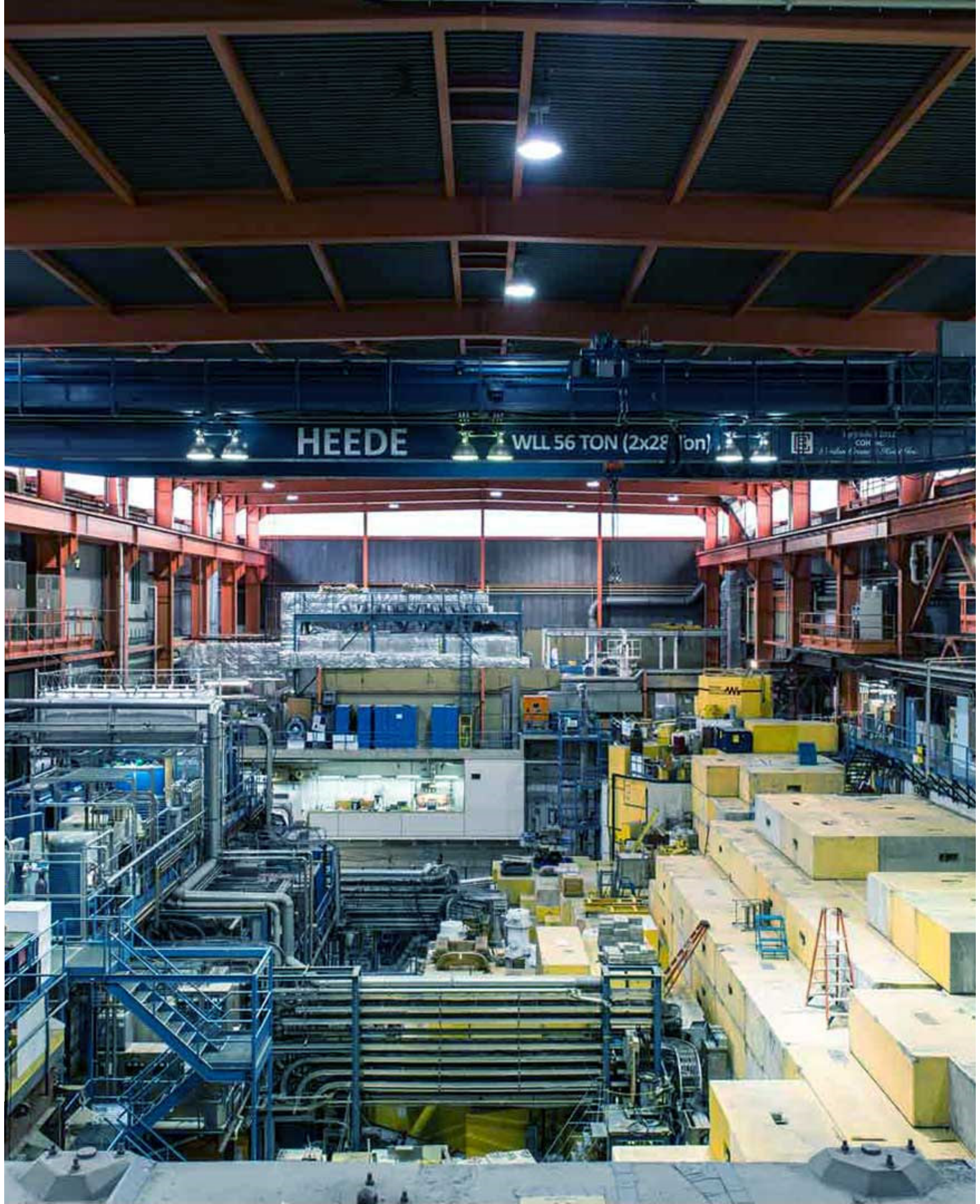
TRIUMF

Looking forward into the CMMS in the Meson Hall

- **M9A / 2021 & M9H / 2024**
  (more beamlines ➡ increased scientific scope)
- **Diamond T2 Target**
  (more muons ➡ experimental precision)
- **M15 Revitalization**
  (luminosity restoration ➡ smaller samples)
- **SiPM based Spectrometers**
  (more bandwidth ➡ broader impact)

⇒ more community & more engaged community



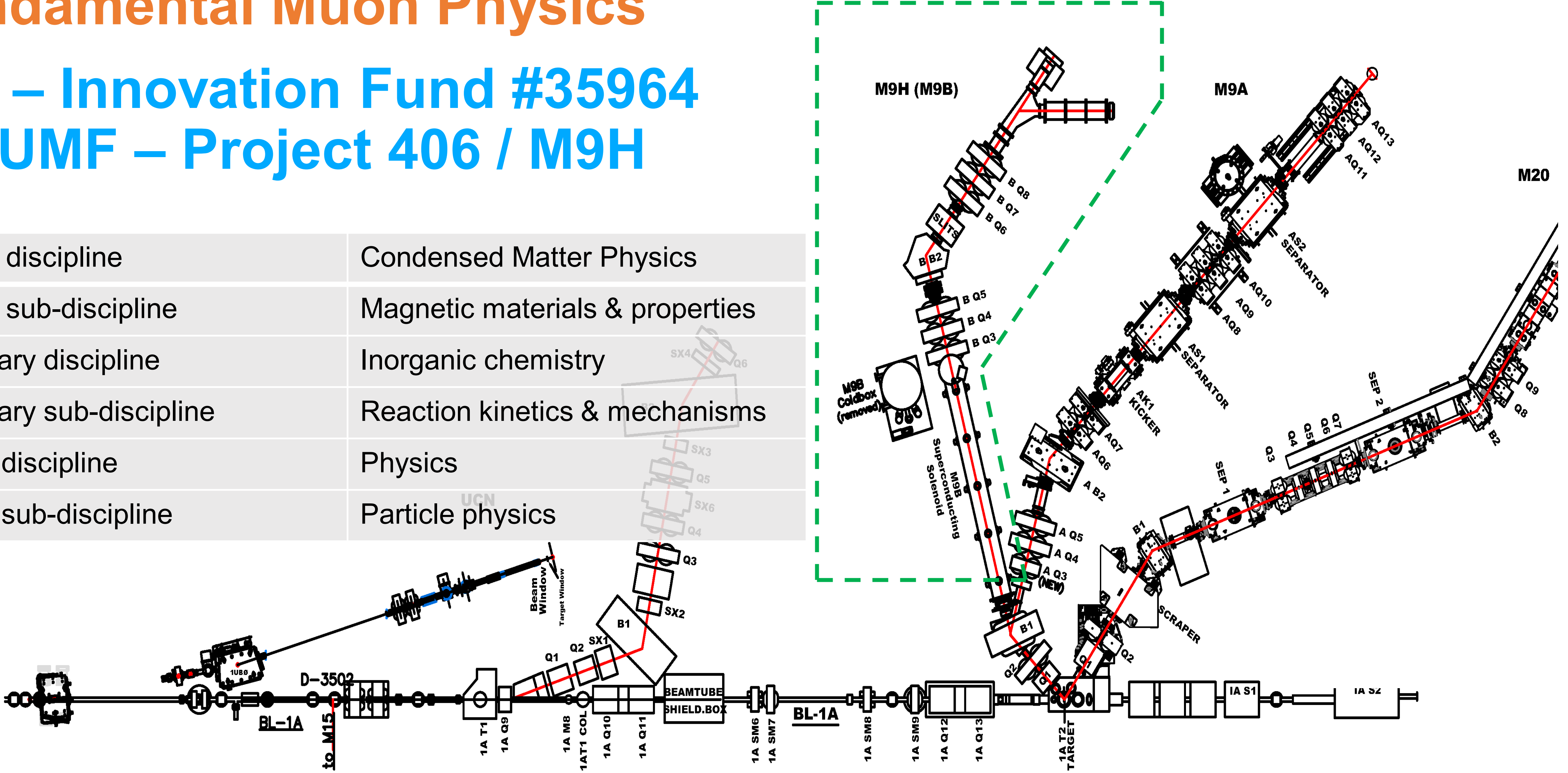
Discovery, accelerated

Syd Kreitzman

High-Momentum and High-Luminosity Muon Beamlines for Molecular and Materials Science and Fundamental Muon Physics

CFI – Innovation Fund #35964
TRIUMF – Project 406 / M9H

Primary discipline	Condensed Matter Physics
Primary sub-discipline	Magnetic materials & properties
Secondary discipline	Inorganic chemistry
Secondary sub-discipline	Reaction kinetics & mechanisms
Tertiary discipline	Physics
Tertiary sub-discipline	Particle physics



Project Community

- PI: Jeff Sonier SFU (CFI lead)
- Co-applicants:
  - Andrea Bianchi U. Montréal
  - Jess Brewer UBC
  - Don Fleming UBC
  - Khashayar Ghandi Mt. Allison
  - Robert Kiefl UBC
  - Graeme Luke McMaster
  - William MacFarlane UBC
  - Paul Percival SFU
  - Jeffery Quilliam U. Sherbrooke

UBC, McMaster, U. Montréal, Mt. Allison comprised the CFI Partners in the multi-university application

TRIUMF

Project Leader:	Syd Kreitzman
Project Sponsor:	Jens Dilling
Grants Accountant:	Francis Pau
Project Engineer:	Mahdiar Khosravi*
Dept/Teams:	CMMS / Proj. Management/ Beamlines / Vacuum / Design Office / Electrical/ Sci-Tech Dept./ Controls/ /Machine Shop / Accounting/ Purchasing/ Legal /w University Coordination

*principle author of all items labeled by a document number x154377

P406 (M9H) Project Objectives

- Beamline:
  - 100 k$\mu^{+/-}$/(sec-cm^2) @ >70 MeV/c momenta; >80% spin polarization (longitudinal) in zero field.
  - Transversely spin polarized muons with >30 kμ^+/(sec-cm^2) @ 70-101 MeV/c *

- Experimental Station:
  - Sample temperature and pressure of 0.03 – 300 K and 1.5 GPa
  - Sample temperature and pressure of 273 – 900 K 50 MPa
  - DR sample changeover time < 5 hrs @ 0.1 K for Ø30 mm sample

- Operation:
  - Maximizing beam uptime and operating reliability
    (⇒ persistent field LHe cooled recondensing solenoid + new power supplies & control systems).
  - Adhering to TRIUMF's operational safety standards

*assuming standard T2 target operating conditions.

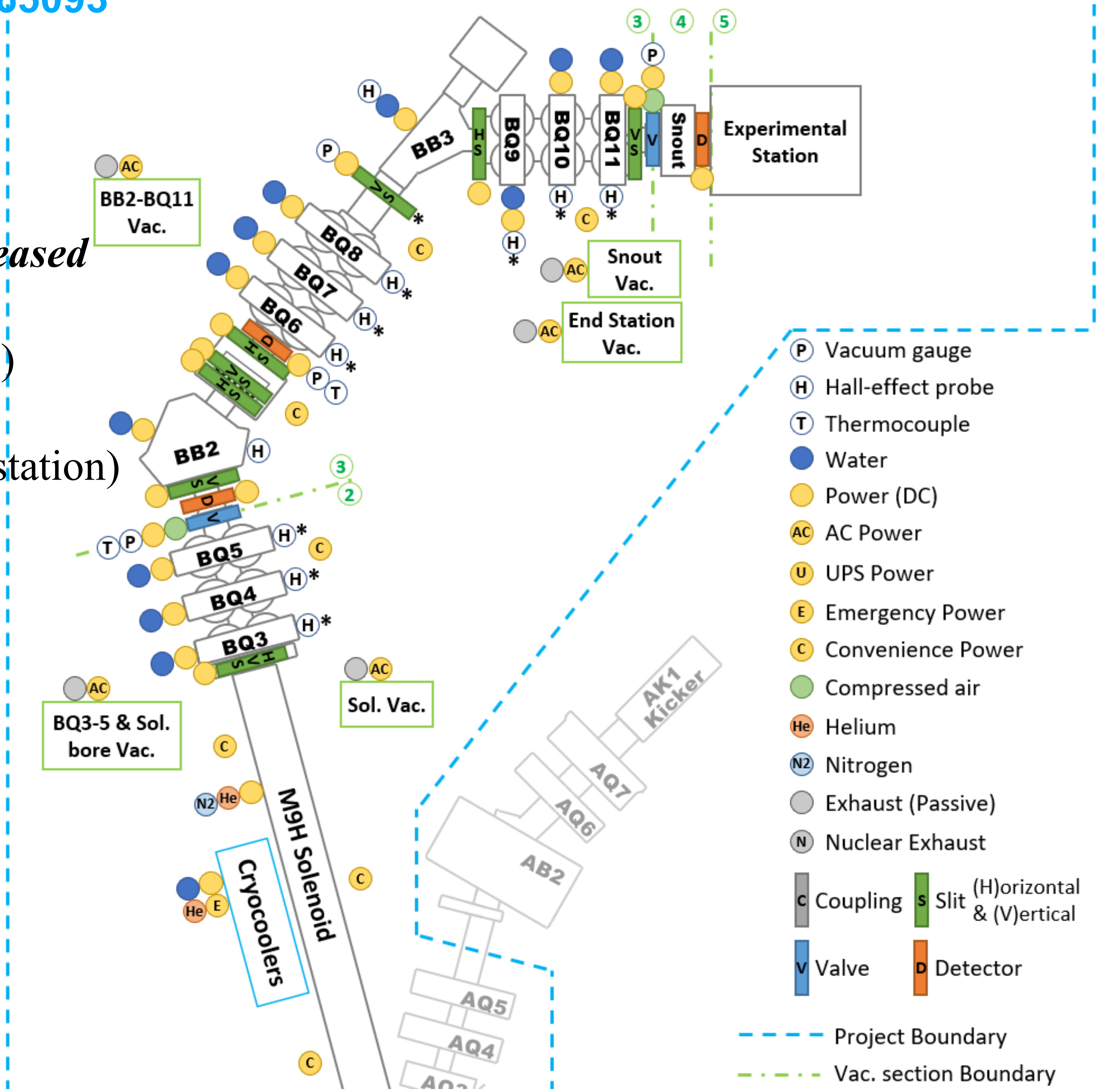
P406 Science Impacts

- Quantum Materials
  - high-pressure (the tuning parameter) μSR studies of novel electronic and magnetic phases in qms
  - i.e. superconductivity, low-dimensional and topological systems, quantum phase transitions
- Environmental and Energy:
  - Chemistry under extreme conditions, i.e. kinetics & radiolysis in pressurized-water nuclear reactors
  - Green chemistry, i.e. ionic solutions and kinetics
  - Hydrogen storage and Li battery lifetime research via μ- elemental analysis
  - Muon Catalyzed Fusion (which was the impetus for the U. of Tokyo's original M9B beamline)
- Cultural Object Analysis:
  - Non-destructive μ- elemental analysis for determining concentration of archaeologically important high-Z elements
- Nuclear Physics:
  - Nuclear hyperfine structure in heavy Muonic atoms

P406 Project Scope

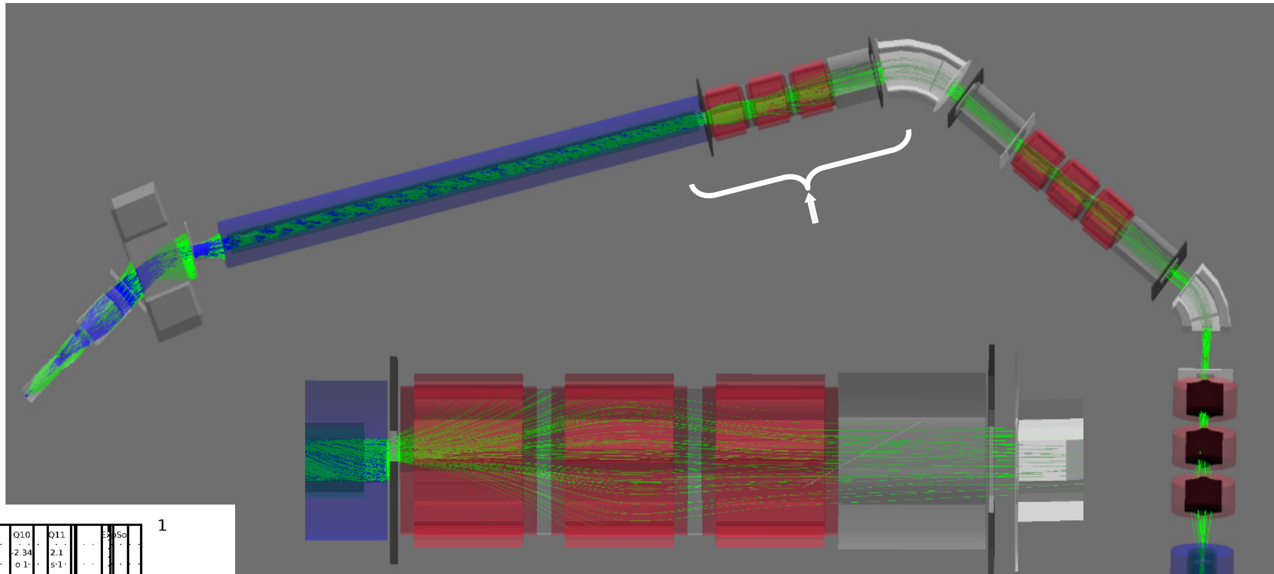
Part of Doc-165093

- Beamline modifications downstream of B1 only
- Beamline and Services Group:
  - Replacement solenoid: ***Tender document has been released***
  - New solenoid shielding & modification to M9A (AQ3)
  - Replacement of magnet power supplies (Q3-Q11 & B2)
  - New beamline diagnostics and beam control elements
  - New vacuum systems groups (solenoid/beamline/exp. station)
  - Spare Helium Liquefier compressor
  - Controller update (PLC/EPICS)
  - Services: electrical, water, and compressed air
  - Decommissioning M9B elements
  - Commissioning M9H
- Experimental Station Group
  - Helmholtz magnet
  - Dilution refrigeration
  - Versatile SiPM based μSR spectrometer /w High Transverse Field capabilities
  - Extreme Environment Sample Enclosures

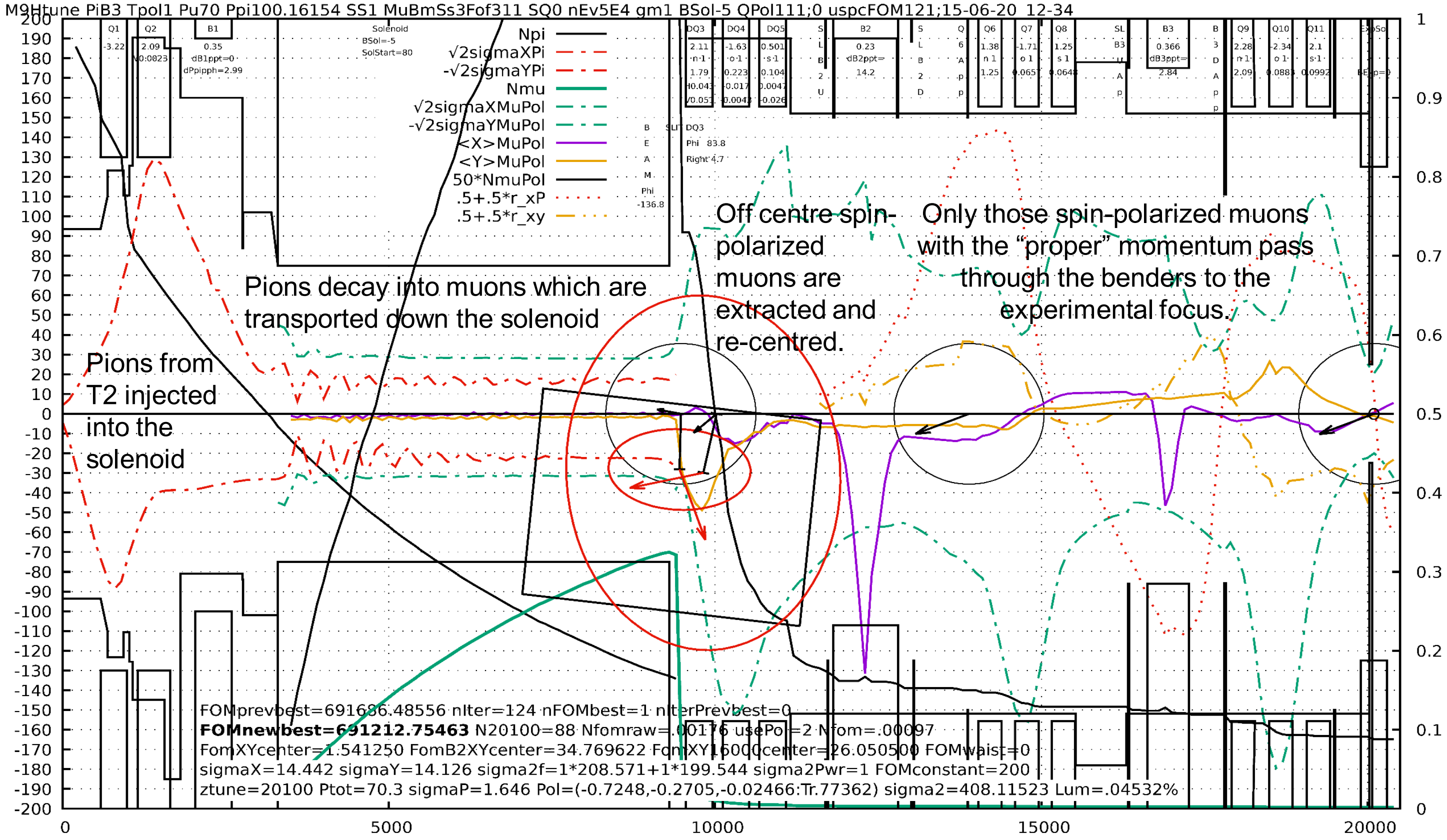


Optical Design Verification

- Supported issuance of solenoid tender document
- Verifies delivery of transversely spin polarized muons for the momenta in the 70-110 MeV/c range
- Defines location of diagnostics and beamline control elements



Overall M9H G4beamline simulation displaying a transversely spin polarized tune

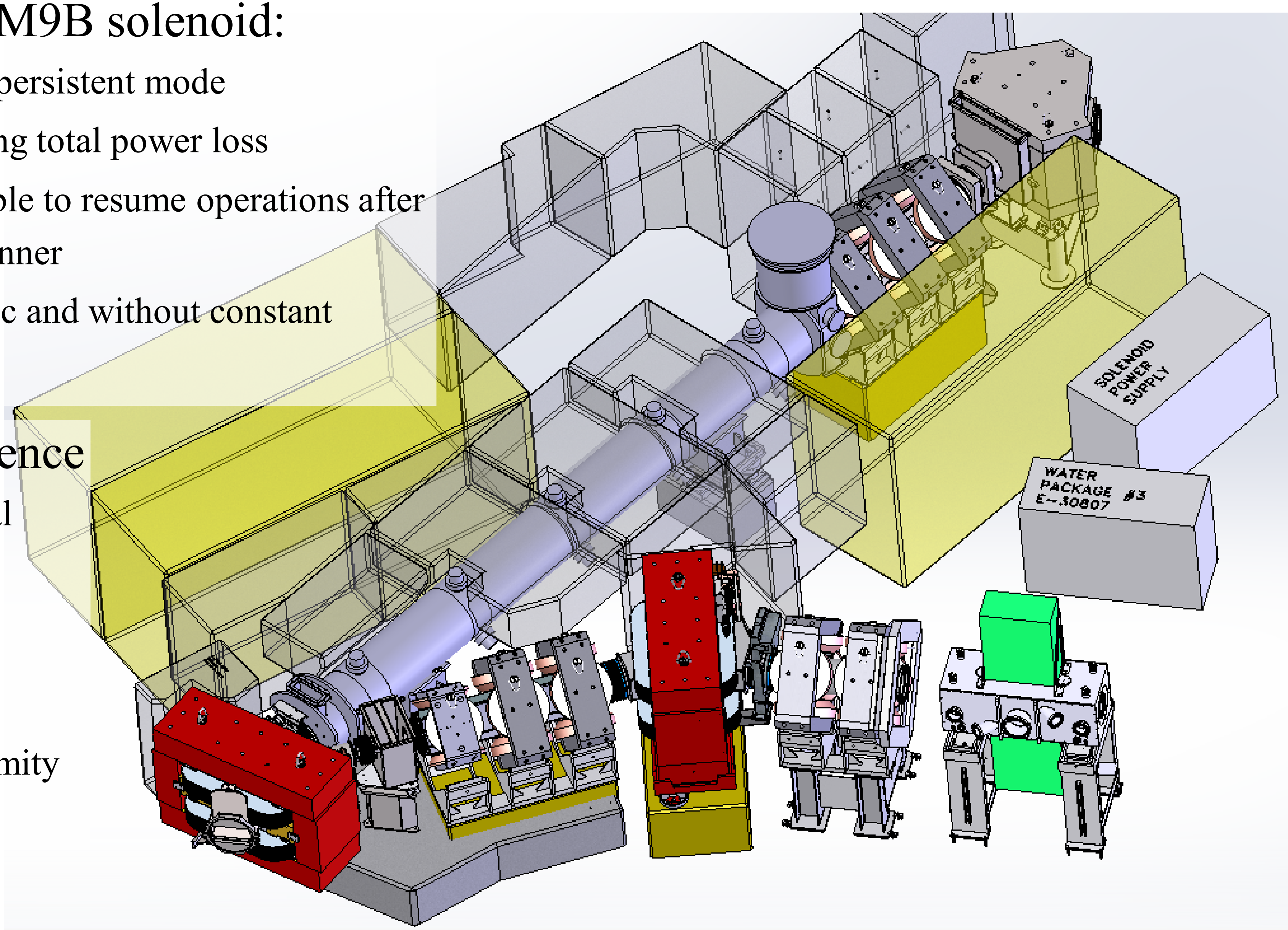


An enhanced beam envelope diagram which displays a luminosity optimized simulated tune for a 70 MeV/c X-Polarized μ^+ beam.

This beam was not possible with the previous incarnation of the beamline, which could not accommodate the extremities of the phase space in which this beam lies.

The heart of the beamline – new 5T Persistent transport Solenoid

- Major upgrades compared to M9B solenoid:
  - 5T RT[1]-bore solenoid, operates in persistent mode
  - Maintain SC state for 12 hrs., during total power loss
  - Impervious to power bumps and able to resume operations after power interruptions, in a timely manner
  - Routine operation largely automatic and without constant supervision
- Tender Specification due diligence
  - Reviewed by stakeholders, potential contractors, senior engineers
- Risks
  - Resources during shutdown
  - Insertion of solenoid in close proximity of M9A



1. Room-Temperature

M9H / P406 – Gate 2 Review Mahdiar Khosravi : Doc-186120

Gate 2 Report: Posted Aug. 12, 2020

Review Panel	Distribution:
Chair: ***Jens Dilling***	Sponsor, PI, Project Leader, Project Manager, Chair, Panel, projectmanagement@triumf.ca, director@triumf.ca S. Dunsiger, O. Kester, Y. Bylinsky, B. Richert, F. Mammarella, D. Rowbotham, R. Kruecken
Members: • *Eric Guétré* • *Alexey Koveshnikov* • *Thomas Lindner* • *Art Olin* • *Cam Marshall* • *Patrick de Perio* • *Gerald Morris*	**Outcome**

Decision	Yes	No
Gate review accepted?	☒	☐

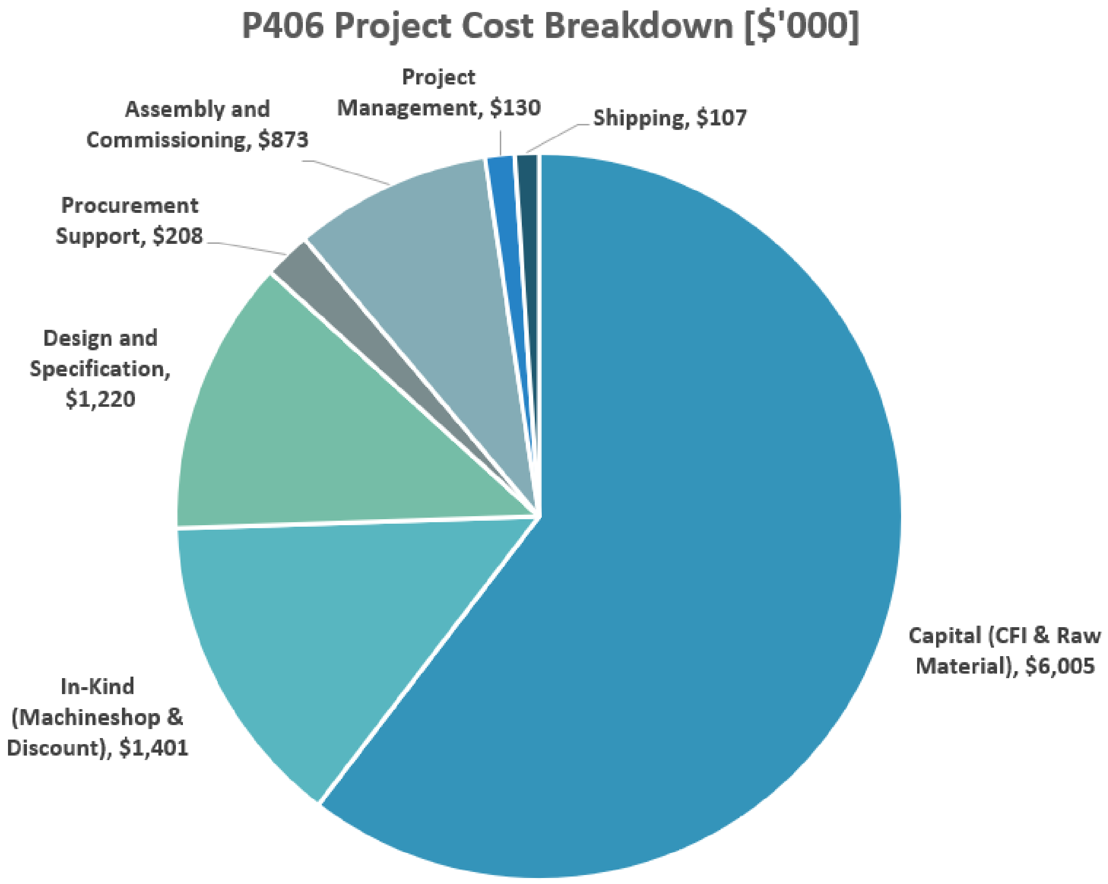
1. Invitation to Tender issued	July 22, 2020
2. Inquiries received up to	September 7, 2020
3. Closing Time for submission of Bids	October 2, 2020
4. Evaluation completed	November 2, 2020

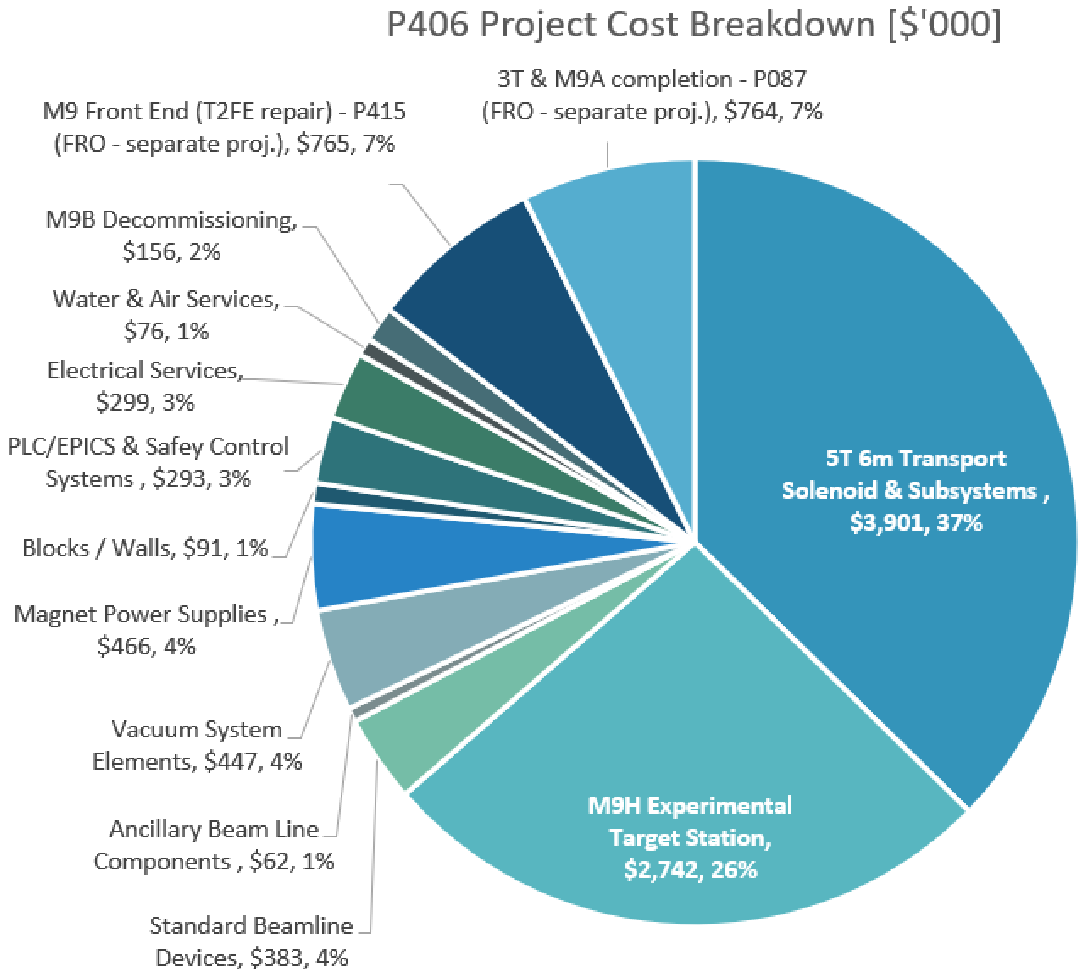
P406 project documentation	Doc. #
Actions from previous review	154376
Requirements:	165094
Optics Design Note:	154377
Mechanical Concept Rev.:	184977
Budget:	154378
Schedule:	154382
System architecture:	165093
Project plan:	165089
Risk registry:	154414
Hazard analysis:	154420
Decommissioning plan:	165236

Budget

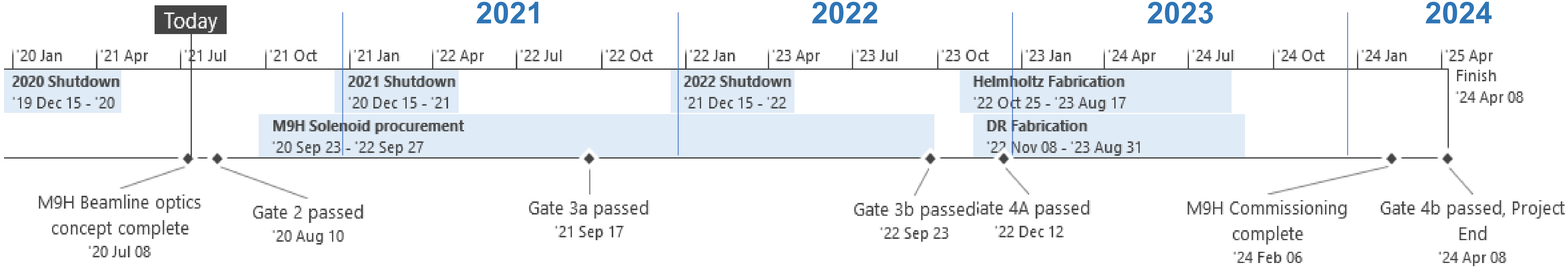
40% CFI
+ 40% BC/ON/QC
+ 20% TRIUMF Inkind
= $10.7M

P406 Budget – Document 154378





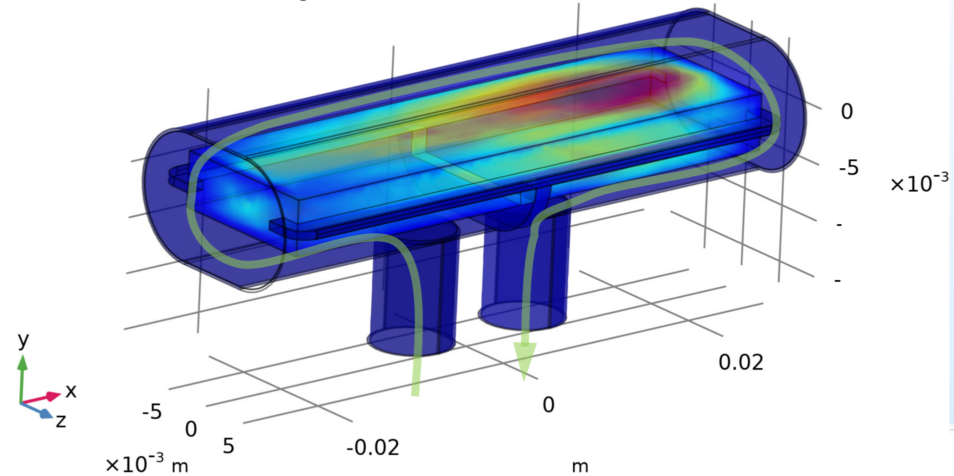
Schedule

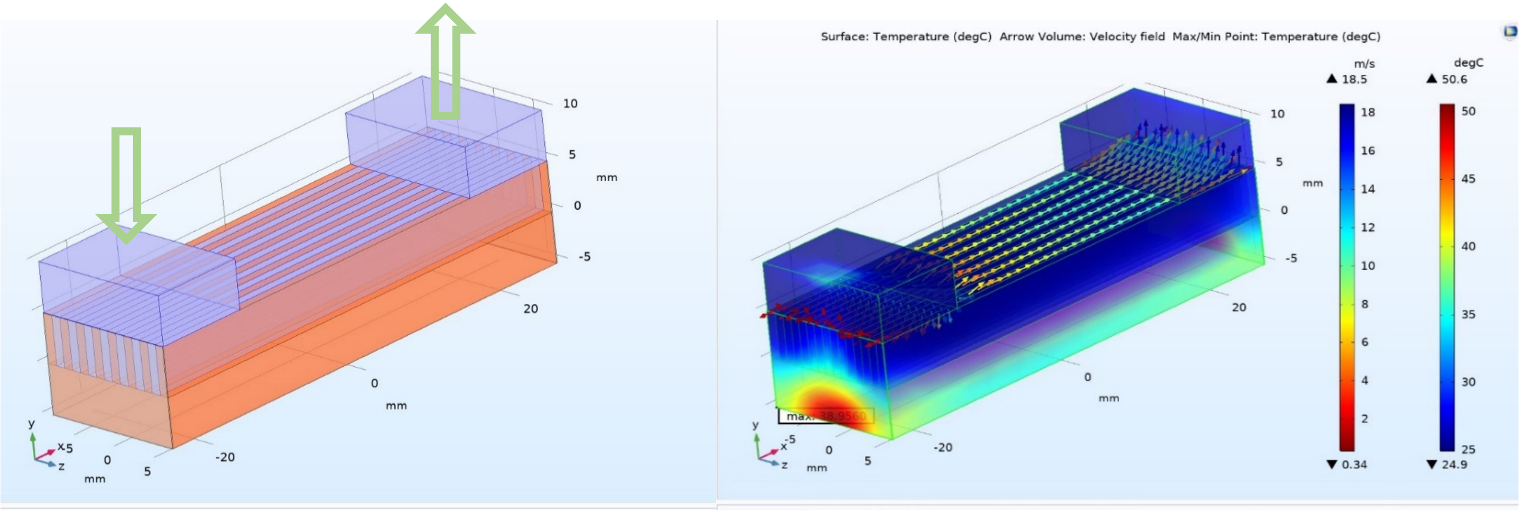


Shutdown 2020-2021	Rest of 2020-2021	2022	Shutdown 2022-2023
- Removal of: • M9B Solenoid • Q345 quad for upgrade • Other Q345 section equip. • Q678 section equip. • Q91011 section equip. - Backfill void spaces - Survey area and services	- Beamline detailed design - Exp. station tenders - Commence beamline 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

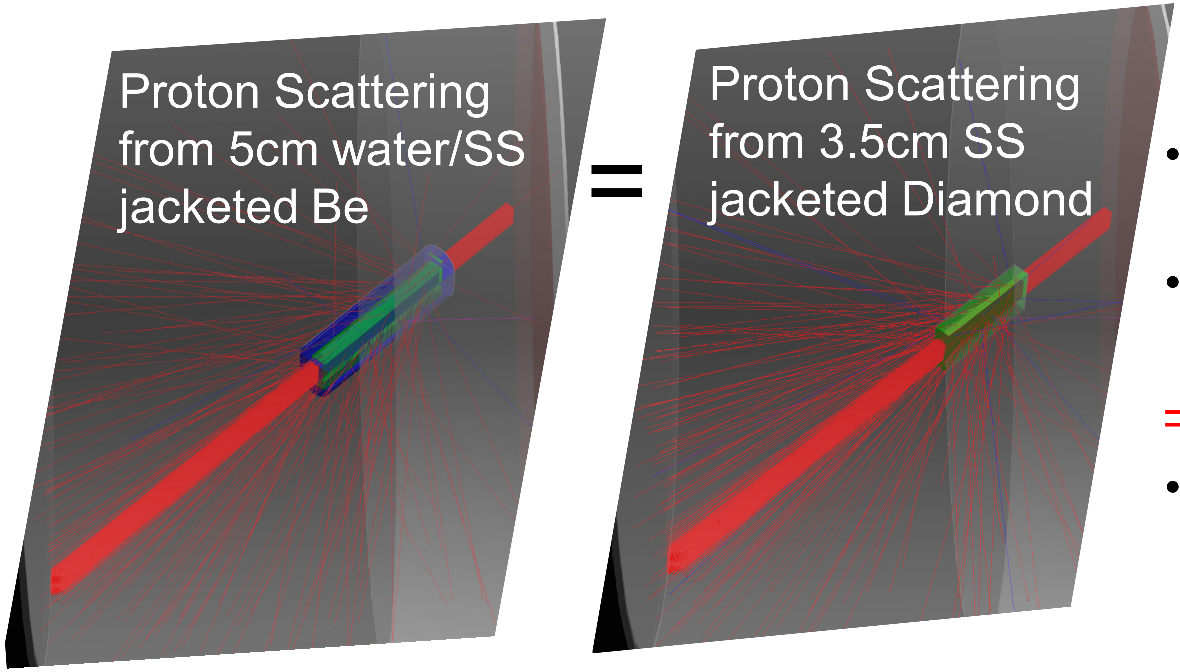
CVD Diamond T2 Target ? … the idea

5cm water/SS jacketed Be





5cm finned diamond target model and thermal performance
(assuming laminar flow)

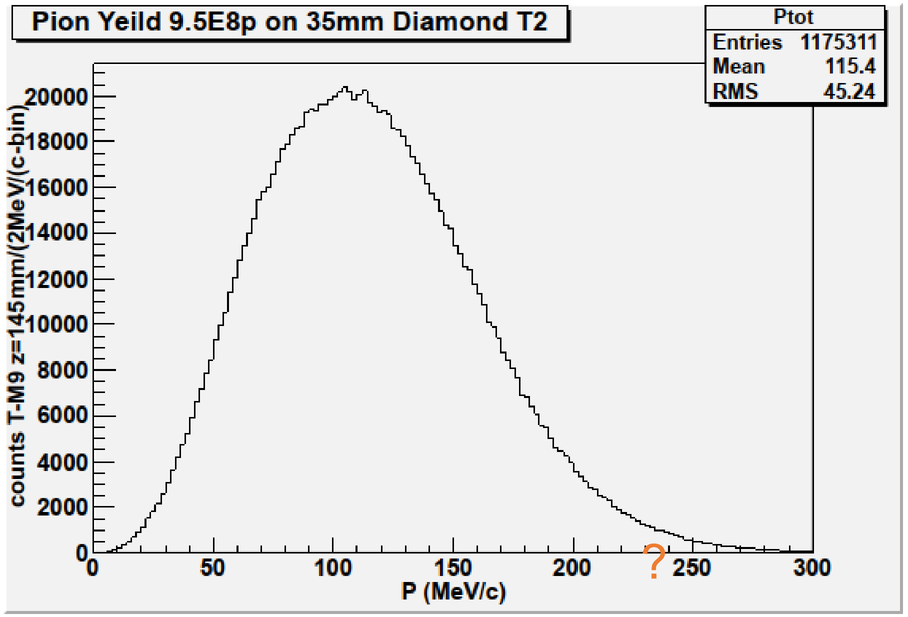


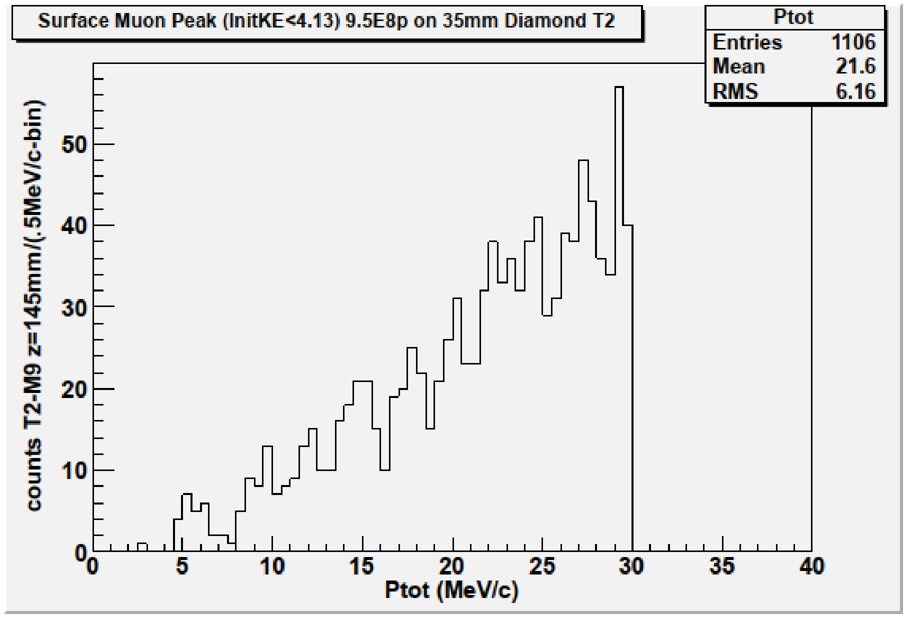
- CVD diamond has thermal conductivity > Cu
  - ➢ tight jacket & distances to muon emitting surfaces minimized
- Diamond has a greater pion production/mm vs Be and target dimensions can be reduced, while maintaining p scattering

⇒ **higher luminosity surface muon source & @ final focus**

- Available in 1mm customized rectangular slabs
  - ➢ cost of material for 1 target <$10,000

Diamond vs Be T2 Pion and Surface Muon production





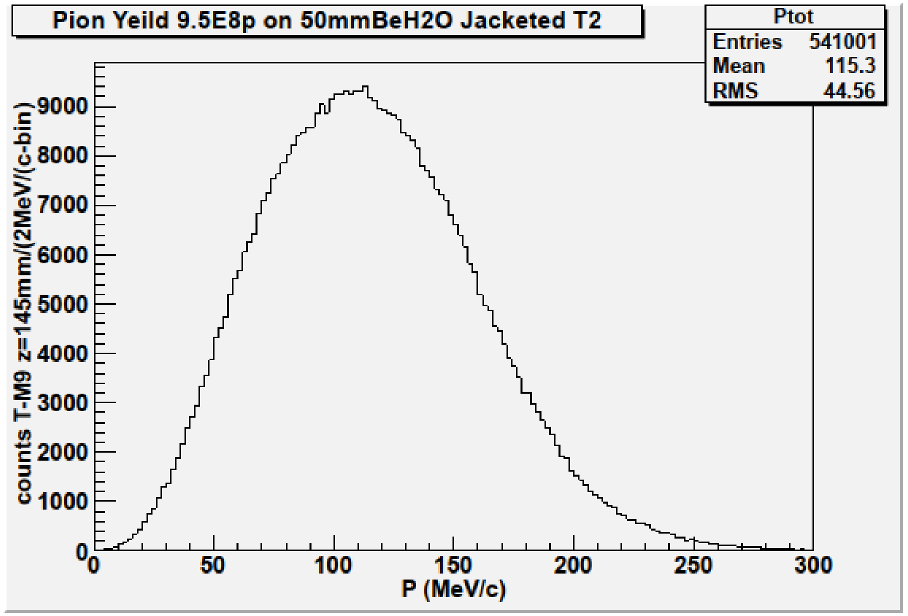
3.5cm SS jacketed Diamond target performance

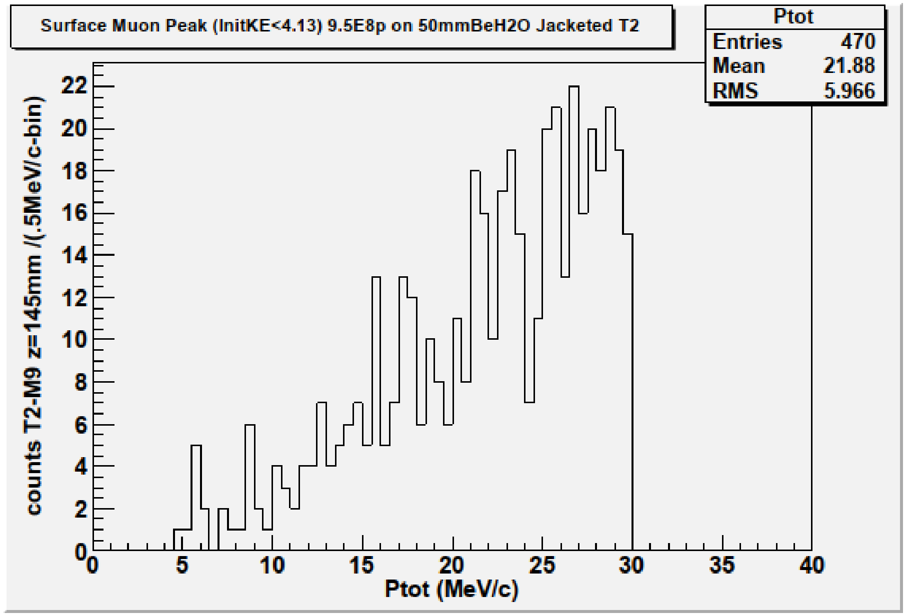
> 2x

5cm water/SS jacketed Be target performance

… for the equivalent scattering of the proton beam downstream of T2

? → ☺

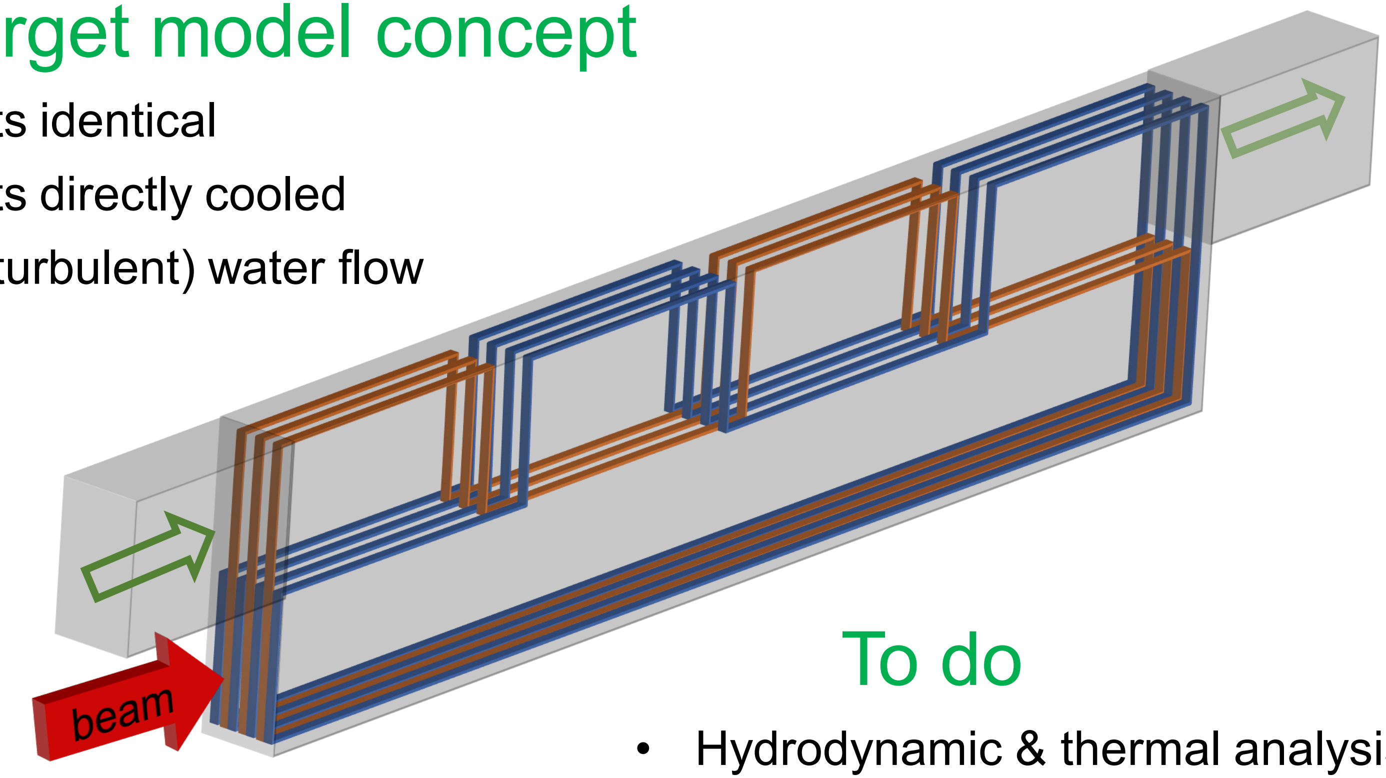




CVD Diamond T2 Target: further work needed

Staggered cooling fin CVD diamond target model concept

- All segments identical
- All segments directly cooled
- Interlaced (turbulent) water flow



To do

- Hydrodynamic & thermal analysis
- Assessment of potential target ageing issues
- Engineer an enclosure design that minimizes weld collars in the direction of the muon emission surfaces (viz. all the sides, except the direction of the cooling fins)

M15 Revitalization: Scope

Restore M15's beam luminosity and modernize in its critical systems which have become unsustainable … thereby ensuring the beamline's future relevance in the world of quantum material research, which is "small sample" dependent.

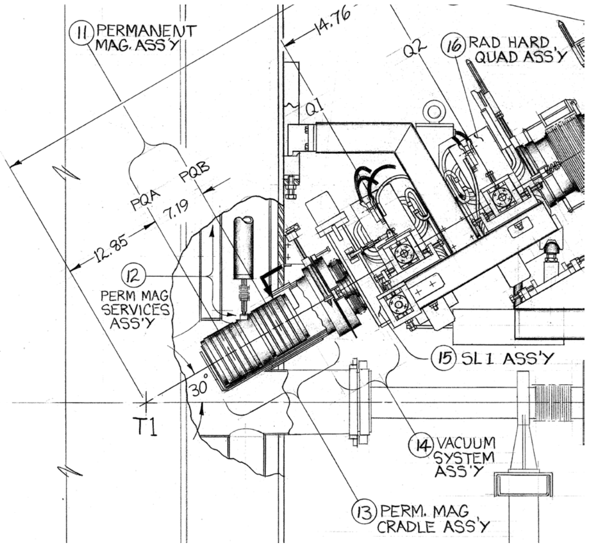
i. Replace the degraded two permanent quads in M15 that form the high acceptance muon beam extraction doublet → restoration of luminosity for small samples

ii. Replace the unserviceable set (four) of high voltage (HV) stacks and feedthroughs that generate the E-Fields in the two Wien Filter/Spin Rotators.

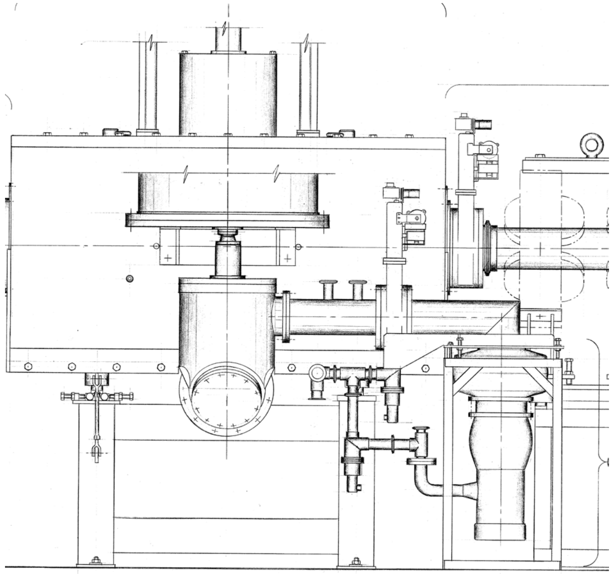
iii. Add a pair of steering power supplies to the final triplet to "fine tune" beam steering into small samples.

iv. Upgrade the M15 control system to current TRIUMF standards.

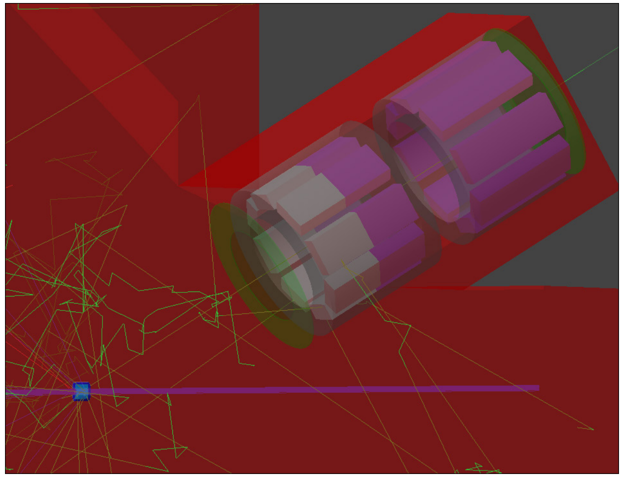
M15 Revitalization: Major Sub-system Upgrades



A view of the first two permanent quads in relation to the front end of M15 in proximity to T1.

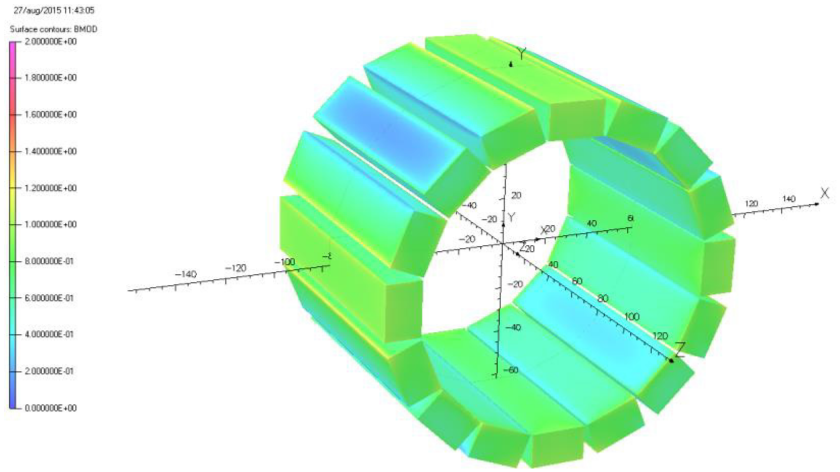


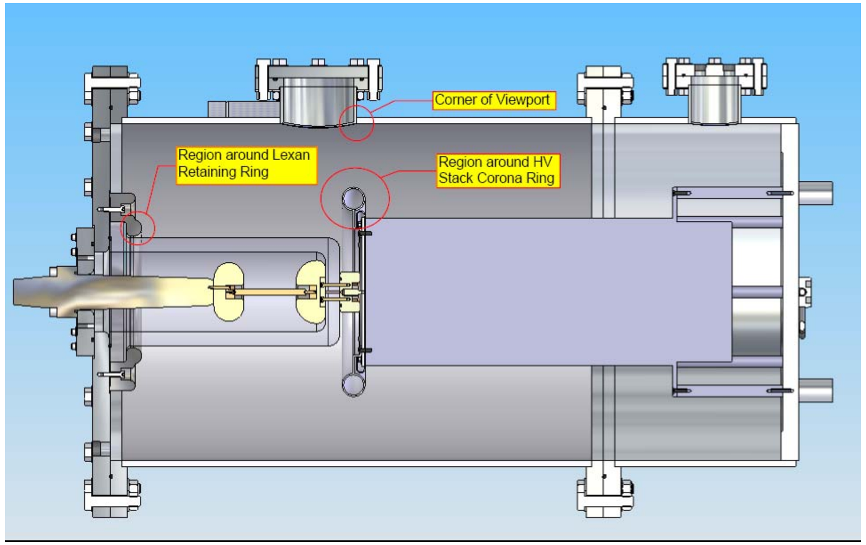
The GEANT4 simulation layout of the water jacketed 12mm Be T1 target and the two M15 permanent quads used to calculate the 30-year dose into PQA.



At left the current M15 oil & paper wrapped HV cables and (leaky) vacuum insulated feedthrough schema is shown. The upgrade path will use an SF6 insulated (resistively protected) 200KV similar in design to the modern M9A 300KV stacks shown on the right.

A preliminary design for a new set of Sm_2Co_{17} Halbach permanent quads consistent with the original specs.





M15 Revitalization: Plan of Action & WBS

Proposal Commitment (i.e. Gate 0) for current 5Yr Plan submitted on May 12, 2020
& Project adopted at part of the $25M TRIUMF infrastructure NRC funding envelope

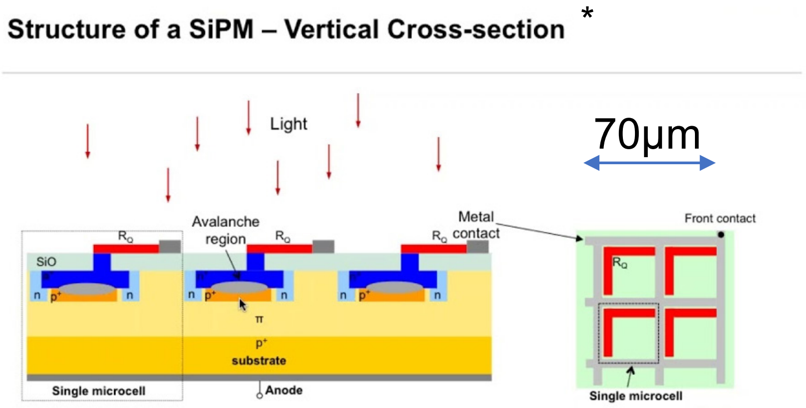
M15 Revitalization Budget and WBS	Design/Specification (wks)					TRIUMF Cost Centre Fabrication					Outside or TRIUMF Fab + Fab Management						Device Assembly & Test					System/Device Installation & Commissioning					Capital +	Prof & Tech	Total Dev
	Physicist	Engineer	Designer	PM team	Cost	# Units	Management	Materials &/c	MS or	Cost	Cost	Vendor	Physicist	Engineer	PM team	Cost	Physicist	Engr	Tech	PM team	Cost	Physicist	Engr	Tech	PM team	Cost	Cost Centre	Mpwr Cost	Cost
$K/wk \\ $K/unit	3.2	3.1	1.9	2.7	$K	Required	Required	Components	Cost Cent	$K	$K/unit	Discount	tot wks	tot wks	tot wks	$K		wks/unit		tot wks	$K		wks/unit		tot wks	$K	O+K*P		AG+AF
Device/System				+Gates 0-3				$K/unit	wks/unit	3.85		tot $K								+Gate 4a					+Gate 4b		$K	$K	$K
Removal/Storage Old A/B Quads	0.0	3.0	4.0	2.0	22.2	1	1	2.5	3.00	14.1	0.0		0.0	0.0		0.0	0.0	0.1	0.5	2.0	6.7		0.5	4.0	0.0	9.2	14.1	38.1	52.2
New Permanent A/B Quads	2.0	3.0	8.0		30.8	1	1	2.5	3.00	14.1	119.9	fixed 25% contingency for material selection		1.0		135.6	2.5	0.2	1.0	2.0	15.9		1.0	8.0	0.5	19.7	133.9	82.2	216.1
Removal Old HV Stacks/Feedthrus	0.0	2.0	2.0		9.9	1	1	1.0	0.50	2.9	0.0	all 4 units	0.0	1.0		3.1	0.0		0.5		1.0			1.0	0.5	3.3	2.9	17.2	20.1
New Glassman Stacks & PS	1.0	1.0	0.0		6.2	1	1	0.05	0.20	0.8	164.9			1.0		167.9	0.0		0.0	1.0	2.7		0.5	1.0		3.4	165.7	15.5	181.2
New HV Feedthru Assemblies	3.0	5.0	8.0		40.1	4	1	1.0	1.00	19.4	6.0			1.0		26.9	0.3		0.5		7.0		0.5	1.0		13.8	43.2	63.9	107.1
Beam Steering for Final Triplet	1.0	2.0	2.0		13.1	2	1	0.5		1.0	3.0		0.5	0.5		9.1	1.0		2.0		14.0	0.5	0.4	0.1		5.7	7.0	35.9	42.9
Update Obsolete M15 Contol System	2.0	3.0	6.0		27.0	1	1	0.0	0.50	1.9	50.0			0.0		50.0	0.0	2.0	8.0		21.4	2.0	1.0	1.0		11.3	51.9	59.7	111.6
Storgae of Activated old Quads	0.0	1.5	2.5		9.4	1	1	8.0	1.50	13.8	0.0			0.0		0.0	0.0		1.0		1.9		0.5	0.5		2.5	13.8	13.8	27.5
HV Saftey Upgrade	0.0	2.0	1.0		8.0	1	1	2.0		2.0				0.5		1.5	0.3	0.3	1.0		3.5	0.5	0.5	0.5		4.1	2.0	17.1	19.1
	9.0	22.5	33.5	2.0				21.1	48.9				4.5	5.0			5.8	2.6	18.0	5.0		3.5	6.7	20.2	1.0		434.5	343.4	777.9
checksums					166.8					69.9						394.1					74.1					72.9	434.5	343.4	777.9
Total Costs (Cost Centre=Capital)	28.7	68.8	64.0	5.4	166.8			21.1	48.9	69.9	364.5	0.0	14.3	15.3	0.0	394.1	18.3	7.8	34.4	13.6	74.1	11.1	20.5	38.6	2.7	72.9	434.5	343.4	777.9
Total Cost (Cost Centre = Man Power)	28.7	68.8	64.0	5.4	166.8			21.1	48.9	69.9	364.5		14.3	15.3	0.0	394.1	18.3	7.8	34.4	13.6	74.1	11.1	20.5	38.6	2.7	72.9	385.6	392.3	777.9

M15 Revitalization: Milestones

Description	Dates
Definition of project (Gate 1); Project planning (Gate 2)	5/21; 10/21
Design (new or upgrade) Permanent Quad (PQ) cradle; PQ Gate 3 and Tender;	1/22; 3/22
Fab of PQ cradle; HV Stacks and Feedthroughs (HV S&F) Design; Controls Design	4-6/22; 6-8/22; 9/22-3/23
PQ installation & Gate 4A; HV S&F Gate 3 and RFQ; Commissioning PQ & Gate 4B	1/23; 3/23; 4/23
Construction of HV S&F enclosures; HV S&F installation; Gate 4A; Controls Fab	5-8/23; 2/24; 4/24; 5/23-12/23
Controls Installation; HV S&F Gate 4B; HV S&F Operations	1/24; 5/24; >5/24

SiPM Based Spectrometers for the CMMS: Motivation

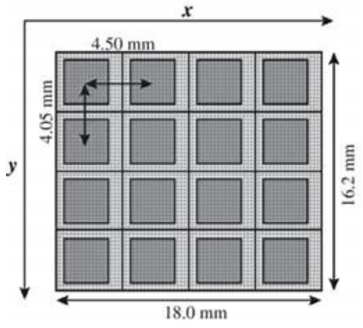
The “Silicon Photo-Multiplier” or SiPM is an advanced solid state photon triggered avalanche detector with high quantum efficiency and single photon resolution. Arrays of SiPMs can replace large area PMTs.



Cross-section of a possible design of a SiPM. All of the microcells have a common anode. The avalanche region, also known as high-field region, is shown in gray.

Top view of a SiPM showing four microcells.

*Hamamatsu documentation



SiPM array suitable for a MuSR detector

The primary advantage if SiPMs is their insensitivity to magnetic fields:

- ➢ the devices can be mounted directly on scintillator surfaces in magnet bores
  - ➢ no light guides
    - ➢ reduced path length dispersion and more detected photons/particle
      - ➢ higher timing resolution
        - ➢ increased experimental bandwidth & scientific impact

TRIUMF has recently developed (courtesy of Miles Constable and Leonid Kurchaninov / Sci. Tech. Dept.) the technology of “fast” summing 12-16 x 36mm^2 arrays to enable it to replace its PMT based detectors with the much higher performance SiPM based devices.

SiPM Spectrometers: Large Area Prototype Test

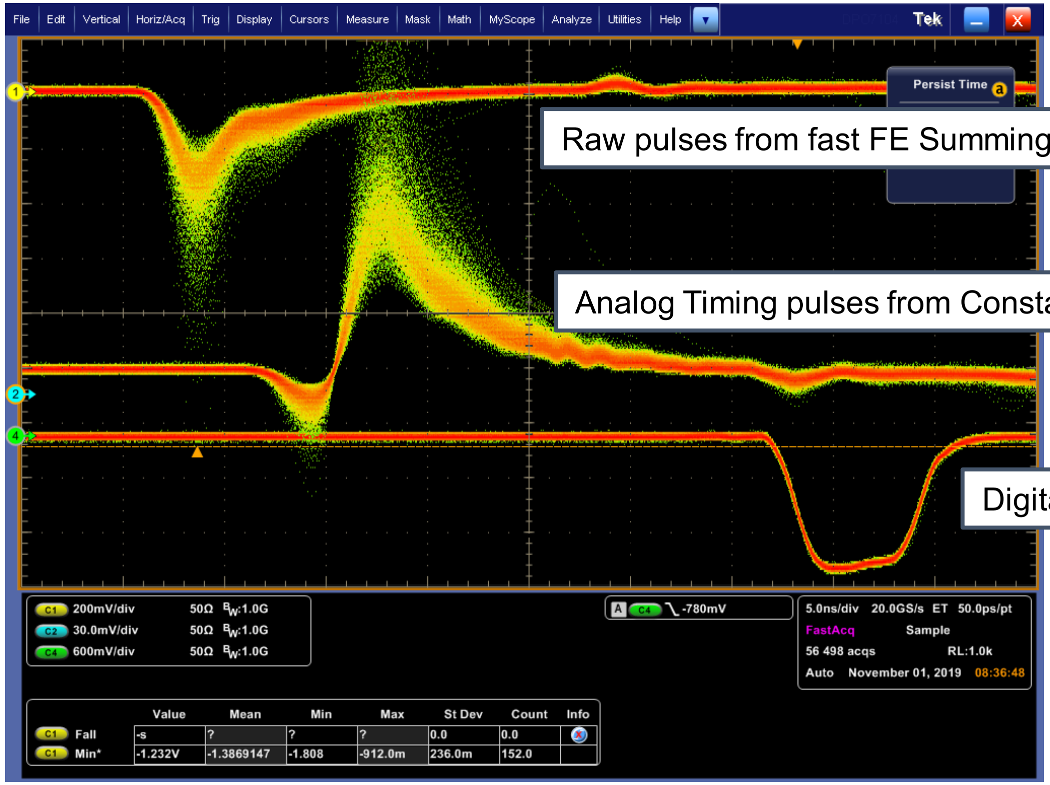
- M20C
- .3T magnet
- Sum Σ_{12e+} & Sum $\Sigma_{8\mu+}$ PreAmp Front End
- Muon detector in snout vacuum
- Left/Right Positron detectors
- Front & Back Faces of Left e+ detector (covered in 12 SiPMs)
- Signal vacuum feedthrough for muon detector

SiPM Spectrometers: Prototype Signal Response

Raw pulses from fast FE Summing Amplifiers

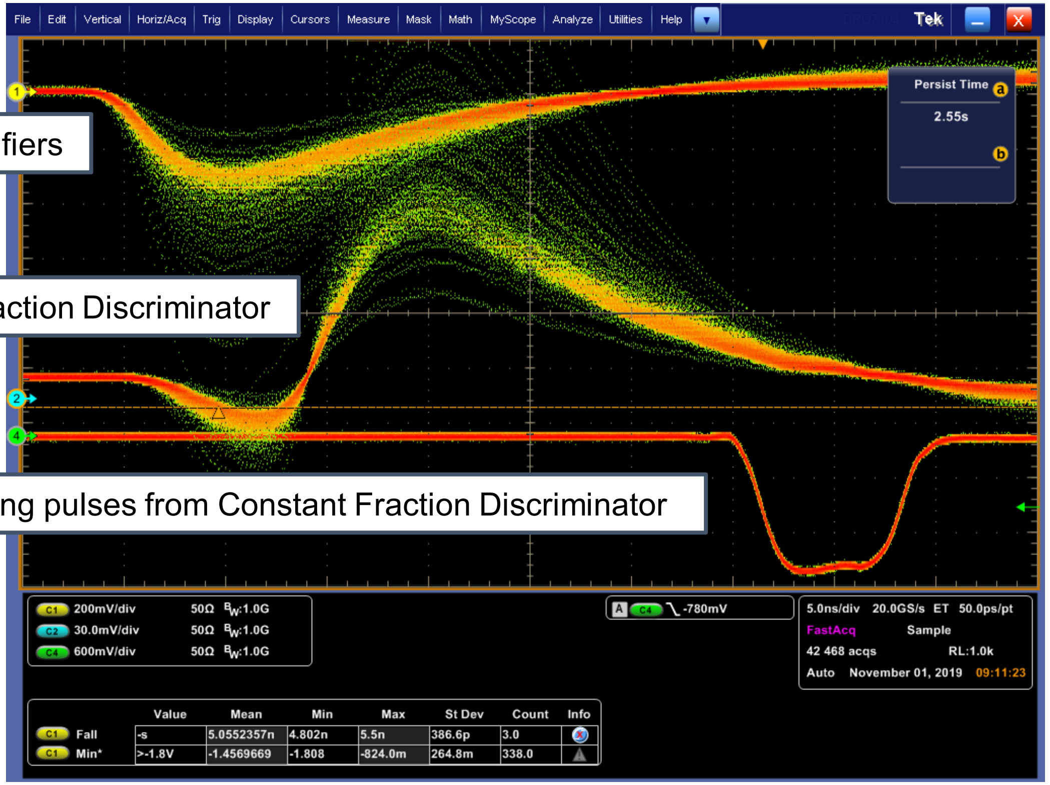
Analog Timing pulses from Constant Fraction Discriminator

Digital Timing pulses from Constant Fraction Discriminator



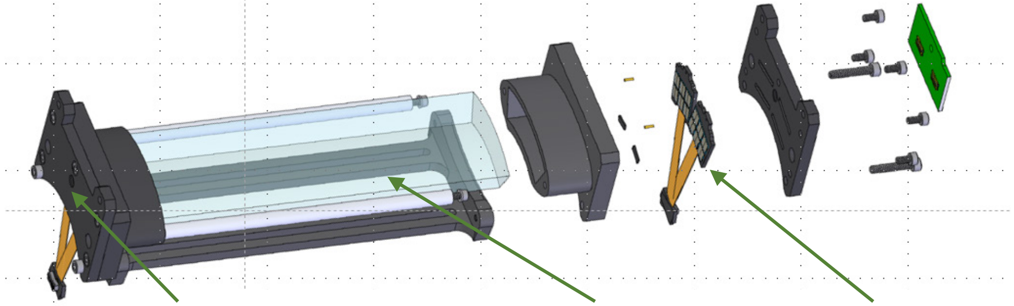
	Value	Mean	Min	Max	St Dev	Count	Info
C1 Fall	-s	?	?	?	0.0	0.0	
C1 Min*	-1.232V	-1.3869147	-1.808	-912.0m	236.0m	152.0	

Signal response and CFD timing pulse from the in vacuum Muon detector using Σ_8 (Σ_3 SiPMs) and the Mark III+ FE.



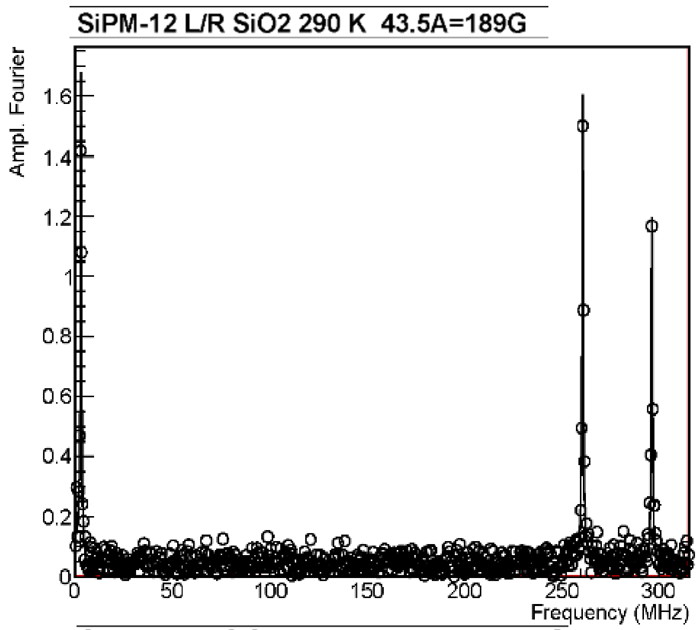
	Value	Mean	Min	Max	St Dev	Count	Info
C1 Fall	-s	5.0552357n	4.802n	5.5n	386.6p	3.0	
C1 Min*	>-1.8V	-1.4569669	-1.808	-824.0m	264.8m	338.0	

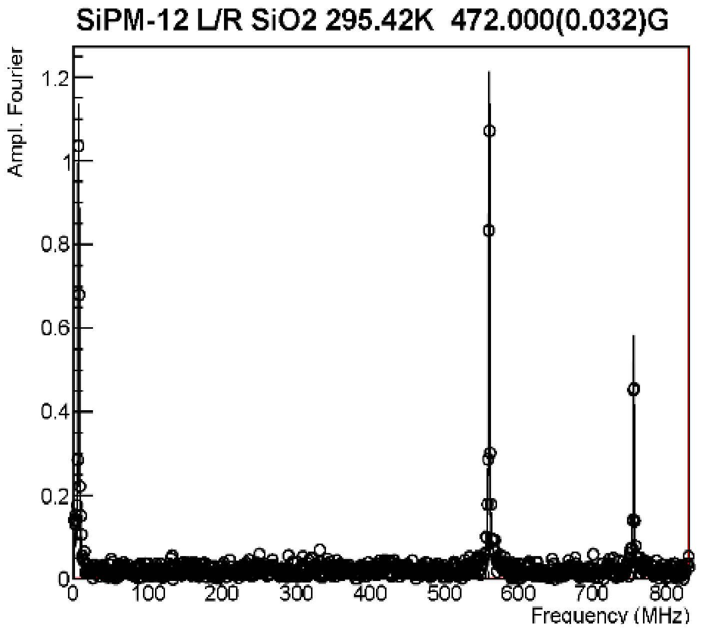
Signal response and CFD timing pulse from the 3T Spectrometer e+ detectors using Σ_2 (Σ_{12} SiPMs) and the Mark IV FE. In this test the analog average of the end cap Σ_{12} signals were used, rather than detecting and time stamping these individually.

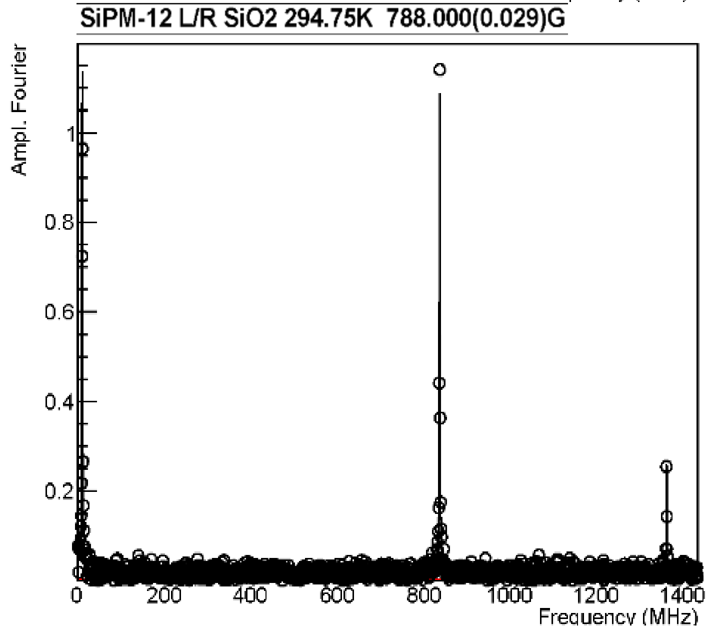


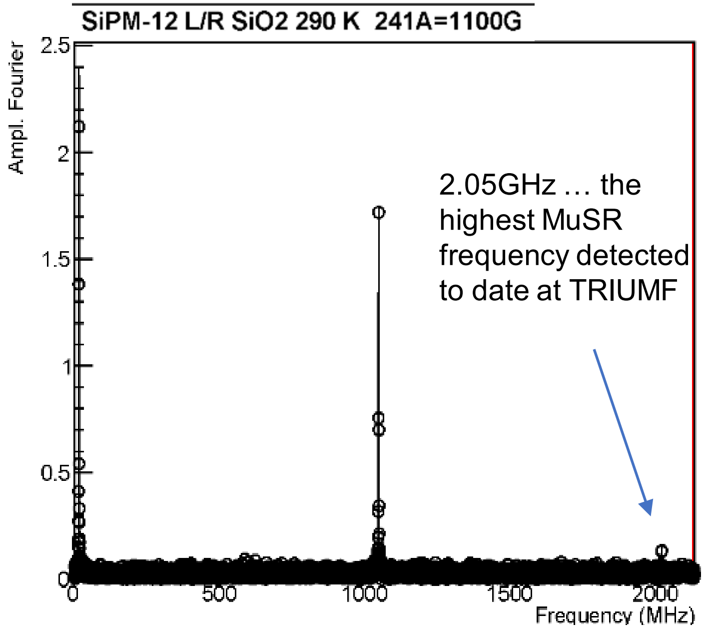
Test detector assembly above identical to that in 3T Spectrometer

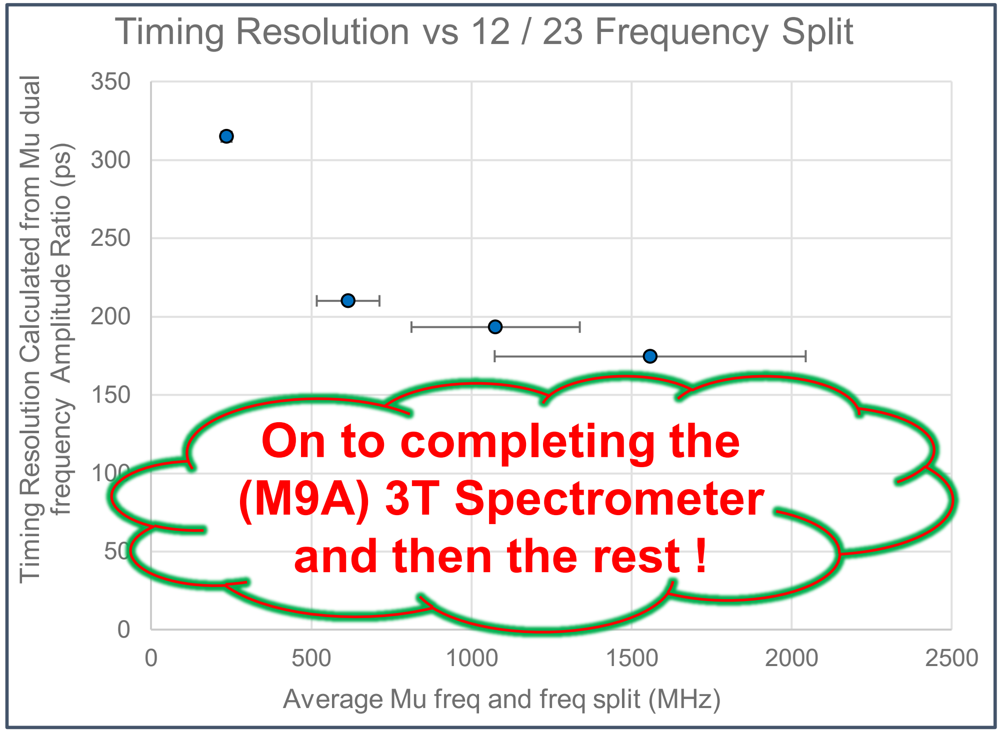
SiPM Spectrometers for the CMMS: Prototype Performance





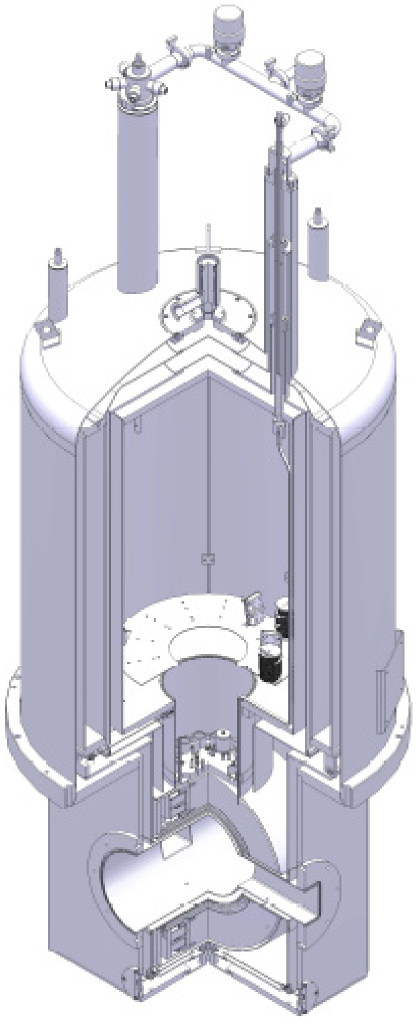






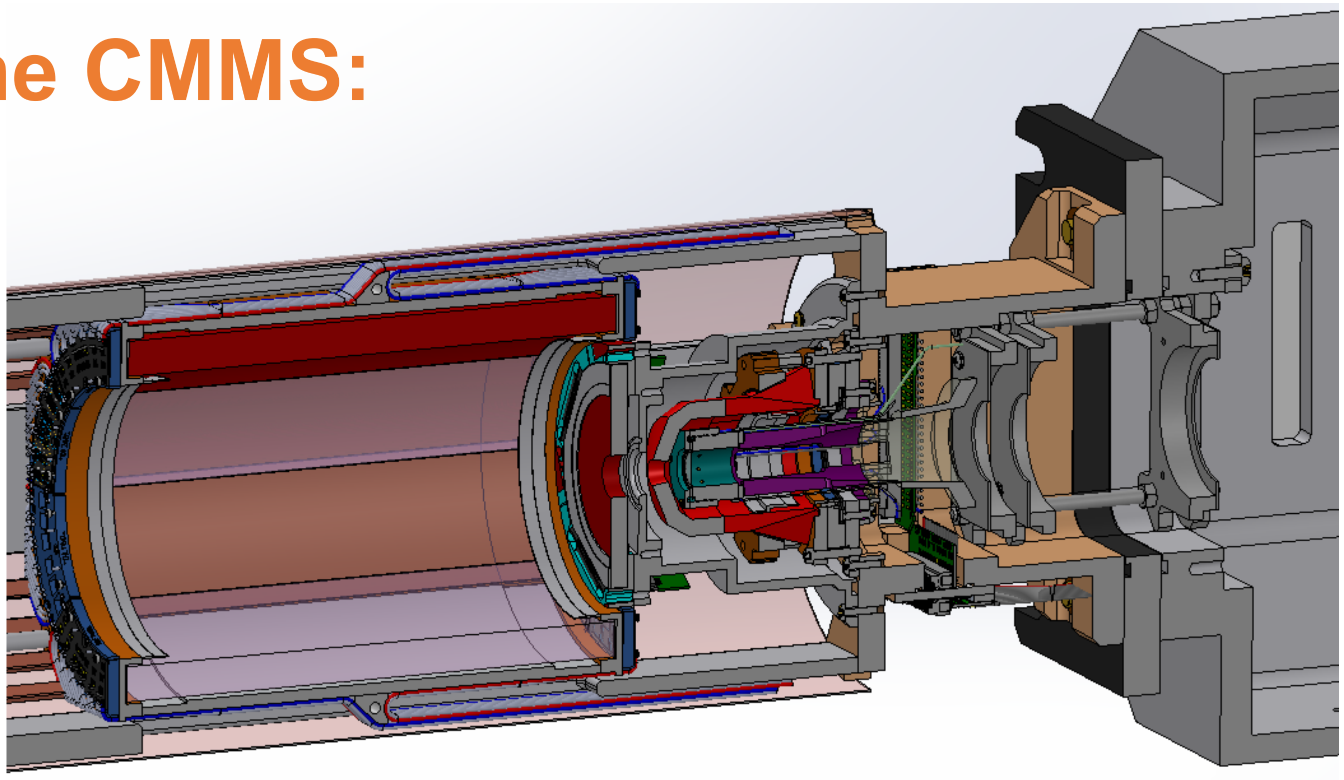
The timing resolution, as deduced from pairs of Muonuim transitions in a sample of fused SiO2, using a 3T Spectrometer transverse SiPM based large area detector pair.

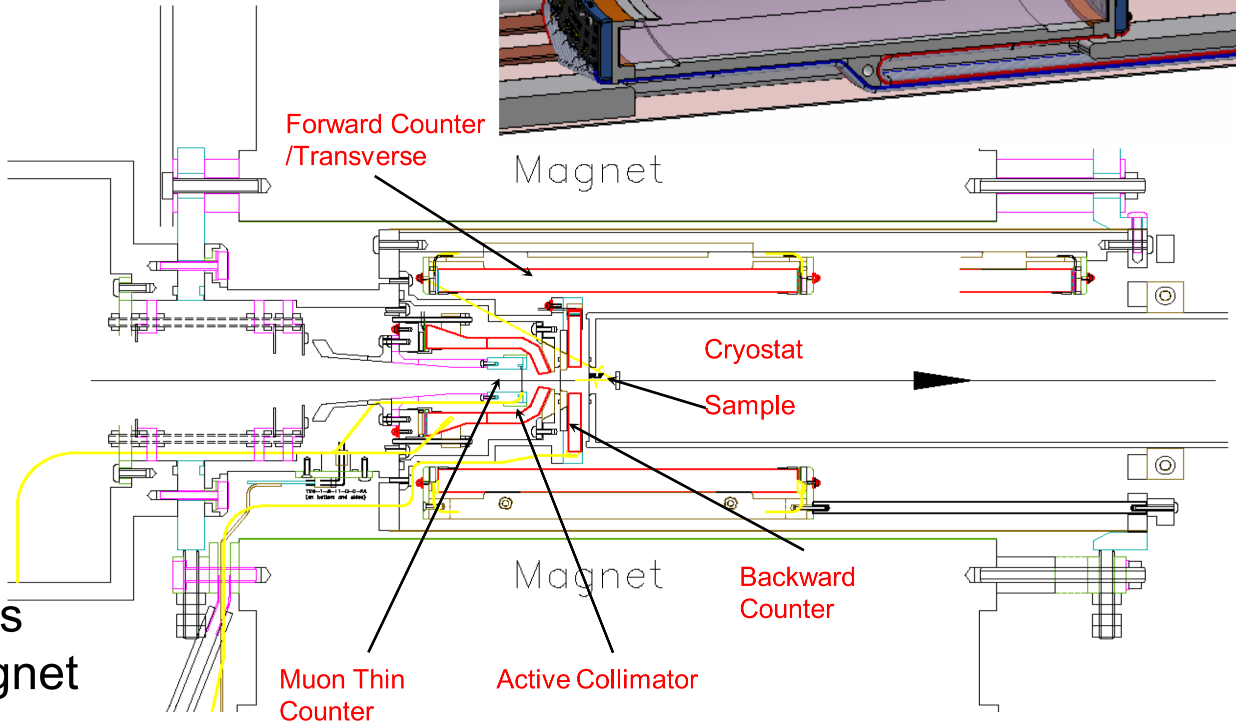
SiPM Spectrometers for the CMMS:



3T Oxford dual bore access
“M9“ Superconducting Magnet

3T: ….
the first
of many



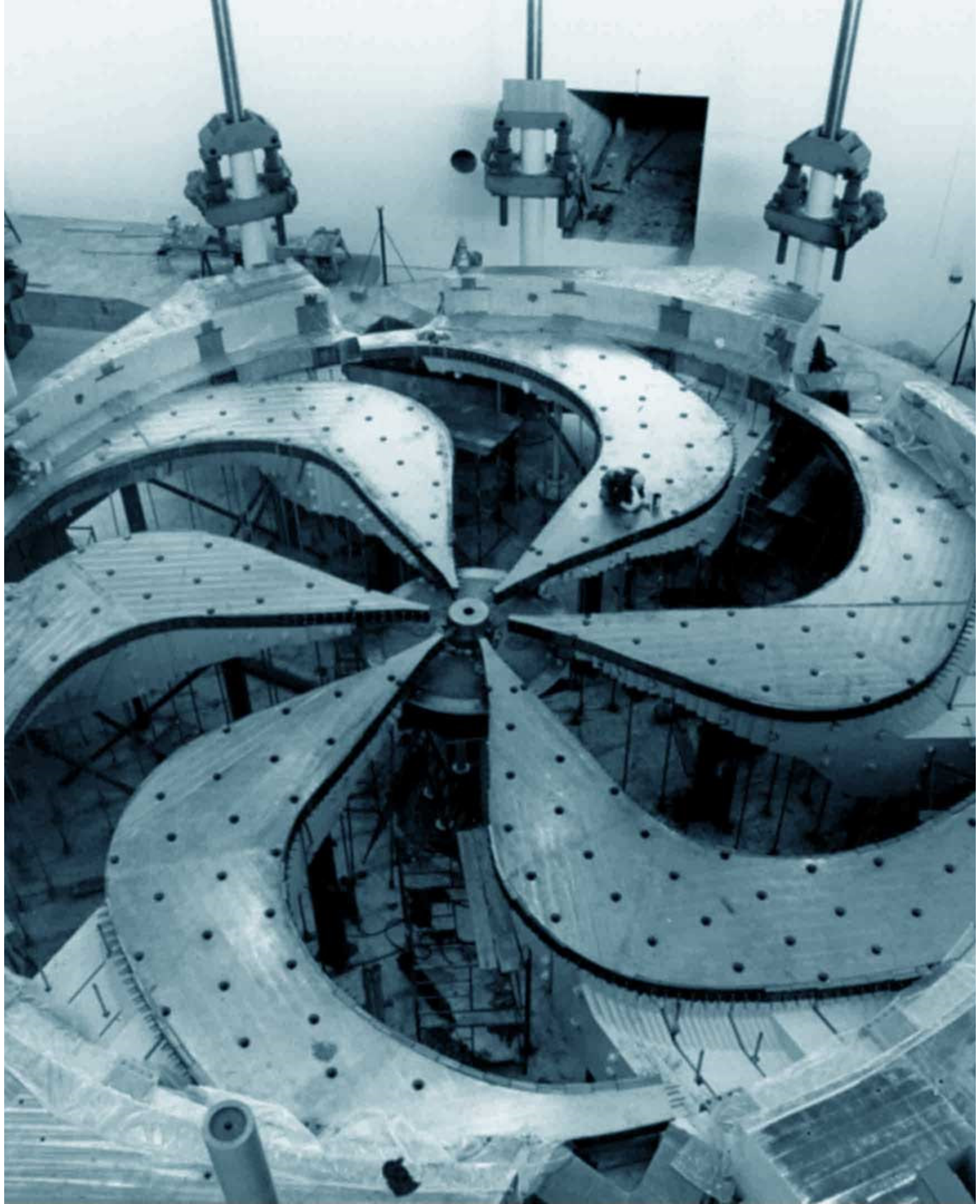


Designed by:
R. Henderson,
Miles Constable (Sci Tech)
& CMMS team

TRIUMF

Thank You

Merci



Discovery,
accelerated