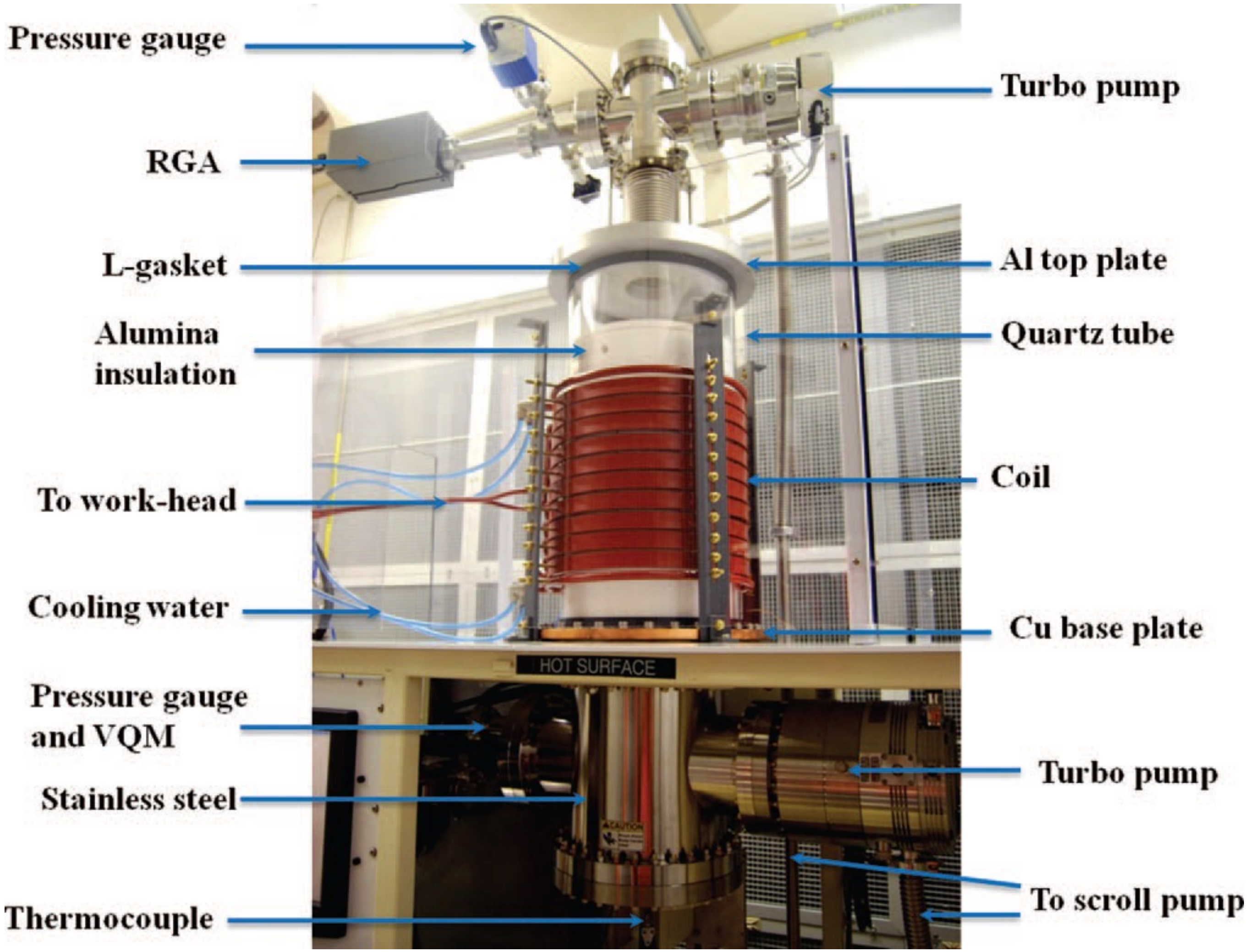
• SRF Niobium-Hydrogen Issue Path Forward

- We need to develop clean UHV furnaces for annealing the cavities to eliminate after chemistry
- Annealing time and temperature needs to be optimized for better H_2 degassing without grain structure change
- Specific heat measurements on samples @ 2 K as a function of magnetic field will help optimize cavity process procedures

Induction Furnace (proposed loaning to KEK for collaborative work)



S&T Lessons Learned 1974 – 1992

- First Low Temperature Physics Graduate Student at IITM, Chennai Sept 1974 – Jan 1980
  - CSIR project on development of cryogenics technology
    - Cryostats Development (continuous flow, thermal insulation etc.)
    - Cryogenic Instrumentation (wide range cryogenic thermometry - Si and Ge diodes)
    - Physisorption Measurements (Molecular Sieves and Charcoals) at 77, 20 and 4.2 K
    - Mechanical Properties of Materials (low temperature attachments and instrumentation)

“Semiconductor Junctions as Cryogenic Temperature Sensors”, M. Ganapati Rao, Temperature its Measurement and Control in Science and Industry, AIP Vol 5, 1982 pp 1205-1211

“Miniature Silicon Diode Cryogenic Thermometers” M. G. Rao, R. G. Scurlock and Y. Y. Wu Cryogenics, Vol 23 1983 pp 635-638

“Cryogenic Pressure Sensor Calibration Facility” M. G. Rao, D. Junarenal” Advances in Cryogenic Engineering Vol 35 1990 1573-1581

“Precision Thermometer with Cold Integrated Electronic System Using 15 bit A/D Converter” M. G. Rao and R. G. Scurlock, Proceedings of the Symposium on Low Temperature Electronics And High Temperature Superconductors Edited by S. I. Raider et al, Volume 88-9 1988 pp 524-528

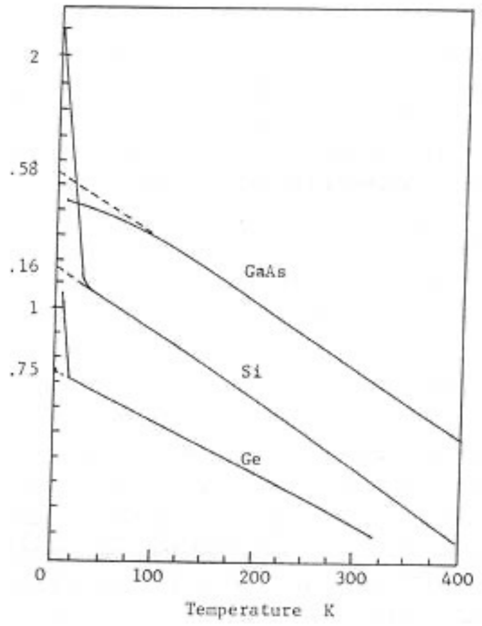
.“Simultaneous Pressure and Temperature Measurements on Helium in the High Speed Rotating Frame” R. M. Igra, M. G. Rao and R. G. Scurlock, Advances in Cryogenic Engineering Vol. 33 1988 pp 1005-1012

“A Silicon Diode Thermometer with Integrated Circuit Instrumentation Package for Operation Between 77.5 K and 290 K” M. G. Rao and R. G. Scurlock, Proceedings of the International Congress on Instrumentation in Aerospace Simulation Facilities 92-ICIASF’87 Record CH2449

. ”Thermometric Characteristics of the Improved Miniature Si diodes” R. M. Igra, M. G. Rao and R. G. Scurlock, Proceedings of the 11th ICEC, Berlin 1986 pp 617-621

“Cryogenic Instrumentation with Cold Electronics – A Review” M. G. Rao and R. G. Scurlock Advances in Cryogenic Engineering Vol. 31 1986 pp 1211-1220

“Recent Advances in Si and Ge Diode Cryogenic Thermometers” M. G. Rao and R. G. Scurlock, Proceedings of the 10th ICEC, 1984 pp 418-421



Low temperature characteristic (T < 20 K) is exponential and extrinsic in nature and effected by mismatch in thermal expansion (synthetic sapphire and metallization technics

High temperature characteristic (20 K >T < 475 K) is linear and intrinsic influenced by junction leakage current

CEBAF Linac Cryogenic Instrumentation Requirements and a Review of the Available Sensors

CEBAF-PR-88-022 Dec 1988 Myneni, Ganapati

First quarter CM was built with platinum resistors and thermocouples

S&T Lessons Learned 1974 – 1992 contd.

- AMI superconducting wire LHe level sensor issue
  - The first quarter CM LHe level sensor was indicating full without any liquid!?
  - Reason was the level sensor is superconducting due to cold helium gas

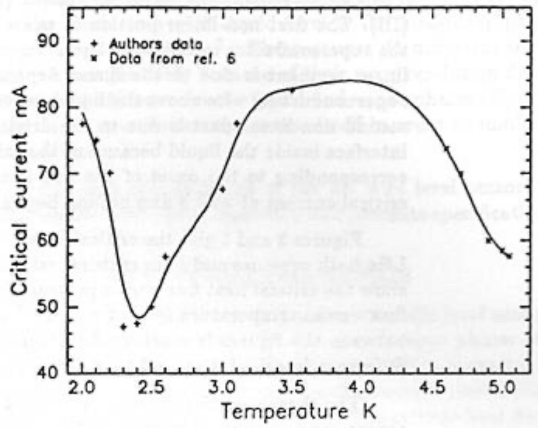


Figure 3 Critical current vs temperature for LHe level sensor

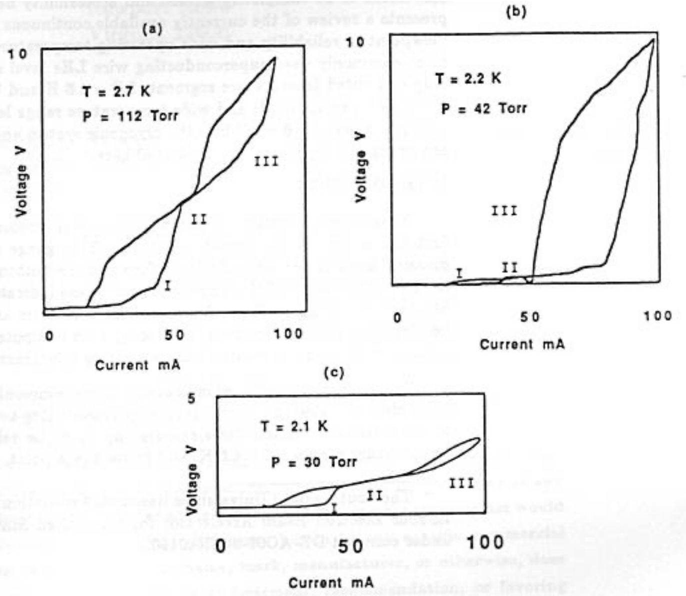


Figure 1 V - I Characteristics of LHe level sensor at different temperatures

1) Review of Liquid Helium Level Sensors CEBAF-PR-91-002 Jan 1991 Myneni, Ganapati R
2) Cryogenic Liquid Level Measuring Apparatus, CEBAF first US patent
3) New Liquid Helium Level Sensor CEBAF-TN-89-185 Nov 1989 Myneni Ganapati R
4) Cryogenic Pressure-Temperature and Level-Temperature Sensors, D. B. Juanarena and M. G.Rao, Cryogenics Vol 32 1992 pp 39-44
5) Integrated Cryogenic Sensors" D. B. Juanarena and M. G. Rao, Supercollider3 Edited by John Nonte 1991 pp 861-871
6) Cryogenic Pressure Sensor Calibration Facility" M. G. Rao, D. Junarena , Advances in Cryogenic Engineering Vol 35 1990 1573-158

S&T Lessons Learned 1974 – 1992 contd.

- With in a few weeks of arriving at CEBAF 1987, I have recognized that oil lubricated turbo pumps are a major concern
- Additionally, particulate laden ion pumps are also of obvious issue
- A magnetic bearing turbo pump system for clean evacuation was implemented but no takers
- Residual Gas Analyzers (RGA) use was proposed for leak detection but no resources available (Hyden consigned RGA’s helped to make the point)

A clean dry vacuum gauge calibration systems was proposed and implemented

- European Q-disease due to hydrides announced

S&T Lessons Learned 1974 – 1992 contd.

- Cold leaks due to poor flange surfaces threatened the viability of CEBAF
  - Surface treatments implemented and flange bolt holes modified
  - Flange torquing and re-torquing processes developed
  - Leak rate specification changed from 10^{-8} atm cc/s to 10^{-10} atm cc/s
  - Cavity pair He desorption integrated leak technique successfully utilized (~3×10^{-11} atm cc/s)

High Sensitivity Leak Detection Method & Apparatus US Patent

Ultra High Vacuum Pumping System and High Sensitivity Helium Leak Detector US Patent

Sensitive Hydrogen Leak Detector US Patent

Mechanical Properties of RF Window Frame and Cavity Flange Niobium, NbCEBAF-TN-91-058 Aug 1991 Myneni, Ganapati R

Cycling of RF Window Flange Indium Seals CEBAF-TN-91-057Aug 1991 Myneni Ganapati R, Kneisel Peter

High Sensitivity helium Leak Detection Method" M. G. Rao J. Vac. Sci. Technol. A 11(4) 1993 pp 1598-1601

S&T Lessons Learned 1974 – 1992 contd.

- Cryosorption applications :
  - Micro-porosity is essential for achieving low ultimate pressures (science)
    - Coconut charcoals have micro-porosity and also high pore volume
      - LHe dewars with these charcoals at the bottom of the inner vessel have better than 1% evaporation rate
      - Cryosorption panels with coconut charcoal achieve low ultimate pressures (in particular H_2 PP)

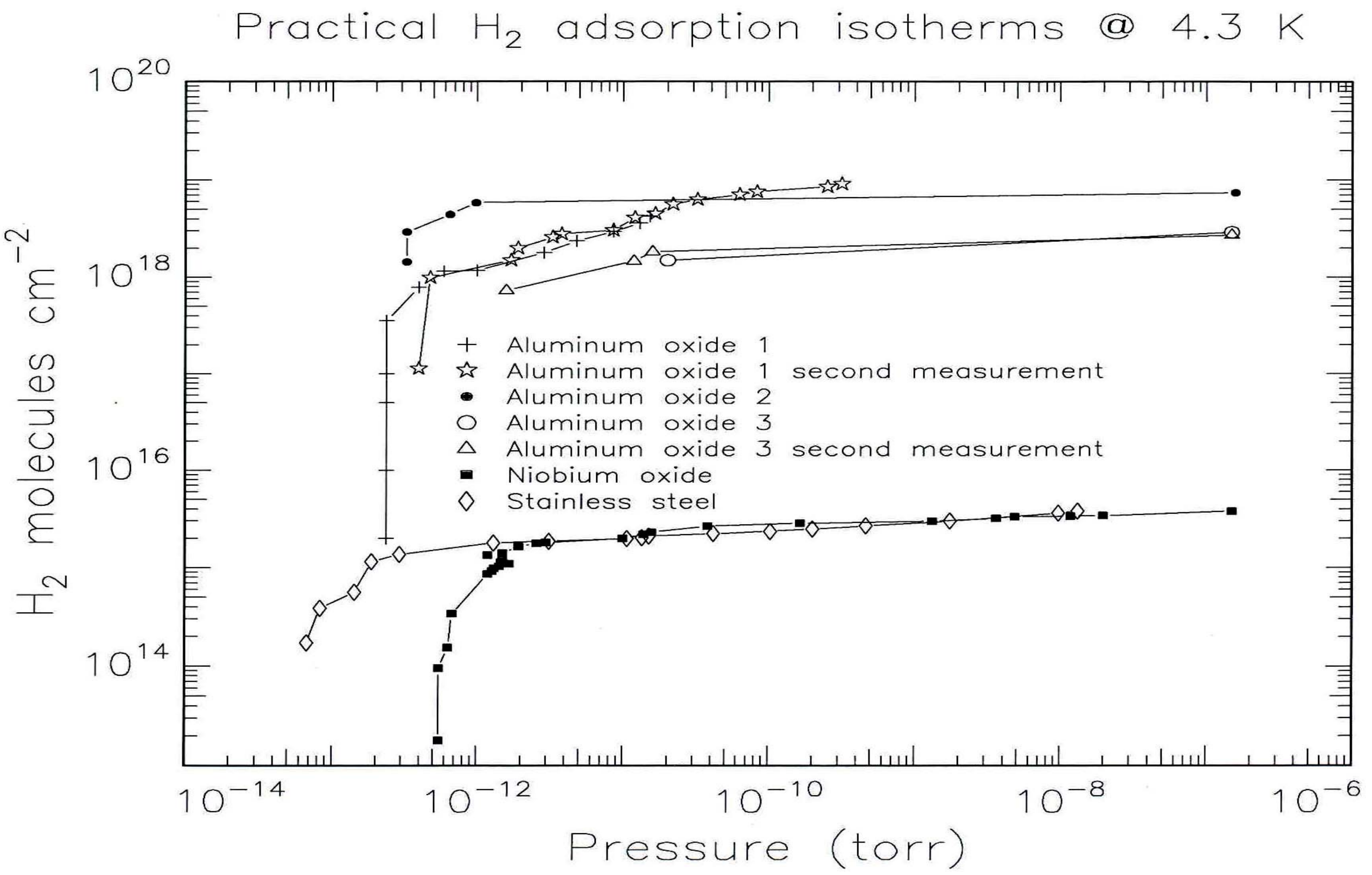
- Cryogenic concrete (CC) UK patent with Southampton University
  - Containment for LNG storage tanks
  - Contains free water and chemical water (science)
  - Successfully developed high performance and reliable CC by removing the free water and passivating the concrete

- Metal sponge (anodized aluminum with micropores, CEBAF patent) for the SSC beam line vacuum system to maintain pressures below 10^{-10} Torr at 4.2 K

Cryosorption Pumping of H2 and He with Metals and Metal Oxide at 4.3K M.G.Rao, P.Kneisel and J.Susta, *Cryogenics*, 34, 377-380 (1994).

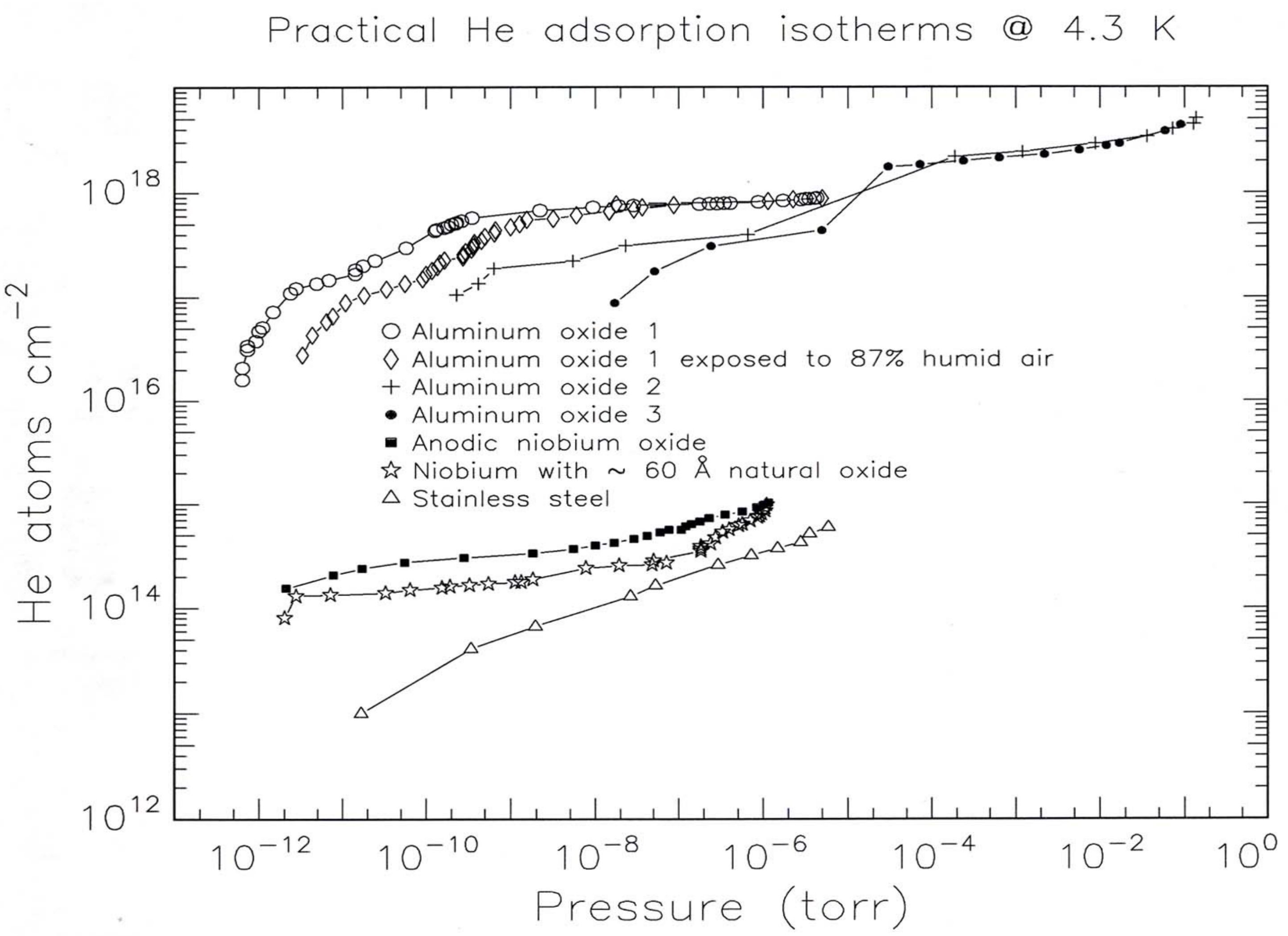
Metal Sponge for Cryosorption Pumping Applications US Patent

Hydrogen Isotherms



Myneni Ganapati, KEK, Ibaraki, Japan Oct 17, 2022

Helium Isotherms



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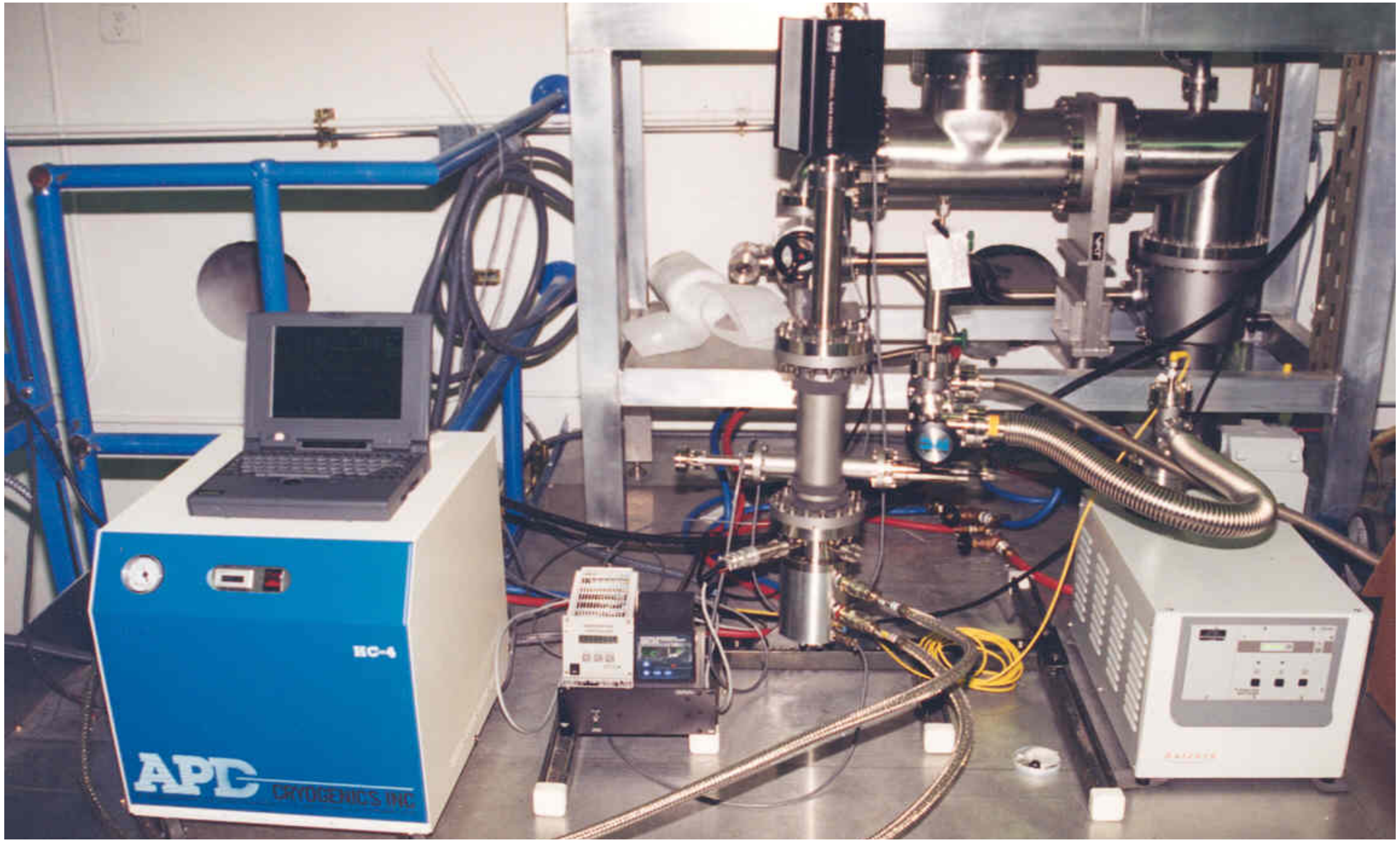
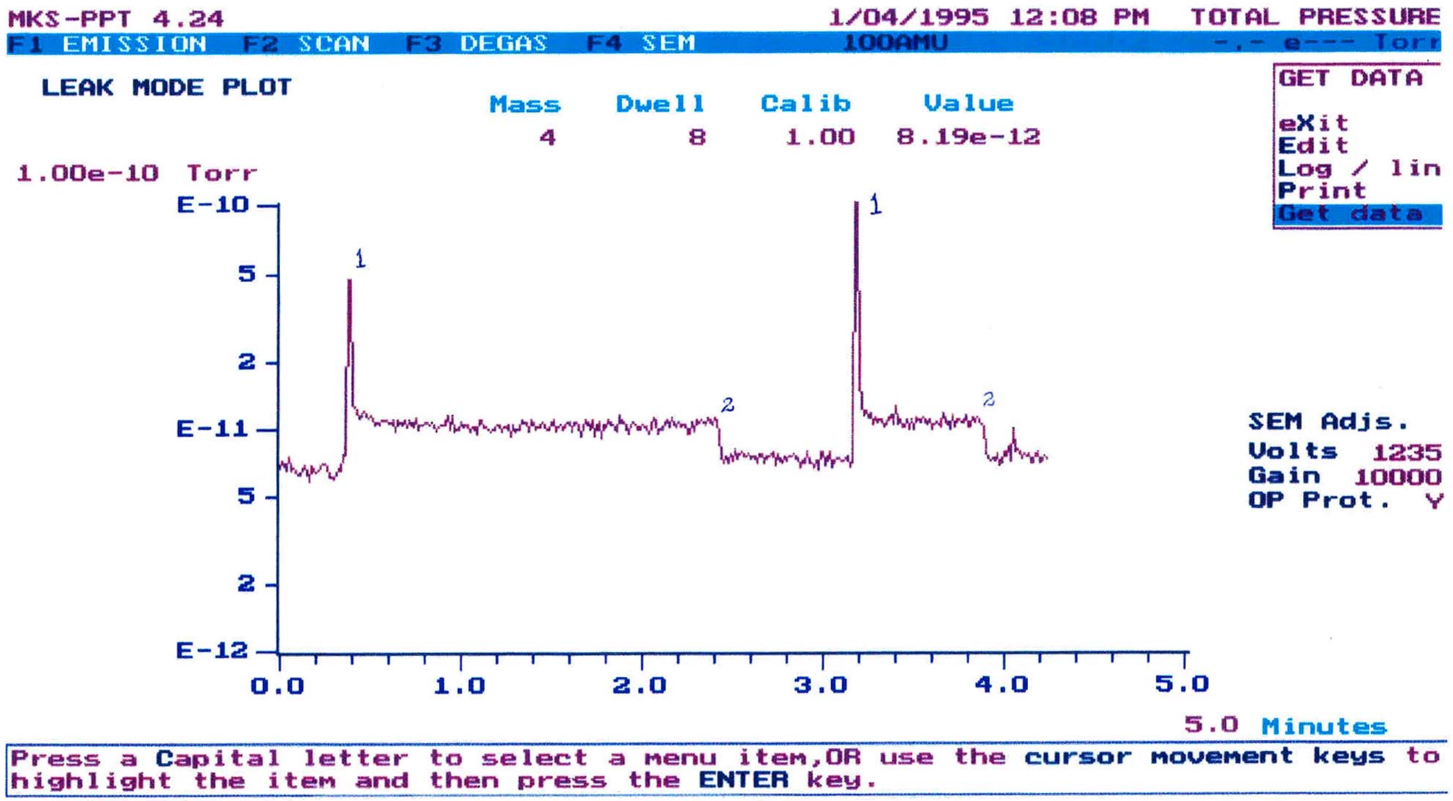
Extreme Sensitivity He Leak Detector - US Patent



Calibrated leak

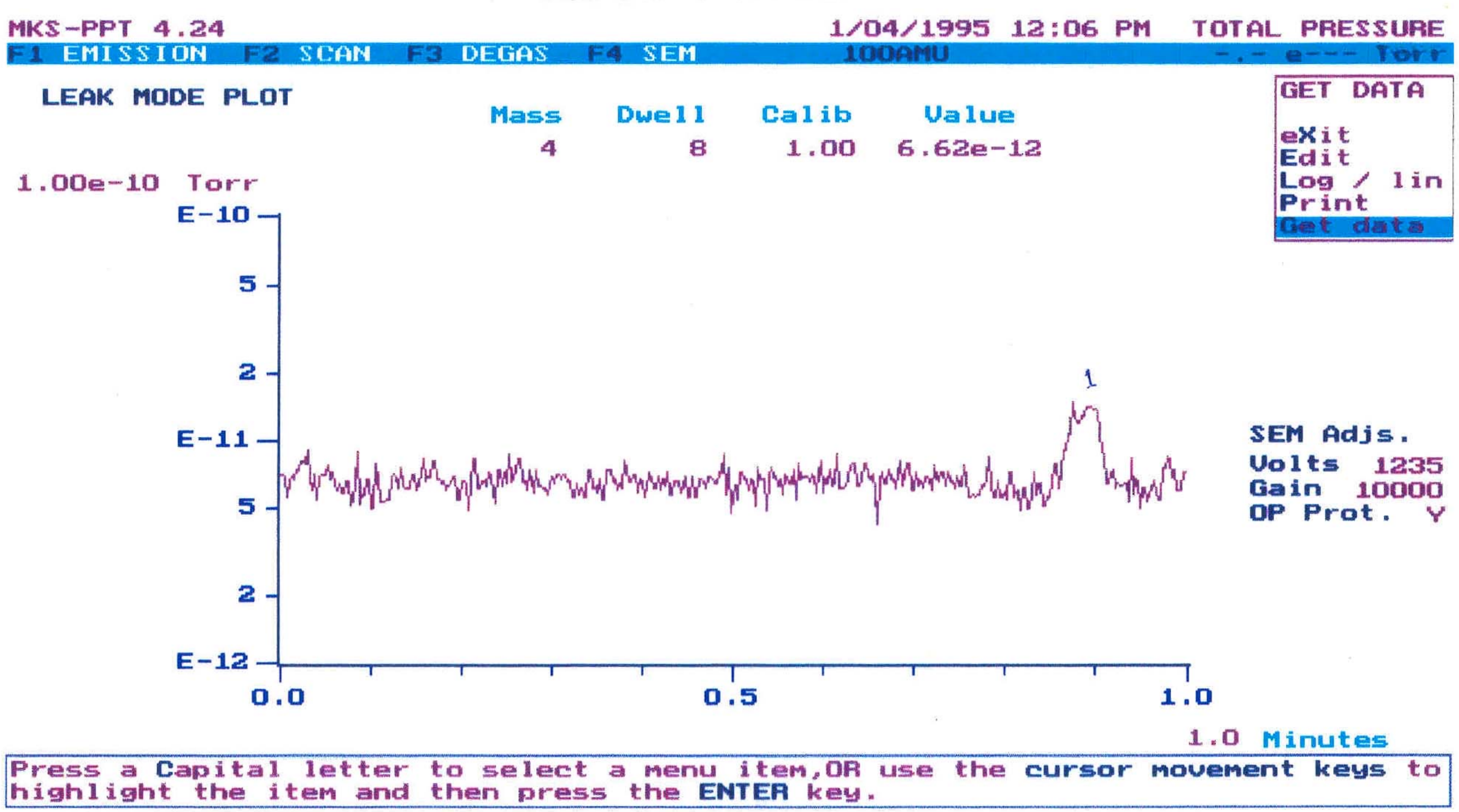
A 1x10-12 atm cc s-1 Calibrated Leak Opened and Closed to the Leak Detector



1. Calibrated leak opened to the leak detector
2. Calibrated lead isolated from the leak detector

Back streaming of Helium through turbo pump

Leak Detector Connected to the Turbopump



1 Backstreaming of atmospheric helium through the turbopump

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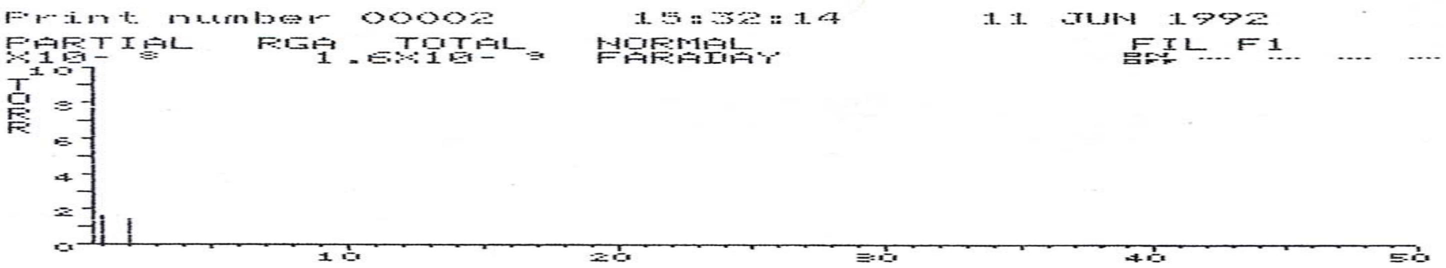
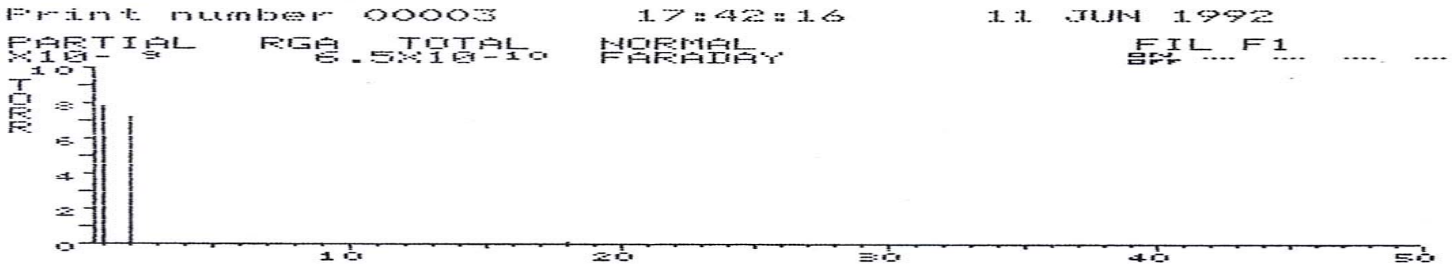
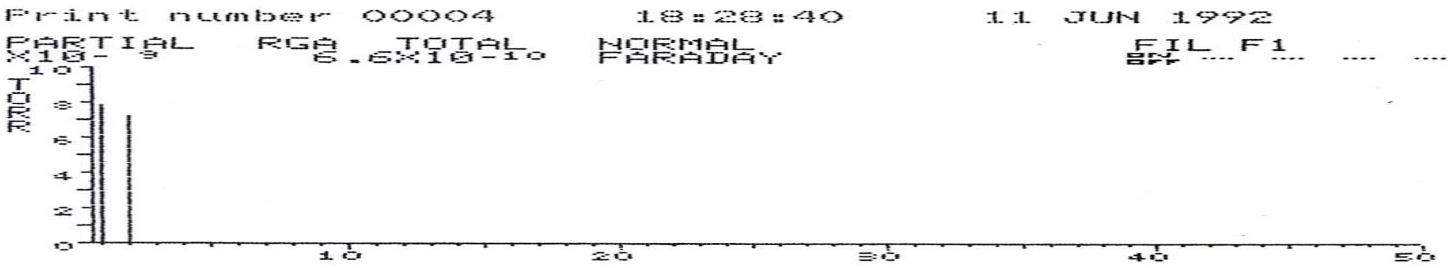
Unbaked clean dry vacuum system RGA spectra



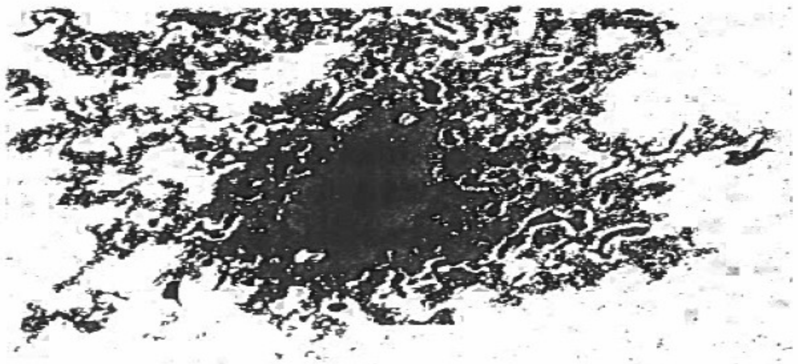


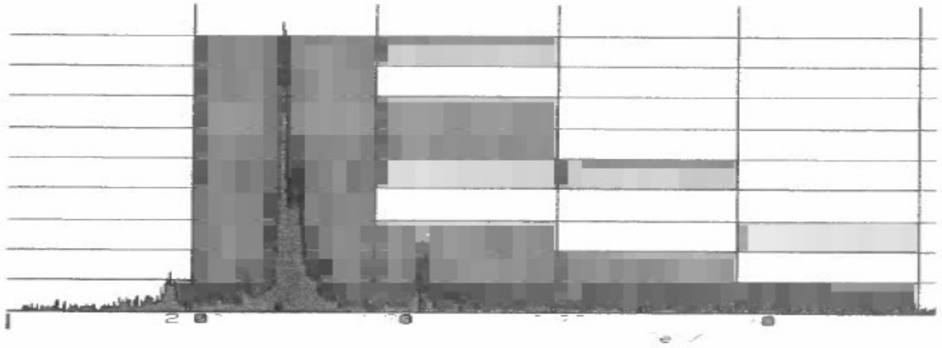


Ion Pumps

- Ion pumps are big source of particulates and they are transported to cavity surfaces via Brownian motion
- Ion pumps can't pump hydrogen effectively
- Ion pumps are known to generate CH_4

Metallic Titanium particulates from ion pumps





S&T Lessons Learned 1974 – 1992 contd.

Quality Control of Niobium

QC of Niobium is implemented via thermal conductivity and mechanical property measurements:

These two experimental systems were automated using LabVIEW with the help of Mark Iacobacci (now an Ophthalmologist at Tidewater Eye Centers on South Side)

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Hydride effect on elongation

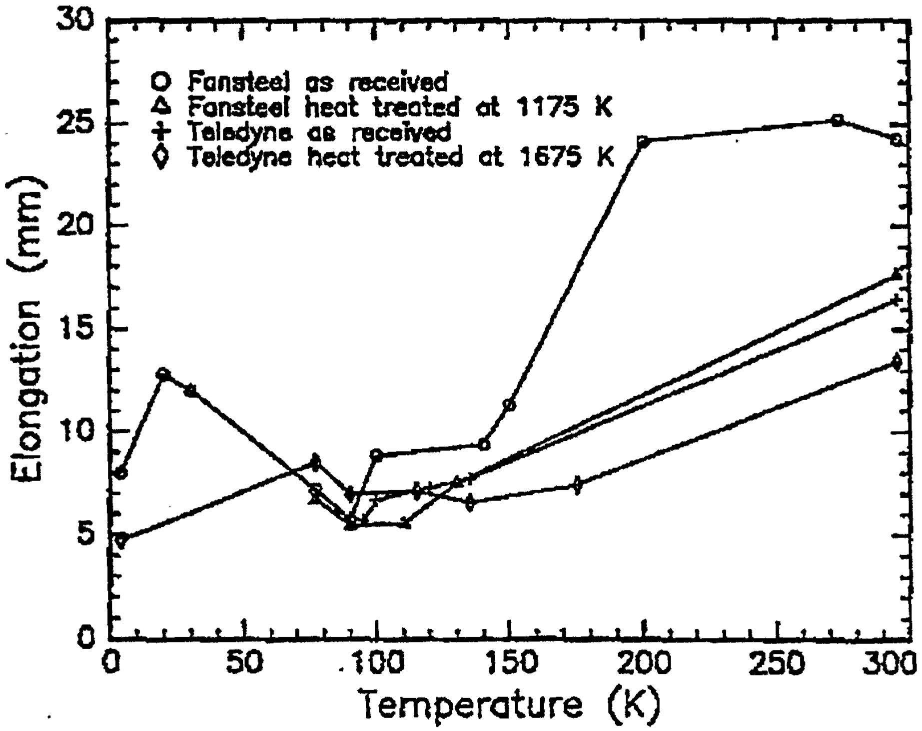

Figure 2. Elongation at break vs. temperature.

1) Mechanical Properties of High RRR Niobium at Cryogenic Temperatures" M. G. Rao and P. Kneisel , Advances in Cryogenic Engineering Vol. 40 1994 pp 1383-1390
2) Superconductivity Cavities From High Thermal Conductivity Niobium for CEBAF CEBAF-PR-91-001 Jan 1991 Kneisel Peter, Mammosser John, Myneni Ganapati R., Saito Kenji
3) Preliminary Results of Tensile Tests on Niobium at Room Temperature and 4.2 K CEBAF-TN-88-097 Oct 1988 Kneisel Peter., Myneni Ganapati R
4) Mechanical Properties of RF Window Frame and Cavity Flange Niobium, NbCEBAF-TN-91-058 Aug 1991 Myneni, Ganapati R

The proposed R&D on Hydrogen-Niobium was ignored!!

S&T Lessons Learned 1992 – 2002

- Photo cathode life time enhancement by improving the injector vacuum (provided the state of the art vacuum diagnostics, imparted training and thereby prevented vacuum leaks)
- Eliminate linacs thunderstorm sensitivity (modified the wave guide vacuum interlocks) JLab-TN-00-023
- He processing of cavities to raise the CEBAF energy from 4 GeV to 6 GeV
- FEL C50 cryomodule with no field emission J. Vac. Sci. Technol. A 17 (4) 1999 pp 2104-2108
- Optimization of SNS cavity annealing temperature for removing hydrogen while maintaining mechanical stability
- Contamination control workshop 1997
- Extreme High Vacuum Workshop 2000
- Hydrogen in Material and Vacuum Systems International Symposium 2002
- Hydrogen Workshop (UHPM-Japan, Uppsala-Sweden, NIST, ODU, UNY & UVa)

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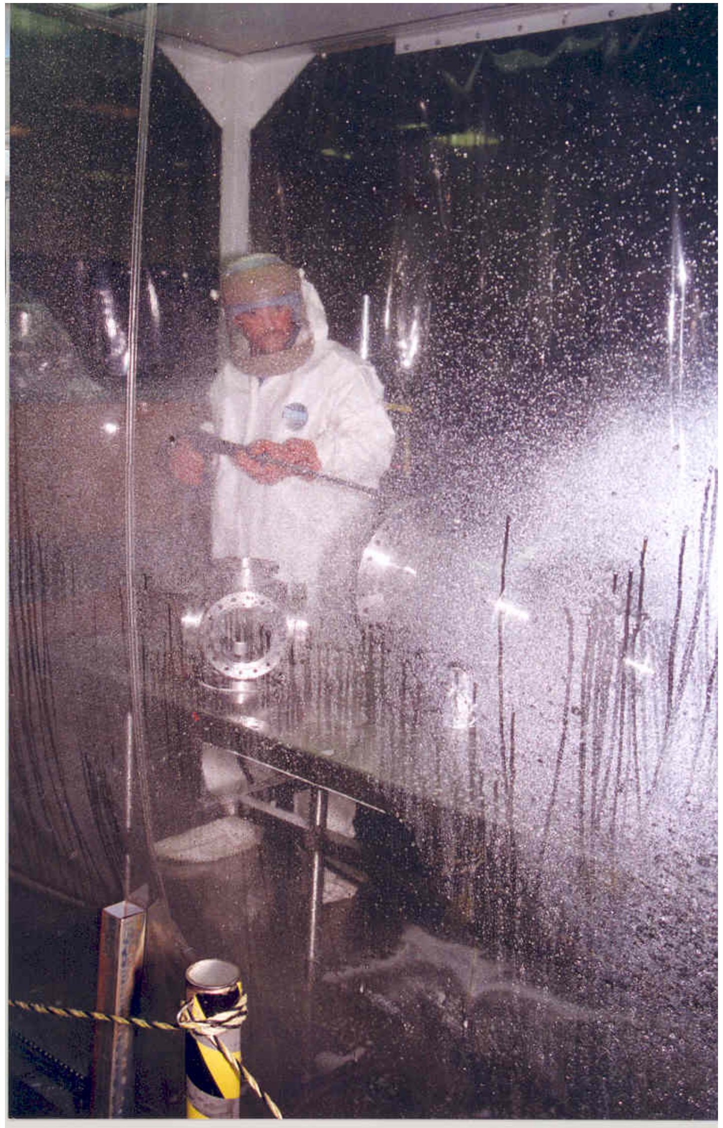
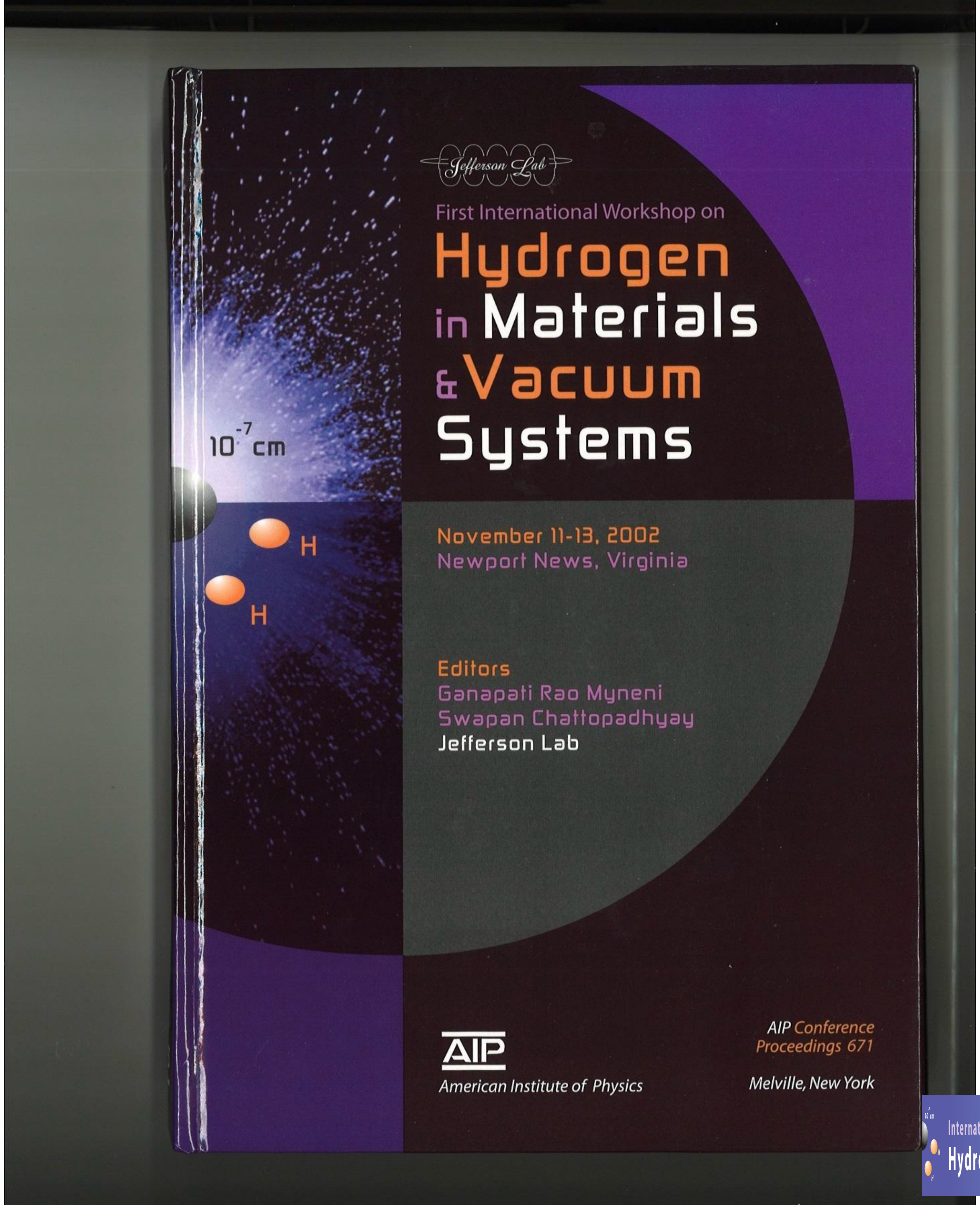
High Pressure DI Hot Water or Steam Cleaning



Vacuum Contamination Work Shop at JLab 1997

Minimizing Organic and Particulate Recontamination Addressed, several courses were held In subsequent years

UHV Particulate Counter



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S&T Lessons Learned 2002 – 2022

- Niobium and hydrogen interactions investigations
- UHPM materials workshops
- Collaboration interactions with ESS, KEK, SCK-CEN (MYRRHA), DAE Institutions in India and CBMM
- NIST, UVa, ODU, NCSU, MSU and VT Collaborations
- Large Grain Niobium Technology and the associated Workshops
- LG Nb as injector electrode and C100 HOM load thermal issue
- Informal Virginia ADS Consortium, a precursor to VNECA and VNEC
- ADS & ThU International workshops
- Medium Grain Niobium Technology

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Historical remarks on SRF Technology*

- Stanford and UCCI
  - X-band cavities reached very high gradients and quality factors
  - L-band ingot niobium cavities poorly performed due to contamination & vacuum leaks

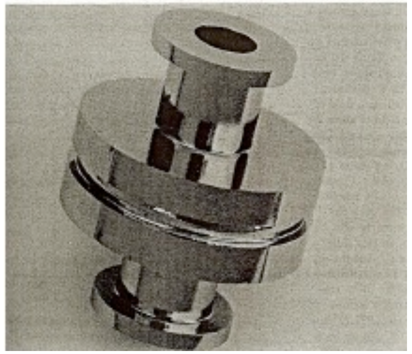
- CEBAF at JLab
  - Even for low gradient (5 MV/m) and quality factor (2e9) specs - Vacuum leaks set back at the beginning
  - 6 GeV energy reach, 50% higher than design via helium processing (mostly H removal)
  - 12 GeV upgrade vows (filed emission etc.)

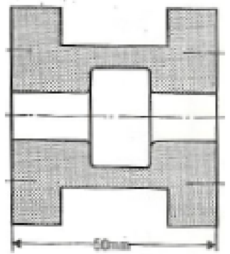
- XFEL success may be attributed to good QA procedures

* *SRF TECHNOLOGY—PAST, PRESENT AND FUTURE OPTIONS**

G. Myneni#, A. Hutton, Jefferson Lab, Newport News, VA 23606, U.S.A Proceedings of EPAC08, Genoa, Italy MOPP130
CERN Courier View Point, "SRF technology comes full circle" 20 October 2008. Ganapati Myneni

Historic record performance





Stanford ca. 1970

BCP

Qo ~ 1e11 @ 1.2 K CW

Hpk ~ 108 mT

Siemens ca. 1973

EP	**BCP**
130 mT	**109 mT**

Reactor grade Ep'd Siemens fine grain cavity Hpk ~ 159 mT Qo ~ 1e10 @ 1.45 K

Extrinsic and intrinsic contamination of Nb determines the performance of the cavities

Extrinsic

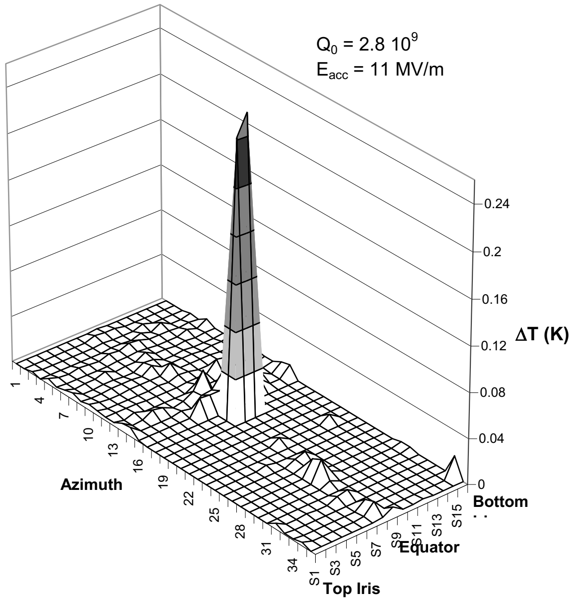
- Surface contamination
  - Molecular and particulate

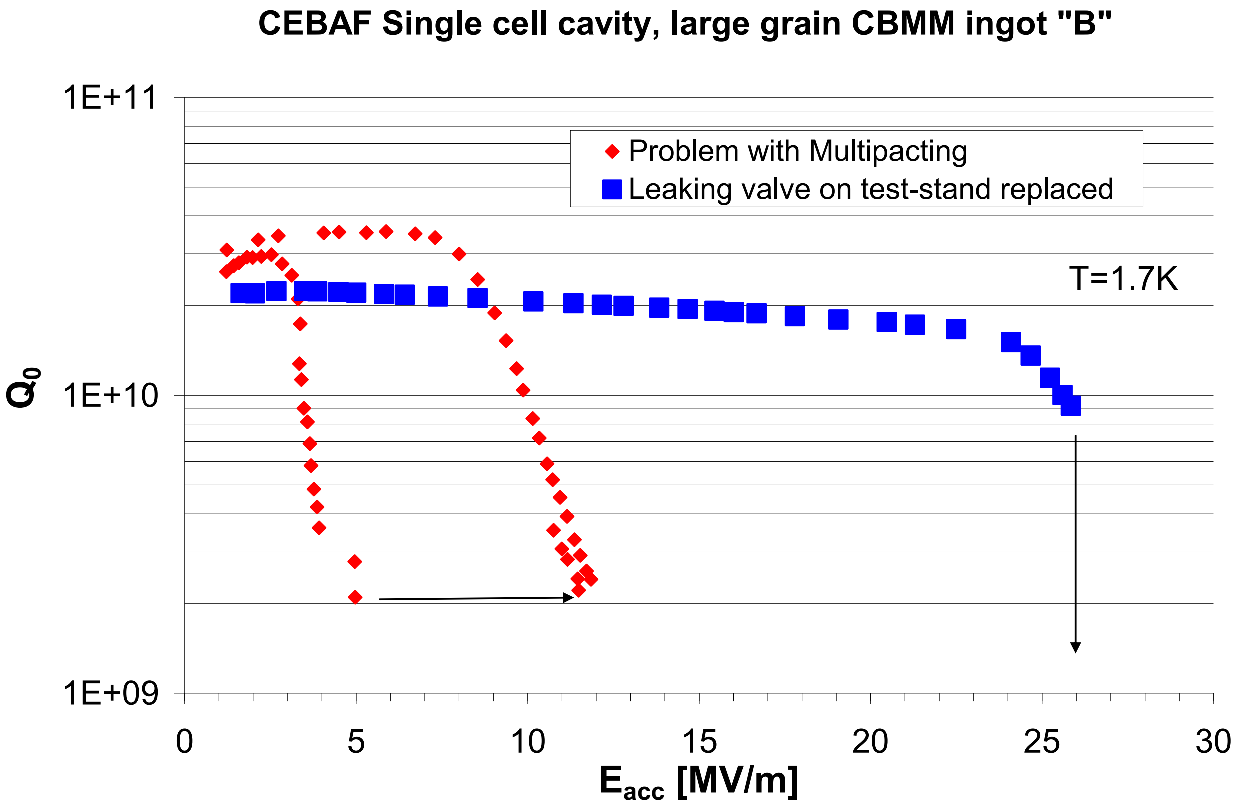
Intrinsic

- Niobium is a prolific hydrogen absorber in the absence of the natural surface oxide
  - Hydride formation
  - Dislocations

Multipactoring problem resurfaces

T-map showing MP at equator





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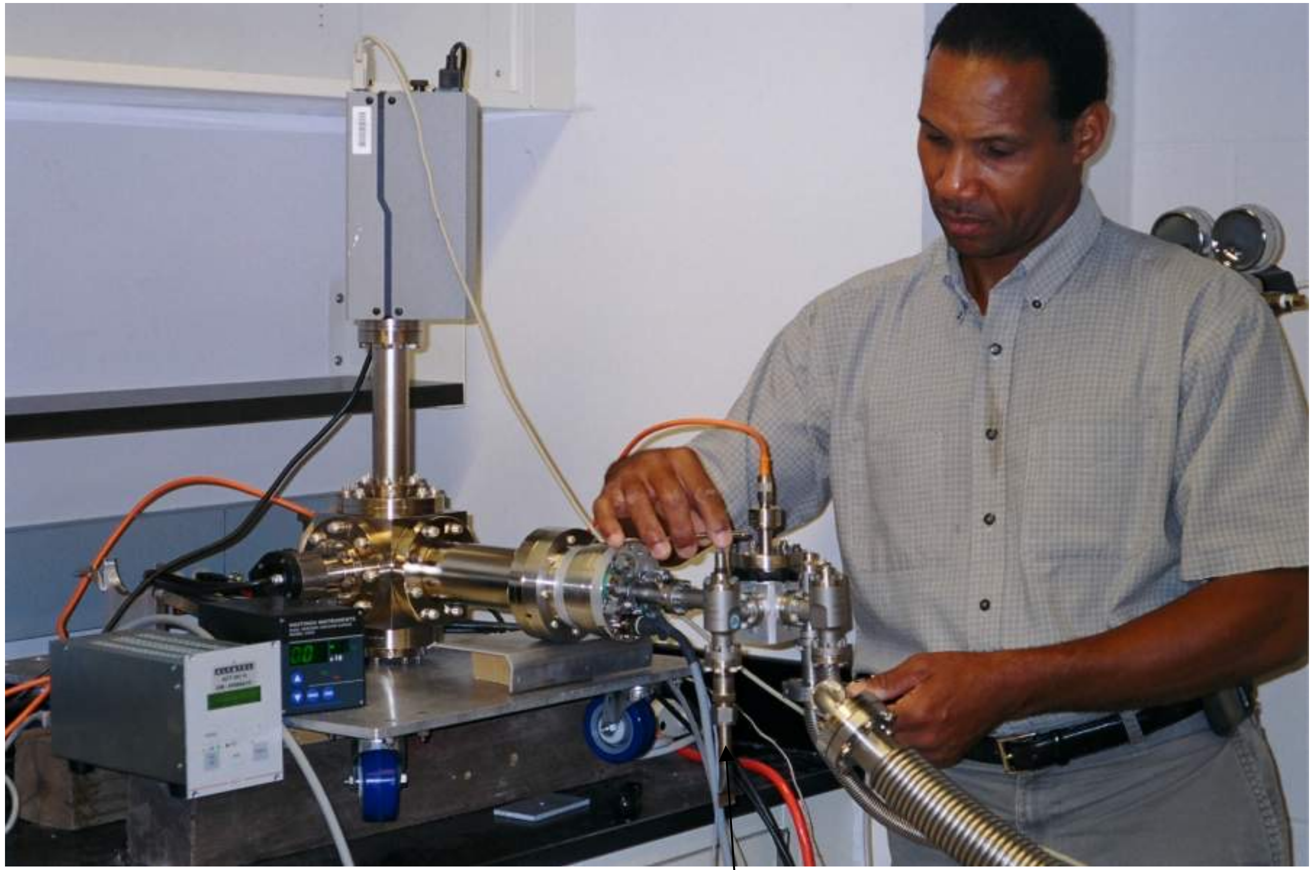
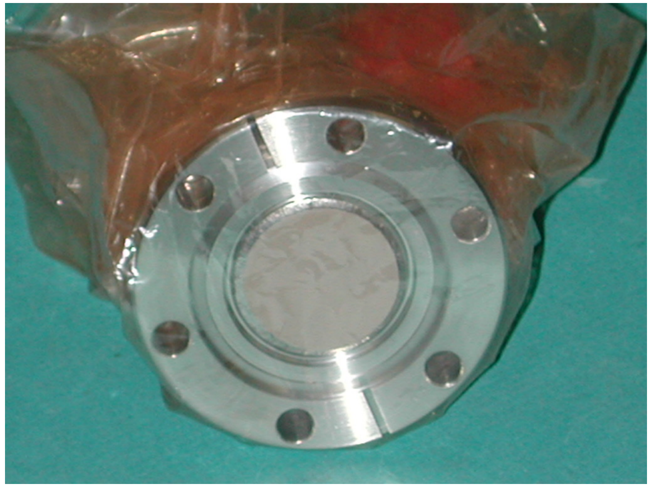
Active NEG Backed Turbo Pump

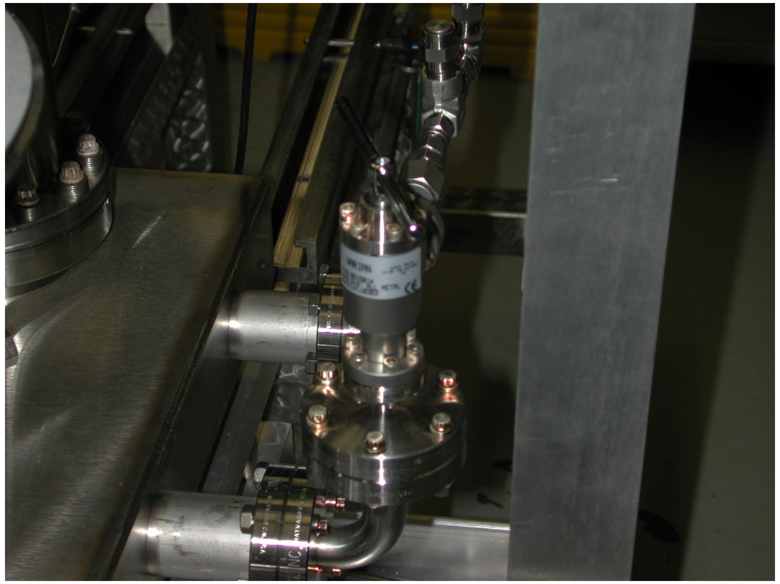
A Road Map to Extreme High Vacuum
May 2008 Journal of Physics Conference Series 114(1):012011 DOI: 10.1088/1742-6596/114/1/012011
P Adderley Ganapati Myneni



Contamination Free Back Up Pump

UHV Nano-filter (diffuser)





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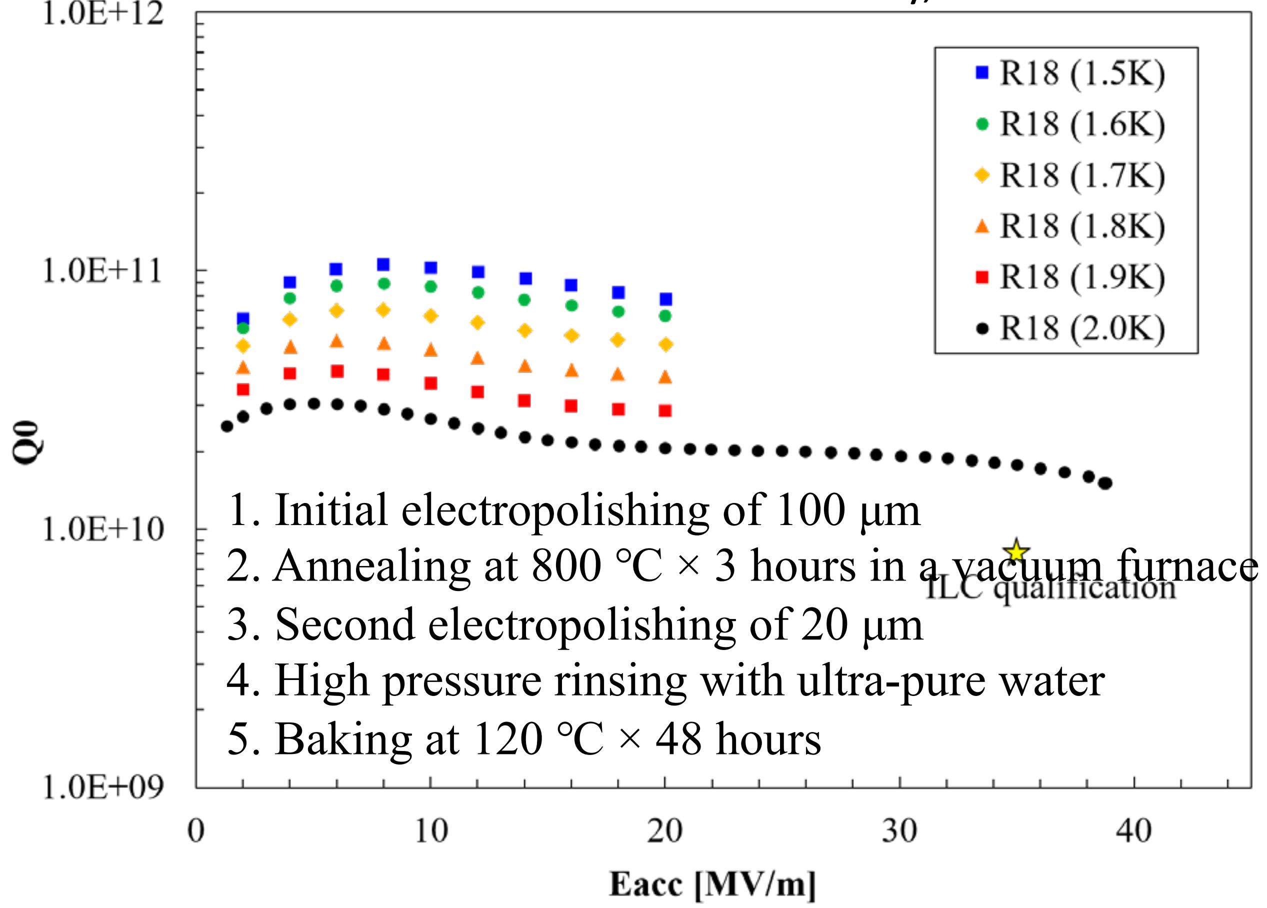
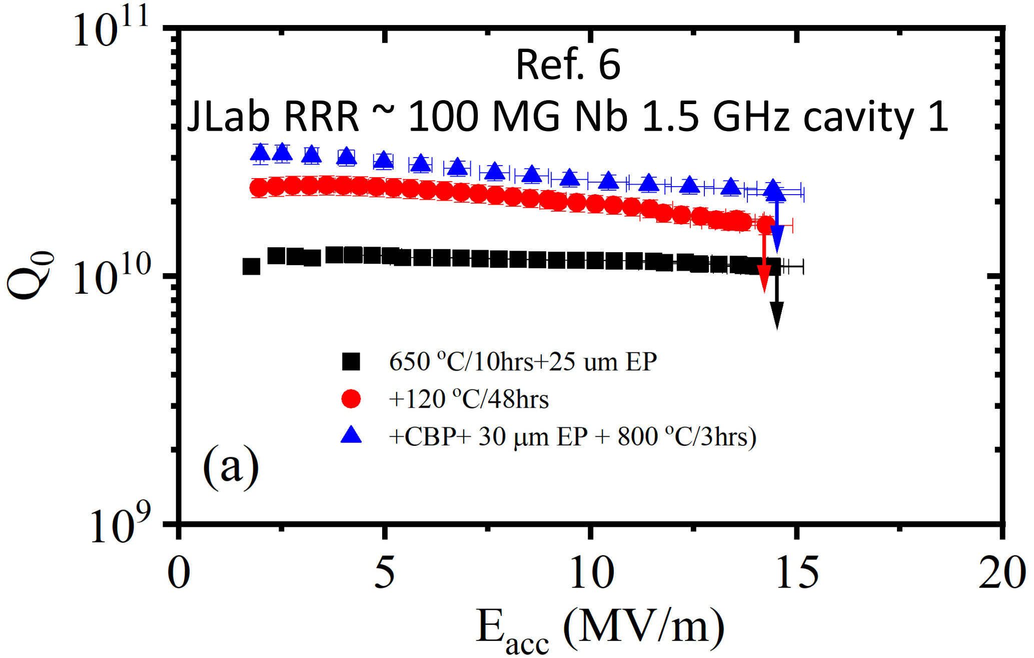
Intro to Nb Technologies for SRF

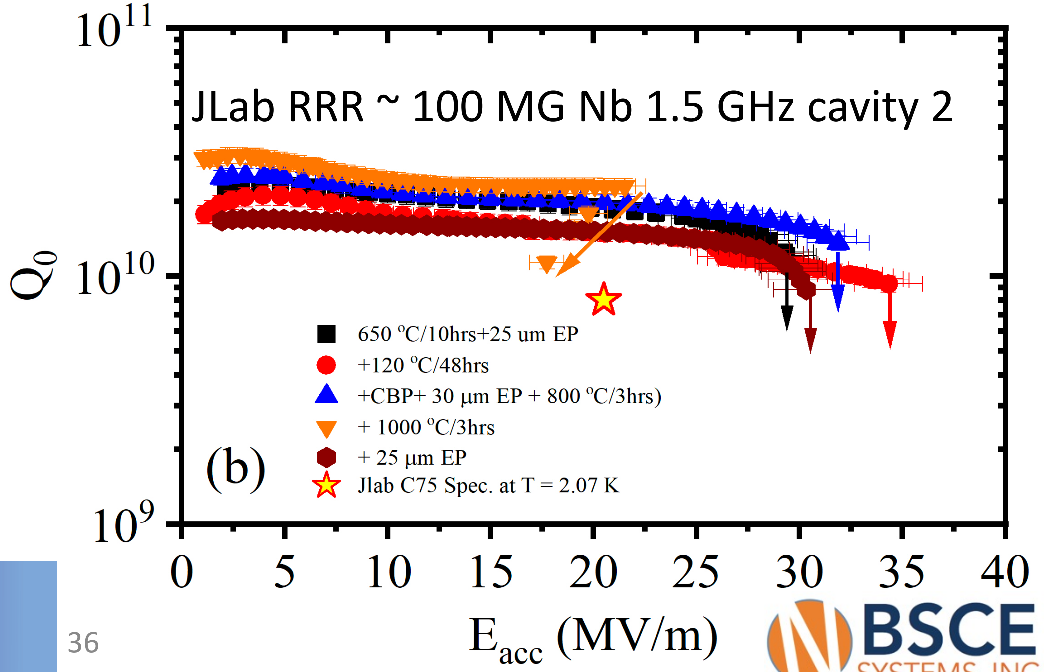
Fine Grain (FG) **Rolled Nb sheets**	**Medium Grain (MG)** **Forged Ingot Nb discs**	**Large Grain (LG)** **Ingot Nb discs**
Up to fourteen manufacturing steps Labor intensive	E-beam melted ingot of larger dia. forged to required dia and then sliced	E-beam melted ingot of required dia. is sliced
Grain Size ASTM 5 ~ 50 µm	ASTM 0 – 3, < 1 mm	Large non uniform grains >>1 cm
Widely used complex technology prone to contamination	New kid on the block and very clean surfaces	Proven clean surface technology
Uniform & adequate mechanical properties	Better uniform mechanical properties	Non uniform mechanical properties
Requires stringent QA & expensive	Better Cost advantage	Cost advantage

MG Nb cavities performance

KEK RRR ~ 500 MG Nb 1.3 GHz cavity, Ref 5 T. *Dohmae et al*







KEK EB welder is modern – no weld defects

JLab EB welder is ancient & refurbished – weld defects limit gradient

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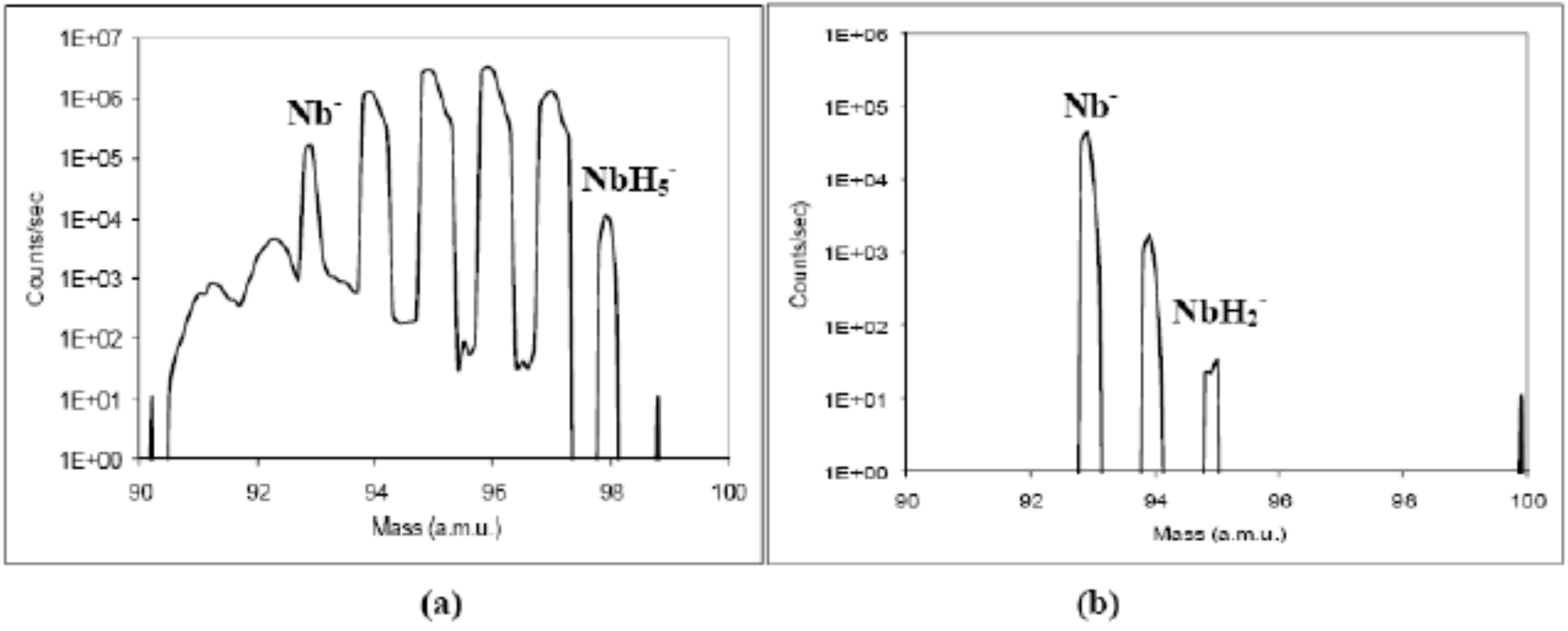


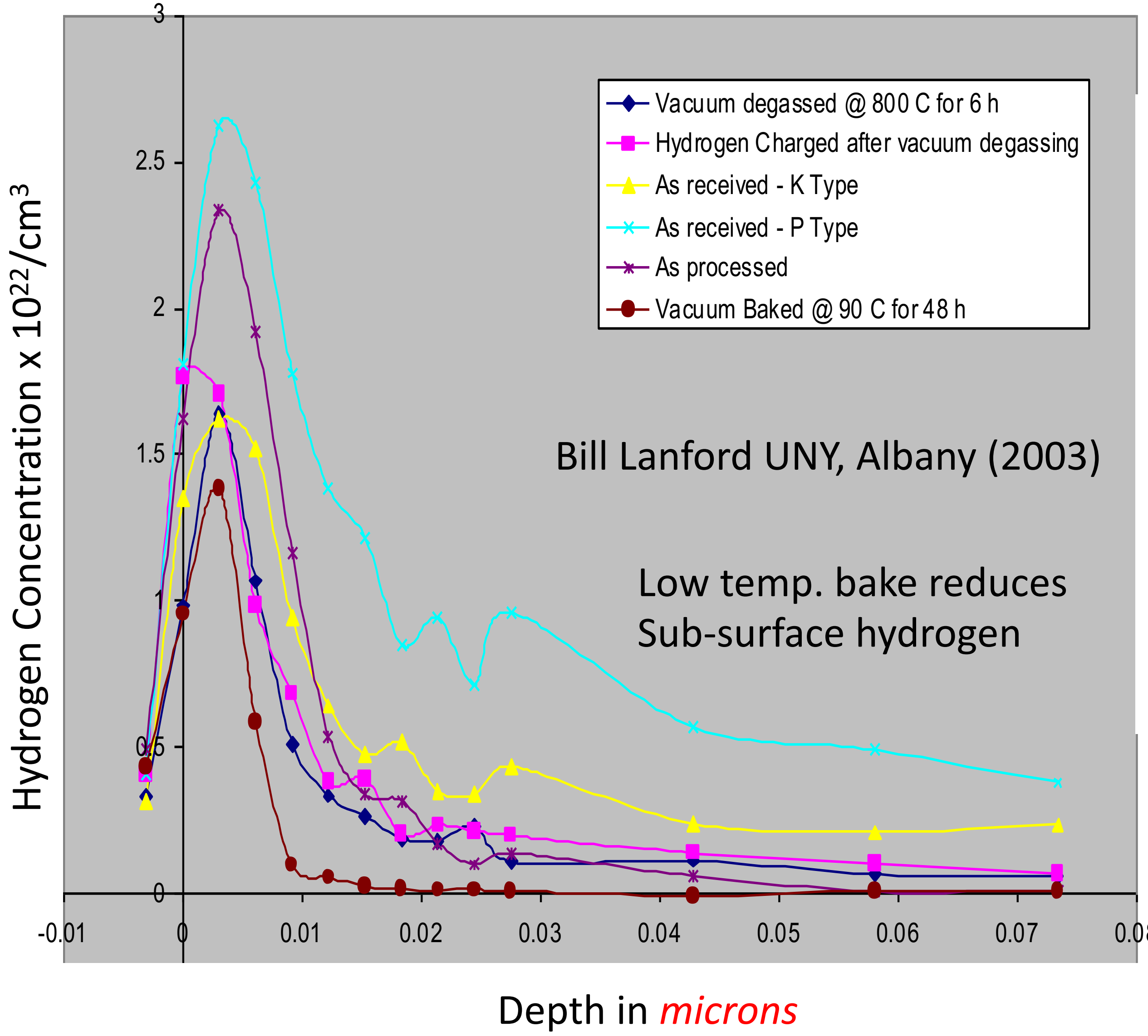
FIGURE 1. SIMS mass spectra showing difference in H between (a) non-heat treated and (b) heat treated sample.

Currently used furnaces contaminate the cavity surfaces, chemical re-etching reintroduces H

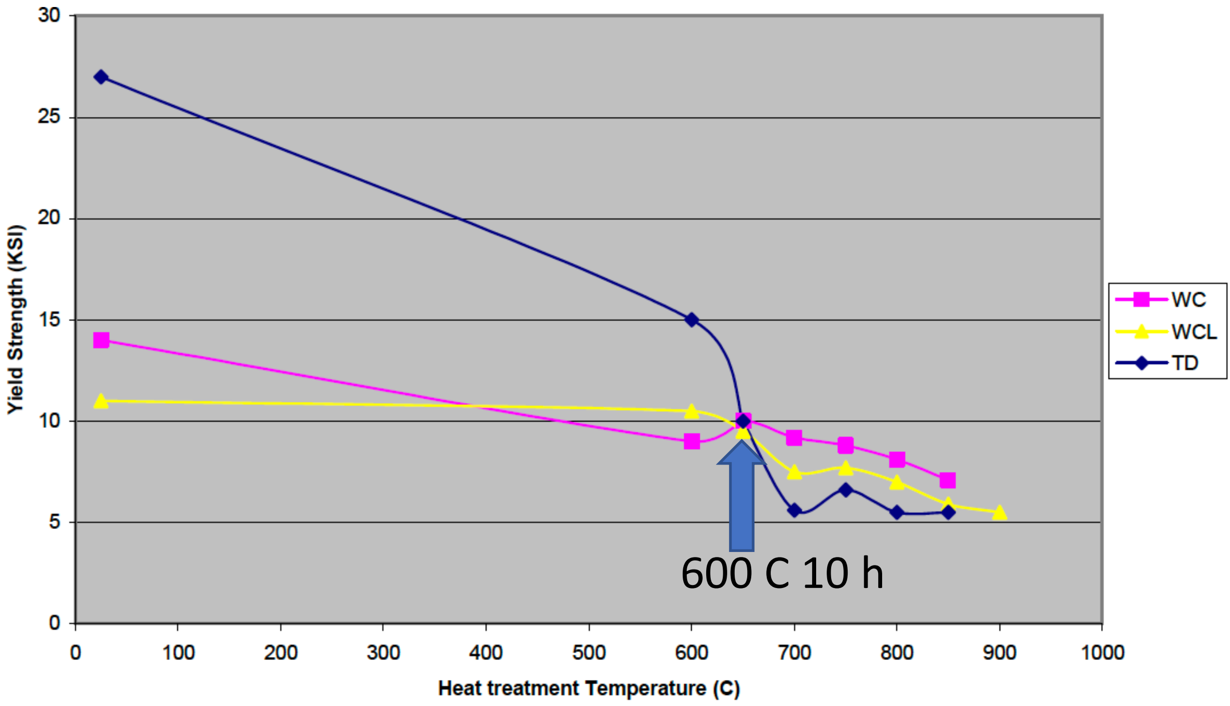
G. Ciovati, G. Myneni, F. Stevie, P. Maheshwari, and D. Griffis, Phys. Rev. ST Accel. Beams 13, 022002 (2010).

The hydrogen problem

Hydrogen depth profile in SRF niobium - NRA

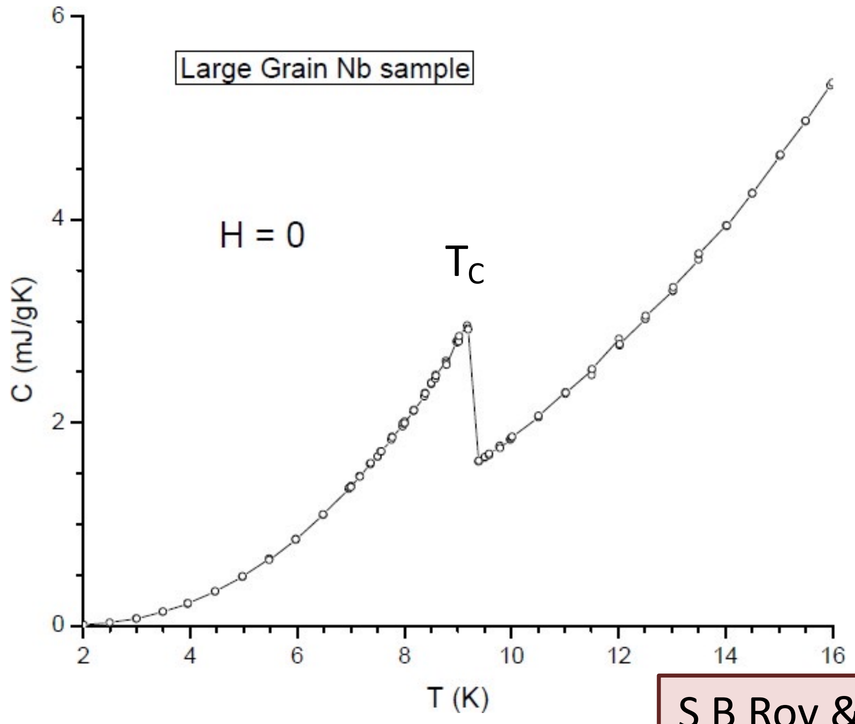


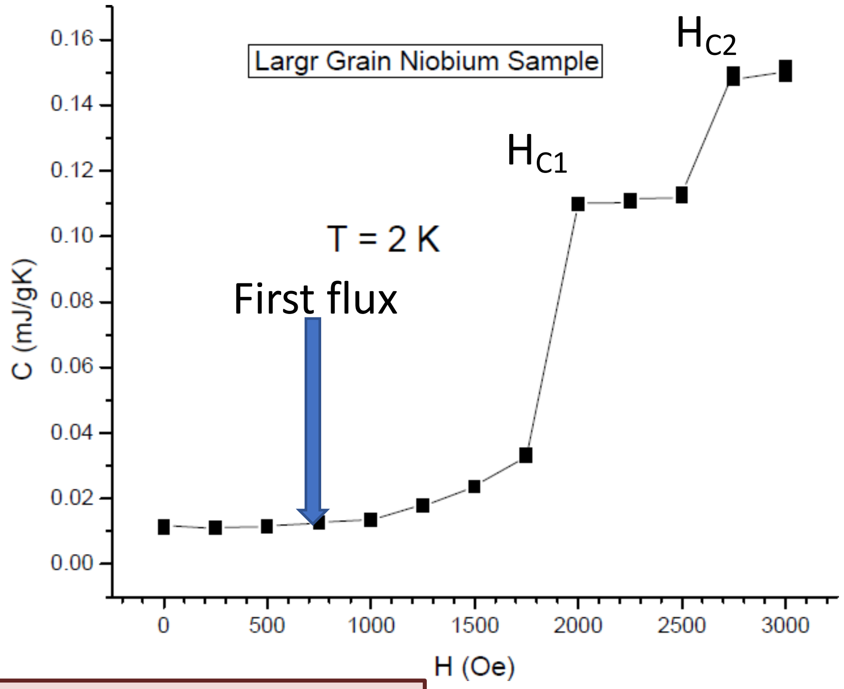
Nb yield strength as a function of annealing temperature



H_2 degasses at ~ 600 °C with out changing the grain structure

Temperature and magnetic field dependence of heat capacity of superconducting large grain Niobium

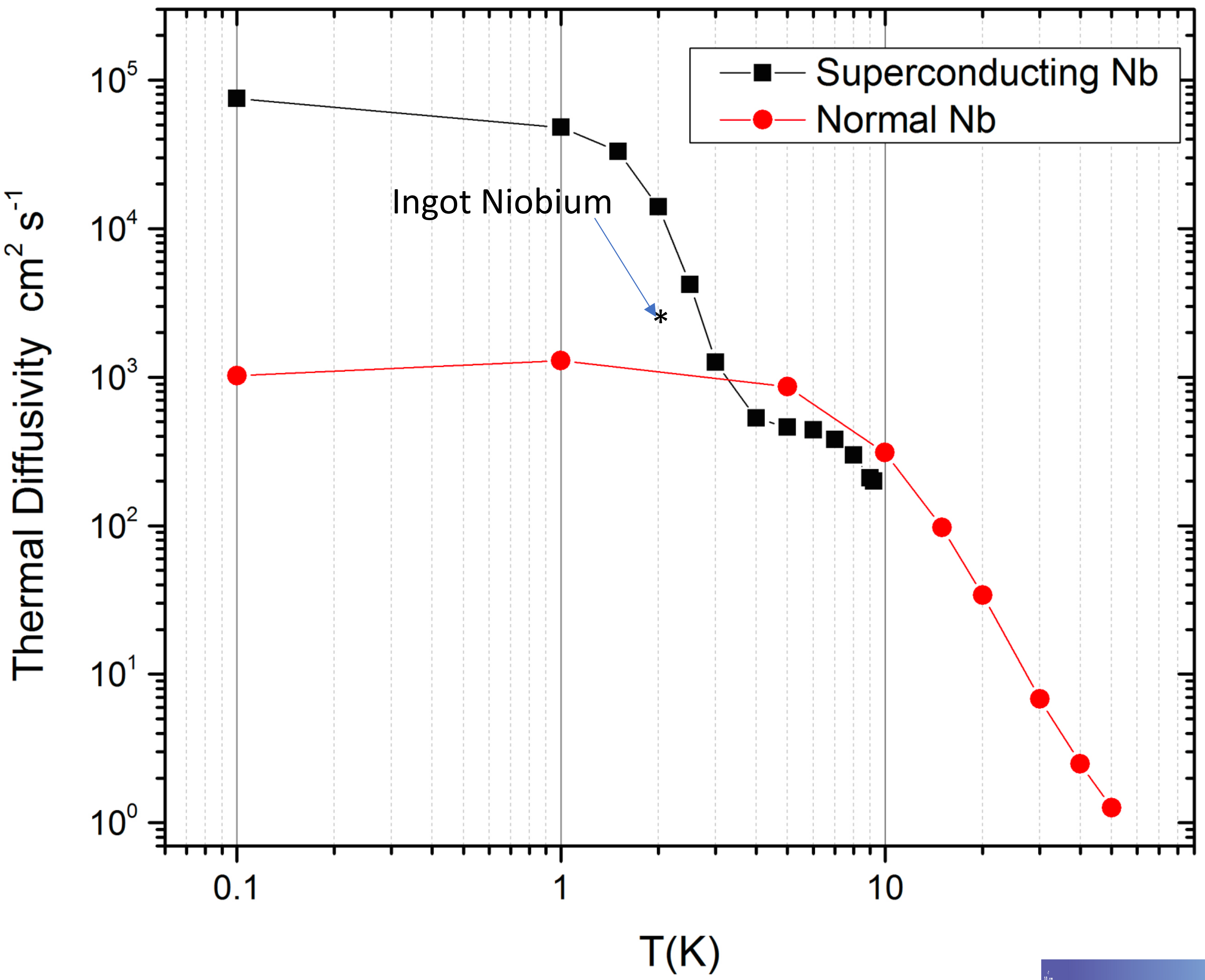




S B Roy & G. Myneni (unpublished)

During cavity operation heat is deposited in the sc layer of ~60 nm τ (1.5 GHz) ~ 6.6×10^{-10} s

Thermal diffusivity$_{2K}$ α_{2K} ~ $k/\rho C$ = 2333 cm^2 s^{-1}



Myneni Ganapati, KEK, Ibaraki, Japan Oct 17, 2022

International Symposium On Hydrogen In Matter (ISOHIM) Publications

Hydrogen in Materials and Vacuum Systems AIP CP 671
http://www.virtualjournals.org/dbt/dbt.jsp?KEY=APCPCS&Volume=671&Issue=1

Hydrogen in Matter AIP CP 837
http://www.virtualjournals.org/dbt/dbt.jsp?KEY=APCPCS&Volume=837&Issue=1

Single Crystal Large Grain Niobium AIP CP 927
http://www.virtualjournals.org/dbt/dbt.jsp?KEY=APCPCS&Volume=927&Issue=1

Superconducting Science and Technology of Ingot Niobium AIP CP 1352
http://scitation.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1352&Issue=1

Science and Technology of Ingot Niobium For Superconducting Radio Frequency Applications AIP CP 1687

https://aip.scitation.org/toc/apc/1687/1?expanded=1687

ADS&ThU International Workshops

1st International ADS&ThU Workshop 2010, USA

http://www.phys.vt.edu/~kimballton/gem-star/workshop/index.shtml

2nd International ADS&ThU Workshop 2011, India

http://www.ivsnet.org/ADS/ADS2011/

3rd International ADS&ThU Workshop, 2014, USA

http://adsthu.org/index.html

4th International ADS&ThU Workshop 2016, UK

https://indico.cern.ch/event/509528/contributions/

5th International ADS&ThU Workshop 2019, Belgium

https://events.sckcen.be/event_website_pages/view/5c87a995-edd4-4c2e-9c19-041f0a340409/5c87a990-a15c-4fa4-946c-041f0a340409/9f207fff04

6th International ADS&ThU Workshop, July/August 2023, Hawaii, USA

Academics & Industrialization

- 12 PhD thesis and 2 MS thesis co-advisor - HBNI, IITM, NCSU, ODU, Soton U & VCU - 12 Patents on accelerator technologies
- Established International Symposium On Hydrogen In Matter not for profit Virginia Corporation which supports grad and post docs attendance at conferences and also hosts ISOHIM's and ADS&ThU International Workshops.
- Created informal VA ADS Consortium, at the suggestion of late Prof. Srikumar Banerjeee (former Chairman of Indian Atomic Energy Commission & Secretary Department of Atomic Energy – Govt. of India) to foster US-India Nuclear Energy Partnership, while at UVa serving as Associate Director of HBNI and UVa Collaboration. A precursor to VNECA & VNEC.
- SRF Fellow on Phased Retirement at Jefferson Lab.
- CEO and President of BSCE Systems Inc. a Virginia Corporation, which has ~$5M angel investment commitment but require additional $25 M to develop the first VA ASMR with medical isotope applications.
- BCSC Systems and Taurus teleSYS team represents Virginia's proven rapid prototyping engineering experience of over 100 years

International Symposium on Hydrogen in Matter (ISOHIM)

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2. “A Comparison of Outgassing Measurements for Three Vacuum Chamber Materials” M.L.Stutzman, P.Adderley, B.M.Poelker, M.Baylac, J. Clark, A.Day, J.Grames, J.Hansknecht, G.R.Myneni, P.M.Rutt and C.K.Sinclair in International Workshop on Hydrogen in Materials and Vacuum Systems , edited by G. Myneni and S. Chattopadhyay, AIP Conference Proceedings

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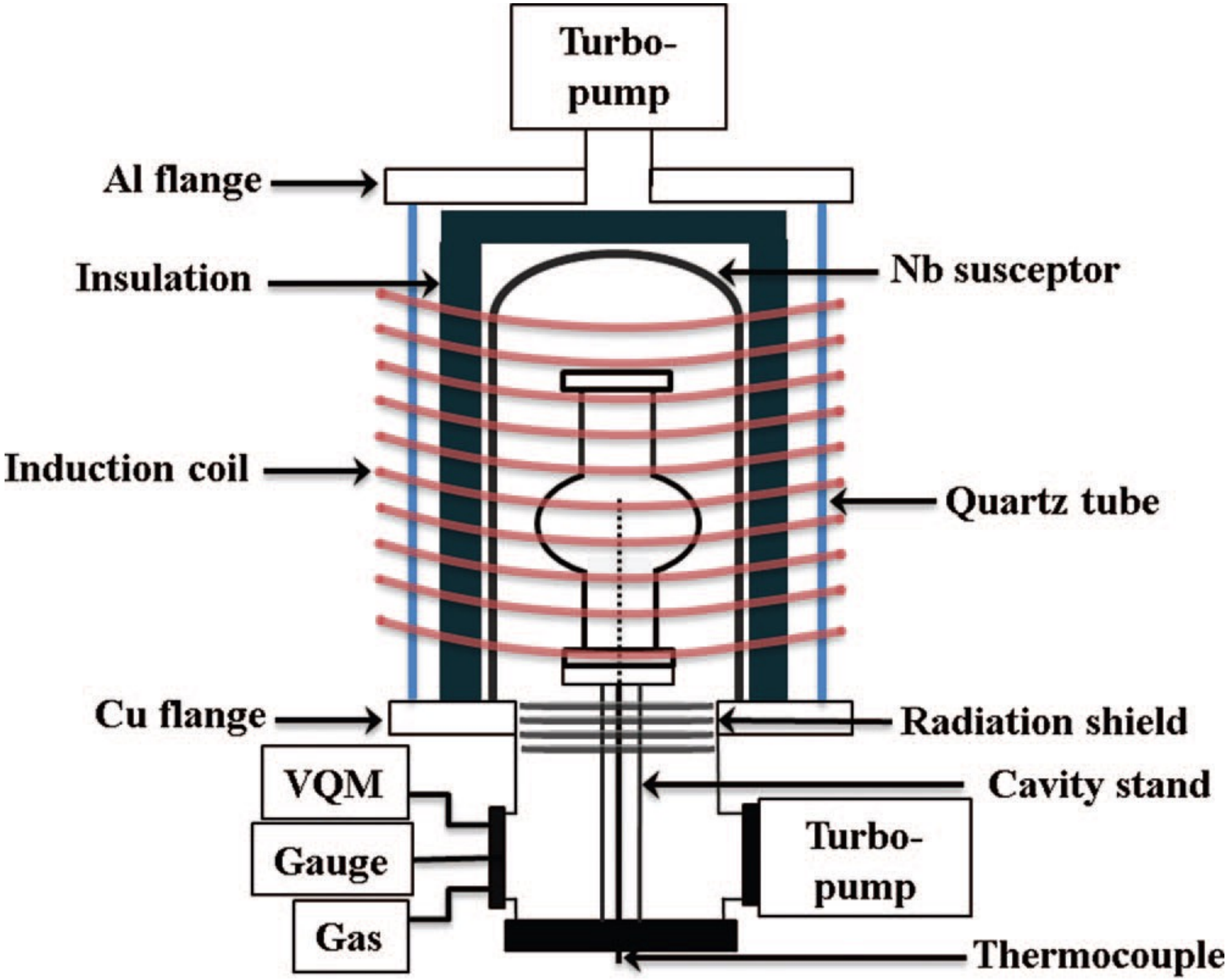
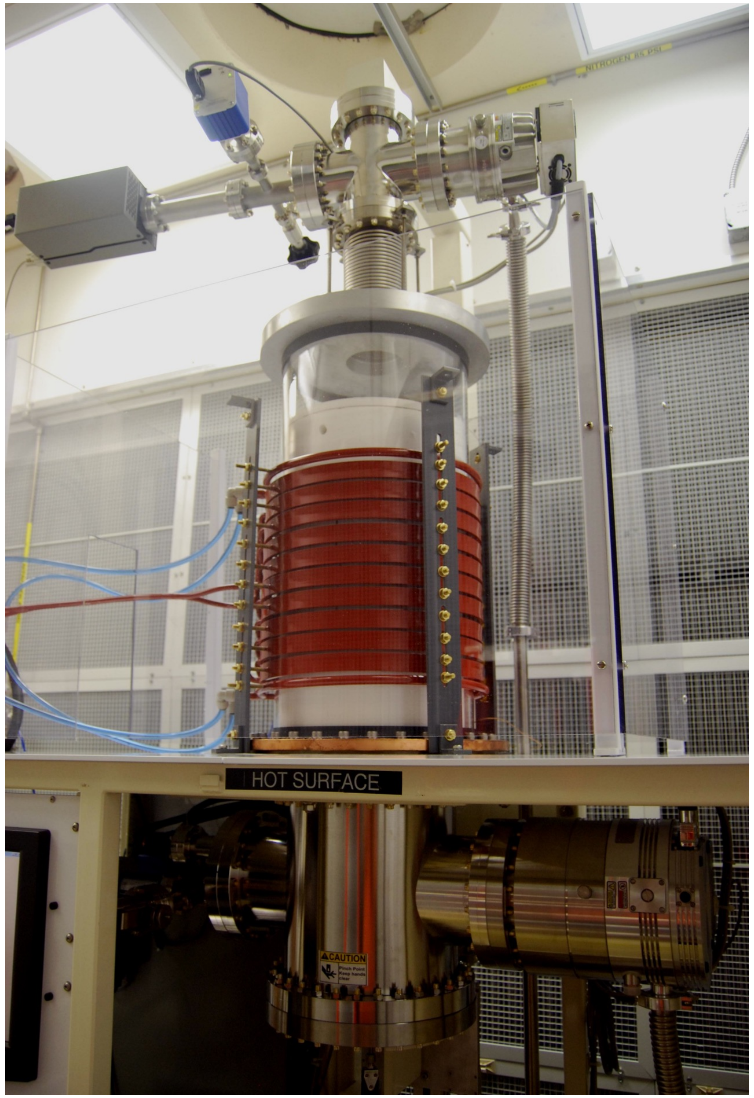
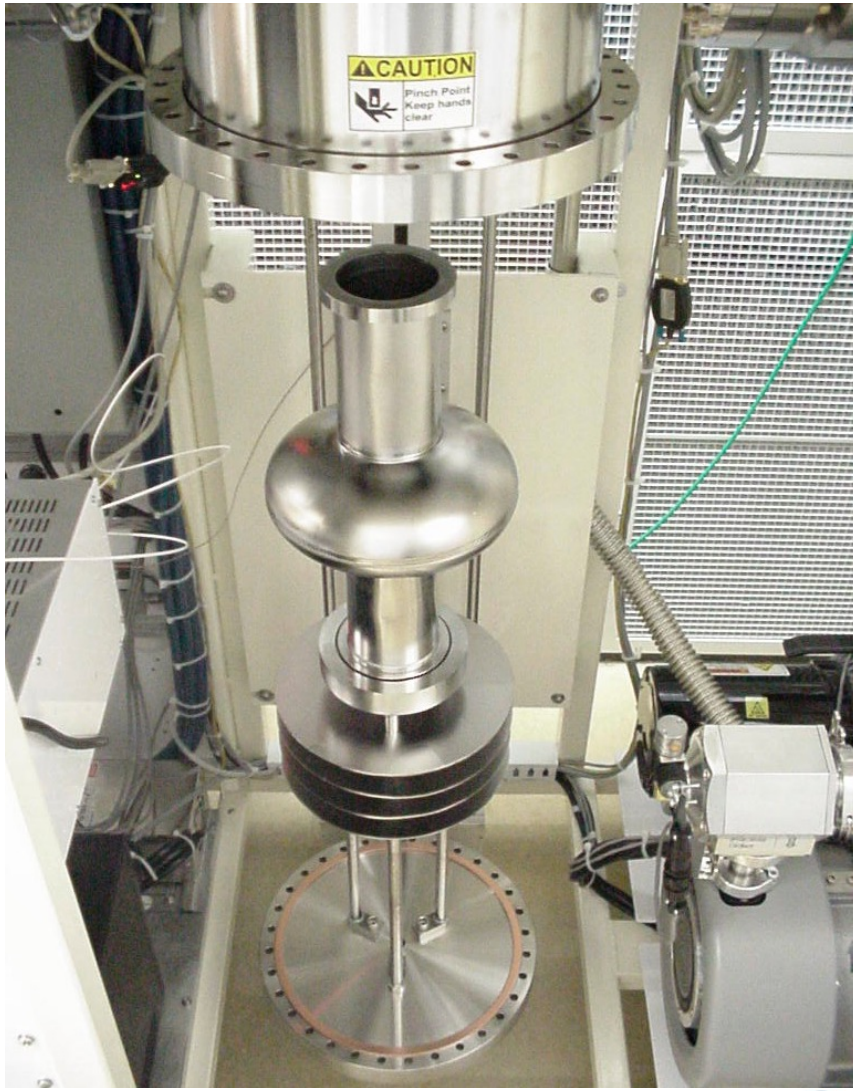
Schematic of ultra clean induction furnace



Clean UHV furnace – US patent issued





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