Overview of CANS

David V. Baxter

Low Energy Neutron Source
Center for Exploration of Energy and Matter (CEEM),
Indiana University

OUTLINE

- What is a CANS and what could it do?
- Role of CANS in the international neuron ecosystem
- Example of innovations from small pulsed sources (HUNS, RANS, LENS)
- Opportunities for the future
- Conclusions

n-Source Energy budgets:

- D-D, D-T (<*μl*): >4x10^{11} n/J
- Fission (*Dl*): 3x10^{10} n/J
- High-E proton spallation (*l*): 2x10^{11} n/J
  - ESS, SNS, JSNS, SINQ, ISIS
- Low-E Proton (p,n)Be ~13MeV (*ml*): 3x10^{9} n/J
  - LENS, CPHS, RANS, ESS-B, HBS, SONATE,…
- Threshold (d,n)Be (p,n)Li (<*ml*): 0.5-1x10^{9} n/J
  - Astrophysics, BNCT, Fusion materials research
- Electron on W (high-Z target) (*cl*): 2x10^{9} n/J
  - HUNS, Bariloche, RPI, …

n-Source Energy budgets:

- D-D, D-T (<*μl*): >4x10^{11} n/J
- Fission (*Dl*): 3x10^{10} n/J
- High-E proton spallation (*l*): 2x10^{11} n/J
  - ESS, SNS, JSNS, SINQ, ISIS
- Low-E Proton (p,n)Be ~13MeV (*ml*): 3x10^{9} n/J
  - LENS, CPHS, RANS, ESS-B, HBS, SONATE,…
- Threshold (d,n)Be (p,n)Li (<*ml*): 0.5-1x10^{9} n/J
- Electron on W [high-Z target] (*cl*): 2x10^{9} n/J
  - HUNS, Bariloche, RPI, …

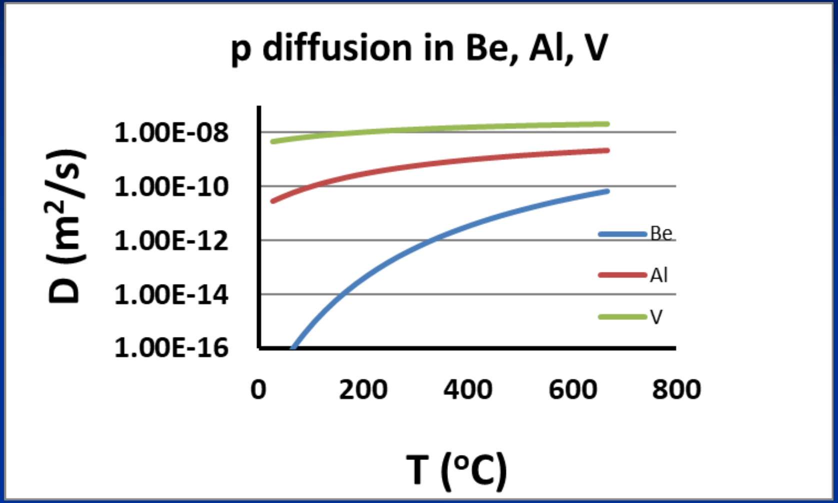
O(10^{14} n/s) requires target power ~50-100kW for CANS

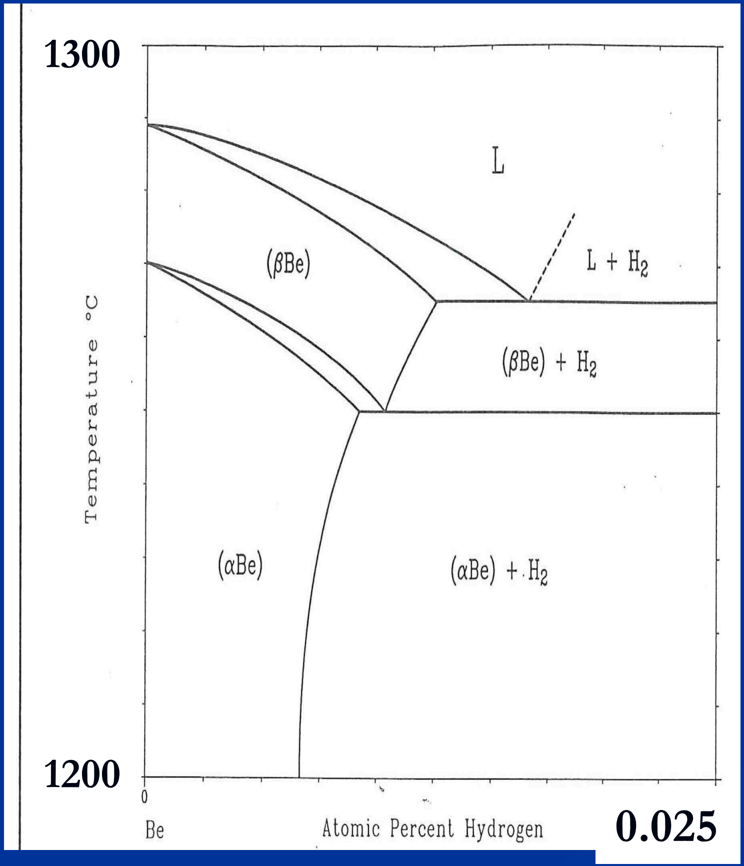
Target Issues

Hydrogen blistering surface cooling are major issues

Hydrogen problem with Be

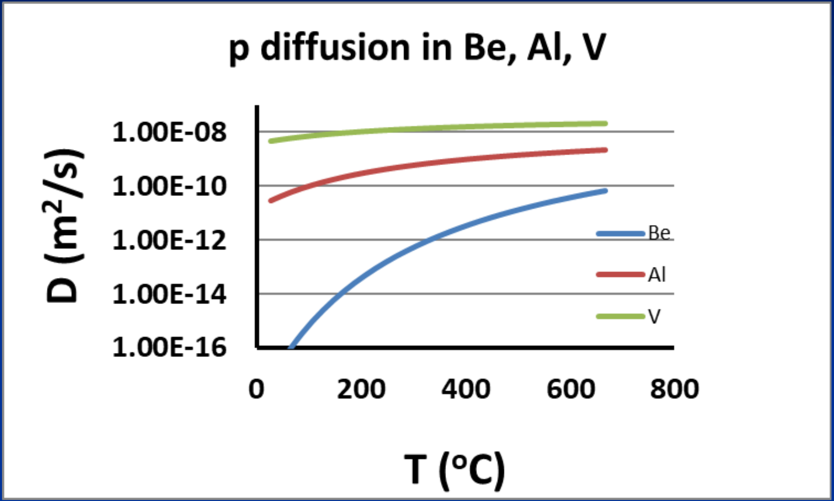
Solubility of H in Be is less than 0.08% at 1200°C!! Diffusivity in Be is VERY small.

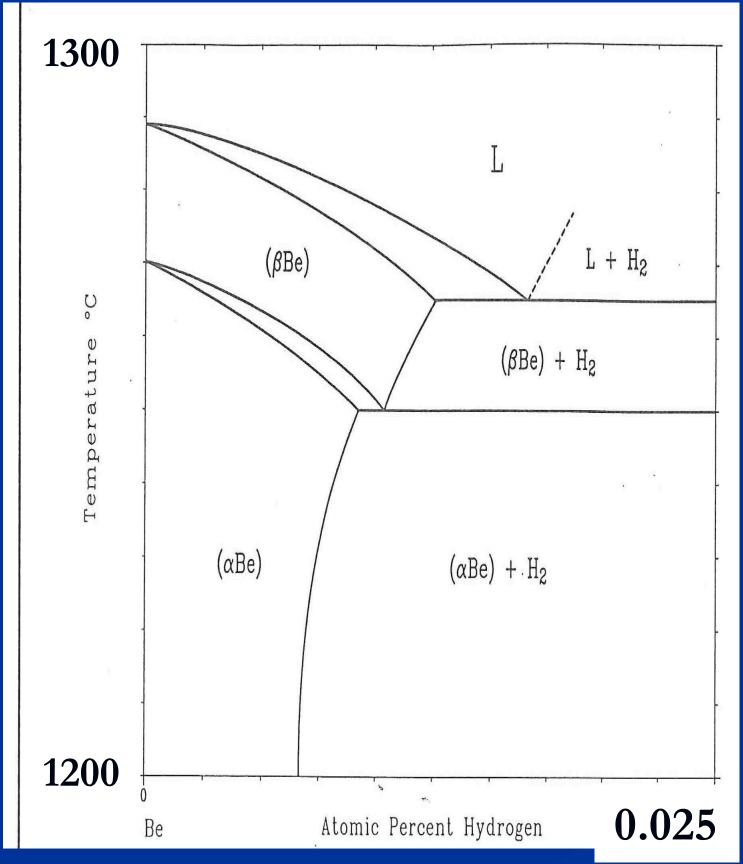




Hydrogen problem with Be

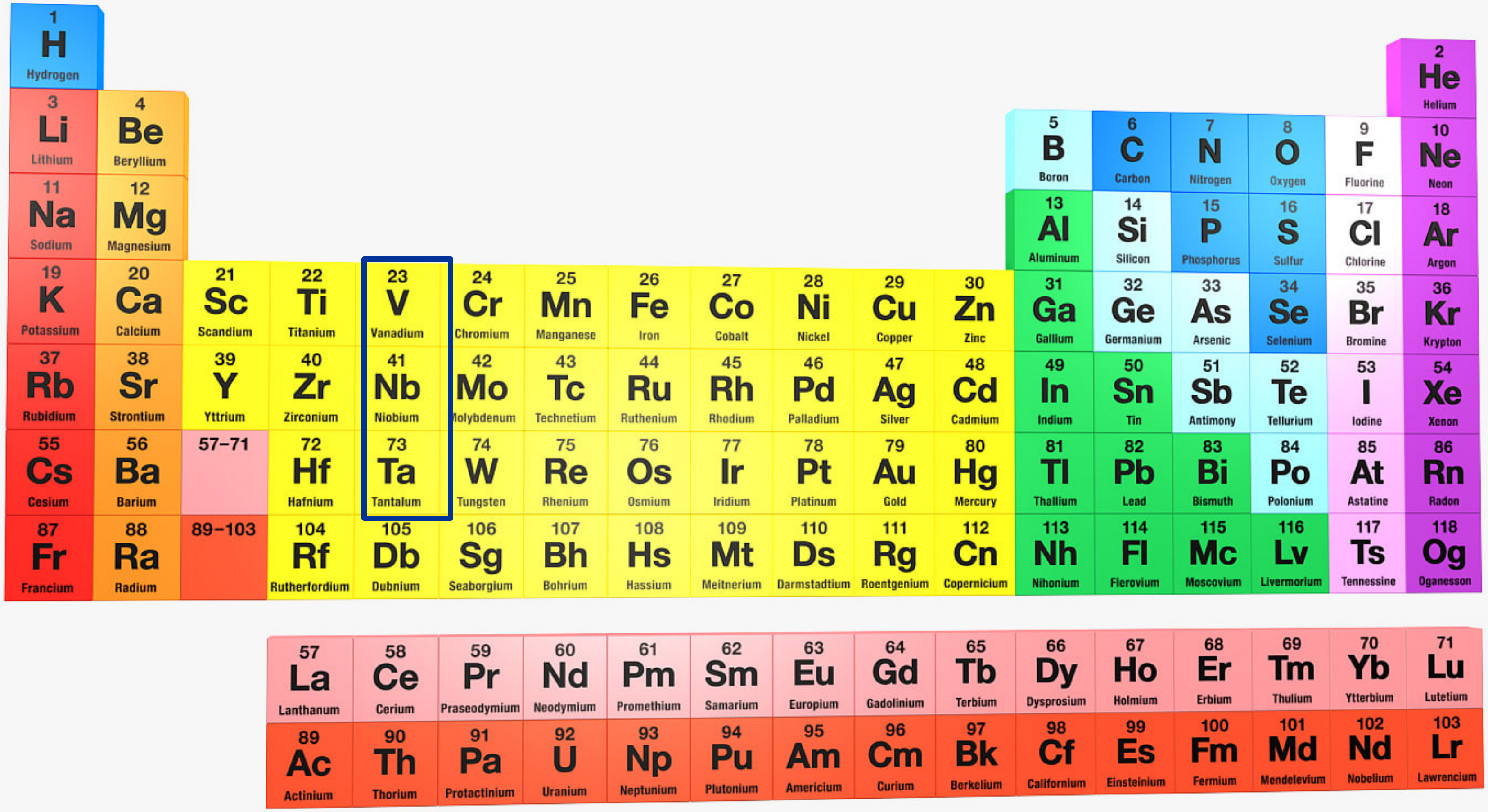
Solubility of H in Be is less than 0.08% at 1200°C!! Diffusivity in Be is VERY small.





Protons that stop within the Be stay where they rest, and quickly accumulate to the point where the solubility in Be is exceeded.

Can this be avoided by separating the n-production and hydrogen sinking roles of the target?

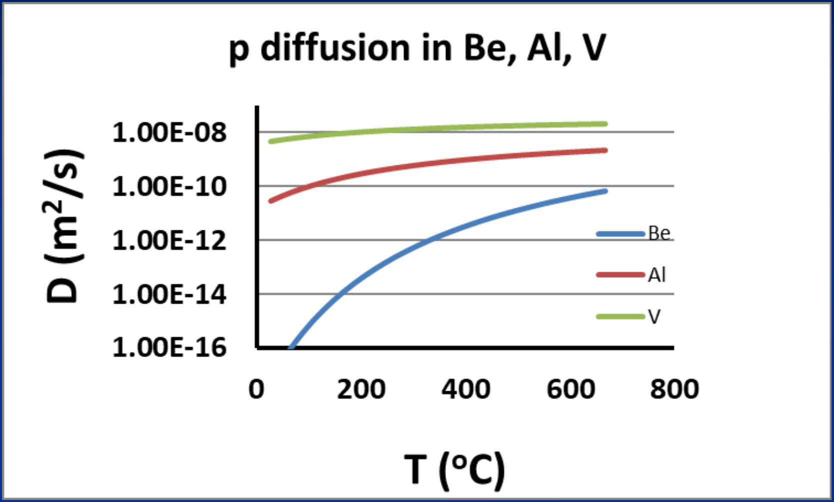


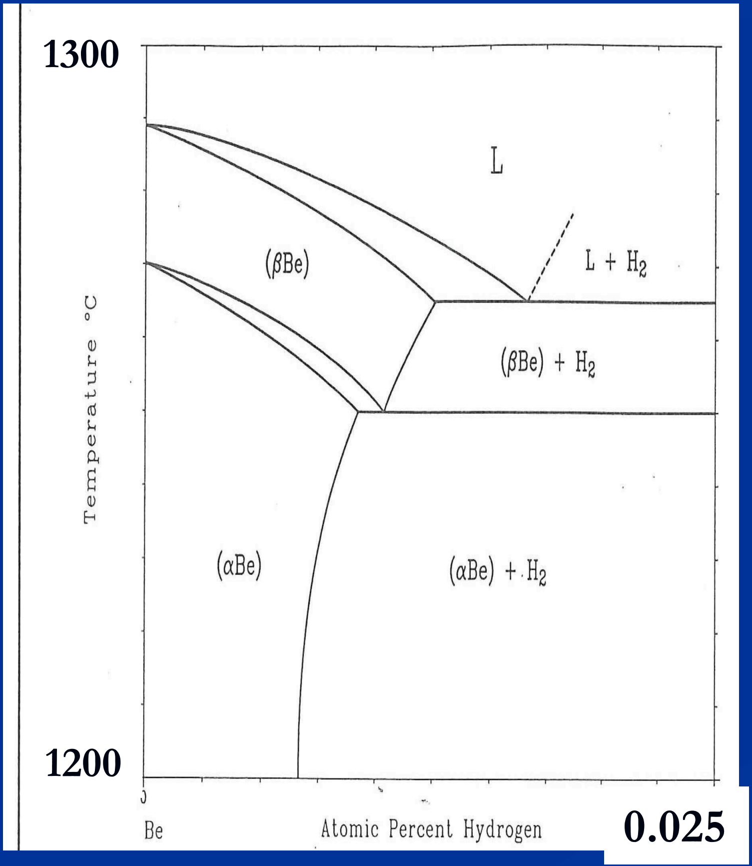
1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57–71	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89–103	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson
			57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
			89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

A quick review of the periodic table, phase diagrams and hydrogen diffusivity, leads you to focus on early transition metals as prime candidates.

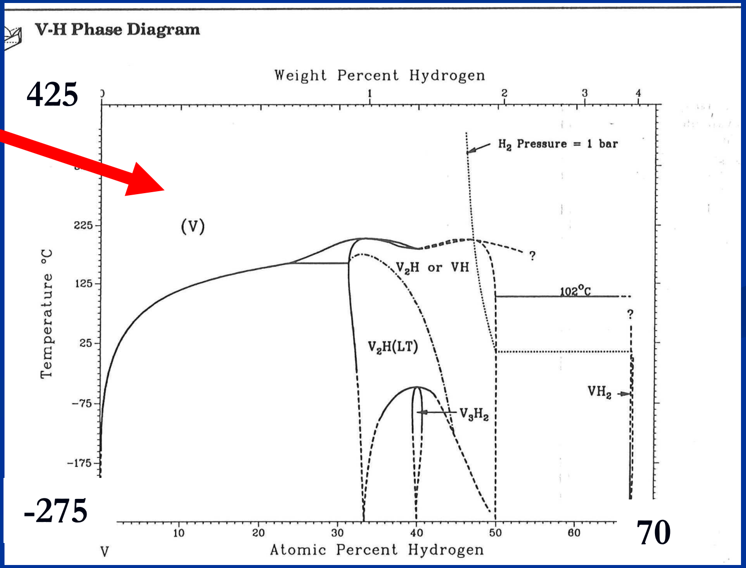
Hydrogen problem with Be

Solubility of H in Be is less than 0.08% at 1200°C!! Diffusivity in Be is MANY orders of magnitude lower than in V, Nb, Ta, or even Al!

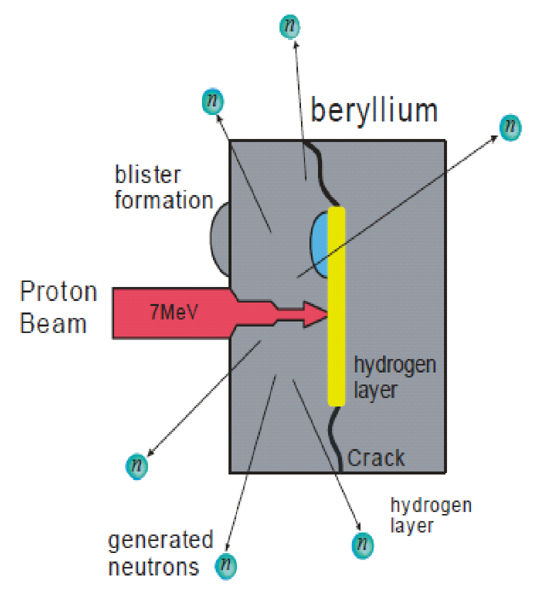


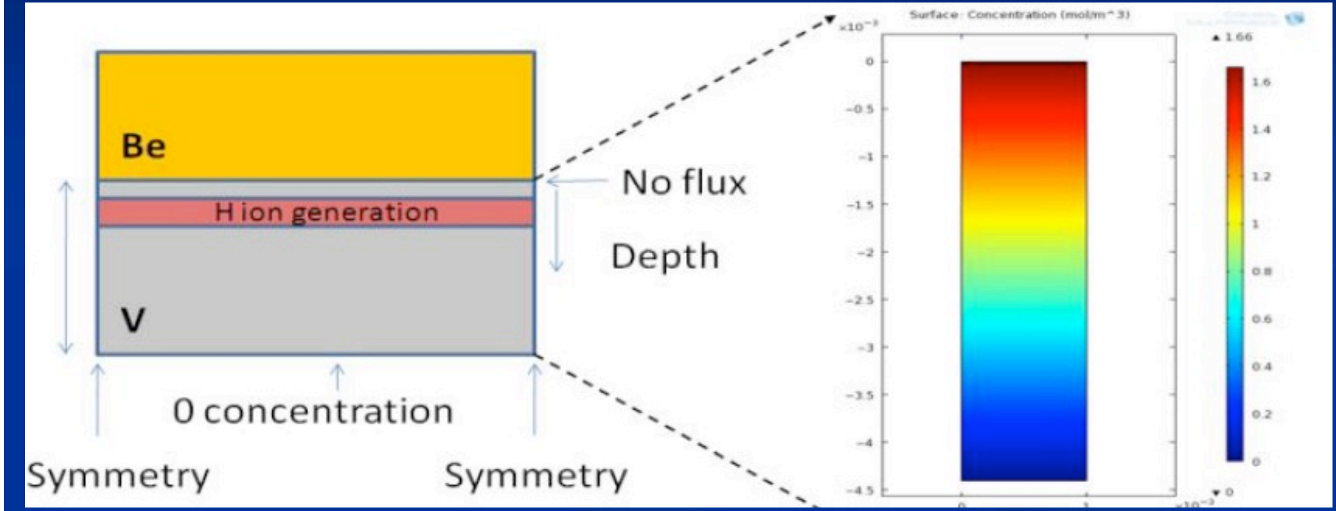


Solubility in V is more than 30% at elevated temp.



Target design limitations





Y. Yamagata et al.

Difficulty with the (p,n)Be target design is the buildup of H within the target at the depth of the Bragg peak.

- You need to avoid having the Bragg peak remain within the Be
  - Limit the Be thickness
  - Back the Be with another material
- At 13 MeV, proton range in Be is 1.3 mm.

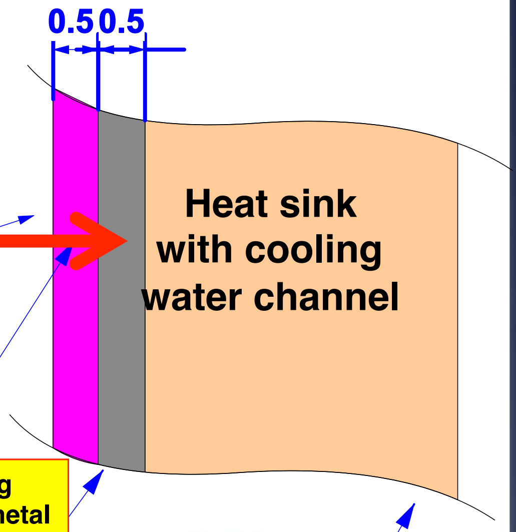
BNCT target for 8MeV p on Be

Patent 特開2014-81211

Design of the blistering tolerant neutron target

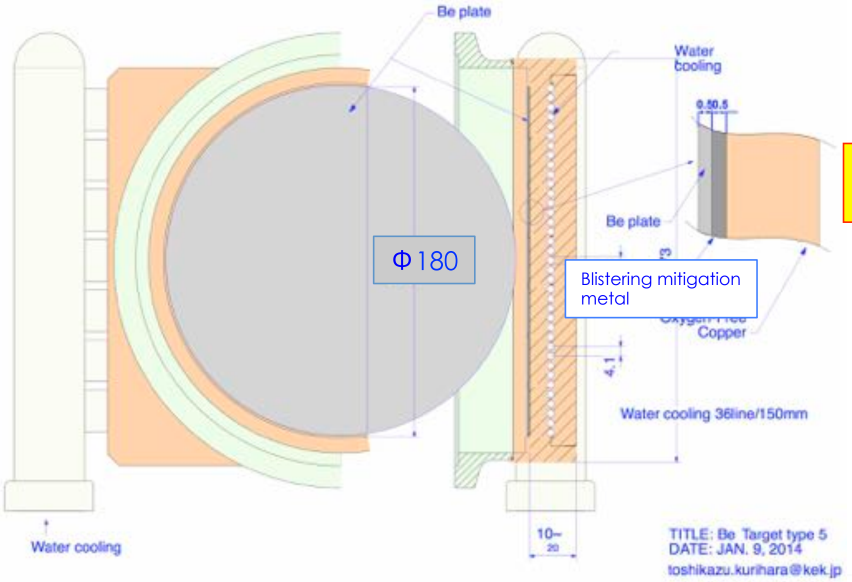
Ibaraki target (separated function)
Target thickness is 0.5mm
needs backup plate for beam window

Proton beam

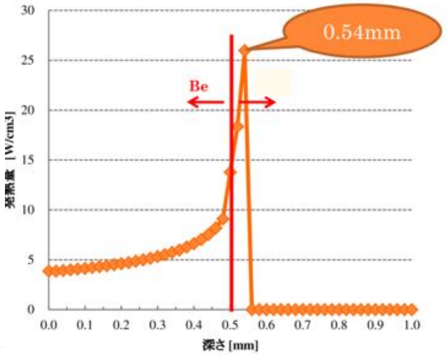


Be

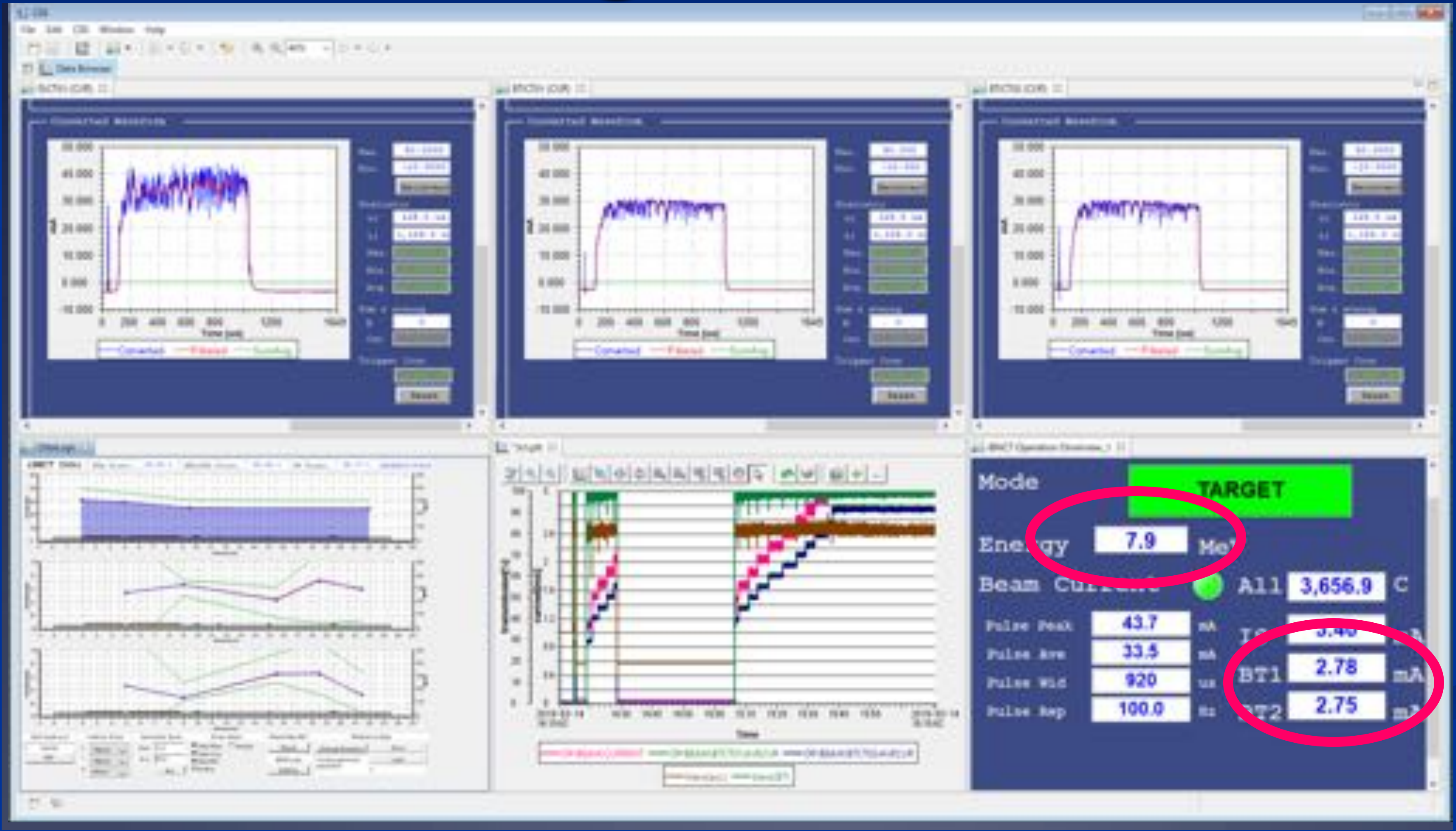
Blistering mitigation metal



TITLE: Be Target type 5
DATE: JAN. 9, 2014
toshikazu.kurihara@kek.jp



22kW on target: KEK, Tsukuba



Mode TARGET

Energy 7.9 Me

Beam Current

All 3,656.9 C

Pulse Peak 43.7 mA

Pulse Ave 33.5 mA

Pulse Wid 920 us

Pulse Rep 100.0 Hz

IC 3.40 mA

BT1 2.78 mA

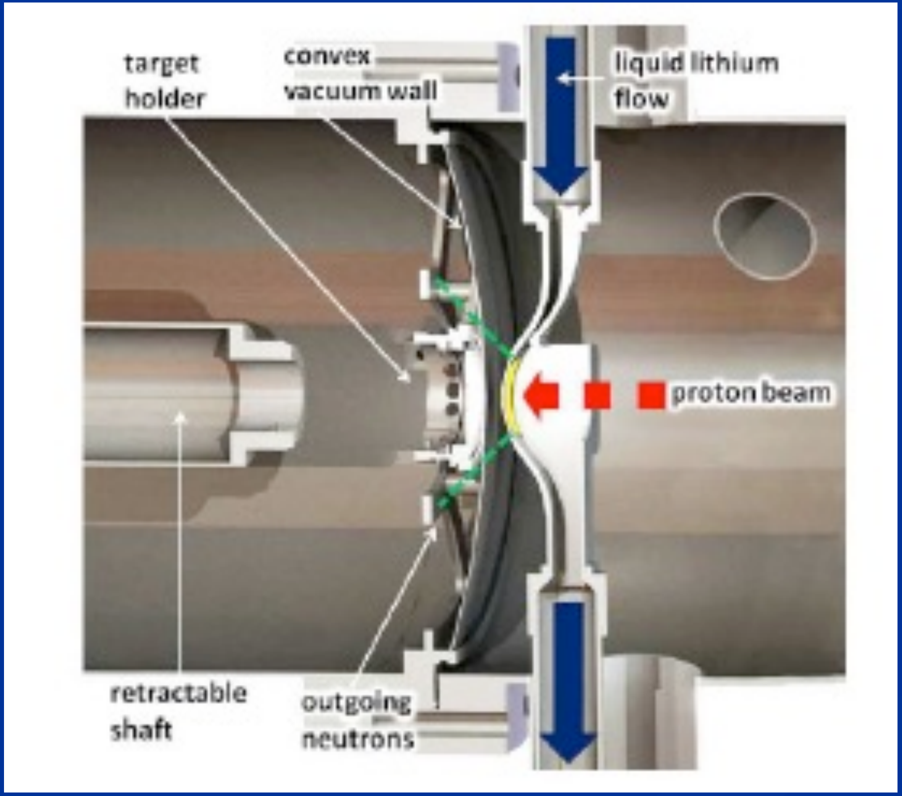
BT2 2.75 mA

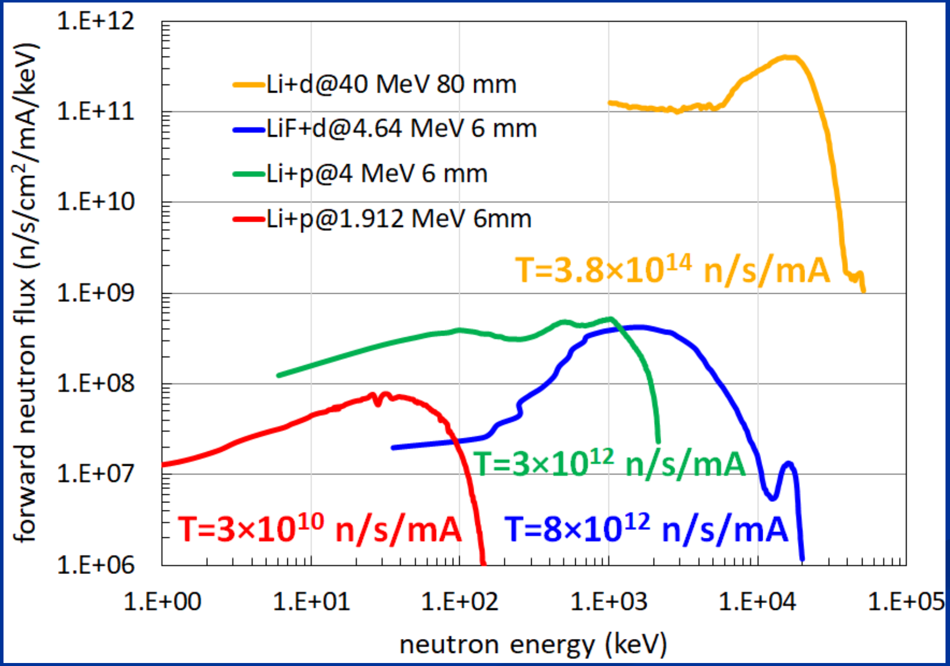
SARAF Li Target

Soreq Applied Research Accelerator Facility (Israel), currently at 2.3kW for Astrophysical applications. The liquid target flows at up to 10m/s, 1.5mm thick, 18mm wide., with the flow configuration determined by a stainless steel backing plate. Eventual goal is for 200kW operation.

Claim up to 4kW/cm^2 with water jet cooling and up to 8.4kW/cm^2 with l-Ga on solid targets.

I. Mardor et al., Eur. Phys. J. **<u>54</u>**, 91 (2018)





I. Silverman at UCANS-8

(p,n) target status

- 20kW power on Be composite has been demonstrated at KEK (Kurihara at UCANS)
- A number of groups are proposing such power levels for Li targets as well.
- 80-100 kW on a reasonable foot print seems to be possible with either option
    - For Be, details yet to be worked out on bonding, conduction at these power.

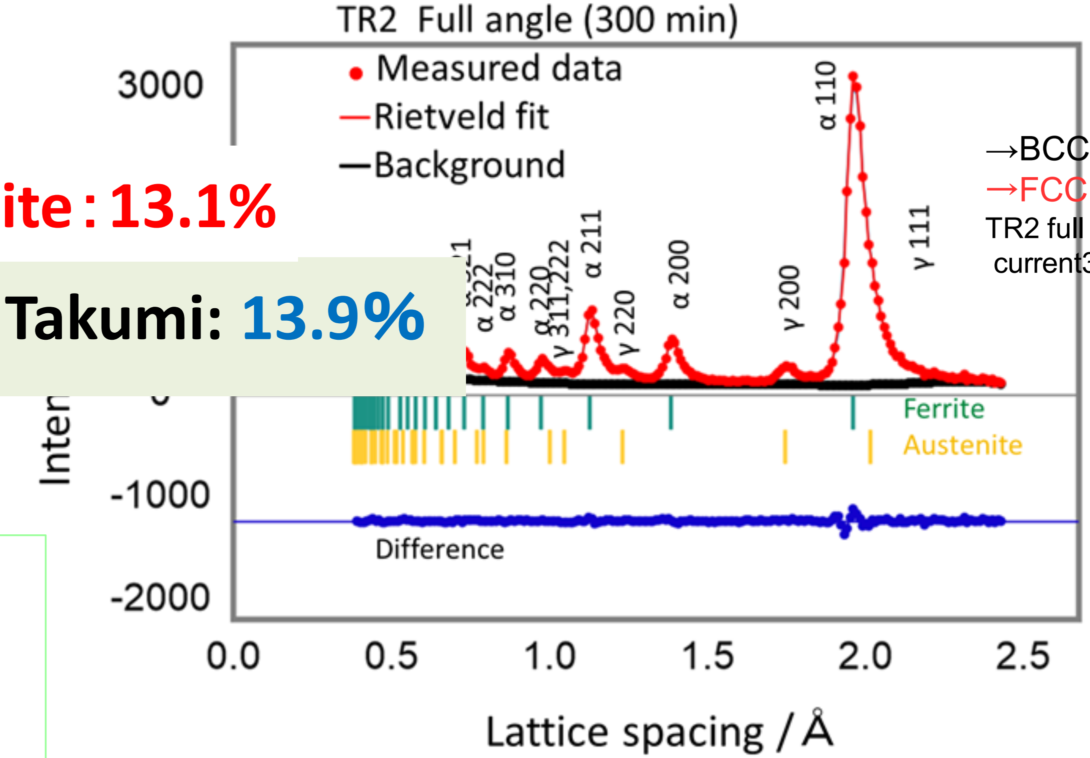
Volume fraction estimation with RANS diffractometer

retained **austenite** evaluation

Institute steel and iron Japan Research Group activity (2014-2016),
Nippon Steel & Sumitomo Metal Co. JFE-Steel, Kobe steel, Daido steel

Controlled samples produced

9mm×10mm×9.5mm



Austenite : 13.1%

J-PARC Takumi: 13.9%

→BCC peaks
→FCC peaks
TR2 full angle(300min, current32μA)

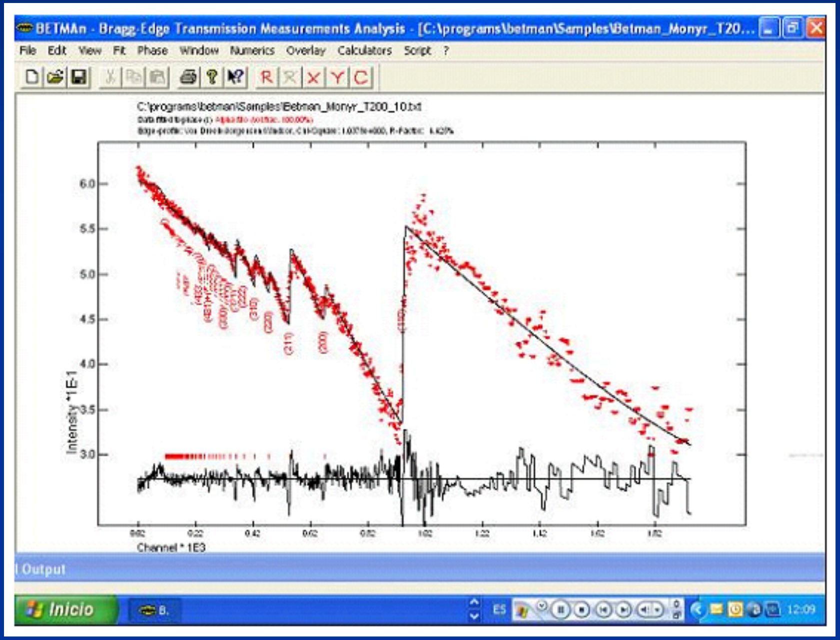
2minutes for 1 diffraction
Volume fraction estimatioln:30minutes- 5 hours measurements according to requested accuracy

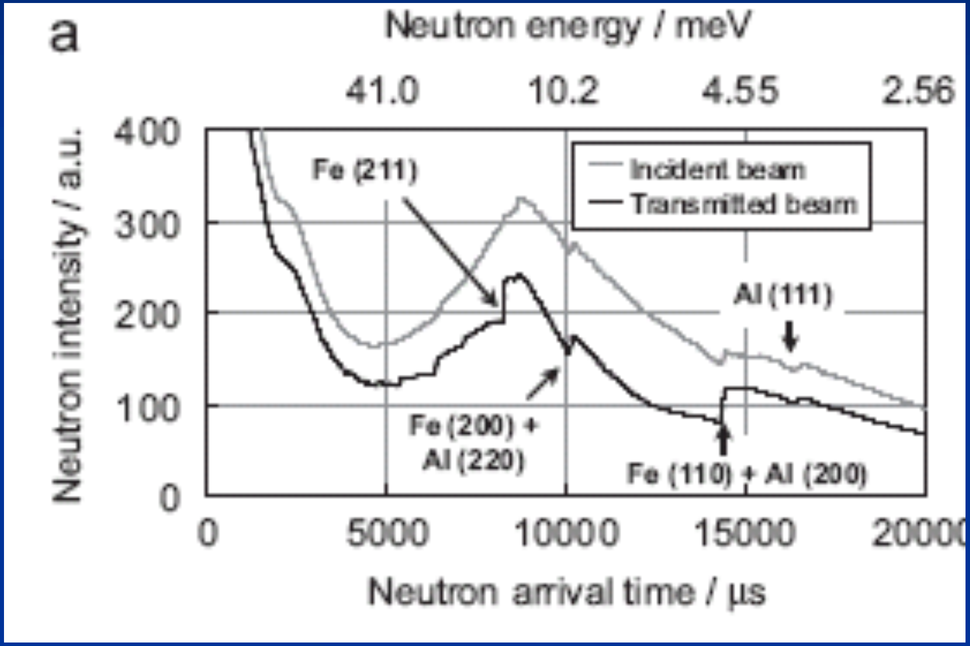
The result of measurement during uniaxial rotation (30 min) for round robin sample is consistent with J-PARC measurement within 1%

-> Compact source has high potential to use on-site

Y.Ikeda et al, Tetsu to Hagane **vol.104, No.3** (2018) pp.18-24

Bariloche: Bragg edge diffraction



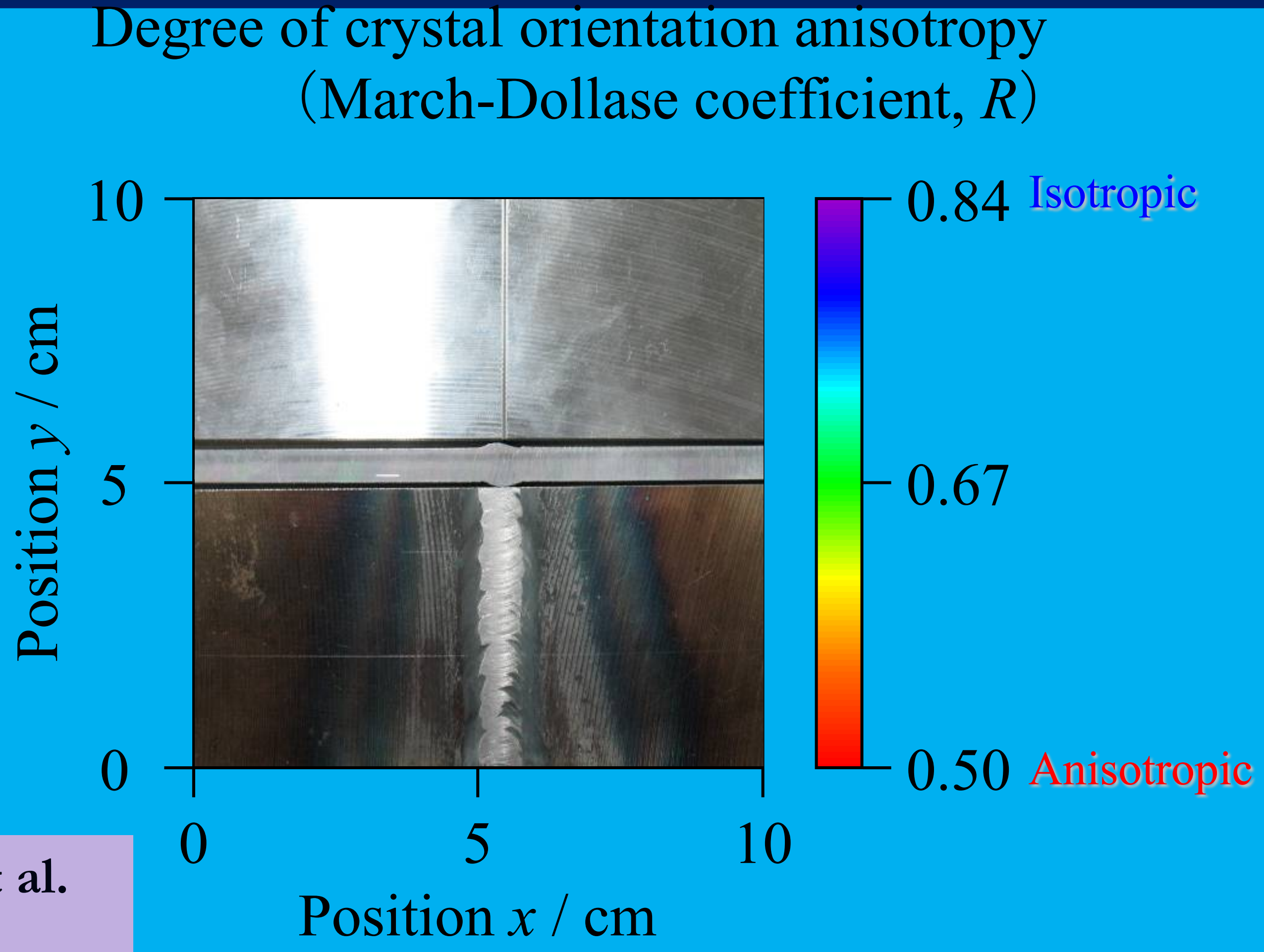


Refinement of Bragg-edge transmission of Mo from the Bariloche group

A similar effort at Hokkaido Univ., including spectroscopic imaging, Sato et al. NIMA *623* 597 (2010)

Imaging of anisotropy of crystal orientation

Pixel size：800μm



Degree of crystal orientation anisotropy
（March-Dollase coefficient, R）

Y. Kiyanagi et al.
(Hokkaido)

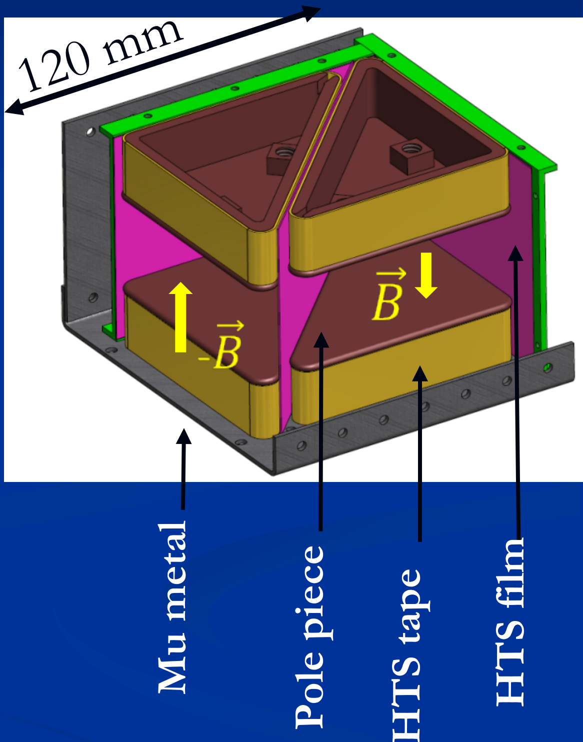
It is clearly demonstrated texture around welded area became weak

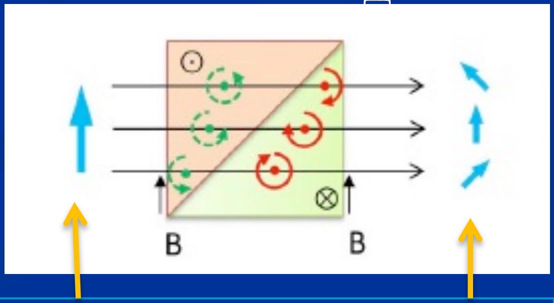
Ideas have been transferred to the RADEN @ JPARC, VENUS @ SNS, …

HTS Magnetic Wollaston Prisms

- **(Classical View) A neutron WP allows you to encode neutron trajectory information into the neutron phase (spin orientation). With this you can decouple momentum resolution from neutron intensity facilitating:**
  - Increased energy resolution in neutron scattering
  - Spin-echo approaches to real-space correlations in materials
  - New contrast mechanisms to neutron radiography

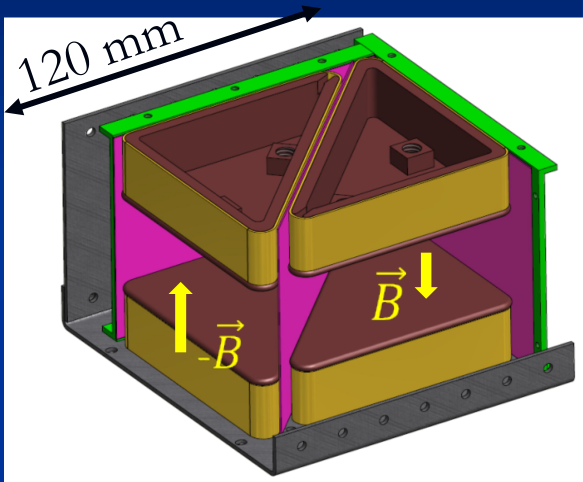
See Li et al. Rev. Sci. Inst. **86**, 023902 (2014), Li and Pynn, J. Appl. Cryst, **47**,1849 (2014) & perspective by F. Mezei, J. Appl. Cryst **47**,1807 (2014)



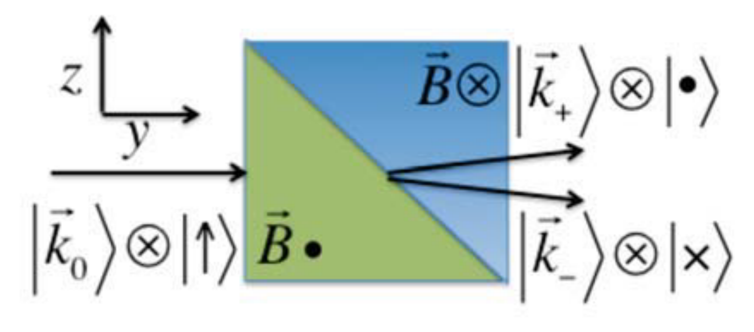


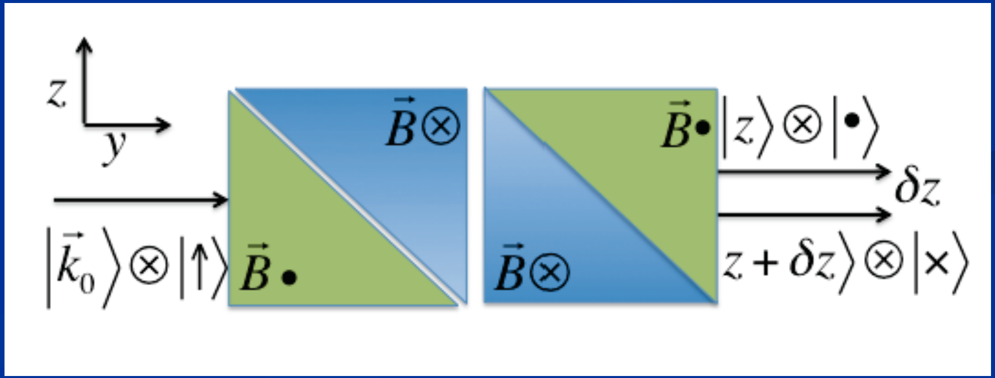
Neutron spin orientations

HTS Magnetic Wollaston Prisms

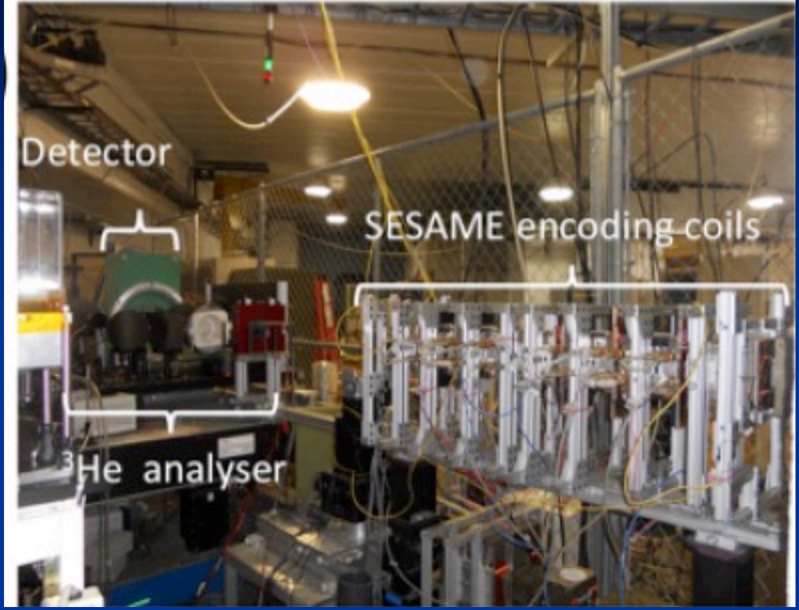


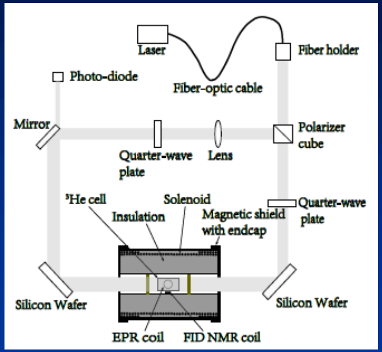
- (Quantum View) A neutron WP acts as a birefringent medium for neutrons. It allows one to entangle the neutron spin with either momentum or position:
  - Introduction of entangled spin states into neutron scattering





SESAME Instrument



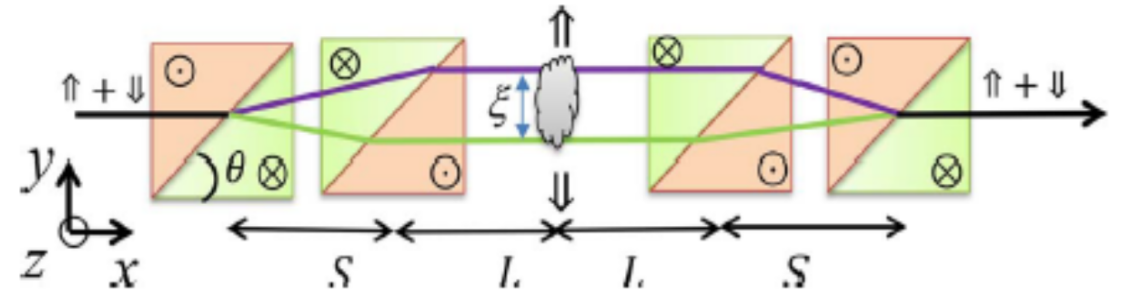


On-line ^{3}He polarization (SEOP) analysis

S. R. Parnell et al., Rev. Sci. Inst. (2015)

$$P_s(\xi)/P_o(\xi)=\exp(\Sigma_t[G(\xi)-1])$$

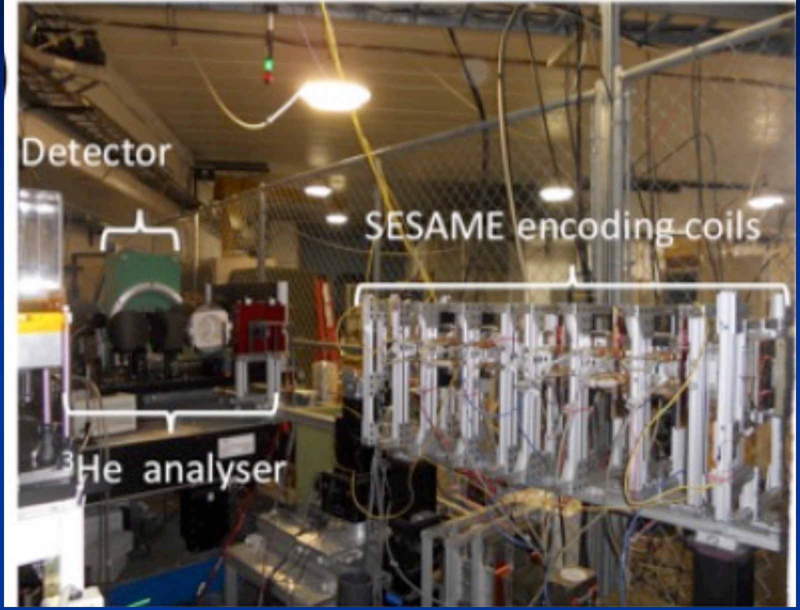
Real space correlations are determined directly from measuring the normalized polarization of the outgoing beam.

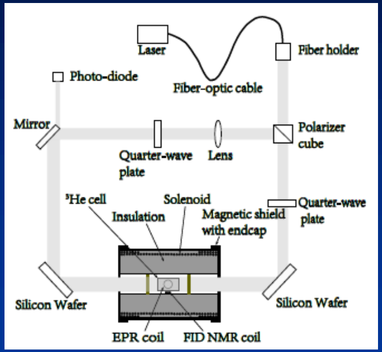


$$\xi = cBS\lambda^2 B\cot(\theta)\ ;\ \ c=2.476\text{x}10^{14}\ \text{T}^{-1}\ \text{m}^{-2}$$

$$\xi = 30\text{nm at } \lambda=0.5\text{nm, B}=1\text{mT, S}=0.5\text{m}$$

SESAME Instrument



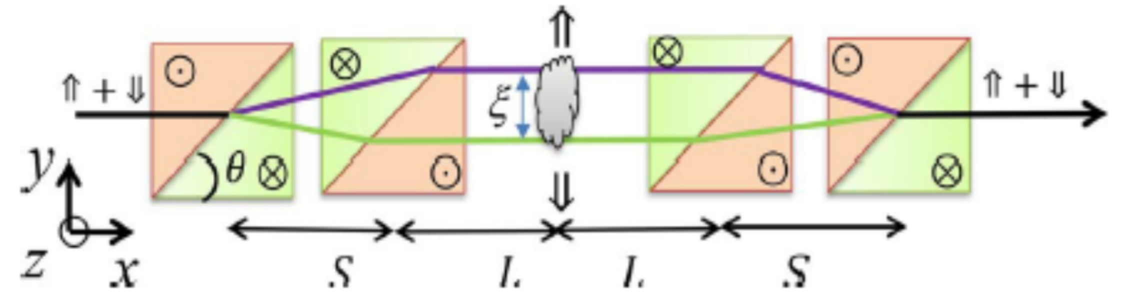


On-line ^{3}He polarization (SEOP) analysis

S. R. Parnell et al., Rev. Sci. Inst. (2015)

$$P_s(\xi)/P_o(\xi)=\exp(\Sigma_t[G(\xi)-1])$$

Real space correlations are determined directly from measuring the normalized polarization of the outgoing beam.



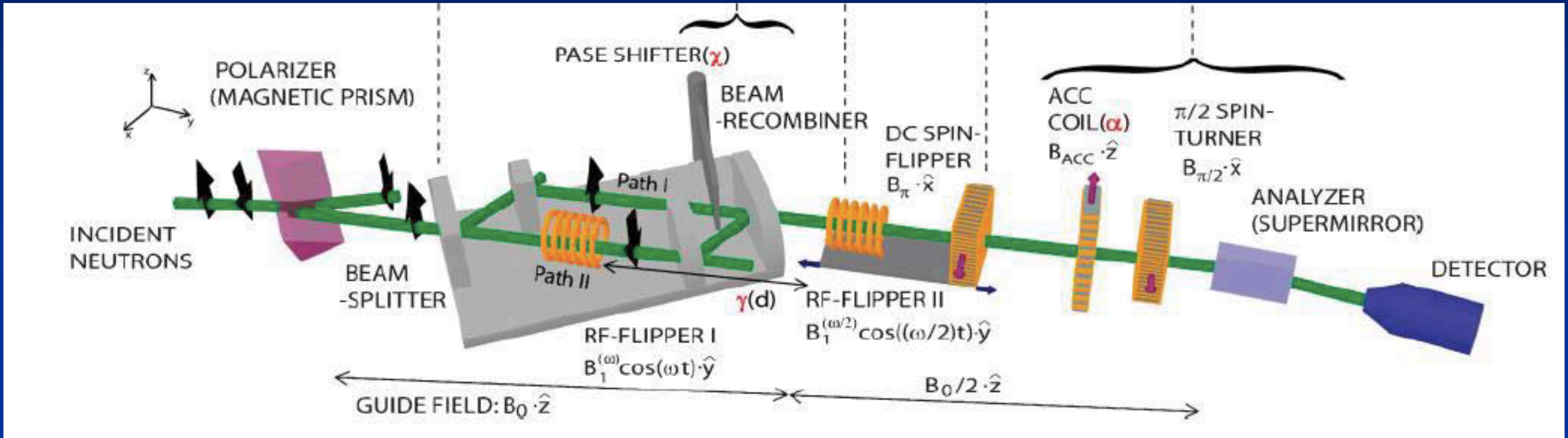
$\xi = cBS\lambda^2 B\cot(\theta)$; $c=2.476\text{x}10^{14}\ T^{-1}\ m^{-2}$

$\xi = 30\text{nm}$ at $\lambda=0.5\text{nm}$, $B=1\text{mT}$, $S=0.5\text{m}$

What if we measure more than just the polarization as a function of ξ?

Neutrons and QIS

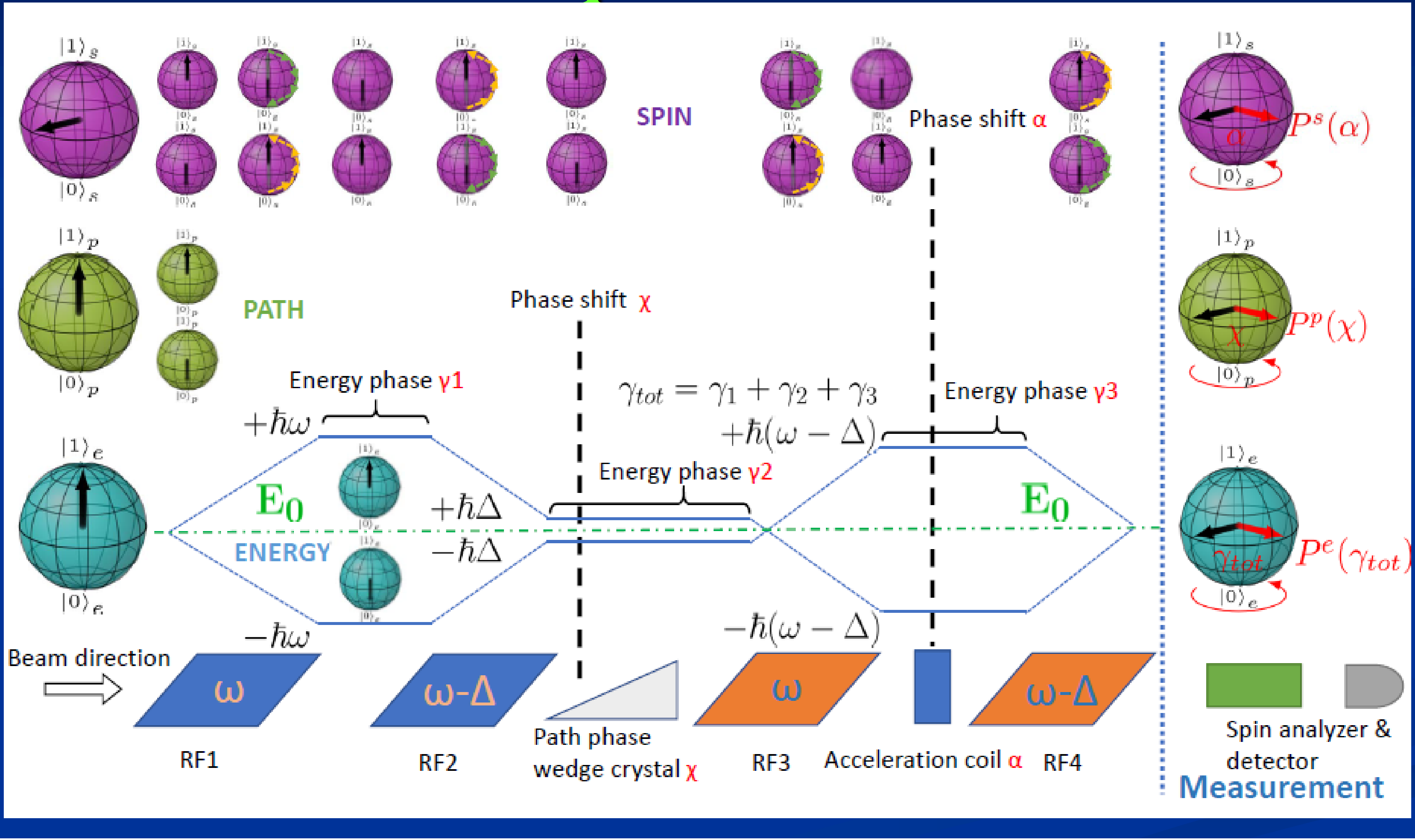
Hasegawa et al., PRA **81,** 032121 (2010)



$$M = E\left[\sigma_x^s \sigma_x^p \sigma_x^e\right] - E\left[\sigma_x^s \sigma_y^p \sigma_y^e\right] - E\left[\sigma_y^s \sigma_x^p \sigma_y^e\right] - E\left[\sigma_y^s \sigma_y^p \sigma_x^e\right]$$

- Neutron interferometry has been used for fundamental tests of QM for some time (e.g. above contextuality measurement with triply entangled beams) *M*=2.558(4) (NCHVT require <2).
- Problems: the entanglement geometry is macroscopic and fixed by interferometer geometry, no easy way to direct beam to a sample of interest.

Transmission entangled beam Expt. at ISIS



This affords an experiment like Hasegawa's, but with a MICROSCOPIC and CONTROLAB:LE entanglement length ξ! NOW ADD SAMPLES!

The results are….

- We calculate the witness:

$$S = E\left(0, \frac{\pi}{4}\right) + E\left(0, -\frac{\pi}{4}\right) - E\left(\frac{\pi}{2}, \frac{\pi}{4}\right) + E\left(\frac{\pi}{2}, -\frac{\pi}{4}\right)$$

$$E(\alpha, \chi) = \frac{N(\alpha, \chi) + N(\alpha + \pi, \chi + \pi) - N(\alpha, \chi + \pi) - N(\alpha + \pi, \chi)}{N(\alpha, \chi) + N(\alpha + \pi, \chi + \pi) + N(\alpha, \chi + \pi) + N(\alpha + \pi, \chi)}$$

where α and χ are the spin and path phases between states and *N* is the measured neutron count.

  - For this combination of phases , QM maximally violates classical theory (up to S=2.828), non-contextual result is S<2,
- We find <u>S = 2.16</u>(2) (3.03(2) with spin, path, E)
  - (max we could measure is $2\sqrt{2}$ times the neutron polarization, (0.77); i.e. 2.18 is max expected).
- Conclusion, we really do have an entangled state of spin & path – a Bell state – for EACH neutron

Conclusions

- CANS facilities have made important contributions, particularly in innovation and education.
- Partnerships with International-scale facilities have proven fruitful (HUNS/JPAC; LENS/ORNL,ISIS)
- To date, operational CANS targets have been demonstrated at significant power levels:
  - 20kW total beam power (KEK, Japan)
  - Up to 8kW/cm^2 (Soreq, Israel), Ga cooling
  - => CANS are poised to reach (far) beyond the University scale over the next few years/decade.

Acknowledgements

- Thanks to the LENS crew:
  - Jak Doskow, Tom Rinckel, Roger Pynn, Mike Snow, Gerardo Ortiz, Steve Parnell, Steve Kuhn, Fankang Li*, Jiazhou Shen*, Shufan Lu*, Abu Ashik Irfan*, Sam McKay*, Alex Todd*
- Funding/Beam time:
  - DOE, NIST (DOC), NSF, IU, HFIR, ISIS
- Thanks for slides from:
  - Yoshie Otake (RANS)
  - Toshikazu Kurihara (KEK)
  - Yoshiaki Kiyanagi (Nagoya)
  - Ido Silverman (Soreq)