ESS Accelerator Cryoplant Process Design

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Abstract. The European Spallation Source (ESS) is a neutron-scattering facility being built with extensive international collaboration in Lund, Sweden. The ESS accelerator will deliver protons with 5 MW of power to the target at 2.0 GeV, with a nominal current of 62.5 mA. The superconducting part of the accelerator is about 300 meters long and contains 43 cryomodules. The ESS accelerator cryoplant (ACCP) will provide the cooling for the cryomodules and the cryogenic distribution system that delivers the helium to the cryomodules. The ACCP will cover three cryogenic circuits: Bath cooling for the cavities at 2 K, the thermal shields at around 40 K and the power couplers thermalisation with 4.5 K forced helium cooling. The open competitive bid for the ACCP took place in 2014 with Linde Kryotechnik AG being selected as the vendor. This paper summarizes the progress in the ACCP development and engineering. Current status including final cooling requirements, preliminary process design, system configuration, machine concept and layout, main parameters and features, solution for the acceptance tests, exergy analysis and efficiency is presented.

1. Introduction

The European Spallation Source (ESS) is a world-class neutron science facility, funded by at least 17 European countries, currently under construction in Lund, Sweden. Initial operation is expected in 2019 using a 570 MeV proton beam and 7 instruments. Full operation with a 2 GeV proton beam and 22 instruments is planed for 2023.

In the ESS accelerator, the bulk of the acceleration is carried out by 3 types of superconducting radio frequency (SRF) cavities. There are a 13 double spoke cavity cryomodules (CMs) [1], 9 medium beta elliptical CMs and 21 high beta elliptical CMs [2]. All the SRF cavities operate in saturated 2 K He II baths. Each of the CMs also contains a 40 K thermal shield (TS) and requires helium cooling of the RF power couplers. The power coupler cooling returns the helium at ambient temperature and thus is a liquefaction load. There are no superconducting magnets in the ESS accelerator. The CMs will be connected to the accelerator cryoplant (ACCP) by a cryogenic distribution system [3], which will be mainly composed of a cryogenic distribution line with 43 valve boxes.

One dedicated cryoplant is used to serve the accelerator superconducting section. The ACCP is the largest and most complicated of the ESS cryoplants. The cooling requirements and the initial concept design have been developed and improved over the years [4-9]. The ACCP was procured in an open bid procedure, which covers the design, the warm compressor station and the cold box, the plant control system, installation and commissioning. A formal invitation to the bid was issued in June 2014. The contract was awarded to Linde Kryotechnik AG (LKT) in December 2014 and signed in March 2015.

2. Cooling requirements

Detailed thermal performance studies and analysis have been performed to estimate the heat load imposed on the CMs, cryogenic distribution system (CDS) and that due to beam losses. The ACCP design heat loads are listed in table 1. Related descriptions about the safety margin, operation modes, project stages and the operational parameters are described in in our previous papers [4-9].

The 2 K heat loads consists of the isothermal load, which is applied to the liquid helium bath enfolding the cavities and the non-isothermal load from the CDS. The isothermal load, including the statics and dynamics from RF loses in the cavity walls and beam losses, will determine the helium mass flow through the 2 K circuit handled by the cold compressors. The non-isothermal load will strongly affect the 2 K return temperature at the inlet of the first cold compressor.

The installed cooling capacities of the ACCP are 3050 W at 2 K circuit, 9.0 g/s liquefaction rate at 4.5 K and 11380 W at 40-50 K circuit.

Table 1. Accelerator cryoplant heat loads.

Operation modes		2 K Load, W			4.5 K Load		40-50 K, W
		Isothermal	Non-isothermal	Total	4.5 K, W Total	Liqu., g/s	Total
Stage 1 2019-2023	Nominal	1860	627	2478		6.8	8551
	Turndown	845	627	1472		6.8	8551
	4.5 K Standby	-	-	-	1472	6.8	8551
	TS Standby	-	-	-	-	-	8551
	Maximal Liquefaction	Loads in standby mode plus maximum liquefaction rate at rising level into the storage tank					
Stage 2 2023-…	Nominal	2226	824	3050		9.0	11380
	Turndown	1166	824	1990		9.0	11380
	4.5 K Standby	-	-	-	1990	9.0	11380
	TS Standby	-	-	-	-	-	11380
	Maximal Liquefaction	Loads in standby mode plus maximum liquefaction rate at rising level into the storage tank					

3. Process design

Based on the comprehensive industry studies from two potential venders, Linde Kryotechnik AG (LKT) and Air Liquide Advanced Technologies (ALAT), solid experience and well-developed concepts from CERN [10], DESY [11, 12], FNAL [13], SNS and JLab [14-16], some key design choices, including mixed compression for the 2 K cycle, no liquid nitrogen (LN$_2$) pre-cooling, one integrated cold box, waste heat recovery and process control system strategy, have been integrated into the ACCP specification, finally implemented into its proposal by LKT. The simplified process design is shown in figure 1, which mainly consists of three oil-lubricated screw compressors, six gas dynamic bearing turbines, three cold compressors and several heat exchanger blocks.

There are four main pressure levels: sub-atmospheric pressure in series with cold compressors (SP), low pressure slightly above atmospheric pressure (LP), middle pressure (MP) and high pressure (HP) connected to the inlet of the cold box. Following this classification, the warm compressor station contains three stages. One stage after three cold compressors compresses helium from SP directly to MP level (SP stage). A second compressor (LP stage) is used to compress helium from LP level to the same MP level. At this pressure level, additional flow is coming back from the cold box. The total flow is compressed in a single compression stage (HP stage) from MP to HP. The middle pressure can
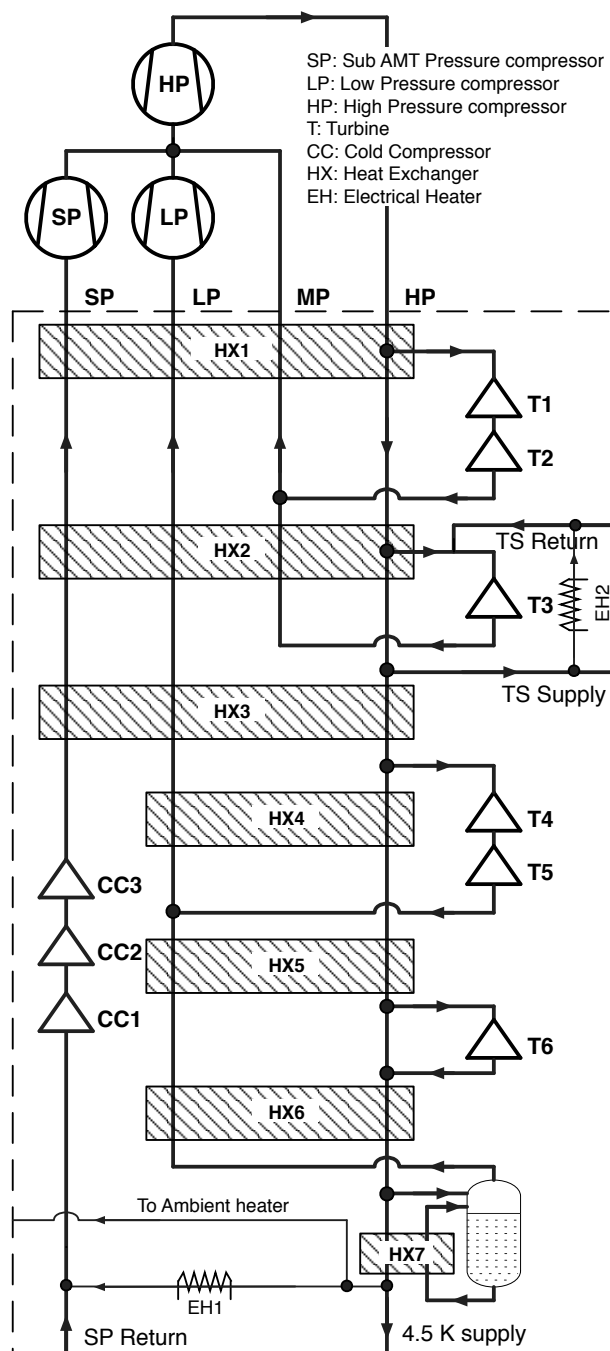
Figure 1. Simplified ACCP process flow design.

be regulated consistent with the operation conditions. The adaptable middle pressure ensures operation of turbines and screw compressors at highest efficiencies during all operation modes.

The screw compressors are chosen in a way that the flow in each stage is compressed by a single screw compressor. Moreover, all three screw compressors are of identical screw block size, which allows a small number of spare parts, high redundancy at the same time, and reduced installation efforts and costs.

The "mixed" compression cycle based on a combination of cold compressors (CC1-CC3) in series with a warm sub-atmospheric compressor (SP compressor) is used to produce refrigeration at 2 K. The compressed helium from the SP circuit is directly discharged to the suction side of the HP compressor. The still low enthalpy of the gas at the outlet of the cold compressors is used for heat exchangers at corresponding temperature level. The SP and LP compressors share the same bulk oil removal system, minimizing the investment cost of the system. Such a cycle can accommodate a large dynamic range without additional electrical heating. In addition, the SP compressor provides flexibility and advantages during transient operation modes (i.e. start-up of pumping down, in which the cold compressors are far from their design conditions and difficult to tune). The main drawback of this type of cycle is the risk of contamination from air leak. Welded joints will be used wherever possible and all components interfacing sub-atmospheric circuits and ambient atmosphere, such as safety valves, dynamic seal of valve stems and instrumentation will be protected from air intake either by a helium or vacuum guard.

The floating pressure cycle [13, 14] is a common control strategy to provide flexibility and energy saving potential. Suction and discharge pressures of the HP compressor are varied proportionally. The mass flow of the compressor is thus adapted without a frequency converter keeping the volumetric flow rates unchanged. Variable frequency drives (VFD) are applied to control the capacity of the SP and LP compressors to adapt the capacity to the flow rate of returning gas. High efficiency and power savings are achieved with these arrangements in the turn down modes.
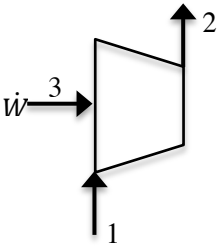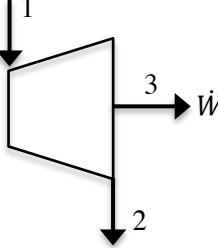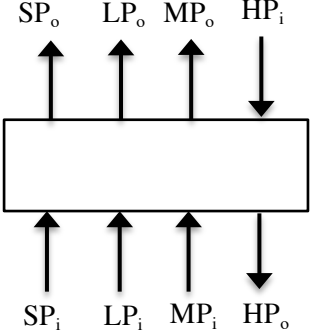
The different capacity requirements for the two ACCP stages are matched by an exchange of cold compressor wheels & flow parts and turbine flow parts, in combination with the capacity control of the warm compressors described above. High efficiency can be achieved in both stages of the project.

The floating pressure cycle and LKT's expander technology perform in highest process efficient over the broad operation map, resulting in nearly constant process efficiency over a very large capacity range of the refrigerator and related power savings. These features have been proven by the several similar plants at XFEL-DESY [11, 12], FNAL [13] and JLab [16].

For the acceptance tests of the overall performance of the ACCP, two built in electrical heaters as well as one external ambient heater are used. The first test heater (EH1) is located upstream of the 4.5 K supply line and directed to the SP return line. This heater is used to simulate the cumulated static and dynamic heat loads in the 2 K or 4.5 K system depending on the mode tested. The second heater (EH2) is connected between the TS supply and TS return for shield circuit tests. Measuring with the flow meter downstream of the ambient heater located outside the cold box will test the liquefaction load for the coupler cooling. All cold equipment is incorporated in one cold box, which provides a compact, flexible, space and cost efficient set-up.

4. System exergy analysis and efficiency

Table 2. Exergy destruction for the main components at steady state in a cryoplant.

Components	Warm/Cold compressor	Turbines	Heat exchanger
Schematic			
Rate of exergy destruction	$\dot{X}_{des} = \dot{W} + \dot{X}_1 - \dot{X}_2$	$\dot{X}_{des} = \dot{X}_1 - \dot{X}_2 - \dot{W}$ $\dot{W} = \dot{m} \cdot (h_1 - h_2)$	$\dot{X}_{des} = \dot{X}_{HP_i} + \dot{X}_{MP_i} + \dot{X}_{LP_i} + \dot{X}_{SP_i} - \dot{X}_{HP_o} - \dot{X}_{MP_o} - \dot{X}_{LP_o} - \dot{X}_{SP_o}$

A popular modern method of analyzing a thermodynamic cycle is to define a quantity of exergy at each state point [17-21]. The definition of exergy uses the first and second laws simultaneously to indicate the ideal reversible work to achieve a given state conditions in a given environment:

$$X_{s,1} = W_{max} = H_1 - H_0 - T_0(S_1 - S_0) \tag{1}$$

Where,

$X_{s,1}$, Exergy of the system at state 1;

W_{max}, Maximum useful work;

H_1, H_0, Enthalpy at state 1 and 0;

S_1, S_0, Entropy at state 1 and 0.

State 0 is defined as the surroundings at room temperature and atmospheric pressure.

Equation (1) can be expressed on a rate basis as well:

$$\dot{X}_{S,1} = \dot{W}_{max} = \dot{m}[h_1 - h_0 - T_0(s_1 - s_0)] \tag{2}$$

The exergy can never be generated; It can only be destroyed. This effect can be used to optimize thermodynamic systems. The best way to determine the amount of exergy destruction is with an exergy balance. For a given component in the cryoplant at steady state, the exergy balance on a rate basis can be written as:

$$\dot{X}_{in} = \dot{X}_{out} + \dot{X}_{des} \tag{3}$$

Where,

$\dot{X}_{in}$ and $\dot{X}_{out}$: Rates at which exergy enters and leaves the component;

$\dot{X}_{des}$: Rate of exergy destruction, which represents irreversibilities in the process expressed in units of value significance, such as Watts.

The exergy destructions of the main components at steady state in a cryoplant are illustrated in table 2.

A detailed exergy analysis of the ACCP process at the various operation modes has been performed, identifying the exergy destruction of individual process components. One example, the exergy destruction of the ACCP at stage 2 nominal design case, is presented in figure 2.
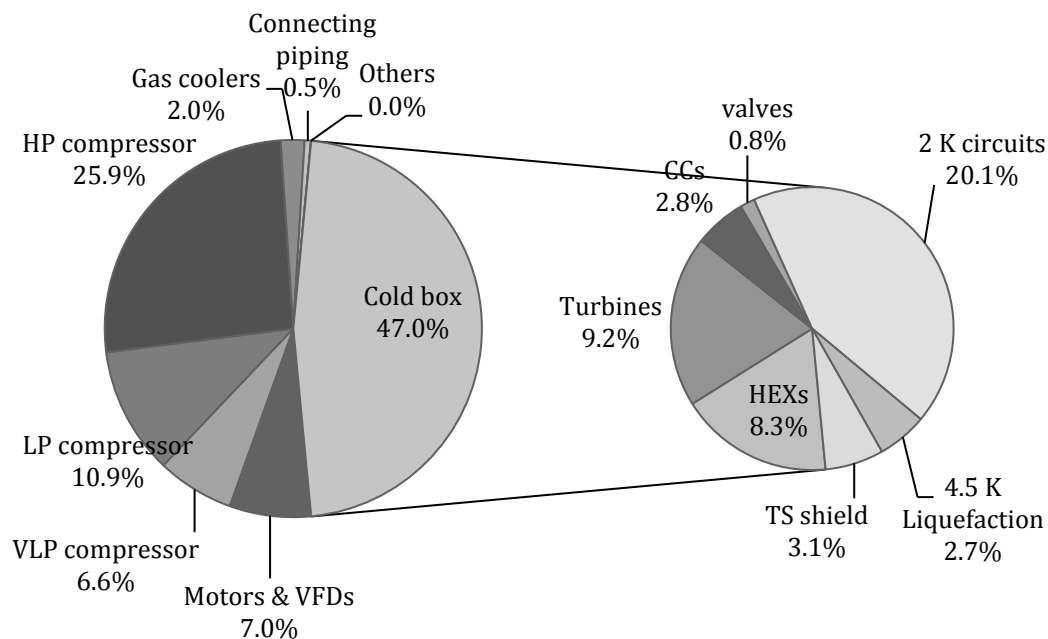

Figure 2. The exergy destruction of the ACCP at stage 2 nominal design case.

The electrical power input into the compressor motors equals the exergy input to the ACCP (100%). A large amount of exergy, 53% in total, is dissipated in the warm compressor system, including 43.5% in compressors (SP/LP/HP), 7% in electrical motors and VFDs, 2% in gas coolers, 0.5% in the interconnecting piping between the warm compressor system and the cold box and others, i.e. valves, mixtures and bypass, which are neglected. Finally, the 47 percent of the exergy input is passed onto the cold box. In the cold box, in an among of total power input to the plant, 9.2% is

destructed in turbines due to its isentropic efficiency and un-recovered extracted mechanical power; 8.3% is destructed in heat exchanges caused by non-ideal heat transfer, pressure drop and process design; 2.8% is dissipated in the cold compressors due to its entropy efficiency and the driven-motor efficiency; 0.8% is lost in the all valves; the remaining exergy is delivered out of the cold box boundary, served for the 2 K circuit (20.1%), 4.5 K liquefaction (2.7%) and TS shield (3.1%), which represents the final ACCP exergy efficiency of 25.9 % corresponding in a electrical power input of 2.37 MW into the system at stage 2 nominal design case. The cold box efficiency in this case is about $25.9\%/47\% \approx 55.2\%$ which can be considered as very good value obtained in large 2 K refrigerators.

The exergy efficiencies at various operation modes of both stages are given in figure 3. The following observations may be made from figure 3:

- The ACCP system is designed for the nominal design mode at stage 2 and can reach the exergy efficiency of 25.9%.
- To adapt the different capacity requirements for stage 1 at nominal design mode, the reasonable good exergy efficiency of 24.5% can be obtained by an exchange of cold compressor wheels & flow parts and turbine flow parts, in combination with the capacity control of the warm compressors.
- Benefited from the floating pressure concept and VFDs equipped in warm compressors (SP/LP stages) and cold compressors, at turn-down operation modes, the related good efficiencies of 21% for stage 2 and 18.3% for stage 1 can be achieved.
- At 4.5 K standby modes, the LP compressor runs at higher capacity utilization and SP compressor is switched off, which result 18.1% of exergy efficiency for stage 2 and 15.6% of exergy efficiency for stage 1.
- Since the operation conditions at TS standby mode are far away from the optimal design, the system will have about 5% of exergy efficiency at both stages with only one stage compressor (HP) and one turbine (T3) involved in operation.
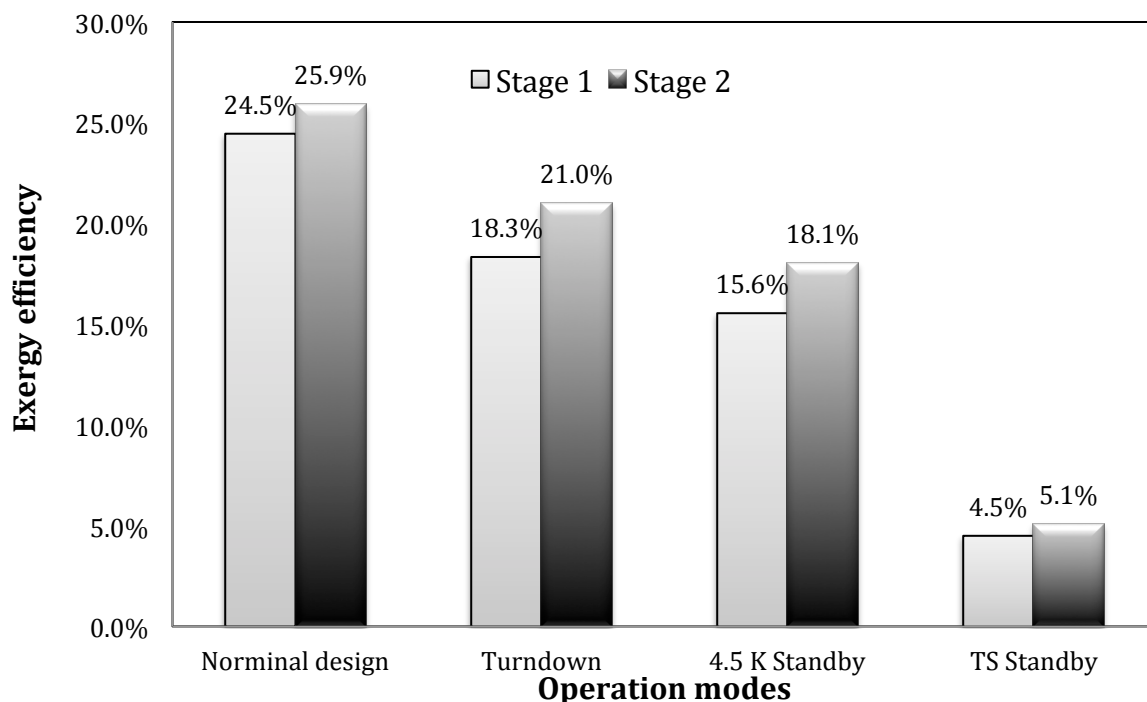

Figure 3. Exergy efficiencies at various operation modes of both stages.

5. Conclusion
The current status and the preliminary process design of the ACCP are summarized in this paper. With the help of the exergy analysis, the exergy destructions of the key components and the overall efficiencies at various operating modes are investigated. The second-law efficiency of 25.9% at stage 2 nominal design case are achievable using the current selected machines and process design.

The ACCP project was kicked off in May 2015, and the preliminary design is well under way. The main components, including warm compressor system, plate fin heat exchanger set, turbines, cold compressors and valves, will be ordered within this year. The site acceptance test is expected to be finished at the beginning of July 2018.

References
[1]   Bousson S, Darve C, Duthil P, Elias N, Molly S, Reynet D and Thermeau J P 2014 *Advances in Cryogenic Engineering, AIP Conference Proceedings (Anchorage, Alaska, USA)* 1573, pp 665-672
[2]   Darve C, Bosland P, Devanz G, Olivier G, Renard B and Thermeau J P 2014 *Advances in Cryogenic Engineering, AIP Conference Proceedings (Anchorage, Alaska, USA)* 1573, pp 639-646
[3]   Fydrych J, Arnold P, Hees W, Tereszkowski P, Wang X L and Weisend II J G 2014 *ICEC 25 - ICMC 2014 (Enschede, The Netherlands)*, To be published
[4]   Wang X L, Koettig T, Gallimore T and Hees W 2012 *The 12th cryogenics 2012 (Dresden, Germany)* pp 46-51
[5]   Weisend II J G and Darve C 2014 *Advances in Cryogenic Engineering, AIP Conference Proceedings (Anchorage, Alaska, USA)* 1573, pp 633-638
[6]   Weisend II J G, Arnold P, Frdrych J, Hees W, Jurns J and Wang X L 2014 *ICEC 25 - ICMC 2014 (Enschede, The Netherlands)*, To be published
[7]   Wang X L, Weisend II J G, Koettig T, Hees W and Darve C 2014 *HVAC&R research* **20** 296
[8]   Arnold P, Fydrych J, Hees W, Jurns J, Wang X L and Weisend II J G 2014 *Proceeding of IPAC2014 (Dresden, Germany)* pp 2756-2758
[9]   Arnold P, Fydrych J, Hees W, Jurns J, Wang X L and Weisend II J G 2014 *Proceeding of LINAC2014 (Geneva, Switzerland)* pp 939-941
[10]   Claudet S 2005 *Proceeding of 2005 particle accelerator conference (Konxville, Tennessee, USA)* pp 9-13
[11]   Petersen B 2010 *Presentaion, Project X collabration meeting (FNAL, USA)*
[12]   Wilhelm H 2015 *Presentation, HEPTech academia meets industry on cryogenics (Grenoble, France)*
[13]   White M and Martinez A 2014 *Advances in Cryogenic Engineering, AIP Conference Proceedings (Anchorage, Alaska, USA)* 1573, pp 179-186
[14]   Ganni V and Knudsen P 2010 *Advances in Cryogenic Engineering, AIP Conference Proceedings (Tucson, AZ, USA)* 1218 pp 1057-1071
[15]   Ganni V 2009 *Proceeding of PAC09 (Vancouver, BC, Canada)* pp 1931-1935
[16]   Arenius D, Ganni V, Creel J, Dixon K, Knudsen P and Wilson Jr. J 2006 *Cryogenic operation workshop 2006, Presentation, (Stanford Linear Accelerator Center, Standford, California, USA)*

[17]   Klein S and Nellis G 2012 *Thermaldynamics*, (New York: Cambridge University Press)
[18]   Kreith F 2000 *The CRC handbook of thermal engineering*, (Boca Raton: CRC Press LLC)
[19]   Wagner U 2002 *CERN accelerator school (CAS), superconductivity and cryogenics for accelerators and detectors (Erice, Italy)*
[20]   Jacob Thoma R, Ghosh P and Chowdhury K 2012 *Energy* **37** 207
[21]   Jacob Thoma R, Ghosh P and Chowdhury K 2011 *Cryogenics* **51** 287