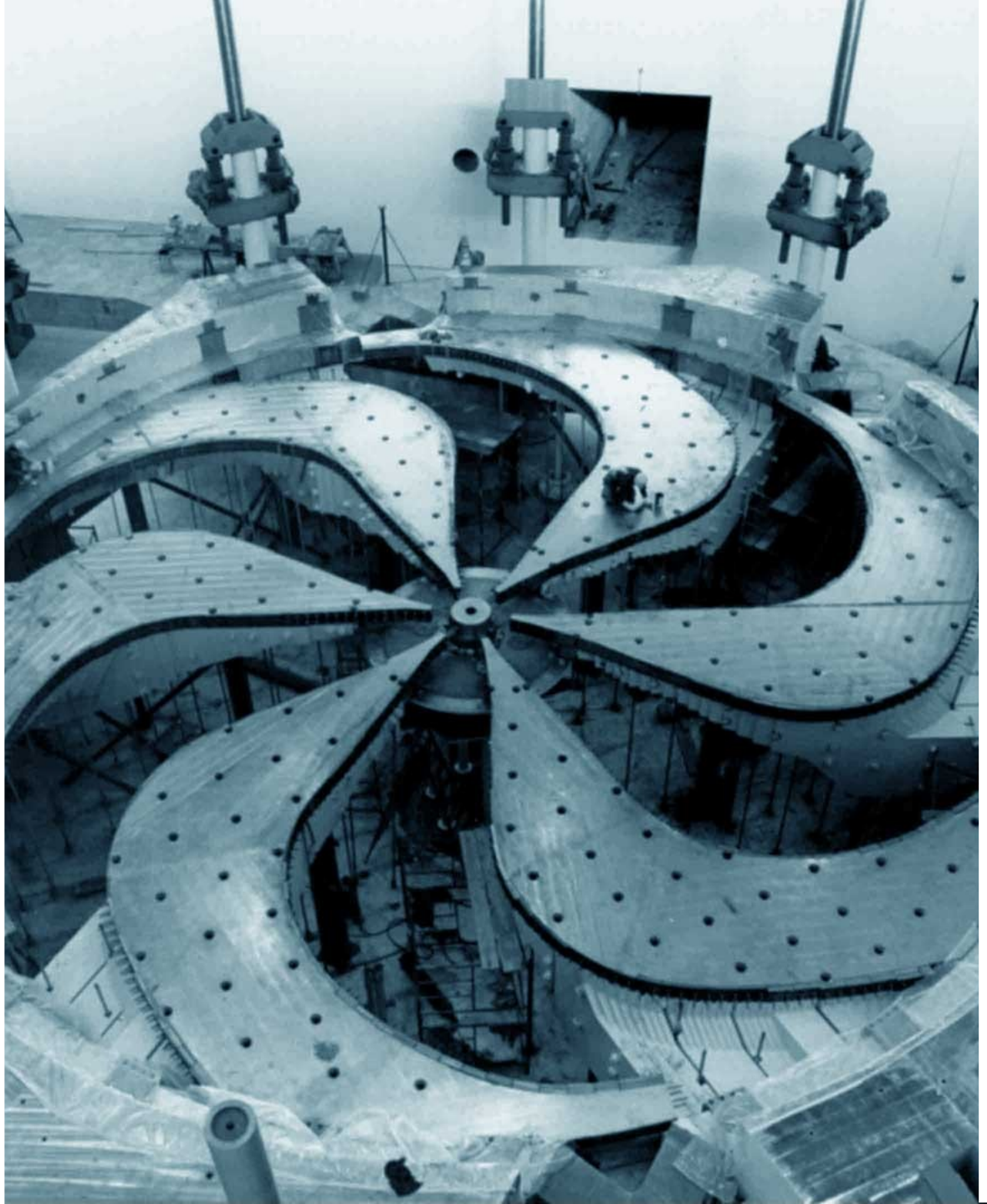
TRIUMF

Polarised Radioactive Isotope Science (POLARIS) at TRIUMF



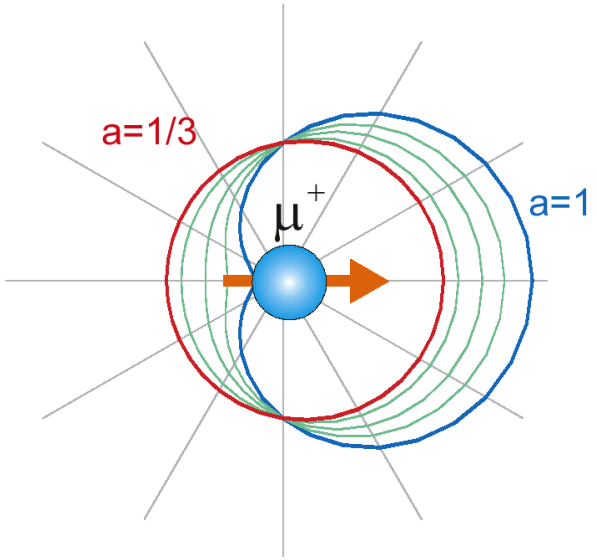
TRIUMF Science Week
19 August 2020

Comparison of Spin Resonance Techniques

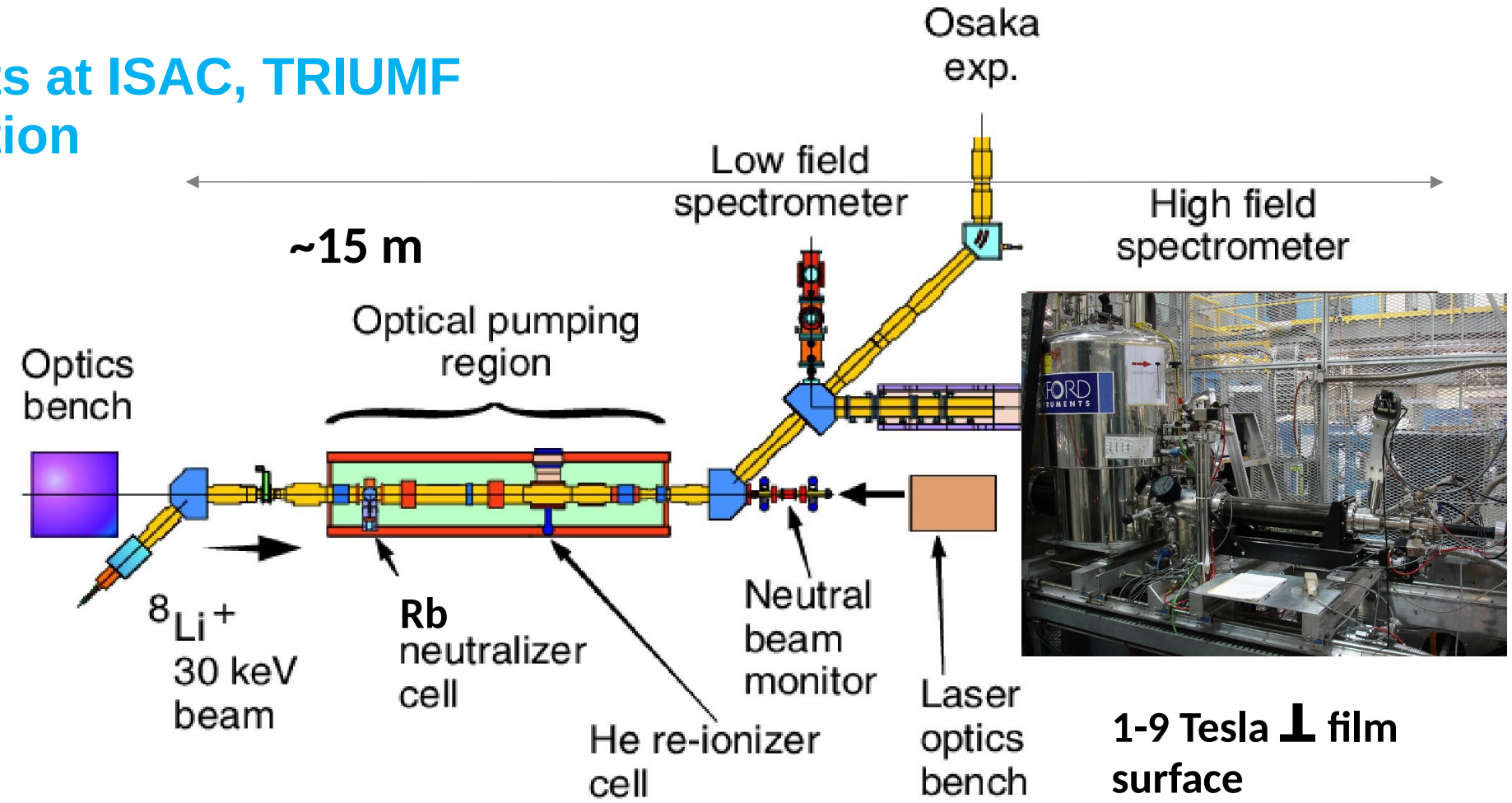
	NMR	Bulk μSR	8Li βNMR
Polarisation	<0.1	>0.8	
Detection	Electronic pickup	Anisotropic β decay	
Sensitivity	10^{17} spins	10^{7} spins	
T_1 range (s)	10^{-5}-10^{2}	10^{-11}-10^{-4}	10^{-3}-10^{3}
Range	0.5 mm	0.5 mm	5-300 nm

$^{8}Li^{+} \rightarrow {}^{8}Be^{2+} + e^{-} + \nu_e$

Lifetime=1.2 s



β-NMR Experiments at ISAC, TRIUMF
Current Configuration



1-9 Tesla ⊥ film surface
5-315 K

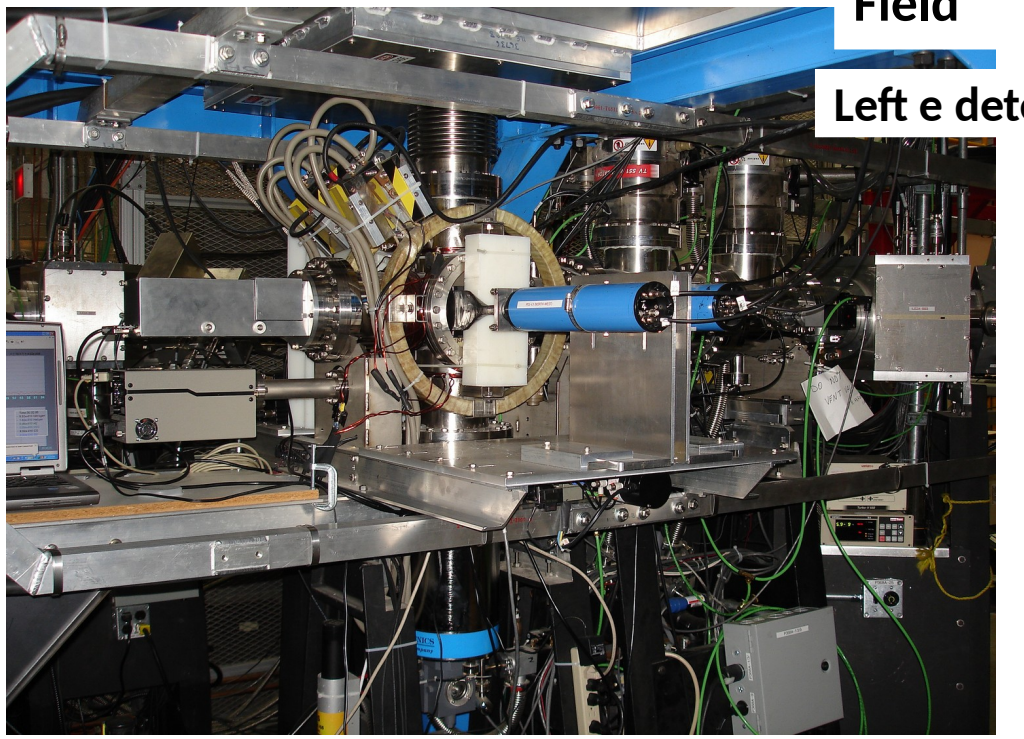
Unpolarised Li^+ is neutralised by charge exchange in Rb vapour.
Neutral Li is optically pumped with circularly polarised light.
Remaining charged fraction is deflected (removed) electrostatically.
He gas strips one electron to yield spin-polarised Li^+ ion.
Polarised ion beam is delivered, flipping helicity via ½ wave plate.
Scheduled switching @ 0.1 Hz

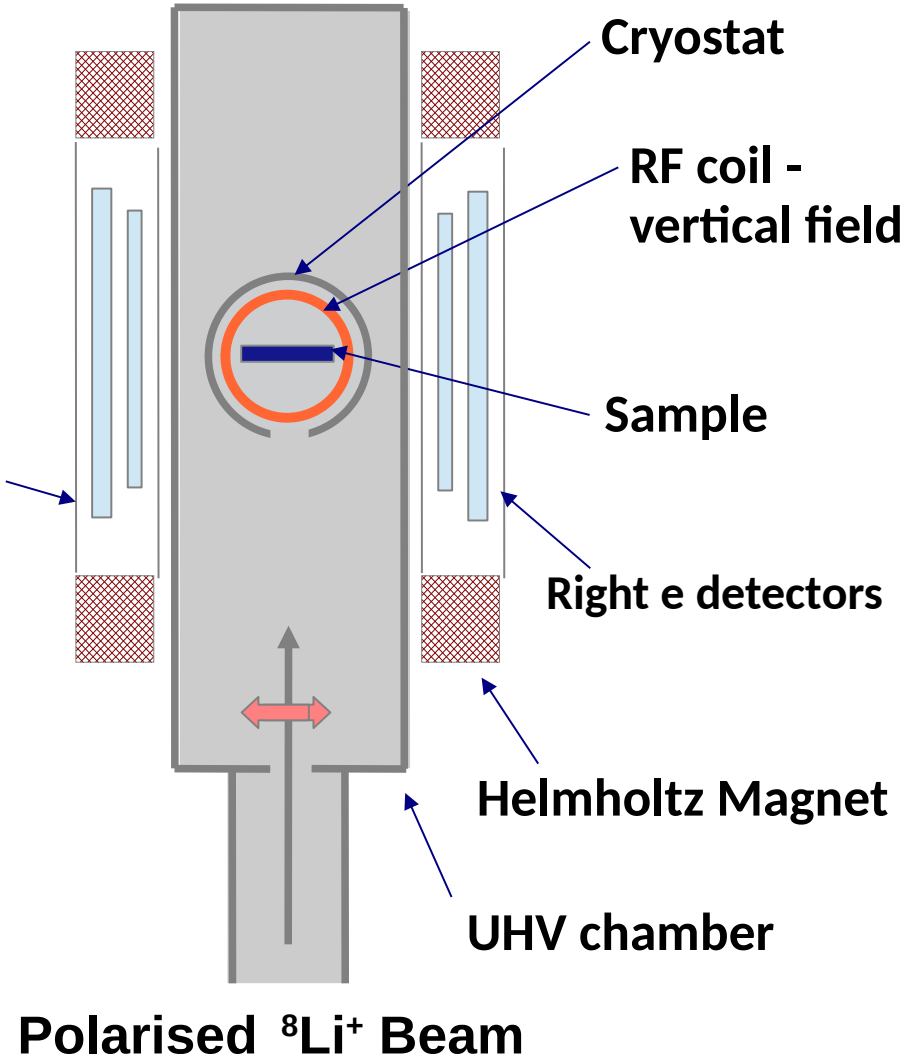
Low field / Zero field Spectrometer

- Spin is transverse to momentum.
- Simple, symmetric detectors external to UHV.

Plastic scintillators + photomultipliers

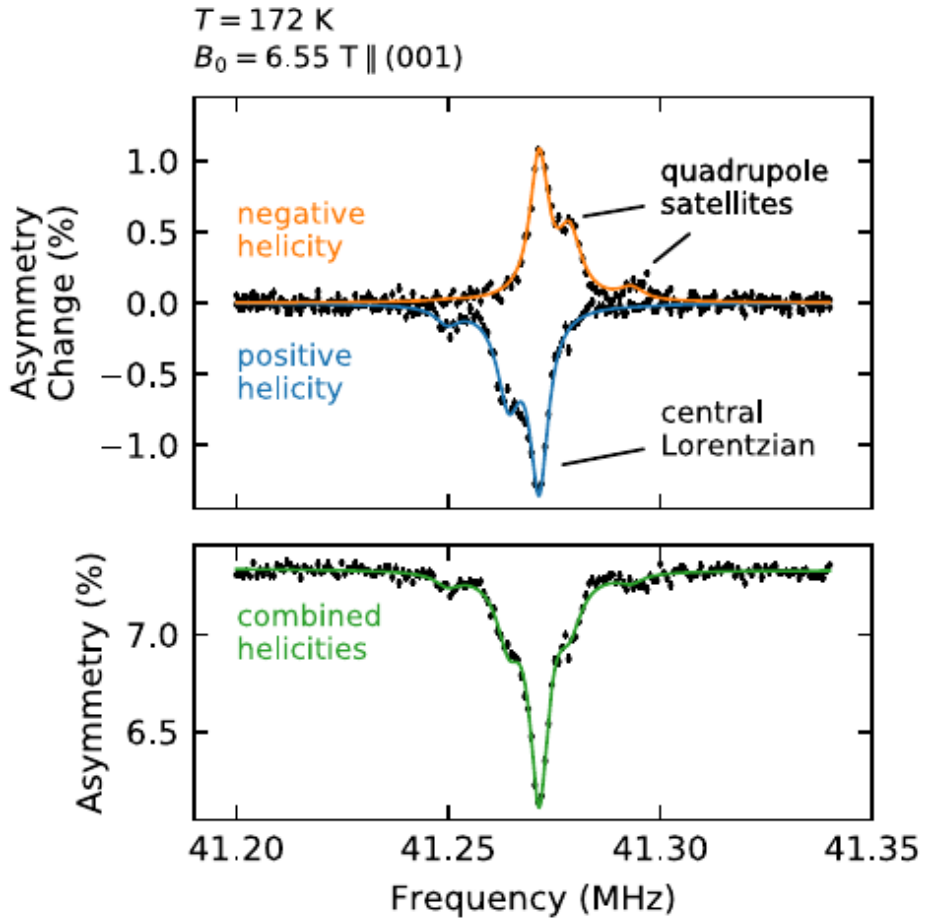
- UHV construction
- Temperature range : 4 – 300 K.
- Magnetic field : 0 – 24 mT

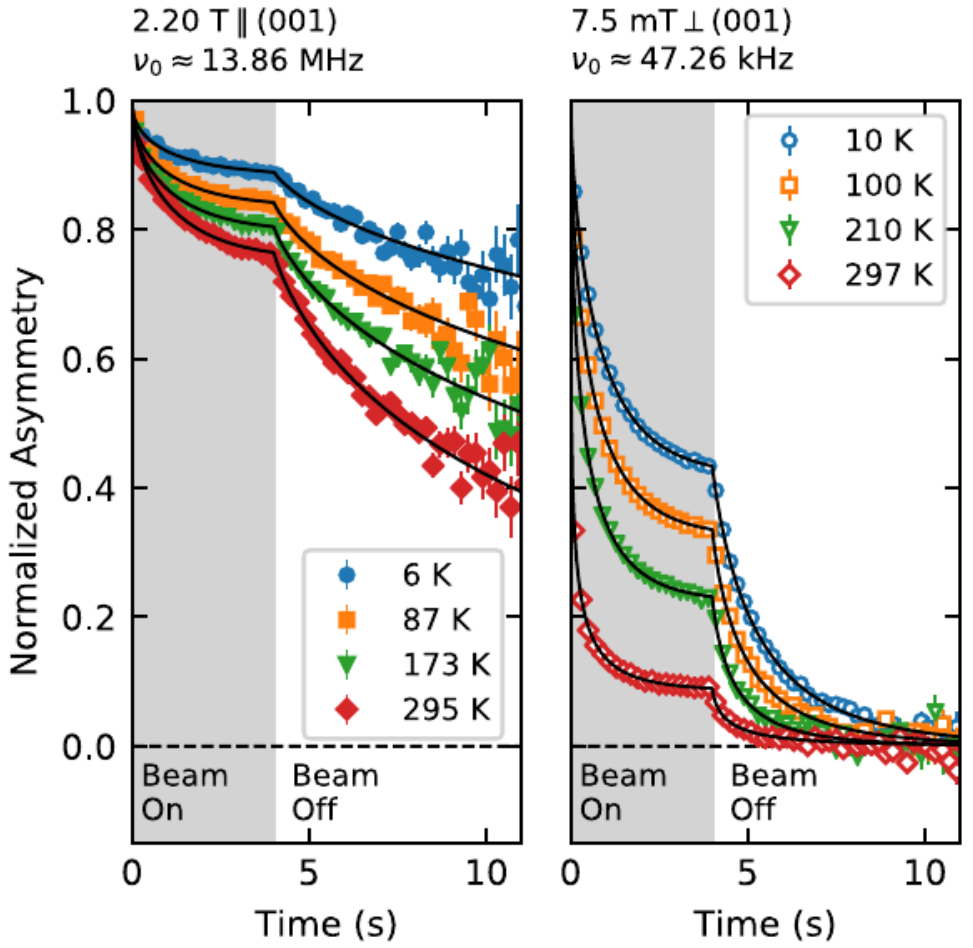




2nd downstream endstation - Zhongyuan Yao SRF R&D

8Li Resonance Spectra and Spin-Lattice Relaxation – Long Pulse Technique

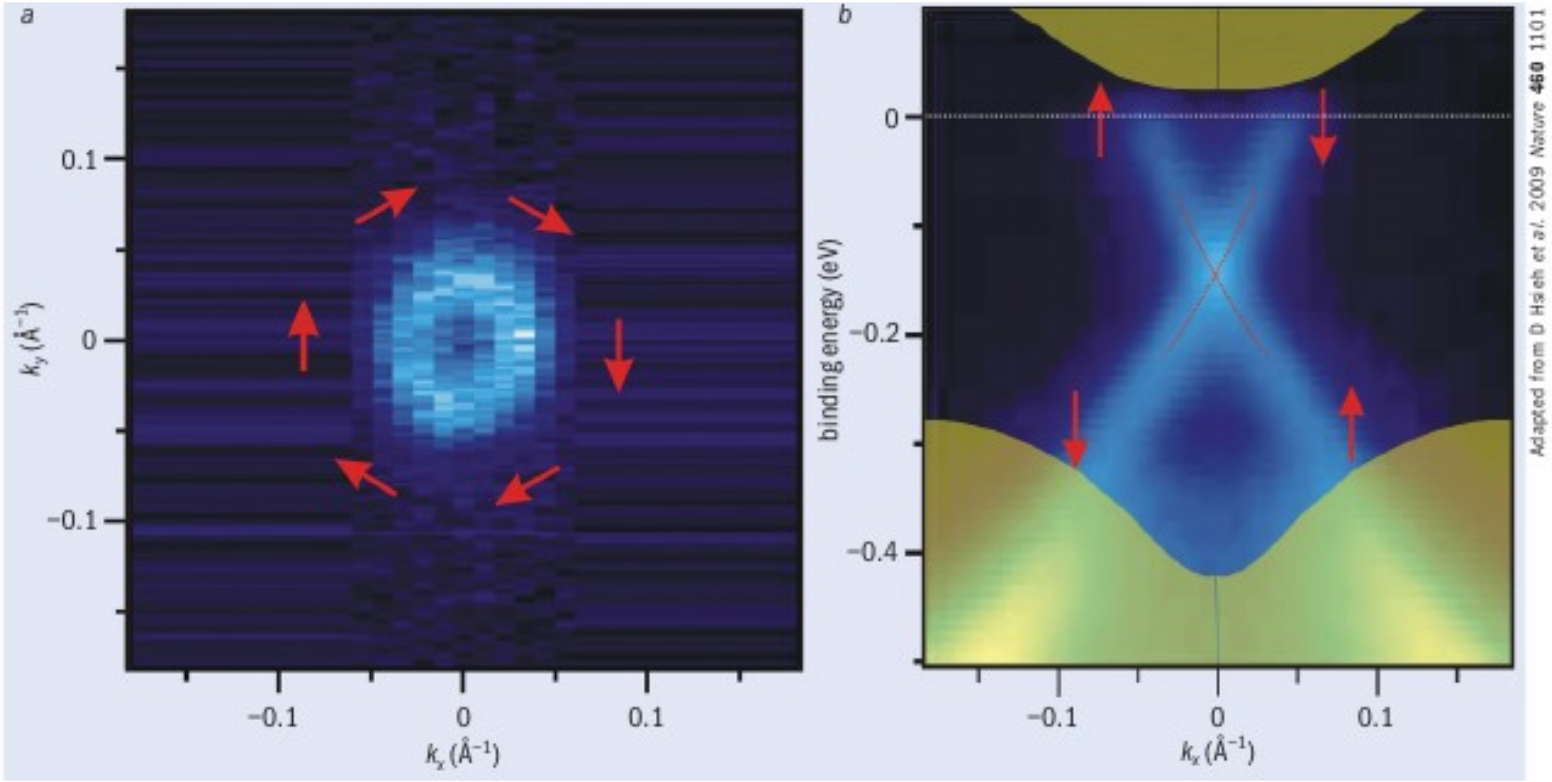




Bi_2Te_2Se

R M L McFadden et al, Phys Rev B 99, 125201 (2019)

Topological Insulators : New Electronic State of Matter with Spin Transport Applications

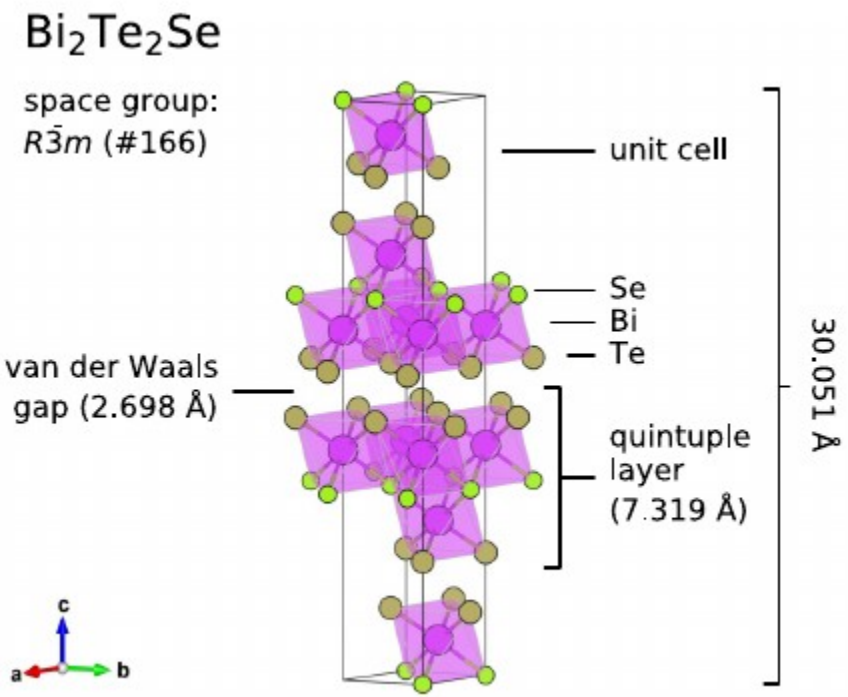


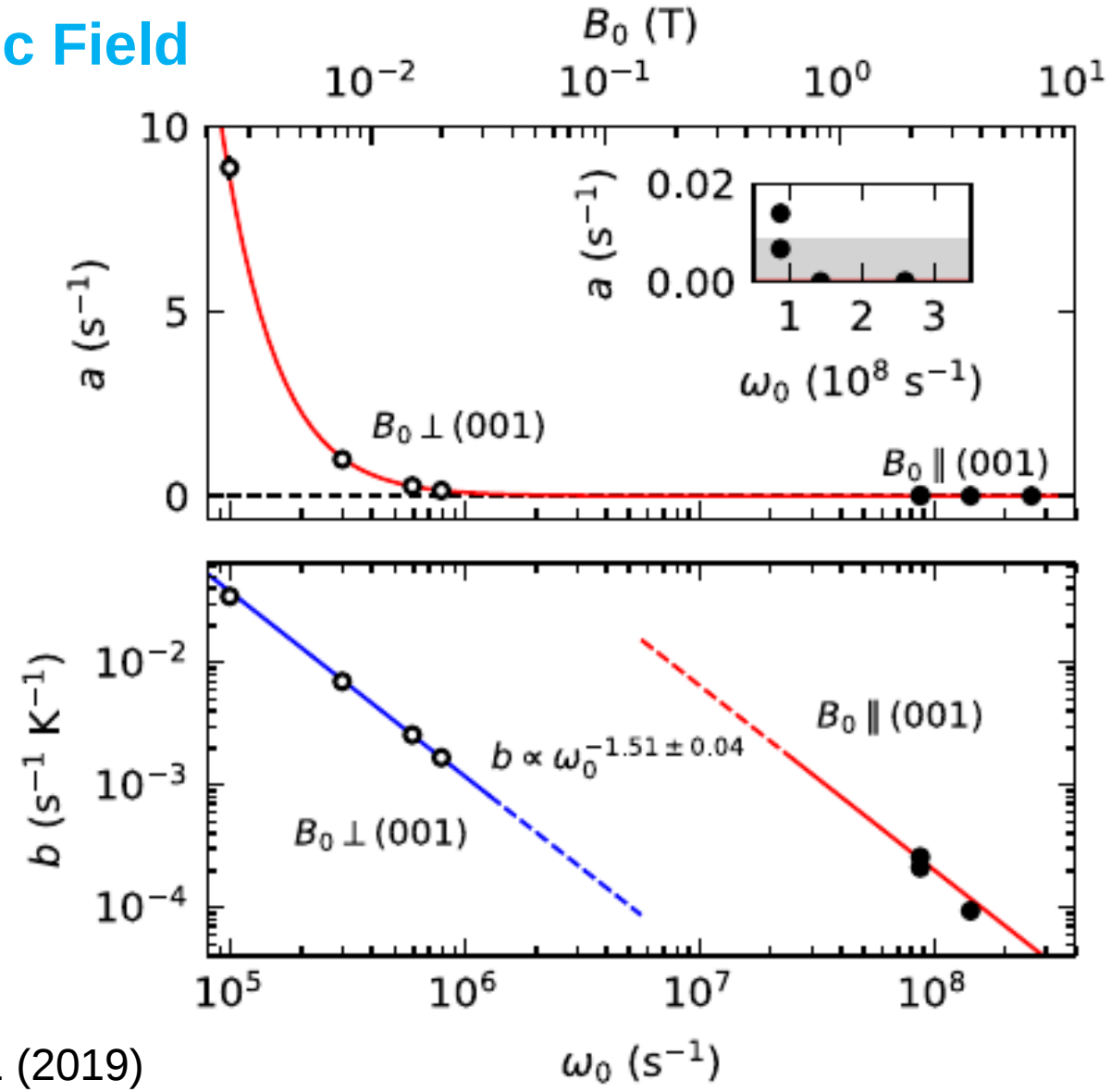
a) $Bi_{2-x}Ca_xSe_3$ Fermi-surface map measured by spin-resolved, angle resolved photoemission spectroscopy

b) Surface bands intersect at a “Dirac point” within the bulk band gap

D Hsieh et al, Nature 460, 1101 (2009)

Anisotropy and Unusual Magnetic Field Effects in Topological Insulator



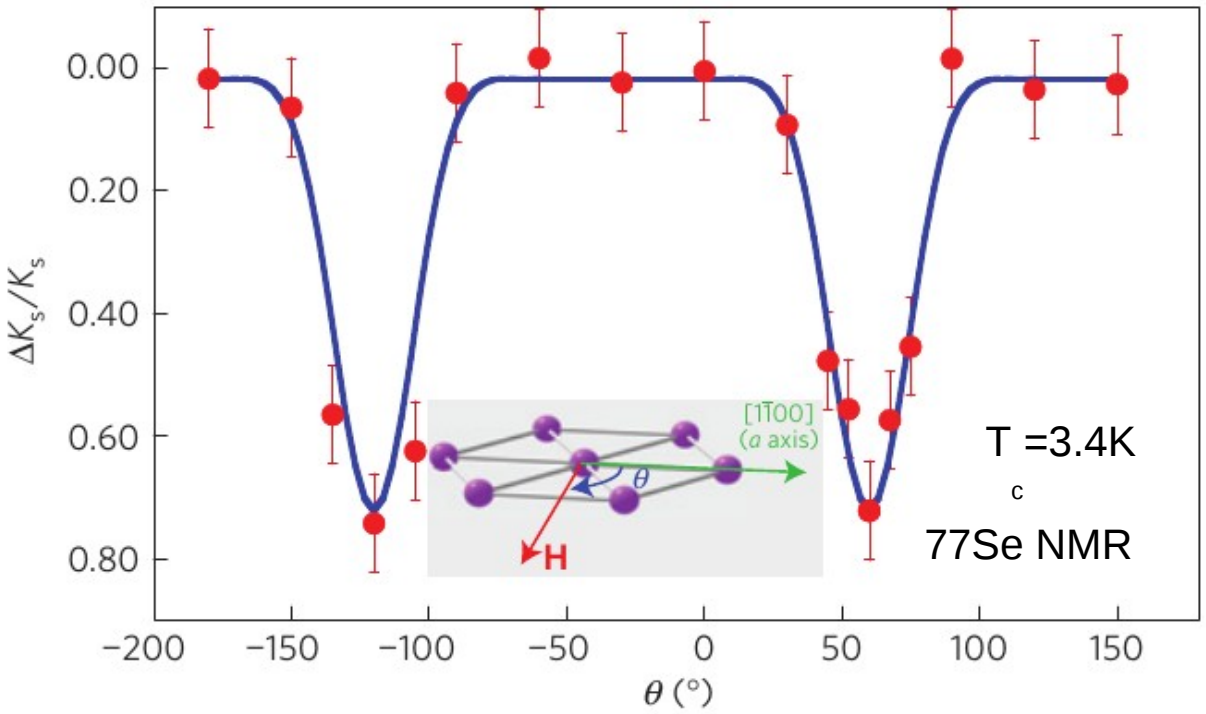


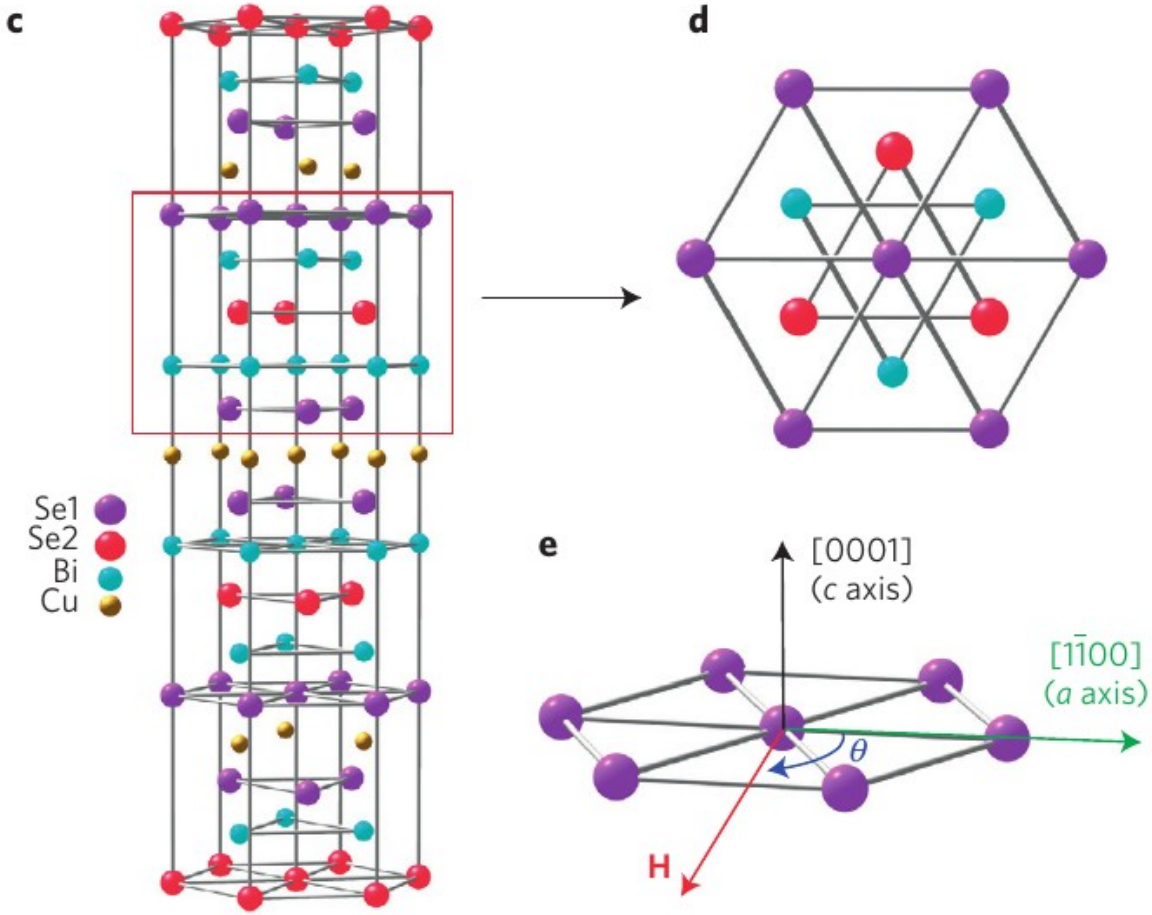
R M L McFadden et al, Phys Rev B 99, 125201 (2019)

TRIUMF

Spin Rotation Symmetry Breaking in the Superconducting State of $Cu_xBi_2Se_3$

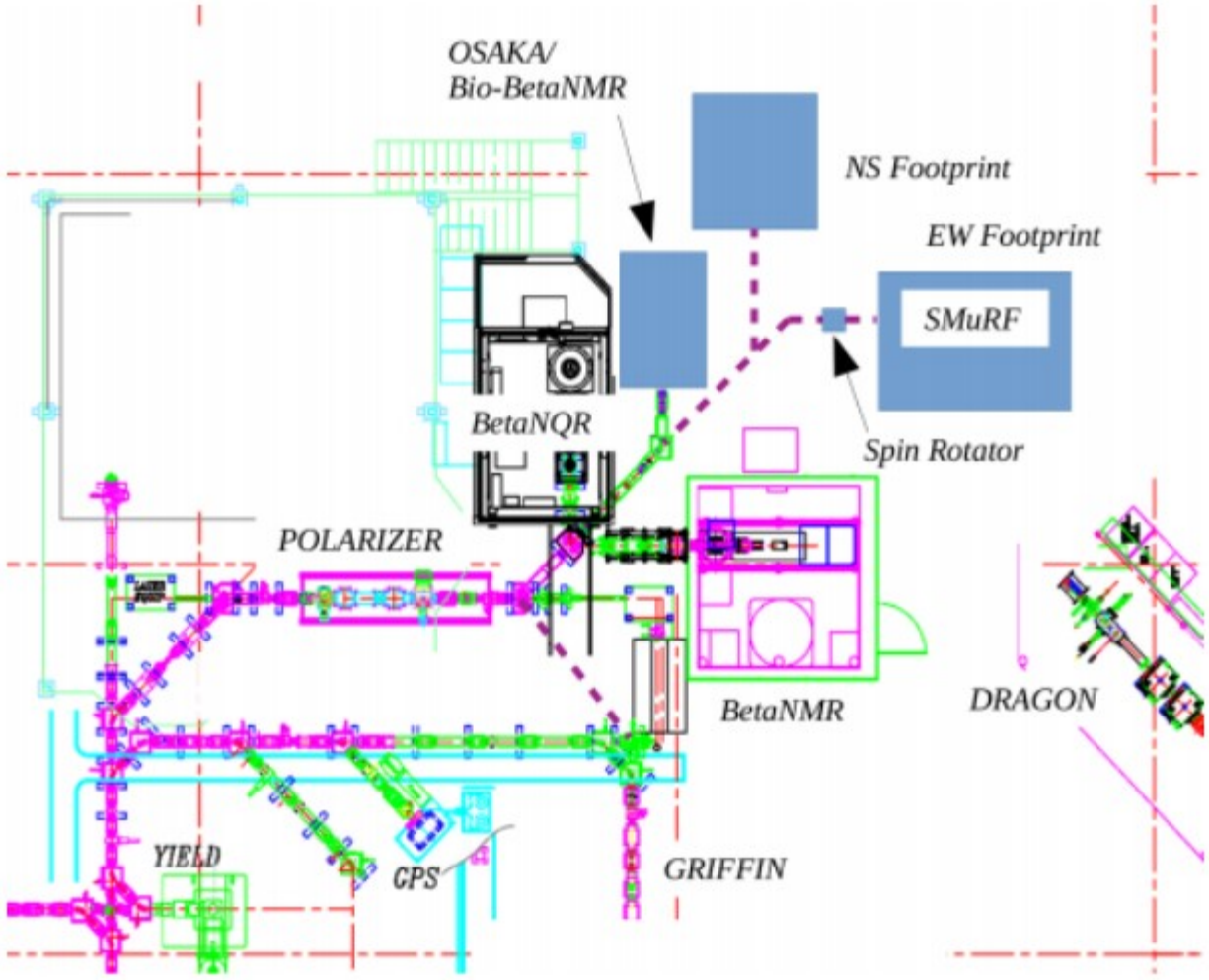
$\Delta Ks = K(3\ K) - K(1.4\ K)$





K Matano et al, Nature Physics 12, 852 (2016)

Proposed Layout in ISAC-1 Hall



OSAKA / Bio-BetaNMR :
dedicated β-NMR spectrometer for liquids and high vapour pressure applications, focussing on systems of biochemical and medical relevance; chemical Shift Measurements by ^{31}Mg, ^{54}Cu, ^{74}Cu, ^{75}Cu, ^{230}Ac, ^{232}Ac β-NMR

North South Footprint : Nuclear Structure and Symmetry
2x2.5 m footprint for modular experiments including resonant ionisation decay-spectroscopy;

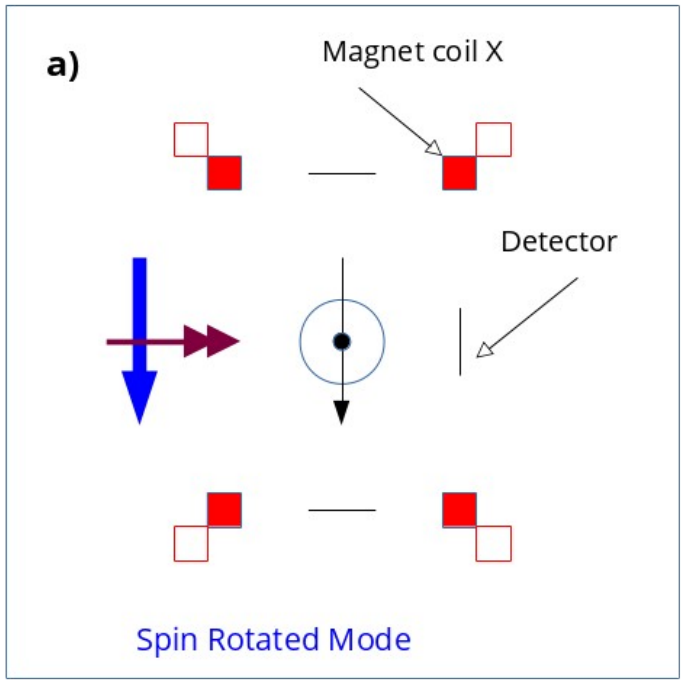
East West Footprint : Physical Science
dedicated 2.5x3 m high voltage platform, 0.1-30 keV ions
radio frequency spin echo and adiabatic inversion
vector magnet (0-2 Tesla || beam, 0-0.5 Tesla ⊥ beam)
1.5-300 K closed cycle cryostat

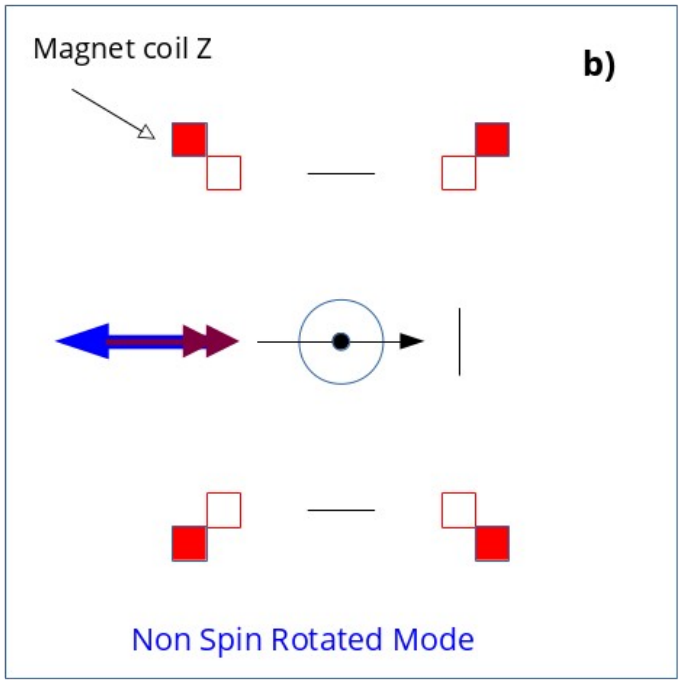
GRIFFIN : Nuclear Structure and Symmetry
3 m low energy polarised beam transport

POLARIZER beamline and Laser Upgrade

Spin Manipulation at Radio Frequencies (SMuRF)

Dunsiger,
Morris





Radioactive Ion Spin polarisation

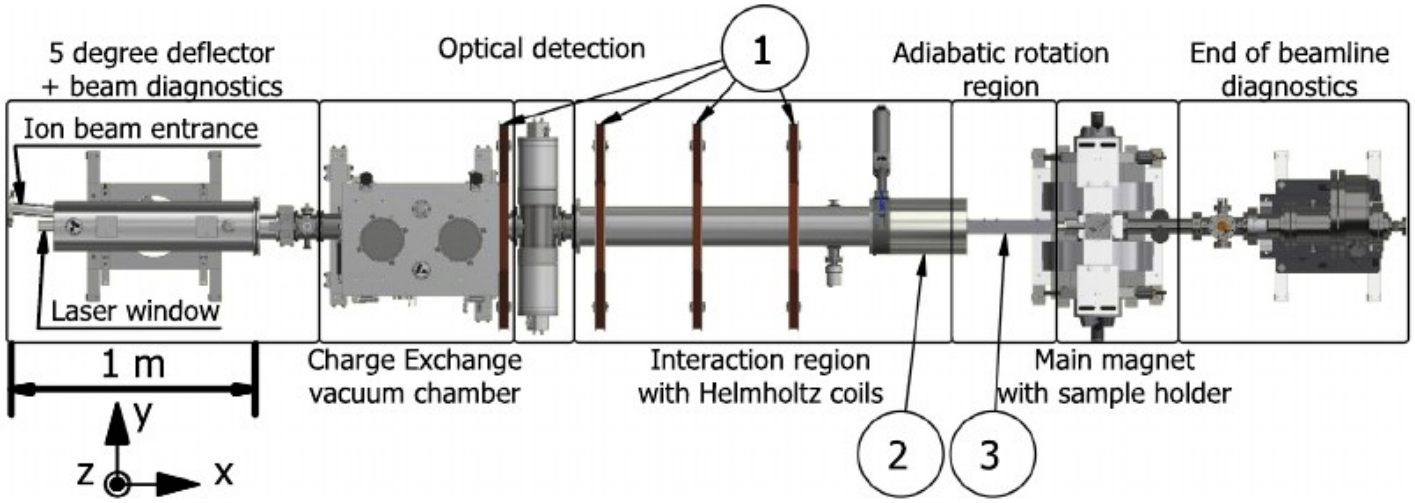
Radioactive Ion momentum

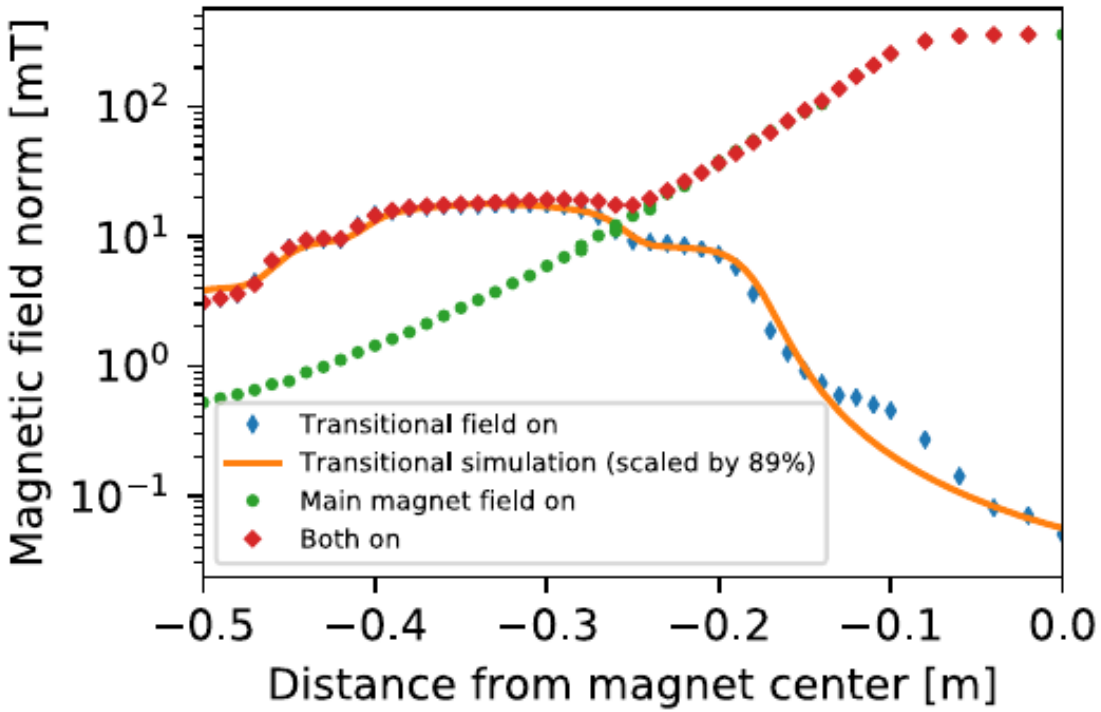
Magnetic field at sample position

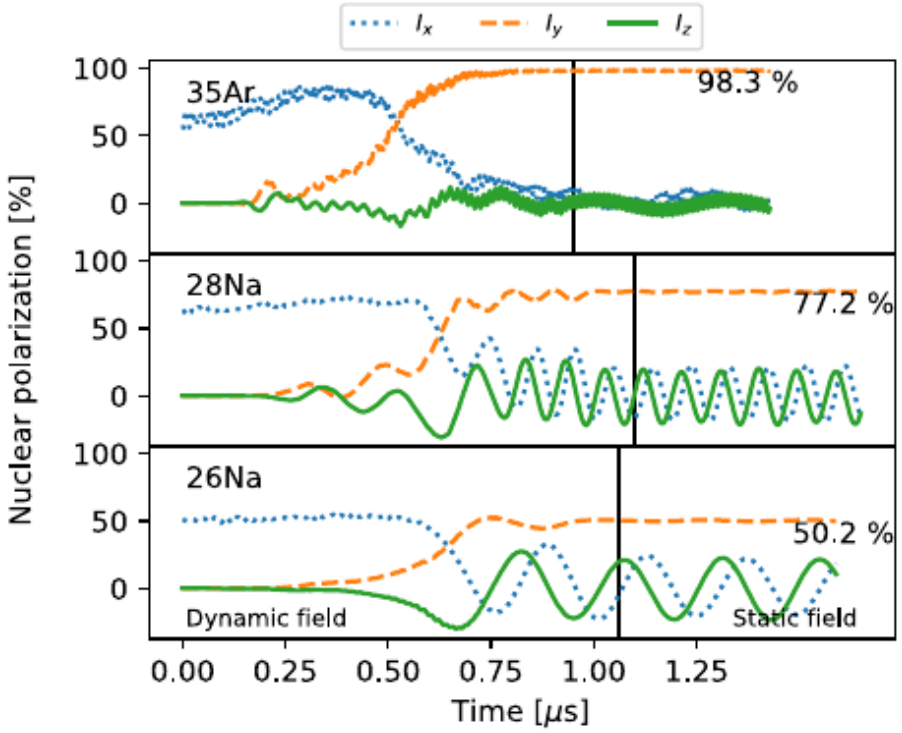
Radioactive ion spin rotation via Wien Filter (0.7 Tesla, 5600 V cm^{-1}, 0.2 m effective length)
(Design Note TRI-DN-01-5)
Longitudinal and Transverse detectors
Closed cycle vector superconducting magnet (0-2 Tesla ⊥ film surface; 0-0.5 Tesla ∥ film)

Adiabatic Spin Rotation on VITO Beamline ISOLDE

W Gins et al, Nuclear Inst. and Methods in Physics Research, A 925, 24 (2019)

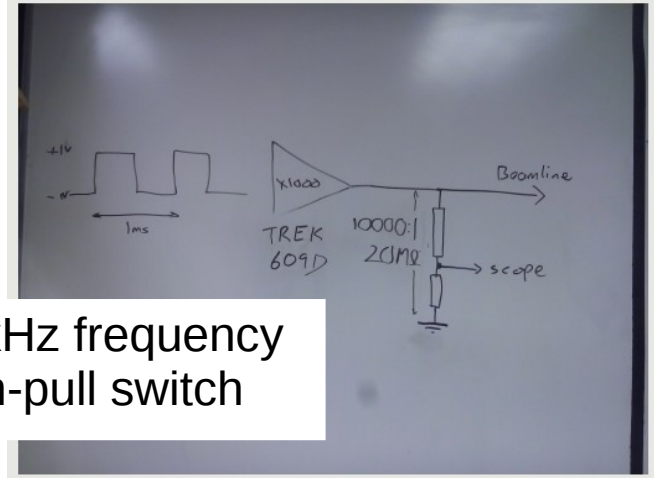


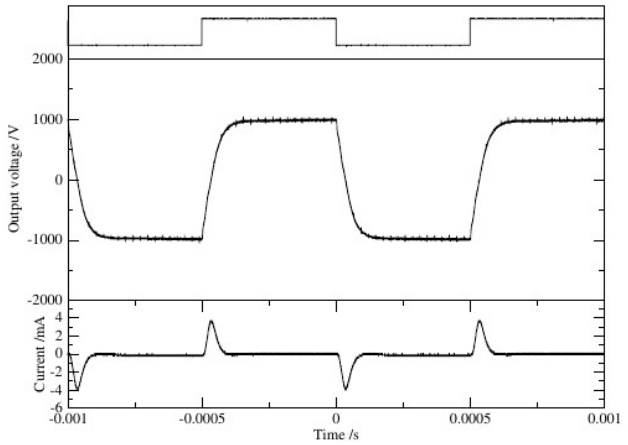




Rapid Switching of Beam and Helicity
Quasi continuous Beam on Three Channels

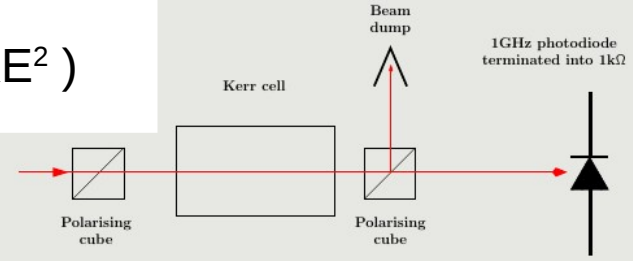
Rapid switching at kHz frequency using Trek HV push-pull switch

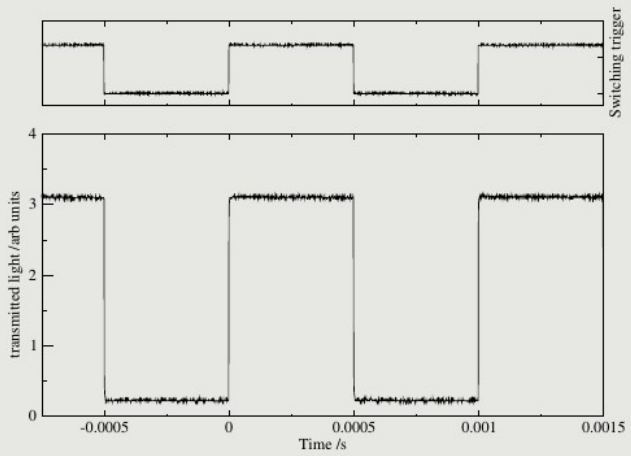




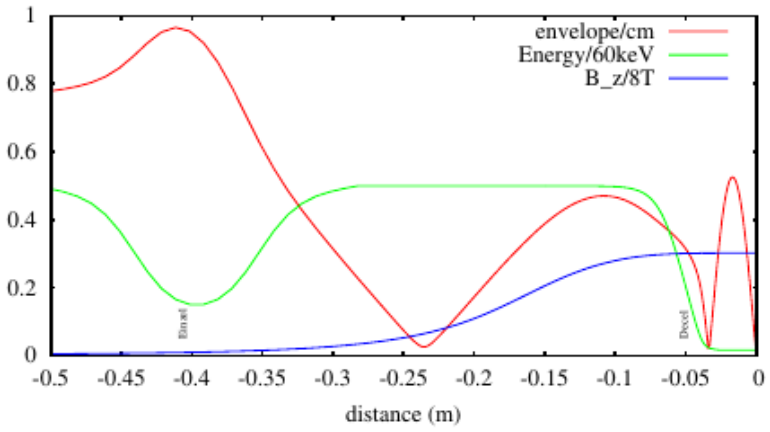
Proposed set-up identical to ILT:YCB3 plates into and out of TITAN. Routine pulsing at > 1kHz with 50:50 duty cycle

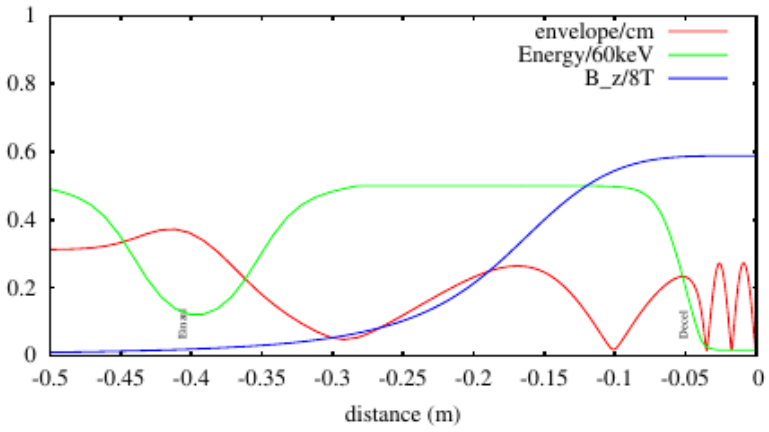
Kerr cell: birefringence under application of electric field ($\Delta n = \lambda K E^2$)

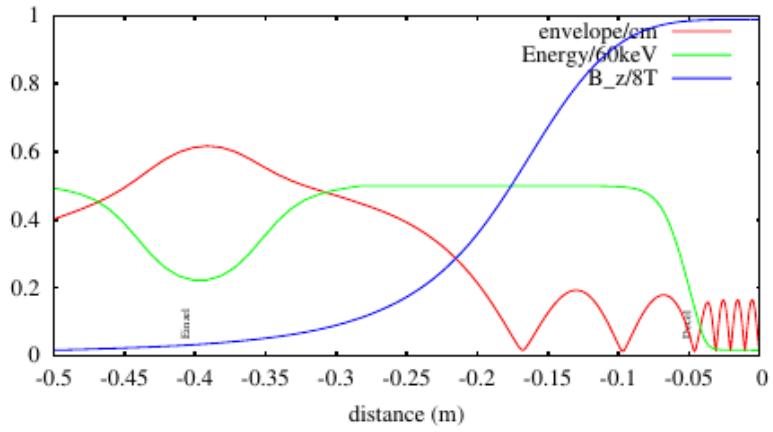




Feasibility of Micro Beam Envelopes



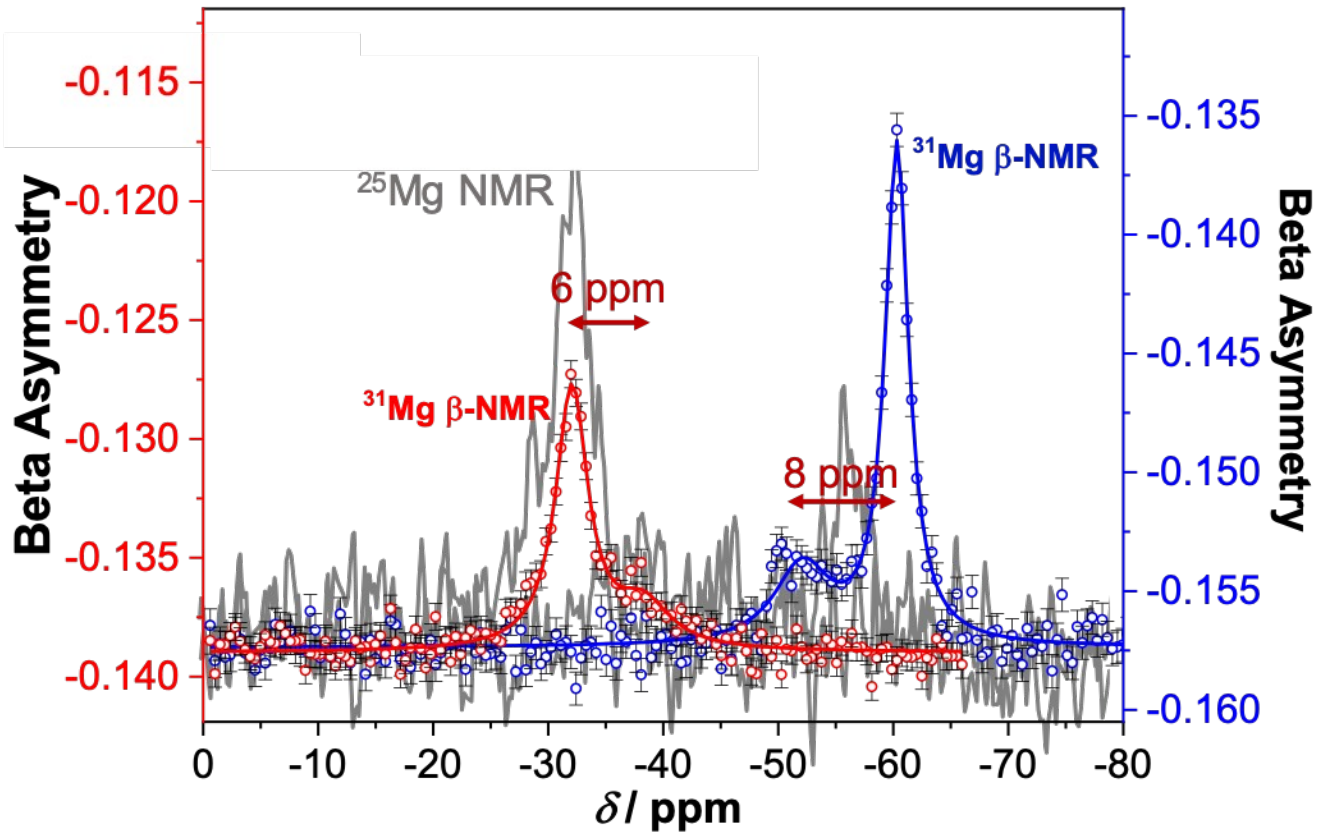




Simulated beam profile for 1000 eV implantation energy (decelerated from 30 keV) through a solenoid at 2.4, 4.7, 8.0 Tesla. The sample position is at a distance of 0 m. Note the envelope has a series of nodes. The minima in envelope are of radius a = 150 μm laterally in the x-y plane.
(R Baartman, TRIUMF).

^{31}Mg β-NMR of $MgCl_2$ in EMIM-Ac and EMIM-DCA

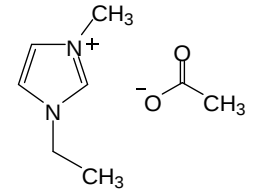
Stachura



D. Szunyogh, *et.al.* Dalton Trans. 2018, **47**, 14431-14435.

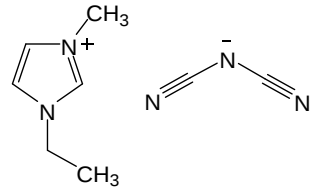
EMIM-Ac

1-ethyl-3-methyl-imidazolium-acetate



EMIM-DCA

1-ethyl-3-methyl-imidazolium-dicyanamide



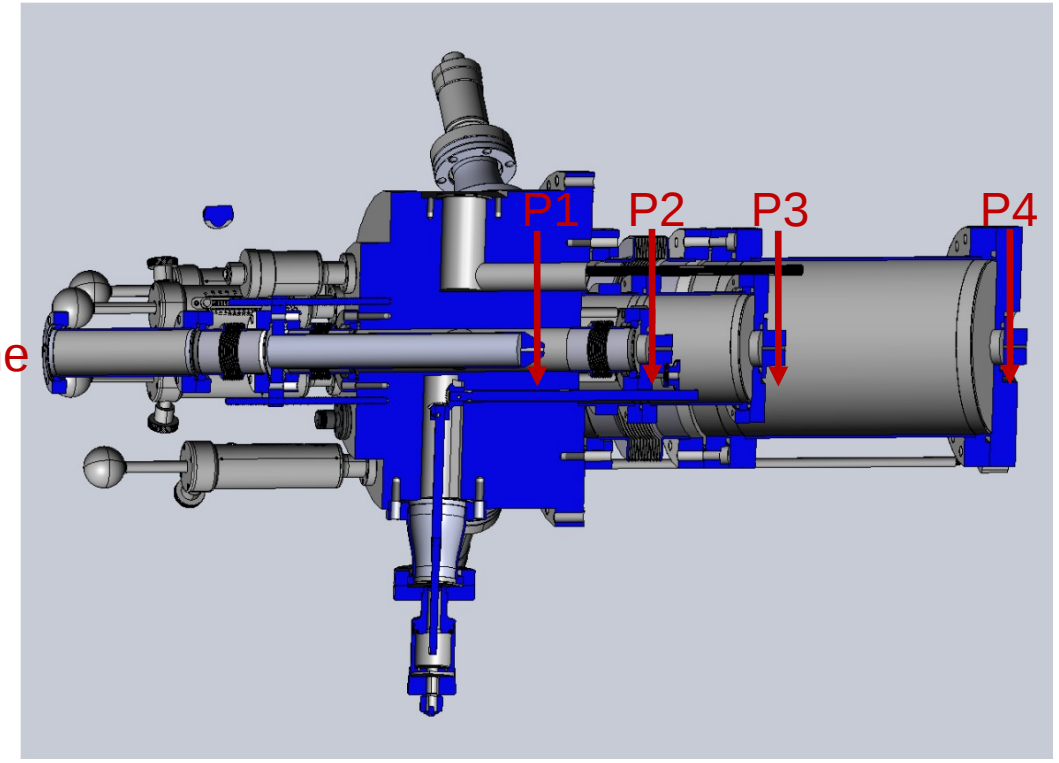
β-NMR	Properties	NMR
^{31}Mg	isotope	^{25}Mg
1/2	spin	5/2
3.41 T	magnetic field	11.7 T
22 °C	temperature	72 °C
2-4 uL	sample volume	550 uL
40 min	time of exp.	72 hours

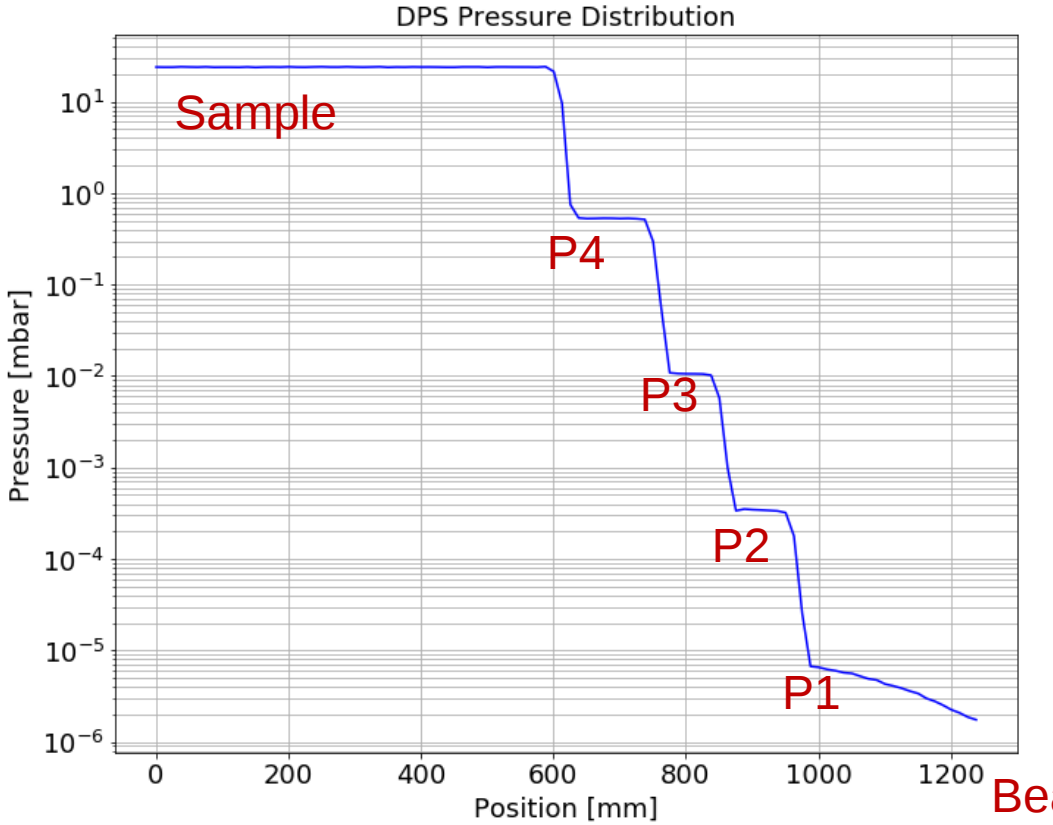
New bio-β-NMR Spectrometer at TRIUMF including Differential Pumping System

Commercial 7T superconducting magnet: 1 ppm homogeneity over 84 mm

Enable experiments between 230-365 K at pressures > 30 mbar (compatible with liquids)

- ✓ Three-stage system with four apertures of 4 mm (P1, P2, P3, and P4)
- ✓ Apertures fixed in length and size (4-5 mm); adjustable position





Pressure distribution simulated using Molflow+ - E Kallenberg

TRIUMF

The World's Rarest Drug

The Rarest Drug on Earth – A documentary from Vancouver-based Avocado Video, presented as part of TELUS' STORYHIVE initiative

- Probe site coordination geometry: types, number and geometric arrangement of coordinating atoms
- Allow for experiments at physiologically relevant concentrations
- Relative population (if several probe sites are present)
- Probe site dynamics on a ms timescale (exchange dynamics, molecular reorientational correlation times)

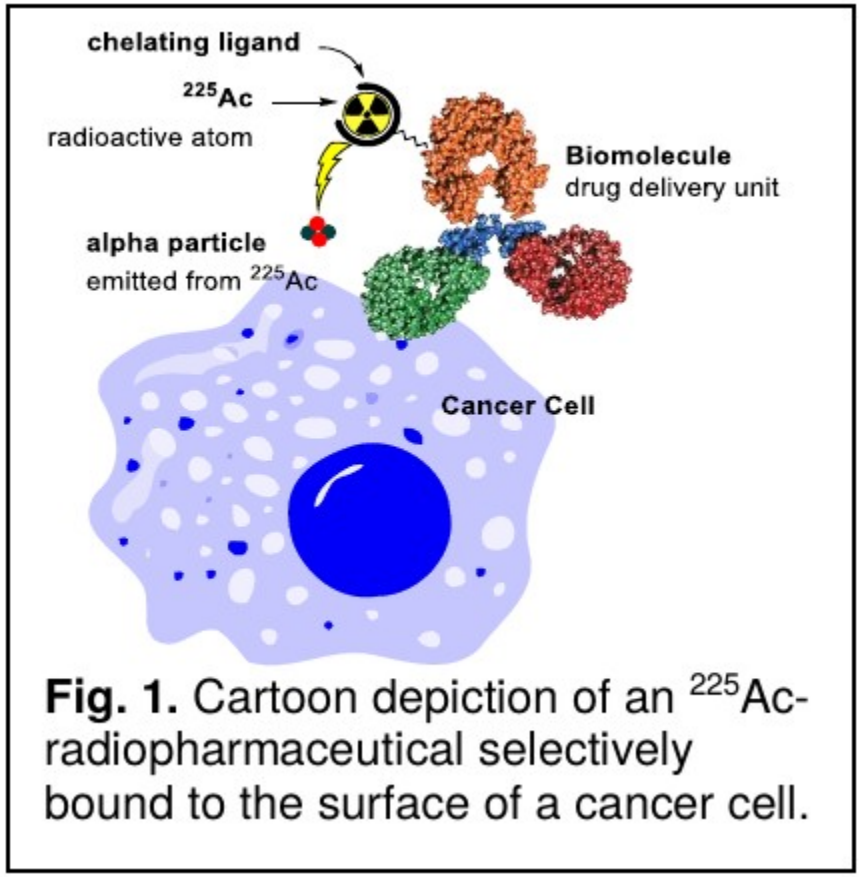


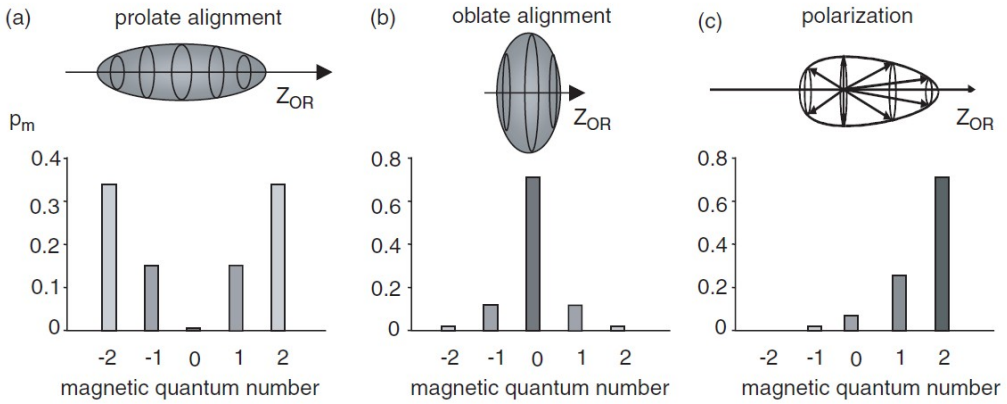
Fig. 1. Cartoon depiction of an ^{225}Ac-radiopharmaceutical selectively bound to the surface of a cancer cell.

Isotope	Half-life [s]	Spin	Decay mode	Magnetic moment [u_N]	Quadruple moment [b]	Yields [1/s]
^{230}Ac	122	+1	β^- (100%)	unknown	unknown	$3 \cdot 10^4$ *
^{232}Ac	119	(+1)	β^- (100%)	unknown	unknown	$1 \cdot 10^4$ *

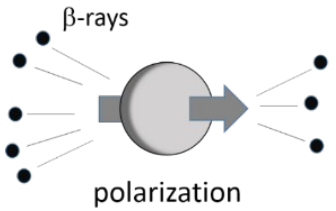
* The provided yields were measured using Re surface ion source. Yields of e.g. ^{225}Ac measured in Dec 2016 and Sep 2018 showed, however, an order of magnitude increase in yields when using TRILIS. This enhancement has also been showed for other measured isotopes.

Gamma Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN)

Rajabali, Garnsworthy



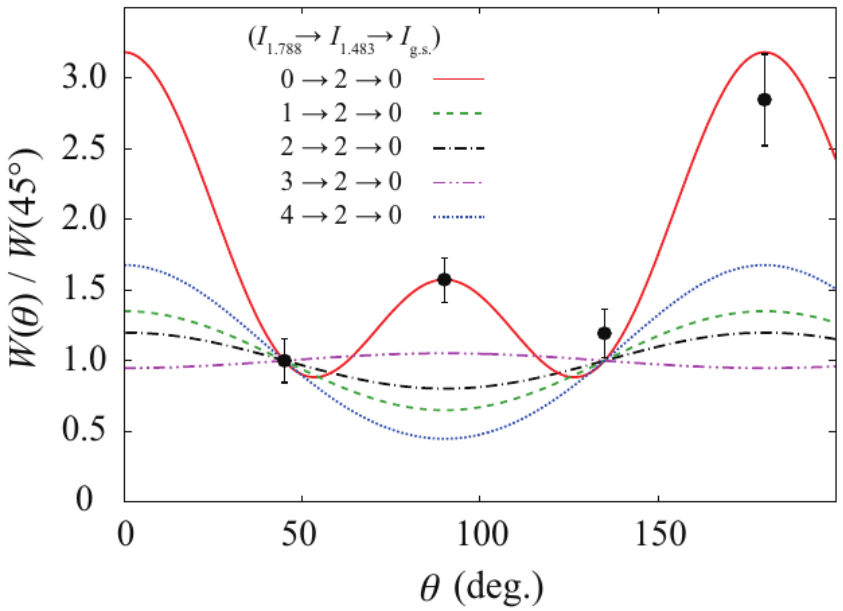
$$A = \begin{cases} -1 & (I_f = I_i - 1), \\ \dfrac{-1/(I_i+1) - 2\tau\sqrt{I_i/(I_i+1)}}{1+\tau^2} & (I_f = I_i), \\ \dfrac{I_i}{I_i+1} & (I_f = I_i + 1). \end{cases}$$

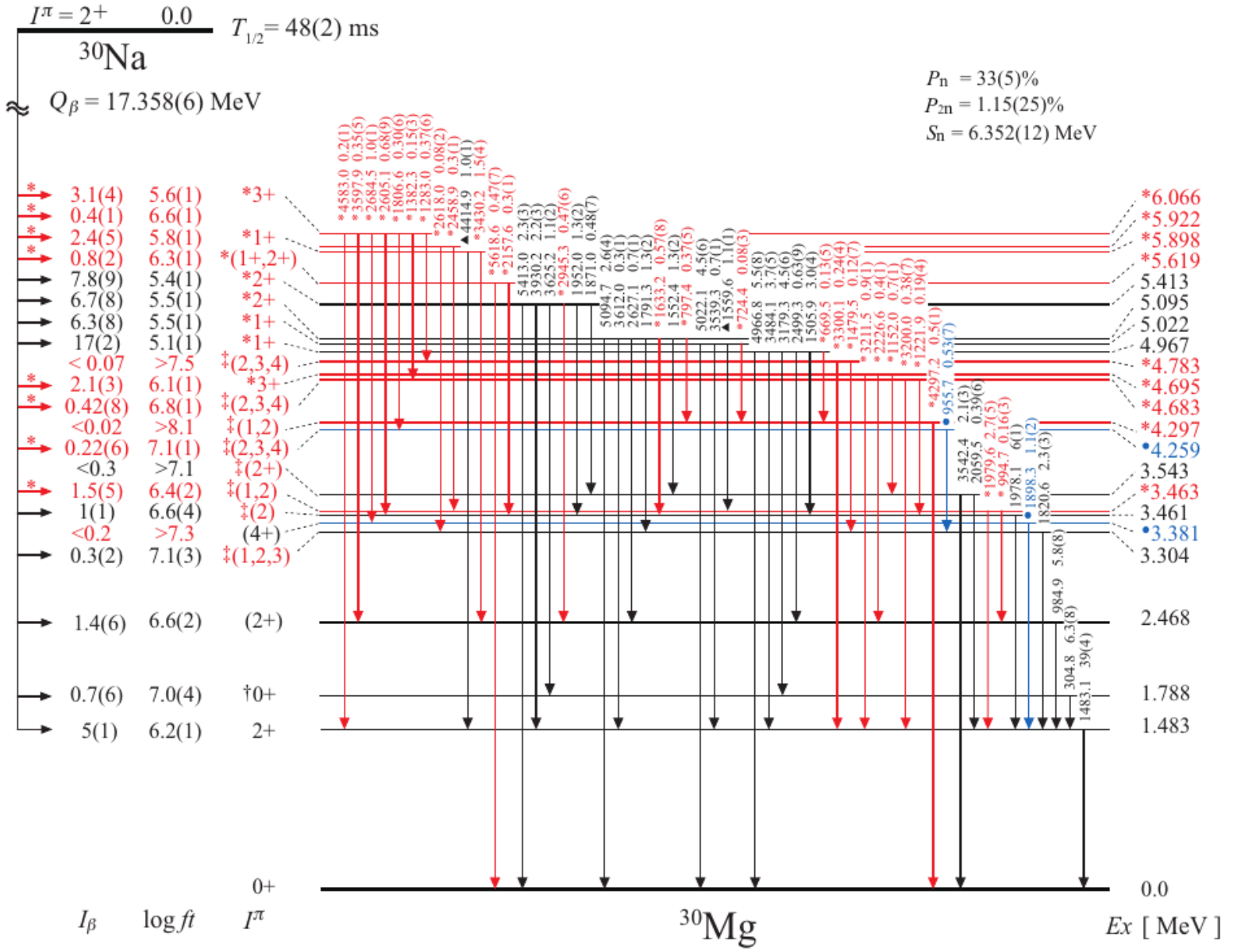


H Nishibata et al. Physical Review C 99, 024322 (2019)

The asymmetry parameter A is a constant depending on the daughter state spin value. Spin polarization is measured by counting the beta decay along the orientation axis.

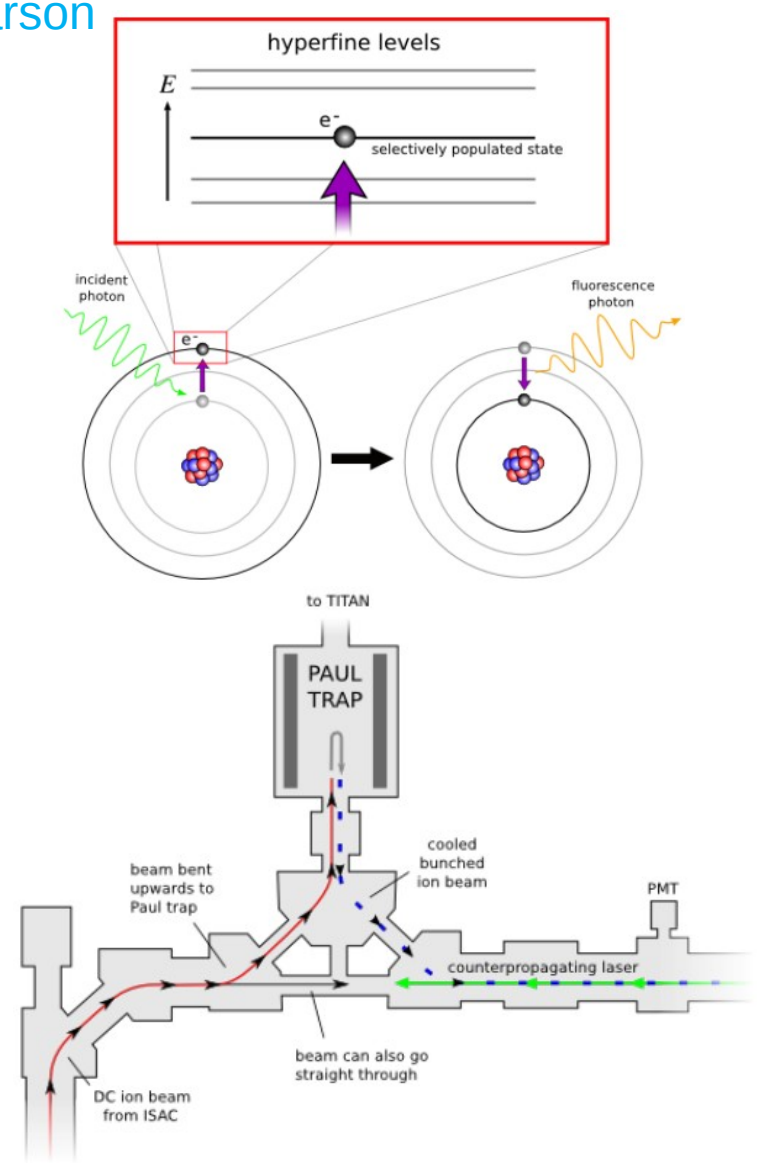
Revised β Decay Scheme
30Na → 30Mg





Collinear Fast-Beam Laser Spectroscopy

Pearson



Individual half lives of a ground and isomeric state of 98, 98mRb

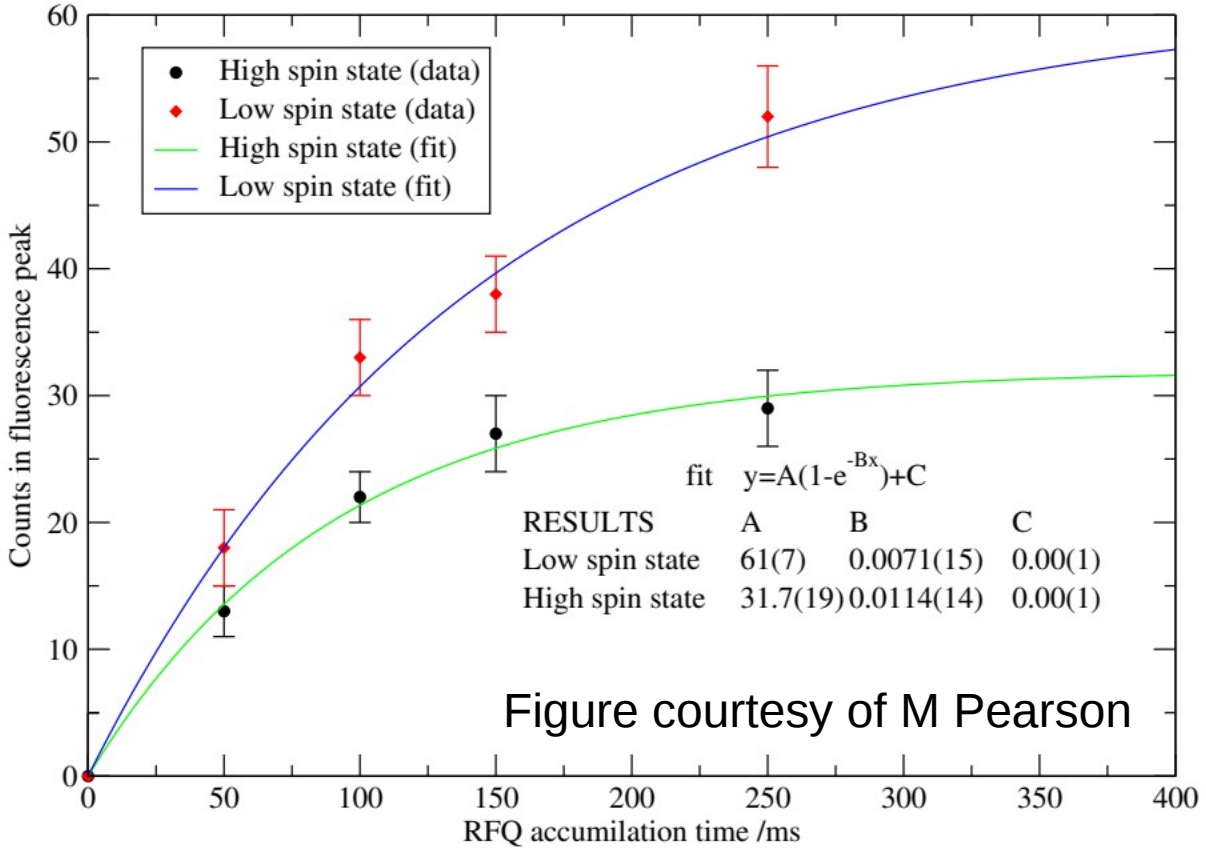


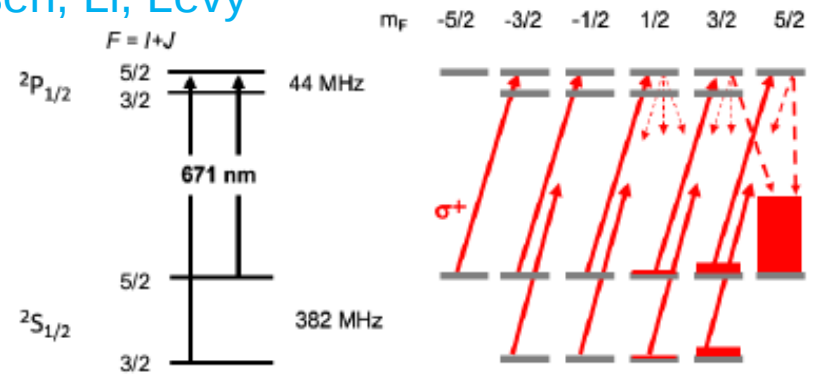
Figure courtesy of M Pearson

Accepting light signals whose timing coincides with the presence of an ion “bunch,” the background signal due to laser scattering and “dark counts” in the photomultiplier is greatly suppressed

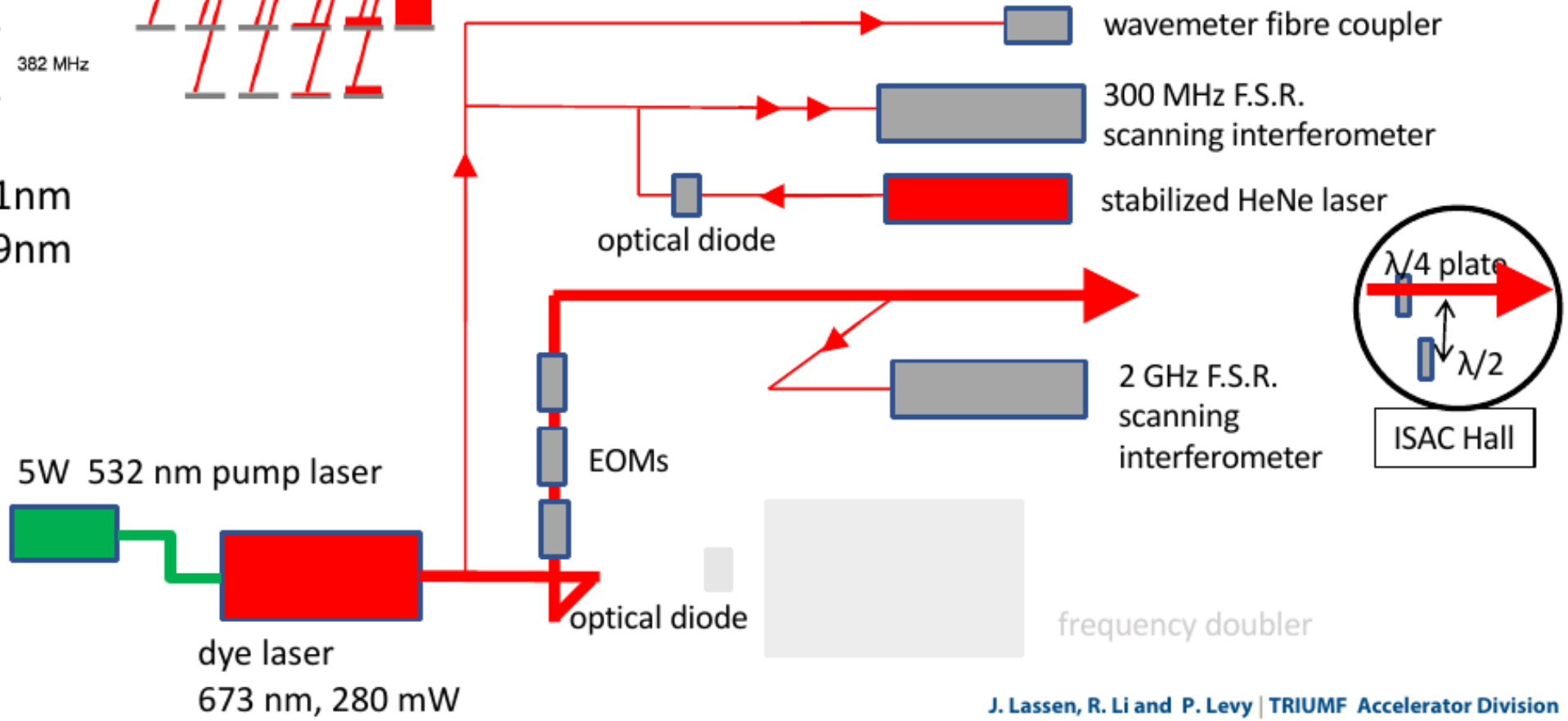
Present System : optical pumping 8Li (I=2); 9,11Li; 31,32Na

Lassen, Li, Levy

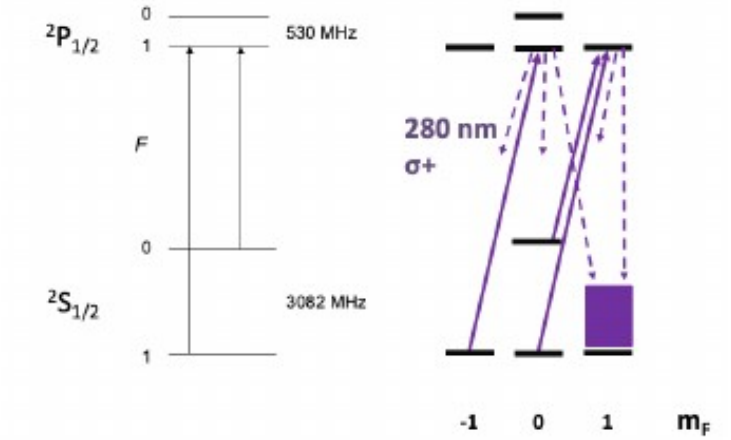
electro-optic modulator (EOM) puts 381 MHz sidebands on laser frequency,
-> both ground state hyperfine levels are pumped



Li 671nm
Na 589nm



Present System : optical pumping 31Mg+ (I=1/2)



Mg^+ (280nm)

5

wavemeter fibre coupler

300 MHz F.S.R.
scanning interferometer

stabilized HeNe laser

optical diode

λ/4 plate

λ/2

ISAC Hall

2 GHz F.S.R.
scanning
interferometer

EOMs

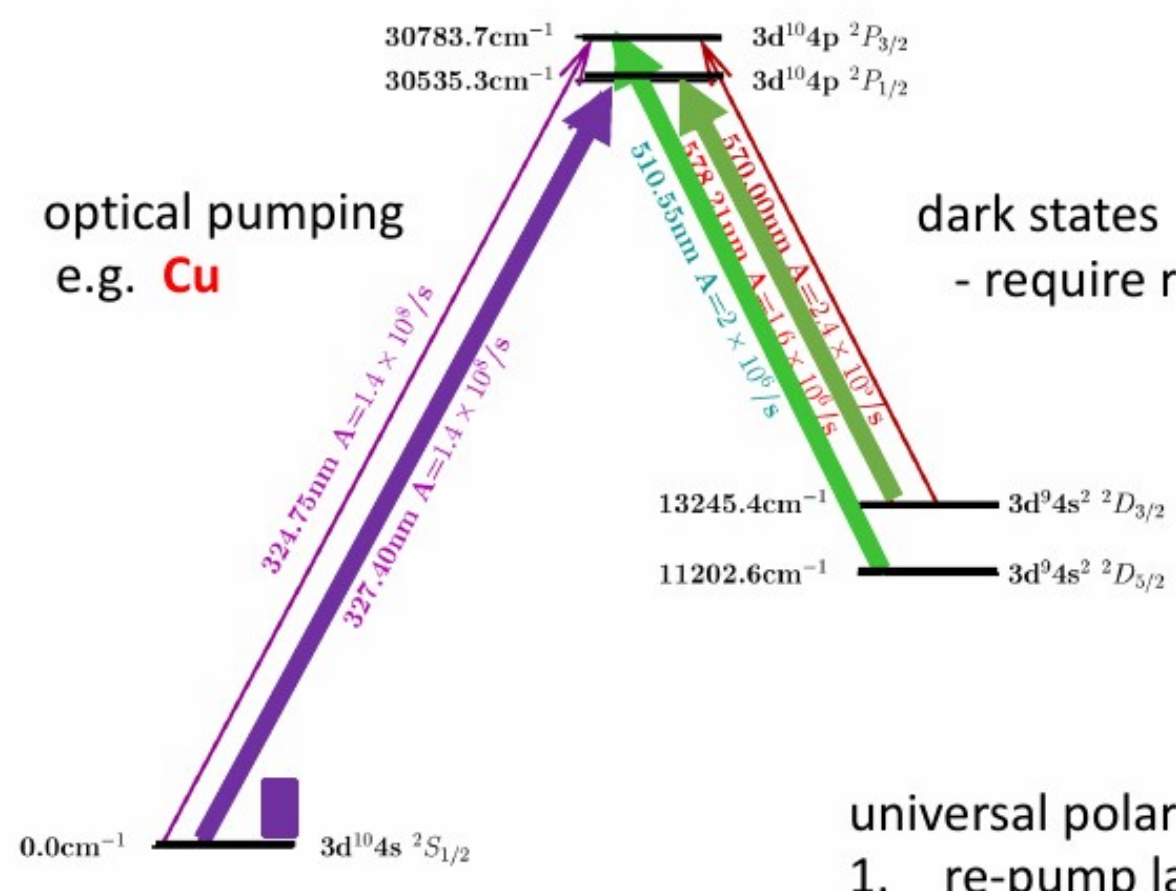
10W 532 nm pump laser

280 nm, 60 mW

frequency doubler

dye laser
560 nm, 800 mW

optical diode



327nm D1 polarizing and **578nm re-pump** form a closed system.

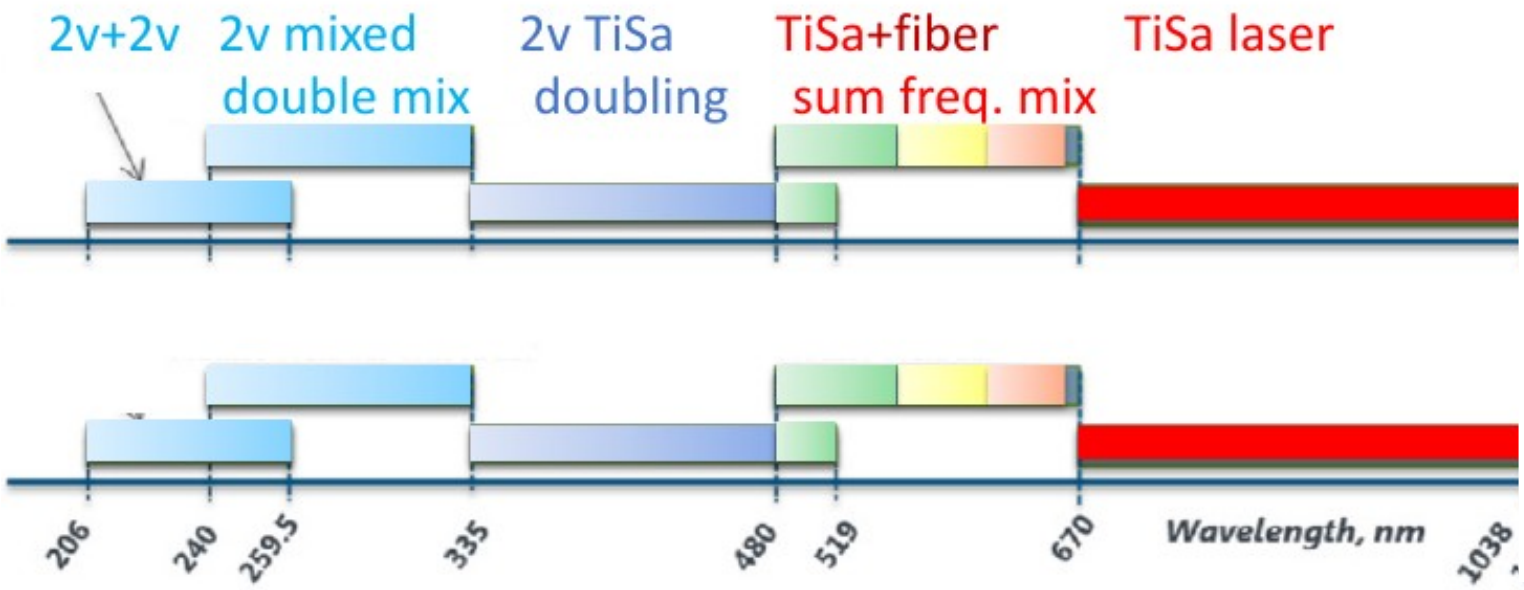
510nm light depopulates lowest metastable level

most commonly encountered level scheme

universal polarizer requires:

1. re-pump laser system
2. universal wavelength coverage

New Capabilities with Second Generation Lasers



polarizer upgrade: floating re-ionization cell to avoid beam optics re-tune when changing beam energy change

new spectroscopy chamber section for rapid re-configuration guide field coils

2x cw TiSa laser
2x fiber laser
2x sum freq. mixing
2x double mixed
2x freq. doubling => 1x (2v +2v)
diagnostics, optics & opto-mechanics for beam delivery

new capabilities:

λ-system polarization
for POLARIS beams: Ac, Al, Ag, Cu, Zn beams

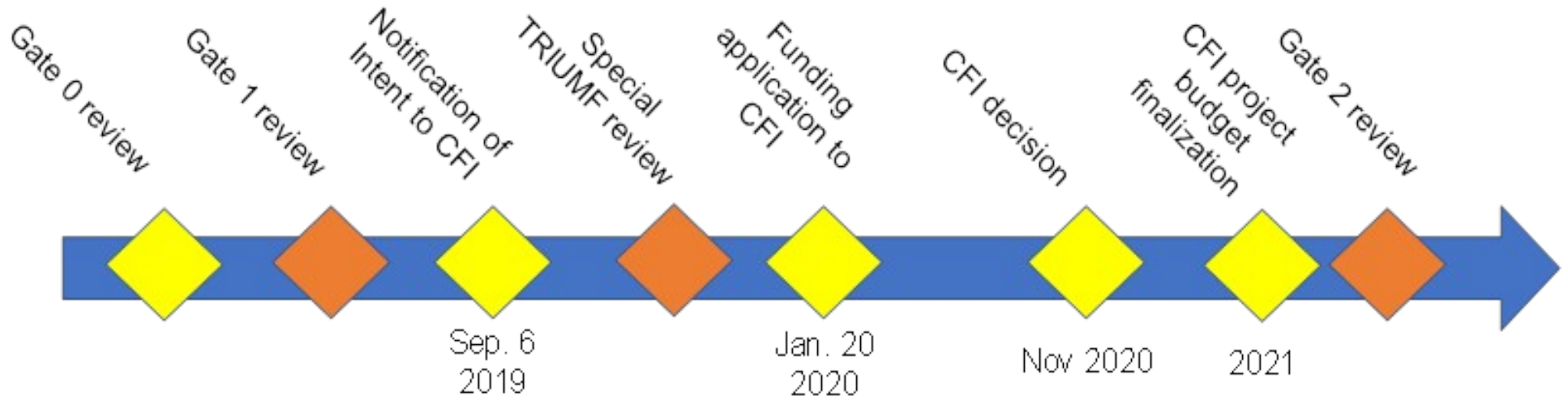
Key performance indicators over a five-year period for the CMMS

	Publications		Citations		Experiments		Highly Qualified Personnel						Theses
	μSR	β-NMR	μSR	β-NMR	μSR	β-NMR	Canadian			International			
Year							PDF	MSc PhD	U	PDF	MSc PhD	U	
2014	45	8	408	36	50	17	6	31	6	15	28	1	7
2015	23	5	356	81	59	16	4	19	8	12	24	2	5
2016	25	1	426	18	59	18	6	22	8	14	34	3	5
2017	12	5	362	58	43	14	3	22	2	11	33	3	7
2018	20	1	443	28	42	12	4	21	3	14	34	2	4

Highly successful low energy μSR program available at the Paul Scherrer Institute:
*61 associated publications between 2014-2018
(14 in high-impact factor journals (Nature journals, PNAS, PRL, ACS nano))
*typically 170 instrument days per year.
*166 individual visitors (375 visits); oversubscription rate 2.2, on average

It is anticipated an expanded β-NMR facility offering a complementary technique with comparable available beamtime will enjoy a similar level of activity.

Timeline



CFI-IF 2020 application
R Kiefl, University of British Columbia – Principal Investigator
University of Alberta, McMaster University, Université de Sherbrooke

Hopes and Dreams

Dramatically expand the β-NMR facility at TRIUMF, broadening our scientific community

Offer unique sample environments for experiments on Quantum Materials and Devices, polymers, battery materials, defects in semiconductors, aqueous solutions of biochemical and radiopharmaceutical relevance

Expand the range of polarised ions and atoms available for fundamental investigations of nuclear structure and symmetry

Keep your fingers crossed!