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KSTAR ACHIEVED THIRTY-SECOND-LONG PLASMA OPERATIONS AT ION TEMPERATURES OF 100 MILLION °C

KSTAR demonstrated the world-leading technology for continuous fusion plasma operation

The Korean artificial sun, the Korea Superconducting Tokamak Advanced Research device (KSTAR), broke its world record for continuous plasma operation by maintaining a plasma ion temperature of over one hundred million degrees Celsius for thirty seconds.

On November 22, the KSTAR Research Center at the Korea Institute of Fusion Energy (KFE) announced that during the 2021 campaign it had succeeded in in accomplishing this important performance goal.

WHAT'S INSIDE THIS ISSUE:

Fusion technology continues to gain attention as a method of generating clean, carbon-free energy from fusion reactions, which is the same mechanism that generates solar energy inside the Sun. The Sun's extreme density and temperature can sustain those fusion reactions. But on the Earth, maintaining the proper conditions for fusion requires special fusion devices. These systems turn hydrogen isotopes into a plasma state, where electrons are separated from the hydrogen ions. For this to occur continuously, the plasma temperatures inside the fusion device must be maintained at over one hundred million degrees C.

KSTAR has been conducting experiments since 2008, to develop advanced technologies for the continuous operation of the super-hot plasma. In 2018, KSTAR achieved plasma ion temperatures exceeding one hundred million degrees. In 2020, it operated such super-hot plasmas for twenty seconds, which was then the longest operating time in the history of fusion research. With the new record-extending ten seconds, KSTAR has achieved another world-class milestone.

Great advances in KSTAR's heating systems and plasma control technologies, which are based on optimized magnetic field conditions, have contributed to increase plasma stabilities in the Internal Transport Barrier (ITB) Mode for fusion reactor operations.

Now KSTAR is planning to improve its power supply systems and install a new tungsten divertor to further prolong operating time. The tungsten divertor is expected to help suppress increases in tokamak wall temperature during the long periods of operation. Researchers will also explore ways to further increase the stability of the ITB Mode, using several measures including real-time feedback control technologies. The KSTAR's planned goal is to operate for three hundred seconds at one hundred million degrees by 2026.

"The Korea Institute of Fusion Energy (KFE) was established as an independent research institute, a legal entity in 2020, to enable more pioneering fusion research with a more stable research environment," commented Dr. Suk Jae Yoo, President of KFE. "We will strive to contribute to the national energy goals by securing the core fusion technologies in time," he added.

KSTAR control room

2021 KSTAR HIGHLIGHTS & INTERVIEWS

WHAT THIRTY SECONDS OF KSTAR MEANS

On its 30,127th shot, KSTAR successfully achieved thirty-second-long continuous operation at plasma ion temperatures of over one hundred million degrees. Since its first operation at such high temperature in 2018, there have been a series of new operating records: eight seconds in 2019 and twenty seconds in 2020. The record in 2021 was 1.5 times longer than the previous one.

“The thirty-second-long continuous operation was made possible, thanks to the team's efforts to prove the proposed pioneering plasma operation method. Now, our superconducting fusion device (KSTAR) has a shot at continuous operation at temperatures above one hundred million degrees, both physically and from an engineering viewpoint. Continuous operation at one hundred million degrees is the prerequisite for fusion energy,” commented Dr. Hyunsun Han from KFE's Advanced Operation Scenario Research Team.

KSTAR sustains these core plasma temperatures of more than one hundred million degrees using an Internal Transport Barrier (ITB) mode, which is known to be one of the most advanced plasma operation modes. In 2021, researchers struggled with some unexpected phenomena while sustaining the ITB mode. The limited KSTAR operation time for their subject put more pressure on them.

“We had high hopes because we had already achieved continuous operation for twenty seconds the year before. However, sustaining the plasma for thirty seconds was significantly different from doing so for twenty seconds.”

The researchers eventually found the solution by increasing the strength of the magnetic field, breaking the record. Yet a few regrets remained. According to Dr. Han, the solution is not yet optimum, because more resources are required to enhance the magnetic field. They will keep researching to find the optimal condition for economic energy generation.

HIGH BETA OPERATION FOR TWELVE SECONDS

KSTAR achieved twelve seconds of continuous high beta operation in 2021. Beta is a parameter involving ion temperature, ion density, and long-time confinement. The three features are the basic conditions for fusion energy generation. The beta value provides a measure of the fusion devices' performance in an objective, comparable number. The higher and longer the beta number, the better the energy confinement performance.

“There are various types of fusion devices globally, including superconducting based devices like the KSTAR in Korea, the EAST in China, and the JT-60SA in Japan. Each differs in size and material, not to mention the magnitude and layout of magnetic fields. We can use the beta value to compare their performances. It shows the efficiency of each device by calculating the energy it confined per the strength of the magnetic field,” explained Dr. Jisung Kang, who has been carrying out KSTAR beta research at KFE.

He added that improving the energy confinement of fusion devices is one of the most crucial issues currently being discussed by the fusion community. This is because fusion energy can be deployed onto the grid only when it is efficient enough to produce more energy than it consumes. Accordingly, besides the operating time at one hundred million degrees, recording a high beta value is one of the most important milestones in fusion research.

“As more air is blown into a balloon, the risk of it bursting goes up. If we say the magnetic field is like the strength of the balloon, the air inside can be compared to the plasma. The tension between the magnetic field and the plasma inside inherently causes instabilities. One bad move disrupts the plasma like a bursting balloon. Or at best it drops the plasma performance. The high beta study is designed to find operating scenarios that can overcome such instabilities and strike a balance between the magnetic field and the plasma.”

According to him, maximum heating does not necessarily lead to maximum plasma reaction nor the best confinement performance. Therefore, it is crucial to find a scenario that can balance them while increasing the beta value. There are roughly four factors involved: when to heat, what to heat with, how much fuel to use, and when to optimize the plasma magnetic structure. The optimal combination is never easy to find because even a millisecond difference can produce a different result. At the same time, physical and engineering problems such as magnetic field optimization and impurity scrapping from plasma interaction materials are waiting to be solved.

The twelve-second record shows how KSTAR researchers have painstakingly managed the critical factors one by one. The record more than doubled the five-second record set in 2020. Dr. Kang attributed the recent success to the new Neutral Beam Injection facility introduced in 2021.

A NEW WAY TO CONTROL THE ELM

In 2021, KSTAR introduced a new real-time method to control edge localized mode (ELM) which is considered to be one of the main unresolved problems in fusion research. Through international joint research with the U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory (PPPL), researchers discovered a new physical property of the ELM suppression by resonant magnetic perturbation (RMP).

“The conventional way to control ELM using the RMP is highly effective but is typically offset by lower plasma performance. However, in the 2021 KSTAR experiments, it was found that RMP can actually improve plasma performance, which is quite contrary to the conventional belief, by controlling effectively the magnitude and structure of the three-dimensional magnetic field in real-time. Furthermore, we succeeded in maintaining ELM control in high-performance plasma for twenty-five seconds.” Dr. Gunyoung Park, who is leading the KSTAR 3D Field physics working group, explained the result. “Our discovery of the new physics phenomenon will serve as a stepping stone for real-time control of ELMs for long pulses.”

Based on this collaborative research, Dr. Sang Kyeun Kim of PPPL was invited to give a talk at the 63rd annual meeting of the American Physical Society (APS) Division of Plasma Physics regarding the real-time adaptive ELM control and received much attention from many fusion researchers attending across the world.

Meanwhile, it is also notable that Artificial Intelligence (AI) technology - machine learning - was newly employed during the 2021 KSTAR campaign in ELM research.

The new approach was suggested by a young researcher, Dr. Giwook Shin, who is also a member of the KSTAR 3D Field physics working group.

"In general, an ELM and its crash event are followed by strong heat and energy flows which can cause irreparable damage to the internal components of the fusion device. That is why the main focus of research until now was on minimizing the damage by applying the RMP only after the ELM-crash. However, in my approach, I tried taking preemptive measures using AI before the ELM happens."

Dr. Shin developed an AI algorithm that was applied to the KSTAR PCS (plasma control system) in 2021 and then demonstrated to be effective through actual experiments. When the AI gives a heads-up just before the ELM happens, researchers can apply the RMP preemptively to prevent the ELM-crash.

Up to now, the strength of the RMP needs to be preset before and has the limitation of being maintained throughout each plasma plasma experiment. That is why researchers expect having real-time ELM control with preemptive measures to be important for a future fusion plant that should run for twenty-four hours.

Beginning 2022, Dr. Park and Dr. Shin have already set their next goal: "We will extend the ELM-suppressed H-mode operating time to more than forty seconds based on the ELM control methods that we have learned, including the real-time ELM control method from the PPPL collaboration, and the preemptive RMP methods utilizing the AI technology. Hope we can suggest a new direction for the fusion community as well as for the ITER."

While announcing these highlights, new challenges for the KSTAR researchers have already begun. The 2022 campaign will start earlier than ever, with a tungsten divertor upgrade planned. More pioneering research is to come.

Recent Research

BURNING WASTE TO GENERATE ENERGY: PLASMA PYROLYSIS GASIFICATION TECHNOLOGY

From semi-conductors to agriculture, plasma technology has known no boundaries. Now, plasma is being exploited for waste disposal. In the Institute of Plasma Technology located in Gunsan, Dr. Ji Hun Kim is developing plasma pyrolysis gasification technology. It incinerates waste while generating energy using the synthetic gas produced from pyrolysis.

Dr. Ji Hun Kim of Institute of Plasma Technology

Plasma pyrolysis gasification is a technology for incinerating waste using plasma hotter than ten thousand degrees. Through pyrolysis, the plasma gasifies the organic part of the waste into hydrogen, carbon monoxide, etc, and melts the inorganic part into slag, or leaves nothing due to complete thermal decomposition at temperatures as hot as fourteen hundred degrees.

Waste plasma gasification device

Other than burnt ashes and slag the technology is inherently free of toxic gas emissions or secondary contamination. The slags can even be used in construction sites. Unlike traditional incineration technology, it can also process fiberglass, complex flame retardants, asbestos, and medical wastes. The amount of pyrolysis gas is small in volume, significantly decreasing the size of the gas purification facility and almost halving the whole size of the incinerator.

In addition, it can purify gas emitted during processing and recycle it into clean hydrogen. It can also be used to fuel a gas turbine or a steam turbine. In case of the latter, it is even applicable to a high temperature and high-pressure boiler, making the energy generation more efficient by up to 20~30%. It is also possible to generate energy in a fuel cell by gasifying the high calorific waste.

Economic and efficient

While the KFE in Daejeon is working on fusion energy research, the Institute of Plasma Technology in Gunsan is pioneering applied research to contribute to industry and the environment. The Environmental Technology Research Team, which Dr. Kim is part of, established the plasma pyrolysis facility in 2014 to study plasma gasification and has since been accumulating data. Since 2018, it has researched and developed innovative technologies that will fundamentally change daily waste problems.

“The only disadvantage of the technology is that this type of facility consumes a lot of electricity when using plasma, and involves expensive construction. In other words, the costs outnumbered the benefits, making it difficult to enter the waste management market which mostly consisted of small-to-medium-sized businesses. In 2016, for example, Alter-NRG, a British company, failed in its attempt to commercialize plasma waste processing technology at a scale of 1,100 tons per day. Since then, research on plasma waste processing technology has been stagnant across the world as well as commercialization.” said Dr. Kim.

Nevertheless, the tide is now changing in the waste management market. Thanks to recent progress in fuel cell and plasma technology, the underlying technology has advanced so that energy generation has been made possible using synthetic gas from waste incineration. Government and industry are showing interest as they have been suffering with waste management issues.

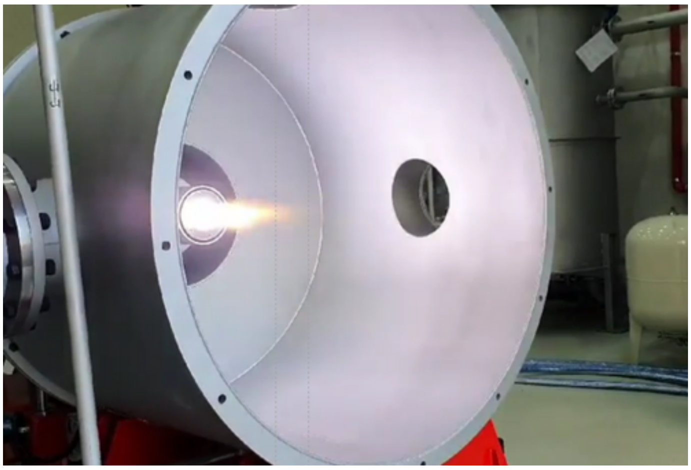
From March to July 2021, the Institute of Plasma Technology developed an economic model with the KOSPO (Korea Southern Power Co.), which will serve as the foundation for clean plasma energy development. The study conducted a cost-benefit analysis based on the assumption the facility can manage seventy tons of waste per day. It comprehensively included the process of waste burnt and gasified by the plasma and then supplied to a fuel cell, evaluating the energy generated and the cost of waste processing. It turned out that the technology has a solid basis for commercialization.

The first clean energy challenge begins at Ulsan

On August 31, an MOU was concluded between KFE, KOSPO, Ulsan Metropolitan City, GS Engineering & Construction, SK ecoplant, and SK securities. They aim to generate clean energy using the plasma, making clean hydrogen out of vinyl and the plastic parts of disposable goods.

The KOSPO, the leader of the consortium, plans to start plant construction in Ulsan in 2022 and finish by December 2024. The KFE is responsible for the plasma gasification technology, while the SK ecoplant and GS Engineering & Construction will take care of the fuel cell application and gasification plant construction, respectively. The plant will go through a trial run in 2022 and then be commissioned in 2024.

The key to the plasma pyrolysis gasification technology lies in the massive plasma torch which heats and sustains the pyrolysis reactor's temperature of over fourteen hundred degrees. KFE is developing the pyrolysis reactor, including a massive torch. The new torch's capacity will be 500KW which is almost twenty times larger than conventional ones. Once the plant is commissioned in 2024, seventy tons of waste will be used to generate 16MW of electricity per day - the amount that thirty thousand households consume a day.



500kW plasma torch

“By combining plasma technology with fuel cell application technology, recycling waste into energy becomes possible. We will try to make the plasma-fuel cell collaboration project the ultimate alternative for waste management businesses, and seek possible export opportunities,” commented Dr. Kim.

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