Estimation of acceptable beam trip frequencies of accelerators for ADS and comparison with experimental data of accelerators

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Abstract. Frequent beam trips as experienced in existing high power proton accelerators may cause thermal fatigue problems in ADS components which may lead to degradation of their structural integrity and reduction of their lifetime. Thermal transient analyses were performed to investigate the effects of beam trips on the reactor components, with the objective of formulating ADS design that had higher engineering possibilities and determining the requirements for accelerator reliability. These analyses were made on the thermal responses of four parts of the reactor components; the beam window, the cladding tube, the inner barrel and the reactor vessel. Our results indicated that the acceptable frequency of beam trips ranged from 43 to 2.5×10^4 times per year depending on the beam trip duration to keep the plant availability 70 %. In order to consider measures to reduce the frequency of beam trips on the high power accelerator for ADS, we compared the acceptable frequency of beam trips with the operation data of existing accelerators. The result of this comparison showed that the beam trip frequency for durations of 10 seconds or less was within the acceptable level, while that exceeding five minutes should be reduced to about 1/35 to satisfy the plant availability conditions.

1. Introduction

To realize effective transmutation of minor actinides (MA) by an accelerator-driven subcritical system (ADS), a high-power spallation target should be installed at the centre of the core. In the case of JAEA’s reference ADS [1], proton beam power of ~30 MW is necessary to keep the thermal power at the subcritical core at 800 MW. Frequent beam trips, as experienced in existing high power proton accelerators, may cause thermal fatigue problems in ADS components which may lead to degradation of their structural integrity and reduction of their lifetime.

In general, beam trips are caused by two reasons: one is the failure of the accelerator components, and the other is the interruption by a Machine Protection System (MPS) to protect the accelerators against failures. For reference, the beam trip frequency caused by the “dead component” is assessed on the basis of techniques such as Failure Mode and Effect Analysis (FMEA) [2]. For these assessments, the reliability parameters of accelerator components, such as a failure rate, are usually used. However, the influence for the thermal shock damage on the ADS reactor system caused by beam trips has not been evaluated sufficiently. Conversely, it is not yet clear what times in the ADS reactor system are acceptable for the beam trips. The purpose of the present study is to evaluate of the acceptable frequency of beam trips from transient analyses of the ADS reactor system.

2. Design Study of Future ADS

2.1. General Scheme

JAEA's reference design of ADS is a tank-type subcritical reactor, where lead-bismuth eutectic (LBE) is used as both the primary coolant and the spallation target, where the details are discussed in another report in this Meeting [3]. The proton accelerator for the ADS must have high power intensity, more than 20 MW, with good economic efficiency and reliability. To realize such an accelerator, energy efficiency must be enhanced to assure the self-sustainability for electricity of the whole system. Taking account of these requirements, the superconducting linac (SC-Linac) is regarded as the most promising choice. Considering the production efficiency of the spallation neutrons in LBE, the accelerated energy of the SC-Linac was set at 1.5 GeV. In order to keep the thermal power at 800 MW, the beam current was adjusted from 8 to 18 mA (i.e. 12 to 27 MW) depending on the effective multiplication factor (k_{eff}). Taking into account these requirements, the maximum beam current of the SC-Linac was set at 20 mA.

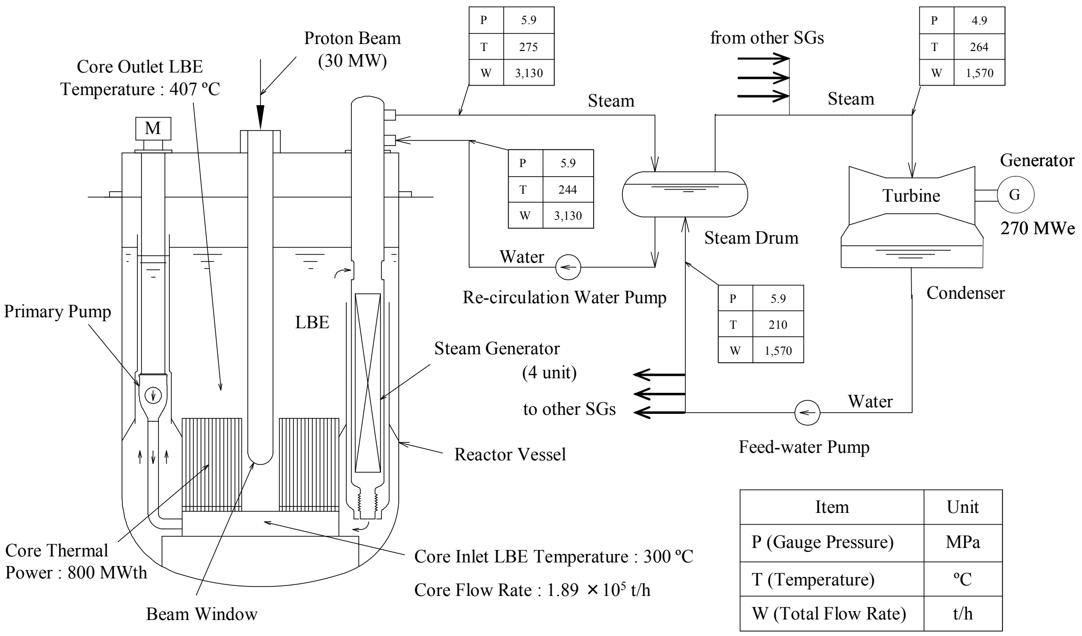
Basic parameters of the SC-Linac, such as the number of cryomodules, the output power of the klystron and the total length of the SC-Linac, were optimized for accelerated energies from 100 MeV to 1.5 GeV [4]. The SC-Linac consists of a series of 89 cryomodules, which were designed for a 972 MHz RF wave. One klystron was provided for each cryomodule giving a total of 89 klystrons. These klystrons were classified into three categories, according to rated output power: 197, 425, and 750 kW.

2.2. Cooling system

The ADS plant was assumed to have a primary LBE cooling system and a water/steam system for power conversion through a saturated steam cycle. *FIG. 1* is a simplified flow diagram of the ADS. As shown in this figure, all other components of the primary system, including four steam generators, two primary pumps and auxiliary heat exchangers, are accommodated within the reactor vessel. The heat generated in the target and the subcritical core is removed by forced convection of the primary LBE, and transferred through the steam generators to water/steam for power conversion.

As shown in *FIG. 1*, Primary LBE coolant flows upward through the subcritical core and exits into an upper plenum. Then, the coolant flow divides equally among four steam generators. The flow passes through heat transfer sections in the steam generators and enters a lower plenum. The LBE coolant is then returned back into the subcritical core by primary pumps. The water/steam system has four steam drums, four re-circulation water pumps, a turbine

FIG. 1. Simplified flow diagram of ADS plant



Item	Unit
P (Gauge Pressure)	MPa
T (Temperature)	℃
W (Total Flow Rate)	t/h

generator unit, and a feed-water pump. Steam generated in the steam generators is directed to the steam drums. The steam from all four steam drums is combined and drives the turbine generator unit. The steam is cooled down into water in a condenser at the turbine exit, and the feed-water pump returns the water back to the steam drums through a feed-water heater that is not shown in the figure. The re-circulation water pump delivers the water from the steam drum to the steam generator.

Preliminary analysis was performed for transients in the ADS plant caused by the beam trip [5]. The primary LBE cooling system and the water/steam power conversion system were modeled with a simple one-dimensional flow network. As a result, about 400 seconds of turbine operation may be possible without the beam. When the duration of the beam trip exceeds this limit, the pressure of the steam drum and the LBE temperature become too low to prevent its freezing.

3. Estimation of Acceptable Beam Trip Frequency

3.1. Restriction from the subcritical reactor

As shown in *FIG. 2*, four parts of the reactor component, i.e. the beam window, the cladding tube, the inner barrel and the reactor vessel, were picked as representatives to discuss the influence of thermal shock. In the following discussion, the expected life time of the subcritical reactor is defined as 40 years and no replacement of the inner barrel and the reactor vessel is assumed during this period. On the other hand, the replacement of the beam window and the cladding tube is assumed once every two years. And the harshest conditions for the thermal load were applied.

As for the beam window, a beam trip causes a rapid temperature drop, which in tern causes thermal stress because of the temperature difference between the inner and the outer surfaces of the beam window. The temperature response of the beam window (inner diameter: 450 mm, thickness: 2 mm, material: 9Cr-1Mo steel, beam power: 30 MW) was evaluated using the finite element method FINAS code [6]. In the evaluation, the beam is assumed to be restarted five seconds after the beam trip. *FIG. 3(a)* shows the temperature change for the apical region of the beam window. On the beam trip at *t* = 0, the surface temperature starts to drop rapidly and asymptotically approaches the coolant temperature within about three seconds. The maximum thermal stress of 179 MPa is expected at a time 0.5 seconds after the beam trip. This thermal stress is much lower than what would cause buckling failure. The acceptable number of these thermal shocks is estimated to exceed 10^5, which means that several beam trips per one hour may be acceptable for two years of the expected life time of the beam window (about 15,000 hours). It should be noted that this estimate is based on the

FIG. 2. Influence of beam trip transient on reactor structure

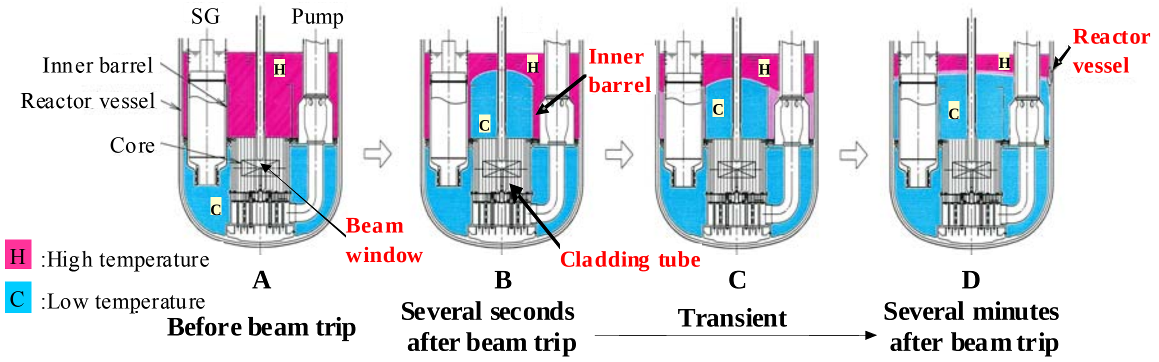
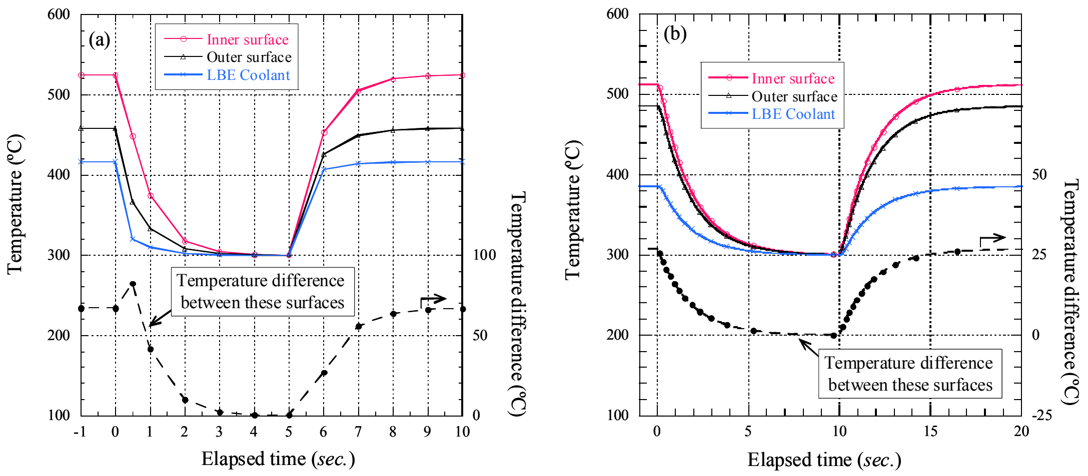


FIG. 3. Change of the surface temperature after the beam trip for (a) the beam window, and (b) the cladding tube.



material data without radiation damage, and therefore experimental verification for the effect of the proton and neutron irradiation is indispensable.

As for the cladding tube, a beam trip causes a rapid temperature drop similar to that for the beam window. The temperature response of the cladding tube was evaluated using the finite element method ABAQUS code [7]. Design parameters used for the evaluation are listed in Table I. The distance from the center of the active core to the cladding tube was 27.9 cm. In the evaluation, the beam is assumed to be restarted 10 seconds after the beam trip. And the corrosion depth of the outer surface is estimated as 125 μm. *FIG. 3(b)* shows the change of the surface temperature in such a position that the strain range caused by the beam trip and restart becomes the maximum of 6.2×10^{-4}. This position is located on the outer surface at 50.4 cm below from the top of the active core. After the beam trip, the temperature difference between the inner and outer surface starts to drop rapidly and asymptotically approaches zero within about five seconds. Considering the magnitude of the strain range, the acceptable number of beam trips for the cladding tube is estimated to exceed 10^6 times.

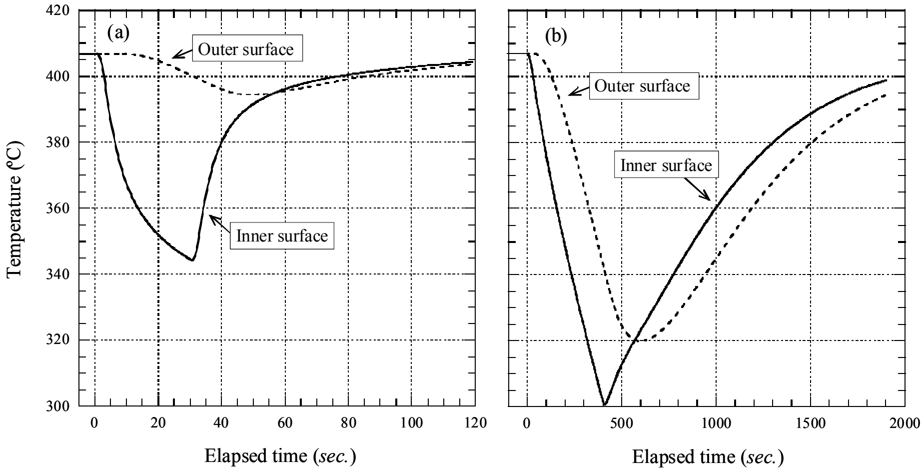
The inner barrel is a cylindrical structure made of 3 cm thick 9Cr-1Mo steel and installed to straighten the LBE flow above the subcritical core. During normal operation, it is kept at the average outlet temperature 407 °C. In the case of the beam trip, the inner surface of the cylinder is immediately cooled by the cold LBE (about 300 °C), causing a temperature difference between the inner and outer

Table I: PARAMETERS USED FOR THE EVALUATION OF THE CLADDING TUBE

Fuel composition	(Pu+MA)N + ZrN*
Bond	He
Cladding	9Cr-1Mo steel
Pin outer diameter	7.65 mm
Thickness of cladding tube	0.5 mm
Pellet smear density	95 %
Pin pitch	11.48 mm
Pin length	3050 mm
Active height	1000 mm
Gas plenum height	1050 mm
Production rate of fission product (FP) gas	27 %
Release rate of FP gas	100 %
Linear power rating	343 W/m (average)
Coolant velocity	2.0 m/s
Inlet temperature	300 °C

* Fuel is composed of 50.3 % (MA+Pu)N, which is a mixture of MA nitride (MAN) and Pu nitride (PuN), and 49.7 % zirconium nitride (ZrN) in weight basis.

FIG. 4. Change of the surface temperature after the beam trip for (a) the inner barrel, and (b) the reactor vessel.



surfaces. The temperature for 120 seconds after the beam trip was calculated by means of the ABAQUS code. In the calculation, the temperature for the outer surface is taken to be the steady value, 407 °C, because it is difficult for the cold LBE to reach the outer surface in a short period of time. And the beam is assumed to be restarted 30 seconds after the beam trip. According to the results, shown in *FIG. 4(a)*, the temperature difference of 54 °C will be observed at 24 seconds after the beam trip, which will cause maximum stress of 144 MPa. At the re-start of the beam, the stress in the inverse direction will be added to the inner barrel. The stress range for fatigue evaluation, therefore, is 159 MPa. Considering this magnitude of stress, the acceptable number of beam trips for the inner barrel is estimated at about 10^5 times. If the duration of the beam trip is less than 24 seconds, the stress to the inner surface becomes smaller than the maximum. In this example, the stress at the inner surface at five and ten seconds after the beam trip is 74 and 121 MPa, which is roughly equivalent to exceed 10^6 and 10^6 beam trips, respectively. Therefore, the influence of the thermal shock to the inner barrel could be reduced, provided that the beam was reinjected into the subcritical core within about ten seconds after the beam trip.

As for the reactor vessel, the beam trip causes a temperature change between the inner and outer surfaces similar to that for the inner barrel, and the formation of temperature stratification and the lowering the LBE level because of thermal shrinkage both cause thermal stress. The stress range for the fatigue evaluation was estimated for the reactor vessel made of 5 cm thick 9Cr-1Mo steel under the assumption that the beam is restarted 120, 300 and 400 seconds after the end of the beam trip. The result for the beam trip duration with 400 seconds is shown in *FIG. 4(b)*. We observed that the peak value of the temperature difference between the surfaces occurred at 293 seconds after the beam trip. The maximum stress range calculated from the axial and circumferential stress was about 379 MPa. Considering this magnitude of the stress, the acceptable number of beam trips for the reactor vessel is estimated at about 3×10^4 times. The results for 120 and 300 seconds are given in Table II.

3.2. Acceptable number of beam trips per year

Taking account of the above discussions, the acceptable number of the beam trips for each component is summarized in Table II. In this table, the elapsed time after the beam trip when the stress range or the strain range is maximized and the expected life time for each component are also listed. The acceptable frequency of beam trips, obtained by dividing the

Table II: ACCEPTABLE NUMBER OF THE BEAM TRIP FOR EACH COMPONENT

Component	Expected life time (year)	T_{max} [a)] (*sec.*)	Acceptable number [b)] (times)	Acceptable frequency (times/year)
Beam window	2	0.5	$> 1\times10^5$	$> 5\times10^4$
Cladding tube	2	0	$> 1\times10^6$	$> 5\times10^5$
Inner barrel	40	24.4	$> 1\times10^6$ (5 *sec.*)	$> 2.5\times10^4$
			1×10^6 (10 *sec.*)	2.5×10^4
			1×10^5 (30 *sec.*)	2.5×10^3
Reactor vessel	40	293	$> 1\times10^6$ (120 *sec.*)	$> 2.5\times10^4$
			1×10^5 (300 *sec.*)	2.5×10^3
			3×10^4 (400 *sec.*)	7.5×10^2

a) The value represents the elapsed time after the beam trip when the stress range or the strain range is maximized.
b) The value in parentheses represents the beam trip duration.

Table III: ACCEPTABLE FREQUENCY OF BEAM TRIPS ACCORDING TO THE BEAM TRIP DURATION

Criteria	Acceptable value (times/year)	Component or condition that imposed limits
0 *sec.* $\leq T \leq$ 10 *sec.*	25,000	Inner barrel
10 *sec.* $< T \leq$ 5 *min.*	2,500	Inner barrel, Reactor vessel
$T >$ 5 *min.*	43	system availability

acceptable number of beam trips by the expected life time for each component, ranges from 750 to 2.5×10^4 times per year. For the beam trip duration over 400 seconds, it was assumed that the acceptable frequency of beam trips was restricted by the availability of the system because the restart procedure of the system usually takes a long period of time, typically several hours, once the power generation turbine stops.

Therefore, the acceptable frequency of beam trips was classified by three criteria, according to the beam trip duration, as shown in Table III. The acceptable frequency of beam trips for the inner barrel was adopted for the criteria for a beam trip of 10 seconds or less, because the acceptable frequency of beam trips for the inner barrel was lower than that for the beam window and the cladding tube. For the medium beam trip duration (10 *sec.* $< T \leq$ 5 *min.*), the acceptable frequency of beam trips for the inner barrel was adopted. For the beam trip duration over five minutes, the acceptable frequency of beam trips was assumed to be once a week so that the system availability was 70 % or more. In this estimation, the effective full power days was assumed to be 300 for one year, that is, 43 weeks per year.

4. Estimation of the beam trip frequency based on the current experimental data

In order to develop measures for reducing beam trip frequency, it is important to know the present level of accelerator technology. First, the beam trip frequency of the JAEA's SC-Linac for ADS is estimated from operation data of existing accelerators in this section. Pioneering experimental data obtained from the Los Alamos Neutron Science Center (LANSCE) and the High Energy Accelerator Research Organization (KEK) was used for this estimation. Next, comparing the difference between the acceptable frequency of beam trips and the current experimental data, strategies to overcome the beam trip problem on ADS are discussed.

4.1. Estimated number of beam trips per year

LANSCE is a spallation neutron source based on a linac [8]. The accelerator facility is one of the most powerful linear proton accelerators in the world. The proton linac delivers two proton beams at 800 MeV: the H^+ and the H^- beam. The H^+ beam can deliver 1.25 mA and the H^- beam can deliver 70 μA. Each injector system includes a 750 keV Cockcroft-Walton type generator. The heart of the RF system is the klystron system which provides RF power at 805 MHz to the side coupled linac.

A thorough failure analysis has been conducted for years at LANSCE. The average value of beam trips for H^+ was 1.62 trips/h whilst this value was 0.78 for the H^- beam. Detailed statistics give no room for doubt; the H^+ injector was responsible for 86 % of beam trips. Next to the injector is the RF system, responsible for 8 % of all beam trips linked to the H^+ beam. Detailed information can be found in Ref.9.

An electron/positron injector linac at KEK [10], capable of providing electrons at energies up to 8 GeV and positrons up to 3.5 GeV, is used as a multi-purpose injector not only for the KEK B Factory (KEKB), but also for the Photon Factory (PF). At present, it delivers full-energy beams of 8-GeV electrons to the KEKB High-Energy Ring and 3.5-GeV positrons to the KEKB Low-Energy Ring. The whole linac consists of 55 S-band (2856 MHz) main accelerator modules. 50 MW pulse klystrons with a time duty factor of 0.02 % were developed.

Statistics on interruptions and the down time distribution of KEK klystrons were obtained from the operation data in FY2005. The scheduled beam time and the down time for the whole system was 6,815 *h* and 52.5 *h*, respectively. The total number of interruptions was 16,421, including 13,453 accidental interruptions and 2,968 censored events. Accidental interruptions were caused by the failure of the RF system. Censored events were the manual terminations for regular maintenance every two weeks.

Because 85 % of all beam trips were caused by the injector and the RF system of LANSCE, the beam trip frequency of the JAEA's SC-Linac for ADS, N_{ads}, was roughly estimated as:

$$N_{ads} \sim N_{inj} + N_{rf} \qquad (1)$$

where the N_{inj} and N_{rf} are the beam trip frequency caused by the injector and the RF system of the JAEA's SC-Linac for ADS, respectively. And the N_{inj} and N_{rf} are estimated as:

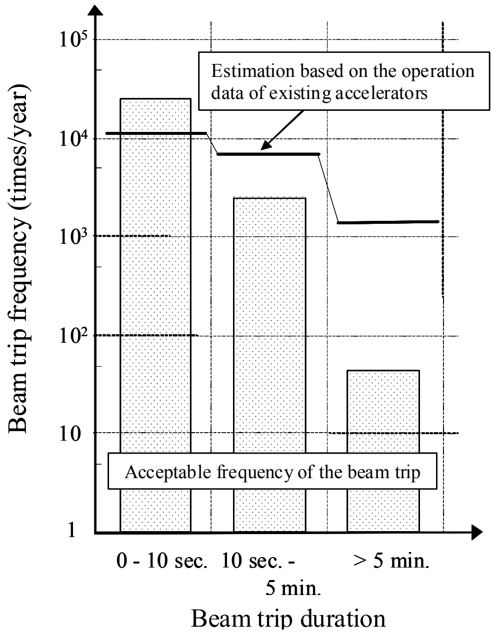
$$N_{inj} = \frac{T_s}{\bar{t}_i + \bar{\tau}_i}, \quad N_{rf} = N_{kly} \frac{T_s}{\bar{t}_r + \bar{\tau}_r}, \qquad (2)$$

where T_s is the total scheduled beam time per year for the ADS plant (7,200 *h*/year), $\bar{t}_i$ and $\bar{\tau}_i$ are the mean time between beam trips and MTTR (Mean Time To Repair) obtained from the data of the LANSCE H^+ injector: 0.77 *h* and 3.4×10^{-2} *h*, respectively [9]. N_{kly} is the number of klystrons of the JAEA's SC-Linac for ADS, that is 89. And $\bar{t}_r$ and $\bar{\tau}_r$ are the mean time between beam trips and MTTR obtained from the data of the RF system of the electron/positron injector linac at KEK: 54.6 *h* and 7.3×10^{-2} *h*, respectively [11]. Finally, we got the value of N_{ads} is 21,000 times/year.

4.2. Comparison and discussion

From the above analysis, using the distribution of beam trip durations obtained from the data of the LANSCE and the KEK [11], the down time distribution of the JAEA's SC-linac is a straight line as shown in *FIG. 5*. Further, the acceptable frequency of beam trips is shown in this figure as a histogram. Comparing the two shows that even at the present technological level of accelerators, the beam trip frequency for durations of 10 seconds or less is within the acceptable level. On the other hand, for the beam trip frequency with duration exceeding five minutes, it is necessary to improve the technology level to about 35 times of present accelerator technology.

FIG. 5. Comparison of the acceptable frequency of beam trips and the estimated frequency of the JAEA's SC-linac for ADS



5. Conclusion

Frequent beam trips as experienced in existing high power proton accelerators may cause thermal fatigue problems in ADS components which may lead to degradation of their structural integrity and reduction of their lifetime. Thermal transient analyses were performed to investigate the effects of beam trips on the reactor components, with the objective of formulating ADS design that had higher engineering possibilities and determining the requirements for accelerator reliability. These analyses were made on the thermal responses of four parts of the reactor components; the beam window, the cladding tube, the inner barrel and the reactor vessel. Our results indicated that the acceptable frequency of beam trips ranged from 43 to 2.5×10^4 times per year depending on the beam trip duration to keep the plant availability 70 %.

In order to consider measures to reduce the frequency of beam trips on the high power accelerator for ADS, we compared the acceptable frequency of beam trips with the operation data of existing accelerators. The result of this comparison showed that the beam trip frequency for durations of 10 seconds or less was within the acceptable level, while that exceeding five minutes should be reduced to about 1/35 to satisfy the plant availability conditions.

As the acceptable frequency of beam trips is different for each ADS reactor system design, this solution for the beam trip problem is not valid for all ADS accelerators. However, we believe that this evaluation technique of the beam trip is of potential utility in ADS system planning.

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