Quantum Materials / Molecular and Materials Science

Presentation (G. Luke)

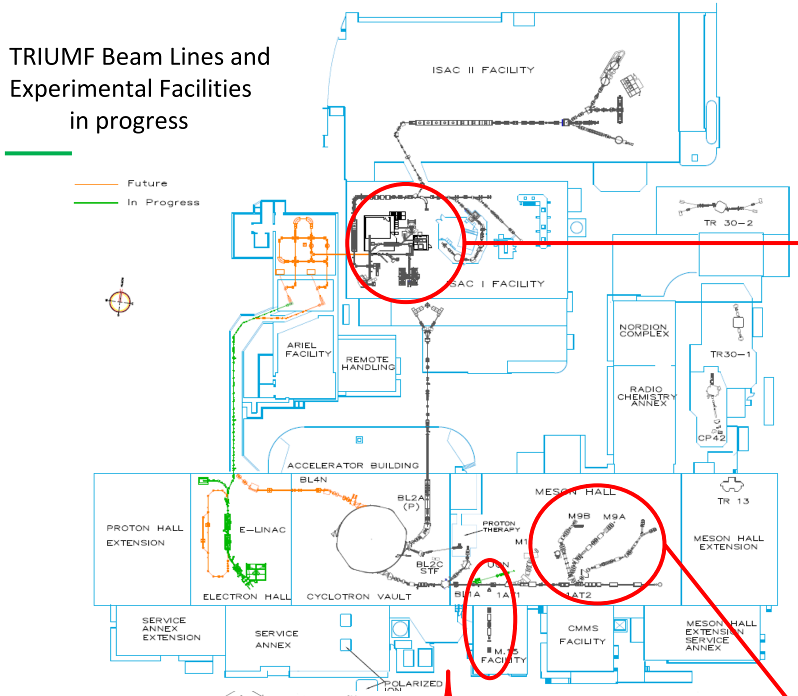
- Current facility projects
- Proposed developments

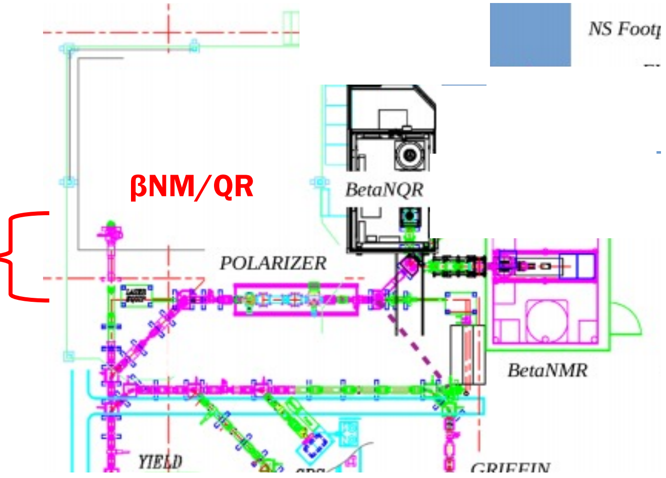
Discussion

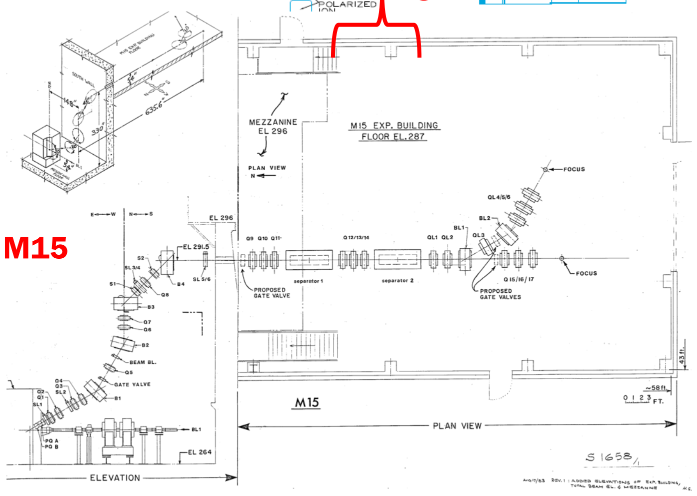
Green technology (I. McKenzie, K. Ghandi, K. Kojima)

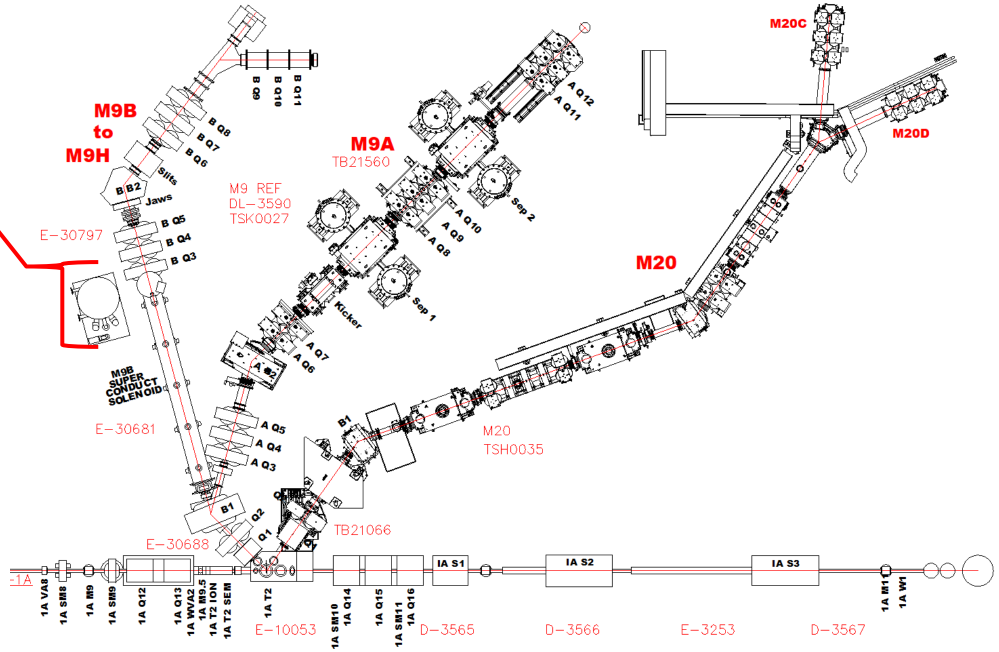
Discussion

TRIUMF CMMS Current Beamlines





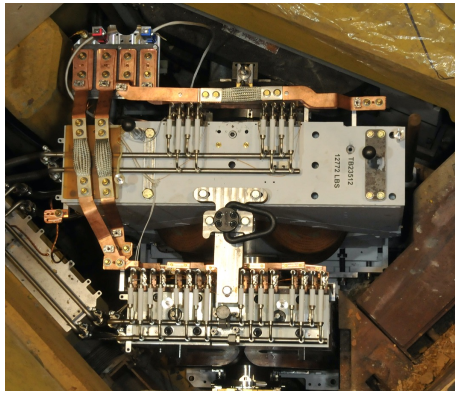




Status of Active CMMS Projects: Summary

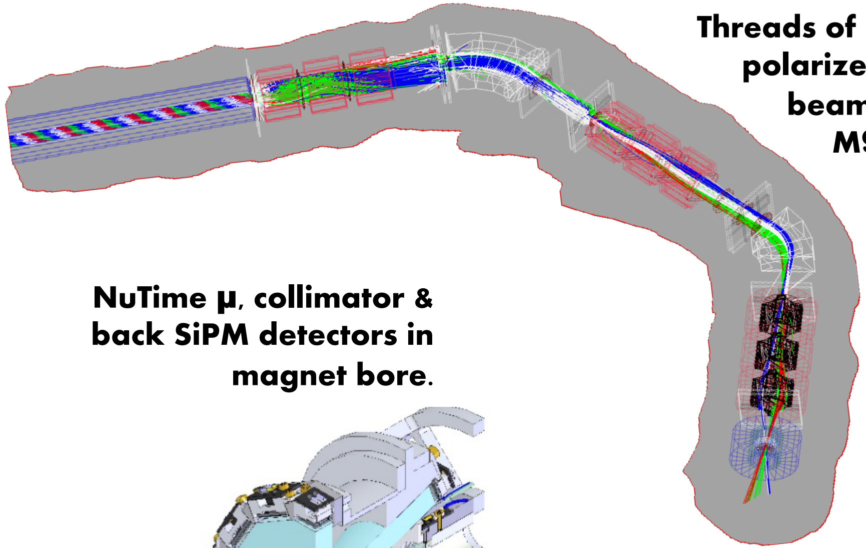
i. M9A: Beamline, optics and control systems complete.
Testing of slit control elements in progress. Separator conditioning pending.
Optics simulations indicate high luminosity small (5mm^2) sample tunes.

ii. Expanding Muon Beam Lines at TRIUMF (i.e. M9H):
CFI approved as of Nov. 2017 for the full $10.7M. Project well underway: Solenoid/DQ3 under construction. **Gate 3 review competed.** ITTs for remaining major components (DR, exp Magnet) due May 2022. Optical design indicates high luminosity tunes for transverse polarization.
DQ3 slit design optimizations being evaluated.



Looking down onto the new M9 Q1-Q2 installed in the FE pit

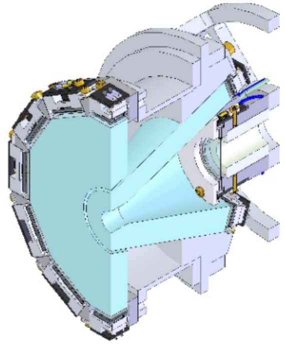
iv. 3T/M9H Spectrometer Developments:
Mark III/IV of μ+/e+ SiPM front-end achieves 200ps timing resolution with beam -> a new generations of general purpose MuSR detectors.
Evaluation of new configurations, i.e. summing amplifiers deployed in the magnet.



Threads of polarized beam in M9H.

iv. 7T NuTime Spectrometer:
Unparalleled μSR Knight shift precision; ~3ppm @ 7T.
New “fat pipe” ^{4}He cryostat forSiPM based detectors tested to 2.5K
“In beampipe” SiPM design of muon, veto and back counters, continue to advance.

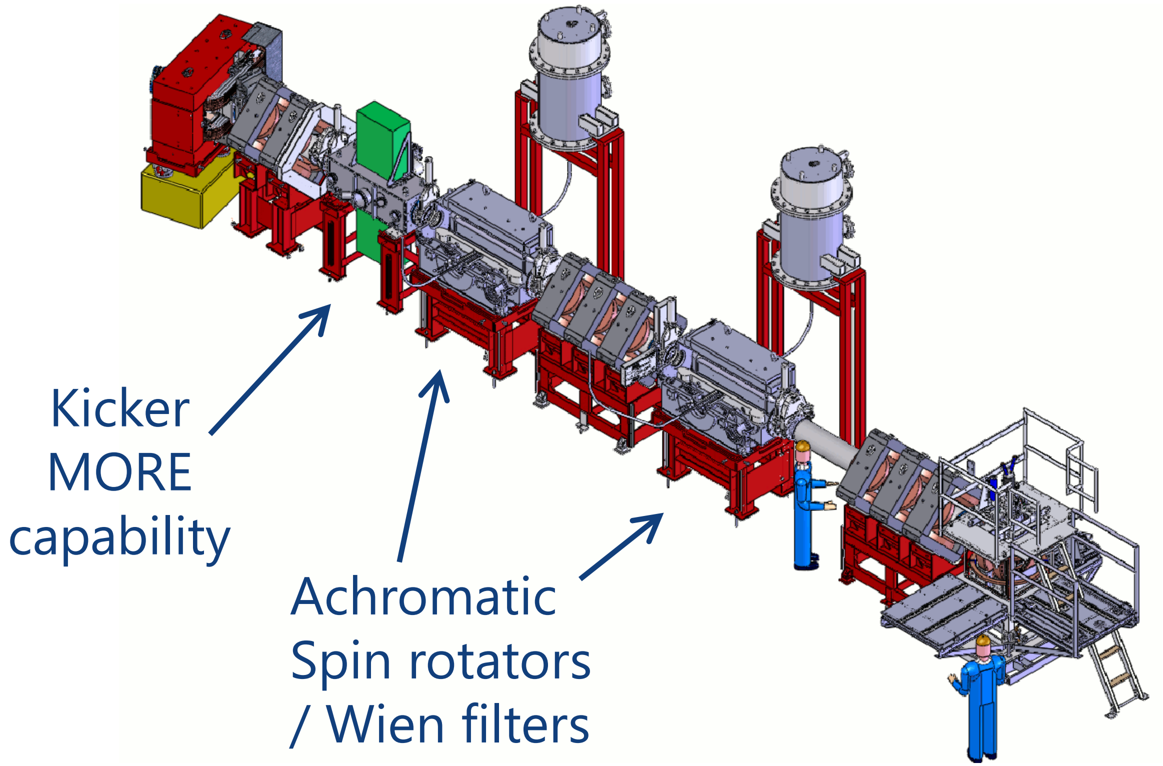
NuTime μ, collimator & back SiPM detectors in magnet bore.



vi. ^{3}He cf/.5K cryostat: RTI funded. Delayed by fabricator, ETA mid 2022

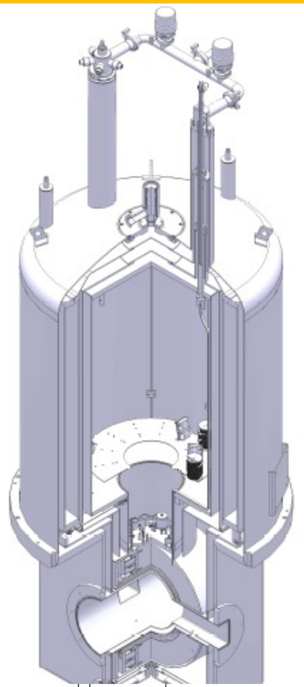
vii. βNQR upgrade:. Completed. Initiates βNRM experimental capability for polarization || Sample face -> direct Meisner Effect sub-surface sensitivity in Nb cavity material.

M9A almost ready to Roll, or rather Spin

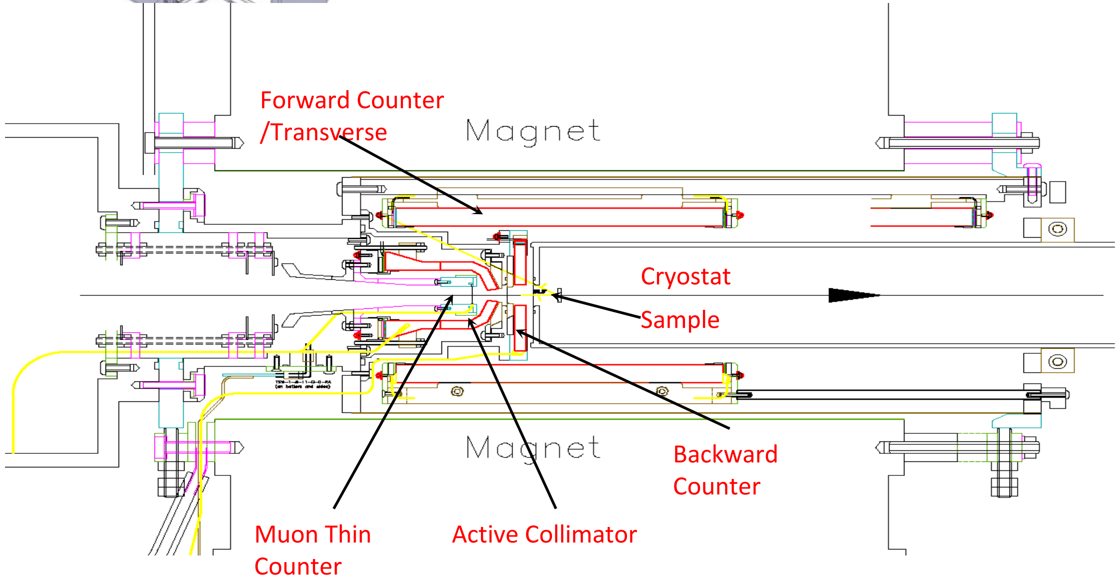


To do or done:

- Final polarity check for quads, slits operational ✅
- Publish a commissioning plan ✅ / safety docs ✅
- Condition Spin Rotators/Separators
- Establish low intensity tunes
- Initiate safety surveys as beam intensity grows
- Tune for high intensity … install existing DAQ system



- 3T Oxford dual bore access “M9“ superconducting magnet
- Design well advanced but COVID slowed



Scheduling of M9A

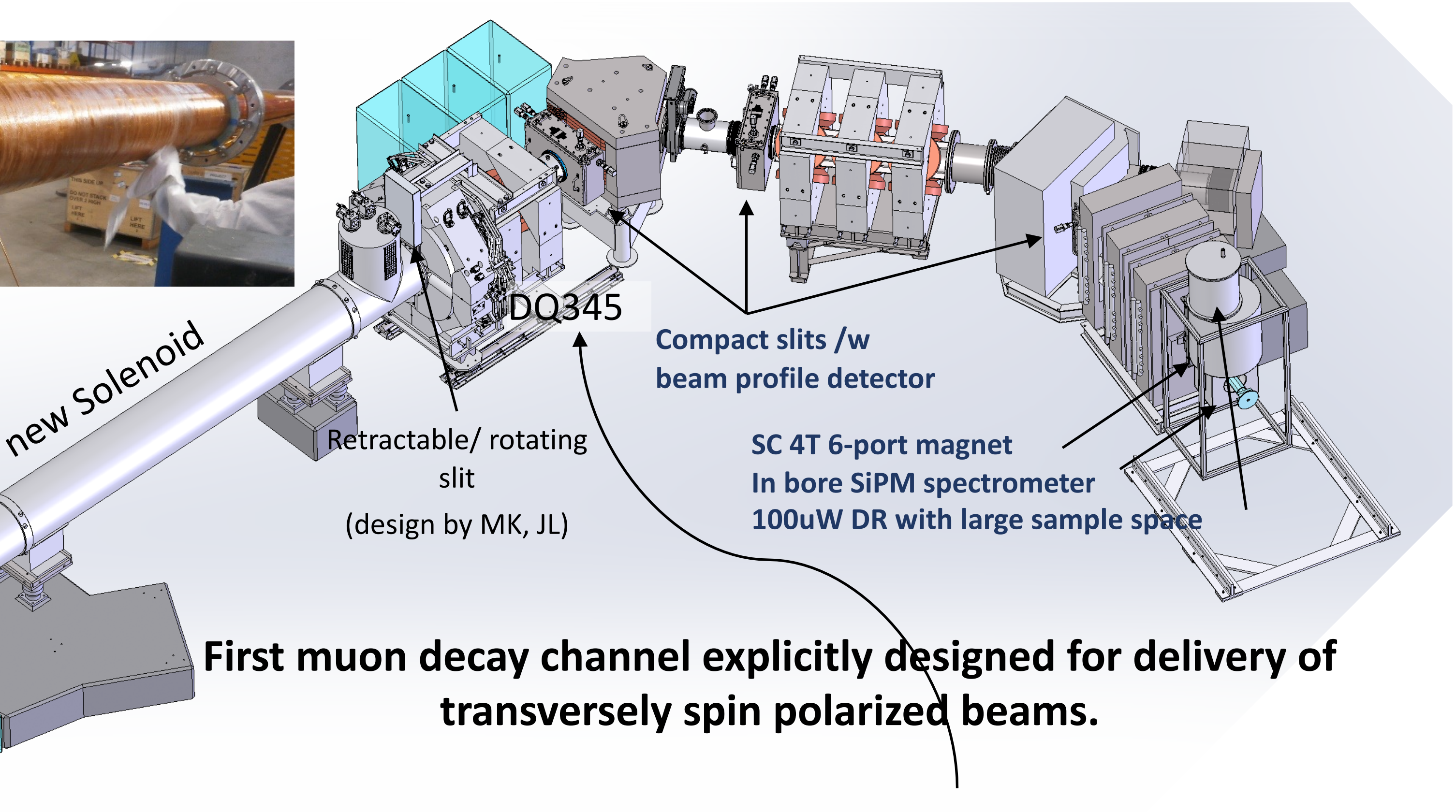
Dates	Shifts	M9		M15		M20		ISAC	
(incl)	(8 hr)	Expt.	Appar.	Expt.	Appar.	Expt.	Appar.	Expt.	Appar.
30 May a (22) 7 Jun a	20	---	---	2180/2147/2215 GML,CLB	DR	S2129 JIC		---	---
7 Jun p (23) 14 Jun a	20	"	"	1862 JES	"	2151,2146 GML	Lampf	"	"
14 Jun p (24) 21 Jun a	20	"	"	2147/2180 GML	"	2210,2219 KK,YU	"	"	"
21 Jun ☽ (25) 28 Jun a	19	"	"	2160/2161 YC,KK	"	2219,2212,2157 KK,YU	"	"	"
5 Jul p (27) 12 Jul a	20	"	"	2210 KK,YU	"	2206 IW	Helios	1945/2220/2101 IDM/SRD/WAM	β-NMR / β-NQR
12 Jul ☽ (28) 19 Jul a	19	"	"	2212/2207 MG,YU/KYC	"	2192 IDM	"	---	---
20 Jul ☽ (29) 26 Jul a	16	"	"	2208 BAF	"	2021,2178 SI	"	2220/L131 SRD/MS	β-NMR / pol
26 Jul p (30) 2 Aug a	20	"	"	2156 KK	"	2125,2166 IDM	"	---	---
2 Aug ☽ (31) 9 Aug a	19	"	"	2146 GML	"	2014/2015 PWP	"	β-NMR	β-NMR / β-NQR
9 Aug p (32) 16 Aug a	20	"	"	2185 TH	"	2126 IDM	"	---	---
16 Aug p (33) 23 Aug a	20	"	"	1915 JES	"	2207/2221 KYC/AMH	Lampf	"	"
23 Aug ☽ (34) 30 Aug a	19	"	"	2221/TBA AMH/?	"	1612 REL	HodgePodge	"	"
6 Sep p (36) 13 Sep a	20	"	"	2153 YC	"	TBA	Lampf	"	"
13 Sep ☽ (37) 20 Sep a	19	"	"	2179 KK	"	1957/2176 MM/JS	"	"	"
20 Sep p (38) 27 Sep a	20	"	"	2143/1906 YS/MM	"	2176/2177 JS	"	"	"
27 Sep p (39) 3 Oct a	17	"	"	1906 MM	"	2152 KK	"	"	"

PIF

PIF

- Tight beam schedule with only M15 and M20.
- Maximize efficiency.
- Proposal to schedule free blocks on M9A (~20% total) for short rapid access experiments (2 days max).
- Support for remote experiments by TRIUMF staff.
- Remainder (~80%) for longer experiments (5 days +) through MMS-EEC.

M9H: Reinventing the Muon Decay Beamline: CFI/etc funded



First muon decay channel explicitly designed for delivery of transversely spin polarized beams.

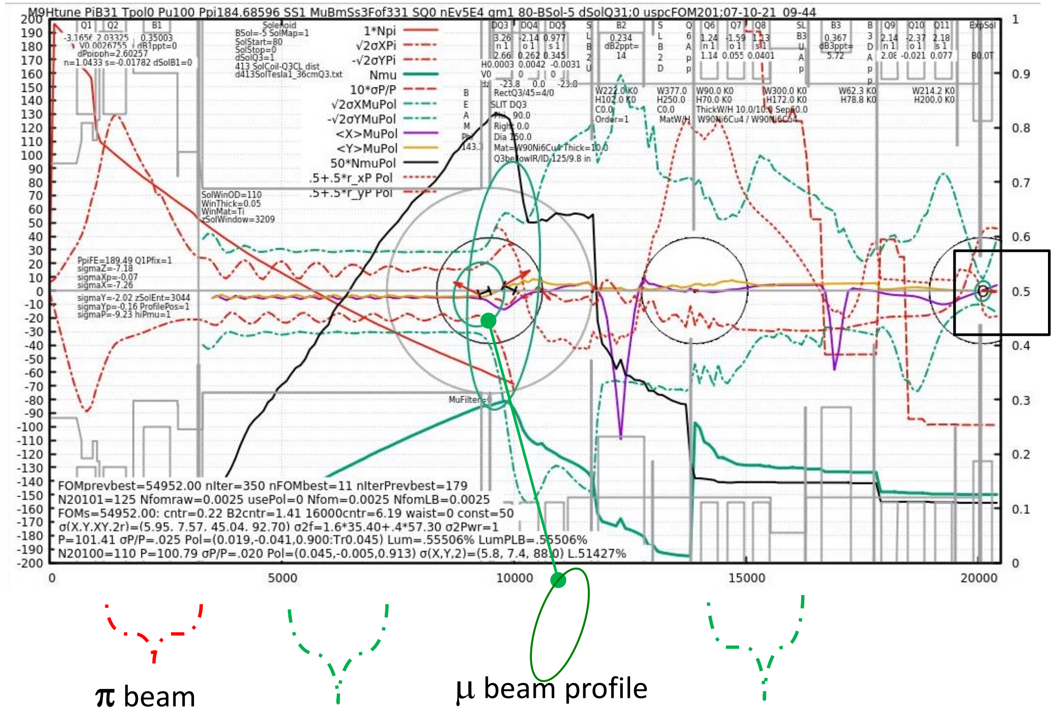
M9H Solenoid compared to previous M9B version:

- 5T recondensing RT-bore solenoid, operates in persistent mode wit a robust 10hr hold time during total power loss or interruption
- Routine operations, semi-automated cool downs
- Awarded to Tesla Engineering, U.K

Post Solenoid Triplet:

- Quad placement very tight to solenoid exit to capture beam “phase space”.
- Triplet encompasses strong horizontal and vertical steering capabilities to collect off-axis spin polarized muons

"Unconventional" Tuning Paradigm extended to M9H
Decay Muons: both LF (below) and TF polarizations benefit



π beam injected into solenoid

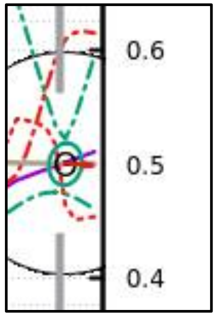
Decays into μ beam in solenoid

μ beam profile exiting solenoid, sigmaXY=750

Simplex tune paradigm utilizes the excess beam intensity loses during transport to reduce final beam spot area.

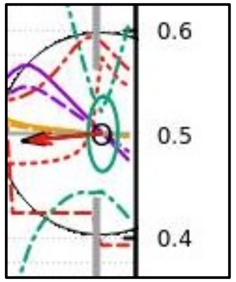
Deploying slits on a previously "luminosity" simplex tuned beam, and reoptimizing ->

Ratio of beam stopping in the sample / cell walls increases by ~ order of magnitude.



sigmaX =5.8mm
sigmaY =7.4mm
sigmaXY=43mm²

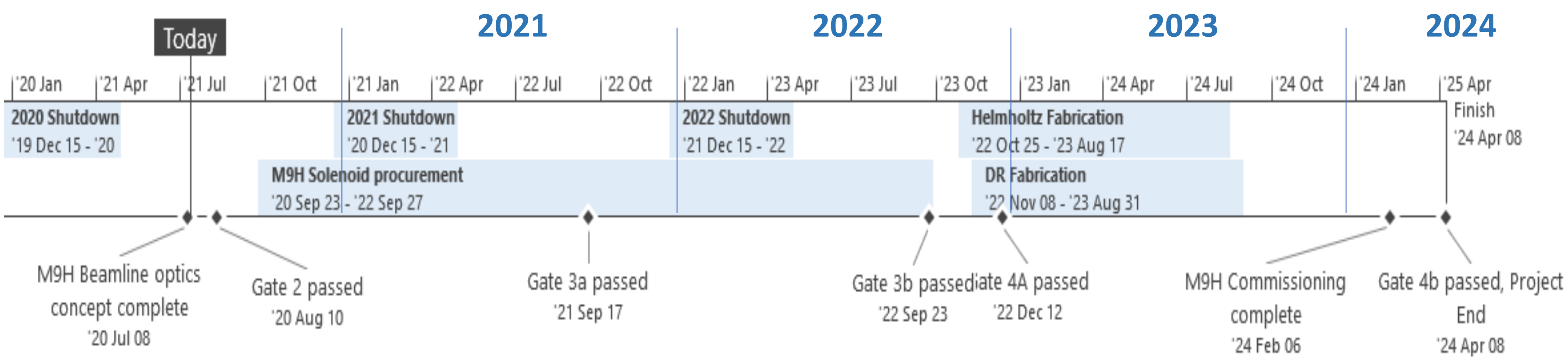
LF polarized beam spot reduction factor = 4;
Luminosity loss ~ 0%



sigmaX =5.5mm
sigmaY =14.5mm
sigmaXY=82.6mm²

TF polarized beam spot reduction factor = 3;
Luminosity loss = 18%

The M9H – Schedule



Shutdown 2020-2021	Rest of 2020-2021	2022	Shutdown 2022-2023
- Removal of: • M9B Solenoid • Q345 quad for upgrade • Other Q345 section equip. • Q678 section equip. • Q91011 section equip. - Backfill void spaces - Survey area and services	- Beamline detailed design - Exp. station tenders - Commence beamline implementation • AC upgrades • Power supplies • Controls (PLC/EPICS) • DAQ	- Continue implementation of beamline sections - Exp. station detailed design	Install: • M9H solenoid group • Upgraded Q345 section • Upgraded Q678 section • Q91011 section • Services • Vacuum system

Short- and Long-Term Mitigation of LHe Supply Crisis

- TRIUMF has committed to keep current programs intact with a short term policy of accepting spot-price purchasing LHe.
- Increased demand for LHe from UCN.
- The CMMS is about to place orders for a new 4T magnet and a DR for M9H. Equipment which can support He conservancy, i.e. dry and/or recondensing systems will look more attractive..
- The value of beam time has always ”driven” considerations related to cryogenic equipment. i.e. a cryogenic technology that maximized “experimental beamtime”, i.e. fast sample changes, was considered the “best” choice.

  The new (possibly recurring?) circumstances regarding He availability force us to change the choice paradigm from:

  maximum beam time / per run → maximum beam time / per year

- Fortunately, industry has recognized this with new products:
- TRIUMF should strive to maximize on-site He storage capacity:
  - ➢ Opportunistically fill the current high-pressure 3300L storage
  - ➢ Consider increasing the storage infrastructure to 4400 L (i.e. an additional high pressure tank.)

i.e.

- Designed to take a **large experimental heat-loads**

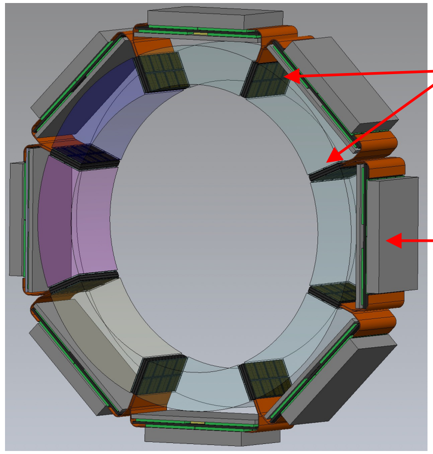
- Provides **fast sample exchange time:** t<20 minutes RT to <2.0K.

- but: **Initial cool down 15-24 hrs**.

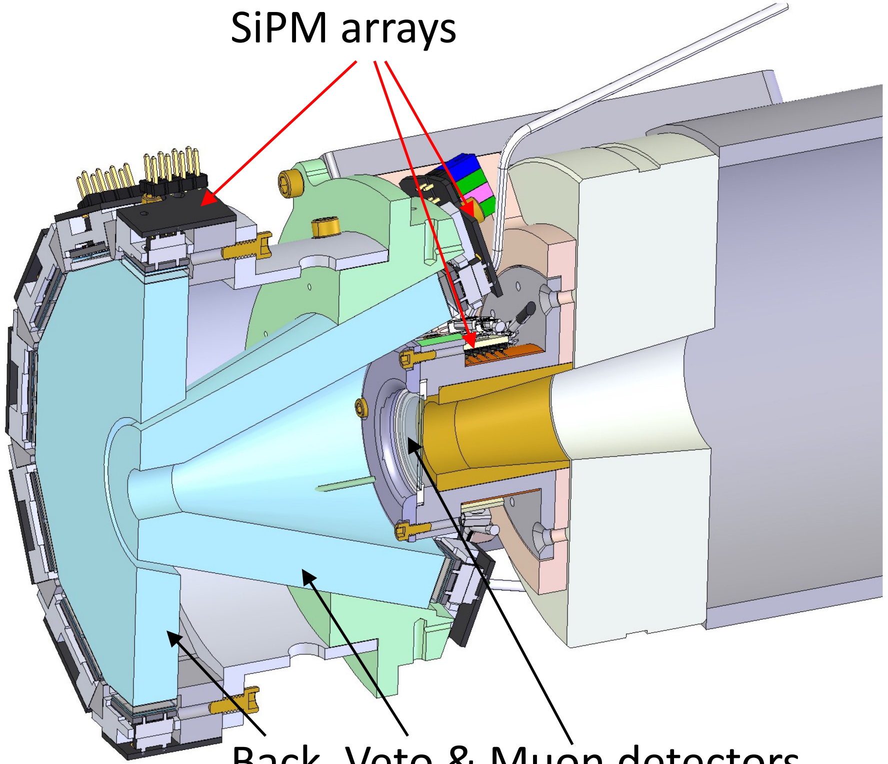
Status of Active CMMS Projects: Detector R&D

Progress with new generations of spectrometers with SiPM Detectors:

- Using compact avalanche diode “Silicon photo-multiplier detectors instead of the old standard PMTs off many advantaged
  - smaller
  - operate in high magnetic fields, i.e. >
  -> no light guides needed
  -> superior timing
  -> more scientific impact



Transverse high timing resolution detector set for M9H spectrometer



Detector set for NuTime spectrometer, being built in the Scintillator Shop

THErAPIE: BL1A CFI Submission (July 15, 2022)

- TRIUMF High-Energy Accelerator Proton Irradiation Experiments)
- BL1A replacement to support isotope production and μSR
- Total Project Costs: $28,254,267
- CFI Request: $9,730,480
  - Beamline elements: $9.4M
  - Remote Handling & Shielding: $1.9M
  - Isotope Production Facilities: $3.9M
  - Muon Spectroscopy Endstations: $2.5M
  - Distributed Radioisotopes for Theranostics: $2.4M
  - Personnel: $7.9M

THErAPIE: Applicants and Matching Funds

- University of British Columbia
- McMaster University
- University de Montreal
- University of Guelph
- University de Sherbrooke
- TRIUMF
- St. Joseph's Healthcare (London)
- University of Saskatchewan
- Simon Fraser University

+ long list of other users

BKDF	$4.5M
Ontario Research Fund	$3.85M
Quebec Provincial	$0.55M
Innovation Saskatchewan	$0.33M
University of British Columbia	$1.5M
BWXT	$3.85M
TRIUMF	$5.07M

20 Year Vision and 5 Year Plan

20 Year Vision

- A world-class accelerator centre driving use-inspired research—from the life sciences to quantum and green technologies
- A national innovation hub translating discovery science into health and sustainability solutions
- An inclusive multidisciplinary talent incubator, attracting and developing the best people from around the world

CMMS

- Advance Quantum Technologies:
- Enable green technology solutions:
- Engage with new complimentary initiatives:
- i.e. THz, CANS (Accelerator based neutrons)

5 Year Plan

- Realize the experimental capabilities of new muon and βNMR beamline infrastructure / beamtime.
- Establish new detector technologies, inclusive of increasing experimental automation.
- Proactively engage user groups: collaborations, outreach, new applications

Cohering with the TRIUMF 20 yr. Vision .. starting in this 5YP

New TRIUMF vision items … match new facility capabilities, i.e.

- M9H : ➔ new quantum materials / sustainability / battery research;
- M9A : ➔ hydrogen storage / new quantum materials;
- Increased βNMR beam-time (15 weeks vs 5) and/or experimental capacity :

  ➔ quantum materials / battery research

Manpower Requirements to turn TRIUMF Vision into Action

- New facility scientist with a specific “sustainability” and complimentary outreach mandate
- New facility scientist to enable and maintain a βNMR user facility.
- Additional technical staff:
  - dedicated to supporting the experimental infrastructure (customized and specific sample prep & environments) required to sustain the additional technical loads expected
  - Support for beamline and cryogenic maintenance … which increasingly is unavailable from historical TRIUMF resource groups

= 2 Scientists + 2 technicians ?

Materials Characterization and Computation Centre?

- Central facility for quantum materials
- Build on TRIUMF CMMS core competencies in μSR, βNMR and cryogenics and expand with new characterization tools
- Support researchers across Canada to access specialized equipment (SQUID, PPMS with low-temperature capabilities, + ?)
- DFT and related numerical calculations to support experiments (including muon and ^{8}Li stopping sites)

Desirability?
Feasibility?
Personnel?
Space?

Nuclear Hydroelectric Solar Wind

Energy Storage

TRIUMF's strength on Materials Science

Solar cell degradation:
water+heat+UV…

Muon provides
Hydrogen information

Rep. Prog. Phys. **72** (2009) 116501 S F J Cox

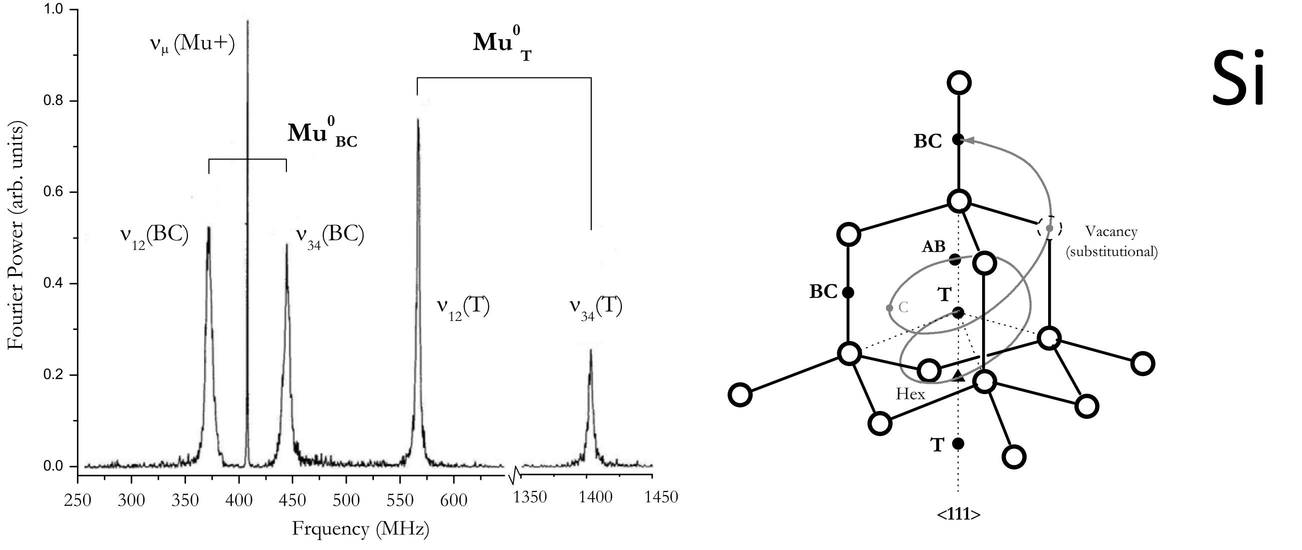
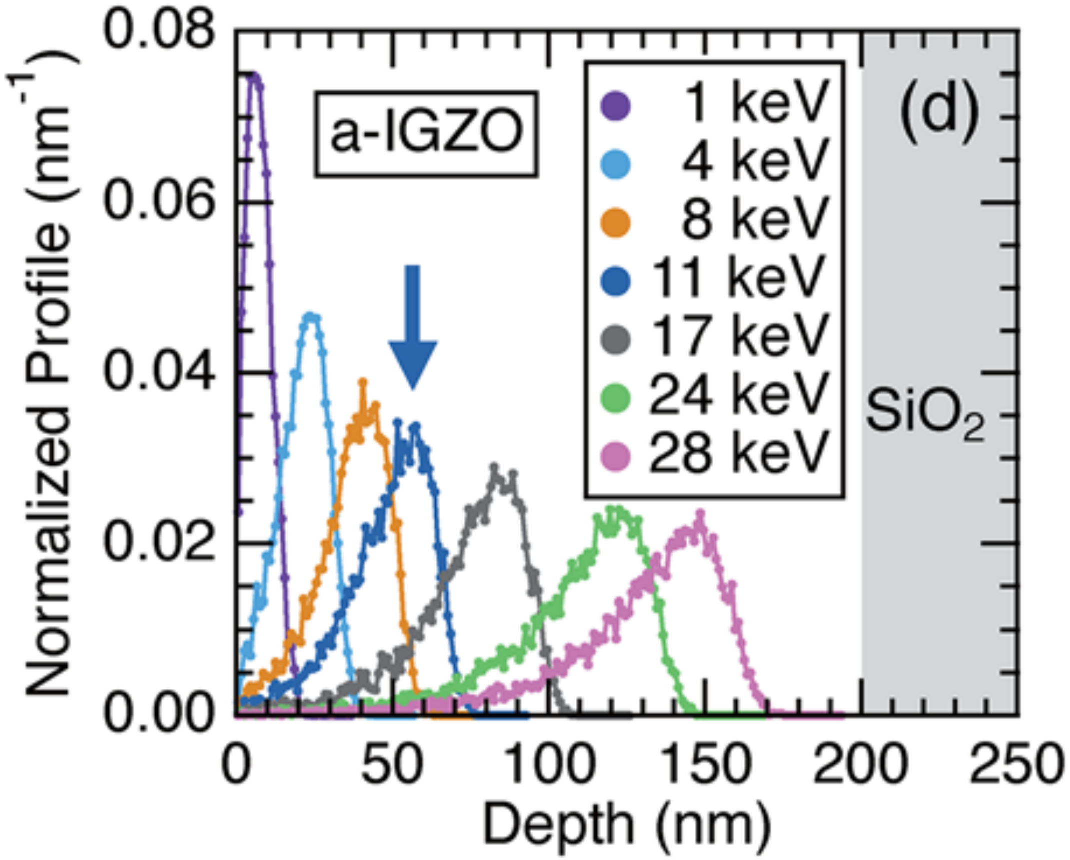


Figure 4. High transverse field μSR spectrum of $Si_{0.8}Ge_{0.2}$, showing hyperfine splittings for the two paramagnetic muonium states, bond centred (BC) and tetrahedral cage centred (T). Also seen is the Larmor precession for an electronically diamagnetic state, here labelled as the positive ion Mu^+. This is a TRIUMF spectrum recorded at 55 K by King *et al* (2005); $\nu_\mu = 407$ MHz in the applied field of 3 T—compare the original 10 mT Berkeley spectrum for Si by Brewer *et al* (1973)! In the paramagnetic muonium states, the hyperfine field

S.F.J Cox, Rep. Prog. Phys. 72 (2009) 116501 (review)

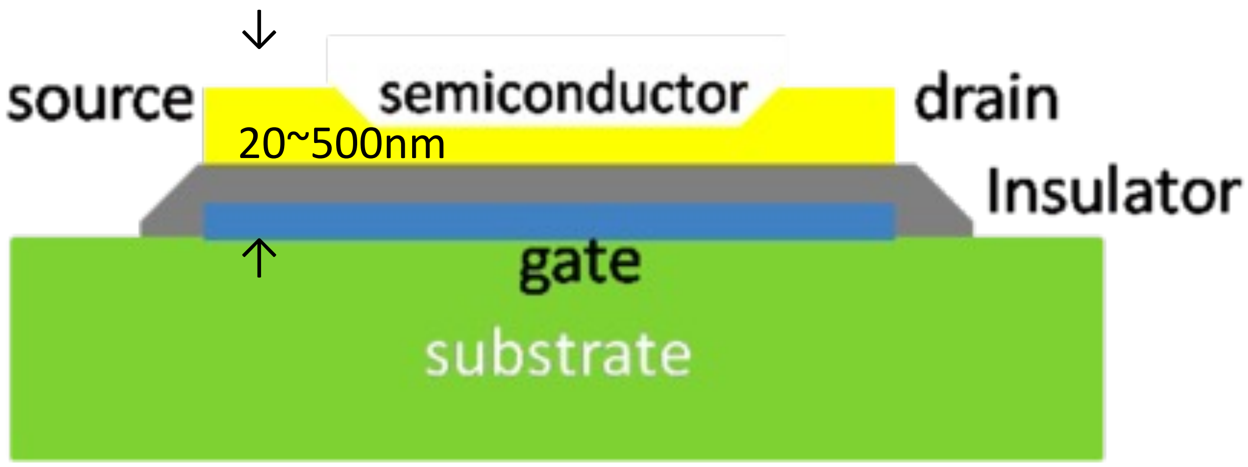
More conventional usage of Muons:
Magnetic probes for Quantum Matters,
such as Superconductors, Quantum Magnet, …

TRIUMF's strength on Materials Science



K.M. Kojima et al. Appl. Phys. Lett. **115**, 122104 (2019)
(PSI Low Energy Muon)

Thin Film Transistor (TFT)



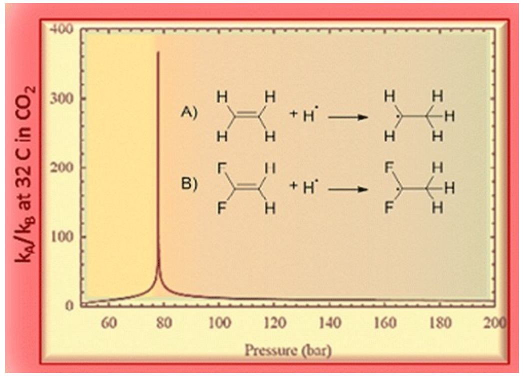
wikipedia.org/wiki/Organic_field-effect_transistor

β-NMR provides film information
in-situ device characterization (in future?)

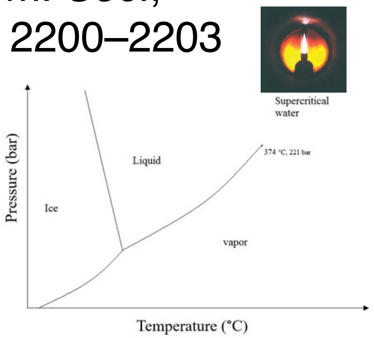
TRIUMF had a long history of contribution to green tech which dates to 2001:

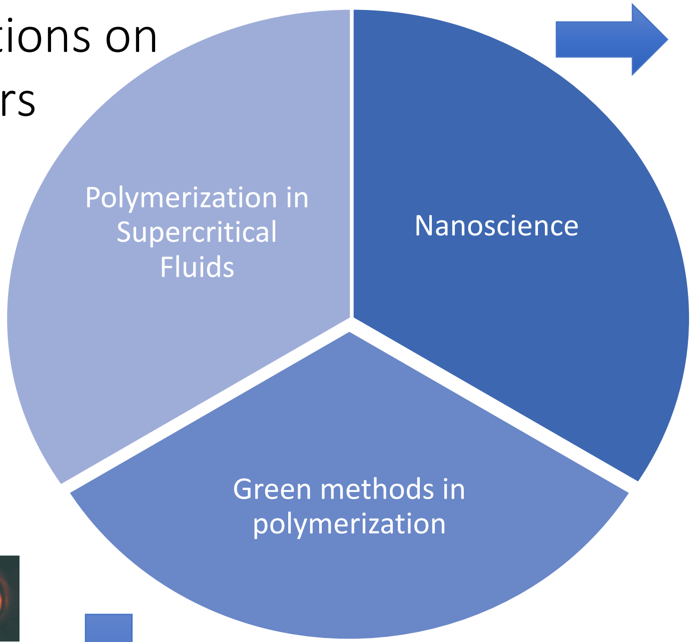
Experiment 943 Muonium and muoniated free radical formation and reactivity in sub- and supercritical carbon dioxide

Recently moved to applications on Nanomaterials and Polymers

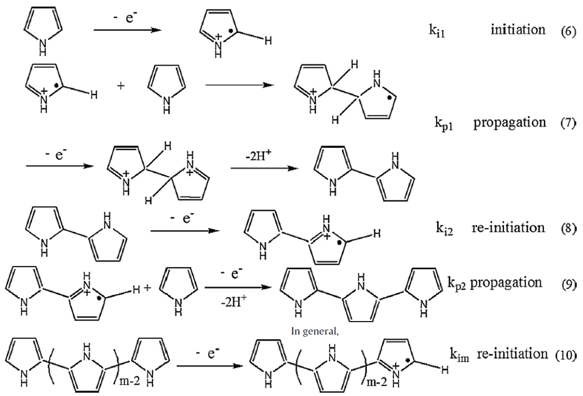


J. Am. Chem. Soc., 2014, 136, 2200–2203

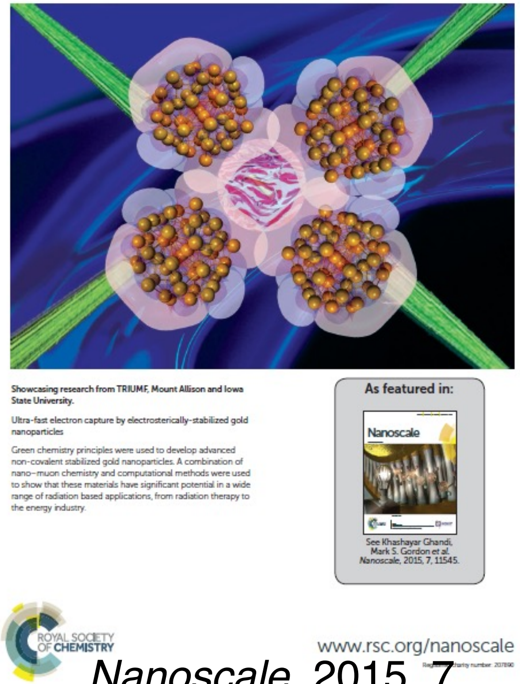




Synthetic Metals 2013, 175, 183– 191



How to make nanocomposites for biosensing, agriculture & medical applications with minimal harm or ideally benefit to the environment?

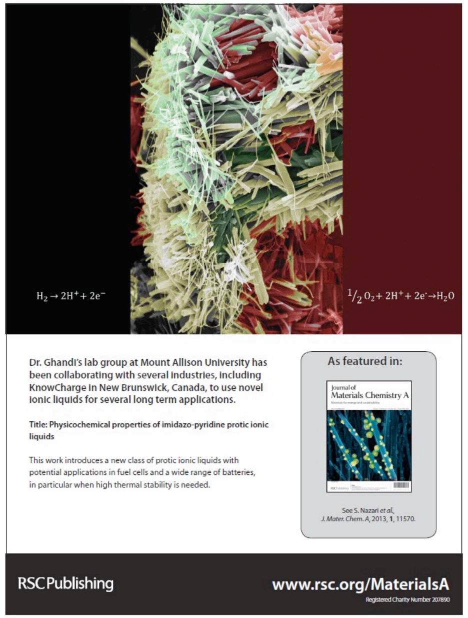


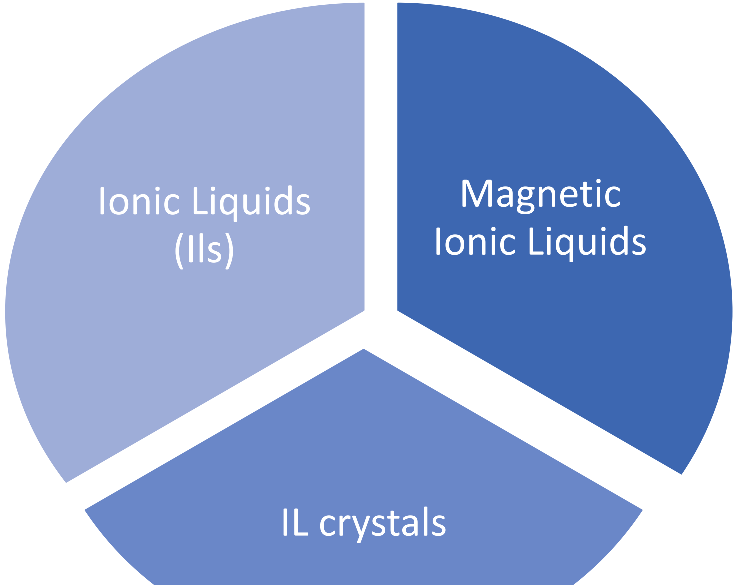
Nanoscale, 2015, 7, 11545-11551

The mechanisms of polymerization and using it to develop sustainable polymerization processes for health (Antimicrobial) & environmental industry

Fundamental science nourished applications and innovations

Fate of molten salts (ionic liquids) in Batteries and as Reagents for green technologies

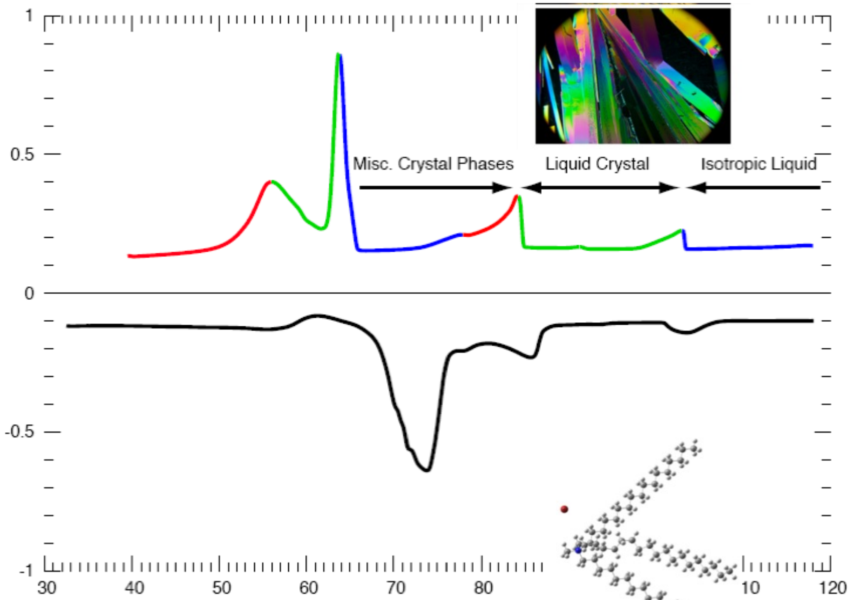




New magnetic nanomaterial for medical and industrial applications

Magnetic Nanocomposite Material and Processes, US Patent, 06.12.2012, H01F 1/42, 13484898, Inventors: Khashayar Ghandi, P. Themens

J. Mater. Chem. A, 2013, 1, 11570



Polymeric Ionic liquid crystals

From 2006 my NSERC DG has been on beta decay probes of green tech: Effect of green solvents on chemical reactions and material formation: characterization of transient intermediates

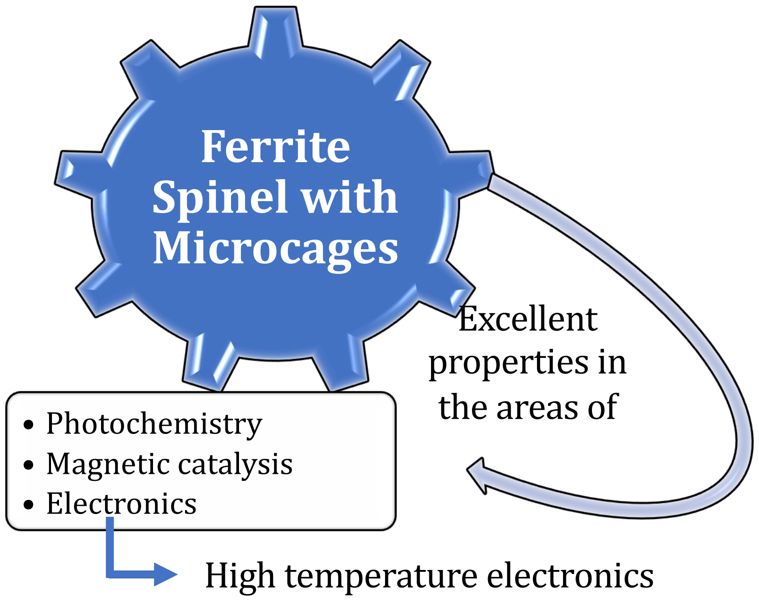
Gen IV Nuclear Reactors: important source of clean electricity; a valuable supply towards net zero

	Neutron Spectrum	Coolant	Temperature (°C)	Pressure	Fuel Cycle	Size(s) (MWe)	Uses
GFR	Fast	He	850	High	Closed	1200	Electricity & Hydrogen
LFR	Fast	Pb or Pb-Bi	480–800	Low	Closed	20–180 300–1200 600–1000	Electricity & Hydrogen
MSR	Thermal or Fast	Liquid Salts	750–1000 700–800	Low	Open or Closed	1000–1500 1000 or less	Electricity & Hydrogen
SFR	Fast	Na	550	Low	Closed	300–1500 1000–2000	Electricity
SCWR	**Thermal or Fast**	**scH_2O**	**510–650**	**High**	**Open or Closed**	**300–700 1000–1500**	**Electricity & Hydrogen**
VHTR	Thermal	He	900–1000	High	Open	250–300	Electricity & Hydrogen

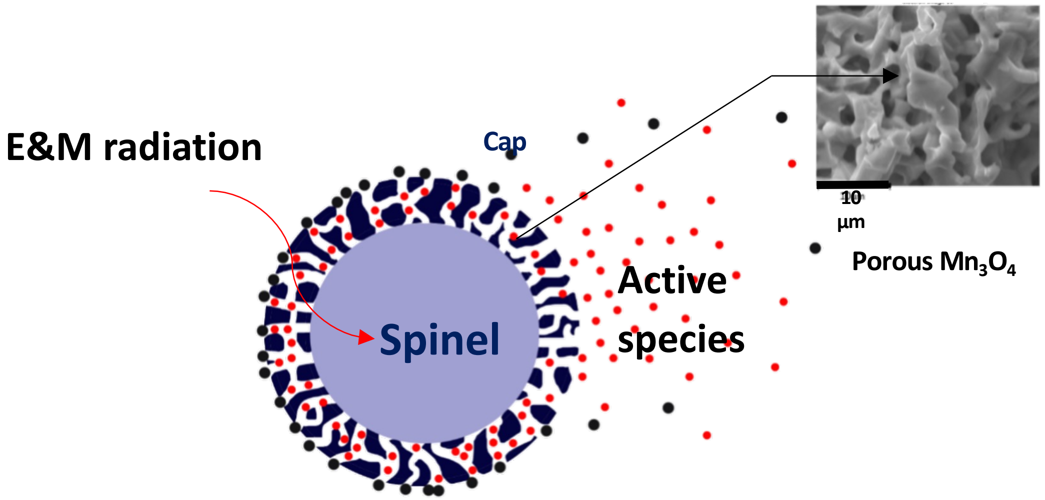
GFR: Gas-Cooled Fast Reactor; Lead Fast Reactor; MSR: Molten Salt Reactor; SFR: Sodium Fast Reactor; SCWR: Supercritical Water-cooled Reactor; VHTR: Very High Temperature Reactor

The most important aspect is sustainability: multifaceted - efficiency, radiation; waste.

Design of new inorganic materials for health & green tech needs unique characterization techniques at TRIUMF



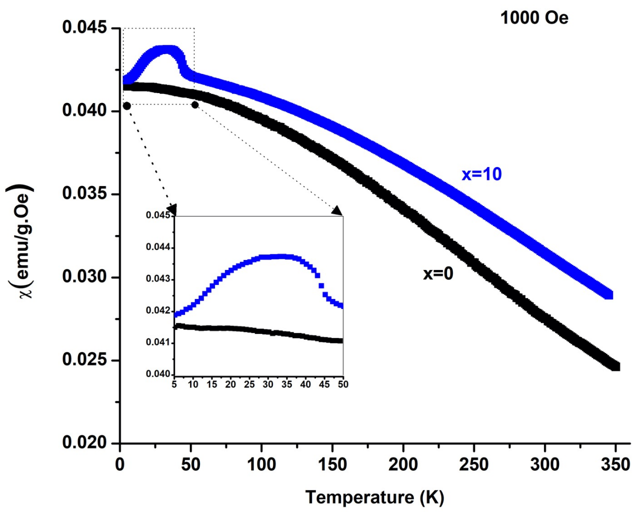
Porous magnetic heterojunction semiconducting spinels as catalysts in clean technology

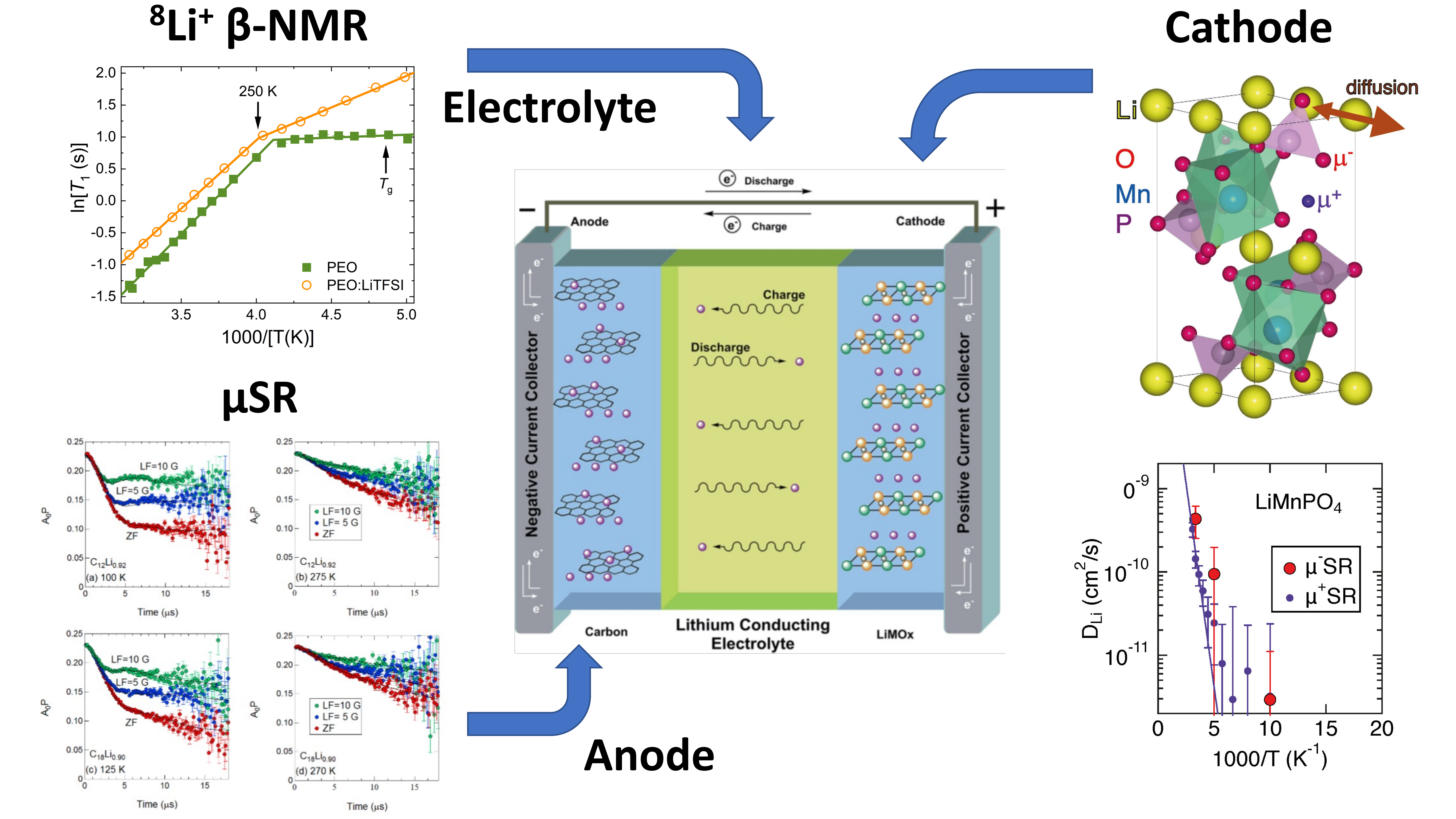


Applications in clean energy & environment

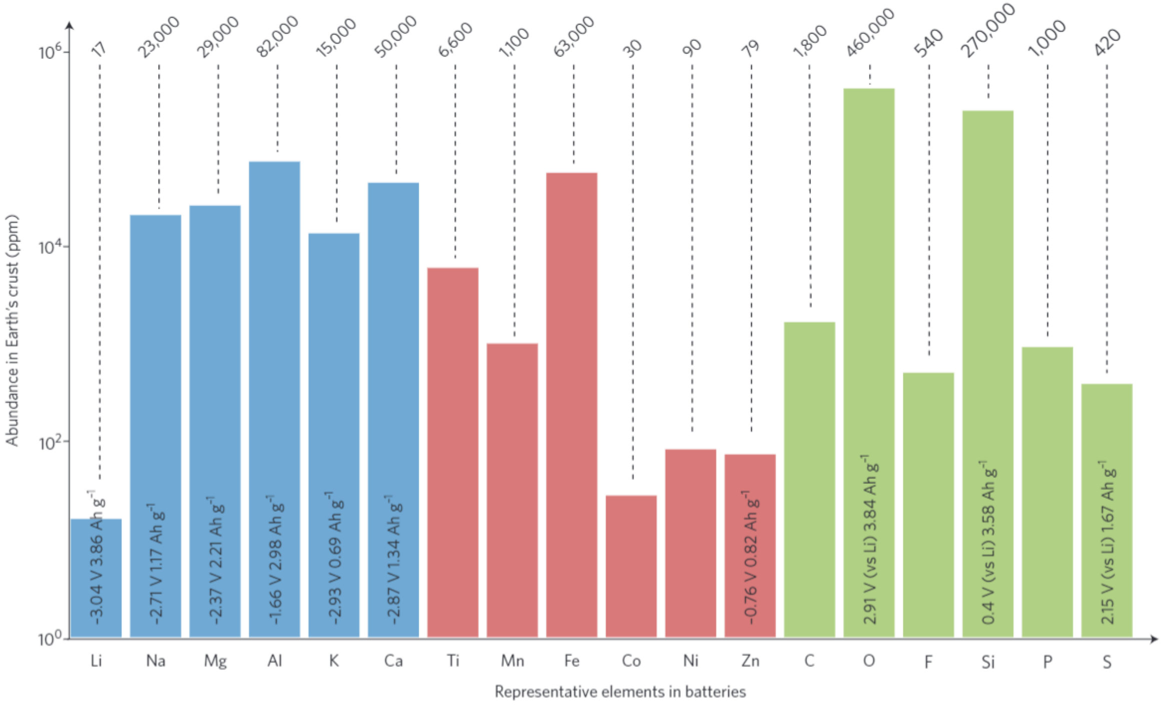
- Solar Power
- Semiconducting behavior (Wide band gap, p-n junction, fast carrier transport)
- Batteries: High-capacity anodes

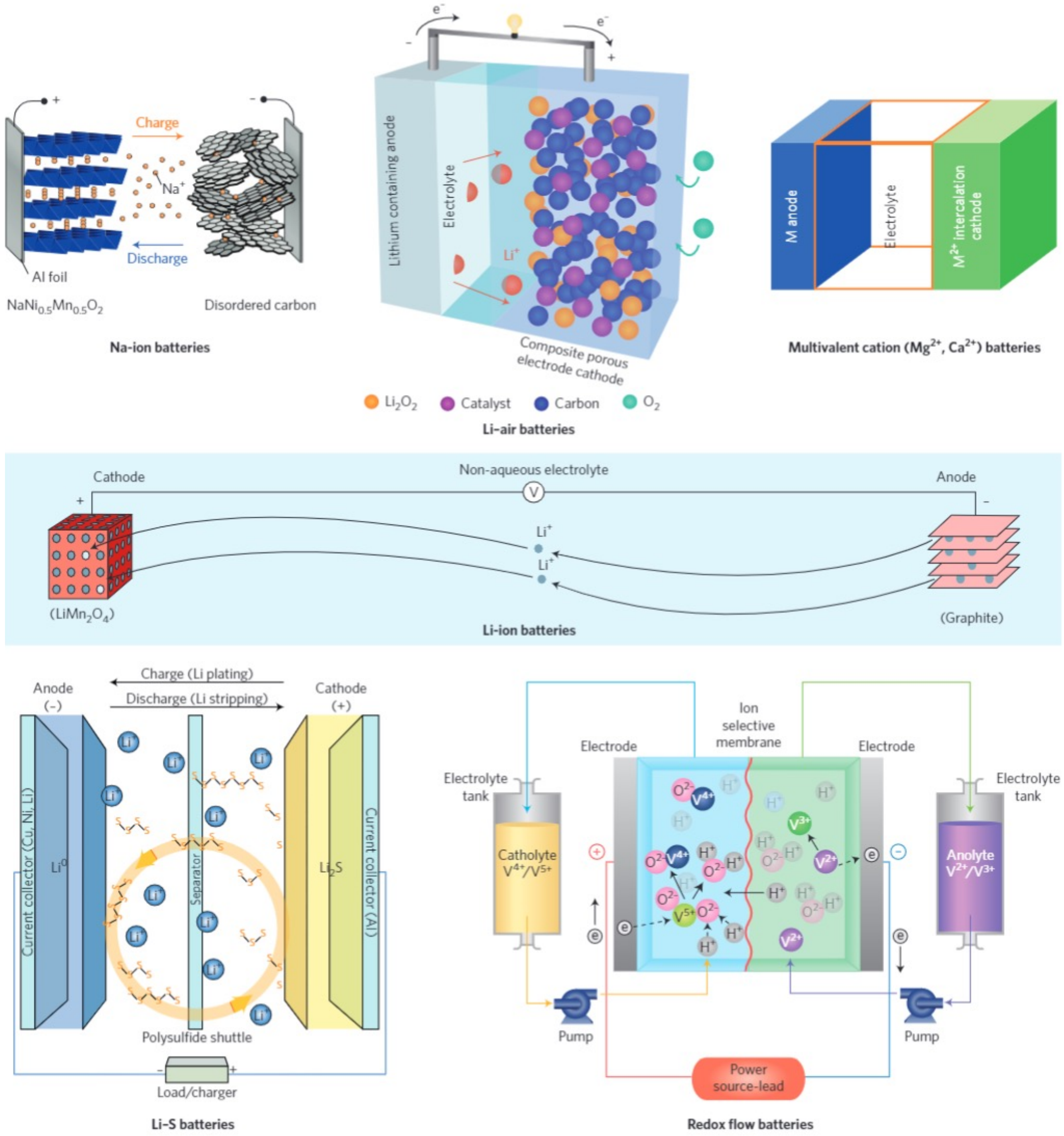
- Nuclear industry
- Formation on nuclear fuel rods during reactor operation
- Environment
- Photocatalysts and chemical sensors in wastewater treatment





8Li+ β-NMR
Electrolyte
Cathode
Anode
μSR
250 K
Tg
PEO
PEO:LiTFSI
ln[T1 (s)]
1000/[T(K)]
Discharge
Charge
Anode
Cathode
Negative Current Collector
Positive Current Collector
Carbon
Lithium Conducting Electrolyte
LiMOx
Li
O
Mn
P
diffusion
μ-
μ+
LiMnPO4
μ-SR
μ+SR
DLi (cm2/s)
1000/T (K-1)
LF=10 G
LF=5 G
ZF
A0P
Time (μs)
C12Li0.92
(a) 100 K
(b) 275 K
C18Li0.90
(c) 125 K
(d) 270 K





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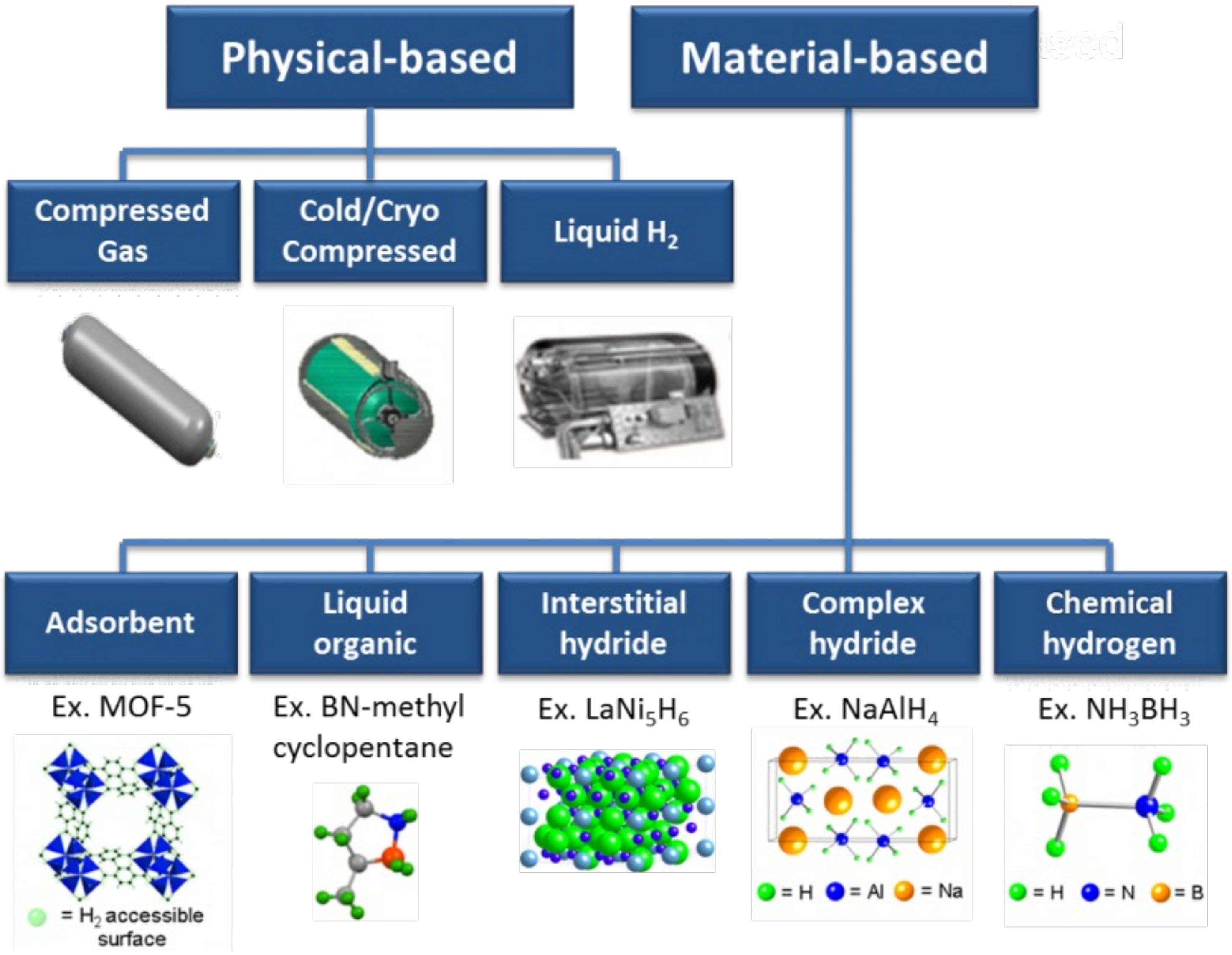
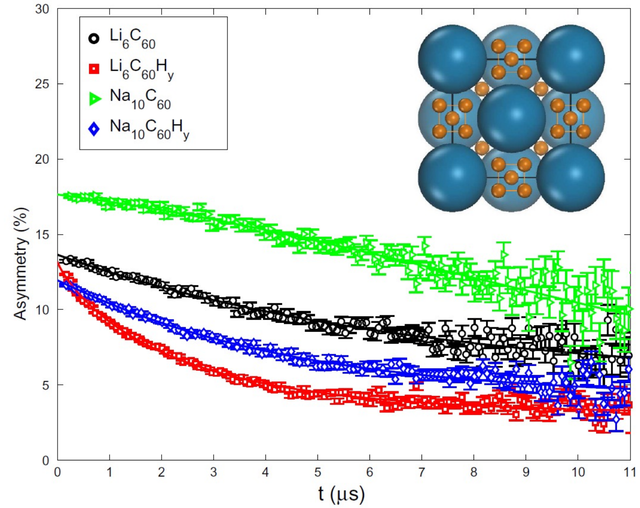
How is hydrogen stored?





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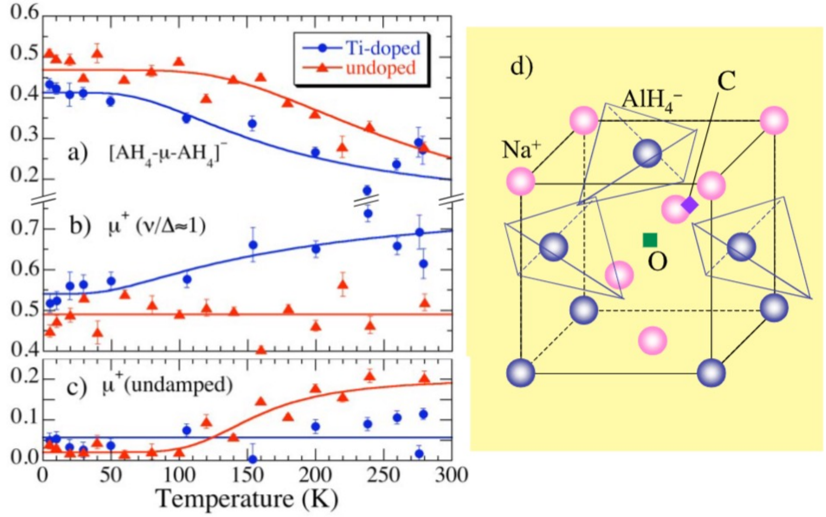

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Enabling Green Technology Solutions

- New climate and sustainability research program with dedicated support for internal and user-driven work in green technology development
- Visitor program with rapid access to required facilities
- Coordination with major research facilities (national and international), companies, and federal government