Beamline for European Materials Engineering Research /BEER/

proposed for construction at European Spallation Source in Lund, Sweden

European economy has always been based on technological progress and innovations supported by continuous improvement of engineering materials. From advanced high strength steels for more fuel-efficient lightweight cars or high temperature superalloys for aerospace engines (Fig. 1) to smart materials for novel sensors and actuators or life-saving medical implants, engineering materials are fundamental to most technology breakthroughs. Remaining globally competitive in future will require ***increasingly rapid innovations in material engineering area – particularly, shortening the time needed to discover, develop and deploy new engineering materials to the market***. To achieve that goal, Europe needs to continuously invest into the entire engineering materials value chain – covering material discovery, design, processing, testing, optimization and production. Only such policy will allow us dealing successfully with urgent societal challenges related to energy, renewables, climate changes, health care or job security.

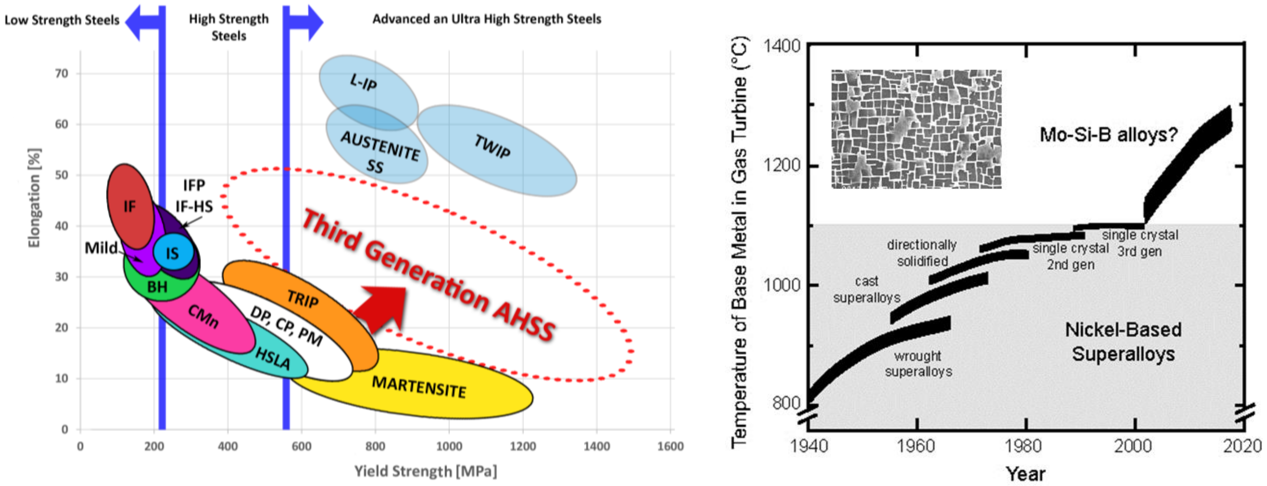


Fig. 1 *Advanced high strength steels demanded by the evergrowing car industry (left) and trend in the development of superalloys used extensively in the hottest parts of the gas turbine engines of airplanes (right).*

Neutron diffraction has already become a well-established method for characterization of internal stresses, textures and deformation processes in bulk engineering materials. Dedicated engineering beamlines exist at most large scale neutron facilities worldwide. ***European Spallation Source /ESS/, presently under construction in Lund, Sweden,*** will operate the world's most powerful neutron spallation source (Fig. 2). ESS beamlines will bring new opportunities for researchers in the fields of life sciences, energy, environmental technology, cultural heritage, fundamental physics and materials engineering. Building a dedicated engineering beamline at ESS thus represents a unique opportunity to make a major and very effective step towards increasing the competitiveness of the material engineering research in Europe.

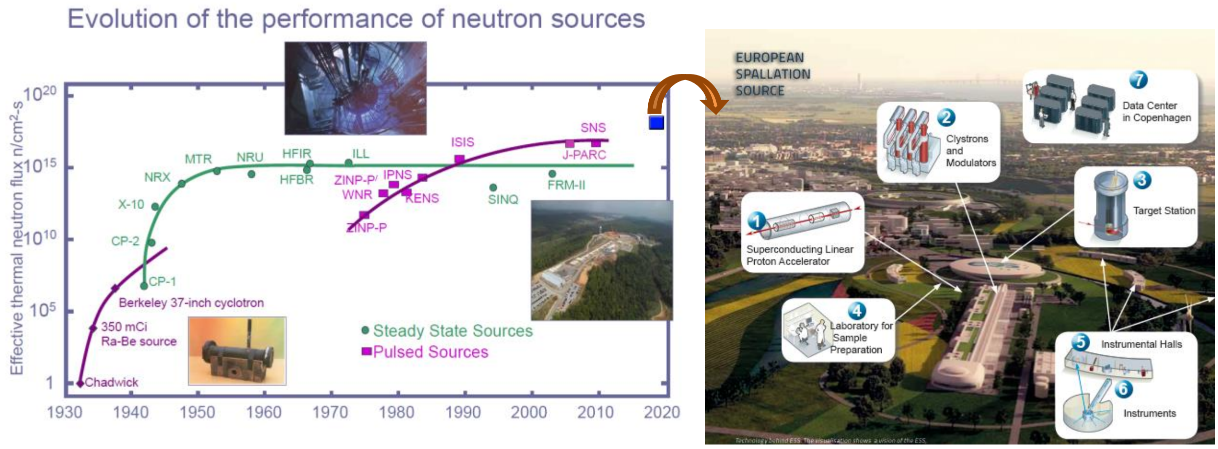
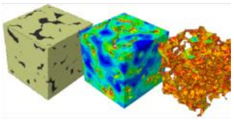


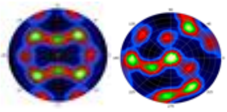
Fig. 2 *European Spallation Source /ESS/ to be built in Lund, Sweden till 2020,* http://europeanspallationsource.se/

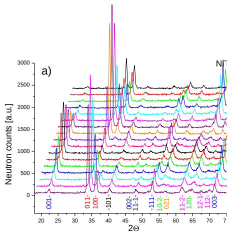
The vision behind the proposal for construction of the dedicated material engineering beamline at ESS (***Beamline for European Material Engineering Research /BEER/***) is to extend the current scope of engineering diffraction research towards the material engineering and metallurgy area by:

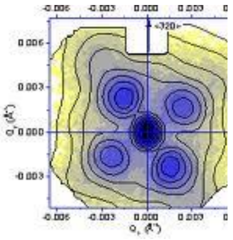
i) ***adopting state of art technologies*** for efficient and precise characterization of residual stress and texture of engineering materials and in-situ studies during material deformation by neutron diffraction,
ii) ***developing new strategies*** for time-resolved in-situ investigations of engineering materials under extreme thermomechanical loading conditions used in production, processing and/or testing,
iii) ***providing space for innovative in-situ neutron diffraction studies*** during long time testing of engineering materials and for unique experiments on user-defined sample environments.

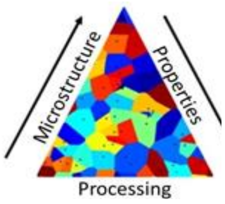
Sciencewise, the novelty is mainly related with the targeted ***in-situ processing experiments*** (ii) promising material engineers a new opportunity to follow nondestructively evolution of microstructure, texture and internal stress in engineering materials exposed to high temperatures, stresses, fast loading/heating/cooling and complex thermomechanical loads. Under such conditions, microstructure of engineering materials becomes unstable due to thermally activated processes, such as diffusional transformations, creep, recovery, recrystallization, grain growth, precipitation, melting or solidification. These processes have their intrinsic kinetics (independent from the rates of external forces) varying from milliseconds to days and hence their progress is only partially controlled by the externally applied forces. Neutron diffraction studies focusing such phenomena were already performed on state of art neutron diffractometers and reported in the literature. However, since it is difficult to keep microstructure, temperature and stress in large samples to be homogeneous in space and constant in time while collecting the diffracted neutrons, reports in the literature are relatively scarce. Significant shortening of the measurement time and installation of dedicated sample environment on neutron diffractometers are needed to carry out these in-situ processing experiments.











Since the expected outcome of the in-situ neutron diffraction studies consists mainly in gathering comprehensive information on the material microstructures evolving during the production/processing/testing, the diffractometer has been designed as an ***in-situ multidetector engineering instrument*** (Fig. 3), allowing for application of other methods simultaneously with the diffraction. Particularly, small angle neutron scattering /SANS/ will be used for detection and analysis of the kinetics of nanoscale precipitation and neutron imaging will be employed for detection of sample inhomogeneities, texture or strain mapping. Partial information on texture evolution during material processing and testing will be reconstructed from TOF diffraction patterns recorded simultaneously by multiple detectors. This concept of next generation engineering diffractometer will require to develop novel methods for reconstruction of the targeted microstructural information from the in-situ recorded neutron data from the TOF, SANS and/or imaging detectors. It is planned that inverse microstructure model fitting will be employed to analyze large throughput neutron data from multiple detectors. It shall be noted that the microstructural information (phase fractions, grain size, texture, internal stress, precipitates, defects etc.) will be deduced from neutrons passing through the large sample volume during a very short time. This information, although it won't be so easily visualized as the images from electron microscopes, might be equally as rich. The key point, however, is that, on the BEER diffractometer, the microstructural information will be collected from bulk samples exposed to precisely defined high temperature, stress and processing history – i.e. it will be linked to well defined but potentially fast varying external variables. Such true in-situ studies can be hardly accomplished in an electron microscope. Obviously, a microstructure evolution model of the material will be central to the analysis of such in-situ neutron data and material modelling will thus be deeply integrated into the BEER research. The vision of the proposers is that the in-situ neutron results from BEER will be used by material engineers to improve our understanding of novel engineering materials, particularly to speeding up the determination of microstructure-processing-property relations, facilitating the development of multiscale models of material deformation and, ultimately, ***making thus the development of engineering materials much faster and cost effective.***

The design of the BEER diffractometer exploits as much as possible the high brilliance of the long-pulse ESS source (Fig. 3) offering very high flux on a sample which exceeds by an order of magnitude the flux achievable by any existing instruments of similar type. Ultimately, it should be possible to make ***neutron diffraction measurements within a single neutron pulse***. It will become possible to follow fast processes in engineering materials with an unprecedented data acquisition time of 3-70 ms depending on the width of the wavelength band and repetition rate of 14 Hz. This is needed to meet the challenges related with the planned in-situ processing studies. On the other hand, the long pulse, does not allow for sufficient Δd/d resolution needed for most of the diffraction studies. This is solved by introducing dedicated neutron optics and chopper system, which permit to adjust the measurement time, intensity and resolution in a very broad range, ***yielding the instrument a versatility*** that cannot be realized at other neutron sources. Taking advantage of the possibility to extract both cold and thermal neutrons and using appropriate chopper system, it will be possible to perform ***SANS experiments simultaneously with diffraction***.

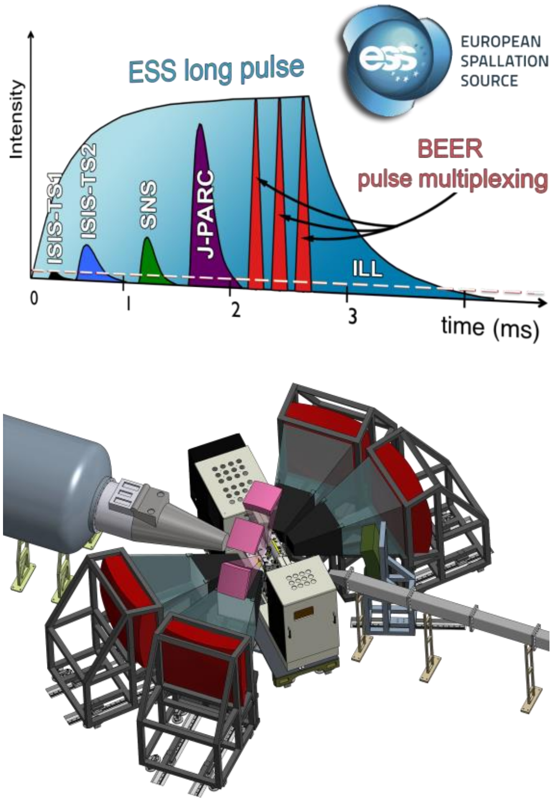


Fig. 3 *Long-pulse of ESS compared to other neutron sources (top) and BEER diffractometer hosting suit of detectors for TOF diffraction and SANS with Gleeble simulator for in-situ thermo-mechanical experiments (bottom).*

Besides conventional in-situ diffraction, the diffractometer will be operated in special modes as continuous measurement without stopping the imposed external loads for detection of neutrons, simultaneous diffraction and SANS or special high resolution mode for mapping residual strains from precisely defined peak positions or determination of micro-strains from peak profile analysis. The special high resolution mode will be achieved by introducing a ***pulse multiplexing technique*** consisting in extracting several short pulses out of the long ESS pulse (Fig.3) by a modulation chopper and increasing thus the diffracted intensity while maintaining the high resolution. This technique will enable performing high resolution strain scanning about 10-times faster compared to what can be achieved today on state of art engineering instruments. The key innovations proposed for neutron optics of the ESS engineering diffractometer thus consist in: 1) wide detector coverage, 2) TOF diffraction with unprecedented versatility in trading resolution for intensity, 3) opportunity of single pulse measurements, 4) pulse multiplexing and 5) simultaneous diffraction and SANS/imaging.

Following the vision of novel in-situ experiments during processing of engineering materials, special sample environments ***(Gleeble simulator (Fig. 4), advanced thermomechanical loading rigs, quenching dilatometer Bahr)*** capable of bringing large bulk engineering material samples to well-defined homogeneous material states by imposing controlled sequences of mechanical and thermal loads featuring high deformation rates, high heating/cooling rates and complex loading histories, will be first ever installed on a neutron beamline. These sample environments will make it possible to perform the targeted in-situ processing experiments simulating real industrial processing of engineering materials on the neutron diffractometer. In such experiments, evolution of microstructure, texture and residual stress during processing of engineering materials will be focused and related to materials performance. Alternatively, the experiments will also help to optimize the large scale industrial processing technologies.

Fig. 4 *Mobile Conversion Units of the Gleeble simulator capable of running high speed thermomechanical loading tests at high temperature that simulate the conditions engineering materials are exposed to in large scale industrial processing.*

There is, however, more sophisticated sample environments planned for the BEER. Robotic technologies and laser tracking systems (Fig. 5) will be used for sample handling and positioning in ***fully automated strain scanning and texture experiments***. A commercial six-axes-robot is already used by HZG on the diffractometer STRESS-SPEC at FRM II facility for routine texture measurements. Major advantages of robotic technologies, in addition to the obvious benefits of the automated sample handling, is that large samples, that do not fit into an Euler cradle, can be handled. Moreover, furnaces or even stress rigs can be positioned by the robot. Introduction of the robotic technologies, together with the high flux and dedicated neutron optics, will ensure efficient use of the neutron beam time.

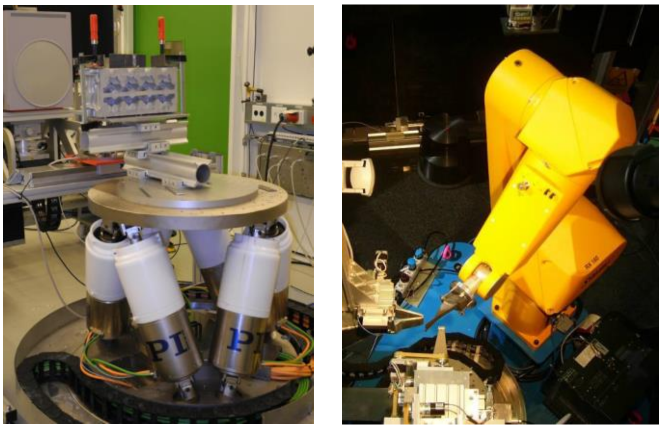


Fig. 5 *Hexapod sample positioner (left) used on the HEMS beamline at synchrotron DESY and Stäubli-6-axis robotic arm (right) used on the STRESS-SPEC at FRM II reactor for strain scanning and texture experiments (payload 30 kg).*

There will be special beamline regimes for:

i) ***long time off-beam testing*** of engineering materials with occasional neutron diffraction measurements enabling first ever to investigate microstructure evolution during long time testing of engineering materials by neutrons.

ii) ***in-operandi experiments on user defined sample environment***, as e.g., friction stir welding or laser beam welding machines (Fig. 6) enabling to apply neutron methods directly during processing of engineering materials.

These experiments will be telling us how microstructure evolution during long time testing correlates with their lifetime to failure in service, what kind of microstructure and internal stress form during advanced processing (Fig. 6) and how it is distributed within the affected volume of the processed engineering materials, respectively.

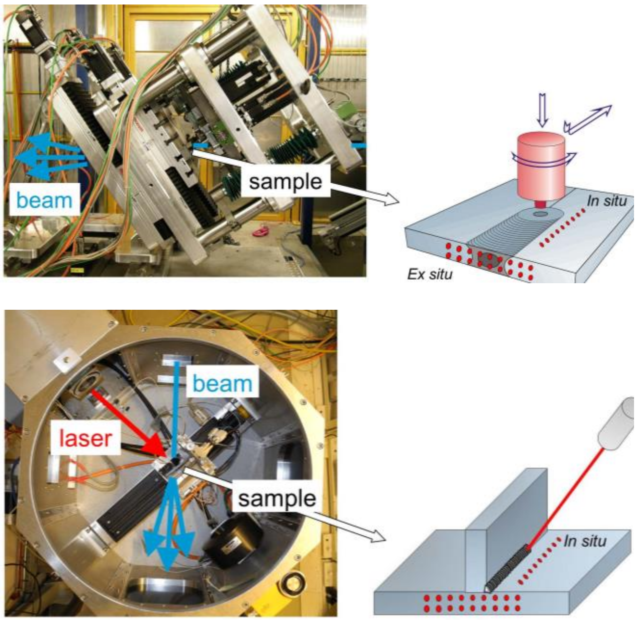


Fig. 6 *Small scale Friction Stir Welding (top) and Laser Welding (bottom) machines operated by HZG on high-energy synchrotron X-ray beamline HARWI II at synchrotron DESY in Hamburg, Germany.*

Meanwhile, high energy synchrotron X-rays are already used to follow very fast kinetic processes in engineering materials and/or scan engineering materials with much higher spatial resolution. Synchrotron X-rays are, however, are not suitable for probing large grain size engineering materials in bulk volumes. Further complementarities in application of X-rays and neutrons to engineering problems consist in different scattering power of various elements, scattering geometry and magnetic scattering of neutrons. It is anticipated that similarly oriented material engineering beamlines will be built at high energy synchrotron X-ray sources and that a ***single user community will use both energetic X-rays and neutrons for doing this kind of engineering research***.

Due to the newly introduced science, high neutron flux, novel neutron optics and special sample environments, the material engineering beamline at ESS will be unique among the worldwide neutron engineering instruments when commissioned around 2020. It will open new research opportunities for the existing engineering diffraction community and will enlarge this community significantly towards the very broad metallurgy area attracting new users and industrial customers to ESS. When the user program will start in 2023, ***BEER shall become the key instrument for advanced materials engineering research by neutrons***.

The beamline BEER has been proposed for construction at ESS in Czech-German collaboration by teams from the Nuclear Physics Institute of the ASCR, Czech Republic and Helmholtz-Zentrum Geeshacht, Germany.