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Construction Status of High Resolution Chopper Spectrometer (HRC) at J-PARC

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ABSTRACT

We constructed High Resolution Chopper Spectrometer (HRC) at the beam line BL12 at Materials and Life Science Facility, J-PARC to study dynamics in condensed matters in a wide energy-momentum space with high resolutions. The construction status and the performance of HRC are described.

1. Introduction

High Resolution Chopper Spectrometer (HRC) was installed at the 12th beam line (BL12) at Material and Life Science Facility (MLF), J-PARC for a wide range of dynamical studies of materials with high resolutions and relatively high energy neutrons [1-3].

Originally, HRC was proposed as a project of High Energy Accelerator Research Organization (KEK). Also, Versatile Inelastic Neutron Spectrometer (VINS) was proposed by the University of Tokyo [4,5]. KEK started the construction of HRC at BL12 with a small amount of money. Some parts were manufactured, but they could not be installed at J-PARC and just stored at the Tsukuba campus of KEK. The construction of VINS at BL23 was approved by the committee of the instrumentation at J-PARC, but, it was not funded. In 2008, both institutes proposed to merge these projects to construct one chopper spectrometer, and the budget was concentrated to complete HRC at BL12, as a joint project between KEK and the University of Tokyo. KEK mainly built shieldings and a vacuum scattering chamber, the University of Tokyo mainly prepared detectors. Devices such as a Fermi chopper, a T0 chopper, a guide tube, detector electronics, a cabin and a deck were also installed or delivered by the end of March 2010. Then, HRC was almost completed.

2. High resolution experiments on HRC

High resolution experiments using relatively high energy neutrons are advantageous especially for studies on spin systems, and we have proposed three types of experiments on HRC as indicated in the energy(E)-momentum(Q) space in Fig. 1 [3]. The 1st technique is for high resolution experiments in a conventional energy-momentum space (A in Fig.1). If the energy resolution, $\Delta E/E_i = 1\%$ (E_i: incident neutron energy), is realized, the resolutions are $\Delta E = 1$ meV and $\Delta Q = 0.03$ Å^{-1} for $E_i = 0.1$ eV. This experimental condition is useful for the determination of a dispersion relation of excitations and a detail of the dynamical structure factor simultaneously. The 2nd technique is an access to the 1st Brillouin zone with low angle detectors and high energy neutrons (B in Fig.1). The resolutions are ΔE = 5 meV and ΔQ = 0.07 $Å^{-1}$ for E_i = 0.5 eV and $ΔE/E_i$ = 1%. In this condition, an energy-momentum space around Q = 0.5 $Å^{-1}$ and E= 20 meV is accessible at low scattering angles. Observation of ferromagnetic spin waves from a polycrystalline sample becomes possible, and it should be useful for material development. The 3rd one is a possibility of eV region neutron spectroscopy (C in Fig.1). The resolutions are ΔE = 10 meV and ΔQ = 0.1 $Å^{-1}$ for E_i = 1 eV and $ΔE/E_i$ = 1%. With these resolutions, dispersive excitations at around Q = 1 $Å^{-1}$ are observable and this condition is useful for observing high energy magnetic excitations. If eV neutrons are utilized, observations of electronic excitations are expected. Also, it is useful for measuring vibrational modes of hydrogens, if the detector area is extended to higher angles.

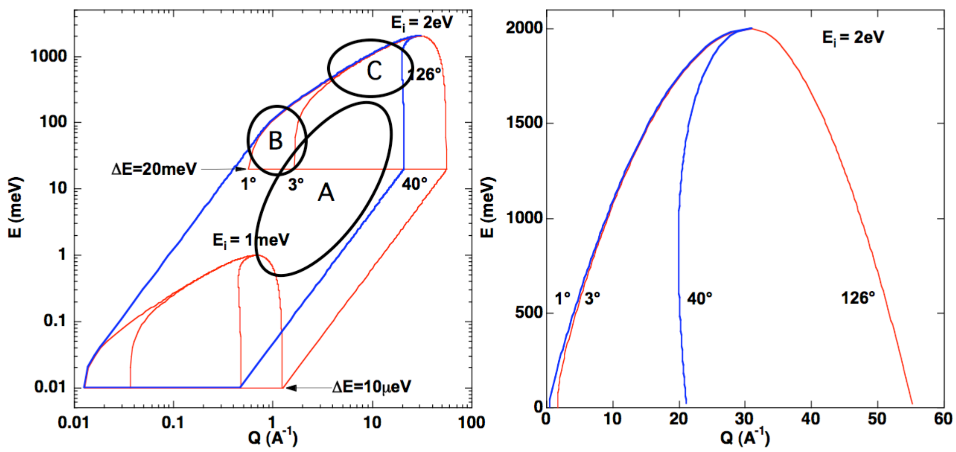

Fig.1 The energy-momentum space for the three techniques of high resolution experiments proposed on HRC (left: log scale, right: linear scale).

3. Initial design

The initial design of HRC is briefly summarized [1-3]. The size parameters of HRC were chosen to be L_1 = 15m (distance between the neutron source and the sample), L_2 = 4m (distance between the sample and the detector) and L_3 = 1m (distance between the Fermi chopper and the sample). HRC at BL12 faces the decoupled moderator of which area is 10 cm × 10cm, and the maximum sample size is assumed 5 cm × 5 cm. In this geometrical condition, the energy resolution is estimated to be $ΔE/E_i$ = 2.5% for the optimum condition where the chopper opening time ($Δt_{ch}$) equals to the pulse width ($Δt_m$), with the incident beam divergence of Δφ = 5 mrad [1,2]. To realize $ΔE/E_i$ = 2.5%, some pairs of L_1 and L_2 are possible, and the intensity at the detector position can be calculated for the set of L_1 and L_2 [3]. The intensity at the detector position is maximized at L_1 = 9 m and L_2 = 5 m, however, an unrealistically large space is required. For the limited area of the given space at BL12, the intensity at the detector position is maximized at L_1 = 15m and L_2 = 4m.

The energy resolution can be improved for the condition, $Δt_{ch} < Δt_m$, with a reduction of the peak intensity. For $ΔE/E_i$ = 1%, the peak intensity becomes 75% of that for the optimum condition, and this reduction is small and acceptable [1,2].

The energy resolution ($ΔE/E_i$) decreases with increasing the energy transfer (E) and $ΔE/E_i$ = 0.5% at E = E_i if $ΔE/E_i$ = 1% at the elastic scattering (E = 0). The Q resolution is almost constant over the energy-momentum space, and $ΔQ/k_i$ = 0.5% (k_i: incident neutron wave number) for the incident beam divergence ($\Delta\phi$ = 5 mrad) on HRC, if $\Delta E/E_i$ = 1% at E = 0. Therefore, the Q resolution is matched with the beam divergence (roughly speaking, $\Delta Q/k_i = (\Delta E/E_i)/2 = \Delta\phi$ for the matching condition). Since the energy dependence of the pulse width (Δt_m) is almost proportional to $E_i^{-1/2}$ for the decoupled-moderator at J-PARC, this performance on the resolutions is valid at any point in the energy-momentum space for any E_i [1,2].

In the initial design, detectors are configured on the spherical surface in order to maintain uniformly the resolution condition with a constant L_2 [2]. To increase the neutron flux, a supermirror guide tube is mounted on the primary flight path. The guide tube is a tapered shape, and the flat supermirrors are mounted on the trapezoidal side between the square moderator of 10cm × 10cm and the square sample of 5 cm × 5cm.

4. Actual construction

On the primary flight path, a supermirror guide tube was installed only at the shutter section (m = 3, A in Fig. 2 (left)) and the biological shielding section (m = 3.65, B in Fig. 2(left)), where m is the ratio of the critical wavenumber of the super mirror to that of natural nickel. A collimator without mirrors was installed in the down stream section. The neutron beam is shaped with the B_4C teeth in the collimator (C and D in Fig. 2 (left)). The collimator section will be replaced by the supermiror guide tube (m = 4) soon. The m values were dependent on the budgets when they were funded. The flux gain of the guide tube is shown in Fig. 2 (right). By replacing the collimator by the supermirror guide tube, a great gain will be expected, also the collimation for high energy neutrons will be improved.

The T0 chopper [6] was installed at 8.5 m from the neutron source. At this position, the beam cross section is 76 cm × 76cm. The size of the blade of the T0 chopper was chosen to be 78 cm × 78 cm including ± 1mm margin for the beam cross section. When the blade center is on the beam line center initially, the blade is removed out of the beam cross section after 408 ms with 100 Hz of the rotational frequency and 30 cm of the rotational radius. In this condition, neutrons having energies less than 2.2 eV can be utilized on HRC.

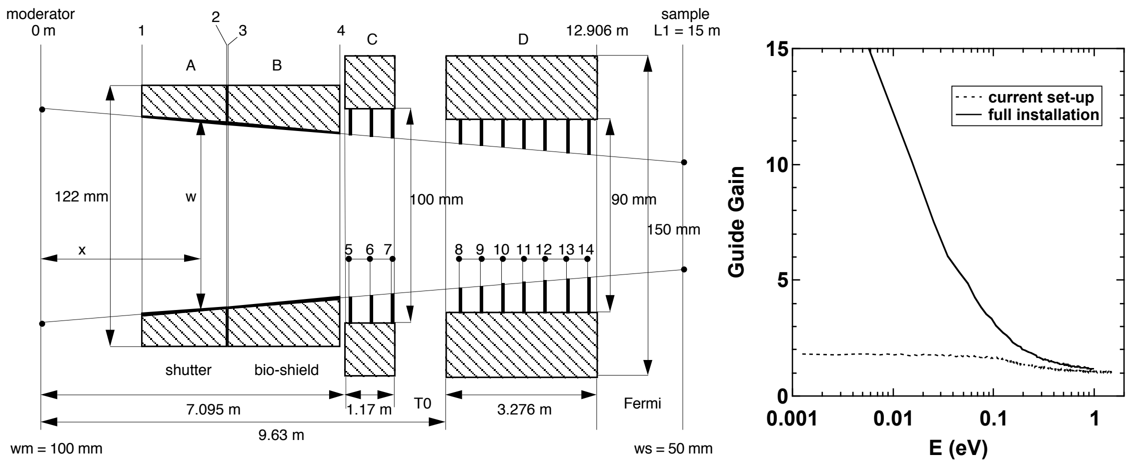

Fig. 2 Current set-up (left) in the primary flight path on HRC: supermirror guide tube (A and B) and collimator (C and D), and expected flux gain (right). By replacing the collimator with the guide tube, a large gain is expected (full installation).

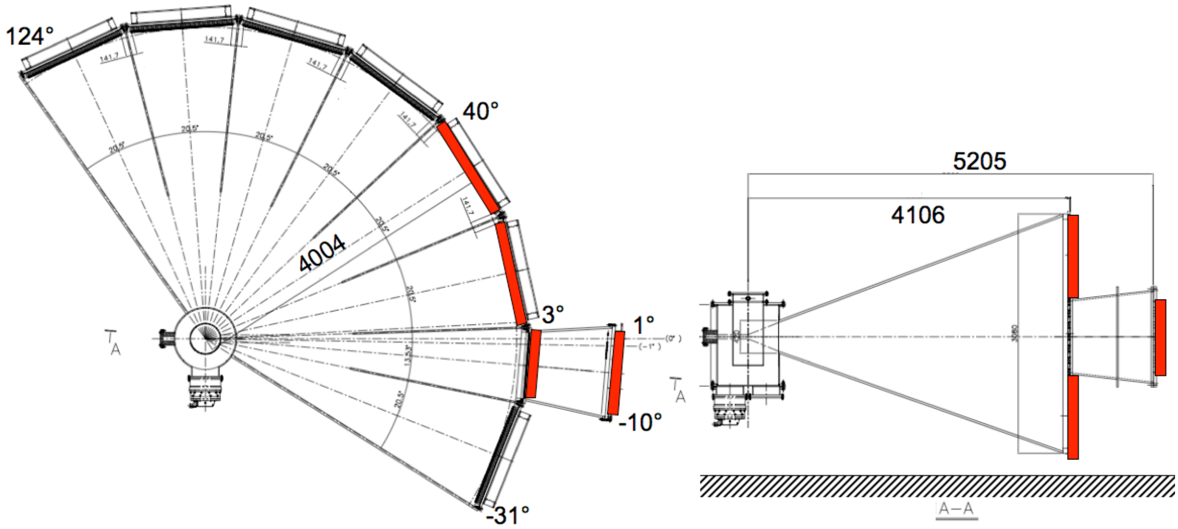

Fig. 3 Vacuum scattering chamber (left: top view, right: vertical cross section) and the installed detector area (red area).

The Fermi chopper was installed at L_3 = 1m. At present, we are using a Fermi chopper used at KEK (Tsukuba). We also developed the Fermi chopper based on a magnetic bearing system with the rotational frequency range of 100 – 600 Hz [7]. The 1st model of the Fermi chopper made in Japan was manufactured, where the slit package is of a current type. The slit package for high resolutions with eV neutrons is still invesigated.

To realize the initial design, we first tried to design the vacuum scattering chamber so that the position sensitive detectors of 1m length can be mounted on the spherical surface at L_2 = 4m outside the vacuum through thin Al windows. However, no company could submit us the quotation. Therefore, we changed the design to mount the position sensitive detectors with 2.8m of the effective length inside the vacuum scattering chamber. In this new design, the number of detectors and electronics can be reduced. We try to realize the uniformity of the resolutions on the data analysis. It is possible to install detectors from -31° to 124° of scattering angles, but at present, it covers only from -10° to 40°, due to the recent situation of He-3, and therefore, the installed detector area is only 30 % of the whole area, as shown in Fig. 3. In the main part from 3° to 40°, 128 position sensitive detectors (effective length: 2.8 m, diameter: 0.75”, He-3 gas pressure: 18 atm) are mounted inside the vacuum chamber for conventional experiments. At low angles from 1° to -10°, 123 shorter position sensitive detectors (0.6m or 0.8m, 0.5” or 1”, 10 atm or 20 atm, used at KEK (Tsukuba) or purchased newly) are mounted, some detectors are mounted at L_2 = 4 m and the others are at L_2 = 5.2 m at the lowest angles for some trial experiments of low angle inelastic scattering. The collimation of low angles should be investigated and improved for trial experiments.

The installation of the supermirror guide tube (the shutter section and the biological shielding section), the collimator, the shieldings and the electric power supply were completed by December 2008. Since the proper vacuum scattering chamber was not yet installed at that time, the vacuum scattering chamber of the chopper spectrometer, INC, used at the KENS facility (KEK, Tsukuba) was transferred to BL12, and we stared test experiments. The first monochromatinc neutron beam at J-PARC was generated in January 2009 by mounting the Fermi chopper used at KENS. The proper vacuum scattering chamber was installed in September 2009, and then the detector system was installed in October 2009. The detector electronics system was installed in December 2008 by

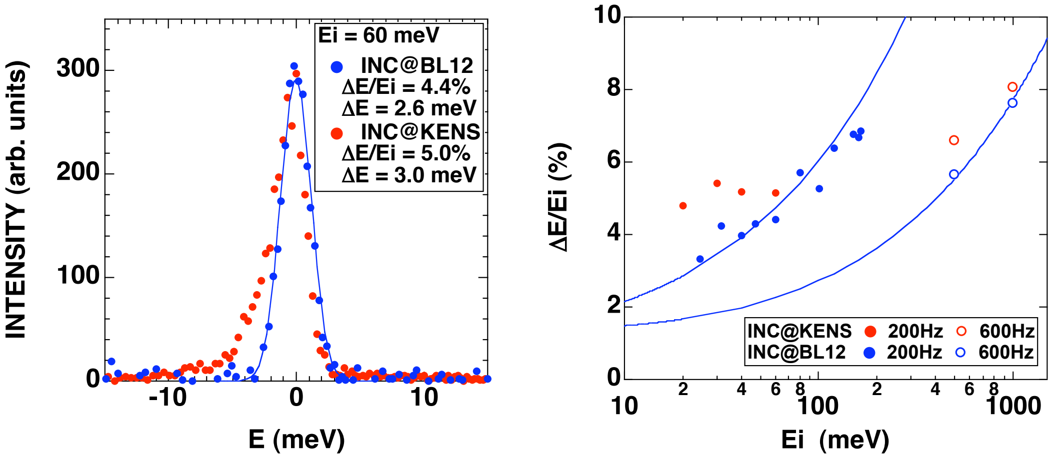

Fig. 4 Observed energy resolution on INC at KENS and at BL12: (a) energy spectrum from vanadium (peaks are normalized), (b) Ei dependence of resolution width. The solid line in (a) is a Gaussian fit for BL12, and those in (b) are the calculation by eq. (1) for BL12.

transferring the system used at KENS (histogram mode data system). Then it was replaced by the standard system at MLF (event mode data system) and new modules were installed with increasing the number of detectors. We successfully converted the event mode data to the dynamical structure factor and visualized them in January 2010, and then the improvement of the computing system is still in progress. The T0 chopper and the cabin were installed in March 2010. The new Fermi chopper and the supermirror guide tube for the replacement of the collimator were delivered in March 2010, they will be installed soon.

5. Some results and current problems

First, we started test experiments by using the vacuum scattering chamber of INC (L_2 = 2.5 m). The energy spectrum of the elastic scattering from vanadium with E_i = 60 meV was measured as shown in Fig. 4, where the optimum slit package (the slit width is w = 1.2 mm and the rotor diameter is D = 100 mm) was used in the Fermi chopper and the Fermi chopper was running at f = 200 Hz. Also the energy spectrum measured on INC at KENS in the same condition for the Fermi chopper was plotted in Fig. 4(a). The observed energy width (FWHM) at BL12 was ΔE = 2.6 meV ($\Delta E/E_i$ = 4.4 %), and this well agreed with the calculation by the following equation [8]:

$$\frac{\Delta E}{E_i} = \left[\left(\frac{2\Delta t_{ch}}{t_{ch}}\left(1+\frac{L_1}{L_2}\right)\right)^2 + \left(\frac{2\Delta t_m}{t_{ch}}\left(1+\frac{L_3}{L_2}\right)\right)^2\right]^{1/2}, \qquad (1)$$
$$t_{ch} = \frac{L_1 - L_3}{v_i}, \quad E_i = \frac{1}{2}mv_i^2, \quad \Delta t_{ch} = \frac{w}{2\pi Df}, \quad \Delta t_m(\mu s) = \frac{\alpha}{\sqrt{E_i(eV)}},$$

where L_1 = 15.325 m, L_2 = 2.5 m, L_3 = 1.295 m and α = 2.5 for INC at BL12, and L_1= 8.21 m, L_2 = 2.5 m, L_3 = 1 m and α = 1.8 for INC at KENS. The energy spectrum of the elastic scattering from vanadium was measured for various conditions of the Fermi chopper, and the observed energy width at BL12 was well described by eq. (1), as shown in Fig. 4 (b). We observed symmetric and well-controlled resolution function at BL12. At KENS, the resolution function had an asymmetric tail, and the resolution width was 5% almost independent of the incident neutron energy. The tail observed at KENS is caused by higher energy neutrons emitted later and passing through the opening time width of the Fermi chopper. At KENS, the energy resolution was almost constant due to the existence of the tail. At BL12, such a tail vanished due to the improved pulse shape of the decoupled moderator as well as the length of the primary flight path L_1. At J-PARC, the resolution function is symmetric and well controlled without such a tail.

After installing the proper vacuum scattering chamber (mainly L_2 = 4 m), the integrated intensity and the energy width of the elastic scattering peak from vanadium were measured with various operation conditions of the Fermi chopper, as shown in Fig. 5. The transmission is the integrated intensity divided by the energy dependence of the incident neutron flux that was assumed to be $1/E_i$. In this measurement, we temporarily chose L_2 = 5.166 m and L_3 = 1.365 m. The sloppy chopper (w = 2.4 mm) and the optimum chopper (w = 1.2 mm) were used. In the optimum chopper, the chopper opening time (Δt_{ch}) roughly equals to the pulse width (Δt_m). The transmissions for both choppers are normalized by each other. The solid lines in Fig. 5 are the calculations by eq. (1) for the resolution width and by the following equation for the transmission [9]:

$$T = \frac{w}{w+t}\frac{\Delta t_{ch}}{\sqrt{1+(\Delta\phi/(w/D))^2}}F(\beta),$$
$$F(\beta) = \begin{cases} 1-\frac{8}{3}\beta^2 & \left(\beta < \frac{3}{4}\right) \\ \frac{16}{3}\beta^{1/2} - 8\beta + \frac{8}{3}\beta^2 & \left(\frac{3}{4} < \beta < 1\right) \\ 0 & (1<\beta) \end{cases}, \quad \beta(v_i) = \frac{D}{2w}\pi Df\left|\frac{1}{v_i} - \frac{1}{4\pi Rf}\right|, \tag{2}$$

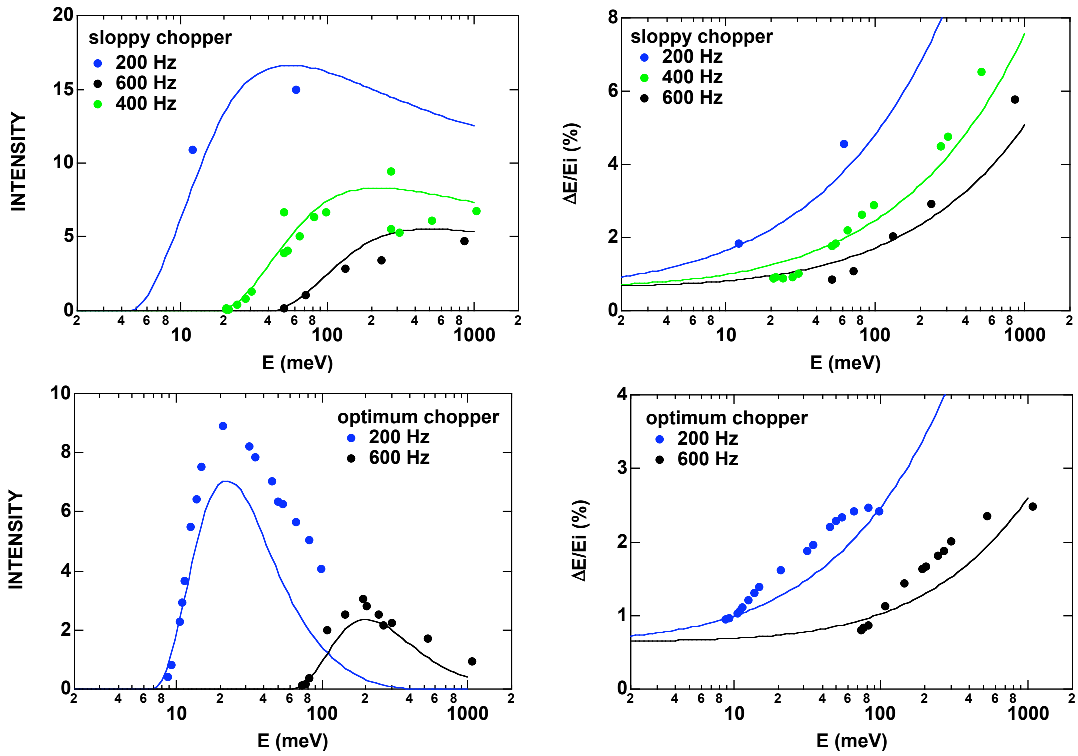

Fig. 5 Observed transmission intensities and resolution widths for the sloppy and optimum choppers with various conditions of chopper operation. The solid lines are calculations.

where t is the thickness of the slit material (0.5 mm), R is the curvature of the slit in the Fermi chopper (R = 1.3 m for the sloppy chopper, R = 0.82 m for the optimum chopper). The calculated transmissions were scaled to the observations at one measurement point and there is no adjustable parameter for the energy resolutions. The observed transmissions and resolutions are well described by the calculations. This indicates again the well-controlled resolution function.

Roughly speaking, we have two problems at present. One is the background noise, and the other is the calculation speed.

Figure 6 shows an observed TOF spectrum from vanadium integrating along the length of 2.8m detectors without the T0 chopper. The distance between the sample and the detected position within the detector was not corrected. Although the elastic scattering signal from the sample is smeared, the background noise originating from high energy neutrons still exists even at 30 meV. Although the background noise is emphasized in this analysis, the background noise is too high to measure inelastic neutron scattering. Since the T0 chopper was installed in March 2010, we expect the great reduction of the background noise. Also, by replacing the current collimator by the full guide tube, the collimation for high energy neutrons will be much improved and it should be effective for the reduction of the background noise.

Figure 7 shows magnetic excitations from the one-dimensional (1D) antiferromagnet $CsVCl_3$ measured on HRC at 120 kW of the beam power. The 1D axis of the single crystal was mounted to be perpendicular to the incident neutron beam, and the measurement was performed at T = 20 K just above the Néel temperature (13 K). The dispersion curve of the antiferromagnetic excitations starting at around 1 $Å^{-1}$ was clearly observed. It took 15 hours for the sample and 22 hours for the empty can. This is the first inelastic data observed on HRC. In the data acquisition system, neutron signals are recorded with event by event [10]. The event mode data are converted to the histogram data, and then visualized as the dynamical structure factor in the four-dimensional energy-momentum space [11]. When the visualization software was installed in January 2010, the calculation speed of the conversion from the event mode data to this dynamical structure factor was about 3 hours for the sample data of 8 GB. The same calculation time was required for the empty can data. Recently, the improvement of the base component of the software, called Manyo-Library, was reported. By installing the new Manyo-Library, the calculation speed

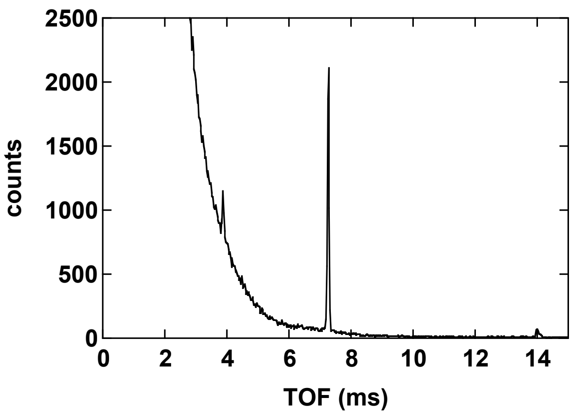

Fig. 6 TOF spectrum integrated over the positions without any geometrical correction (the sum of detectors between 3° and 40°). The large peak is the elastic scattering with E_i = 36 meV.

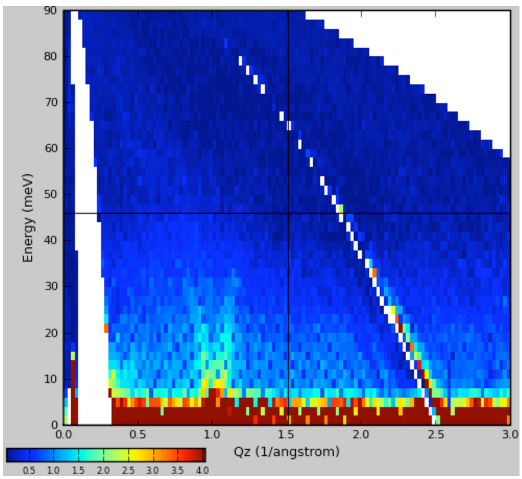

Fig. 7 Magnetic excitations in $CsVCl_3$ measured at 20K.

was greatly improved. It was 6 minutes for the 8 GB data. That is an improvement by a factor of 26. From now on, we will replace this computer by a new faster one and introduce a multi-processor system. We expect increase of calculation speed by more factor 10.

6. Summary

In summary, the construction of HRC was almost completed in collaboration with KEK and the University of Tokyo. Some performance in the initial design was realized in the actual construction, some performance was limited by the actual design and budget, and some performance is still in progress. We have just constructed HRC and its actual performance will be investigated with some improvements of the computing system.

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